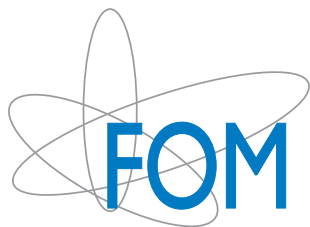


Measurements on top quark pairs in proton collisions recorded with the ATLAS detector



Ido Mussche

Dutch title: *Metingen aan topquarkparen
in protonbotsingen in de ATLAS-detector*
Cover: Merel Smit



This work is part of the research program of the 'Stichting voor Fundamenteel onderzoek der Materie' (FOM), which is part of the 'Nederlandse organisatie voor Wetenschappelijk Onderzoek' (NWO). It was carried out at the 'Nationaal Instituut voor Subatomaire Fysica' (Nikhef) in Amsterdam, the Netherlands. The research has been supported by the VICI grant 680-47-309, titled "Beyond the top; a new era of particle physics" of prof. dr. S.C.M. Bentvelsen.

Measurements on top quark pairs in proton collisions recorded with the ATLAS detector

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
prof. dr. D.C. van den Boom
ten overstaan van een door het college van promoties
ingestelde commissie,
in het openbaar te verdedigen in de Agnietenkapel
op dinsdag 9 oktober 2012, te 10:00 uur

door

Ido Mussche

geboren te Arnhem

Promotor: Prof. dr. S. Bentvelsen
Copromotor: Dr. P. Ferrari

Overige Leden: Prof. dr. F. Linde
Prof. dr. G. Raven
Prof. dr. E. Laenen
Prof. dr. T. Peitzmann
Dr. M. Decowski
Dr. W. Verkerke
Dr. M. Vreeswijk

Faculteit der Natuurwetenschappen, Wiskunde en Informatica

Contents

Preface	1
1 Top quarks and the Standard Model	3
1.1 The Standard Model	3
1.1.1 Quantum electrodynamics	4
1.1.2 Weak interactions	7
1.1.3 Strong interactions	9
1.1.4 The history of the top quark	10
1.1.5 Predictive power of the Standard Model	12
1.1.6 Unresolved issues in the Standard Model	12
1.2 Physics at the Large Hadron Collider	14
1.3 Top quarks in the Standard Model	15
1.3.1 Production	16
1.3.2 Top quark mass and Higgs	22
1.3.3 Decay	23
1.4 Top quarks in models beyond the Standard Model	26
1.4.1 Resonances	26
1.4.2 Top quark charge asymmetry	27
1.5 Summary	33
2 Properties and performance of the ATLAS detector	35
2.1 The Large Hadron Collider	35
2.2 The ATLAS detector	38
2.2.1 Coordinates in ATLAS	39
2.2.2 Magnet system	40
2.2.3 The inner detector	40
2.2.4 Calorimetry	45
2.2.5 The muon spectrometer	48
2.2.6 The ATLAS trigger system	52
2.3 Summary	54
3 Simulation and reconstruction of top quark pair events	57
3.1 Event generation	58
3.1.1 Hard scattering	58
3.1.2 Parton showering	59

Contents

3.1.3	Hadronization	61
3.1.4	Underlying event	61
3.2	Detector simulation and response	62
3.3	Event samples for analysis	62
3.3.1	Signal samples: top quark pairs	62
3.3.2	Background samples	63
3.4	Object reconstruction	65
3.4.1	Electron reconstruction	66
3.4.2	Muon reconstruction	67
3.4.3	$\cancel{E}_T$ reconstruction	69
3.4.4	Hadronic jet reconstruction	70
3.5	Initial and final state radiation in top quark events	74
3.5.1	Parameters	75
3.5.2	Effect of Λ_{QCD} and Q_0 on jet multiplicity	76
3.5.3	Effect of Λ_{QCD} and Q_0 on reconstructed top quark mass	77
3.5.4	Conclusions on ISR and FSR	80
4	Selection and characteristics of data	81
4.1	Introduction	81
4.1.1	Pile-up	83
4.1.2	Data quality	83
4.2	Object definitions for analyses	84
4.2.1	Electrons	85
4.2.2	Jets	85
4.2.3	Muons	85
4.2.4	Corrections to leptons	86
4.3	Multijet background	86
4.3.1	Muon channel	87
4.3.2	Electron channel	87
4.4	W +jets background normalization	88
4.5	Basic event selection	89
4.5.1	Event yields	90
4.6	Distributions in data: 2010 versus 2011	91
4.6.1	Electron properties	91
4.6.2	Muon properties	93
4.6.3	Jet properties	93
4.6.4	Event variables	95
4.6.5	Identification of b -jets	98
4.6.6	W +jets background normalization after b -tagging	102
4.7	Top quark reconstruction	102
4.7.1	Reconstruction with $\sum p_T$ method	103
4.7.2	Reconstruction with Kinematic Likelihood Fitter	105
4.8	Comparison of the KL-fitter and $\sum p_T$ algorithms	109
4.9	Summary	111

5	Measurement of the $t\bar{t}$-production cross section	113
5.1	The simultaneous template fit	114
5.1.1	The construction of the fit	114
5.2	Properties of data	117
5.2.1	Data categorization	117
5.3	Extraction of ratios	119
5.3.1	First fit ratio and heavy flavor uncertainty	119
5.3.2	Second fit ratio	124
5.3.3	Third fit ratio	125
5.4	Construction of the templates	125
5.4.1	Background templates	125
5.4.2	Signal templates	126
5.5	Fit results	127
5.5.1	Statistical uncertainty	128
5.6	Systematic uncertainties	130
5.7	Cross section results	135
6	Measurement of the top quark charge asymmetry	137
6.1	Top quark charge asymmetry at the parton level	137
6.1.1	Integrated asymmetry	138
6.1.2	Differential asymmetry	139
6.2	Properties of the data set	141
6.2.1	Event yield	141
6.2.2	Control plots on background-subtracted data	142
6.3	Standard Model asymmetries after selection	146
6.3.1	Asymmetry in $t\bar{t}$ simulation	147
6.3.2	Asymmetry in Standard Model background simulation	150
6.4	Results for A_{int}	152
6.4.1	Unfolding	153
6.4.2	Systematic uncertainties	156
6.4.3	Final results after unfolding A_{int}	157
6.4.4	Discussion on new physics expectations	158
6.5	Results for $A_{diff}(y)$	158
6.6	Summary	161
	References	163
	Summary	171
	Samenvatting	175



Preface

In this thesis I describe measurements on top quark pairs that are produced in collisions in the Large Hadron Collider (LHC). The measurements of the production rate of top quarks (Chapter 5) and the so-called charge asymmetry (Chapter 6) are direct tests of the contemporary theory of elementary particles and fundamental forces, the Standard Model. These measurements form a part of the LHC programme designed to verify the theory as precisely as possible, and potentially extend or even overthrow it. The ultimate goal is to increase understanding of physics at the smallest scales, and thus of the tiny building blocks of everything we see around us. Hence, research in the subfield of top quark physics forms a contribution to extending our knowledge of nature.

For this reason I joined the top quark subgroup in the collaboration of the ATLAS-experiment in 2008, before the LHC became operational. The top quark with its high production rate at LHC and its involved decay properties would form a significant marker of the possibilities of the experiment. In the beginning that meant that analyses were tested on simulated events. When the accelerator finally started running, a defect after just a few days caused a shutdown and a subsequent delay of more than a year. Only in November 2009, the first proton collisions were produced, as I have experienced from close by during the period when I was stationed at CERN.

The LHC finally produced the first high-energy collisions (7 TeV) in 2010. This allowed us to publish the observation of top quarks and measurements on their production rate in the most important decay channel, albeit with adjusted analyses; the calibration was improved to levels higher than anticipated, due to the longer preparation time. With the prosperous running of LHC and the resulting wealth of collision events, it was tempting to continue top quark research. Especially since Tevatron experiments reported intriguing results that could be verified with the LHC. This led to the measurement of the top quark charge asymmetry in the final chapter.

The thesis consists of six chapters. Chapter 1 describes the theoretical motivation for top quark research and addresses the role of the top quark in the Standard Model. Also presented are some hypotheses and alternative models that could influence top quark observables. The accelerator and all subcomponents of the ATLAS detector are described in Chapter 2. Chapter 3 discusses the process of simulating collision events and the detector response, and the reconstruction of the different types of particles in ATLAS.

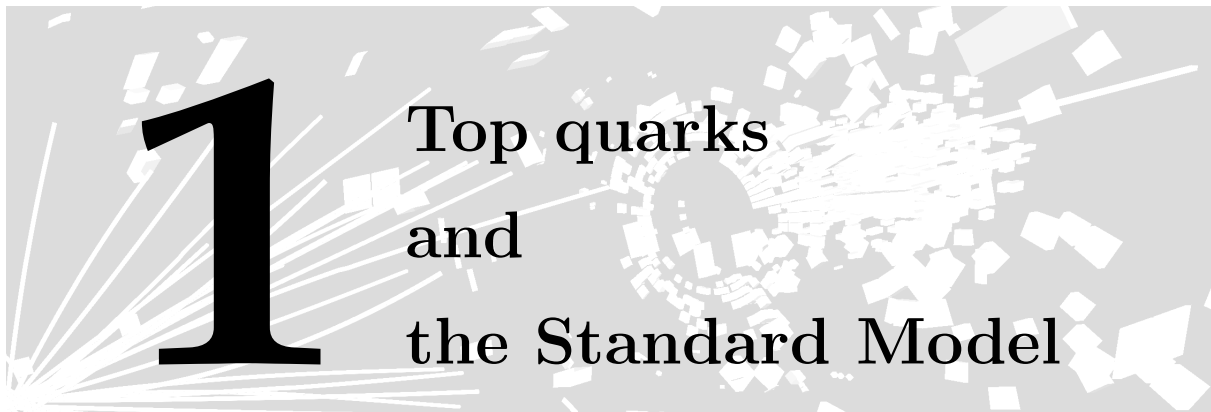
In Chapters 4-6 we make use of the recorded data. Chapter 4 introduces the selection of collisions that is designed to effectively isolate top quark events, and compares the relevant

observables in the 2010 and 2011 data sets. These are the data sets on which the analyses in the later chapters are conducted. Chapter 5 is a description of the measurement of the production rate of top quark pairs in data from 2010 and Chapter 6 shows the measurement of the charge asymmetry making use of the data recorded in 2011.

For all analyses in this thesis we make use of work of hundreds or even thousands of other people. In addition to all engineers and physicists that are responsible for the design and construction of the experiment, also on the level of data analysis many stepping stones are required before reaching a final measurement. Because subgroups in the ATLAS collaboration studied the efficient reconstruction of electrons, jets, muons and various other objects, and others distributing the data from CERN to all around the world, we can make use of all this information to conduct research on top quarks.

Besides these people, I would like to thank the people that supervised me and contributed to my research. First Stan Bentvelsen, who gave me the opportunity to start doing research at Nikhef and kept being enthusiastic and interested during the entire period. Secondly, I want to thank Pamela Ferrari for the supervision, especially during the period at CERN when the first data arrived and when working from deadline to deadline. A great thanks to Menelaos Tsiakiris and Hegoi Garitaonandia for the teamwork during the top quark cross section measurement, the skills I gained during this period helped me greatly in the subsequent asymmetry analysis.

Ido Mussche, September 2012, Amsterdam

A stylized, grayscale illustration of a particle collision. A large, bold number '1' is positioned on the left. To its right, the text 'Top quarks and the Standard Model' is written in a serif font. The background features a complex pattern of white lines and squares on a gray background, suggesting a particle detector or a complex mathematical structure.

1 Top quarks and the Standard Model

Particle physics is the branch of physics that studies elementary particles and their interactions at the subatomic scale. In the past century, during which particle physics developed, an almost complete description of particles and the forces they exert emerged. This combined description is currently known as the Standard Model. One interesting particle that stands out from the others is the ‘top quark’, the heaviest elementary particle known today. The top quark is one of the six quarks in the Standard Model, but it is far heavier than the other five, and has a much shorter lifetime. These properties provide a special role for the top quark in particle physics theory. The central topic of this thesis is the top quark and how it may reveal shortcomings in the current theory.

In this chapter we discuss the physics of particles and their interactions as defined by the Standard Model [1–3]. Thereafter we discuss the properties of the top quark and its relevance in contemporary research. This includes its production rate (the ‘cross section’) at the Large Hadron Collider (LHC) and the asymmetry in the production of top quarks with respect to their antiparticles, antitop quarks.

1.1 The Standard Model

The Standard Model deals with elementary particles and fundamental forces. Elementary particles do not consist of other, smaller constituents and are considered pointlike. Atoms consist of a nucleus surrounded by one or more electrons. By zooming in to an atomic nucleus, we first see a structure of protons and neutrons. But, the protons and neutrons turn out to be made up of smaller constituents again, *up* (u) and *down* (d) quarks and gluons. Quarks are believed to be elementary particles. Similarly, the theory states

that electrons that surround the atomic nucleus contain no underlying structure and are elementary. Analogously to the elementary particles, fundamental forces are forces that cannot be expressed in terms of more elementary interactions. The current state of particle physics yields a combined description of three of the four fundamental forces: electrodynamics, and the strong and weak interaction. Gravity is recognized as the fourth fundamental force, but is not part of the Standard model as there are problems in unifying a particle description of gravity with the theory of general relativity.

In the framework of particle physics, a distinction is made between matter particles and interaction particles (force carriers). Six leptons and six quarks form the elementary particles that make up all matter (fermions). Besides the matter constituents, there are a number of force carriers: bosons. They are responsible for the different fundamental forces we distinguish. Figure 1.1 shows a schematic overview of the elementary fermions and bosons. The u and d quarks that jointly make up most of the ordinary matter, are part of the first generation, together with the electron and electron-neutrino. These four leptons have heavier associates in a second and third generation. The up -type quarks are *charm* (c) and *top* (t), of the second and third generation, respectively. They share their electric charge quantum number ($Q = \frac{2}{3}$), but the mass increases with each generation. The same holds true for the *down*-type quarks, the *strange* (s) and *bottom* (b). They form the second and third generation, but have a charge of $-\frac{1}{3}$ instead. In the lepton sector of fermions, charged electron-type leptons—the muon (μ) and tau (τ) and their accompanying neutrinos—complete the second and third generation. All twelve fermions have antiparticles as well. Antiparticles are particles with identical mass, but opposite quantum numbers.

In the following sections we will discuss the separate fundamental forces, the corresponding gauge bosons, and their inclusion in the Standard Model.

1.1.1 Quantum electrodynamics

Quantum electrodynamics (QED) is the theory that describes interactions of all electrically charged particles via the exchange of photons, the gauge bosons of QED [4]. Except for neutrinos ($Q = 0$), all known elementary fermions interact through the electromagnetic force. An electron-positron annihilation that results in a quark-antiquark pair via a photon (as shown in Figure 1.2(a)) is an example of the electromagnetic force.

The history of quantum electrodynamics as a relativistic quantum field theory is long and started from attempts to describe electromagnetic effects with pointlike elements, or ‘quanta’, in the beginning of the previous century. With contributions of many scientists the physics and the mathematical framework developed to accommodate the quantized description of electromagnetic processes. Perturbation theory, for example, could be used in order to provide approximate solutions to a complex problem. Complex problems are effectively converted into calculable problems, using free particle solutions with small perturbations.

The coupling constants parametrize the interaction strengths among particles and can

		1	2	3	electric charge	spin	
Fermions	Quarks	u 2.5 MeV	c 1.3 GeV	t 172 GeV	+2/3	1/2	
		d 4.9 MeV	s 100 MeV	b 4.5 GeV	-1/3	1/2	
	Leptons	e 0.51 MeV	μ 106 MeV	τ 1.78 GeV	-1	1/2	
		ν_e	ν_μ	ν_τ	0	1/2	
	Bosons	Gauge	γ electromagnetic force			0	1
			g strong nuclear force			0	1
Z, W^{+/-} weak nuclear force			0, +1/-1	1			
Scalar	H			0	0		

Figure 1.1 – Fermions and bosons in the Standard Model. The electric charge and spin are displayed for each of them, as well as the masses of the charged fermions.

serve as a perturbation parameter. Then, the amplitudes of interaction processes can be computed perturbatively, and the expansion terms can be represented by Feynman diagrams. Figure 1.2 shows a first order Feynman diagram, where electron-positron annihilation leads to a virtual photon producing a quark-antiquark pair. All particles and the propagator have a physical four-momentum vector and the interactions are described by the vertices between the photon and the charged particles. Perturbations, or corrections to this process can come from radiation, as displayed in the middle graph. A real photon is radiated off by the initial electron. Another type of correction is virtual, where a radiated photon is absorbed by another electron (right). Observables are proportional to the square of the sum of all possible Feynman amplitudes. In Feynman diagrams that represent these amplitudes, every vertex is proportional to the square root of the coupling strength, $\sqrt{\alpha}$. In QED, the coupling strength has a value of $\alpha_{em} \cong \frac{e^2}{\hbar c} \approx \frac{1}{137}$. This means that the lowest order diagram (often with two vertices) should in principle be the largest contribution to the observable that is to be calculated. The subsequent perturbations to

the first order diagram contribute proportionally to the number of vertices and hence lead to smaller corrections each time.

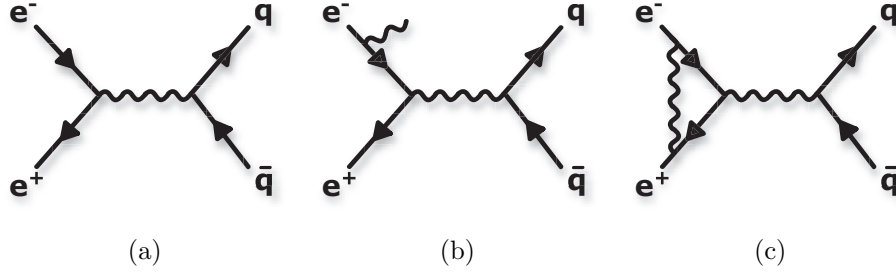


Figure 1.2 – (a) First order Feynman diagram for $e^- + e^- \rightarrow \gamma \rightarrow q + \bar{q}$. (b) Example of a real correction and (c) example of a virtual loop.

In the 1930s, perturbation theory was used to calculate electromagnetic effects to first order, but, beyond that, divergences in the computations (integrals leading to infinities) occurred. Again in terms of Feynman diagrams, this originated from virtual loops that yield divergences in the integrals. The four-momenta of the particles within the loop are unconstrained, making integrals infinitely large. The solution came from renormalization: the integral that leads to divergences is regularized by introducing a cutoff mass. Below this cutoff scale the integrals are finite, calculable and independent of the cutoff mass. The infinite terms that do depend on the cutoff mass then can be absorbed in the physical constants like mass and charge of the electron. As a consequence, the bare electron mass as it appears in the equations is different from the mass that would be measured in an experiment. Effectively, the physical mass is equal to the bare mass, plus the divergent terms that are infinite if the cutoff mass runs to infinity. Renormalization is an important addition to the theory as it connects the theoretical value with the physical observable. It is established that QED is completely renormalizable [5].

The Standard Model is based on the mathematical principle of symmetries and conserved quantities that accompany them. The Lagrangian of the Standard Model consist of fields related to fermions as well as to force carriers. In QED, the Lagrangian can be written as

$$L = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (F_{\mu\nu}F^{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu),$$

where ψ and A_μ represent the fermion field and the photon field respectively. The other symbols are operators. In the first part (the kinetic term), the covariant derivative D_μ replaces the normal derivative ∂_μ .

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + ieA_\mu.$$

The replacement of the derivative operator by the covariant derivative is what couples an interaction described by the photon field, to the fermion fields. A set of transformations

exist, which, when applied to the photon and fermion fields leave the Lagrangian invariant. A global transformation, or phase transformation of the type $\psi \rightarrow \psi e^{i\theta}$ does so, even without the presence of a covariant derivative. ‘Local’ transformations, where the transformation depends on a coordinate of spacetime, are of the type $\psi \rightarrow \psi e^{i\theta(x)}$. The Lagrangian can only be made locally invariant when the derivative operator is replaced by the covariant derivative, introducing a field A_μ . As a consequence of this adjustment, the Lagrangian acquires an extra term $\bar{\psi} A_\mu \psi$, exactly the term describing the interaction of the fermion field with a photon field. Imposing local gauge invariance thus leads to the correct description of the interactions in QED. The set of $\psi \rightarrow \psi e^{i\theta(x)}$ transformations forms the symmetry group $U(1)$.

Numerous experiments have verified the accuracy of QED. The currently most accurate experimental confirmation is the measurement of the anomalous magnetic moment of the electron [6]. The magnetic moment directly probes the interactions of the electron with the vacuum. The sub-per-billion precision of this measurement proves that the quantum loop corrections to the magnetic moment predicted by QED are accurate.

1.1.2 Weak interactions

The weak force affects all fermions: quarks and leptons. Its relative strength is much lower than the other two forces, hence the name. The weak force carriers are the W^+ , W^- and Z bosons. The description of the weak force originates from interpretations of the observation of the beta decay of nuclei. In beta decays, a neutron decays into a proton emitting an electron. Fermi drew an analogy with photon emission in radioactive decays [7]. He proposed the idea that neutrons decay into three particles: an electron, a proton and a neutrino. This realization led to the concept of a new force, different from the electromagnetic force with a strength given by Fermi’s constant, G_F . Later, mediating bosons were proposed for this type of decay. The interaction is analogous to QED, with incoming and outgoing fermions and boson propagators.

Following predictions of Yang and Lee in the late 1950s [8], Wu observed that weak decays are not symmetric in spatial reflection, i.e., parity is violated. Electrons coming from polarized cobalt nuclei were more likely to decay in the direction opposite to the cobalt’s spin. The solution to explain this effect was that only left-handed particles, particles with spin reversed with respect to the momentum (helicity = $-1/2$), could interact through the weak force. Helicity is equal to the ‘chirality’ in the ultrarelativistic limit, hence for massless particles. The more general concept, the chirality of a particle, is defined by the matrix operator γ_5 that has eigenvalues of $+1$ and -1 . A left- and right-handed component can be obtained by applying projection operators to fields:

$$P_L = \frac{1 - \gamma^5}{2}, \quad P_R = \frac{1 + \gamma^5}{2}.$$

The fact that the weak force only applies to left-handed particles is its essential characteristic. The weak interaction follows the $SU(2)_L$ symmetry group, introducing three

massless vector fields, $W_\mu^{1,2,3}$.

Electroweak symmetry breaking

Both in weak interactions and QED, particles interact by exchanging bosons, the force carriers. Glashow, Weinberg and Salam contributed to the model in which the two forces could be unified into one force, the electroweak force. This unification states that both original forces really are manifestations of one force. The problem at first was that the relative strength of the weak interaction is much lower than that of electrodynamics. The strength of the weak interaction (G_F) is five orders of magnitude smaller than the electromagnetic coupling constant α_{em} . It turns out that imposing a large mass on the weak force carriers can explain this difference in strength. A heavy weak interaction boson results in a low rate of weak processes. The hypothesis of a massive boson was consistent with the lack of empirical evidence for massless weak bosons at the time. But, artificially adding mass terms, of the type ‘ $-m^2 W_\mu W^\mu$ ’ to the Lagrangian to accommodate heavy bosons would break local gauge symmetry (and therefore make the theory non-renormalizable). Similarly, introducing fermion mass terms of the type ‘ $-m\bar{\psi}\psi$ ’ breaks local gauge invariance.

A solution came from the incorporation of the Higgs mechanism into the theory [9–11]. This mechanism is based on spontaneous symmetry breaking. The Lagrangian of the combined electroweak description remains gauge invariant, but a nonzero expectation value in the ground state breaks this symmetry. To achieve this, the mechanism introduces a complex scalar field ϕ (a doublet of the form (ϕ^+, ϕ^-)). The scalar field adds an extra term to the Lagrangian:

$$L_{\text{scalar}} = (D^\mu \phi)^\dagger (D_\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2,$$

$$D_\mu = \partial_\mu - i\frac{g}{2} W_\mu^i \tau^i - ig' Y_\phi B_\mu.$$

In the Lagrangian term, λ and μ are constants that determine the shape of the potential. If both have positive values, the potential takes the form of a quadratic function with a center that corresponds to the minimum, $|\phi_0|^2$. Choosing $\mu < 0$, however, leads to a potential shape resembling a sombrero, with a local maximum in the center and the minimum at $\phi_0 = \frac{-\mu}{2\lambda}$. In other words, the symmetry is broken in the ground state.

The covariant derivative D_μ extends from the one in QED quoted before. It contains the regular derivative, a weak term and the QED term. The coupling constants g and g' correspond to the QED and the weak force. The vector fields B_μ and W_μ^i are the four massless boson fields of $U(1)$ and $SU(2)$. Furthermore, the generators of the symmetry groups contain the Pauli matrices τ^i (weak interaction) and the hypercharge Y (QED).

Rewriting in the unitary gauge, the scalar field ϕ is expanded around the minimum

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}, \quad v = \sqrt{\frac{-\mu}{\lambda^2}},$$

where the minimum is expressed in terms of the vacuum expectation value v and the real scalar Higgs field $H(x)$. The field breaks symmetry and additionally introduces quadratic terms for the vector fields in the Lagrangian: they correspond to mass terms. The gauge bosons couple to the scalar Higgs field, proportional to their mass. It directly follows that the boson fields have the following masses:

$$\begin{aligned} m_A &= 0 && (\text{photon}), \\ m_W &= \frac{1}{2}gv, \\ m_Z &= \frac{1}{2}\sqrt{g^2 + g'^2}, \\ m_H &= \sqrt{2\lambda v^2} && (\text{Higgs}), \end{aligned}$$

where g and g' are the gauge couplings of $SU(2)$ and $U(1)$ that entered through the covariant derivative. The Fermi constant G_F is related to the weak coupling constant g through $G_F \sim \frac{g^2}{m_W^2}$ (ignoring some constants). The vacuum expectation value v is experimentally determined to be 246 GeV, and the coupling constants are also known. The measured W and Z boson masses (80.4 GeV and 90.1 GeV, respectively¹) match the values following from these equations. The consequence of the introduction of the Higgs mechanism is the existence of a new fundamental scalar boson, the Higgs boson. Its mass is theoretically not well constrained as it is determined from λ (corresponding to the amount of self-coupling) which is a free parameter.

The Higgs field can be used to generate masses for the fermion as well. Similar to the boson sector, gauge invariant terms of the type

$$L_{\text{Yukawa}} = -\lambda_f(\bar{\psi}\phi\psi)$$

can be added to the Lagrangian. The factor λ_f is the Yukawa coupling that is connected to a specific fermion f . If the field ϕ is replaced by the Higgs doublet ϕ_0 (or its conjugate in case of up -type quarks) in the ground state, the mass terms for the quarks and leptons follow immediately as a function of v and λ_f . In this way the mass term originates from the interaction of the fermion field with the Higgs field. Since the Yukawa coupling λ_f is unknown, the theory does not predict fermion masses directly.

1.1.3 Strong interactions

Strong interactions form the third fundamental force and are described in the theory of quantum chromodynamics (QCD). The strong force only acts on quarks and its propagator bosons are gluons. The strong interaction is the force responsible for binding the quarks inside hadrons (composite particles consisting of quarks). QCD is a quantum field theory and is also based on the formalism that was developed in QED. The development of QCD in the 1960s came from questions on the apparent structure in the mesons and

¹In this thesis we use a convention with $c = 1$ and express mass, momentum and energy in eV.

baryons that were discovered up until then. This structure led to the hypothesis of quarks as elementary constituents of hadrons and an accompanying extra degree of freedom. Since baryons and mesons had to be neutral to this newly introduced quantum number (otherwise a multitude of extra hadrons is expected) the analogy with color led to the naming convention. Three differently colored quarks (red, blue, green) form baryons. Mesons are then built from a quark-antiquark pair of color and anticolor (e.g., red plus antired). Eight different types of gluons exist, with different superpositions of colors and anticolors.

QCD is a non-Abelian theory, just like the weak interaction. Gluons are allowed to couple with themselves, making vertices solely containing gluons possible. This is contrary to electromagnetic couplings. A characteristic property of QCD is the so-called ‘asymptotic freedom’. This states that the coupling strength between two colored objects, parametrized by α_s , becomes smaller with decreasing distance between the objects. At small distances quarks act as free particles. But, the force becomes stronger at larger distances unlike any other force. Pulling apart quarks (in for example proton-proton collisions) will ultimately build a field strong enough to form new quarks that together form bound states again.

Top quark pairs are produced through strong interaction processes.

1.1.4 The history of the top quark

The Standard Model of electroweak interactions was already developed when the first member of the third generation of quarks was proposed. At the time, three quarks were known (u , d , s) and one missing quark was predicted to complete the second generation, the charm quark (c). Also, the electron and muon were known, but the tau lepton still had to be discovered.

CP violation in kaons

It was discovered in 1964 that CP violation (charge-parity symmetry violation) occurred in the decay of neutral kaons [12]. Long-lived kaons (K_L) were expected to decay into three pions, as the three pions form the same CP-eigenstate (-1). However, in a small fraction of the cases, a decay to two pions was also measured, which has a CP-value of 1. This constituted direct evidence that CP is not conserved.

Kobayashi and Maskawa proposed a number of solutions to extend the theory such that it would describe CP violation without contradicting other observations. Among the solutions was a complex extension to the weak charged current matrix (Cabibbo matrix) that provides T symmetry (time) violation². To retain unitarity, complex phases had to be added to the (extended) mixing matrix which in turn made CP violation possible. The name of the top and bottom quarks came from a later paper proposing a six-quark

²A theorem in quantum field theory yields that the combined operation of CPT always conserves symmetry, therefore T violation would accommodate the observed CP violation.

model [13] where the top and bottom quark are the ‘heavy’ partners of the up and down quark.

Experimental evidence for a third generation

The confirmation of the third family came from experiments through the discovery of the tau [14] and the bottom quark (b -quark) [15]. These results led to the general belief that the top quark should exist and therefore to the searches for the top quark in experiments. Initially, the mass and production rate of the top quark were not well predicted. There were models where the top quark was lighter than the W boson for example ($m_t < 80$ GeV), leading to other decay and production mechanisms than if it would be heavier. However, gradually it became clear that the top quark would have to be heavier than any other particle in the Standard Model. The top quark mass is a parameter that is related to other Standard Model parameters, through virtual corrections. Fits of masses and couplings, assuming the validity of the Standard Model, showed a preference for the top quark mass to be in the region of 140-185 GeV. In 1995, the experiments of CDF and D0 in the Tevatron collider published the first observation of the top quark. Figure 1.3 shows the reconstructed mass of the top quark for background (dotted), signal+background (dashed) and data (solid line) as published by CDF [16]. The data is inconsistent with the background by 4.8 standard deviations. A fit to the mass shows a mass peak around 175 GeV. Together these formed evidence for the existence of the top quark. This was confirmed by D0 [17]. Since then its existence has been firmly established.

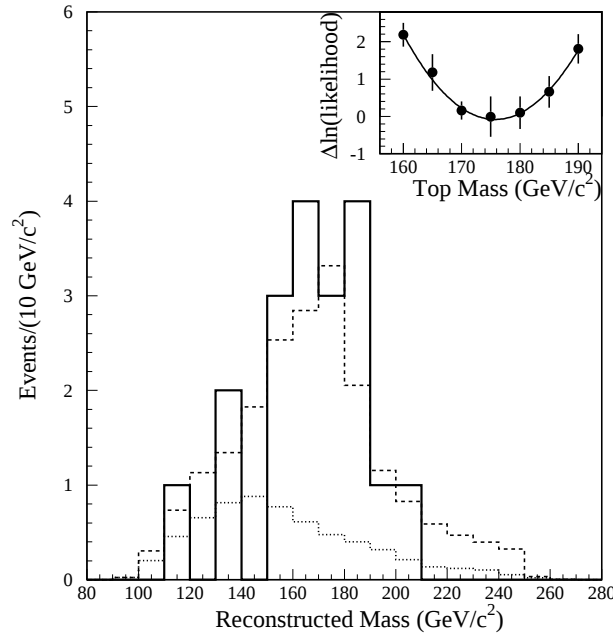


Figure 1.3 – Reconstructed mass of the top quark at the CDF experiment, at the Tevatron collider [16].

1.1.5 Predictive power of the Standard Model

There are 18 free parameters in the Standard Model, parameters that are not fixed by the theory. The exact choice of parameters is arbitrary to some level, but generally contains

- the nine fermion masses;
- the three coupling constants corresponding to the three interactions;
- the Higgs couplings λ and μ ;
- three CKM mixing angles and a mixing phase.

This is a large number, but the number of independent measurements that can be done to constrain the values of the parameters by far exceeds it. From the moment the structure of the Standard Model was established, an enormous amount of measurements have confirmed the coherence and correctness of the predictions that follow from the theory. Among those measurements were the observation of the predicted particles that had not been found and their interaction rates. The discovery of weak neutral currents in 1973 [18] was followed by the confirmation that Z boson mediated processes were indeed parity violating [19]. This was a direct confirmation of the electroweak theory. Moreover, all predicted, yet unconfirmed particles revealed themselves one by one. Additionally, the discovery of the W and Z bosons [20, 21] was succeeded by a measurement of the Z boson width ruling out more than three generations of particles [22]. The different neutrinos, with the tau neutrino directly observed in 2000, were found as well. Besides the phenomenology, also the mass, couplings, and spin properties agreed with the Standard Model, demonstrating the validity of the theory.

A fit to the Standard Model parameters by using data from LEP and others became increasingly more accurate. Figure 1.4 shows the difference between the directly measured value and the predicted value of each parameter from such fits, as published in 2009 [23]. The difference is normalized to the uncertainty of the measured value, generating a pull value. The predicted value for a particular observable is obtained by excluding its direct measurement from the fitting procedure and using only the information of the remaining observables. Differences from the predictions can be sizeable, but all weighted differences stay below 3σ , demonstrating the predictive power of the Standard Model.

1.1.6 Unresolved issues in the Standard Model

Although there is huge amount of experiments confirming the correctness of the Standard Model, the picture is not complete yet. First of all, the Higgs particle needs to be found with properties that match the requirements of the Higgs mechanism, such as the strength of the coupling to fermions and its spin properties. Recently, a new particle that looks to be the Standard Model Higgs boson has been observed [24, 25], with a mass around 125-126 GeV. But, even with a confirmed Higgs particle there are a number of open issues.

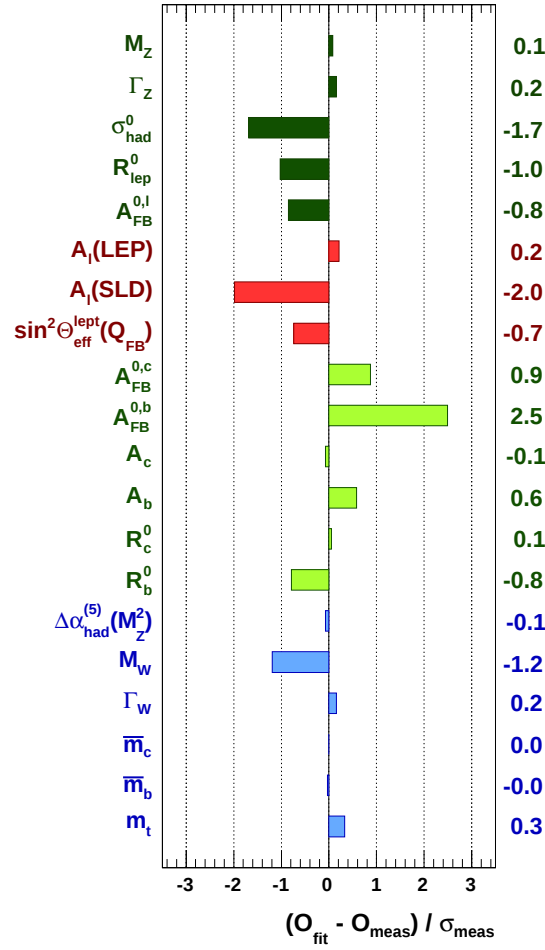


Figure 1.4 – Difference between fit values and directly measured values of Standard Model parameters, figure taken from [23].

Neutrino mass

In the basic version of the Standard Model, neutrinos are massless. But, measurements of neutrino oscillations showed that neutrinos do have a small mass. An extension of the Standard Model that accommodates massive neutrinos is possible, increasing the number of free parameters. As a consequence right-handed neutrinos must exist.

Naturalness problems

Some parts of the Standard Model are reckoned to be unnatural. The hierarchy problem, for example, comes from the unnaturally large quantum corrections to the Higgs mass. The Higgs mass is not predicted by the theory. Virtual loops with top quarks and W bosons modify the Higgs propagator. But, the corrections to the propagator are proportional to the energy scale at which the Standard Model is believed to be valid (TeV scale) and therefore of a size much larger than the mass value itself. These independent quantum corrections would have to be fine-tuned to end up at a mass as low as 100 or 200

GeV. This seems unnatural. One solution, in which such quantum corrections elegantly cancel out, is supersymmetry [26–28]. In the theory of supersymmetry an entire set of new particles, ‘superpartners’ to the existing particles, is predicted. No experimental evidence for supersymmetry exists yet.

Dark matter and gravity

According to measurements, the motions of certain galaxies follow patterns that indicate large quantities of non-radiating matter in the universe. The latest prediction yields that approximately 17% of the particle density in the universe is formed by baryonic matter, conventional particles. The remaining 83% of the particle density of the universe is composed of dark matter [29]. This dark matter must be heavy enough to account for the gravitational effects that it is supposed to explain, but interact only weakly with other particles. There is no candidate to explain dark matter in the Standard Model. Supersymmetric particles could play this role, but no experimental evidence supports the theory yet. Another problem is that gravity itself is not incorporated in the Standard Model. As it is considered a fundamental force, it would be natural to include it in a similar way in the formalism of the Standard Model as the other three. But, no successful quantum theory of gravity yet exists.

1.2 Physics at the Large Hadron Collider

The Large Hadron Collider at CERN is a particle collider built to probe physics at the scale of Higgs bosons, top quarks and possibly more exotic particles. It has been operational since November 2009. After a period of low energy runs, protons were collided with a center-of-mass (CM) energy of 7 TeV in 2010, reaching a maximum luminosity ($\mathcal{L}$) of $10^{32} \text{ cm}^{-2}\text{s}^{-1}$. In 2011 the luminosity increased by one order of magnitude, at the same beam energy. The CM-energy and luminosity both exceed the values of the Tevatron that ran at 1.98 TeV with $\mathcal{L} = 10^{32} \text{ cm}^{-2}\text{s}^{-1}$. The increase in these factors extends the reach of physics processes that can be probed. The production cross section of heavy particles increases with the amount of energy available. Figure 1.5 shows the cross section for several benchmark processes versus the CM-energy. It is expressed in nb (nanobarn, 1 barn = 10^{24} cm^2). There is a discontinuity at 4 TeV, depicting the transition from proton-antiproton collisions (Tevatron) to proton-proton collisions (LHC). Production processes that depend on quark-antiquark annihilation are sensitive to this difference. In proton-proton collisions valence antiquarks do not exist. The antiquarks in the ‘sea’ have a lower fractional momentum, in general. At 7 TeV the probability of creating a $b\bar{b}$ pair is four to five orders of magnitudes larger than the probability of producing for example a W or Z boson. Top quarks are produced with a cross section of $\sim 0.1 \text{ nb}$. In the data collected in 2010, about 35 pb^{-1} , top quarks are already produced abundantly at the LHC, according to the model. Higgs boson production, in the bottom of the plot, for mass hypotheses of 120, 200 or 500 GeV, range from 10^{-2} to 10^{-4} nb .

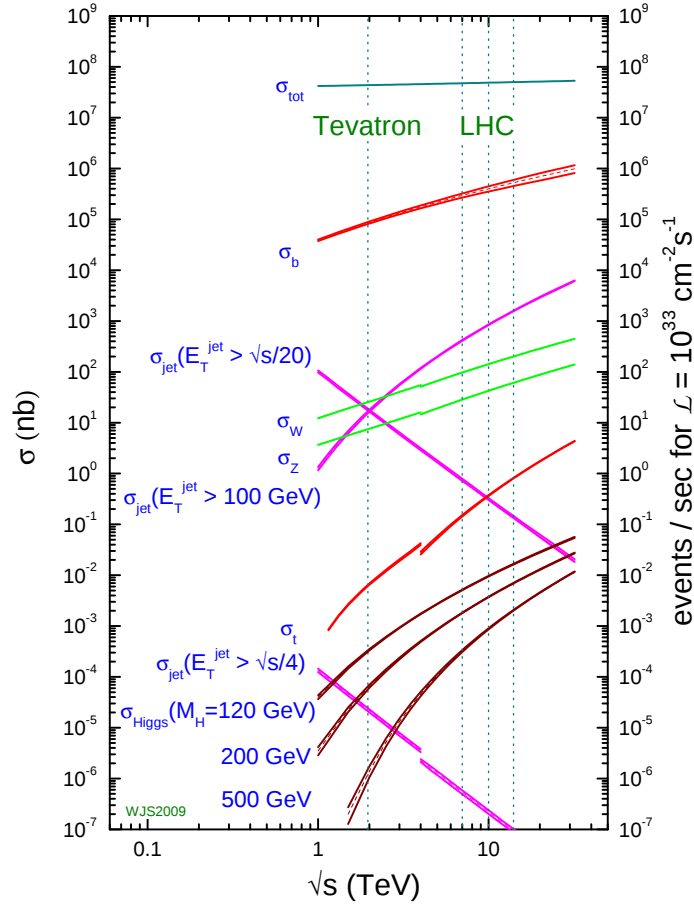


Figure 1.5 – Cross section predictions for benchmark processes as a function of the CM-energy $\sqrt{s}$. Vertical lines indicate the CM-energy (1.96 TeV) at the Tevatron and the LHC (7, 10, 14 TeV).

1.3 Top quarks in the Standard Model

The top quark is the central topic of this thesis. It is important and interesting for several reasons, but its most striking feature is its mass. Figure 1.6 illustrates the mass of particles in the Standard Model. The plot shows the quarks, leptons and bosons that have a nonzero mass (ignoring neutrinos masses) on a logarithmic scale. The top quark mass of 172.9 ± 0.6 (stat) ± 0.9 (syst) GeV [30] is two or more orders of magnitude higher than all the other quarks. Moreover, it is also heavier than the massive gauge bosons, about as heavy as a W and Z boson together.

It can be argued that the top quark is the only quark with a ‘natural mass’. The interaction with the Higgs vacuum is expressed in the Yukawa coupling (see Section 1.1.2) of the top quark, λ_t , and is almost equal to unity: $\lambda_t = \frac{\sqrt{2}m_t}{v} \sim 1$, with $v = 246$ GeV. Whereas for the other five quarks the coupling is much smaller. The large mass of the top quark

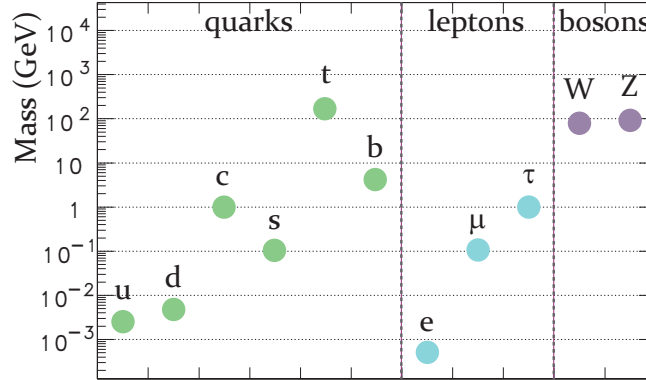


Figure 1.6 – Masses of the Standard Model particles.

thus yields a strong interaction with the Higgs. It also has implications on the lifetime, couplings and decay.

As it is heavier than the W boson, the top quark can, in contrast to the other quarks, decay into a W boson and a b -quark. The full decay width is $\Gamma_{\text{top}} = 2.0^{+0.7}_{-0.6}$ GeV [31], and therefore the top quark has a lifetime of $\tau_{\text{top}} \simeq 5 \cdot 10^{-25}$ s. This lifetime is shorter than the time it takes for a quark (or antiquark) to form a color-neutral bound state with other quarks. No mesons or baryons can be formed that contain top (or antitop) quarks, as the top quarks decay too rapidly. As a consequence, the quantum numbers of the top quark are preserved in the decay products, including its spin. A top quark is a spin 1/2 fermion, and the spin effects of top quarks are well predicted and can be inferred from the angular distributions of their decay products. The probability that the spin of the top quark flips by gluon radiation before decaying is negligible [32].

Top quarks are produced in pairs, mostly, through the strong interaction. On much rarer occasions, top quarks are produced through the weak interaction, resulting in single top quarks (or antitop quarks), rather than pairs. Our aim is to measure $t\bar{t}$ properties and will treat single top quark production in the analyses as background processes.

1.3.1 Production

Using the factorization theorem, the production of $t\bar{t}$ pairs in proton collisions is calculable in perturbative QCD. This theorem yields that the proton-proton collisions that produce a top quark pair can be factorized into two independent parts. The cross section can be expressed as a convolution between the parton distribution functions (PDFs) and the parton-parton collision. Figure 1.7 displays the factorization. The kinematics of the partons within the protons are described by PDFs. The PDFs are determined empirically, in deep inelastic scattering (DIS) experiments. The other part, the partonic cross section, displayed by the purple circle, is calculable within the framework of QCD. The advantage

of the factorization approach is that the PDFs absorb all non-calculable effects of the partonic cross section. The factorization scale, the scale at which the partonic cross section and the PDFs are separated is represented by μ_f . We will discuss the elements of factorization in more detail in the following.

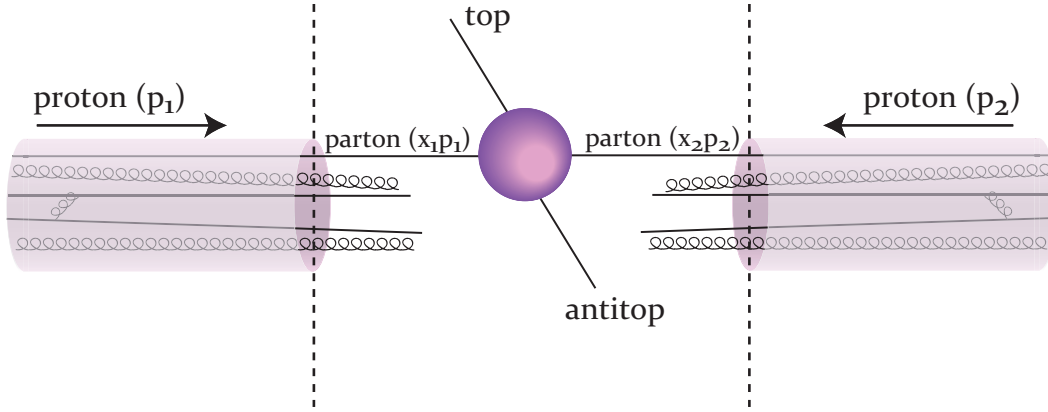


Figure 1.7 – Schematic overview of a factorized proton-proton collision.

Parton distribution fractions

The proton (or any hadron) consists of partons. We divide the proton in the quarks that make up its quantum numbers (valence quarks) and virtual partons that emerge and annihilate within (sea quarks and gluons). Each of the partons carries a fraction x of the total longitudinal momentum of the proton. The probability density of partons of a specific type within a proton can be expressed as a function of this momentum fraction x , with $0 \leq x \leq 1$. This is displayed in Figure 1.7. The interacting partons in the protons have momentum fraction x_1 and x_2 . Deep inelastic scattering experiments are able to determine the parton densities within protons. Besides the momentum fraction, the density depends on the factorization scale, or to the energy scale of the experiment at which the proton is probed, expressed in Q^2 . Figure 1.8 illustrates the parton density fractions for two energy regimes, $Q = 10, 100$ GeV. The different lines correspond to different quark flavors and the gluon which is scaled down with a factor 10. The probability increases for lower x values, for all partons. This is especially apparent in the right plot with higher energy scale.

At the LHC, the beam energy is sufficiently high for partons with small momentum fraction to form a top quark pair. A top quark pair at rest has a mass $m_{t\bar{t}}$ of about 350 GeV, whereas the CM-energy $\sqrt{s}$ was 7 TeV in 2010 and 2011. The fraction of the energy contained in the partonic interaction is $\sqrt{\hat{s}} = x_1 x_2 \sqrt{s}$. That means that with the LHC beam conditions partons of relatively low x values can still pass the threshold of 350 GeV. Assuming $x_1 = x_2$, at the Tevatron ($\sqrt{s} = 1.96$ TeV) x_1 and x_2 need to be at least ~ 0.2 , to produce a $t\bar{t}$ pair at threshold. At the LHC this is approximately 0.05. In the

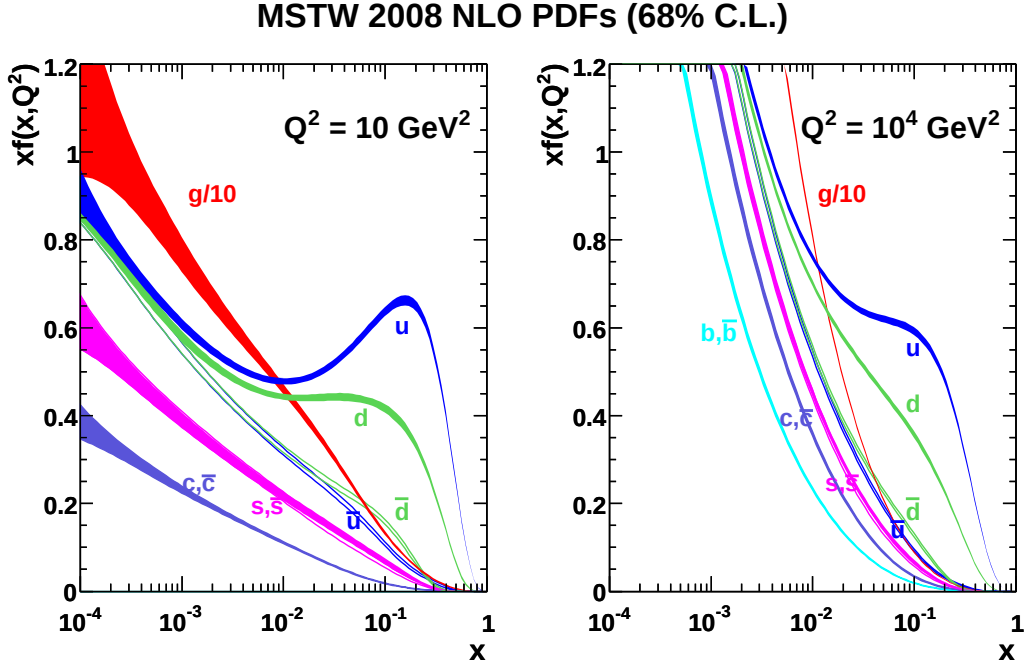


Figure 1.8 – Parton density fractions in the proton, from MSTW2008nlo [33]. The gluon contribution is reduced with a factor 10 for visibility.

low momentum range gluons become more important in the proton. This means that top quark production through gluon fusion is relatively large compared to the Tevatron.

Top quark production through gluon fusion is magnified by the fact that there are no valence antiquarks in LHC collisions (proton-proton), contrary to the situation at the Tevatron (proton-antiproton), boosting the relative fraction of gluon fusion to the top quark production cross section even more.. The fraction of gg , $q\bar{q}$ and qg events are 80.0%, 19.1% and 0.85% respectively, at the LHC ($\sqrt{s} = 7 \text{ TeV}$, NLO). These numbers are obtained with the MC@NLO event generator (we discuss events simulation with MC@NLO in the next chapter). At the Tevatron ($\sqrt{s} = 1.96 \text{ TeV}$, NLO), on the other hand, the fraction of events that come from gg is only 14%. The majority of events (87%) comes from the $q\bar{q}$ channel.

There is some level of arbitrariness in this categorization. For example, a gluon that splits into an quark-antiquark pair of which one undergoes an interaction with a third quark to form a $t\bar{t}$ pair, could be assigned to the $q\bar{q}$ or qg category, depending on whether the splitting is assigned to the PDF or the hard scattering component of the calculation. Nevertheless, the separation of the production channels is useful in understanding the kinematics of the top quark. The top quark charge asymmetry that is discussed later depends on the production channel.

The difference in production mechanisms between the LHC and the Tevatron has an impact on a number of observables, for example the charge asymmetry that is covered

in Section 1.4.2. Another consequence is that, although the production cross section is measured at the Tevatron, the contribution of gluon fusion to the cross section has never been checked. A measurement at higher CM-energy and with different hadron composition (proton-proton instead of proton-antiproton) as in the LHC is therefore a valuable check of the theory.

Partonic cross section

The partonic cross section for the production of $t\bar{t}$ pairs through partons i and j , $ij \rightarrow t\bar{t}$, is the part that is calculable within perturbative QCD. The subprocesses that contribute at leading order with α_s^2 are gluon-gluon fusion and quark-antiquark annihilation. All leading order diagrams are shown in Figure 1.9.

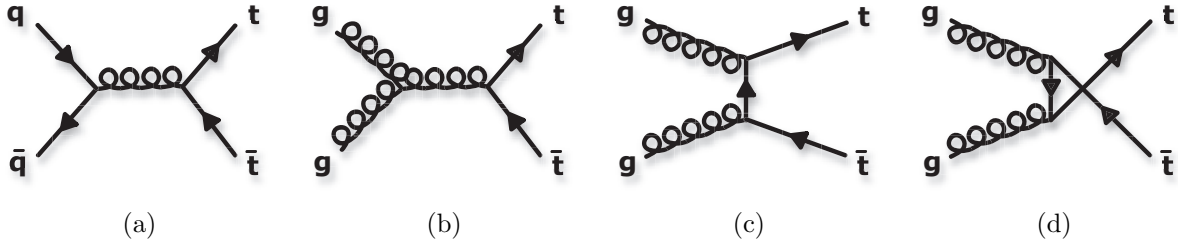


Figure 1.9 – Leading order ($O(\alpha_s^2)$) Feynman diagrams for top quark pair production.

At next-to-leading order many more diagrams are allowed and contribute to the top quark pair production cross section. Particularly, besides direct production, gluon splitting and flavor excitation as in Figure 1.10 occur. In flavor excitation, the top quark (or antitop quark) scatters off an initial state quark or gluon, through gluon exchange. This introduces the possibility of quark-gluon initial states, besides the gluon-gluon and quark-antiquark that were present at leading order already. In addition to gluon splitting and flavor excitation, real and virtual corrections to the leading order direct production add to the total next-to-leading order terms, of size α_s^3 . Examples of both are shown in Figure 1.10 as well. Beyond this order, thus at next-to-next-to-leading order, the number of diagrams explodes. Two-loop diagrams, one-loop interference terms, and radiation of two gluons become possible. A full calculation to this order is not finished yet. Approximations to the cross section at higher orders are made, however, using the theory of resummation, as we will quote later.

Full cross section for $t\bar{t}$ production

The full cross section for $t\bar{t}$ production can be expressed as [34]:

$$\sigma_{pp \rightarrow t\bar{t}}(s, m_t^2) = \sum_{i,j=q,\bar{q},g} \int_{4m_t^2}^s d\hat{s} \underbrace{L_{ij}(\hat{s}, s, \mu_f^2)}_{\text{parton luminosity}} \cdot \underbrace{\hat{\sigma}_{ij \rightarrow t\bar{t}}(\hat{s}, m_t^2, \mu_f^2, \mu_r^2)}_{\text{partonic cross section}}, \quad (1.1)$$

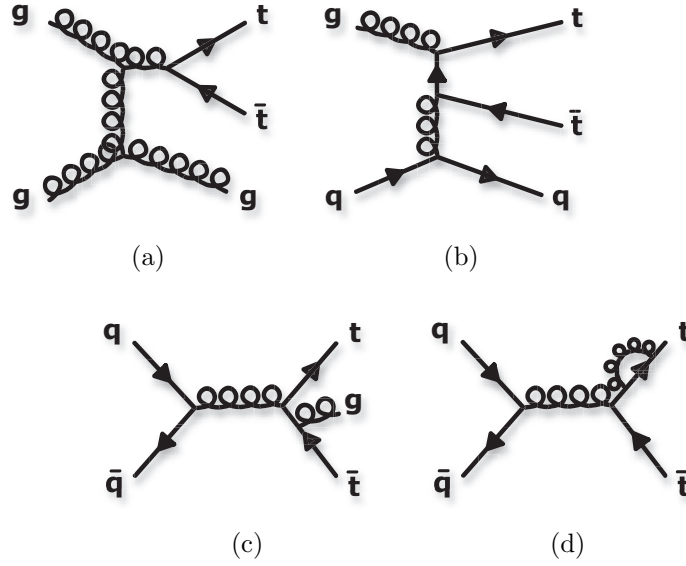


Figure 1.10 – A few examples of Feynman diagrams contributing to next-to-leading order ($O(\alpha_s^3)$) top quark pair production. This involves $2 \rightarrow 3$ (a,b,d) and $2 \rightarrow 2$ processes (c).

where the parton luminosity L_{ij} is defined in terms of the PDFs $f_{i/p}$ and $f_{j/p}$:

$$L_{ij}(\hat{s}, s, \mu_f^2) = \frac{1}{s} \int_{\hat{s}}^s \frac{ds'}{s'} f_{i/p}(\mu_f^2, \frac{s'}{s}) f_{j/p}(\mu_f^2, \frac{\hat{s}}{s'}). \quad (1.2)$$

The variables s and $\hat{s}$ are the hadronic and partonic CM-energy squared, respectively. The s' in the parton luminosity is the integration variable. The PDFs f depend on the factorization scale and the energy. We will discuss the components briefly.

First, it is important to notice that the cross section $\sigma_{pp \rightarrow t\bar{t}}$ only depends on the square of the CM-energy (s) of the protons and the mass of the top quark. Both are physical observables. The two main ingredients to the cross section are the parton luminosity (built from the two PDFs) and the partonic cross section. The parton luminosity depends on the fraction of the momentum carried by the parton and the factorization scale, μ_f . The input to the partonic cross section are the mass of the top quark and both the factorization and normalization scale. The normalization scale μ_r defines the scale at which α_s is evaluated. Both scales are manually inserted and are non-physical. Generally they are set to the top quark mass, $\mu_r = \mu_f = m_t$. A measured total cross section does not depend on the factorization or renormalization scales. Observation of a dependence on these parameters signals the presence of unaccounted higher order effects.

The product of the parton luminosity and the partonic cross section is integrated over the allowed energy regime. The minimal energy required to produce two top quarks at rest is $(2m_t)^2$. The upper boundary of the integral is the total proton-proton CM-energy; the case where all longitudinal energy of the protons is contained in the colliding partons. Finally, the sum over these integrals for all possible initial parton states forms the total

cross section.

Figure 1.11 shows the components of the cross section for the Tevatron (left) and the LHC (right). The parton luminosity, partonic cross section and hadronic cross section are plotted as a function of the partonic CM-energy $\sqrt{\hat{s}}$ of the two colliders³. The parton luminosity L_{ij} (top graphs) differs between the two colliders as a result of the proton-proton vs proton-antiproton nature. At the Tevatron quark-antiquark production dominates, whereas gluon-gluon combinations have lower values all over the spectrum. At the LHC instead quark-antiquark is below the gluon-gluon luminosity in the region below 3 TeV and equal to it above this point. The quark-gluon luminosity is the largest, but since the partonic cross section (middle plots) itself is small as it is produced only at next-to-leading order, the total contribution remains minimal.

The total hadronic cross section (bottom plots) is the convolution of the two previously discussed quantities. The overall shape (sum) of the cross section versus the CM energy of the partons is similar between the Tevatron and the LHC, however, the contributions of $q\bar{q}$, gg and qg differ. The dashed line indicates the point where the integral $\int_{4m_t^2}^{\hat{s}}$ covers 95% of the total cross section. For the Tevatron this is at 600 GeV, just over the threshold of 350 GeV. For the LHC it is much higher.

Current cross section calculations and measurements

The cross section of $t\bar{t}$ production is calculated up to a precision of next-to-leading order, with gluon resummation corrections of next-to-leading log (NLO+NLL). In addition, contributions of higher orders become available: NNLO_{approx} (not complete) and new soft resummation calculations, NNLL. One of the most precise predictions for LHC collisions at 7 TeV comes from NLO+NNLL [35]:

$$\sigma_{t\bar{t}}(pp \rightarrow t\bar{t} + X, 7 \text{ TeV}) = 158.7_{-13.5}^{+12.2} (\text{scale}) \text{ }_{-4.4}^{+4.3} (\text{PDF}) \text{ pb}, \quad (1.3)$$

and for comparison, at the Tevatron at 1.96 TeV:

$$\sigma_{t\bar{t}}(p\bar{p} \rightarrow t\bar{t} + X, 1.96 \text{ TeV}) = 6.722_{-0.410}^{+0.238} (\text{scale}) \text{ }_{-0.115}^{+0.160} (\text{PDF}) \text{ pb}. \quad (1.4)$$

The scale uncertainty originates from variations of the factorization and renormalization scales, μ_f and μ_r , by a factor of 2. A top quark pole mass of 173.3 GeV was used for both numbers, together with the MSTW2008nnlo68cl PDF (NNLO) [33]. The dependence on the top quark mass is shown in Figure 1.12, for the Tevatron (a) and the LHC (b). For the Tevatron, the current best measured values of the mass and cross sections of the top quark by D0 and CDF are shown on top of the theoretical band. Their values agree with predictions within uncertainties. This thesis aims to populate the LHC plot by

³The LHC plots are calculated for a CM-energy of 14 TeV. Although current beam conditions are set to 7 TeV, qualitatively similar behavior is expected.

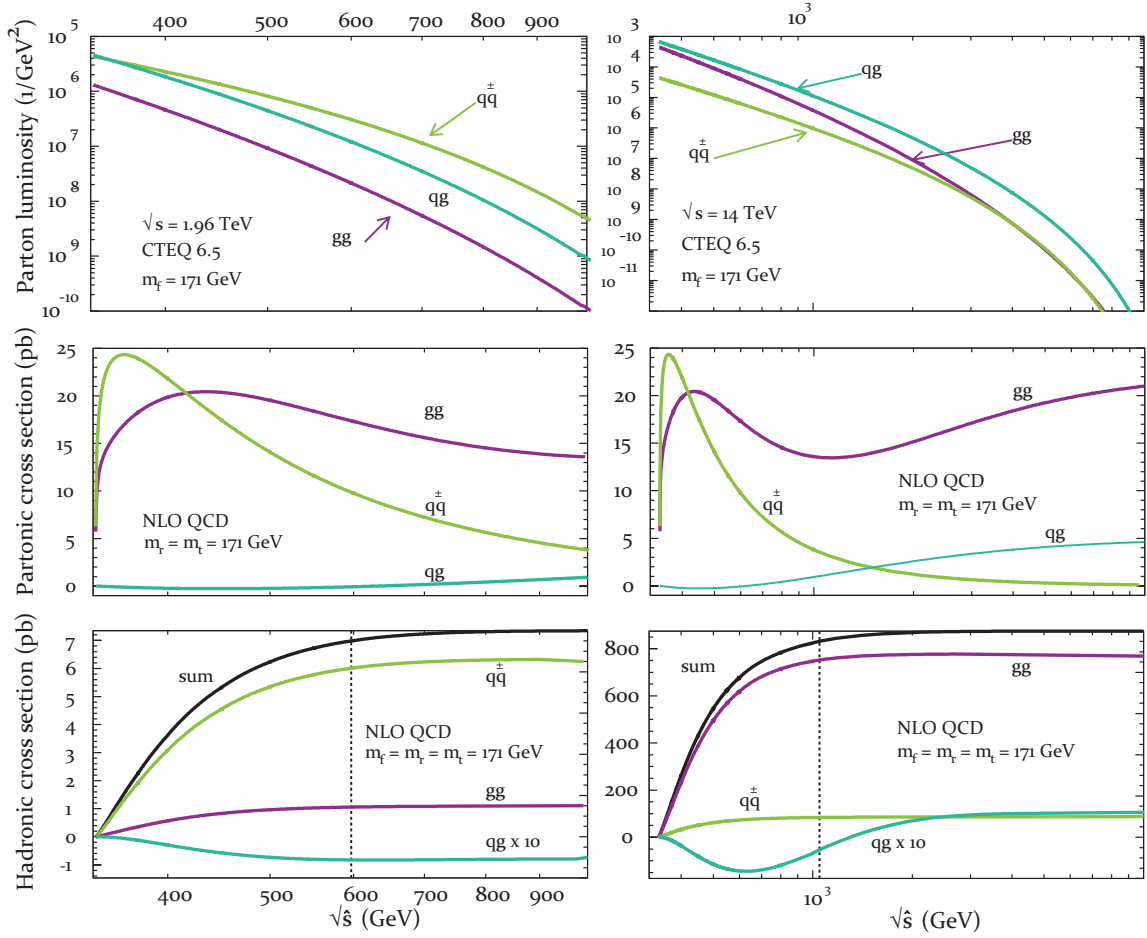


Figure 1.11 – From top to bottom: Parton luminosity, partonic cross section and total hadronic cross section as a function of $\sqrt{s}$ for the Tevatron (left) and the LHC (right). The dashed line shows the point where the saturation level of the cross section is 95% [34].

measuring the cross section. Although the top mass is not measured directly, the cross section inherently yields an indirect measurement of the top quark mass.

