Precision Measurements of the Top Quark Pair Production Cross Section in the Single Lepton Channel with the ATLAS Experiment

Dissertation

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Greet me with banners and balloons
And my hard drive smashed to pieces
Nothing left for me to say when I write my master's thesis
It's all gonna change when I write my master's thesis

*John K. Samson, When I write my master's thesis,
Provincial, 2012*

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Introduction

A new era in the field of particle physics started on March 30th 2010, when proton beams at the Large Hadron Collider (LHC) at CERN were collided at collision energies of 7 TeV for the first time. Building and operating such a unique and advanced machine is an impressive success and display of the technological progress itself. Furthermore, the collisions provide access to an unexplored energy regime and are studied at the two multi-purpose detectors ATLAS and CMS and the more specific experimental setups LHCb and ALICE.

In the world of particle physics, higher energies correspond to smaller scales. Being able to look closer into the fundamental laws of nature will hopefully allow us to satisfy Goethe's Faust's urge to know *'was die Welt im Innersten zusammen hält'* better. The hunt for the fundamental constituents of matter and their interactions is an ancient question, but answering this question only gained speed since the middle of the last century, when technological progress first allowed to actually look for these particles in high energy particle collisions. Currently, the Standard Model of Particle Physics (SM) serves as the most precise description of point-like particles – quarks and leptons – and their interactions through gauge bosons. But as successful as the Standard Model has been so far, as limited is it when reaching higher energies. The last missing piece of the Standard Model, the Higgs boson as manifestation of the mass generating mechanism, is still to be found at the LHC. The allowed mass range is shrinking and will be fully covered once the data taken by the LHC experiments in 2012 is analyzed. Whether it is found or not, the Standard Model is only able to explain the existence of visible matter – covering merely 5% of all matter in the universe. At extremely small scales gravity will become as influential as the other three fundamental forces, electromagnetism, the weak and the strong force, but cannot be described in the context of the SM. Furthermore, even the three forces included cannot be united to an underlying structure at small scales, and the Standard Model is expected to break down as full source of explanations at the TeV scale, which is now reached in the collisions. Several theoretical ideas exist to either extend or replace the Standard Model and solve some or all of its problems, and new particles are expected to unveil the identity of such theories. However, no scent for new physics beyond the Standard Model has been found so far in the data taken and analyzed by the LHC experiments. In light of this, a deep and precise understanding of the Standard Model processes is crucial to understand and calibrate the detector performance, to develop advanced analysis techniques and to finally spot any tiny deviation hinting at new physics.

In this context, this work focusses on the heaviest quark in the Standard Model, the top quark. Of all quarks it was the latest to be discovered in 1995 at the Tevatron and takes up a special position, since in contrast to all other quarks it decays that fast, that no bound states of quarks containing top quarks can be formed. This feature allows to access information about the bare top quark itself through its decay products. Due to its large mass the coupling to the hypothetical Higgs boson is expected to be close to unity, which adds further information about the Higgs without detecting it directly. With the distinct signature of two top quarks decaying into a W boson and a b quark, the dominant production mechanism in proton–proton collisions, top quark pair production, forms an important background for many searches of the Higgs boson and new physics beyond the Standard Model. Hence, understanding and measuring the top quark pair production cross section to greatest precision not only allows to further test the predictions of the Standard Model in perturbative QCD calculations, but also reduces a significant source of uncertainty for many searches. Once the set of events containing top quarks is well understood, its characteristic quantities can be measured and models for physics beyond the SM that involve couplings to top quarks or similar final states can be surveyed.

Precision measurements of the top quark pair production cross section will be presented, exploiting the large amount of data taken by the ATLAS experiment in the years 2010 and 2011. Novel and advanced techniques, such as a multivariate discriminant, the full usage of a b -jet identification algorithm output distribution or the profile likelihood technique to further constrain sources of systematic uncertainties are utilized in two consecutive measurements and an outlook is given to extend the methodology for future measurements.

The thesis is organized as follows: Chapter 2 gives an overview over the current theoretical understanding of the world of particle physics with an emphasis on top quark physics and an overview of current predictions and measurements of top quark pair production. It is followed by chapter 3, introducing the experimental setup at the Large Hadron Collider and the ATLAS experiment. Chapter 4 defines the different physics objects under investigation and shows several studies to measure the performance of the object reconstruction. Furthermore, the signal and background processes are discussed together with the techniques to obtain an appropriate description of such. The general strategy of the analyses presented in this work is the topic of chapter 5, introducing all necessary tools and techniques. Two subsequent measurements of the top quark pair production cross section in the single lepton channel are presented with 35 pb^{-1} of data and 0.7 fb^{-1} of data in chapters 6 and 7, respectively, before chapter 8 gives a short outlook to a possible extension of the presented measurements to a simultaneous measurement of the top quark decay branching ratio R_b and $\sigma_{t\bar{t}}$. The thesis is concluded in chapter 9.

In this work, the convention $\hbar = c = 1$ is applied and valid for all formulas and distributions. Masses, energies and momenta are therefore expressed in the unit of [eV], while length and time are expressed in the unit $[\frac{1}{\text{eV}}]$.

The Top Quark in the Context of the Standard Model

2.1. Introduction

The analyses presented in this thesis deal with measurements of the production of top quark pairs at the Large Hadron Collider, as predicted in the framework of the Standard Model of Particle Physics. The first part of this chapter will focus on the theoretical framework in general, while the second part will describe the production and properties of top quarks in more detail and give an overview of the current experimental knowledge of top quark production.

The Standard Model currently provides the best predictions and explanations for the behavior of elementary particles and their properties are measured to great precision in many experiments. No significant deviations from the theoretical predictions are observed so far. However, the Standard Model is limited to an energy up to the TeV-range and has several shortcomings to act as a complete *theory of everything*: It can only explain the visible matter, which makes up only 5% of the matter in the universe¹, it does not include gravity and cannot solve the hierarchy problem, there is no further unification of the forces, the missing Higgs boson is still not found, and more. Since the LHC now gives access to a new energy domain, where the Standard Model is expected to unveil its problems, new particles indicating the nature of an underlying theory with the Standard Model as low energy approximation are expected to be observed. Several theories are formulated to solve one or several of the problems, predicting different types of new particles and interactions to be observed at the LHC. The most prominent theories include supersymmetry, extra-dimensions and technicolor models.

¹while 23% are dark matter and the remaining 72% dark energy

2.2. The Standard Model Of Particle Physics

The Standard Model of Particle Physics, in the remainder referred to as Standard Model or SM, is currently the most precise theoretical framework to describe the world of elementary particles. Quantum Mechanics and Special Relativity are combined into a *Quantum Field Theory* to predict interactions and properties of the elementary particles. The Standard Model is based on the idea of combining local gauge symmetries, and leads to conservation laws according to the Noether Theorem. In such a local gauge symmetry, the field behaves invariant under a local gauge transformation $U(x)$,

$$\psi'(x) = U(x)\psi(x) = e^{ia(x)}\psi(x), \quad (2.1)$$

where $\psi(x)$ and $\psi'(x)$ are wave functions of the field satisfying the above equation.

The Standard Model combines the gauge group of a unification of electromagnetism (Quantum Electrodynamics or QED) and weak interactions with the one of Quantum Chromodynamics (QCD), the theory of strong interactions. The fourth fundamental force, gravity, is not included in the Standard Model, limiting its validity to energy scales at which gravity appears small compared to the other three interactions.

The theory predicts the elementary matter particles, six leptons and six quarks with their anti-particle partners, and the mediating gauge bosons for electroweak and strong interactions. In addition, the Standard Model includes a mass-generating mechanism: the Higgs field and its associated boson, the Higgs boson. While all other particles of the Standard Model are observed and well-measured, the Higgs boson remains yet undetected, although measurements at the LHC are continuously limiting the possible mass range for a SM Higgs boson and will shed light on its existence or non-existence in the near future.

The matter particles in the Standard Model, always expressed as fermion fields², can be grouped into leptons, shown in table 2.1 and quarks, shown in table 2.2, and occur in three generations or families with increasing masses. Each of the elementary matter particles has its own anti-particle with opposite quantum numbers, like charges, but the same mass.

Particle	Generation	Charge [e]	Mass	Interactions
$e^\pm$	1	± 1	511 keV	electromagnetic, weak
ν_e	1	0	< 2 eV	weak
$\mu^\pm$	2	± 1	105.7 MeV	electromagnetic, weak
ν_μ	2	0	< 2 eV	weak
$\tau^\pm$	3	± 1	1.78 GeV	electromagnetic, weak
ν_τ	3	0	< 2 eV	weak

Table 2.1.: Leptons and their properties in the Standard Model [1].

The gauge bosons, particles with spin 1, act as mediators of the interactions between the matter particles and are associated to the different interactions as listed in table 2.3.

²i.e. spin 1/2 particles

Particle	Generation	Charge [e]	Mass	Interactions
u	1	2/3	1.7–3.3 MeV	strong, electromagnetic, weak
d	1	-1/3	4.1–5.8 MeV	strong, electromagnetic, weak
c	2	2/3	1.27 GeV	strong, electromagnetic, weak
s	2	-1/3	101 MeV	strong, electromagnetic, weak
t	3	2/3	173.2 GeV	strong, electromagnetic, weak
b	3	-1/3	4.19 GeV	strong, electromagnetic, weak

Table 2.2.: Quarks and their properties in the Standard Model [1]. Quark masses are given in the $\overline{MS}$ scheme, except for the top quark mass, where the measured world average is quoted [2].

Gauge Boson	Interaction	Charge [e]	Isospin	Color	Mass
γ	electromagnetic	0	0	–	$< 6 \times 10^{-18}$ eV
$W^\pm$	weak	± 1	0	–	80.399 ± 0.023 GeV
Z^0	weak	0	1	–	91.1876 ± 0.0021 GeV
gluon	strong	0	0	8 combinations	0

Table 2.3.: Gauge bosons of the Standard Model and their associated interactions, charges and masses [1].

2.2.1. Electroweak Interactions and the Higgs Mechanism

Proposed by Glashow, Salam and Weinberg [3, 4, 5] in the 1960s, the theory of electroweak interactions unifies Quantum Electrodynamics with the theory of weak interactions. It combines the symmetry groups $SU(2)$ and $U(1)$ into a $SU(2) \otimes U(1)$ symmetry group. The Pauli-matrices, in the form of the weak isospin T , with $T_i = \frac{\tau_i}{2}$ (where $i = 1, 2, 3$), act as generators of the $SU(2)$ and the corresponding massless gauge fields W_μ^i . The Abelian $U(1)$ group is generated by the hypercharge³ $Y = 2(Q - T_3)$ and contains one massless gauge field B_μ .

Since left-handed⁴ fermions occur as doublets with isospin $T_3 \neq 0$, while right-handed fermions only appear as singlets with $T_3 = 0$, only the former transform under the $SU(2)$ symmetry. On the other hand, fermions of both helicity states transform under the $U(1)$ symmetry. Therefore, the interactions have to be described with separate Lagrangians and their covariant derivatives for both types of fermions:

$$D^\mu = \partial^\mu + ig \frac{\tau_i}{2} W_\mu^i + i \frac{g'}{2} Y B^\mu \quad (2.2)$$

for left-handed fermions and

$$D^\mu = \partial^\mu + i \frac{g'}{2} Y B^\mu \quad (2.3)$$

for right-handed fermions. The variables g and g' describe the coupling constants of the $SU(2)$ and $U(1)$, respectively.

³where Q denotes the electric charge and T_3 the third component of the weak isospin

⁴A massless fermion is identified as left-handed if the direction of motion and spin are opposite to each other, and as right-handed otherwise. For massive leptons the handedness is defined as the chirality, describing the behavior under right- and left-handed transformations.

From that, the gauge bosons can be derived as linear combinations of the gauge fields, where the *Weinberg-angle* θ_W ⁵ describes the mixing between the $SU(2)$ and $U(1)$. It is defined as

$$\sin \theta_W = \frac{g'}{\sqrt{g^2 + g'^2}} \quad (2.4)$$

and measured [1] to be

$$\sin^2 \theta_W = 0.23116 \pm 0.00013. \quad (2.5)$$

The Weinberg-angle also relates the electromagnetic charge to the coupling constants of the $U(1)$ and $SU(2)$

$$e = g \sin \theta_W = g' \cos \theta_W. \quad (2.6)$$

The neutral gauge bosons, mediating the neutral currents of electromagnetism and weak interactions, can then be written as

$$\gamma = A_\mu = W_\mu^3 \sin \theta_W + B_\mu \cos \theta_W \quad (2.7)$$

and

$$Z^0 = Z_\mu = W_\mu^3 \cos \theta_W - B_\mu \sin \theta_W. \quad (2.8)$$

Similarly, the charged bosons are expressed as

$$W^\pm = W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2), \quad (2.9)$$

associated to the $SU(2)$ symmetry of the combined symmetry.

In the model of electroweak interactions itself the gauge bosons γ , Z^0 and $W^\pm$ are massless itself, since they are linear combinations of massless gauge fields. The Lagrangian of this model can be written as

$$\mathcal{L}_{EW} = \psi_L^\dagger \gamma^\mu (i\partial_\mu - g \frac{\tau_i}{2} W_\mu^i - \frac{g'}{2} Y B_\mu) \psi_L + \psi_R^\dagger \gamma^\mu (i\partial_\mu - \frac{g'}{2} Y B_\mu) \psi_R - \frac{1}{4} W_{\mu\nu}^i W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}, \quad (2.10)$$

with the first two terms describing the interactions between particles, mediated by the gauge bosons, and the second two terms the interactions between the gauge fields themselves. The wave function ψ_L describes the behavior of a left-handed fermion doubled and the wave function ψ_R the behavior of a right-handed fermion singlet. The interactions between the gauge fields are expressed through

$$W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - ig \epsilon^{ijk} W_\mu^j W_\nu^k \quad (2.11)$$

and

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu. \quad (2.12)$$

While experimental verification for the existence of the gauge bosons exists, the $W^\pm$ and Z^0 bosons are found to have non-zero masses of the order of 100 GeV. This cannot be explained with the electroweak model alone, and the most popular and straight-forward extension is the addition of the Higgs field as an additional field [6, 7, 8, 9].

⁵also called the *weak mixing angle*

The new field should act invariantly under transformations of the $SU(2)$ of the electroweak theory and is constructed with hypercharge $Y = 1$ and weak isospin $T_3 = \frac{1}{2}$ as a doublet of two complex scalar fields, described as

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \quad (2.13)$$

This proposal adds an additional term to the Lagrangian of the Standard Model of the form

$$\mathcal{L}_{Higgs} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) + \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2. \quad (2.14)$$

The terms $\mu^2 \phi^\dagger \phi$ and $\lambda (\phi^\dagger \phi)^2$ resemble a potential $V(\phi^\dagger \phi)$, defined by the choice of the parameters μ and λ . If the parameters are chosen to be $\mu^2 < 0$ and $\lambda > 0$ the vacuum expectation value v of the potential is given by

$$v = \pm \sqrt{\frac{-\mu}{\lambda}}, \quad (2.15)$$

and one possible configuration is shown in figure ???. A non-zero vacuum expectation value is

Figure 2.1.: Axially symmetric Higgs potential $V(\phi)$ for the case $\phi_1 = \phi_2 = 0$ and $\phi_3 = v$, in the configuration $\mu^2 < 0$, $\lambda > 0$.

equivalent to spontaneous symmetry breaking around the minimum, which creates a real Goldstone boson, the Higgs boson, with a mass of $m_H = \sqrt{2}\mu$ and spin 0. In this extended version of the electroweak theory the gauge boson masses are expressed in terms of the vacuum expectation value with

$$m_W = \frac{1}{2}g v, \quad (2.16)$$

$$m_Z = \frac{1}{2}v\sqrt{g^2 + g'^2} \quad (2.17)$$

and

$$m_\gamma = 0. \quad (2.18)$$

These values are confirmed by experimental measurements, but the value of the parameter μ and thus the Higgs mass remain unknown. However, experimental tests at the LEP, Tevatron and, most recently,

the LHC experiments⁶ limit the allowed mass range for the Higgs boson in the SM significantly to $115.5 \text{ GeV} < m_H < 127 \text{ GeV}$ ⁷ [10, 11, 12, 13].

The Higgs mechanism does not only generate the masses of the mediating gauge bosons, but also the masses of the fermions, which couple to the Higgs field with the *Yukawa coupling* G_f and add another term $\mathcal{L}$ to the SM Lagrangian. The coupling constant G_f is then another parameter of the Standard Model, leading to fermion masses with

$$m_f = \frac{1}{\sqrt{2}} G_f v. \quad (2.19)$$

Since the top quark is the elementary matter particle with the highest mass, it consequently has the largest coupling to the Higgs field, $G_t \approx 1$. Precise knowledge of its mass, together with precise measurements of the W boson mass and many quantities in the electroweak sector, led to the best indirect predictions of the Higgs boson mass in a global electroweak fit.

Electroweak theory also describes the mixing of the weak eigenstates of quarks in the Cabibbo-Kobayashi-Maskawa-matrix (CKM matrix) [14, 15]. Flavor changing currents between quarks are only possible in weak interactions mediated by charge carrying W bosons. The weak eigenstates q' of the down-type quarks (charge $-\frac{1}{3}$) connect to their mass eigenstates with the unitary, diagonalizable CKM matrix V_{CKM} with

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (2.20)$$

The quark mixing parameters are experimentally well tested and constrained from global fits to many measurements in the electroweak sector of the SM but only valid under the above assumptions of three generations [1]:

$$V_{CKM} = \begin{pmatrix} 0.97428 \pm 0.00015 & 0.2253 \pm 0.0007 & 0.00347 \pm 0.00016 \\ 0.2252 \pm 0.0007 & 0.97345 \pm 0.00015 & 0.0410 \pm 0.0011 \\ 0.00862 \pm 0.00026 & 0.0403 \pm 0.0011 & 0.999152 \pm 0.00030 \end{pmatrix}. \quad (2.21)$$

2.2.2. Quantum Chromodynamics

Developed in the 1960s and early 1970s, Quantum Chromodynamics, or QCD, describes the world of strong interactions between quarks with a non-Abelian local gauge symmetry group $SU(3)$. The quantum number of the strong interaction is called *color* and occurs in three types, *red*, *green*, *blue*, and the respective anti-colors. The mediating gauge bosons are called *gluons* and are realized as an octet of linear combinations of the three color charges⁸. Only colorless bound states are invariant under transformations of the $SU(3)$, which means that bound states of quarks can only occur as

⁶ATLAS and CMS

⁷at 95% C.L.

⁸And a ninth combination as a color singlet, which is not realized in nature.

mesons in the $|q\bar{q}\rangle$ configuration and as *baryons* in either the $|qqq\rangle$ or $|\bar{q}\bar{q}\bar{q}\rangle$ configuration, with all color charges involved. Since bound states of quarks are experimentally observed, this additional part of the Standard Model is necessary. In a model based solely on the electroweak theory bound states of quarks could violate Pauli's principle, saying that fermions have to differ in at least one quantum number in a bound state system.

Another important feature of QCD is what is called *confinement*: Quarks, which always carry a single color charge, cannot appear as free particles, i.e. outside of bound states. As a consequence of this, when trying to separate quarks from one another it becomes energetically preferable to create another pair of quarks with opposite color charge from the vacuum, which then builds new bound states with the two initial quarks. When quarks are generated in high energy particle collisions they transform into *jets* of hadrons, and their decay products, due to this. The only exception is the top quark, which decays into a lighter quark and an additional W boson, before bound states can be formed. The generators of the $SU(3)$ symmetry group are the eight three-dimensional matrices, with $a = 1, \dots, 8$

$$T_a = \frac{1}{2}\lambda_a, \quad (2.22)$$

expressed in terms of the Gell-Mann matrices λ_a , analogous to the Pauli-matrices generating the $SU(2)$ of weak interactions. With these, the covariant derivative is written as

$$D_\mu = \partial_\mu + ig_s T_a G_\mu^a \quad (2.23)$$

with the gluon fields G_μ^a and the coupling constant g_s . This leads to the Lagrangian of Quantum Chromodynamics with the quark field ψ_q

$$\mathcal{L}_{QCD} = \bar{\psi}_q(i\gamma^\mu\partial_\mu - m)\psi_q - g_s\bar{\psi}_q\gamma^\mu T_a\psi_q G_\mu^a - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}. \quad (2.24)$$

The field strength tensors $G_{\mu\nu}^a$ include a term describing the self-interaction between the gauge bosons, since the gluons carry color charge⁹ and couple to the gauge field itself:

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f_{abc} G_\mu^b G_\nu^c. \quad (2.25)$$

The structure constant f_{abc} describes the relation between the generators of the $SU(3)$ via

$$[T_a, T_b] = if_{abc} T_c, \quad (2.26)$$

while the coupling constant g_s can be related to α_s as

$$\alpha_s = \frac{g_s^2}{4\pi}. \quad (2.27)$$

However, the coupling constant (or α_s) is not a constant but has to be defined in an energy-dependent way to account for divergences occurring from additional internal loops when trying to determine the color charge of a quark. Therefore, α_s has to be expressed as a function of an arbitrary energy scale

⁹unlike their massless equivalent in electroweak theory, the charge neutral photon γ

μ^2 . In the context of the Standard Model, a common scale $\Lambda_{QCD} \approx 200$ MeV is defined which allows to evaluate the coupling constant at an energy scale $Q > \Lambda_{QCD}$ with the formula

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f) \log \frac{Q^2}{\Lambda_{QCD}^2}} \quad (2.28)$$

in leading order. The parameter n_f describes the number of active quark types, denoted as f for flavor, i.e. $n_f = 6$ if $Q^2 \geq m_q^2$ is fulfilled for all six quarks of the Standard Model. For this configuration the theory of strong interactions in the SM is *asymptotically free*, meaning that quarks can be considered as *free* at small scales or high energies, since the value for $\alpha_s(Q^2)$ decreases for higher energies [16, 17, 18].

2.3. Top Quark Physics

As can be seen in table 2.2, the top quark is the heaviest of the quarks, significantly heavier than the other quark in its generation, the bottom quark. Once the bottom quark was experimentally discovered in 1977, the existence of a charge $\frac{2}{3}$ -quark in the third quark generation was well expected but could only be observed with the collision energies reached at the Tevatron collider. The top quark was the last quark discovered by both the CDF and DØ collaborations in 1995 [19, 20].

The top quark is special not only due to its large mass, but also due to its short lifetime. This means a *free* top quark produced in a collision decays before it hadronizes, i.e. there are no bound state hadrons made of top quarks. This allows to experimentally test the properties of the bare top quark itself through its decay products without diluting information in the hadronization process. As top quark properties are precisely predicted by the Standard Model, top quark physics provides a sensitive probe of the validity of the Standard Model and a tool to indirectly learn about the Higgs boson and to potentially discover physics beyond the Standard Model. Studying top quark physics is only possible in the data taken by the CDF and DØ experiments at the Tevatron accelerator and by the experiments at the LHC, which can be considered as a 'top quark factory' due to the high rate of top quark production. Theoretical predictions and an overview of recent experimental tests especially for top quark pair production, the topic of this thesis, are described in the remainder of this section.

2.3.1. Top Quark Production

At $p\bar{p}$ or pp colliders providing sufficient collision energies to create such particles of high mass, top quarks can be produced in pairs via the strong interaction and as single top quarks in electroweak processes. The most probable production mechanism is the simultaneous production of a top quark and an antitop quark. The electroweak production of a single top quark together with a bottom quark or a W boson is less likely. The production cross section for top quarks, both in pairs and as single quarks, is strongly dependent on the collision energy provided by the accelerator, as shown in figure ??, and the LHC experiments will acquire a large data set of events with top quarks. Studying these will open up a new field of precision measurements of the Standard Model, as W and Z physics

was at the Tevatron and LEP experiments and the processes involving top quarks have to be well understood before exploring less likely processes, such as Higgs physics or searches for new physics in similar final states.

Figure 2.2.: Cross sections of important physics processes at center-of-mass energies reached at the Tevatron and the LHC [21]. The vertical lines indicate the center-of-mass energy at the Tevatron during its RunII and the design center-of-mass energy at the LHC of $\sqrt{s} = 14$ TeV, which is currently operating at $\sqrt{s} = 7$ TeV. The top quark pair production cross section is denoted as σ_t , showing the production rate in $p\bar{p}$ collisions at lower energies, and in pp collisions at higher energies.

2.3.1.1. Top Quark Pair Production

Pairs of a top quark and an antitop quark can be produced in two ways, both shown in figure ??: gluon fusion and $q\bar{q}$ annihilation. While at the Tevatron collider, in $p\bar{p}$ collisions, $q\bar{q}$ annihilation

Figure 2.3.: Leading-order production mechanisms for top quark pairs at a pp -collider. At $\sqrt{s} = 7$ TeV the gluon fusion dominates over $q\bar{q}$ annihilation with a ratio of approximately 80:20.

was the dominating process, the ratio between the contributions of the two production mechanisms inverts at the LHC. This is due to two reasons: the higher center-of-mass energy and the fact, that proton-proton beams collide at the LHC. First of all, $q\bar{q}$ annihilation is disfavored in general at a pp collider compared to a $p\bar{p}$ collider. The antiquark has to be a sea quark in pp collisions, while in $p\bar{p}$ collisions it can be one of the valence quarks of the antiproton, which is more likely to occur at any center-of-mass energy. In addition, at the Tevatron the pair of top quarks is produced right at the threshold of $2m_t$, i.e. the partons participating in the collision have to carry a high fraction x of the proton's momentum. As seen in figure ?? for the CTEQ66 PDF set [22] used in the presented analyses, at high values of x the up and down valence quarks from the proton¹⁰ dominate, making $q\bar{q}$ annihilation more likely than gluon fusion at the Tevatron with $\sqrt{s} = 1.96$ TeV. At the higher center-of-mass energy of $\sqrt{s} = 7$ TeV partons with small fractions x are already able to produce top quark pairs. Since gluons dominate the parton distribution function of the proton up to high x , gluon fusion becomes the dominating process, even further by the non-existence of valence antiquarks in the LHC's pp collisions.

¹⁰or anti-up and anti-down valence quarks from the antiproton

Figure 2.4.: Parton distribution function for protons in the CTEQ66 PDF set [22] at $Q^2 = 100$ GeV [23].

While no complete calculation of the top quark pair production cross section higher than next-to-leading order (NLO) exists, several different theoretical calculations of the total top quark pair production cross section at the precision of approximate next-to-next-to-leading order (NNLO) are available. They use different techniques for the higher order approximations and will be briefly summarized here. The top quark pair production cross section, often denoted as $\sigma_{t\bar{t}}$, is dependent on the top quark mass and evaluated for values of m_t close to the world average top mass of $m_t = 173.2$ GeV, the value depending on the exact calculations. An overview of the current available NNLO predictions, as described in the following, is shown in figure ??.

Figure 2.5.: Different approximate NNLO predictions for top quark pair production at $\sqrt{s} = 7$ TeV in pp collisions, as described in the text.

Langenfeld, Moch, Uwer [24, 25]

The calculations considered as theoretical reference for the measurements presented in this work are performed at approximate NNLO by including several different terms, such as next-to-next-to-leading-logarithm (NNLL) enhancements at the threshold, corrections from Coulomb terms in two-loops and scale dependent terms at NNLO. The factorization and renormalization scales can be varied independently. The calculations are provided as a function of the top quark mass. The Hathor framework [26] allows to access the parametrizations and obtain the predicted cross sections for different mass points or center-of-mass energies. For a top quark mass of $m_t = 172.5$ GeV¹¹, renormalization and factorization scales of $\mu = m_t$ and the CTEQ66 PDF set, which is used within the context of the presented analyses¹², a top quark pair production cross section of

$$\sigma_{t\bar{t}} = 164.6^{+4.3}_{-9.3}(\text{scale})^{+7.2}_{-6.5}(\text{PDF}) \text{ pb} \quad (2.29)$$

is predicted. The scale uncertainties are derived by varying the renormalization and factorization scale by factors of 2 and 0.5, while the PDF uncertainties are obtained using the error set for the used PDF set.

Kidonakis [28]

Kidonakis applies two-loop soft anomalous dimension matrices for the resummation of soft-gluon corrections at NNLL. Renormalization and factorization scales are both set to $\mu = m_t$ in the calculations and the PDF set of MSTW2008NNLO [29] is used. At a top mass of $m_t = 173$ GeV, including uncertainties from scale variations with $\frac{1}{2} \leq \mu/m_t \leq 2$ and the PDF error set, the top pair production cross section in pp collisions is calculated to be

$$\sigma_{t\bar{t}} = 163^{+7}_{-5}(\text{scale})^{+9}_{-9}(\text{PDF}) \text{ pb.} \quad (2.30)$$

Ahrens et al. [30]

The calculations of Ahrens et al. are also based on NNLL resummations and use a combination of two approaches. One is based on an integration over the top quark pair invariant mass distribution, while the other one uses kinematic distributions of a single particle. Techniques from soft-collinear effective field theory are used in a resummation of threshold logarithms in NNLL, which become important when $m_{t\bar{t}}$ is close to the partonic center-of-mass energy $\sqrt{\hat{s}}$, i.e. the top quark pairs are produced at rest. Approximate NNLO results are then calculated for a fixed order in perturbation theory and matched to the available exact NLO calculations at the threshold. The total cross section is derived by integrating over the distribution of choice in both approaches and quoted as the average of the two, while the scale uncertainties take into account both scale variations and also differences in kinematic distributions. This approach yields

$$\sigma_{t\bar{t}} = 155^{+8}_{-9}(\text{scale})^{+8}_{-9}(\text{PDF}) \text{ pb,} \quad (2.31)$$

using the MSTW2008NNLO PDF set, assuming a top quark pole mass of $m_t = 173.1$ GeV and setting renormalization and factorization scales to $\mu = m_t$.

¹¹ $m_t = 172.5$ GeV is assumed for the Monte Carlo generated samples in the experimental analyses presented and hence the cross section is calculated accordingly.

¹²A similar calculation using the MSTW2008NNLO PDF set, which is better comparable to the other predictions, yields $\sigma_{t\bar{t}} = 165.8^{+4.4}_{-7.0}(\text{scale}) \pm 9.1(\text{PDF}) \text{ pb}$ [27].

Beneke et al. [31]

This calculation performs a resummation in NNLL accuracy, but includes terms from Coulomb enhancement, the exchange of virtual Coulomb gluons near the threshold as well as soft gluon radiation into the calculation. The calculation is done in the limit of top quark pair production at rest, i.e. $m_{t\bar{t}} \rightarrow \sqrt{s}$. With the choice of the factorization and renormalization scales to be $\mu = m_t$ and a top quark mass of $m_t = 173.3$ GeV and the MSTW2008NNLO PDF set, a total cross section for top quark pair production at the LHC for $\sqrt{s} = 7$ TeV is calculated to be

$$\sigma_{t\bar{t}} = 162.6^{+7.4}_{-7.6}(\text{scale})^{+15.4}_{-14.7}(\text{PDF}) \text{ pb.} \quad (2.32)$$

Cacciari et al. [32]

These studies match approximate NNLO calculations from reference [33] to leading logarithm accuracy at next-to-next-to-leading order. Soft-gluon resummation at NNLL is included using two-loop anomalous dimension matrices and find only small corrections to the central value and reduction of the systematic uncertainties compared to NLL approximations. Using factorization and renormalization scales of $\mu = m_t$, a top quark mass of $m_t = 173.3$ GeV and the MSTW2008NNLO PDF set yields

$$\sigma_{t\bar{t}} = 158.7^{+12.2}_{-13.5}(\text{scale})^{+4.3}_{-4.4}(\text{PDF}) \text{ pb} \quad (2.33)$$

for the LHC at $\sqrt{s} = 7$ TeV.

2.3.1.2. Single Top Quark Production

With smaller production rates, top quarks can also be produced as single quarks in electroweak interactions in pp and $p\bar{p}$ collisions. Three different mechanisms contribute to single top quark production and their leading-order Feynman diagrams are shown in figure ?? . The timelike production (s-channel) produces a bottom quark together with the single top quark, while in the spacelike production (t-channel) an additional, mostly light flavor, quark is produced. The third production mechanism is the production of a single top quark in association with an on-shell W boson (Wt-channel). The first observation of single top quark production was achieved by the Tevatron experiments CDF and DØ in 2009 [34, 35] and was only possible applying several multivariate analysis techniques due to the low cross sections of the processes and large backgrounds. In addition to measuring a quite rare process, the discovery of single top quark production also gives first direct access to the electroweak coupling of the top quark in form of the CKM-matrix element $|V_{tb}|$. While at $\sqrt{s} = 1.96$ TeV the Wt-channel has a negligible contribution to the combined single top quark production cross section, and the observation was made by combining s- and t-channel, the contributions from the three production mechanisms are significantly different at the LHC. The spacelike production dominates, with major additional contributions from the Wt-channel and only minor contribution from the timelike production.

Best theoretical predictions are given by approximate NNLO calculations from Kidonakis [36, 37, 38] and yield, at $\mu = m_t$ and $m_t = 172.5$ GeV with the MSTW2008NNLO PDF set, production cross sections of

$$\sigma_t = 64.57 \pm 1.33(\text{scale})^{+1.38}_{-0.68}(\text{PDF}) \text{ pb} \quad (2.34)$$

for the t-channel [36],

$$\sigma_t = 15.74 \pm 0.40(\text{scale})^{+0.66}_{-0.68}(\text{PDF}) \text{ pb} \quad (2.35)$$

Figure 2.6.: Leading-order production mechanisms for the production of single top quarks at a pp -collider. Inversed charge currents are of course possible in the same way.

for the Wt -channel [38] and

$$\sigma_t = 4.63 \pm 0.07(\text{scale})_{-0.10}^{+0.12}(\text{PDF}) \text{ pb} \quad (2.36)$$

for the s-channel [37]. In pp -collisions at the LHC the production of single top quarks dominates over the production of single antitop quarks in t- and s-channel production, corresponding to the charge asymmetry of W boson production, and the sum of both cross sections is given above. Uncertainties are obtained by varying factorization and renormalization scales between $\frac{1}{2}$ and 2 of their values and by the error set provided by the PDF of choice.

2.3.2. Top Quark Decay

While top quarks can be produced both in strong (top pairs) and electroweak (single top) interactions, the decay of a top quark always obeys the principles of electroweak theory. After its short lifetime of about 0.5×10^{-24} s, the top quark decays into a W boson and a down-type quark. The probability

for each type of the down-type quark to occur as decay product is given by the CKM matrix elements involving top quarks, see equation ???. Under the assumption of a unitary CKM matrix and three generations of quarks this means that top quarks decay almost uniquely into a W boson and a bottom quark ($t \rightarrow W^+ + b$ and $\bar{t} \rightarrow W^- + \bar{b}$), which can be also written in terms of branching ratios

$$R_b = \frac{\mathcal{BR}(t \rightarrow Wb)}{\mathcal{BR}(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} \approx 1 \quad (2.37)$$

and can be measured experimentally. If a deviation from the expected value for R_b is found, this would be a direct hint for an additional generation of quarks, i.e. the need to extend the CKM matrix, or processes involving top quark decays beyond the Standard Model. Measurements were performed using events with top quark pairs both at CDF [39], which measured $R_b > 0.61$ @ 95% C.L and $|V_{tb}| > 0.78$ @ 95% C.L, the latter under the assumption of a SM CKM matrix, in 160 pb^{-1} of data, and DØ [40]. The DØ measurement uses significantly more data, 5.4 fb^{-1} , and measures $R_b = 0.90 \pm 0.04$ and a Standard Model value for $|V_{tb}| = 0.95 \pm 0.02$ with statistical and systematical uncertainties, showing some deviation from the Standard Model predictions. A recent measurement by the CMS collaboration, counting b -tagged jets in the dilepton channel, measures $R_b = 0.98 \pm 0.04$, consistent with the Standard Model, in 2.2 fb^{-1} of data [41]. A possibility to extend the measurements of the top quark pair production presented in this thesis to a simultaneous measurement of $\sigma_{t\bar{t}}$ and R_b , not yet measured by the ATLAS experiment, will be outlined in chapter 8.

The events from top quark pair production and single top quark production are classified by the decay products of the W boson from the top quark decay. W bosons can decay leptonically,

$$W \rightarrow \ell \nu, \quad (2.38)$$

or hadronically,

$$W \rightarrow q\bar{q}. \quad (2.39)$$

Each possible decay occurs at the same frequency. But while the leptonic decay can occur in the three final states $(e\nu_e)$, $(\mu\nu_\mu)$ and $(\tau\nu_\tau)$, there are six possibilities for the hadronic decay. Due to its mass the W boson can produce either a $(u\bar{d})$ or $(c\bar{s})$ pair, which are always color neutral as pair and can thus form the three color combinations $(R\bar{R})$, $(G\bar{G})$ and $(B\bar{B})$. Hence, each of the nine decay modes is favored in about 11% of all cases.

The main focus of this thesis is the top quark pair production, i.e. events with two W bosons and two bottom quarks from the top quark decays. These events can be grouped for analyses into three types with different signatures in the detector, based on the W boson decay modes.

If both W bosons decay into a pair of light quarks, the final state is called *allhadronic* or *fully hadronic*, shown in figure ??, and the experimental signature includes two jets from b -quarks and four jets from the light quarks. In the case when only one W boson decays hadronically and the other one decays leptonically the event is referred to as *lepton+jets* or *single lepton* event¹³. An example Feynman diagram for this process is shown in figure ?. The signature in the detector consists of four jets, two of which originating from bottom quarks, a charged lepton and a neutrino, measured as energy imbalance in the detector. The third type of events has W bosons decaying leptonically, see

¹³or sometimes as *semileptonic* event, although the decays themselves are either strictly hadronic or strictly leptonic

Figure 2.7.: The *allhadronic* decay mode of top quark pair production.

Figure 2.8.: The *lepton+jets* decay mode of top quark pair production.

figure ?? In this *dileptonic* decay channel two jets from b -quarks are accompanied by two charged leptons and a significant amount of missing transverse energy, due to the two neutrinos escaping the detector. The frequency of occurrence for each of the three classes of events can be calculated from

Figure 2.9.: The *dilepton* decay mode of top quark pair production.

the branching ratios of the W boson and is displayed in figure ?? . Measurements in the different channels have their own advantages and disadvantages. Measurements in the allhadronic channel are difficult to perform, since there is no charged lepton leaving a clear signature and background from QCD multijet production is large, although the process occurs at a higher rate than the other two. Dileptonic events are rather rare but have the advantage of a very clear and distinctive signature in the detector, only diluted by the missing transverse energy attributed to the two neutrinos. The channel of choice in this work is the lepton+jets channel¹⁴ offering a good trade-off between high statistics, a clear identifier from the charged lepton and missing transverse energy and manageable backgrounds.

Figure 2.10.: Possible decay modes for top quark pair production and their frequency of occurrence. Most measurements in the lepton+jets and dilepton channel only include the events with τ -leptons, if they decay leptonically.

2.3.3. Experimental Measurements of Top Quark Pair Production

The cross section for top quark pair production differs significantly between the Tevatron (7 pb^{-1}) and the LHC (165 pb^{-1}) and the top quark pairs are produced close to the production threshold at the Tevatron and quite boosted in most cases at the LHC. Still, the main background processes and the methodology for the measurements are quite comparable. Theoretical predictions at approximate NNLO reach a precision of the order of 7%. Similar precision is achieved by the most precise measurements using combinations of channels or in the lepton+jets channel at all experiments, including the most precise single measurement of $\sigma_{t\bar{t}}$ presented in this thesis. Most measurements are performed in the allhadronic channel, in the lepton+jets channels (e +jets and μ +jets) or a in combination of both¹⁵, and the dileptonic channels ee , $e\mu$ and $\mu\mu$ ¹⁶. However, several measurements are also performed analyzing events with hadronically decaying tau leptons or events where the

¹⁴including events with electrons or muons and jets, as well as events with taus if the tau lepton decays leptonically

¹⁵which also includes the W boson decays $W \rightarrow \tau\nu \rightarrow e/\mu\nu\nu$

¹⁶again including leptonic tau decays

charged leptons are not or not fully reconstructed.

The most precise measurements in each of the *traditional* channels by each of the four experiments capable of measuring $\sigma_{t\bar{t}}$ are shown in table ??¹⁷.

Experiment	Dileptonic		Lepton+Jets		Allhadronic	
	$\sigma_{t\bar{t}}$ [pb]	$d\sigma/\sigma$ [%]	$\sigma_{t\bar{t}}$ [pb]	$d\sigma/\sigma$ [%]	$\sigma_{t\bar{t}}$ [pb]	$d\sigma/\sigma$ [%]
CDF	$7.4^{+0.9}_{-0.9}$ [42]	12	7.82 ± 0.55 [43] ¹⁸	7.0	7.2 ± 1.3 [44]	18
DØ	$7.36^{+0.90}_{-0.79}$ [45]	12	$7.78^{+0.77}_{-0.64}$ [46]	9.9	6.9 ± 2.0 [47]	29
ATLAS	176^{+17}_{-15} [48]	9.7	$179.0^{+11.8}_{-11.7}$ [49]	6.6	167 ± 80 [50]	48
CMS	$169.9^{+18.4}_{-18.4}$ [51]	10.8	164.4 ± 14.3 [52]	8.7	136 ± 45 [53]	33

Table 2.4.: Most precise experimental measurements including statistical, systematic and luminosity uncertainties of the top quark pair production cross section at the experiments ATLAS, CDF, CMS and DØ. Measurements at the LHC experiments ATLAS and CMS were performed at $\sqrt{s} = 7$ TeV, while at the Tevatron CDF and DØ experiments the production cross section was measured at $\sqrt{s} = 1.96$ TeV. All measurements assume a top quark mass of $m_t = 172.5$ GeV.

Combinations of results in the different channels are performed by all experiments at different stages. These combinations allow to exploit knowledge from statistically independent datasets with partially correlated uncertainties to gain precision. The most recent results are shown in table ??. The

Experiment	Channels	$\sigma_{t\bar{t}}$ [pb]	$d\sigma/\sigma$ [%]
CDF	dileptonic, 2× lepton+jets, allhadronic	7.50 ± 0.48 [54]	6.4
DØ	dileptonic, lepton+jets	$7.56^{+0.63}_{-0.56}$ [45]	8.3
ATLAS	dileptonic, lepton+jets, allhadronic	177^{+11}_{-10} [55]	6.2
CMS	dileptonic, lepton+jets, allhadronic	165.8 ± 13.3 [56]	8.0

Table 2.5.: Combined measurements of the top quark pair production cross section as performed by the listed experiments.

methods applied in all channels and by all experiments follow the same principles. If possible, the dominant backgrounds are estimated directly from data and validated in control regions. Simpler methods, especially at low statistics, apply a rigid event selection optimized for a good signal-to-background ratio and count the expected background events to find the observed number of signal events and extract the cross section. More sophisticated analyses extract the cross section from a likelihood fit to a template distribution, either a single kinematic variable, like invariant masses of involved objects or secondary vertex masses, or the output of a multivariate analysis technique. Sensitivity is improved by extending the phase space and applying softer selection criteria as well as by categorizing events in classes of jet multiplicities or number of *b*-tagged jets. Incorporating some sources of systematic uncertainties as nuisance parameters in the likelihood fit can further reduce the overall uncertainty of the measurements.

¹⁷as of March 2012

¹⁸This analysis is somewhat different to all the others. Instead of measuring $\sigma_{t\bar{t}}$ it measures the ratio between top quark pair and *Z* boson production. This cancels systematic uncertainties from the luminosity determination but includes uncertainties from the theoretical *Z* boson cross section.

Experimental Setup

3.1. Introduction

The analyses presented in this thesis use data of proton-proton collisions collected by the ATLAS experiment at the Large Hadron Collider (LHC) at CERN throughout the years 2010 and 2011. This chapter describes the experimental setup of the LHC to accelerate and collide protons at a center-of-mass energy of $\sqrt{s} = 7$ TeV, in section 3.2, and the ATLAS detector in detail in section 3.3.

3.2. The Large Hadron Collider

The Large Hadron Collider [57] at CERN is the most powerful particle accelerator worldwide. It is located close to Geneva, Switzerland, in the 27 km long tunnel that previously hosted the electron-antielectron collider LEP [58] from 1989 to the year 2000. The tunnel itself lies 100–120 m underground and crosses the border of France and Switzerland. The LHC is designed to serve proton and ion beam collisions at center-of-mass energies of up to $\sqrt{s} = 14$ TeV (for protons) to the four main experiments: the two multipurpose detectors ATLAS [59, 60] and CMS [61], LHCb [62], focussing on b -physics and ALICE [63], studying the quark-gluon plasma in heavy ion collisions.

3.2.1. Design

The accelerator chain with the LHC as final destination for the protons is shown in figure 3.1 and makes use of the large accelerator program at CERN. All accelerators in the chain, except for the LHC itself, were already existing and are also providing beams for several smaller experiments. Starting from a bottle of hydrogen gas, the protons set out for their path to final collisions in the only linear accelerator of the chain, the LINAC2. After being accelerated to 50 MeV they are transferred to the Proton Synchrotron BOOSTER and further accelerated to 1.4 GeV. The protons then enter the oldest part of the chain, the Proton Synchrotron (PS), that was built in 1959. Having reached an

Figure 3.1.: Accelerator chain of the Large Hadron Collider with the four main experiments.

energy of 25 GeV they continue their path in the Super Proton Synchrotron (SPS), where they are accelerated to the LHC injection energy of 450 GeV while traveling through the 7 km circumference ring. From the SPS, two transfer lines serve the LHC, injecting proton beams into the two contrari-ous beam pipes of the LHC. Both proton beams are accelerated simultaneously in the Large Hadron Collider, and are brought to collision at four interaction points after reaching their final energies of currently 3.5 TeV per beam after about 20 minutes of acceleration and further beam optimization. The crossing points of the beam pipes are located at the center of the four big LHC experiments: ALICE, ATLAS, CMS and LHCb.

The protons (and ions) are accelerated in bunches, separated packages of several billion particles, in the full accelerator chain. A radio-frequency (RF) acceleration technique (time-dependent elec-tromagnetic fields) leads to bunches of particles with a well defined energy. The LHC is designed to store up to 2808 bunches of particles, which then have a time difference of 25 ns. Each bunch can be compressed to a size as small as $16 \mu\text{m} \times 8 \text{ cm}$ (transversal $\times$ longitudinal) at the interaction points.

The particles are kept on their circular trajectory through eight arc and eight straight sections¹ by 1232 superconducting dipole magnets, providing magnetic fields of up to 8.6 T. Almost 400 super-conducting quadrupole magnets are used in addition to correct the beam position and to focus the beams at the interaction points. All magnets are cooled down to a temperature of 1.9 K using fluid helium to maintain superconductivity.

