Measurement of the top-antitop production cross-section with the ATLAS experiment at the LHC

Settore scientifico-disciplinare FIS/04

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Abstract

The top quark, discovered at the Tevatron $p\bar{p}$ collider in 1995, has been observed in $pp$ collisions at the LHC by both the ATLAS and CMS experiments in 2010. The analysis developed by the candidate and presented in this thesis has been subject of the first publication of the ATLAS experiment on top quark physics: the measurement of the top-antitop ($t\bar{t}$) total production cross-section.

The analysis is here updated with the full 7 TeV $pp$ collision data collected between August 2010 and August 2011. Final states containing one electron or muon, jets and missing energy are selected, requiring at least one of the jets to be tagged as coming from the hadronization of a $b$-quark. The cross-section is extracted using a counting method, for which an accurate background estimation is crucial. For this reason, the data-driven methods used to extract the main QCD and $W$+jets backgrounds are described and discussed. The results of the cross-section measurement using 2011 data are also used to derive an indirect measurement of the top quark mass.

Analysing the data collected in 2010, corresponding to an integrated luminosity of $35 \text{ pb}^{-1}$, a cross-section of:

$$\sigma_{t\bar{t}} = 156^{+36}_{-30} \text{ pb}$$

is extracted, while with the $2.05 \text{ fb}^{-1}$ of data analysed in 2011 a cross-section of:

$$\sigma_{t\bar{t}} = 164^{+20}_{-17} \text{ pb}$$

is obtained. The latter result is used to extract the following top mass value:

$$m_{\text{pole}}^{\text{top}} = 173.3^{+6.3}_{-6.0} \text{ GeV}/c^2.$$  

The cross-section results are in good agreement with the theoretical predictions and with the other measurements done in ATLAS and CMS. The top mass obtained from this cross-section measurement agrees with the world average value.
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Introduction

The top quark is the heaviest known fundamental particle in nature, as well as the most recently discovered quark.

Its existence was suggested already in 1977 when its weak isospin partner, the $b$-quark, was discovered, and its mass was constrained from electroweak precision data in the following years. It was finally discovered, exactly in the mass range predicted by electroweak fits, in 1995 by the CDF and DØ experiments at the Fermilab Tevatron, a $p\bar{p}$ collider at a centre-of-mass energy of $\sqrt{s} = 1.8$ TeV \cite{1}. For 15 years the Tevatron has been the only place where top quarks were produced and studied directly \cite{2} \cite{3} \cite{4} \cite{5}. In 2010 the top quark was observed by both the ATLAS and CMS experiments at the Cern Large Hadron Collider (LHC), the world largest particle accelerator, colliding protons at a centre-of-mass energy of $\sqrt{s} = 7$ TeV.

At hadron colliders the top quark can be produced in pairs ($t\bar{t}$), via strong interaction, or singly, via electroweak processes, with the $t\bar{t}$ production being dominant. The $t\bar{t}$ production cross-section measurement at the LHC has been of central importance in the physics programme of the two experiments during the past two years, for several reasons.

In the Standard Model (SM) theoretical frame, top quarks are predicted to decay to a $W$-boson and a $b$-quark nearly 100% of the times. Events with a $t\bar{t}$ pair can then be classified as “single-lepton”, “dilepton”, or “all hadronic”, according to the decay of the two $W$-bosons: a pair of quarks or a lepton-neutrino pair. The most precise $t\bar{t}$ production cross-section measurements both at the Tevatron and at the LHC colliders are performed selecting events in the single-lepton channel, combining a high branching ratio ($\sim 30\%$ excluding the events with a $\tau$ lepton) with the presence of a high $p_T$ electron or muon allowing to trigger the events and to reduce the QCD multi-jet background.

Given these final states involving high energy jets, electrons, muons and missing transverse energy, measuring the $t\bar{t}$ production cross-section is important to test the capability of the detector in reconstructing such complex signatures, which are also typical of many new physics processes. For the same reason $t\bar{t}$ is an important background in many searches for new physics.

The uncertainties on the theoretical predictions on this measurement are now less than 10%. Comparing experimental measurements performed in different channels, allows a precision test of the predictions of perturbative QCD. New physics may also give rise to additional $t\bar{t}$ production mechanisms or modifications of the top quark decay channels. With the rapidly increasing integrated luminosity, the experimental measurement uncertainty is now becoming smaller than the theoretical one. Such a precise measurement can
also be used to extract an indirect measurement of the top-quark mass.

The candidate has been working on the measurement of the $t\bar{t}$ production cross-section in the single-lepton channel (i.e. with a single electron or muon in the final state). The analysis, together with an analogous measurement requiring two leptons in the final state, was published as the first $t\bar{t}$ cross-section measurement in ATLAS [29]. The analysis developed by the candidate is based on counting the number of events in data which survive a selection studied to isolate $t\bar{t}$ events in the single-lepton final states, subtracting the expected number of background events, and comparing with the predicted number of signal events.

Chapter 1 of this thesis gives an introduction to the Standard Model, underlying the importance of the top quark physics in this framework. In Chapter 2 the LHC collider and the ATLAS detector are described, and some details on the reconstruction of physics objects used to identify $t\bar{t}$ final states are given in Chapter 3. The selection applied to data and simulation events in order to isolate a $t\bar{t}$ signal in the single-lepton channel and to compare the observation with the prediction is described in Chapter 4. The details of the $t\bar{t}$ cross-section measurement, performed with data collected during 2010 and 2011, are reported in Chapter 5 including an indirect top mass determination based on the cross-section measured with 2011 data. Chapter 6 describes in detail the data-driven background determination used for the cross-section analysis.
Chapter 1

The Quark Top

1.1 The Standard Model of particle physics

The interactions of the known fundamental spin-1/2 fermion constituents of matter, through the exchange of spin-1 gauge bosons, is successfully described by the Standard Model of elementary particle physics (SM). The fermions and gauge bosons included in the framework of the SM are listed in Figure 1.1.

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
<th>Gauge Bosons</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>charge</td>
<td>spin</td>
</tr>
<tr>
<td>2.4 MeV</td>
<td>1/6</td>
<td>1/2</td>
</tr>
<tr>
<td>4.8 MeV</td>
<td>-1/6</td>
<td>1/2</td>
</tr>
<tr>
<td>4.2 GeV</td>
<td>-1/6</td>
<td>1/2</td>
</tr>
<tr>
<td>171.2 GeV</td>
<td>2/3</td>
<td>1/2</td>
</tr>
<tr>
<td>91.2 GeV</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 1.1. The known fundamental fermions and gauge bosons and their properties: mass, charge and spin.

Both quarks and leptons occur in pairs, differing by one unit of electric charge $e$, and are replicated in three generations with a strong hierarchy in mass. The top quark mass
is measured to be five orders of magnitude larger than the mass of the electron, and at least 11 orders of magnitude larger than the smallest measured neutrino mass (assumed to be massless in the formulation of the SM reported here). The origin of this flavour symmetry breaking and the consequent mass hierarchy are still not understood but can be accommodated in the SM as shown below.

The forces among the fundamental fermions are mediated by the exchange of the gauge bosons of the corresponding quantized gauge fields. The gravitational force cannot be included in the framework of the SM. Its strength in any case is small, compared to that of the other interactions at the typical energy scales of particle physics.

The SM is a particular quantum field theory, based on a set of fields corresponding to the known fermions and on the gauge symmetries $SU(3)_C \times SU(2)_L \times U(1)_Y$. It includes the strong interaction and the electroweak interaction theories.

The strong interaction theory, coupling three different colour charges (“red”, “green” and “blue”) carried by the quarks and the eight massless gauge bosons (gluons), is called Quantum Chromodynamics (QCD), and is based on the gauge group $SU(3)_C$. This is an exact symmetry, and the gluons carry both a colour and an anticolour charge. At increasingly short distances (or large relative momenta), the interaction becomes arbitrarily weak (asymptotic freedom), making possible a perturbative treatment. Via the strong interaction, quarks can form bound colour-singlet states called hadrons, consisting of either a quark and an antiquark (mesons) or three quarks (baryons). The fact that only colour-neutral states and no free quarks are observed in nature is referred to as the “confinement” of quarks in hadrons. This fact has the important experimental consequence that quarks produced in high energy particle interactions manifest themselves as collimated streams of hadrons called “jets”. The energy and direction of a jet are correlated to the energy and direction of its parent quark. The process by which the quark evolves into a jet is called “hadronization”, and consists of a parton shower, which can be perturbatively calculated, and a fragmentation process, which is a non-perturbative process modelled using Monte Carlo (MC) techniques. Due to its large mass, the top quark decays faster than the typical hadronization time of QCD ($\Gamma_{\text{top}} \gg \Lambda_{\text{QCD}}$), being the only quark that does not form bound states. Its decay offers the unique possibility to study the properties of an essentially bare quark.

The theory of electroweak interactions developed by Glashow, Salam and Weinberg is based on the $SU(2)_L \times U(1)_Y$ gauge group of the weak left handed isospin $T$ and hypercharge $Y$. Since the weak ($V - A$) interaction only couples to left-handed particles, the fermion fields $\Psi$ are split up into left-handed and right-handed fields $\Psi_{L,R} = \frac{1}{2}(1 + \gamma_5)\Psi$, arranged in weak isospin $T = 1/2$ doublets and $T = 0$ singlets:

$$
\begin{pmatrix}
    u \\
    d \\
\end{pmatrix}_L,
\begin{pmatrix}
    c \\
    s \\
\end{pmatrix}_L,
\begin{pmatrix}
    t \\
    b \\
\end{pmatrix}_L,
\begin{pmatrix}
    u_R \\
    d_R \\
\end{pmatrix},
\begin{pmatrix}
    c_R \\
    s_R \\
\end{pmatrix},
\begin{pmatrix}
    t_R \\
\end{pmatrix},
\begin{pmatrix}
    \nu_e \\
    \nu_\mu \\
    \nu_\tau \\
\end{pmatrix}_L,
\begin{pmatrix}
    e_R \\
    \mu_R \\
    \tau_R \\
\end{pmatrix}
$$

In the doublets, neutrinos and up-type quarks ($u, c, t$) have the weak isospin $T_3 = +1/2$, while the charged leptons and down-type quarks ($d, s, b$) carry the weak isospin...
$T_3 = -1/2$. The weak hypercharge $Y$ is then defined via the electric charge and the weak isospin to be $Y = 2Q - 2T_3$. Consequently, members within a doublet carry the same hypercharge: $Y = -1$ for leptons and $Y = 1/3$ for quarks, as implied by the product of the two symmetry groups.