1.3.2 Top quark mass and Higgs

The mass of the top quark (m_t) is an input to the Standard Model. Before the top quark mass was measured, precision measurements of the W and Z boson masses already predicted its value, through radiative corrections in the form of virtual loops. In the Higgs mechanism, the W and Z boson mass are connected to the mixing angle (Weinberg angle), by $m_W/m_Z = \cos \theta_W$. The masses of the weak bosons in turn depend on m_t , through radiative corrections. Figure 1.13 shows the loops involving top quarks. A top/bottom loop modifies the W boson and a complete top loop does so for the Z boson. The mass of the W boson is proportional to the aforementioned term $\sqrt{g^2/G_F}$ (see Section 1.1.2) and can be re-expressed using $e = g \sin \theta_W$ as:

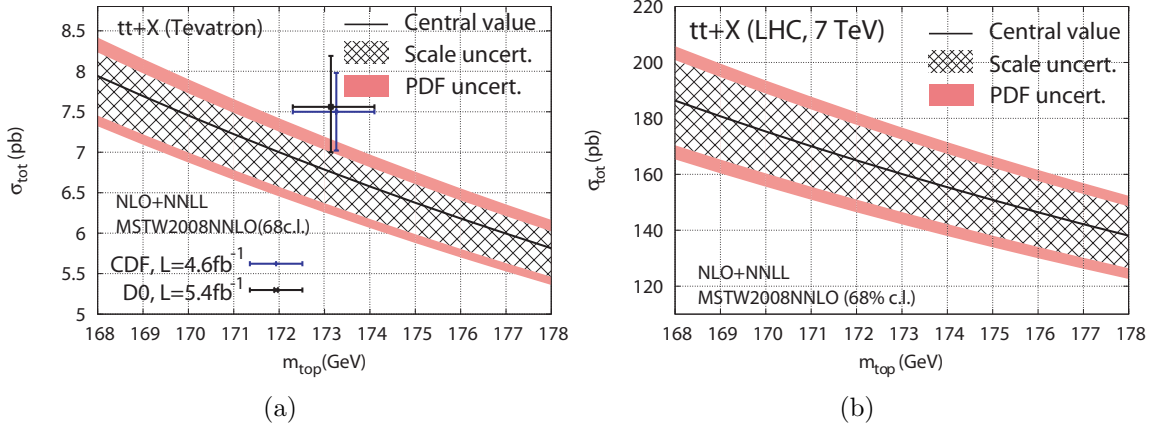


Figure 1.12 – Cross section versus top quark mass for the Tevatron (a) and the LHC (b). Figure taken from [35].

$$m_W^2 = \frac{\pi\alpha_{EM}}{\sqrt{2}G_F} \left(\frac{1}{\sin^2 \theta_W} + \frac{\Delta r}{2\sin^2 \theta_W} \right). \quad (1.5)$$

Here, G_F and α_{EM} (absorbing e) are the Fermi and electromagnetic coupling constant respectively, both determined from experiments (see Section 1.1.2). The term with Δr represents all radiative corrections. The quark loop corrections that contribute to Δr depend quadratically on their mass. As the top quark is far heavier than the others, its mass (m_t) practically dominates in the calculation. The other sizeable corrections come from the Higgs boson. The corrections through Higgs loops depend only logarithmically on its mass, however. This means that Eq. 1.5 strongly relates the top quark mass to well measurable Standard Model parameters.

The Higgs boson mass (m_H), on the other hand, is theoretically loosely constrained (only via logarithmic terms) and therefore more difficult to estimate. Through the constraints from W boson and top quark masses, however, it is possible to narrow down the allowed mass region. Figure 1.14 shows the interdependence between the Higgs boson, top quark and W boson masses. The W boson mass is $80,390 \pm 16$ MeV, and the top quark mass 172.9 ± 1.1 GeV. The recent observation referred to earlier (Section 1.1.6) is consistent with the circumstantial evidence of the Standard Model preferring a Higgs boson with a low mass.

1.3.3 Decay

The top quark decays through the weak interaction, into a W^+ (W^-) boson and a down-type quark (antiquark). More than 99% of the time, this quark is a b -quark, $\Gamma(t \rightarrow Wb)/\Gamma(t \rightarrow Wq) = 0.99_{-0.08}^{+0.09}$ [30]. The other two allowed decay modes (to Wd or Ws) are suppressed by the CKM matrix values V_{td} and V_{ts} that are close to zero.

Consequently, the W boson decay modes determine the signature of top quark pair events.

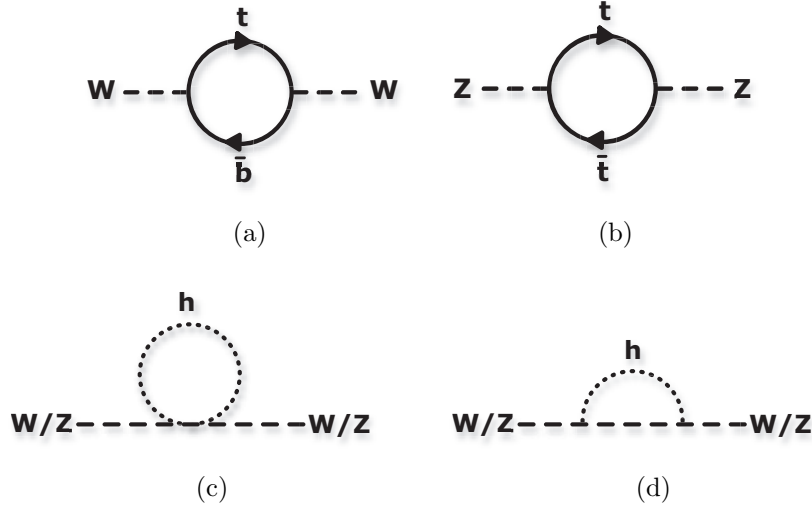


Figure 1.13 – Lowest order virtual loop corrections to the W and Z propagator, by heavy quarks (a, b) and the Higgs boson (c, d).

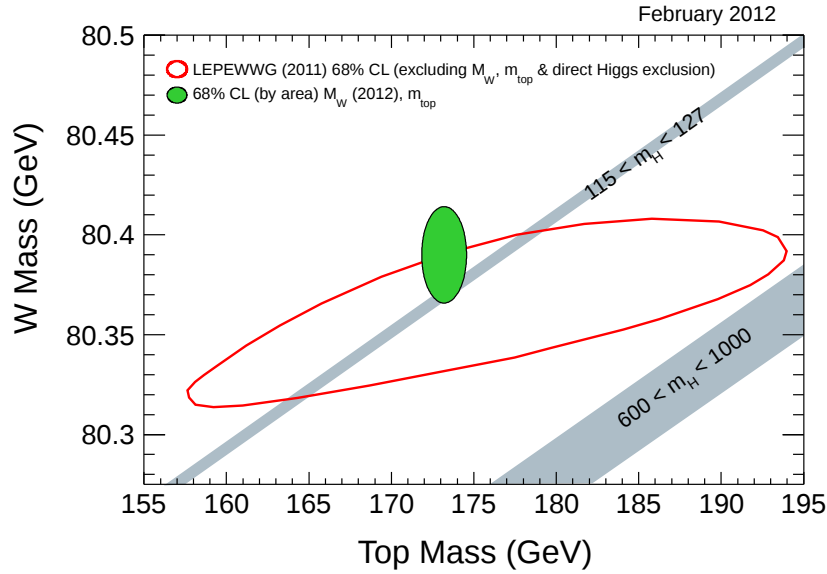


Figure 1.14 – Higgs exclusion plot in terms of W boson and top quark mass [36]. The ellipse shows the 1σ area of the most precise measurements of the top quark and the W boson mass. The contour shows the preferred region of the values of the W boson, top quark and Higgs boson mass, according to a fit to other Standard Model parameters. The contours thus narrow down the Higgs mass. The gray areas show the values of the Higgs mass that are not excluded experimentally.

The decay modes for W^+ bosons are summarized in Table 1.1 (W^- decay modes are the charge conjugates, with equal numbers). In approximately 2/3 of the cases W bosons decay into a quark and an antiquark of different type ($W \rightarrow q\bar{q}'$). The other 1/3 of the time the W boson decays to a lepton-neutrino pair, almost evenly spread over the three

lepton flavors (e , μ , τ). The mass differences of the leptons lead to minor alterations.

Table 1.1 – W^+ boson decay modes.

Decay mode	Branching fraction
$e^+\nu_e$	$(10.75 \pm 0.13) \%$
$\mu^+\nu_\mu$	$(10.57 \pm 0.15) \%$
$\tau^+\nu_\tau$	$(11.25 \pm 0.20) \%$
$q\bar{q}'$	$(67.60 \pm 0.27) \%$

We classify the signature of a top quark pair by the decay of the W bosons. The analyses in this thesis focus on the single-lepton decay channel. This is the hybrid mode where a lepton, two b -quarks and two light flavored quarks are expected in the detector. Of all produced top quark pairs, a fraction of $4/9$ is expected to decay into this mode. But, disregarding the more challenging tau lepton decay modes and selecting only events with electrons or muons, a final fraction of roughly 30% remains. Figure 1.15 illustrates the single-lepton decay mode. We define the ‘hadronic side’ as the side where the W boson decays hadronically, and likewise, the ‘leptonic side’ as the branch that belongs to the leptonically decaying W boson. We also speak of a hadronic top quark and leptonic top quark in this sense, from here onwards.

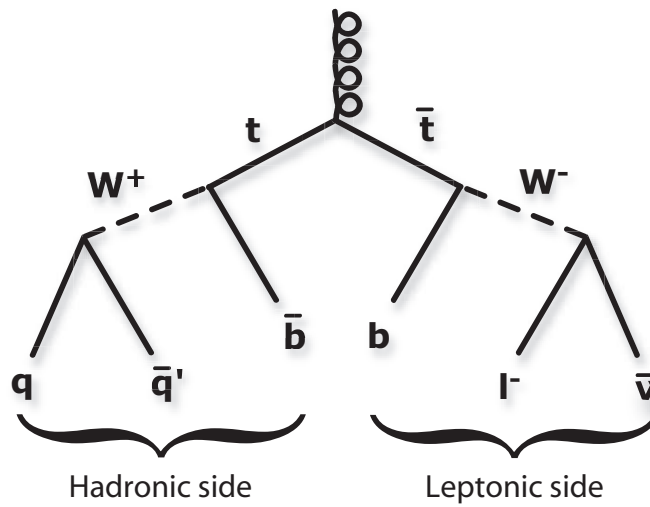


Figure 1.15 – Top quark pair decay for the one-lepton final state.

1.4 Top quarks in models beyond the Standard Model

The top quark is not only important as a check for Standard Model parameters or Higgs searches: also in Beyond-Standard-Model (BSM) physics it plays an important role. Firstly, in the search for supersymmetry, a large part of the physics background often originates from top quark decays. Moreover, the top quark can be a decay product of one of the supersymmetric particles, possibly distorting top quark observables with respect to the Standard Model.

Besides supersymmetry, other BSM models can affect the top quark properties. Many models predict new heavy particles, heavier than the top quark itself, additional to the ones incorporated in the Standard Model. This opens the possibility of top quark pairs being produced in the decay of such a heavy particle. The presence of a new heavy particle is for example expected to enhance the top quark production cross section. A precise measurement of this quantity thus reveals the existence of such particles, but there are more direct measurements that can be performed for this purpose. In the following sections, we discuss the possibility of discovering a heavy particle from the analysis of resonances and charge asymmetry.

1.4.1 Resonances

There are proposals for extensions of the Standard Model with heavy bosons called X with a mass in the TeV range that can decay to a top quark pair, $pp \rightarrow X \rightarrow t\bar{t}$. This introduces new production channels for top quark pairs, since the massive top quark is more likely to be present in the decay of heavy bosons than the lighter quarks. Figure 1.16 represents the lowest order Feynman diagram for $t\bar{t}$ production through a heavy boson.

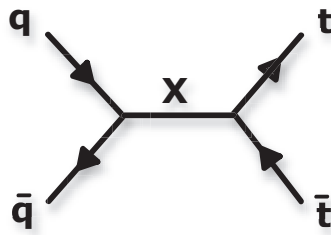


Figure 1.16 – Example of top quark pair production through a heavy resonance X .

We mention three examples of models that could produce such a heavy boson:

- Z' . The Z' particle plays a role in numerous extensions of the Standard Model, among which an alternative scenario for electroweak symmetry breaking [37, 38]. The Z' can show up as a resonance in top quark production. It is a spin-1 color singlet and its predicted mass is usually in the range of 100-500 GeV, but can be heavier as well.

- **Axigluons.** One family of models is the theory of chiral color, where eight extra massive gauge bosons are predicted, with axial-vector coupling. These bosons, so-called axigluons, are heavy: the experimental lower limit lies around 1 TeV. [39].
- **Kaluza-Klein gluons.** Randall-Sundrum models, based on the existence of additional dimensions. In these models Kaluza-Klein (KK) excitations occur, where the existence of heavy bosons (color-octets) are predicted, similar to axigluons, but with vector couplings [40].

More examples exist; they have in common that they alter top quark production, more specifically, the distribution of the invariant mass of the top quark pair, $m_{t\bar{t}}$. New particles can manifest themselves through a peak in the $m_{t\bar{t}}$ distribution. A narrow or wide peak on top of this distribution, or a less pronounced effect through interferences with the Standard Model, signals the presence of these particles. Therefore the $m_{t\bar{t}}$ distribution provides a model-independent sensitivity for BSM physics. The $t\bar{t}$ invariant mass distribution is especially sensitive to heavy resonances when producing top quarks through the s -channel.

Figure 1.17 shows a few examples of the invariant mass distributions as a result of BSM models, superimposed on the Standard Model. The black line depicts the QCD prediction, in the range between 1150 and 2500 GeV. A simple peak on top of that, due to a Z' of 2 TeV is shown in blue. The red and green line depict color octets: an axial-vector particle g_A and a vector particle g_V , both of 2 TeV as well. Axigluons are of the first kind, Kaluza-Klein gluons of the second. Contrary to the Z' and g_A , the interference term in the vector particle is non-negligible and modifies the shape of the QCD distribution. This is in addition to the resonance mass term that results in a peak structure around 2 TeV.

1.4.2 Top quark charge asymmetry

Another generic window to new physics is the ‘top quark charge asymmetry’. We define an asymmetry in terms of outgoing angles of the (anti)top quark with respect to the beam axis. Figure 1.18 shows the hard interaction, with incoming partons and an outgoing top quark pair, in the center-of-mass frame. The angle that the top quark with positive charge makes with the beam axis is defined as θ . Assuming the special case where the production process is charge symmetric, and taking the quark-antiquark interaction as the production mechanism, the partial cross section of $q\bar{q} \rightarrow t\bar{t} + X$ and the process with the final state top quarks interchanged, $q\bar{q} \rightarrow \bar{t}t + X$, are equal for every θ . In this notation X are extra partons, not the aforementioned heavy boson:

$$\frac{d\sigma(q\bar{q} \rightarrow t\bar{t} + X)}{d\cos\theta} = \frac{d\sigma(q\bar{q} \rightarrow \bar{t}t + X)}{d\cos\theta}.$$

A potential asymmetry with respect to this angle can be parametrized in several ways. In general, it is expressed by the number of top quarks (N_t) and the number of antitop quarks ($N_{\bar{t}}$) that are found in the detector, as a function of the rapidity y :

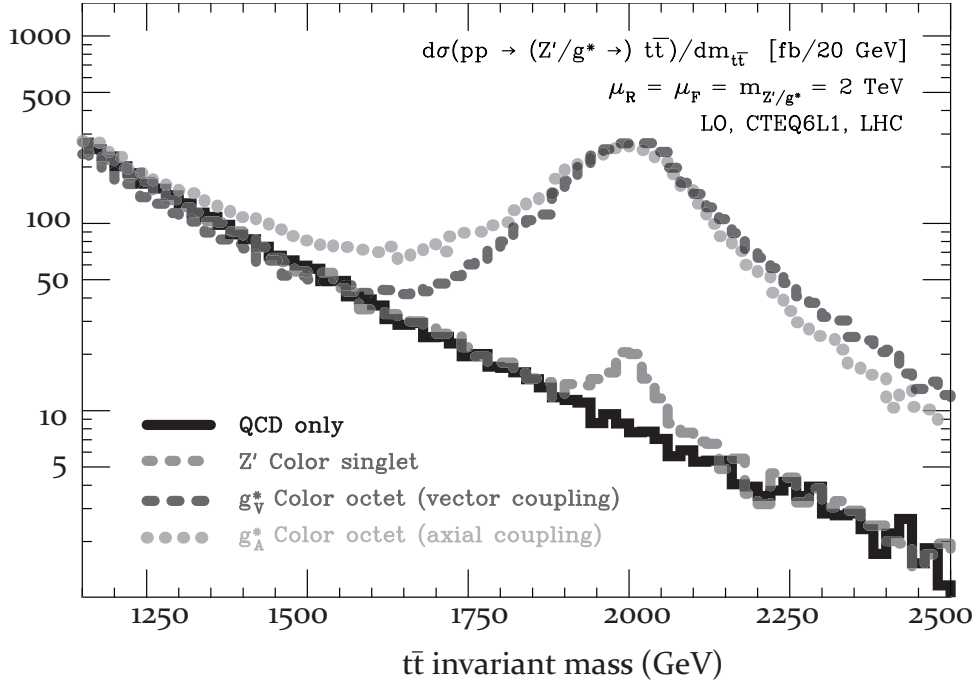


Figure 1.17 – The invariant mass of the top quark system ($m_{t\bar{t}}$), for different models beyond the Standard Model [41].

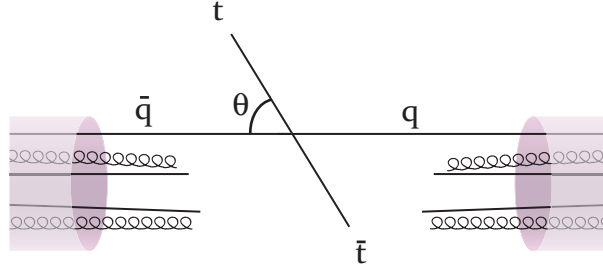


Figure 1.18 – A quark-antiquark scatter producing a top quark pair.

$$A_C(y) = \frac{N_t(y) - N_{\bar{t}}(y)}{N_t(y) + N_{\bar{t}}(y)}.$$

The rapidity is defined as $y = \frac{1}{2} \ln \frac{E+P_z}{E-P_z}$, which takes the particles mass into account, contrary to the pseudorapidity. $A_C(y)$ would be equal to 0 over the full range of y when the production process is charge symmetric and, similarly, non-zero where it is charge asymmetric. The top and antitop quarks produced in a pair are *a priori* not expected to behave asymmetrically in any way in leading order, the diagrams of the production process we have shown in itself appear charge invariant. A small asymmetry is incorporated in

the Standard Model, however, due to interferences between diagrams that contribute to the next-to-leading order. Although the Standard Model asymmetry is small, many BSM models predict larger asymmetries. We first discuss the Standard Model and after that the physics models that predict different asymmetries.

Origin of charge asymmetry in the Standard Model

The top and antitop quark are produced symmetrically at leading order ($O(\alpha_s^2)$). One order higher, at NLO, effects that make the top and antitop behave differently occur [42]. It turns out that this asymmetry originates from radiative corrections to processes that contain initial state quarks, $q\bar{q} \rightarrow t\bar{t}$ or $qg \rightarrow t\bar{t}$. The gluon fusion process ($gg \rightarrow t\bar{t}$), in contrast, does not predict any asymmetric behavior. Table 5.6 shows a summary of the symmetric and asymmetric contributions, at LO and NLO.

Table 1.2 – Symmetric and asymmetric production processes.

	$O(\alpha_s^2)$	$O(\alpha_s^3)$
$gg \rightarrow t\bar{t}$	Symmetric	Symmetric
$q\bar{q} \rightarrow t\bar{t}$	Symmetric	Asymmetric
$qg \rightarrow t\bar{t}q$		Asymmetric

One origin of the asymmetry is the $q\bar{q}$ production process. The asymmetry originates from the interference between Feynman diagrams with real and virtual radiation. Cancellations and enhancements occur, when the sum of the individual amplitudes per diagram is squared. Figure 1.19 shows two examples of such an interference. The top plot depicts a tree level diagram with initial state radiation ($2 \rightarrow 3$) and final state radiation ($2 \rightarrow 3$). The squared sum contributes to next-to-leading order, $O(\alpha_s^3)$. The bottom plot shows the diagrams for an interference of a virtual loop (box diagram, $2 \rightarrow 2$) and a plain Born diagram ($2 \rightarrow 2$). This leads to contributions of $O(\alpha_s^2)$, $O(\alpha_s^3)$ and $O(\alpha_s^4)$. Hence, both examples contribute to the total next-to-leading order $O(\alpha_s^3)$ cross section.

The interferences can be merged into a combined description with the technique of unitary cuts. This is shown graphically in Figure 1.20. In (a), one of the combined diagrams is depicted. The parts left and right of the dashed line represent a diagram and a complex conjugate diagram. Specifically, the vertical cut (“cut 2”) through two lines is the split between the box diagram and the Born diagram. The diagonal cut through three lines corresponds directly to the initial and final state radiation diagrams. Likewise, in (b), the same diagram, but with interchanged particle lines is represented with the absorptive cuts.

The total contributions to the $O(\alpha_s^3)$ cross section from 1.20(a) and (b) are related directly: when disregarding the color factors, there are only sign differences between the two, due to the interchanged particles lines (independent of the position of the cut line). Hence,

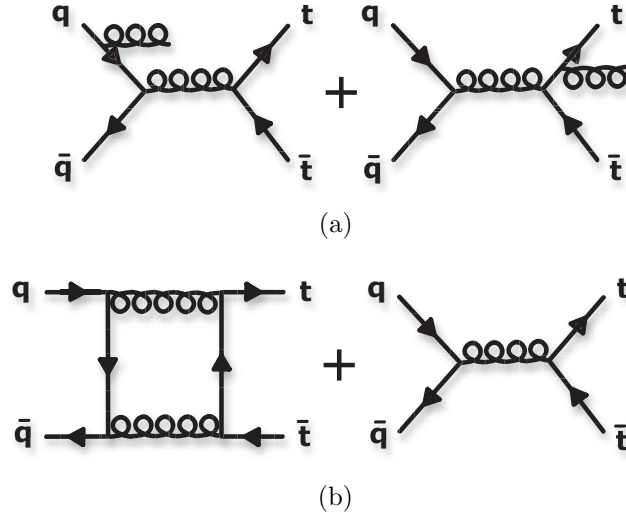


Figure 1.19 – Top quark pair production diagrams contributing to charge asymmetry by interference at next-to-leading order. (a) initial state radiation with final state radiation; (b) virtual loop (box) with tree level process.

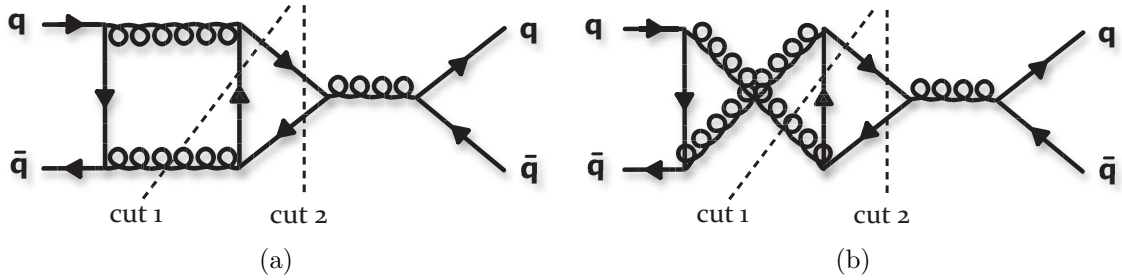


Figure 1.20 – Interferences between diagrams in Figure 1.19 expressed in unitary cuts.

including the color factors C leads to the mechanism of asymmetry. Although the top quark loop (the triangle) looks similar in (a) and (b), the flow of color charge is different. The color factors, C_a and C_b , can be derived from the corresponding cut diagrams in (a) and (b) and simplified to

$$C_a = \frac{1}{16N_C^2}(f_{abc}^2 + d_{abc}^2), \quad C_b = \frac{1}{16N_C^2}(-f_{abc}^2 + d_{abc}^2),$$

where N_C is the number of colors, f_{abc} are the structure constants of the $SU(3)$ group coming from the commutation relation and similarly, d_{abc} originates from the anticommutator. The term with d_{abc} is positive in both cases. And, because they both are positive contributions to the total cross section, including the color factors creates non-canceling terms and break the symmetry. The order of this effect is estimated to be $\frac{5}{12}\alpha_s$ [42]. Besides the second order effect in $q\bar{q}$ collisions, also the qg channel interaction yields a small asymmetry.

The asymmetry due to the color effect in the calculation translates in practice into the

net effect that top quarks on average are forced away from the incoming quark. Or in other words, the top quark is more often emitted in the direction of the incoming quark, and the antitop quark more often in the direction of the antiquark. This is an effect that translates into angular differences that depend on the actual collision conditions of the accelerator.

Difference between the LHC and the Tevatron

The fact that (anti)top quarks are preferably emitted in the direction of the (anti)quark, has different implications for the Tevatron and the LHC. At the Tevatron, the proton-antiproton collisions hold two advantages to measure this effect. Firstly, there is the availability of valence antiquarks in antiprotons boosting the $q\bar{q}$ production channel: quark annihilation processes constitute 87% of top quark production at the Tevatron. Secondly, the asymmetric beam conditions (proton-antiproton) also make the measurement easier as the direction of the quark and antiquark are predictable. Hence, the top quark charge asymmetry appears as a forward-backward asymmetry at the Tevatron, as shown in Figure 1.21. More top quarks are expected in the forward direction, while more antitop quarks are produced in the backward direction.

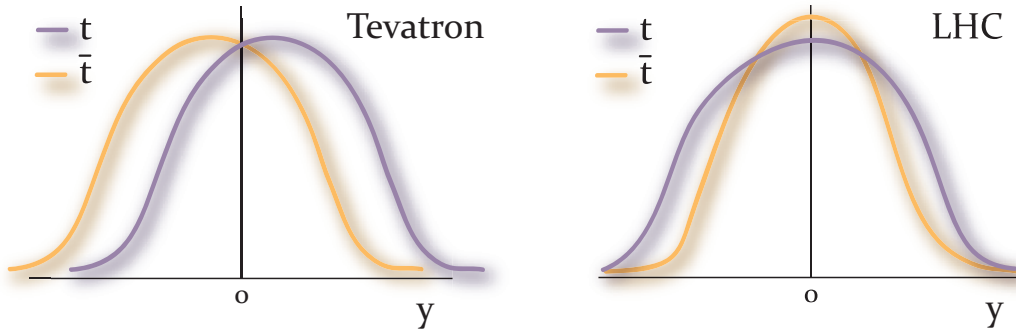


Figure 1.21 – Distribution of top quarks and antitop quarks as a function of rapidity y , for the Tevatron (left) and the LHC (right) collisions.

At the LHC, the direction of the incoming quark and antiquark is not known, since it collides protons. Hence, a forward-backward asymmetry does not occur in the lab-frame, the terms forward and backward would have to be defined per event, which is impossible in practice. Moreover, the contribution of gluon fusion is large (80%, $\sqrt{s} = 7$ TeV), diluting the asymmetry in the first place. The top quark charge is measurable, however. In proton-proton collisions, the antiquark in $q\bar{q}$ production is a sea quark that has lower fractional momentum than an valence quark. That means that the top quark that is produced in such an event (which, due to charge asymmetry, is emitted preferentially in the direction of the incoming quark), traverses a path closer to the z -axis than the antitop quark. Hence, there are more top quarks expected in the forward direction (large rapidity) and more antitop quarks in the central direction (low rapidity).

In 2011, the CDF collaboration measured deviations from Standard Model at the level up to 3.4σ in some parts of phase space [43]:

$$\begin{aligned} A_{t\bar{t}} (m_{t\bar{t}} < 450\text{GeV}) &= 0.116 \pm 0.153 & (\text{SM: } 0.040 \pm 0.006), \\ A_{t\bar{t}} (m_{t\bar{t}} > 450\text{GeV}) &= 0.475 \pm 0.114 & (\text{SM: } 0.088 \pm 0.013). \end{aligned}$$

This parametrization of the charge asymmetry (expressed in the rest frame of the $t\bar{t}$ system) is compared for events with low and high mass $m_{t\bar{t}}$. The asymmetry is higher than expected and shows an invariant mass dependence. Because the asymmetry could expose non-Standard Model physics, it is of interest to measure this quantity at ATLAS, despite the difficulties the LHC inherently has with respect to this measurement.

Charge asymmetry in BSM models

The number of models that could explain a deviation of the top quark charge asymmetry from the expected value is large and largely overlaps with the examples mentioned in the previous section. The effect that models have on the charge asymmetry, however, has to be consistent with both the measured cross section and $m_{t\bar{t}}$ spectrum: if a model predicts a large asymmetry accompanied by a large enhancement of the production cross section, it can be ruled out via the latter.

A charge asymmetry results from diagrams of top quark production mediated by heavy particles, for example by axigluons, g_A [44]. Axigluons were introduced in Section 1.4.1. The tree level diagram of top quark production through axigluons can interfere with itself, or with the plain Standard Model tree level diagram, both resulting in an asymmetry [45]. The latter interference is shown in Figure 1.22(a). This means that in addition to the Standard Model asymmetry, a term coming from the ‘self-interference’ and a term of the interference with the Standard Model gluon contribute to the total asymmetry. The sign and magnitude of the additional asymmetry depends on the mass and couplings of the specific axigluon model. An axigluon mass larger than the top quark pair ($m_{g_A} > 350$ GeV) leads to a negative asymmetry in general, hence an effect opposite to the Standard Model. This is the case because the denominator in the propagator term is negative in case the axigluon mass exceeds the mass of the $t\bar{t}$ -pair. A positive asymmetry can be achieved when the coupling strength of axigluons is of opposite sign for different quark flavors. A heavy axigluon also shows up in the $m_{t\bar{t}}$ distribution and increases the cross section.

A neutral Z' boson, listed in Section 1.4.1, can also cause asymmetric $t\bar{t}$ production, depending on its properties. When choosing a model where the exchange of a Z' boson is flavor changing [46], the t - and u -channel processes are allowed, which leads for example to the diagram in Figure 1.22(b). The component of the asymmetry that is obtained from the interference with the Standard Model gluon is negative, but the self-interference is not. A positive asymmetry can be achieved only when the coupling of the Z' boson to quarks is sufficiently strong. The Z' boson will be easier observed from the asymmetry than from the $m_{t\bar{t}}$ distribution, due to the possibility of t - and u -channel diagrams. Heavy Z' bosons can increase the asymmetry to an extent that is already excluded by the charge

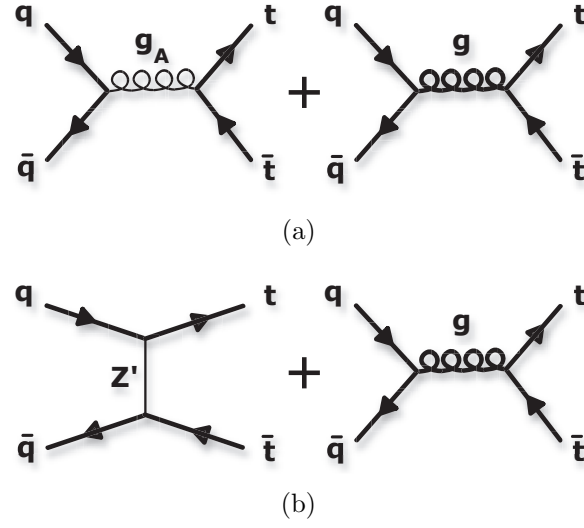


Figure 1.22 – (a) Diagrams for axigluon (g_A) mediated tree level top quark production in the s -channel and the Standard Model gluon (g) mediated process. (b) Diagrams for Z' mediated tree level top quark production in the t -channel and the Standard Model gluon mediated process.

asymmetry measurements at the Tevatron, assuming a maximal deviation of 50% of the SM cross section [47].

Precision measurements do exclude or limit parts of the discussed models, due to the effect the new heavy particles have on other measured processes, through loop corrections.

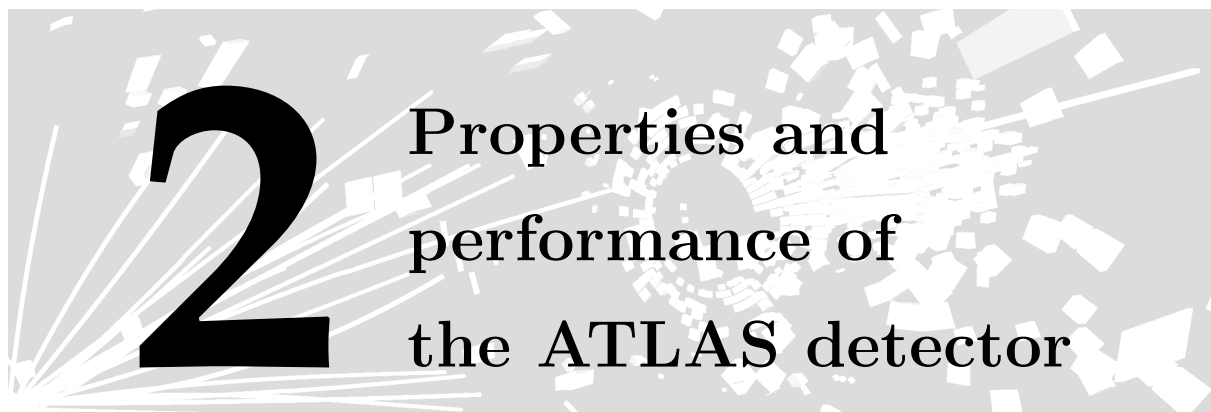
1.5 Summary

Almost all measurements performed before, during and after the development of the Standard Model confirm the theory. The mechanism that describes electroweak symmetry breaking is about to be confirmed by the discovery of a Higgs particle, when it satisfies the requirements. Besides the Higgs research, there are other studies that scrutinize the validity of the Standard Model. The top quark is a strong probe of the Standard Model, and can help to discover new physics models.

The production cross section of the top quark is predicted very precisely. The conditions of the LHC differ from the Tevatron: there is more center-of-mass energy available, and the LHC produces proton-proton collisions instead of proton-antiproton collisions. These differences influence the mechanism of production. Gluon-gluon fusion dominates over the other partonic production processes at the LHC. And also the abundance of energy makes it possible to create top quark pairs far beyond the 350 GeV threshold. Therefore, a cross section measurement at the LHC genuinely is a new measurement and an independent check of the Standard Model. An enhanced cross section points to the existence of new production processes that would have to come from non-Standard Model theory.

In addition to the cross section, the kinematics of the $t\bar{t}$ system can provide a hint of new physics. The $t\bar{t}$ invariant mass spectrum is very well established. Numerous models anticipate peaks at resonance masses or more involved modifications to the spectrum. Secondly, the top quark charge asymmetry could also reveal the presence of new physics. Small differences in the kinematic properties of the top and its antiparticle, during pair production, are predicted within the Standard Model; larger discrepancies have to come from new physics.

In this thesis the production cross section and the top quark charge asymmetry are measured. Both play a role in confirming the Standard Model or revealing physics beyond it.

A decorative banner featuring a large, bold black number '2' on the left. To its right, the text 'Properties and performance of the ATLAS detector' is written in a black serif font. The background is a light gray with a complex pattern of white lines and squares, resembling particle tracks or a detector's internal structure.

2 Properties and performance of the ATLAS detector

Top quarks are produced abundantly in collisions in the Large Hadron Collider (LHC). In the first inverse femtobarn (1 fb^{-1}) of data obtained in 2011, approximately corresponding to the amount of data we use in the analysis, according to the Standard Model already over $1.6 \cdot 10^5$ top quark pairs are expected. But, top quarks decay immediately to lighter particles and it is only the set of final decay products that actually can be measured in the detectors. The top quark analyses that are performed in this thesis are based on collision data collected with the ATLAS detector, one of the four large detectors at the LHC.

In this chapter we introduce the LHC and the characteristics of the particle collisions. After that, we discuss the ATLAS detector and the details and performance of its sub-detectors. Besides the hardware components of the detector itself, this includes the trigger system and the subsequent system of data acquisition and distribution to sites around the world.

2.1 The Large Hadron Collider

The LHC at CERN is at the moment the largest and most energetic particle collider in the world. It is a hadron collider which produces proton-proton collisions, most of the time. In 2010 and 2011, protons were collided with a CM-energy of 7 TeV. In 2012 this is 8 TeV, and the CM-energy will increase to maximally 14 TeV in the following years. Besides proton-proton collisions, lead ions are collided during a short period of the year, using the same accelerator infrastructure. This type of collisions is used to study the so-called ‘quark-gluon plasma’, and will not be considered in this thesis. Some of the aspects of the proton-proton collisions have already been discussed in Chapter 1.

The LHC is located in the Geneva area, in the tunnel formerly used for the LEP collider. The circular tunnel lies between 45 m and 170 m below the surface; a large section is located below the French and Swiss countryside, but it partly runs underneath the mountains of the Jura. The structure of the LHC that is located in the tunnel contains two rings and is able to accelerate proton beams in opposite directions. These two rings are built in a superconducting dipole magnet system that creates a field of up to 8 T to keep the protons on the circular path. Besides the dipoles, the magnet system contains quadrupoles and other multipoles to focus the proton beams. The superconducting magnets operate at a temperature of 2 K.

Before protons collide in the main LHC ring, they are accelerated in a system of pre-accelerators. Figure 2.1 shows the layout of the accelerator system. First, electrons are stripped off of a hydrogen source. The remaining protons are introduced in the linear accelerator (LINAC2) and accelerated to 50 MeV. The LINAC2 then inserts the protons into the Proton Synchrotron Booster (PSB), the first circular pre-accelerator. Together with the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) it forms a system where the protons are accelerated to 1.4 GeV, 26 GeV and finally to 450 GeV¹. In the SPS, the protons are contained in distinct bunches, clouds of up to 10^{11} protons. When the proton bunches reach the required energy of 450 GeV, they are inserted into the main ring of the LHC. Finally, when the beam energy of the proton bunches in the LHC amounts to the chosen beam energy (3.5, 4, or 7 TeV), the opposing beams are focused at their collision points. Particle detectors are built around these interaction points to observe the products resulting from collision events.

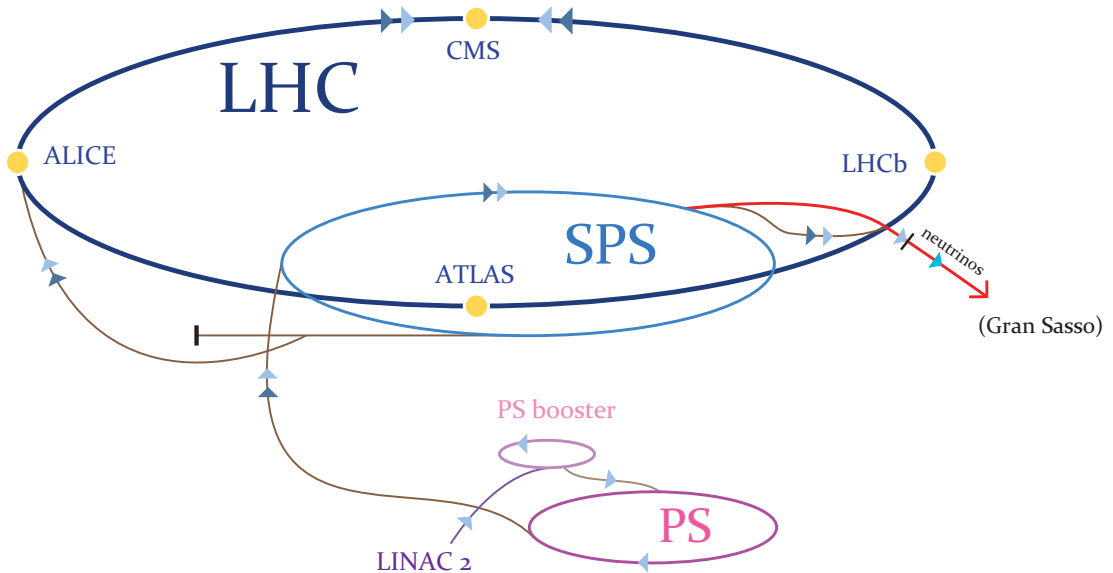


Figure 2.1 – Schematic view of the LHC accelerator complex and particle detectors.

¹What we now call pre-accelerators are actually genuine accelerators formerly responsible for many physics discoveries, including that of the neutral current (PS) and W and Z bosons (SPS).

The LHC started operations in 2008, but a technical malfunction after ten days caused major damage to the machine. Only a year later, in November 2009, the first proton collisions were recorded, at the injection energy of 450 GeV. From then on, the beam energy has been ramped up gradually to 1.18 TeV, and finally 3.5 TeV in 2010. Since then, the LHC has been running steadily at these conditions, corresponding to a CM-energy of 7 TeV, delivering over 5 fb^{-1} of data to ATLAS and CMS, at the end of 2011. The total integrated luminosity per day delivered (dark area), and the fraction recorded by ATLAS (light area) are depicted in Figure 2.2, for 2010 and 2011. We use data of 2010 (cross section measurement) and a fraction of 2011 data (charge asymmetry measurement). More detailed information on the luminosity conditions during data taking are discussed in Section 4.1.

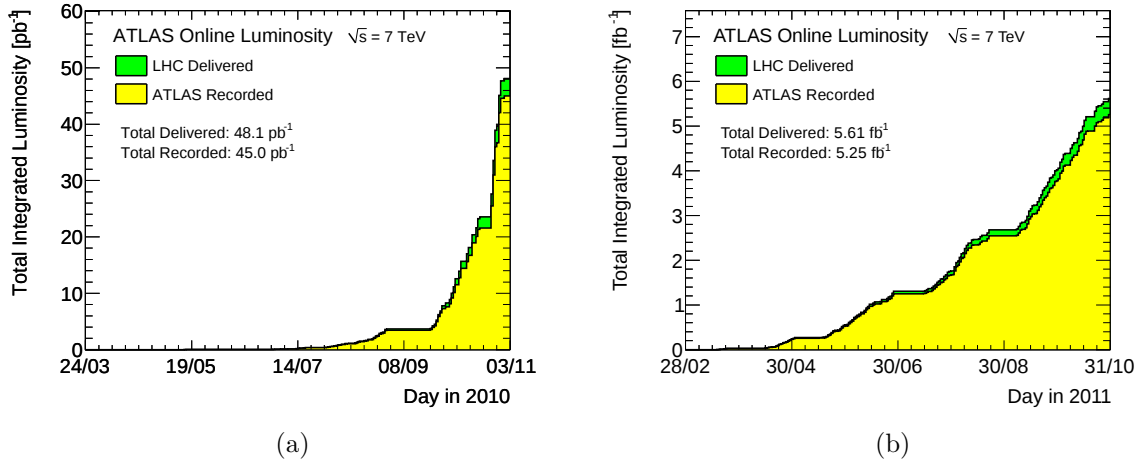


Figure 2.2 – Integrated luminosity in 2010 and 2011. The order of magnitude of the scales on the y -axis differs between the plots.

The four main detectors, positioned at the four interaction points of the LHC, are ATLAS, CMS, ALICE and LHCb. ATLAS and CMS, located at opposite sides of the ring, are two detectors that aim to measure a large spectrum of physics processes in order to be able to test various aspects of the Standard Model. To do so, the entire set of outgoing particles has to be detected. Both detectors therefore have active material covering the majority of the space surrounding the collision point, to prevent particles from escaping unnoticed. The physics goals of CMS and ATLAS are equivalent, yet the performance of subcomponents can differ from one to the other. ALICE is an experiment dedicated to measure lead ion collisions. It aims to answer a number of specific questions on the substructure of nuclei, quark confinement and the quark-gluon plasma. The amount of outgoing particles that are the product of lead-lead collisions in ALICE is huge and the detector is optimized to identify particles in this dense environment. LHCb is constructed at the fourth collision point of the LHC ring and measures the decay of mesons containing b -quarks. Decays that involve such mesons contain information on Standard Model parameters, like the CKM matrix values, and can measure the amount of CP violation, all to a large precision. LHCb measures particles produced in the forward direction. The na-

ture of the physics analyses at ALICE and LHCb does not require them to have hermetic coverage around the point of interaction.

2.2 The ATLAS detector

The ATLAS detector (A large Toroidal LHC ApparatuS) is the largest detector of the LHC. Figure 2.3 shows a schematic view of ATLAS. It is 25 m in height, 44 m in length and constructed in a cavern about 100 m below surface level, in the LHC ring. The detector is composed of several layers of subdetectors built around the collision point of the protons (or lead ions). First of all, this assures that outgoing particles always traverse multiple layers of detection material (unless the particles do not possess enough transverse momentum to leave the beam pipe). Besides the coverage, the concentric subdetector layers each possess complementary properties to support particle identification and momentum reconstruction for a large spectrum of particles. The innermost detector part is the inner detector, specialized in tracking and momentum determination. After the tracking system follow calorimeters, that absorb and measure the energy of electrons, photons and hadrons. Finally, the muon spectrometer detects muons, the only measurable particles that are expected to traverse the calorimeters.

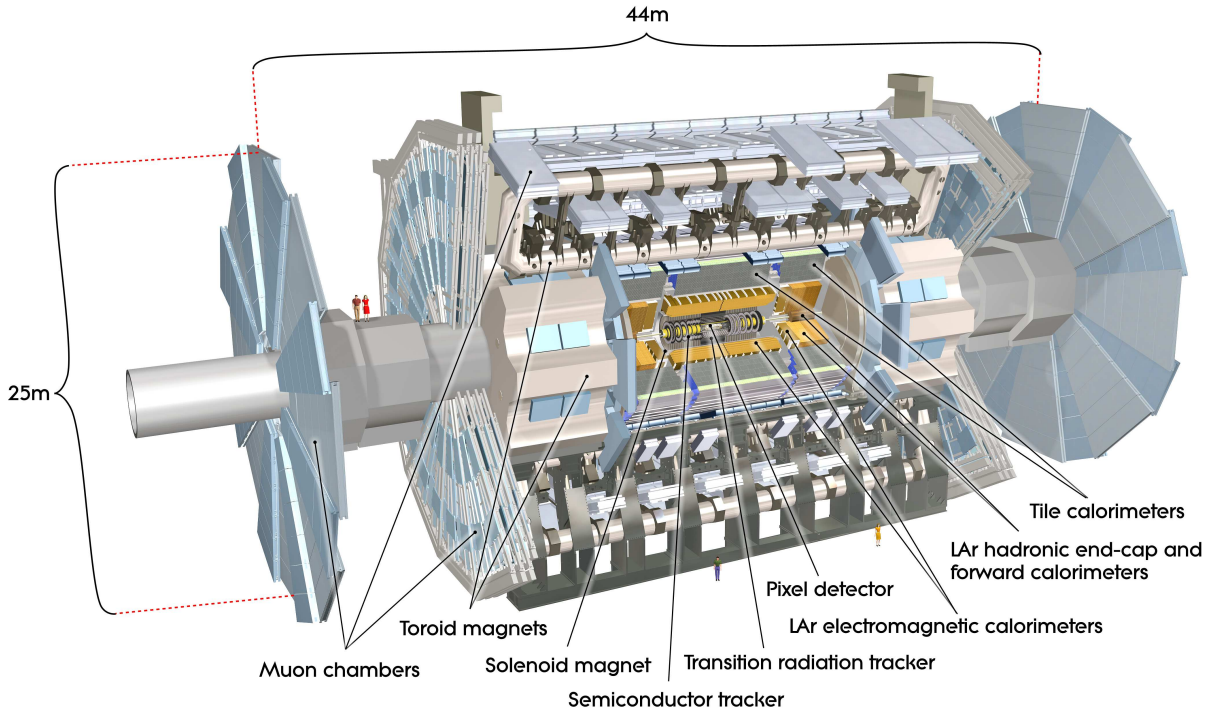


Figure 2.3 – Cutaway view of the ATLAS detector.

The design goals of ATLAS and its subdetectors are based on a large set of benchmark studies of physics at the TeV scale. The balance between affordability and desired perfor-

mance in terms of tracking, energy determination and identification of particles resulted in the list summarized in Table 2.1.

Table 2.1 – Summary of ATLAS performance goals. Listed are the design resolution and well as the η -range in which particles can be measured of the main subdetector parts (E and p_T are given in units of GeV). The last column shows a subset of this range that can be used for triggering events.

Subdetector	Required resolution	η measurement	η trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%p_T \oplus 1\%$	± 2.5	
EM Calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadr. Calorimetry			
(barrel & endcap)	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
(forward)	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \eta < 4.9$	$3.1 < \eta < 4.9$
Muon spectrometer	$\sigma_{p_T}/p_T = 10\%$ (at $p_T = 1$ TeV)	± 2.7	± 2.4

We will discuss the properties of all active subdetector components and the magnet systems in the following sections. Before doing so, we briefly introduce the coordinate system.

2.2.1 Coordinates in ATLAS

ATLAS uses Cartesian and angular systems of coordinates. The center of the detector, where the expected nominal interaction point lies, defines the origin. In the Cartesian system the x -axis points inwards, in the direction of the center of the LHC. The y -axis is directed upwards. The z -axis runs parallel to the beam axis, perpendicular to x and y . It points towards the counter clockwise direction of the LHC, when viewed from above.

In most cases it is more practical to use a pseudo-spherical system. The azimuthal angle ϕ ($[-\pi, \pi]$) is the direction of the projection of a vector on the $x-y$ plane (the angle with respect to the positive x -axis in the $x-y$ plane). The polar angle θ ($[0, \pi]$) is the inclination with respect to the z -axis, but we usually use $\eta \equiv -\ln(\tan \theta/2)$, the pseudorapidity. In this definition $\eta = 0$, $\theta = 90^\circ$ and $z = 0$ are equivalent. The advantage of using the pseudorapidity over the polar angle itself is that the particle flux is approximately constant over equal distances in η . Moreover, $\Delta\eta$, the difference between the pseudorapidity of two vectors is invariant under Lorentz boosts along the z -axis, in case of massless particles. The opening angle between two vectors can be expressed as

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

This quantity is used throughout the analyses, for example in isolation criteria of reconstructed objects.

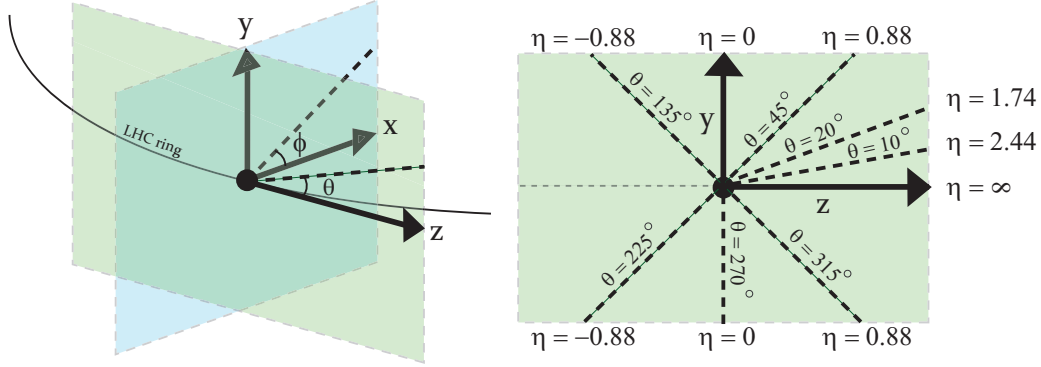


Figure 2.4 – ATLAS coordinates with respect to the LHC (left) and conversion of polar angle θ to pseudorapidity η (right).

2.2.2 Magnet system

ATLAS takes its name from the large magnet system that is incorporated in the detector. Magnetic fields allow momentum determination of high energy particles. Electrically charged particles are curved by the Lorentz force when they traverse a magnetic field. This curvature makes it possible to measure momentum and charge of the particles in the tracker system: the amount of curvature of the track of a charged particle inside the magnetic field is inversely proportional to the momentum. Charged particles with infinite momentum would travel in a straight line, whereas very low momentum particles can even spiral back.

There are two superconducting magnet systems in ATLAS. The first is a solenoid, located around the inner detector. The solenoidal field of 2 T is directed along the beam line, which means charged particles coming from the interaction point are bent in the $x - y$ plane in the inner detector. The amount of material in the solenoidal magnet is kept low: it has a thickness less than 1 radiation length. This is important, as the magnet is located inside both the calorimeter and muon spectrometer.

The second magnet system consists of three toroids: a barrel toroid and two endcap toroids that surround most of the detector. The toroids are made of coils encased in vacuum vessels. The toroids generate a field between 0.5 and 1 T in the muon spectrometer. The field is circular (runs in the ϕ -direction), so that it bends muons in the z -direction of the detector. The uniformity of the field is lower than that of the solenoidal field. The resulting curvature of the track in the $y - z$ plane allows momentum determination of the muons. This effect is equivalent to what happens in the inner detector, but in a different bending plane.

2.2.3 The inner detector

The ATLAS detector is designed such that the first layers around the point of interaction perform track reconstruction of charged particles in a region of $|\eta| < 2.5$. The purpose of

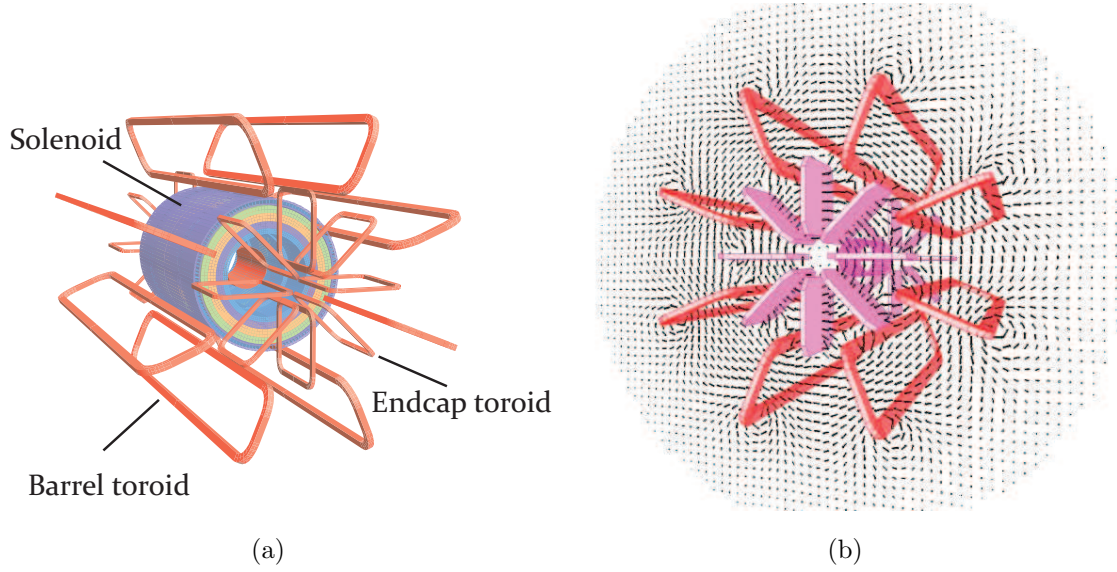


Figure 2.5 – (a) Schematic view of ATLAS magnet system, total size is ca. 20×25 m. (b) Simulation of the field induced by toroidal magnets.

the inner detector is to precisely measure the direction and momentum of the tracks and identify primary and secondary vertices within the collisions. Secondary vertex identification is important identification of b -quarks, so-called ‘ b -tagging’. In addition, the inner detector performs electron identification. The inner detector can be subdivided into the pixel detector, the semi-conductor detector (SCT) and the transition radiation tracker (TRT), see Figure 2.6. The solenoidal magnet system surrounds these three subcomponents to induce a magnetic field inside the tracker layers to accommodate the momentum measurement in the inner detector.

The pixel detector

Closest to the interaction point, a system of highly granular silicon detectors forms the pixel detector. The configuration consists of three barrel layers, and three endcap layers on each side. The first layer is placed 50.5 mm from the center of the beam pipe. Each layer is formed from modules of 2×6 cm² that in turn are made up of silicon pixels of 50×400 μm^2 (a small fraction of the pixels has a length of 600 μm). In each layer the modules overlap slightly, to keep a hermetic active detection surface. A charged particle traversing the sensor creates electron-hole pairs that are separated under the influence of the applied potential. When the resulting pulse signal exceeds a set threshold, the signal is read out. Usually, depending on the incident angle, one particle excites clusters of pixels, rather than only one. Therefore, it is useful to use the time the signal was above threshold (time-over-threshold, ToT, instead of just the binary signal, to increase the spacial resolution of a hit. Due to the ToT method, for the long side of the pixels (parallel to the z -axis) a design resolution of 115 μm is expected. The resolution in the transverse direction is 10 μm . In Figure 2.7 the efficiency of the pixel detector is plotted

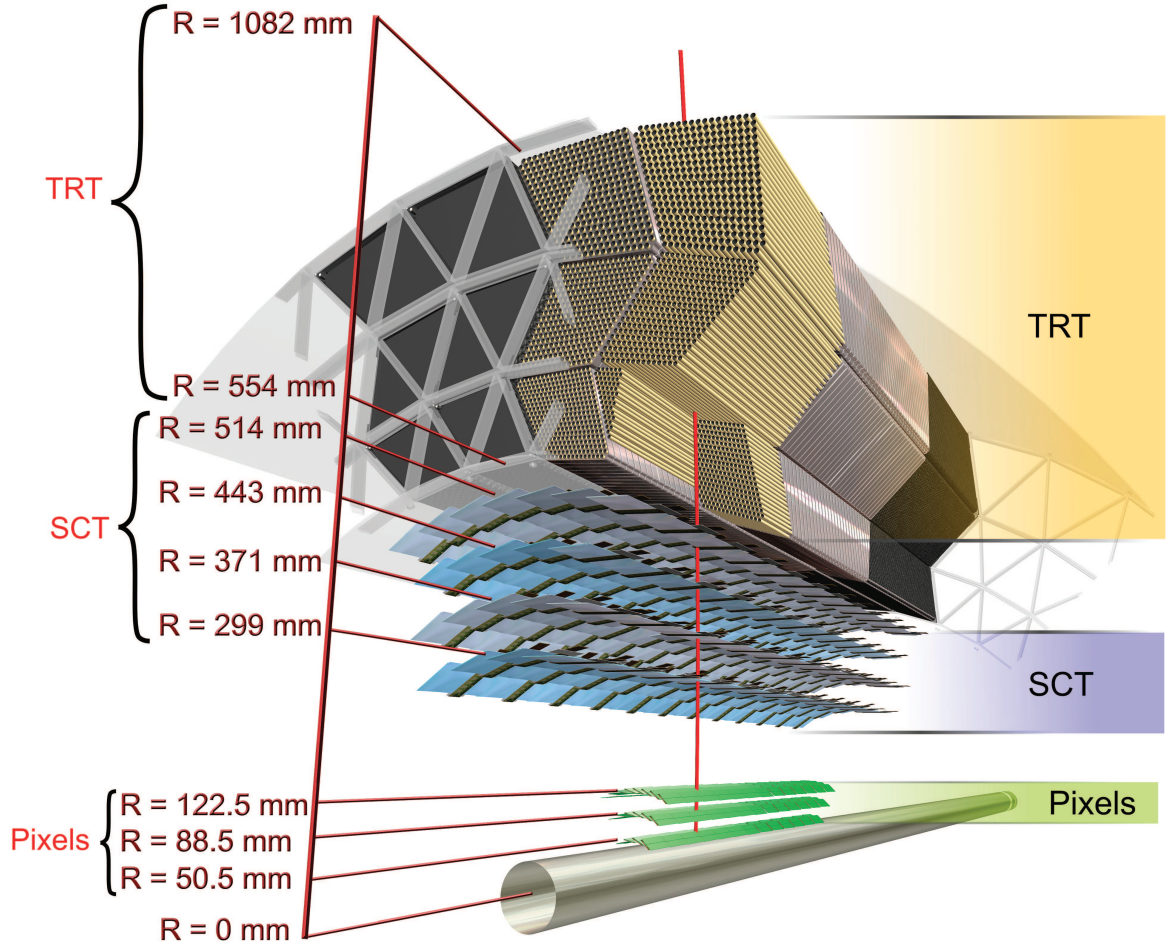


Figure 2.6 – Components of the inner detector

against the individual layers and disks. It is the percentage of hits in that disk or layer that can be associated to a track. Dead pixel modules are excluded from this efficiency, but dead regions in modules do contribute. It shows that for the majority of the layers and disks the efficiency reaches 99%. The outermost disks, however, have an efficiency of 97% and 98%. Furthermore, the first layer reaches almost to 100%, this is a result of the way the tracks are selected in the analysis. The probability of recording a random hit is below 10^{-10} hits per pixel per bunch crossing [48].

The semi-conductor tracker

The semi-conductor tracker (SCT) is a silicon strip detector built around the pixel detector. It contributes to the efficient identification of charged particles, and to the momentum resolution of their tracks. Like the pixel detector it contains silicon sensors, but subdivided in long narrow microstrips. The strips are on average $80 \mu\text{m}$ wide, but the width can vary between 54 and $94 \mu\text{m}$. The length is typically 126 mm . An SCT sensor is made of 768 strips, and two sensors, glued back to back, form an SCT module. The sensors

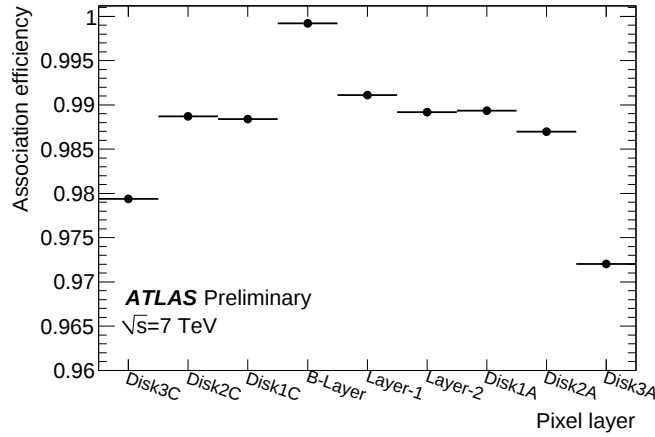


Figure 2.7 – Hit efficiency of tracks in the pixel detector [49], obtained in 2010 data.

are glued together with a small rotation angle to obtain a two-dimensional measurement. This angle recovers some of the resolution in the longitudinal direction. The modules form four concentric layers around the pixel detector, from 30 to 51 cm distance of the beam pipe center. Nine disks on each side make up the endcaps of the SCT. With this setup each particle leaves at least eight hits in the SCT detector. The longitudinal resolution is $580 \mu\text{m}$, the polar resolution ($R\phi$) is only $10 \mu\text{m}$, comparable to the pixels.

Figure 2.8 shows the hit efficiency for the SCT, for the individual barrel layers and for the endcaps. The values are obtained from a 2010 run (155112), at $\sqrt{s} = 7 \text{ TeV}$. This efficiency is defined as the number of hits per possible hit of a track. The possible hits are obtained from SCT only tracks or inner detector combined tracks. Dead modules are excluded from the efficiency, dead regions in the modules do affect the number. In the barrel the efficiency is, on average, 99.9%; the individual numbers do not drop below 99.8%. The average efficiency in the endcap reaches to 99.8%, with only sporadic lower values. The inner and outer layers and disks have a biased value, due to the track selection criteria.