¹remnants of the design of the old LEP tunnel to reduce synchrotron radiation of accelerated electrons

The number of collisions at interaction points is expressed as instantaneous luminosity $\mathcal{L}$, the number of interactions per second and unit area [$\text{cm}^{-2}\text{s}^{-1}$]. The integrated luminosity $\int \mathcal{L} dt$ describes the number of collisions collected over a certain time interval and is expressed in inverse picobarns, $\text{pb}^{-1} = 10^{36} \text{ cm}^{-2}$, or inverse femtobarns, $\text{fb}^{-1} = 10^{39} \text{ cm}^{-2}$ through the remainder of this thesis. It can be translated into the number of collected events for a certain physics process with cross section σ by the formula $N = \sigma \int \mathcal{L} dt$. Since the most interesting physics processes have small cross sections, a high instantaneous luminosity of the accelerator is desired. The luminosity can be changed by varying the beam parameters, following the formula

$$\mathcal{L} = \frac{N_b^2 n_b^2 f_{\text{rev}} \gamma}{4\pi \sigma_x \sigma_y} F. \quad (3.1)$$

In this formula N_b stands for the number of particles per bunch, n_b for the number of bunches per beam and f_{rev} for the revolution frequency. These parameters are initially set for each fill of the LHC. The relativistic gamma factor γ and the geometric luminosity reduction factor F , which describes the reduced region of interaction due to the beams crossing with a certain crossing angle, are constant values for a given setup. The beam cross sections in x and y, σ_x and σ_y , can be reduced by focussing the beam further at the interaction point and thus can lead to an increased luminosity.

3.2.2. Commissioning and Performance

The member states of CERN decided in 1994 to build the Large Hadron Collider after the shutdown of the LEP accelerator in 2000. Initially, the plan was to start with collisions at $\sqrt{s} = 10 \text{ TeV}$ and only later upgrade the accelerator for running at $\sqrt{s} = 14 \text{ TeV}$. After acquiring more funding it was decided in 1996 to aim for a center-of-mass energy of $\sqrt{s} = 14 \text{ TeV}$ already in the first run period of the LHC. However, during the construction of the accelerator it became clear that the initial running would take place at a lower center-of-mass energy (7 to 10 TeV) to reduce the risk of magnet quenches, and that additional training of the magnets would take place and additional quench protection systems would be installed in a first longer shutdown.

The first proton beams were circulated through the full LHC ring on September 10th 2008, but on September 19th a faulty connection between a dipole and a quadrupole magnet caused mechanical damages on several magnets and the release of helium into the tunnel. The exchange and repair of magnets and the installation of an additional safety system to prevent such events in the future took more than a year, and the first proton-proton collisions at injection energy ($\sqrt{s} = 900 \text{ GeV}$) took place on November 23th 2009. Already on November 29th 2009 the LHC overcame the Tevatron as the most powerful particle accelerator in the world when colliding two beams with beam energies of 1.05 TeV each. During the winter of 2009–2010 the magnets were carefully trained to reach higher energies, leading to the initial collisions at the highest collision energy that was considered safe with the current accelerator setup, $\sqrt{s} = 7 \text{ TeV}$, on March 30th 2010.

The LHC went through a commissioning phase of varying beam parameters with largely increasing luminosities until the annual winter shutdown at the end of 2010, see figure ??, with a four week period of first heavy ion collision at the end of the year. About 48 pb^{-1} of proton-proton collisions under stable beam conditions were provided at the interaction point hosting the ATLAS experiment in

2010². Operation of the LHC resumed in March 2011 with significantly increased beam luminosities, delivering more than 5 fb^{-1} of data to the ATLAS experiment until November 2011, see figure ??, when another heavy ion collision period started to end the 2011 run. The LHC is expected to run throughout the year 2012 at a center-of-mass energy of $\sqrt{s} = 8 \text{ TeV}$, adding another $10\text{--}15 \text{ fb}^{-1}$ of data to the available data set. Afterwards a longer shutdown is planned to upgrade the machine and detectors for operation at $\sqrt{s} = 14 \text{ TeV}$ and design beam parameters.

Figure 3.2.: Delivered integrated luminosity by the LHC in 2010 (left) and 2011 (right) in green, recorded integrated luminosity at the ATLAS experiment in yellow [64].

The integrated luminosity of collision events recorded by the ATLAS experiment during the run periods at $\sqrt{s} = 7 \text{ TeV}$ in 2010 and 2011, which are analysed in this thesis, was measured with high precision using van-der-Meer scans provided by the LHC, yielding a 3.4% uncertainty for the 2010 run [65] and a 3.7% uncertainty as a preliminary result for the 2011 run [66]. The data analysed in this work is a subset of the recorded data, due to strict data quality requirements and the availability of data at the time of performing the analysis.

3.3. The ATLAS Detector

The ATLAS detector [59, 60], **A Toroidal LHC ApparatuS**, is located at Point 1, one of the four interaction points of the LHC accelerator, in a large cavern underground. The setup and dimensions of the $44 \text{ m} \times 25 \text{ m}$ detector can be seen in figure ?. ATLAS is one of the two multipurpose detectors at the LHC, designed to cover a wide range of possible physics processes. It allows for precise measurements of Standard Model processes as well as searches for the Higgs boson over the full mass range and searches for signatures of physics beyond the Standard Model. Therefore, the detector needs to cover the full 4π -solid angle around the interaction point and to measure electrons, muons, taus, jets and an energy imbalance from invisible particles, called missing transverse energy, over a large range of particle momenta. In addition, due to the high beam intensity multiple interactions can happen simultaneously and need to be clearly separated in reconstruction, i.e. the primary vertex or origin of the particles needs to be measured with high precision. Many interesting

²About 45 pb^{-1} were recorded, and about 35 pb^{-1} were considered good enough for final data analyses – the 2010 data set of ATLAS.

physics processes contain jets originating from b -quarks, which can be identified by stemming from a displaced secondary vertex, which also requires a high resolution of the innermost part of the detector.

The detector itself, and especially the inner detector close to the beam pipe, suffers from high doses of radiation and steady operation has to be ensured in this environment for a long time. Opening and closing the detector is only possible during several month long shutdowns of the accelerator, which means that non-operating parts cannot be replaced and will diminish the performance of the detector. The read-out and trigger systems have to handle up to 40×10^6 collisions per second and have to select interesting events for further reconstruction and analysis within a very short time span. As shown in figure ??, the detector consists of about 100 million read-out channels distributed over the inner tracking device located in a magnetic field provided by a solenoid, the calorimeter system and the muon system with the name-giving toroid magnets.

Figure 3.3.: Schematic drawing of the ATLAS detector and its subcomponents [67].

3.4. Detector Coordinates

In the context of describing the ATLAS detector and the physics involved, a right-handed coordinate system (ϕ, η, z) is used instead of the cartesian coordinate system (x, y, z) . ϕ and η are expressed with respect to x, y and z . To define these, the origin of the (x, y, z) coordinate system is located in the center of the detector and the z -axis is defined counter-clockwise, while the positive y -axis goes upwards with the increasing height of the detector. The x -axis is pointing towards the center of the LHC. The ϕ -coordinate can then be expressed as the azimuthal angle of the xy plane, counting positive clockwise and negative counterclockwise. The pseudorapidity η is an approximation of the y , valid for particles with small masses compared to their transverse momenta and expressed in terms

of the opening angle θ to the z -axis

$$\eta = -\ln \tan\left(\frac{\theta}{2}\right). \quad (3.2)$$

The distance Δy , and $\Delta\eta$, respectively, between two particles is invariant under Lorentz-transformations. The coordinates of a final state particle are usually given with respect to the interaction point, which is not necessarily exactly in the center of the detector. In this coordinate system the distance between two objects is given by quantity

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}. \quad (3.3)$$

The momenta and energies of particles in this work are commonly expressed as transverse momentum

$$p_T = \sqrt{p_x^2 + p_y^2} = |p| \sin \theta \quad (3.4)$$

and transverse energy

$$E_T = E \sin \theta, \quad (3.5)$$

while the missing transverse energy, an energy imbalance in the detector hinting at an escaping particle like a neutrino, is expressed as E_T^{miss} .

3.5. Magnets

The momentum of a charged particle is determined by measuring the curvature of its trajectory through the detector. To achieve this, all tracking devices need to be placed in a magnetic field to bend the particles' trajectories. The ATLAS detector contains a solenoid magnet to provide a magnetic field for the inner detector and barrel and endcap toroidal systems of eight magnet coils to induce the magnetic field inside the muon system. Both magnet systems consist of superconducting magnets, operating at a temperature of about 4.5 K.

3.5.1. The Solenoid

The solenoid magnet covers the space between $1.22 \text{ m} < r < 1.32 \text{ m}$ of the detector geometry, in between the inner detector and the calorimeter system. The main design constraint is therefore that the material budget of the magnet is reduced as much as possible to reduce energy losses of particles traversing it before reaching the calorimeters. Alongside the z -axis the solenoid covers a distance of 5.8 m. To further reduce passive detector material the magnet is assembled inside the same vacuum vessel as the calorimeter. A magnetic field of 2 T is produced in the central region of the inner detector.

3.5.2. The Toroid

Three independent air-core toroid systems, each consisting of eight coils, are used in the barrel region³ and endcap regions⁴ on each side. The endcap toroids are rotated by 22.5° to ensure optimal bending power in the transition region. The magnetic field provided in the central part is 3.9 T and grows to 4.1 T in the forward region. While each of the eight coils in the barrel region is housed inside its own cryostat, the full endcap toroid system shares one cryostat on each side.

3.6. The Inner Tracking Detector

The ATLAS inner detector, shown in figure ??, covers a cylindrical volume of 6.2 m length with a radius of 1.15 m around the beam pipe and consists of three subsystems, providing information about a charged particles' path through the detector and its momentum in the pseudorapidity range $|\eta| < 2.5$. It is laid-out to provide a momentum resolution of $\frac{\sigma_{p_T}}{p_T} = \sqrt{(0.05\%)^2 + (1\%)^2}$.

All three subsystems make use of the fact that charged particles⁵ interact with the material of the detector by ionization without losing much of their own energy. These concepts of detection only work for charged particles, particles without an electromagnetic charge are not visible to the inner detector. The inner detector is placed in a solenoidal magnetic field, described in section 3.5, which allows to also measure a particles' momentum by the curvature of its track in the detector. While a high precision measurement of the vertex associated to a track allows to identify jets from heavy-flavor quarks and tau-leptons, the transition radiation tracker is used to identify electrons by their characteristic radiation losses traversing material with different densities.

Figure 3.4.: The ATLAS inner detector with the pixel detector, the semiconductor tracker (SCT) and the transition radiation tracker (TRT) [67].

The pixel detector and the semiconductor tracker need to be cooled down to -10°C , which is provided by an evaporative cooling system using a fluorocarbonid fluid (C_3F_8).

³ $4.7 \text{ m} < r < 10.1 \text{ m}$, length of 25.3 m

⁴ $0.8 \text{ m} < r < 5.4 \text{ m}$, length of 5 m

⁵In the energy range of interest here they are called minimal interacting particles (MIPs).

The three subsystems of the inner detector are described moving outwards from the beam pipe in the following.

3.6.1. The Pixel Detector

The pixel detector is located closest to the beam pipe, with the innermost layer only 5 cm from the center, i.e. the average interaction point. Its main aim is to provide a high precision measurement of the impact parameter of a track, giving input to the identification of τ -leptons and jets from heavy flavor quarks. To achieve this, this part of the detector has the highest granularity and, whilst covering the smallest amount of space, contains 80% of all read-out channels of the ATLAS detector. The detector contains 80 million read-out channels distributed over 1744 modules that are arranged in three layers⁶ parallel to the beam pipe in the barrel region and perpendicular to the beam pipe on three disks on each side of the end cap region. Each read-out channel corresponds to a $250\ \mu\text{m}$ thick and either $50 \times 400\ \mu\text{m}^2$ or $50 \times 600\ \mu\text{m}^2$ large n^+ -on- n -doped silicon pixel as sensor⁷. 2880 pixel cells are connected to one frontend (FE) chip and 16 chips are mounted on one module, sharing the same read-out chain and the same voltage supplies.

The sensors are embedded in a layered structure in between a supply unit with the module controller chip (MCC) and the connection to the global read-out system on one side and the read-out chips on the other side to ensure full coverage, leaving almost no areas with only dead material. The connection between the sensor itself and the read-out electronics is achieved via bump bond connections.

The pixel detector is operated at a 150 V depletion voltage⁸ to separate electron-hole pairs created by a traversing charged particle. The current is amplified and measured, counting a hit in a certain pixel sensor if it exceeds a threshold, which is calibrated to provide the best signal-to-noise separation for each pixel sensor.

Due to the exposition to a high radiation dose the performance especially of the innermost layer of the pixel detector will decrease over time and it is planned to be replaced by the so-called *Insertable b-layer (IBL)* during the long shutdown of the LHC in 2013/2014.

3.6.2. The Semiconductor Tracker (SCT)

The SCT detector uses the same detection principle and material, semiconducting silicon, as the pixel detector, but instead of small rectangular pixels larger strip sensors are used⁹. The strips are arranged parallel to the beam pipe in the barrel region and perpendicular to it in the endcap region. The detector consists of four layers in the central part and nine layers in the forward region ($|\eta| > 2.2$). The innermost SCT layer is located at a radius of about 25 cm away from the center of the beam pipe. To increase the spatial resolution measurement of a hit and to obtain three dimensional hit information, each layer is equipped with two modules at a stereo angle of 40 mrad and a pitch of $80\ \mu\text{m}$. The silicon strips are distributed over 4088 modules, leading to a sum of about 6.3 million read-out channels from this part of the detector.

⁶The layer closest to the beam pipe is referred to as L0 or b-layer. The outer layers are called L1 and L2.

⁷The size depends on the position on the module.

⁸The bias voltage will need to be increased with operating time of the detector to account for radiation damages.

⁹each strip is about 13 cm long

3.6.3. The Transition Radiation Tracker (TRT)

The TRT detector is not only used for tracking the particles' trajectories through the detector via ionization, but also makes use of the principle of transition radiation. Highly relativistic particles emit photons when experiencing a change of the dielectric constant ϵ_r of the material they are traversing. Since electrons have low mass and high energies when produced in the hard interaction they tend to create a high number of photons, while heavier particles, such as pions, create less transition radiation. For the particle detection via ionization itself the TRT consists of about 350000 cylindrical straws with a radius of $r = 2$ mm each, arranged in one cylindrical volume in the barrel, starting at a detector radius of 55 cm, and two volumes in the endcap regions. The straws are filled with a gas mixture of Xenon, Oxygen and CO_2 and while the outer shell acts as cathode, each straw contains an anode wire in the center to measure the current caused by a traversing charged particle at an operation voltage of 1600 V. The ability to identify electrons and distinguish them from heavier particles using transition radiation is achieved by intertwining the straws with material of changing dielectric constants. Since the photons created from transition radiation cause a considerably larger signal amplitude in the straws a distinction between the ionization from the initial charged particle and the transition radiation is possible. Hence the straw read-out operates with two different thresholds to detect hits at the same time – a lower threshold to detect the charged particles from the main interaction and a higher threshold to detect the photons emitted due to transition radiation. The actual ability to distinguish between electrons and particles with higher masses was tested and calibrated in test beam measurements and then refined in operation with collisions. Additionally, a drift time measurement in each straw can be used to further determine the path of the charged particle through a straw. The spatial resolution of a TRT straw is a factor of 10 worse than for the silicon trackers, but since a charged particle leaves between 22 and 36 hits in the detector¹⁰ and extends the lever arm of the measurement it still significantly improves the resolution of the inner detector as a whole.

3.7. Calorimeter System

The purpose of the ATLAS calorimeter system is to measure the energy of charged and neutral particles, such as photons, electrons, τ -leptons, as well as jets originating from quarks and gluons over a range from a few GeV up to several TeV. It is also used to measure an energy imbalance of an event, which corresponds to missing transverse energy and hence particles that escape the detector undetected¹¹. The calorimeter is segmented into cells transversal and along the particles' direction of flight through the detector and its different components can be seen in figure ?? (left). In the central region of the detector ($|\eta| < 3.2$) the electromagnetic calorimeter has a fine granularity and provides a high resolution for energy measurements of photons and electrons, while the hadronic calorimeter outside the electromagnetic calorimeter and in the forward region contains coarser segments, still providing enough information for precision measurements of jets and missing transverse energy. The forward hadronic calorimeter, designed to compensate for radiation damage in the environment close

¹⁰compared to 3 in the pixel detector and 4 to 9 in the SCT detector

¹¹Neutrinos will cause missing transverse energy, but also many particles in models for physics beyond the Standard Model, such as Supersymmetry.

to the beam, covers the detector space up to $|\eta| < 4.9$. The latter ensures that all particles visible to the detector will be detected and therefore makes the measurements of missing transverse energy possible. An important requirement for a good calorimeter is that all electromagnetic and hadronic

Figure 3.5.: Overview of the calorimeter system of the ATLAS experiment [67] (left) and distribution of the material budget in terms of interaction length λ [67] (right).

showers are stopped within the detector volume and that punch-through into the muon system is negligible. This can be achieved by the thickness and density of the material used in the calorimeter and the supporting structure. For this reason, a particle crossing the electromagnetic calorimeter will experience more than 24 (26) radiation lengths X_0 in the barrel (endcap) region. After passing the complete calorimeter a particle has traversed about 11 interaction lengths λ on average, see figure ?? (right) for the η -dependence, which sufficiently suppresses punch-through.

Both calorimeter parts are sampling calorimeters, a mixture of passive absorber material with a high number of protons in the nucleus and active detector material to read out the signal caused by energy deposition.

3.7.1. The Electromagnetic Calorimeter

Over the full range of $|\eta| < 3.2$ the electromagnetic (EM) calorimeter uses lead plates as passive and liquid argon as active detector material and it is thus often abbreviated as LAr EM calorimeter. The active detector material is interspersed with Kapton electrodes arranged in an accordion-shaped geometry to ensure full coverage of the phase space in ϕ without gaps in the azimuthal direction. Due to this structure each particle crossing the detector will experience about the same amount of material.

The EM calorimeter is divided into three parts, each in their own separate cryostat system: the barrel part of the calorimeter covers the region up to $|\eta| < 1.475$, with a subsequent endcap calorimeter for the range $1.375 < \eta < 3.2$ on each side. In addition, a thin liquid argon layer is assembled as presampler in the region up to $|\eta| < 1.8$ to correct for inhomogeneous energy losses in the inner detector and its support structure. The barrel part is separated into two half-shells with a 6 mm gap at $z = 0$, while the endcap parts consist of an inner and an outer wheel divided up into $1.375 < |\eta| < 2.5$ and $2.5 < |\eta| < 3.2$. Furthermore, the barrel region of the detector is segmented into three longitudinal layers with thickness of about $4X_0$, $16X_0$ and $2X_0$ ¹², counting outwards. The

¹²at $\eta = 0$

innermost layer is very finely binned ($\Delta\eta = 0.0031$) and allows to precisely match calorimeter information with tracking information as well as to distinguish close-by showers. This feature also allows to measure the direction of photons with high precision, for which the tracking detector cannot provide information. The middle layer is designed to contain the main energy deposition of each electromagnetic shower with a granularity of $\Delta\eta = 0.025$ and the thin outermost layer is used to correct for leakage into the successive hadronic calorimeter.

The energy resolution of the EM calorimeter is given by

$$\frac{\Delta E}{E} = \frac{11\%}{\sqrt{E[\text{GeV}]}} \oplus 0.4\%, \quad (3.6)$$

where the first term describes the statistical fluctuations in the sampling material and the constant second term systematic uncertainties from an inhomogeneous material distribution.

3.7.2. The Hadronic Calorimeters

The hadronic calorimeters are designed to fully contain energetic jets originating from quarks and gluons, that interact via the strong interaction with the nuclei of the material. While the central part ($|\eta| < 1.7$) is equipped with a sampling calorimeter using scintillating tiles and iron plates, the forward region (up to $|\eta| < 4.9$) consists of a liquid argon hadronic calorimeter and a dedicated forward calorimeter.

3.7.2.1. The Hadronic Tile Calorimeter

In the central region, the hadronic calorimeter consists of a barrel part ($|\eta| < 1.0$) and two extended barrel calorimeters¹³, covering the region $0.8 < |\eta| < 1.7$ and covers the area with an inner radius of $r_i = 2.28$ m up to a radius of $r_o = 4.25$ m. The active detector material is made of polystyrene scintillator tiles with a thickness of 3 mm, alternating with iron plates as passive absorbers with increasing radii. In the longitudinal direction the detector consists of three layers with thickness in terms of interaction length moving outwards of 1.4λ , 4.0λ , 1.8λ at $\eta = 0$. The segmentation in η and ϕ is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the innermost two layers and 0.2×0.1 in the outermost layer.

In the Tile Calorimeter, wavelength shifters are attached to each side of a scintillator tile, which are separately read out using photomultipliers. This provides a very fast signal and can be used in the trigger system.

3.7.2.2. The Hadronic LAr Calorimeters

Located in the same cryostat as the endcaps of the EM calorimeter on each side of the detector are the hadronic endcap calorimeter (HEC), covering the region of $1.5 < |\eta| < 3.2$, and a dedicated forward calorimeter (FCAL) in the very forward region close to the beam pipe ($3.1 < |\eta| < 4.9$). Both use the same technology and active material as the LAr EM calorimeter. Since the EM calorimeter also extends up to $|\eta| < 3.2$, good coverage in the transition region between the different calorimeter

¹³one on each side

components is achieved.

The HEC consists of two wheels on each side of the detector, both divided into two segments along the longitudinal direction. Copper plates of 25–50 mm thickness are used as absorber material and alternate with 8.5 mm thin gaps filled with liquid argon and the read-out wires. The FCAL is located inside the HEC, towards the beam-pipe, and designed to operate constantly under high radiation exposure due to its location. It consists of three sections, the innermost one using copper as absorber material and the outermost two using tungsten as passive detector material, both alternating with LAr gaps. The choice of material allows to achieve optimal measurements of both electromagnetic and hadronic showers.

3.8. Muon System

The ATLAS muon system uses four different types of muon chambers to achieve optimal performance both for precision measurements of the muons' trajectories, and thus momenta, up to $|\eta| < 2.7$ and 1–3 TeV¹⁴ and for fast triggering of events with muons up to $|\eta| < 2.4$. Monitored Drift-Tube Chambers (MDTs) and Cathode Strip Chambers (CSCs) are used for the tracking measurements, while Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs) are used for triggering and supplemental measurements. The arrangement and design of the muon system is shown in figure ???. The chambers are arranged in three cylindrical layers at $r = 5, 7.5, 10$ m in the barrel region and four wheels on each side of the endcap region at $z = \pm 7.4, 10.8, 14.0, 21.5$ m. The muon system has a small, uncovered, gap at $\eta \approx 0$ due to the cable support for the inner detector solenoid, and additional regions with significantly reduced acceptance in the lower half of the detector due to its support structure.

It is placed within the magnetic field provided by the system of toroid magnets, which are arranged to facilitate a field orthogonal to the muons trajectories in almost all detector regions. The magnetic field in the region $|\eta| < 1.0$ is generated solely by the barrel toroids, while the region $1.4 < |\eta| < 2.7$ is served by the endcap magnets. The region in between ($1.0 < |\eta| < 1.4$) is referred to as 'transition region', where the magnetic field is a combination of the fields from both the barrel and the endcap toroids.

Due to the large dimensions of the muon system the position of each chamber has to be known with great precision to fully exploit the precision of the measurement in each single chamber in the reconstruction. A mechanical and optical positioning and alignment system is used for this, complemented by software-based alignment with cosmic muons and muons from collision events.

3.8.1. Monitored Drift-Tube Chambers (MDTs)

Aluminium tubes with a diameter of 3 cm and filled with an $ArCO_2$ mixture¹⁵ are arranged in three to eight layers of tubes. MDT chambers are installed in three layers of chambers in the full barrel region (up to $|\eta| < 2.0$) and all but the innermost layer, which is equipped with a Cathode Strip Chamber, of the endcap wheels. The resolution per tube is about $80 \mu\text{m}$ and $35 \mu\text{m}$ per chamber.

¹⁴Design goal is a momentum resolution of 10 % for a 1 TeV muon.

¹⁵in a 93/7 mixture

Figure 3.6.: The ATLAS muon system with the four different detector components [67].

3.8.2. Cathode Strip Chambers (CSCs)

Instead of another layer of MDT chambers, Cathode Strip Chambers are installed on the innermost wheel ($2.0 < |\eta| < 2.7$) to cope with the higher background rates close to the beam pipe and provide a more precise measurement with a detector with finer granularity. The chambers are multi-wire proportional chambers filled with an $ArCO_2CF_4$ mixture¹⁶, where the cathode is segmented in strips. A position resolution down to $60 \mu m$ per wire pitch can be achieved.

3.8.3. Resistive Plate Chambers (RPCs)

In the barrel region ($|\eta| < 1.05$), RPCs with a space-time resolution of about $1 \text{ cm} \times 1 \text{ ns}$ are installed to provide a very fast trigger signal usable in the hardware based trigger levels. A resistive plate chamber consists of two bakelite plates with a thickness of 2 mm and a $C_2H_2F_4$ gas filled gap in between. Each bakelite plate is read out via two orthogonal strips using capacitive coupling. While one layer of the strips is arranged in parallel to the MDT wires, the other one is arranged orthogonally, allowing a complementary measurement of both the η and ϕ position of the track.

¹⁶The gas mixture is 30% Ar, 50% CO_2 and 20% CF_4 .

3.8.4. Thin Gap Chambers (TGCs)

The TGCs in the forward region $1.05 < |\eta| < 2.4$ consist of two cathode plates with a distance of 2.8 mm to each other and an anode wire placed in between the cathodes, with a distance of 1.8 mm to the next wire. The chambers are filled with a gas mixture of CO_2 and C_5H_{10} and operated at a voltage of 3.1 kV, optimized to create fast signals due to a small drift time. While the anode wires are placed parallel to the MDT wires, the read out strips of the cathode plates are arranged orthogonally, providing additional information in ϕ .

3.9. Trigger System

At design luminosities of the LHC of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with a bunch-spacing of 25 ns the collision rate at the interaction point inside the ATLAS detector is roughly 40 MHz. This large amount of data can neither be fully reconstructed nor stored for further analysis. Therefore, the amount of data collected by the detector has to be reduced down to approximately 200 Hz within a very short time frame. Since most of the collisions do not lead to the production of new or interesting particles, but rather well-known high statistics processes at low momenta, referred to as 'minimum bias events', a careful selection of the events chosen for further evaluation has to be applied. To do so, ATLAS uses a three stage trigger system, shown in figure 3.2. With increasing precision and granularity, the trigger system makes use of the fact that the most interesting physics processes have designated signatures: a large amount of missing transverse energy and/or highly energetic jets or leptons. The level-one (L1) trigger is a purely hardware based trigger, while the level-two (L2) and event filter (EF) triggers¹⁷ use software to combine information and form a fast decision.

3.9.1. The L1 Trigger

The first stage of the trigger system, the L1 trigger, is built to reduce the data rate to 75 kHz and to reach a decision about the importance of an event¹⁸ within a latency of 2 μs . To achieve this short latency, fast electronic boards are used, which only require coincidence or vetos¹⁹ of several signals. Only a fraction of the full ATLAS detector is used at this first stage of decision making, namely the calorimeter (at reduced granularity) and the dedicated muon chamber systems RPC, in the barrel, and TGC, in the endcap. The L1 muon trigger looks for a signal originating from a high- p_T muon, while the L1 calorimeter trigger tries to identify events with highly energetic electrons, photons, jets or τ -leptons and/or a certain amount of energy deposited in the detector or missing transverse energy. Therefore, the energy deposition is measured as E_T in trigger towers of a $\Delta\eta \times \Delta\phi$ granularity of 0.1×0.1 and $\sum E_T$ as well as E_T^{miss} are calculated from the sum of active trigger towers. For each type of objects several triggers with different p_T/E_T thresholds exist, that can be

¹⁷which are in combination often called 'High Level Trigger' or HLT

¹⁸i.e. whether to further analyse it or discard it directly

¹⁹A veto can be used, for example, to require a certain isolation of the energy deposition.

Figure 3.7.: The trigger and read-out chain of the ATLAS detector [67], the data taking rate at the EF trigger has been updated to approximately 200Hz.

used to seed the successive higher level trigger algorithms and can be operated independently with different prescales²⁰.

3.9.2. The L2 Trigger

The software-based L2 trigger algorithms are seeded by so-called Regions-of-Interest (ROI) from the L1 trigger, containing the η , ϕ and p_T information from the trigger towers that caused the selection of the event. The L2 algorithms have access to the full amount of data taken in all subdetectors at full precision and granularity, but only use this information in the defined ROIs to reduce the time needed for reconstruction, achieving a latency of 1–10 ms depending on the type of the event. A reduction of the data rate to 1 kHz is gained mostly by more precise p_T measurements for leptons using information from the inner tracking detector, and by requiring isolation in the calorimeter or a combination of several objects.

3.9.3. The EF Trigger

Further reduction to the ≈ 200 Hz that can be fully reconstructed and stored for final analyses happens at the level of the Event Filter trigger (EF). Using roughly a factor of 3 more computing

²⁰Prescaling a trigger by a factor of n means reducing the amount of passing events, by only accepting every n th event, that passes all requirements.

nodes than the L2 trigger, the full event signature is reconstructed with algorithms similar to the ones used for final reconstruction. More complex and refined algorithms compared to L2 can be used, and additional information that requires complex computations, such as b -jet tagging or precise vertex measurements, becomes available.

Every event passing the EF trigger is then passed on to the full reconstruction and will be available, organized in trigger streams, for final analyses.

Objects and Processes

4.1. Introduction

Through the remainder of this work, the focus will be on measurements in the *lepton+jets* channel of top quark pair production. This chapter will describe how the involved physics objects are reconstructed and identified, and how signal and background processes are modeled and estimated. Since this thesis describes two measurements of the top quark pair production cross section with different approaches and in different data sets, 35 pb^{-1} taken in 2010 [68] and 0.7 fb^{-1} taken in 2011 [49], the exact selections applied are described in the chapters dedicated to the corresponding analyses. However, the general strategy to select a set of events enriched with top quark production remains applicable in both cases.

A typical Feynman diagram for the lepton+jets channel is shown in figure ??, and its signature in the detector includes exactly one charged lepton¹, a significant amount of missing transverse energy stemming from the neutrino, escaping undetected, and high- p_T -jets. While the leading-order Feynman diagram predicts exactly four jets, two of them originating from b -quarks, initial and final state radiation, as well as overlapping additional events from soft interactions² can lead to additional jets in the event. In addition, one or more of the jets can be either misidentified or not measured due to the detector acceptance. Hence, the requirement of the number of jets in an event is normally less strict than the prediction from the Feynman diagram, requiring ≥ 3 jets for all analyses presented in this work. The purity of the selected sample can be improved by requiring one or more of the jets to be identified as b -jets. Prior to object-based decisions, events are selected by the choice of triggers that fired for a given event, here always single lepton triggers, and by certain requirements on the quality of the data. The reconstruction and performance of all involved objects is crucial for performing precision measurements, and is described in detail in section 4.2.

Unfortunately, even a strict event selection will not lead to an absolutely pure sample of events containing top quarks. Several Standard Model processes will lead to the same signature in the detector and have to be modeled carefully. Monte Carlo simulated events are used to study the predictions for signal and background processes and to develop measurement strategies, but are either supported

¹the analyses consider electrons and muons, as well as taus if they decay leptonically

²so-called *pile-up* events

or replaced by data-driven measurements of the background processes in the final measurement. The dominant backgrounds to top quark pair production in the lepton+jets channel are production of a W boson in association with additional jets, referred to as W +jets events, QCD multijet production with one of the jets misidentified as a charged lepton, single top quark production, production of a Z boson in association with jets and diboson production. The simulated or data-driven models used to obtain predictions for signal and background processes are described in section 4.3.

4.2. Physics Objects

4.2.1. Event Properties

Events in data and simulated samples are selected for the analyses following the basic topology of top quark events and are preselected by utilizing a single lepton triggers to be fired, which are described in general in section 3.9. The exact trigger settings depending on the run periods are included in the following sections, when discussing the associated efficiencies. While the details of the object definitions will be given in this section and the exact cut values are listed in chapters 6 and 7, a typical event selection will always rely on the following:

- the event is selected by a single, high p_T lepton trigger, i.e. an electron or a muon trigger, see sections 4.2.2.4 and 4.2.3.4
- exactly one high p_T lepton is reconstructed and identified as isolated
- a significant amount of missing transverse energy stems from the neutrino in the W boson decay
- several jets, typically ≥ 3 , are found
- b -jet identification can be used to further improve the discrimination between signal and background
- the transverse mass of the W boson decaying leptonically $m_T(W) = \sqrt{2p_T^\ell p_T^\nu (1 - \cos(\varphi^\ell - \varphi^\nu))}$ can be used for further selection

In addition to these global requirements, more event quantities are used to select only events taken at well understood detector conditions and clearly stemming from pp collision events. These event level requirements are described in the following.

4.2.1.1. Good Run Lists

Since top quark pair production produces physics objects reconstructed in all parts of the detector, only those data events can be considered for final analyses for which the full detector was functioning. Therefore, `GoodRunsLists` (GRLs) are used to define a set of data-taking runs and *luminosity blocks*

(LBs), of 2 minutes for most of the time³, for which the data was found to be of good enough quality for further analysis. The GRLs are globally defined for all top quark analyses of a certain data set and used for all studies shown in this thesis.

4.2.1.2. Bad Jets

Events are discarded from the data set if at least one jet in the event with positive energy and transverse momentum > 20 GeV is identified as LooseBad by the jet data quality group. The definition in terms of variables and cut values slightly differs between the data taken in 2010 and 2011, but is optimized in both cases to take into account three sources of badly reconstructed jets. Jets stemming from cosmics or other non-collision backgrounds, from coherent noise in the electromagnetic calorimeters and from energy spikes in the hadronic endcap calorimeters (HEC spikes) are identified using energy fractions and quality requirements in the different detector parts.

4.2.1.3. Non-collision Background Rejection

To ensure that the event under study is produced by a proton-proton collision and not by the occurrence of cosmic muons or other sources of non-collision background, a primary vertex of the event has to be reconstructed which has to have at least four tracks associated to it.

4.2.1.4. Muon-Electron Overlap

An event is rejected if a muon and an electron, as defined in the following, are found to share the same track in the inner detector.

4.2.1.5. Pile-Up Reweighting

While the Monte Carlo simulated events are generated assuming fixed beam conditions, the conditions varied significantly during data-taking, resulting in a different amount of soft interactions coinciding with the hard interaction. The pile-up level for data taken in 2010 is closer to the configurations in simulation and lower than for data taken in 2011. Therefore, a re-weighting of the simulated events to account for a different level of pile-up based on the number of primary vertices in the event is only implemented as a source of systematic uncertainties in the 35 pb^{-1} analysis, but not as the default configuration. For the simulated events used in the 0.7 fb^{-1} analysis, a reweighting is applied based on the exact configurations in the different run periods.

³Luminosity blocks are defined as a short time range for which both the accelerator and detector conditions can be considered as constant.

4.2.2. Muons

4.2.2.1. Definition

The key part in the identification and reconstruction of muons is the muon system of the ATLAS detector, but a muon also leaves traces in the inner detector and the calorimeter. Hence, information from all detector parts can be used to reconstruct the track of a muon in the detector and to precisely determine its transverse momentum. Within the ATLAS collaboration two different sets of algorithms are used, Muid and Staco (both [69]), but in the context of the presented analyses only Muid muons are considered and described in the following. Both sets of algorithms reconstruct different types of muons, depending on the information available, as sketched out in figure ?? . If information from the muon system, the calorimeter and the inner detector is available, the MuidCombined algorithm forms a track in the muon system and looks for an associated track in the inner detector. A global fit to both the ID and MS tracks is performed to generate the final track of the *combined muon*, which is then used to determine the transverse momentum of the muon. The energy deposition in the calorimeter is used to correct the momentum measurement. A *standalone muon* is generated by the MuidStandalone algorithm, which is based on tracking information by the Moore sub-algorithm and a momentum measurement solely from the muon system. The track is then extrapolated to the inner detector, and subsequently to the point of origin, accounting for energy deposition alongside the track in the calorimeter. While these two algorithms are seeded by hits in the muon system, the other two Muid reconstruction algorithms, MuGir1 and MuTagIMO start with a track in the inner detector. MuGir1 can create a combined muon or a *segment-tagged muon*, depending on the success of a full detector fit of a combined track in the inner detector and the muon system. MuTagIMO always generates a segment-tagged muon, associating track segments found by the Moore algorithm to the inner detector track as a seed. Segment-tagged muons always rely on the measurement of the transverse momentum in the inner detector. An additional algorithm⁴ is used to reconstruct muons without information from the muon system itself, so-called *calorimeter-tagged* muons, analyzing the energy deposition along an extrapolated track from the ID.

To group the types of muons in classes suitable for different types of analyses, the quality status words as shown in table ?? are used. Since events with top quarks, where muons are produced in the W boson decay, are expected to contain well-identifiable muons, only *tight muons* are considered in the analyses presented in this work. An additional requirement that the muon has to be reconstructed by the MuidCombined algorithm is applied. Using looser algorithm criteria would increase the background level from misidentified muons without a significant increase of selected signal events. In addition, quality requirements on the inner detector track associated with the muon are imposed: the muon is expected to leave a hit in the innermost layer of the pixel detector⁵, more than one hit in the pixel detector, more than five hits in the SCT and be associated to less than two holes in pixel and SCT together. If the track lies within the acceptance of the TRT, the extended track is expected to have hits in the TRT as well and only a low fraction of outliers⁶.

⁴independent of Staco or Muid

⁵excluding muons that cross dead areas of this layer

⁶If the number of hits is denoted with n_h , the number of outliers with n_o and $n = n_h + n_o$ this requirement is defined as follows. If the extended track falls within the region of $|\eta| < 1.9$, $n > 5$ and $n_o < 0.9n$ have to be fulfilled. Tracks

Figure 4.1.: Classification of muons by the type of the reconstruction method, depending on the availability of a signal in the different detector parts.

Quality Definition	MuidCombined	MuidStandalone	MuGirl	MuTagIMO
TIGHT	✓	if $ \eta > 2.5$	with extended track	-
MEDIUM	✓	✓	with extended track	-
LOOSE	✓	✓	✓	✓

Table 4.1.: Object quality definitions used to define muons reconstructed by the MuID algorithm in ATLAS. The presented analyses select only *tight* muons for final measurements.

In the context of top analyses muons with a transverse momentum of $p_T > 20$ GeV in the central detector region, i.e. $|\eta| < 2.5$ are used.

4.2.2.2. Isolation

The events of interest from top quark pair production contain a so-called *prompt* muon, stemming directly from the hard interaction itself. In contrast, *non-prompt* muons occur inside jets as decay products. Variables related to the isolation of a muon can be chosen as tools to select prompt over non-prompt muons with a high probability. While the muons of interest will leave a well separated signal in the detector with no spread of energy around them, muons produced inside jets will be accompanied by a significant amount of energy deposition along their trajectory. This energy deposition is typically measured in a cone of radius ΔR around the reconstructed muon track and can be measured both in the calorimeter, the $E_{\text{T}}\text{Cone}$ variable, and as transverse momentum in the inner

with $|\eta| \geq 1.9$ are always fulfilling the requirements if $n < 5$, and if they additionally fulfill $n_o < 0.9n$ otherwise.

detector, the $PtCone$ variable. In the latter case, instead of direct energy deposition the transverse momenta of the tracks in the cone with ΔR is considered. In both cases the energy or momentum associated to the muon itself is subtracted. Radii of $0.2 < \Delta R < 0.4$ are typically considered for the cone size of both variables. It is possible to test the performance of these variables already with a small amount, 0.35 nb^{-1} , of data taken at the beginning of the first LHC run at $\sqrt{s} = 7 \text{ TeV}$ in 2010. Tight central muons were selected with $p_T > 6 \text{ GeV}$ with a very loose trigger selection, leading to a sample strongly dominated by non-diffractive minimum bias events⁷. These minimum bias events contain muons inside of jets in the most cases and are therefore a good test to compare the Monte Carlo predictions⁸ with the data. Figure ?? shows excellent agreement between data and predictions for both the calorimeter and the track based isolation variables with a cone size of $\Delta R = 0.3$.

Figure 4.2.: Comparison of data and Monte Carlo simulated non-diffractive minimum bias events in 0.35 nb^{-1} of data taken by the ATLAS experiment in early 2010. The studies were performed by the author in the context of reference [70].

A medium size cone with $\Delta R = 0.3$ has been found optimal for top quark physics, considering prompt muon selection efficiency and non-prompt muon rejection, and a muon is considered *isolated* in this context if it passes the following requirements:

- $EtCone30 < 4 \text{ GeV}$
- $PtCone30 < 4 \text{ GeV}$
- $\Delta R(\mu, \text{nearest jet}) > 0.4$

The last requirement, the distance of the muon to the jet⁹ closest in R enhances the suppression of background from multijet events, where muons occur inside jets, and can be misidentified as isolated otherwise. Figure ??, created with the same set of events as above, shows the correlation between the track based isolation variable and the distance between the muon and the nearest jet with $p_T > 20 \text{ GeV}$. A significant amount of muons in this sample dominated by what are background events for top analyses, have a small amount of additional transverse momentum carried by the tracks close to the muon track and would be considered as isolated without requiring $\Delta R(\mu, \text{nearest jet}) > 0.4$. By imposing this additional criterion this set of events can be discriminated against.

⁷Details of the study can be found in [70]

⁸PYTHIA was used for event generation here.

⁹with a $p_T > 20 \text{ GeV}$

Figure 4.3.: Distribution of muons with $p_T > 6$ GeV in 0.35 nb^{-1} of data taken by the ATLAS experiment in early 2010. The studies were performed by the author in the context of reference [70].

The choice of the cut value at 0.4 is driven by the jet radius of $R = 0.4$ for the jets used in this work, see section ???. The cut value is also supported by the fact that the efficiency to select muons in $t\bar{t}$ events as a function of the energy/momentum deposition variables saturates at about this cut value, see figure ?? for different cone sizes.

4.2.2.3. Performance

The best environment to study the performance of the muon reconstruction and isolation are $Z \rightarrow \mu\mu$ events. These events are expected to contain highly energetic isolated muons and can be well separated from background events by imposing constraints on the invariant mass of the muon pair and both muons carrying opposite charges. Figure ?? shows the resolution of the invariant dimuon mass for combined muons for 205 pb^{-1} of data taken in 2011 and Pythia generated Monte Carlo predictions for $Z \rightarrow \mu\mu$ events. A significant difference in the width of the distributions is visible. Therefore, the momentum of muons in Monte Carlo predicted events used in the analyses is smeared to match data based on a function derived from the comparison of the invariant dimuon mass distributions, taking into account the ID and MS components separately.

$Z \rightarrow \mu\mu$ events are also used to measure the reconstruction efficiency, as shown in figure ??, using the *Tag & Probe* technique. It is based on selecting events with a pair of muons, of which one is required to pass all selection requirements while the other one has to be an opposite charge muon or, in the case of the reconstruction efficiency measurement, an inner detector track. The pair of these candidates has to have an invariant mass close to the Z boson mass. The details of this technique and its application will be shown in section 4.2.2.4. For top analyses, the reconstruction efficiency for muons is split in two parts, ε_{reco} for the pure reconstruction efficiency of a combined muon and

Figure 4.4.: Efficiency to select $t\bar{t}$ events in the μ +jets channel as a function of the imposed cut on $\Delta R(\mu, \text{jet})$ for track and calorimeter based isolation variables at different cone sizes. In addition, the same variables normalized to the transverse momentum of the muon are shown, but not used in the analyses due to consequent potential problems in the QCD background estimation if they were used instead. A muon with $|\eta| < 2.5$, $p_T > 20$ GeV, no electron, at least 4 jets with $p_T > 25$ GeV and missing transverse energy > 25 GeV are required in the Monte Carlo generated events beforehand and the efficiency to select these preselected events is shown. Obviously a smaller cone radius of $\Delta R = 0.2$ would lead to a better signal selection efficiency, but also a higher probability to select background events as well.

Figure 4.5.: The invariant dimuon mass for pairs of combined MuId muons with opposite charge, $p_T > 20$ GeV, $|\eta| < 2.5$ and $\text{EtCone30} < 2$ GeV [71].

ε_{ID} for the efficiency of a combined muon to pass the selection criteria for a muon in top analyses, i.e. the isolation requirements. The dependency of the efficiency on kinematic variables, denoted as x , is determined and a scale factor is calculated comparing the efficiencies in data and Monte Carlo simulated events,

$$SF(x) = \frac{Z_{T\&P}(x)(\text{data})}{Z_{T\&P}(x)(\text{MC})}. \quad (4.1)$$

This scale factor is then applied to the selected muons in the simulated events to correct for differences between data and simulation. For the analysis based on 35 pb^{-1} a combined reconstruction and identification scale factor for top analyses is found to be independent of kinematic variables and yields $SF_{\text{reco+ID}} = 0.999 \pm 0.002(\text{stat.}) \pm 0.003(\text{syst.})$. For the analysis using 0.7 fb^{-1} of data the scale factors are determined and provided as function of p_T , η and φ .

Figure 4.6.: Reconstruction efficiency for a combined Muon with $p_T > 20 \text{ GeV}$ with respect to the inner detector tracking efficiency for data and simulated Monte Carlo events as measured in $Z \rightarrow \mu\mu$ events. The muons are selected with the *Tag & Probe* technique and the dependence on the pseudorapidity of the muons is shown. The lower part of the plot shows the ratio of the measured efficiency in data and simulation [71].

4.2.2.4. Muon Triggers

Trigger Chains

The analyses presented in this work make use of single lepton triggers, specifically single muon triggers to select events in the μ +jets channel. At the event filter level these are available with different thresholds of the transverse momentum of the muon, but a lower trigger threshold also leads to a higher rate for these triggers. Therefore, low- p_T -triggers, which were available at the initial luminosities of the LHC had to be pre-scaled when the luminosity increased. Since the offline muon p_T -cut used for the analyses is at 20 GeV , a trigger with a lower threshold has to be chosen to make sure that the trigger is fully efficient at 20 GeV . Otherwise the trigger turn-on would introduce

an additional systematic uncertainty on the measurement. The trigger chains used in the presented analyses for different data taking periods¹⁰ are shown in table ??

Run Period	EF	L2	L1	$\int \text{Ldt}$	Comments
A-E3 (2010)	-	-	MU10	0.8 pb ⁻¹	not considered for final analyses here, but applied in [72]
E4-F2 (2010)	mu10_MSonly	mu10_MSonly	MU0	2 pb ⁻¹	combined muon triggers were not yet commissioned
G1-G5 (2010)	mu13	mu13	MU0	5 pb ⁻¹	combined trigger
G6-I2 (2010)	mu13_tight	mu13_tight	MU10	28 pb ⁻¹	combined trigger with tighter L1 seeding
B2-G5 (2011)	mu18	mu18	MU10	0.7 fb ⁻¹	

Table 4.2.: Trigger chains used in the run periods for the data used in the presented measurement. During the initial run periods A-E3 the TGC part of the muon system was not usable for higher level triggering due to timing issues and only the L1 decision was usable. This small amount of data was taken into account with the L1_MU10 trigger and associated out-of-time trigger objects for the first observation of top quarks at ATLAS [72], but discarded for the subsequent precision measurements.