The $SU(2)_L \times U(1)_Y$ gauge group does not accommodate mass terms for the gauge bosons or fermions without violating the gauge invariance. A minimal way to incorporate these observed masses is to implement spontaneous electroweak symmetry breaking (EWSB) at energies around the mass scale of the $W$ and $Z$-bosons, often referred to as the “Higgs mechanism” [11], by introducing an $SU(2)$ doublet of complex scalar fields $\phi = (\phi^+, \phi^0)^T$.

As shown below, when the neutral component obtains a non-zero vacuum expectation value, the $SU(2)_L \times U(1)_Y$ symmetry is broken to $U(1)_{QED}$, giving mass to the three electroweak gauge bosons $W^\pm$ and $Z^0$ while keeping the photon massless, and leaving the electromagnetic symmetry $U(1)_{QED}$ unbroken. From the remaining degree of freedom of the scalar doublet, an additional scalar particle, the Higgs boson, is obtained.

### 1.1.1 The Lagrangian of the Standard Model and the Higgs mechanism

Once the gauge symmetries and the fields with their quantum numbers are specified, the Lagrangian of the SM is fixed by requiring it to be gauge-invariant, local, and renormalizable. The SM Lagrangian can be divided into several pieces:

$$L_{\text{SM}} = L_{\text{Gauge}} + L_{\text{Matter}} + L_{\text{Yukawa}} + L_{\text{Higgs}}. \quad (1.1)$$

The first piece is the pure gauge Lagrangian, given by:

$$L_{\text{Gauge}} = -\frac{1}{4} \text{Tr} \ G^{\mu \nu} G_{\mu \nu} - \frac{1}{8} \text{Tr} \ W^{\mu \nu} W_{\mu \nu} - \frac{1}{4} B^{\mu \nu} B_{\mu \nu}, \quad (1.2)$$

where $G^{\mu \nu}$, $W^{\mu \nu}$, and $B^{\mu \nu}$ are the gluon, weak, and hypercharge field-strength tensors. These terms contain the kinetic energy of the gauge fields and their self interactions.

The next piece is the matter Lagrangian, given by:

$$L_{\text{Matter}} = \bar{Q}^i_L i \gamma^\mu D^\mu Q^i_L + \bar{u}^i_R i \gamma^\mu D^\mu u^i_R + \bar{d}^i_R i \gamma^\mu D^\mu d^i_R + \bar{L}^i_L i \gamma^\mu D^\mu L^i_L + \bar{e}^i_R i \gamma^\mu D^\mu e^i_R + \text{h.c.}, \quad (1.3)$$

where $Q^i_L$ and $L^i_L$ are the quark and lepton doublets, and a sum on the index $i$, which represents the generations, is implied. This piece contains the kinetic energy of the fermions and their interactions with the gauge fields, which are contained in the covariant derivatives $D^\mu$. For example:

$$D^\mu Q^i_L = \left( \partial^\mu + i g S^G_{\mu} + \frac{i g}{2} W^\mu + \frac{i g'}{6} B^\mu \right) Q^i_L, \quad (1.4)$$

since the field $Q^i_L$ participates in all three gauge interactions.

The next piece of the Lagrangian is the Yukawa interaction of the Higgs field with the fermions, given by

$$L_{\text{Yukawa}} = -\Gamma_{d}^{ij} Q^i_L \epsilon^i \phi_j u^j_R - \Gamma_{d}^{ij} Q^i_L \phi_j d^j_R - \Gamma_{e}^{ij} \bar{L}^i_L \phi_j e^j_R + \text{h.c.}, \quad (1.5)$$

$^1\epsilon = i \sigma_2$ is the total antisymmetric tensor in two dimensions, related to the second Pauli matrix $\sigma_2$, required to ensure each term separately to be electrically neutral.
where the coefficients $\Gamma_u, \Gamma_d, \Gamma_e$ are $3 \times 3$ complex matrices. They do not need to be diagonal, so that in general a mixing between different fermion generations is allowed (see Section 1.1.2).

Finally, the last term is the Higgs Lagrangian, given by:

$$L_{\text{Higgs}} = (D^\mu \phi)^\dagger D_\mu \phi + \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2. \quad (1.6)$$

This piece contains the kinetic energy of the Higgs field, its gauge interactions, and the Higgs potential. The sign of the quadratic term is chosen such that the Higgs field has a non-zero vacuum-expectation value on the circle of minima in the Higgs-field space given by $\langle \phi^0 \rangle = \mu/\sqrt{2} \equiv v/\sqrt{2}$, with $v \approx 246$ GeV.

Using gauge symmetries, it is always possible to rotate $\phi$ so that $\phi^+ = 0$ and $\phi^0$ is real, and the Higgs doublet can be written as:

$$\phi = \begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix}, \quad (1.7)$$

where $H$ is a scalar field with zero vacuum-expectation value, corresponding to the physical Higgs boson. Writing $\phi$ in this way, the $(D^\mu \phi)^\dagger D_\mu \phi$ term in Equation 1.6 introduces mass terms for the gauge bosons. In particular the masses of the physical $W$ and $Z$-bosons can be written as:

$$M_W = g \frac{v}{2}, \quad M_Z = \sqrt{g^2 + g'^2} \frac{v}{2}. \quad (1.8)$$

Moreover, by using the expression in Equation 1.7 in the Yukawa Lagrangian term (Equation 1.5), mass terms for fermions are introduced. Quark and lepton masses can be written as:

$$m_f = y_f \frac{v}{\sqrt{2}}, \quad (1.9)$$

where $y_f$ is the Yukawa coupling term for the fermion mass eigenstate $f$, setting at the same time the mass of the fermion and its coupling with the Higgs boson. The top quark, being the heaviest among the fermions, is therefore also characterized by the largest Yukawa coupling $y_t \approx 1$. Given its strong coupling with the Higgs boson, it could be a key to access information on new physics.

### 1.1.2 Fermion generations and mixing

As already discussed when introducing the Yukawa coupling matrices, fermion families can mix. In the quark sector, the mixing between the weak eigenstates of the down-type quarks $d', s'$ and $b'$, and the corresponding mass eigenstates $d$, $s$ and $b$, is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix [12] [13]:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (1.10)$$

$^2$The Yukawa coupling terms are obtained by diagonalizing the matrices $\Gamma_{u,d,e}$. 
Since the CKM matrix is not diagonal, charged current weak interactions can cause transitions between quark generations with coupling strengths of the $W^\pm$ boson to the physical up- and down-type quarks given by the above matrix elements. By convention, the mixing takes place between down-type quarks only, while the up-type mass matrix is diagonal.

The CKM matrix contains all the SM flavour-changing and CP-violating couplings. This unitary matrix has diagonal entries close to unity and off-diagonal entries that are around 0.2 between the first and second generation, around 0.04 between the second and third generation and even smaller for the transition of the first to the third generation [14]. In particular, the matrix element $V_{tb}$ is constrained indirectly making use of the unitarity of the CKM matrix and assuming three quark generations (and recently by direct measurement of the single top production cross-section as well, see Section 1.2.2) to be very close to 1: $|V_{tb}| > 0.999$ at 90% confidence level (C.L.). Hence the top quark in the SM is forced to couple almost exclusively to bottom quarks. This affects both the top quark production, suppressing the electroweak single top production mechanisms with respect to the pair production one (see Section 1.2), and its decay, allowing to rely on the presence of $b$-quark jets in the final state to isolate and reconstruct top events (see Section 1.3).

In the lepton sector, if the neutrinos are assumed to be massless, such a mixing does not take place. However, from experimental evidence [15], neutrinos also have mass, which has led, among other things, to the introduction of an analogue leptonic mixing matrix, the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [16]. For the purpose of this thesis, a mixing in the lepton sector would have no effect, and therefore a massless neutrino SM formulation is taken.

In summary, the SM is a unitary, renormalizable theory, that can be used to perturbatively calculate processes at high energies. It incorporates 18 parameters that have to be provided through measurements:

- 9 Yukawa couplings for the fermion masses,
- 4 parameters for the CKM mixing matrix,
- 3 coupling constants $g_S$, $g$, $g'$ for $SU(3)_C$, $SU(2)_L$ and $U(1)_Y$, respectively,
- 2 parameters from EWSB: $v$ and $m_H$.

At the currently accessible energy scales, the SM describes successfully the interactions of fundamental fermions and gauge bosons. Its predictions have been verified at recent colliders (SPS, LEP, Tevatron and LHC), with very high precision. Only the Higgs boson remains to be observed.

1.2 Top quark production

The energies needed to produce top quarks are currently only accessible at hadron colliders. The Tevatron proton-antiproton ($p\bar{p}$) collider started operation at $\sqrt{s} = 1.8$ TeV in 1987.
and ended in September 2011, after having reached $\sqrt{s} = 1.96$ TeV. From 2010, with the turn-on of the Large Hadron Collider (LHC, see Section 2.1), Tevatron lost its monopoly of top quark production.

In the SM framework, top quarks can be produced in pairs ($t\bar{t}$) predominantly via the strong interaction or singly via the electroweak interaction. The dominant process at both Tevatron and LHC is $t\bar{t}$ production.

The proton can be considered to accommodate three “valence” quarks ($uud$) which dictate its quantum numbers. These valence quarks typically carry much of the momentum of the proton. There are also virtual or “sea” quarks and gluons in the proton which carry less momentum individually. When two protons (or a proton and an antiproton) collide, a hard interaction occurs between one of the constituents (“partons”) of the first proton and one of the partons of the second proton. Soft interactions involving the remainder of the hadron constituents produce many low energy particles which are largely uncorrelated with the hard collision.

In the centre-of-mass frame, in which the protons (or the proton and the antiproton) are rapidly moving, the hard interactions between partons are fast relative to the time for them to interact. As a result, the hadronic collision can be factorized \cite{17} into a parton collision weighted by “parton distribution functions” (PDFs), $F_i(x_i)$, which express the probability for the parton $i$ to carry the momentum fraction, $x_i$, of its parent hadron. These PDFs are properties of specific hadrons and are independent from the specific hard scatter interaction at parton level. They encompass non-perturbative soft processes. As a result, they are extracted from the study of inelastic interactions involving hadrons.