The transition radiation tracker

The transition radiation tracker (TRT) is the outermost component of the inner detector, spanning the distance to the beam pipe center of 0.5 m to 1.1 m. It provides a separate contribution to the momentum measurements of charged particles, but in addition the hybrid nature of the subdetector makes it particularly useful in electron identification. It contains drift tubes with a thickness of 4 mm, filled with gas. A charged particle traversing the tube ionizes the gas. A potential is applied between the tube and an anode wire drawn through the center of the tube. The potential causes the electrons that are liberated by the particle traversing the gas to drift towards the wire. And vice versa, the ions are drawn towards the cathode tube. This induces a small current that is read out at one end of the tube. The length of the tubes is 144 cm in the barrel where it forms

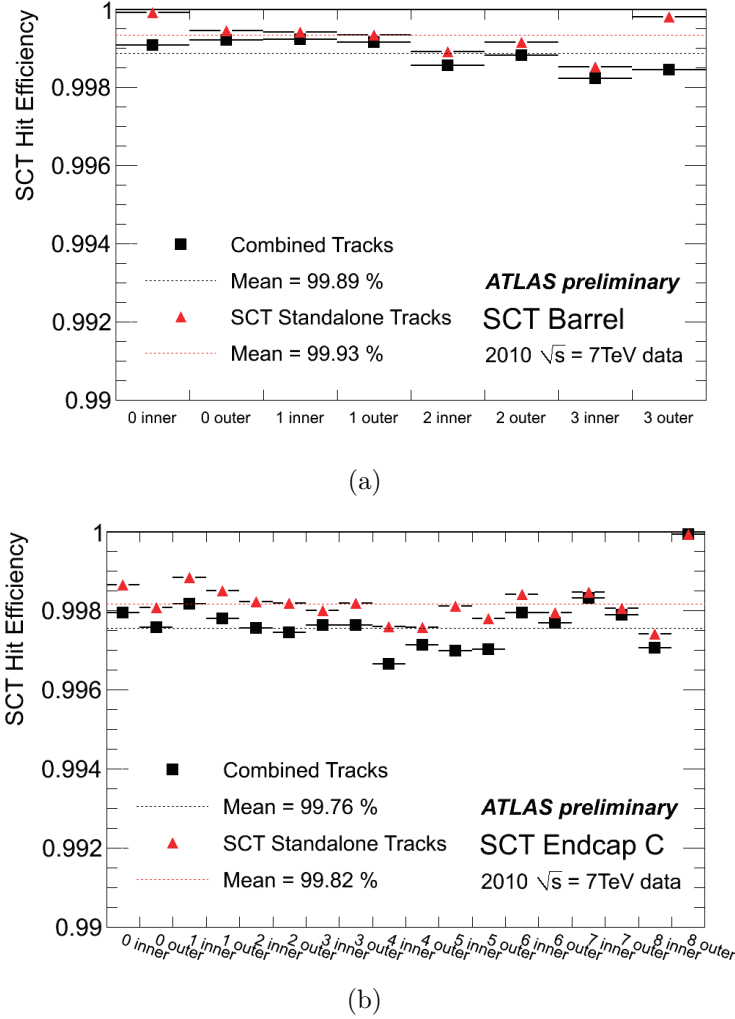


Figure 2.8 – Hit efficiency of tracks in the SCT detector [50] in the barrel (a) and endcap C (b).

three 32 straw thick layers. The endcap wheels (nine on each side) are made of 37 cm long straws. Each endcap contains 160 layers of tubes. The name of the subdetector comes from the feature that the tubes are interleaved with material of different refractive indices. A high energetic particle that crosses material of different dielectric properties will radiate off photons with an approximate energy of order keV, so-called ‘transition radiation photons’. The xenon in the gas mixture in the tubes absorbs these transition radiation photons. The amount of radiation severely depends on the mass of the particle: an electron, due to its relatively small mass, travels faster than a charged pion of the same energy and therefore emits more of such transition radiation. Effectively this can be used for particle identification, as signal pulses with large amplitudes in the tubes indicate the presence of electrons, whilst charged pions leave behind a different signature. The resolution of the drift radius is $130\ \mu\text{m}$. There is no longitudinal coordinate to the hit produced by the straw.

Figure 2.9 shows the hit efficiency for the TRT barrel, as a function of the distance-of-closest-approach of the track to the tube center. Here, the hit efficiency is defined as the fraction of straw tubes with a hit and the total number of straws traversed by the track (excluding known dead straws). A mean of 94% is reached with collision data of 2010, for both the barrel and endcap (not shown). The plot on the right-hand side shows the probability of obtaining a hit above a high threshold (6 keV), as a function of the γ -factor of the particle ($\gamma = E/m$). In the low end of the spectrum the dependence is flat, but for values above 1000 the probability of reaching the threshold increases linearly. An electron with a momentum of 10 GeV will be distinguishable from a charged pion with the same momentum, due to this effect. The separation is expected to work well in the range from 1 to 150 GeV.

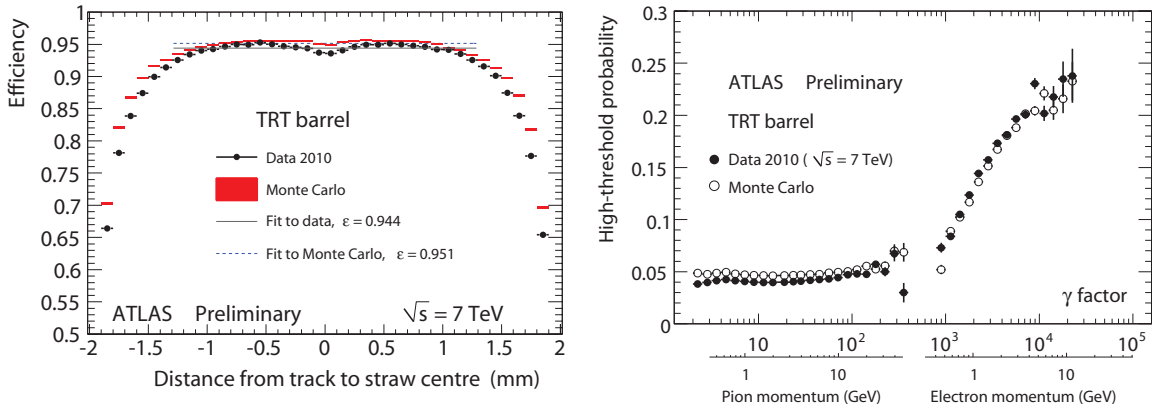


Figure 2.9 – (a) Hit efficiency of tracks in the TRT detector in the barrel. (b) Probability of obtaining a hit above 6 keV, as a function of the γ factor of the particle [51].

2.2.4 Calorimetry

A system of calorimeters surrounds the inner detector and solenoid magnet. Its purpose is to measure the energy of the outgoing particles by means of absorption, but several different techniques are used. Figure 2.10 shows a cutaway view of the calorimetry system. The two main components are the electromagnetic and hadronic calorimeters. The electromagnetic calorimeter is dedicated to measure the energy of photons and electrons. Hadronic showers that are induced by for example quarks, gluons and tau leptons are best measured in the hadronic calorimeter.

Electromagnetic calorimeter

The electromagnetic calorimeter consists of a barrel in $|\eta| < 1.475$ and two endcaps in the region $1.375 < |\eta| < 3.2$. They are sampling detectors, built up from layers of alternating active and passive material. The passive material is lead, where incident particles interact and start a shower of particles. These showers are formed by electrons and photons producing bremsstrahlung and electron-positron pairs. The resulting secondary particles

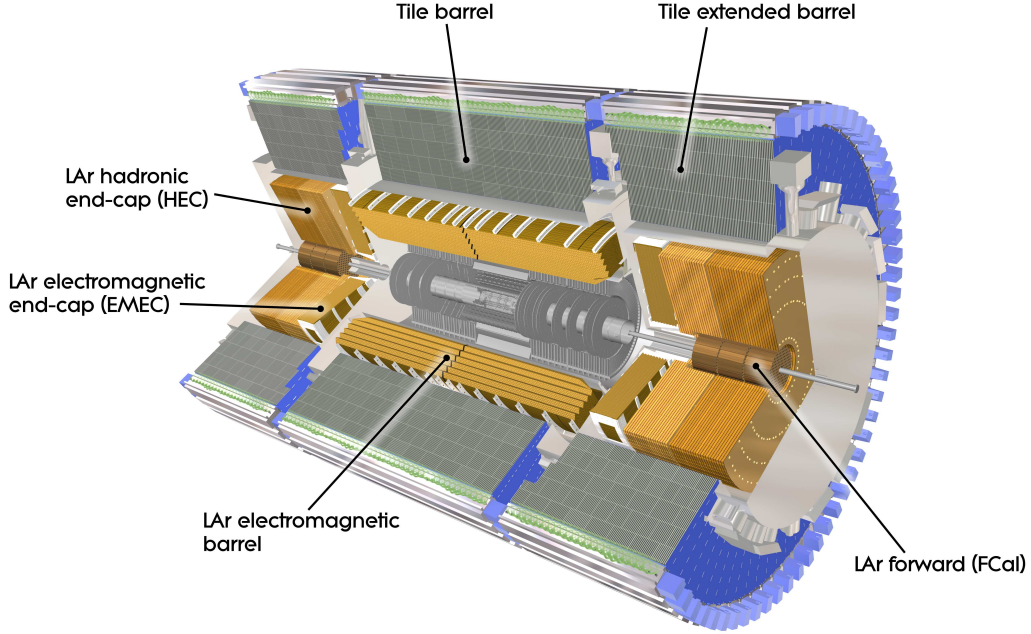


Figure 2.10 – System of electromagnetic and hadronic calorimeters in ATLAS.

are observed in the layer of sampling material, which is liquid argon (LAr) in this case. The charged particles ionize the argon and due to an applied potential, a pulse signal is read out when this happens. Electrodes are installed in the middle of the liquid argon layer for this purpose, at a distance of 2.1 mm from each side.

The plate layer structure is configured in a zigzag method (see Figure 2.11(a)), first of all to ensure that there are enough radiation lengths of material present to absorb the electromagnetic showers. The thickness of the detector is minimally 22 radiation lengths. One radiation length is the distance at which an electron loses a fraction of $(e - 1)/e$ of the energy due to radiation. Secondly, the zigzag setup allows for a complete hermetic coverage in the ϕ direction, without discontinuities. The typical granularity is 0.025×0.025 in $\eta - \phi$ plane, although at the first stage strip cells of $\Delta\eta = 0.003$ are installed for particle identification reasons. The disks in the endcaps (EMEC in the figure) have a larger thickness, up to 38 radiation lengths. Supporting material in large pseudorapidity region decreases the resolution on the energy in this range. In the overlap region (crack region) between the barrel and endcap ($1.37 < |\eta_{cluster}| < 1.52$), the resolution is limited. For this reason we flag electrons found in this region as ‘bad’ and ignore them in analyses in this thesis.

The momentum of the track that belongs to a candidate electron (p) is compared to the cluster energy as measured by the calorimeter (E), in Figure 2.12 [52]. It shows the ratio E/p on the x -axis, for collision data of $\sqrt{s} = 7$ TeV and simulation, after a number of selection cuts. The electrons in this plot are required to have a momentum

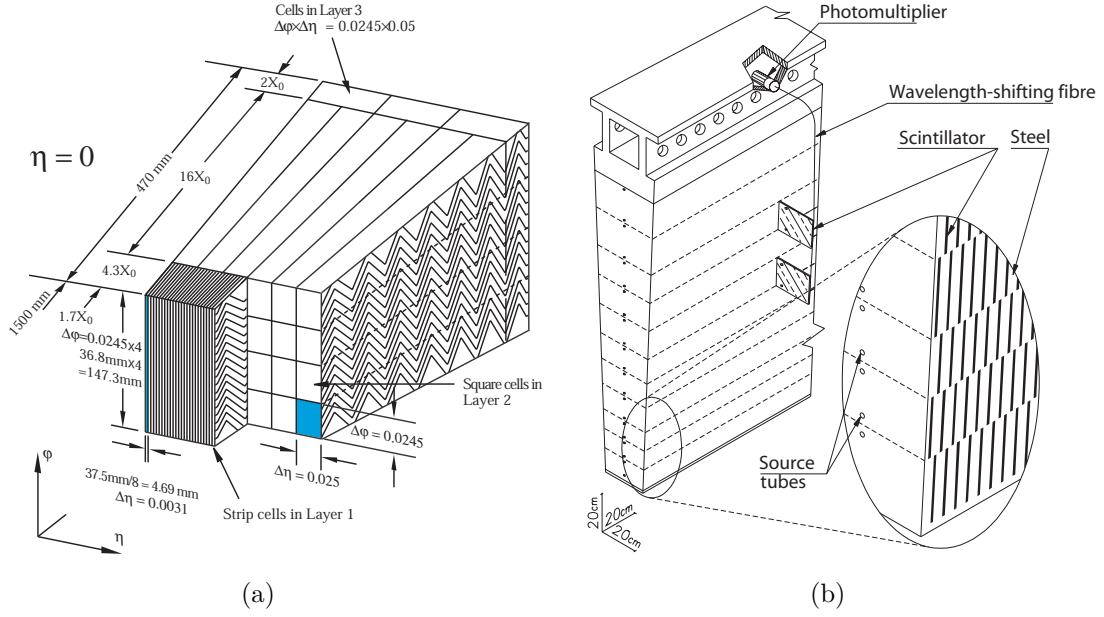


Figure 2.11 – Schematic views of the electromagnetic calorimeter (a) and hadronic tile calorimeter (b).

above 7 GeV. The simulation contains hadrons, secondary electrons (conversions), and prompt electrons from semi-leptonic decays of charm and beauty hadrons. The electron contribution in simulation peaks almost at unity, as expected, with a tail towards the high end of the distribution. The tail arises from bremsstrahlung and an overestimation of cluster energy in some specific cases. Hadrons dominate this distribution at first, but when tighter cuts are applied they are largely removed. The data matches the simulation reasonably well, showing that the calorimeter performance is as expected.

Hadronic calorimeter

The hadronic calorimeter (HCAL) is meant to measure hadronic particle jets that originate from quarks and gluons. They have the property of penetrating the electromagnetic calorimeter. The HCAL consists of a barrel of almost 6 m ($|\eta| < 1.0$), two extended barrels ($0.8 < |\eta| < 1.7$), and two endcaps ($1.5 < |\eta| < 3.2$). They all are sampling detectors as well, but the differences between them are the active and passive materials used. The barrel parts are built from tiles of steel and scintillators. The steel acts as the absorber and the shower it induces in the active material, scintillator tiles, is detected by photomultiplier tubes. The granularity is 0.1×0.1 in η - ϕ space, which is an order of magnitude larger than in the electromagnetic calorimeter, but suitable for the hadronic showers that are wider than electromagnetic showers. The depth in terms of interaction length varies from 7.4 to 9.7. The interaction length is the mean distance a hadron travels before interacting with a certain material. The endcap (HEC) uses copper as passive material and liquid argon as the active readout layer.

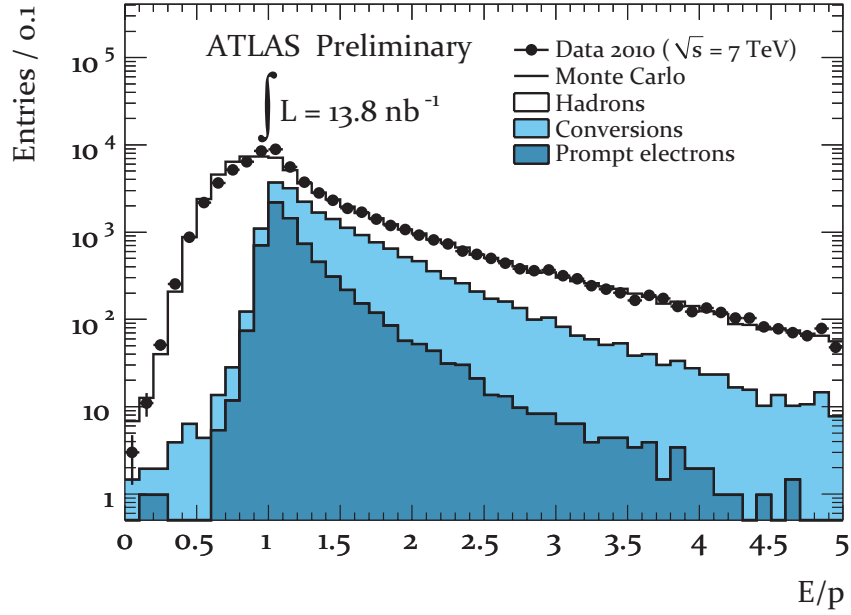


Figure 2.12 – Distribution of E/p for candidate electrons.

The calorimeter response for hadrons is assessed by the E/p distribution of energy clusters that can be matched to good tracks. In this ratio, E is the sum of the energy deposited in all longitudinal layers, evaluated before corrections for non-compensation or dead material losses, and p is the associated track momentum. Figure 2.13 shows the mean E/p as a function of the track momentum, for two η -regions. The background that is formed by neutral hadrons is subtracted. The data set is obtained in 2010 with a CM-energy of 7 TeV. The agreement between data (dots) and simulation (squares) is within 2% for particles below 10 GeV and within 5% for particles above this value.

Forward calorimeter

Finally, the region between $3.1 < |\eta| < 4.9$ is covered with the forward calorimeter (FCAL) to include even the most forward particles. The hermetic design ensures that the computation of the sum of all energy deposits and subsequent energy imbalances (missing transverse energy) can be measured precisely. The FCAL is made from three modules made with copper/liquid argon plates. The first module aims at measuring electromagnetic deposits. The other two are optimized for a high absorption length to absorb all hadronic energy deposits. Finally, by inserting a shielding plug after the three detection layers, the FCAL prevents possible background in the forward muon spectrometer.

2.2.5 The muon spectrometer

The muon spectrometer forming the outer part of ATLAS surrounds the calorimeters and is designed to measure the tracks of all outgoing muons. Its inner radius is 5 m, but the outer parts run up to 10 m. Muons are the only detectable collision products that are

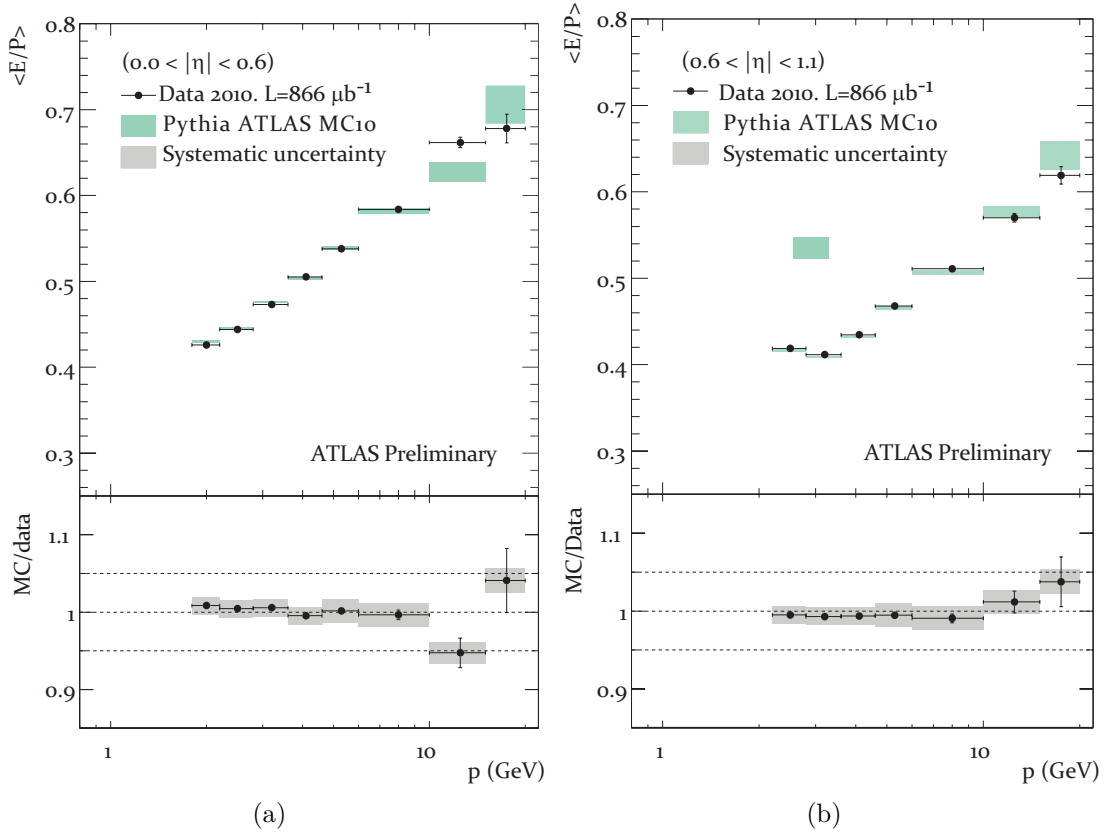


Figure 2.13 – Mean E/p after background subtraction as a function of track momentum for (a) $|\eta| < 0.6$ and (b) $0.6 < |\eta| < 1.1$.

expected to traverse all previously described subdetectors.

In the processes of interest in LHC physics, muons with large momenta (> 10 GeV) appear frequently. Some Higgs boson decays, supersymmetric decays and, of particular interest for this thesis, top quark decays, produce such energetic muons. One of the goals of the muon spectrometer is to efficiently trigger the recording of events that contain high-momentum muons. The other is to measure their tracks precisely and reconstruct the muon momentum from the bending radius of the track due to the applied magnetic field. The design goal is to measure muons over a wide range of momenta to a resolution of 3%, and a muon with a momentum of 1 TeV with a resolution of at most 10%. The curvature of such a high- p_T muon, expressed in the sagitta, is about $500 \mu\text{m}$, hence a resolution better than $50 \mu\text{m}$ is demanded. To achieve the resolution and trigger goals, three concentric layers of detection material are placed in the barrel, and endcaps (also consisting of three layers) fill the forward areas on each side. The layers consist of different subcomponents, each with a dedicated role in the observation of the muons.

The high-precision track coordinates in the z -direction (and R -direction, by construction) are provided by the monitored drift tubes (MDTs). The drift tubes in MDTs are 1-6 m long gas-filled tubes of radius 1.5 cm, with a central tungsten-rhenium anode wire.

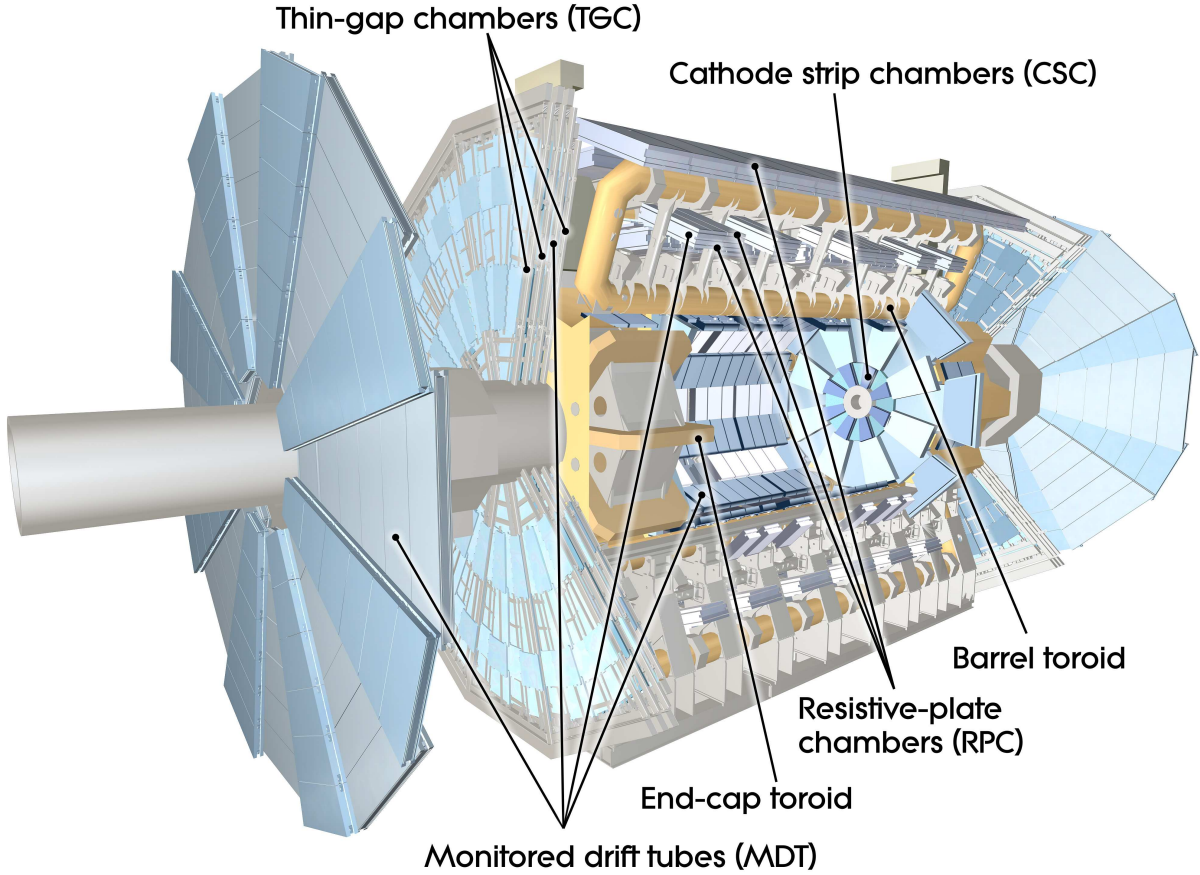


Figure 2.14 – Muon spectrometer of ATLAS.

A potential of 3000 V is applied between the tubes and the wire. A traversing charged particle ionizes the gas (Ar/CO₂) and causes electrons to drift to the wire. Readout channels at the end of the tubes measure a pulse when the charges induce a current over threshold. The timing is important, because it yields the information on the distance between the track of the particle and the center of the tube and determines the resolution in this coordinate. The drift tubes are stacked in multilayers of three or four tubes thickness, of 1-2 m width. Two multilayers mounted on each side of a frame form an MDT chamber. MDT chambers, of which more than 1000 are installed, form the main component of the three layers of the muon spectrometer. In this way they contribute to the track information in the region $|\eta| < 2.7$. The resolution on a track is $35 \mu\text{m}$ per chamber. In the endcap region of $2.0 > \eta > 2.7$ the MDTs in the inner layer are replaced with cathode strip chambers (CSCs). They are multiwire proportional chambers, capable of processing higher particle rates and have better time resolution as well. CSCs are segmented into strips that are placed perpendicularly on top of each other and in this way improve the resolution in the ϕ -direction.

The resistive plate chambers (RPCs) and thin gap chambers (TGCs) form the trigger

component of the muon spectrometer. The RPCs are gaseous detectors, but contain parallel plates instead of wires. A potential of 9800 V is applied between two plates at a distance of 2 mm. The free charges liberated by the traversing charged particle form an avalanche that is detected by readout strips mounted on the anode plate. The time resolution of the RPCs is 1.5 ns. The TGCs are endcap trigger chambers, also based on the principle of multiwire proportional chambers. But, the distance between the wires and the cathodes is optimized to make sure the drift time is faster than the time between two consecutive bunch crossings (25 ns). Besides the time properties of RPCs and TGCs their setup also adds value by the extra coordinate (ϕ) they provide for the track.

Figure 2.15 shows the different areas of the muon spectrometer in η - ϕ space. The CSCs and barrel and endcap regions are introduced already. The BEE are the sectors containing barrel extended endcap chambers, the transition region is the region between the barrel and the endcap, and the feet are the support structure in which detection chambers are missing. The right plot shows the variation of the efficiency of reconstructing a muon as function of the different regions. This efficiency is obtained with a tag-and-probe method in $Z \rightarrow \mu\mu$ events. It includes information of the inner detector tracks as well and is plotted relative to the inner detector efficiency. The efficiency is always above 90% and in good agreement with the simulation.

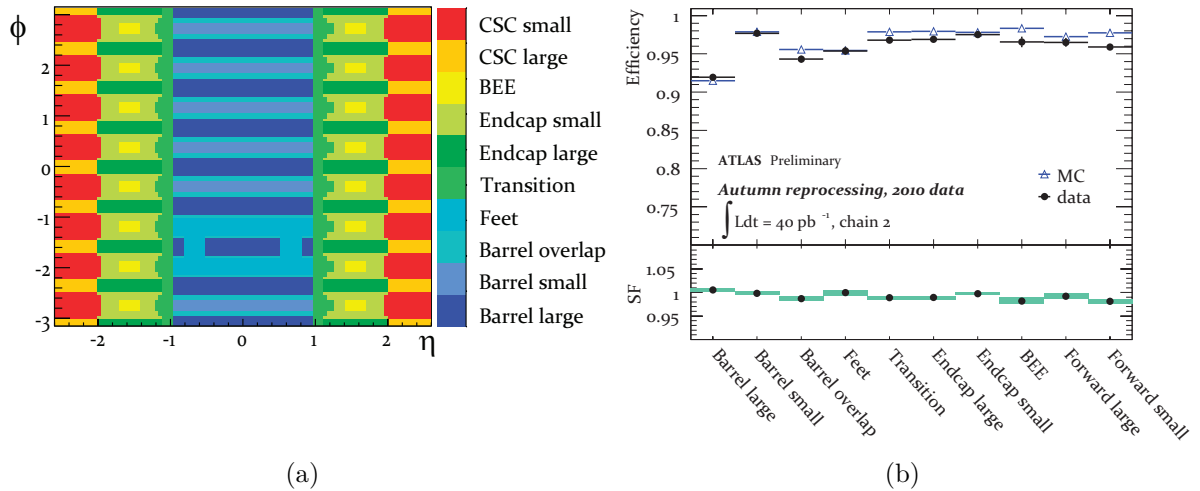


Figure 2.15 – (a) Map of coverage of the muon detector, divided in detector subregions. (b) Reconstruction efficiency of muons as a function of detector subregion [53].

The resolution of muons is studied via the width of the Z boson resonance in muon pairs, in data obtained in 2010. Figure 2.16 shows the invariant mass distribution for oppositely charged muons with a transverse momentum larger than 20 GeV, in the region $|\eta| < 1.05$ (barrel). The muons are reconstructed using both inner detector information as well as the muon spectrometer. The resolution on the mass is 2 GeV, which is comparable, but slightly worse than the $Z \rightarrow \mu\mu$ events that are simulated with PYTHIA. Additional alignment and calibration corrections should solve this.

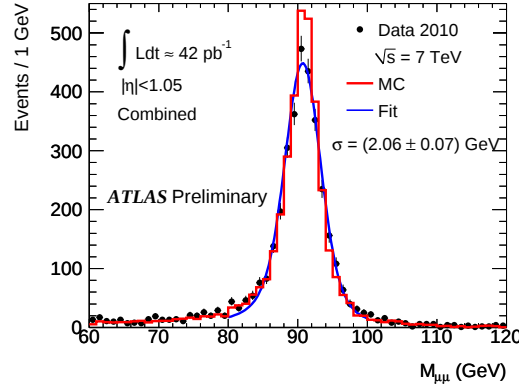


Figure 2.16 – Invariant mass distribution for combined muons with 42 pb^{-1} .

2.2.6 The ATLAS trigger system

Under optimal conditions, the amount of collisions produced per second by the LHC approaches one billion. This is too much to record for analysis. The storage space required for an average event is in the order of megabytes, which means that about one petabyte of data would have to be processed and stored, per second. On the other hand, the vast majority of collisions are uninteresting for high-momentum event studies. This is the case when partons in the two protons collide without exchanging some minimum of transverse momenta, so-called ‘soft collisions’. For these reasons a system of online selection is designed that instantly decides, per event, whether or not to record it. The trigger system is built to have three stages of decision, Level 1 (L1), Level 2 (L2) and Event Filter (EF), with a design output rate of 200 events per second.

Level 1 trigger

The L1 trigger is a hardware trigger that uses information from the muon trigger components and the calorimeters. The muon triggers (RPCs and TGCs) and calorimeters are read out in sets of multiple modules, to reduce processing time. In the muon element of L1, the algorithm searches patterns of hits in the RPC and TGC that are consistent with muons that stem from the interaction point. The number of muons above a certain p_T threshold is input to the final decision made in L1. From the calorimeter element of L1, large energy depositions that indicate photons, electrons or hadrons are identified. Areas in $\eta - \phi$ around the clusters are labeled as regions of interest. Global quantities like the total transverse energy and the energy imbalance are also used as flags for interesting events. When the information of the muon and calorimeter is combined and matches any of the proposed signatures, the information is passed on to L2. For instance, a signature can be one isolated electromagnetic cluster above 20 GeV in combination with two jets of 20 GeV.

To maintain a sustainable output rate, it is possible to prescale a trigger. This means that for example only one in five events that fulfill the requirements is saved. The entire process

of L1 deciding whether proceed takes maximally $2.5 \mu\text{s}$. The output rate is reduced from 40 MHz to 75 kHz in the design.

Level 2 trigger

The L2 trigger is software based. It returns to the regions of interest as they were defined by the L1 and acquires the complete, fully granular detector data within these regions. That means that the inner detector data is included in the decision. The algorithm then attempts to reconstruct objects and perform an improved selection with respect to L1. The resulting design output rate of L2 is 2 KHz.

Event filter trigger

When an event successfully passes the previous steps, the event filter performs a complete analysis on it. At this point it makes use of the full detector information and all reconstruction and analysis algorithms that are available. An event is accepted if it passes L1, L2 and the event filter based on the same objects, passing the complete trigger chain.

The event filter assigns the events to different streams, depending on its characteristics. For example, an event with a high- p_T muon and three high- p_T jets will be stored both in the muon stream and the jet-tau- $\cancel{E}_T$ stream. This grouping makes it easier to select a set of events for a particular offline analysis. In our analysis we look at the e/γ stream for $t\bar{t} \rightarrow e + \text{jets}$ events and in the muon stream for $t\bar{t} \rightarrow \mu + \text{jets}$.

The output rate of the event filter is designed to be about 200 Hz, a number that is limited mostly by the anticipated storage space availability.

Trigger chains

Offline, we select events based on the ‘trigger chain’ they passed. The trigger chain is the sequence of algorithms a candidate object is subject to. This can for example be an electron passing the quality and energy thresholds of the subsequent L1, L2 and event filter algorithms. The naming of the trigger chain is characterized by the final requirements, e.g., we select events that fulfill `EF_mu13_tight`, meaning that the online momentum threshold for this muon was 13 GeV, and the quality indication is ‘tight’ (corresponding the to the quality definitions of the purest set of muons).

The ATLAS detector runs with numerous trigger chains simultaneously, and the menu of trigger chains varies over time, depending on the LHC luminosity conditions.

Performance

Figure 2.17(a) shows the output rate of the different trigger levels for run 167607, recorded in 2010. This was the run with the highest peak luminosity in that year. Level 1 reaches about 30 kHz, L2 4 kHz and event filter finally reduces the rate to 500 Hz. That means that the output rates of L2 and the event filter top the design values quoted before. An output rate this high cannot be maintained for a longer period of time, because the

data distribution will clog and the storage space will fill up too fast as well. However, for shorter time periods these figures are reachable. The small dip halfway is due to a hardware synchronization that was performed at this time. Figure 2.17(b) subdivides the output rate of the event filter for the same run into the four main trigger streams. The e/gamma stream, containing photons and electrons, forms the largest contribution and takes up to 100 Hz. The other streams produce output of order 20-40 Hz. Not all streams are included in this figure.

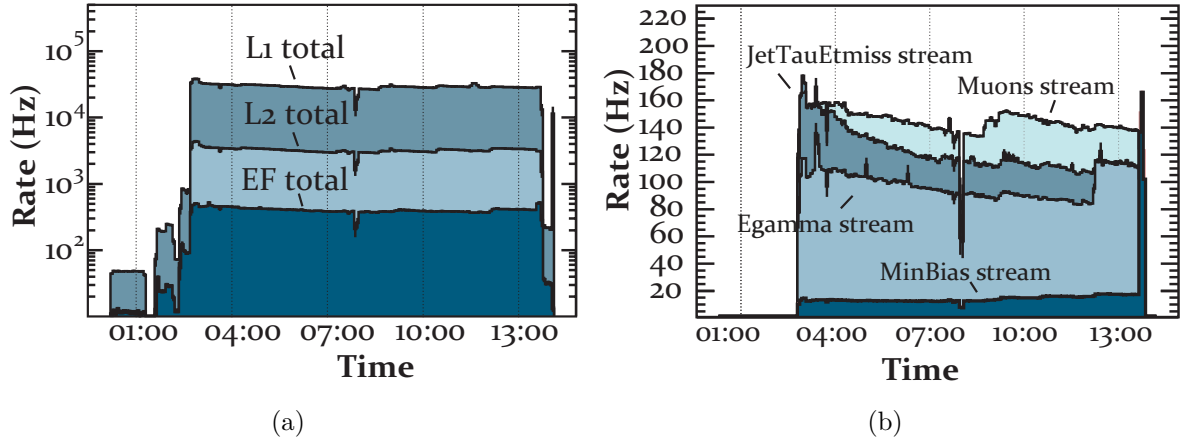


Figure 2.17 – (a) Trigger rates of ATLAS, per trigger stage, for a run in 2010. (b) Event filter trigger rates divided into the important physics streams, for the same run in 2010.

Data distribution

The different trigger streams contain events with the complete reconstructed information. They are stored on tape at CERN. Slimmed event information, containing the information relevant to most physics analyses is extracted from the raw output. This information is sent from CERN, the Tier-0 center, to a number of Tier-1 centers, around the world. In turn, these Tier-1 sites distribute the data to a finer web of Tier-2 centers. All of this happens within hours after reconstructing the events, making all data quickly available to collaborators around the world. The analysts, finally, run their analysis on a version of the event files that is stored on a Tier-2 site, using the computing power of that computer center.

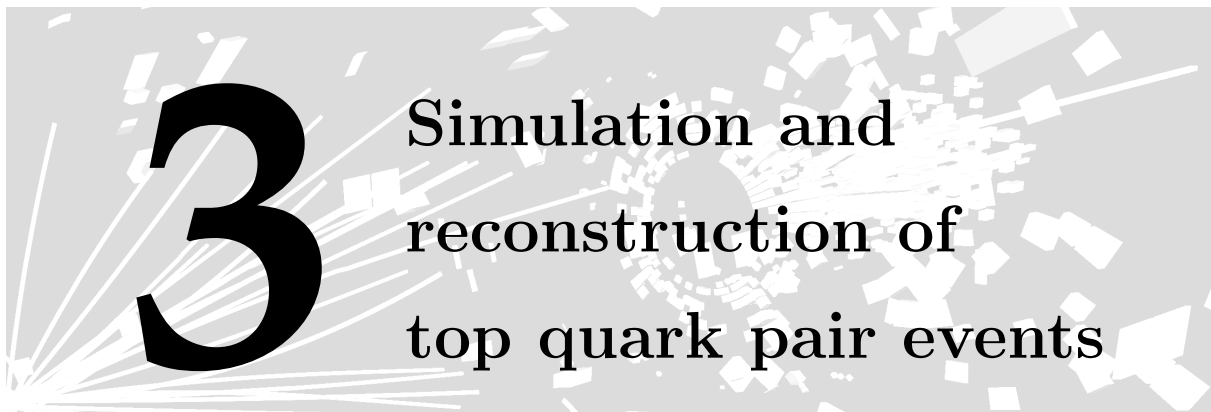
2.3 Summary

The ATLAS detector operates according to expectations, the different subdetectors achieve high efficiencies. Table 2.2 shows the fraction of operational channels per subdetector at the end of 2011, and in brackets at a moment before data start-up in 2009. Most percentages are well above 95%, with some exceptions. The fractions tend to decrease slightly over time, due to failure of equipment or other reasons.

Table 2.2 – Fraction of operating time for subdetectors in ATLAS, at the end of 2011 and in parentheses in 2009.

Subdetector	Number of channels	Appr. operational fraction
Pixels	80 M	95.9% (98.5%)
SCT	6.3 M	99.3% (99.5%)
TRT	350 k	97.5% (98.2%)
LAr EM Calorimeter	170 k	99.9% (99.1%)
Tile Calorimeter	9800	99.5% (99.5%)
Hadronic endcap	5600	99.6% (99.9%)
Forward Calorimeter	3500	99.8% (100%)
LVL1 Calo trigger	7160	100% (N.A.)
LVL1 Muon RPC trigger	370 k	98.4% (N.A.)
LVL1 Muon TGC trigger	320 k	100% (N.A.)
MDT	350 k	99.7% (99.3%)
CSC	31 k	97.7% (N.A.)
RPC	370 k	93.8% (95.5%)
TGC	320 k	99.7% (99.5%)

The Large Hadron Collider is running smoothly since 2009 and produced a substantial number of collision events in 2009, 2010 and 2011. The CM-energy is ramped up to 7 TeV, and the milestone of 1 fb^{-1} of data recorded by ATLAS was already achieved before summer of 2011. At the moment of writing, over 5 fb^{-1} of data is recorded. The amount of data that has been recorded in the first years of the LHC and the good detector conditions make it possible to investigate top quarks very precisely.



3 Simulation and reconstruction of top quark pair events

As in nearly all particle physics research, we compare observable quantities in data to their theoretical predictions in order to be able to quantify the level of understanding of the observations. The predictions are obtained by detailed simulation of the collisions and detector response. For instance, to measure the production cross section of top-antitop quark pair ($t\bar{t}$) events, we compare the number of events observed in data to the number we expect according to the Standard Model predictions. Besides this overall rate, also differential distributions—for example, the angular distribution of hadronic jets—are compared between the predictions and observations.

We describe the simulation of collisions between protons at LHC energies in this chapter. The simulation of collision events in ATLAS consists of several steps, as indicated in Figure 3.1. At the first step, particle collisions are generated with Monte Carlo event generators. This encompasses the simulation of the hard scattering between partons in the protons, their decay products (including the emission of extra partons), the hadronization to evolve the partons to colorless physical particles, and the description of the behavior of the proton remnants. During a second step, the produced particles are fed to a simulation that mimics the response of the ATLAS detector. In this step the interactions and decays of the particles with the magnetic field and the detector elements are simulated. During the last step, the digitization, the electronic signals that result from the energy losses of particles in the detector geometry are described. In this way, the output format of the detector response matches the actual format of the data. Finally, a sets of algorithms is applied in order to reconstruct physics objects from the digitized output of both the data and the simulation chain.

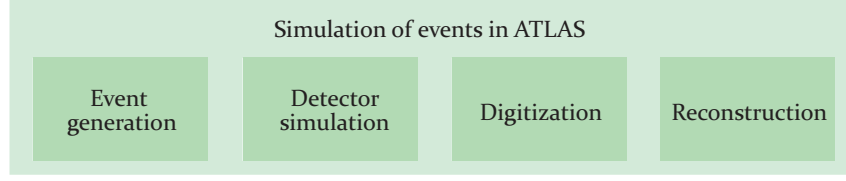


Figure 3.1 – Consecutive steps in the simulation of collision events.

In this chapter, we discuss the four steps of event simulation (event generation, detector simulation, digitization and reconstruction) in more detail. This includes a separate study on the emission of extra partons during the generation of $t\bar{t}$ events, and the effect this may have on our results in the analyses that are conducted later.

Section 3.1 treats the different phases of the generation of events. In Section 3.2 we discuss the simulation and response of the ATLAS detector. The simulated samples of signal and background that we use throughout the analyses are described in Section 3.3, followed by the reconstruction of the physics objects in Section 3.4. Finally, in Section 3.5, we present a more detailed analysis of the effect of initial and final state radiation in top quark pair events.

3.1 Event generation

The generation of a collision event is split up according to the factorization principles we described earlier in Section 1.3.1, and as depicted in Figure 3.2. The factorized event generation process distinguishes between the hard scattering of the partons in the protons, the parton showers, the hadronization of the partons, and the subsequent decays of hadrons and leptons. Each part corresponds to a process at a different energy scale and is treated as an independent step. In the following we discuss these steps, where we include the treatment of so-called ‘underlying events’ that occur in addition to the hard scattering as well.

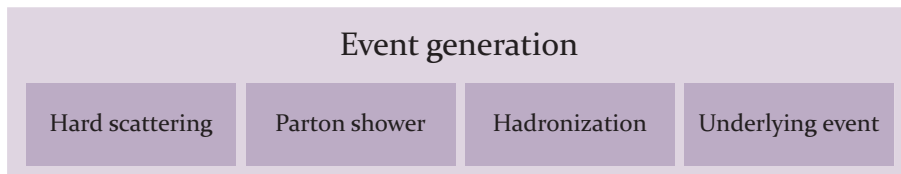


Figure 3.2 – Processes of the event generation.

3.1.1 Hard scattering

The process in which two partons of the colliding protons interact, and outgoing partons emerge from the propagator, is described by the hard scattering. Quark-antiquark annihilation, forming a gluon that splits into a top-antitop quark pair is an example of a hard scattering, as discussed in Section 1.3.1. The energy scale connected to this part of the

collision process can be up to the order of several TeV. The partonic cross section of the physics process connected to this hard scattering consists of matrix elements and phase space factors. The matrix elements can be calculated with perturbative techniques, we discussed this in Section 1.3.1 in view of top quarks.

In an event generator, candidate events are obtained by pulling a random configuration of the partons from the possible positions in phase space. In this way, all incoming and outgoing partons obtain a defined four-momentum. The differential cross section of that candidate event, the weight, can then be calculated from the probability obtained with the PDFs, the value of the matrix element and the phase space factor. The weight then corresponds to the probability of the occurrence of this particular candidate event. To obtain a sample of events that is proportional to the total cross section and has physical observables, an accept-reject method is deployed. This results in simulated events with characteristics of real events, produced according to the probability for the events to occur as predicted by the Standard Model. The set of generated outgoing partons are subject to decay and parton showering.

3.1.2 Parton showering

Each colored and charged parton coming out of the hard scattering has a probability to emit quarks, gluons or photons. This process of radiation results in a shower of partons. In practice, this shower is not calculable beyond a limited number of tree level splittings and neither are virtual emission nor absorption. Therefore, this step of event generation is approximated with parton shower models.

A parton shower model treats the branching as a step-by-step evolution from the energy scale of the hard scattering, down to a low cutoff scale. The cutoff scale is arbitrary, but of order 1 GeV, usually, and corresponds to the energy scale at which the strong coupling constant approaches a value at which tree level approximation is no longer valid. At any time, a parton a has a probability of splitting into partons b and c . The momentum of the initial parton a , is divided over partons b and c that are assigned with momentum fraction z and $(1 - z)$, respectively. Subsequently, the partons b and c each have a probability to branch themselves as well.

We will make a distinction between initial state radiation (ISR) and final state radiation (FSR), which is only valid at leading order. Initial state radiation is formed by the gluons or quarks that are emitted from a parton that is involved in the hard scatter, before it undergoes the interaction. Final state radiation is radiation of the partons that are the result of the hard scattering, or of any other spectator partons not involved in it. This is depicted in Figure 3.3(a). The radiation is usually of electromagnetic or strong interaction nature. An example of evolution of the parton shower is given in Figure 3.3(b).

The splitting evolution is handled in terms of a ‘pseudo time’ variable t that depends on the momentum scale Q , by $t = \ln(Q^2/\Lambda^2)$ (Λ is the QCD scale, the scale at which the coupling constant of QCD becomes of order 1). In this picture, when going from a large value of Q^2 , losing energy and running down to the cutoff scale is equivalent to t running

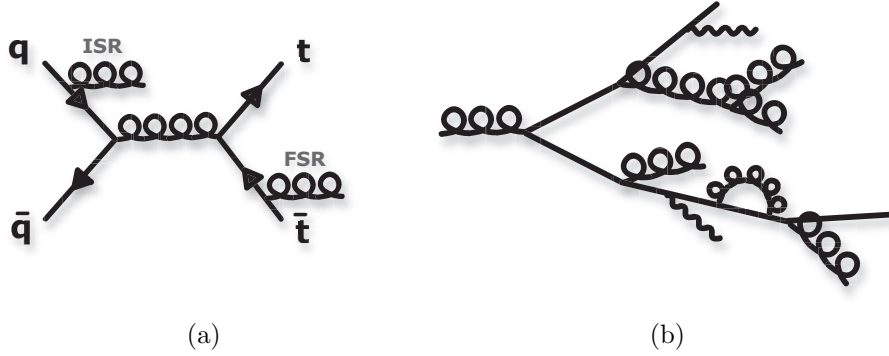


Figure 3.3 – (a) Hard scattering ($t\bar{t}$ event) with initial and final state radiation. (b) Example of parton shower evolution.

from t_{max} to a smaller value. This corresponds to FSR. ISR is treated the other way around and evolves starting from t_0 to the momentum scale of the hard scattering.

The differential probability of a branching of type $a \rightarrow bc$ is given by

$$d\mathcal{P}_a = \sum_{b,c} \frac{\alpha_{abc}}{2\pi} P_{a \rightarrow bc}(z) dt dz,$$

where $P_{a \rightarrow bc}$ are the splitting kernels, depending on the type of parton. This splitting kernels are $g \rightarrow gg$, $g \rightarrow q\bar{q}$, $q \rightarrow qg$, $q \rightarrow q\lambda$ and $l \rightarrow l\lambda$, where the latter two are non-QCD (lepton and photons). For QCD splittings $\alpha_{abc} = \alpha_s$, for QED $\alpha_{abc} = \alpha_{EM}$. The integral of the probability of a parton to branch to a specific b and c for a given t , is then expressed as

$$\mathcal{I}_{a \rightarrow bc}(t) = \int_{z^-(t)}^{z^+(t)} \frac{\alpha_{abc}}{2\pi} P_{a \rightarrow bc}(z) dz.$$

Hence, $\mathcal{I}$ runs over the range of possible z values. The probability for the parton to branch to *any* b and c , during a time δt , is the sum of $\mathcal{I}$ over all final states. Finally, the probability of parton a to branch at time t is composed of the sum of all integrals $\mathcal{I}$ multiplied with an exponential suppression factor:

$$\frac{d\mathcal{P}_a}{dt} = \left(\sum_{b,c} \mathcal{I}_{a \rightarrow bc}(t) \right) \cdot e^{-\int_{t_0}^t dt' \sum_{b,c} \mathcal{I}_{a \rightarrow bc}(t')}.$$

The suppression factor, the exponent, is known as the Sudakov form factor and represents the probability that parton a did not branch in the given time interval. The equation looks slightly different for FSR, as the integral will run from t to t_{max} whilst the Sudakov factor is defined from the lower cutoff t_0 .

The choice of shower parameters is important for our studies. Different settings of the event generators—of the value of the momentum cutoff scale, for example—may alter the energy that is contained in the jet (more final state showering), the parton-jet mapping (extra jets) and therefore the jet multiplicity. This affects the top quark reconstruction and as a consequence, the cross section measurement. We study these effects in simulation, in Section 3.5.

3.1.3 Hadronization

After the parton shower, ‘colored’ partons remain that undergo a transition to ‘colorless’ hadronic particles. The hadrons, or decay products of hadrons are the observable particles in the detector. The transition from quarks and gluons to colored hadrons is the hadronization (or fragmentation) step. Hadronization is a non-perturbative process (α_s is large), and therefore has to be modeled. Different models exist that describe hadronization, of which ‘cluster fragmentation’ [54] and ‘Lund string fragmentation’ [55] are the most used.

In cluster fragmentation, the shower has ended with the creation of quark-antiquark (color-anticolor) pairs. Color neutral clusters are formed from neighboring sets of quarks. The clusters, in turn, decay into hadrons that can be observed.

In string fragmentation, a color ‘string’ is formed between the quark and antiquark that belong to a pair. The string represents a color field that increases in potential energy when the quarks move apart. The string can break when enough energy is contained, producing new $q\bar{q}$ pairs.

The energy regime at which hadronization starts is at the cutoff scale for parton showers, ~ 1 GeV. A higher cutoff value, and thus an earlier terminated shower, would result in less partons, that each have higher virtuality. This has an effect on the number of hadrons and in this way on the number of jets that are found in the simulated event. The hadronization phase of the event is tuned to match data collected by previous experiments. The potential decay of the resulting hadrons follows the Standard Model theory, yet the relative branching fractions are obtained empirically.

3.1.4 Underlying event

The proton remnants, i.e., the quarks and gluons that are not involved in the hard scattering, can also interact with each other. This is called the underlying event. Partons in the proton that are not involved in the hard scattering can produce secondary interactions of any type. Generally, a $2 \rightarrow 2$ QCD process is assumed to occur, as this has by far the largest cross section. The secondary interactions can be of high transverse momenta in some cases, but most of the time they only produce soft interactions. But, theoretically all processes in the Standard Model contribute to the underlying event. The treatment of the underlying event is tuned to pre-LHC data.

Outgoing partons of the underlying event are subject to the parton showering and hadroniza-

tion steps as well. Underlying events can affect the particle multiplicity in an event, especially in jet-rich events, but it is relatively unlikely to affect rare high- p_T processes like top quark production.

3.2 Detector simulation and response

The energy deposits of the generated particles in the ATLAS detector are mimicked with the GEANT4 toolkit [56]. With this software, a complete simulation of all geometrical and material properties of the ATLAS detector is constructed. This makes it possible to model the interaction of particles with the detector parts within the magnetic field that is present in the ATLAS detector. The modeling includes potential decays of the particles. Each particle of the generated event will lose energy according to the particle's characteristics and the properties and layout of the material it traverses.

The behavior of the detection material responses to the particle are modeled too, in the process of ‘digitization’. When a particle hits a sensitive area, the energy that it deposits is translated to an electronic signal. In this way, any generated particle produces hits and signals, equivalent to the data output. By the step of digitization, the generated events are transformed into the format that is identical to the output of the ATLAS detector when recording data. Subsequent reconstruction of physics objects is performed equivalently for data and simulation.

Figure 3.4 shows an example of a reconstructed event, in a cutaway view of the simulated ATLAS geometry. It displays the support structure of ATLAS, including the magnet system, in gray colors. The MDT chambers are shown in blue. The event contains tracks in the inner detector, and energy deposits in the electromagnetic and hadronic calorimeter. A reconstructed muon and the total transverse energy imbalance ($\cancel{E}_T$, discussed later in this chapter) in the event are shown with a solid and dashed line, respectively.

3.3 Event samples for analysis

In this thesis we make use of several event generators to model signal ($t\bar{t}$) and background events.

3.3.1 Signal samples: top quark pairs

There is a multitude of event generators that attempts to describe the production of $t\bar{t}$ events. Most differences among them originate from the amount of extra radiation that are included in the matrix element calculation and the interface to the parton showering stage. In this thesis, the nominal sample of use is a combination of MC@NLO, HERWIG, and JIMMY for the underlying event. The matrix elements are calculated with MC@NLO, a next-to-leading order (NLO) generator [57]. The generated partons are input to the parton showering and hadronization schemes in HERWIG [58]. JIMMY simulates the underlying event. Alternatively we use POWHEG [59] (also NLO) as a matrix element generator that

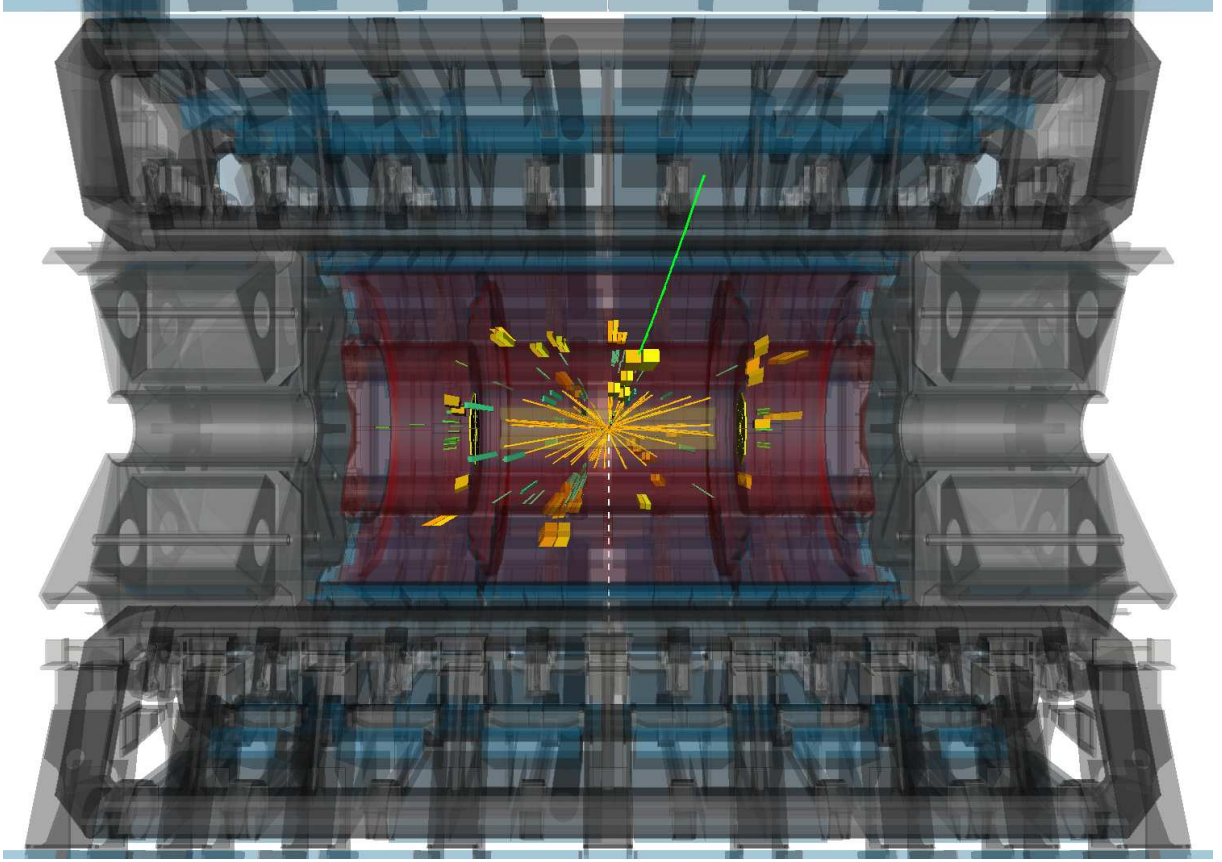


Figure 3.4 – Event display of event 2456382 of run 183602 in 2011. It shows hits and tracks in the inner detector, energy clusters in the calorimeters corresponding to hadronic jets and a reconstructed muon in white (going upwards). The reconstructed $\cancel{E}_T$ is depicted with the dashed line.

can be used in combination with HERWIG, but also with PYTHIA [60]. Finally, we use ACERMC [61], a leading order generator, for some systematic uncertainty evaluations at lowest order. The yields of the different generated samples are normalized to the calculated NNLO value of the inclusive cross section. This is done by applying a ‘K-factor’. The samples are summarized in Table 3.1. The top mass is taken to be 172.5 GeV in these simulations.

3.3.2 Background samples

The decay mode of $t\bar{t}$ we are interested in, is the single-lepton decay channel: $t\bar{t} \rightarrow W^+b + W^-\bar{b} \rightarrow q\bar{q}b + l^-\bar{\nu}b$ (or the charge conjugated version). A schematic view of this mode is shown in Section 1.3.3. The decay products are two b -quarks and two lighter quarks, together resulting in four hadronic jets, and a lepton, all with substantial transverse momentum. Additionally, the neutrino that is invisible to the detector produces an energy imbalance in the transverse plane, the missing transverse energy.

Table 3.1 – Generators for $t\bar{t}$ simulation. The cross section represents only the fraction of $t\bar{t}$ events in which one or more W bosons decay leptonically.

Generator	$\sigma(7 \text{ TeV})$	K-factor
MC@NLO+HERWIG	80.20 pb	1.11
POWHEG+HERWIG	79.12 pb	1.13
POWHEG+PYTHIA	79.12 pb	1.13
ACERMC+PYTHIA	58.23 pb	1.53

The backgrounds to $t\bar{t}$ processes come from processes that have similar signatures. This encompasses W and Z boson production with associated extra jets, the production of single top quark events and plain multijet production. We discuss the background samples below, and summarize the numbers in Table 3.2.

- **W+jets.** Production of a single W boson that decays into a lepton-neutrino pair, see an example in Figure 3.5(a). Extra jets can result from radiation of the partons, and especially relevant is the splitting to a $b\bar{b}$ -pair that can occur. In this case the signature is very similar to top quark decay. The cross section of W boson production in combination with a leptonic decay at a CM-energy of 7 TeV ranges from 20.6 nb for $W+0$ jets (exclusive) to 21 pb (three or more orders of magnitude) for $W+5$ jets (inclusive). ALPGEN (leading order, no virtual corrections) describes a fixed number of jets above a $p - T$ threshold in the hard scattering with the matrix element and is interfaced to either PYTHIA or HERWIG for additional showering and hadronization process. It is used as the default generator for W +jets events. The events with high jet multiplicity form the major background to the analyses described in this thesis.

The normalization of W +jets events is subject to a large uncertainty, in events with four or more jets this is estimated to reach 48% [62]. In addition, the amount of b and c quarks produced in association with the W boson is theoretically uncertain. In Chapter 4 we discuss the methods we implemented to reduce the dependence on simulation. For example, for the charge asymmetry analysis we use a data-driven method to obtain the normalization, whilst taking the shapes of the observable distributions from the simulated samples.

- **Z+jets.** Production of a single Z boson that decays into a charged-lepton pair, with extra jets, as in Figure 3.5(b). The cross section (times branching ratio to a charged-lepton pair) is an order of magnitude smaller than W bosons decaying to lepton-neutrino pairs. This type of background can be reduced strongly when a second lepton is vetoed during event selection. It is described in ALPGEN, similar to W +jets.
- **Single top.** Production of a single top or antitop quark. This process occurs

through the weak force and produces a top quark in combination with a light quark, a b -quark or a W boson, and possibly with extra jets, making it a background difficult to reduce. The cross section is sufficiently low, however. The total cross section, combining the three production channels, is below 40 pb. The largest channel, the t -channel (as in Figure 3.5(d)) producing a top quark in conjunction with a b -quark has a cross section of 24 pb (taking only the events in which the W boson decays into a lepton-neutrino pair). Single top production is described with MC@NLO+ HERWIG and ACERMC + PYTHIA. The K-factors can take values below 1, in case of the t -channel [63].

- **Diboson.** Production of a WW , ZZ or WZ pair, all of which can result in leptons, jets and missing transverse energy. The first is depicted in 3.5(c). The cross section is low, compared to all other processes, 15.9 pb in total, at a CM-energy of 7 TeV. The generator we use for this type of processes is MC@NLO + HERWIG.
- **Multijet.** Processes producing only quarks and gluons and hence a number of observable hadronic jets. Multijet production is the most common result of an inelastic proton-proton collision. Estimates for the cross section (depending on the number of jets produced) can be of order 10^7 , but are affected by large uncertainties. The production rate is huge, but the signature itself is quite different from the single-lepton top quark decay. Still, when a jet is misidentified as a lepton, or a real lepton is present in a jet, multijet events can contaminate the selection. Since the uncertainty of the cross section of the production of n jets is large, we do not rely on simulated samples for this process. Instead, we use data-driven techniques to assess this background, as will be discussed in Chapter 4.

Table 3.2 – Generators for background simulation. The cross sections only represent the events in which at least one of the bosons decays leptonically. The K-factors indicate the correction to obtain a value at NNLO-level.

Type	Generator	$\sigma(7 \text{ TeV})$	K-factor
W +jets	ALPGEN+HERWIG	26182 pb	1.22
Z +jets	ALPGEN+HERWIG	2541 pb	1.22
Single top (Wt , s -channel)	MC@NLO+HERWIG	16.0 pb	1-1.1
Single top (t -channel)	ACERMC+PYTHIA	24.2 pb	0.9
Diboson	MC@NLO+HERWIG	15.94 pb	1.30-1.60

3.4 Object reconstruction

After the detector simulation and digitization steps, the output format of simulated events is identical to data. From then on, data and simulation are subject to the same set of algo-

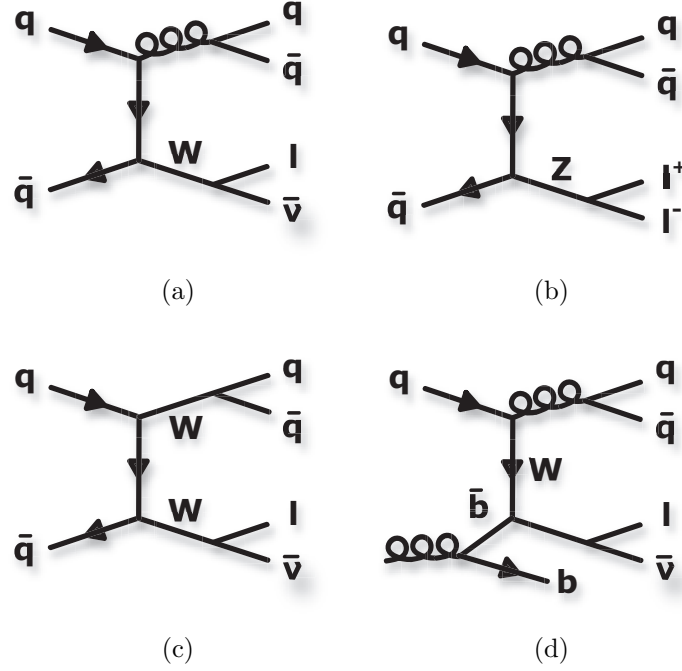


Figure 3.5 – Example diagrams of physics background: (a) W +jets (2 extra jets), (b) Z +jets (2 extra jets), (c), diboson (WW), and (d) single top (t -channel).

gorithms for reconstructing physics objects. In this section, we describe the reconstruction of electrons, muons, hadronic jets and missing transverse energy.