While the EF algorithms associated to EF_mu13, EF_mu13_tight and EF_mu18 search for combined muons and are very similar to the offline algorithms described in section 4.2.2.1, the mu10_MSonly trigger chain relies solely on reconstruction of muon tracks within the muon system. This reconstruction is less precise and the p_T -threshold less sharp, but a good understanding of these chains was achieved earlier due to the higher statistics available and the simplicity of taking only one detector part into account.

The Monte Carlo simulation of events includes a modeling of the trigger chains, but due to rapid changes in the configuration during data taking, especially in the early days the latter of the LHC operation, was not always equivalent to the data taking conditions. Therefore correction factors for the simulated events used in the final measurements have to be derived and the procedure is described in the following. The MC simulated events used in the 35 pb⁻¹ analysis are required to pass the mu13_tight chain, while the ones for the 0.7 fb⁻¹ analysis have to pass the mu18 chain.

Efficiency and Scale Factor Determination with Tag & Probe

This section describes the measurement of trigger efficiencies and scale factors to correct for the differences between simulated events and actual collision data, using the Tag & Probe method. Presented are measurements with the data taken in 2010 and the general strategy and setup used¹¹. In the presented work a slightly older version of Monte Carlo simulated events was used, which,

¹⁰The run periods are ordered alphabetically and are supposed to contain data sets with stable detector conditions.

¹¹The results presented here are very close to the ones used in the 35 pb⁻¹, derived with the settings developed here, and the 0.7 fb⁻¹ results, and are provided by other members of the ATLAS collaboration.

instead of `mu13_tight`, had the `mu10_MSonly` available. Unless stated otherwise the efficiencies are calculated for the triggers as named in table ??.

Figure 4.7.: Illustration of the *Tag & Probe* technique for a selection of muons from $Z \rightarrow \mu\mu$ events. After the preselection as of the events it is then tested if the *probe* muon matches a muon trigger object within a radius of $\Delta R = 0.15$ in the presented analysis.

The principle of the *Tag & Probe* algorithm, which relies on a selection of $Z \rightarrow \mu\mu$ events, is illustrated in figure ??: At first, the *tag* muon, passing the muon selection requirements as stated before and matching to a trigger object of the trigger under study within a radius of ΔR is selected. Next a second muon is sought–after, fulfilling the same object identification and isolation requirements, except for the trigger matching. It is then checked that this muon carries the opposite charge to the tag muon and that the invariant dimuon mass of the muon pair yields a value close to the Z boson mass of 91 GeV. If this is true the second muon is considered a *probe* muon and a matching trigger object is searched for within ΔR . The efficiency of a reconstructed and selected muon to fire the trigger can then be expressed as

$$\epsilon_{\text{trigger}} = \frac{N_{\text{matched probe}}}{N_{\text{probe}}}. \quad (4.2)$$

Only muons fulfilling all requirements stated previously are considered and the additional selection applied for this study is

- *tag* muon: has to match a trigger object of the trigger of choice within $\Delta R = 0.15$ (EF) or $\Delta R = 0.2$ (L1)
- *probe* muon: opposite electric charge than the tag muon
- $\Delta(m_{\mu_t, \mu_p}, m_Z) \leq 12$ GeV

The selection used for the Tag & Probe method creates a rather background free sample, as shown in figure ??, using the simulated samples as described in section 4.3 and a b -jet enriched QCD multijet

sample. These criteria allow to create a high statistics sample of truly isolated muons, about 600 probe muons per 1 pb^{-1} , for further analysis.

Figure 4.8.: Simulated $Z \rightarrow \mu\mu$ and background events as a function of $m_{\mu\mu}$, before and after requiring the muon pair within the 12 GeV window around the Z boson mass. The normalization corresponds to 10 pb^{-1} and shows a low background contribution after the Z window criterion is applied. All other muon and muon pair selection criteria are already applied.

Distributions of the selected probe muons for data compared to simulation are shown in figure ?? and are in good agreement. In the final analyses correction scale factors for the muon reconstruction and identification have to be applied as well, which is not done here¹², explaining the remaining differences between data and Monte Carlo simulation.

The Tag & Probe method allows to calculate efficiencies both for data and for MC simulated events as functions of different variables, as shown in figures ?? and 4.1. Figure ?? shows a clear structure in the pseudorapidity for the efficiency, which is expected due to the non-uniformity of the muon trigger system in η . The selection cut on the muon transverse momentum of 20 GeV ensures that the efficiency as a function of the transverse momentum is stable. The dependency on variables related to the activity in the event, the number of jets and the distance between muon and closest jet, is small. The efficiency as a function of the number of jets shows a drop for events with four or five jets in data, but a higher efficiency for events with more jets. Since statistics is still quite low, this can be caused by statistical fluctuations, which is supported by the non-existent dependency of the efficiency on the distance of the muon to the closest jet. Due to the detector structure, the efficiency as a function of ϕ , however, varies significantly, as shown in the upper part of figure 4.1. Moreover, the structure, and also the differences between data and simulation, are only visible for those muons that fall into the central part of the detector, i.e. $|\eta| < 1.05$, as shown in the lower part of figure 4.1. Further studies show that the efficiencies in data show the same features through all trigger levels, i.e. the differences between data and MC are dominantly caused by efficiency losses at L1.

Scale factors to calibrate MC simulated events are calculated as ratios of efficiencies for data and simulation in bins of pseudorapidity and ϕ . To estimate the systematic uncertainties on the scale factors, the selection requirements of the tag muon and the muon pair are varied and the change

¹²Since these analyses were carried out in parallel and only ratios are important where differences between data and MC cancel out

Figure 4.9.: Comparison of data and simulated events for the probe muons after the Tag & Probe selection algorithm as functions of the kinematic quantities of the probe and the number of jets in the event.

of the measured efficiency is obtained. However, if the variation has the same influence on data and simulated events, the uncertainties will cancel in the scale factor calculation. The following parameters are varied, all of them separately:

- no isolation requirement on the tag muon
- the trigger matching radius ΔR to 0.1 and 0.5
- $\Delta(m_{\mu\mu}, m_Z)$ to 10 and 15 GeV

The corresponding differences on efficiencies and scale factors are determined and the deviations from the central value are added in quadrature to calculate the overall systematic uncertainty.

For the first measurement of top quark pair production at ATLAS with 2.89 pb^{-1} [72] global scale factors for the barrel and the endcap region were calculated, due to limited statistics. In data the L1_MU10 and EF_mu10_MSonly triggers were used and compared to the EF_mu10_MSonly trigger chain in the Monte Carlo simulated events. The efficiencies are shown in table ?? and the corresponding scale factors in table ??, which were applied as global scale factor in the analysis.

Figure 4.10.: Trigger efficiencies measured with the Tag & Probe method for data and $Z \rightarrow \mu\mu$ simulated events as functions of the probe muon kinematics (p_T and η), as well as the distance of the muon to the closest jet and the number of jets in the event. The latter two serve to prove that the efficiency measurement is valid in the multijet environment characteristic for top quark physics.

Run Period	Barrel		Endcap	
	$\epsilon_{data}[\%]$	$\epsilon_{MC}[\%]$	$\epsilon_{data}[\%]$	$\epsilon_{MC}[\%]$
A-E3 (L1_MU10)	$74.6^{+3.0}_{-3.2}$	–	$84.8^{+2.4}_{-2.6}$	–
E4-F2 (EF_mu10_MSonly)	$70.6^{+1.8}_{-1.8}$	77.9 ± 0.1	$87.7^{+1.3}_{-1.8}$	90.0 ± 0.1

Table 4.3.: Trigger efficiencies for data and MC simulated events, the latter always relying on EF_mu10_MSonly, in the first 2.89 pb^{-1} of data taken by the ATLAS experiment in 2010. The uncertainties are statistical only.

For the data set of 35 pb^{-1} , the scale factor determination in bins of pseudorapidity and φ is possible, and is found necessary in the barrel region, as indicated in figure 4.1. The performance in the endcap

Figure 4.11.: Trigger efficiencies from the Tag & Probe algorithm for data and simulated events as a function of the ϕ -distribution of the probe muons. Clear differences can be seen between the efficiencies for data and MC, depending on the pseudorapidity of the muon. The upper plot shows efficiencies for all muons falling into the acceptance of $|\eta| < 2.5$. The lower left plot shows the efficiency for probe muons in the barrel region ($|\eta| < 1.05$) with higher granularity to highlight the differences between data and simulation following the exact arrangement of muon trigger stations along ϕ . The lower right distribution corresponds to muons in the endcap region $1.05 \leq |\eta| < 2.5$ and shows uniform efficiencies.

region is uniform, and no binning is necessary. In the barrel region, a dependency can be accounted for using nine different regions in the $\eta - \phi$ phase space, combining three sections in η with three

Run Period	Barrel	Endcap
A-E3 (L1_MU10)	$0.959^{+0.039}_{-0.041}$ (stat.) $^{+0.013}_{-0.002}$ (syst.)	$0.943^{+0.027}_{-0.029}$ (stat.) $^{+0.006}_{-0.010}$ (syst.)
E4-F2(EF_mu10_MSonly)	$0.906^{+0.023}_{-0.024}$ (stat.) $^{+0.011}_{-0.006}$ (syst.)	$0.975^{+0.014}_{-0.015}$ (stat.) $^{+0.006}_{-0.016}$ (syst.)
combined	$0.919^{+0.020}_{-0.020}$ (stat.) $^{+0.010}_{-0.003}$ (syst.)	$0.967^{+0.013}_{-0.013}$ (stat.) $^{+0.005}_{-0.012}$ (syst.)

Table 4.4.: Scale factors for the first 2.89 pb^{-1} of data taken by the ATLAS experiment in 2010. The combined result takes the relative weights of the integrated luminosities for the two data periods with different trigger settings into account.

sections in φ ¹³:

- η_1 : $-1.05 \geq \eta > -0.6$
- η_2 : $-0.6 \geq \eta \geq 0.6$
- η_3 : $0.6 > \eta \geq 1.05$
- φ_1 : $-\pi \geq \varphi > 5\pi/16$ or $11\pi/16 \geq \varphi < \pi$
- φ_2 : $5\pi/16 \geq \varphi > \pi/2$
- φ_3 : $\pi/2 \geq \varphi > 11\pi/16$

The bin ranges are chosen in such a way that within each bin no scale factor differs from the average scale factor in that bin by more than three standard deviations of the statistical uncertainty assuming 20 bins over the full φ range. The resulting scale factors with respect to EF_mu10_MSonly in Monte Carlo, integrated over the run periods E4-I2, are shown in table ??.

Detector Region	Scale Factor
Endcap	$0.993^{+0.003}_{-0.004}$ (stat.) $^{+0.001}_{-0.001}$ (syst.)
$\eta_1\varphi_1$	$0.970^{+0.015}_{-0.016}$ (stat.) $^{+0.003}_{-0.003}$ (syst.)
$\eta_1\varphi_2$	$0.797^{+0.047}_{-0.048}$ (stat.) $^{+0.018}_{-0.005}$ (syst.)
$\eta_1\varphi_3$	$0.940^{+0.044}_{-0.046}$ (stat.) $^{+0.004}_{-0.004}$ (syst.)
$\eta_2\varphi_1$	$0.964^{+0.007}_{-0.007}$ (stat.) $^{+0.003}_{-0.001}$ (syst.)
$\eta_2\varphi_2$	$0.829^{+0.023}_{-0.024}$ (stat.) $^{+0.005}_{-0.005}$ (syst.)
$\eta_2\varphi_3$	$0.884^{+0.022}_{-0.023}$ (stat.) $^{+0.003}_{-0.003}$ (syst.)
$\eta_3\varphi_1$	$1.036^{+0.015}_{-0.015}$ (stat.) $^{+0.002}_{-0.010}$ (syst.)
$\eta_3\varphi_2$	$0.769^{+0.046}_{-0.047}$ (stat.) $^{+0.004}_{-0.008}$ (syst.)
$\eta_3\varphi_3$	$1.001^{+0.041}_{-0.044}$ (stat.) $^{+0.004}_{-0.005}$ (syst.)

Table 4.5.: Scale factors with respect to EF_mu10_MSonly in simulated events for the 35 pb^{-1} taken in the run periods E4-I2 in the year 2010. The binning in the $\eta - \varphi$ phase space is described in the text.

¹³Due to a change of software releases and trigger chains used in the MC simulated events a slightly different binning is used for the scale factors finally used in the analyses presented in the remainder of this work, but the differences are found to be small.

During data taking in the year 2010 the performance of the trigger system evolved significantly over time, since the timing of the different systems, in particular, was carefully calibrated with data. Therefore, the trigger efficiency both increased and stabilized as a function of the data taken, as seen for the different run periods integrated over the full detector region and separated into barrel and endcap in figure ???. While the efficiency level on average is quite stable, the improvements in performance are clearly visible. Also visible is the change from EF_mu13 to EF_mu13_tight, the former seeded by L1_MU0, the latter by L1_MU10, after run period G, as a slight decrease in efficiency due to tighter level 1 trigger conditions.

Since beam conditions varied and the instantaneous luminosity increased significantly the influence of pile-up events has to be investigated. Figure ??? shows no dependency of the efficiency on the number of primary vertices in the event, a direct indicator of pile-up.

The validity of a scale factor obtained using $Z \rightarrow \mu\mu$ events in the phase space suitable for measurements of top quark pair production is tested on Monte Carlo simulated events and compatible trigger efficiencies are found for both cases. Since the trigger efficiency and the scale factor are independent of the number of jets and the distance between the muon and the closest jet, no additional correction needs to be applied for the extrapolation to top quark analyses.

For the analysis using 0.7 fb^{-1} of data taken in 2011 the same methodology was used to estimate scale factors. Due to the large amount of statistics available, in addition to a binning in $\eta - \varphi$ similar to the one presented above, several bins of the transverse momentum of the muon were introduced, accounting for a feature in the trigger modeling for high p_T muons in the simulation. Since not enough statistics is available at very high momentum in this case the analysis is limited to muons with $p_T < 150 \text{ GeV}$.

4.2.3. Electrons

4.2.3.1. Definition

Isolated electrons with a high transverse momentum, as expected in top quark pair production, are reconstructed using an algorithm seeded by clusters in the electromagnetic calorimeter. Two additional algorithms are available at ATLAS to reconstruct low- p_T -electrons, electrons inside jets from inner detector tracks and electrons in the forward region without any tracking information. The clusterization in the calorimeter is based on a *sliding window* algorithm, in which a fixed cone in $\Delta\eta \times \Delta\varphi$ is moved over the calorimeter cells and the position which yields the maximum energy deposition within the cone is chosen as the cluster position. Final clusters are built from these initial clusters and are used as seeds for the electron reconstruction. Matching the clusters to an inner detector track and shower shape distributions typical for electron induced showers are used to distinguish electrons from photons. In addition, information from the TRT detector based on the transition radiation is used to separate electrons from hadrons. Depending on a set of cuts on the shower shapes, the track matching and the existence of a hit in the innermost pixel layer, status words are used to distinguish good quality electrons from looser electron candidates [73].

Figure 4.12.: Time dependence of the trigger efficiencies for all probe muons within $|\eta| < 2.5$ (upper) and for muons in the barrel (lower left) and endcap (lower right) region. The increase in statistics and decrease in statistical uncertainty is visible, as well as the improvements of the trigger calibration over time. The uncertainties shown here are statistical uncertainties only.

4.2.3.2. Selection

In the context of the analyses presented only electrons reconstructed with the standard cluster-seeded algorithm are considered, requiring that they are of `tight_withtrackmatch` (35 pb^{-1}) or `tight` (0.7 fb^{-1}) quality with respect to the status words. Due to the so-called *crack region*, including the gaps in the calorimetry at the transition between barrel and endcap, electrons within this detector region are excluded. Therefore the electron acceptance in the analyses is limited to

Figure 4.13.: Trigger efficiency for the 35 pb^{-1} of data taken with the EF_mu10_MSonly, EF_mu13 and EF_mu13_tight triggers in the year 2010 as a function of the number of primary vertices in the event.

$|\eta| < 2.47$, excluding $1.37 \leq |\eta| \leq 1.52$, with η the pseudorapidity of the corresponding cluster in the electromagnetic calorimeter. The selection of the electron is based on its energy is applied to the transverse energy E_T , defined as $E_T = \frac{E_{cluster}}{\cosh(\eta_{track})}$, with cut values of 20 GeV (35 pb^{-1}) or 25 GeV (0.7 fb^{-1})¹⁴. The same definition for isolation in the calorimeter for muons, EtCone, is used for electrons as well to suppress background from misidentified electrons, but a correction of the transverse momentum is applied beforehand. The energy deposition in a cone of $\Delta R = 0.2$ is found to be $< 4 \text{ GeV}$ (35 pb^{-1}) or $< 3.5 \text{ GeV}$ with an additional correction for underlying pile-up events (0.7 fb^{-1}). Due to several hardware problems in the calorimeter, like dead or non-nominal HV channels, non-functioning front-end readout boards or noisy channels, certain detector regions are temporarily or permanently masked and excluded by the usage of *object quality maps*, checking the $\eta - \phi$ position of each cluster for each run period of stable detector conditions. During data taking in 2011 six neighboring front-end boards were lost for reconstruction when the corresponding controller board stopped working for the run periods E–H. This is taken into account for both data and simulated events by weighting the run periods with and without this *LAr hole* in the analysis.

¹⁴due to the higher trigger thresholds used for this analysis

4.2.3.3. Performance

The performance of the electron reconstruction and identification algorithms is tested in a similar fashion to the one for muons, by using $Z \rightarrow ee$ events to obtain a clean sample of highly energetic, isolated electrons. In addition, $W \rightarrow e\nu$ events can be used to enhance statistics, and $J/\Psi \rightarrow ee$ events add information about low- p_T -electrons [74]. Based on these studies the electron energy has to be smeared in Monte Carlo simulated events to match data in the dielectron mass distribution. In the data taken in 2010 an additional correction to the energy scale of the electrons had to be applied. The resolution of the invariant dielectron mass for a $Z \rightarrow ee$ selection after applying all corrections and the systematic uncertainties on the resolution are shown in figure ??.

Figure 4.14.: Resolution of the dielectron mass in a selection of events with a high probability to contain $Z \rightarrow ee$ decays, after applying all energy corrections for the full 2011 data set [75].

Reconstruction and identification efficiencies are estimated in data and Monte Carlo using the Tag & Probe method for the electrons as used in final analyses and translated into scale factors as described in equation ??, which are applied to the Monte Carlo simulated events.

The analysis using the data taken in 2010 applies an unbinned scale factor for the reconstruction efficiency of $SF_{\text{reco}} = 1.000 \pm 0.015$, while the identification scale factor, including all final selections applied at analysis level, is determined in six bins of transverse energy and eight bins of the pseudorapidity of the associated electromagnetic cluster. With higher statistics, as available for the analysis of data taken in 2011, a finer binning is possible, and the reconstruction scale factor is provided for three different regions of the pseudorapidity of the electron cluster, while the identification scale factor is broken up into 18 η -bins and 5 bins of the transverse energy.

4.2.3.4. Electron Triggers

Single electron trigger chains are used to pre-select events in the $e+\text{jets}$ channel of top quark pair production. The chains used for top analyses in the start-up phase of the LHC, like the first observation of top quark pairs at ATLAS [72], and for the analyses presented in this work are shown

in table ??.

Run Period	EF	L2	L1	$\int \text{Ldt}$	Comments
A-D (2010)	-	-	EM10	0.3 pb ⁻¹	not used for final analyses
E1-E3 (2010)	g17_etcut	g17_etcut	EM10	0.5 pb ⁻¹	not used for final analyses
E4-I2 (2010)	e15_medium	e15_medium	EM13	35 pb ⁻¹	
B2-G5 (2011)	e20_medium	e20_medium	EM18	0.7 fb ⁻¹	

Table 4.6.: Trigger chains used in the corresponding run periods for the data used in the presented measurement to select $e+jets$ events. The increased trigger threshold of 20 GeV for the 2011 data causes the offline selection criterion on electrons to be increased to 25 GeV.

The efficiencies of the triggers are estimated using the Tag & Probe method, as described in detail for muon triggers in section 4.2.2.4, using selections of $Z \rightarrow ee$ and $W \rightarrow e\nu$ events [74]. The efficiencies found in data are compared to simulated events using the e15_medium (2010) or e20_medium (2011) trigger chains. For the 2010 analysis an unbinned scale factor of $SF_{\text{trigger}} = 0.995 \pm 0.005$ is applied to the simulated events, while for the analysis using 0.7 fb⁻¹ of data taken in 2011, 18 bins in the pseudorapidity of the electron cluster are evaluated separately.

4.2.4. Jets

4.2.4.1. Definition

The jets used in the presented measurements are reconstructed using the *anti-kt* reconstruction algorithm [76] with a distance parameter of $R = 0.4$, which provides an infrared and collinear safe¹⁵ alternative to the cone algorithms widely used in the past. Topological clusters at the electromagnetic scale serve as inputs to the jet algorithm and are defined in a three-step procedure. First of all, the algorithm searches for calorimeter cells containing an energy deposition $E > T_1 \times \sigma$, where σ denotes the expected noise level of the corresponding cell and T_1 the applied threshold. Starting from these seeding cells all neighboring cells with $E > T_2 \times \sigma$ are added to the cluster, and in the final step the cells directly neighboring the outer bounds of the cluster are added if they fulfill the requirement of $E > T_3 \times \sigma$. The algorithm is used in the (4/2/0) configuration, describing the noise thresholds ($T_1/T_2/T_3$). Since the algorithm takes into account the noise level of each cell individually it is a powerful tool to suppress the influence of noise in the clusters. Before feeding the clusters into the jet reconstruction algorithm an additional splitting is applied if there are several local maxima, to account for several initial partons being grouped into the same cluster. The energy of the topological cluster at this step is the sum of energy deposition in the cells associated to the cluster.

¹⁵This means that the jet reconstruction is not dependent on additional soft gluon radiation between jets and not dependent on collinear splitting of the initial parton.

The reconstructed jets are then calibrated based on their pseudorapidity η and transverse momentum p_T from the electromagnetic to the hadronic scale to correct for energy losses due to the applied thresholds and due to the detector acceptance and non-active parts of the sampling calorimeters. Corrections for additional proton-proton interactions, i.e. pile-up, and for the origin of a jet from a vertex displaced from the center of the detector are applied additionally. The correction functions are derived from simulated events, and average energy scale corrections can be seen in figure ?? for jets in different detector regions.

Figure 4.15.: Average energy correction applied to jets with a certain transverse momentum in different η -ranges, as determined in Monte Carlo simulated events [77].

Since electrons will always be reconstructed as jets as well, the overlap between the two classes of objects has to be removed from the analysis. Therefore, only jets that do not overlap with an electron accepted for the analyses, as defined in section 4.2.3, within a radius of $\Delta R = 0.2$ are considered for the final analyses.

The analyses presented here group the selected events in terms of the jet multiplicity, the number of jets in an event that pass a certain selection. Using the reconstructed jets as described above, only jets within the central detector range of $|\eta| < 2.5$ and with a transverse momentum of $p_T > 25$ GeV are counted and jets with negative energy are discarded.

4.2.4.2. Performance

The performance of the jet reconstruction and calibration is validated in data events and with different techniques based on well understood event signatures, such as γ +jets, or balances between objects in different parts of the detector, as in dijet events [77]. In general, very good agreement is found and only for the analysis using data taken in 2010 an additional p_T -smearing of the jets is necessary to

account for remaining differences between data and simulation. The associated uncertainties on the calibration and reconstruction will be discussed in some detail in section 5.6.

4.2.4.3. b -Jet Tagging

Important for top physics, and used in the analysis of 35 pb^{-1} of data, is the ability to identify jets originating from b -quarks. Within the ATLAS collaboration several algorithms for the identification of b -jets, abbreviated as b -taggers, are available with different levels of complexity and performance. All algorithms make use of the fact that b -quarks have a lifetime of about 10^{-12} s , significantly longer than the lighter quarks. Therefore, jets containing B -hadrons can be identified by the direct presence of a secondary vertex in the event or tracks associated to jets that originate away from the primary vertex. The algorithms use different quantities, like the secondary vertex position or the impact parameter of tracks, and the performance of the algorithms can be further improved by using multivariate analysis techniques and combining several methods.

In the early data taking period, which is of relevance for the presented analysis, only relatively simple algorithms are considered and calibrated, namely the SV0 [78] and the JetProb [79] b -tagging algorithms. While most easy analyses in the top physics sector rely on the SV0 tagger, which uses a direct reconstruction of a secondary vertex associated to a jet, the 35 pb^{-1} analysis presented in this work uses information from the JetProb tagger.

In this algorithm the probability of each track associated to the jet under investigation to originate from the primary vertex is calculated using the signed impact parameter significance $S_{d_0} = \frac{d_0}{\sigma_{d_0}}$. This quantity is rather symmetric around zero for light jets, but favors positive values for jets originating from heavy quarks. The probability of a jet to contain no decay products from B -hadrons¹⁶ is then expressed as a product over the probability for all tracks to originate from the primary vertex and is used to classify a jet (JetProb). For further application, the distribution is transformed to $-\log_{10}(\text{JetProb})$.

Both the efficiency to correctly identify b -jets and the rate with which light jets are misidentified as b -jets, the *mistag rate*, have to be carefully measured in data and compared to the predictions in simulated events. This is typically done at one or more so-called *working points* of the algorithm, a certain value x of the output distribution at which the probability for a true b -jet to be identified as such is above a certain value $n\%$. For the JetProb algorithm the 50%, 70%, 80% and 90% efficiency¹⁷ working points are calibrated [80]¹⁸, which is crucial for the usage of the b -tagging in the presented analysis, as will be shown in more detail later, and is the driving factor for the choice of the b -tagging algorithm in this work.

The b -tag efficiency can be measured in different types of data samples: jet events with muons inside the jet, hinting at decays of heavy quarks, and $t\bar{t}$ events. However, the usage of $t\bar{t}$ events for calibration would create a correlation between assumptions made in the calibration and the measurement of the top quark pair production itself. Therefore, the results obtained with the p_T^{rel} method, which are available over the full jet p_T range, are used for the direct calibration, but also give a good agreement with the result obtained with the other methods [80]. The p_T^{rel} method is based on MC derived

¹⁶In general, the same algorithms can also be used to separate c -jets, but the separation power is significantly worse.

¹⁷the efficiency of a working point is derived in a simulated $t\bar{t}$ sample

¹⁸The results for the 50% and 70% efficiency working points are described in Reference [80], while the higher efficiency working points were calibrated later with exactly the same method.

template fits of the muon momentum transverse to the jet direction, that are applied in different p_T - and η -regions and determine the fraction of b -jets before and after a cut on the algorithm's output is applied. The results obtained with this method for data and Monte Carlo simulated events at the 50% efficiency working point are shown in figure ?? and the resulting correction factors obtained with different methods for both the 50% and 70% working points are shown in Figure ??.

Figure 4.16.: b -tagging efficiencies as a function of transverse momentum and pseudorapidity for the JetProb algorithm at the 50% efficiency working point, as measured using the p_T^{rel} method [80].

Figure 4.17.: Correction factors for simulated events to identify jets originating from B -hadrons correctly for the 50% and 70% working points of the JetProb algorithm, as obtained with several calibration methods on data, depending on the transverse momentum of the jet [80].

Similarly, the mistag efficiencies depending on the jet's transverse momentum and its pseudorapidity are measured in an inclusive jet sample. Two different methods are used [80], based on either the mass distribution of a secondary vertex or on the negative part of the impact parameter significance distribution for the tracks in the jets. Data and Monte Carlo predictions are compared and translated

into scale factors to be applied for final measurements accordingly,

$$SF_{WP}(\text{flavor}, p_T, \eta) = \frac{\mathcal{P}_{\text{data},WP}(\text{flavor}, p_T, \eta)}{\mathcal{P}_{\text{MC},WP}(\text{flavor}, p_T, \eta)}, \quad (4.3)$$

where $\mathcal{P}_{\text{data},WP}$ describes the tagging¹⁹ probability at the working point WP as measured in data and $\mathcal{P}_{\text{MC},WP}$ the same quantity in simulated events.

When used in the standard way of applying a cut on a certain output value of the b -tagging algorithm and requiring one or more jets to be identified as b -jets by this method, the scale factors for each jet in the simulated samples are obtained depending on the true flavor of the jet²⁰. If the algorithm output lies above the cut-off of the working point, the associated weight ω_j of the jet corresponds to the scale factor, while an inefficiency scale factor for jets is formulated based on the Monte Carlo simulated tagging probabilities²¹ for this jet and the scale factor at a working point

$$\omega_j = \frac{1 - \mathcal{P}_{\text{data}}(\text{flavor}, p_T, \eta)}{1 - \mathcal{P}_{\text{MC}}(\text{flavor}, p_T, \eta)} = \frac{1 - SF(\text{flavor}, p_T, \eta) \times \mathcal{P}_{\text{MC}}(\text{flavor}, p_T, \eta)}{1 - \mathcal{P}_{\text{MC}}(\text{flavor}, p_T, \eta)}. \quad (4.4)$$

The event weight correction from b -tagging calibration is then the product over the ω_j for all selected jets in the event.

In this case, only the b -tag and mistag scale factors for the working point of choice need to be known together with the MC based tagging efficiencies. However, as will be discussed in detail in chapter 6, the analysis of the data taken in 2010 uses the output of the b -tagging algorithm JetProb as a discriminating variable to separate $t\bar{t}$ events from background events, instead of requiring a certain number of jets identified as b -jets. The rate of selected events remains unchanged, but the shape of the distribution has to be corrected with scale factors to account for differences in data and simulation. For that reason the scale factor per jet in simulated events is not only defined based on the transverse momentum, the pseudorapidity and the true flavor of the jet, but additionally separated in terms of the output value of the JetProb algorithm for this jet. For a jet with a b -tagging probability below the lowest available working point (50%), the inefficiency scale factor for this working point as defined above is applied, and for a jet with an output value above the highest efficiency working point (90%) the weight corresponding to the scale factor of this working point is applied. In between, the following formula is valid, in the corresponding (flavor, p_T , η) bin of the jet,

$$SF_{xy} = \frac{\mathcal{P}_{\text{data},WP_x} - \mathcal{P}_{\text{data},WP_y}}{\mathcal{P}_{\text{MC},WP_x} - \mathcal{P}_{\text{MC},WP_y}} = \frac{\mathcal{P}_{\text{MC},WP_x} \times SF_x - \mathcal{P}_{\text{MC},WP_y} \times SF_y}{\mathcal{P}_{\text{MC},WP_x} - \mathcal{P}_{\text{MC},WP_y}}, \quad (4.5)$$

for a jet with a JetProb output $x \geq -\log_{10}(\text{JetProb}) > y$, i.e. the b -tagging algorithm classifies the jet as in between the two working points. This formalism is valid for any number of working points available, but more points will obviously improve the agreement in shape between data and simulated events. For this reason, the JetProb algorithm is chosen over the SVO algorithm for the presented analysis, although the performance in terms of separation power for the two algorithms is rather similar.

The event weight is again calculated as a product over the jet weights ω_j , and a good agreement of data and simulation has to be achieved in control regions before being able to apply this procedure

¹⁹or mis-tagging, in case of light jets

²⁰The jets are classified as B, C or N/A, for light jets, based on their origin in the event generation.

²¹The MC based b -tagging efficiencies are derived using $t\bar{t}$ Monte Carlo simulated events.

in the final analysis, which will be shown in the corresponding chapter 6.

The analysis of data taken in 2011 does not use any b -tagging information for selection or signal discrimination.

4.2.5. Missing Transverse Energy

A significant amount of missing transverse energy is expected for events in the ℓ +jets channel of top quark pair production, since the neutrino from the W boson decay escapes the detector without any trace. In top analyses, an object based reconstruction algorithm, referred to as `ReFFinal`, is used to determine the amount of missing transverse energy from the energy imbalance of an event. In this approach, topological clusters in the calorimeter, as described in section ??, with initial calibration at the electromagnetic energy scale are used as a starting point. Clusters associated to the basic physics objects (electrons²², jets) with the same definitions as for usage in the final analyses, are included in the calculation of missing transverse energy at their corresponding energy scales, i.e. clusters associated to jets are calibrated to the hadronic scale as described above. In addition to the jets with high transverse momentum as selected for analyses, low p_T , or *soft*, jets with $p_T < 20$ GeV are included at the electromagnetic scale, as well as clusters not associated to any of the physics objects, called *cell out* terms. Muons, again reconstructed in the same way as for the analyses, are included with their transverse momentum as measured by the muon track. The energy deposition of a muon traversing the calorimeter as minimal ionizing particle is included as well. The components of missing energy ($i = x, y$) can then be expressed as the sum of terms

$$E_i^{\text{miss}} = E_i^\mu + E_i^e + E_i^{\text{jet}} + E_i^{\text{soft jet}} + E_i^{\text{cell out}}, \quad (4.6)$$

and translated into the transverse quantity

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}, \quad (4.7)$$

with E_i^{obj} the sum of the energies of all corresponding objects in that event.

The associated weights with which each physics object enters the missing energy calculation, are stored and used to correct missing transverse energy accordingly, when correcting resolutions and energies of jets, electrons or muons. This feature is an advantage of the object based definition of missing transverse energy: whenever any of the physics objects needs to be changed or corrected, the change can be easily propagated into missing transverse energy.

²²with $p_T > 10$ GeV

4.3. Physics Processes And Modeling

4.3.1. Event Simulation

Regardless of the exact physics process, the procedure to generate simulated events for comparison with data and for the development of the analysis remains the same. Based on the inputs from different event generators, as described in more detail in the following sections, the detector response is simulated with GEANT4 [81]. The same reconstruction methods for the physics objects are applied to data and simulated events and both are fed through the identical analysis chain.

Due to the high interaction rates at the LHC, additional pp interactions coincide with the pp collision of interest. To describe these *pile-up* events in the simulated samples, minimum bias events generated with PYTHIA6 [82] are added to the initial events at the digitization step before the reconstruction. The beam conditions vary significantly for the data taken in the year 2010 and the data sample from 2011. This is taken into account by different pile-up configurations in the simulated events used in the analyses. For the 2010 analysis a bunch spacing of 150 ns is assumed in a double bunch train configuration, where the trains are separated in time by 225 ns. The amount of pile-up significantly increased over the course of data taking in 2011, and the Monte Carlo is generated with a bunch spacing of 50 ns.

Remaining differences between data and simulation are accounted for in a reweighting procedure of the simulated events, see section 4.2.1.5, either for the default settings (2011) or as a source of systematic uncertainties (2010), based on the number of primary vertices, and the configurations are weighted differently for each run period.

4.3.2. Signal Process – Top Quark Pair Production

4.3.2.1. Monte Carlo Model

Top quark pair production is simulated using the MC@NLO event generator [83] version v3.41 interfaced with HERWIG [84](v6.510) and JIMMY [85] to model the parton showering and the underlying event. The CTEQ66 [22] model of the parton distribution function is used for this process, and the showering uses a corresponding CTEQ66 HERWIG tune and an ATLAS specific tuning for JIMMY, AUET1 [86]. The assumed central value for the top quark mass is $m_t = 172.5$ GeV. The sample is split into a subsample including only the all-hadronic decay channel, not used in the analyses, and another sample containing the dileptonic and the lepton+jets channels.

While the setup with MC@NLO predicts an inclusive top quark pair production cross section at NLO plus parton shower, more precise predictions for the total rate of top quark pair production are available at approximate NNLO, see section 2.3.1.1, the simulated $t\bar{t}$ sample is rescaled via a so-called *k-factor* to the prediction from the Langenfeld *et al.* [24, 25] calculations evaluated with the Hathor framework [26], $\sigma_{t\bar{t}} = 164.6_{-9.3}^{+4.3}(\text{scale})_{-6.5}^{+7.2}(\text{PDF})$ pb. The *k-factor* also includes a correction factor for the $W \rightarrow \ell\nu$ decay branching ratio, since MC@NLO event generation was performed assuming a branching ratio of 0.111 per flavor instead of the correct value of 0.108 [1].

In addition to this central sample used for the design of the analyses, several samples are generated with varied settings and generators to estimate systematic uncertainties caused by the differences

between models. To study the differences between available NLO signal generators, $t\bar{t}$ production is also modeled using POWHEG [87], interfaced both with HERWIG/JIMMY and PYTHIA to also compare the impact of different parton shower models.

Since none of the NLO generators for $t\bar{t}$ production allow for variation of the amount of initial- and final-state-radiation²³, ACERMC [88] samples with PYTHIA showering are generated with default settings for ISR and FSR as well as samples, where the corresponding parameters in PYTHIA²⁴ are varied by a factor $\frac{1}{2}$ and 2 either separately for ISR and FSR or for both at the same time. The PDF set MRST2007LOMOD [29] is used in the generation of these samples.

Finally, to estimate the dependence of the measurements of $\sigma_{t\bar{t}}$ on the top quark mass samples are produced with MC@NLO and HERWIG/JIMMY showering at all mass points between 140 and 210 GeV in steps of 10 GeV, and at $m_t = 165, 167.5, 175$ and 177.5 GeV. NNLO cross sections for different mass points are obtained using Hathor and the samples are rescaled accordingly.

4.3.3. W/Z Boson Production With Additional Jets

4.3.3.1. Signatures

The dominant background to $t\bar{t}$ production in the lepton+jets channel arises from the production of a W boson, decaying leptonically, in association with additional jets. The additional jets can either be light jets or originate from heavy c or b quarks (Wc ²⁵, $Wc\bar{c}$, $Wb\bar{b}$), the latter producing final states identical to that of a top quark pair. The production of a Z or γ^* boson²⁶ with additional jets contributes to a smaller extent to the lepton+jets final state, since leptonic $Z(\gamma^*) \rightarrow \ell\ell$ decays produce two charged leptons, while a typical lepton+jets selection requires exactly one. Heavy quark production in addition to the Z boson can occur in the same way as for W bosons, but the contribution from these events is found to be small as long as no explicit selection of events with jets identified by a b -tagging algorithm is applied. Therefore it is not considered separately in the presented analyses.

Cross sections are calculated using FEWZ [89] at next-to-next-to-leading order for the inclusive $W \rightarrow \ell\nu$ boson production to be $\sigma_W = 10.46 \pm 0.52$ nb and for the inclusive $Z(\gamma^*) \rightarrow \ell\ell$ boson production to be $\sigma_Z = 1.070 \pm 0.054$ nb in the range $40 \text{ GeV} < M_{\ell\ell} < 2000 \text{ GeV}$, which is of relevance here.

4.3.3.2. Monte Carlo Model

The hard process for W/Z +jets is modeled using the leading-order event generator ALPGEN [90], version v2.13, with the underlying event and parton showering provided by HERWIG/JIMMY in the same configuration as for $t\bar{t}$ production. MLM matching [90] is applied to match the matrix elements from ALPGEN with the parton showers using clustering parameters of RCLUS = 0.7 and ETCLUS = 20

²³abbreviated as ISR and FSR

²⁴For the analysis based on data from 2011 additional samples are available with intermediate parameter variations.

²⁵used synonymously for Wc and $W\bar{c}$ production

²⁶Since the resulting final states are indistinguishable for Z and γ^* boson production, both will be referred to as Z boson production in the remainder of this work.

GeV. The leading-order parton distribution functions from CTEQ6L1 [91] are used in the generation of the hard process. ALPGEN is used with minimum parton transverse momentum of 15 GeV and an angular separation of $\Delta R = 0.7$ for the additional light jets. Variations of the parameters and the factorization and renormalization scales used will be discussed as sources of systematic uncertainties in section ???. No filtering is applied for W +jets production, but Z +jets production is limited to the range of $40 \text{ GeV} < M_{\ell\ell} < 2000 \text{ GeV}$. The samples for W/Z +jets production are available for the different decay flavors $W \rightarrow e\nu$ ($Z \rightarrow ee$), $W \rightarrow \mu\nu$ ($Z \rightarrow \mu\mu$) and $W \rightarrow \tau\nu$ ($Z \rightarrow \tau\tau$) separately, and are divided into the exclusive $2 \rightarrow 2$ to $2 \rightarrow 6$ modes, i.e. $W/Z+0$ partons up to $W/Z+4$ partons, while the $2 \rightarrow 7$ process is generated inclusively. These leading-order samples are finally scaled to the NNLO predictions using k -factors, as given above.

The production of a W boson in association with jets from heavy quarks is modeled separately, also with ALPGEN and HERWIG/JIMMY with the parameters as listed above. Processes up to $2 \rightarrow 6$ exclusively and $2 \rightarrow 7$ inclusively exist, which means samples are available for $Wb\bar{b}/Wc\bar{c}+0$ partons up to +3 partons, and $Wc+0$ partons up to +4 partons. Due to the high cross sections, Wc samples are generated with additional cuts on the c -jets: a minimum parton transverse momentum of 10 GeV and the distance ΔR between c -jet and light jet above 0.7. $Wb\bar{b}$ and $Wc\bar{c}$ samples are generated without phase space cuts.

The W +heavy flavor jet samples are rescaled using the same k -factor as the W +jet samples, assuming that the relative difference between LO and NNLO cross sections is independent of the jet flavor.

4.3.3.3. Heavy Flavor Overlap Removal

A significant overlap between the samples for W +jets and W +heavy flavor jets exists, since b - and c -jets can be created as additional jets in the parton shower in the W +jet sample, and also directly in the matrix element calculations in the dedicated samples with heavy flavor jets. To be able to use both samples in analyses correctly, this overlap between events has to be removed. Since the matrix element calculation gives the best results at large angles between quarks, while parton shower modeling is more accurate for collinear effects, the events are classified based on the distance between the jets, ΔR . Events are removed from the W +light flavor sample if there are pairs of heavy flavor quarks with $\Delta R > 0.4$ added from the parton shower. Events from the Wc +jets samples are discarded, if the parton shower produces a heavy quark pair with $\Delta R > 0.4$ and $Wc\bar{c}$ +jets are vetoed against if either the $c\bar{c}$ pair in the matrix element is simulated with $\Delta R < 0.4$ or if the parton shower adds a $b\bar{b}$ pair with $\Delta R > 0.4$. Finally, events are removed from the $Wb\bar{b}$ +jets samples if the $b\bar{b}$ pair created in the matrix element fulfills $\Delta R < 0.4$.

4.3.3.4. Data-Driven Estimations of W +Jets Production

W +Heavy Flavor Jets Scale Factors

In both presented analyses the normalization of W +jets production is determined by the final fit to extract $\sigma_{t\bar{t}}$ directly, but the ratio of W +jets with heavy flavor jets compared to W +light jets was found to be not modeled correctly by the Monte Carlo predictions and is therefore corrected beforehand. Scale factors to correct the heavy flavor fraction of events are derived in $W+2$ jets events by comparing data and prediction in several flavor sensitive distributions, like the secondary

vertex mass distribution. They are then extrapolated to the higher jet multiplicities as needed for signatures in top quark pair production. For the analysis based on 35 pb^{-1} of data taken in 2010 a scale factor of $SF_{Wb\bar{b}/Wc\bar{c}} = 1.30 \pm 0.65$ is derived and applied for all studies and results, taking the uncertainties into account for the estimation of systematic uncertainties of the final result. Since the total W +jets cross sections have to be preserved, the W +light flavor samples are assigned a scale factor as well, keeping the number of W +jets events conserved. For the analysis using 0.7 fb^{-1} of data from 2011, similar studies found the need to increase the $Wb\bar{b}/Wc\bar{c}$ fraction by a factor of $SF_{Wb\bar{b}/Wc\bar{c}} = 1.63 \pm 0.76$ and the fraction of Wc events by a factor of $SF_{Wc} = 1.11 \pm 0.35$ compared to the predictions from ALPGEN. Again, W +light jet samples are then rescaled accordingly to preserve the total number of W +jets events.

W +Jets Normalization From Charge Asymmetry

For the 0.7 fb^{-1} analysis, instead of using the rescaled ALPGEN to NNLO cross sections for control distributions and as the starting value for the cross section extraction a data-driven estimation of the W +jets background is used. The larger uncertainties from the Monte Carlo predictions are still considered. This data-driven estimation is based on the charge asymmetry in W boson production at the LHC. Since W bosons are produced in $q\bar{q}$ -annihilation, the mode $u\bar{d} \rightarrow W^+$ has a higher probability than the mode $\bar{u}d \rightarrow W^-$, because the colliding protons contain two up quarks, but only one down quark as valence quarks. This difference in W^+ and W^- boson production is well understood and can be identified with the lepton charge in the final states under study, in which all other contributing processes are charge symmetric. This fact can be used to extract scale factors accounting for different normalization of W +jets events in data and Monte Carlo simulated events and is exploited in bins of jet multiplicity after the full event selection is applied. The results obtained with this method for the e +jets and the μ +jets channels in 0.7 fb^{-1} of 2011 ATLAS data are shown in table ?? for different jet multiplicities and explained in general in [92].

N_{jets}	μ +jets	e +jets
= 1 jet	0.983 ± 0.034	0.948 ± 0.080
= 2 jets	0.942 ± 0.076	0.907 ± 0.058
= 3 jets	0.870 ± 0.097	0.881 ± 0.123
= 4 jets	0.849 ± 0.142	0.839 ± 0.166
≥ 5 jets	0.687 ± 0.180	1.098 ± 0.331

Table 4.7.: Scale factors to be applied to selected W +jets events, following the event selection outlined in section 7.2, for different jet multiplicities and lepton flavors.

4.3.4. Other Electroweak Backgrounds

4.3.4.1. Single Top Quark Production

Monte Carlo Model

Single top quark production, as described in section 2.3.1.2, is generated at $m_t = 172.5 \text{ GeV}$ using

the MC@NLO generator with the CTEQ66 set of parton distribution functions and HERWIG/JIMMY showering. The s -, t - and Wt - processes are generated separately and the samples are rescaled to the corresponding NNLO production cross sections. Samples with different top quark masses are available in the range [140, 210] GeV in steps of 10 GeV, but no NNLO calculations are available for different masses. If the mass variation samples are used, the NLO cross section is assumed at all mass points as obtained from MC@NLO and cross-checked with MCFM[93].

4.3.4.2. Diboson Production (WW , WZ , ZZ)

Signature

A small amount of background to the measurement of top quark pair production stems from diboson production in all flavors of the charged gauge bosons of electroweak interaction, the W and Z bosons. Both, the W and the Z bosons can decay leptonically or hadronically in the configurations (WW), (WZ) and (ZZ), but while a leptonic $Z \rightarrow \ell\ell$ decay always yields two charged leptons²⁷, the $W \rightarrow \ell\nu$ decay produces a charged lepton and, through the neutrino, a significant amount of missing transverse energy. The other boson can create two jets, leading to a signature very similar to top quark pair production²⁸.

Production cross sections at next-to-leading order are calculated using MCFM [93] to be $\sigma_{WW} = 44.9 \pm 2.2$ pb, $\sigma_{WZ} = 18.5 \pm 1.3$ pb and $\sigma_{ZZ} = 9.23 \pm 0.46$ pb, limited to $m_Z > 60$ GeV when a Z boson is produced.

Monte Carlo Model

The contribution from diboson production is estimated using events simulated with MC@NLO and HERWIG for parton showering. The samples are pre-filtered to only contain events with at least one charged lepton with $p_T > 10$ GeV and $|\eta| < 2.8$ and are rescaled to next-to-leading order cross sections as given above, taking the filter efficiencies into account.