A specific process production cross-section, like the top pair production, is then calculated as:

$$\sigma(pp \rightarrow t\bar{t} + X) = \sum_{i,j} \int dx_i dx_j \times F_i(x_i, \mu) F_j(x_j, \mu) \hat{\sigma}_{ij}(x_i, x_j, m_{top}^2, \mu^2),$$

(1.11)

where the sum runs over gluons and light quarks in the colliding protons, and $\hat{\sigma}_{ij}$ is the perturbative cross-section for collisions of partons $i$ and $j$. The factorization scale, defines the splitting of perturbative and non-perturbative elements. Usually, this scale is treated in common with the appropriate scale for the renormalization of the perturbative cross-section, since both parameters are arbitrary. This common scale, $\mu$, is usually taken to be equal to the top quark mass ($m_{top}$). An exact calculation would not depend on these scales. Finite order calculations are instead sensitive to them, at a level which has to be assessed as an uncertainty in the theoretical calculation, usually by bounding the predictions with $\mu = m_{top}/2$ and $\mu = 2m_{top}$ calculations.

1.2.1 Top pair production

Initial leading order (LO) cross-section calculations for $t\bar{t}$ production ($\sigma_{t\bar{t}}$) at hadron colliders were performed in \cite{18}. At LO two production sub-processes can be distinguished: $q\bar{q}$ annihilation and $gg$ fusion. The corresponding relevant Feynmann diagrams are shown in Figure 1.2. At energies close to the kinematic threshold, $q\bar{q}$ annihilation is the dominant process if the incoming quarks are valence quarks, as is the case of $pp\bar{p}$ collisions. At
Tevatron, about 85% of $\sigma(t\bar{t})$ is due to $q\bar{q}$ annihilation \[19\]. At higher energies, the $gg$ fusion process dominates for both $p\bar{p}$ and $pp$ collisions. This is the case at LHC, where, at the current centre-of-mass energy of 7 TeV, about 80% of $\sigma(t\bar{t})$ is due to $gg$ fusion.

Figure 1.2. Feynman diagrams of the LO processes for $t\bar{t}$ production: (a) quark-antiquark annihilation ($q\bar{q} \rightarrow t\bar{t}$) and (b) gluon-gluon fusion ($gg \rightarrow t\bar{t}$).

Next-to-leading order (NLO) calculations \[20\] accounted for associated quark production and gluon bremsstrahlung, and virtual contributions to the LO processes \[3\]. Corrections at NLO including full spin information are nowadays also available \[21\]. Analytic expressions for the NLO QCD corrections to inclusive $t\bar{t}$ production were derived too \[22\].

The calculation at fixed NLO accuracy has been refined to systematically incorporate higher order corrections due to soft gluon radiation \[19\] \[23\] \[24\]. These resummations of the soft gluon logarithms, called “approximated next-to-next-to-leading order” (Approx. NNLO) or “next-to-leading logarithm” (NLL) in the following, yield an increase of $\sigma(t\bar{t})$ with respect to the NLO value. Calculations by different groups implementing the resummation approach are in good agreement. Recently, these procedures have been automatized with the HATHOR code \[25\], allowing for studies of the theoretical uncertainty by separate variations of the factorization and renormalization scales and offering the possibility to obtain the cross-section as a function of the running top quark mass. In the following, the theoretical predictions for the $t\bar{t}$ total production cross-section are obtained using the HATHOR code, using the CTEQ66 \[26\] PDFs.

The $\sigma_{t\bar{t}}$ has been measured by the Tevatron experiments CDF \[27\] and DØ \[28\] and by the LHC experiments ATLAS \[29\] \[30\] and CMS \[31\] \[32\]. The agreement between the predicted and measured values at different centre-of-mass energies for $p\bar{p}$ and $pp$ collisions is shown is Figure 1.3.

1.2.2 Single top production

Top quarks can be produced singly via electroweak interactions involving the $Wtb$ vertex. There are three production modes which are distinguished by the virtuality $Q^2$ of the $W$-boson ($Q^2 = -q^2$, where $q$ is the four-momentum of the $W$):

- $t$-channel
  A virtual $W$-boson strikes a $b$-quark (a sea quark) inside the proton. The $W$-boson is space-like ($q^2 < 0$). Feynman diagrams representing this process are shown in

\[3\] At the centre-of-mass energy of the LHC (7 TeV), the NLO corrections to the LO $t\bar{t}$ production cross section are of the order of 50%.

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Figure 1.3. \( t\bar{t} \) production cross-section at hadron colliders as measured by the CDF and DØ experiments at the Tevatron and by CMS and ATLAS at the LHC, updated with published results by the end of March 2011. The theoretical predictions for \( pp \) and \( p\bar{p} \) collisions include the scale and PDF uncertainties, obtained using the HATHOR tool with the CTEQ6.6 PDFs and assume a top-quark mass of 172.5 GeV.

Figure 1.4. Representative Feynman diagrams for the three single top quark production modes: (a) \( t \)-channel, (c) \( s \)-channel, and (d) \( W \)-associated production process.

Figure 1.4 (a). Production in the \( t \)-channel is the dominant source of single top quarks at the Tevatron and at the LHC.

- **\( s \)-channel**
  This production mode is of Drell-Yan type and is also called \( t\bar{b} \) production. A time-like \( W \)-boson with \( q^2 \geq (m_{\text{top}} + m_b)^2 \) is produced by the fusion of two quarks belonging to an \( SU(2) \)-isospin doublet. See Figure 1.4 (b) for the Feynman diagram.

- **\( W \)-associated production**
  The top quark is produced in association with a real (or close to real) \( W \)-boson \((q^2 = M_W^2)\). The initial \( b \)-quark is a sea-quark inside the proton. Figure 1.4 (c) shows the Feynman diagram. The cross-section is negligible at the Tevatron, but of
considerable size at LHC energies where associated $Wt$ production even exceeds the $s$-channel.

At LO, the cross-section for each of the production modes is proportional to the square of the CMK matrix element $V_{tb}$. The measurement of these production cross-section is the only direct way to measure $V_{tb}$ without assuming the unitarity of the CKM matrix. Recently, CDF [33] and DØ [34] first and then ATLAS [35] and CMS [36], observed the single top production, allowing a direct measurement of $V_{tb}$ which is in good agreement with the indirect determination, suffering however from larger uncertainty.

As for $t\bar{t}$ production, approximate NNLO predictions are currently available for the three production modes described above [37] [38] [39]. For the work described in this thesis, the single top production is considered as a background process, and these theoretical cross-sections are used to normalize the predicted yields obtained with the MC simulation (see Section 4.3).

### 1.3 Top quark decay

As discussed in Section 1.1, the top quark decays before hadronizing, coupling almost exclusively with a $b$-quark, implying a $Wtb$ charged current vertex. Being heavier than the $W$-boson, the top quark decays with a branching ratio close to 100% to an on-shell $W$-boson and a $b$-quark, $t \rightarrow Wb$. A $W$-boson decays in about 1/3 of the cases into a charged lepton ($e$, $\mu$ or $\tau$) and a neutrino, with all the three lepton flavours being produced at equal rate. In the remaining 2/3 of the cases, the $W$-boson decays into a quark-antiquark pair, and the abundance of a given pair is instead determined by the magnitude of the relevant CKM matrix element. Specifically, the CKM mechanism suppresses the production of $b$-quarks as $|V_{cb}|^2 \simeq 1.7 \times 10^{-3}$. Thus, the hadronic $W$-boson decay can be considered as a clean source of light quarks.

![Figure 1.5. Top quark pair branching fractions.](image)

From an experimental point of view, one can characterise a $t\bar{t}$ pair decay by the number of $W$s which decay leptonically. The following signatures can be identified (see Figure 1.5):

- $e+jets$ 15%
- $\mu+jets$ 15%
- $\tau+jets$ 15%
- $e\tau$ 1%
- $\tau\mu$ 2%
- $\tau\mu$ 2%
- $\mu\mu$ 2%
- $\mu\tau$ 2%
- $\mu\mu$ 2%
- $ee$ 1%
• **Fully leptonic or dilepton** ($t\bar{t} \rightarrow W^+b W^−\bar{b} \rightarrow \ell^+\nu b \ell^−\bar{\nu}\bar{b}$): represents about 1/9 of the $t\bar{t}$ events. Both $W$-bosons decay into a lepton-neutrino pair, resulting in an event with two charged leptons, two neutrinos and two $b$-jets. This mode allows a clean sample of top events to be obtained, but suffers both from a poor statistics and from the presence of two neutrinos escaping the detector.

• **Fully hadronic or all hadronic** ($t\bar{t} \rightarrow W^+b W^−\bar{b} \rightarrow \bar{q}q' b q\bar{q}'\bar{b}$): represents about 4/9 of all the $t\bar{t}$ decays. Both $W$-s decay hadronically, giving six jets in the event: two $b$-jets from the top decay and four light jets from the $W$-boson decay. In this case, there is no high $p_T$ lepton to trigger on, and the signal is not easily distinguishable from the abundant SM QCD multi-jets production, which is expected to be orders of magnitude bigger. Another challenging point of this signature is the presence of a high combinatorial background when reconstructing the top mass.

• **Semi-leptonic or single-lepton** ($t\bar{t} \rightarrow W^+b W^−\bar{b} \rightarrow \ell^+\nu b q\bar{q}'\bar{b}$): again, about 4/9 of the whole decays. The presence of a single high $p_T$ lepton and of four or more jets (two of them coming from $b$-quarks) allows to suppress the QCD and the $W$+jet backgrounds respectively. The $p_T$ of the neutrino can be reconstructed, as it is the only source of missing energy (see Section 4.1) for signal events. This is the most useful channel at hadron colliders in general.

Decays that involve $\tau$ leptons are usually not considered in analyses of the semi-leptonic and dileptonic decay modes since $\tau$ leptons are difficult to identify. These analyses, however, include the events in which the $\tau$ decayed to an electron or muon. Analyses involving the identification of an hadronically decaying $\tau$ are treated apart.