3.4.1 Electron reconstruction

Energy deposits (clusters) in the electromagnetic calorimeter that can be matched with a charged particle track form electron candidates in our offline selection. A match between the cluster and the track is established if the extrapolated inner detector track is within a window of $\eta \times \phi = 0.05 \times 0.1$ around the energy cluster in the calorimeter. A threshold of 2.5 GeV is imposed on the cluster energy. The electron candidate has to pass a number of quality cuts, to eliminate noise from photon conversions and jets that fake an electron. Among them are a minimum number of hits in the pixel and SCT detectors and a constraint on the width of the electromagnetic shower. The transverse energy of an electron is defined as $E_T = E_{clus} / \cosh(\eta_{track})$, using the total energy of the cluster and the direction of the matched track. The cluster energy is corrected for energy losses before the calorimeter, and for lateral and longitudinal leakage.

The efficiency of measuring electrons and muons is usually split up in a trigger component, a reconstruction component, and an identification component. Each efficiency represents one step in the process from going from a loosely defined inner detector track, to a well-defined ‘tight’ lepton that passes trigger, lepton quality requirements and the analysis-specific lepton selection (‘identification’). The latter is analysis-specific, since for example

top quark analyses use different isolation criteria than others. To some extent, the trigger efficiency is analysis-dependent as well, since the choice of the trigger and its momentum threshold depend on the typical transverse momentum or energy range of the lepton in the physics analysis. All three efficiencies are measured independently in data using so-called tag-and-probe methods and compared to simulated values. Scale factors are introduced to scale the simulation to match the data efficiencies, as a function of η , p_T or E_T . These scale factors are supplied by the ATLAS performance subgroups.

Trigger efficiency

The trigger efficiency for electrons in the 2010 data set is shown in Figure 3.6(a) as a function of the transverse energy of the electron. The efficiency is obtained from a tag-and-probe method in a $W \rightarrow e + \nu$ sample. Events are triggered with a trigger orthogonal to the lepton trigger, the $\cancel{E}_T$ trigger, after which a selection aimed to isolate the signal events is applied. After subtracting the residual background events, a pure sample of $W \rightarrow e + \nu$ events remains. The electron then forms the probe, and the electron trigger efficiency is the ratio of events where an offline electron was found, with respect to all selected events. After the turn-on curve in the low- p_T range, the efficiency forms a plateau where it reaches an efficiency of about 99%. The difference between simulation and data is small, but any difference in data and simulation efficiencies is corrected for with a scale factor in the later analyses.

Reconstruction efficiency

The efficiency of reconstructing electrons, the step from a loosely defined inner detector track to a ‘tight’ electron is also obtained from tag-and-probe studies. A pure sample of electron probes is defined from $Z \rightarrow e + e$ events where the ‘tag’ is one of the two electrons. The reconstruction efficiency obtained from the latter is shown in Figure 3.6(b). It is given in bins of η and is 95% in the region $|\eta| < 1$ and 90% beyond this region. This is due to the requirement on the number of hits in the silicon detector [64].

The resolution of reconstructed electrons is obtained from the same type of Z boson events. The reconstructed mass of the Z boson in data is compared to simulation. For example, events in 2010 data with electrons in the range $|\eta| < 2.47$ show a width of 1.88 ± 0.08 , whereas in simulation this is 1.60 ± 0.02 [64]. Electrons in simulation are corrected for the measured energy resolution.

3.4.2 Muon reconstruction

Muons are reconstructed from inner detector and muon spectrometer information. In the muon spectrometer, series of hits in a muon chamber (two multilayers) are combined and a straight track is fitted through. The hit position follows from the drift circles in each tube: a large drift circle, constructed from the time spectrum of the signal, indicates that the muon has passed through close to the borders of the tube. Vice versa, a small drift circle means the muon passed through the center. The fit through a series of hits in a

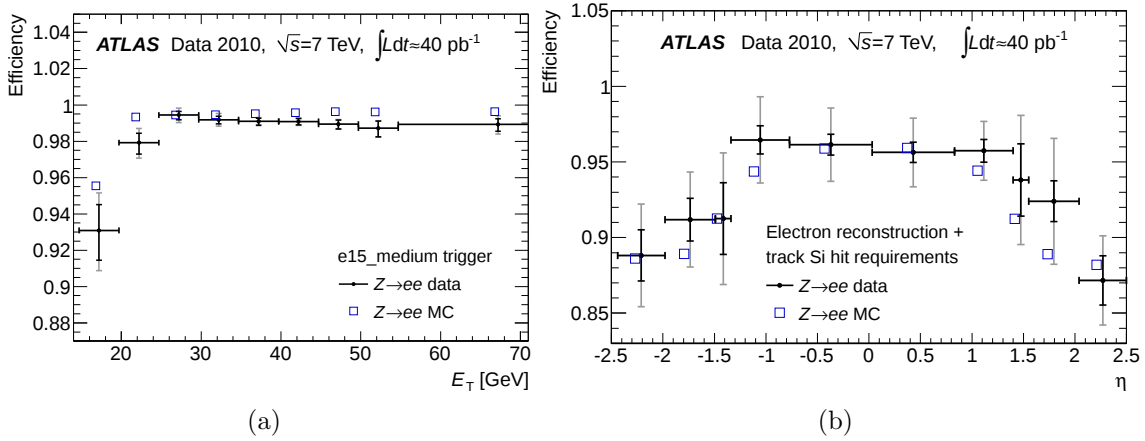


Figure 3.6 – (a) Electron trigger efficiency in data and simulation, as a function of the transverse energy of the electron. (b) Electron reconstruction efficiency, as a function of η . Both plots show the statistical (black) and systematical (gray) component of the total uncertainty [64].

chamber form a segment. Multiple of such segments, or partial tracks, are combined. If this track can be combined with an inner detector track (if their position matches) it is considered a muon candidate. A refit to all hits in the track then defines the muon candidate and its parameters.

Like electrons, muons are detected and reconstructed efficiently in the ATLAS detector, but nonetheless a small fraction is missed in the trigger, reconstruction and identification steps.

Trigger efficiency

The trigger for muons changed during the data taking period. We used `EF_mu10_MSonly` (online only the muon spectrometer was used for reconstruction), `EF_mu13` and `EF_mu13_tight` for different time periods. For the naming convention, we refer back to Section 2.2.6. The reason for choosing different triggers is that some triggers are prescaled during the runs, meaning that only a fraction of the events is recorded, rather than all. We therefore always use the trigger with the lowest p_T threshold that was not prescaled during that data taking period. For 2011, we switch to `EF_mu18` (muon) for the entire year. In all cases the offline p_T threshold remains set to 20 GeV. The trigger efficiency for 2010 data is measured in tag-and-probe studies similar to what was done with electrons, and is shown as a function of p_T in Figure 3.7(a). In $Z \rightarrow \mu\mu$ events, one of the two muons is used as the trigger tag, and the times the other muon is triggered as well are counted to calculate the efficiency. Starting from 20 GeV the trigger efficiency for muons is about 80%. The difference between data and simulation is accounted for by scale factors.

Similar to electrons, the muon momentum resolution is measured from the invariant mass distribution of Z boson events and corrections are applied to the simulation where the values deviate from the measured distribution in data.

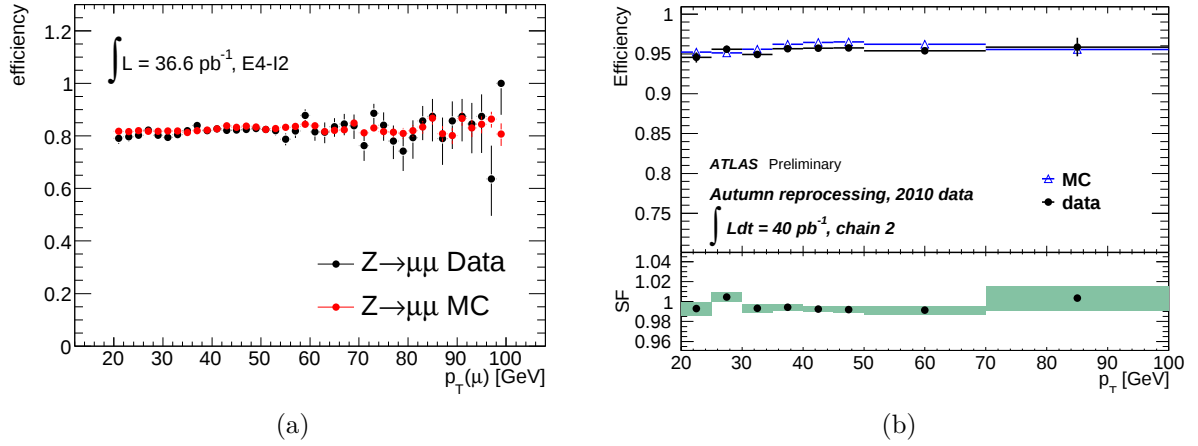


Figure 3.7 – (a) Muon trigger efficiency [65] for simulation and data. (b) Muon reconstruction efficiency of simulation and data. The bottom area shows the relative difference between data and simulation [66].

Reconstruction efficiency

The reconstruction efficiency of muons is shown in Figure 3.7(b), also as function of the transverse momentum of the muon. An inner detector track that, together with a well reconstructed muon of opposite charge, forms an invariant mass within 10 GeV of the Z boson mass, is defined as the probe. The reconstruction efficiency is defined as the times this probe is reconstructed as a muon as well. This efficiency is about 95% over the measured range.

3.4.3 $\cancel{E}_T$ reconstruction

The missing transverse energy, $\cancel{E}_T$, is the momentum imbalance that is measured in the transverse plane. The z -components are not useful, since the hard scattering usually has nonzero longitudinal momentum. Conservation of momentum dictates that the total transverse momentum vector that is the sum of all outgoing objects should be equal to zero. Undetected particles that emerge from the collision, i.e., neutrinos, will result in missing transverse energy. A precise reconstruction of the missing transverse energy is valuable for top quark events, since it can point to the presence of neutrinos. Fake $\cancel{E}_T$ can result from errors or miscalibrations in any of the ingredients of the total summed energy. The magnitude of $\cancel{E}_T$ is the squared sum of the total x - and y -component of the energy deposited.

The value for $\cancel{E}_T$ is obtained from the sum of all calorimeter deposits, but depend on the reconstructed particles in the event. The deposits associated to a jet are scaled to match the jet energy scale. Those deposits associated to an electron are corrected to the calibrated electron energy. All other deposits are included at electromagnetic scale. There is one exception: the contribution of the muons to the $\cancel{E}_T$ calculation is computed from the track momentum. Subsequently, the calorimeter deposits that are associated to the

muon are subtracted.

Figure 3.8 shows the missing transverse energy in a sample aimed to select $W \rightarrow \mu\nu$ events. This is a frequently produced process, with a neutrino in the decay that creates an energy imbalance and is used for validation of the $\cancel{E}_T$ observable. The figure shows $\cancel{E}_T$ for several types of events that are expected to pass the selection, superimposed with the data set of 2010. The sum of the simulated samples match the data reasonably well.

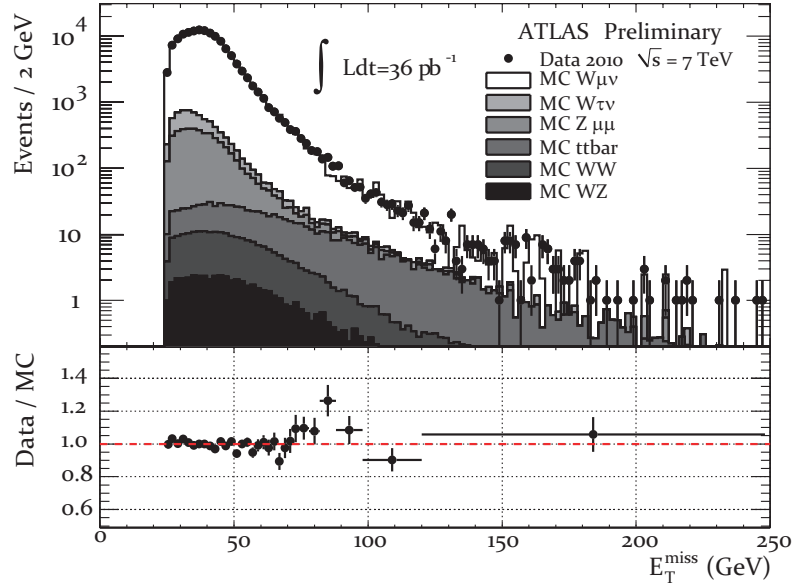


Figure 3.8 – Missing transverse energy in 2010 data, after selection aimed to isolate $W \rightarrow \mu\nu$ events.

3.4.4 Hadronic jet reconstruction

Gluons and quarks shower and hadronize into multiple particles that form hadronic jets. A jet consists of particles that are assumed to have originated from a single parton, depositing energy in the hadronic calorimeters. The reconstruction of jets, assembling them from energy deposits that belong together, is not straightforward. Associating particles to their original partons is ambiguous, as there is overlap between jets in the detectors when there is a lot of activity in the events. Moreover, choices have to be made for the reconstruction and calibration of the four-momentum of a hadronic jet as well. The reconstruction of jets is important to top quark studies. We select events based on the multiplicity of events: in the single-lepton channel of the top quark pair decay at least four jets are expected. Besides counting jets, we need their kinematical properties, as this provides direct information on the decay products of the top quark.

Different jet algorithms exist, varying in performance and treatment of soft and collinear radiation. The input to the jet algorithms we use are clusters of calorimeter cells. They

are groups of calorimeter cells that are formed from individual seed cells. If a cell has a signal-to-noise ratio over 4, it is used as a seed to the cluster formation. The assumed noise is this ratio is estimated from other, random events. Cells neighboring the seed cell, in 3D, with signal-to-noise ratios over 2 are added iteratively. In this way a cluster of above-threshold cells is formed. Finally all adjacent cells surrounding the cluster are added as well. If the clusters have local maxima the formation is run from that maximum as well, to find finer clusters if they exist. The energy of the cluster is the sum of all included cells. The direction is obtained from the weighted average of the angular position of the hit cells, and the mass is set to zero. Alternatively to clusters, ‘towers’, squared areas of cells are used in some analyses. The clusters are input to the actual jet algorithms, the following sections discuss the ‘cone’ and ‘anti- k_T ’ algorithms we make use of.

Figure 3.9 shows an example of a hadronic jet in one quadrant of the ATLAS detector. The figure contains the tracks the parton leaves behind in the inner detector, and the energy it deposits in the calorimeters. Ideally, a reconstructed jet contains all energy that is carried by the original parton.

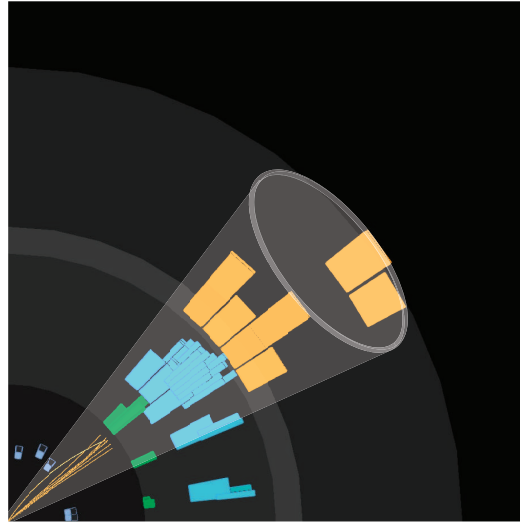


Figure 3.9 – Quadrant of the ATLAS detector, with tracks in the inner detector and energy deposits in the electromagnetic and hadronic calorimeter, surrounded by a cone-shaped jet.

Fixed-cone jet algorithm

The fixed-cone algorithm is based on the principle of constructing symmetric cones around energy deposits, accumulating the energy that is deposited within it. The algorithm starts from the calorimeter cluster with the highest transverse momentum, the seed, and checks whether it is above a certain threshold, for example 1 GeV. A cone of radius $\Delta R = 0.4, 0.7$ is formed around the seed and all objects contained in that cone are combined. A new, combined four-momentum can be composed of the combined objects. The cone rotates to the new center that is thus based on the relative energy contributions and direction of the objects contained before. All objects contained in this cone are used for a new

combination. This process iterates until the cone does not move anymore and is considered a stable jet. Starting from the second seed in line, multiple jets can be formed in a similar way. Spatial overlap between different jets can occur. In this case a split-merge technique is applied. When the overlapping fraction of energy is above a threshold, the jets are merged. Otherwise they are split, each assigned with a fraction of the attributed energy.

This jet algorithm is not infrared safe, meaning that a little extra radiation can potentially lead to different jet topology, even after having applied the split-merge technique. In Section 3.5 we study the effect of tuning the radiation parameters in simulation, using particle jets obtained with the cone algorithm. In ATLAS, the cone algorithm has been default for years, but is replaced by better performing jet finders since collisions started at the LHC.

Anti- k_t jet algorithm

The anti- k_t jet clustering algorithm [67] is the current default jet algorithm in ATLAS. It follows a sequential recombination scheme based on the ‘distance between entities’. An entity can be a particle or candidate jet or cluster. The distance d_{ij} between entities i and j and the distance d_{iB} between i and the beam are defined as

$$d_{ij} = \min(1/k_{t,i}^2, 1/k_{t,j}^2) \frac{\Delta R_{ij}^2}{R^2}, \quad d_{iB} = k_{t,i}^2, \quad (3.1)$$

where $k_{t,i}$ is the transverse momentum of the entity i . The geometrical distance is $R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$, and R is the free radius parameter, usually of value 0.4. The calorimeter clusters, with well-defined four-momenta, are the entities that are input to the distance comparison. The minimum distance that exists between them, d_{ij} , and the minimum distance of any cluster to the beam, d_{iB} , are compared. When $\min(d_{ij}) < \min(d_{iB})$, the two entities are combined, forming a single new entity. Else, the entity i is considered a jet and taken out of the iteration. The procedure is repeated until all clusters are either part of a jet, or a jet itself.

The result of this approach is that soft clusters are preferably combined with a hard cluster, before clustering among themselves. It is a direct consequence of the inverse of the momentum squared in the definition of d_{ij} , and distinguishes the anti- k_t from other algorithms. Soft and collinear radiation do not alter the jet assignment, contrary to the cone algorithm. Another positive effect is that the jets have a cone shape as consequence of this algorithm (unless there is overlap between two jets, in that case only the hardest jet remains conical), rather than more exotically shaped jets that can result from other infrared and collinear safe algorithms that we will not discuss here.

The output of the jet algorithm is a number of well-defined jets.

Jet calibration

The clusters, and subsequently the reconstructed jets, are initially calibrated to the electromagnetic scale, which is appropriate for electrons and photons. But, the reconstructed jets contain all kinds of hadrons. Besides that, not all energy is detected and noise affects the measured energy as well. Therefore corrections have to be applied to the jet energy. This is done following the EM+JES calibration scheme. This scheme uses ‘truth jets’ for comparison. Truth jets are constructed by running the anti- k_t algorithm over truth particles: truth particles are simulated particles after the hadronization phase that are stable (i.e., have sufficient lifetime). The truth particles skip the detector simulation and are directly inserted to the jet algorithm. The jets resulting from the generated particles are compared to the jets that are reconstructed from energy clusters after detector simulation, to obtain knowledge on the response.

A reconstructed jet is matched to a truth jet if their relative distance is small enough, $\Delta R < 0.3$. Both jets have to be isolated: no jet of $p_T > 7$ GeV can be in the area of $\Delta R < 1$. The response

$$\mathcal{R}_{\text{EM}}^{\text{jet}} = E_{\text{EM}}^{\text{jet}} / E_{\text{truth}}^{\text{jet}}, \quad (3.2)$$

is computed in bins of transverse energy and rapidity. Calibration functions $\mathcal{F}_i$ are fitted to the response, in each η -bin. The measured electromagnetic energy of each jet is corrected with this calibration function to obtain the energy at the hadronic scale, by

$$E_{\text{EM+JES}}^{\text{jet}} = \frac{E_{\text{EM}}^{\text{jet}}}{\mathcal{F}(E_{\text{EM}}^{\text{jet}})|\eta}, \quad (3.3)$$

where the calibration functions $\mathcal{F}$ are binned in η . Figure 3.10 shows the average correction that is obtained as a function of the transverse momentum of the jet, for three regions of pseudorapidity. The corrections are larger in the central region. For instance, for a 20 GeV jet in $0.3 \leq |\eta| \leq 0.8$, the correction factor is 2, while more forward jets require smaller corrections. Jets with a radius parameter R of 0.6 are used in this plot, but the $R = 0.4$ shows similar behavior.

Besides the jet energy, the direction is also modified. The origin of the jet is replaced from the origin of the detector (0, 0, 0) to the vertex it belongs to. Furthermore, some calorimeter regions are better in reconstructing the energy, or more sensitive. The direction of the jet is corrected for this effect as well. The size of the correction is of order 0.01 in most regions, but in the transition regions of the detector it can run up to 0.06. In our analysis we use the pseudorapidity before origin correction to accept events, but the corrected value as input to the top quark reconstruction.

The treatment of the calibration of the jet energy induces a systematic uncertainty. But, apart from that, the uncertainty on the energy of jets is also influenced by uncertainties on the detector, the detector simulation, the event simulation uncertainty and pile-up. All

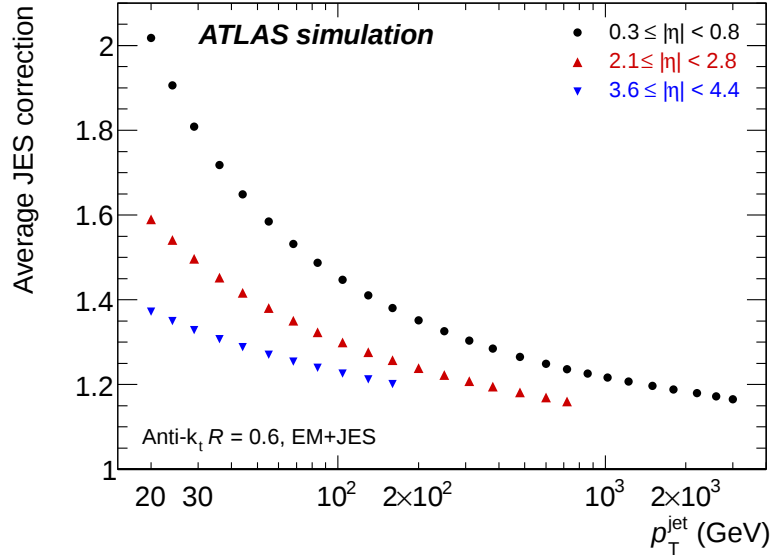


Figure 3.10 – Average energy correction factor for anti- k_t jets of $R = 0.6$ [68].

these effects add to the systematic uncertainty on the jet energy scale that we evaluate later on in the analyses.

Reconstruction efficiency

The jet reconstruction efficiency is measured in data by the ATLAS performance subgroup, from so-called ‘track-jets’. These are jets made up of sets of tracks in the inner detector that originate from the same vertex. In minimum bias events where two back-to-back track-jets are found, the one with the highest momentum is considered the tag if it can be matched to a calorimeter jet. The other track-jet is used to probe the efficiency. The efficiency is defined as the ratio of events where the track-jet can be matched to a calorimeter jet. The reconstruction efficiency is shown in Figure 3.11, as a function of the transverse energy of the jet. The efficiency reaches a plateau of 100% around $p_T = 25$ GeV. Due to the use of the inner detector, this efficiency measurement is only valid up to $\eta = 2.5$.

3.5 Initial and final state radiation in top quark events

We discussed the treatment of parton showering in the process of event simulation. In this section we examine the effect that extra emittance of partons has on top quark events.

Initial and final state radiation (ISR, FSR) are responsible for extra particle jets in the event, on top of the jets that result from the partons coming from the hard scattering process itself. ISR can have large transverse momenta and produce jets of the same order of momentum of the top quark decay products. FSR parton momenta are lower, but those partons contain energy that originates from the hard scatter and hence contain

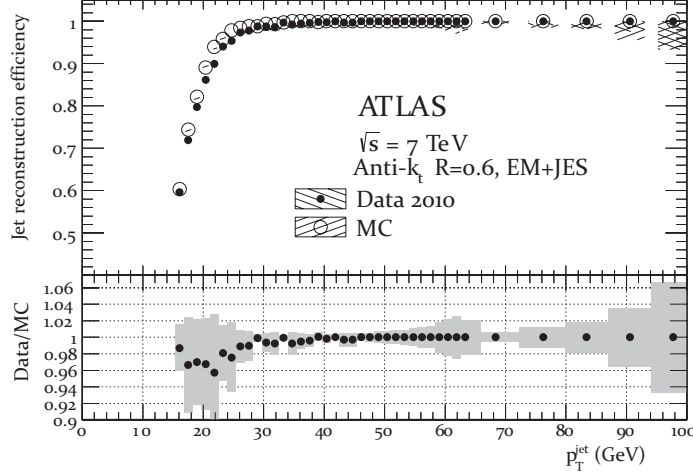


Figure 3.11 – Jet reconstruction efficiency from track-jets, as a function of the transverse momentum [68].

information on the process that produced the top quarks. As a result, the effect of ISR and FSR on the top quark acceptance and reconstruction is different.

Tuning the initial and final state radiation energy scale parameters in the event generator results directly in differences in the final jet multiplicity. In this way the treatment of ISR and FSR introduces a systematic uncertainty in any top quark study. We study the behavior of $t\bar{t}$ events in samples of events generated with ACERMC, together with PYTHIA. As mentioned before, ACERMC is an LO event generator, which means that all radiation effects are treated by PYTHIA and tuning parameters in the latter is unambiguous. The CM-energy of the studied samples is 14 TeV, the LHC design value.

3.5.1 Parameters

There are several parameters involved in the treatment of ISR and FSR in PYTHIA, but we investigate two parameters in particular:

- Λ_{QCD} . This parameter represents the energy scale at which the (running) strong coupling constant α_s becomes of order 1. This parameter is of order 200 MeV (depending on the exact definition), in PYTHIA it is nominally set to 192 MeV. A larger value of Λ_{QCD} results in a stronger coupling, and thereby in more radiation.
- Q_0 . This is the cutoff value of the virtuality at which the partons are no longer evaluated, incorporated in the integral over pseudo-time that was introduced before. Nominally, Q_0 takes a value of 1 GeV, a higher value stops showering early and results in less partons.

Both parameters are separately tunable for ISR and FSR, even though this can result in unphysical situations. The samples we utilized are obtained from varying one of the four (2×2) parameters, conserving the values of all other parameters. The generated events do

not pass through the full reconstruction scheme of ATLAS, but use the ‘fast reconstruction algorithm’, ATLFAST, where the generated particle momenta and direction are smeared according to measured resolution that is obtained in the full simulation scheme. Hence, the detector simulation and the reconstruction step are replaced with a procedure to translate the generated list of particles to a set of physics objects. The output is a collection of reconstructed physics objects.

3.5.2 Effect of Λ_{QCD} and Q_0 on jet multiplicity

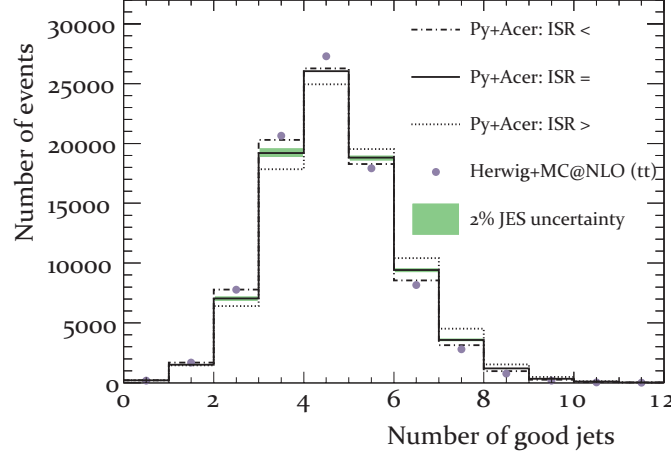
Whether an event is selected in the top quark analysis depends among other things on the number of high- p_T jets. We examined the influence of ISR and FSR on the number of jets in the event. The parameter Λ_{QCD} is varied in a systematic way by a factor of two with respect to the nominal value, producing samples for $\Lambda_{QCD} = 0.096$ and 0.384 GeV, in addition to the nominal 0.192 GeV.

The effect on the number of ‘good’ jets in top quark events, before any event selection, is shown in Figure 3.12. A jet is considered good if its transverse momentum is above 20 GeV and the pseudorapidity is $|\eta| < 2.5$. The sample with a higher value of Λ_{QCD} (‘ISR >’ and ‘FSR >’), is depicted with a dotted line, the lower value (‘ISR <’ and ‘FSR <’) with a dash-dotted line. In the left plot, displaying the effect of tuning ISR only, it shows that there indeed are more jets when $\Lambda_{QCD} = 0.384$ GeV. Events with 6 or 7 jets occur up to 10% more often, with respect to the nominal. And vice versa, a low value for Λ_{QCD} has a significant negative effect on the number of jets above 20 GeV in the event. Two elements are added for comparison. The green areas reflect the uncertainty resulting from a 2% variation of the jet energy scale, applied to the PYTHIA samples. And $t\bar{t}$ events generated with MC@NLO are shown (blue dots). The effect of the variation of Λ_{QCD} , with respect to the number of jets, is of the same order as changing to a different generator.

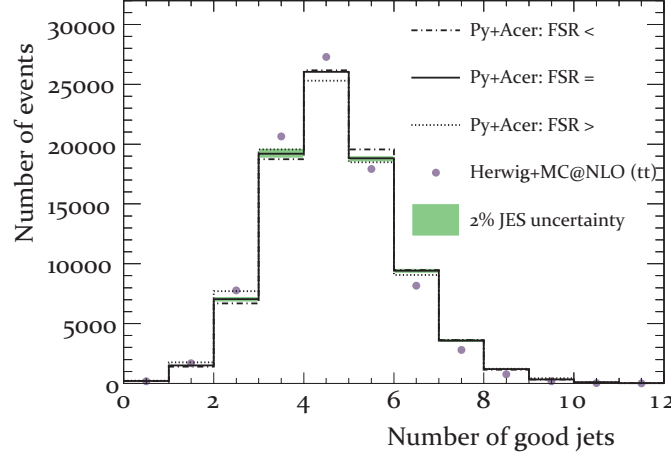
For FSR, the effect is opposite, although less pronounced. A higher value of Λ_{QCD} for FSR leads to slightly less high- p_T jets. The reason is that FSR jets are softer, and extra splitting will lead to more soft jets, eventually failing to pass the 20 GeV momentum cut. The effect is much smaller than for ISR and also in comparison to the MC@NLO events.

The cutoff parameter Q_0 is varied with a factor two, namely to 0.5 and 2 GeV, for both ISR and FSR. The effect of varying Q_0 is negligible for the jet acceptance. The effect of Q_0 in the studied range on the jet acceptance is of order 1%. Due to the 20 GeV threshold, the radiation at cutoff threshold will barely influence the formation of the high- p_T jets we are interested in.

Only ISR shows a measurable effect with respect to the jet multiplicity, whereas FSR does not affect it significantly. To assess the effect of FSR, we study the reconstructed top quark mass on the hadronic side of the decay, a purely hadronic observable.



(a)



(b)

Figure 3.12 – Effect of varying Λ_{QCD} in ISR (a) and FSR (b), for $t\bar{t}$ events with a CM-energy of 14 TeV. Statistical uncertainties are negligible.

3.5.3 Effect of Λ_{QCD} and Q_0 on reconstructed top quark mass

We study the effect on the reconstructed top quark mass using the same simulated samples containing variations of Λ_{QCD} and Q_0 . The mass of the (anti-)top quark that decays hadronically is reconstructed from three particle jets, after a selection aimed to increase the purity of $t\bar{t}$ (although for this study we disregard background samples).

Event selection

We expect at least four high- p_T jets, a high- p_T lepton and a neutrino, in top quark pair events. Based on earlier studies, we select an event when it contains:

- Exactly one muon or electron, with $|\eta| < 2.5$;

- At least four jets within $|\eta| < 2.5$, with a transverse momentum above 20 GeV, of which at least three must have a momentum over 40 GeV;
- Missing transverse energy larger than 20 GeV.

All selected objects have an absolute value of pseudorapidity $|\eta| < 2.5$. For muons and electrons an isolation cone of 6 GeV is defined and jets that overlap with electrons within $\Delta R < 0.2$ are removed. Approximately 30% of the events pass the selection. The origin of the loss are events with two-lepton decays, or involving a tau lepton, and events where a jet or lepton is misreconstructed.

Reconstruction of the hadronic side of decay

The top on the hadronic side (i.e., the top quark that decays hadronically) is reconstructed using the so-called $\sum p_T$ -algorithm, which is based on the following: of all jets with a transverse momentum above 20 GeV, in the selected events, we make all possible combinations of three jets. The resulting vectors are compared. The vector with the highest transverse momentum forms the candidate top quark. This method is based on the assumption that top quarks are produced with large transverse momentum. Additionally, we omit the candidate if none of the two-jet combinations within the three-jet combination have an invariant mass that is consistent with a W boson mass of 80.4 GeV, quantified by a window of 20 GeV around this value (in later chapters we call this the W boson mass constraint). It is a robust algorithm, resulting in a visible mass peak, but it leads to significant fraction of events where the wrong jet combination is picked, i.e., so-called combinatorial background. The $\sum p_T$ algorithm is used as a benchmark reconstruction algorithm, throughout ATLAS studies.

Results

The resulting distribution is plotted in 3.13(a), for the case of nominal radiation settings. The distribution peaks at a value close to the top quark mass. The distribution is fitted with a Gaussian on top of a polynomial background, the latter describing the background formed by combinatorial mistakes. The mean of the Gaussian distribution is at 157.4 GeV, which is lower than the input mass of 172 GeV. Radiation outside the cone of the jets and misreconstruction of background in jets are responsible for this deficit.

The variation of Λ_{QCD} for FSR results in a shifted location of the peak: for $\Lambda_{QCD} = 0.384$ the distribution peaks at 154.3 GeV, with $\Lambda_{QCD} = 0.096$ it peaks at 159.9 GeV. This is a 2% effect. The comparison is shown in 3.13(b), for the subregion of 100-210 GeV, and overlayed to a $\pm 2\%$ uncertainty of the jet energy scale. The shift is of comparable size. The event sample with events generated with MC@NLO (not shown in the plot) has a mass peak around 160.2 GeV. This shows that the radiation settings cause differences almost of the same order as obtained when switching between the LO and NLO generator. The explanation for the shift is that extra radiation will not be contained in the three jets that are used for reconstruction. The energy can either be outside the cone of the jet, or be contained in another jet in the event that is not used. In contrast, changing Λ_{QCD} for ISR

shows no significant shift of the mass of the top quark, whereas its effect on acceptance showed be large. Also the cutoff parameter Q_0 does not influence the distribution, neither for ISR nor for FSR.

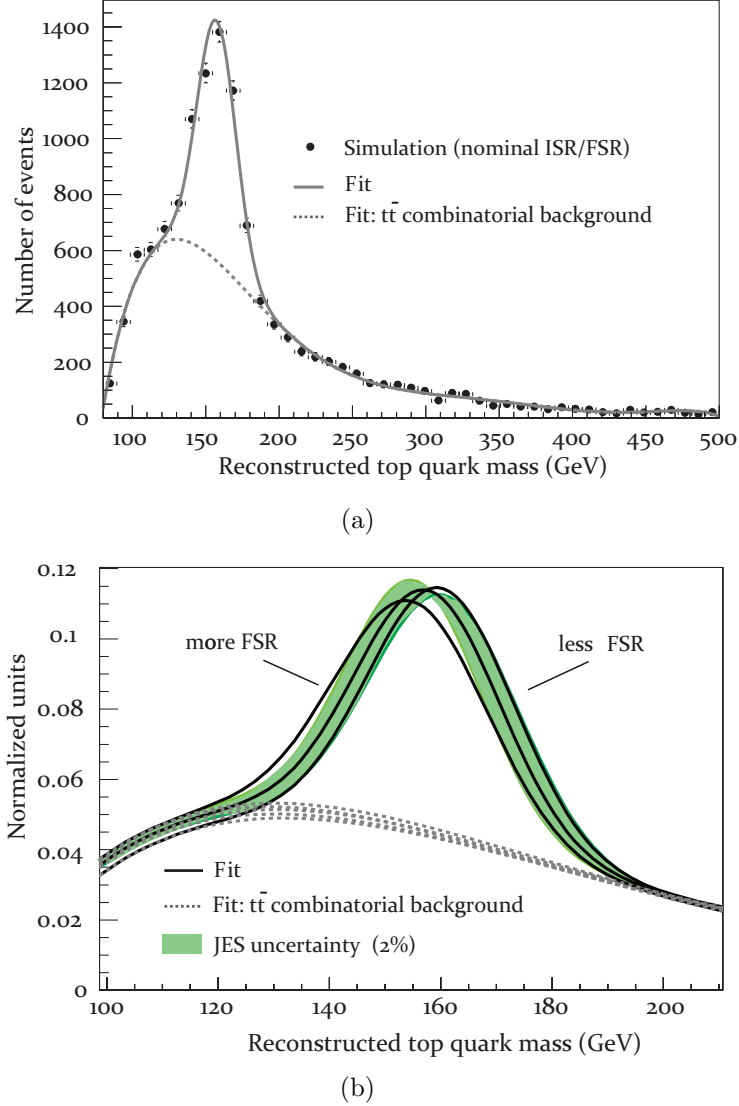


Figure 3.13 – (a). Reconstructed top quark mass for nominal sample, with the fit function displayed on top. The background contribution in the fit is depicted with a dashed line. (b) Reconstructed top quark mass for values of $\Lambda_{QCD} = 0.092, 0.196, 0.384$ in FSR for $t\bar{t}$ events with a CM-energy of 14 TeV. The colored area represents a jet energy scale uncertainty of 2%.)

Besides the shift in mass, the number of events in the peak area decreases for larger amounts of final state radiation. The number of events in the peak area of the mass distribution (see again 3.13(a)) can be used as a measure for the cross section. In Chapter 5 we indeed make similar, but more involved use of the top quark mass distribution to measure the cross section. In this way the amount of radiation will have an effect on the

measurement. The number of events in the peak decreases (increases) with 10.4% (8.2%) for $\Lambda_{QCD} = 0.384$ ($= 0.096$) in FSR. This partly due to the acceptance difference, but mostly due to the reconstruction that is affected. For ISR, the effect is smaller, of order 5%, because only the acceptance is majorly affected.

3.5.4 Conclusions on ISR and FSR

The value for the parameter Λ_{QCD} for both ISR and FSR can have a significant effect on the selection and reconstruction of top quark events. The effects are different. A higher value of Λ_{QCD} in ISR leads to more high-momentum jets and therefore a higher acceptance rate of events. Increased FSR distorts the information that is contained in the decay products of the top quark and affects the reconstructed mass. All effects are of order 5-10%, maximally, in the parameter range we evaluated. The effects are of comparable size to the jet energy scale uncertainty, and to the difference between the ACERMC + PYTHIA sample and the HERWIG + MC@NLO sample. Since these are sizeable effects, we assign systematical uncertainties to this part of event simulation. For the measurement of the production cross section of top quark pairs in Chapter 5, we use ACERMC+PYTHIA samples with ISR and FSR minimized and maximized, similar to what we used here, to evaluate the relative effect on our measurement.



4

Selection and characteristics of data

This thesis describes measurements performed with data sets recorded at different times, by the ATLAS detector. The data is divided in two distinct periods. The first data set, used to perform the top quark pair production cross section measurement in Chapter 5, is produced in 2010 and corresponds to an integrated luminosity of 35 pb^{-1} . In Chapter 6, we make use of 1.04 fb^{-1} of data that is obtained in the period between April and July 2011 to measure the top quark charge asymmetry.

In this chapter, we introduce the data sets and scrutinize the characteristics of the objects we are interested in. This includes the standard event selection that is applied in all analyses, and the distributions of the observables we are interested in. Furthermore, we include a description of the background estimates that are obtained with data-driven techniques. Finally, in Section 4.7, we treat the reconstruction of the top quarks with the Kinematic Likelihood Fitter that will ultimately be used in the analyses in Chapters 5 and 6.

4.1 Introduction

In 2010 and 2011, proton beams ran with an energy of 3.5 TeV each. The maximum instantaneous luminosity was $7 \cdot 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ in the first week of 2010 data taking and the total integrated luminosity reached $90 \mu\text{b}^{-1}$. At that time only one colliding bunch was present in each beam. Since then, the luminosity numbers increased strongly over time, due to the LHC improving the beam conditions. The beam focusing improved to form a smaller interaction area, the number of protons per bunch was increased and, on top of that, the number of bunches per beam was raised to 6 at the end of October (the

end of the 2010 LHC run). The resulting maximum instantaneous luminosity was almost five orders of magnitudes higher at the end of this data taking period: $2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. The total recorded data we analyze, split up in periods following the ATLAS convention, is shown in Table 4.1. This includes the instantaneous luminosity and the average number of interactions per bunch crossing. The total integrated luminosity delivered by the LHC over the entire period, reached 50 pb^{-1} , of which ATLAS recorded 45 pb^{-1} . The periods we list form a consistent set of data, corresponding to 42.7 pb^{-1} . The data quality requirements reduce these numbers slightly, as is described later.

In 2011, the instantaneous luminosity increased even further, to $1.3 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. The average number of events per bunch crossing ranges from 6 to 8, producing extra interactions in the events we are interested in. In addition, the bunch spacing was reduced to 50 ns, resulting in additional activity in events. The phenomenon of extra interactions and activity that contaminate the events of interest is called ‘pile-up’ and is described in the following sections. The total recorded luminosity of the 2011 data set we analyze corresponds to 1.2 fb^{-1} before quality requirements.

Table 4.1 – Data periods used for the analyses in 2010 and 2011. Listed are the integrated luminosity recorded by ATLAS, the peak stable luminosity and the peak average events per bunch crossing.

Year	Period	Int. luminosity (pb^{-1})	Peak luminosity ($\times 10^{32} \text{ cm}^{-2}$)	Peak evts per bunch crossing
2010	E	1.12	0.0391	1.56
	F	1.96	0.102	2.00
	G	8.81	0.701	2.75
	H	8.81	1.47	3.17
	I	23.0	2.03	3.71
	Total	42.7	2.03	3.71
2011	B	17.0	2.44	8.48
	D	179	6.65	7.30
	E	50.2	8.37	7.60
	F	152	11.1	8.07
	G	561	12.7	8.02
	H	278	12.7	6.89
	Total	1237	12.7	8.48

4.1.1 Pile-up

We define as pile-up the occurrence of extra activity in the detector that results from proton scatterings in the same, or neighboring, bunch crossings that do not correspond to the interaction that triggered the event. The average number of events per bunch crossing (at peak luminosity) was 0.01 at the LHC start-up, and increased to almost 4 by the end of 2010. This means that any interaction that triggered ATLAS to record an event is most of the time polluted by extra vertices and signals. If additional protons from the same bunch that triggered the event collide, it is called in-time pile-up. If interactions from the preceding or succeeding bunches of protons leave behind signals in the collision of interest, they form out-of-time pile-up. In 2010, the bunch spacing of the proton beams was such that out-of-time pile-up was negligible.

The simulation samples we use are already corrected for pile-up effects. Additional interactions are simulated and added to the primary hard scatter. As a result, the distribution of the number of vertices with more than four good tracks in simulation is reasonably compatible with data in 2010. But, since in simulation only one setup value for pile-up is simulated for the full year and in reality pile-up conditions change during the year, small differences remain. This residual difference between data and simulation is considered as a systematic uncertainty.

In 2011 out-of-time pile-up becomes more relevant. The final data runs we use here are collected with a configuration of 1318 bunches in the beam (compared to ~ 130 towards the end of 2010 and at the beginning of 2011). The time window between consecutive bunches (bunch spacing) is reduced to 50 ns. Out-of-time pile-up from neighboring bunches generates extra signals in the recorded event, more calorimeter activity, for instance, but not necessarily extra vertices. Simulated events are produced under the assumption of a certain distribution of the number of pile-up interactions, but in the presence of out-of-time pile-up, the simulation needs to be reweighted according to the pile-up conditions of the particular data set. Reweighting is performed using the average number of interactions per bunch crossing. This is an observable that is extracted from the data. Figure 4.1 shows the distributions of data (only period D of data) and simulation, before reweighting. The number of interactions in data is lower in this period than was anticipated in simulation. Events in the simulation are reweighted according to the data sets that are being studied. That means that in this particular example, weights in the range 0.0-4.0 occur.

4.1.2 Data quality

Not all events in the data meet identical and optimal detection quality requirements. The operation of the detector is monitored by a series of checks of standard distributions, of all subdetector parts, trigger figures, and of reconstructed physics objects. Collision recorded in a time window with approximately constant luminosity, form a ‘lumiblock’. A lumiblock is typically a minute long. The condition of all subdetector parts is stored per lumiblock, making it possible to select lumiblocks that satisfy the (sub)detector quality

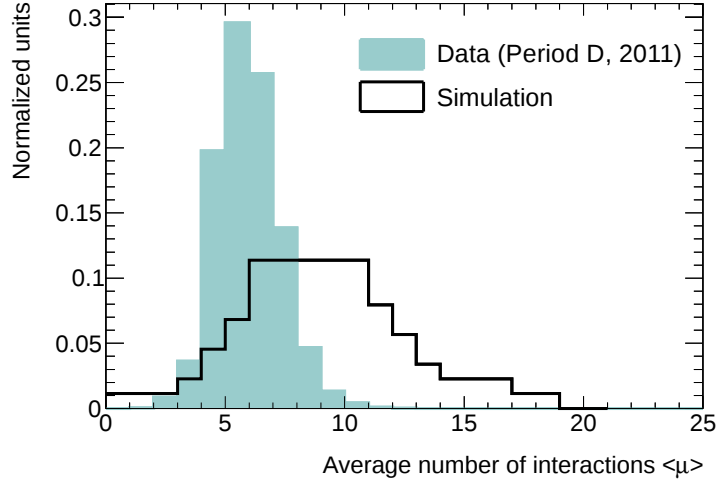


Figure 4.1 – Average number of interactions per bunch crossing, before reweighting.

checks a specific analysis requires. In top quark analyses, where all subdetectors are of importance, a considerable fraction of lumiblocks is not accepted. This is mostly due to problems in the detector control or readout in one of the subsystems that occasionally occurs. After applying the quality criteria of all subdetector components, in total 35.3 pb^{-1} is left of the initial 42 pb^{-1} collected in 2010. In 2011, the data set is reduced from 1.24 fb^{-1} to 1.04 fb^{-1} due to the quality restrictions.

After the quality filter, the sample can still contain signals that do not originate from a hard interaction, as noise or cosmic ray events may have triggered the event. For this reason, a quality requirement on the track vertices is imposed. Vertices are reconstructed from all tracks that are present within a collision, and a vertex is considered of good quality when at least five tracks originate from it. Due to pile-up there can be multiple good vertices in one event. Events are selected if there is at least one ‘good’ vertex.

A hardware problem in the liquid argon calorimeter, caused by a readout device that broke down, affects the acceptance and energy resolution of electrons and jets. We account for this issue by discarding all events that contain jets that overlap with the troubled region of the detector, starting from run 180614 (April 30th, 2011). The electron quality requirements are also adapted such that unreliable measured values are avoided. We apply the same selection to a subset of the simulation to account for the acceptance and rescale the luminosity loss due to this effect.

4.2 Object definitions for analyses

In this section, we describe the identification and reconstruction of the objects that are relevant to the $t\bar{t}$ analysis: electrons, muons, jets and missing transverse energy (E_T). Since we have to deal with ambiguities and overlap between these objects we discuss them in the order that overlap is resolved.

4.2.1 Electrons

An event is selected if it was triggered by one of the chosen single-electron triggers. We require a trigger that is efficient for the kinematic region above 20 GeV. For electrons we used `EF_e15_medium` in 2010, hence with an online transverse energy threshold of 15 GeV (see Section 2.2.6 for the naming conventions). For 2011, we switch to `EF_e20_medium` (electron), the lowest unprescaled trigger, which has an online threshold of 20 GeV for the transverse energy. Consequently, as described in Section 3.4.1, we apply a threshold of 20 (25) GeV for the transverse energy of reconstructed electrons in the 2010 (2011) analysis. The margin between the online and offline energy threshold is added to avoid inefficiencies around the threshold region (turn-on effects), see Section 3.4.1.

We require that the triggered object matches the reconstructed object, so that the electron we use in the analysis is the one that triggered the event.

The absolute pseudorapidity (of the cluster) is required to be within 2.47, with the transition region of the detector, $1.37 < |\eta| < 1.52$, excluded. Finally, isolation criteria are applied: if the amount of energy in a cone of $\Delta R = 0.2$ around the electron candidate exceeds 4 GeV it is considered a jet, because then it is likely to be a misidentified jet, or an electron produced in the decay of the jet.

4.2.2 Jets

We use jets reconstructed with the anti- k_t algorithm, as discussed in Section 3.4.2, with $\Delta R = 0.4$. The p_T threshold of jets to be used in the analysis is 20 GeV, but in the event selection jets with a transverse momentum of at least 25 GeV are considered for the jet multiplicity cut. For 2010, we set the maximal absolute value of the pseudorapidity to 2.5. In 2011, the calibration of jets has developed, making it possible to use jets in a range up to $|\eta| < 4.5$. This means that in 2011 we can make use of very forward jets.

Events with jets that contain energy deposits falling in the unresponsive part of the calorimeter are discarded. Jets are removed if an accepted electron is present within $\Delta R = 0.2$.

4.2.3 Muons

The muon is required to have a transverse momentum above 20 GeV and $|\eta| < 2.5$, because of the trigger requirements (see Section 3.4.2). Muons too are required to be isolated, to avoid accepting fake muons, or muons produced in the core of a jet. Therefore, the calorimeter energy in a cone of $\Delta R = 0.3$ around the muon must be below 4 GeV. In addition, the combined transverse momentum of all tracks within that cone cannot exceed 4 GeV either, to attempt to select only muons that originate from the hard scatter. And finally, muons that are within $\Delta R = 0.4$ from a jet are vetoed as well, to remove any potentially remaining overlap. If two back-to-back muons satisfy the signature of a cosmic muon, they are both removed.

4.2.4 Corrections to leptons

There are a number of corrections that are applied to leptons in top quark events. Firstly, the efficiency differences in simulation and data are accounted for: as mentioned in Section 3.4, we measure the trigger, reconstruction and identification efficiencies of leptons in both data and simulation. The relative differences between the respective efficiencies are corrected for by applying scale factors to the simulated events. We summarize the scale factors in Table 4.2, with the reconstruction and identification step convoluted. The methods to obtain the scale factors differ between the data sets (2010, 2011) and the lepton flavors.

For 2010, the scale factor of the electron trigger corresponds to a single number, whereas the reconstruction and identification scale factors are parametrized as a function of η and E_T . For muons it is the other way around, the reconstruction and identification scale factors correspond to a single number, while the trigger scale factor is expressed in bins of η and ϕ . Most scale factors are close to, or compatible with 1.

In 2011 data, the binning is finer and in terms of more observables. Because of this, larger values for the scale factors may occur in some areas of the detector, due to statistical fluctuations. For example, the muon scale factors can run up to 1.6 for high momentum muons in certain parts of the endcaps. All events we select are weighted with the product of the trigger and reconstruction/ID scale factors.

Table 4.2 – Scale factors to correct for lepton data-simulation difference in efficiencies.

Year	Lepton flavor	Type	Value (range)	Dependent on
2010	e	Trigger	0.995	
		Reco+ID	0.907-1.055	η, E_T
	μ	Trigger	0.657-1.046	η, ϕ
		Reco+ID	0.999	
2011	e	Trigger	0.966-0.997	η
		Reco+ID	0.953-1.117	η, E_T
	μ	Trigger	0.85-1.57	η, ϕ, p_T
		Reco+ID	0.81-1.02	η, ϕ

4.3 Multijet background

As explained in Section 3.3.2, the uncertainty on the cross section of multijet processes is large, and the numbers of events that need to be produced to have a reliable simulated sample is so large that simulation of multijet events is not feasible. Therefore the shape

and normalization of multijet events are estimated from data. The procedure we follow is somewhat different for the electron and muon channels.

We distinguish between fake leptons and non-prompt leptons. A fake lepton is an object, usually a jet, that is falsely identified as a lepton, because of a reconstruction inefficiency. A non-prompt lepton is a lepton that is a decay product of a pion or a B meson, for example. Photon conversions also lead to non-prompt leptons. Typically fake leptons are electrons, because the identification of jets, photons and electrons are all largely based on calorimeter information. Fake muons are rare, because it is more difficult for other particles to traverse the other detectors and subsequently leave a track in the muon detector

We discuss the methods for both channels in the following sections¹.

4.3.1 Muon channel

In the muon channel the fraction of genuine (but non-prompt) muons is large. Non-prompt muons from meson decays are typically non-isolated, as activity coming from the other decay products is usually present. A matrix method is deployed to estimate the amount of multijet events in the muon channel [69]. A ‘loose’ sample of muons is obtained by removing the isolation criteria. This is done such that the loose selection is a subset of the ‘tight’ or standard sample, which is the nominal muon selection. The number of events in the loose and standard sample can be expressed as a sum of the real muon (‘real’) and the fake and non-prompt component (‘fake’):

$$\begin{aligned} N^{loose} &= N_{real}^{loose} + N_{fake}^{loose}, \\ N^{standard} &= \epsilon_{real} N_{real}^{loose} + \epsilon_{fake} N_{fake}^{loose}. \end{aligned}$$

The efficiency ϵ_{real} (ϵ_{fake}) is the fraction of events in the standard selection with respect to the loose sample, of the real (fake) component. This set of equations can be solved for $N_{standard}$, the number we are interested in, as a function of the two efficiencies and the total number of events in the loose and standard sample. The efficiencies are obtained from control regions. The efficiency of a prompt muon to end up in both the loose and standard selection can be extracted from $Z \rightarrow \mu\mu$ events. The efficiency of a non-prompt or fake muon to be found in both loose and standard is obtained from a multijet enriched sample, with $\cancel{E}_T < 10$ GeV. Including the efficiencies and measuring the number of events in the loose and standard selection leads to an estimate of the normalization of misidentified muons in the data sample.

4.3.2 Electron channel

In the electron channel non-prompt electrons, photon conversions and misidentified jets contaminate the electron selection in unknown amounts. Since no representative control

¹The final yields of the multijet background are listed in Tables 4.3 and 4.4.

region could be defined in the 2010 data set, a binned likelihood fit is applied to a data sample in the sideband area. The sideband is formed by the region with small missing transverse energy, $\cancel{E}_T < 35$ GeV (see selection criteria).

The fit is built up from templates for the $\cancel{E}_T$ distribution of $t\bar{t}$, W +jets, Z +jets. The multijet template is obtained from an ‘anti-electron sample’, a sample of data orthogonal to the standard selection, where one quality cut on the electrons is inverted. This selection results in a multijet-rich sample, from which a template of the multijet background can be obtained.

The fit, containing the simulated templates and the anti-electron template, is then applied to the data in the sideband region. The relative fractions of the other components can be extrapolated to the signal region using the shapes of the template in this range. Consequently, an estimate for the multijet component in the signal region follows from this. Since the fit is applied in different jet bins, it supplies an estimate for the multijet content as a function of the number of jets in the event. In this way the normalization of multijet events can be established. The shapes of other distributions can be extracted from the anti-electron sample, and are scaled to the normalization obtained in the fit.

As of 2011, a matrix method similar to the one described for the muons is deployed to assess the fraction of background in the electron channel. Loose and tight electrons are defined, where tight is the default electron and loose electrons are less stringent quality cuts and relaxed isolation criteria. The number of fake leptons is subsequently obtained from the efficiencies to go from loose to tight in combination with the values for loose and tight electrons as measured in data.

4.4 W +jets background normalization

In this section we address the normalization of the yield of W +jets. Ideally, the contribution of W +jets is obtained from data as there are substantial theoretical uncertainties on the normalization. As this is practically difficult, we make use of simulation for W +jets, especially for the shapes of kinematic observables, and try to reduce the dependence on the yield. The treatment of W +jets differs between the 2010 and 2011 analyses.

In the cross section measurement conducted with the 2010 data, we perform a template fit that returns an estimate for the total amount of background. Hence, we do not make use of the yield of W +jets events in the signal region. However, the yields of W +jets samples are used in supporting calculations that constrain the final result, for example for ratios of cross sections in bins with low jet multiplicities. Systematic uncertainties are assigned where the simulation is used.

For 2011 data, the number of W +jets events in the signal region is obtained from data-driven methods. It makes use of the property that W^+ events are produced in larger amounts than W^- events in the LHC. This is a direct result of the abundance of u -quarks in the proton-proton collisions, compared to d -quarks. The ratio of W^+/W^- events is theoretically more stable than the cross section itself [33]. The charge of the W boson

is contained in the charge of the lepton that we measure. The total number of W +jets events after all selection can be expressed as:

$$N_W(data) = \frac{r_{sim} + 1}{r_{sim} - 1} (N_{total}^+(data) - N_{total}^-(data)).$$

The ratio r_{sim} is the ratio of W^+/W^- events in simulation, $N^+(N^-)$ is the total amount of data events with a lepton of positive (negative) charge. A small correction is applied to N^+ and (N^-) : single top and diboson events also have charge asymmetric production mechanisms at the LHC, but are produced in much lower amounts than W +jets. Nevertheless, we correct the data by subtracting the estimated number of single top and diboson events in that set. The ratio r_{sim} is thus obtained from a sample of simulated W +jets that passes all selection requirements, and is measured to be $r_{sim} = 1.58 \pm 0.08$ in the electron channel and 1.72 ± 0.07 in the muon channel [70]. The sources of systematic uncertainty that this fraction is sensitive to are the lepton scale factors and the jet energy scale uncertainty.

Inserting the measured amount of data events (corrected for single top and diboson contamination) results in $N_W = 8244$ (13374) events in the electron (muon) channel, corresponding to scale factors of 1.05 and 0.77 respectively. We assign a relative uncertainty of 15% and 12% to these numbers, obtained by propagating the uncertainty on data and on r_{sim} to the number of W +jets events.

In the plots that will follow in this chapter, the uncertainty on the data-driven background estimates is included as a dashed area. For 2011 plots this includes, besides the multijet background, the uncertainty of obtaining W +jets from data.

4.5 Basic event selection

In this section we present our event selection for the 2010 and 2011 data sets².

We summarize the offline selection criteria.

- **Good vertex.** At least one vertex with more than four tracks should be present in the event.
- **One lepton.** We require exactly one lepton (electron or muon), with $E_T/p_T > 20$ GeV, with $|\eta| < 2.5$. For 2011 data, we change the threshold for electrons to 25 GeV. The muon momentum and rapidity cuts are equal in 2010 and 2011.
- **Four or more jets.** An event needs to have at least four jets with p_T above 25 GeV, with $|\eta| < 2.5$ for 2010 data and $|\eta| < 4.5$ for 2011 data.

²Only a few exceptions in terms of the electron and jet properties have changed between 2010 and 2011, due to event trigger evolution and improvements in understanding of the detector. In the cross section analysis and in the charge asymmetry analysis we deviate from the basic selection, to include more events in control regions or purify the sample, but the basic strategy to select top quark events is similar.

- **Missing transverse energy and transverse W boson mass.** In the e +jets (μ +jets) channel, we require $\cancel{E}_T \geq 35$ (20) GeV. This cut is identical in 2010 and 2011 selection and supported by studies on the fake or non-prompt leptons in multijet background, that are of different origin in the two channels. In the electron channel, more multijet background is expected and stricter cuts are set to enhance the signal-to-background ratio. Besides $\cancel{E}_T$, the selection is also based on the m_T^W observable, the transverse mass of the W boson obtained from the lepton and $\cancel{E}_T$ components (we will present the exact definition in Section 4.6.4). In the e +jets channel, a threshold on m_T^W is set to $m_T^W \geq 25$ GeV. To reduce background in the μ +jets channel, a triangular cut is applied, $\cancel{E}_T + m_T^W \geq 60$ GeV, cutting away the majority of multijet events [69].

4.5.1 Event yields

The selection cuts are applied to the events in data and to the signal and background simulation, scaled to the estimated luminosities, 35.3 pb^{-1} and 1.04 fb^{-1} , respectively. For the data set of 2010, the resulting numbers of events are listed in Table 4.3. The uncertainties listed reflect the statistical uncertainty only, except for the data-driven multijet estimate to which a 50% systematic uncertainty is assigned.

The number of signal events in the electron channel is estimated to be 190, the major background is W +jets with 174 events. The total number of events in data is 397, which is in agreement with the total expected number of events. Due to the different selection criteria, the muon channel has a larger event yield: almost 50% more signal events are expected compared to the electron channel. The contribution of W +jets is also relatively larger. The observed number of events, 646, is within the range that is expected from the combined signal and background estimates.

Note that we discuss the event yields of signal and backgrounds in the data set of 2010 although the measured number of $t\bar{t}$ events is the observable that is measured in the next chapter. The approach in that analysis uses more data-driven input and fits the contribution of signal and background to the measured number of events.

The equivalent table for 2011 data is shown in Table 4.4. The difference is that since the W +jets estimation is data-driven now, we include the systematic uncertainty in the table, like we do for the multijet background. The contribution to the uncertainty that originates from the limited number of events in this background is shown in brackets for comparison to Table 4.3. The number of signal events is 5603 (7960) in the electron (muon) channel. The relative contribution of background increases, as a result of the relaxation of the threshold on the jet pseudorapidity, from $|\eta| < 2.5$ to $|\eta| < 4.5$. Top quark pair events are expected to produce more central activity, compared to the background that results from electroweak processes, W +jets single top and Z +jets and to the multijet background. The result of the increased η range is that the purity of $t\bar{t}$ events reduces, but we allow this since the analysis that will be performed on this data set is mostly limited by the number of signal events and not on the systematical uncertainty on background estimates that is

Table 4.3 – Expected and observed event yields in 2010 data.

	e+jets			μ +jets		
<i>Components</i>						
$t\bar{t}$	190	$\pm$	1	280	$\pm$	1
W +jets	174	$\pm$	2	313	$\pm$	3
Z +jets	20	$\pm$	1	20	$\pm$	1
WW/ZZ/WZ	3	$\pm$	1	4	$\pm$	1
Single top	11	$\pm$	1	15	$\pm$	1
Multijet (data-driven)	22	$\pm$	11	51	$\pm$	26
<i>Total</i>						
Sum Backgrounds	229	$\pm$	11	405	$\pm$	26
Total Expected	418	$\pm$	11	684	$\pm$	26
Observed	397	$\pm$	20	646	$\pm$	25

introduced is this way. Moreover, identifying b -quarks, as we will introduce later, reduces the background significantly. The number of observed events in data is compatible with the expectations in both the electron and the muon channel.

4.6 Distributions in data: 2010 versus 2011

As we saw above, the event yields in data and simulation are compatible. In this section we will evaluate the distributions of reconstructed kinematic variables of selected events, and compare the 2010 and 2011 data sets.

4.6.1 Electron properties

The momentum of the electrons are shown in Figure 4.2, on a logarithmic scale. The momentum runs from 20 GeV for 2010 data (left) and from 25 GeV for 2011 data. It contains the cumulative contributions of signal ($t\bar{t}$), W +jets, multijet background and the sum of all other backgrounds. The latter contains diboson, single top and Z +jets components. The hashed blocks reflect the total statistical uncertainty plus the systematic uncertainty as a result of the data-driven multijet approach. Finally, the data is plotted on top of the sum of all expected contributions. The shapes of the background events are comparable. Multijet events produce electrons of low momentum, mostly. For both data sets the expected distribution for the sum of signal and background matches the data well.