4.3.5. QCD Multijet Background

4.3.5.1. Signature

The last class of background processes to top quark pair production originates from QCD multijet processes with misidentified isolated charged lepton. Events with b -jets, containing muons or electrons, in-flight decays of charged pions or kaons and photons, likely to be misidentified as electrons, contribute significantly to this background. Even though the probability to misidentify a jet as a charged, high- p_T , isolated lepton is low, the high cross section for QCD multijet production makes this source of background contribute significantly to the selected sample. By requiring a certain amount of missing transverse energy and a cut on the transverse W boson mass, this source of background can be further reduced, but has to be carefully evaluated. The estimation of this background from simulated events is rather difficult, since the rate at which so-called *fake* leptons are reconstructed is

²⁷while $Z \rightarrow \nu\nu$ does not produce any

²⁸In the case of ZZ production only if one charged lepton is not reconstructed and selected for the analysis.

not well modeled by the GEANT detector simulation. Therefore, data-driven techniques to estimate the contribution from QCD multijet production have to be put in place and are used for all QCD multijet predictions in this thesis.

4.3.5.2. Data-Driven Estimation

Estimation in the Muon+Jets Channel

The dominant source of *fake* muons in QCD multijet events are in fact not fakes, but real muons produced as decay products of B -hadrons inside of jets. They are referred to as *non-prompt*, since they are produced not at the primary interaction vertex but only in the showering process leading to jets. Since the discrimination of non-prompt muons and prompt muons stemming from the hard interaction is based on variables indicating the *isolation* of the muons in terms of energy deposition and distance, these variables need to be well understood to estimate the backgrounds, see section 4.2.2.2. The measurement of the contribution from QCD multijet background is based on the so-called *matrix method*, distinguishing between *tight* muons passing all isolation criteria and *loose* muons passing only a subset of the isolation criteria. Distinguishing *real* (prompt) and *fake* (non-prompt) muons, the method is based on the formulas²⁹

$$N^{\text{loose}} = N_{\text{real}}^{\text{loose}} + N_{\text{fake}}^{\text{loose}} \quad (4.8)$$

and

$$N^{\text{tight}} = \epsilon_{\text{real}} N_{\text{real}}^{\text{loose}} + \epsilon_{\text{fake}} N_{\text{fake}}^{\text{loose}}, \quad (4.9)$$

and the efficiencies for a loose real and fake muon to fulfill the criteria of the tight selection, i.e.

$$\epsilon_{\text{real}} = \frac{N_{\text{real}}^{\text{tight}}}{N_{\text{real}}^{\text{loose}}} \quad (4.10)$$

and

$$\epsilon_{\text{fake}} = \frac{N_{\text{fake}}^{\text{tight}}}{N_{\text{fake}}^{\text{loose}}}. \quad (4.11)$$

Once ϵ_{real} and ϵ_{fake} are measured in samples containing only real or only fake muons, which will be described in detail in the following, the number of fake muons passing the tight muon selection can be determined as

$$N_{\text{fake}}^{\text{tight}} = \frac{\epsilon_{\text{fake}}}{\epsilon_{\text{real}} - \epsilon_{\text{fake}}} (N_{\text{real}}^{\text{loose}} \epsilon_{\text{real}} - N^{\text{tight}}) \quad (4.12)$$

or translated into weights or probabilities for loose muons to also be identified as tight muons.

The work described in the following relates to measurements and studies using the 35 pb^{-1} of data taken in 2010 and the associated object definitions, but the same methods were also used³⁰ in the larger data set from 2011 and will be summarized at the end of the section.

The selected analysis muons, as defined in section 4.2.2, are referred to as *tight* in the following, while the *loose* muons are selected by the same criteria, but only have to fulfill the isolation criterion of $\Delta R(\mu, j) > 0.4$, and not the requirements based on energy depositions around the muon axis, $E_{\text{T}}\text{Cone30} < 4 \text{ GeV}$ and $P_{\text{T}}\text{Cone30} < 4 \text{ GeV}$. It is important to choose the definition of a loose

²⁹which can be interpreted as a matrix of equations that is to be solved

³⁰by others

muon in such a way that the tight requirement yields a significant reduction of fake muons, since otherwise statistical fluctuations have too much influence on the efficiencies and hence the predicted number of QCD multijet events in the signal region. As shown in figure ??, the calorimeter and track based isolation requirements offer complementary information of the $\Delta R(\mu, j)$ variable in a QCD multijet dominated minimum bias sample. The efficiencies for loose real and fake muons to also fulfill the additional isolation requirements have to be measured in control regions of the phase space offering a background free sample of real or fake muons. To measure ϵ_{real} , i.e. the efficiency for real muons, the same strategy as for measuring trigger and reconstruction efficiencies is used, the Tag & Probe method in a sample of $Z \rightarrow \mu\mu$ events, as described in detail in section 4.2.2.4 for the 35 pb^{-1} data set.

The dependency of the efficiency for a real muon on its kinematic quantities is checked as a function of several parameters and shown in figure ??. The average efficiency is found to be 97.8%, with only a small dependency on the pseudorapidity of the muon.

Figure 4.18.: Efficiency for a real, prompt muon fulfilling the loose selection criteria as defined above, to also fulfill the tight selection criteria $E_{\text{T}}^{\text{Cone30}} < 4 \text{ GeV}$ and $P_{\text{T}}^{\text{Cone30}} < 4 \text{ GeV}$, as a function of the muon’s transverse momentum and pseudorapidity.

The measurement of the similar efficiency for fake, or non-prompt, loose muons requires a careful selection of a QCD multijet enriched control region. Typical choices of control regions include reversal of those selection cuts applied to the final event selection in the analysis, that are used to suppress the QCD multijet background, specifically cuts on the missing transverse energy or the leptonic W boson transverse mass. A control region of $E_T^{\text{miss}} < 10 \text{ GeV}$ was used for the first measurement of top quark pair production at ATLAS [72], but contribution from real muons to this control region was found to be quite high. If used, an iterative procedure to subtract the contribution from real muons in $W/Z + \text{jets}$ is found to be necessary. Therefore, two different control regions, CR1 and CR2, yielding a more stable and background-free environment, are presented here and used for the analyses³¹. In both cases only events containing at least one loose muon with $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$ and at

³¹while a study in the $E_T^{\text{miss}} < 10 \text{ GeV}$ region was carried out separately and yields very comparable results

least one jet with $p_T > 25$ GeV and $|\eta| < 2.5$ are considered. The control regions are then defined as follows, with d_0 being the impact parameter of the track with respect to the primary vertex and

$$m_T(W) = \sqrt{2(p_T^\mu \times E_T^{\text{miss}} - p_x^\mu \times E_x^{\text{miss}} - p_y^\mu \times E_y^{\text{miss}})}, \quad (4.13)$$

- CR1: $m_T(W) < 20$ GeV and $m_T(W) + E_T^{\text{miss}} < 60$ GeV
- CR2: $d_0^{\text{sig}} = \frac{d_0}{\sqrt{\text{cov}(d_0)}} > 3$

While the selection for CR1 is fully orthogonal to the event selection used in the μ +jets channel, which includes a cut on $m_T(W) + E_T^{\text{miss}} > 60$ GeV, CR2 is not, but the background contribution from real muons is found to be extremely low based on MC simulated events. Background contributions for both control regions are estimated using Monte Carlo predictions for W/Z + jets events, see figure ?? and subtracted from data to create a pure QCD multijet event sample to be used in the fake efficiency estimation, as listed in table 4.1.

Figure 4.19.: Number of selected loose muons in data and the amount of predicted real muons in the control regions CR1 and CR2, which is then subtracted before the fake efficiency is determined. The last bin in the figure for the d_0 significance indicates the overflow bin, i.e. the distribution has a long tail towards higher values.

Process	CR1	CR2
Data	92718	16505
W+Jets	1621	180
Z+Jets	2344	71
Data after subtraction	88753	16254

Table 4.8.: Number of selected loose muons in the control regions CR1 and CR2 before background subtraction, the number of predicted real muons from W/Z +jets events and the amount of loose muons after background subtraction, all for 35 pb^{-1} of data.

The fake efficiency is then measured as described in equation ?? and can be displayed as a function of several kinematic quantities of the muons, as shown in figure 4.2. A clear dependency on $|\eta(\mu)|$ is visible, while the fake rate is quite stable as a function of $\varphi(\mu)$ and other kinematic quantities. Therefore, ϵ_{fake} is parameterized in eight bins of the pseudorapidity with the values given in table 4.2.

Figure 4.20.: Efficiency for a loose fake muon to also pass the requirements, $E_{\text{T}}\text{Cone30} < 4$ GeV and $P_{\text{T}}\text{Cone30} < 4$ GeV, for a tight muon, as a function of the muon kinematics η and φ obtained in 35 pb^{-1} of data using two different control regions, as indicated in the histograms.

Detector Region	$\epsilon_{\text{fake}}^{\text{CR1}}$	$\epsilon_{\text{fake}}^{\text{CR2}}$
$0.0 \leq \eta < 0.3$	0.346	0.255
$0.3 \leq \eta < 0.6$	0.343	0.285
$0.6 \leq \eta < 0.9$	0.342	0.291
$0.9 \leq \eta < 1.2$	0.365	0.301
$1.2 \leq \eta < 1.5$	0.384	0.332
$1.5 \leq \eta < 1.8$	0.341	0.301
$1.8 \leq \eta < 2.1$	0.297	0.243
$2.1 \leq \eta < 2.5$	0.272	0.233

Table 4.9.: Fake efficiencies as measured in data for different detector regions in $|\eta(\mu)|$, obtained in the control regions CR1 and CR2.

A visibly higher fake efficiency is measured in CR1, the data sample with significantly larger available statistics and slightly higher backgrounds from real muons. A possible explanation for the differences can be seen in figure 4.3, where the fake efficiencies are shown as a functions of the two variables defining the control regions, $m_T(W)$ and d_0^{sig} . While the fake efficiencies from both control regions are stable within statistical uncertainties as functions of $m_T(W)$, the fake efficiency obtained in CR1 shows a clear dependency on the parameter d_0^{sig} for values below the cut at $d_0^{\text{sig}} = 3$ used to define CR2. For $d_0^{\text{sig}} > 3$ both efficiencies are stable and agree very well with each other. Since high

values of d_0^{sig} identify very pure QCD multijet events, especially those with heavy flavor jets including non-prompt muons, the conclusion can be drawn that the region with $d_0^{sig} < 3$ is still contaminated by real muons, which have a higher probability to fulfill the tight requirements and lead to an increase of the fake efficiency. This presumption is further justified by a study done varying both the amount of W/Z +jets contribution and also the relative fraction of W boson production in association with heavy quarks. In both cases, the fake efficiencies obtained in CR1 show a higher, but still small variation than the efficiencies from CR2. Furthermore, if contributions from real muons are not subtracted at all an increase of the fake efficiency is observed for muons with $d_0^{sig} < 3$, but only marginally in the region $d_0^{sig} > 3$.

Figure 4.21.: Efficiency for a loose fake muon to pass the requirements, $E_{tCone30} < 4$ GeV and $P_{tCone30} < 4$ GeV, for a tight muon, as a function of the variables indicating the respective control regions, d_0^{sig} and $m_T(W)$. Fake efficiencies agree for both control regions for very pure QCD multijet events in the region with a high d_0^{sig} value.

Finally, the stability of the fake efficiency measurement can be checked by varying different conditions, like the smearing of jets or muons, which both yielded no difference in the measured efficiencies. The dependency on the detector conditions and on the amount of pile-up events can be tested by further splitting of the data sample into the different run periods, as shown in figure ??, and looking at the average efficiencies, which also agree very well within statistical uncertainties.

To translate the efficiencies into predictions for the amount of QCD multijet events in the signal region, an $|\eta|$ -binned reweighting is applied to a selection of data events passing the standard selection of an analysis, but only requiring a loose, instead of a tight, muon. Based on $|\eta(\mu)|$ and the information if the muon fulfills the tight requirements, a weight is calculated as

$$\omega_{MM}(|\eta|) = \frac{\epsilon_{\text{real}}(|\eta|) \times \epsilon_{\text{fake}}(|\eta|)}{\epsilon_{\text{real}}(|\eta|) - \epsilon_{\text{fake}}(|\eta|)} \quad (4.14)$$

Figure 4.22.: Fake efficiencies for the control regions CR1 and CR2 divided into the different run periods, i.e. time frames of stable detector conditions. No obvious dependency can be spotted.

for loose muons failing the tight requirements, and

$$\omega_{MM}(|\eta|) = \frac{(\epsilon_{\text{real}}(|\eta|) - 1) \times \epsilon_{\text{fake}}(|\eta|)}{\epsilon_{\text{real}}(|\eta|) - \epsilon_{\text{fake}}(|\eta|)} \quad (4.15)$$

for loose muons fulfilling also the tight requirements. Each event is then considered with the weight associated to the selected muon. The advantage of this method is that due to the reweighting the events can be easily handled in the further steps of the analysis, also predicting the shapes of the QCD multijet background, instead of only predicting an overall rate.

For the event selection, which will be described in detail in section 6.2, this corresponds to the results shown in table ??.

While the overall agreement between predictions and the selected data events will be shown in chapter 6 in detail, a good way to test the quality of the QCD multijet predictions is to look at distributions for the final event selection before the cut to discriminate against QCD, namely $m_T(W) + E_T^{\text{miss}} > 60 \text{ GeV}$, is applied. Distributions for signal and control regions, obtained with both QCD multijet estimates, are shown in figures 4.4 and 4.5. The uncertainty assigned to the estimation is 30%, based on comparisons within the two control regions and with results from a third measurement, using the control region $E_T^{\text{miss}} < 10 \text{ GeV}$. The difference of up to 30% between the results obtained with different control regions is more conservative than systematic uncertainties obtained from variations in the selection and modeling. Figure 4.5 shows an overall good agreement of the distributions for data and Monte Carlo based predictions including the QCD multijet predictions from

N_{jets}	CR1		CR2	
	N_{QCD}	$N_{\text{QCD}}/N_{\text{selected}} [\%]$	N_{QCD}	$N_{\text{QCD}}/N_{\text{selected}} [\%]$
= 1 jet	542.1	2.7	316.3	1.6
= 2 jets	272.1	5.4	179.6	3.5
= 3 jets	114.7	8.9	78.9	6.1
= 4 jets	28.8	6.6	18.5	4.3
≥ 5 jets	15.4	8.1	10.9	5.6

Table 4.10.: Predictions of QCD multijet events for the selection of the 35 pb^{-1} analysis, as described in chapter 6, obtained with fake efficiency measurements in two different control regions, CR1 and CR2.

data both in the background dominated events with two and three jets and in the signal dominated events with four or five and more jets. The low tail of the distribution, dominated by QCD multijet production, gives a particularly good indication if the estimation works and can be extrapolated into the signal region. Therefore, the results obtained with CR2, $d_0^{\text{sig}} > 3$, will serve as the main estimate in the measurement presented in chapter 6. Figure 4.4 shows some overestimation of the QCD multijet background, already indicated by the higher values of $\varepsilon_{\text{fake}}$ measured in CR1, as stated above, and is therefore not considered for the final analysis.

Since both estimates use the same set of data events, the prediction taken from CR1 cannot be used as a different QCD multijet model to estimate systematic uncertainties. For that reason, a complementary sample is created, selecting events with muons, that are of loose isolation, but do not fulfill the tight requirements, in the low $m_T(W) < 10 \text{ GeV}$ region.

For the analysis of data taken in 2011 a matrix-method approach, using $m_T(W) < 20 \text{ GeV}$, i.e. CR1, as the control region to measure $\varepsilon_{\text{fake}}$ with very similar specifications and results is used. The resulting prediction of QCD multijet events is shown in chapter 7. A tighter selection criterion on the amount of missing transverse energy is applied in this analysis, suppressing the QCD multijet background further. In this environment both control regions lead to a comparably good estimate and the one obtained with higher statistics is chosen.

Estimation in the Electron+Jets Channel

In the e +jets channel, different methods are used to estimate the QCD multijet production. Not only electrons inside of jets can be misidentified as isolated electrons, but also photons or jets from light meson decays identified as electrons can contribute to this source of background events. For the 35 pb^{-1} data sets a so-called *anti-electron* method is used, named by the inversion of one or more of the electron identification criteria³². A data sample, representing the QCD multijet events, is selected by applying all analysis cuts, as described for the dedicated analyses in chapters 6 and 7, but requiring an anti-electron³³ instead of an electron as in the normal case, creating an orthogonal sample to the one used for final analyses. This sample is used to predict all shapes of QCD multijet production.

To measure the rate of QCD multijet events, a sample of data events with anti-electrons is studied in

³²typically one of the cuts applied to define a *tight* electron

³³The word anti indicates the inverted cuts, not an actual anti-particle.

Figure 4.23.: Transverse W boson mass distribution for events selected with the full top selection aside from an explicit cut on $m_T(W) + E_T^{\text{miss}} > 60$ GeV, for the control region $\mu+2$ jets and the signal regions $\mu + 3, 4, \geq 5$ jets. The shaded areas indicate a 30% uncertainty on the QCD multijet background, which is obtained using the fake efficiency measurement in CR1.

the side-band region $E_T^{\text{miss}} < 35$ GeV. Then, Monte Carlo based templates for the E_T^{miss} distribution are created for the top processes, $t\bar{t}$ and single top, and W/Z +jets processes, including also the diboson contributions. Together with the distribution for QCD multijet production, obtained from the anti-electron selection, the three MC templates are fitted to data and the optimal mixture of QCD multijet, $t\bar{t}$ and W/Z +jets events is determined. The normalization of the QCD multijet template is then extrapolated into the signal region. This procedure predicts the fractional amount of QCD multijet events in the signal region, with the exact results for both analyses shown in the respective chapters. A 50% uncertainty is assigned to the prediction, stemming from comparisons with different anti-electron models. The exact anti-electron model used in the analysis is chosen to be the one giving the best performance of the likelihood fit to the E_T^{miss} distribution and an alternative anti-electron model yielding the largest difference to the default is used as an alternative shape model

Figure 4.24.: Transverse W boson mass distribution for events selected with the full top selection aside from an explicit cut on $m_T(W) + E_T^{\text{miss}} > 60$ GeV, for the control region $\mu+2$ jets and the signal regions $\mu + 3, 4, \geq 5$ jets. The shaded areas indicate a 30% uncertainty on the QCD multijet background, which is obtained using the fake efficiency measurement in CR2.

for the estimation of systematic uncertainties.

In the 0.7 fb^{-1} data set, the anti-electron method is only used to create an alternative QCD multijet model to estimate shape uncertainties, while the default model is derived using a matrix method, as described above in the $\mu + \text{jets}$ channel. To define a *loose* electron the electron quality word is changed to *medium* with an additional requirement of at least one hit in the innermost pixel layer, as well as the $\text{EtCone20} < 6$ GeV, compared to 3.5 GeV as the cut value for the *tight* electron definition. The efficiency for real loose electrons to pass the tight criteria is measured in similar fashion to the muon channel in $Z \rightarrow ee$ events, while the efficiency for fake electrons is measured in the control region defined by $5 \text{ GeV} < E_T^{\text{miss}} < 20 \text{ GeV}$. A 50% uncertainty is assigned to this estimate as well, based on comparisons of different estimation techniques and control regions.

General Analysis Strategy

5.1. The Idea

To measure the top quark pair production cross section in the ℓ +jets channel, the key feature is to distinguish between top quark pair production and the dominant background processes, W +jets production and QCD multijet production. This can be achieved by imposing harsh cuts on the event selection leading to a signal enriched sample with small backgrounds. In such a case, a simple counting experiment can be used to extract the cross section and is typically done for measurements with low statistics. However, once the statistics of the available data set grows, the limiting factor will be the systematic uncertainty. To perform precision measurements of the quantity $\sigma_{t\bar{t}}$, a different approach is used in this work, trying to exploit the data set in hand as much as possible to also reduce systematic uncertainties and reach a precision competitive to measurements at the Tevatron and to theoretical predictions at approximate NNLO for $\sigma_{t\bar{t}}$.

Both analyses presented in the remainder of this work share the same general ideas, presented in detail in this chapter, with some modifications for the specific analyses, as described in chapters 6 and 7. Instead of selecting a sample of events with a high signal-to-background (S/B) ratio by selecting events with at least 4 jets and possibly b -tagged jets, here the selection is rather loose, requiring only ≥ 3 jets without any b -tagging selection applied. Based on this selection, the sample is split in terms of jet multiplicities, 3, 4, ≥ 5 jets, where the three-jet-sample will be background dominated and the higher multiplicity samples rather signal dominated. This approach allows to extrapolate knowledge gained about the background processes in the events with three jets to the higher jet multiplicity bins. Further separation between signal and background processes can be achieved by taking into account kinematic distributions of either the single physics objects (lepton, jets, missing transverse energy) or the full event topology, that distinguish between the two types of events in terms of shape. In an additional step several discriminating variables can be combined by advanced multivariate analysis techniques, like a projective likelihood, into one single variable with increased separation power. Finally, a template fit of all signal and background distributions in this variable to data can be used to extract the best fit value of $\sigma_{t\bar{t}}$, using information about the rate of predicted events and also the shape of the distribution. With such a method, the analyses presented here will be fully dominated by systematic uncertainties. Since the kinematic distributions, the rate

predictions in different jet multiplicity bins and lepton channels (e +jets vs. μ +jets) and the shapes of the final discriminant not only contain information about the different physics processes, but also about systematic shifts possibly preferred by data, a further reduction of systematic uncertainties can in principle be achieved in-situ. This is implemented using a profile likelihood technique, which includes several sources of systematic uncertainties as nuisance parameters in the fitting function, obtaining also preferred central values and possibly reduced uncertainties for each source of systematic uncertainties from the fit to data.

5.2. Extended Phasespace

A typical selection of events with a high probability of originating from top quark pair production in the ℓ +jets channel includes a requirement of finding at least four jets in the event. This is motivated by the corresponding Feynman diagram, always predicting two b -jets from the two top quark decays and an additional pair of jets from the hadronic W boson decay. Additional jets can always occur due to initial and final state radiation, so the selection is not limited to events with exactly four jets, but also includes events with more jets. However, since the definition of jets to count for the analysis does not cover the full available phase space in η and p_T and also, to a lesser extent, not every jet is identified as such, a significant amount of top quark pair production leads to a signature with fewer than four jets. The breakdown of $t\bar{t} \rightarrow \ell$ +jets and as the dominant background from W +jets production, into subsets of events defined by the jet multiplicity is shown in figure ???. As can be seen, a substantial amount of $t\bar{t}$ events fall into the category for events with three jets, even more than into the category of events with five or more jets. Even though the relative contribution from the W +jets background is steeply falling as a function of the jet multiplicity, it still significantly contributes to the third jet bin, leading to a significant decrease in the signal-to-background ratio (S/B) towards lower jet multiplicities. In the presented analyses events with three jets are included in the analysis, since valuable information about the background processes and systematic uncertainties can be gained in this category. Moreover, splitting the sample into jet multiplicities of three, four and five and more jets, allows to exploit the knowledge about the relative correlation between the different jet multiplicities both for the contributing processes and the influence of systematic uncertainties. Even though a measurement of $\sigma_{t\bar{t}}$ only in events with three jets is rather difficult, the inclusion of this set of events into a combined measurement in the different jet bins can reduce the statistical and systematic uncertainties significantly.

5.3. Discriminating Variables

5.3.1. Topological and Kinematic Variables

To distinguish between $t\bar{t}$ production and the dominant background from W +jets production more than 70 kinematic distributions are compared and the separation power of the variables is studied. The variables can be classified as being either related to certain physics objects in the event, or to the full event topology itself. Object based kinematics include the transverse momenta, p_T ,

Figure 5.1.: Predicted fraction and number of selected events for the 0.7 fb⁻¹ analysis in the μ +jets channel for top quark pair production and the dominant W +jets background process, shown as a function of the number of selected jets in the event.

pseudorapidities, η , and the coordinate ϕ of both the charged lepton and the four jets with the highest transverse momenta in the event¹. The jets are ordered by their transverse momenta, and the jet with the highest p_T value is referred to as *leading jet*. Missing transverse energy and the angular difference $\Delta\phi(E_T^{\text{miss}}, \ell)$ between the missing transverse energy and the charged lepton are considered as a measure for the neutrino in the event. The transverse mass $m_T(W)$, see equation 4.3, momentum $p_T(W)$ or pseudorapidity $\eta(W)$ of the leptonically decaying W boson can be reconstructed.

Mass distributions of the two leading jets, the three leading jets or the third and fourth jet, for events with $n_{\text{jets}} \geq 4$, can be used as representatives of the hadronic decay products. Finally, the event topology, constructed from some or all of the selected physics objects, can be built. A set of event shape variables is constructed from the momentum tensor of the four (three, if $n_{\text{jets}} = 3$) leading jets and the charged lepton,

$$M_{ij} = \frac{\sum_{k=1}^{N_{\text{obj}}} p_{ik} p_{jk}}{\sum_{k=1}^{N_{\text{obj}}} p_k^2}. \quad (5.1)$$

Using the eigenvalues of M , $\lambda_0 > \lambda_1 > \lambda_2$, variables can be defined as follows:

- Aplanarity $\mathcal{A} = \frac{3\lambda_2}{2}$
- Planarity $\mathcal{P} = \frac{3(\lambda_2 + \lambda_1)}{2}$
- Sphericity $\mathcal{S} = \lambda_1 - \lambda_2$

and will always fall in the range $[0, 1]$.

Another set of event variables stems from the sum of transverse momenta of the leading four (three)

¹or of the leading three jets, in case of $n_{\text{jet}} = 3$

jets,

$$H_T = \sum_{i=0}^{N_{\text{jets}}} p_T^i. \quad (5.2)$$

Variations can be created by either including the transverse momentum of the charged lepton (H_T^ℓ) and missing transverse energy (H_T^{all}) or limiting the jets considered in the sum of momenta, denoted as $H_{T,i}$, where i shows with which jet the counting starts, for example excluding the leading jet for $H_{T,2}$. Furthermore, the sensitivity of this type of variables to variations of the jet energy scale can be significantly reduced by calculating ratios of the H_T variables and either the sum of energy of all jets, centrality

$$C = \frac{H_T}{\sum_{i=0}^{N_{\text{jets}}} E^i}, \quad (5.3)$$

the sum of p_z components of all selected objects,

$$H_{T,p} = \frac{H_T}{p_z(\nu) + p_z(\mu) + \sum_{i=0}^{N_{\text{jets}}} p_z^i}, \quad (5.4)$$

or the sum of p_z components of only the jets,

$$H_{T,pp} = \frac{H_T}{\sum_{i=0}^{N_{\text{jets}}} p_z^i}. \quad (5.5)$$

All H_T related variables include either the leading three jets, in the case of $n_{\text{jets}} = 3$, or the leading four jets if there are at least four jets in the event. The variable sets $H_{T,ip}$ and $H_{T,ipp}$ use only a limited subset of the selected jets, with i describing the first considered jet in the sum.

If used, the z -component of the momentum of the neutrino, stemming from the reconstruction of missing transverse energy, is calculated using the relation $m_W = \sqrt{(p_\nu + p_\ell)^2}$, which can be solved if the W boson mass is constrained to be $m_W = 80.425$ GeV. Exploiting the knowledge of the full four-vector of the charged lepton, as well as E_x^{miss} and E_y^{miss} , an equation for p_ν^2 can be derived. If this equation has two solutions, the one closer to 0 is chosen, and in the case of no real solution, missing transverse energy is iteratively scaled down until a solution is found.

With the aim to create variables rather independent of variations of the jet energy scale, ratios of transverse momenta of different jets can be calculated, for example the fraction of momentum of the leading four jets carried by the leading jet, or the ratio between the sum of the first leading jets and the sum of the third and fourth jet.

A final set of variables can be created from measures of distance: the minimum distance in R between two jets, distances in η or R between the two leading jets, the pseudorapidity of the most forward jet or the variable $\sum_{i=0}^{N_{\text{jets}}} \eta^2(j_i)$, taking into account the squared pseudorapidities of all jets.

5.3.2. Separation Power

The separation power for each variable to discriminate between top quark pair production and W +jets production can be estimated using different measures. Looking at normalized distributions for $t\bar{t}$ events and W +jets events, as shown in figures ??, 5.1 and 5.2, already allows to identify variables with

a strong separation power, like η_ℓ , compared to variables with a weak separation power, like the invariant mass of the third and fourth jet. To quantify the separation power, the overlap or the difference between the distribution for $t\bar{t}$ versus W +jets production can be calculated by calculating the difference in each bin. This is shown here with the analysis setup as described in chapter 7. Variables with significant separation power are shown in table 5.1. In general, the performance of variables in the e +jets and μ +jets channels are comparable, and the final choice of variables was mostly driven by investigations in the μ +jets channel, making sure that the variables also have significant separation power in the e +jets channel.

5.3.3. Correlations

Since the multivariate analysis method of choice, a projective likelihood discriminant, as described in section 5.4, works under the assumption of uncorrelated input variables, the correlation between the different variables has to be investigated. Linear correlation coefficients between the variables are calculated, and shown in figure 5.3 for μ +4 jets events. In general, the correlation is found to be independent of the choice of the lepton, μ or e , and of the jet multiplicity. Figure 5.3 shows the correlations separately for $t\bar{t}$ signal and W +jets background, but no major differences between the two processes can be found. As expected, strong correlation can be seen between related variables, such as the family of H_T variables, which are also correlated with the transverse momentum of the leading jet, or the variables describing the event shapes, such as aplanarity $\mathcal{A}$ and sphericity $\mathcal{S}$. The normalized H_T variables, including also centrality $\mathcal{C}$, show only a weak correlation to the non-normalized H_T variables, but a stronger correlation can be seen with the event shape variables.

(a) Pseudorapidity of the charged lepton for $t\bar{t}$ and W +jets production in μ +4 jets and e +4 jets events. Top quark pair production tends to produce more central leptons than W +jets production.

(b) Transverse momentum of the leading jet for $t\bar{t}$ and W +jets production in e +jets channel for different jet multiplicities. $t\bar{t}$ production tends to produce harder jets, but the separation power degrades with higher jet multiplicities, since the dominant W +jets background will look more signal-like at higher jet multiplicities.

(c) Missing transverse energy and transverse mass and momentum of the reconstructed W boson in the leptonic decay branch, for both $t\bar{t}$ and W +jets events in the μ +4 jets channel.

Figure 5.2.: Kinematic quantities of the selected objects that can be used to distinguish between top quark pair production and W +jets production.

(a) Event shape quantities. A transformation of $\mathcal{A} \rightarrow \exp(-8 \times \mathcal{A})$ smoothens the distribution and enhances the separation power.

(b) H_T , the variation H_T^{all} including the E_T^{miss} and $p_T(\ell)$, and $\mathcal{C}$, a weighted representation of H_T

(c) Normalized H_T distributions: $H_{T,3p}$, taking only the third and fourth jet into account, divided by the z-component of the momentum of all selected objects, and its transformation $H_{T,3p} \rightarrow \exp(-4 \times H_{T,3p})$, as well as the H_T distribution normalized to the z-component of the momentum of only the leading four jets.

Figure 5.3.: Event topologies used to distinguish between top quark pair production and W +jets production, as shown in μ +jet events.

(a) Measures of distance, the sum of η^2 for all jets, the minimum distance between two jets and the maximal pseudorapidity of any selected jet.

(b) Invariant masses of the leading two jets, the leading three jets and the third and fourth jet following the p_T -ordering.

(c) Ratios of transverse momenta of jets create variables with little sensitivity to jet energy scale variations: the fraction of momentum carried by the leading jet compared to the sum of all jets, and the relations between the momenta of the second leading and leading jet as well as the fourth and the leading jet.

Figure 5.4.: Additional event related variables with separation power between top quark pair production and W +jets production in the e +jets channel.

variable	difference [%] (μ +jets)			difference [%] (e+jets)		
	3 jets	4 jets	≥ 5 jets	3 jets	4 jets	≥ 5 jets
$p_T(j_1)$	64	51	38	57	45	35
$p_T(j_2)$	69	59	41	61	51	38
$p_T(j_3)$	59	61	43	55	54	40
$p_T(j_4)$	–	50	46	–	46	39
$\eta(\ell)$	34	38	42	32	40	45
$p_T(\ell)$	< 20	< 20	< 20	29	< 20	< 20
E_T^{miss}	42	29	< 20	42	27	23
$\Delta\phi(E_T^{miss}, \ell)$	34	28	21	26	< 20	21
$p_T(W)$	40	32	22	35	26	22
$\mathcal{P}$	29	42	35	29	37	38
$\mathcal{S}$	31	35	31	29	32	35
$\mathcal{A}$	30	43	36	30	28	38
$\exp(-8 \times \mathcal{A})$	30	43	36	30	28	38
$m(j_1, j_2, j_3)$	31	30	28	32	31	29
$m(j_1, j_2)$	29	26	29	29	28	33
$m(j_3, j_4)$	–	23	< 20	–	23	22
H_T	73	58	39	65	49	36
H_T^{all}	79	58	38	70	51	37
H_T^ℓ	71	55	38	66	51	37
$H_{T,2}$	72	59	40	64	52	35
$H_{T,3}$	73	53	47	51	47	42
H_{Tp}	39	42	36	36	36	38
$H_{T,2p}$	36	43	38	< 20	41	43
$H_{T,3p}$	27	42	43	28	42	47
$\exp(-4 \times H_{T,3p})$	28	42	44	28	39	47
$H_{T,pp}$	24	29	22	24	25	24
$H_{T,2pp}$	23	31	26	26	31	30
$H_{T,3pp}$	< 20	29	29	20	31	34
$\mathcal{C}$	25	31	23	26	27	25
$\eta_{max}(j)$	23	26	< 20	23	25	23
$\sum_j \eta^2$	24	29	23	25	26	25
$\Delta R_{min}(j, j)$	< 20	< 20	< 20	27	< 20	< 20
$p_T(j_3)/p_T(j_1)$	23	< 20	25	24	< 20	26
$p_T(j_4)/p_T(j_3)$	–	32	< 20	–	26	< 20
$p_T(j_4)/p_T(j_1)$	–	31	29	–	< 20	25

Table 5.1.: Difference in shape calculated from the non-overlapping parts of the distributions for W +jets and $t\bar{t}$ production for a selection of variables with good separation power.

(a) Top quark pair production

(b) W+jets production

Figure 5.5.: Linear correlation coefficients between various discriminating variables in $\mu+4$ jets events for $t\bar{t}$ production and W+jets production.

5.3.4. Choice of Variables

The choice of variables used in the analyses is not only based on the separation power for each variable. The set of variables has to fulfill the following requirements:

- only a few well understood variables to reduce sensitivity to unknown correlations between them and to mismodelling of the correlations
- separation power is visible in all jet multiplicities, but optimal for the higher jet multiplicities
- use complementary information from different types of variables
- not too strong correlations between variables
- for the 35 pb^{-1} analysis, chapter 6, variables are chosen to be as insensitive as possible to variations of the jet energy scale, which is expected to be one of the dominant systematic uncertainties
- for the 0.7 fb^{-1} analysis, chapter 7, after gaining good understanding of the techniques, additional sensitivity to the dominant systematics can be added to further reduce these uncertainties in the final cross section extraction
- good agreement between data and Monte Carlo simulation in control regions ($n_{\text{jets}} = 1, 2$) and the signal region, which will be shown in the dedicated analysis chapters

Based on these constraints sets of four variables are chosen for both analyses, sharing three of them in both:

- pseudorapidity of the lepton, η^ℓ
- transformed version of aplanarity, $\exp(-8 \times \mathcal{A})$
- sum of transverse momenta of the third and fourth jet² divided by the sum of z -components of all selected objects and transformed to $\exp(-4 \times H_{T,3p})$

The exact settings for the transformations of $\mathcal{A}$ and $H_{T,3p}$ are chosen to spread the distribution and reduce the difference in statistics between different bins. These variables are either insensitive to jet energy scale variations by definition (η^ℓ) or by construction ($\mathcal{A}$, $H_{T,3p}$) and build the smallest set of variables fulfilling the requirements as listed above. This set of variables uses complementary information of the objects in the events, yields a good separation power already by itself and is therefore chosen as basic configuration of the measurement. The initial set of three variables is complemented by a different fourth variable in both analyses to improve the sensitivity. For the analysis of data taken in 2010 a strong separator is chosen to increase discrimination: the average b -jet identification algorithm output for the two most b -like jets, $\bar{w}_{JP}$. A detailed description of the motivation and choice of this variable can be found in chapter 6. In contrast, the analysis of 0.7 fb^{-1} of data from 2011 uses the transverse momentum of the leading jet, $p_T(j_1)$, as the fourth variable with the aim to both increase separation, but moreover purposefully add sensitivity to jet energy scale variations to be exploited in the profile likelihood fit to extract $\sigma_{t\bar{t}}$ and to reduce the impact of this source of systematic uncertainty.

²or only third jet, if $n_{\text{jets}} = 3$

5.4. Projective Likelihood Discriminant

5.4.1. Theory

The combination of several discriminating variables into one global discriminant $\mathcal{D}$ is done using a projective likelihood approach. The discriminant based on k variables can be expressed as signal over signal-plus-background probability for an event i

$$\mathcal{D}_i = \frac{p_{i,S}(x_1, x_2, \dots, x_k)}{p_{i,S}(x_1, x_2, \dots, x_k) + p_{i,B}(x_1, x_2, \dots, x_k)}. \quad (5.6)$$

Under the assumption that the probabilities for each variable x_j are not correlated with each other, the equation can be factorized into

$$\mathcal{D}_i = \frac{\prod_{j=1}^k p_{i,S}(x_j)}{\prod_{j=1}^k p_{i,S}(x_j) + \prod_{j=1}^k p_{i,B}(x_j)}. \quad (5.7)$$

The $p_{i,S}(x_j)$ and $p_{i,B}(x_j)$ describe normalized probability density functions for an event i and the variable j to be signal and background, respectively. Possible correlations between variables are not accounted for and can lead to a degradation of the performance of the method. The probabilities $p_{i,S/B}(x_j)$ can in principle be derived from normalized binned histograms of the input distributions or from unbinned functions, fitted to initial input distributions. The presented analyses make use of the latter approach, which has the advantage of not relying on discrete binning, but needs careful checks at each step of deriving the unbinned functions.

5.4.2. Implementation in TMVA

The implementation of the projective likelihood in the TMVA framework [94], v4.1.0, is used within the presented analyses, in the context of the data analysis framework ROOT [95], v5.28, which is used throughout the whole analysis chain. TMVA includes several multivariate analysis techniques, as well as pre- and post-processing methods to gain optimal separation for a given problem. The likelihood discriminant function $\mathcal{D}$ as described above, and the corresponding functions $p_{S/B}(x_j)$ are created in an initial *training* step. Signal and background processes are handled as `TTrees`, basic object structures in ROOT, and while $t\bar{t}$ production is obviously considered as signal, only W +jets production is treated as background in the training step. This process is by far the dominant background and the choice of variables is driven by the separation power between $t\bar{t}$ and W +jets. Adding other background processes in this step would dilute the information, if the backgrounds tend to behave similar to $t\bar{t}$, for example single top quark production. While the analysis of 35 pb^{-1} of data is sensitive to the amount of W +heavy flavor jet production due to the usage of b -tagging, the analysis of 0.7 fb^{-1} is not. For that reason, the W +heavy flavor processes are only included in the background sample for the training set in the 35 pb^{-1} analysis.

Since the events used to construct the probability density functions $p_{S/B}(x_j)$ in the training phase, and the events to evaluate the function and derive the templates for the different processes have

to be statistically independent, only half of the Monte Carlo simulated events for $t\bar{t}$ and W +jets production are used in the training step and the other half in the final *evaluation* step. The splitting of the MC samples into two subsamples is based on the event number associated to each event. If this integer value for an event is even-numbered, the event is used for the training procedure and is used for the evaluation procedure otherwise. In both cases distributions are internally reweighted to the total sum of predicted events.

As stated above, the analyses use unbinned functions $p_{S/B}(x_j)$ to describe the probabilities for an event to be signal or background. These probability distribution functions are derived from fits of spline functions to histograms of the input variables for signal and background, see figure ???. The binning of the input histograms, based on an average number of events per bin, and a smoothing procedure of the spline functions can be set manually, to achieve a good agreement between input histogram and fitting function. The exact settings vary between the two analyses and also between the different lepton channels and jet multiplicities to account for differences in available statistics of the simulated MC events.

In the *evaluation* step, the likelihood value $\mathcal{D}_i$ is calculated for each event i in data and all Monte Carlo simulated samples for signal and background, using the reduced set of events for $t\bar{t}$ and W +jets that was not used in the training. For all other background processes, all MC simulated events are used and template distributions are built for each process. The shape of the likelihood output distributions $\mathcal{D}$ strongly depends on the choice of input variables, and are therefore shown in detail in chapters 6 and 7 for the corresponding analyses.

(a) $\exp(-8 \times A)$ (b) $\exp(-4 \times H_{T,3p})$

Figure 5.6.: Example input distributions for signal and background in the $\mu+4$ jets channel overlaid with the corresponding probability distribution $p_{S/B}$ as used for the calculation of the discriminant $\mathcal{D}$.

5.5. Cross Section Extraction Using Profile Likelihood Fitting

5.5.1. The Idea

The aim of the presented analyses is to extract the best fitting value for the top quark pair production cross section, $\sigma_{t\bar{t}}$, from a fit of the templates derived from Monte Carlo simulated events to a data distribution. Here, the distribution is the likelihood discriminant $\mathcal{D}$, as described previously, available for events in the μ +jets and e +jets channels with different jet multiplicities ($n_{\text{jets}} = 3, 4, \geq 5$). While the discriminant $\mathcal{D}$ is divided into 20 bins per channel and jet multiplicity here and a global discriminant with 120 bins is formed for the final fit, the fitting procedure itself is valid for any binned distribution. The best fitting value of $\sigma_{t\bar{t}}$ is derived not only as a function of the signal and background normalization, but also as a function of several nuisance parameters representing sources of systematic uncertainties. Allowing to vary the latter systematics leads to a better knowledge of the uncertainties themselves and to a possible reduction of the overall uncertainty of the measurement. The likelihood function and the minimization technique, implemented using ROOT [95] and the built-in minimization procedure Minuit2 [96], as well as the technique to handle and create continuous systematic uncertainties are described in the following.

5.5.2. The Likelihood Function

The top quark pair production cross section, $\sigma_{t\bar{t}}$, is extracted from a likelihood fit of signal and background templates to data. A likelihood function $\mathcal{L}$ can be defined, as described in the following, and a minimization procedure of $-\ln(\mathcal{L})$ returns the preferred value for the parameter of interest, here the top quark pair production cross section.

For a binned distribution $\mathcal{D}$ with k bins, predictions for signal and background processes can be compared to data assuming Poisson probabilities and formulating the extended maximum likelihood function

$$\mathcal{L}_{\beta}(\vec{\beta}) = \prod_k \frac{\mu_k^{n_k} \exp(-\mu_k(\vec{\beta}))}{n_k!}. \quad (5.8)$$

The number of observed data events per bin k is defined as n_k , while the sum of signal and background events is expressed as the number of expected events μ_k . Each signal and background process is associated to a parameter β_j ³, which is $\beta_j = 1.0$ for the initial prediction from Monte Carlo simulation, normalized to the luminosity of a given data set. The number of expected events in a bin k can therefore be expressed as the sum over the predictions for all processes j for this bin k : $\mu_k(\vec{\beta}) = \sum_j \beta_j \nu_{jk}$, with ν_{jk} the predicted number of events for a process j in the bin k . The β_j are the parameters adjusted to achieve a minimal value of $-\ln(\mathcal{L})$, and the preferred β_j are returned as the final result of the fit. However, while the parameter of interest, $\beta_0 = \sigma_{t\bar{t},\text{measured}}/\sigma_{t\bar{t},\text{predicted}}$, needs to be allowed to take any possible value, the parameters β_j for the background processes are constrained by the uncertainties of their predictions. The knowledge about the uncertainties is

³with the top quark pair production normalization associated to β_0

implemented in a Gaussian term

$$\mathcal{G}_\beta = \prod_j \frac{1}{\sqrt{2\pi}\Delta_j} \exp\left(-\frac{(\beta_j - 1)^2}{2\Delta_j^2}\right), \quad (5.9)$$

which is multiplied with $\mathcal{L}_\beta$. Up to here, only variations of the β_j are allowed in the minimization procedure, i.e. only variations of the amount of signal and background.

In the presented analyses the aim is to also include sources of systematic uncertainties as *nuisance parameters* δ_i in the fitting procedure and also obtain preferred values for each systematics. This extends the likelihood function to

$$\mathcal{L}_{\beta,\delta}(\vec{\beta}, \vec{\delta}) = \prod_k \frac{\mu_k^{n_k} \exp(-\mu_k(\vec{\beta}, \vec{\delta}))}{n_k!} \times \prod_j \frac{1}{\sqrt{2\pi}\Delta_j} \exp\left(-\frac{(\beta_j - 1)^2}{2\Delta_j^2}\right) \times \prod_i \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\delta_i^2}{2}\right). \quad (5.10)$$

An additional term for Gaussian constraints on the nuisance parameters δ_i is added, but moreover the number of expected events μ_k turns into a function of the parameters β_j and δ_i :

$$\mu_k(\vec{\beta}, \vec{\delta}) = \sum_j \beta_j \nu_{jk} \prod_i \varepsilon_{jik}(\delta_i). \quad (5.11)$$

The term ε_{jik} , representing the variation of bin contents as a fit of the nuisance parameter δ_i , becomes necessary since initially only the $\pm 1\sigma$ variations, corresponding to $\delta_i = \pm 1.0$, of each source of systematic uncertainty are known. For each source of systematic uncertainty i , the deviation from the nominal prediction for process j and bin k can be expressed as

$$\lambda_{jik}^\pm = \frac{\nu_{jik}^\pm}{\nu_{jk}}. \quad (5.12)$$

To translate this knowledge into a number of expected events per process and bin for any possible value of δ_i , a procedure called *vertical template morphing* [97] is implemented. As illustrated in figure ?? a quadratic interpolation based on Lagrange polynomials is performed in the range $[-1\sigma, 1\sigma]$, based on the *up* and *down* variations of a systematic uncertainty i and the nominal prediction in each bin. Beyond the well-known range of 1σ a linear extrapolation is implemented in such a way that the function remains differentiable at the $\pm 1\sigma$ points. The template morphing procedure of quadratic interpolation and linear extrapolation for a given source of systematics i for a physics process j in the bin k is expressed by the shift parameter ε_{jik} ,

$$\varepsilon_{jik}(\delta_i) = \begin{cases} \lambda_{jik}^+ + (\delta_i - 1)[(\frac{3}{2}\lambda_{jik}^+ - 1) + (\frac{1}{2}\lambda_{jik}^- - 1)] & \text{for } \delta_i > 1, \\ \frac{1}{2}\delta_i[(\delta_i - 1)\lambda_{jik}^- + (\delta_i + 1)\lambda_{jik}^+] - (\delta_i - 1)(\delta_i + 1) & \text{for } |\delta_i| \leq 1, \\ \lambda_{jik}^- + (\delta_i + 1)[(-\frac{1}{2}\lambda_{jik}^+ + 1) + (-\frac{3}{2}\lambda_{jik}^- + 1)] & \text{for } \delta_i < -1, \end{cases} \quad (5.13)$$

and the product over all systematic uncertainties included in the likelihood function leads to the number of expected events for a given process. Initially, the nuisance parameters have the value $\delta_i = 0.0 \pm 1.0$, representing the nominal situation with a 1σ uncertainty. Both the central value and the uncertainty can take different values in the fitting procedure. This procedure is only valid for systematic uncertainties that can be assumed to follow a continuous distribution in the $[-1\sigma, 1\sigma]$

Figure 5.7.: Illustration of the quadratic interpolation in vertical template morphing to translate the availability $\pm 1\sigma$ shifted distributions for a systematic uncertainty i into a continuous function of the parameter δ_i . An example distribution showing possible shifts in a full distribution is displayed, and the interpolation is applied in each bin and process separately.

range, and therefore not all sources of systematics as described in section 5.6 can be included in the fitting function.