For the $t\bar{t}$ cross-section determination described in this thesis, only the semi-leptonic decay channel is used.

### 1.4 Top and Higgs masses from precision EW measurements

The SM comprises a set of free parameters that are a priori unknown. However, once these are measured, all physical observables can be expressed in terms of those parameters. To make optimal use of the predictive power of the theory, it is therefore crucial to measure these parameters with the highest possible precision. In this way it is possible to probe the self-consistency of the SM and any contributions beyond it. Being a renormalizable theory, predictions for any observable can be calculated to any order and checked experimentally.

Electroweak processes depend mainly on three parameters: the coupling constants $g$ and $g'$ and the Higgs vacuum expectation value $v$. Their values are known with high precision thanks to the measurement of observables like the electromagnetic fine structure constant $\alpha$, the Fermi constant $G_F$ and the mass of the $Z$-boson $m_Z$. With these input values, the theoretical framework can be used to predict other quantities such as the $W$-boson mass. Given the present precision measurements, the $W$-boson mass is sensitive to the mass of the top quark and to the mass of the Higgs boson through higher order
radiative quantum corrections [10]. The constraints that can be derived on the mass of the top quark are much stronger than for the Higgs boson mass, mainly because the dependence of such corrections on the top mass is quadratic, while the dependence on the Higgs mass is logarithmic.

These predictions for the top quark mass were available before the discovery of the top quark. The agreement between predicted and observed values of $m_{\text{top}}$ is shown in Figure 1.6 (left) as a function of time [41]. At present the most precise measurement of $m_{\text{top}}$ comes from the combination of the CDF and DØ results [42] (see Figure 1.6 (right) for a summary of the measurements entering the combination):

$$m_{\text{top}} = 173.2 \pm 0.9 \text{ GeV}/c^2. \quad (1.12)$$

The latest prediction from precision electroweak data yields [43]:

$$m_{\text{top}} = 178.9^{+11.7}_{-8.6} \text{ GeV}/c^2. \quad (1.13)$$

The successful prediction of $m_{\text{top}}$ before the top quark discovery gives some confidence in the precision and predictive power of the radiative corrections in the SM. Therefore, the SM fit to the electroweak precision data including the direct measurements of $m_{\text{top}}$ and $M_W$ are now used to infer $m_H$.

Direct searches for the Higgs boson at LEP and Tevatron have ruled-out at the 95% confidence level (C.L.) the masses $m_H < 114.4 \text{ GeV}/c^2$ [44] and $156 < m_H < 177 \text{ GeV}/c^2$ [44].
Recent results from the LHC experiments (see Section 2.1) have significantly extended the 95% C.L. excluded region. The mass ranges excluded at 95% C.L. by ATLAS are $112.7 < m_H < 115.5$, $131 < m_H < 237$ and $251 < m_H < 468$ GeV/$c^2$ [46], while the CMS one is $127 < m_H < 600$ GeV/$c^2$ [47]. Figure 1.8 shows the upper limit on the SM Higgs production cross-section as a function of $m_H$, for the ATLAS and CMS experiments. Given these results, at present there is only a small mass region between 115.7 and 127 GeV not excluded at 95% C.L.

Figure 1.7 (left) shows the $\Delta \chi^2$ of the latest fit as a function of $m_H$. The preferred value is slightly below the LEP exclusion limit. Figure 1.7 (right) shows the 68% C.L. contour in the ($m_{top}$, $M_W$) plane from the global electroweak fit. The direct and indirect determinations of $m_{top}$ and $M_W$ are visible. Also displayed are the isolines of a SM $m_H$ between the lower limit of 114 GeV/$c^2$ and the theoretical upper limit of 1000 GeV/$c^2$. As can be seen from the figure, the direct and indirect measurements are in good agreement, showing that the SM is not obviously wrong.

It seems, however, that there is some tension in the fit of the precision electroweak data to the SM. Precision measurements of $M_W$ and $m_{top}$ at the Tevatron and LHC, could resolve or exacerbate this tension. Improvements in the precision of the $m_{top}$ or the $M_W$ measurements translate into better indirect limits on $m_H$. 
Figure 1.8. The ATLAS (top) and CMS (bottom) combined 95% C.L. upper limits on the signal strength modifier $\mu = \sigma/\sigma_{SM}$, obtained with the CLs method, as a function of the SM Higgs boson mass in the range 110-600 GeV/c$^2$. The observed limits are shown by solid symbols. The dashed line indicates the median expected $\mu^{95\%}$ value for the background-only hypothesis, while the green (yellow) bands indicate the ranges expected to contain 68% (95%) of all the observed limit excursions from the median. The mass regions where the black line lays below one are excluded at 95% C.L.

An important point to note is that, while the direct $m_{top}$ measurements are usually interpreted as representing the top pole mass ($m_{top}^{pole}$), their calibration through current MC simulations raises certain ambiguities of interpretation. Therefore conclusions based on such comparisons need to be drawn with great care. Deriving $m_{top}$ from the measured $\sigma_{t\bar{t}}$, ...
as shown in Section 5.4, avoids the use of simulation for calibration and allows the determination of $m_{\text{top}}$ using a well defined mass definition in an understandable approximation. See [5] for a detailed discussion on this argument.
The LHC and the ATLAS experiment

ATLAS (A Toroidal LHC ApparatuS) is one of the four main experiments at the Large Hadron Collider (LHC) at CERN. In this Chapter a brief introduction to the LHC collider and its physics program is given, together with a description of the ATLAS detector.

2.1 The LHC collider

The LHC \cite{49} is currently the largest and highest-energy particle accelerator in the world. It’s located at CERN, inside the 27 km long circular tunnel at a depth varying between 50 and 175 meters below the ground, which also housed the Large Electron Positron Collider (LEP).

The LHC can provide both proton-proton (\textit{pp}) and heavy ion (\textit{HI}) collisions. For \textit{pp} collisions, the design luminosity is $10^{34}$ cm$^{-2}$s$^{-1}$ and the design centre-of-mass energy for the collisions is 14 TeV. The LHC started its operations in 2008, and during 2010 and 2011 runs, collisions at 7 TeV centre-of-mass energy have been provided. The maximum instantaneous luminosity that has been reached in 2010 is slightly higher than $2 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$, while during 2011 run a peak of $\sim 4 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$ has been achieved.

\textit{HI} collisions are foreseen with lead ions at an energy of 2.8 TeV per nucleon, reaching a peak luminosity at regime of $10^{26}$ cm$^{-2}$s$^{-1}$. In 2010 \textit{HI} running collisions at 2.76 TeV per nucleon took place, reaching a peak instantaneous luminosity of $30 \cdot 10^{24}$ cm$^{-2}$s$^{-1}$.

The LHC is mainly composed by superconducting magnets, operating at a temperature of 1.9 K provided by a cryogenic system based on liquid helium. The LHC is equipped with a 400 MHz superconducting cavity system and it is made of different types of magnets. Dipole magnets (for a total of 1232) are used to keep the beams on their circular trajectory, while quadrupole magnets (392) are needed to keep the beams focused, in order to maximize the chances of interaction in the four different collision points, where the two beams cross. Close to each of these four intersections the two beam pipes, in which the protons (or ions) circulate in opposite direction, merge in a single straight section where the collisions take place. In these regions, triplet magnets are used to squeeze the beam in
the transverse plane, to focus it at the interaction point. In this way, the travelling beam can be significantly larger than it needs to be at the interaction point, reducing intra-beam interactions.

At the collision points, four big experiments have been built: ATLAS [50] at Point 1, CMS [51] at Point 5, LHCb [52] at Point 8 and ALICE [53] at Point 2. ATLAS and CMS are multi-purpose experiments, designed to study high transverse momentum events for the search of the Higgs boson and other phenomena beyond the Standard Model (BSM). LHCb has instead been designed especially to study $b$-physics, and ALICE for heavy ion collisions (HI), to study the formation of the so-called quark-gluon plasma.

Colliding particles are grouped together into a number of bunches, each containing $\sim 10^{11}$ protons. The design number of bunches is 2808, so that interactions happen every 25 ns. During the commissioning phase, the number of colliding bunches has been progressively increased to reach the design value. At the end of 2010 the maximum number of colliding bunches has been 348, while 1092 has been then reached in June 2011.

Before being injected into the LHC, particles are accelerated step by step up to the energy of 450 GeV, by a series of accelerators. For protons, the first system is the linear accelerator LINAC2, which generates them at an energy of 50 MeV. Protons then go through the Proton Synchrotron Booster (PSB) and arrive to 1.4 GeV. After that they are injected into the Proton Synchrotron (PS), where they are accelerated to 26 GeV. Finally, the Super Proton Synchrotron (SPS) is used to further increase their energy to
450 GeV. The accelerator complex is shown in Figure 2.1.

The LHC started its operations on September 10th 2008, with the first beams circulating into the rings, in both directions, without collisions. After a commissioning phase, the first collisions were expected few days later. Unfortunately, on September 19th a major accident happened, due to a defective electrical connection between two magnets and 53 magnets were damaged. This caused a long stop of the machine, to do all the necessary reparations, to check the electrical connections and to improve the safety systems. During the Autumn 2009, after more than one year, the operations started again, with the first collisions at a centre-of-mass energy of 900 GeV recorded by the four experiments on 23 November 2009.

After the 900 GeV collisions data taking, the centre-of-mass energy was further increased to 2.36 TeV, beating the Tevatron’s previous record of 0.98 TeV per beam and giving collisions at the highest energy ever reached before. After some months, on 30 March 2010, the first collisions at 7 TeV were registered, starting a new running period that went on until the beginning of November, when the LHC provided the first heavy ion collisions. After the lead ions collisions period and a technical stop during the winter, pp collisions have started again on 13 March 2011. At the end of the 2010 pp running period, ATLAS accumulated an integrated luminosity of 45 pb$^{-1}$ out of the total 48.9 pb$^{-1}$ delivered by the LHC (Figure 1.3). Data taking has re-started in March 2011 and presently 5.5 fb$^{-1}$ have been accumulated.

Figure 2.2 and 2.3 show the integrated and peak luminosity registered by the four experiments during the 2010 and 2011 7 TeV pp runs.
2.1.1 Physics at the LHC

The LHC physics program covers a variety of topics in particle and nuclear physics. The main fields of research are listed below.