Table 4.4 – Expected and observed event yields in 2011 data. The numbers in brackets show the contribution of the statistical uncertainty on the W +jets background.

	e+jets			μ +jets		
<i>Components</i>						
$t\bar{t}$	5603	$\pm$	40	7960	$\pm$	47
W +jets (data-driven)	8244	$\pm$	1237 [90]	13374	$\pm$	1605 [98]
Z +jets	723	$\pm$	15	1262	$\pm$	20
WW/ZZ/WZ	124	$\pm$	4	192	$\pm$	5
Single top	448	$\pm$	7	609	$\pm$	8
Multijet (data-driven)	1159	$\pm$	579	2198	$\pm$	1099
<i>Total</i>						
Sum Backgrounds	10701	$\pm$	1366 [587]	17637	$\pm$	1945 [1104]
Total Expected	16304	$\pm$	1366 [588]	25597	$\pm$	1946 [1105]
Observed	16182	$\pm$	127	26741	$\pm$	164

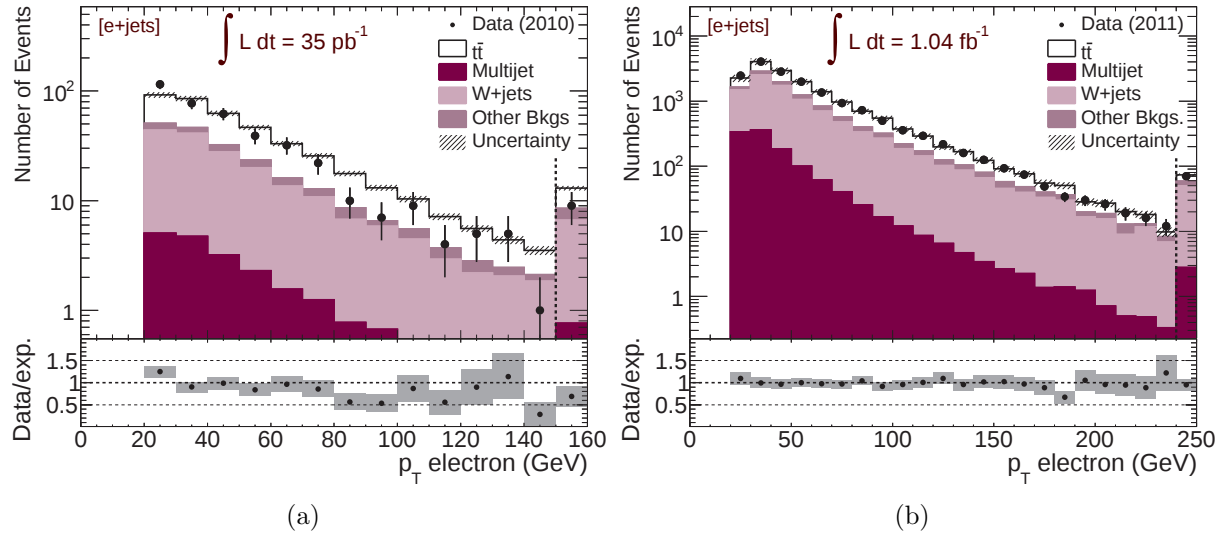


Figure 4.2 – Electron momentum for data in 2010 (left) and in 2011 (right), after all cuts. The last bin shows the sum of the values beyond the plotted range.

The angular properties of the electrons in the sample are shown in Figure 4.3. The rapidity of the electrons (top) shows the acceptance gap at the crack region at $1.37 < |\eta_{cluster}| < 1.52$, a detector region where no active material is present. (In 2010 data there is no visible empty bin, as the binning is not fine enough to show it.) Furthermore, the signal contribution is larger at the central region, as the $t\bar{t}$ pair is expected to be produced

more centrally. A difference between the multijet estimates in 2010 and 2011 is visible in the high- η regions. This is due to the change from the anti-electron selection to the matrix method for obtaining the multijet estimate. The difference is not likely to affect our measurements in the following chapters, since we already assign large uncertainties to this contributions. The data is compatible with the expected shape.

The ϕ -distributions, shown in 4.3, show more irregular behavior. In principal, the production of events is symmetric and electrons are expected to be produced isotropically in ϕ , resulting in a flat distribution. Due to acceptance irregularities, small deviations can arise. The liquid argon hardware problem in 2011, described earlier, does have a strong impact on this distribution. During part of the data taking period, the region $\phi = (-1.2, -0.5)$ and $\eta \geq 0$ might be affected by mismeasurements. The data events recorded during this period that contain jets and electrons in this area are removed from the selection, to avoid selecting unreliable events. Since there are some runs recorded from before the problem occurred, a small number of data points populate the gap. The simulation is corrected for this problem.

4.6.2 Muon properties

For the muons in the selected sample (in the muon channel), we examine the same distributions for 2010 and 2011 data. Figure 4.4 shows the momentum of muons for both periods. The momentum threshold as well as the angular requirements for muons to pass the selection are unaltered with respect to the previous chapter. One exception is added to correct for a software bug in 2011: scale factors for muons with a p_T larger than 150 GeV were not well defined. Therefore all events that contain muons above this threshold are removed³. There is no prominent difference between the distribution observed in data, and the expectation.

The angular distributions of data and simulation of the muons, shown in Figure 4.5, mostly agree within their uncertainty. The shape of η is different with respect to electrons. At $\eta = 0$, the muons cannot be reconstructed as there is no detector material at that point. The feet of ATLAS, the support structure holding the detector, also produce areas that are insensitive to muon detection, at $\phi = -2.0$ and $\phi = -1.1$, for different values of η . This is visible in both ϕ -plots. It is, just as other non-flat behavior in the shape, well described in simulation. One data point in the η distribution lies significantly above the expectations (at $\eta = 0.25$), but we cannot associate this to a specific detector or physical effect. With regard to the overall match of the data and expectation in this distribution, we therefore assume it to be a fluctuation.

4.6.3 Jet properties

Jets are studied separately for the electron and muon channel, although the properties of jets should not depend on the flavor of the lepton in the event. We therefore show only

³In later releases the software bug was corrected, restoring the full muon spectrum in the data set.

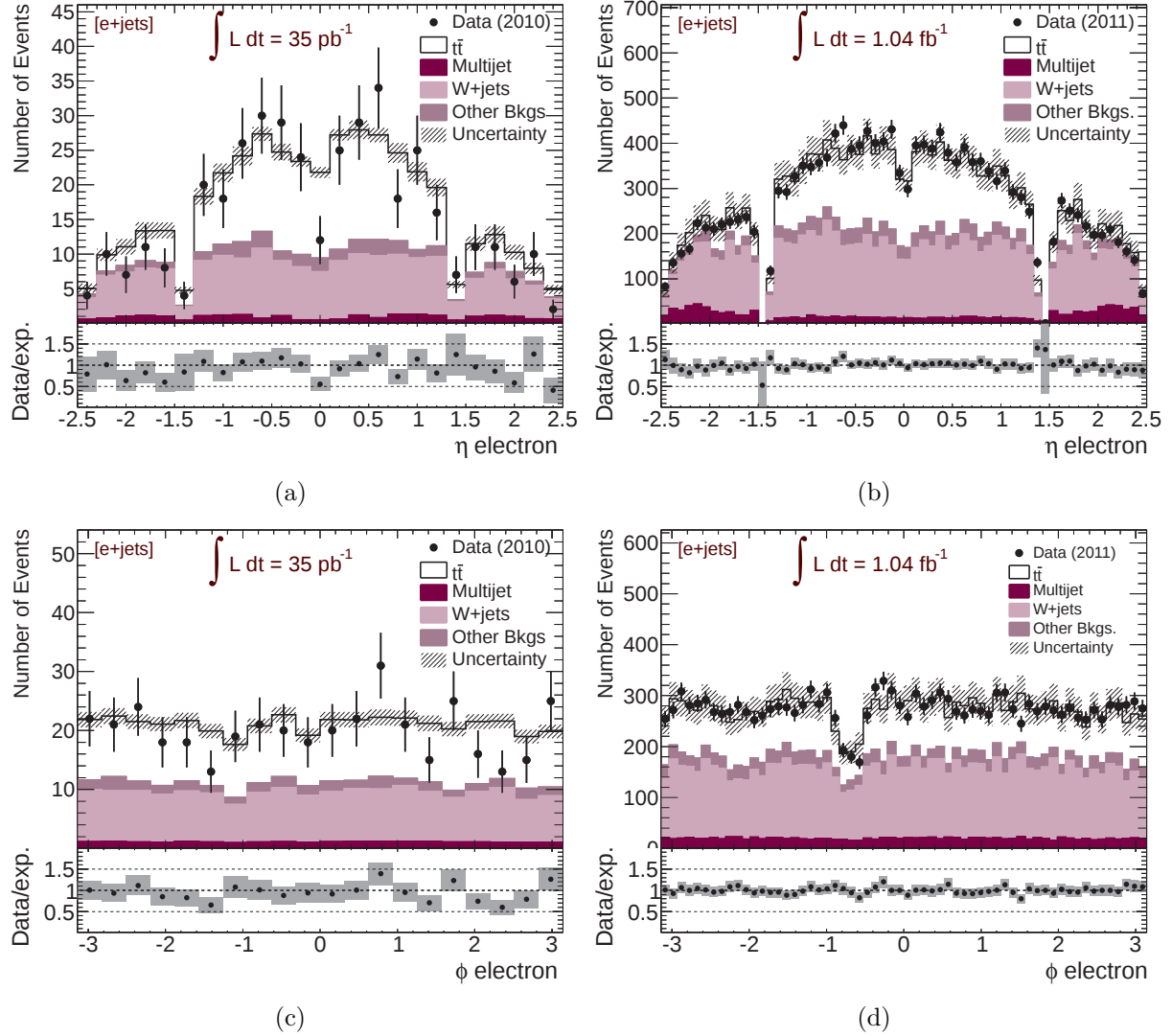


Figure 4.3 – Electron polar and azimuthal angles, for 2010 (left) and 2011 data (right), after all cuts.

figures of one of the channels, for the purpose of clarity. We chose the muon channel, as it is better populated. The jet multiplicity before requiring a certain number of jets is shown in Figure 4.6. The contribution of signal is largest for high jet multiplicities and supports the choice to use events only when at least four jets are present. The momentum of the most energetic jet in the event is shown in Figure 4.7, for the range of 0-500 GeV. Simulation predicts $t\bar{t}$ events to have the most energetic jet over 50 GeV, in the high- p_T range the relative contribution of background becomes larger again. Data is well described with simulation for this variable, in both data sets.

The foremost change concerning jet requirements in 2011 is the extension of the allowed pseudorapidity range for jets from $|\eta| < 2.5$ to $|\eta| < 4.5$. This is visible in the η -distribution of the jet with the highest momentum in the event, shown in Figure 4.8.

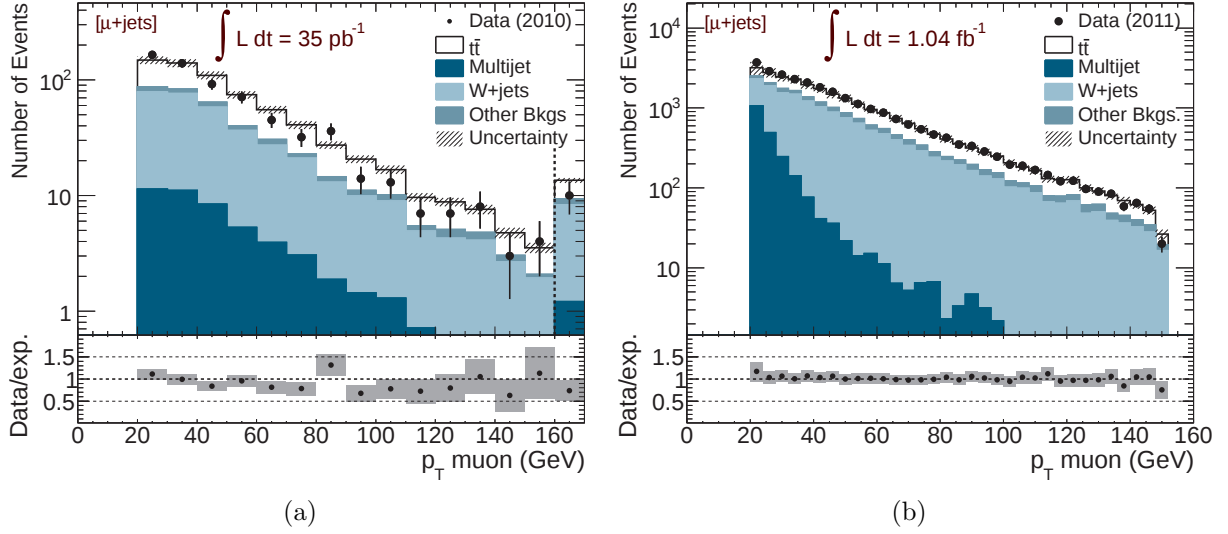


Figure 4.4 – Muon momentum for data in 2010 (a) and 2011 (b), after all cuts. The last bin of (a) shows the sum of the values beyond the plotted range.

As mentioned before, $t\bar{t}$ produces more central jets, on average. The ϕ -angle shows no irregularities, except for the bump in 2011 resulting from the problem in the calorimeter.

4.6.4 Event variables

Besides the leptons and jets, we are interested in event-wide variables, and especially the total transverse energy vector and consequently the missing transverse energy. The missing transverse energy is depicted in Figure 4.9. The magnitude of $\cancel{E}_T$ in data is in agreement with simulation for both time periods. This is also true for the electron channel (not shown).

Contrary to η , the ϕ -component of $\cancel{E}_T$ is available, since it includes information only from the x - and y -components. The difference between the muon and $\cancel{E}_T$, projected on the transverse plane, $\Delta\phi$, is shown in the same figure as well. It contains information on the angle between the neutrino and the lepton that result from a W boson. The range of possible angles is large, but the shape of the $t\bar{t}$ contribution is somewhat different than the backgrounds: around $\Delta\phi = 1$, the contribution of $t\bar{t}$ seems relatively large. The W +jets background, for example, shows a steady slope with respect to this variable, with the most likely value being a back-to-back configuration for the lepton-neutrino pair. The W boson in top quark decay is more likely to be boosted with respect to the W boson in W +jets production, leading to slightly smaller angles between the lepton and the neutrino on average. The prediction overestimates the number of events in data for high values of $\Delta\phi$ (above $\Delta\phi = 1$), but the distributions are still compatible.

One important variable (used in the selection criteria) is the transverse W boson mass (m_T^W), that is constructed from lepton and $\cancel{E}_T$ information. When selecting events in the

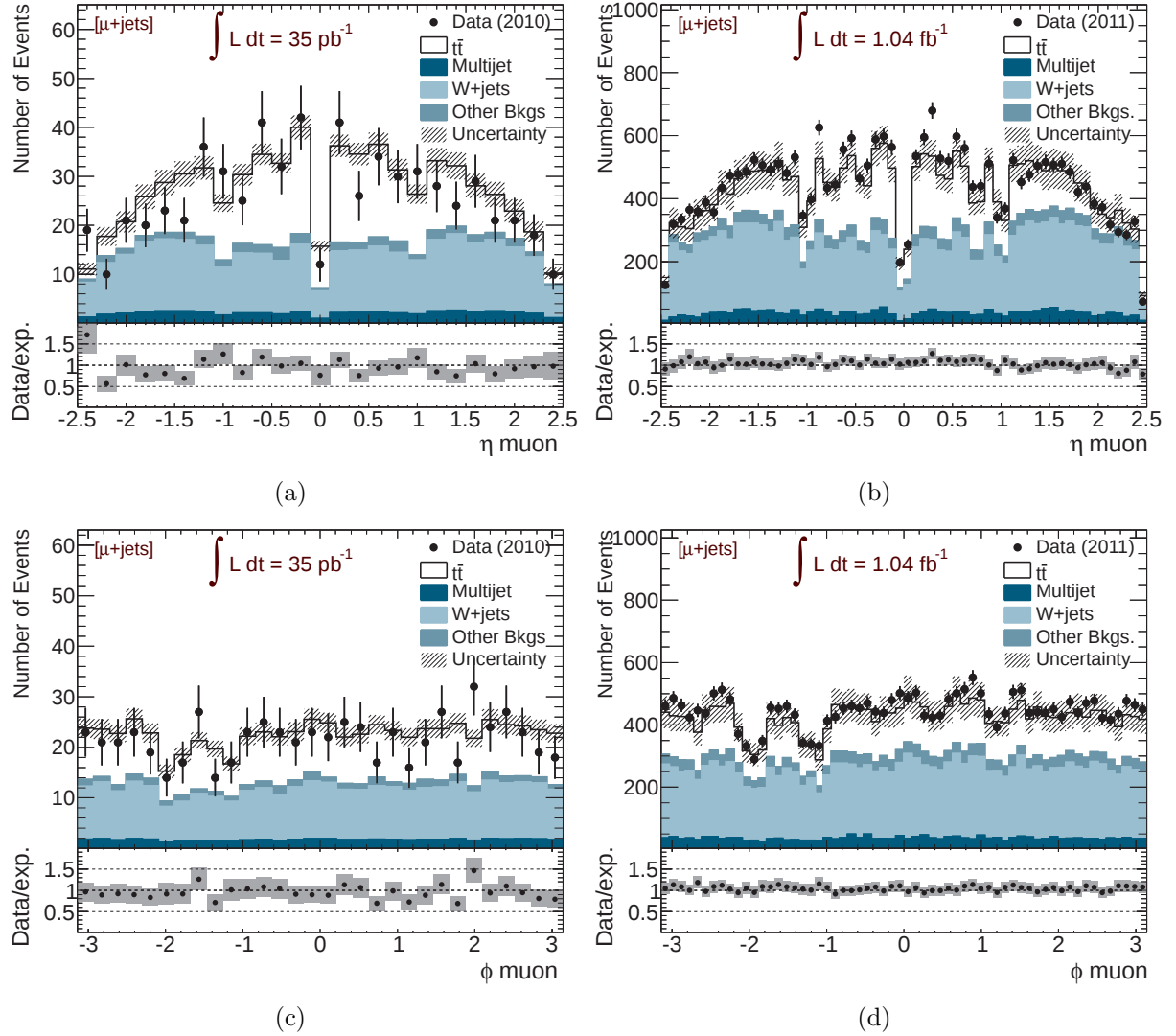


Figure 4.5 – Muon η and ϕ angles in 2010 (left) and 2011 (right), after all cuts.

single-lepton decay channel of $t\bar{t}$, one of the W bosons is required to decay into a neutrino and a lepton. Whilst the lepton is actually measured by the detector, the kinematical properties of the neutrino are best estimated using $\cancel{E}_T$. As there is no z -component to $\cancel{E}_T$, a full mass reconstruction of this W boson is not possible. The mass in the transverse plane, however, can be computed and is expressed as

$$M_T^W = \sqrt{(p_T + \cancel{E}_T)^2 - (p_x + \cancel{E}_x)^2 - (p_y + \cancel{E}_y)^2},$$

where the lepton and missing transverse momentum in the x and y direction are combined. The distribution of M_T^W peaks just below the W boson mass for physics processes that indeed contain W bosons. Figure 4.10 shows the reconstructed transverse mass, after all cuts. The signal ($t\bar{t}$) and W +jets background both peak at the expected position

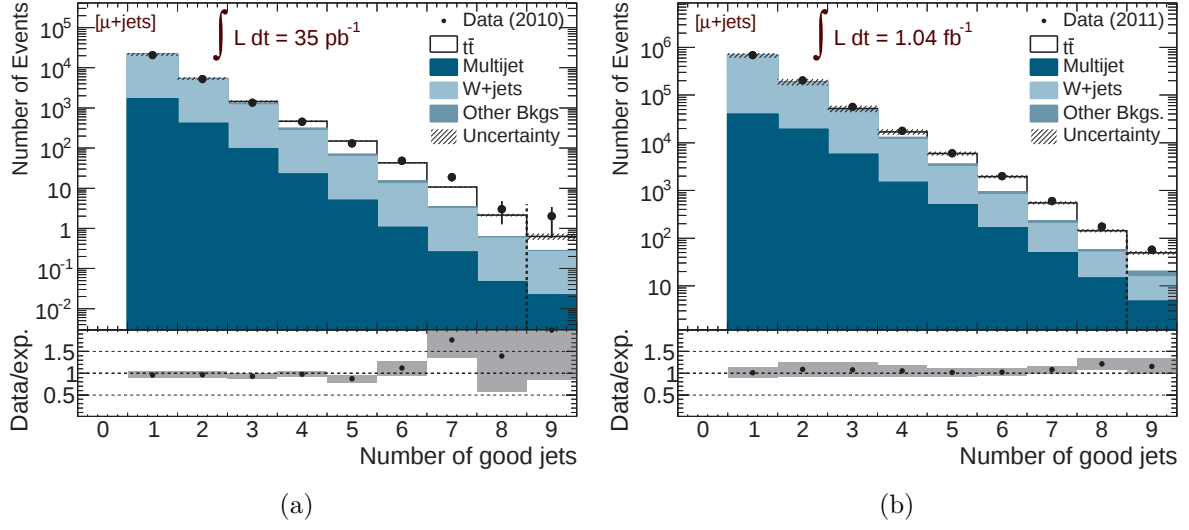


Figure 4.6 – Jet multiplicity in 2010 (a) and 2011 (b), after all other cuts. The jets need to have $p_T > 25 \text{ GeV}$. The last bin shows the sum of the values beyond the plotted range.

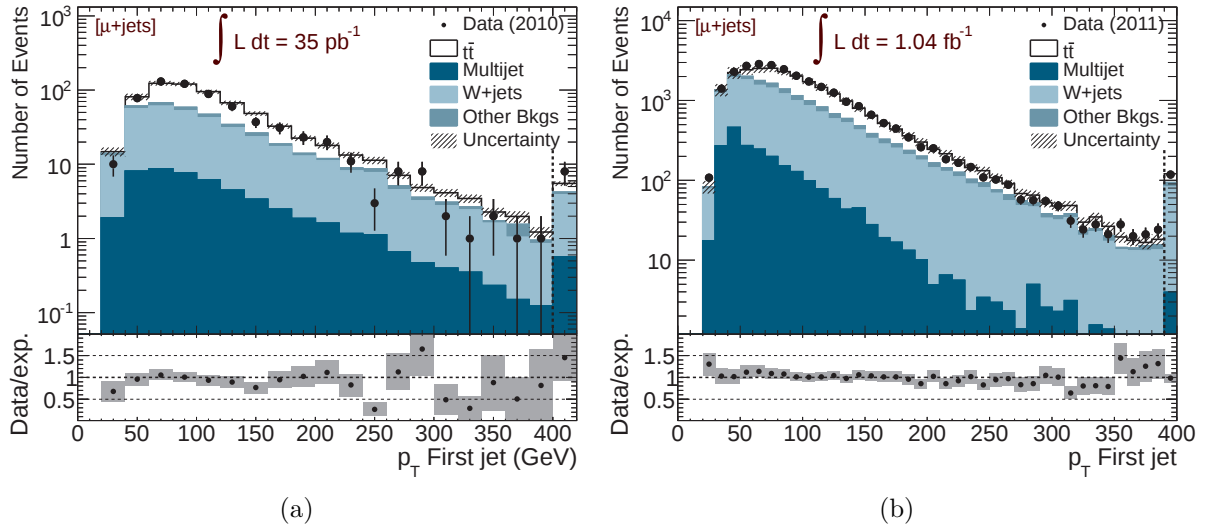


Figure 4.7 – Transverse momentum of the hardest jet in the event for 2010 (a) and 2011 (b), after all cuts. The last bin shows the sum of the values beyond the plotted range.

around 80 GeV. A genuine W boson decaying into lepton-neutrino pair is present in $t\bar{t}$ and W +jets. Due to the differently applied cuts in the electron and muon channel, the shape is dissimilar between the two. In the electron channel (top plots) a straight cut at 25 GeV is imposed to cut away the majority of multijet background events. In the muon channel it suffices to apply only the triangular cut ($\cancel{E}_T + m_T^W \geq 60 \text{ GeV}$), resulting in a different shape on the lower side of the spectrum. The muon channel has a residual slope that originates from the exponentially decreasing value of m_T^W for multijet events, whereas in the electron channel, this is cut off. The agreement in both channels gives confidence

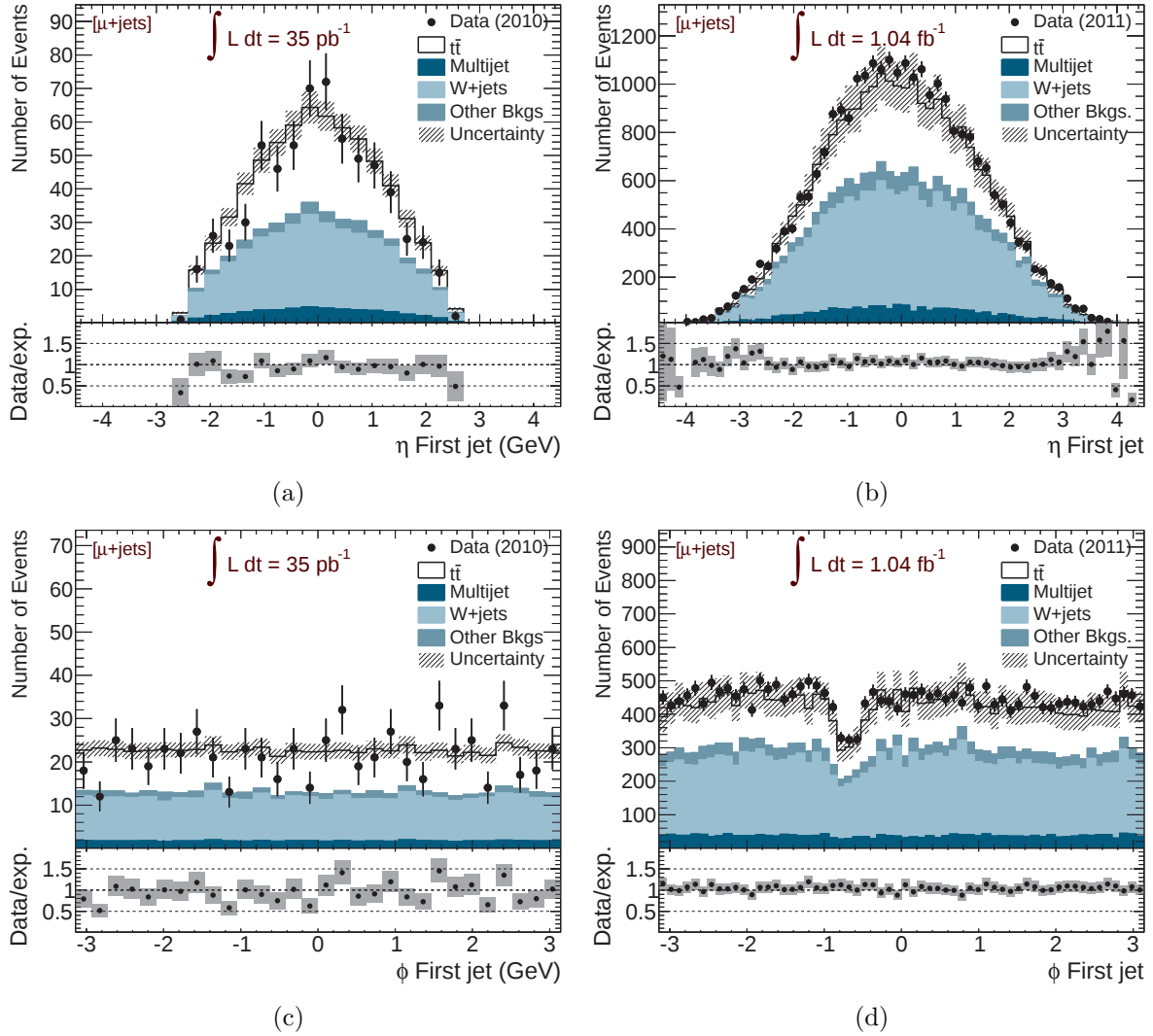


Figure 4.8 – η and ϕ of the hardest jet in the event for 2010 (a) and 2011 (b), after all cuts.

in the assumption that the multijet background is well estimated, also in terms of the shape of m_T^W .

4.6.5 Identification of b -jets

The identification of jets that originate from b -quarks is an important feature in our analyses, as it is a good differentiator between signal and background. In this section we will present the procedure of tagging b -jets. There are several methods to distinguish jets coming from b -quarks from light quark jets. We use the SV0 algorithm [71] to do the identification. The SV0 algorithm takes advantage of the fact that a b -quark hadronizes to form a B hadron. The B hadron has an average lifetime of about 1.5 ps, see for example [72], which implies it has a mean decay length $c\tau$ of 450 μm , before it decays

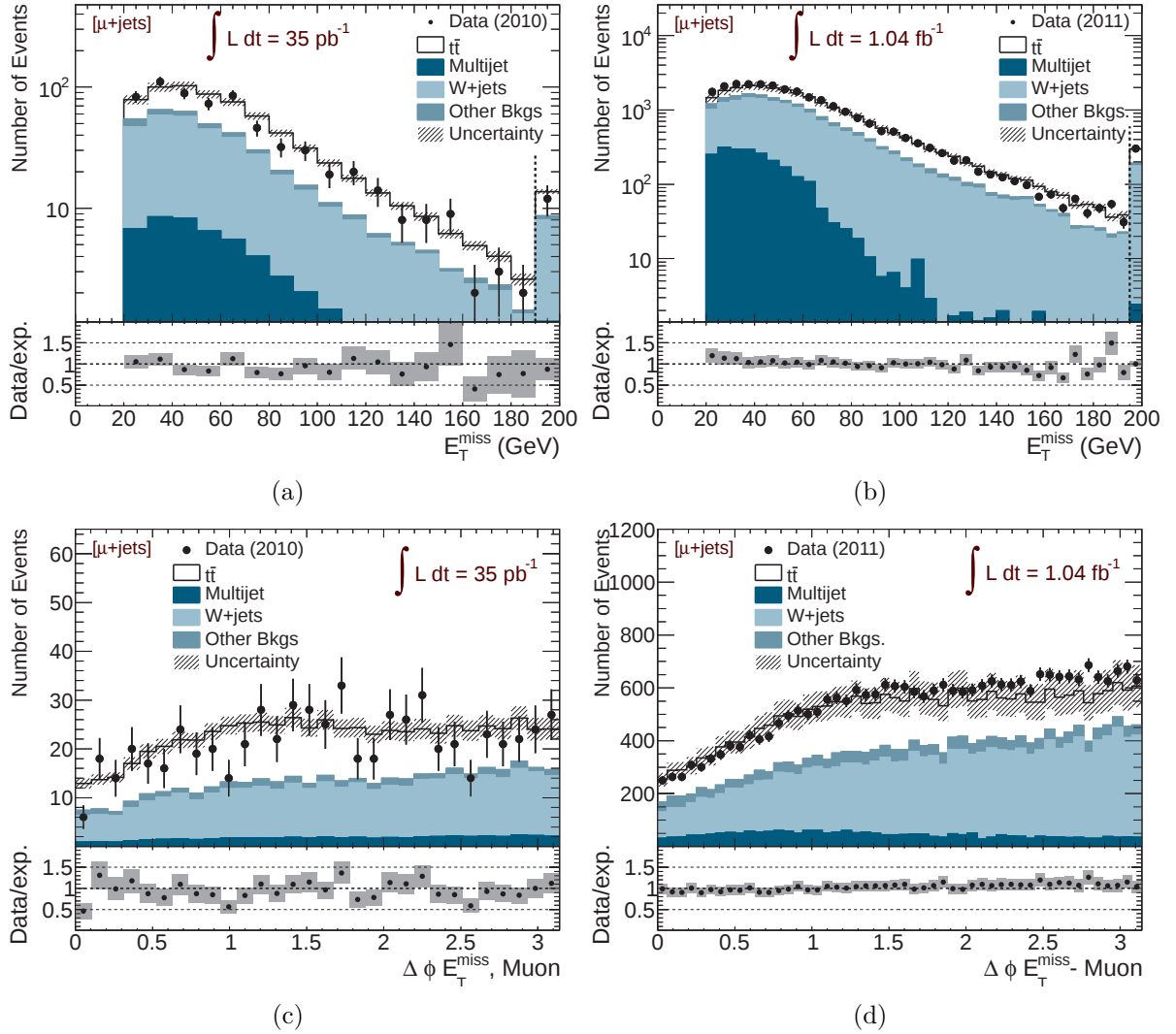


Figure 4.9 – (a,b) Missing transverse energy, after selection for 2010 (left) and 2011 (right). The last bin shows the sum of the values beyond the plotted range. (c,d) Difference between the ϕ component of $\cancel{E}_T$ and the lepton.

into lighter particles. The boosted state in which a B hadron is produced enhances the distance it travels to millimeter scale. At this scale it becomes possible to detect a ‘secondary vertex’ in the collision, defined as a vertex with a distance L from the primary vertex.

The reconstruction of a secondary vertex starts with selecting tracks that are matched to a jet; i.e., tracks that are within a distance ΔR from the axis of the jet. Quality cuts, like a minimum number of hits in the inner detector and a momentum threshold of 0.5 GeV, are applied to the tracks. Tracks with a transverse or longitudinal distance to the primary vertex larger than 2 mm are disregarded since they are too far away and are therefore likely to be misreconstructed or to originate from photon conversions. The remaining

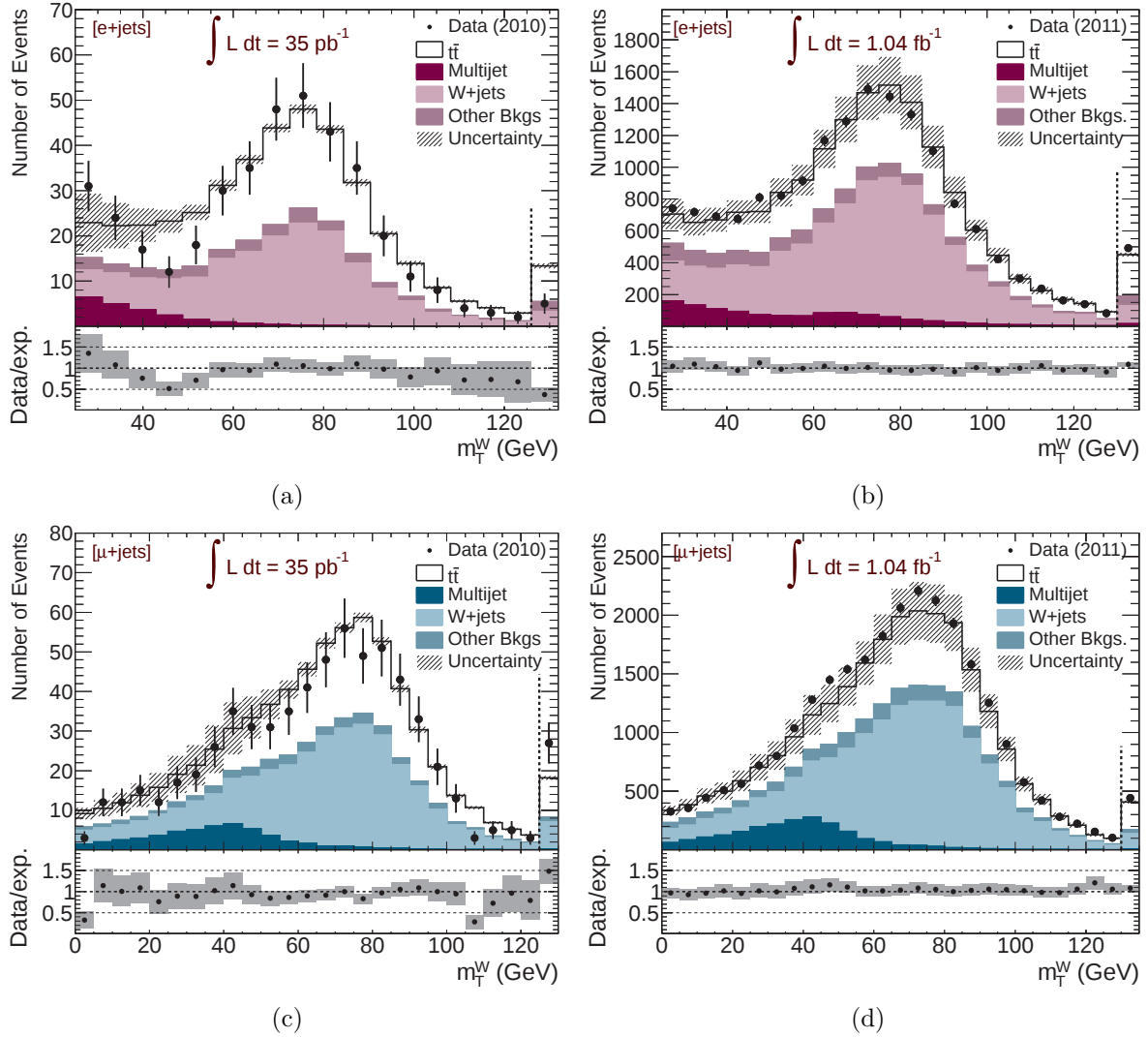


Figure 4.10 – Transverse W boson mass, m_T^W for the electron (a,b) and muon channel (c,d) after all cuts. The last bin shows the sum of the values beyond the plotted range.

tracks are input to the SV0 algorithm.

The algorithm reconstructs vertices from all remaining track pairs in the jet and selects those with a significant displacement from the primary vertex. The vertex mass is required to be inconsistent with K_s^0 and Λ^0 decays and photon conversions. Finally, the vertex position is not allowed to coincide with material in the pixel detector.

In the final step one single secondary vertex is fitted to all of the two-track vertices. Iteratively, tracks that contribute to a low goodness-of-fit (χ^2) value are removed, until this value reaches a threshold value. The measure for the probability of a jet to originate from a b -quark is then expressed in the decay length significance, $L/\sigma(L)$, where L is the distance to the primary vertex and $\sigma(L)$ the uncertainty on this value. Figure 4.11 (left) shows the distribution of this weight variable for different source of jets; coming from light

quarks, c -quarks, tau leptons and b -quarks. The vector from the primary to the secondary vertex is projected on to the jet axis, allowing the weight to take negative values for cases where the secondary vertex is on the opposite side of the jet with respect to the primary vertex. Negative weights do occur, but indicate an unlikely b -jet candidate and result from the limited resolution. We consider a jet b -tagged if the SV0 algorithm assigns a weight larger than 5.85 to it (indicated by the line with arrow). The contamination from other sources (fake b -jets) in the form of c -jets is one order of magnitude lower, from the τ lepton, light quark, and gluon jets it is minimal. The working point is chosen based on optimization between efficiency, purity and light quark rejection.

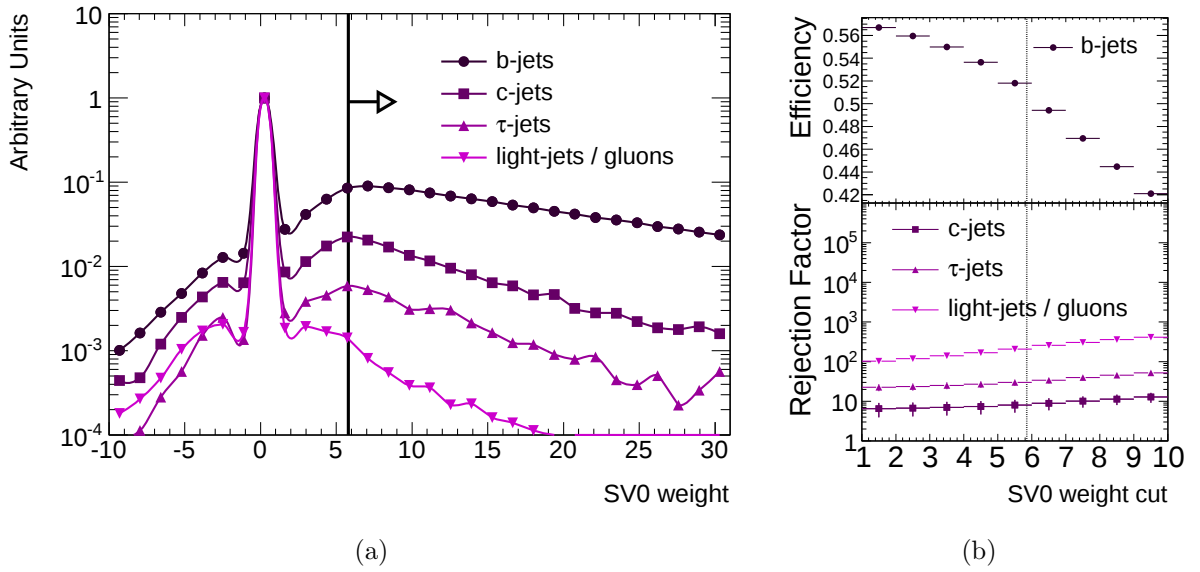


Figure 4.11 – (a) Distribution of SV0 weight for the different contributions of jet sources. (b) Efficiency curve for SV0 weight and rejection factor for non- b sources.

The right plots in Figure 4.11 display the efficiency and rejection factor, as a function of the cut-off value of the SV0 weight. The weight cut at 5.85 corresponds to an efficiency of 50% calculated with simulations of signal from MC@NLO. The efficiency indicates that we can expect roughly only $\sim 25\%$ of the signal events to yield two b -tagged jets. The rejection factor, which is the inverse of the mistag rate, at this point is 271 for light quarks, 9 for charm quarks and 38 for tau leptons.

As a result about 20-25% of the events with two b -quarks are recognized as such. About 50% of the two b -quark events end up to have only one b -tagged jet. The number of b -tagged jets in the selection for top quark events is plotted in Figure 4.12, and proves this statement. Signal events are mostly present in events with tagged jets, but still a significant part has zero b -tags found. Since in the bins with b -tagged jets the $t\bar{t}$ contribution is dominant, it proves that b -tagging is useful for differentiating top quarks from the background.

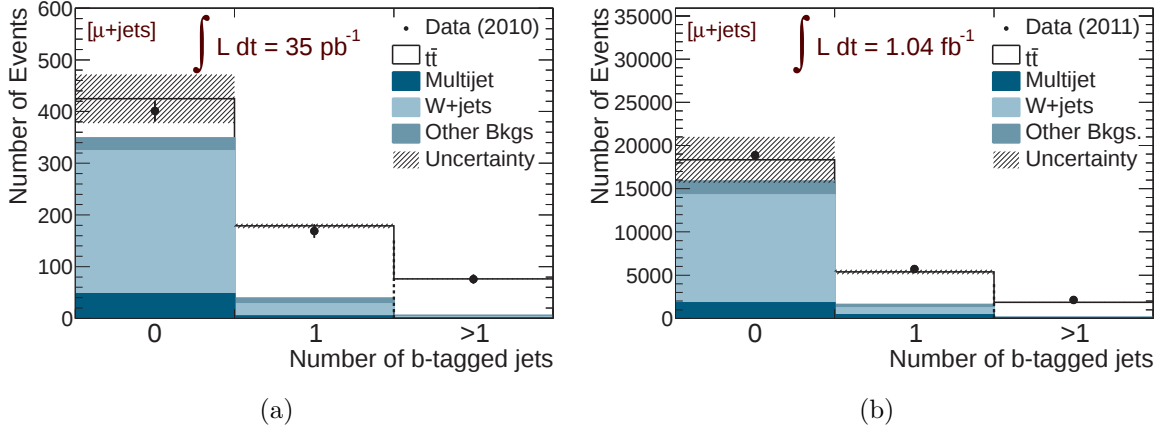


Figure 4.12 – Number of b -tagged jets in selected events in 2010 and 2011.

4.6.6 W +jets background normalization after b -tagging

The amount of W +jets events before b -tagging in 2011 data was estimated with a data-driven approach, as discussed in Section 4.4. The normalization after requiring at least one b -tagged jet, on top of the applied selection criteria, $N_W^{\geq 4, \text{tagged}}$, is obtained by correcting the total amount of events before b -tagging with correction factors obtained partly from data and partly from simulation in events with two jets. It follows the scheme in [73].

$$N_W^{\geq 4, \text{tagged}} = N_W^{\geq 4}(\text{data}) \cdot f^{2, \text{tagged}}(\text{data}) \cdot k^{2 \rightarrow \geq 4}(\text{sim.}).$$

Here, $N_W^{\geq 4}$ is the amount of W +jets events after all selection requirements, but before b -tagging. The factor $f^{2, \text{tagged}}$ is the fraction of W +2 jet events that have at least one b -tagged jet, and is obtained from data using the same charge asymmetry property as used for events with four or more jets. Finally, $k^{2 \rightarrow \geq 4}$ represents the ratio $f^{4, \text{tagged}}/f^{2, \text{tagged}}$ in our simulated samples.

For our selection, we obtain $f^{2, \text{tagged}} = 0.036 \pm 0.005$ (0.043 ± 0.005) in the electron (muon) channel. The correction ratio is evaluated to be $k^{2 \rightarrow \geq 4} = 1.91 \pm 0.21$ and 2.04 ± 0.23 , for the two channels respectively. The total number of W +jets event then amounts to $N_W^{\geq 4, \text{tagged}} = 567$ (1165) in the electron (muon) channel, to which we conservatively assign a 30% uncertainty.

4.7 Top quark reconstruction

One straightforward algorithm for the reconstruction of top quarks from the hadronic decay products, the $\sum p_T$ method, has already been discussed in Section 3.5. Another method we utilize is the ‘Kinematic Likelihood Fitter’ (KL-fitter) [74], which attempts to reconstruct both top quarks in the event. In the following section we present the performance of the two reconstruction algorithms.

4.7.1 Reconstruction with $\sum p_T$ method

In the $\sum p_T$ reconstruction algorithm the combination of three jets, from all possible 3-jet combinations, that together form the vector with the largest transverse momentum is considered the top quark candidate on the hadronic side. The jets in the range $20 < p_T < 25$ GeV are also used in this combination. The aforementioned additional requirement of having a 2-jet combination within the 3-jet combination that has a transverse mass compatible with the W boson mass, we ignore for now. There is no distinction made between b -tagged and untagged jets in this procedure⁴.

The reconstructed mass of the top quark is shown in Figure 4.13. There is a mass peak visible, on top of the background. The background is formed by the physics background processes introduced, but also by combinatorial background. Combinatorial background originates from cases where one or more of the chosen three jets do not originate from the top quark.

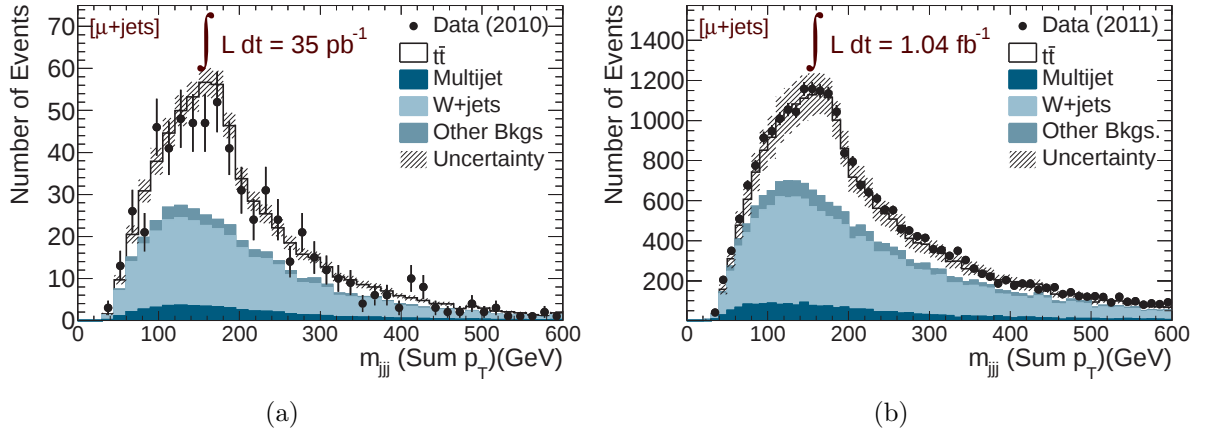


Figure 4.13 – (a,b) Reconstructed invariant mass of the top quark ($\sum p_T$), for 2010 and 2011.

We plot the invariant mass of the three 2-jet combinations that are possible of the three jets used for the top quark candidate in Figure 4.14. We sort the jets by their transverse momentum, jet 1 is the highest. Following this convention $m_{j_1j_2}$ is the 2-jet combination obtained from the jets with the highest p_T , within the chosen three jets. And similarly we have $m_{j_1j_3}$ and $m_{j_2j_3}$. In all cases the W boson mass peak is visible around 80 GeV, albeit of different height. First of all, there is combinatorial background present in these plots. By construction, the W boson is reconstructed properly only in one of the three options. Secondly, the b -quarks in the top quark decay chain are expected to be of higher transverse momentum, on average. The b -quark is much lighter than the W boson, in the rest frame of the top quark this deficit is compensated by a boosted b -quark. The result is that the likelihood of the combination $m_{j_2j_3}$ being the right one, given that the top quark

⁴The algorithm was originally aimed at first data, under the assumption that b -tagging would not be sufficiently calibrated at the time LHC collisions started.

was well reconstructed is the largest. This distribution also shows the clearest peak. The data matches this behavior reasonably well.

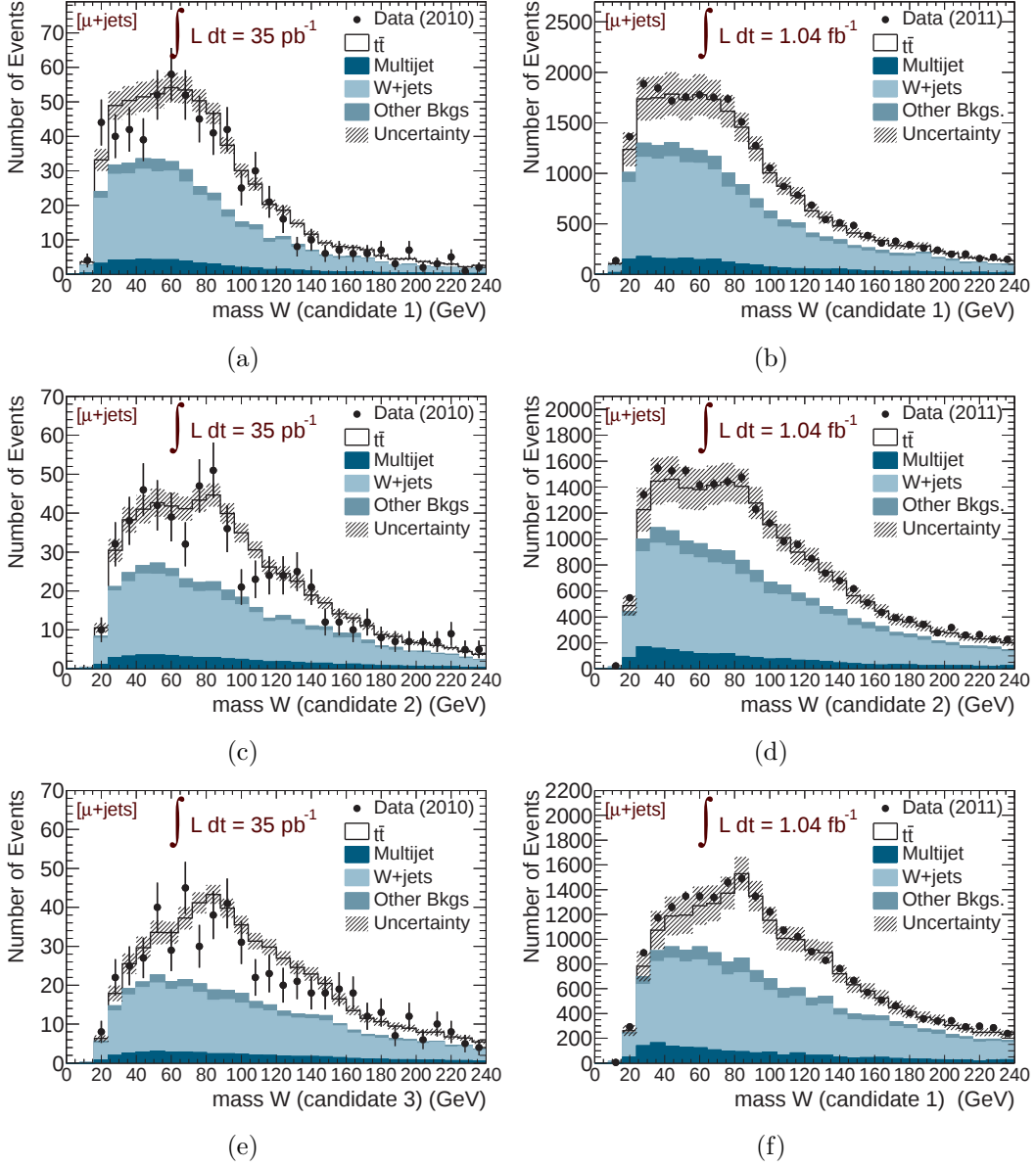


Figure 4.14 – (a,b) Reconstructed invariant mass of the W boson candidate from (a) jet 1 and 2, (b), jet 1 and 3, (c) jet 2 and 3 (sorted in terms of transverse momentum).

In Section 3.5, we additionally applied a W boson mass constraint, where events only pass if the invariant mass of one of the three W boson candidates is close enough to 80.4 GeV. This was applied to 14 TeV collisions, but the procedure has also been used for simulated collision events of a CM-energy of 10 TeV in [75]. The results lead to a more distinct mass peak that could work as a measure for the number of well reconstructed top quarks and consequently a cross section measurement. A disadvantage is that it leads to

a reduction of signal events. We apply the W boson mass constraint to the reconstructed top quark events in our data at 7 TeV, to investigate the feasibility of the algorithm at this CM-energy. Figure 4.15(a) shows all W boson candidates (three candidates per event). We reconstruct the top quark only in case at least one jet pair has an invariant mass in a window of 20 GeV around 80 GeV, the limits set in the original paper. This leads to a 55% reduction of signal events in simulation. The distribution of the top quark mass under these conditions is shown in Figure 4.15(b). A shoulder is formed as a result of the W boson mass constraint, in the region of 100 GeV, in both signal and background, compared to Figure 4.13. The signal shows a broad ‘peak’ in the region 150-160 GeV, revealing the top quark as an excess on top of the combinatorial background in the mass spectrum. The low selection efficiency of this method, however, is problematic. Extending the mass window to a 30 or 40 GeV range around the central value leads to more selected events, but less pronounced peaks. This makes the extraction of the cross section via fits to the top quark mass peak difficult.

In conclusion, the method of reconstructing the mass on one side of the decay proves to work by producing a mass peak at the expected value. Adding the W boson mass constraint enhances the peak, but at the cost of efficiency. For the cross section measurement a higher efficiency and a more pronounced mass peak are preferred. Using information from both sides of the decay in a more advanced algorithm will improve the distribution.

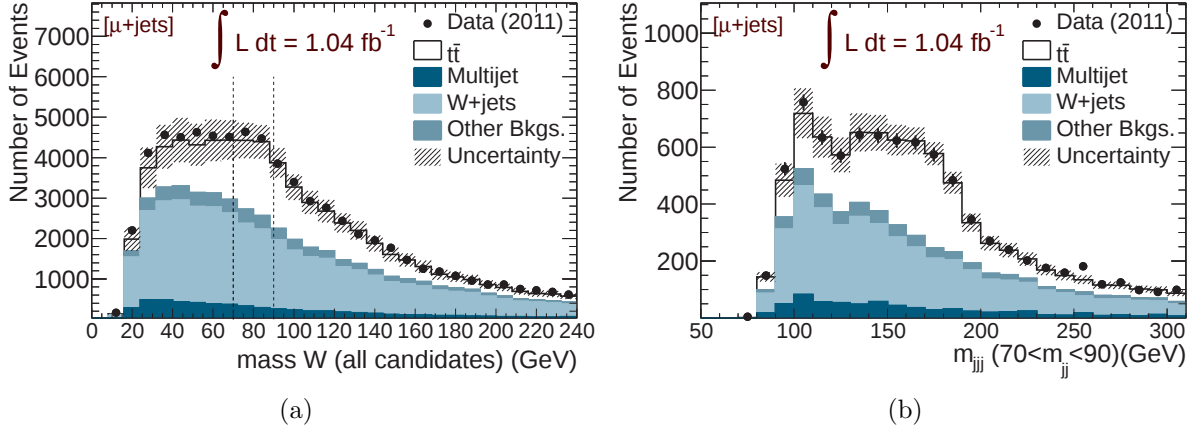


Figure 4.15 – (a) Reconstructed invariant mass of all W boson candidates (three per event). The dashed line indicates a window of 20 GeV around the expected mass, outside which events can be excluded. (b) Reconstructed invariant mass of the top quark, for events with one of the three W boson candidates within a window of 20 GeV around the expected mass.

4.7.2 Reconstruction with Kinematic Likelihood Fitter

The Kinematic Likelihood Fitter package (KL-Fitter) is used to obtain a full reconstruction of semi-leptonic $t\bar{t}$ events using a maximum likelihood method. The goal is to associate detector objects to partons and leptons of the $t\bar{t}$ decay, in order to use the kinematic

properties of the top quarks to increase the resolution of the detector objects. The kinematic constraints are enforced by varying the energy and angles of the detector objects within their resolution, for each permutation of association of the objects to partons and leptons of the top quark decay. In this way, we assign a likelihood to each permutation. The maximization is performed by the Bayesian Analysis Toolkit [76].

The input to the KL-Fitter algorithm consist of the calibrated energy and angular information of the jets, lepton and $\cancel{E}_T$ as measured by the ATLAS detector. Only the four jets with the highest transverse momentum are selected. The assumption is that these four jets come from the hard scattering process and originate from either the two b-quarks or the two light quarks in the top quark decay. Table 4.5 lists the 17 observables that are used. For jets and leptons the angles $\tilde{\Omega}_i = (\tilde{\eta}, \tilde{\phi})$ and energy $\tilde{E}$ are input. Secondly, we use the measured x - and y -component of the missing transverse energy, $\tilde{E}_x$ and $\tilde{E}_y$.

Table 4.5 – Summary of input and fit parameters for the KL-fitter.

Detector object	Observables	(#)	Particles	Fit parameters	(#)
jets ($\times 4$)	$(\tilde{\eta}_i, \tilde{\phi}_i)$	(12)	light quarks ($\times 2$)	E, η, ϕ	(6)
lepton	$(\tilde{\eta}_l, \tilde{\phi}_l), \tilde{E}_l$	(3)	b -quarks ($\times 2$)	E, η, ϕ	(6)
$\cancel{E}_T$	$\tilde{E}_x, \tilde{E}_y$	(2)	lepton	E	(1)
			neutrino	p_x, p_y, p_z	(3)
			top quark	$\hat{M}_t$	(1)

The likelihood is built up out of two elements: transfer functions and mass constraints.

Transfer functions

The transfer functions represent conditional probabilities. They define the probability of measuring the value for an observable quantity at detector level given its true value at parton level. In this way the resolution of the measurement is taken into account. The transfer functions for the angles $\mathcal{W}(\tilde{\Omega}_i|\Omega_i)$ are defined as a Gaussian, with Ω_i representing the true angular coordinates (η, ϕ) and $\tilde{\Omega}_i$ the observable values of these quantities. The Gaussian distribution accommodates the resolution on these variables. The angular transfer functions are only applied to transfer from quarks to jets; the lepton angular resolution is neglected and is approximated by a delta function.

The functions to transfer the energy from parton to detector level look somewhat different. The resolution effects on the lepton and jet energies cannot be represented by a plain Gaussian distribution due to detector losses of several kinds, calibration effects and initial and final state radiation. To accommodate this behavior, the transfer function for energy is parametrized as the sum of two Gaussian distributions:

$$\mathcal{W}(\tilde{E}_i|E_i) = \frac{1}{2\pi(c_2 + c_3c_5)} \left(e^{-\frac{(\Delta E - c_1)^2}{2c_2^2}} + c_3 e^{-\frac{(\Delta E - c_4)^2}{2c_5^2}} \right),$$

with $\tilde{E}_i$ and E_i being the measured and true value respectively, and ΔE the difference between them. The five parameters c_i are determined from simulation for different bins of rapidity and depend on the true energy. Figure 4.16 shows an example of the fit that parametrizes the resolution (obtained from [77]), in an arbitrary rapidity-momentum range. The extra Gaussian (component 2) accommodates the tail effects of the resolution distribution.

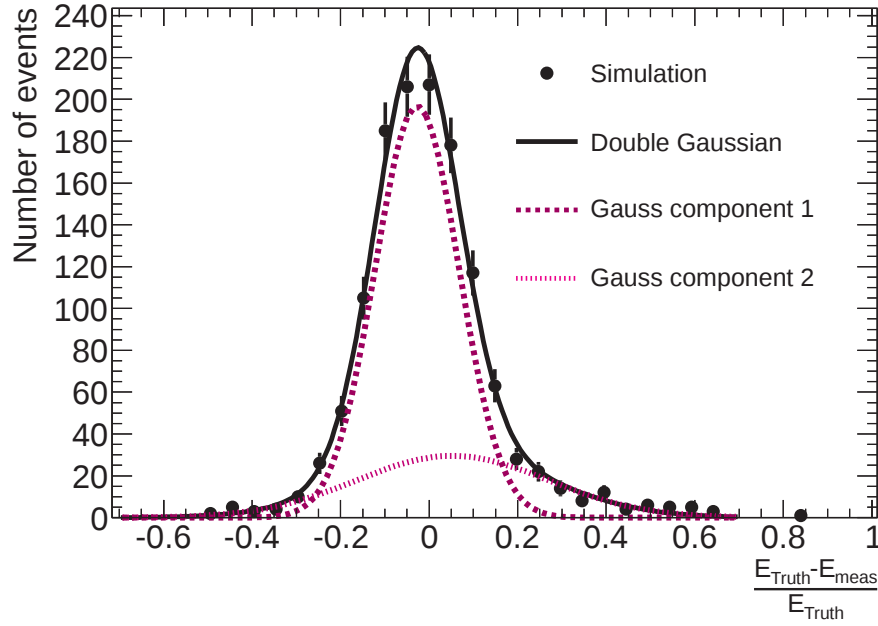


Figure 4.16 – Example of the energy resolution for light jets with $0.8 < |\eta| < 1.37$ and $205 \text{ GeV} < p_T < 235 \text{ GeV}$.

For the missing transverse energy ($\cancel{E}_T$) we define two transfer functions, $\mathcal{W}(\tilde{\cancel{E}}_x|E_x^\nu)$ and $\mathcal{W}(\tilde{\cancel{E}}_y|E_y^\nu)$. In these functions, the x - and y -components of the parton momentum are mapped to the measured missing energy components.

Implementations of the mass constraints

The other terms in the likelihood function constrain the combined masses formed by the jets, leptons and $\cancel{E}_T$ objects, with Breit-Wigner functions. The mass of the combination of the two jets assigned as light quarks (m_{jj}) is expected to be close to the W boson mass of 80.4 GeV. In the likelihood function it is constrained with a Breit-Wigner function around this value, with a width Γ_W of 2.1 GeV. In the likelihood this is expressed by the term $f_{BW}(m_{jj}|M_W, \Gamma_W)$. The combined mass of the charged lepton and the neutrino, $m_{l\nu}$ is restricted similarly to the W boson mass, $f_{BW}(m_{l\nu}|M_W, \Gamma_W)$.

The masses of the hadronic and leptonic top quarks are required to be equal, but the absolute value of the pole mass is kept unconstrained. The top quark pole mass is a free parameter ($\hat{M}_t$), but we do impose a fixed width for Γ_t of 1.5 GeV. The unconstrained mass value in the fit prevents a bias towards the expected value in the mass distribution of background events. The top mass constraints in the likelihood function are expressed as $f_{BW}(m_{l\nu j}|\hat{M}_t, \Gamma_t)$ and $f_{BW}(m_{jjj}|\hat{M}_t, \Gamma_t)$.

The likelihood is written as:

$$\begin{aligned} \mathcal{L}(p_1, \dots, p_{17}) = & \prod_{i=1}^4 (\mathcal{W}(\tilde{E}_i|E_i) \cdot \mathcal{W}(\tilde{\Omega}_i|\Omega_i)) \\ & \cdot \mathcal{W}(\tilde{E}_l|E_l) \cdot \mathcal{W}(\tilde{E}_x|E_x^\nu) \cdot \mathcal{W}(\tilde{E}_y|E_y^\nu) \\ & \cdot f_{BW}(m_{jj}; M_W, \Gamma_W) \cdot f_{BW}(m_{l\nu}; M_W, \Gamma_W) \\ & \cdot f_{BW}(m_{l\nu j}; \hat{M}_t, \Gamma_t) \cdot f_{BW}(m_{jjj}; \hat{M}_t, \Gamma_t) \\ & \cdot \delta_b, \end{aligned}$$

where the index i runs over the four jets. The delta function δ_b prevents b -tagged jets to be assigned to the position of a light quark: a zero probability is assigned to that permutation. The fit parameters are listed in Table 4.5.

The negative log of the likelihood is minimized, considering all permutations of parton-jet assignments. The reconstructed mass distributions for the best permutation are shown in Figure 4.17. It is important to notice that the constraint on the difference between the two top quark masses does not bias the background shape.