Once the full likelihood function $\mathcal{L}_{\beta,\delta}(\vec{\beta}, \vec{\delta})$, is defined, the minimization of $-\ln(\mathcal{L})$ is performed with `Minuit2`, obtaining fit results for all normalization parameters β_j and nuisance parameters δ_j . Hessian symmetric uncertainties and the full covariance matrix for all fit parameters are extracted from the second derivatives of $-\ln(\mathcal{L})$ at the minimum, while asymmetric uncertainties can be obtained from the MINOS algorithm available in the `Minuit2` package.

Finally, the reduction of the full likelihood to a one-dimensional function $\mathcal{L}_{\beta_0}$ only depending on the parameter of interest, $\beta_0 = \sigma_{fi,\text{measured}}/\sigma_{fi,\text{predicted}}$, is performed in the *profiling* [98] step. After finding the global minimum, $gmin$, in the general minimization procedure, the likelihood as a function of β_0 can be expressed as subtraction of a local minimization, $lmin$, with fixed parameters except for β_0 , from the global minimum:

$$-\ln(\mathcal{L}_{\beta_0}(\beta_0)) = \ln(\mathcal{L}_{\beta\delta}(\vec{\beta}^{gmin}, \vec{\delta}^{gmin})) - \ln(\mathcal{L}_{\beta\delta}(\beta_0, \beta_1^{lmin}, \dots, \delta^{lmin})). \quad (5.14)$$

This profile likelihood equation behaves like a log-likelihood function and allows to test the performance of the likelihood, to extract the 1σ -uncertainty on β_0 from the minimum with $-\ln(\mathcal{L}_{\beta_0}(\beta_0^{lmin})) + 0.5$ and to understand the dependency of β_0 on each other fit parameter.

The stability of the described procedure and the sensitivity to various effects has to be carefully evaluated, as described in section 5.7 and the corresponding analysis chapters.

5.6. Sources of Systematic Uncertainties

5.6.1. Definition

Systematic uncertainties represent uncertainties caused by imperfect knowledge of various parameters affecting the measurement through settings for the predictions based on Monte Carlo simulation or the data-driven estimates. In contrast to statistical uncertainties they are not reduced with increased statistics of an available data set, but have to be carefully evaluated in dedicated studies. Since the presented measurements are both limited by the systematic uncertainties and aiming at reducing their influence with the profile likelihood technique, a good understanding is crucial. Systematic uncertainties are typically expressed as $\pm 1\sigma$ variations of a parameter compared to the default settings, but can also include comparisons between independent models.

In general, one can distinguish between systematic uncertainties from assumptions of the physics model made in the simulation of Monte Carlo generated events or during the estimation of backgrounds in data, and detector or reconstruction related uncertainties. Both sources of uncertainties will be discussed in the following. While the exact values might change between the 2010 and 2011 data set analyses, the sources of systematic uncertainties and the procedure to obtain a proper description are valid in both cases. The influence on the likelihood discriminant $\mathcal{D}$ for the different sources of systematic uncertainties will be shown in the chapters 6 and 7.

5.6.2. Model Uncertainties

5.6.2.1. Signal Generator

The uncertainty of the usage of MC@NLO as the default generator to produce simulated $t\bar{t}$ events is estimated in comparison to events generated with POWHEG, the only other MC generator for top quark pair production at next-to-leading-order. Since MC@NLO is always interfaced with HERWIG/JIMMY, POWHEG with HERWIG/JIMMY showering is used in the comparison. The difference between generators is not a continuous function, but a discrete setup, and hence this systematic uncertainty is not included in the profile likelihood fitting. Instead, pseudo-experiments are used to measure the difference in the parameter β_0 between the usage of MC@NLO and POWHEG, a procedure explained in detail in section 5.7. The resulting difference on $\sigma_{t\bar{t}}$ is translated into the uncertainty of the measurement as symmetrized uncertainty of half the original size.

5.6.2.2. Parton Shower

The parton shower modeling of the signal process is performed by HERWIG/JIMMY, interfaced with MC@NLO for the matrix element generation, in the default setup of the analysis. A different parton

shower modeling is available from the PYTHIA generator, which cannot be interfaced to MC@NLO directly. Therefore, POWHEG samples with showering from HERWIG/JIMMY and PYTHIA are created and scaled to the difference between MC@NLO and POWHEG with the same HERWIG/JIMMY showering in each bin. This uncertainty is non-continuous and therefore estimated separately using pseudo-experiments, quoting half of the resulting difference in σ_{fit} as symmetric uncertainty.

5.6.2.3. Initial and Final State Radiation (ISR/FSR)

The behavior of initial and final state radiation in generators exceeding leading-order precision is not well understood, and therefore the LO event generator ACERMC is used for simulation of events with various amount of ISR and FSR when interfaced with PYTHIA for the showering. The PYTHIA parameters responsible for ISR and FSR are varied to simulate less and more radiation. Six samples are produced: ISR^+ , ISR^- , FSR^+ , FSR^- and the variation of both parameters at the same time, ISRFSR^+ and ISRFSR^- . To account for differences between ACERMC and the default MC@NLO samples, a seventh ACERMC sample is generated with the default settings for ISR and FSR, and all variation samples are normalized to the ratio ACERMC/MC@NLO in each bin of the distribution.

For the 35 pb^{-1} analysis ISR and FSR variations are treated outside of the likelihood function, since the continuity of the corresponding δ parameter was not known at the time of the analysis. Therefore, the difference on the measurement of σ_{fit} is estimated externally based on pseudo-experiments and half of the biggest difference between any of the six variations is quoted as symmetric systematic uncertainty. For the 0.7 fb^{-1} analysis Monte Carlo simulated events with different, intermediate settings of the ISR and FSR parameters became available and allowed to successfully test the assumption of a continuous parameter. Therefore, $\text{ISR}^\pm$ and $\text{FSR}^\pm$ are included in the definition of $\mathcal{L}_{\beta\delta}$ for this analysis. In the fitting procedure simultaneous variations of both parameters are allowed and the use of the $\text{ISRFSR}^\pm$ templates is not necessary.

5.6.2.4. Parton Distribution Functions

Since the signal Monte Carlo samples are generated with the CTEQ66 parton distribution set, the corresponding errors from CTEQ66 are taken into account to reweight the signal sample for each of the 44 errors separately. Template distributions $\mathcal{D}$ are created for all of them and are used to subsequently create envelope distributions for upwards and downwards shifts of the PDFs. In each bin of the discriminant $\mathcal{D}$ the positive and negative fluctuations are added in quadrature to create the up/down templates used to evaluate systematic uncertainties from pseudo-experiments outside the profile likelihood fit. This takes into account both variations in rate and shape, and the rate-wise variations are found to be very similar to the ones using the full PDF4LHC [99] recommendations creating an envelope from CTEQ66, NNPDF20 and MSTW2008, which is rather difficult to do for full distributions. The variations in shape are small and originate mostly from changes in the distribution of the lepton pseudorapidity with the different PDF settings.

5.6.2.5. W +Jets Generator Settings

The leading-order generator ALPGEN used to generate the dominant W +jets background processes allows to vary several internal settings. The impact of changes of these settings is studied in samples on generator level, comparing kinematic distributions and deriving reweighting functions to correctly propagate the influence of changes in the generator to the fully reconstructed simulated events. The reweighting functions are derived as a function of the transverse momentum of the leading jet and provided for each jet multiplicity up to $n_{\text{jet}} \geq 6$ separately. Varied parameters include

- functional form of factorization scale, *iqopt*: $m_W^2 + \sum_j p_T(\text{jet})$ (default), m_W^2 (*iqopt2*), $m_W^2 + p_T(W)$ (*iqopt3*)
- scale factor of the factorization scale, *qfac*: 0.5, 1.0 (default), 2.0
- scale factor of the renormalization scale, *kfac*: 0.5, 1.0 (default), 2.0
- minimal parton p_T for the matching, *ptjmin*: 10, 15 (default), 20, 25 GeV
- underlying event model: HERWIG/JIMMY(default), PYTHIA PERUGIA, PERUGIA soft, PERUGIA hard

Studies show that the variations *iqopt2* and *ptjmin10* provide the most meaningful and significant deviations from the nominal setup and are therefore considered in both presented analyses. Template distributions are created for both settings and are used to estimate the differences on the measured value for $\sigma_{t\bar{t}}$ using pseudo-experiments. Both deviations are symmetrized around the nominal value and added in quadrature, since they are of uncorrelated origin.

5.6.2.6. W +Heavy Flavor Contribution

Since only the analysis using b -jet-tagging is directly sensitive to the relative amount of $Wb\bar{b}$, $Wc\bar{c}$ and Wc contributions in the W +jets background samples, associated uncertainties on the W +heavy flavor fraction are considered in the analysis of 35 pb^{-1} of data. $Wb\bar{b}$ and $Wc\bar{c}$ events are treated together, but separately from Wc events, due to the different production mechanism. Scale factors for the W +heavy flavor events are derived in studies of events with two jets, as described in section 4.3.3, and corrections are therefore applied to the nominal Monte Carlo simulated events. The uncertainty on the $Wb\bar{b}/Wc\bar{c}$ scale factor is found to be 50% in events with two jets, while the used scale factor for Wc events is $SF_{Wc} = 1.0 \pm 0.4$. The uncertainties are derived from two different methods to measure the scale factors and account for differences between the results. However, these analyses are performed in events with two jets and the uncertainties need to be extrapolated to the higher jet multiplicities. An additional 25% uncertainty between the different jet bins is added, based on variations of ALPGEN parameters, similar to those used in section 5.6.1.1, causing differences in the relative amount of W +heavy flavor events of different jet multiplicities. This leads to six different templates for these systematic uncertainties that are implemented as nuisance parameters in the profile likelihood function.

5.6.2.7. QCD Multijet Model

Alternative models for the shape of the QCD multijet prediction are derived from the anti-electron method, described in section 4.3.5, i.e. reversal of several electron identification requirements, in the e +jets channel. Even though the anti-electron method in principle predicts the shape of QCD multijet production independent of the lepton flavor and could therefore also be used in the μ +jets channel, the analysis relying on b -tagging is found to show a large sensitivity to the predicted amount of fake leptons from decays inside of heavy quark jets. Since the flavor composition of the QCD multijet events faking isolated leptons differs between the e +jets and μ +jets channel, the anti-electron prediction does not serve as a valid model in the μ +jets channel if a b -tagging variable is used to build the discriminant. Furthermore, different matrix method estimates cannot be used either, because they contain the same events with different event weights applied and can lead to misleading correlations. Therefore, the alternative model in the μ +jets channel is created from a selection of events containing *loose-but-not-tight* muons in the region $m_T(W) < 10$ GeV. The contribution of real muons to this selection is found to be negligible using Monte Carlo simulated events.

5.6.2.8. Background Cross Sections

Uncertainties on the background predictions from theoretical calculations or data-driven estimates, as described in section 4.3, are included in the profile likelihood fitting as Gaussian constraints. Hence, these uncertainties are not included as nuisance parameters, but affect the statistical precision of the measurement.

A large uncertainty is associated with the W +jets background, not only regarding the overall normalization, but also regarding the ratio between events with n and $n+1$ jets. For this reason the W +jets contribution is fitted separately in events with 3, 4, ≥ 5 jets and in the e +jets and μ +jets channels. The theoretical uncertainty of 4% on inclusive W +jets production is propagated to the higher jet multiplicities based on the Berends scaling assumption [100, 101] of a constant ratio of events in neighboring jet bins, describing the relative behavior of number of events with different jet multiplicities with

$$N_W^{n\text{-jets}} = N_W^{2\text{-jets}} \times \sum_{i=2}^n \left(\frac{N_W^{2\text{-jets}}}{N_W^{1\text{-jets}}} \right)^i. \quad (5.15)$$

The uncertainty on this assumption is studied and found to be 24%. Based on this, the 4% uncertainty for the predicted inclusive W boson production is propagated to the signal region and a 42% uncertainty is used for events with three jets, 48 % for events with four jets and 54% for the prediction of events with five or more jets.

The smaller electroweak backgrounds are treated as fully correlated among the different channels and jet multiplicities, with a 30% uncertainty assigned to Z +jets production⁴, 10% uncertainty on single top quark production and 5% uncertainty on diboson production.

As an additional ingredient to the uncertainty on the prediction for all Monte Carlo based physics processes, the uncertainty on the luminosity of a given data set has to be considered. If the assumed luminosity varies, the amount of predicted background events varies simultaneously. Therefore, the

⁴In principle, Berends scaling and the problem of modeling the ratio of events in different jet bins applies for Z +jets production in the same way as for W +jets production, but the contribution from this process is rather small.

luminosity uncertainty is added in quadrature to the theoretical uncertainty.

The predictions for QCD multijet production are also treated separately in $e/\mu + \text{jets}$ events and different jet multiplicities. As described in section 4.3.5, uncertainties are assigned to the data driven estimates based on comparisons of different methods. Initially, a 30% uncertainty is assigned to the QCD multijet estimate in the $\mu + \text{jets}$ channel, and a 50% uncertainty in the $e + \text{jets}$ channel, but both are implemented as 50% uncertainty Gaussian constraints in the analyses to achieve consistency between the channels. However, tests performed with different constraints show no difference between the fit results using 30% and 50% uncertainties, and only a slight reduction of uncertainties in the former case.

5.6.2.9. Pile-Up Model

In the 35 pb^{-1} data analysis, the Monte Carlo simulated events are not reweighted to account for different bunch settings in data and MC, but this difference is treated as a source of systematic uncertainty. Reweighting scale factors as a function of the number of primary vertices found in an event are derived comparing MC simulated $t\bar{t}$ events to data, and the scale factors are applied prior to the event selection, keeping the normalization of each sample constant. It is found that the simulated events contain more pile-up than data actually shows, and the behavior does not differ in the $e + \text{jets}$ and $\mu + \text{jets}$ channels. The reweighting scale factors applied to study the systematic uncertainties are shown in table 5.2

Number of Vertices	Scale Factor
= 1	1.9290
= 2	1.3025
= 3	0.8380
= 4	0.6225
= 5	0.4636
≥ 6	0.4345

Table 5.2.: Reweighting scale factors for events with different numbers of vertices, to be applied to Monte Carlo simulated events.

A more advanced reweighting based on the accelerator settings in different run periods of data taking is applied to the simulated events as default in the analysis of 0.7 fb^{-1} . No additional systematic uncertainty is applied, but tests are implemented to understand the stability of the measurement against different pile-up settings.

5.6.2.10. Monte Carlo Statistics

Limitations of the statistics of the Monte Carlo events used for the predictions, especially in the case of $W + \text{jets}$ production, can influence the precision of the performed measurements. Therefore, the statistics of the predicted templates is sampled assuming Gaussian statistics in pseudo-experiments and the influence on the expected uncertainty is measured as systematic uncertainty from the available MC statistics.

5.6.3. Detector and Reconstruction Uncertainties

5.6.3.1. Muon Scale Factors

Uncertainties on the scale factors for the trigger efficiency, reconstruction and identification efficiency for the muons are propagated to the cross section extraction in the form of template distributions for *up* and *down* 1σ variations and are incorporated in the profile likelihood function. The uncertainties on the trigger efficiency scale factors are dominating over those for reconstruction and ID, and an envelope of all scale factor uncertainties is created, varying all three scale factors up or down with their 1σ uncertainties simultaneously.

5.6.3.2. Muon Momentum Scale and Resolution

Muon momentum scale and resolution are varied within their 1σ uncertainties based on external studies of resolution and scale in $Z \rightarrow \mu\mu$ events. The smearing uncertainty is decomposed into different terms for the muon p_T smearing in the muon spectrometer (MS) and the inner detector (ID). This source of uncertainties is treated as a nuisance parameter in the cross section extraction, with one parameter associated to an envelope of the variations in the 35 pb^{-1} analysis, and with three parameters describing the muon momentum scale, the MS smearing and the ID smearing separately, in the more precise analysis of the data set with higher statistics, 0.7 fb^{-1} .

5.6.3.3. Electron Scale Factors

Identically to the approach for muon scale factors, the uncertainties on the electron trigger efficiency, and the reconstruction and identification of the analysis electrons, are propagated to the measurement of $\sigma_{t\bar{t}}$ as one combined nuisance parameter. Templates for the $\pm 1\sigma$ variations are created.

5.6.3.4. Electron Energy Scale and Resolution

Uncertainties on the energy scale and resolution of the selected electron are estimated in dedicated studies using $Z \rightarrow ee$ events. In both cases separate templates for the $\pm 1\sigma$ variations are created and associated to separate nuisance parameters for the final measurements.

5.6.3.5. Jet Energy Scale

Due to the high number of jets present in the selected events, a high sensitivity of the measurement to variations of the jet energy scale (JES) is expected. The jet energy scale uncertainty is effectively a combination of several different sources of uncertainties, based on independent parts of the detector, Monte Carlo model assumptions made in the evaluation of the jet energy scale and more. While most analyses consider an envelope of all those sources of uncertainties as global jet energy scale uncertainty, the large sensitivity of the presented measurements to this uncertainty demands a more careful treatment. Therefore, the jet energy scale uncertainty is decomposed into its underlying

uncertainties, which are then treated as uncorrelated nuisance parameters in the final fit. This allows the fitting procedure to adjust each individually. Unless explicitly stated otherwise, as for the pile-up influence term in the 0.7 fb^{-1} analysis, full correlation of a given source of JES uncertainty in p_T and η of all the jets is assumed⁵. A discussion of the impact of this assumption and various tests can be found in chapter 6.

Figure 5.4 shows the contribution of different components to the total jet energy scale uncertainty, for central and forward jets. Uncertainties reach up to 6% for low p_T jets, while the smallest uncertainties are achieved in the region between 50 GeV and a few hundred GeV, increasing towards higher values due to the increasing influence from the calorimeter response term.

The different sources of jet energy scale uncertainties are discussed in the following and a detailed description for all but the b -jet component can be found in Reference [77].

Figure 5.8.: Total jet energy scale uncertainty and its breakdown into different components as a function of the transverse momentum of the jet, for central jets in the detector region $0.3 \leq |\eta| < 0.8$ and forward jets in the detector region $2.1 \leq |\eta| < 2.8$ [77]. Jet energy scale uncertainties for anti- k_t jets with a radius parameter of $R = 0.6$ are shown, but the behavior is very similar to the one for jets with $R = 0.4$, as used in the presented analyses.

Calorimeter Response

The uncertainty on the calorimeter response for jets is found to be 1.5% – 4% [102, 103], depending on η and p_T of a jet and can be studied as single particle responses for all particles contained in a jet. In simulation energy deposition per calorimeter cell can be directly associated to the single particles inside the jet. Both test-beam measurements with pions, and in-situ measurements using up to $900 \mu\text{b}^{-1}$ of data taken in 2010 are combined with additional sources of uncertainties, for example comparisons of different simulation models for neutral particles. For jets with a high transverse momentum, $p_T > 100 \text{ GeV}$, the overall jet energy scale uncertainty is dominated by this term.

⁵Technically, this means that if the $+1\sigma$ shifted JES uncertainty is applied to one jet in the event it is also applied to every other jet in the event, regardless of their separation in η and p_T .

η -Intercalibration

To achieve a uniform calorimeter response behavior for jets, a calibration has to be applied to correct for differences in the detector⁶ as a function of the jet direction. The calibration itself and the associated uncertainty are studied in a selection of dijet events with one jet measured in the central detector region, where the calorimeter response is well understood. The second jet acts as probe jet and has to carry the same amount of transverse momentum as the central reference jet, since the transverse momentum of the system has to be conserved. This p_T -balance is then exploited to derive correction factors for the relative response as a function of the pseudorapidity of the jets. The method can be extended to gain statistics to include all jet pairs and declare the more central jet as a reference jet. Comparing the relative response in data and Monte Carlo simulated events allows to estimate the uncertainty as the average deviation from the Monte Carlo response. This term is dominating the overall jet uncertainty for lower p_T jets, $p_T < 60$ GeV, especially in the forward region.

Noise Term

As described in section ??, a topological cluster algorithm based on the signal-to-noise ratio in neighboring calorimeter cells is used to reconstruct jets. Therefore, a difference of the noise model in the MC simulated events compared to data, can influence the topological clusters and the calorimeter response for jets. To estimate this source of systematic uncertainty, noise measurements are performed in data and propagated to Monte Carlo. The noise thresholds in the clustering algorithm are changed accordingly to reconstruct jets with otherwise exactly the same settings as in the default Monte Carlo setup. The differences in jet response of jets obtained with this method and the default jets reconstructed in simulation are taken as systematic uncertainties. The noise threshold only affects jets with a low transverse momentum, $p_T < 45$ GeV, and is found to be 1% independent of the pseudorapidity of the jet.

Parton Shower Model

The default jet energy scale calibrations are derived from Monte Carlo simulated events using the PYTHIA generator for the parton shower model. However, assumptions made in the showering and hence the composition of jets, can affect the calibration. Therefore, the response using PYTHIA showering is compared to events simulated with ALPGEN and interfaced with HERWIG/JIMMY for the parton showering. The difference is quoted as systematic uncertainty.

Underlying Event Model

To access uncertainties from the underlying event model on the jet energy scale, the default PYTHIA underlying event model used in ATLAS is compared to the PERUGIA2010 tune for PYTHIA. PERUGIA2010 is a special tuning of the underlying event model to fit jet and event shapes as measured at LEP and the Tevatron.

Pile-Up Model

The pile-up model differs both in data and Monte Carlo simulated events, but also between the

⁶such as different detector material or the amount of dead material as a function of the pseudorapidity

35 pb⁻¹ of data from 2010 and the 0.7 fb⁻¹ from 2011, due to the increased luminosity from the LHC. The influence of pile-up on the jet energy scale is extracted from the energy deposition in calorimeter cells in minimum bias events and applied as an offset correction at the electromagnetic scale. The uncertainty on this procedure can be estimated by variations of analysis settings, such as the choice of triggers or requirements on the minimum amount of transverse momentum for tracks and jets used in the measurement. While the analysis of 35 pb⁻¹ uses the pile-up jet energy scale uncertainty as described in Reference [77], as fully correlated along the transverse momentum of the jets in the event, the 0.7 fb⁻¹ includes four different nuisance parameters for the pile-up jet energy scale uncertainty in different η and p_T regions, as listed in table 5.3. The values are derived from studies of the 2011 data set, with a significantly larger amount of pile-up, and are treated separately to avoid too strong constraints on the uncertainty at high p_T caused by high statistics of lower p_T central jets.

	$0 < \eta < 2.1$	$2.1 \leq \eta < 4.5$
$20 < p_T < 50$ GeV	5%	7%
$50 \leq p_T < 100$ GeV	2%	3%
$p_T \geq 100$ GeV	0%	0%

Table 5.3.: Additional JES uncertainty contribution from pile-up, as used in the 0.7 fb⁻¹ analysis. Each non-vanishing component is treated as an independent nuisance parameter in the final fit.

Effect From Close-By Jets

A multijet environment, as in top physics, requires an additional uncertainty on the jet energy scale. If two jets are found very close to each other, the precision of the calorimeter response might degrade due to an overlap of energy depositions from two jets. This is taken into account by the close-by jet energy scale uncertainty, parameterized as a function of the transverse momentum of the jet and the distance ΔR between the jet and the nearest neighboring jet. The uncertainties are derived from comparisons of data and Monte Carlo simulated events in a selection of QCD dijet events [104] and are found to vary between 1.7% and 2.8% for anti-kt jets with $R = 0.4$. This uncertainty is included as a separate nuisance parameter for the 35 pb⁻¹ analysis and included in the other jet energy scale uncertainty terms for the 0.7 fb⁻¹ analysis⁷.

Flavor Composition

The calorimeter response can differ for jets produced from gluons or quarks at parton level, since the jet showering is sensitive to the parton flavor. While all calibrations are derived on inclusive QCD multijet samples, analyses measuring different physics processes with a different quark/gluon-jet contribution have to account for a systematic uncertainty from this difference in response. The average difference in calorimeter response is measured in data using dijet events, expected to be dominated by gluon jets, and γ -jet events, where the jet originates from a quark. Template fits to sensitive distributions, like the jet width and the number of tracks in the event are used to

⁷this effectively leads to an overestimation of this source of systematic uncertainty, but also accounts for differences in the 2010 data set used to derive the uncertainty and the 2011 data set as analysed

measure the contributions from both parton flavors and the associated uncertainties. Knowing the quark/gluon-fraction for the $t\bar{t}$ signal process from Monte Carlo prediction, one can then apply the associated uncertainties to the correct flavor composition. The 0.7 fb^{-1} analysis uses the assumption about the quark/gluon-fraction derived from $t\bar{t}$ MC for all simulated signal and background processes in the same way as the close-by term: included in the other sources of uncertainties, due to the technical implementation. The 35 pb^{-1} analysis assumes a more conservative knowledge about the flavor composition of the background samples, i.e. everything except for $t\bar{t}$ and the data-driven QCD multijet background. A 50:50 ratio for the quark/gluon-fractions is implemented, which is found highly conservative for the dominating W +jets background. In this analysis, the flavor composition term is implemented as an independent nuisance parameter in the profile likelihood function.

b -Jet Energy Scale

An additional uncertainty is applied to all true b -jets in the Monte Carlo simulated events, to account for differences in the response for jets originating from heavy quarks. Especially for the analysis of 35 pb^{-1} of data relying on b -jet identification, a correct treatment of this additional uncertainty is necessary and the b -jet jet energy scale uncertainty is implemented as a nuisance parameter in both analyses.

The uncertainty depends on the transverse momentum of the jet, decreasing towards higher values, and is shown in table 5.4.

p_T -range [GeV]	Uncertainty [%]
$20 < p_T < 40$	2.50
$40 \leq p_T < 80$	2.00
$80 \leq p_T < 210$	1.70
$210 \leq p_T < 600$	1.10
$p_T \geq 600$	0.76

Table 5.4.: Additional JES uncertainty contribution the difference in calorimeter response for jets originating from b -quarks.

5.6.3.6. Jet Energy Resolution

In the 2010 data set and the corresponding MC simulated events a slightly worse jet energy resolution is found in data compared to MC. Therefore, the jets in Monte Carlo events are smeared to match data in the default setup. Samples with no smearing applied are used to derive template distributions describing the 1σ -up variation of the corresponding nuisance parameter, while the *down* variation is derived from symmetrizing the difference to the nominal distribution.

For the 0.7 fb^{-1} analysis the jet energy resolution is found to be in good agreement between data and MC simulated events, and a smearing of the jets is only applied to describe the corresponding systematic uncertainty, treated in the same way as above to derive $\pm 1\sigma$ templates.

5.6.3.7. Jet Reconstruction Efficiency

To account for differences in the reconstruction efficiency for jets, based on found track jets, between data and Monte Carlo simulated events, the efficiencies are measured in both samples with a Tag & Probe approach in QCD dijet samples. The resulting difference is propagated as uncertainty to the measurements by randomly dropping jets from the Monte Carlo simulated samples, based on their transverse momenta and pseudorapidities. This creates a one-sided uncertainty and the deviation from the nominal distribution is mirrored to create $\pm 1\sigma$ templates describing the associated nuisance parameter.

5.6.3.8. Uncertainties of E_T^{miss}

Due to the object based approach of obtaining the missing transverse energy uncertainties on the physics objects used in the analyses (muons, electrons, jets) are directly propagated into the calculation of missing energy, taking into account the weights with which the objects enter the calculation. Additional terms for *soft jets* and the *cell out* terms have to be accounted for. Both are varied simultaneously within their $\pm 1\sigma$ uncertainties, and in the case of the 0.7 fb^{-1} analysis an additional flat 10% uncertainty, fully correlated to the above two terms, is applied to account for uncertainties from the pile-up model. In both analyses one nuisance parameter is used to describe this uncertainty on the missing transverse energy.

In addition, a second source of systematic uncertainty is considered for the 0.7 fb^{-1} analysis, since a full front-end board of the liquid argon calorimeter was not usable for data-taking over the early 2011 data-taking period. This uncertainty enters the profile likelihood function as an additional nuisance parameter.

5.6.3.9. b -Jet Tagging Uncertainty

Since the analysis of 35 pb^{-1} of data makes use of the b -tagging algorithm JetProb, see section 4.2.3.6, the calibration uncertainties for the algorithm have to be propagated into the measurement. No cut is applied on the amount of b -tagged jets, and hence the normalization of the predicted events for signal and background do not change with a different calibration. However, the shape of the b -tag output distribution can vary, if the b -tag or mistag calibration factors are varied by their uncertainties. Four different working points of the JetProb algorithm, 50%, 70%, 80% and 90%, are considered and all have a $\pm 1\sigma$ uncertainty on both the b -tag calibration and the mistag calibration assigned. Therefore, 8 *up* and 8 *down* templates are created using equation ?? and associated to 8 nuisance parameters⁸. In reality, the systematic uncertainties between the different working points are not fully uncorrelated. The correlation coefficients are of the order of 50–70% since the uncertainties are obtained both from variations within each method used to measure the calibration factors and from comparisons between different methods. Nevertheless, assuming no correlation at all gives a more conservative estimate of the uncertainty, since shape effects cancel out otherwise.

⁸four for the b -tag calibration, four for the mistag calibration

5.7. Method Testing

5.7.1. Pseudo-Experiments

The cross section extraction using a profile likelihood technique, as described in section 5.5, has to be carefully tested using Monte Carlo simulated events before applying the procedure to data. Pseudo-experiments (PEs) are performed to test the performance and stability of the method with pseudo-data sets created from the MC simulated templates of the likelihood discriminant $\mathcal{D}$. The distribution $\mathcal{D}$ for a pseudo-data set is created from the sum of events predicted by each physics process in each bin of the distribution. The prediction per process and bin is assumed to follow Poisson statistics and drawn from a random Poisson distribution with mean μ , where μ is the original prediction for this bin and process. Moreover, while the prediction for $t\bar{t}$ production is kept at its nominal value, random shifts of the normalization parameters β_i ($i > 0$) and the nuisance parameters δ_i are applied, drawn from a Gaussian distribution based on the knowledge of the $\pm 1\sigma$ range. In the default setup, the Gaussian distributions are limited to the $\pm 1.25\sigma$ range for each parameter, since knowledge of the nuisance parameters beyond this point is limited. Changes of the nuisance parameters are propagated into the template distributions using the vertical template morphing as described in section 5.5.

For specific tests the different β_i and δ_i can be shifted to different values, which allows to verify the sensitivity of the fit to a certain parameter, or can be kept fixed at certain values to test the behavior of the fit without this parameter under a certain assumption.

As described in section 5.5 only continuous sources of systematic uncertainties are included in the fitting function itself, while the contribution from discrete sources of systematic uncertainties have to be evaluated separately. To estimate these *out-of-fit* systematics, pseudo-experiments are drawn as described above, but with an additional shift of the template corresponding to the uncertainty under study to the $\pm 1\sigma$ variation, or the alternative model. The difference between the average fit result for β_0 with this setup and with the setup without the additional shift⁹ is quoted as systematic uncertainty on $\sigma_{t\bar{t}}$ and added in quadrature to the uncertainties obtained directly from the fit.

Typically a series of 1000 pseudo-experiments is performed with a given setup and the fit results for all parameters are stored in histograms. The average fitted value for a parameter is then extracted using a Gaussian fit to the distribution of fit results. In addition to the fit result itself, the pull distribution for each parameter, defined as deviation of the fit result from the default value divided by the uncertainty on the fit result, is extracted in the same way.

5.7.2. Definition of Expected Uncertainties

Based on pseudo-experiments the expected uncertainty of the method can be evaluated before applying it to data. Performing the fit and PEs without any nuisance parameter δ_i , the spread of the Gaussian distribution of the fitted values for β_0 represents the *expected statistical uncertainty* on

⁹In general, a better strategy would be to use the exact same pseudo-data set with both fitter setups and quote the average difference between the two as systematic shift. However, this is not possible in the current implementation of the profile likelihood fit used in this work, and the described method yields equivalent results for large numbers of PEs, reducing the statistical component of the procedure.

the method. Extending the likelihood function $\mathcal{L}_{\beta\delta}$ to include all nuisance parameters and performing a series of pseudo-experiments in this configuration leads to a combined statistical and systematic uncertainty¹⁰. The *expected systematic uncertainty*, corresponding to the parameters in the fit, can be extracted from a quadratic subtraction of the expected statistical uncertainty from the combined one.

The procedure described to obtain the expected statistical uncertainty can be modified to include also the uncertainty from the limited amount of Monte Carlo statistics available for the measurement, see section 5.6.1.6. Instead of drawing the new value per bin and process from a Poisson distribution with mean μ (μ being the predicted value), a modified expectation value μ^* is first drawn from a Gaussian distribution with mean μ and the width corresponding to the statistical uncertainty of the MC distribution in this bin. The modified expectation value μ^* is then treated as mean of the Poisson distribution, from which the new value for the construction of the pseudo-data distribution is drawn. A series of PEs is performed with this setup and the width of the distribution describing the parameter of interest, β_0 , is extracted from a fit of a Gaussian distribution to a histogram containing the results for all fits. The width corresponds to the combined statistical uncertainty and the uncertainty caused by the limited MC statistics. By quadratically subtracting the expected statistical uncertainty, the pure uncertainty from template statistics is derived and added to the other sources of systematic uncertainties quadratically.

5.7.3. Extraction of Systematic Uncertainties Inside the Fit

Both pseudo-experiments and the fit to data itself return only a combined uncertainty of the measurement of $\sigma_{t\bar{t}}$. To be able to confirm expectations about the influence of different sources of uncertainties and to understand the limitations of the reached precision, it is useful to estimate the influence of each systematic uncertainty to the measurement separately. Therefore, nuisance parameters are excluded from the fit one at a time, and the quadratic difference between the overall uncertainty with and without that given parameter is quoted as its influence on the overall systematic uncertainty. Applying this procedure to all sources of systematic uncertainties represented by nuisance parameters and adding the contributions in quadrature yields a slightly higher combined uncertainty than returned from the full fit. This can be explained, since excluding each nuisance parameter separately neglects correlations between the different sources of systematics accounted for in the global fit.

5.7.4. Stability Tests

Instead of performing pseudo-experiments as described above with the nominal prediction for $t\bar{t}$ production, the stability of the method can be tested as a function of the top quark pair production cross section. The top quark pair production cross section used to normalize the signal template is varied in steps of 10 pb in the range [120,200] pb, and 1000 PEs are performed at each point. The average measured cross section at each point can be extracted from a Gaussian fit to the sum of the individual fit results and can be displayed as a function of the input cross section, as will be shown explicitly in chapters 6 and 7 for the individual analyses. A linear fit to this distribution is expected

¹⁰where the systematics term only includes the sources of systematic uncertainties that are actually included as nuisance parameters

to show no offset and a slope of exactly one in case of perfect linearity of the method. If a deviation from these values is observed, the final result has to be corrected for the non-linearity to make the measurement independent of the expected signal cross section.

In the same way the pull distributions for different input cross sections can be evaluated for different input cross sections and should peak at zero with a width of one. Visible deviations from these values would hint at an over- or underestimation of the uncertainties.

5.7.5. Tests With Distortions

In addition to the tests described above more advanced series of pseudo-experiments or single fits can be performed to check the coverage of the estimated uncertainties. For example, pseudo-experiments with several nuisance parameters shifted to their $\pm 1\sigma$ deviations at the same time can show that the combined uncertainties on these parameters cover observed deviations of the measured $t\bar{t}$ cross section and that the correct values for the corresponding δ_i are extracted on average. Including templates for systematic uncertainties with non-linear behavior inside the 1σ envelope can also be used to test the coverage of the systematic uncertainties. New templates can be created with the fitted uncertainties on a given nuisance parameter, re-defining the $\pm 1\sigma$ range of the parameter. Using the new templates in the fit should yield no change of the fitted parameters and no further reduction of the uncertainty on the given δ_i . Additionally, different models can be inserted for the different nuisance parameters, for example different models of correlations in η and p_T for the JES uncertainties or uncertainties with a modified dependency on the object kinematics. All these tests are described in the corresponding sections in the chapters 6 and 7 for the corresponding analyses.

Measurement of $\sigma_{t\bar{t}}$ in 35 pb^{-1} of Data

6.1. Introduction

Based on the analysis strategy as outlined in chapter 5, a measurement of the top quark pair production cross section in the lepton+jets channel is performed in 35 pb^{-1} of data taken by the ATLAS experiment in the year 2010 at a center-of-mass-energy of $\sqrt{s} = 7 \text{ TeV}$. A combination of kinematic information about the objects in the event, event shape distributions and the output of a b -jet tagging algorithm, JetProb, used to build a likelihood discriminant $\mathcal{D}$ and a profile likelihood fitting technique is applied to extract $\sigma_{t\bar{t}}$. A preliminary version of this analysis was first presented at the Moriond 2011 conference and published as a conference result [105]. The final version of the analysis, corresponding to the setup shown in the following, is published in Reference [68].

6.2. Data Sample And Event Selection

The data sample is taken with the ATLAS detector in the 2010 run periods E4-I2, requiring a fully functioning detector with the implementation of a GoodRunsList. Only events selected by a single lepton trigger (mu10_MSonly, mu13 or mu13_tight for μ +jets events and e15_medium for e +jets events) are considered and the resulting data set corresponds to $35 \pm 1 \text{ pb}^{-1}$, corresponding to a 3.4 % uncertainty on the luminosity, see section 3.2.2. Monte Carlo simulated events are used to predict signal and background process contributions and shapes in the MC10 configuration of the ATLAS simulation. The QCD multijet background is estimated on data using a matrix method in the μ +jets channel and an anti-electron method in the e +jets channel, as described in section 4.3.5.

Events are selected, with the physics objects and corrections as described in section 4.2, by the following requirements for both data and simulated events:

- fired the single lepton trigger of choice
- containing exactly one electron with $E_T > 20 \text{ GeV}$ or muon with $p_T > 20 \text{ GeV}$ matched to the corresponding trigger object in the central detector region

- μ +jets: $E_T^{miss} > 20$ GeV and $m_T(W) + E_T^{miss} > 60$ GeV
- e +jets: $E_T^{miss} > 35$ GeV and $m_T(W) > 25$ GeV
- events are grouped by the jet multiplicity, counting jets with $p_T > 25$ GeV within $|\eta| < 2.5$
- events with one or two jets are considered as control region
- events with three, four or five and more jets are used for the measurement
- event level requirements as described in section 4.2.1

After applying this selection, the number of expected and observed events in the μ +jets and e +jets channels are shown in figure ?? and tables 6.1 and 6.2. A good agreement between the sum of expected events and the number of observed events can be seen. Since data and MC also agree well in the control region, $n_{\text{jet}} = 1, 2$, the assumptions made for the background model can be confirmed and used in the remainder of the analysis.

Figure 6.1.: Observed and expected events as functions of the jet multiplicity in the μ +jets and e +jets channel for 35 pb⁻¹.

The signal-to-background ratio (S/B) and signal significance, $\sigma_{SB} = S/\sqrt{S+B}$, differ widely between the channels and jet multiplicities and are shown for the signal region, $n_{\text{jets}} = 3, 4, \geq 5$, in table 6.3.

6.3. Variables

6.3.1. Kinematic and Topological Variables

Three kinematic quantities are used to distinguish between $t\bar{t}$ and W +jets production: the pseudorapidity of the charged lepton η^ℓ , the event aplanarity $\mathcal{A}$ and the momentum ration $H_{T,3p}$, as defined in section 5.3. The variables are combined into a likelihood discriminant $\mathcal{D}$ together with a continuous b -tagging distribution, as described in section 6.3.2, and the signal cross section is extracted in a profile likelihood fit of $\mathcal{D}$ to data.

Since electrons in the calorimeter crack region are discarded, the distribution for η^e is modified to

$$\eta^e = \begin{cases} \eta(e) & \text{for } |\eta| < 1.37. \\ \eta(e) - 0.15 & \text{for } 1.52 < \eta < 2.47. \\ \eta(e) + 0.15 & \text{for } -2.47 < \eta < -1.52. \end{cases} \quad (6.1)$$

For muons, the pseudorapidity is used directly, $\eta^\mu = \eta(\mu)$. To achieve a smoother, more uniform distribution, the aplanarity is transformed to $\mathcal{A} \rightarrow \exp(-8 \times \mathcal{A})$, and the momentum ratio to $H_{T,3p} \rightarrow \exp(-4 \times H_{T,3p})$.

The discriminating power of the variables is shown in figures 6.1 (η^ℓ), 6.2 ($\mathcal{A}$) and 6.3 ($H_{T,3p}$) and a good performance in both lepton channels and all jet multiplicity bins is visible.

The variable $H_{T,3p}$ is not defined for events with $n_{\text{jets}} < 3$, but the agreement in shape between data and Monte Carlo simulated events for the other two variables, η^ℓ and $\mathcal{A}$, can be tested in the background dominated sample of events with $n_{\text{jets}} = 2$. The general description of the object kinematics, especially for the background processes, is verified. Figure 6.4 shows good agreement between data and prediction for η^ℓ and $\mathcal{A}$ on the one hand, and the transverse momenta of the leading jet and the muon on the other hand. More distributions have been examined in the context of the analysis to validate the background model. Hence, the background models used to measure $\sigma_{t\bar{t}}$, especially the dominating ones (W +jets and QCD multijet production) are confirmed and considered to give a good description of the backgrounds also in events with higher jet multiplicities.

The comparison of distributions for data and Monte Carlo for the input variables is shown in figure 6.5 for η^ℓ , figure 6.6 for the aplanarity $\mathcal{A}$ and figure 6.7 for $H_{T,3p}$. No significant differences between data and prediction are observed within the statistical uncertainties, and the same holds true for the other kinematic distributions considered in section 5.3.

Figure 6.2.: Normalized distributions for the pseudorapidities of the charged leptons in μ +jets and e +jets events for simulated $t\bar{t}$ and W +jets events.

Process	1 Jet	2 Jets	3 Jets	4 Jets	≥ 5 Jets
$t\bar{t}$	20.2 $\pm$ 8.9	84.6 $\pm$ 21.5	164.8 $\pm$ 22.5	155.7 $\pm$ 18.2	108.5 $\pm$ 26.6
W +jets	18017.0 $\pm$ 2108.0	4333.9 $\pm$ 994.7	976.3 $\pm$ 413.5	221.6 $\pm$ 138.8	58.5 $\pm$ 38.4
Fakes (QCD Multijet)	316.3 $\pm$ 94.9	179.6 $\pm$ 53.9	78.9 $\pm$ 23.7	18.5 $\pm$ 5.6	10.9 $\pm$ 3.3
Single Top	58.3 $\pm$ 10.2	63.8 $\pm$ 10.5	31.0 $\pm$ 6.7	10.5 $\pm$ 3.6	3.6 $\pm$ 2.1
Z +jets	704.4 $\pm$ 144.4	212.6 $\pm$ 49.7	58.4 $\pm$ 25.8	13.9 $\pm$ 9.6	4.5 $\pm$ 3.6
Diboson (WW, WZ, ZZ)	67.0 $\pm$ 9.6	56.0 $\pm$ 8.7	15.5 $\pm$ 4.4	3.1 $\pm$ 1.8	0.6 $\pm$ 0.8
Total Predicted	19183.2 $\pm$ 2376.0	4930.5 $\pm$ 1139.0	1324.8 $\pm$ 496.6	423.3 $\pm$ 177.6	186.6 $\pm$ 74.0
Data Observed	20076	5039	1289	436	190

Table 6.1.: Selected events in the μ +jets channel split up by the different jet multiplicities. Uncertainties from limited MC statistics, theoretical cross sections, QCD multijet estimate, JES, luminosity and ISR/FSR for $t\bar{t}$ are considered. They signal region is highlighted in grey.

Process	1 Jet	2 Jets	3 Jets	4 Jets	≥ 5 Jets
$t\bar{t}$	14.7 $\pm$ 5.3	62.7 $\pm$ 12.4	116.9 $\pm$ 16.5	108.8 $\pm$ 14.7	75.5 $\pm$ 19.1
W+Jets	8484.0 $\pm$ 1094.5	2164.3 $\pm$ 496.7	523.6 $\pm$ 224.9	124.1 $\pm$ 76.8	34.6 $\pm$ 23.2
Fakes (QCD, γ +Jets)	409.0 $\pm$ 204.5	161.1 $\pm$ 80.6	63.5 $\pm$ 31.8	11.6 $\pm$ 5.8	7.9 $\pm$ 3.9
Single Top	35.5 $\pm$ 7.1	41.7 $\pm$ 7.9	21.1 $\pm$ 5.3	7.2 $\pm$ 2.9	2.7 $\pm$ 1.7
Z+Jets	165.9 $\pm$ 38.4	146.8 $\pm$ 42.7	60.3 $\pm$ 27.9	21.4 $\pm$ 14.8	7.8 $\pm$ 6.0
Diboson (WW,WZ,ZZ)	35.5 $\pm$ 6.4	28.8 $\pm$ 6.0	8.6 $\pm$ 3.1	1.9 $\pm$ 1.5	0.4 $\pm$ 0.6
Total Predicted	9144.7 $\pm$ 1356.2	2605.4 $\pm$ 646.3	794.0 $\pm$ 309.5	274.9 $\pm$ 116.5	128.9 $\pm$ 54.5
Data Observed	9849	2568	755	261	123

Table 6.2.: Selected events in the e +jets channel split up by the different jet multiplicities. Uncertainties from limited MC statistics, theoretical cross sections, QCD multijet estimate, JES, luminosity and ISR/FSR for $t\bar{t}$ are considered. The signal region is highlighted in grey.

N_{jets}	μ +jets		e +jets	
	S/B	σ_{SB}	S/B	σ_{SB}
3 Jets	0.14	4.53	0.17	4.15
4 Jets	0.58	7.57	0.66	6.56
≥ 5 Jets	1.39	7.94	1.41	6.65

Table 6.3.: Expected signal-to-background ratio and signal significance in the different jet bins and lepton channels of the analysis.

Figure 6.3.: Normalized distributions of $\exp(-8 \times \mathcal{A})$ in μ +jets and e +jets events for simulated $t\bar{t}$ and W +jets events.

Figure 6.4.: Normalized distributions of $\exp(-4 \times H_{T,3p})$ in μ +jets and e +jets events for simulated $t\bar{t}$ and W +jets events.

Figure 6.5.: Comparison between data and background model in the control region $\mu + 2$ jets, for the two variables entering the likelihood discriminant $\mathcal{D}$, η^ℓ and the transformation of $\mathcal{A}$, and the transverse momenta of the leading jet and the muon. A good agreement confirms the assumptions made to construct the background models.