- **Higgs boson**
  As discussed in Section 1.1, the Higgs boson is the only particle within the SM that has not been discovered so far. One of the main tasks of the LHC experiments is to look for a direct Higgs boson production. Presently, no evidence has been found within the considered mass range, but the exclusion limits set by the LEP and Tevatron experiments have been significantly extended, as shown in Section 1.4. If the Higgs boson will be identified at the LHC its mass and couplings will be also determined.

- **Standard Model physics**
  Precision measurements of masses and properties of known SM particles and interactions, including top quark mass and couplings, $b$-quark physics and CP violation, are essential tests of the validity of the theory.

- **Physics beyond the Standard Model**
  Many searches for new particles and interactions are currently carried on. In particular, many studies are dedicated to the search of Supersymmetry (SUSY), which is one of the theoretically favoured candidates for BSM physics. SUSY models, like other BSM models, involve new, highly massive particles. These usually decay into high-energy SM particles and stable heavy particles that are very unlikely to interact with ordinary matter. These kinds of events are expected to be characterised by
several high-momentum jets and missing transverse energy (see Section 3).

- **Heavy ion physics**
  
  Pb-Pb collisions might give the possibility to discover new phenomena as well. ALICE is dedicated to HI physics, but also the other experiments have a HI program, even though they have not been designed to this purpose. In particular, thanks to the good performance of the calorimeter system, the ATLAS experiment has observed events with “jet quenching” already with few pb$^{-1}$ of data [54]. This new phenomena is characterised by the presence of large di-jet asymmetries, not observed in $pp$ collisions and it may point to an interpretation in terms of strong parton energy loss in a hot, dense medium, the so-called “quark-gluon plasma”.

  The very high luminosity of the LHC is needed to pursue these studies, since the cross-sections of the processes of interest are very low. The high luminosity regime introduces however some difficulties as well. One of them is the presence of the so called “pile-up”, i.e. the superposition of several inelastic scattering events on top of the events of interest. At design luminosity, 23 pile-up events per bunch crossing are expected.

  Another difficulty due to the nature of $pp$ collisions is that QCD processes will dominate over the processes physicists are most interested in. This imposes strong demands on the capability of the detectors to identify the experimental signatures of interest.

  The physics program previously discussed translates therefore into a set of requirements which the LHC detectors have to face:

- **Fast response, high granularity and resistance to radiations**
  
  The high event rate requires a fast and sophisticated electronics, able to discriminate events and minimize the pile-up effect. A highly granular detector is needed to handle the high particle fluxes as well. The detectors must be resistant to high doses, both in terms of operation and ageing.

- **Trigger**
  
  The detector output bandwidth is limited, and therefore the 40 MHz interaction rate must be reduced to 200 Hz to be written on tape. The capability to trigger efficiently on interesting events with a very high background rejection is therefore crucial.

- **Full coverage**
  
  In order to identify interesting events over the dominant QCD background, it is important to detect all the particles produced in a collision. This requires a coverage over $2\pi$ in azimuthal angle and pseudorapidity $|\eta| < 5$ (for the definition of pseudorapidity see Section 2.2).

- **Particle identification**
  
  The capability to precisely reconstruct and identify electrons, muons, photons, tau leptons and jets is an essential requirement for the LHC experiments.
2.2 The ATLAS detector

The ATLAS experiment is positioned at Point 1, in a cavern at a depth of 100 m. With its height of 25 m and its length of 44 m, it is one of the biggest detectors ever built. It weighs about 7000 tons and it has a cylindrical symmetry. After the cavern was completed, the construction started in 2003 and it went on until July 2007. Since 2009 it has been recording cosmic-ray events and, since November 2009, \( p p \) collision events at rates of up to 200 Hz.

A brief summary of the coordinate system and nomenclature is given below.

- The nominal interaction point is defined as the origin of the coordinate system.
- The \( z \)-axis is parallel to the beam and the \( x \)- and \( y \)-axes are perpendicular to the beam, forming a right-handed cartesian coordinate system where \( x \) points towards the centre of the LHC ring and \( y \) points upward. The \( x-y \) plane is called the transverse plane.
- The azimuthal angle, \( \phi \), is measured around the \( z \)-axis and the polar angle, \( \theta \), is measured from the \( z \)-axis.
- The pseudorapidity, defined as \( \eta = -\ln \tan(\theta/2) \), is often preferable as a polar coordinate, since pseudorapidity spectra are invariant under Lorentz boosts along \( z \)-axis for massless particles.
- The distance \( \Delta R \) in \( \eta - \phi \) space is defined as \( \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \).
- Particles are often described by their transverse momentum \( p_T \) and transverse energy (projections in the transverse plane), as these variables are a better indicator of interesting physics than the standard energy and momentum and since they are assumed to be 0 for the colliding partons in the initial state.

The ATLAS detector is composed of different sub-detectors, as shown in Figure 2.4. Each of them plays an important role in the particles reconstruction. The sub-detectors are arranged in cylindrical layers around the interaction point.

Closest to the beam pipe is the Inner Detector (ID), used to reconstruct the trajectory of charged particles. The ID is enclosed by a solenoidal magnet, which provides a strong magnetic field to bend the charged particles and measure their momentum and charge. The Electromagnetic (EM) Calorimeter surrounds the ID and is designed to precisely measure the energy of electrons and photons. Outside the EM Calorimeter there is the Hadronic (Had) Calorimeter, which measures the energy of hadronic particles. Finally, the calorimeters are enclosed by the Muon Spectrometer (MS), designed to reconstruct and identify muons, which usually escape the previous detector layers. The MS is embedded in a toroidal magnetic field and consists in tracking chambers, to provide precise measurements of momentum and charge, and detectors used for fast triggering.

ATLAS includes a three-level trigger system for evaluating and recording only the most interesting events during a run. The trigger is configurable at every level to provide a constant stream of data under any beam conditions.

In the following, the various systems composing the detector will be described in detail.
2.2.1 The Inner Detector

The ID is the innermost system of the ATLAS detector. Its schematic view is shown in Figure 2.4. It is composed of three subdetectors: two silicon detectors, the Pixel Detector and the SemiConductor Tracker (SCT), and the Transition Radiation Tracker (TRT). It is embedded in an axial magnetic field of 2 T and its overall dimensions are 2.1 m in diameter and 6.2 m in length.

The ID measures the tracks produced by the passage of charged particles. So it measures the charged particles position and, thanks to the magnetic field, also their $p_T$ and charge. In addition, thanks to the high precision of the track reconstruction, the ID is able to measure the position of the primary vertex in a collision, and to eventually identify secondary vertexes due to pile-up or in flight decays of unstable particles.

A detailed description of the sub-detectors is given below and a summary of their main characteristics is reported in Table 2.1.

The Pixel Detector

The Pixel Detector is the closest system to the collision point and it is built directly around the beryllium beam pipe in order to provide the best possible primary and secondary vertex resolution. It is composed by three cylindrical layers in the barrel region (at radii 50.5 mm, 88.5 mm and 122.5 mm) and two end-caps, each consisting of three disks (located at 495
The LHC and the ATLAS experiment

Figure 2.5. Schematic view of the Inner Detector.

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Radius [cm]</th>
<th>Element size</th>
<th>Spatial resolution [µm]</th>
<th>Hits/track</th>
<th>Readout channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>5 - 12</td>
<td>50 µm × 400 µm</td>
<td>10 (R-φ) × 115 (z)</td>
<td>3</td>
<td>80 × 106</td>
</tr>
<tr>
<td>SCT</td>
<td>30 - 52</td>
<td>80 µm</td>
<td>17 (R-φ) × 580 (z)</td>
<td>8</td>
<td>6 × 106</td>
</tr>
<tr>
<td>TRT</td>
<td>56 - 107</td>
<td>4 mm</td>
<td>130</td>
<td>30</td>
<td>3.5 × 105</td>
</tr>
</tbody>
</table>

Table 2.1. Summary of the main characteristics of the three ATLAS ID subdetectors.

mm, 580 mm and 650 mm from the detector centre). The Pixel Detector provides three precision measurement points for tracks with pseudorapidity \(|\eta| < 2.5\) and it has a full coverage in \(\phi\). The detector structure is made of low-mass carbon fibers and integrates the cooling system, resulting in a total contribution to the radiation length \(X_0\) crossed by the particles produced in the collisions of about 3% per layer. Moreover, all the detector components are designed to sustain a radiation dose of \(\sim 500\) kGy, which is the one expected to be absorbed during the detector lifetime. The basic elements of the Pixel Detector are the silicon sensor “modules”, identical for barrel and disks. The 250 µm thick modules are divided into 50 µm wide and 400 µm long pixels, with 47232 pixels on each of the 1744 modules. The total number of channels for the whole detector is \(\sim 80.4\) millions.

The SCT Detector

The SCT is the second element of the tracking system, going from the beam pipe outwards. It is composed by four cylinders in the barrel region, with radii between 299 mm and 514 mm and a full length of 1492 mm. Each of the two end-caps consists of nine disks. It provides typically eight strip measurements (four space-points) for particles originating in the beam-interaction region. The detector consists of 4088 modules. The strips in the barrel are approximately parallel to the solenoid field and beam axis, and have a constant...
pitch of 80 µm, while in the end-caps the strip direction is radial and of variable pitch.

The TRT Detector

The TRT is the outermost system of the ID and its sensitive volume covers radial distances from 563 mm to 1066 mm. The detector consists of 298304 proportional drift tubes (straws), 4 mm in diameter, with a read out of ∼ 351000 electronic channels. The straws in the barrel region are arranged in three cylindrical layers and 32 φ-sectors; they have split anodes and are read out from each side. The straws in the end-cap regions are radially oriented and arranged in 80 wheel-like modular structures. The TRT straw layout is designed so that charged particles with transverse momentum $p_T > 0.5$ GeV and with pseudorapidity $|\eta| < 2.0$ cross typically more than 30 straws.

The TRT can also be used for particle identification. Its tubes are interleaved with layers of polypropylene fibres and foils: a charged particle passing through the boundary region between materials with a different refraction index emits X-ray radiation whose intensity is proportional to the relativistic factor. The TRT works with two threshold levels (defined at the level of the discriminator in the radiation-hard front-end electronics): the ratio of the high threshold hits versus all the hits can be used to identify electrons (see Section 3.1).