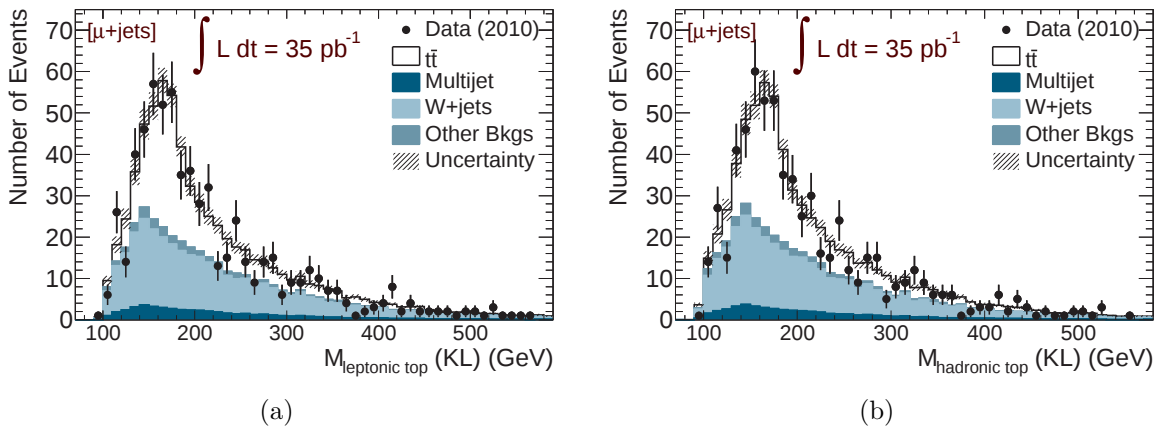


Figure 4.17 – KL-Fitter reconstructed mass for simulation and data, for the leptonically (a) and hadronically decaying top quark (b).

4.8 Comparison of the KL-fitter and $\sum p_T$ algorithms

We compare the properties of the top quarks on the hadronic side with both reconstruction algorithms, to each other and to the true properties as simulated by the generator. We apply an extra cut, with respect to the basic selection: at least one jet should be tagged as a b -jet. As we have seen, this leads to a reasonably pure sample of signal events. (Note that the b -tag veto in the likelihood of the KL-fitter only leads to a permutation that is not allowed, it does not discard events.) Figure 4.18 shows the reconstructed invariant mass of the top quarks on the hadronic side, for both reconstruction algorithms, after requiring at least one b -tagged jet. First of all, the reconstruction with the two algorithms results in reasonably different distributions of the top quark mass. The kinematic fit is superior in terms of width, showing a narrower peak. The KL-fitter mass also has a higher turn-on point, the distribution starts above 90 GeV. This is in contrast to the mass obtained with the $\sum p_T$ method, which can take values as low as 40 GeV. In all cases the data matches with the expectations.

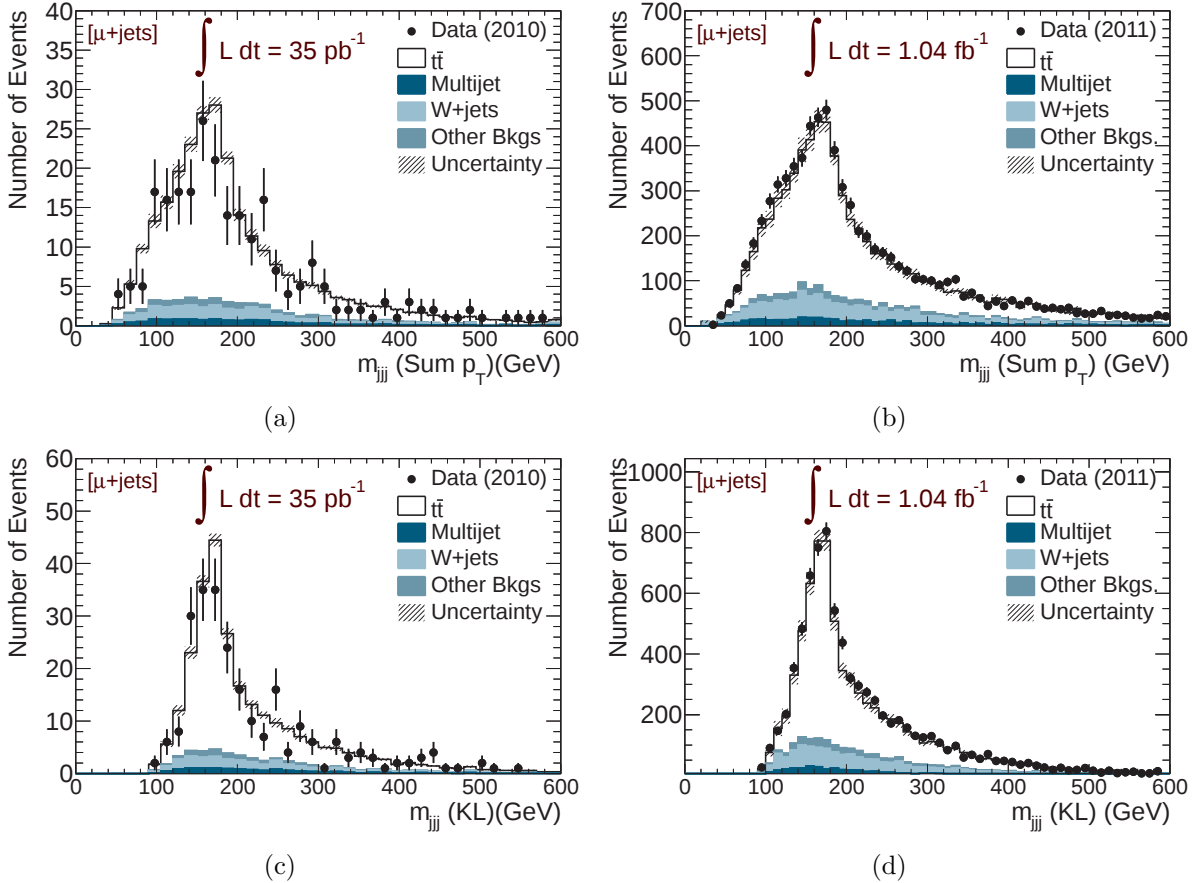


Figure 4.18 – Hadronic top quark mass in 2010 and 2011 data, reconstructed with the $\sum p_T$ method (a,c) and KL-Fitter (b,d).

We compare the two algorithms in simulation at reconstruction level with the simulation

at parton level, to show the difference in performance. At the parton level, we take the top quark at the point where it is created in the hard scatter in simulation. In the simulation, the top quark mass is set to a fixed value, 172.5 GeV, making a straight comparison of reconstructed and simulated masses impossible. We therefore examine the momentum and angular distributions. We define the difference in momentum of the top quark as $\Delta p_T = p_T(reco) - p_T(parton)$, where $p_T(reco)$ is the p_T as reconstructed with one of the algorithms. This quantity is shown in Figure 4.19. The KL-fitter algorithm shows a distribution of Δp_T centered around zero, with tails to both sides. The tail towards the positive side is slightly higher, indicating that the reconstruction has a tendency to overestimate the transverse momentum more often than the other way around. The $\sum p_T$ algorithm is much more biased, the distribution of Δp_T peaks around 50 GeV. This is expected, as the algorithm explicitly maximizes the momentum. The equivalent variables for the angles, $\Delta\eta$ and $\Delta\phi$ are displayed as well, and show equivalent spectra. For both reconstruction algorithms, there is a peak at 0, with symmetric tails. The KL-fitter is superior to a small extent. The spatial difference between the reconstructed top quark at reconstruction and parton level is expressed in ΔR . This distribution shows that a large part of the events has a top quark reconstructed in the vicinity of the original top quark. The KL-fitter performs better as well, with a larger peak close to zero. It is not possible to deploy an unambiguous matching algorithm to match the reconstructed and parton level quark. Even misreconstructed quarks can coincidentally get very close to the parton level top quark direction. We measure a fraction of 32% of events within $\Delta R = 0.4$ of the original top quark for the KL-fitter algorithm and 26% for the $\sum p_T$ procedure. The actual number of well reconstructed events will be somewhat lower, due to the effect of coincidental matches.

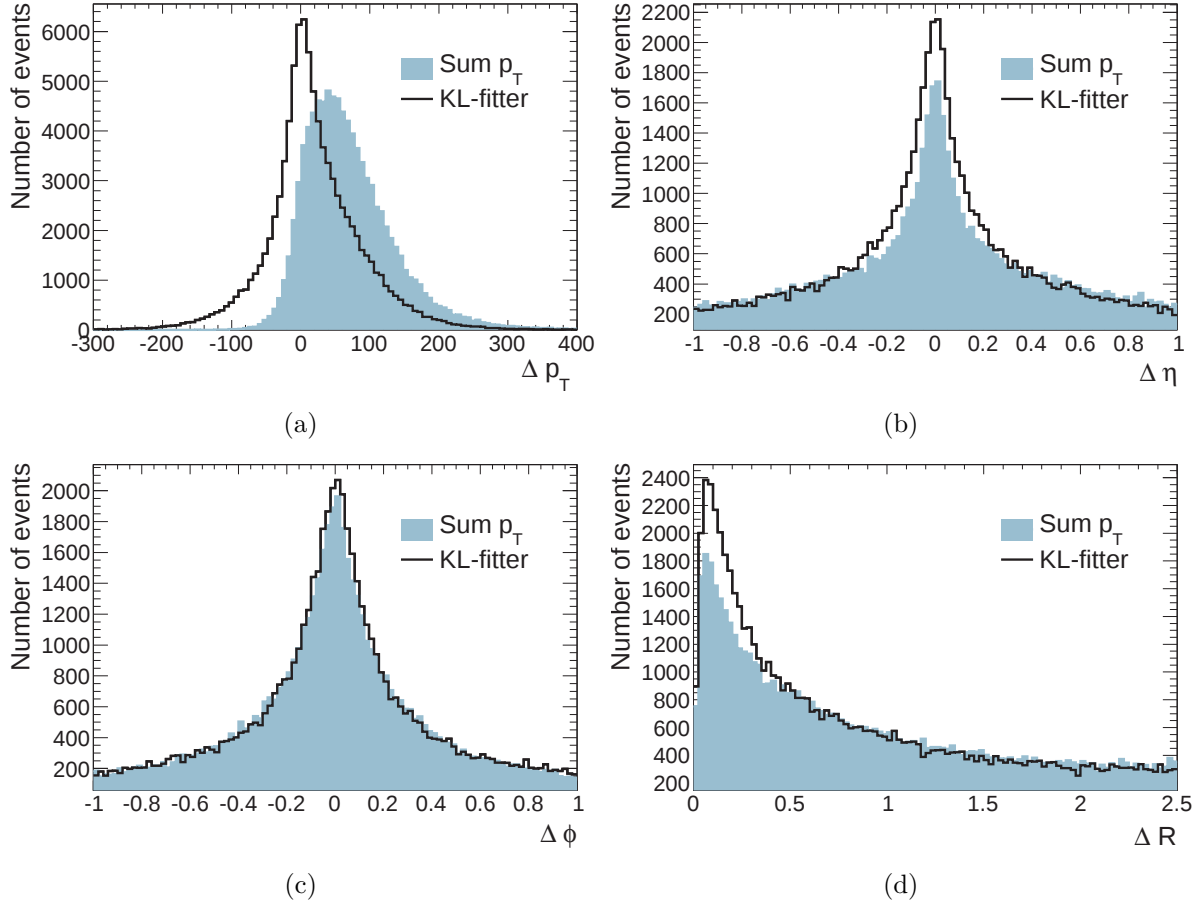
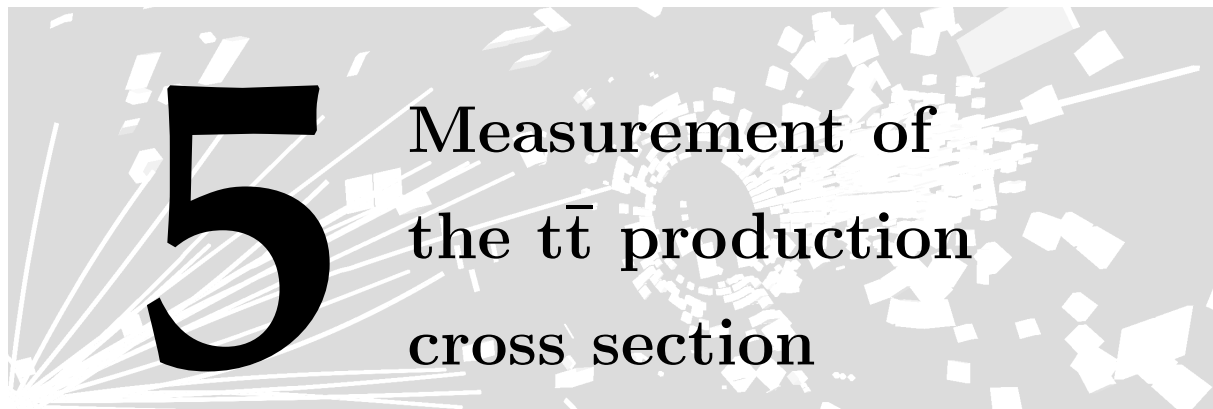


Figure 4.19 – Resolution of KL-fitter and $\sum p_T$ algorithm, with respect to the simulated quark on the hadronic side.

4.9 Summary

We introduced the data that will be used in the analyses of the coming chapters. For the cross section chapter this amounts to 35 pb^{-1} , recorded in 2010. The charge asymmetry measurement will be performed on a part of the 2011 data set, 1.04 fb^{-1} . There are small differences in the conditions of the data in terms of pile-up and detector status, but we apply a common event selection and compared the distribution of the important objects in our analysis. Comparing the data with the expected shape and normalization of simulated and data-driven background, we showed that overall the agreement is very good. The procedure of tagging jets when they are likely to originate from b -quarks, b -tagging, works very well, and gives a handle to purify the sample and suppress backgrounds. We discussed two top reconstruction algorithms. The first is straightforward and makes an optimal combination of jets to form the top quark on the hadronic side of the decay. The second algorithm is a kinematic fitter that attempts to reconstruct both sides of the decay. It contains input from jets, the lepton and the missing transverse energy. Both algorithms show the invariant mass peak, but the KL-fitter is superior in all terms. It has

the advantage of reconstructing a top quark on the leptonic side of the decay as well, and thus gives information on the complete $t\bar{t}$ -system. We make use of the KL-fitter algorithm where possible. We will, however, make use of the $\sum p_T$ algorithm in case of incomplete information, that is, when we take control regions with only three jets available.



5 Measurement of the $t\bar{t}$ production cross section

This chapter describes the measurement of the production cross section of top quark pairs ($t\bar{t}$), performed with the full data set recorded by the ATLAS detector in 2010. The production rate of top quark pairs is measured by the CDF [78] and D0 [79] collaborations for a CM-energy of 1.96 TeV, at the Tevatron. ATLAS presented a measurement that confirmed top quark pair production in the proton-proton collisions with a CM-energy of 7 TeV at the LHC, with the first 3 pb⁻¹ of data [80]. The measurement in this chapter (using 35 pb⁻¹) aims to establish the cross section in the single-lepton decay channel of $t\bar{t}$ events.

The analysis that is conducted is based on a ‘simultaneous template fit’. The preselected data are categorized in subsets, characterized by having different jet multiplicities and a different number of b -tagged jets. The expected signal-to-background ratio differs between each subset. We established template shapes of the invariant mass distribution of the top quark for the expected signal and background, in each of these subsets. Data-driven constraints relate the number of signal and background events in the different subsets. The templates are then fitted to the data in the six subsets of the data simultaneously, respecting the constraints. The estimate of the total number of signal events in the complete data set that follows from this procedure is directly proportional to the top quark production cross section.

The chapter is outlined as follows. We first introduce the fit method and likelihood construction. The sections that follow describe the input components to the fit, the subdivision of the data and the expected component of signal and background in the resulting subsets. Thereafter, the fit ratio measurements and template extraction are discussed. Finally, we present the results and estimates of the systematic uncertainties

that are introduced throughout the procedure.

5.1 The simultaneous template fit

The measurement of the top quark production cross section with b -tagging is done by fitting shape templates to the invariant mass distribution of the hadronic top, m_{jjj} . We use the KL-fitter reconstruction algorithm or the $\sum_{p_T}$ algorithm (Section 4.7) to obtain m_{jjj} , depending on the number of jets in the event. The concept behind this measurement is to slice the data into six subsamples with different compositions of $t\bar{t}$ and background events. We categorize each event by its jet multiplicity and b -jet multiplicity: the number of jets can be either 3, or ≥ 4 (events with less jets were omitted before), the number of b -jets can take values of 0, 1, or ≥ 2 .

In the events with low jet multiplicity and without b -tags high background is expected, as a decaying $t\bar{t}$ pair should produce at least four jets, with a high probability of at least one b -tag. In the slices of data with 4 or more jets, of which some are b -tagged, relatively more signal will be present. The reason for including the 3-jet events into the analysis is that it improves the background characterization in the 4-jet slice.

The power of the simultaneous fit comes from the constraints that relate the six subsets. It is possible to define ratios that predict the population of one slice by extrapolation from another slice of data. The values and uncertainties of three of such ratios are measured externally and are included to the likelihood to constrain the fit and improve the result. Two constraints are implemented as Gaussian PDFs that have a mean and width estimated from data-driven methods. They are allowed to vary within this range, according to the Gaussian shape. The third ratio is fixed to the value obtained from simulation. The following sections cover the details on the estimation of these constrained ratios. Besides the data-driven constraint estimates, the shape templates for the background are taken from data control samples as well. The implementation of data-driven methods reduces the overall dependency on Monte Carlo simulations, with the aim to suppress systematic uncertainties.

5.1.1 The construction of the fit

We use twelve templates to fit to the invariant mass (m_{jjj}) distributions in six subregions (slices) of phase space. The contributions to the likelihood for each slice of data can be expressed as

$$[f(x)]_i^j = [N_B \cdot \mathcal{T}_B(x) + N_S \cdot \mathcal{T}_S(x)]_i^j,$$

where $x = m_{jjj}$ and i, j being the number of jets and b -tags respectively. The signal and background templates $\mathcal{T}_S$ and $\mathcal{T}_B$ are separately defined for each subsample. Hence we have twelve normalized templates as a fixed input to the fit. The template construction is described in Section 5.4. The function $f(x)$ is the measured spectrum in the category corresponding to indices i and j . N_B and N_S are scalar fit parameters.

Figure 5.1 shows a schematic view of the subsamples. The six boxes on the left represent the six subsamples, each built up out of a signal and background contribution, $[N_S]_i^j$ and $[N_B]_i^j$. The sum of all events with 3 jets and all events with ≥ 4 jets is shown on the right. In the following our notation will be $[N_S]_4 = \sum_{j=0}^2 ([N_S]_4^j)$, and $[N_S]_3 = \sum_{j=0}^2 ([N_S]_3^j)$, i.e., summing over all b -tag slices.

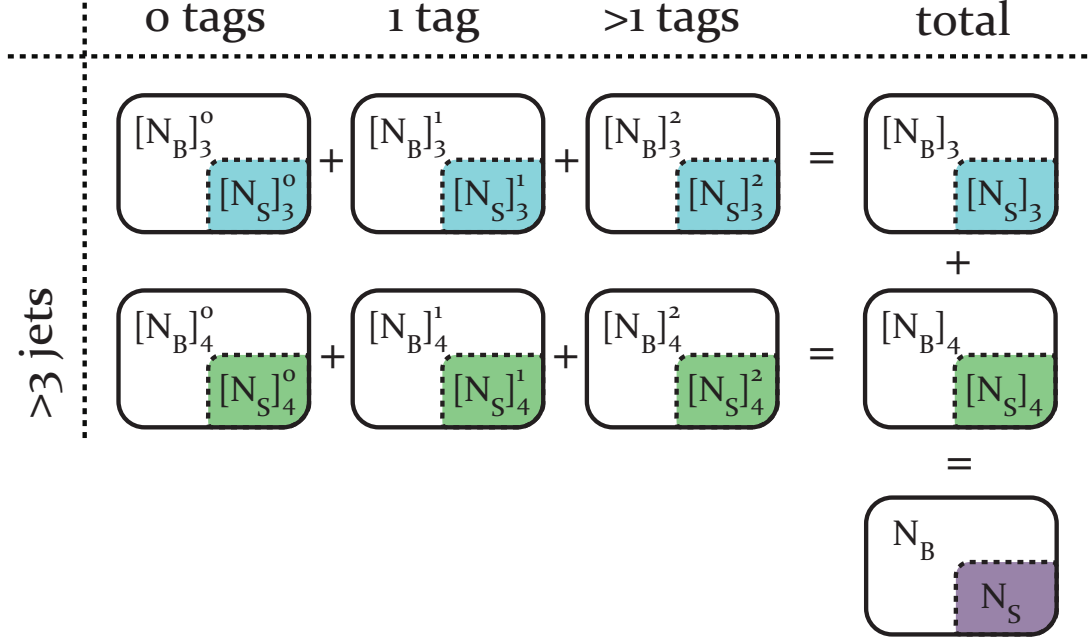


Figure 5.1 – Overview of the structure of subsamples. The white region of the square represents the background and the colored region indicates the signal. The six squares on the left side correspond to the data slices. The horizontal and vertical sum are used as well.

The six data slices are fitted simultaneously to make use of several connections amongst them. We define three ratios:

$$\begin{aligned}
 R_1 &= [N_B]_3^1 / [N_B]_3 && \text{(constrained),} \\
 R_2 &= [N_S]_4 / [N_S]_3 && \text{(constrained),} \\
 R_3 &= \frac{[N_B]_3^1 / [N_B]_3}{[N_B]_4^1 / [N_B]_4} && \text{(fixed)}
 \end{aligned}$$

The ratios, relating the subsets in the fit in different ways (see Figure 5.1), are measured externally, as supplemental input to the likelihood. The subsidiary measurements are implemented as a Gaussian distribution for the ratios R_1 and R_2 , for R_3 we obtain a value direct from simulation. Section 5.3 treats the measurement of these ratios and discusses the reasons that motivate the choice of the ratios. We define the likelihood in

five terms:

$$\begin{aligned}
 \mathcal{L} = & \prod_{n=1}^{N_{evt}} \underbrace{\left(\prod_{i=3}^4 \prod_{j=0}^2 \frac{[f(x)]_i^j}{[N_S]_i^j + [N_B]_i^j} \right)}_{\text{Template PDFs}} \cdot \underbrace{P(N_{obs}; N_S, N_B)}_{\text{Poissonian}} \\
 & \cdot \underbrace{G_1(\tilde{R}_1; R_1, \sigma_1)}_{\text{Gaussian}} \cdot \underbrace{G_2(\tilde{R}_2; R_2, \sigma_2)}_{\text{Gaussian}} \cdot \underbrace{\delta(\tilde{R}_3; R_3)}_{\text{Delta}}. \quad (5.1)
 \end{aligned}$$

In the first term, the six fit equations $[f(x)]_i^j$ describing the template probability density functions are normalized by the total number of events in that slice. This term is the core of the simultaneous template fit. The Poissonian term is introduced to treat the total number of events as a random variable, rather than a fixed number. This allows the total number of events to be adjusted during minimization (of the negative log of the likelihood, $-\log(\mathcal{L})$), if the fit requires it. Then there are two Gaussian terms for the ratios $\tilde{R}_1$ and $\tilde{R}_2$, with a mean R and width σ obtained from subsidiary measurements. Finally, there is a delta function, representing the inclusion of a fixed ratio R_3 , also obtained externally. Section 5.3 is dedicated to the determination of the central value and of the ranges the first two fractions are allowed to vary within. The negative log of this likelihood is minimized with MINUIT [81].

The six output parameters can be reparametrized in several ways. The total number of signal events is the measure for the cross section calculation. As a spin-off, we can extract the efficiency of tagging a b -quark from the fit result.

B-tagging efficiency

The efficiency for tagging a jet in $t\bar{t}$ events is derived from events with exactly three jets. We write the number of events in the 3-jet/1-tag subset as a function of the true jet originators, i.e., b -quarks, light quarks or tau leptons. To do so, we define f_{qqq} , f_{qqb} and f_{qbb} where the subscript indicates how many of the jets came from b -quarks. From signal simulation it follows that the fraction of events with exactly three jets, where the jets originate from two b -quarks and one other object (usually quarks), f_{qbb} is 64.7%. Similarly, f_{qqb} is 32.0% and f_{qqq} is 3.5%, all obtained from simulation¹. The probability of each of these topologies to end up in the 3-jet/1-tag category depends directly on the b -tag efficiency and the fake rate. The fake rate r_f is defined as the fraction of non- b particles or partons that get misidentified b -quark jets. We define the efficiency $[\epsilon_S]_3^1$ as

¹The difference between the percentages of f_{qqb} and f_{qbb} comes from kinematical arguments. At least one jet is not detected in 3-jet events that come from $t\bar{t}$. The b -jet is on average produced with a higher momentum than the other decay products and is more often detected.

the ratio of events with one b -tag, normalized to all events with three jets as:

$$\begin{aligned}
[\epsilon_S]_3^1 = \frac{[N_S]_3^1}{[N_S]_3} &= f_{qbb} \cdot (2 \cdot (1 - r_f) \cdot B_{\text{eff}} \cdot (1 - B_{\text{eff}}) + (1 - B_{\text{eff}})^2 \cdot r_f) \\
&\quad + f_{qqb} \cdot ((1 - r_f)^2 \cdot B_{\text{eff}} + 2 \cdot r_f \cdot (1 - r_f) \cdot (1 - B_{\text{eff}})) \\
&\quad + f_{qqq} \cdot 3 \cdot r_f \cdot (1 - r_f)^2,
\end{aligned}$$

with $[\epsilon_S]_3^1$ a parameter that is determined by the fit. The b -tag efficiency (B_{eff}) and fake rate (r_f) are unknowns and need to be determined from the data. Under the assumption that the fake rate is small (in simulation we find a value of 0.025 for r_f), the expression above simplifies to

$$[\epsilon_S]_3^1 = f_{qbb} \cdot 2 \cdot B_{\text{eff}} \cdot (1 - B_{\text{eff}}) + f_{qqb} \cdot B_{\text{eff}}.$$

As we neglect the fake rate, the b -tag efficiency can be extracted from this equation. Systematic uncertainties are assigned to the values of f_{qbb} and f_{qqb} , since they are obtained from simulation. Likewise an uncertainty is considered for the fake rate approximation. The additional results obtained from this aspect of the fit are discussed in Section 5.5.

5.2 Properties of data

The input to the fit procedure consists of several elements: template shapes of the signal and background, constraints on ratio parameters, and finally the data distributions of m_{jjj} in each subset.

5.2.1 Data categorization

The data set that is used in this analysis is described in the previous chapter, as well as the selection requirements and reconstruction. In this section we create the six subsets of data that are used in the fit, as described earlier. The normalization of the categories for the electron channel is shown in Table 5.1 for the signal ($t\bar{t}$), sum of all background events, and data. The sum of all backgrounds contains W +jets, Z +jets, diboson, single top and multijet events. The uncertainty reflects the statistical uncertainty, except for the data-driven multijet component in background events, to which a systematic uncertainty is added. In the electron channel the data is compatible with expected values, within uncertainties. This is true for the ensemble, some of the subsets show discrepancies larger than 1σ .

A more schematic view of the relative population per bin in the electron channel is shown in Figure 5.2(a). Each of the six squares shows the amount of signal and background in a specific subregion, together with the data values. The signal and background are depicted with histograms in light and dark gray. The data are shown with the black

Table 5.1 – Expected and observed event yields in electron channel. The error margins reflect the statistical uncertainty, except for the multijet background where the systematic uncertainty is added.

	$t\bar{t}$	Sum of bkgs	S/B	Total Exp.	Data
<i>3-jet exclusive</i>					
0 b -tag	38.5 ± 0.4	606.7 ± 32.9	0.1	645.2 ± 32.9	593 ± 24
1 b -tag	56.3 ± 0.5	46.3 ± 7.4	1.2	102.6 ± 7.4	134 ± 12
>1 b -tags	20.6 ± 0.3	5.7 ± 2.2	3.6	26.4 ± 2.2	39 ± 6
Total	115.4 ± 0.8	658.8 ± 42.3	0.2	774.2 ± 42.3	766 ± 28
<i>4-jet inclusive</i>					
0 b -tag	51.7 ± 0.5	196.1 ± 13.3	0.3	247.8 ± 13.4	239 ± 15
1 b -tag	91.9 ± 0.7	25.9 ± 6.1	3.5	117.8 ± 6.1	110 ± 10
>1 b -tags	45.9 ± 0.5	6.4 ± 2.7	7.2	52.3 ± 2.7	48 ± 7
Total	189.5 ± 1.0	228.4 ± 22.0	0.8	417.9 ± 22.0	397 ± 20

Table 5.2 – Expected and observed event yields in muon channel. The error margins reflect the statistical uncertainty, except for the multijet background where the systematic uncertainty is added.

	$t\bar{t}$	Sum of bkgs	S/B	Total Exp.	Data
<i>3-jet exclusive</i>					
0 b -tag	55.4 ± 0.5	1116.0 ± 28.9	0.0	1171.4 ± 28.9	1116 ± 33
1 b -tag	79.1 ± 0.6	79.3 ± 9.8	1.0	158.4 ± 9.8	183 ± 14
>1 b -tags	29.1 ± 0.4	6.2 ± 0.3	4.7	35.3 ± 0.5	39 ± 6
Total	163.6 ± 0.9	1269.8 ± 106.7	0.1	1433.4 ± 106.7	1338 ± 37
<i>4-jet inclusive</i>					
0 b -tag	73.5 ± 0.6	320.6 ± 8.6	0.2	394.1 ± 8.6	401 ± 20
1 b -tag	133.6 ± 0.8	42.8 ± 9.0	3.1	176.4 ± 9.0	169 ± 13
>1 b -tags	67.4 ± 0.6	5.4 ± 0.4	12.4	72.9 ± 0.7	76 ± 9
Total	274.5 ± 1.2	403.1 ± 51.5	0.7	677.6 ± 51.5	646 ± 25

circles. In the bins with b -tagged jets, the absolute normalization (scale) is adjusted ($\times 4$ and $\times 10$) for both the signal and background component, for visibility reasons. The aim is to emphasize the signal to background (S/B) ratio rather than the absolute differences in numbers of events. The maximal value of S/B is 7.3 in the subset with four or more jets of which at least two are b -tagged. The discrepancies between the central values of data and expectation emerge especially in the 3-jet subsets, where the number of b -tagged jets is underestimated. The difference is covered by the statistical uncertainties on the values, however.

For the muon channel the signal and background estimates in the different bins are displayed in Table 5.2 and Figure 5.2(b). The number of events in the muon channel is about twice as high as the electron channel, making it less vulnerable to statistical fluctuations. The agreement between data and simulation is good, even better than in the electron channel. The S/B ratio varies from 0.1 (3-jet/0-tag) to 12.5 (in the 4-jet/ >1 -tags subset), which proves the goal of the categorization is reached in simulation at least.

5.3 Extraction of ratios

As mentioned before, we include three subsidiary measurements on ratios in the likelihood of the fit. Two are introduced as a Gaussian probability density function, with a predefined mean and resolution.

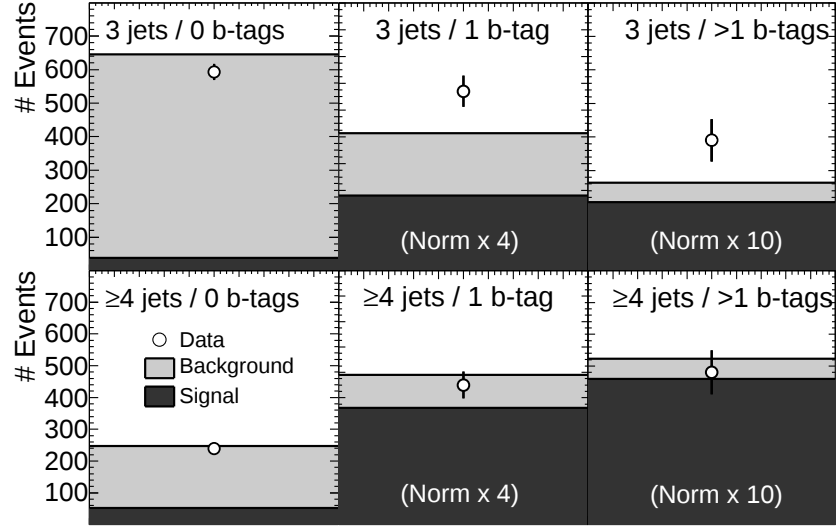
The Gaussian constraints on the relation between the six subsets in the constructed likelihood reduce the statistical uncertainty on the measured cross section. It is possible to define numerous ratios that fix or constrain the relation between the background in two different subsets, but the constraints on the relation can rely only partly on data-driven methods. Therefore it is not advantageous to insert too many constraints as this will increase the systematic uncertainty as a result of the simulation dependence. The best results in terms of the reduction of the total uncertainty are obtained by adding one fixed ratio as well (R_3), which is discussed in Section 5.3.3.

5.3.1 First fit ratio and heavy flavor uncertainty

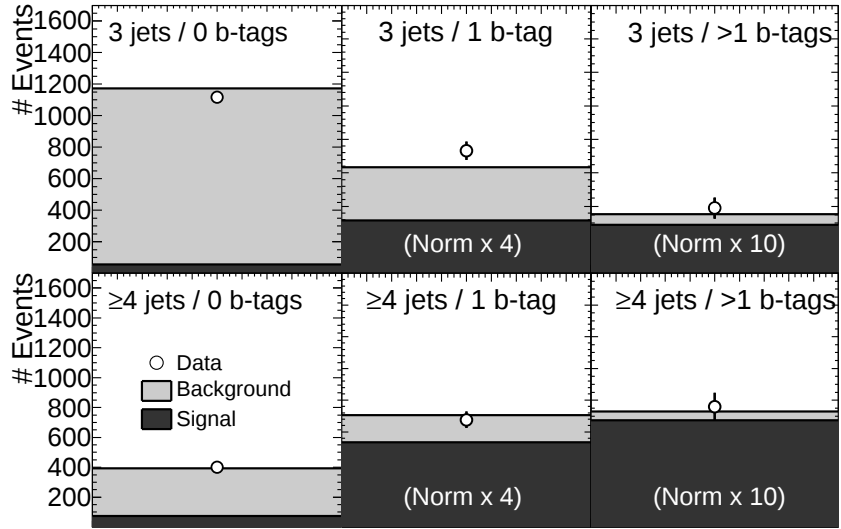
The approach that is chosen for the extraction of the first fit ratio (R_1) limits the range of the tagging rate in background events by extrapolating from information in the 2-jet data sample. The 2-jet events form a control region orthogonal to the data used in our measurement and contain a large fraction of background events. We can define an extrapolation factor $f_{2 \rightarrow 3}^{\hat{j}}$. It relates the 2-jet efficiency that can be obtained from data to the 3-jet efficiency that will be constrained:

$$[\epsilon_B]_3^{\hat{j}} = f_{2 \rightarrow 3}^{\hat{j}} \cdot [\epsilon_B]_2^{\hat{j}}, \quad (5.1)$$

where $[\epsilon_B]_2^{\hat{j}}$ is the background tagging efficiency in 2-jet events, for a certain b -tag requirement $\hat{j}$. And $[\epsilon_B]_3^{\hat{j}}$ is the equivalent variable in 3-jet events. The index $\hat{j}$ is extended



(a)



(b)

Figure 5.2 – Bin population in the electron channel (a) and muon channel (b). The bins with b -tagged events in both signal and background are scaled up with a factor 4 or 10 to match the labeling of the y-axis. No relative scaling between signal and background is applied.

from the index j we used so far. It can assume three values: (1) one b -tag inclusive, (2) one b -tag exclusive, (3) two b -tags inclusive. Note that a zero b -tag exclusive value is 100% anti-correlated with (1). We will determine which configuration to use, based on which gives the smallest overall uncertainties. The result is shown later in this section. Simulation gives an estimate of the factor $f_{2 \rightarrow 3}^j$, but we obtain the value of the variable

$[\epsilon_B]_2^1$ from data. We measure the number of events of data after all selection with exactly two jets and subtract the number of expected signal events from it:

$$[\epsilon_B]_2^{\hat{j}} = \frac{N_2^{\hat{j}}(\text{data}) - [N_S]_2^{\hat{j}}(\text{sim.})}{N_2(\text{data}) - [N_S]_2(\text{sim.})} \quad (5.2)$$

$N_2^{\hat{j}}$ is total number of events with two jets in data, $[N_S]_2^{\hat{j}}$ is the amount of $t\bar{t}$ events in this slice, established from simulated events. Background events dominate this control region. N_2 and $[N_S]_2$ are numbers of events without any b -tag requirement. To the number of $t\bar{t}$ events in the 2-jet bin that is obtained from simulation, we assign a 100% uncertainty, because this contains the signal process that we are trying to measure.

In conclusion, there are three configurations for $f_{2 \rightarrow 3}$ to choose from, which we test with respect to the impact the heavy flavor uncertainty on W +jets in the following.

Uncertainty of heavy flavors in W +jets.

One important aspect in the background estimates is the presence of b - and c -quarks (heavy quark flavors) in the production of W +jets. The quark flavor composition of the W +jets background is not well known; there is a large uncertainty on the number of c - or b -quarks in this background². An under- or overestimate of the number of c - or b -quarks in the W +jets background can severely affect our measurement of the cross section. The dependency of the likelihood on this uncertainty is introduced when we apply b -tagging: the subset populations migrate when the composition of b - and c -quarks is modified. And hence the connections between the amount of background in the subsets and therefore the fit constraints change. This is unavoidable to some extent, but we attempt to minimize the sensitivity to this specific uncertainty.

Treatment of heavy flavors in W +jets simulation

The simulation of the hard process or matrix element of W +jets production in this analysis is performed with ALPGEN. But, the hadronization and parton shower are done in HERWIG. Matching is applied to assign jets produced in the shower to partons of the matrix element. That means that if a jet does not match with one of the partons of the matrix element, that event is vetoed. In this way it is possible to define samples with a fixed number of partons with certain kinematic properties.

In the primary sample, events with N number of partons are produced ($W + Np$), where the partons are treated as massless. We refer to the the primary sample as ‘ W +light jets’. Next to W +light jets ALPGEN separately produces $W+c$, $W+c\bar{c}$, and $W+b\bar{b}$ samples. In this case the c - and b -quarks are treated as partons with mass. ($W+c$ includes $W+\bar{c}$.)

²The same is true for Z +jets. We do not discuss heavy flavor uncertainty in Z +jets, because this background is negligible in the decay channel of subject.

The use of the ensemble of the above described W boson production suffers from overlap between samples. For example an event with a $b\bar{b}$ pair can be generated in ‘ $W+2$ light jets’ and in $W+b\bar{b}$. To solve this, first of all events are vetoed from the W +light jets sample when any c - or b -quarks are present in the matrix element. Secondly, events are classified according to the opening angle between two heavy quarks, if present. This choice is based on the knowledge that the matrix element is best suited for large opening angles and the parton shower on the other hand describes collinear quarks better. A threshold of 0.4 for the opening angle ΔR is set: above this value the matrix element is favored and below this value the parton shower description.

That means that events in W +light jets and $W+c$ are removed if a heavy quark pair with $\Delta R > 0.4$ is produced in the parton shower. In $W+c\bar{c}$ events are vetoed if ΔR of the created $c\bar{c}$ pair in the matrix element is below 0.4, or if a $b\bar{b}$ pair with opening angle above 0.4 is found in the parton shower. Similarly in $W+b\bar{b}$ events are omitted if the $b\bar{b}$ pair in the matrix element has an opening angle below threshold.

This leaves us with a orthogonal and complete set of simulated W +jets events. Depending on the number of extra jets in the subsample, the fraction of removed events ranges from 5 to 10%. We use the classification and its uncertainty as tools for the calculation of uncertainty of the relative ratios of these events.

Observations from W +jets in data

It is not possible to obtain a pure sample of W +jets events in data if more than three jets are involved, as it is not possible to isolate W +jets events from the $t\bar{t}$ contamination in this region. In 2-jet events it is easier, however. The fraction of b -tagged events among $W+2$ jets events is measured in data and shows an underestimation of the $W+b\bar{b}$ and $W+c\bar{c}$ fractions of 30% [82]. Our estimates of these two fractions are corrected for this observation in the analysis and a 50% (correlated) uncertainty is assigned to this correction that is obtained from internal ALPGEN generator studies. Similarly, an uncertainty of 40% on the fraction of $W+c$ events without a shift of the central value is deduced [82].

Figure 5.3 shows the distribution of m_T^W in the 2-jet (left) and 3-jet (right) channel for the different contributions of W +jets (no other background included) in simulation. The 30% correction is applied to simulation in these distributions. The plots in the top represent events after all selection cuts except b -tagging. The contribution of light quarks in the ensemble is 76% (70%) in the 2-jet (3-jet) events. The heavy quark contribution of 25-30% stems from $W+c$ and $W+c\bar{c}$ mostly, for the remainder $W+b\bar{b}$ contributes. The bottom plots (c,d) contain events that have at least one b -tagged jet in the event. Here, the fraction of events coming from heavy flavors is about 80%, of which $W+b\bar{b}$ now contributes significantly, especially in the 3-jet events, 37% of the total number of events. If the uncertainty of the heavy flavor fraction, and the uncertainty within the different types of heavy flavors are considered, this figure proves that it is important that the uncertainty on the heavy flavor fractions are handled well.

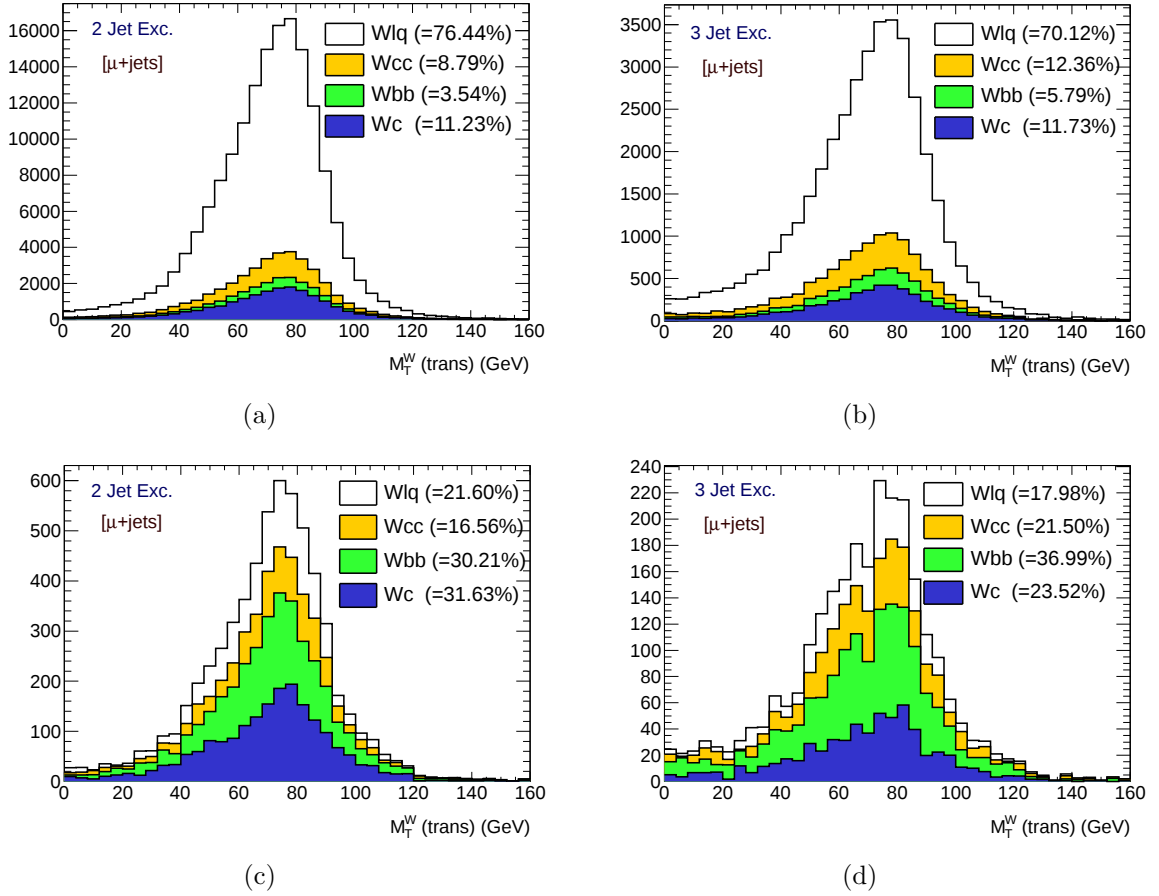


Figure 5.3 – Heavy flavor contributions in the W +jets background in simulation in the muon channel, in 2-jet and 3-jet events after all cuts, except b -tagging (a,b). The bottom plots show the equivalent plots after additionally requiring at least one b -tag.

Variations with respect to extrapolation factor

We use the uncertainties on the fraction of $W + c\bar{c}$ and $W + b\bar{b}$ events as described above. Events are reweighted following the maximally and minimally shifted values of the fraction of the respective types, simultaneously for $W + c\bar{c}$ and $W + b\bar{b}$ (similar production mechanisms), but separately for $W + c$. This results in 2x2 samples. Note that only the fraction is varied: in all cases the total number of events of W +jets is kept equal. Normalization uncertainties are assigned elsewhere.

Secondly, variations are applied in specific jet multiplicity slices of the data to account for possible correlated or uncorrelated behavior within the jet multiplicity. An additional 20% uncertainty in the 3-jet slice that is assumed to be uncorrelated is applied.

We return to the three alternatives for $f_{2 \rightarrow 3}^j$. As explained previously, they differ only in the number of b -tags that is included in the b -tag efficiency (1-tag exclusive and 1-tag or

2-tag inclusive)³. The different variations in heavy flavor fractions are applied separately. The quadratic sum of all deviations from the nominal value of the respective extrapolation factor is taken as indication for the final uncertainty on R_1 .

The systematic uncertainty due to heavy flavor uncertainty (HF) on the scale factors are shown in Table 5.3 and are compared to the statistical uncertainty. The statistical uncertainty dominates, in each case. Although the uncertainty on the heavy flavor is of order 15%, we cannot make conclusive statements on the final uncertainty due to the limited number of events in simulation. Especially in the 2-tag bin, there are not enough events to establish a reasonable central value for $f_{2\rightarrow 3}^j$ that can be used in the fit. The other two possibilities are comparable, in both their statistical and systematic uncertainty. This is true in both the e +jets and the μ +jets channel.

Concerning the uncertainty on $[\epsilon_B]_2^j$, the 1-tag exclusive bin suffers less from the 100% uncertainty that is assigned to the $t\bar{t}$ subtraction step in Eq. 5.2.

In conclusion, we obtain the lowest total uncertainty, on the product $[\epsilon_B]_2 \cdot f_{2\rightarrow 3}$ for the 1-tag exclusive bin compared to the 1-tag exclusive bin: 40% vs. 44% for the electron channel and 26% vs. 28% in the muon channel.

Table 5.3 – Intermediate uncertainties on scale factors $f_{2\rightarrow 3}^j$.

	$f_{2\rightarrow 3}^j$	Stat. uncertainty	HF uncertainty
e +jets	1-tag incl.	25.0 %	+15.6 / -15.8 %
	1-tag excl.	29.6 %	+16.2 / -16.4 %
	2-tag incl.	81.5 %	+11.3 / -11.2 %
μ +jets	1-tag incl.	19.3 %	+17.4 / -17.7 %
	1-tag excl.	22.5 %	+17.3 / -17.6 %
	2-tag incl.	57.3 %	+18.3 / -18.1 %

The nominal value of $[\epsilon_B]_3^1$ is 0.065 (0.085) for the electron (muon) channel to which we associate the uncertainty obtained by the procedure above. The central value and uncertainty define the mean and sigma in the Gaussian term in the fit, R_1 and σ_1 .

5.3.2 Second fit ratio

The numbers of events per jet multiplicity for signal events are related through the ratio $R_2 = [N_S]_4/[N_S]_3$. This applies to the total sum of signal events per jet bin, independently of the population in terms of b -tag multiplicity. Although these ratios can be defined for

³More involved extrapolation factors were tested as well, taking into account more than one b -tag requirement, but in all cases systematic effects inflated.

both signal and background, only the one for signal is constrained in the fit by a Gaussian function, with a mean and width computed from simulation. The mean is acquired by performing the fit on the simulation of signal generated by MC@NLO. This central value is compared to the values coming from alternative signal simulation samples (POWHEG, ACERMC). The width is determined by the quadratic sum of the variation between the simulated samples of the different generators. For the electron channel the value is 1.57 ± 0.31 , for the muons 1.60 ± 0.31 . These numbers correspond to R_2 and σ_2 in the likelihood description (Eq. 5.1).

5.3.3 Third fit ratio

The third ratio is $R_3 = \frac{[N_B]_3^1/[N_B]_3}{[N_B]_4^1/[N_B]_4}$. The values are 1.65 in the electron channel, and 1.54 in the muon channel. They follow directly from simulated samples, although for the multijet contribution in background data is used. Test fits showed the best trade-off between statistical and systematical uncertainty when implementing the PDF as a delta function.

5.4 Construction of the templates

The shape templates of the m_{jjj} distribution in the several subsets are derived in different ways for signal and background. The signal templates are constructed from simulated distributions, whilst for the background shapes they are obtained from data.

5.4.1 Background templates

The background events passing our selection come from several sources, of which W +jets events contribute most. It is shown that the shape of m_{jjj} for all background sources can approximately be described by the same function, if all selection cuts are applied [83]. We exploit the fact that the associated jets in W boson production and multijets produce similar shapes for the mass of the three-jet combination. The shape is that of an exponential with a cut-off at low mass. Since W +jets events are difficult to isolate from $t\bar{t}$ events in data, we derive their shape from multijet background events, in data.

The number of events coming from multijet production passing our selection is limited. We therefore examine a complementary sample of data where the amount of multijet events is enhanced. This sample is defined by ‘inverting’ the lepton requirement: all events that contain a lepton satisfying the quality cuts are removed. All other cuts used for the nominal selection remain identical, except for the dedicated multijet-removing cut containing the transverse W boson mass. As we veto good leptons, the reconstruction of m_T^W is affected, because computing this observable requires a lepton candidate. But, events that pass our trigger selection must have a lepton candidate which, due to the inverted selection, by construction must be of lower quality. One source of these low quality leptons are fake leptons. This can be a jet that is misidentified as an electron, because deposits in the hadronic calorimeter were below threshold. Non-prompt leptons

are the other source. Those are leptons that do not originate from the hard process itself, but are produced somewhere in a secondary process (in a jet for example). Muons that pass the trigger and are not of good quality are mostly non-prompt, whereas electrons are mainly fakes. The reconstructed p_T threshold for these fake or non-prompt leptons is lowered from 20 GeV to 5 GeV. For each event that contains such a lepton that can be matched to a trigger hit, it is possible to reconstruct a value for m_T^W .

The obtained multijet enhanced sample is used to extract a fixed shape template for the distribution of m_{jjj} for the ensemble of W +jets, multijet and other background contributions. The fit requires six templates for the background, that is one template per subregion for all backgrounds. In the three-jet events, the KL-fitter reconstruction algorithm cannot be applied, as it requires at least four jets to work out the kinematics of the event. Therefore, for three-jet events we use the more straightforward $\sum p_T$ algorithm to reconstruct the mass of the hadronically decaying top, resulting in a wider peak around the top quark mass as we showed in Section 4.7.

The templates are obtained by fitting a hybrid smooth function to the respective samples. The function is composed of a Gaussian in the low mass region and an exponential on the high mass side:

$$f(x) = \begin{cases} \alpha e^{\frac{-(x-x_0)^2}{2\sigma^2}} & \text{for } x < x_c \\ \beta e^{\frac{-(x-x_0)}{2\gamma}} & \text{for } x \geq x_c \end{cases} \quad (5.3)$$

The cross over point between the two terms is $x_c = x_0 + \frac{1}{2}\sigma^2/\gamma$. This ensures the continuity and smoothness of the function. The function $f(x)$ is fitted to the distribution in each separate subset of data and physics channel. Figure 5.4 displays the curve resulting from the fit for one of the six bins: the data sample in the electron channel for the 3-jet/1-tag slice with inverted lepton cuts is fitted with the function $f(x)$. The fit in this example has a χ^2 per degree of freedom of 1.5.

5.4.2 Signal templates

In contrast to background, where we use data, we determined the different signal templates from simulation. This is done in each slice of number of jets and b -tags. The m_{jjj} distribution is built up from well-reconstructed top quarks and combinatorial background: from simulation we know that we in reality fail to correctly reconstruct all of the hadronic top quarks in the signal events. This is due to undetected objects (jets) or the wrong jet assignment in the algorithm. Also in case of signal we use the KL-Fitter for reconstruction of the top quarks in events with four or more jets and the $\sum p_T$ method for the 3-jet bins.

The analytic function we use to fit to the distribution is the same as for the background, but is extended by adding a Gaussian function, to parametrize the extra events in the top quark mass peak. The mean of the additional Gaussian is free to float in a window around 170 GeV. The fit results are displayed in Figure 5.5.

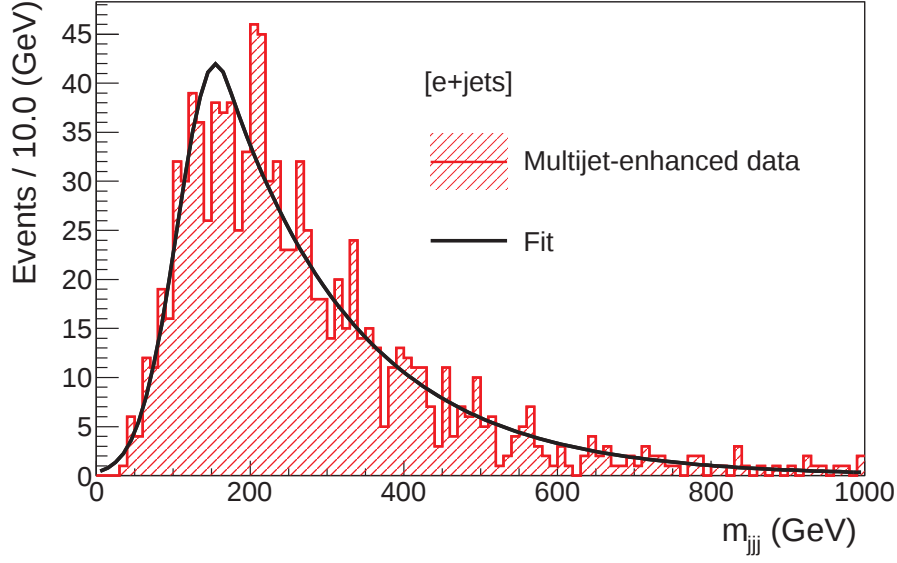


Figure 5.4 – Example of background template extraction in the 3-jet/1-tag subregion. The function in Eq. 5.3 is fitted to the m_{jjj} distribution (obtained with the $\sum p_T$ algorithm) in the multijet-enhanced data (dashed area) in the electron channel.

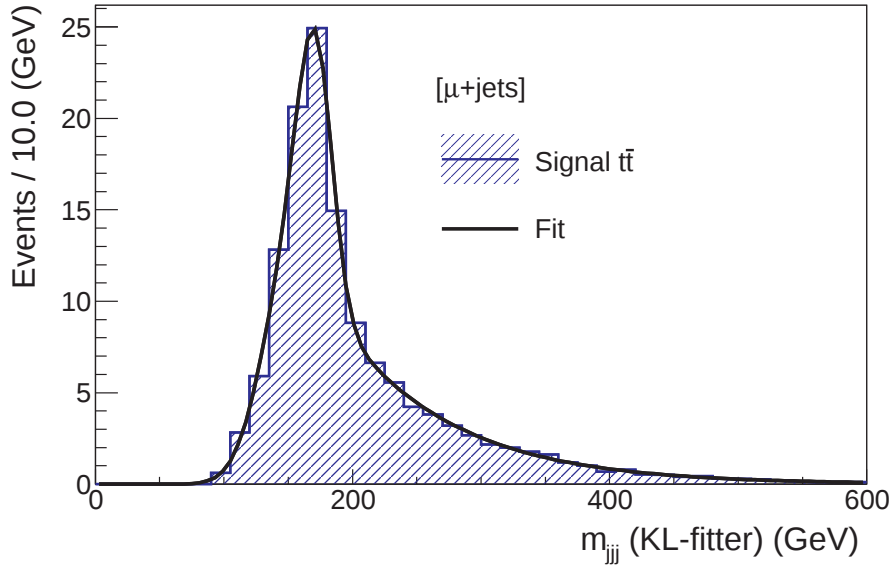


Figure 5.5 – Example of signal template extraction in the 4-jet/1-tag subregion. The distribution of the hadronic top mass as constructed with the KL-fitter in simulation of $t\bar{t}$ (dashed area) is fitted with the function in Eq. 5.3 with an additional Gaussian in the top pole mass region.

5.5 Fit results

The fit is applied to the electron and muon data separately. The resulting fit curves are shown in Figure 5.6. The figure shows the fit curves (solid line) for the six slices of data,

for both the electron (a) and the muon channel (b). The dashed line indicates the total background contribution.

Table 5.4 shows a summary of the fit results in terms of the relevant parameters: N_S , N_B and B_{eff} . The uncertainties reflect the statistical component only, evaluated with pseudo-experiments.

Table 5.4 – Summary of final fit results.

Parameter	e+jets	μ +jets
N_S	367 ± 38	400 ± 47
N_B	769 ± 42	1538 ± 58
B_{eff}	0.51 ± 0.04	0.51 ± 0.04

5.5.1 Statistical uncertainty

The statistical uncertainty that is quoted is obtained by performing pseudo-experiments. We applied the fit procedure to 10,000 pseudo-datasets, of which the input parameter values are randomly pulled from the probability density functions that describe them. Specifically, each pseudo-experiment represents a possible set of observed data points. The minimization of the likelihood for this pseudo-dataset works identically to the actual fit, including the implicit constraints that are defined. The fit results are collected to estimate the uncertainties on each parameter of interest. This procedure is used rather than the statistical uncertainty that follows from the minimization of the data fit, because it takes into account that the input parameters are statistically limited as well.

Correlations

We investigate the correlations between the fit parameters. Figure 5.7(a) shows the correlation coefficients in the parametrization we chose:

- B_{eff} (b -tagging efficiency per jet)
- $[\epsilon_B]_3^1$ (background b -tagging efficiency per event)
- N_B (total number of background events)
- N_S (total number of signal events)
- $R_{B43} = \frac{[N_B]_4}{[N_B]_3}$ (ratio between 4-jet and 3-jet slice for background)
- $R_{S43} = \frac{[N_S]_4}{[N_S]_3}$ (ratio between 4-jet and 3-jet slice for signal)

First, it should be noted that the number of signal and background events are highly anti-correlated (-0.75). This is expected, since the total number of events is almost fixed,

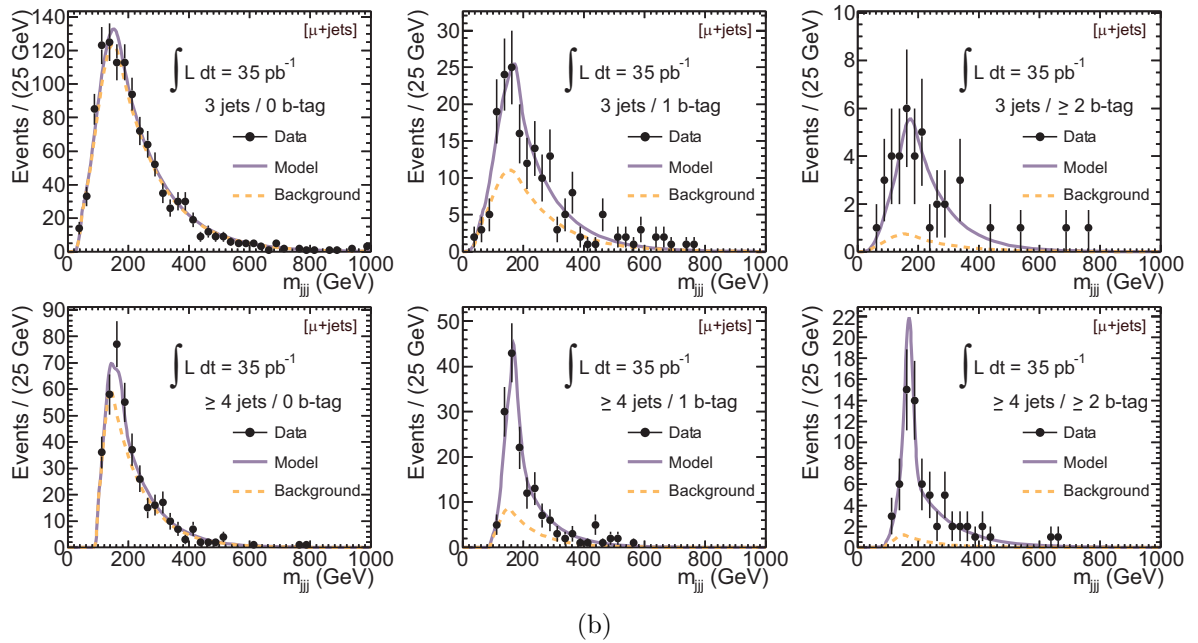
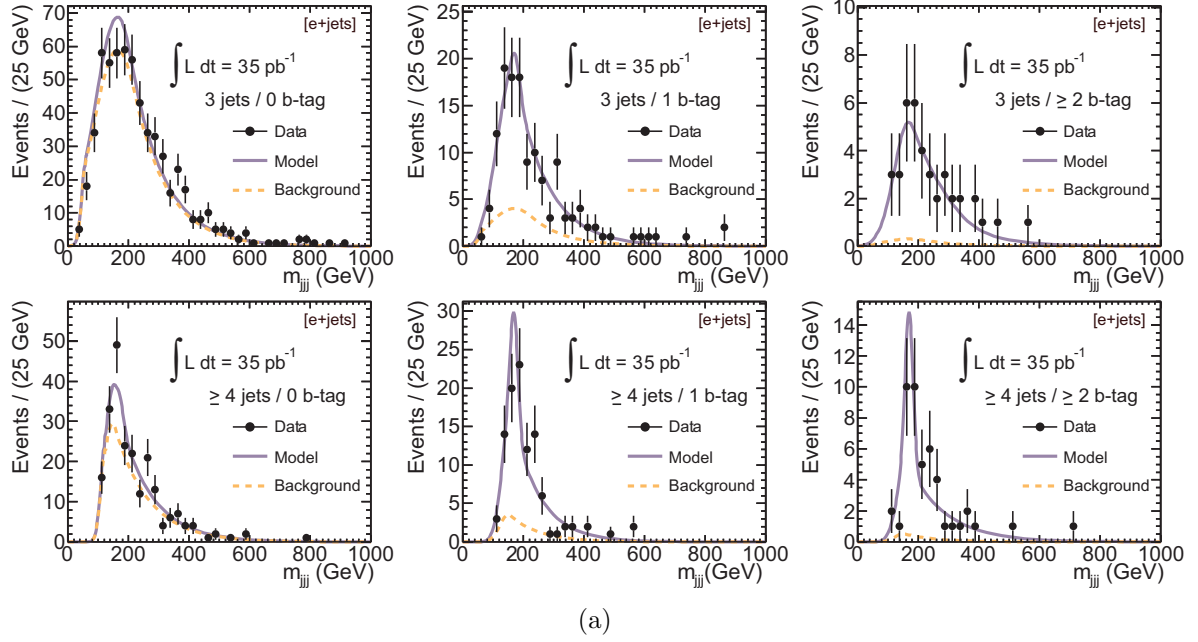


Figure 5.6 – Fit results in the electron channel (a) and muon channel (b). For each channel the six subsets of the simultaneous fit are shown.

except for the variation allowed by the Poisson extension in the fit. But, B_{eff} and $[\epsilon_B]_3^1$ have a large anti-correlation coefficient with N_S as well. If during the minimization of the fit the number of signal events is pulled towards a higher value, it affects the b -tagging efficiency directly. In other words, if too much signal is present, it has to indicate a lack of b -tagged jets. Likewise, if N_S increases (hence, N_B decreases), the amount of background events in the 3-jet/1-tag slice is reduced. While the direction of such correlations are expected, the magnitude depends strongly on the parametrization that we chose.

In Figure 5.7(b), the correlation (μ -channel) between the b -tag efficiency and the number of signal events (N_S) is shown. The point (black star) at $N_S=400$, $B_{\text{eff}}=0.51$, corresponds to the final fit result. The squares represent the results of the pseudo-experiment fits. The ellipses indicate the estimated 1σ and 2σ statistical uncertainties. When the fit is applied to simulation (red dot) 433 signal events are measured, with a b -tagging efficiency of 0.53. The simulation is consistent with the 1σ region defined by the pseudo-experiments based on data.