Figure 6.6.: Comparison between data and Monte Carlo prediction for the lepton pseudorapidity η^ℓ in the signal region.

Figure 6.7.: Comparison between data and Monte Carlo prediction for $\exp(-8 \times \mathcal{A})$ in the signal region.

Figure 6.8.: Comparison between data and Monte Carlo prediction for $\exp(-4 \times H_{T,3p})$ in the signal region.

6.3.2. Continuous b -Tagging

In addition to three kinematic distributions described above, a special variable $\bar{w}_{JP}$ is used in the construction of the likelihood discriminant. Instead of requiring a jet to be identified as a b -jet by a b -tagging algorithm, the idea here is to use the output of the b -tagging algorithm directly as a continuous distribution. The JetProb algorithm, based on the probability for jets to stem from the primary vertex, as described in section 4.2.3.6, is chosen for this purpose, since more working points are calibrated for JetProb than for the other available algorithm, SV0. Several distributions, like the b -tag output for the leading jet, the lowest p_T jet and the average over all jets in the event, are considered in initial studies to find the best discriminator. The distributions for the b -tagging output of the most b -like and the second most b -like jet in the event, $\max w_{JP}$ and $\max_2 w_{JP}$, as shown in figure ??, give a good separation between $t\bar{t}$ production and W +jets production. The distributions are very similar in the e +jets and μ +jets channels.

Since top quark pair production always leads to final states with two real b -jets, while W +jets production does so only at a small fraction¹, events with two jets with a high probability to originate from b -quarks are likely top quark events. Therefore, the distributions as shown in figure ?? are combined to form the discriminating variable used in this analysis, the average b -tagging output of the two most b -like jets, $\bar{w}_{JP}$. The separation power of this variable is shown in figure ??, and the large tail towards high values is visible for simulated $t\bar{t}$ events.

Before using the variable $\bar{w}_{JP}$ in the analysis, a calibration has to be applied to correct for differences in the algorithm output for data and Monte Carlo simulated events. The procedure and equations are described in section 4.2.3.6, and correcting scale factors are available for four working points of the JetProb tagger: at 90%, 80%, 70% and 50% efficiency, corresponding to the values of $w_{JP} = 0.60, 1.40, 2.05$ and 3.25 . A new event weight is calculated as product over the scale factors for all selected jets in the simulated event, and since no cut is applied, the number of predicted events per physics process remains constant, while the shapes of the distributions can change. No calibration is applied to data and to the QCD multijet background, since the latter is obtained directly from data. A good agreement between data and simulated events is achieved after the calibration is applied, see figure ??, for events with four or five and more jets. However, at lower jet multiplicities the agreement degrades especially for events with two unlikely b -jets, i.e. low values of $\bar{w}_{JP}$, which is not fully covered by the uncertainties associated with the mistag calibration. Since the signal sample of events with exactly three jets is dominated by such events from W +jets production, the variable $\bar{w}_{JP}$ is not used in this jet bin. Moreover, studies showed that the implementation of such a strong, but possibly not well described variable, would make the cross section measurement overly sensitive to fluctuations in the third jet bin. Even though the exclusion of $\bar{w}_{JP}$ decreases the separation power of the likelihood discriminant $\mathcal{D}$ for events with three jets alone, the third jet bin still adds valuable information from the ratio of events with different jet multiplicities, since different systematic uncertainties can affect the ratio of events in different ways and can be constrained exploiting that knowledge.

¹when a $b\bar{b}$ pair is added either in the matrix-element or the parton showering

(a) b -Tagging distribution of the most b -like jet in an event, as classified for the JetProb tagger.

(b) b -Tagging distribution of the second most b -like jet in an event, as classified for the JetProb tagger.

Figure 6.9.: Normalized distributions of the b -tagging output for the two most b -like jets separately, in $\mu + 4$ jets and $\mu + \geq 5$ jets events for simulated $t\bar{t}$ and W +jets events.

Figure 6.10.: Normalized distributions of $\bar{w}_{JP}$, the average JetProb output value for the two most b -like jets, in μ +jets and e +jets events for simulated $t\bar{t}$ and W +jets events.

Figure 6.11.: Data and MC simulated distributions of $\bar{W}_{JP}$ for events with four or five and more jets, the categories for which $\bar{W}_{JP}$ is considered in the likelihood discriminant.

6.3.3. Likelihood Discriminant

The four variables, η^ℓ , $\exp(-8 \times \mathcal{A})$, $\exp(-4 \times H_{T,3p})$ and $\bar{w}_{JP}$, are combined into a likelihood discriminant $\mathcal{D}$, based on the differences between top quark pair production as signal and W +jets production as background. The likelihood discriminant is built and then evaluated for data and all signal and background processes using the TMVA framework, as described in section 5.4. The separation power of the likelihood discriminant can be seen in figure 6.8. Since $\bar{w}_{JP}$ is not considered for events with three jets, the separation power of the discriminant is significantly weaker than for the higher jet multiplicities. While a good separator peaks at 1 for signal and 0 for background, the distributions for three jet events average at about 0.5 for both signal and background. Statistics is limited especially for $e+\geq 5$ jets, degrading the separation power as well.

Figure 6.12.: Normalized distributions of the likelihood discriminant $\mathcal{D}$ in μ +jets and e +jets events for simulated $t\bar{t}$ and W +jets events.

Since the input distributions are well modeled by the Monte Carlo simulated events, a good agreement between data and Monte Carlo prediction is expected for the discriminant $\mathcal{D}$ as well. Data and prediction, scaled to the luminosity of the data set, are shown in figure 6.9, confirming this assumption. The distributions shown in figure 6.9 act as input to the extraction of $\sigma_{t\bar{t}}$ with a profile likelihood fitting technique in the following.

Figure 6.13.: Comparison between data and predicted signal and background events in the likelihood discriminant $\mathcal{D}$.

6.4. Overview of Systematic Uncertainties

All sources of systematic uncertainties as described in section 5.6 are expected to have an influence on the measured top quark pair production cross section. All uncertainties that can be considered as continuous are included as nuisance parameters in the profile likelihood fit function $\mathcal{L}_{\beta\delta}$. Sources of systematic uncertainties representing discrete settings, for example the difference between the two event generators MC@NLO and POWHEG, are evaluated using pseudo-experiments. A summary of the systematic uncertainties considered in this analysis is shown in table 6.4, also indicating which ones are treated as nuisance parameters in the fit.

The influence of different uncertainties on the predicted number of events and the likelihood discriminant $\mathcal{D}$ can be seen in figure ?? for the μ +jets channel and figure 6.10 for the e +jets channel. Total systematic modeling and detector uncertainties are shown separately, and are constructed from the different template distributions assuming full correlation of uncertainties across the different physics processes and no correlation between the different sources of uncertainties. The model uncertainties also include the uncertainties on the predictions for the different background processes, which are implemented as Gaussian constraints on the corresponding normalization parameters β_i in the likelihood.

The uncertainties can act on the shape of the distribution, the overall number of predicted events, the ratio of events with different jet multiplicities or all together. As an example, the b - and mistag calibration uncertainties cannot change the number of predicted events, but can only lead to differences in the shapes of $\mathcal{D}$ for various physics processes. As expected, the b -tag uncertainties have a significant influence on the shape of the discriminant $\mathcal{D}$ for $t\bar{t}$ events, and to a much smaller extend on the W +jets backgrounds, while the picture is inverted for the uncertainties on the mistag calibration. This behavior can be seen in figure ??, showing the ratio of default and $\pm 1\sigma$ varied distributions at the 50% efficiency JetProb working point in $\mu+4$ jets events for $t\bar{t}$ and W +jets processes. Since the discriminant for $t\bar{t}$ events in the $\mu+4$ jets channel peaks at a value of $\mathcal{D} = 1$, and at $\mathcal{D} = 0$ for $W + \text{jets}$, the variation in the corresponding outermost bins has the largest influence on the measurement, and there the behavior as described above is visible.

On the other hand, many systematic uncertainties have a large influence on the ratio of events predicted at the different jet multiplicities. This is especially true for jet related uncertainties or theoretical models predicting a different amount of additional radiation in the events, as can be seen in figure 6.11. The final combined fit to extract the signal cross section, $\sigma_{t\bar{t}}$, makes use of both shape uncertainties and differences in the jet multiplicity distribution. Therefore, the classification of events with $n_{\text{jets}} = 3, 4, \geq 5$ improves the performance of the method over the same method applied to a $n_{\text{jets}} \geq 3$ selection of events.

Systematic Uncertainty	Nuisance Parameter	Comments
Background Normalization	-	included in statistical uncertainty through Gaussian constrains
Signal Generator	-	
Parton Shower Model	-	
ISR and FSR	-	ISR [±] , FSR [±] , ISRFSR [±] – largest difference taken as symmetric uncertainty
PDF	-	
W+Jets Generator Settings	-	reweighting for <i>iqopt2</i> and <i>ptjmin10</i>
W+Heavy Flavor Contribution	✓	six different parameters: $Wb\bar{b}/Wc\bar{c}$ and Wc separately for $n_{\text{jets}} = 3, 4, \geq 5$
QCD Multijet Model	-	from anti-electron (e +jets) and loose-not-tight (μ +jets) selection
Pile-Up Model	✓	
Monte Carlo Statistics	-	
Muon/Electron Scale Factors	✓	uncorrelated between the channels
Muon Momentum Scale and Resolution	✓	one combined parameter for the envelope
Electron Energy Scale	✓	
Electron Energy Resolution	✓	
Calorimeter Response (JES)	✓	
η -Intercalibration (JES)	✓	
Noise Term (JES)	✓	
Parton Shower Model (JES)	✓	
Underlying Event Model (JES)	✓	
Pile-Up Influence on JES	✓	
Close-By Jets (JES)	✓	
Flavor Composition (JES)	✓	flavor composition from $t\bar{t}$ MC for signal, 50:50 quark/gluon contribution for all backgrounds
b -Jet Energy Scale	✓	
Jet Energy Resolution	✓	
Jet Reconstruction Efficiency	✓	
E_T^{miss} Uncertainties	✓	fully correlated uncertainties on soft jet and cell out terms
b -Tagging Calibration	✓	one δ for each of the four working points
Mistagging Calibration	✓	one δ for each of the four working points

Table 6.4.: Sources of systematic uncertainties and their treatment in the cross section extraction. The first set of uncertainties is related to assumptions on the physics model, while the second set is related to detector and reconstruction effects.

Figure 6.14.: Sum of all sources of systematic uncertainties (yellow band) for physics modeling uncertainties (left) and detector uncertainties (right) for the sum of predicted signal and background, compared to data in the μ +jets channel.

Figure 6.15.: Sum of all sources of systematic uncertainties (yellow band) for physics modeling uncertainties (left) and detector uncertainties (right) for the sum of predicted signal and background, compared to data in the e +jets channel.

(a) b -Tagging calibration uncertainty on the 50% efficiency JetProb working point.

(b) Mistag calibration uncertainty on the 50% efficiency JetProb working point.

Figure 6.16.: Shape changes of the likelihood discriminant $\mathcal{D}$ caused by the b -tag and mistag calibration uncertainties at the 50% efficiency working point, and their difference between $t\bar{t}$ and W +jets events.

(a) Calorimeter Response Jet Energy Scale Uncertainty (b) Flavor Composition Jet Energy Scale Uncertainty

(c) Final State Radiation Uncertainty

(d) Signal Generator (POWHEG vs MC@NLO symmetrized)

Figure 6.17.: Distribution of all selected simulated $t\bar{t}$ events in the different analysis channels and the sensitivity of the relative amount of events in each channel on different sources of systematic uncertainties.

6.5. Cross Section Extraction

6.5.1. Expected Uncertainties

Pseudo-experiments, as described in section 5.7.1, are performed to estimate the expected uncertainties on the measured cross section. A series of 1000 pseudo-experiments is performed, only using Monte Carlo simulated events as inputs, and a Gaussian function is fitted to the distribution of single fit results. For the parameter of interest, β_0 , the distribution should peak at $\beta_0 = 1$, with the RMS of the fitted Gaussian representing the expected uncertainty.

Expected statistical uncertainties for the full fit and fits in the μ +jets and e +jets channels separately are obtained from fits without nuisance parameters and the results are shown in figure ?? . As expected, all distributions represent Gaussian functions with a mean of $\beta_0 = 1$. Due to the different statistics available in the two individual lepton channels the expected statistical uncertainty varies between 7.6% in the μ +jets channel and 9.7% in the e +jets channel. When combined, the statistical uncertainty of the full fit is reduced to 6.1%. Furthermore, the influence of the different jet multiplic-

Figure 6.18.: Expected statistical uncertainties for the combined fit and single channel fits, as estimated with a series of 1000 pseudo-experiments.

ities based on the statistical significance can be estimated. Expected statistical uncertainties for full fits in the combined ℓ +jets channel are shown for the different jet multiplicities $n_{\text{jets}} = 3, 4 \geq 5$ in figure ?? . The smallest uncertainty is expected for events with 4 jets, with 8.2%. The fit to events with five and more jets has a better signal-to-background ratio, but suffers from lower statistics, leading to a statistical uncertainty of 9.4%. The events with exactly three jets are dominated by background, and hence the statistical uncertainty is large: 28.9%.

Including all nuisance parameters δ_i in the fitting function $\mathcal{L}_{\beta\delta}$ and performing another series of pseudo-experiments allows to estimate the combined statistical and systematic uncertainty of the full fit, as shown in figure 6.12. The uncertainties only account for the ones included in the fit as nuisance parameters, other sources of systematics are estimated in dedicated series of PEs, as shown later. The expected combined fit uncertainty for the full fit yields 8.2%, corresponding to an expected

Figure 6.19.: Expected statistical uncertainties for the combined fit in different jet multiplicity bins, as estimated with a series of 1000 pseudo-experiments.

systematic uncertainty of 5.5% from the fit², while the uncertainty grows to 11.1% (8.1% systematics) in the μ +jets channel alone, and 13.6% (9.5% systematics) in the e +jets channel alone. A slight deviation of the mean value from $\beta_0 = 1$ is visible, and is accounted for in a calibration procedure, as discussed in section 6.5.2.

Figure 6.20.: Expected statistical and systematic uncertainties for the combined fit and single channel fits, as estimated with a series of 1000 pseudo-experiments. Only the systematic uncertainties treated as nuisance parameters inside the fit are considered here.

6.5.2. Calibration

Pseudo-experiments are performed to test for, and, if necessary, correct for a possible bias of the analysis. As described in section 5.7.4, a series of PEs is carried out with varying input values for $\sigma_{t\bar{t}}$ and the deviation from a strictly linear behavior is tested for the full fit setup. Since the test

²determined by subtracting the expected statistical uncertainty in quadrature

of linearity, as shown in figure ??, shows an offset of 1.6 pb, with a slope compatible with 1, as expected, a correction is applied. This deviation is observed independent of the number of PEs, as tested in series of 1000, 5000 and 10000 PEs. To account for the offset, the signal cross section as

Figure 6.21.: Results of pseudo-experiments performed with different input cross sections, $\sigma_{t\bar{t}}$.

measured by the fit is corrected to be

$$\sigma_{t\bar{t},\text{true}} = \frac{\sigma_{t\bar{t},\text{fitted}} + 1.644}{0.994}, \quad (6.2)$$

taking the small deviation from 1 in the slope into account. Figure ?? also shows the pull distribution, $\frac{\beta_0^{\text{fitted}} - \beta_0^{\text{input}}}{\sigma_{\beta_0}}$, for the different input cross sections. While the pulls are centered around 0, the distributions show a spread slightly smaller than unity, hinting at an overestimating of uncertainties by the fit to data, compared to the uncertainties returned by the pseudo-experiments. For final, observed, uncertainties, the uncertainties as measured by the fit are quoted, i.e. the more conservative estimate is taken. Another reason for this behavior is the cutoff at 1.25σ of the uncertainties for the sampling in the pseudo-experiments. Extending the allowed range increases the number of failing fits, but leads to pull widths closer to unity.

The linearity and performance of the fit is also tested in the separate lepton channels and corresponding correction functions are derived. The μ +jets channel shows an offset of (1.916 ± 1.0526) pb and a slope of the fitted linear function of 0.9718 ± 0.0066 . Deviations from zero and unity are smaller in the e +jets channel, with an offset of (-0.7170 ± 1.2254) pb and a slope of 0.9708 ± 0.0077 , but are applied as correction factors for consistency reasons.

6.5.3. Fit Results

A profile likelihood fit, as introduced in section 5.5, is used to measure the top quark pair production cross section performing a template fit of the likelihood discriminant $\mathcal{D}$ to data. Since the inclusion

of nuisance parameters in the fitting function $\mathcal{L}_{\beta\delta}$ not only changes the uncertainties as returned by the fit, but also the measured central value, both the fit result allowing only variations of the normalization parameters β_i , and the full fit results are shown in table 6.5. Finally, the results of the full fit after applying the corrections from the method calibration are shown as final results.

Channel	Statistical [pb]	Full Fit [pb]	Full Fit Corrected [pb]
μ +jets	185^{+14}_{-13}	181^{+19}_{-18}	184^{+19}_{-18}
e +jets	193^{+17}_{-17}	191^{+23}_{-22}	196^{+24}_{-23}
combined	188^{+11}_{-11}	184^{+16}_{-15}	187^{+16}_{-15}

Table 6.5.: Fit results for the combined fit and the single channel fits, as statistical only, full fit and the corrections from section 6.5.2 applied. Uncertainties are only considered for the sources of uncertainties that are included in the fitting function.

The agreement between data and Monte Carlo simulated events for the combined channel fit is shown in figure 6.13, both for the version with and without nuisance parameters. Once the nuisance parameters are included the agreement of data and simulated events improves compared to the fit allowing only the normalization parameters β_i to vary. In general, good agreement between data and adjusted predictions is achieved. Results for the full fit of $\mathcal{L}_{\beta\delta}$ in both the μ +jets and e +jets channels are shown in figure 6.14. While the achieved data – Monte Carlo agreement in the μ +jets channel alone is very good, the lower statistics in the e +jets channel does not allow to constrain the fit parameters well enough to achieve such a good agreement. However, in the combined fit the e +jets channel benefits from the constraining power of the μ +jets channel, improving the overall agreement between data and simulation in the full fit.

The complete fit results for all β_i and δ_i for the combined fit to the ℓ +jets channels are shown in table 6.6. The starting value for all normalization parameters is $\beta_i = 1.0^3$, while the nuisance parameters are initially set to $\delta_i = 0.0 \pm 1.0$. If the uncertainties on the δ_i are reduced to values smaller than unity, the fit is able to constrain this uncertainty further based on the distributions in data. The parameter tables for the μ +jets and e +jets fits can be found in appendix A. Only a few uncertainties are significantly constrained beyond the expected uncertainties and the average preferred values for the δ_i are centered around the starting value of zero, as shown in Figure 6.15. As can be seen in figure 6.15 as well, no significant differences between the preferred values for the nuisance parameters in the combined fit and the single channel fits are observed. As expected, the uncertainties are reduced best in the combined fit.

The linear correlation coefficients between the fit results for the different parameters β_i and δ_i in the combined fit are shown in figure 6.16. As expected, the W +jets normalizations in the different channels and jet multiplicities are correlated to each other, as well as the W +jets and QCD multijet parameters in the same channel. The latter is visible especially for events with three jets, where the backgrounds are dominating, since the two background processes lead to similar likelihood discriminant distributions. Furthermore, variations of the b -tagging correction factors are correlated to changes of the parameter of interest, β_0 , since $t\bar{t}$ production produces two b -jets. Finally, correlations between the different JES parameters, but especially the flavor component term of the jet energy scale uncertainty, are correlated with the fitted amount of W +jets events. The flavor

³The initial uncertainties on the β_i correspond to the Gaussian constraints on the background normalization.

component uncertainty for backgrounds is constructed under an assumption of 50% quark-fraction and 50% gluon-fraction, leading to a quite large conservative variation of the amount of W +jets. Some of the JES components are also correlated to each other and especially to the global calorimeter response term of the jet energy scale uncertainty.

The validity of the measurement can be tested by the profiling procedure as described in section 5.5. The likelihood function $\mathcal{L}_{\beta\delta}$ is reduced to a function of the parameter of interest, β_0 , and the behavior of the likelihood value as function of β_0 can be displayed. Figure 6.17 shows the behavior over the full fit range of β_0 and in the region around the minimum of the function. The distribution is expected to be smooth and show a Gaussian behavior around the minimum, allowing to extract the 1σ uncertainty on β_0 by varying the value for $-\ln(\mathcal{L})$ by ± 0.5 around its minimum. Both expectations are confirmed by figure 6.17.

Furthermore, the evolution of the different normalization and nuisance parameters as a function of the main fit parameter β_0 can be studied, and is shown in figures 6.18 and 6.19 as an overview and with the same ordering of histograms as the parameters in table 6.6. No discontinuities or instable behavior should be observed in the region around the fitted value, as indicated by the red line, and the uncertainties on the parameters should not vary significantly over the allowed range for β_0 . The only discontinuities in parameters are observed for very small values of β_0 , hinting at internal normalization issues and low statistics, but they do not affect the measurement since distributions are found to be smooth in a large range around the expected and fitted values of β_0 .

Figure 6.22.: Fit results for the combined ℓ +jets channels, without and with the inclusion of nuisance parameters. An improvement of the agreement between data and simulation can be seen once nuisance parameters are included.

(a) μ +jets (b) e +jets

Figure 6.23.: Separate fit results for the μ +jets and e +jets channels with nuisance parameters included in the fitting function.

Figure 6.24.: Preferred values of nuisance parameters $\delta_i \pm \sigma_{\delta_i}$, as returned by the full combined fit. The distribution centers around the starting value of $\delta_i = 0.0$, while the uncertainties on some parameters can be reduced to values smaller than the initial definition of $\pm 1\sigma$. On average, the observed nuisance parameters agree well with the expected ones, and also agree between the combined fit and the different single channel fits.

Parameter	Value	Error	Error Up	Error Down
$\beta(t\bar{t})$	1.1142	0.0918	0.0964	-0.0889
$\beta(W \rightarrow \mu + 3 \text{ jets})$	0.8700	0.0841	0.0972	-0.0788
$\beta(W \rightarrow \mu + 4 \text{ jets})$	0.8519	0.1230	0.1402	-0.1147
$\beta(W \rightarrow \mu + 5 \text{ jets})$	0.7415	0.2076	0.2362	-0.1901
$\beta(W \rightarrow e + 3 \text{ jets})$	0.9014	0.1015	0.1047	-0.0987
$\beta(W \rightarrow e + 4 \text{ jets})$	0.8407	0.1537	0.1595	-0.1481
$\beta(W \rightarrow e + 5 \text{ jets})$	0.5492	0.2633	0.2776	-0.2504
$\beta(Z + \text{jets})$	1.1189	0.2815	0.2806	-0.2850
$\beta(\text{Single top})$	1.0059	0.1059	0.1059	-0.1059
$\beta(\text{Diboson})$	1.0007	0.0600	0.0600	-0.0600
$\beta(\text{QCD in } \mu + 3 \text{ jets})$	0.8961	0.4786	0.4805	-0.4801
$\beta(\text{QCD in } \mu + 4 \text{ jets})$	0.9931	0.4730	0.4734	-0.4735
$\beta(\text{QCD in } \mu + 5 \text{ jets})$	0.6472	0.4718	0.4726	-0.4719
$\beta(\text{QCD in } e + 3 \text{ jets})$	1.0680	0.4880	0.4906	-0.4909
$\beta(\text{QCD in } e + 4 \text{ jets})$	1.0107	0.4966	0.4972	-0.4972
$\beta(\text{QCD in } e + 5 \text{ jets})$	0.8565	0.4912	0.4919	-0.4918
$\delta(\text{b-tag WP1})$	-0.6763	1.0609	1.0662	-0.9637
$\delta(\text{b-tag WP2})$	0.6062	0.9607	0.9551	-0.9620
$\delta(\text{b-tag WP3})$	-0.0890	0.9099	0.9058	-0.9139
$\delta(\text{b-tag WP4})$	0.1376	0.8712	0.8837	-0.8635
$\delta(\text{mistag WP1})$	0.3651	0.9975	0.9772	-1.0081
$\delta(\text{mistag WP2})$	-0.3292	0.9727	0.9727	-0.9704
$\delta(\text{mistag WP3})$	0.2834	0.9886	0.9847	-0.9882
$\delta(\text{mistag WP4})$	0.0279	0.9947	0.9949	-0.9947
$\delta(\text{Jet ID})$	1.0277	0.5341	0.5444	-0.5161
$\delta(\text{JER})$	0.5942	0.9116	0.9086	-0.9261
$\delta(W + \text{bb/cc Fraction } 3 \text{ jets})$	-0.6014	0.9564	0.9555	-0.9602
$\delta(W + \text{bb/cc Fraction } 4 \text{ jets})$	0.2517	0.8627	0.8727	-0.8570
$\delta(W + \text{bb/cc Fraction } 5 \text{ jets})$	-0.3720	0.9242	0.9489	-0.9059
$\delta(W + c \text{ Fraction } 3 \text{ jets})$	0.4486	0.9460	0.9453	-0.9467
$\delta(W + c \text{ Fraction } 4 \text{ jets})$	0.0665	0.9758	0.9756	-0.9761
$\delta(W + c \text{ Fraction } 5 \text{ jets})$	-0.1275	0.9975	0.9976	-0.9975
$\delta(\text{Pileup})$	0.2230	0.7710	0.7637	-0.7772
$\delta(\mu \text{ SFs})$	-0.0563	0.9874	0.9874	-0.9869
$\delta(e \text{ SFs})$	0.0837	0.9398	0.9411	-0.9368
$\delta(\mu \text{ Momentum Smearing})$	-0.1202	1.3489	1.1447	-1.3361
$\delta(e \text{ Energy Resolution})$	0.1472	0.7577	0.7472	-0.7535
$\delta(e \text{ Energy Smearing})$	0.2214	0.7646	0.7446	-0.7698
$\delta(\text{Missing Et})$	0.1082	0.9111	0.7673	-0.8815
$\delta(\text{JES Eta})$	1.0496	0.4629	0.4727	-0.5168
$\delta(\text{JES Calo})$	-0.5960	0.4951	0.5904	-0.4349
$\delta(\text{JES Alpgen})$	-0.5506	0.5959	0.7623	-0.4963
$\delta(\text{JES Noise})$	-0.2108	0.7986	0.8586	-0.6445
$\delta(\text{JES Pile-Up})$	0.1552	0.6668	0.5965	-0.6867
$\delta(\text{JES Perugia})$	-0.0310	0.3277	0.2560	-0.9828
$\delta(\text{JES b-Jet})$	-0.3104	0.6816	0.7134	-0.6296
$\delta(\text{JES flavor})$	0.5871	0.7088	0.5715	-1.0327
$\delta(\text{JES close-by})$	-0.3157	0.5178	0.5462	-0.4831

Table 6.6.: Resulting fit parameters and uncertainties from the combined ℓ +jets channel fit.

Figure 6.25.: Linear correlation coefficients between the different β_i and δ_i as returned by the full fit of $\mathcal{L}_{\beta\delta}$. The parameters associated to uncertainties not included in the fitting function have their correlation coefficients set to zero.

Figure 6.26.: Negative log-likelihood value as function of the parameter of interest, β_0 , from the profiling procedure in the combined fit. The red line indicates the fitted value $\beta_0 = 1.1142$.

Figure 6.27.: Behavior of fitting parameters β_i ($i = 1, \dots, 15$) and δ_i ($i = 0, \dots, 16$) as function of the parameter of interest β_0 in the full combined fit. No unexpected behavior is observed, confirming the sanity of the measurement and profiling procedure. The red line indicates the fitted value of $\beta_0 = 1.142$.

Figure 6.28.: Behavior of fitting parameters δ_i ($i = 17, \dots, 31$) as function of the parameter of interest β_0 in the full combined fit. No unexpected behavior is observed, confirming the sanity of the measurement and profiling procedure. The red line indicates the fitted value of $\beta_0 = 1.1142$.

6.5.4. Observed Uncertainties

The observed uncertainties are obtained from the fit to data directly, the statistical component from the fit including only normalization parameters β_i and the combined statistical and systematic uncertainty from the full fit. The observed statistical uncertainties of +5.7%/-5.6% (full fit), +7.5%/-7.2% (μ +jets) and +9.0%/-8.7% (e +jets) are slightly smaller than the expected statistical uncertainties, see section 6.5.1. This also translates into slightly smaller combined uncertainties, accounting for the statistical and the systematic uncertainties from the nuisance parameters. The combined uncertainty on the combined channel fit is found to be +8.6%/-8.0%, while the uncertainties increase to +10.3%/-9.8% in the μ +jets channel and +12.0%/-11.3% in the e +jets channel.

The additional uncertainties not included as nuisance parameters in the fit, and the one from the available statistics of the Monte Carlo samples, are evaluated with pseudo-experiments, created with the nuisance parameters adjusted to the fitted parameters. To estimate the influence of each single source of uncertainty that is considered in the fit, the fit is performed with all but one corresponding nuisance parameter, and the quadratic difference on the overall uncertainty from the fit is quoted. This procedure does not take internal correlation effects between the different fit parameters into account, and thus the sum of all uncertainties might lead to a value larger than the direct fit uncertainty. For the full fit in the combined channels the different sources of uncertainties, grouped by their origin, are shown in table 6.7. As can be seen, the uncertainties that are handled inside the fit are dominated by the ones from the jet energy scale, the b -tagging calibration and the W +jets heavy flavor content. While the latter two are influential due to the good ability to separate different flavor contributions in the measurement, the jet energy scale uncertainties are important due to the high number of jets present in each event. Several sources of jet energy scale uncertainty are considered for the presented measurement and a further breakdown of the influence from the different sources can be found in table 6.8. The dominating JES uncertainty is found to be the uncertainty on the flavor content, which is expected due to a very conservative assumption made about the quark/gluon fractions in the dominant background.

In addition, the uncertainties on the signal model have a large contribution to the overall uncertainty, since they change the shape, the normalization and the ratio of events with different jet multiplicities significantly, but are not allowed to be constrained by the data, since they are discrete uncertainties by nature.

Tests with few nuisance parameters show that the relative influence of the different uncertainties does not vary significantly in the separate μ +jets and e +jets measurements. For the sake of comparing the results obtained in the separate channels with the main combined result, the assumption is made that the external sources of systematic uncertainties contribute to all channels in the same way. These external uncertainties, MC statistics, signal modeling, W +jets shape uncertainty and QCD multijet shape uncertainty, are in general independent of the lepton flavor and are not influenced by the increase of statistics in the combined measurement. Of course, the QCD multijet model assumptions used for the shape uncertainty estimation differ between the channels, but the influence of this source on the overall uncertainty is rather small. The overall systematic uncertainty from the sources of systematics not included in the fit is derived from a quadratic sum of the different sources and found to be $\pm 7.1\%$.

Statistical Uncertainty (%)	+ 5.8	- 5.7
Physics Objects (%)		
Jet Energy Scale	+ 3.9	- 2.9
Jet Reconstruction Efficiency	+ 0.01	- 0.3
Jet Energy Resolution	+ 0.3	- 0.01
Muon Scale Factors	+ 1.2	- 1.1
Muon Smearing	+ 0.4	- 0.4
Electron Scale Factors	+ 1.6	- 1.4
Electron Smearing	+ 0.0	- 0.0
Electron Energy Scale	+ 0.5	- 0.3
Missing Transverse Energy	+ 0.01	- 0.01
Background Models (%)		
W + Jets Heavy Flavor Content	+ 2.7	- 2.4
W + Jets Shape (*)	+ 1.0	- 1.0
QCD Multijet Shape (*)	+ 0.8	- 0.8
Signal Models (%)		
ISR/FSR (*)	+ 5.2	- 5.2
NLO Generator (*)	+ 4.2	- 4.2
Hadronisation (*)	+ 0.4	- 0.4
PDF (*)	+ 1.5	- 1.5
Others (%)		
b -Tagging Calibration	+ 4.1	- 3.8
Pile-Up Simulation	+ 0.01	- 0.01
MC Template Statistics (*)	+ 1.1	- 1.1
Total Systematic (%)	+ 9.7	- 9.0

Table 6.7.: Observed uncertainties from statistics and sources of systematic uncertainties for the full combined fit. Sources of systematic uncertainties that are not included as nuisance parameters are marked with a (*), and are evaluated in series of pseudo-experiments.

6.6. Additional Tests

Many different sets of tests are performed to prove the stability of the presented measurement and its ability of constraining uncertainties beyond their initial $\pm 1\sigma$ variations. Most of the studies rely on pseudo-experiments or the exchange of the input templates for certain systematic uncertainties, and some of the studies will be presented here. Since the different jet energy scale uncertainties can be constrained significantly below their initial $\pm 1\sigma$ range, several tests are performed to test the sensitivity of the analysis to modeling assumptions made for the JES uncertainty. For the tests described in the following a slightly different setup of the analysis is used as the default reference, with a fit result very close to the final presented one: $\beta_0 = 1.12 \pm 0.10$, which translates into $\sigma_{t\bar{t}} = 185^{+18}_{-16}$ pb, and consistent results for the other fit parameters⁴. The resulting combined uncertainty from jet energy scale should cover a scenario in which all transverse momenta are miscalibrated globally,

⁴no systematic uncertainties external to the fit are estimated here, since only the fitter behavior is to be tested

JES Component (%)			
ALPGEN Model	+	0.87	- 0.88
PERUGIA tuning	+	0.53	- 0.72
b -Jet Energy Scale	+	0.87	- 0.66
Calorimeter Response	+	1.02	- 0.97
Noise	+	1.18	- 1.02
Flavor Composition	+	2.99	- 1.92
Close-By Jet	+	0.75	- 0.59
Pile-Up	+	0.53	- 0.59
η -Extrapolation	+	1.22	- 0.59
<hr/>			
Total JES Uncertainty (%)	+	3.93	- 2.90

Table 6.8.: Observed uncertainties from the different sources of jet energy scale uncertainties on the combined fit. A nuisance parameter δ_i is associated to each of the sources separately.

i.e. if the central jet energy scale is shifted. Such a scenario is created artificially by shifting the transverse momenta of all jets found in a MC simulated event down by 1.5%. The full analysis is repeated with this setup, including all systematic uncertainties and the creation of the necessary templates. While the shapes of the likelihood discriminant $\mathcal{D}$ do not change much in this scenario, the number of predicted events and especially the division of the events in different jet multiplicity bins does. Performing the full fit in this setup yields $\beta_0 = 1.13 \pm 0.09$ or $\sigma_{t\bar{t}} = 187$ pb. This corresponds to a shift of the central value of 0.8%, and a small reduction of uncertainties, clearly covered by the JES related sources of uncertainties, which account for +3.9%/-2.9%. Furthermore, as can be seen in figure ??, only the nuisance parameters related to jets differ with respect to the nominal fit, and tend to be fitted to larger negative values on average. This is expected, since the transverse momenta are shifted to smaller values.

Three different studies are performed to test assumptions made about correlations as a function of pseudorapidity and transverse momentum of the different jets in the event in the calorimeter response uncertainty. This uncertainty is chosen, since studies suggest that the correlation of this uncertainty for jet pairs well separated in pseudorapidity or transverse momentum can be smaller than one [77]. First, the uncertainties are modified to introduce an additional dependence on the transverse momentum, by varying an additional factor $x \times \sigma$ from $x = 0.6$ to $x = 1.5$ linearly over the range $[0, 200]$ GeV. Compared to the default setup, the fit result of $\beta_0 = 1.13 \pm 0.10$, translated into $\sigma_{t\bar{t}} = 186^{+18}_{-16}$ is obtained. This corresponds to a difference of 0.77% in the measured cross section, while the contribution from the calorimeter response uncertainty is measured to be approximately +0.6%/-0.8%, i.e. in agreement with the observed shift. In the second test the calorimeter response uncertainty is modified depending on the pseudorapidity of the jet, following the recipe

$$x = \begin{cases} 1.1 & \text{for } |\eta| < 0.5. \\ 0.9 & \text{for } 0.5 \geq |\eta| < 1.0. \\ 1.2 & \text{for } 1.0 \geq |\eta| < 1.5. \\ 0.8 & \text{for } 1.5 \geq |\eta| < 2.0. \\ 1.3 & \text{for } 2.0 \geq |\eta| < 2.5. \end{cases} \quad (6.3)$$

While the actual values are rather arbitrary, the larger shifts of uncertainties are implemented in the less well-understood forward region. With this setup a fit parameter of $\beta_0 = 1.13 \pm 0.10$ is obtained, corresponding to $\sigma_{t\bar{t}} = 187_{-16}^{+17}$ pb, which is also covered by the uncertainty associated to the calorimeter response term. The agreement between the different fit parameters and the default setup can be seen in figure ??, showing deviations between the results only for the different JES parameters, as expected. Overall, the agreement between the different setups is found to be good, proving the validity of the models.

Figure 6.29.: Observed fit parameters for a nominal fit with the default settings and three different scenarios: (1) jet energy scale of all jets shifted down by 1.5%, (2) a p_T dependent calorimeter response of the JES uncertainty and (3) a η dependent calorimeter response of the JES uncertainty.

The influence of a decorrelation of the calorimeter response uncertainties for jets with different transverse momenta is evaluated in a third test. The default setup makes the assumption of a 100% correlation of uncertainties between jets with different transverse momenta, and studies show that this is true for the majority of jet pairs, while a smaller correlation of 80% is observed for few cases. For the presented test a conservative assumption is made, and the calorimeter response uncertainty is separated into three different uncorrelated terms and three nuisance parameters in the fit:

- 50% uncertainty, fully correlated over the full range of jet p_T .
- linear increase of the uncertainty from 0% to 50% in the range $0 < p_T < 200$ GeV.
- linear decrease of the uncertainty from 50% to 0% in the range $0 < p_T < 200$ GeV⁵.

The fit yields $\beta_0 = 1.12 \pm 0.07$ and $\sigma_{t\bar{t}} = 185_{-16}^{+17}$ pb, i.e. no difference in the measured cross section is observed. The uncertainties are slightly reduced due to a better ability of the fit to adjust to data, and the fit parameters not corresponding to the calorimeter response change insignificantly within

⁵In both cases jets with $p_T > 200$ GeV are assigned the same shift in uncertainty as jets at $p_T = 200$ GeV.

their uncertainties. This test proves that there is no effect of over constraining the uncertainty from the low p_T range to the high p_T range or vice versa, since these are handled separately here.

More tests were performed, but not explained in detail here for the sake of brevity⁶. No significant deviations of the fitter performance and the measured cross section not covered by the uncertainties are observed when including shape variations, for example sinusoidal or step-functions, modifying the behavior within the $\pm 1\sigma$ ranges. A more realistic model of the flavor composition and the related uncertainties for the dominant W +jets background is used, which leads to a reduction of the fit uncertainties, but does not change the resulting top quark pair production cross section. Instead of creating the pseudo-data set from a Gaussian sampling of the initial values $\beta_i = 1.0$ and $\delta_i = 0.0$, systematic variations of one or more nuisance parameters can be used. In such a setup one can test the ability of the fit to discover such variations, i.e. the ability to extract the correct input value for the nuisance parameter. Furthermore, the resulting shift in the signal cross section should be covered by the uncertainty associated to the varied source of systematic uncertainty. This is found to be true for a selection of nuisance parameters varied, and the overall uncertainty of the measurement is found to cover even very pessimistic scenarios in which several systematic uncertainties are shifted to their respective $\pm 1\sigma$ uncertainties simultaneously.

A series of two consecutive fits is performed, reducing the $\pm 1\sigma$ templates of one uncertainty to the templates created using the fitted $\pm 1\sigma$ uncertainties. In a second iteration of the fit, the fit parameters should not change with respect to the initial fit, and the uncertainties of this special parameter should not be reduced any further. Taking into account the convolution with the Gaussian constraint, these assumptions are verified, showing that the reduction of uncertainties is not an artificial effect of the fit. The stability of the fit result is tested by changing the number of bins for the likelihood discriminant $\mathcal{D}$ and by performing fits to the separate input variables themselves or likelihood discriminants constructed from subsets of the input variables. Within the statistical uncertainties all these fits agree with the main result.

6.7. Discussion of Results

6.7.1. Main Results

Combining the knowledge about the measured top quark pair production cross section and the associated uncertainties, the following main result of this analysis is obtained

$$\sigma_{t\bar{t}} = 187 \pm 11(\text{stat.})_{-17}^{+18}(\text{syst.}) \pm 6(\text{lumi.}) \text{ pb} = 187_{-21}^{+22} \text{ pb}, \quad (6.4)$$

from a fit to the combined ℓ +jets channel in the jet multiplicity bins $n_{\text{jets}} = 3, 4, \geq 5$ and under the assumption of a top quark mass of $m_{\text{top}} = 172.5$ GeV. No dependence of the top quark mass is shown here, but a direct extraction of the top quark mass from this cross section measurement is shown in the following.

Under the assumption that the systematic uncertainties estimated outside of the profile likelihood fit

⁶Additional tests are documented in ATLAS internal documentation related to this analysis, see ATL-COM-PHYS-2011-1012.

have the same impact on the combined measurement and on the measurements in the μ +jets and e +jets channels separately, the single channel results are found to be

$$\sigma_{t\bar{t}} = 184_{-13}^{+14}(\text{stat.}) \pm 18(\text{syst.}) \pm 6(\text{lumi.}) \text{ pb} = 184_{-23}^{+24} \text{ pb} \quad (6.5)$$

in the μ +jets channel and

$$\sigma_{t\bar{t}} = 196_{-17}^{+18}(\text{stat.})_{-20}^{+21}(\text{syst.}) \pm 6(\text{lumi.}) \text{ pb} = 196_{-27}^{+28} \text{ pb} \quad (6.6)$$

in the e +jets channel, see also figure ???. The combined measurement achieves an overall precision of 11.7%, while the uncertainties increase to 13.0% (μ +jets) and 14.3% (e +jets) in the single lepton flavor channels. The presented main result is the most precise measurement of the top quark pair production in the dataset taken by the ATLAS and CMS experiments in 2010, followed by the corresponding measurement of the CMS collaboration [106], which uses a similar technique. Instead of combining several variables into one discriminant, this analysis uses one flavor sensitive variable, the mass of the secondary vertex. The CMS analysis is limited to events with at least one b -tagged jet on one hand, but is extended to events with one and two jets on the other hand. The latter allows to perform a simultaneous measurement of $\sigma_{t\bar{t}}$ and the relative amount of W +heavy flavor contribution to the W +jets background in a profile likelihood fit. Both the CMS [107] and the ATLAS [68] collaboration perform measurements that do not rely on b -jet identification as well, which have larger associated uncertainties, but are found to be in good agreement with the more precise ones. No significant deviation from the different theoretical predictions for top quark pair production at NNLO, as described in section 2.3.1.1 is observed.

A more detailed discussion of all results and a larger scale comparison with other measurements can be found in chapter 7.

6.7.2. Extensions of the Measurement

The preliminary version of the presented analysis [105], which measures

$$\sigma_{t\bar{t}} = 186 \pm 10(\text{stat.})_{-20}^{+21}(\text{syst.}) \pm 6(\text{lumi.}) \text{ pb} = 186_{-23}^{+24} \text{ pb}, \quad (6.7)$$

with a slightly higher overall uncertainty, is combined with measurements in the dilepton channel of top quark pair production to achieve a higher precision, and exploited for an extraction of the top quark mass from the cross section measurement. Both analyses will be briefly discussed here and make use of inputs described in this work. The differences between the presented final measurement and the preliminary version are caused by an updated version of the jet calibration, influencing missing transverse energy as well, and by improvements of the understanding of different sources of systematic uncertainties. Notably, in the preliminary version, the b -tagging calibration for the JetProb tagger is only available at the 50% and 70% efficiency working points, leading to some remaining disagreement between data and prediction for jets with a low probability to originate from a b -quark. While the $\bar{w}_{JP}$ distribution is used in all jet multiplicity bins in this analysis, the low w_{JP} region is modified for each jet to only consist of one larger bin, since the calibration of the normalization is found to be sufficient. Furthermore, slightly different models for the QCD multijet background are used.

Figure 6.30.: Comparison between the combined and single channel measurements presented here (first three) with different other measurements using the same amount of data. An analysis not using any b -tagging information is performed by the ATLAS collaboration [68] on the same data set as the presented analysis, and two measurements in the single lepton channel are performed by the CMS collaboration using the data taken in 2010 [107, 106]. The measurements show a good agreement within uncertainties with each other and also agree well with the theoretical prediction at approximate NNLO from Langenfeld et.al. [24, 25] used as a reference in this work. The main measurement in this data set as presented in this work is the most precise out of all available measurements using the data taken by the experiments in 2010.

6.7.2.1. Combinations [108, 109]

Since the top quark pair production cross section is not only measured in the ℓ +jets channel, different analysis channels can be combined to improve the precision of the measurement. Combinations of the presented analysis⁷ with the most precise measurement within the ATLAS collaboration in the dilepton channel in 35 pb⁻¹ of data [110] and 0.7 fb⁻¹ of data [48] are performed. While the data samples for the dilepton and lepton+jets analyses are orthogonal, many of the sources of systematic uncertainties are correlated between the channels and can be included as such in a combined profile likelihood fit. The dilepton analysis is, in both cases, performed as a counting experiment without requiring a b -tagged jet and divided into the ee , $e\mu$ and $\mu\mu$ channels. A combined profile likelihood ratio function is created including the three bins from the dilepton channel and the full likelihood distributions from the single lepton analysis⁸ and nuisance parameters corresponding to the same source of systematic uncertainty are only included once. The results of both combinations are shown

⁷in the preliminary version

⁸For technical reasons, an approximation of the likelihood function by a Gaussian is used in the ℓ +jets channel, constructed from the covariance matrix returned by the fit. Checks were performed to ensure that this procedure yields the same results in the profiling.

in table 6.9.