The cooling system

For the Pixel Detector and the SCT, cooling is necessary to reduce the effect of the radiation damage on the silicon. They share a cooling system, which uses $C_3F_8$ fluid as a coolant. The target temperature for the silicon sensors after irradiation is $0^\circ$ C for the Pixel Detector and $-7^\circ$ C for the SCT. Because the TRT operates at room temperature, a set of insulators and heaters isolates the silicon detectors from the ATLAS environment.

The whole ID system is embedded in a 2 T solenoidal magnet. The inner and outer diameters of the solenoid are 2.46 m and 2.56 m and its axial length is 5.8 m. The flux is returned by the steel of the ATLAS hadronic calorimeter and its girder structure. As a result there is a negligible field within the EM Calorimeter volume and a small field in the Had Calorimeter volume. To achieve the desired performance, the solenoid layout has been carefully optimised to keep the material thickness in front of the calorimeter as low as possible: the solenoid assembly contributes a total of ∼ 0.66 $X_0$ at normal incidence.

2.2.2 The Calorimeters

The calorimeter system includes the EM and the Had Calorimeters. The first is dedicated to the measurement of electrons and photons, the latter to the measurement of hadrons. The calorimeter system is hermetic out to $|\eta| < 4.9$ and it is $\sim 9 - 13 \lambda$ thick, enough to capture the 99% of the hadronic showers from single charged pions up to $\sim 500$ GeV. The various parts of the calorimeter system use different techniques suited to the widely varying requirements of the physics processes of interest and of the radiation environment over a large $\eta$-range. A schematic view of the calorimeter system is shown in Figure 2.6.
The main purpose of the calorimeters is to measure the energy of the particles and their position. One of the most important requirements is to provide good containment for electromagnetic and hadronic showers, as well as limit the punch-through into the muon system. Therefore, calorimeter depth is an important consideration. The total thickness of the EM calorimeter is more than $22X_0$ in the barrel and more than $24X_0$ in the End-Caps. It contains electron and photon showers up to $\sim 1$ TeV and it also absorbs almost $2/3$ of a typical hadronic shower. The approximate 9.7 (10) interaction lengths ($\lambda$) of the active EM + Had calorimeter in the Barrel (End-Caps) are adequate to provide good resolution for high-energy jets. The total thickness, including 1.3 $\lambda$ from the outer support, is $11\lambda$ at $\eta = 0$ and has been shown both by measurements and simulations to be sufficient to reduce punch-through well below the irreducible level of prompt or decay muons.

Some details on the different calorimeter regions are given below.

**The Electromagnetic Calorimeters**

The EM calorimeter is a lead Liquid-Argon (LAr) detector [55]. To ensure the maximum azimuthal coverage, the EM calorimeter was designed with an accordion geometry, as shown in Figure 2.6: the readout electrodes and the lead absorbers are laid out radially and folded so that particles cannot cross the calorimeter without being detected. It is divided into one Barrel part ($|\eta| < 1.475$) and two End-Caps ($1.375 < |\eta| < 3.2$), each one with its own cryostat. The position of the central solenoid with respect to the EM calorimeter demands optimisation of the material in order to achieve the desired calorimeter performance. As a consequence, the central solenoid and the LAr calorimeter share a
unique vacuum vessel. The Barrel calorimeter consists of two identical half-barrels, separated by a small gap (4 mm) at $z = 0$. Each End-Cap is mechanically divided into two coaxial wheels: an inner wheel covering the region $1.375 < |\eta| < 2.5$, and an outer wheel covering the region $2.5 < |\eta| < 3.2$.

Over the region devoted to precision physics ($|\eta| < 2.5$), the EM calorimeter is segmented into three longitudinal parts: the strips, middle and back sections. While most of the electrons and photons energy is collected in the middle, the fine granularity of the strips is necessary to improve the $\gamma - \pi^0$ discrimination and the back measures the tails of highly energetic electromagnetic showers, and helps to distinguish electromagnetic and hadronic deposits. For the End-Cap inner wheel, the calorimeter is segmented in two longitudinal sections and has a coarser lateral granularity than for the rest of the acceptance.

Since most of the central calorimetry sits behind the cryostat, the Solenoid, and the 1-4 $\lambda$ thick ID, EM showers begin to develop well before they are measured in the calorimeter. In order to take into account and correct for these losses, up to $|\eta| = 1.8$ an additional presampler layer is mounted in front of the sampling portion (i.e. accordion) of the calorimetry. The presampler is 11 mm (5 mm) thick in the Barrel (End-Cap) and includes fine segmentation in $\eta$. Differing from the rest of the calorimetry, the presampler has no absorber layer. In practice, it behaves almost like a single-layer LAr tracker.

The transition region between the Barrel and End-Cap EM calorimeters, $1.37 < |\eta| < 1.52$, is expected to have a poorer performance because of the higher amount of passive material in front; this region is often referred to as “crack region”.

The Hadronic Calorimeters

The Had Calorimeter is realized with a variety of techniques depending on the region: Central, End-Cap and Forward.

In the central region there is the Tile Calorimeter (Tile) [56], which is placed directly outside the EM calorimeter envelope. The Tile is a sampling calorimeter which uses steel as absorber and scintillating tiles as active material. It is divided into a Barrel ($|\eta| < 1.0$) and two Extended Barrels ($0.8 < |\eta| < 1.7$). Radially, the Tile calorimeter goes from an inner radius of 2.28 m to an outer radius of 4.25 m. It is longitudinally segmented in three layers of approximately 1.5, 4.1 and 1.8 $\lambda$ thickness for the Barrel and 1.5, 2.6, and 3.3 $\lambda$ for the Extended Barrel.

The Hadronic End-Cap Calorimeter (HEC) consists of two independent wheels per end-cap, located directly behind the End-Cap EM calorimeter and sharing the same LAr cryostats. It covers the region $1.5 < |\eta| < 3.1$, overlapping both with the Tiles and the Forward Calorimeter. The HEC uses the LAr technology. Each wheel is divided into two longitudinal segments, for a total of four layers per End-Cap. The wheels closest to the interaction point are built from 25 mm parallel Copper plates, while those further away use 50 mm Copper plates. The outer radius of the Copper plates is 2.03 m, while the inner radius is 0.475 m (except in the overlap region with the Forward Calorimeter where this radius becomes 0.372 m). The Copper plates are interleaved with 8.5 mm LAr gaps, providing the active medium for this sampling calorimeter.
The Forward Calorimeter

The Forward Calorimeter (FCal) covers the 3.1 < |\eta| < 4.9 region and is another LAr based detector. Integrated into the End-Cap cryostats, it is approximately 10 \lambda’s, and consists of three 45 cm thick independent modules in each End-Cap: the absorber of the first module is Copper, which is optimised for electromagnetic measurements, while for the other two is Tungsten, which is used to measure predominantly the energy of hadronic interactions. Both materials have been chosen for their resistance to radiation. The region where the FCal is set, is very close to the beam pipe, so that the expected radiation dose is very high. Therefore the electrode structure is different from the accordion geometry, consisting in a structure of concentric rods and tubes parallel to the beam axis. The LAr in the gap between the rod and the tube is the sensitive medium.

To correct hadronic objects for the calorimeter non-compensation an additional correction is applied, as described in Section 3.3. The performance of the calorimeter system is summarized in Table 2.2.

<table>
<thead>
<tr>
<th>Detector component</th>
<th>Energy resolution ($\sigma_E/E$)</th>
<th>$\eta$ coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM calorimetry</td>
<td>10%/$\sqrt{E}$ $\pm$ 0.7%</td>
<td>$\pm$3.2 (±2.5 for the trigger)</td>
</tr>
<tr>
<td>Hadronic calorimetry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barrel &amp; End-Cap</td>
<td>50%/$\sqrt{E}$ $\pm$ 3%</td>
<td>$\pm$3.2</td>
</tr>
<tr>
<td>Forward</td>
<td>100%/$\sqrt{E}$ $\pm$ 3.1%</td>
<td>$\pm$4.9</td>
</tr>
</tbody>
</table>

Table 2.2. Nominal detector performance goals and coverage for the ATLAS calorimetric system.

2.2.3 The Muon Spectrometer

The layout of the MS is shown in Figure 2.7. The muon system has two different functions: it is needed for high precision tracking of muons and also for triggering on them. Muons frequently indicate an interesting event and, therefore, a muon-based trigger is useful for selecting some new physics signals. On the other hand, in order to precisely measure the decays of new particles, one needs to make accurate measurements of each muon’s momentum.

The momentum measurement is based on the reconstruction of the muon’s trajectories bent by a magnetic field.

The large volume magnetic field is provided by the Barrel toroid in the region |\eta| < 1.4, by two smaller End-Cap magnets in the 1.6 < |\eta| < 2.7 region and by a combination of the two in the transition region (1.4 < |\eta| < 1.6). This magnet configuration provides a field mostly orthogonal to the muon trajectories, centered on the beam axis, perpendicular to the solenoidal field that serves the ID. Since the toroidal magnet system of the
MS is completely independent of the Solenoid in the ID, ATLAS is able to acquire two independent measurements of a muon momentum.

The performance of the toroids in terms of bending power is characterized by the field integral $\int R \cdot B \, dl$, where $B$ is the field component normal to the muon direction and the integral is computed along an infinite momentum muon trajectory, between the innermost and outermost muon-chamber planes. The Barrel Toroid provides 1.5 to 5.5 Tm of bending power in the pseudorapidity range $0 < |\eta| < 1.4$, and the End-Cap Toroids approximately 1 to 7.5 Tm in the region $1.6 < |\eta| < 2.7$. The bending power is lower in the transition regions where the two magnets overlap ($1.4 < |\eta| < 1.6$).

The momentum measurement is performed over most of the $\eta$-range by the Monitored Drift Tubes (MDT). At large $\eta$ and close to the interaction point, Cathode Strip Chambers (CSC) with higher granularity are used: they have been designed to withstand the demanding rate and background conditions. The stringent requirements on the relative alignment of the muon chamber layers are obtained by the combination of precision mechanical-assembly techniques and optical alignment systems both within and between muon chambers.