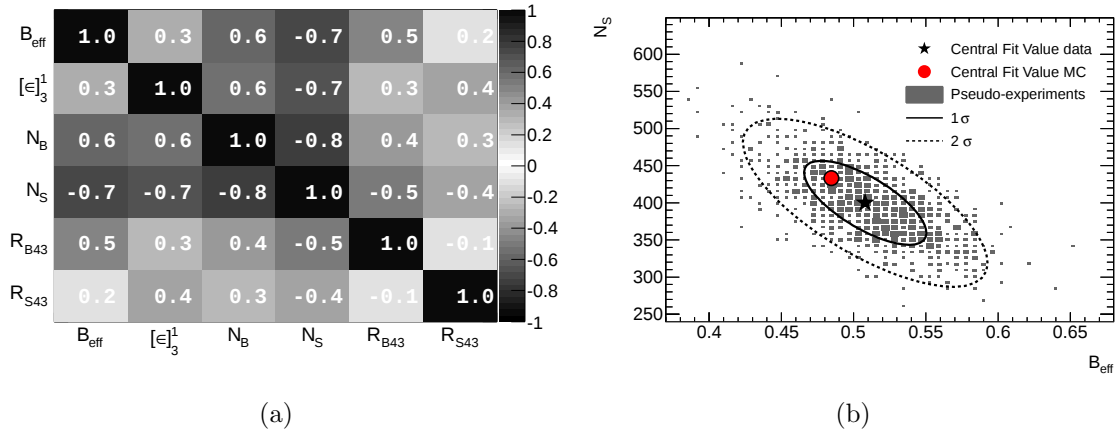


Figure 5.7 – Correlations in the muon channel. (a) Full correlation matrix. (b) Number of signal events N_S vs. B_{eff} .

5.6 Systematic uncertainties

In this section we describe the treatment and propagation of the uncertainties connected to the cross section values obtained with the simultaneous likelihood fit. An extended view of the final results in terms of the statistical and systematic uncertainties is displayed in Table 5.5.

The effect of each source of systematic uncertainty on the analysis results is determined by varying every parameter within its assessed uncertainty. The parameters that are input to the fit are recalculated considering the deviation and subsequently the fit is reapplied. The impact of a certain nuisance parameter may for instance affect both the estimate of the scale factor $f_{2\rightarrow 3}$, and the shapes of the distributions. We describe the specific features of systematic uncertainties below.

Table 5.5 – Summary of individual systematic uncertainties contribution to the cross section determination for the fit. All numbers are relative errors expressed as a percentage.

	$\Delta N(e)/N$ [%]	$\Delta N(\mu)/N$ [%]	Combined [%]
<i>Object selection</i>			
Lepton reco, ID, trigger, scale, smear	± 4.2	± 1.2	± 2.4
Jet energy scale	+2.6/-0.1	+4.5/-0.0	+3.8/-0.0
Jet energy resolution	± 2.4	± 1.0	± 1.6
Jet reconstruction efficiency	± 3.3	± 2.6	± 2.9
<i>b</i> -tagging	+0.4/-1.2	+1.7/-1.2	+1.2/-1.2
<i>Background rate and shape</i>			
Heavy flavor	+5.5/-5.9	+6.3/-5.2	+6.0/-5.5
Shape templates	± 5	± 4	± 4.4
W+jets	+1.8/-1.8	+1.9/-1.9	+1.8/-1.8
Multijet normalization	+5.1/-1.8	+0.5/-0.7	+2.3/-1.1
<i>Signal simulation</i>			
ISR/FSR	+4.2/-4.4	+5.1/-4.4	+4.7/-4.4
PDF	± 1.7	± 1.7	± 1.7
Parton shower	± 0.2	± 0.6	± 0.4
NLO generator	± 2.0	± 1.5	± 1.7
Pile-up	± 0.5	± 0.5	± 0.5
<i>Total</i>			
Sum systematics	+12.3/-11.3	+11.1/-9.1	+11.1/-9.9
Statistical error	± 10.5	± 11.7	± 7.9
Total uncertainty	+17.1/-16.4	+14.7/-13.2	+13.5/12.5

Lepton identification and resolution

The difference between the performance of lepton identification in simulation and data is corrected for with scale factors. The scale factors that incorporate the trigger and reconstruction efficiency difference are supplied by the performance groups in ATLAS using studies of Z boson decays and include statistical and systematic uncertainties. We assume that the quadratic sum of these two in both positive and negative direction models the systematic uncertainty with respect to our final result.

The energy and momentum resolution of the leptons is accounted for as well, by smearing

the simulation such that the distributions match the data. This is done effectively by convolution with a Gaussian probability density function.

Jet energy scale and resolution

The uncertainty on the energy scale of jets is studied in both simulation and data [84]. In data single response studies are performed, comparing the momentum of isolated tracks to the energy deposited in the calorimeter [85]. The simulation studies compare calorimeter jet energies to ‘truth jet’ energies, the energy of the jet formed directly by a generated particle, skipping the simulation of the detector response. A grid in η - p_T space is defined based on the outcome, with maximal upward and downward shifts for each cell region in this surface. This grid is applied to the nominal values of jet energies to estimate the effect of these variations on the final results. Effects coming from multiple collisions per bunch crossing (pile-up) and of jets in a high jet multiplicity environment (close-by jets) are accounted for as well.

The resolution of the energy and efficiency of finding jets are also estimated from a combination of data and simulation. The resolution in data is larger than in simulation and to resemble this behavior the energy of jets is convoluted with a Gaussian function in the nominal simulation samples. The difference between the results when using the nominal and the non-smeared sample are taken as the 1σ uncertainty. We assess the reconstruction efficiency by discarding a small fraction of jets according to the measured efficiency. This results in a variation as well. Both the jet energy resolution and the reconstruction efficiency generate symmetric uncertainties.

Initial and final state radiation

The uncertainty on initial and final state radiation (ISR/FSR), in the form of extra jets in the detector is estimated by varying parameters in leading-order simulation samples. The effect of more jets primarily influences the selection efficiency and population of the different jet multiplicity categories in the method. On top of that it bears a reduction of the ability to find the right permutations in a top quark reconstruction algorithm. This was studied for a different analysis in more detail in Section 3.5. For the current analysis we used a leading-order $t\bar{t}$ sample where ISR and FSR were increased simultaneously to maximize the effect on the top quark mass. Similarly one sample that minimizes the top quark mass is used. The generator settings are such that the probability of splitting off extra partons is larger or smaller respectively, within reasonable ranges. The final fit result of these two variations is compared with a nominal leading-order sample, instead of the default NLO signal samples to maintain a fair comparison. The relative differences are quoted as the 1σ uncertainty.

Parton density functions

The parametrization of the parton density functions (PDFs) affects the cross section measurement directly. The PDFs describe the probability density of the two partons of the

colliding protons as a function of the longitudinal momentum fractions (x_1, x_2) at energy scale Q^2 . PDFs enter the equation of top quark pair production through convolution with the partonic cross section. The full equation is given in Eq. 1.1. The nominal description of PDFs that we use is CTEQ6.6 [86]. Alternatively, MWST2008nlo68cl [33] and NNPDF20 [87] are tested. The estimate of the total uncertainty with respect to the cross section due to PDFs takes input from two distinct parts: the uncertainty within a PDF and the deviations between the different PDFs. The method uses reweighting of events, rather than regeneration. Simulation samples are reweighted according to the ratio of the probabilities of the PDF that is subject to testing (f_{PDF}) and the original PDF (f_{PDF_0}):

$$W = \frac{f_{PDF}(x_1, f_1, Q)}{f_{PDF_0}(x_1, f_1, Q)} \cdot \frac{f_{PDF}(x_2, f_2, Q)}{f_{PDF_0}(x_2, f_2, Q)},$$

where x_1 and x_2 are the momentum fractions of the partons with respective flavors f_1 and f_2 . For each PDF an error set is defined, yielding a 1σ variation of one parameter. The CTEQ PDF error set consist of 44 up and down variations originating from 22 parameters. A total error within the PDF is then calculated using

$$\Delta\epsilon = \frac{1}{2} \sqrt{\sum_{i=0} (\epsilon_i^+ - \epsilon_i^-)^2},$$

where i is a number corresponding to the varied parameter and $\epsilon_i^{+(-)}$ is the uncertainty on the cross section for the positive (negative) variation. Similar calculations are done for the other two PDF error sets. Finally, a window around the largest upward and downward shift of the cross section of either the different PDF sets or within one PDF is considered. This window therefore includes all reasonably possible values. Half the window size is used as symmetric uncertainty.

NLO generator

The uncertainty on the signal event generator itself (MC@NLO) is evaluated by comparing it to another NLO generator, POWHEG. In this case both generators are interfaced to HERWIG/JIMMY, to keep hadronization and the treatment of the underlying event consistent. The difference in the final result obtained with the two generators is taken to be the symmetric systematic uncertainty. The hadronization and parton showering steps are reproduced in PYTHIA for POWHEG as well, comparing it to HERWIG/JIMMY. Hadronization and parton showering are treated differently for both. Therefore this is a measure for the systematic uncertainty on this step of event simulation. Note that the comparison is not possible with the nominal signal simulation generator MC@NLO the reason being that the interface to PYTHIA is not realized yet.

Pile-up modeling

Pile-up effects are described in Section 4.1.1 for the data set of this analysis. It embodies extra activity in the detector as a result of the occurrence of multiple proton-proton

collisions per bunch crossing. Simulation samples are corrected for this effect, but data-simulation comparisons show residual differences in the tails in terms of the number of reconstructed primary vertices. The simulation of signal and background is therefore reweighted to match the data. This is done by assigning a weight to every event depending on the number of well reconstructed primary vertices that are present. The difference between the final result obtained with the reweighted sample and the original simulation is the symmetric uncertainty quoted in Table 5.5.

Heavy flavor contribution in background

The uncertainty on the quark flavor composition of the W +jets background gives rise to a large systematic uncertainty in the measurement of the cross section. Its details have been discussed in the discussion on fit constraint 1 in Section 5.3.1. The same methods described to evaluate the effect on the scale factor were applied to the full analysis to obtain the final results. Variations in the relative contributions of $W+c\bar{c}$, $W+b\bar{b}$ and $W+c$ are produced, in the overall set of events and in specific subsets (jet bins) and the fit is applied to obtain the uncertainty.

Background rate

The amount of background is a fit parameter and does in principle not need to be accounted for. The only way the uncertainty on the rate of background events enters is through R_1 and R_3 , which are ratios and therefore only moderately dependent on the overall normalization. Nevertheless, this effect is computed by varying the rates of the individual backgrounds and redoing the calculations of scale factors and perform the fit. The result is the difference between the cross section results obtained with the modified rates and the nominal value. On the simulated backgrounds a 1σ variation on the generator cross section is applied. The multijet contributions (data-driven) have an uncertainty assigned in the procedure of obtaining the rate from data. It is varied accordingly, up an down, to estimate the change in the final outcome. The W +jets uncertainty quoted in the table comes from a test where the events are generated with a different generator (SHERPA) and show only small deviations.

Template shapes

The effect of the uncertainty of the shapes of the templates is tested by taking ‘flat’ templates, i.e., each template is described by a horizontal function. This reduces the fit towards a ‘counting experiment’ effectively. This is assumed to be the most extreme case.

Calibration of b -tagging

The b -tagging efficiency uncertainty is fitted for in case of signal. In background, however, it plays an important role in combination with the heavy flavor uncertainty. The uncertainty on the calibration is assessed by varying the scale factors used in the procedure of

matching simulation to data, within their uncertainty.

Luminosity

The uncertainty on the measurement of the luminosity was 3.4% at the time the measurement was performed [88].

5.7 Cross section results

The cross section can be expressed as

$$\sigma(t\bar{t}) = \frac{N_S}{\int \mathcal{L} dt \cdot \epsilon},$$

where the efficiency ϵ incorporates the trigger efficiency, acceptance and top quark reconstruction efficiency. We applied the fit to the data distributions in the muon and electron channel separately. The number of signal events in data is N_S is 367 ± 44 (stat) for the electron channel and 400 ± 38 (stat) for the muon channel. This translates to the cross sections listed in Table 5.6. The individual results are quoted per channel, as well as a combined statistical combination.

Table 5.6 – Summary of final cross section estimates.

Channel	Cross section
$e + \text{jets}$	216 ± 23 (stat) $^{+27}_{-24}$ (syst) ± 7 (lumi) pb
$\mu + \text{jets}$	161 ± 19 (stat) $^{+18}_{-15}$ (syst) ± 5 (lumi) pb
Combined $e/\mu + \text{jets}$	183 ± 14 (stat) $^{+20}_{-18}$ (syst) ± 6 (lumi) pb

The results are in agreement with theoretical expectations at NNLO [35],

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

Figure 5.8 reflects the theoretical prediction for top quark pair production at pp and $p\bar{p}$ colliders in blue and yellow, including the 1σ error band. The best measurements at the Tevatron are included. The combined result of the fit analysis in this chapter is shown in the large plot, and the individual results are compared in the smaller box. The electron fit result is higher than expected, but still within 2σ from the expectation. The muon channel agrees with the theoretical expectations. The combined result is consistent with the predictions as well. The uncertainty of this measurement, however, is not at the level of the theoretical uncertainties yet.

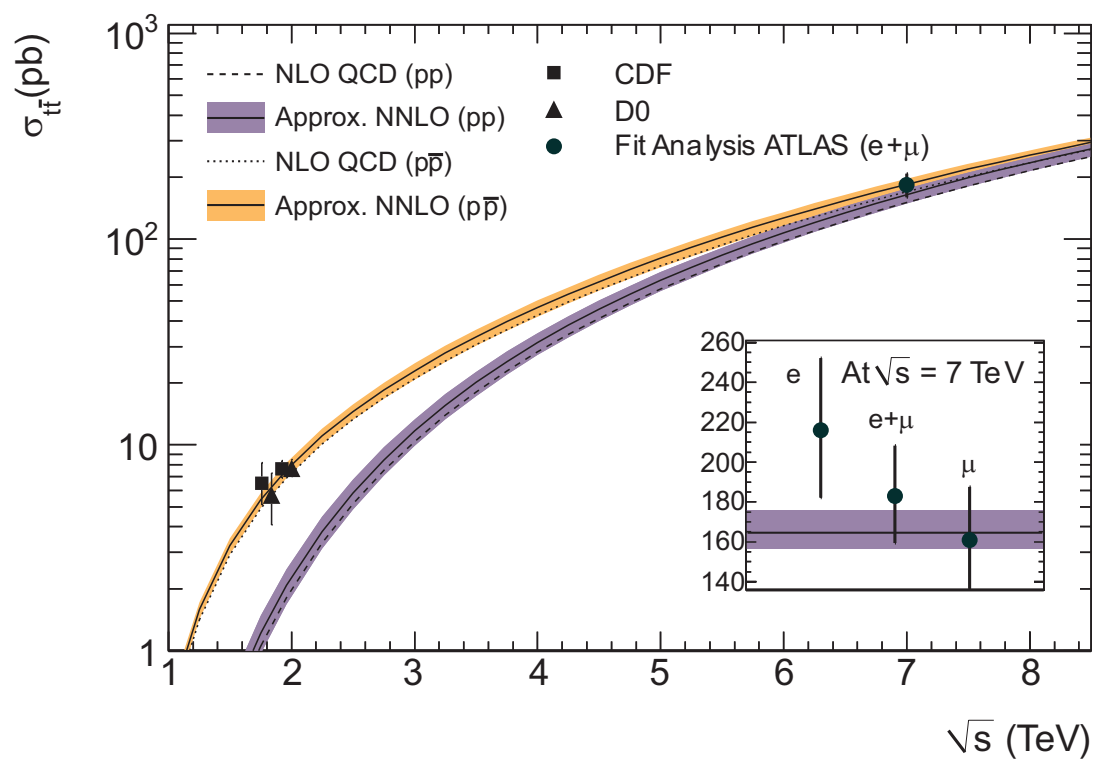
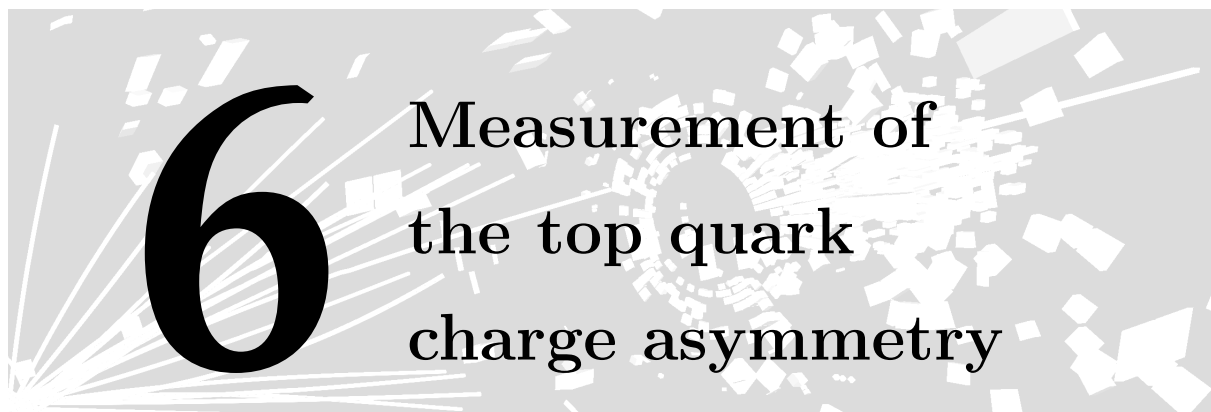


Figure 5.8 – Cross section versus CM-energy $\sqrt{s}$. The cross section results of this chapter are overlaid to the theoretical predictions at (N)NLO. The individual values for the separate channels are shown in the inset.



6 Measurement of the top quark charge asymmetry

The data in the previous chapters shows that we are able to isolate events with top quark pair decay from other physics processes. We have measured the inclusive production cross section with 35 pb^{-1} of data, the initial dataset of 2010. In this chapter we perform a measurement with the 2011 data set described in Chapter 4, with an integrated luminosity of 1.04 fb^{-1} , i.e., over 25 times more. We study the rapidity of the reconstructed top quarks and separate positively and negatively charged top quarks. In this way we can measure the asymmetry between production angles of top and antitop quarks, the so-called top quark charge asymmetry, as described in Chapter 1. A similar measurement by the ATLAS collaboration is published in Ref. [70].

This chapter is organized as follows: First, in Section 6.1 we define two observables to quantify the charge asymmetry. In Section 6.2 we present the relevant kinematic variables and identify differences in distributions of events containing only positively or negatively charged leptons. The asymmetry in top quark events and in physics backgrounds after selection is discussed in Section 6.3. The measurement on data and the comparison with expectation are presented in Section 6.4 and 6.5, for both variables. Section 6.6 summarizes the results.

6.1 Top quark charge asymmetry at the parton level

In Chapter 1 we discussed the source of charge-asymmetric $t\bar{t}$ production in the Standard Model. Here, we translate this to observables feasible for ATLAS. The asymmetry can be parametrized in several ways. We discuss two parametrizations, corresponding to an “integrated asymmetry”, A_{int} and a “differential asymmetry”, $A_{diff}(y)$.

6.1.1 Integrated asymmetry

The integrated asymmetry is the most straightforward and establishes the difference in absolute rapidity ($\Delta|y|$) between the top quark and antitop quark,

$$\Delta|y| = |y_t| - |y_{\bar{t}}|,$$

The distribution of $\Delta|y|$ is symmetric around zero when the production process is invariant under charge conjugation. But, if charge conjugation symmetry does not hold, this changes. When positively charged top quarks are produced more often with a smaller angle with respect to the z -axis, the distribution will be shifted towards the positive side. This is illustrated in Figure 6.1. On the left side are two situations that can occur. In the top graphs, the production is charge symmetric, and hence the distribution of the rapidities of top and antitop quarks are identical. This results in a symmetric distribution of $\Delta|y|$. The bottom graphs depict the situation where production is no longer symmetric under charge conjugation, and top quarks (which are positively charged) are produced in the forward direction more often. This results in differently shaped distributions in y and therefore a shift in the $\Delta|y|$ distribution.

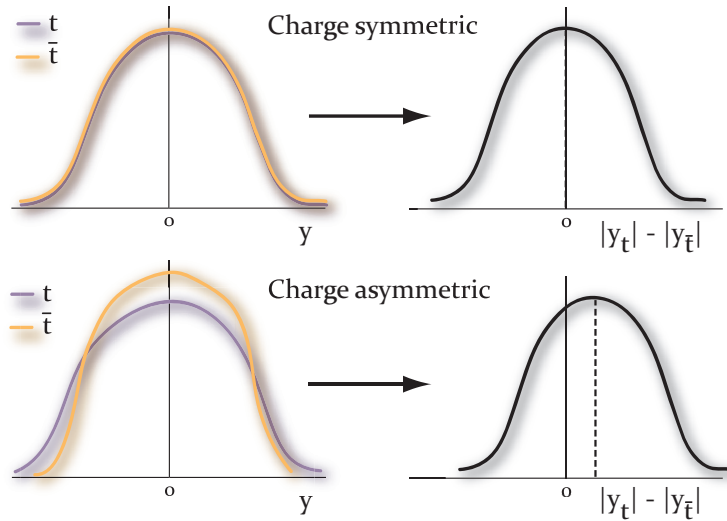


Figure 6.1 – Schematic view of two situations of the rapidity distributions of top quarks and antitop quarks and the effect this has on the absolute rapidity differences.

This shift can be quantified as an asymmetry:

$$A_{int} = A_{(\Delta|y|)} = \frac{N_{\Delta|y|}^+ - N_{\Delta|y|}^-}{N_{\Delta|y|}^+ + N_{\Delta|y|}^-}$$

Here, $N_{\Delta|y|}^+$ and $N_{\Delta|y|}^-$ are the integrals of events with $\Delta|y| > 0$ and $\Delta|y| < 0$, respectively.

In simulation, the asymmetry emerges for top quark pair events generated using NLO calculations (MC@NLO). Figure 6.2 shows the distribution of $\Delta|y|$ for events produced with gluon fusion (gg) and events produced in quark-antiquark or quark-gluon production processes ($q\bar{q}$ and qg), at parton level. The simulation used in this and other plots in this chapter are based on 2 million simulated $t\bar{t}$ events, corresponding to an integrated luminosity of roughly 12 fb^{-1} . The distribution is broken down into a symmetric part and an asymmetric part. Collisions where the initial partons were gluons (80.1% of the events) are shown in light gray. This distribution is predicted to be symmetric, we find $A_{int} = 0.001 \pm 0.001$, which is indeed consistent with zero.

The dark-colored distribution, representing events inferred by quark-antiquark annihilation and quark-gluon collisions, is expected to show asymmetric effects. These two contributions form the remaining 20% of the collisions. The quark-antiquark (19.1%) and quark-gluon processes (0.8%) show an overall asymmetry in $\Delta|y|$ of 0.025 ± 0.002 . The overall asymmetry for the complete sample adds up to $A_{int} = 0.006 \pm 0.001$.

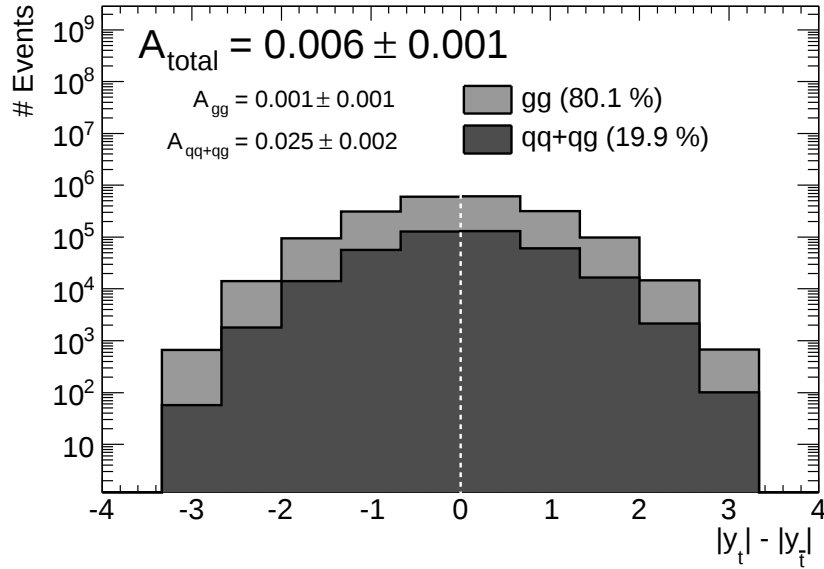


Figure 6.2 – Difference in absolute value of rapidities of the top and antitop quarks, for MC@NLO events at parton level. The distributions are based on ~ 2 million of $t\bar{t}$ events.

6.1.2 Differential asymmetry

The second observable for the top quark charge asymmetry as defined in [42] is:

$$A_{diff}(y) = A(y) = \frac{\frac{dN(t)}{dy} - \frac{dN(\bar{t})}{dy}}{\frac{dN(t)}{dy} + \frac{dN(\bar{t})}{dy}}.$$

The number of top quarks and antitop quarks is determined as a function of rapidity, resulting in an asymmetry that depends on y . Figure 6.3 shows a schematic view of this asymmetry. For charge symmetric production, hence for equal rapidity distributions of top and antitop quarks as in the upper graph, the asymmetry follows a straight line at $A_{diff}(y) = 0$. For charge-asymmetric production, as in the lower graph, this translates into a U-shaped asymmetry, with positive values for high values of the absolute rapidity and negative values around $y = 0$.

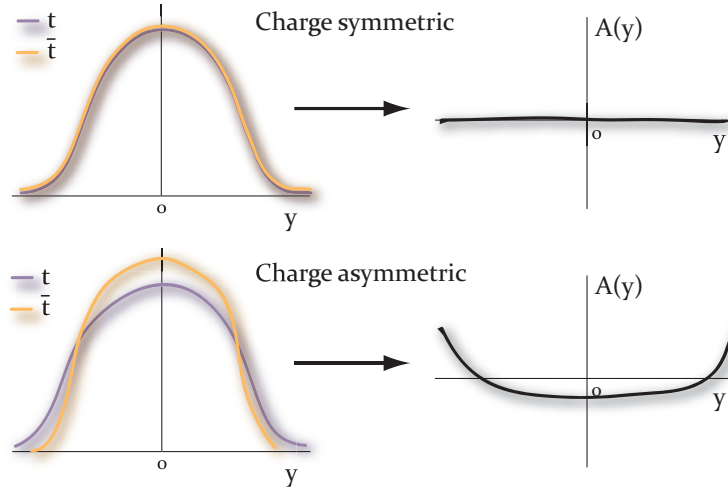


Figure 6.3 – Schematic view of two situations of the rapidity distributions of top quarks (light red) and antitop quarks (dark blue) and its effect on the differential asymmetry distribution.

We measure this effect in simulation, as shown in Figure 6.4. Events in the simulation that originate from charge symmetric gluon fusion are separated from the other two contributions, quark-antiquark and quark-gluon production. The combination of the latter two forms a U-shape, confirming the presence of the asymmetry in $t\bar{t}$ production. The weighted sum of the gg , $q\bar{q}$ and qg (i.e., the mixture as expected in data) is shown as ‘total’. This demonstrates that the asymmetry is visible in the inclusive sample. To quantify this effect, we fit the distribution with a second order polynomial:

$$f(y) = c_0 + c_1 y^2.$$

The skewness is compatible with zero and therefore we omitted the linear term. The values of the coefficients of the two-parameter fit are: $c_0 = (-4.1 \pm 0.6) \cdot 10^{-3}$ and $c_1 = (3.6 \pm 0.3) \cdot 10^{-3}$. The fit function is drawn in the figure as well, for which the χ^2 per degree of freedom is 0.7.

So far, we determined the two parametrizations of the charge asymmetry in $t\bar{t}$ production at parton level. In the following, we will determine the size of the asymmetry in simulated data after full event generation, reconstruction and application of the selection, for both $t\bar{t}$ events and the expected background. After that we measure the asymmetry in data.

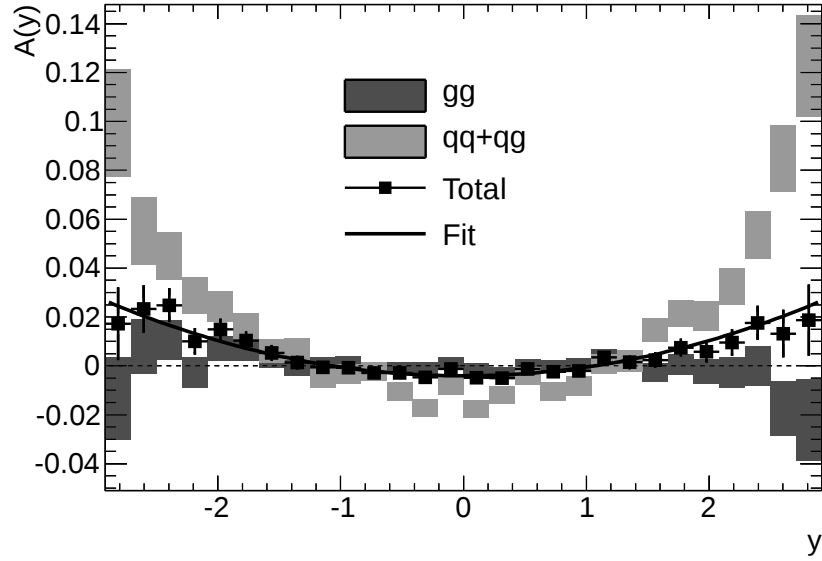


Figure 6.4 – The differential asymmetry distribution for MC@NLO events at parton level. The distributions are based on 2 million $t\bar{t}$ events. The dark gray areas correspond to events with gluon-gluon production process. The light gray areas depict the (asymmetric) remainder, quark-antiquark and quark-gluon processes. The black points are the summed distribution.

6.2 Properties of the data set

We perform this analysis on the 2011 data set, as introduced in Chapter 4. The event selection we apply in this analysis is presented in Section 4.5. Summarizing, we require a lepton (electron or muon) and at least four jets, of which at least one has to be identified as a b -jet. Furthermore, there are thresholds on the missing transverse energy and the transverse W boson mass, their actual values depend on the physics channel. Especially the b -tagging requirement leads to a pure sample of $t\bar{t}$ events.

6.2.1 Event yield

The event yields of signal and background are presented in Table 6.1. It shows the expected and observed number of events that pass the selection, after application of all corrections to the simulation. The W +jets and multijet background are obtained from data-driven techniques. We assigned uncertainties of 30% and 100% to these estimates, respectively. All other physics processes are taken from simulation.

The total number of expected signal events in the electron channel is 3846, for an integrated luminosity of 1.04 fb^{-1} , with a signal to background ratio (S/B) of 3.5. In the muon channel the expected number of $t\bar{t}$ events is 5470, with $S/B = 2.7$.

Table 6.1 – Expected and observed event yields, for an integrated luminosity of 1.04 fb^{-1} , after b -tagging.

	e+jets			μ +jets		
<i>Components</i>						
$t\bar{t}$	3846	$\pm$	32	5470	$\pm$	38
W +jets (data-driven)	567	$\pm$	170	1164	$\pm$	349
Z +jets	41	$\pm$	3	90	$\pm$	5
WW/ZZ/WZ	11	$\pm$	1	15	$\pm$	1
Single top	260	$\pm$	5	347	$\pm$	6
Multijet (data-driven)	147	$\pm$	147	408	$\pm$	408
<i>Total</i>						
Sum Backgrounds	1027	$\pm$	225	2027	$\pm$	537
Total Expected	4872	$\pm$	227	7496	$\pm$	538
Observed	5078	$\pm$	71	7846	$\pm$	89

6.2.2 Control plots on background-subtracted data

We already concluded in Chapter 4 that the shapes and normalization of the background and signal match the data. The following section identifies charge-asymmetric effects in data. We identify possible asymmetries or irregularities within the kinematic properties, since this could propagate into the top quark reconstruction, faking an asymmetry. We do this by subtracting the simulated (single top and diboson) and data-driven (multijet and W +jets) background from data. Subsequently we divide the background-subtracted data according to the charge of the lepton. We compare the events containing positively charged leptons to events with negatively charged leptons.

Fake asymmetry in electrons

One of the issues for electrons that needs attention is the hardware problem in the calorimeter readout, as mentioned in Section 4.1.2. Due to this problem, a sector of the calorimeter was inactive, meaning that most of the data are recorded with a gap in the calorimeter between $0 < \eta < 1.4$ and $-1 < \phi < 0.5$. The gap affects electrons and jets and automatically leads to an asymmetric distribution in terms of η and ϕ . Figure 6.5(a) shows the density of electrons in data, as a function of η and ϕ . The acceptance gap due to the calorimeter problem is visible, as well as the crack region between barrel and endcap on both sides of the detector ($|\eta| \sim 1.4$). The gap is in principle not expected to bias A_{int} or $A_{diff}(y)$, because there is no reason to assume that the acceptance depends on the charge of the lepton, but we nevertheless study the differential distribution of the

electrons.

Figure 6.5(b) shows the distribution of η of selected electrons. In this figure, we compare the events with a positively charged lepton, with the negatively charged events, as a function of η . The category of positive leptons is depicted with histograms, and the negatively charged leptons with dotted markers. For visibility reasons, the error bars of the negatively charged events reflect the sum of the uncertainty of both the positive and negative charged events. This includes the statistical uncertainties of simulated events, as well as the systematic uncertainty on the data-driven background estimates. Since the charge-asymmetric contributions of W +jets and single top events are subtracted, the total yield of the events are expected to be equal. Due to the calorimeter gap, we observe a larger number of events with $\eta < 0$. We express this difference in the ‘fake’ asymmetry A_f :

$$A_f = \frac{N_{\eta>0} - N_{\eta<0}}{N_{\eta>0} + N_{\eta<0}}, \quad (6.1)$$

where N is the number of events with the subscript indicating the range in η . A_f is -0.048 ± 0.027 for events with negatively charged leptons and -0.050 ± 0.029 for events with positively charged leptons. This is a direct consequence of the calorimeter gap, but the fake asymmetry is of equal size and sign for both charges. Therefore, we do not expect that this specific asymmetry influences the top quark charge asymmetry, as the latter is measured by rapidity differences rather than rapidity itself. The ratio of negative to positive events is shown in the bottom plot. The distributions match, but show a few statistical fluctuations in the (badly populated) forward areas.

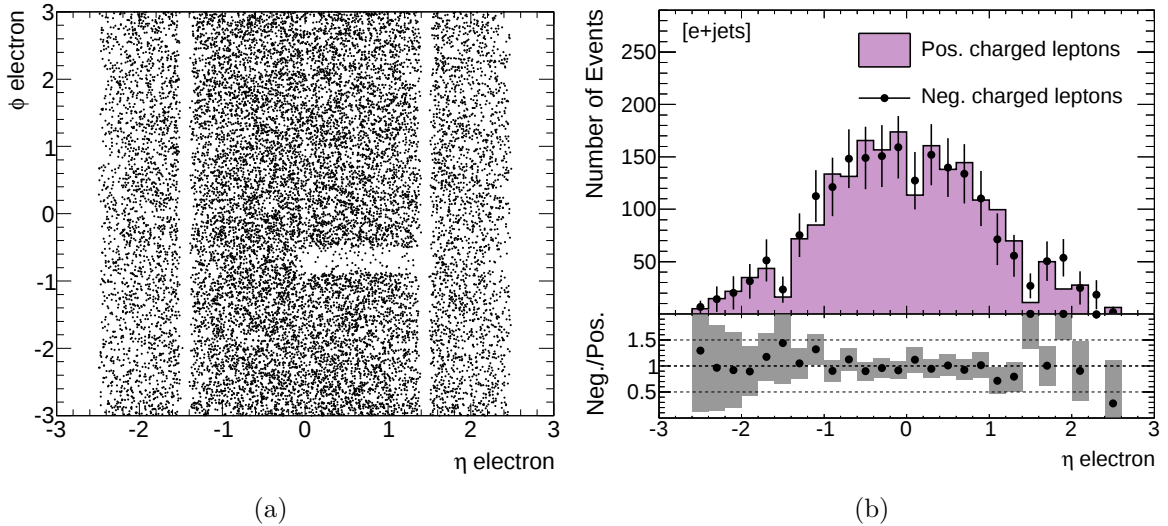


Figure 6.5 – (a) Electron density in data as a function of η and ϕ . (b) Electron η for events with leptons of positive and negative charge.

Figures 6.6(a) and 6.6(b) display the electron charge comparison with respect to the azimuthal angle ϕ . In addition to the lepton charges, the data are divided by splitting up events based on the sign of the pseudorapidity. In (a), showing events with $\eta < 0$,

the histograms match apart from minor differences in a few bins. In (b), representing the other side of the detector, at $\phi = -1$ the calorimeter inactive area emerges, but appears to be reasonably insensitive to lepton charge, as expected.

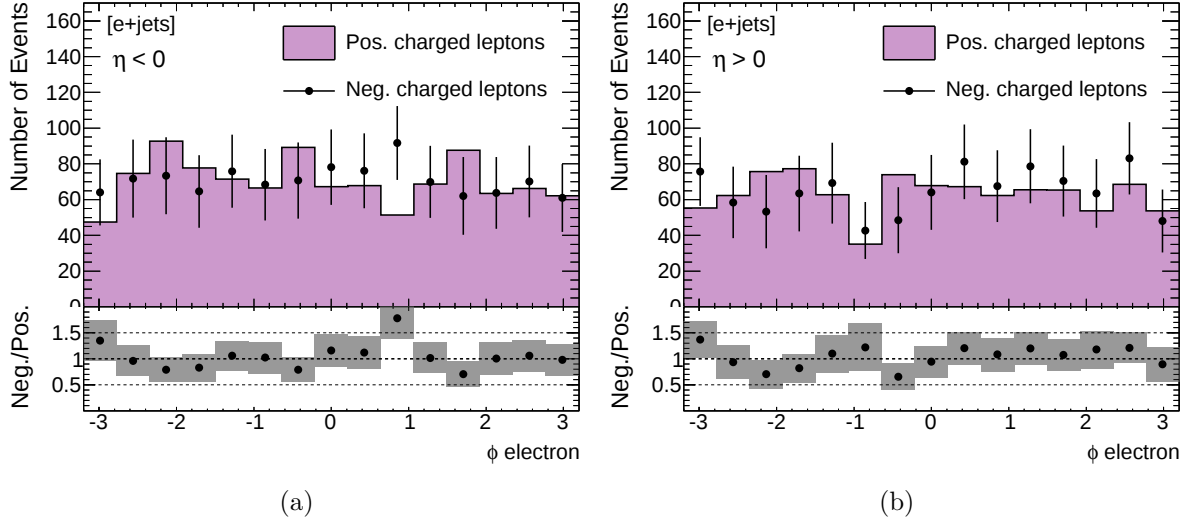


Figure 6.6 – Electron ϕ for events with leptons of positive and negative charge, in the region $\eta < 0$ (a) and $\eta > 0$ (b).

Figure 6.7(a) shows the transverse momentum of the electron. Events with a momentum larger than 140 GeV are summed and drawn as the overflow bin. In terms of momentum the shape differences are minor. There are neither notable outliers, nor a trend in any direction that indicates anomalous behavior. This demonstrates that the momentum of electrons in our selected sample does not depend on the charge.

Fake asymmetry in muons

Considering the muon properties, we follow a similar procedure as for electrons and present p_T (Figure 6.7(b)), η and ϕ (Figure 6.8). The number of events with muons of positive and negative signs agrees well. Furthermore, the agreement in terms of the shape of transverse momentum is good, no unexpected trends emerge. The shape of the pseudorapidity appears to depend on the sign of the muon, as the multiplicity of muons with charge +1 is somewhat higher than of muons with a charge of -1 , if we integrate over the range $\eta < 0$, while for $\eta > 0$ it is the other way around. This is most apparent in the bins surrounding 0. To quantify this observation, we calculate the asymmetry we defined in equation 6.2.2 and obtain $A_f = 0.016 \pm 0.028$ for muons with negative charge. For muons with positive charge, $A_f = -0.045 \pm 0.033$. These numbers are compatible within one standard deviation and hence no asymmetry is obtained. The ϕ distribution in 6.8(b) is compatible with a uniform ratio of 1.

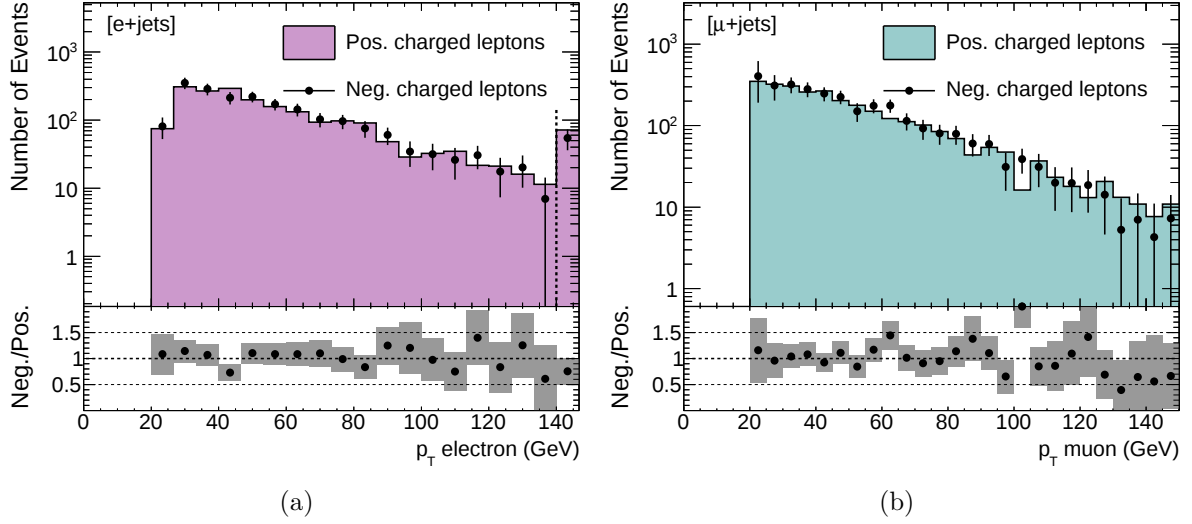


Figure 6.7 – Transverse momentum of the electron (a) and muon (b), for data with background subtracted, and for events with positively and negatively charged leptons. Events with momentum larger than 140 GeV in the electron channel are summed and displayed together in the last bin.

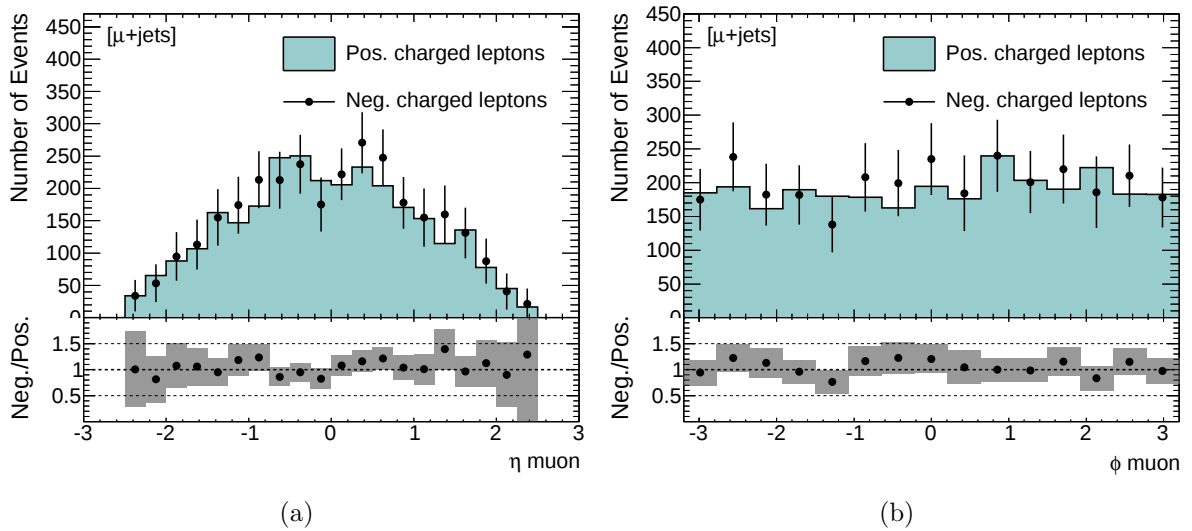


Figure 6.8 – Pseudorapidity η (a) and azimuthal angle ϕ of the muon, for data with background subtracted.

Jets

Thirdly, we consider hadronic jets. In principle, charge conjugation does not induce asymmetries in the kinematic properties of jets, as they are not directly related to the measurement of the lepton. Misinterpretations in terms of under- or overestimations in background could occur, however. In Figure 6.9 the transverse momenta of jets in the electron channel are presented. In (a) the momentum of all jets are compared for events with opposite-signed leptons. In (b-d) the transverse momenta of the first, second and third jets (ranked in terms of momentum) are compared. The normalization and shape of the two distributions in each of the four plots agree within uncertainties. At low momenta ($p_T < 40$ GeV), negative events contribute more in the three jets with the highest transverse momenta, but only for the hardest jet this is significant. In the cumulative plot (a), this effect disappears. We conclude that this difference will not bias the measurement.

The equivalent distributions for the muon channel are shown in Figure 6.10. In (a) the momentum of all jets are compared for events with opposite-signed lepton, and (b-d) shows the momentum of the three most energetic jets. Again, there is no significant difference that displays a tendency towards any direction in either of the distributions.

The pseudorapidity of jets is an input to the reconstruction of the top quark on the hadronic side of the decay. Figure 6.11 shows the η distribution for all jets, in the e +jets (a) and μ +jets channel (b), for η between -4.5 and 4.5. Overall, the jet pseudorapidities do not depend on the lepton charge. The multiplicity of jets with $\eta < 0$ is higher than for the $\eta > 0$, in both data and simulation 5-6% more jets are selected. This is a direct result of the calorimeter gap, and is independent of the lepton charge.

Fake asymmetry in $\cancel{E}_T$ and m_T^W

The transverse energy imbalance, $\cancel{E}_T$, is computed from all measured objects, including the lepton, and is therefore directly influenced by potential dependencies. Subsequently, the transverse W boson mass (m_T^W) is constructed from the lepton four-momentum and the missing energy. Figure 6.12 checks the agreement between the data of both lepton signs, because both quantities are used in background reducing cuts. The missing transverse energy is displayed in the top plot. It shows no anomalous behavior of this observable. Likewise, the positive and negative events in the transverse W boson mass distributions are compatible with each other, in both channels (c, d).

6.3 Standard Model asymmetries after selection

In Section 6.1, we showed the integrated and differential asymmetry in $t\bar{t}$ at ‘parton level’, where the four-vectors of the top quark follow straight from the theoretical prediction of the Standard Model. All observables, hence also the top quark charge asymmetry, are distorted after the detector simulation, subsequent reconstruction of the physics objects and the final event selection. Besides the top quark pair, also some of the physics backgrounds

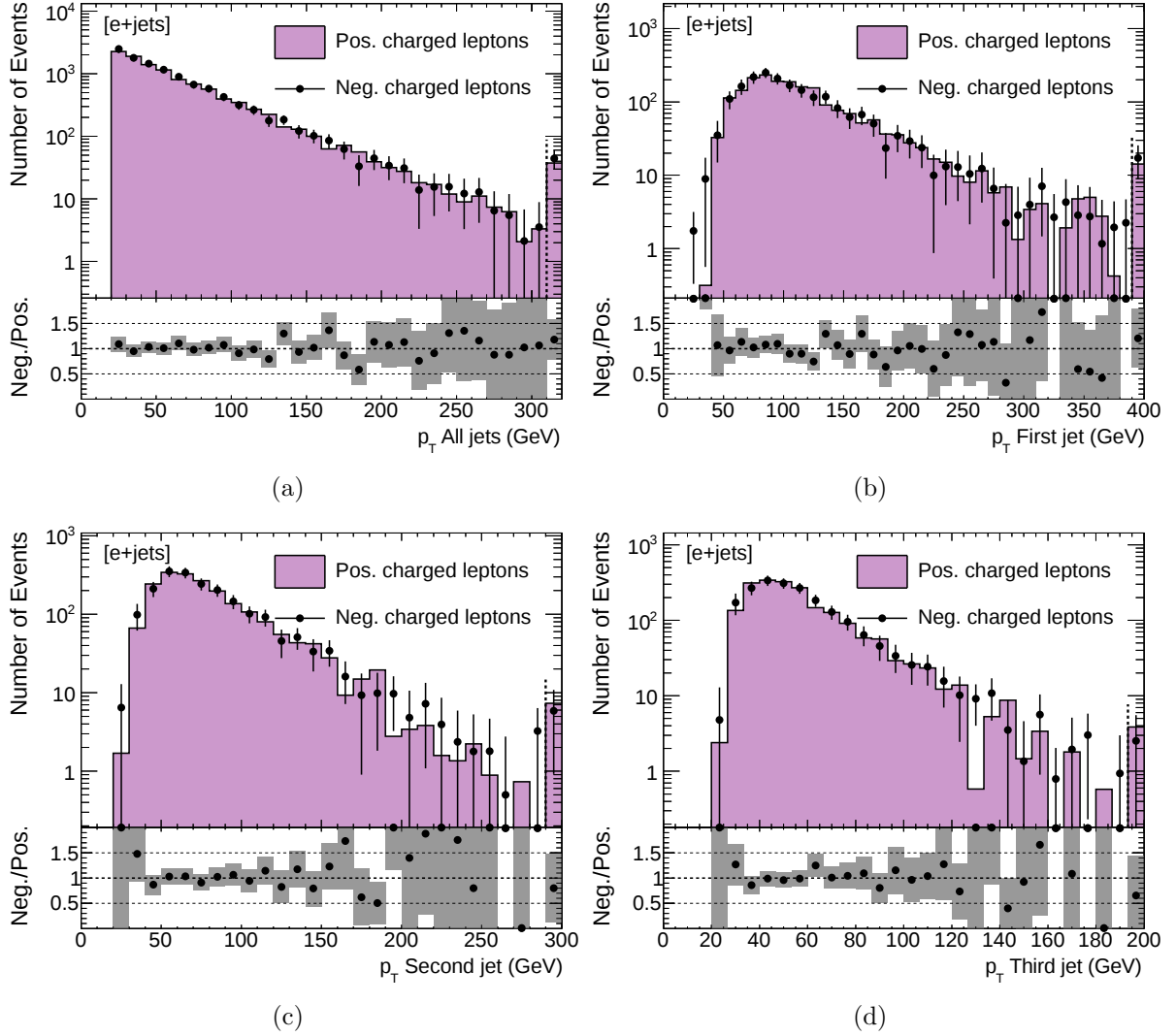


Figure 6.9 – Jet momenta in the electron channel.

experience asymmetric production mechanisms. In this section, we analyze the $t\bar{t}$ asymmetry after full event generation, reconstruction and selection, as well as the contribution of physics background to the asymmetry.

6.3.1 Asymmetry in $t\bar{t}$ simulation

Observables that we obtain from the reconstructed objects we denote by ‘detector level’ simulation. At detector level, we make a distinction between events after ‘minimal selection’ and ‘full selection’. To be able to reconstruct two top quarks at detector level we need four jets, a lepton and missing transverse energy. This corresponds to the minimal selection. The full selection includes, in addition, the multijet-reducing cut (triangular cut) and the requirement of at least one b -tagged jet.

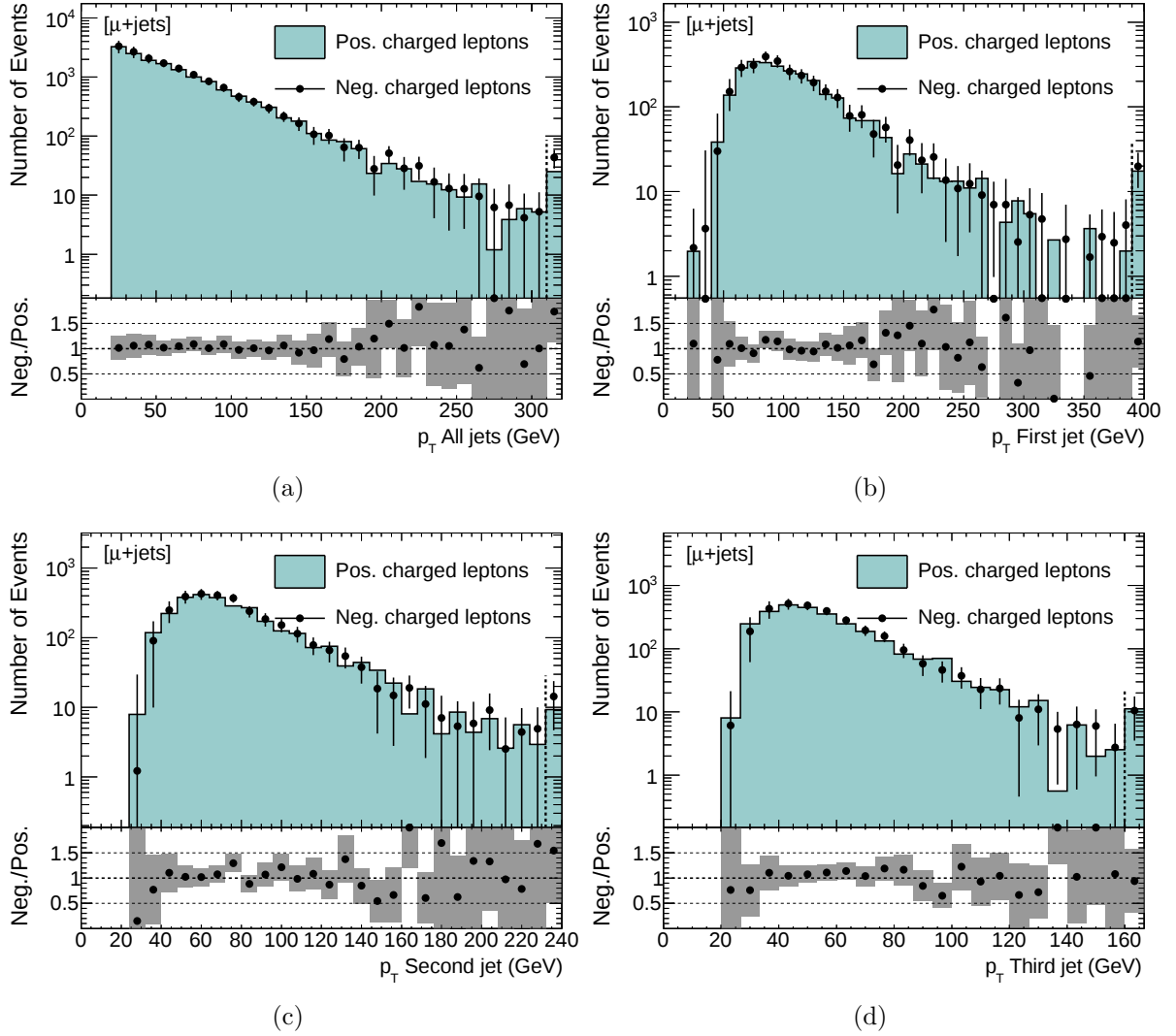


Figure 6.10 – Jet momenta in the muon channel.

Integrated asymmetry

In the electron channel, for the simulation at detector level after minimal selection, we measure a value for the integrated asymmetry A_{int} of -0.002 ± 0.003 . After the full selection is applied the same quantity is equal to -0.009 ± 0.008 . This deviates from the parton level value of $+0.006 \pm 0.001$ and suggests that generation and simulation influences the observable. The statistical uncertainty on A_{int} after full selection is larger, since we select only a fraction of the events. However, even within 1σ uncertainty the detector level value does not agree with the parton level calculation. This means we can expect a similar shift in the value we measure in data. In the muon channel the detector level value of A_{int} is -0.003 ± 0.003 after minimal selection and -0.007 ± 0.007 with full selection. Similar to the electron channel we therefore expect the data value in the muon channel to be shifted towards negative values as well.

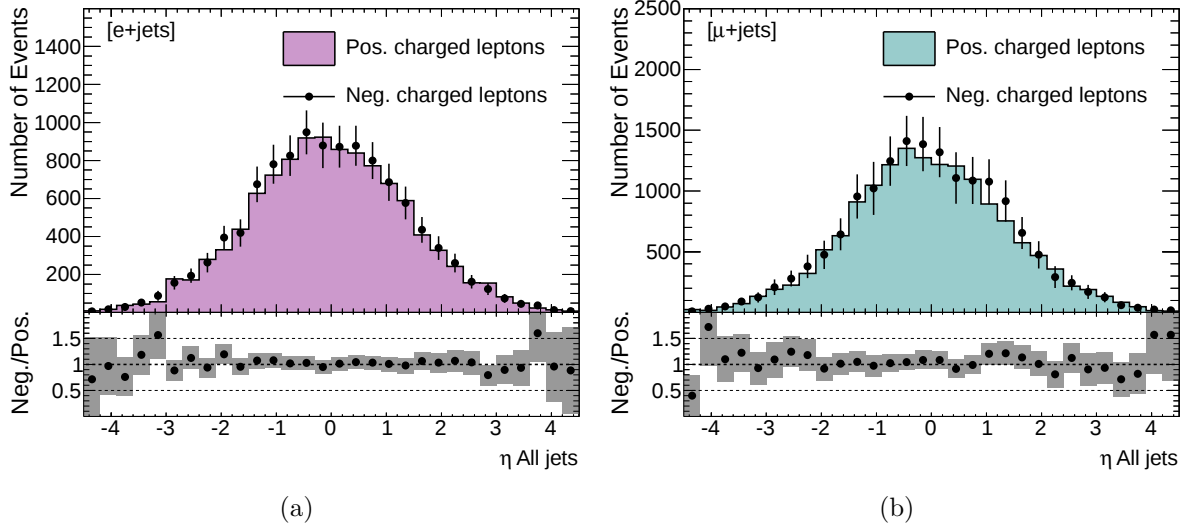


Figure 6.11 – Pseudorapidity of jets in electron (a) and muon channel (b).

Differential asymmetry

We show the distributions for $A_{diff}(y)$ at parton and detector level in Figure 6.13. The asymmetry is plotted with respect to the rapidity. The parton level distribution in both plots is identical to the one shown as “Total” in Figure 6.4. Furthermore, triangles depict the distributions after reconstruction after minimal selection and full selection. They correspond to an integrated luminosity of 1.04 fb^{-1} . Potentially, asymmetric detector effects are folded in this distribution and may affect it.

The electron channel (left) distribution of the asymmetry at detector level shows statistical fluctuations. Especially in the forward regions only a few top quarks are reconstructed. The large uncertainties in the entire range assure that the detector level distributions agree with the parton level, but are also compatible with a straight line through $A_{diff}(y) = 0$. In the muon channel (right), similar arguments can be employed. But, at detector level after minimal and full selection, a deviation emerges at $y > 1$. All values of $A_{diff}(y)$ are below zero in this range. When summing the bins between $y = 1$ and $y = 3$, the asymmetry in simulation at parton level is -0.005 ± 0.001 , whilst simulation after full selection is -0.028 ± 0.012 . This is a difference of 2.5 standard deviations that could indicate the presence of asymmetric behavior of the detector. We further investigated the individual distributions of the top quarks reconstructed on the leptonic and hadronic side of the decay, but could not find a source of this deviation.

We have to conclude that we are not sensitive to measure the differential asymmetry as predicted by the Standard Model, in either of the channels. Secondly, in the muon channel for positive rapidities a significant deviation occurs, and behavior opposite to expectation is expected in data as well in this case. This is consistent with what we see in the integrated asymmetry A_{int} : the asymmetry at parton level (theory level) loses significance after detector simulation, event selection and reconstruction are applied.

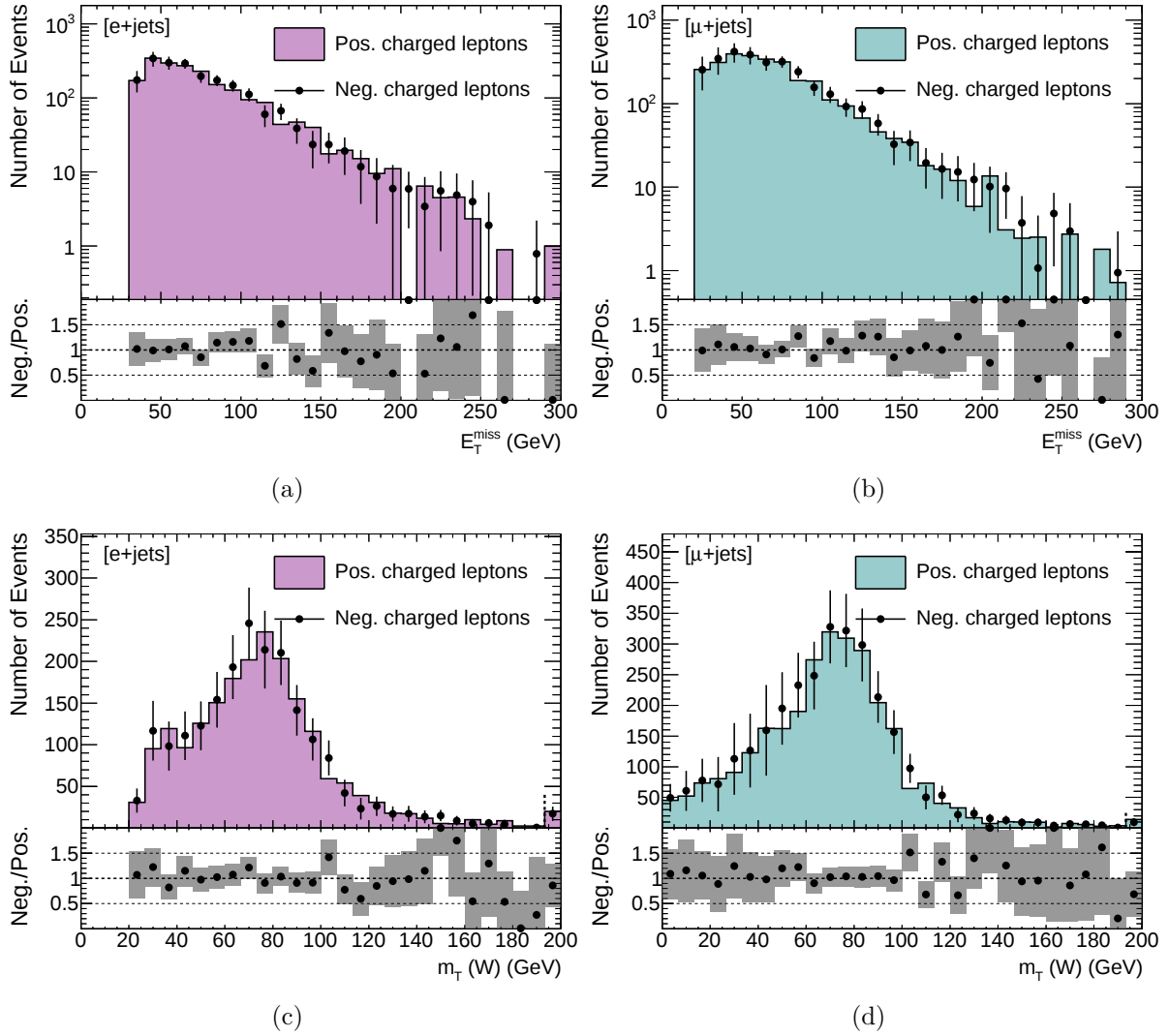


Figure 6.12 – E_T and m_T^W in the electron channel (left) and the muon channel (right).

Mapping the simulation and detector effects is important as it may modify the observable to a large extent.

6.3.2 Asymmetry in Standard Model background simulation

A substantial part of background events originates from W +jets and single top production. These standard model processes are charge-asymmetric, due to their electroweak production mechanisms. The valence quarks of the colliding protons are two up quarks and one down quark. The probability of an up quark interacting with an antiquark of the down-type is therefore higher than a down quark with an antiquark of the up-type. This is described in Chapter 1.