Channel	$\sigma_{t\bar{t}}$ [pb] (35 pb ⁻¹) [108]				$\sigma_{t\bar{t}}$ [pb] (35 pb ⁻¹ – 0.7 fb ⁻¹) [109]			
ee	178	$^{+67}_{-57}$ (stat.)	$^{+37}_{-27}$ (syst.)	$^{+9}_{-5}$ (lumi.)	172	$^{+16}_{-16}$ (stat.)	$^{+30}_{-33}$ (syst.)	$^{+8}_{-7}$ (lumi.)
$\mu\mu$	194	$^{+57}_{-51}$ (stat.)	$^{+20}_{-15}$ (syst.)	$^{+12}_{-5}$ (lumi.)	154	$^{+10}_{-10}$ (stat.)	$^{+19}_{-10}$ (syst.)	$^{+7}_{-6}$ (lumi.)
$e\mu$	164	$^{+26}_{-26}$ (stat.)	$^{+18}_{-18}$ (syst.)	$^{+7}_{-6}$ (lumi.)	176	$^{+7}_{-7}$ (stat.)	$^{+17}_{-14}$ (syst.)	$^{+8}_{-8}$ (lumi.)
dilepton	173	$^{+22}_{-22}$ (stat.)	$^{+18}_{-16}$ (syst.)	$^{+8}_{-7}$ (lumi.)	171	$^{+6}_{-6}$ (stat.)	$^{+16}_{-14}$ (syst.)	$^{+8}_{-8}$ (lumi.)
e +jets	223	$^{+17}_{-17}$ (stat.)	$^{+27}_{-27}$ (syst.)	$^{+8}_{-8}$ (lumi.)	223	$^{+17}_{-17}$ (stat.)	$^{+27}_{-27}$ (syst.)	$^{+8}_{-8}$ (lumi.)
μ + jets	168	$^{+12}_{-12}$ (stat.)	$^{+20}_{-18}$ (syst.)	$^{+6}_{-6}$ (lumi.)	168	$^{+12}_{-12}$ (stat.)	$^{+20}_{-18}$ (syst.)	$^{+6}_{-6}$ (lumi.)
ℓ +jets	186	$^{+10}_{-10}$ (stat.)	$^{+21}_{-20}$ (syst.)	$^{+6}_{-6}$ (lumi.)	186	$^{+10}_{-10}$ (stat.)	$^{+21}_{-20}$ (syst.)	$^{+6}_{-6}$ (lumi.)
combined	180	$^{+9}_{-9}$ (stat.)	$^{+15}_{-15}$ (syst.)	$^{+6}_{-6}$ (lumi.)	176	$^{+5}_{-5}$ (stat.)	$^{+13}_{-10}$ (syst.)	$^{+7}_{-7}$ (lumi.)

Table 6.9.: Cross section measurements and combinations using a preliminary version of the presented analysis [105], and measurements in the dilepton channel with 35 pb⁻¹ of data [110] and 0.7 fb⁻¹ of data [48].

When both measurements using 35 pb⁻¹ are combined, the combined measurement reaches a precision of 10% and is dominated by the uncertainties from the measurement in the lepton+jets channel, especially by the b -tagging calibration, W +heavy flavor content, jet energy scale and the modeling of initial and final state radiation. The combination with a larger data set analyzed in the dilepton channel yields a combined uncertainty of 9.1%, with the uncertainty on the fake lepton estimate in the dilepton channel becoming another significantly contributing source of uncertainty together with the ones listed above.

6.7.2.2. Mass Extraction [111]

A determination of the top quark mass from the cross section measurement is possible because the theoretical cross section calculations are provided as a function of the top quark mass and the cross section measurement can be parametrized as a function of m_{top} as well. The measurement provides not only a complementary approach to the direct measurements of m_{top} , but shows a significantly smaller dependency on the definition of the top quark mass in the Monte Carlo simulation. Direct measurements rely on Monte Carlo simulations to either model observables sensitive to m_{top} or to calibrate the method, but are therefore only able to measure the top quark mass in the definition as implemented in the generator, $m_{\text{top}}^{\text{MC}}$. The comparison of this quantity with theoretical predictions is difficult, since the translation into the well-defined top quark pole mass, $m_{\text{top}}^{\text{pole}}$ contains approximations made in the MC generator. In contrast, the mass extraction from the cross section measurement compares the measured values for $\sigma_{t\bar{t}}$ as a function of m_{top} with different theoretical cross section calculations at NNLO, which are parametrized as a function of $m_{\text{top}}^{\text{pole}}$. This procedure allows to extract the pole mass directly from a likelihood maximization of a combined Gaussian likelihood function, which includes terms for the experimental measurement and the theoretical prediction.

To accomplish such a measurement, the cross section measurement as described in this chapter is repeated for various assumptions of the top quark mass. Both the single top and top quark pair production Monte Carlo samples are exchanged by those using top quark masses of $m_{\text{top}} =$

140, . . . , 210 GeV, in steps of 10 GeV, and the full analysis chain is repeated. The assumption is made that the relative systematic uncertainties do not change as a function of the top quark mass, and only the statistical component is remeasured. This assumption is verified in the samples with the largest mass variations, $m_{\text{top}} = 140, 210$ GeV. For these points, the full analysis is repeated including all dominating sources of systematic uncertainties and an alternative mass extraction is performed using only those and the central point at $m_{\text{top}} = 172.5$ GeV. The difference between this approach and the one assuming constant relative systematic uncertainties is found to be small and added as a systematic uncertainty to the mass measurement. Taking into account only the statistical components of the likelihood function, the measured cross section varies as a function of the top quark mass as shown in table 6.10.

$m_{\text{top}}^{\text{MC}}$	$\sigma_{t\bar{t}}$ [pb]	
140.0	280	$^{+14}_{-15}$ (stat.)
150.0	241	$^{+12}_{-11}$ (stat.)
160.0	219	$^{+11}_{-11}$ (stat.)
170.0	200	$^{+10}_{-10}$ (stat.)
172.5	186	$^{+10}_{-10}$ (stat.)
180.0	186	$^{+9}_{-10}$ (stat.)
190.0	173	$^{+9}_{-9}$ (stat.)
200.0	160	$^{+8}_{-8}$ (stat.)
210.0	155	$^{+8}_{-8}$ (stat.)

Table 6.10.: Results of the cross section measurement with statistical uncertainties only for different assumptions of the top quark mass made in the generation of Monte Carlo simulated events.

Figure ?? shows the dependencies of the theoretical and experimentally observed top quark pair production cross section as a function of the top quark mass, with different NNLO calculations available. The extracted top quark pole mass with respect to the approximate NNLO calculations from Langenfeld et al. [24, 25] is

$$m_{\text{top}}^{\text{pole}} = 166.4_{-7.3}^{+7.8} \text{ GeV}, \quad (6.8)$$

and is compared to the masses obtained with different theoretical models both using this measurement and with a similar measurement performed by the DØ collaboration in figure ?. The uncertainties of these indirect measurements are significantly larger than the ones from direct measurements and especially than the mass world average, but add important information about the top quark pole mass. The pole mass as measured by ATLAS and DØ tends to have lower values than the MC related mass parameter from direct measurements, but the different indirect measurements at different colliders and experiments agree very well with each other. The results are in good agreement with recent results by the CMS collaboration, where the mass extraction is performed in a data set of 1.14 fb⁻¹ and based on the top quark pair production cross section measurement in the dilepton channel [27]. For the same reference calculation from Langenfeld et al. [24, 25], the CMS measurement yields $m_{\text{top}}^{\text{pole}} = 170.3_{-6.6}^{+7.3} \text{ GeV}$.

(a) Mass dependency of measured $\sigma_{t\bar{t}}$ and different theoretical predictions, as used for the extraction of m_{top} .

(b) Comparison of top quark masses extracted from cross section measurements for different theoretical models, as performed by the ATLAS collaboration at the LHC and the DØ collaboration at Tevatron. A measurement in the dilepton channel performed by the CMS collaboration yields consistent results [27].

Figure 6.31.: Extraction of the top quark mass from the presented top quark pair production cross section measurement [111].

Measurement of $\sigma_{t\bar{t}}$ in 0.7 fb^{-1} of Data

7.1. Introduction

With 0.7 fb^{-1} of data provided by the LHC and taken by the ATLAS experiment in the first half of 2011, another measurement of the top quark pair production cross section in the lepton+jets channel is conducted. While the general analysis strategy is the same as for the analysis described in chapter 6 and is based on the ideas outlined in chapter 5, the details of the analyses presented here and in chapter 6 differ. The analysis presented in this chapter does not rely on a b -tagging algorithm, but uses four topological variables, η^ℓ , $p_T(j_1)$, $\mathcal{A}$ and $H_{T,3p}$ to construct the likelihood discriminant $\mathcal{D}$. The latter is used to extract the top quark pair production cross section with a profile likelihood technique, taking systematic uncertainties as nuisance parameters into account. This process leads to the most precise single channel measurement of $\sigma_{t\bar{t}}$ to date, with an uncertainty close to the uncertainties on theoretical predictions on the same quantity. The results of the analysis presented in the following are published in Reference [49].

7.2. Data Sample And Event Selection

A data set of $0.70 \pm 0.03 \text{ fb}^{-1}$ taken during the LHC operation at $\sqrt{s} = 7 \text{ TeV}$ in 2011 in the ATLAS run periods B–G is considered for the analysis. The data events are selected according to a GoodRunsList, common to all top quark physics analyses on the same data set, assuring good data taking conditions of the detector. The selected data events are compared to Monte Carlo simulated events for all signal and background processes except for QCD multijet production, and are reconstructed with the MC10b configuration of the ATLAS detector simulation. QCD multijet production is predicted based on data-driven estimates using a matrix method technique in both the μ +jets and e +jets channels, as described in section 4.3.5. Furthermore, the background predictions for W +jets events are scaled to match the observed W +jets event yields in a measurement of the W +jets charge asymmetry, as described in section 4.3.3.

Both data and simulated events are selected for further analysis if they fulfill the following requirements, based on the object definitions from section 4.2:

- The event fired the mu18 (μ +jets) or e20_medium (e +jets) trigger.
- Exactly one good muon with $p_T > 20 \text{ GeV}$ (μ +jets) or one good electron with $E_T > 25 \text{ GeV}$ in the central detector region.
- In the e +jets channel, the selected electron has to match the trigger object within $\Delta R = 0.15$.
- In the μ +jets channel an additional requirement of $p_T(\mu) < 150 \text{ GeV}$ is implemented to reduce the influence of inefficiencies in the trigger modeling in MC. A matching within $\Delta R = 0.15$ is required for the muon and the trigger object in Monte Carlo simulated events.
- $E_T^{\text{miss}} > 25 \text{ GeV}$ and $E_T^{\text{miss}} + m_T(W) > 60 \text{ GeV}$ in the μ +jets channel.
- $E_T^{\text{miss}} > 35 \text{ GeV}$ and $m_T(W) > 25 \text{ GeV}$ in the e +jets channel.
- Counting all good jets with $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$, events with three, four and five and more jets are considered for the measurement, while events with fewer jets are used to define a control region.
- Further event level requirements to account for pile-up and detector problems, as listed in section 4.2.

The amount of selected events both in data and simulation is shown as a function of the jet multiplicity in figure 7.1, and, including the dominant uncertainties on the predictions, in table 7.1 for the μ +jets channel and table 7.2 in the e +jets channel. The agreement between prediction and observation for the number of events in the different jet bins is found to be good, confirming the modeling assumptions on signal and background in general.

Figure 7.1.: Observed and expected events as function of the jet multiplicity in the μ +jets and e +jets channel for 0.7 fb^{-1} of data taken by the ATLAS experiment in 2011.

The ratio of predicted signal and background events (S/B) and the signal significance $\sigma_{SB} = S/\sqrt{S+B}$ are shown in table 7.3 for the different jet multiplicities in the signal region. Compared to the analysis of 35 pb^{-1} , see table 6.3, the signal-to-background ratio remains the same, but the signal significance increases significantly with the higher statistics of the analyzed data set.

7.3. Variables

7.3.1. Kinematic and Topological Variables

In contrast to the analysis presented in chapter 6, this analysis uses only kinematic quantities of objects and the full event, and no b -jet identification information at all. The three variables, pseudorapidity of the lepton η^ℓ , event aplanarity $\mathcal{A}$ and normalized sum of jet momenta $H_{T,3p}$, are considered in this analysis as well, and the separation power is very similar to the one presented in section 6.3. The transverse momentum of the leading jet is used as the fourth variable in the construction of the likelihood discriminant $\mathcal{D}$, since it adds additional separation power especially for events with three and four jets and also adds sensitivity to uncertainties on the jet energy scale. This behavior is desirable, because it increases the power to constrain the systematic uncertainties on JES in the profile likelihood fitting technique. The separation between $t\bar{t}$ production and W +jets production is shown in figure 7.2 and shows a decrease of the performance towards higher jet multiplicities. Top quark pair production typically produces harder jets than W +jets production, but for higher jet multiplicities the W +jets look more signal-like. The transverse momentum of the leading jet is chosen over jet uncertainty sensitive variables with a higher separation power, like H_T , to have a simple, well defined variable and not rely on the correct modeling of correlations of uncertainties between jets. No b -tag variable or any other usage of b -tag information is included in the analysis, which avoids the large uncertainties from the b -tag and mistag calibrations as well as the W +heavy flavor contributions in the measurement. Moreover, with the significant increase in statistics, a calibration of the full spectrum of a b -tagging distribution requires calibration of the b -tagging algorithm at several working points, especially at low values for light jets. Since, at the time of performing the presented analysis, the transition from simple to significantly more advanced b -tagging algorithms was ongoing within the collaboration, the availability of such a dedicated calibration at several working points especially for the sake of this analysis was not guaranteed. Lastly, with the available amount of statistics, analyses both with and without b -tagging will be limited by systematic uncertainties by far, and adding more separation power would help less than reducing an important source of systematic uncertainties, as is done here.

As already described in the context of the 35 pb^{-1} analysis in chapter 6, the pseudorapidity distribution of the electron is transformed to build a continuous distribution, skipping the calorimeter crack region. Furthermore, to ensure no significant drop of statistics in the distribution, the event aplanarity is transformed to $\mathcal{A} \rightarrow \exp(-8 \times \mathcal{A})$ and $H_{T,3p}$ to $\exp(-4 \times H_{T,3p})$.

The performance of all variables in terms of agreement between data and prediction is first studied in events with exactly two jets, where the distributions are dominated by background. Observing no significant deviations between prediction and data confirms both the validity of the background

Figure 7.2.: Normalized distributions of the transverse momentum of the leading jet in μ +jets and e +jets events for simulated $t\bar{t}$ and W +jets events.

models and of the variables themselves. In general, the distributions of the input variables agree well with simulation in the signal region for events with three, four and five and more jets. Figures 7.3 (μ +jets) and 7.4 (e +jets) show the distributions of the transverse momentum of the leading jet in all jet multiplicity bins, figures 7.5 and 7.6 the ones for the pseudorapidity of the lepton, and figures 7.7 and 7.8 the aplanarity distributions. The variable $H_{T,3p}$ is only defined for events with at least three jets, and shown in figures 7.9 and 7.10.

Figure 7.3.: Distributions of the transverse momentum of the leading jet in data and predicted events for the control region $n_{\text{jets}} = 2$, and the signal regions $n_{\text{jets}} = 3, 4, \geq 5$ in $\mu + \text{jets}$ events.

Process	1 Jet	2 Jets	3 Jets	4 Jets	≥ 5 Jets
$t\bar{t}$	319 ± 74	1342 ± 336	2734 ± 495	2714 ± 388	2030 ± 522
$W + \text{jets}$ (DD)	383223 ± 121118	93436 ± 42653	20140 ± 11661	4643 ± 3194	1075 ± 878
Fakes (QCD Multijet)	24628 ± 12314	10942 ± 5471	3147 ± 1575	868 ± 434	294 ± 147
Single Top	995 ± 248	1148 ± 531	594 ± 154	210 ± 65	84 ± 34
$Z + \text{jets}$	17267 ± 5642	5492 ± 2557	1510 ± 886	436 ± 302	149 ± 121
Diboson (WW, WZ, ZZ)	1093 ± 129	1009 ± 113	308 ± 64	69 ± 21	18 ± 9
Total Predicted	427526 ± 124569	113369 ± 44486	28434 ± 12438	8938 ± 3547	3650 ± 1287
Data Observed	433931	111741	28643	8680	3814

Table 7.1.: Selected events in the μ +jets channel split up according to the jet multiplicity. The W +jets background is obtained from a data-driven (DD) method exploiting the charge asymmetry in W boson production. Uncertainties from jet energy scale, theoretical uncertainties, uncertainty on the luminosity and the limited MC statistics are considered. For the signal, the uncertainty on the initial and final state radiation modeling is included as well. QCD multijet production is obtained from a measurement on data and has a 50% uncertainty associated. The signal region used in the analysis is highlighted in grey.

Process	1 Jet	2 Jets	3 Jets	4 Jets	≥ 5 Jets
$t\bar{t}$	225 $\pm$ 61	1005 $\pm$ 247	1934 $\pm$ 332	1835 $\pm$ 281	1463 $\pm$ 472
$W + Jets$ (DD)	161569 $\pm$ 53156	43165 $\pm$ 19921	10832 $\pm$ 6348	2485 $\pm$ 1749	1033 $\pm$ 842
Fakes (QCD Multijet γ +Jets)	10715 $\pm$ 5358	4757 $\pm$ 2379	1589 $\pm$ 795	507 $\pm$ 254	177 $\pm$ 89
Single Top	570 $\pm$ 137	711 $\pm$ 165	391 $\pm$ 105	156 $\pm$ 51	65 $\pm$ 26
$Z + Jets$	3732 $\pm$ 1541	2444 $\pm$ 1288	996 $\pm$ 636	333 $\pm$ 233	148 $\pm$ 126
Diboson (WW, WZ, ZZ)	599 $\pm$ 66	538 $\pm$ 137	178 $\pm$ 41	45 $\pm$ 16	10 $\pm$ 6
Total Predicted	177408 $\pm$ 54659	52620 $\pm$ 20916	15919 $\pm$ 6869	5361 $\pm$ 2018	2893 $\pm$ 1176
Data Observed	179469	51820	15614	5398	2812

Table 7.2.: Selected events in the e +jets channel split up according to the jet multiplicity. The W +jets background is obtained from a data-driven (DD) method exploiting the charge asymmetry in W boson production. Uncertainties from jet energy scale, theoretical uncertainties, uncertainty on the luminosity and the limited MC statistics are considered. For the signal, the uncertainty on the initial and final state radiation modeling is contained as well. QCD multijet production is obtained from a measurement on data and has a 50% uncertainty associated. The signal region used in the analysis is highlighted in grey.

N_{jets}	$\mu + \text{jets}$		$e + \text{jets}$	
	S/B	σ_{SB}	S/B	σ_{SB}
3 Jets	0.11	16.21	0.14	15.33
4 Jets	0.44	28.71	0.52	25.06
≥ 5 Jets	1.25	33.60	1.02	27.20

Table 7.3.: Expected signal-to-background ratio and signal significance in the different jet bins and lepton channels of the analysis.

Figure 7.4.: Distributions of the transverse momentum of the leading jet in data and predicted events for the control region $n_{\text{jets}} = 2$, and the signal regions $n_{\text{jets}} = 3, 4, \geq 5$ in $e + \text{jets}$ events.

Figure 7.5.: Distributions of the pseudorapidity of the muon in data and predicted events for the control region $n_{\text{jets}} = 2$, and the signal regions $n_{\text{jets}} = 3, 4, \geq 5$ in $\mu + \text{jets}$ events.

Figure 7.6.: Distributions of the pseudorapidity of the electron in data and predicted events for the control region $n_{jets} = 2$, and the signal regions $n_{jets} = 3, 4, \geq 5$ in $e+jets$ events. The distributions are modified to exclude the calorimeter crack region for final usage.

Figure 7.7.: Event aplanarity for data and predicted events for the control region $n_{\text{jets}} = 2$, and the signal regions $n_{\text{jets}} = 3, 4, \geq 5$ in $\mu + \text{jets}$ events.

Figure 7.8.: Event aplanarity for data and predicted events for the control region $n_{\text{jets}} = 2$, and the signal regions $n_{\text{jets}} = 3, 4, \geq 5$ in $e+\text{jets}$ events.

Figure 7.9.: Variable $H_{T,3p}$ in its transformed form for data and predicted events in the signal regions $n_{\text{jets}} = 3, 4, \geq 5$ in μ +jets events. The variable is only defined for events with three or more jets.

Figure 7.10.: Variable $H_{T,3p}$ in its transformed form for data and predicted events in the signal regions $n_{\text{jets}} = 3, 4, \geq 5$ in e +jets events. The variable is only defined for events with three or more jets.

7.3.2. Likelihood Discriminant

As described in section 5.4, the four variables η^ℓ , $\exp(-8 \times \mathcal{A})$, $\exp(-4 \times H_{T,3p})$ and $p_T(j_1)$ are combined into a projective likelihood discriminant $\mathcal{D}$ using the TMVA package. The same set of variables is used in all jet multiplicity bins and the μ +jets and e +jets channels. The creation of the likelihood function is based on the separation between $t\bar{t}$ and W +jets events. Since this analysis is not able to distinguish between W +light jet events and W +heavy flavor jet events, and the latter are available in simulation only with low statistics, they are excluded from the *training* procedure, but not from the final *evaluation* step. While half of the MC samples for $t\bar{t}$ and W +jets are considered for the training, the other half is considered to build the template distributions for the fit. All available statistics is used for all other backgrounds and data to construct the template distributions. All discriminating variables add separation power, but in contrast to the analysis presented in chapter 6, there is no variable with the strong separation power such as the b -tag distribution $\bar{w}_{JP}$. Hence, the likelihood discriminants in all channels show a good separation between $t\bar{t}$ production and W +jets production, but do not peak at one and zero, as can be seen in figure 7.11.

Figure 7.11.: The likelihood discriminant $\mathcal{D}$ in μ +jets and e +jets events for simulated $t\bar{t}$ and W +jets events. Both distributions are normalized to an integral of unity.

Figure 7.12 shows the distribution of the likelihood discriminant $\mathcal{D}$ for data and all predictions in all analysis channels and jet multiplicities, before the fitting procedure is applied. No significant deviations between data and simulation are observed and the fit is applied to achieve the best possible agreement of the setup, taking most systematic uncertainties into account.

7.4. Overview of Systematic Uncertainties

Out of the sources of systematic uncertainties as described in detail in section 5.6, only the uncertainties related to the b -tagging calibration and the W +heavy flavor contribution are not considered in the presented analysis. Since no flavor separation is achieved by any of the included variables, the shape of the likelihood discriminant is not affected by these sources of systematic uncertainties, and both do not change the number of predicted events. No uncertainty on the pile-up model is applied, since the simulated events are already reweighted based on the actual pile-up conditions in data. An additional uncertainty on the missing transverse energy is added to account for the impact of a malfunctioning front-end board in the liquid argon calorimeter. In addition, a few other sources of systematic uncertainties are treated in different ways, compared to the 35 pb^{-1} analysis.

Figure 7.12.: The likelihood discriminant $\mathcal{D}$ in μ +jets and e +jets for data and predicted events.

The uncertainties on the muon momentum scale and resolution are treated as three different nuisance parameters in the fit, one for the smearing in the inner detector, one for the smearing in the muon spectrometer and a third one for the scale uncertainty. The pile-up uncertainty on the jet energy scale is treated as four different parameters with a constant uncertainty, as described in section 5.6 to account for differences at high and low transverse momenta of the jets and distinguish between central and forward jets. Due to the technical implementation to obtain the systematic uncertainties, the flavor component and close-by jet terms of the jet energy scale uncertainty are not considered as unique nuisance parameters, but the corresponding $\pm 1\sigma$ variation is applied to all other JES parameters except for the pile-up and the b -jet JES component. This leads to an overestimation of the two uncertainties, since they are added with the same amount to all other JES variations. Finally, in this analysis initial and final state radiation are treated as nuisance parameters¹ in the fit, since studies of MC generated samples with a different amount of ISR and FSR show that the assumption of continuity is justified. The different sources of systematic uncertainties and their treatment in the profile likelihood fit are listed in table 7.4. The initial uncertainty on the muon trigger scale factors is rather large, increasing up to 7% in some detector regions, to account for a mismatch of the measured efficiencies in different run periods and is known to be a significant overestimation of the uncertainties, as studies performed later show.

¹one for ISR, one for FSR, and this also allows all combinations of the two parameter, i.e. a combined variation of ISR and FSR is not needed

Systematic Uncertainty	Nuisance Parameter	Comments
Background Normalization	–	included in statistical uncertainty through Gaussian constraints
Signal Generator	–	
Parton Shower Model	–	
ISR and FSR	✓	separate parameters for ISR and FSR
PDF	–	
W +Jets Generator Settings	–	reweighting for <i>iqopt2</i> and <i>ptjmin10</i>
QCD Multijet Model	–	from anti-electron (e +jets) and loose-not-tight (μ +jets) selection
Monte Carlo Statistics	–	
Muon/Electron Scale Factors	✓	uncorrelated between the channels
Muon Momentum Scale and Resolution	✓	three different δ parameters for smearing in ID and MS, as well as the muon scale
Electron Energy Scale	✓	
Electron Energy Resolution	✓	
Calorimeter Response (JES)	✓	
η -Intercalibration (JES)	✓	
Noise Term (JES)	✓	
Parton Shower Model (JES)	✓	
Underlying Event Model (JES)	✓	
Pile-Up Influence on JES	✓	four different nuisance parameters for low and high p_T jets in the central and forward detector region
Close-By Jets (JES)	–	accounted for in the other JES uncertainties
Flavor Composition (JES)	–	accounted for in the other JES uncertainties, assuming the $t\bar{t}$ flavor composition for all processes
b -Jet Energy Scale	✓	
Jet Energy Resolution	✓	
Jet Reconstruction Efficiency	✓	
E_T^{miss} Uncertainties	✓	one parameter for the combination of softjet, cellout, pile-up terms, and another for the uncertainty from the missing LAr region

Table 7.4.: Sources of systematic uncertainties and their treatment in the cross section extraction. The first set of uncertainties is related to assumptions on the physics model, while the second set is related to detector and reconstruction effects.

The sum of all systematic uncertainties, assuming no correlation between the different systematics sources and full correlation between the different physics processes, is shown in figure 7.13 (μ +jets)

and figure 7.14 ($e+\text{jets}$). The model uncertainties include the uncertainties on the background normalization, and are significantly larger than the uncertainties from the detector and reconstruction effects. Both separately are already large enough to cover the observed deviations between predicted and observed distributions. In general, the initial sizes of the different sources of uncertainty are rather similar to the ones in the 35 pb^{-1} analysis, but the influence on the final cross section measurement differs due to the different input variables. The uncertainties on the jet energy scale components alone account for large variations of the predicted distributions, see figure 7.15. This is expected and desired by the usage of the transverse momentum of the leading jet as one of the input variables. Moreover, it explains why the fit is able to constrain different nuisance parameters related to jet energy scale to values better than their initial $\pm 1\sigma$ boundaries, since the agreement between data and Monte Carlo prediction is already better than the allowed variations from the uncertainties.

Figure 7.13.: Sum of all sources of systematic uncertainties for physics modeling (left) and detector (right) for the sum of predicted events, including the data-driven QCD multijet estimate, compared to data in the $\mu + \text{jets}$ channel.

Figure 7.14.: Sum of all sources of systematic uncertainties for physics modeling (left) and detector (right) for the sum of predicted events, including the data-driven QCD multijet estimate, compared to data in the $e + \text{jets}$ channel.

Figure 7.15.: Sum of all systematic uncertainties on the different components of jet energy scale in the μ -jets (left) and e -jets (right) channel for the different jet multiplicities. No correlation is assumed between the different sources of uncertainties, but full correlation across the different physics processes, to create the distributions.

7.5. Cross Section Extraction

7.5.1. Expected Uncertainties

The expected uncertainties are estimated in series of 1000 pseudo-experiments, see section 5.7.1. To estimate the statistical uncertainty of the measurement, pseudo-data corresponding to the amount of analyzed data is constructed and the log-likelihood minimization of $\mathcal{L}_{\beta\delta}$ is performed without the nuisance parameters δ_i . The fit parameter corresponding to the top quark pair production cross section, β_0 , is extracted for each pseudo-experiment and the average spread of this parameter corresponds to the expected statistical uncertainty of the measurement. As can be seen in figure 7.16 the average value of β_0 is found to be one, as expected, for the combined fit as well as in μ +jets and e +jets channels separately. The expected statistical uncertainty is the smallest in the combined fit and found to be 2.2%, while the separate channels have an expected statistical uncertainty of 2.9% in the μ +jets channel and 3.6%, due to lower available statistics with tighter selection criteria, in the e +jets channel. In a similar way, the contribution from the separate jet multiplicities can be estimated, performing a series of PEs separately for events with three, four or five and more jets. As expected, due to the large background contribution, a fit to both e +jets and μ +jets events with three jets only yields the highest expected statistical uncertainty of 6.7%. A fit to events with exactly four jets yields 3.5%, while the fit to events with five and more jets yields 3.6% expected statistical uncertainty. While the signal-to-background ratio is significantly larger for events with five and more jets, a higher amount of data is available for the measurement with events with exactly four jets, making both jet multiplicity bins contribute equally.

The evaluation of the expected full fit uncertainty is shown in figure 7.17 for the combined fit and fits in the two separate lepton channels. The smallest total uncertainty of 3.6% is achieved, as expected, in the combined fit, which translates into a contribution of 2.8% from the systematic uncertainties alone. Expected uncertainties increase to 5.1% in both the μ +jets channel (4.2% systematic uncertainty inside the fit) and the e +jets channel with a smaller contribution of 3.6% from the systematic uncertainties alone.

Figure 7.16.: Expected statistical uncertainties for the combined fit and single channel fits, as estimated with a series of 1000 pseudo-experiments.

Figure 7.17.: Expected uncertainties from the combination of statistical and systematic uncertainties for the combined fit and single channel fits, as estimated with a series of 1000 pseudo-experiments.

7.5.2. Calibration

The linear behavior of the fit is tested in series of pseudo-experiments assuming different signal cross sections for $\sigma_{t\bar{t}} = 120, \dots, 200 \text{ pb}$ in steps of 10 pb. 1000 PEs are performed at each value and the average measured value of $\sigma_{t\bar{t}}$ is used in a linear fit over the full range of cross sections to detect any bias, as can be seen in figure 7.18. Within uncertainties, the linear fit agrees well with an offset of zero and a slope of one, showing that no additional calibration to the measurement is necessary. The same behavior is found to be true in tests of linearity in the single μ +jets and e +jets measurements, and the fit results as returned by the fit to data are taken as final results without correction.

Furthermore, figure 7.18 also shows the distribution of pulls, defined as deviation from the expected value of β_0 normalized by the uncertainty on this parameter, at each of the tested cross section values. The distribution is well centered around zero and shows uncertainties slightly smaller than unity. In such a case pseudo-experiments point to an overestimation of the uncertainty of the fit. In addition, a test is performed with pseudo-experiments not limiting the variations of the nuisance parameters to $\pm 1.25\sigma$, and this leads to pull distributions with uncertainties closer to unity, but more fits fail in the minimization step.

7.5.3. Fit Results

To extract the top quark pair production cross section a profile likelihood $\mathcal{L}_{\beta\delta}$ based on the predicted distributions $\mathcal{D}$ for signal, background and the deviations from systematic uncertainties is maximized, as described in section 5.5. The fit results are shown in table 7.5 for a scenario without nuisance parameters for systematic uncertainties (statistical uncertainty only) and the full fit including the systematic uncertainties. The main result of the presented analysis is the combined fit to events in the μ +jets and e +jets channels, but the single lepton channels are shown as well, agreeing with each other within their uncertainties.

The likelihood fit is used to maximize the agreement between data and prediction in the distribution $\mathcal{D}$,

Figure 7.18.: Test for linearity with 1000 PEs at each of the tested input cross sections and the resulting linear dependency, as well as the pull distribution at each of the cross section points.

Channel	Statistical [pb]	Full Fit [pb]
μ +jets	$186.9^{+5.1}_{-5.1}$	$183.7^{+9.8}_{-9.8}$
e +jets	$189.3^{+6.7}_{-6.6}$	$178.7^{+10.0}_{-9.6}$
combined	$187.5^{+4.1}_{-4.1}$	$179.0^{+7.0}_{-6.9}$

Table 7.5.: Fit results for the combined fit and the single channel fits, as statistical only and for the full fit. Uncertainties are only considered for the sources of uncertainties that are included in the fitting function.

and the resulting distributions are shown in figure 7.19. A comparison of the distributions before and after including the nuisance parameters δ_i into the fitting function shows that the agreement improves when the systematic uncertainties are allowed to float and further adjust the predicted distributions. The resulting distributions for fits in the single lepton channels are shown in figure 7.20 and good agreement is found over the full range of the jet multiplicities and distributions.

The detailed results of the combined fit, i.e. the best fitted values for the fit parameters β_i and δ_i , are listed in table 7.6 and the distribution of the nuisance parameters δ_i and their associated uncertainties can also be seen in figure 7.21. The separate μ +jets and e +jets channels prefer different values for some of the parameters, shown in appendix B, associated to jet energy scale uncertainties, which are measured with good precision. This can happen due to internal correlations of parameters or the shift of one nuisance parameter being able to cover a mis-modeling in simulation and is still covered by the associated uncertainties on the nuisance parameters itself in most cases. This emphasizes the fact that the preferred values for the δ_i as returned by the fit are not a direct measurement of a given uncertainty, but should only be interpreted as best suiting scenario in the presented setup of the analysis, as long as no further studies of the parameters are performed.

As can be seen, the uncertainties on the δ_i in particular those associated to the different uncertainties on the jet energy scale are determined to be smaller than one in most cases. This is expected, since the transverse momentum of the leading jet introduced in the analysis is sensitive to the JES. In general, all uncertainties having an effect on jets either directly, like JES, jet reconstruction efficiency, etc., or indirectly through the amount of jets, like ISR and FSR, can be constrained significantly better than the ones affecting the lepton kinematics.

Figure 7.22 shows the linear correlation between the different fit parameters, which can reach up to 50% for some. Strong correlations between normalizations for W +jets in the different lepton channels can be seen and the correlation is significantly stronger than the one for the same parameters in the analysis of 35 pb^{-1} of data, see chapter 6 and figure 6.16. On the one hand, this can be caused by the weaker discrimination power of the likelihood discriminant $\mathcal{D}$, especially for events with four and five and more jets. On the other hand a rescaling of the W +jets backgrounds is applied beforehand. As described in section 4.3.3.3, the starting values, i.e. the normalization corresponding to $\beta_i = 1.0$ (for $i = 1, \dots, 6$), are obtained to correct for a disagreement between data and Monte Carlo in the W charge asymmetry distribution. Each of the different jet multiplicities is adjusted separately to match data best and this means that the final fit only needs to find remaining smaller corrections of the overall W +jets normalization. Initial corrections for observed differences between data and simulation are already included in the prediction. Furthermore, strong anti-correlations can be seen between the W +jets parameter and the QCD multijet parameter in the same lepton and jet multiplicity bin. The template distributions for both processes are very similar to each other and can replace each other in the fit to a large extend. Changing the initial fit constraints on the two backgrounds separately confirms this behavior: if the QCD multijet background is allowed to vary less within the 1σ boundaries, W +jets will vary more, and vice versa. Some correlations and anti-correlations between the jet energy scale uncertainty parameters are found, but are expected since the different uncertainties influence the same variable, $p_T(j_1)$, predominantly. Finally, a strong anti-correlation between the signal and the dominant background normalizations on the one hand and the muon scale factor uncertainty on the other hand is observed. Since the scale factor uncertainty in the μ +jets channels is overestimated, as discussed in section 7.4, and mainly acts on the number of predicted events for a process, and significantly less on the shape of the likelihood discriminant or the ratio of events with different jet multiplicities, an upwards shift would mainly increase the predicted numbers of events. To account for this, the normalization of the different processes would have to be shifted downwards. The full fit prefers a muon scale factor parameter of $\delta_{\mu SF_S} = 0.09 \pm 0.82$, very close to the initial settings.

An evaluation of the behavior of the likelihood function $\mathcal{L}_{\beta\delta}$ by parametrizing each parameter β_i ($i > 0$) or δ_i as function of the signal parameter β_0 is presented in figure 7.24 for the combined fit. While the uncertainties on the fit parameters may vary towards higher values of β_0 , the behavior of all parameters close to the expected value of $\beta_0 = 1.0$ and the measured value of $\beta_0 = 1.0875$ is found to be stable and continuous. The behavior at higher values does not affect the actual preferred values of the parameters, but only the associated uncertainties and might be caused by cancellation effects between different sources of uncertainties and backgrounds, since some uncertainties decrease where others increase.

Parameter	Value	Error	Error Up	Error Down
$\beta(t\bar{t})$	1.0875	0.0432	0.0427	-0.0421
$\beta(W \rightarrow \mu + 3 \text{ jets})$	0.9738	0.0687	0.0710	-0.0684
$\beta(W \rightarrow \mu + 4 \text{ jets})$	0.8649	0.1026	0.1083	-0.1061
$\beta(W \rightarrow \mu + 5 \text{ jets})$	0.9114	0.1557	0.1589	-0.1510
$\beta(W \rightarrow e + 3 \text{ jets})$	1.0510	0.0555	0.0597	-0.0588
$\beta(W \rightarrow e + 4 \text{ jets})$	1.0376	0.0987	0.1057	-0.1025
$\beta(W \rightarrow e + 5 \text{ jets})$	0.8296	0.1206	0.1267	-0.1257
$\beta(Z + \text{Jets})$	0.9572	0.2604	0.2745	-0.2728
$\beta(\text{Single top})$	1.0052	0.1066	0.1069	-0.1065
$\beta(\text{Diboson})$	1.0037	0.0620	0.0620	-0.0620
$\beta(\text{QCD in } \mu + 3 \text{ jets})$	1.2376	0.2928	0.3307	-0.3426
$\beta(\text{QCD in } \mu + 4 \text{ jets})$	1.2720	0.3730	0.4234	-0.4152
$\beta(\text{QCD in } \mu + 5 \text{ jets})$	0.8291	0.3861	0.4044	-0.4095
$\beta(\text{QCD in } e + 3 \text{ jets})$	0.6113	0.2157	0.2286	-0.2339
$\beta(\text{QCD in } e + 4 \text{ jets})$	0.6152	0.3195	0.3406	-0.3462
$\beta(\text{QCD in } e + 5 \text{ jets})$	0.4164	0.3984	0.4221	-0.4170
$\delta(\text{AlpgenJES})$	0.4155	0.4143	0.2725	-0.4030
$\delta(\text{bJES})$	0.0964	0.6818	0.5956	-0.6241
$\delta(\text{CaloJES})$	0.0051	0.4264	0.3410	-0.3654
$\delta(\text{NoiseJES})$	-0.3515	0.3979	0.5469	-0.3047
$\delta(\text{PerugiaJES})$	-0.8653	0.1734	0.1824	-0.1397
$\delta(\text{EtaJES})$	-0.1943	0.2129	0.2166	-0.1978
$\delta(\text{PileupJES low } p_T/\text{central})$	0.5219	0.1669	0.1539	-0.1633
$\delta(\text{PileupJES low } p_T/\text{forward})$	0.4685	0.2566	0.2361	-0.2791
$\delta(\text{PileupJES high } p_T/\text{central})$	0.6366	0.4684	0.3133	-0.4291
$\delta(\text{PileupJES high } p_T/\text{forward})$	0.0430	0.9105	0.6602	-0.6345
$\delta(\text{Jet Efficiency})$	0.1998	0.1357	0.1345	-0.1344
$\delta(\text{JER})$	0.1752	0.9544	0.9510	-0.9565
$\delta(\text{FSR})$	0.0661	0.2086	0.1897	-0.2239
$\delta(\text{ISR})$	0.3392	0.1978	0.1801	-0.2263
$\delta(\mu \text{ SFs})$	0.0923	0.8187	0.7793	-0.7362
$\delta(\mu \text{ Momentum Smearing at MS})$	-0.1197	0.8364	0.7873	-0.8234
$\delta(\mu \text{ Momentum Smearing at ID})$	-0.2356	0.9337	0.9757	-0.8533
$\delta(\mu \text{ Energy Scale})$	0.0437	1.0838	1.0485	-0.9946
$\delta(e \text{ SFs})$	-0.2300	0.9290	0.9152	-0.8999
$\delta(e \text{ Resolution Smearing})$	0.3176	0.7668	0.6538	-0.7566
$\delta(e \text{ Energy Scale})$	-0.7455	0.5967	0.7997	-0.5331
$\delta(\text{Missing } E_T \text{ LAr})$	0.0605	0.5062	0.5167	-0.5230
$\delta(\text{Missing } E_T \text{ SoftJet})$	0.4466	0.4641	0.3333	-0.6785

Table 7.6.: Fit parameters and uncertainties for the combined fit to 0.7 fb^{-1} of data.

(a) combined fit, without systematics included

(b) combined full fit

Figure 7.19.: Fitted distributions compared to data for the full fit and the fit only including statistical uncertainties in the combined channel.

(a) $\mu + \text{jets}$ (b) $e + \text{jets}$

Figure 7.20.: Fitted distributions compared to data in the $\mu + \text{jets}$ and $e + \text{jets}$ channel for the fits including systematic uncertainties.

(a) distribution of nuisance parameters in combined fit (b) distribution of uncertainties on nuisance parameters in combined fit

(c) nuisance parameter distribution in all three analysis channels

Figure 7.21.: Distribution of nuisance parameters δ_i included in the likelihood function with the best fitted values as returned by the fits and their reduced uncertainties σ_{δ_i} . Starting values in all channels are $\delta_i = 0.0 \pm 1.0$, and the fitted values center around zero, while the uncertainties are reduced in most cases. In general, a good agreement between the fit results in the single μ +jets and e+jets channels and the combined fit, is obtained.

Figure 7.22.: Linear correlation coefficients between the normalization parameters β_i and nuisance parameters δ_i , obtained by the fit in the combined μ +jets and e +jets channels.

Figure 7.23.: Likelihood function $\mathcal{L}_{\beta\delta}$ as function of the parameter of interest, β_0 , for the combined fit and the two single channel fits. All functions show a continuous and smooth behavior around the minimum. The grey line indicates the fit result from the combined fit.

7.5.4. Observed Uncertainties

The observed uncertainties are obtained from the full fit directly, with the procedures as described in section 5.7.1. The statistical only uncertainty from the fit to data accounts for 2.2% in the combined fit, which is exactly the same as the expected statistical uncertainty. In the μ +jets channel, the statistical uncertainties account for 2.7%, compared to 2.9% expected uncertainty, and the e +jets channel has an observed statistical uncertainty of 3.5% compared to 3.6% expected. The full fit including all nuisance parameters yields an observed uncertainty of 3.9%, slightly higher than the expected uncertainty of 3.6%. In the separate lepton channels, full fit uncertainties of 5.3% (μ +jets) and 5.6% (e +jets) are observed and can be compared to the expected full uncertainty of 5.1% in both cases. For all three fits, the total observed uncertainty slightly exceeds the expected uncertainty and is hence considered for the final result.

The contributions to the systematic uncertainties from different sources are estimated by either excluding the parameter of choice from the fit and observing a shift in the fit uncertainties or by performing external series of pseudo-experiments with shifted inputs, as described in section 5.7.1, for the uncertainties without associated nuisance parameters. The results of this procedure are shown in table 7.7 for the combined fit. The uncertainties evaluated externally sum up to $\pm 3.78\%$, which are assumed to apply to the μ +jets and e +jets measurements in the same way for comparison in the following.

The measurement is dominated by the uncertainties on the signal model, namely the choice of the signal generator and initial and final state radiation, the available Monte Carlo statistics and uncertainties on the jet energy scale and the muon trigger and reconstruction scale factors. While the influence of the NLO signal generator is evaluated in external series of PEs, ISR and FSR are included as nuisance parameters in the presented measurement, which allows to reduce their impact significantly compared to the analysis of 35 pb^{-1} of data. Compared to the previous analysis the available statistics in data increases significantly, but the amount of Monte Carlo events does not account for this increase and reduces the precision of the measurement. As expected, the jet energy scale uncertainties have an important impact on the measurement due to the presence of at least three jets. A further breakdown of the JES uncertainties is not presented here, since each parameter also includes the variations of the flavor composition and the close-by jet term and does not provide meaningful information.

7.6. Additional Tests

Several tests of the stability of the fitter and the obtained results are performed, both using series of PEs and exchanging assumptions about the predictions. In addition, an investigation of the influence of the fitted parameters β_i and δ_i on distributions other than the likelihood discriminant $\mathcal{D}$ is performed. Results of a subset of the performed studies are presented in the following, avoiding tests similar to the ones presented in section 6.6.

Dependency on Top Quark Mass

As already shown in section ??, the measured top quark pair production cross section depends

Statistical Uncertainty (%)	+	2.19	-	2.18
Physics Objects (%)				
Jet Energy Scale	+	1.57	-	2.14
Jet Reconstruction Efficiency	+	0.28	-	0.72
Jet Energy Resolution	+	0.87	-	0.87
Muon Scale Factors	+	1.81	-	1.93
Muon Smearing and Scale	+	1.01	-	0.93
Muon Momentum Scale	+	0.90	-	0.82
Electron Scale Factors	+	1.24	-	1.37
Electron Smearing	+	0.43	-	0.50
Electron Energy Scale	+	0.76	-	0.80
Missing Transverse Energy	+	1.10	-	0.93
Background Models (%)				
W + Jets Shape (*)	+	0.49	-	0.49
QCD Multijet Shape (*)	+	0.37	-	0.37
Signal Models (%)				
ISR/FSR	+	1.68	-	1.27
NLO Generator (*)	+	3.06	-	3.06
Hadronization (*)	+	0.53	-	0.53
PDF (*)	+	1.01	-	1.01
Others (%)				
MC Template Statistics (*)	+	1.80	-	1.80
Total Systematic (%)	+	4.99	-	4.95

Table 7.7.: Observed statistical and systematic uncertainties for the full combined fit. Sources of systematic uncertainties that are not included as nuisance parameters are marked with a (*), and are evaluated in series of pseudo-experiments.

on the assumption on the top quark mass as used in the event generator, $m_{\text{top}}^{\text{MC}}$. To estimate the dependency and provide a result independent on the assumption, the measurement without systematics is repeated with varied top quark masses $m_{\text{top}} = 140, \dots, 210 \text{ GeV}$ in steps of 10 GeV . This affects both the predictions for $t\bar{t}$ and single top production, and the systematic uncertainties are expected to be independent on the top quark mass for this study. The results from these measurements are shown in table 7.8 for the different mass points, including the nominal assumption of $m_{\text{top}} = 172.5 \text{ GeV}$.

The cross section follows a linear behavior in the range close to the nominal top quark mass of $m_{\text{top}} = 172.5 \text{ GeV}$, and therefore a linear fit is performed in the range 160 GeV to 190 GeV , taking only the statistical uncertainties into account, as can be seen in figure 7.25. To correct for the difference between the measured cross sections with and without the nuisance parameters in the likelihood function, the result of the fit is shifted by the amount the measured value shifts at $m_{\text{top}} = 172.5 \text{ GeV}$. The dependency of $\sigma_{t\bar{t}}$ on the assumed top quark mass is found to be small and can be parametrized as

$$\sigma_{t\bar{t}}[\text{pb}](m_{\text{top}}^{\text{MC}}[\text{GeV}]) = 411.9 - 1.35 \times m_{\text{top}}^{\text{MC}}, \quad (7.1)$$

$m_{\text{top}}^{\text{MC}} [\text{GeV}]$	$\sigma_{t\bar{t}} [\text{pb}]$
140.0	$302.5 \begin{smallmatrix} +6.5 \\ -6.5 \end{smallmatrix} \text{ (stat.)}$
150.0	$253.1 \begin{smallmatrix} +5.5 \\ -5.4 \end{smallmatrix} \text{ (stat.)}$
160.0	$203.0 \begin{smallmatrix} +4.5 \\ -4.5 \end{smallmatrix} \text{ (stat.)}$
170.0	$197.2 \begin{smallmatrix} +4.3 \\ -4.3 \end{smallmatrix} \text{ (stat.)}$
172.5	$187.5 \begin{smallmatrix} +4.1 \\ -4.1 \end{smallmatrix} \text{ (stat.)}$
180.0	$177.0 \begin{smallmatrix} +3.9 \\ -3.9 \end{smallmatrix} \text{ (stat.)}$
190.0	$162.4 \begin{smallmatrix} +3.6 \\ -3.6 \end{smallmatrix} \text{ (stat.)}$
200.0	$151.7 \begin{smallmatrix} +3.4 \\ -3.3 \end{smallmatrix} \text{ (stat.)}$
210.0	$147.6 \begin{smallmatrix} +3.3 \\ -3.3 \end{smallmatrix} \text{ (stat.)}$

Table 7.8.: Results of the cross section measurement with statistical uncertainties only for different assumptions of the top quark mass made in the generation of Monte Carlo simulated events.

for values of $m_{\text{top}}^{\text{MC}}$ in the range around the top quark mass world average value.