Concerning the triggering function of the muon system, it covers the pseudorapidity range $|\eta| < 2.4$. Resistive Plate Chambers (RPC) are used in the barrel and Thin Gap Chambers (TGC) in the end-cap regions. The trigger chambers for the MS serve a threefold purpose: to provide bunch-crossing identification, to provide well-defined transverse momentum thresholds and to measure the muon coordinate in the direction orthogonal to that determined by the precision-tracking chambers.

The barrel chambers are positioned on three cylinders concentric with the beam axis, at radii of about 5, 7.5, and 10 m. They cover the pseudorapidity range $|\eta| < 1$. The
end-cap chambers cover the range $1 < |\eta| < 2.4$ and are arranged in four disks at distances of 7, 10, 14, and 21-23 m from the interaction point, concentric with the beam axis.

The MS reconstruction efficiency and resolution were measured using cosmic ray events in 2008 and 2009 \cite{57}. The reconstruction efficiency, integrated over the detector acceptance, is $\sim 94\%$. At $\eta = 0$ there is a gap in the detector for cable routing. If the region of the detector near this gap is excluded, the reconstruction efficiency is increased to 97\%.

The transverse momentum resolution was determined from this data to be:

$$\frac{\sigma_{p_T}}{p_T} = \frac{0.29 GeV}{p_T} \oplus 0.043 \oplus 4.1 \times 10^{-4} GeV^{-1} \times p_T$$

for $p_T$ between 5 and 400 GeV.

### 2.2.4 Luminosity detectors

One measurement which is very important for almost every physics analysis is the luminosity measurement \cite{58}. As it is a fundamental quantity, three different detectors help in its determination. At $\pm 17$ m from the interaction region there is the LUCID (LUminosity measurement using Cerenkov Integrating Detector) \cite{59}. It detects inelastic pp scattering in the forward direction and it is the main online relative-luminosity monitor for ATLAS. It is also used, before collisions are delivered by the LHC, to check the beam losses. For the beam monitoring, another detector has been inserted: the BCM (Beam condition Monitor).

The other detector used for luminosity measurement is ALFA (Absolute Luminosity For ATLAS) \cite{60}. It is located at $\pm 240$ m from the interaction point. It consists of scintillating fibre trackers located inside Roman pots which are designed to approach as close as 1 mm from the beam.

The last detector is ZDC (Zero-Degree Calorimeter) \cite{60}. It is located at $\pm 140$ m from the interaction point, just beyond the point where the common straight-section vacuum-pipe divides back into two independent beam-pipes. Neutral particles with $|\eta| \geq 8.2$, not being affected by the magnetic fields which bend the proton beams, are detected and measured by the ZDC modules, consisting of layers of alternating quartz rods and tungsten plates.

### 2.2.5 The trigger system

At the present LHC luminosities ($\sim 40\%$ of the design luminosity), protons collide in ATLAS every 50 ns. Something like 100 million channels in the ATLAS detector must be read out by the data acquisition software during LHC operation, resulting in $\sim 1.5$ MB events. Without any filtering, ATLAS would need to process and record $\sim 60$ TB of data every second, currently an impossible task. This is not a dramatic limitation, since interesting physics occurs mostly at rates of 10, 1 or $< 0.1$ Hz and so we are actually interested in a tiny fraction of the produced events. This is however a challenging task. Because only a small fraction of the events can be recorded, these events must be quickly identified looking for interesting signatures. A rapid decision must be made for each event, taking also into account that rejected events are, of course, lost forever.
The ATLAS trigger system \[\text{[1]}\] is designed to record events at a rate of up to 400 Hz, with a reduction of more than five orders of magnitude with respect to the collision rate. ATLAS has implemented a three-levels trigger system to handle the high-rate environment. At each level, physics objects are reconstructed with improved granularity and precision and over a larger fraction of the detector, ending up in a complete event reconstruction in the final trigger stage.

- The first level (L1) trigger is a configurable, pure-hardware trigger designed to make a decision on each event, in less than 2.5 \(\mu\)s, and to provide output at a rate up to 75 kHz. It makes an initial decision based on timing from an electrostatic beam pickup (BPTX), coarse detector information from muon trigger chambers and towers of calorimeter cells, together with multiplicity information from the Minimum Bias Trigger Scintillators (MBTS) and very forward detectors. The L1 provides regions of interest (RoIs) to the next level.

- The second level (L2) triggers make a decision in less than 40 ms and provide output at rates up to 3.5 kHz. The L2 triggers run a simplified version of the event reconstruction in the regions of interest defined by the calorimeter and muon systems. Improved selection criteria, for example to distinguish electrons from photons by track matching, and improved calibrations are applied.

- In the third trigger level, called the “Event Filter” (EF), the complete offline event reconstruction makes a decision in less than four seconds and provides output at 200-400 Hz.

The L2 and EF are software triggers, unlike the L1 trigger, and they are together referred to as the “High-Level Trigger” (HLT). One L1 item may seed many HLT triggers, and many L1 items may seed a single HLT trigger. A full sequence of triggers, from L1 through the EF, is called a trigger “chain”.

A “menu” of possible trigger items is prepared for each data taking run. The menu defines a complete list of which trigger items will be evaluated, which values the parameters of those items will take, and how the lower-level trigger items map into higher-level triggers. Some items are run unprescaled, meaning that any time an event is accepted by the trigger it will be passed on to the next level (or written out in the case of the EF). Others, in particular low-\(p_T\) triggers, may work with relatively high prescales, so that only some of the events which pass the trigger are accepted. Because of the strict timing demands, if an event cannot be evaluated in the allotted time for each trigger stage, it is passed and flagged for later examination.

After the EF, the events are divided into “streams”, each containing the outputs from several different trigger chains. On these streams the full offline event reconstruction is run, and the output is saved for distribution to computing centers around the world. Streams called “Express Stream” and “Calibration Stream” contain an assortment of events which are deemed interesting or useful for calibration of the subdetectors. They are processed first in order to provide new calibrations to the detectors within 24-hour periods.
Chapter 3

Object reconstruction in ATLAS

In this Chapter, the way the physics objects are reconstructed in ATLAS is briefly described. Only the objects used in the analysis presented in Section 5 are considered here, and only general reconstruction and identification algorithms used in ATLAS are described, while the specific kinematical cuts chosen for the analysis are discussed in Section 4.1.

3.1 Electrons

Electron reconstruction and identification algorithms are designed to achieve both a large background rejection and a high and uniform efficiency for isolated high-energy ($E_T > 20$ GeV) electrons over the full acceptance of the detector. Isolated electrons need to be separated from hadron decays in QCD jets and from secondary electrons originating mostly from photon conversions in the tracker material.

Electron reconstruction is based on the identification of a set of clusters in the EM Calorimeter [62]. For each reconstructed cluster, the reconstruction algorithm tries to find a matching track in the ID. While the energy of the electron is determined using the calorimeter information, the more precise angular information from the ID track is used. The corrections applied to the measured cluster energy are based on precise MC simulations validated by comprehensive measurements with 900 GeV data [63].

The baseline ATLAS electron identification algorithm relies on variables which deliver good separation between isolated electrons and fake signatures from QCD jets. These variables include information from the calorimeter, the tracker and the matching between tracker and calorimeter. Cuts are applied on the energy in the Had Calorimeter inside the electron cone, on the shape of the electromagnetic shower, on the track impact parameter, on the number of hits in the different layers of the ID, on the difference between the calorimeter cluster and the extrapolated track positions in $\eta$ and $\phi$, on the ratio of the cluster energy to the track momentum ratio. Electrons passing all the identification requirements are called tight electrons, while loose and medium electrons pass only some of the above listed requirements.
3.2 Muons

Muon reconstruction is based on information from the MS, the ID and the calorimeters. Different kinds of muon candidates can be built, depending on how the detector information is used in the reconstruction. In the analyses described in this thesis, the so called *combined* muons are used. The information from the MS and from the ID is combined through a fit to the hits in the two sub-detectors to derive the muon momentum and direction.

ATLAS uses two different algorithms to reconstruct the muons: STACO \([64]\) and MuId \([65]\). Both muon combination algorithms create combined tracks out of pairs of MS-only and ID-only tracks. To do this, a \(\chi^2\) match is used and corrections are made for energy loss in the calorimeters. However, the two algorithms handle the combined track in a slightly different way:

- STACO does a statistical combination of the track vectors to obtain the combined track vector,
- MuId re-fits the combined track, starting from the ID track and then adding MS measures.

The two algorithms have shown very similar performances and can be both used for the analyses. In this thesis, muons reconstructed with MuId algorithm are used.

3.3 Jets

Hadronic particles deposit their energies mainly in the calorimeter system. In an attempt to resolve particles coming from the hard scatter, these energy deposits may be grouped into objects called jets.

**Jet input objects**

As described in Section 2.2.2, the ATLAS calorimeters have a high granularity (about 187000 independent read-out cells) and a high particles stopping power over the whole detector acceptance (\(|\eta| < 4.9\)). These calorimeter features allow a high quality jet reconstruction in the challenging environment of \(pp\) collisions at the LHC.

Calorimeter cells provide many informations: energy, time, quality, and gain. They are primarily set at the so-called “electromagnetic scale” (EM), as it has been determined by electron test beams and simulations. This energy scale accounts correctly for the energy of electrons and photons, but it underestimates hadron energy, since the calorimeters are non-compensating. As a consequence, EM showers generate larger signal than hadrons depositing the same energy. A specific correction for hadronic signals is therefore needed.

It’s not very convenient to use individual cell signals, because they can be negative, due to noise effects, and because it is difficult to determine the source of the signal without using also the information from neighbour cells. Cells have thus to be collected into larger objects like towers or topological clusters (topoclusters).
The jets considered in this thesis are built starting from topoclusters. Unlike calorimeter towers, that are built projecting the cell energy onto a two-dimensional grid in $\eta$-$\phi$ space, topological clusters reconstruct three-dimensional energy deposits. Starting from seed cells with high signal-to-noise ratio, neighbouring cells with a signal-to-noise ratio above a certain threshold are iteratively added to the cluster.

Jet algorithms

The mapping from partons to jets is a complex problem and it depends strongly on which one is the jet algorithm used. Many solutions have been used or proposed to define jets.