As a result, there are more background events in the sample of events with a positively

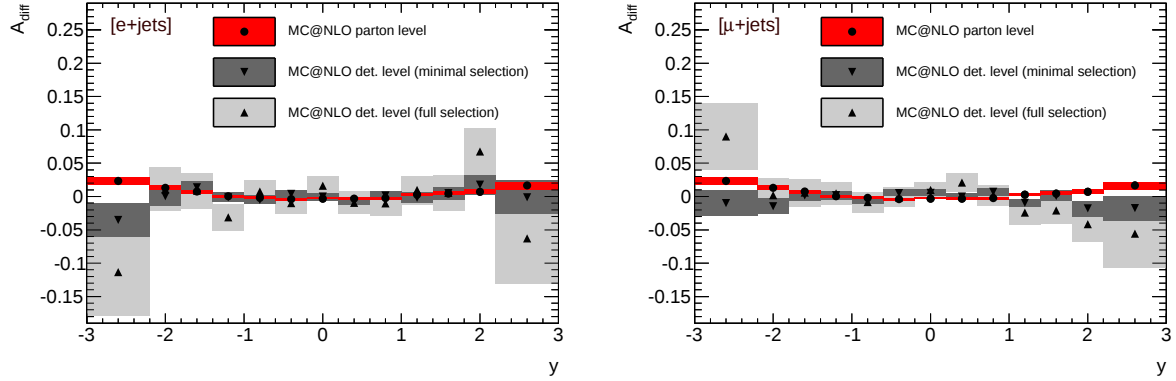


Figure 6.13 – Comparison of the differential asymmetry ($A_{diff}(y)$) at different simulation levels. The asymmetry is shown in terms of rapidity, in the electron channel (left) and the muon channel (right). The parton level (dark red) in both plots is identical to “Total” in Figure 6.4. The error bars represent purely the statistical uncertainty.

charged lepton. Additional to the charge asymmetry, W +jets and single top events are produced less centrally than top quark pairs, on average. These two effects combine and propagate through to our analysis: the lepton in background events will be used by the reconstruction algorithm to form the ‘leptonic’ top quark, whose charge will be positive more often than negative. Consequently, there are more fake top quarks reconstructed in the forward region.

We measured the integrated asymmetry in W +jets and single top simulation events, after minimal selection. The result is summarized in Table 6.2. Both backgrounds induce an asymmetry that is an order of magnitude larger than that of $t\bar{t}$, and of the same sign. In the electron channel the asymmetry is smaller than in the muon channel. Notice that this is an observable that can only be measured after reconstruction, since there are no two top quarks at parton level for these background events.

Table 6.2 – Asymmetries induced by a pure sample of background events, after detector simulation and minimal selection.

	e+jets	μ +jets
W +jets	0.020 ± 0.004	0.031 ± 0.002
Single top	0.012 ± 0.006	0.030 ± 0.005

The differential asymmetry of single top and W +jets events is shown in Figure 6.14, again for the e +jets (left) and μ +jets (right) channels. The top graph depicts the W +jets contribution after minimal selection. This corresponds to what we named ‘detector level at minimal selection’ before. A parabolic shape forms, similar to what we saw in top pair events. The parabolic fit results in values of c_1 of 0.014 (W +jets) and 0.011 (single

top), for the electron channel. For the muon channel $c_1 = 0.022$ (W +jets) and 0.023 (single top). The parton level value for $t\bar{t}$ events for this quantity is $3.6 \cdot 10^{-3}$. We checked that if we apply the full selection, the background effect is eliminated and the remaining asymmetry cannot be distinguished from a straight line at $A_{diff}(y) = 0$. This is due to the low number of remaining background events after selection.

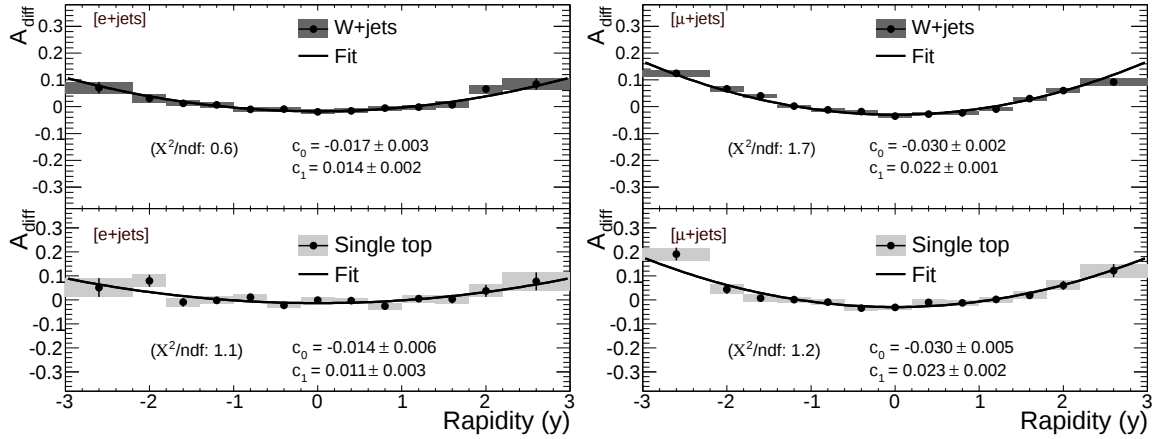


Figure 6.14 – Differential asymmetry $A_{diff}(y)$ for background events at detector level (minimal selection). The plot shows the W +jets and single top contributions, for electron (a) and muon channel (b). The error bars reflect the statistical uncertainty.

To conclude, we showed that distortion and biases that result from the detector, reconstruction and selection steps, are present and form a nuisance to measuring the charge asymmetry. In the following section we adopt an unfolding procedure to map the distortion and bias.

6.4 Results for A_{int}

The observed distributions of $\Delta|y|$ for the electron and muon channel are shown in Figure 6.15, on top of the sum of expected events. The yield of the expected events is somewhat lower than the data, in both channels, as we already saw in the previous section. The shapes of the data in the distributions match the expectations reasonably well.

We measure the integrated asymmetry A_{int} from the background-subtracted data, following the same procedure as we did for the control plots. The results are summarized in Table 6.3. The data should compare to the values of the $t\bar{t}$ sample at detector level after full selection. For the electron channel we obtain in data $A_{int} = 0.008 \pm 0.019$ (stat), compared to -0.009 ± 0.008 (stat) in simulation. Note that the uncertainty on simulation is obtained from the complete set of events, if we scale the uncertainty of simulation to the integrated luminosity of data, we obtain -0.009 ± 0.021 .

The uncertainty in this measurement is large enough to accommodate the differences in the central values. In the muon channel $A_{int} = -0.013 \pm 0.016$ (data) compared to -0.007

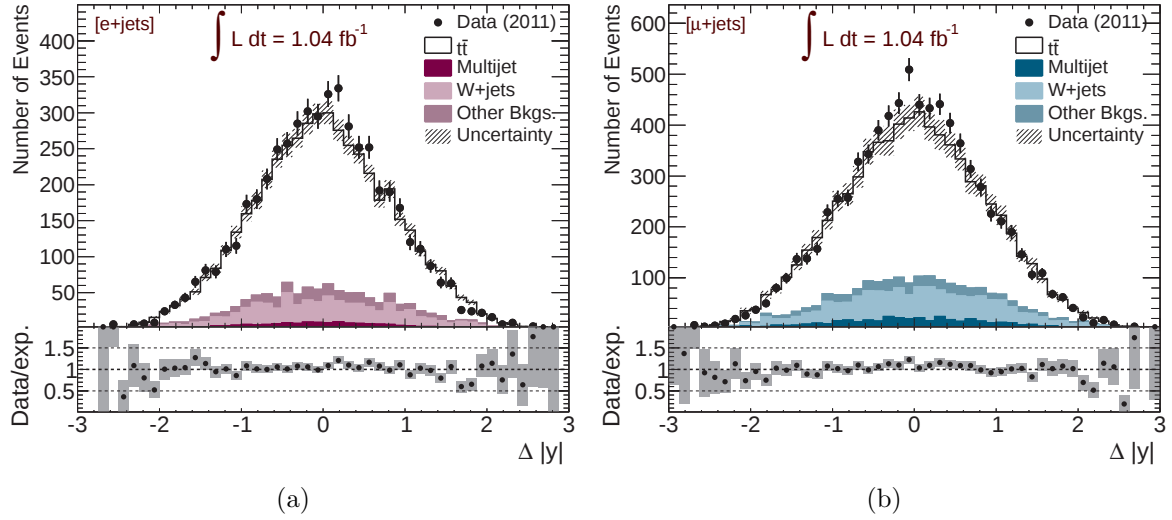


Figure 6.15 – Distribution of $\Delta|y| = |y_t| - |y_{\bar{t}}|$, after all selections, for the electron (a) and muon channel (b).

± 0.007 (or -0.007 ± 0.0019 , when scaled to 1.04 fb^{-1}). The data is in full agreement with Standard Model expectations.

Table 6.3 – Results for integrated asymmetry A_{int} for data compared to simulation at different levels. The uncertainties in this table reflect only the statistical uncertainty, with in brackets the uncertainty when simulation is scaled to 1.04 fb^{-1} .

	Det. level (min sel.)	Det. level (full sel.)	Data - bkg
$e+\text{jets}$	-0.002 ± 0.003	$-0.009 \pm 0.008 [\pm 0.021]$	0.008 ± 0.019
$\mu+\text{jets}$	-0.003 ± 0.003	$-0.007 \pm 0.007 [\pm 0.019]$	-0.013 ± 0.016

6.4.1 Unfolding

To be able to compare the measured values of the charge asymmetry with the theoretical predictions, we take into account the full event generation, acceptance and reconstruction effects by applying an ‘unfolding’ procedure. This means that we take into account how the four-vectors of the generated top quarks transform after all these steps and accordingly transform back the four-vectors of the top quarks as measured in the ATLAS detector. The binned spectrum of an observable can be written as a function of the original (‘true’) spectrum by applying a response matrix to it:

$$m_i = B_{ij}s_j,$$

where m_i is the measured spectrum in terms of i bins, s_j is the simulated spectrum at parton level and B_{ij} is the response matrix. The response matrix thus represents

the showering and hadronization steps in event generation, the detector effects, selection efficiency, and the top quark reconstruction, including the potential migration from one bin to another during each of these steps. Hence, the inverse of the matrix, B_{ij}^{-1} , can be applied to the measured spectrum to obtain the spectrum equivalent to the simulated spectrum, at parton level, s_j .

Inverting the matrix can lead to singularities or unphysical peaks, therefore a smoothing and regularization algorithm is applied. The method used in this analysis is Bayesian unfolding [89] and is implemented using the software package ROOUNFOLD [90].

The motivation for applying the unfolding procedure to the data is to obtain a detector-independent value of the measurement that can be compared directly to theoretical predictions and other experiments. That holds true for existing models predictions and measurements, but especially for future models.

Response matrix

The integrated asymmetry, A_{int} , is calculated from the distribution of $\Delta|y| = |y_t| - |y_{\bar{t}}|$. We divide this distribution in six equally-sized bins and define the response matrix of this quantity. This is done by filling a matrix with the simulated true and reconstructed value of $\Delta|y|$, per event. When the event does not pass the selection criteria and hence no reconstructed value exist, it adds to the inefficiency. The resulting matrices for the electron and muon channel are shown in Figure 6.16. The matrices are similar for both channels. Both show large off-diagonal contributions, proving that full event generation and reconstruction indeed cause bin migration.

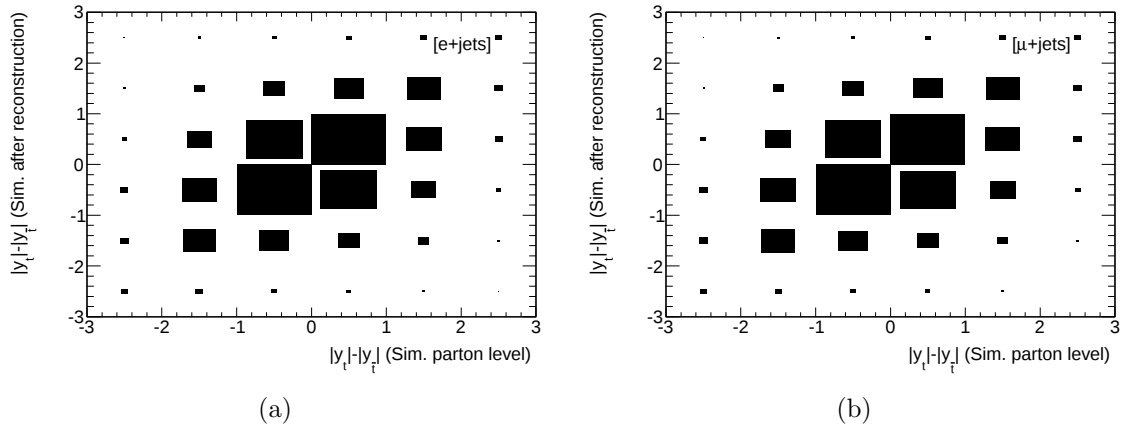


Figure 6.16 – Response matrices B_{ij} for the electron (a) and muon (b) channel. The value of the matrix element is visualized by the size of the boxes.

Unfolding parameters

There are a number of parameters that influence the unfolding procedure. We studied the number of iterations during unfolding that were necessary to converge to a stable

result and the bin size of the matrix and distribution. There is a trade-off between the number of iterations and uncertainty of the unfolded result, therefore we keep the number of iterations as low as possible.

We define the unfolded results as ‘stable’ when the difference with respect to the asymmetry after the previous iteration is smaller than 0.001. The number of iterations required to obtain a stable result is obtained by producing pseudo data in the form of a set of varied $\Delta|y|$ distributions that are obtained by pulling events from a probability distribution function that is based on the reconstructed Standard Model $t\bar{t}$ spectrum of $\Delta|y|$. The unfolding procedure is applied to each pseudo experiment, and the number of iterations that is required to converge to a stable value for the asymmetry is measured. The results show that, regardless of the bin sizes, the unfolding converges 100% of the time within 50 iterations, for the nominal asymmetry. In the chosen configuration of six bins, all pseudo experiments converged within 40 iterations, with an average of 13.4 iterations.

In Figure 6.17 the statistical uncertainty on the unfolded asymmetry is plotted as a function of the number of iterations, for different bin sizes. It shows that a higher number of iterations leads to a larger uncertainty. This is a property of the unfolding procedure. The six- and eight-bin samples reach a plateau. The plot shows that for larger bin sizes, and therefore better populated bins, the increase in uncertainty is smaller.

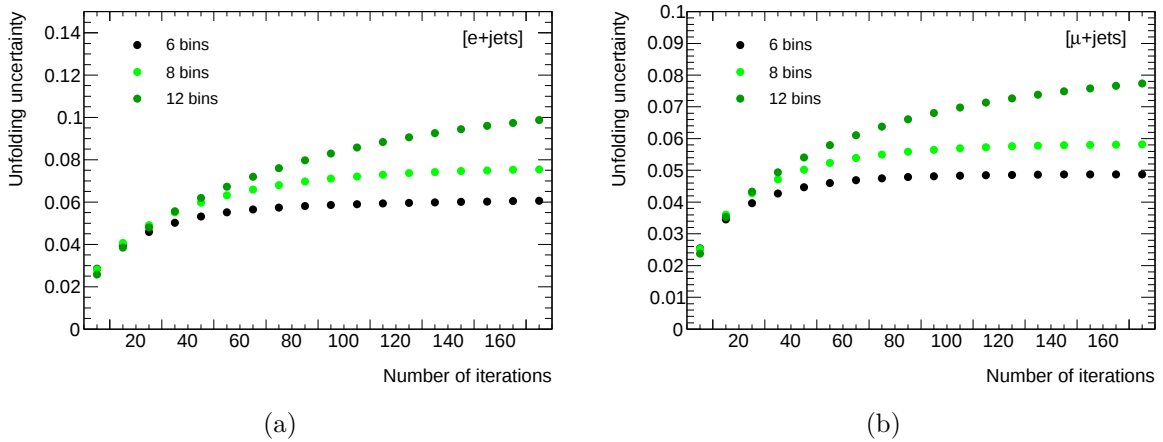


Figure 6.17 – Expected statistical uncertainty on the unfolded asymmetry as a function of the number of iterations, for electron channel (a) and muon channel (b).

We check whether the unfolding procedure can reproduce the original (‘parton level’) asymmetry on average, for different sizes of the asymmetry. We obtain samples with an artificial asymmetry of +10%, +5%, 0%, -5% and -10%, by reweighting the original, simulated samples. From each reweighted sample we extract 1000 pseudo data sets and apply the unfolding procedure. Figure 6.18 shows the unfolded asymmetry as a function of the original asymmetry, for different numbers of iterations. It shows that the five data points belonging to the same number of iterations form a straight line and prove the linearity of the operation. With increasing number of iterations, the slope of the line changes, in both channels. We fit a second order polynomial $f(A) = c_1 A + c_2$ to the five

points. In the electron channel, the slope converges to 0.999, with an offset of 0.001, at 160 iterations. This is close to the reference ($c_1 = 1, c_2 = 0$, dashed line in plot). This means that although we concluded that for an asymmetry close to zero 40 iterations is sufficient, for larger asymmetries more iterations may be required. At 40 iterations, a deviation of 11% from the true value is expected, at 80 iterations only 5%. In the muon channel, these numbers are 9% and 3%, respectively.

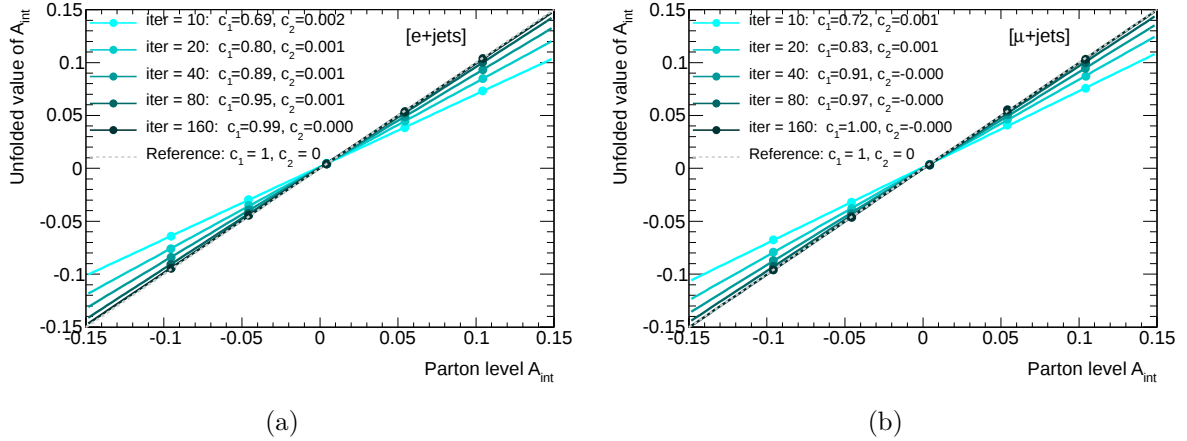


Figure 6.18 – Unfolded asymmetry as a function of the the inserted asymmetry, for electron channel (a) and muon channel (b).

Based on the balance between the increase of the uncertainty and the reduction of a bias for a high number of iterations, we use 80 iterations in combination with six evenly distributed bins and assign the systematic uncertainty due to a potential bias to the final result.

6.4.2 Systematic uncertainties

The sources of systematic uncertainties that contribute to the final result are in principle equal to those in the cross section measurement. However, since we investigate asymmetric effects, most of these sources are expected to have either negligible or relatively small contributions: they simply cancel in the ratio. For example, the jet energy scale uncertainty does not behave differently for events containing positively or negatively charged leptons. Since the statistical uncertainty is large, we only evaluate the expected major sources of uncertainty on the charge asymmetry:

- **Background normalization.** The uncertainty on the data-driven techniques of obtaining the multijet and W + jets background events are 100% and 30% respectively. The other electroweak background of importance are single top events, to which we apply a 30% uncertainty too. We varied the amounts of backgrounds during the background subtraction step to estimate the impact on the final result.
- **Event generator.** We repeated the analysis, including the unfolding procedure, with the $t\bar{t}$ shape and normalization estimates obtained with POWHEG, instead

of MC@NLO. In both cases HERWIG is used to perform parton showering and hadronization.

- Unfolding bias. The linearity tests showed that for 80 iterations a 5% bias may arise.

The largest uncertainty comes from the difference in event generators, a shift of 0.021 (0.024) is observed in the electron (muon) channel. The background subtraction and unfolding biases lead to shifts of 0.008 maximally, where the subtraction of W +jets is the major source of this shift. We include these systematic uncertainties into the final result by quadratically adding their contribution to the uncertainty.

6.4.3 Final results after unfolding A_{int}

Figure 6.19 shows the unfolded results of $\Delta|y|$ compared to the parton level values.

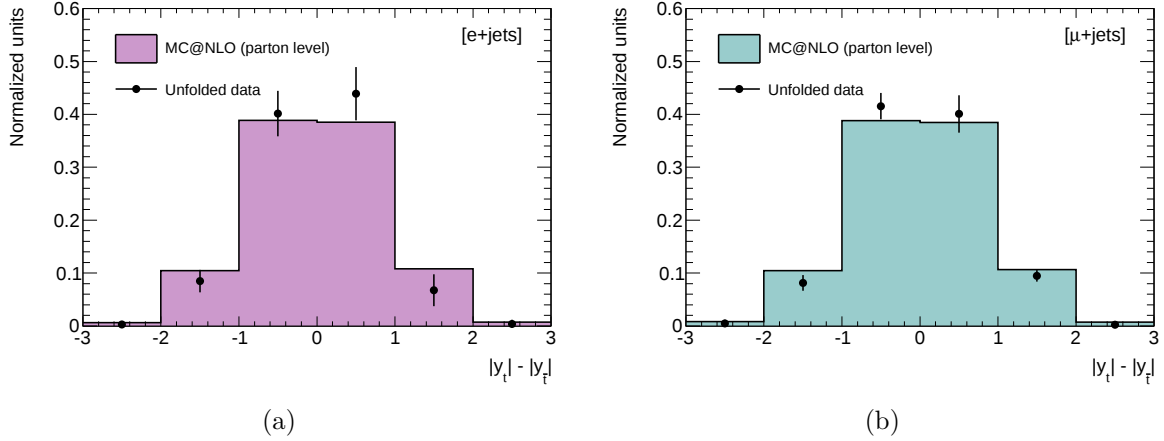


Figure 6.19 – Unfolded distribution of $\Delta|y|$ on top of the MC@NLO prediction at parton level, for electron channel (a) and muon channel (b). The error bars reflect the sum of the statistical and systematic uncertainties.

The measured unfolded value of A_{int} in the electron channel is

$$A_{int}^{unf}(e) = 0.074 \pm 0.058(\text{stat}) \pm 0.023(\text{syst}),$$

and in the muon channel

$$A_{int}^{unf}(\mu) = -0.024 \pm 0.050(\text{stat}) \pm 0.026(\text{syst}).$$

The combination of the results of the two statistically independent samples is

$$A_{int}^{unf}(\text{comb}) = 0.014 \pm 0.038(\text{stat}) \pm 0.024(\text{syst}),$$

where we assumed that all sources of systematic uncertainty are uncorrelated, except the contribution of the $t\bar{t}$ modeling. These values are within the uncertainties well compatible

with the Standard Model. We compare these numbers to similar measurements of the CMS collaboration [91] and the ATLAS paper [70] referred to earlier. CMS quotes $A_{int}=0.013\pm 0.028$ (stat) $^{+0.029}_{-0.031}$ (syst), as a result combined between the electron and muon channel, for 1.09 fb^{-1} . The measurement in ATLAS shows $A_{int}=0.018\pm 0.028$ (stat) ± 0.023 (syst) for 1.04 fb^{-1} . The main difference of the results in this chapter with respect to the ATLAS result comes from different choices in event selection (namely, b -tagging algorithm, muon momentum, jet pseudorapidity) and different choices in the unfolding procedure.

With the combined result for the asymmetry, we can exclude a value of A_{int} larger than 0.102, or smaller than -0.074, with a confidence level of 95%. This is under the assumption that the uncertainties are Gaussian distributed and that the statistical and systematic uncertainties are uncorrelated.

6.4.4 Discussion on new physics expectations

Since the nonzero measurement of the forward-backward asymmetry by the Tevatron experiments for events with $m_{t\bar{t}} > 450\text{ GeV}$, several new physics models have been evaluated at benchmark levels compatible with these results. A range of models that induce a non-zero forward-backward asymmetry have been proposed [92, 93]. The corresponding predictions for the LHC charge asymmetry of A_{int} as we measured in this chapter were included as well. These models predict values of A_{int} between 0.0 and 0.09. Figure 6.20 shows a number of such models, in a 2-dimensional plane. The x-axis depicts the forward-backward asymmetry for $m_{t\bar{t}} > 450\text{ GeV}$ at the Tevatron, the y-axis the value of A_{int} ($= A_C^{new}$) to be measured at the LHC. The value reported by CDF is $A_{FB}(m_{t\bar{t}} > 450\text{ GeV}) = 0.475 \pm 0.114$ [43] (D0 only reports an overall asymmetry, $A_{FB} = 0.08 \pm 0.04$ (stat) ± 0.01 (syst), consistent with the Standard Model [94]).

We cannot exclude any values in this range, using the combined result, although our measurement disfavors the Z' models (mass ranges from 100 to 360 GeV). The statistical limits of the measurements with the current data set (1.04 fb^{-1}) do not allow for stronger statements on exclusion of the models proposed here. Table 6.4 shows the expected uncertainty on the combined result, as a function of the size of the data set. It shows that conducting the same analysis on twice as much data, leads to an expected statistical uncertainty that is comparable to the systematic uncertainty. With a data set of 5 fb^{-1} the expected statistical uncertainty is reduced to 0.017 and taking into consideration that some systematic uncertainties may be reduced when knowledge of the detector and background estimates are improved, a part of Figure 6.20 could be excluded already.

6.5 Results for $A_{diff}(y)$

We already concluded before that for the amount of data we use in this analysis the differential asymmetry $A_{diff}(y)$ is not sufficiently sensitive to measure the Standard Model asymmetry since detector and selection effects distort the results. Moreover, we have showed that the uncertainty on the integrated asymmetry itself already is large. For completeness we show the results of the measured differential asymmetry in Figure 6.21.

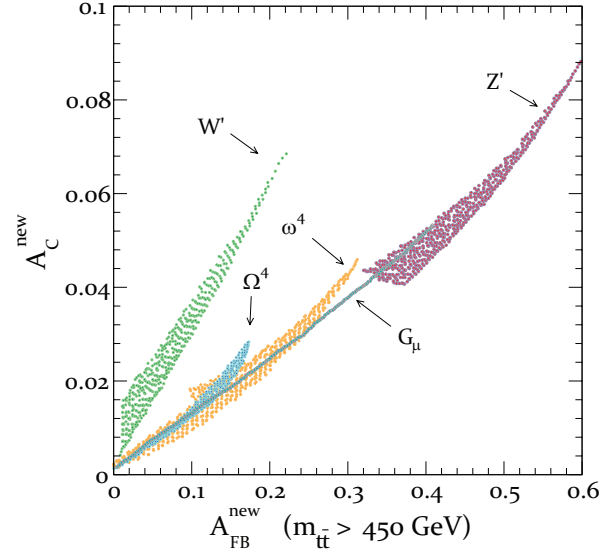
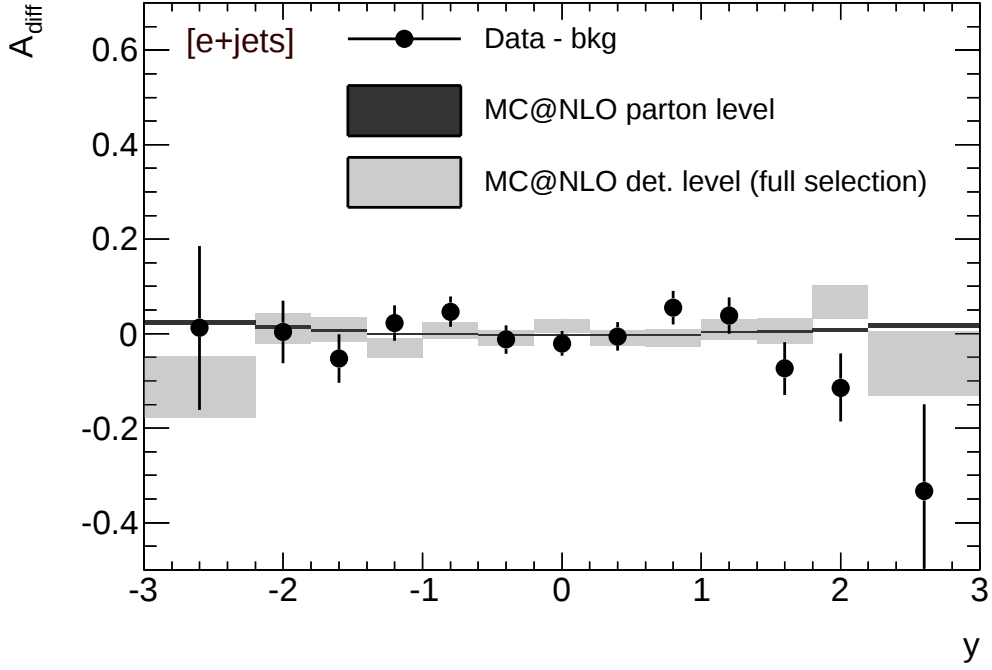


Figure 6.20 – New physics models in 2-d plane of asymmetry measured at the Tevatron (forward-backward asymmetry, x-axis) and at the LHC (charge asymmetry, y-axis). Figure obtained from Ref. [93].

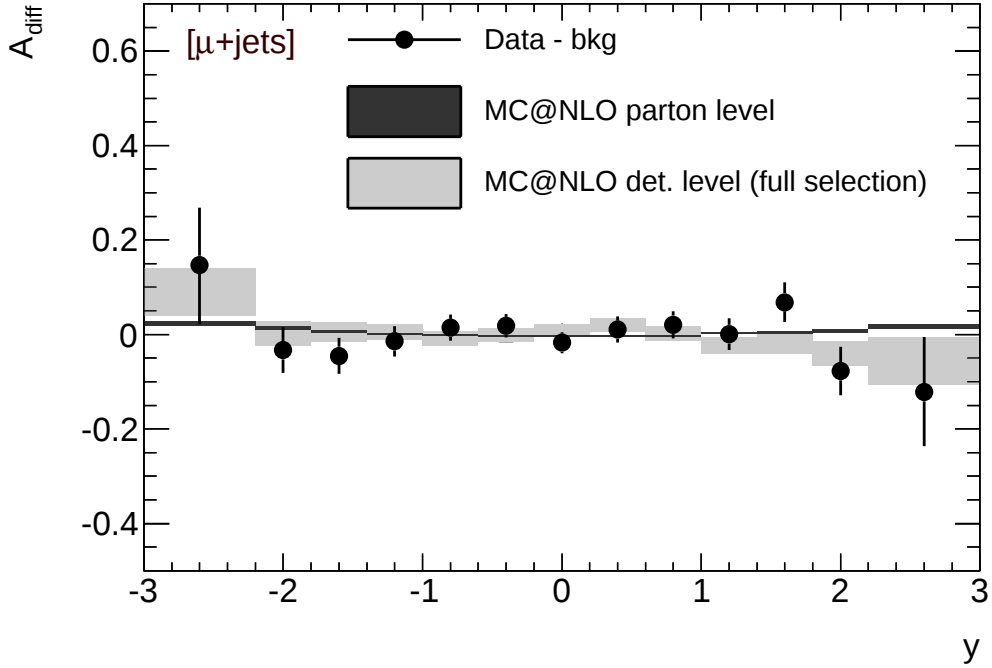
Table 6.4 – Expected uncertainty on the combined value of A_{int} , as a function of the integrated luminosity of the data set.

Size of data set (fb^{-1})	Expected stat. uncertainty
1	0.040
2	0.027
5	0.017
10	0.012

For both the electron and muon channel it shows the background-subtracted data versus the simulation at two levels. A parabola with a positive quadratic term does not fit the shape of the distribution of data, neither for the electron channel, nor for the muon channel. The data agree with the detector level simulation, and a horizontal line through zero. At this precision, we observe no extreme values of the asymmetry that would give indications towards non-Standard Model effects.



(a)



(b)

Figure 6.21 – Asymmetry $A_{diff}(y)$ for data, compared to simulation at different levels, for electron (a) and muons (b). The error bars only reflect the statistical uncertainties and the uncertainty on simulation is not scaled to the integrated luminosity of data in this plot.

6.6 Summary

In this chapter we have measured the top quark charge asymmetry in a data set that corresponds to an integrated luminosity of 1.04 fb^{-1} . We defined two parametrizations of the top quark charge asymmetry, and showed that the predicted asymmetry is present in the NLO event generator that we use to model $t\bar{t}$ events. It can be visualized in both parametrizations. The charge asymmetry is also present in physics background that is produced in electroweak processes, particularly in W +jets and single top events this can be observed. After our event selection, the amount of background is reduced to sufficiently low levels, to assure that the uncertainty on the measured asymmetry due to background is minimized. Insufficient $t\bar{t}$ events pass the selection criteria to be able to measure the top quark charge asymmetry as present in the Standard Model. To avoid potential detector asymmetries, and to be able to compare results with other experiments and future models, we applied an unfolding procedure. We finally measured a value of the integrated asymmetry compatible with measurements by the CMS and ATLAS collaborations. The differential asymmetry to which no detector corrections were applied, showed no anomalous behavior. The measurement of A_{int} cannot exclude any of the models proposed in papers that are compatible with the forward-backward asymmetry, as they are all in the range 0.0-0.1. The measurements show that with the increasing amount of data that are recorded, the exclusion of new physics models will quickly become possible.

References

- [1] Sheldon L. Glashow, *Partial-symmetries of weak interactions*, Nuclear Physics **22**(4) (1961) 579.
- [2] Weinberg, Steven , *A Model of Leptons*, Phys. Rev. Lett. **19**(21) (1967) 1264.
- [3] Abdus Salam, *Weak and Electromagnetic Interactions*, Originally printed in *Svartholm: Elementary Particle Theory, Proceedings Of The Nobel Symposium Held 1968 At Lerum, Sweden*, Stockholm 1968, 367-377.
- [4] R.P. Feynman and Murray Gell-Mann, *Theory of Fermi interaction*, Phys. Rev. **109** (1958) 193.
- [5] G. 't Hooft and M. Veltman, *Regularization and renormalization of gauge fields*, Nuclear Physics B **44**(1) (1972) 189.
- [6] D. Hanneke, S. Fogwell Hoogerheide, and G. Gabrielse, *Cavity control of a single-electron quantum cyclotron: Measuring the electron magnetic moment*, Phys. Rev. A. **83**(5) (2011) 052122.
- [7] E. Fermi, *Versuch einer Theorie der beta-Strahlen*, Z. Phys. **88** (1934) 161.
- [8] T. D. Lee and C. N. Yang, *Question of parity conservation in weak interactions*, Phys. Rev. **104** (1956) 254.
- [9] Peter W. Higgs, *Broken symmetries and the masses of gauge bosons*, Phys. Rev. Lett. **13**(16) (1964) 508.
- [10] F. Englert and R. Brout, *Broken symmetry and the mass of gauge vector mesons*, Phys. Rev. Lett. **13**(9) (1964) 321.
- [11] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, *Global conservation laws and massless particles*, Phys. Rev. Lett. **13**(20) (1964) 585.
- [12] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, *Evidence for the 2π Decay of the K^0 Meson*, Physical Review Letters **13** (1964) 138.
- [13] H. Harari, *A new quark model for hadrons*, Physics Letters B **57** (1975) 265.
- [14] M. L. Perl *et al.*, *Evidence for anomalous lepton production in $e^+ - e^-$ annihilation*, Phys. Rev. Lett. **35** (1975) 1489.

References

- [15] S. W. Herb *et al.*, *Observation of a dimuon resonance at 9.5 gev in 400-gev proton-nucleus collisions*, Phys. Rev. Lett. **39** (1977) 252.
- [16] CDF Collaboration, F. Abe *et al.*, *Observation of top quark production in $\bar{p}p$ collisions with the collider detector at fermilab*, Phys. Rev. Lett. **74** (1995) 2626.
- [17] D0 Collaboration, S. Abachi *et al.*, *Observation of the top quark*, Phys. Rev. Lett. **74** (1995) 2632.
- [18] Gargamelle Neutrino Collaboration, F. J. Hasert *et al.*, *Observation of neutrino-like interactions without muon or electron in the Gargamelle neutrino experiment*, Phys. Lett. **B46** (1973) 138.
- [19] C. Y. Prescott *et al.*, *Parity non-conservation in inelastic electron scattering*, Physics Letters B **77** (1978) 347.
- [20] G. Arnison *et al.*, *Experimental observation of isolated large transverse energy electrons with associated missing energy at $\sqrt{s}=540$ GeV*, Phys. Lett. B **122** (1983) 103.
- [21] G. Arnison *et al.*, *Experimental observation of lepton pairs of invariant mass around 95 GeV/c² at the CERN SPS collider*, Phys. Lett. B **126** (1983) 398.
- [22] D. Decamp *et al.*, *Determination of the number of light neutrino species*, Physics Letters B **231** (1989) 519.
- [23] H. Flacher *et al.*, *Revisiting the Global Electroweak Fit of the Standard Model and Beyond with Gfitter*, Eur. Phys. J. **C60** (2009) 543.
- [24] ATLAS Collaboration, Georges Aad *et al.*, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B (2012) .
- [25] CMS Collaboration, Serguei Chatrchyan *et al.*, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. B (2012) .
- [26] V.A. Gol’fand and E.P. Likhtman, *Extensions of the algebra of poincare group generators and violation of p invariance*, JETP Lett. **13** (1971) 323.
- [27] D. Volkov and V.P. Akulov, *Possible universal neutrino interactions*, JETP Lett. **16** (1972) 438.
- [28] J. Wess and B. Zumino, *Supergauge transformations in four dimensions*, Nucl. Phys. **B70** (1974) 139.
- [29] N. Jarosik *et al.*, *Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Sky Maps, Systematic Errors, and Basic Results*, Astrophys. J. Suppl. **192** (2011) 14.
- [30] K. Nakamura and Particle Data Group, *Review of Particle Physics*, Journal of Physics G Nuclear Physics **37**(7) (2010) 075021.

-
- [31] D0 Collaboration, Abazov *et al.*, *Determination of the width of the top quark*, Phys. Rev. Lett. **106** (2011) 022001.
- [32] W. Bernreuther, *Topical Review: Top-quark physics at the LHC*, Journal of Physics G Nuclear Physics **35**(8) (2008) 083001.
- [33] A.D. Martin, W.J. Stirling, R.S. Thorne, and G. Watt, *Parton distributions for the LHC*, Eur. Phys. J. **C63** (2009) 189.
- [34] S. Moch and P. Uwer, *Theoretical status and prospects for top-quark pair production at hadron colliders*, Phys. Rev. D **78** (2008) 034003.
- [35] M. Cacciari *et al.*, *Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation*, Phys. Lett. **B710** (2012) 612.
- [36] B. Jayatilaka (Duke University), *W mass measurement from CDF*, Presented at Moriond Conference (2012) .
- [37] Christopher T. Hill, *Topcolor assisted technicolor*, Phys. Lett. **B345** (1995) 483.
- [38] Robert M. Harris, Christopher T. Hill, and Stephen J. Parke, *Cross-section for topcolor Z-prime(*t*) decaying to *t* anti-*t*: Version 2.6*, hep-ph/9911288, 1999.
- [39] Paul H. Frampton, Jing Shu, and Kai Wang, *Axigluon as Possible Explanation for $p\bar{p}$; $t\bar{t}$ Forward-Backward Asymmetry*, Phys. Lett. **B683** (2010) 294.
- [40] A.Liam Fitzpatrick, Jared Kaplan, Lisa Randall, and Lian-Tao Wang, *Searching for the Kaluza-Klein Graviton in Bulk RS Models*, JHEP **0709** (2007) 013.
- [41] Rikkert Frederix and Fabio Maltoni, *Top pair invariant mass distribution: A Window on new physics*, JHEP **0901** (2009) 047.
- [42] J. H. Kühn and G. Rodrigo, *Charge asymmetry of heavy quarks at hadron colliders*, Phys. Rev. D **59**(5) (1999) 054017.
- [43] CDF Collaboration, T. Aaltonen *et al.*, *Evidence for a mass dependent forward-backward asymmetry in top quark pair production*, Phys. Rev. D **83**(11) (2011) 112003.
- [44] Debajyoti Choudhury, Rohini M. Godbole, Ritesh K. Singh, and Kshitij Wagh, *Top production at the Tevatron/LHC and nonstandard, strongly interacting spin one particles*, Phys. Lett. **B657** (2007) 69.
- [45] S. Westhoff, *Top-Quark Asymmetry – A New Physics Overview*, arXiv:1108.3341, 2011.
- [46] Sunghoon Jung, Hitoshi Murayama, Aaron Pierce, and James D. Wells, *Top quark forward-backward asymmetry from new *t*-channel physics*, Phys. Rev. **D81** (2010) 015004.
- [47] J. A. Aguilar-Saavedra and M. Pérez-Victoria, *Simple models for the top asymmetry: constraints and predictions*, Journal of High Energy Physics **9** (2011) 97.

References

- [48] The ATLAS Collaboration, *The ATLAS experiment at the CERN Large Hadron Collider*, Journal of Instrumentation **3**(08) (2008) S08003.
- [49] <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/PixelPublicResults>, *Public pixel tracker plots for collision data*, 2010.
- [50] <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SCTPublicResults>, *Public sct plots for collision data*, 2010.
- [51] <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TRTPublicResults>, *Public trt plots for collision data*, 2010.
- [52] The ATLAS Collaboration, *Observation of inclusive electrons in the ATLAS experiment at $\sqrt{s} = 7$ TeV.*, ATLAS-CONF-2010-073 (2010) .
- [53] The ATLAS Collaboration, *Muon Performance in Minimum Bias pp Collision Data at $\sqrt{s} = 7$ TeV with ATLAS*, ATLAS-CONF-2010-036 (2010) .
- [54] B. R. Webber, *A QCD model for jet fragmentation including soft gluon interference*, Nuclear Physics B **238**(3) (1984) 492.
- [55] Torbjörn Sjöstrand and Maria van Zijl, *A multiple-interaction model for the event structure in hadron collisions*, Phys. Rev. D **36** (1987) 2019.
- [56] S. Agostinelli *et al.*, *Geant4 – a simulation toolkit*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **506**(3) (2003) 250.
- [57] S. Frixione and B.R. Webber, *Matching NLO QCD computations and parton shower simulations*, JHEP (0206) (2002) .
- [58] G. Marchesini S. Moretti K. Odagiri P. Richardson M.H. Seymour G. Corcella, I.G. Knowles and B.R. Webber, *Herwig 6.5*, JHEP (0101) (2001) .
- [59] Stefano Frixione, Paolo Nason, and Carlo Oleari, *Matching NLO QCD computations with Parton Shower simulations: the POWHEG method*, JHEP **0711** (2007) 070.
- [60] Torbjorn Sjostrand, Stephen Mrenna, and Peter Z. Skands, *PYTHIA 6.4 Physics and Manual*, JHEP **0605** (2006) 026.
- [61] Borut Paul Kersevan and Elzbieta Richter-Was, *The Monte Carlo event generator AcerMC version 1.0 with interfaces to PYTHIA 6.2 and HERWIG 6.3*, Comput. Phys. Commun. **149** (2003) 142.
- [62] The ATLAS Collaboration, *Estimation of the W +jets background for Top Quark Re-Discovery in the Single Lepton+Jets Channel.*, ATL-COM-PHYS-2010-834 (2010) .
- [63] A. Sherstnev and R.S. Thorne, *Parton Distributions for LO Generators*, Eur. Phys. J. **C55** (2008) 553.

-
- [64] ATLAS Collaboration, G. Aad *et al.*, *Electron performance measurements with the ATLAS detector using the 2010 LHC proton-proton collision data*, Eur. Phys. J. **C72** (2012) 1909.
- [65] L. Cerrito *et al.*, *Lepton trigger and identification for the Winter 2011 top quark analyses*, ATL-COM-PHYS-2011-123 .
- [66] The ATLAS Collaboration, *Muon reconstruction efficiency in reprocessed 2010 LHC proton-proton collision data recorded with the ATLAS detector*, ATLAS-CONF-2011-063 (2011) .
- [67] Matteo Cacciari, Gavin P. Salam, and Gregory Soyez, *The anti- k_t jet clustering algorithm*, Journal of High Energy Physics **2008**(04) (2008) 063.
- [68] ATLAS Collaboration, G. Aad *et al.*, *Jet energy measurement with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 7$ TeV*, 1112.6426, 2011.
- [69] A. Doxiadis, *Searching for the top*, PhD thesis – chapter 7 .
- [70] ATLAS Collaboration, Georges Aad *et al.*, *Measurement of the charge asymmetry in top quark pair production in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector*, Eur. Phys. J. **C72** (2012) 2039.
- [71] The ATLAS Collaboration, *Performance of the ATLAS Secondary Vertex b -tagging Algorithm in 7 TeV Collision Data*, ATLAS-CONF-2010-042 (2010) .
- [72] T. Aaltonen *et al.*, *Measurement of the Λ_b^0 Lifetime in $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ Decays in $p\bar{p}$ Collisions at $s=1.96$ TeV*, Physical Review Letters **104**(10) (2010) 102002.
- [73] Atlas Collaboration, Georges Aad *et al.*, *Measurement of the top quark-pair production cross section with ATLAS in pp collisions at $\sqrt{s} = 7$ TeV*, Eur. Phys. J. **C71** (2011) 1577.
- [74] J Erdmann, K Kroeninger, O Nackenhorst, and A Quadt, *Kinematic fitting of $t\bar{t}$ events using a likelihood approach: The KLFitter package*, ATL-COM-PHYS-2009-551 (2009) .
- [75] ATLAS Collaboration, G. Aad *et al.*, *Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics*, 0901.0512, 2009.
- [76] A. Caldwell, D. Kollár, and K. Kröninger, *BAT-The Bayesian analysis toolkit*, Computer Physics Communications **180** (2009) 2197.
- [77] <https://twiki.cern.ch/twiki/bin/view/atlasprotected/klfittertf>.
- [78] CDF Collaboration, T. Aaltonen *et al.*, *Measurement of the $t\bar{t}$ Production Cross Section in 2 fb^{-1} of $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV Using Lepton Plus Jets Events with Soft Muon b -Tagging*, Phys. Rev. **D79** (2009) 052007.

References

- [79] D0 Collaboration, V.M. Abazov *et al.*, *Measurement of the $t\bar{t}$ production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96 = \text{TeV}$ using kinematic characteristics of lepton + jets events*, Phys. Lett. **B626** (2005) 45.
- [80] ATLAS Collaboration, G. Aad, *et al.*, *Measurement of the top quark-pair production cross section with atlas in pp collisions at $\sqrt{s} = 7 \text{ tev.}$* , Eur. Phys. J. C **71**(arXiv:1012.1792) (2010) 1577.
- [81] F. James, *Minuit function minimization and error analysis reference manual*, CERN Program Library entry **D506**.
- [82] The ATLAS Collaboration, *B-tagging for top physics analyses with early ATLAS data at $\sqrt{s} = 7 \text{ TeV.}$* , ATL-COM-PHYS-2010-846 (2010) .
- [83] M. Tsiakiris, *Top quark pair production cross section in proton-proton collisions at $\sqrt{s} = 7 \text{ tev}$* , UvA PhD thesis – chapter 5 .
- [84] The ATLAS Collaboration, *Update on the jet energy scale systematic uncertainty for jets produced in proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$ measured with the ATLAS detector*, ATLAS-CONF-2011-007 (2011) .
- [85] The ATLAS Collaboration, *ATLAS Calorimeter Response to Single Isolated Hadrons and Estimation of the Calorimeter Jet Scale Uncertainty*, ATLAS-CONF-2010-052 (2010) .
- [86] Pavel M. Nadolsky *et al.*, *Implications of CTEQ global analysis for collider observables*, Phys. Rev. D **78**(1) (2008) 013004.
- [87] NNPDF Collaboration, R. D. Ball, *et al.*, *A determination of parton distributions with faithful uncertainty estimation*, Nuclear Physics B **809** (2009) 1.
- [88] The ATLAS collaboration, *Updated Luminosity Determination in pp Collisions at $\sqrt{s}=7 \text{ TeV}$ using the ATLAS Detector*, ATLAS-CONF-2011-011 (2011) .
- [89] G. D’Agostini, *A multidimensional unfolding method based on Bayes’ theorem*, Nuclear Instruments and Methods in Physics Research A **362** (1995) 487.
- [90] T. Adye, *Unfolding algorithms and tests using RooUnfold*, <http://hepunix.rl.ac.uk/~adye/software/unfold/RooUnfold.html>.
- [91] CMS Collaboration, Serguei Chatrchyan *et al.*, *Measurement of the charge asymmetry in top-quark pair production in proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$* , Phys. Lett. **B709** (2012) 28.
- [92] J.A. Aguilar-Saavedra and M. Perez-Victoria, *Simple models for the top asymmetry: Constraints and predictions*, JHEP **1109** (2011) 097.
- [93] J.A. Aguilar-Saavedra and M. Perez-Victoria, *Asymmetries in $t\bar{t}$ production: LHC versus Tevatron*, Phys. Rev. **D84** (2011) 115013.

- [94] D0 Collaboration, T. Aaltonen *et al.*, *Measurement of the forward-backward production asymmetry of t and $\bar{t}$ quarks in $p\bar{p}$ events*, D0 note 6062-CONF (2010) .

References



Summary

In the Large Hadron Collider (LHC) protons collide with a center-of-mass energy of 7 TeV and higher. With the vast amount of proton collisions that are being produced, we are able to study the elementary particles and interactions with a very high precision. In this thesis we explained why top quark physics is relevant and forms a keystone of the research in ATLAS. We presented the measurements on two relevant observables of top quark pairs. In the following, we summarize the motivation for the measurements, the analysis features and the final results.

The top quark and the Standard Model

The current knowledge of elementary particles is described in a theory known as ‘the Standard Model’. The top quark is one of the six quarks in the Standard Model, but it is about 35 times heavier than the next-to-heaviest quark and has a lifetime of only 10^{-25} seconds. This provides a unique role for the top quark in the Standard Model. The consequences of its high mass are for instance that the production of top quarks in collisions is relatively rare, its decay modes include real W bosons, contrary to the other quarks, and its coupling to the Higgs field is strong. But, in addition, top quark production is sensitive to certain so-called ‘new physics’ models—extensions of, or alternatives to the Standard Model which predict new heavy bosons. Some of these bosons are likely to decay into a pair of top quarks and hence enhance the production rate of top quarks.

The first analysis in this thesis is a measurement of the production rate of top-antitop quark pairs, ‘the top quark production cross section’. Secondly, in the following part the difference between the angular direction of the top and antitop quark, ‘the top quark charge asymmetry’, is measured. Both the cross section and the charge asymmetry are observables that can potentially reveal physics beyond the Standard Model.

Producing and detecting top quarks

Protons are collided head-on with a center-of-mass energy of 7 TeV at the LHC. Enough energy is contained in the protons to create top quark pairs and hundreds of thousands of top quarks events are expected to have been produced already in these collisions.

The ATLAS detector ($25\text{ m} \times 44\text{ m}$) aims to identify all remnants of the proton collisions. The detector is manufactured from different types of sensitive material built in concentric layers around the collision point. The subdetectors are foremost dedicated to the tracking of charged particles, energy reconstruction and the reconstruction of muons. A feature of

the top quark is that its decay products can consist of a variety of different particles—electrons, muons, taus, hadronic jets, neutrinos—and therefore all subdetectors of ATLAS are required to measure the properties of the complete set of particles that results from this type of collisions. Neutrinos can only be detected indirectly, and therefore we make use of conservation of energy in the transverse plane to obtain an estimate of the direction and momentum for this particle.

Decay modes and selection

The top quark decays almost exclusively to a W boson and a b -quark; the W boson subsequently decays to a pair of light quarks or into a lepton-neutrino pair. The categorization of top quark pair events is determined by the W boson decays. Our analyses focused on the single-lepton decay channel of top quark pairs, in which one W boson decays leptonically, and the other hadronically. In this channel we only select electron or muon events and ignore decays involving tau leptons. This amounts to about 30% of all top quark pair events.

The analyses make use of two distinct data sets, collected in 2010 and 2011. The criteria to select a pure sample of top quark pairs overlap between these years. Events with an energetic electron or muon, at least four hadronic jets (resulting from two b -quarks and two light quarks) and sufficient missing transverse energy (neutrino) are selected. In addition, we make use of a b -tagging algorithm that is able to distinguish b -quarks from the other quarks with an efficiency of approximately 50%.

Measurement of the cross section

The production cross section of top quark pairs is measured using a data set with an integrated luminosity of 35 pb^{-1} . The analysis is based on discriminating signal and background events in the invariant mass distribution of the top quark. The invariant mass of the top quark is obtained from a minimization procedure that for every event evaluates the most likely association of the measured particles and jets to the lepton and partons in top quark decay. The mass distribution of the top quark shows an excess around 170 GeV in signal events. In background events or signal events where the association failed, the mass distribution looks different.

A template fit is simultaneously applied to the invariant mass distribution in six different subsets of the data. These subsets are distinguished by the amount of jets that originate from either light quarks or b -quarks in the event, assuring different ratios of signal-to-background in each subset. The simultaneous fitting of templates to the data in these subsets results in an estimate of the number of signal events in the overall sample. From the number of signal events, we extracted a top quark production cross section in the electron and muon channel, and in a combination of the channels:

$$\begin{aligned}\sigma_{t\bar{t}}(\text{e+jets}) &= 216 \pm 23 \text{ (stat)} \quad {}^{+27}_{-24} \text{ (syst)} \pm 7 \text{ (lumi)} \text{ pb}, \\ \sigma_{t\bar{t}}(\mu\text{+jets}) &= 161 \pm 19 \text{ (stat)} \quad {}^{+18}_{-15} \text{ (syst)} \pm 5 \text{ (lumi)} \text{ pb}, \\ \sigma_{t\bar{t}}(\text{comb}) &= 183 \pm 14 \text{ (stat)} \quad {}^{+20}_{-18} \text{ (syst)} \pm 6 \text{ (lumi)} \text{ pb}.\end{aligned}$$

The theoretical value at this center-of-mass energy is $158.7^{+12.2}_{-13.5}$ (scale) $^{+4.3}_{-4.4}$ (PDF) pb. The measurement agrees with the Standard Model prediction, within the experimental precision.

Measurement of the charge asymmetry

The top quark charge asymmetry is measured in a data set with an integrated luminosity of 1.04 fb^{-1} . In the selected events, we utilize the reconstructed event topology that was already introduced in the cross section measurement. The asymmetry is parametrized as the difference between the absolute values of the rapidity of the top and antitop quark in the event, $A_{int} = |y_t| - |y_{\bar{t}}|$. The Standard Model expectation for this observable is $A_{int} = 0.001 \pm 0.006$, but certain new physics models predict much larger values.

After subtracting the background estimations from the data sample, we unfolded the event generation and detector response. The unfolded asymmetry for the two channels and the combined measurement are:

$$\begin{aligned}A_{int}(\text{e+jets}) &= 0.074 \pm 0.058 \text{ (stat)} \pm 0.023 \text{ (syst)}, \\ A_{int}(\mu\text{+jets}) &= -0.024 \pm 0.050 \text{ (stat)} \pm 0.026 \text{ (syst)}, \\ A_{int}(\text{comb}) &= 0.014 \pm 0.038 \text{ (stat)} \pm 0.024 \text{ (syst)}.\end{aligned}$$

The measurement is therefore in agreement with the Standard Model prediction. Although extreme values of the asymmetry are excluded by this result, we showed that in a similar measurement with a ten times larger dataset definitive constraints on most scenarios can be expected.

Conclusion

We conclude that both measurements agree with the predictions of the Standard Model, within the obtained experimental precision. This result is a strong confirmation of our present theoretical predictions on top quark production. With the increasing amount of data that currently becomes available, the precision of the top quark charge asymmetry can be improved significantly in order to reveal or reject new physics scenarios in the very near future.

Samenvatting

In de ‘Large Hadron Collider’ (LHC) worden protonen met een hoge energie op elkaar gebotst. Met de enorme aantallen protonbotsingen die daar gemaakt worden kunnen we elementaire deeltjes, de kleinste vorm van materie die we kennen, heel precies bestuderen.

Dit proefschrift beschrijft waarom onderzoek naar topquarks belangrijk is en waarom het een voornaam onderdeel vormt van het onderzoeksprogramma van het ATLAS-experiment. Daarna volgt een beschrijving van de ATLAS-detector en de methodes om allerlei deeltjes precies te kunnen terugvinden. Vervolgens hebben we twee metingen van relevante observabelen van topquarkparen gepresenteerd. Hieronder vatten we de motivatie voor de twee metingen, de belangrijke onderdelen van de analyse en de uiteindelijke resultaten samen.

Topquarks

De huidige kennis van elementaire deeltjes en krachten wordt beschreven in wat we het ‘Standaard Model’ noemen. Deze theorie werkt erg goed, maar heeft toch een aantal tekortkomingen en daarom worden alle voorspellingen van dit model precies onderzocht en nagemeten. De topquark is één van de zes quarks in het Standaard Model, het is ongeveer 35 keer zo zwaar als het op-één-na-zwaarste quark en heeft een extreem korte levensduur van 10^{-25} seconden, voordat het vervalst. Dit maakt de topquark bijzonder.

Eén van de consequenties van de grote massa van topquarks is dat er veel energie nodig is om ze te kunnen maken, en om die reden zijn ze relatief zeldzaam. De topquark vervalst bovendien zo snel, dat we alleen indirecte metingen kunnen doen. Maar dankzij die massa is topquarkproductie ook gevoelig voor nieuwe fysicamodellen; uitbreidingen van, of alternatieven voor, het Standaard Model. In sommige van deze modellen worden zware nieuwe deeltjes (bosonen) voorspeld, die zelf weer vervallen naar een topquarkpaar: een topquark en zijn antideeltje. Dat effect zou dan weer zichtbaar zijn als bijvoorbeeld een overschot van het aantal topquarks in de detector.

De eerste meting in dit proefschrift is van de mate waarin topquarkparen worden geproduceerd, de zogenaamde ‘top quark production cross section’, ook wel de ‘topquark-doorsnede’. De tweede analyse meet het verschil in hoekverdeling tussen de topquark en de antitopquark, de ‘top quark charge asymmetry’, ofwel de ladingsasymmetrie. Beide metingen hebben het potentieel om nieuwe fundamentele mechanismes buiten het Standaard Model bloot te leggen.

Botsingen en detectie van topquarks

In de LHC worden protons versneld en vervolgens op elkaar gebotst met een botsingsenergie van 7 TeV, ruim genoeg om de zware topquarkparen te kunnen maken. Doordat er al miljoenen protonbotsingen zijn gemaakt, zijn er, ondanks de geringe kans op het ontstaan van topquarks, naar verwachting al honderdduizenden topquarkparen gemaakt.

De ATLAS-detector (25×44 meter groot) is ontworpen om alle deeltjes in de eindtoestand van de protonbotsingen te meten. De detector bestaat uit verschillende types detectiemateriaal die in cilindervormige lagen om het botsingspunt zijn gebouwd. De verschillende subdetectoren zijn bedoeld om de richting en impuls van alle ontstane deeltjes te kunnen meten. Een eigenschap van de topquark is dat de vervalproducten bestaan uit veel types deeltjes: elektronen, muonen, hadronen en neutrino's. Gezien deze zich op verschillende manieren gedragen, hebben we voor onze metingen alle subdetectoren van ATLAS nodig om een compleet beeld van topquarks te krijgen. Neutrino's kunnen slechts indirect worden gedetecteerd, hiervoor maken we gebruik van de wet voor behoud van energie. Uit de balans van de energie in transversale richting kunnen we het afgelegde pad en de impuls van het neutrino achterhalen.

Vervalskanalen en selectie

De topquark vervalt nagenoeg altijd in een W -boson en een bottomquark, een W -boson vervalt op zijn beurt weer in een lichter quarkpaar (hadronisch verval) of een lepton-neutrinopaar (leptonisch verval). Wij hebben gekeken naar topquarkparen waarvan één van de W -bosonen leptonisch vervalt en de andere hadronisch. Hier verwachten we dus vier quarks, één lepton, en één neutrino in de eindtoestand. Binnen deze groep hebben we botsingen (events) geselecteerd waarin elektronen of muonen voorkomen, dit zijn relatief makkelijk te identificeren deeltjes. Onze selectiedoelgroep vormt dus een fractie van 30% van het totale aantal topquarkpaar-events.

De analyses maken gebruik van twee onafhankelijke datasets uit 2010 en 2011. De selectievoorwaarden zijn grotendeels gelijk gebleven: we hebben events geselecteerd waarin precies één muon of elektron, minstens vier hadronische jets en een onbalans in de totale energie (neutrino) voorkomen. Daarnaast gebruiken we in sommige gevallen een techniek om bottomquarks van de andere quarks te onderscheiden.

Meting van de topquarkdoorsnede

De topquarkdoorsnede wordt gemeten met een dataset uit 2010. De analyse is gebaseerd op het onderscheiden van signaalevents (topquarks) en achtergrondruis in de invariante massaverdeling van de topquark. Deze massa kunnen we voor elk event uitrekenen als we de gemeten deeltjes associëren met de verwachte topquarktopologie. In de massaverdeling ontstaat een piek op de plek van de topquarkmassa, rond de 170 GeV. De events waar geen topquarks bij betrokken waren, of waar de associatie mislukt is laten een ander soort verdeling zien.

Van dit verschil maken we gebruik door sjablonen van signaal en achtergrond te fitten aan datasets. Dit doen we in zes subgroepen van de data, waarin steeds is geprobeerd verschillende signaal- en achtergrondverhoudingen te creëren door slimme selectie. De sjablonen worden in de zes subgroepen tegelijk gefit, zodat de onderlinge verhoudingen helpen om een schatting te maken van het totaal aantal signaalevents.

Het resulterende aantal kan worden vertaald in een meting van de doorsnede in de twee vervalskanalen en in een combinatie van deze twee:

$$\begin{aligned}\sigma_{t\bar{t}}(e+jets) &= 216 \pm 23 \text{ (stat)} \quad {}^{+27}_{-24} \text{ (syst)} \pm 7 \text{ (lumi)} \text{ pb}, \\ \sigma_{t\bar{t}}(\mu+jets) &= 161 \pm 19 \text{ (stat)} \quad {}^{+18}_{-15} \text{ (syst)} \pm 5 \text{ (lumi)} \text{ pb}, \\ \sigma_{t\bar{t}}(\text{comb}) &= 183 \pm 14 \text{ (stat)} \quad {}^{+20}_{-18} \text{ (syst)} \pm 6 \text{ (lumi)} \text{ pb}.\end{aligned}$$

De theoretische waarde van de doorsnede, bij deze energie, is $158.7^{+12.2}_{-13.5}$ (scale) $^{+4.3}_{-4.4}$ (PDF) pb. Onze meting komt binnen de meetonzekerheid overeen met deze waarde.

Meting van de ladingsasymmetrie

De topquark-ladingsasymmetrie is gemeten in de dataset in 2011, met ongeveer 30 keer zoveel events als de data gebruikt voor de doorsnedemeting. In de geselecteerde events maken we gebruik van dezelfde reconstructiemethode om de gemeten objecten te associëren met de vervalsproducten van topquarks. Hieruit volgt ook de rapiditeit van de topquarks, de hoek die de topquark en de antitopquark maken met de protonenbundel. We definiëren de ladingsasymmetrie als $A_{int} = |y_t| - |y_{\bar{t}}|$, het verschil tussen de absolute waarde van de rapiditeit van de top- en antitopquarks. Het Standaard Model voorspelt een waarde van $A_{int} = 0.001 \pm 0.006$, maar in nieuwe-fysicamodellen kan deze asymmetrie veel groter zijn.

Nadat we de verwachte achtergrondruis van de geselecteerde data hebben afgetrokken, en voor eventuele onverwachte detectoreffecten, hebben gecorrigeerd meten we de asymmetrie weer in de twee kanalen, en in de gecombineerde mode.

$$\begin{aligned}A_{int}(e+jets) &= 0.074 \pm 0.058(\text{stat}) \pm 0.023(\text{syst}), \\ A_{int}(\mu+jets) &= -0.024 \pm 0.050(\text{stat}) \pm 0.026(\text{syst}), \\ A_{int}(\text{comb}) &= 0.014 \pm 0.038(\text{stat}) \pm 0.024(\text{syst}).\end{aligned}$$

De gemeten waardes vallen samen met de theoretische voorspelling en hiermee kunnen extreme waardes van de asymmetrie kunnen worden uitgesloten. De onzekerheden in de meting zijn nog relatief groot. We hebben laten zien dat met de data die momenteel

Samenvatting

beschikbaar komt er eventueel al gedeeltes van nieuwe fysicamodellen kunnen worden uitgesloten met eenzelfde soort meting, of anders aanwijzingen voor de correctheid van deze modellen kunnen worden gevonden.

Conclusie

De conclusie van deze twee metingen is dat binnen de precisie die we hebben kunnen bereiken de voorspellingen van het Standaard Model worden bevestigd. Dat betekent dus dat deze theorie stand houdt, ook bij deze niet eerder onderzochte botsingen met de hoge energie van 7 TeV. Met de hoeveelheden data die op moment van schrijven worden verzameld, komt een ontdekking of uitsluiting van een groot gedeelte van alternatieve modellen heel dichtbij.