Figure 7.25.: Dependence of the measured top quark pair production cross section on the top quark mass assumed in the Monte Carlo generation. A fit is performed in the mass range around the expected top quark mass. The uncertainties shown here are statistical only.

Application of Fit Parameters

To determine the ability of the fit results to describe data better than the initial predictions, the full set of fit parameter β_i and δ_i is applied to several distributions describing object kinematics and event topologies. While the log-likelihood minimization is applied to the likelihood discriminant $\mathcal{D}$ only, the obtained set of parameters is expected to describe other distributions sufficiently well, too. Figure 7.26 for the μ +jets channel and figure 7.27 for the e +jets channel show such distributions for variables used as input for the likelihood discriminant, $p_T(j_1)$ and $H_{T,3p}$, and variables that are

not used directly in the analysis, $m_T(W)$ and E_T^{miss} . In all cases, a good agreement between data and fitted distributions can be seen, and furthermore the improvement from the initially predicted distributions to the fitted ones is visible. The transformation of the $H_{T,3p}$ distribution in figure 7.27 is a particularly good example of the ability of the fit to not only adjust the overall normalization, but also to influence the shape of distributions. All tested distributions agree better between data and signal plus background model after the fit, independent on whether the distribution itself is used or not in the analysis. This test further confirms the validity of the measurement which not only extracts $\sigma_{t\bar{t}}$, but also adjusts various corrections associated with systematic uncertainties to better describe the full kinematics of the events.

Figure 7.26.: Distributions of data and the best fitted parameters for background normalization and systematic uncertainties in the $\mu + \text{jets}$ channel (left), where the yellow band indicates the statistical uncertainty on the Monte Carlo simulated events. Comparison of the predicted and the fitted distribution as sum of all processes to data (right).

Figure 7.27.: Distributions of data and the best fitted parameters for background normalization and systematic uncertainties in the $e+\text{jets}$ channel (left), where the yellow band indicates the statistical uncertainty on the Monte Carlo simulated events. Comparison of the predicted and the fitted distribution as sum of all processes to data (right).

Pseudo-Experiments with Shifts

Series of 500 PEs are performed for the full fit setup varying one of the nuisance parameters to its $\pm 1\sigma$ boundaries. In such a scenario, the fit should on average be able to detect the shift and measure the value of the nuisance parameter correctly. Figure 7.28 shows three examples, in which one of the parameters is shifted at a time. The parameters associated to the FSR uncertainty and the pile-up term of jet energy scale for jets with low transverse momentum in the central detector region are shifted to $\delta = 1.0$ for the PEs, while the parameter associated to the jet identification efficiency is shifted to $\delta = -1.0$. In all three cases the correct value of the parameter is determined by the

fit with good precision. This study validates the ability of the fit to detect shifts of the nuisance parameters, which is crucial to constrain the uncertainties. This is also repeated for several nuisance parameters being shifted at the same time, and the results do not change.

Figure 7.28.: Fitted values for different nuisance parameters in series of 500 PEs, where the associated nuisance parameter was shifted to a value different from the default of zero. The fit should be able to detect such a shift, which is demonstrated by the histograms.

7.7. Discussion of Results

7.7.1. Main Results

Taking into account all uncertainties from the profile likelihood fit, the external systematic uncertainties and the 3.7% uncertainty on the luminosity of the analyzed data set, the result of the top quark pair production cross section in the combined ℓ +jets channel yields

$$\sigma_{t\bar{t}} = 179.0 \pm 4.1(\text{stat.}) \pm 8.8(\text{syst.}) \pm 6.6(\text{lumi.}) \text{ pb} = 179.0 \pm 11.8 \text{ pb.} \quad (7.2)$$

This corresponds to a precision of 6.6% of $\sigma_{t\bar{t}}$, to date the most precise measurement of this quantity, see section 7.7.2 for further discussion. The measurements in the single channels yield

$$\sigma_{t\bar{t}} = 183.7 \pm 6.4(\text{stat.}) \pm 10.1(\text{syst.}) \pm 6.8(\text{lumi.}) \text{ pb} = 183.7 \pm 13.8 \text{ pb} \quad (7.3)$$

in the μ +jets channel with a precision of 7.5% and

$$\sigma_{t\bar{t}} = 178.7^{+6.3}_{-6.2}(\text{stat.})^{+10.3}_{-10.0}(\text{syst.}) \pm 6.6(\text{lumi.}) \text{ pb} = 178.7^{+13.8}_{-13.5} \text{ pb} \quad (7.4)$$

in the e +jets channel, which corresponds to an overall uncertainty of 7.7%. The results in all three channels are compared to the ones from the analysis presented in chapter 6 in figure 7.29 and show a good agreement both between the different channels of the measurement and between this measurement and the statistically independent measurement in 35 pb^{-1} of data. All six measurements obtain a value for $\sigma_{t\bar{t}}$ above the theoretically predicted value at approximate NNLO, but they agree well with the calculations taking the uncertainties into account.

Since precise measurements of $\sigma_{t\bar{t}}$ are available from the Tevatron at $\sqrt{s} = 1.8 \text{ TeV}$ (RunI) and $\sqrt{s} = 1.96 \text{ TeV}$ (RunII), the top quark pair production cross section can now be studied as a function of the center-of-mass energy in $p\bar{p}$ and pp collisions over a wide range, and can be compared to theoretical calculations as a function of $\sqrt{s}$, see figure 7.30. A good agreement between measurement and prediction is visible, and can be further tested in upcoming pp collisions at the LHC with $\sqrt{s} = 8 \text{ TeV}$ in 2012 and $\sqrt{s} = 14 \text{ TeV}$ in the near future.

While the increase of available statistics by a factor of 20 between the analysis of chapter 6 and this one leads, together with improvements on methodology and uncertainties, to a significantly decreased overall uncertainty, this measurement is now completely dominated by the systematic uncertainties. A further increase of statistics would not add much precision, since the statistical uncertainty is already almost negligible. Still, more data will help to understand and possibly constrain the systematic uncertainties better. However, the luminosity uncertainty from an external measurement and even to a larger extend the systematic uncertainties on the signal modeling will remain limiting factors. A correct treatment and description of initial and final state radiation in the context of NLO generators will be needed, and the differences between the two available signal generators POWHEG and MC@NLO need to be carefully studied. The signal modeling systematics can be constrained by measuring the differential top quark pair production cross section in many distributions. The model leading to the best description of the kinematic distributions of the top quarks and the decay products can be determined and tuned to data for future usage.

Figure 7.29.: Measured top quark pair production cross sections in the lepton + jets channel, for the combined ℓ +jets mode and the separate channels, both for the analysis of 0.7 fb^{-1} of data presented here and the analysis of 35 pb^{-1} of data as presented in chapter 6.

Figure 7.30.: Comparison of approximate NNLO and NLO predictions for $\sigma_{t\bar{t}}$ as a function of the center-of-mass energy and the two presented main results of this thesis, as well as Tevatron measurements at lower energies.

7.7.2. Comparison of Different Measurements

Measurements in all analysis channels² for top quark pair production are available from both the ATLAS and the CMS experiment for data sets of up to 1.1 fb^{-1} . The results from both experiments in

²dilepton, lepton+jets and allhadronic

pp collisions provided by the LHC at a center-of-mass energy of $\sqrt{s} = 7 \text{ TeV}$ are shown in figure ?? and demonstrate a very good agreement between each other within the associated uncertainties. While the analyses in the single lepton and dilepton channels are reaching precision of below 10% and are strongly dominated by systematic uncertainties, the measurements in the allhadronic channel are expected to significantly improve with the full 5 fb^{-1} of data taken by both experiments in 2011. Increasing the precision of the measurements of $\sigma_{t\bar{t}}$ in the ℓ +jets channel by both experiments will be a difficult task, since both analyses already use advanced techniques like profile likelihood fitting to reduce the influence of the systematic uncertainties. Improving the separation power of the discriminant will only marginally increase the precision, since it only affects the statistical component of the measurement. Choosing a discriminator sensitive to major systematic uncertainties to simultaneously fit or constrain these is a more powerful tool, but is already implemented in both the ATLAS analysis, through $p_T(j_1)$, and the CMS analysis, which uses a distribution sensitive to b -tagging and the W +heavy flavor components. Therefore, an improvement can only be achieved by dedicated studies of all different sources of systematic uncertainties with the aim to reduce the a priori size of the uncertainty. Measurements of the differential top quark pair production will be needed to further reduce the uncertainties. This is especially true for modeling uncertainties, such as the generator model, ISR/FSR or scale choices. The latter constitute a dominant uncertainty in the CMS analysis using b -tagging [52], since the choice of the factorization and renormalization scales especially for the W +jets background simulation strongly affects the distribution of events in different jet multiplicity bins. In contrast to the presented analyses, the CMS analysis does not contain different fit parameters for the W +jets background in each of the jet multiplicity bins and is therefore quite sensitive to this uncertainty. The ATLAS analyses yield a slightly larger statistical uncertainty for that reason and include the scale variations only as, relatively small, shape variations, but account for the same effect in a different way.

Compared to measurements at the Tevatron, see section 2.3.1.1, the presented measurement exceeds the precision of any available single measurement as well, while the central values are of course not directly comparable. All analyses show not only a good agreement with each other, but also with the theoretical predictions. Figure ?? includes the prediction at approximate NNLO from Langenfeld et al. [24, 25]. Other theoretical calculations are listed in section 2.3.1.1 and yield very similar values. With different measurements in the ℓ +jets channel now achieving precision below 7%, the sizes of theoretical and experimental uncertainties are now of the same size, but their origin is different. To further improve the understanding of top quark pair production in future measurements, an improvement on the theoretical predictions and on modeling assumptions, will be needed as well. In particular, the prediction of differential distributions at approximate NNLO would help to validate different models in experimental measurements. On the other hand, precise measurements of the $t\bar{t}$ production cross section can be used as inputs and tests for theoretical predictions, for example, to distinguish between different parton density functions and their gluon contributions, since gluon fusion dominates the production mechanism.

7.7.3. Extensions of the Measurement

Combination [55]

In the same way as described in section ?? the analysis of 0.7 fb^{-1} of data is combined with measurements in the dilepton channel [48] and for the first time at ATLAS also in the allhadronic

Figure 7.31.: The two measurements presented in this thesis, see chapters 6 [68] and 7 [49] compared to the best dilepton channel [48] and allhadronic channel [50] measurements from ATLAS, the lepton+jets channel measurements with [52] and without [107] b-tagging, the dilepton channel [51] and the allhadronic channel [53] measurements from CMS. Combinations of the best ℓ +jets, dilepton and allhadronic measurements are performed at both experiments, CMS [56] and ATLAS [55], and manage to reduce the uncertainties further. All measurements show good agreement with the approximate NNLO calculations from Langenfeld et al. [24, 25]. The measurement presented in this chapter provides the highest precision of all single channel measurements, exceeding the precision of the theory calculations and also of the measurements from the Tevatron experiments.

channel [50]. All channels are included in a global profile likelihood function, assuming full correlation between 26 out of 88 uncertainties, which are shared amongst the different channels. The combination yields

$$\sigma_{t\bar{t}} = 177 \pm 3(\text{stat.})^{+8}_{-7}(\text{syst.}) \pm 7(\text{lumi.}) \text{ pb}, \quad (7.5)$$

with a precision of 6% and is dominated by the presented measurement in the ℓ +jets channel. Object identification and energy scale uncertainties contribute significantly to the overall uncertainties of the measurement, as well as different signal model uncertainties, such as the choice of the event generator, the parton shower modeling and the parton distribution functions. As an additional test, the combination is repeated using the BLUE method [112, 113] and yields $\sigma_{t\bar{t}} = 178 \pm 4(\text{stat.}) \pm 11(\text{syst.} + \text{lumi.}) \text{ pb}$, in good agreement with the above result.

Future Extension to a Simultaneous Measurement of $\sigma_{t\bar{t}}$ and R_b

8.1. Introduction

After the measurement technique presented here is established in single measurements as presented in chapter 6 and chapter 7, it can be extended to simultaneous measurements of $\sigma_{t\bar{t}}$ and other quantities the selection of events is sensitive to. In the following, a measurement of the top quark decay branching ratio ratio $R_b = \frac{t \rightarrow Wb}{t \rightarrow Wq}$, where q stands for any kind of quark, together with $\sigma_{t\bar{t}}$ will be outlined, following the general strategy of chapter 5, and initial studies will be shown. However, due to time constraints and availability of correctly simulated dedicated Monte Carlo samples, the analysis is not carried out to a final result. While the measurements presented up to here make the assumption of $R_b = 1$, i.e. top quarks always decaying into a W boson and a b quark, this can be tested by allowing R_b to vary in a final fit to a flavor sensitive discriminant. As already outlined in section 2.3.2, a value for R_b deviating from the expected value close to unity would be a strong hint for new physics through an additional generation of quarks or new processes with top quarks. Furthermore, the latest measurement of R_b and $|V_{tb}|$ in the context of the SM performed by the DØ collaboration [40] detects a small deviation from the expectation, which would be good to probe at the LHC.

8.2. Analysis Strategy

The analysis strategy outlined in chapter 5 can be adopted for a simultaneous measurement of R_b and $\sigma_{t\bar{t}}$ with small modifications. The classification of the events in terms of the jet multiplicity can be exploited to constrain the systematic uncertainties and the backgrounds in a profile likelihood technique, but a different approach is planned for the choice of a discriminant used in the final fit. Since a clear and well-understood flavor separation is needed to distinguish different scenarios of the

top quark decay, using a b -tagging distribution as single discriminant is advisable. Initial studies on the actual choice of the discriminant are shown in section 8.3. Such a variable not only allows to measure R_b simultaneously with the top quark pair production cross section, but can also help to reduce the influence of systematic uncertainties on the calibration of the b -tagging algorithm itself in comparison to a less sophisticated approach, in which events are counted in bins of the number of b -tagged jets per event.

To gain more precision in the separation between $t\bar{t}$ production and W +jets production, the pseudorapidity of the charged lepton could be combined with the b -tagging distribution. Both variables are expected to be uncorrelated¹, and η^ℓ provides a good separation throughout all jet multiplicity bins. Furthermore, the sensitivity of the measurement could be increased by extending it to events in the dileptonic channels, but using the same flavor discriminating variable.

8.3. Initial Studies

8.3.1. Samples and Selection

The studies for a simultaneous measurement of R_b and $\sigma_{t\bar{t}}$ are performed with the same 0.7 fb^{-1} of data as analyzed in chapter 7. The same object definitions and event selections are applied in the following, and the simulated MC events are the same. Both the QCD estimate and the data-driven W +jets estimate as used for the cross section analysis are considered.

Since the $t\bar{t}$ events in both the available MC@NLO and POWHEG samples are simulated with $R_b = 1$, i.e. the top quark decaying into a W boson and a b quark in all cases, additional samples are generated with the leading order generator PROTOS [114, 115]. The sample relies on the CTEQ6L1 [91] PDF set and is interfaced with PYTHIA [82] for the showering. PROTOS allows to vary the values of the CKM matrix elements V_{td} , V_{ts} and V_{tb} , and the samples are generated with $V_{td} = V_{ts} = 0.25$ and $V_{tb} = 0.50$. A truth-based selection is applied to create three classes of events with different quark flavors for further studies: $t\bar{t} \rightarrow WbWb^2$, $t\bar{t} \rightarrow WbWq$ and $t\bar{t} \rightarrow WqWq$, where both down and strange type quarks are denoted with q , a light quark.

However, since PROTOS is a leading order generator for $t\bar{t}$ events and the cross section measurement from chapter 7 shows that precision corresponding to NNLO can be reached with the available data set already, these samples can only be used for studies, but not for the final measurement. To create the template distributions for the final fit, the default NLO samples from MC@NLO would need to be used. Then, the differences in acceptance and transverse momentum of the leading jet, which can be observed in the $WbWq$ and $WqWq$ samples from PROTOS, can be propagated to MC@NLO using a reweighting, and the discriminant value for one or both true b -jets can be replaced by the one of a light jet with the same kinematics. Studies to achieve a good parametrization of the light jet probability functions will be shown in section 8.3.3.

¹which would require a study

²as the default settings

8.3.2. Possible Discriminators

As outlined before, a b -tagging distribution is supposed to serve as single discriminating variable for a profile likelihood fit to extract the top quark decay fraction R_b and the cross section $\sigma_{t\bar{t}}$ simultaneously. While in the analysis described in chapter 6 the distribution from a relatively simple b -tagging algorithm, JetProb, is used as one of the input variables for the likelihood discriminant $\mathcal{D}$, more advanced taggers are available for the larger data set of 0.7 fb^{-1} . Two b -jet identification algorithms [116] are initially considered as possible input to the analysis:

- CombNN, a combination of the IP3D and the JetFitter algorithms in a neural network
- IP3DSV1, a combination of the likelihood ratios from the IP3D and the SV1 algorithms

The IP3D algorithm present in both combined b -taggers makes use of a likelihood ratio comparing impact parameter related distributions to predicted distributions for b -jets and light jets, and is based on a similar technique as the JetProb algorithm used in chapter 6. The JetFitter algorithm uses a Kalman filter to reconstruct the decay chain of a jet and the associated secondary vertex as well as decay length significances. Finally, the SV1 b -tagging algorithm constructs a likelihood ratio for variables related to the secondary vertex within a jet: the invariant mass of the tracks pointing to the vertex, an energy ratio of tracks associated with the secondary vertex and all tracks in the jet and the number of vertices with two tracks associated. Both algorithms are commissioned in 7 TeV collisions [116], and considered in the following.

Different distributions are studied in the PROTOS sample described above for both algorithms to select one with an optimal separation between the scenarios $t\bar{t} \rightarrow WbWb$, $t\bar{t} \rightarrow WbWq$ and $t\bar{t} \rightarrow WqWq$. Figure 8.1 for the CombNN algorithm and figure 8.2 for the IP3DSV1 algorithm show several distributions, such as the algorithm output for the leading, most b -like and least b -like jet as well as average algorithm outputs for all selected jets, the two most b -like jets³ and the two least b -like jets. As expected, the best separation between all three models is achieved, when information about the two most b -like jets is combined, since this distribution can not only distinguish between the existence of one b -jet at all, but also further separate between the $WbWb$ and $WbWq$ cases. In addition, the CombNN algorithm leads to a better separation in the average output distribution than the IP3DSV1 algorithm and is therefore considered as the distribution of choice for such an R_b measurement.

As can be seen in figure 8.3, using the default MC and data-driven predictions, the distribution $\bar{w}_{combNN}$ also provides a good separation power between $t\bar{t}$ and W +jets production, where the latter peaks at such low values that its separation even from the $t\bar{t} \rightarrow WqWq$ scenario should be possible. However, figure 8.3 still shows a disagreement between data and predicted events even when the b -tagging calibration is applied in the same fashion as described in section 4.2.3.6 for a continuous distribution. The calibration is available at three working points with 60%, 70% and 80% tagging efficiency for true b -jets and does not lead to a good enough agreement. Further studies and more working points or a refined calibration will be needed to fully exploit the variable without being limited by large systematic uncertainties in the future.

³which corresponds to the variable considered in chapter 6

Figure 8.1.: Different distributions of the b -tag algorithm's CombNN output for events with exactly four jets in the μ +jets channel, and their power to distinguish between different top quark decay scenarios.

8.3.3. b -Tagging Parametrization for Light Jets

Since the PROTOS leading order samples are not usable for the final analysis, the default MC@NLO $t\bar{t}$ samples have to be used to construct templates for the profile likelihood fit. The idea is to split the MC@NLO samples into three parts, representing the decay modes $WbWb$, $WbWq$ and $WqWq$. While the $WbWb$ sample corresponds to the initial settings, the other two have to be reweighted to account for differences in acceptance and possibly the transverse momenta of the jets⁴, based on the relative behavior of the different samples in PROTOS. After this, the final discriminant $\bar{w}_{\text{combNN}}$ is constructed, but the b -tagging algorithm output for one, in the case of $WbWq$, or both, for $WqWq$, true b -jets is replaced by the output value for a light jet with the same kinematic quantities. To do so, probability density distributions for light jets as a function of the kinematics have to be constructed, and for each jet a random number following the corresponding distribution has to be drawn. The construction of the probability density distributions is done using the default W +jets samples, selecting only events with true light jets and studying the dependence of the b -tag output value as a function of the kinematics. While no obvious dependence on φ or the number of jets is

⁴a preliminary study shows a small difference in the jet kinematics

Figure 8.2.: Different distributions of the b -tag algorithm's I3PDSV1 output for events with exactly four jets in the μ +jets channel, and their power to distinguish between different top quark decay scenarios.

Figure 8.3.: Separation power and data and MC agreement for the average CombNN output of the two most b -like jets. Here, $t \rightarrow Wb$ is always assumed.

found, the output value strongly depends on the pseudorapidity and the transverse momentum of the jet. Figure ?? and figure 8.4 show the b -tagging output distributions for light jets in different bins of

the pseudorapidity and the transverse momentum. One can see differences especially in the location of the peak and the width of the tails, which have to be accounted for.

Figure 8.4.: b -tag weight distributions w_{combNN} for light flavor jets with different momenta in bins of pseudorapidity.

Prior to the application of the probability density distributions to the MC@NLO $t\bar{t}$ sample, the validity of the procedure has to be tested in W +jets events itself. The true b -tag algorithm output for each light jet can be compared to one drawn with the parametrization procedure, and both the average deviation from truth and the average overall distribution for all events can be compared with and without the parametrization applied. A thorough test of the procedure and a better data MC agreement have to be in place, before a precision measurement of R_b and $\sigma_{t\bar{t}}$ can be performed.

Figure 8.5.: b -tag weight distributions w_{combNN} for light flavor jets reconstructed in different detector regions in η , shown in bins of the transverse momentum of the jet.

Conclusions

In the first one and a half years of operation at a center-of-mass energy of $\sqrt{s} = 7$ TeV, the ATLAS experiment collected enough data to perform precision measurements of many parameters of the Standard Model. An accurate knowledge of the top quark pair production cross section constitutes an important building block for tests of the Standard Model. It facilitates measurements of the different properties of the top quark, searches for the Higgs boson and new physics beyond the SM, where $t\bar{t}$ production both serves as a dominant source of background and also as window to new physics connected with top quarks. Furthermore, the comparison with measurements in different analysis channels, at different center-of-mass energies at the Tevatron and with theoretical predictions available up to approximate NNLO mark a great test of the Standard Model itself.

Two measurements of the top quark pair production cross section in pp collisions are presented in this thesis and yield

$$\sigma_{t\bar{t}} = 187 \pm 11(\text{stat.})_{-17}^{+18}(\text{syst.}) \pm 6(\text{lumi.}) \text{ pb} = 187_{-21}^{+22} \text{ pb} \quad (9.1)$$

with 35 pb^{-1} of data and

$$\sigma_{t\bar{t}} = 179.0 \pm 4.1(\text{stat.}) \pm 8.8(\text{syst.}) \pm 6.6(\text{lumi.}) \text{ pb} = 179.0 \pm 11.8 \text{ pb} \quad (9.2)$$

with 0.7 fb^{-1} of data. Both measurements are performed relying on a similar analysis strategy, developed in the context of this thesis, and focus on the single lepton decay channel of top quark pair production. In both cases, a projective likelihood discriminant is built from four variables in the e +jets and μ +jets channels for events with $n_{\text{jets}} = 3, 4, \geq 5$. The distributions are used in a negative log-likelihood fit of predicted events to data, including systematic uncertainties as nuisance parameters. A set of three distributions – the pseudorapidity of the lepton, the event aplanarity and $H_{T,3p}$, a sum of transverse momenta of the weaker jets, normalized by the z -component of the momentum of all selected objects – is common to the analyses, with the fourth variable differing. The analysis of 35 pb^{-1} of data makes use of a continuous distribution created from the output of a b -tagging algorithm and taking the average output for the two most b -like jets into account. This distribution leads to an extremely clean separation between $t\bar{t}$ production and W +jets production as

dominant background, due to the different flavor composition of the samples. However, large uncertainties on the calibration of the b -tagging algorithm and the heavy flavor fraction in W +jets events limit the precision of the measurement. An overall precision of 12% is achieved by this analysis, the dominant uncertainties being jet energy scale related uncertainties, the above named b -tagging and heavy flavor uncertainties and modeling assumptions for initial and final state radiation for the signal process. The uncertainty is reduced to 6.6% for the measurement in 0.7 fb^{-1} of data, by the large increase of statistics, but also by a refined analysis strategy. Instead of the b -tagging variable, the fourth variable is chosen to be sensitive to one of the dominant uncertainties. The transverse momentum of the leading jet is included in the projective likelihood discriminant to improve the ability to constrain the jet energy scale uncertainties further in the profile likelihood fit. The description of the uncertainty for initial and final state radiation is included as nuisance parameter in this analysis as well, which leads to a great reduction of the influence of this source of uncertainty. The analysis with 0.7 fb^{-1} is the most precise measurement of the top quark pair production cross section at any collision energy to date and while both measurements are found to be in good agreement with theoretical predictions at NNLO, this analysis exceeds even the precision of the calculations. While the jet energy scale uncertainty still is of importance, the dominating uncertainty comes from different physics modeling of the signal process – the comparison between MC@NLO and POWHEG as signal generator. To further improve the measurement, systematic uncertainties need to be reduced and will require careful studies. A future analysis would need to be designed to constrain systematic uncertainties even better by itself and will need a better understanding of the differences in the modeling of the signal processes. Measurements of the differential top quark pair production cross section as function of the top quark kinematics and its decay products will be needed for that purpose. Knowing the top quark pair production cross section and the sample of top quark events precisely then allows to proceed with precision measurements of the top quark properties to further test the Standard Model and gain access to rare effects, such as spin correlations and the helicity of the W boson from the top quark decay, the invariant mass spectrum as tool to search for new physics, or couplings to bosons, as in $t\bar{t}H$, $t\bar{t}\gamma$ or $t\bar{t}Z$ measurements. Cross section measurements can be extended to differential measurements of the cross section versus kinematic properties of the top quark pairs, top quarks or decay products to confirm and improve the theoretical modeling of such processes, and the production of top quark pairs in association with additional jets can be studied. As an example of the direct extension of the cross section measurement, a simultaneous measurement of the top quark decay branching fraction R_b and $\sigma_{t\bar{t}}$ is outlined based on the same analysis strategy.

While no hints for new physics beyond the Standard Model have been found at the LHC yet, the knowledge of the Standard Model has been significantly improved. Amongst others, the presented measurements support the great success of the theory itself, open up a broad field of precision physics with top quarks and serve as great environment to develop and calibrate novel analysis techniques requiring a deep understanding of all physics objects.

Appendix A

Separate Lepton Channel Fits in 35 pb^{-1} of Data

Separate profile likelihood fits are applied to the μ +jets and e +jets selections of the measurement described in chapter 6. The detailed output of the fit is given in table A.1 for the μ +jets channel and in table A.2 for the e +jets channel.

Parameter	Value	Error	Error Up	Error Down
$\beta(t\bar{t})$	1.0947	0.1100	0.1132	-0.1073
$\beta(W \rightarrow \mu + 3 \text{ jets})$	0.8390	0.0881	0.1081	-0.0823
$\beta(W \rightarrow \mu + 4 \text{ jets})$	0.8095	0.1361	0.1590	-0.1256
$\beta(W \rightarrow \mu + 5 \text{ jets})$	0.7000	0.2177	0.2669	-0.1951
$\beta(Z + \text{Jets})$	1.2045	0.2699	0.2710	-0.2691
$\beta(\text{Single top})$	1.0009	0.1059	0.1059	-0.1060
$\beta(\text{Diboson})$	1.0003	0.0600	0.0600	-0.0600
$\beta(\text{QCD in } \mu + 3 \text{ jets})$	0.9950	0.4769	0.4780	-0.4786
$\beta(\text{QCD in } \mu + 4 \text{ jets})$	0.9758	0.4770	0.4773	-0.4773
$\beta(\text{QCD in } \mu + 5 \text{ jets})$	0.6601	0.4714	0.4722	-0.4714
$\delta(\text{b-tag WP1})$	-0.3402	1.3189	1.2711	-1.1716
$\delta(\text{b-tag WP2})$	0.3101	0.9935	0.9917	-0.9932
$\delta(\text{b-tag WP3})$	0.1882	0.9484	0.9455	-0.9518
$\delta(\text{b-tag WP4})$	0.5011	0.8998	0.9114	-0.8932
$\delta(\text{mistag WP1})$	-0.0213	0.9597	0.9518	-0.9660
$\delta(\text{mistag WP2})$	-0.1540	1.0271	1.0252	-1.0242
$\delta(\text{mistag WP3})$	0.1666	1.0545	1.0516	-1.0507
$\delta(\text{mistag WP4})$	-0.1583	1.0050	1.0050	-1.0043
$\delta(\text{Jet ID})$	0.6450	0.5962	0.6280	-0.5244
$\delta(\text{JER})$	0.4403	0.8521	0.8728	-0.8053
$\delta(W + \text{bb/cc Fraction } 3 \text{ jets})$	-0.1881	0.9864	0.9860	-0.9869
$\delta(W + \text{bb/cc Fraction } 4 \text{ jets})$	-0.0880	0.9014	0.9097	-0.8959
$\delta(W + \text{bb/cc Fraction } 5 \text{ jets})$	-0.7676	0.9719	0.9972	-0.9202
$\delta(W + c \text{ Fraction } 3 \text{ jets})$	0.0475	0.9700	0.9697	-0.9700
$\delta(W + c \text{ Fraction } 4 \text{ jets})$	-0.0054	0.9849	0.9848	-0.9850
$\delta(W + c \text{ Fraction } 5 \text{ jets})$	-0.1186	0.9985	0.9985	-0.9985
$\delta(\text{Pile-Up})$	0.2643	0.8574	0.8495	-0.8656
$\delta(\mu \text{ SFs})$	0.0257	0.9978	0.9976	-0.9974
$\delta(\mu \text{ Momentum Smearing})$	-0.4159	1.3104	1.1639	-1.0863
$\delta(\text{Missing Et})$	0.2799	0.8019	0.7566	-0.8098
$\delta(\text{JES Eta})$	1.3279	0.5426	0.5509	-0.5267
$\delta(\text{JES Calo})$	-0.7640	0.5242	0.5689	-0.5390
$\delta(\text{JES Alpgen})$	-0.9921	0.6663	1.4466	-0.6249
$\delta(\text{JES Noise})$	-0.1509	1.6434	1.5892	-1.0199
$\delta(\text{JES Pile-Up})$	0.2353	0.7277	0.6638	-0.7967
$\delta(\text{JES Perugia})$	-0.1854	0.4410	0.3202	-0.9645
$\delta(\text{JES b-Jet})$	-0.5270	0.9148	0.9389	-0.8876
$\delta(\text{JES flavor})$	0.9748	0.7030	0.6277	-0.9626
$\delta(\text{JES close-by})$	-0.5826	0.6049	0.6402	-0.5856

Table A.1.: Resulting fit parameters and uncertainties from the μ +jets channel fit.

Parameter	Value	Error	Error Up	Error Down
$\beta(t\bar{t})$	1.1569	0.1340	0.1387	-0.1302
$\beta(W \rightarrow e + 3 \text{ jets})$	0.9125	0.1238	0.1289	-0.1184
$\beta(W \rightarrow e + 4 \text{ jets})$	0.8255	0.1811	0.1914	-0.1709
$\beta(W \rightarrow e + 5 \text{ jets})$	0.5877	0.3118	0.3380	-0.2902
$\beta(Z + \text{Jets})$	0.9498	0.2979	0.2982	-0.2978
$\beta(\text{Single top})$	1.0026	0.1060	0.1060	-0.1060
$\beta(\text{Diboson})$	1.0002	0.0600	0.0600	-0.0600
$\beta(\text{QCD in } e + 3 \text{ jets})$	0.9823	0.4898	0.4913	-0.4913
$\beta(\text{QCD in } e + 4 \text{ jets})$	0.9934	0.4972	0.4976	-0.4975
$\beta(\text{QCD in } e + 5 \text{ jets})$	0.8402	0.4915	0.4919	-0.4919
$\delta(\text{b-tag WP1})$	-0.1909	0.9032	0.8891	-0.9048
$\delta(\text{b-tag WP2})$	0.3075	1.0001	0.9962	-1.0008
$\delta(\text{b-tag WP3})$	-0.2798	0.9464	0.9439	-0.9496
$\delta(\text{b-tag WP4})$	-0.3639	0.9481	0.9550	-0.9418
$\delta(\text{mistag WP1})$	0.4424	1.0426	1.0253	-1.0455
$\delta(\text{mistag WP2})$	-0.1792	0.9706	0.9695	-0.9718
$\delta(\text{mistag WP3})$	0.1642	0.9688	0.9694	-0.9684
$\delta(\text{mistag WP4})$	0.1351	0.9947	0.9948	-0.9947
$\delta(\text{Jet ID})$	0.5451	0.7317	0.7282	-0.7284
$\delta(\text{JER})$	0.0030	0.9988	0.9988	-0.9988
$\delta(W + \text{bb/cc Fraction } 3 \text{ jets})$	-0.3250	0.9732	0.9725	-0.9742
$\delta(W + \text{bb/cc Fraction } 4 \text{ jets})$	0.4604	0.9304	0.9374	-0.9294
$\delta(W + \text{bb/cc Fraction } 5 \text{ jets})$	0.2962	0.9447	0.9487	-0.9449
$\delta(W + c \text{ Fraction } 3 \text{ jets})$	0.4988	0.9732	0.9727	-0.9737
$\delta(W + c \text{ Fraction } 4 \text{ jets})$	0.0869	0.9895	0.9894	-0.9896
$\delta(W + c \text{ Fraction } 5 \text{ jets})$	0.0044	0.9993	0.9993	-0.9993
$\delta(\text{Pile-Up})$	0.1042	0.8821	0.8796	-0.8843
$\delta(e \text{ SFs})$	-0.0856	0.9957	0.9954	-0.9944
$\delta(e \text{ Energy Resolution})$	0.0958	0.7579	0.7499	-0.7523
$\delta(e \text{ Energy Smearing})$	0.1140	0.7771	0.7659	-0.7785
$\delta(\text{Missing Et})$	-0.4504	1.0825	1.1318	-0.9228
$\delta(\text{JES Eta})$	0.4977	0.9027	0.6941	-1.2107
$\delta(\text{JES Calo})$	-0.0392	0.5651	0.5652	-0.5454
$\delta(\text{JES Alpgen})$	0.2204	0.7569	0.6982	-0.7581
$\delta(\text{JES Noise})$	0.4935	0.9550	0.7630	-1.0639
$\delta(\text{JES Pile-Up})$	0.5822	0.7261	0.6014	-0.8808
$\delta(\text{JES Perugia})$	-0.6908	0.6448	0.7792	-0.5608
$\delta(\text{JES b-Jet})$	-0.0537	0.8185	0.8084	-0.7677
$\delta(\text{JES flavor})$	-0.0634	0.5514	0.5771	-0.4963
$\delta(\text{JES close-by})$	-0.0521	0.7675	0.7677	-0.7322

Table A.2.: Resulting fit parameters and uncertainties from the $e + \text{jets}$ channel fit.

Appendix B

Separate Lepton Channel Fits in 0.7 fb^{-1} of Data

Separate profile likelihood fits are applied to the μ +jets and e +jets selections of the measurement described in chapter 7. The detailed output of the fit is given in table B.1 for the μ +jets channel and in table B.2 for the e +jets channel.

Parameter	Value	Error	Error Up	Error Down
$\beta(t\bar{t})$	1.1160	0.0593	0.0593	-0.0593
$\beta(W \rightarrow \mu + 3 \text{ jets})$	1.0397	0.0876	0.0911	-0.0872
$\beta(W \rightarrow \mu + 4 \text{ jets})$	0.8622	0.1089	0.1167	-0.1068
$\beta(W \rightarrow \mu + 5 \text{ jets})$	0.9204	0.1567	0.1661	-0.1576
$\beta(Z + \text{Jets})$	0.9335	0.2949	0.3030	-0.2968
$\beta(\text{Single top})$	1.0094	0.1067	0.1073	-0.1064
$\beta(\text{Diboson})$	1.0018	0.0620	0.0620	-0.0620
$\beta(\text{QCD in } \mu + 3 \text{ jets})$	0.9915	0.3033	0.3670	-0.3580
$\beta(\text{QCD in } \mu + 4 \text{ jets})$	1.2970	0.3699	0.4130	-0.4125
$\beta(\text{QCD in } \mu + 5 \text{ jets})$	0.8821	0.3902	0.4152	-0.4019
$\delta(\text{AlpgenJES})$	0.7507	0.2718	0.2008	-0.3420
$\delta(\text{bJES})$	-0.1401	0.4653	0.4753	-0.4517
$\delta(\text{CaloJES})$	-0.1072	0.5086	0.4648	-0.4230
$\delta(\text{NoiseJES})$	0.1008	0.4683	0.4065	-0.4152
$\delta(\text{PerugiaJES})$	-0.3773	0.4004	0.4201	-0.2995
$\delta(\text{EtaJES})$	-0.3037	0.3002	0.2944	-0.2787
$\delta(\text{PileupJES low } p_T/\text{central})$	0.2810	0.2740	0.2490	-0.2953
$\delta(\text{PileupJES low } p_T/\text{forward})$	-0.1011	0.3615	0.3847	-0.4184
$\delta(\text{PileupJES high } p_T/\text{central})$	-0.9128	0.3320	0.5316	-0.3336
$\delta(\text{PileupJES high } p_T/\text{forward})$	-0.1190	0.4955	0.5716	-0.5770
$\delta(\text{Jet Efficiency})$	0.2101	0.2105	0.2111	-0.2091
$\delta(\text{JER})$	0.4308	0.9721	0.9716	-0.9727
$\delta(\text{FSR})$	-0.2464	0.2720	0.4650	-0.2113
$\delta(\text{ISR})$	0.0956	0.4067	0.4289	-0.3389
$\delta(\mu \text{ SFs})$	-0.4504	0.9812	0.8858	-0.8939
$\delta(\mu \text{ Momentum Smearing at MS})$	0.0782	0.8582	0.7844	-0.8720
$\delta(\mu \text{ Momentum Smearing at ID})$	-0.4699	0.8648	0.9733	-0.7945
$\delta(\mu \text{ Energy Scale})$	0.1163	1.2847	1.1632	-1.1384
$\delta(\text{Missing } E_T \text{ LAr})$	-0.0084	0.5962	0.6176	-0.6017
$\delta(\text{Missing } E_T \text{ SoftJet})$	0.1191	0.5604	0.4807	-0.5359

Table B.1.: Resulting fit parameters and uncertainties from the μ +jets channel fit.

Parameter	Value	Error	Error Up	Error Down
$\beta(t\bar{t})$	1.0861	0.0598	0.0606	-0.0589
$\beta(W \rightarrow e + 3 \text{ jets})$	1.0542	0.0598	0.0722	-0.0655
$\beta(W \rightarrow e + 4 \text{ jets})$	1.0080	0.0959	0.1208	-0.1134
$\beta(W \rightarrow e + 5 \text{ jets})$	0.8412	0.1076	0.1527	-0.1451
$\beta(Z + \text{Jets})$	0.9982	0.1745	0.2934	-0.2912
$\beta(\text{Single top})$	1.0059	0.0993	0.1070	-0.1068
$\beta(\text{Diboson})$	1.0013	0.0616	0.0620	-0.0620
$\beta(\text{QCD in } e + 3 \text{ jets})$	0.5112	0.2022	0.2933	-0.3026
$\beta(\text{QCD in } e + 4 \text{ jets})$	0.7165	0.2592	0.3620	-0.3771
$\beta(\text{QCD in } e + 5 \text{ jets})$	0.4760	0.3183	0.4280	-0.4258
$\delta(\text{AlpgenJES})$	0.0653	0.2270	0.4174	-0.4660
$\delta(\text{bJES})$	1.1565	0.4473	0.4676	-0.5571
$\delta(\text{CaloJES})$	-0.0068	0.2007	0.3769	-0.3876
$\delta(\text{NoiseJES})$	-0.9344	0.2821	0.4050	-0.2815
$\delta(\text{PerugiaJES})$	-0.9371	0.1773	0.2478	-0.1991
$\delta(\text{EtaJES})$	0.4215	0.2941	0.3140	-0.4205
$\delta(\text{PileupJES low } p_T/\text{central})$	0.5620	0.1939	0.2463	-0.2689
$\delta(\text{PileupJES low } p_T/\text{forward})$	0.4255	0.4088	0.4238	-0.5185
$\delta(\text{PileupJES high } p_T/\text{central})$	0.5213	0.4679	0.4456	-0.5665
$\delta(\text{PileupJES high } p_T/\text{forward})$	-0.5535	0.7159	1.3063	-0.8162
$\delta(\text{Jet Efficiency})$	0.0675	0.1431	0.2015	-0.1893
$\delta(\text{JER})$	-0.0827	0.8795	0.9775	-0.9744
$\delta(\text{FSR})$	-0.1209	0.2160	0.2471	-0.2155
$\delta(\text{ISR})$	0.1829	0.2548	0.2785	-0.2856
$\delta(\text{e SFs})$	-0.0714	0.5651	0.9969	-0.9959
$\delta(\text{e Resolution Smearing})$	0.0895	0.6706	0.6618	-0.6555
$\delta(\text{e Energy Scale})$	-0.6413	0.5848	0.8199	-0.5459
$\delta(\text{Missing } E_T \text{ LAr})$	0.0258	0.6546	0.6934	-0.6986
$\delta(\text{Missing } E_T \text{ SoftJet})$	-0.2822	0.4509	0.9700	-0.5990

Table B.2.: Resulting fit parameters and uncertainties from the $e + \text{jets}$ channel fit.

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How the time is never now,
and we know who we should love,
but we're never certain how.
I know you might roll your eyes at this,
but I'm so glad that you exist.

The Weakerthans, The Reasons, Reconstruction Site, 2003

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Hiermit versichere ich, dass ich die Dissertation mit dem Titel "Precision Measurements of the Top Quark Pair Production Cross Section in the Single Lepton Channel with the ATLAS Experiment" selbstständig und ohne unerlaubte Hilfe angefertigt habe.

Göttingen, den 14.03.2012

Anna Henrichs

Curriculum Vitae Anna Henrichs

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Personal Details

Birthdate 29.04.1983, in Cologne (Köln)
Citizenship German

Research Interest

As a particle physicist I am intrigued by the ability to study the production and behaviour of the elementary constituents of matter in collisions of particles with highest energies, as provided by the Large Hadron Collider at CERN and the associated experiments.

My focus is the precise measurement and understanding of processes predicted by the Standard Model of Particle Physics and their sensitivity to yet unknown physics beyond the Standard Model. I am especially interested in final states involving many objects (leptons, jets, missing transverse energy), such as processes with top quarks. Measurements of these processes require a deep understanding of the experimental setup, which makes operating and calibrating the detector, as well as studying its performance an important part of my work.

Scientific Education & Experience

04/08 - NOW

Georg-August-Universität Göttingen, Germany

PhD research position under the supervision of Prof. Dr. A. Quadt, focussing on measurements of top quark pair production and top quark decay, as well as work on calibration and operation of the ATLAS Pixel detector.

CERN, Geneva, Switzerland

02/09 - 12/10

Based at CERN to work on the commissioning of the ATLAS Pixel detector, preparation, development and accomplishment of a precision measurement of the top quark pair production cross section, and related studies on detector performance, especially on multijet backgrounds and trigger efficiencies.

07/08 - 08/08

Based at CERN to work on the commissioning and calibration of the ATLAS Pixel detector.

RWTH Aachen, Germany

03/08

Graduation: Diplom (*grade 1.6*) (equivalent to a Msc. degree)

02/07 - 03/08

Diploma thesis under the supervision of Prof. Dr. M. Erdmann: *Measurement of the Top Quark Fraction in Events with 3 Jets and 1 Muon at the DØ Experiment* (grade 1.0).

Work on the understanding of final states from top quark decays that are not predicted by a corresponding Feynman diagram, but can occur due to detector effects and misidentification. The final measurement relies on advanced multivariate analysis techniques, such as boosted decision trees.

10/02 - 03/08

Study of physics at the RWTH Aachen.

Università degli Studi di Trieste, Italy

Curriculum Vitae *Anna Henrichs*

01/06 - 07/06 Study abroad with an ERASMUS scholarship from the DAAD.

Montessori-Gymnasium Köln - Bickendorf, Germany

07/95 - 06/02 Graduation: Abitur, with advanced courses in physics and english (*grade 1.6*).

Scientific Schools

10/09 Helmholtz Alliance School on Advanced Statistical Methods, Karlsruhe, Germany

08/09 Scottish Universities School of Physics, St.Andrews, Scotland

09/08 Autumn School for High Energy Physics, Maria Laach, Germany

Teaching

03/11 - 06/11 & 03/10 - 04/10 Teaching assistant for semester projects for second year physics students: *Singing Tesla Coil* and *Charge Calibration of the ATLAS Pixel Detector*.

08/09 Supervision of a summer student from the University of Göttingen at CERN, working on multivariate analysis techniques.

06/09 - 08/09 Conception of a project and supervision of a summer student from the University of Liverpool, via the RISE scholarship of the DAAD, working on trigger signatures for top physics.

10/08 - 04/09 Teaching assistant for third year lecture for physics students, *Introduction to Nuclear and Particle Physics*.

09/08 Teaching assistant for an electronics lab course for bachelor and master students of physics.

09/06 - 08/08 Teaching assistant for first and second year lectures for physics students in Göttingen and Aachen, *Physics I, III, IV*.

06/07 - 10/07 Teaching assistant for advanced physics lab course, *Particle Trapping*.

Responsibilities

06/11 - NOW Co-editor for a journal paper on the precision measurement of the top pair production cross section using kinematic distributions (in preparation).

Outreach

11/08 Tour guide for the *Weltmaschine* exhibition on the Large Hadron Collider in Berlin, organised by the Federal Ministry of Education and Research (30000 visitors).

04/08-12/08 Participation in the *Rent-a-Scientist* program to explain particle physics to high school students.

Curriculum Vitae *Anna Henrichs*

Language Skills

German	native
English	fluent
Italian	good knowledge
French	basic knowledge
Finnish	basic knowledge
Latin	written

General Skills

Programming & analysis tools: C/C++, Python, Java, ROOT, TMVA, $\text{\LaTeX}$
Operating systems: MacOS, Linux, Windows
Development tools: Eclipse, SVN, CVS, Savannah

Göttingen, den 14.03.2012

Anna Henrichs