In ATLAS the so called anti-$k_T$ algorithm [66] has been adopted as default. It is part of the wider class of “Cluster Algorithms”, based upon pair-wise clustering of the initial constituents. Two “distances” are defined: $d_{ij}$ between entities (particles, proto-jets) $i$ and $j$ and $d_{iB}$ between entity $i$ and the beam ($B$):

$$d_{ij} = \min\left(k_{T_i}^2, k_{T_j}^2\right) \frac{\Delta R_{ij}^2}{\Delta R^2}, \quad d_{iB} = k_{T_i}^2,$$

where $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$, and $k_{T_i}$, $y_i$ and $\phi_i$ are the transverse momentum, the rapidity and the azimuth of particle $i$.

The clustering proceeds by identifying the smallest distance among all the entities in the event:

- if it is a $d_{ij}$, $i$ and $j$ are combined in a single entity,
- if it is $d_{iB}$, $i$ is considered as a single jet and it is removed from the list of entities.

The distances are then recalculated and the procedure repeated until no entities are left.

Two parameters characterising the particular algorithm are introduced: $\Delta R$ and $p$. For large values of $\Delta R$, the $d_{ij}$ are smaller, and thus more merging takes place before jets are complete. The $p$ parameter, instead, causes a preferred ordering of clustering: if the sign of $p$ is positive, clusters with lower energy will be merged first, if it’s negative the clustering will start from higher energy clusters. In the anti-$k_T$ algorithm $p = -1$, meaning that objects with high relative momentum $k_T$ are merged first.

Compared to other jet algorithms like the “Cone Algorithms” (like SisCone [67]) or the other Cluster Algorithms (k$_T$ [68] and Cambridge/Aachen [69]), anti-$k_T$ is less sensitive to low energy constituents, its clustering procedure is faster, there is no need of introducing new parameters to decide whether two jets have to be split or merged (the so called “split & merge” procedure, present in the Cone Algorithms) and the resulting jet area is more regular.

The choice of the $\Delta R$ parameter is analysis dependent: the typical default values used in ATLAS are $\Delta R = 0.4$ and $\Delta R = 0.6$. For top quark pair events, characterized by many jets in the final state, a smaller cone size is more suitable, so that $\Delta R = 0.4$ has been chosen.
**Jet calibration**

The ATLAS calorimeters are non-compensating, and the energy of hadronic particles is underestimated. In order to reconstruct the energy of the jets, a calibration procedure is needed. ATLAS has developed several calibration schemes with different levels of complexity.

The jets used in the analyses described in this thesis are calibrated using the simplest scheme, the so called “EMJES”. The goal of the Jet Energy Scale (JES) calibration, here called EMJES because it is applied on top of the EM scale, is to correct the energy and momentum of jets measured in the calorimeter, using as reference the kinematics of the corresponding jets in the MC simulation. The jet energy scale calibration is derived as a global function depending on $p_T$ and $\eta$.

### 3.4 $b$-jets reconstruction

The aim of $b$-tagging algorithms is to identify jets containing $b$-flavoured hadrons. For each selected jet they provide $b$-weights reflecting the probability that it originates from a $b$-quark. The discrimination of $b$-quark jets from light quark jets originates mainly in the relatively long lifetime of $b$-flavoured hadrons, resulting in a significant flight path length $L \sim$ mm. This leads to measurable secondary vertices and impact parameters of the decay products.

The transverse impact parameter $d_0$ is the distance in the transverse plane $(x,y)$ between the point of the closest approach of a track to the primary vertex; the longitudinal impact parameter $z_0$ is the $z$-coordinate of this point. Various $b$-tagging algorithms (or “taggers”) can be defined, based on these discrimination variables ($L$, $d_0$ and $z_0$), on secondary vertex properties and on the presence of leptons within $b$-quark jets. Each tagging algorithm defines a “weight” $w$, associated to the probability for a given jet to have been originated from a $b$-quark. For each tagging algorithm, different “working points”, i.e. different threshold on the $w$ variable cut to define a “tagged” jet, can be used. The choice of the working point sets the tagging efficiencies for $b$, $c$- and light quark jets. Figure 3.1 (left) shows the light quark jet rejection (defined as the inverse of the light quark jet tagging efficiency) as a function of the $b$-quark jet tagging efficiency (also called simply $b$-tagging efficiency), obtained varying the working point for the different considered taggers.

In the following, the two algorithms used for the $t\bar{t}$ cross-section measurements in 2010 and 2011 respectively are described.

- **SV0 algorithm**
  
  The SV0 tagging algorithm is based on the reconstruction of secondary vertices from tracks within a jet. A track is associated to a jet if its distance from the jet axis in $\Delta R$ is lower than a given threshold. The SV0 algorithm starts by reconstructing two-track vertices significantly displaced from the primary vertex. The algorithm then removes two-track vertices with a mass consistent with a $K^0_s$ meson, a $\Lambda^0$ baryon or a photon conversion. For each jet, the tracks contained in all the surviving two-track vertices are fitted to a single secondary vertex. The weight $w$ is defined as the signed
decay length significance, $L/\sigma(L)$, of the reconstructed secondary vertex, where the sign of $L/\sigma(L)$ is given by the projection of the decay length vector on the jet axis.

- **JetFitterCombinedNN**
  The JetFitterCombinedNN algorithm is the combination of two tagging algorithms: JetFitter and IP3D. JetFitter exploits the topology of weak $b$- and $c$-hadron decays inside the jet, using a Kalman Filter to define a common line on which the primary vertex and the $b$- and $c$-hadron decay vertices lie, as well as their position on this line, giving an approximated flight path for the $b$-hadron. The discrimination between $b$-, $c$- and light jets is based on a likelihood which uses the masses, momenta, flight-length significances and track multiplicities of the reconstructed vertices as inputs. The second tagger (IP3D) does not attempt to directly reconstruct decay-vertices, but uses instead the $d_0$ and $z_0$ significances of each track to determine a likelihood probability for the jet to originate from a $b$-quark. The JetFitter and IP3D tagger results are combined using an artificial neural network (NN) to determine a single weight $w$. Figure 3.1 (right) shows the distribution of the JetFitterCombinedNN tagger weight comparing 2011 data and MC.

Performance and calibrations for the described $b$-tagging algorithms are described in [70] and [71] for the SV0 tagger, and in [72] for the JetFitterCombinedNN tagger.
3.5 Missing transverse energy

Neutrinos, as well as other BSM particles which are expected not to interact with the detector, can be reconstructed using the difference between the initial state and final state total momentum. In hadron colliders, such as the LHC, the initial momentum of the colliding partons along the beam axis is not known a priori, so that the amount of total missing energy cannot be determined. However, the initial momentum transverse to the beam axis is in good approximation zero, so that the missing energy can be measured in the transverse plane (missing transverse energy or $\mathbf{E}_T$).

The $\mathbf{E}_T$ measurement in an event with a top quark pair decaying semileptonically gives the possibility to reconstruct the energy of the neutrino, coming from the leptonic $W$-boson decay.

The $\mathbf{E}_T$ reconstruction presently used in ATLAS for physics analysis, includes contributions from transverse energy deposits in the calorimeters, corrections for energy losses in the cryostat and measured muons. Its components along the coordinate axes in the $xy$-plane are:

$$E_{x(y)} = E_{x(y)}^{\text{calo}} + E_{x(y)}^\mu + E_{x(y)}^{\text{CellOut}},$$

and the missing transverse energy is simply defined as:

$$\mathbf{E}_T = \sqrt{(E_x)^2 + (E_y)^2}.\quad (3.3)$$

The calorimeter term $E_{x(y)}^{\text{calo}}$ is built starting from the calorimeter cells over the range $|\eta| < 4.9$. Only cells belonging to topoclusters (see Section 3.3) are considered. The most refined scheme developed in ATLAS (the so called “RefFinal” calibration) calibrates cells energy on the base of the reconstructed high-$p_T$ physics object they belong to: electrons, photons, hadronically decaying $\tau$-leptons, jets and muons. Depending on the type of associated object, the cells are separately and independently calibrated. The calorimeter term components is then evaluated by summing different terms:

$$E_{x(y)}^{\text{calo}} = E_{x(y)}^e + E_{x(y)}^\gamma + \sum E_{x(y)}^{\text{jets}} + E_{x(y)}^{\mu(\text{calo})} + E_{x(y)}^{\text{CellOut}},\quad (3.4)$$

where each term is calculated from the negative sum of cell energies calibrated according to the corresponding objects. The $E_{x(y)}^{\mu(\text{calo})}$ term is the contribution to $\mathbf{E}_T$ from the energy lost by muons in the calorimeter (see below). The $E_{x(y)}^{\text{CellOut}}$ term is calculated from the cells in topoclusters which are not included in the reconstructed objects.

The $\mathbf{E}_T$ muon term $E_{x(y)}^\mu$ is calculated from muon momenta, combining the information from MS and ID for isolated muons with $|\eta| < 2.5$, or using the MS information only for non-isolated muons and for muons outside the $\eta$ range of the ID. The energy lost by the muon in the calorimeters ($E_{x(y)}^{\mu(\text{calo})}$) is added to the calorimeter term in the latter case.

The cryostat between the LAr barrel electromagnetic calorimeter and the Tile barrel hadronic calorimeter has a thickness of about half an interaction length and it can lead $^1$A muon is non-isolated if there is a jet in the event within a distance $\Delta R = 0.3$.  

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to significant energy losses in hadronic showers. The $E_T$ cryostat term $E_{x(y)}^{cryo}$, calculated exploiting the correlation of energies between the last layer of the LAr calorimeter and the first layer of the Had calorimeter, takes into account this lost energy.
Chapter 4

Top pairs selection in the single lepton channel

As discussed in Section 1.3, the selection of events coming from semileptonic $t\bar{t}$ decay relies on the identification and reconstruction of electrons, muons, jets and $b$-jets. Another important ingredient for this purpose is the reconstruction of neutrinos, which however don’t interact in the detector. Their energy can be partially reconstructed as missing transverse energy ($E_T$).

The first step to perform a cross-section measurement is to select the signal events in which we are interested, isolating them from events coming from other processes or which have been badly reconstructed. The same event selection has to be also applied to MC-simulated events, in order to be able to compare with the signal and background process expectation.

In the analysis described in this thesis, the events of interest are the events coming from the semi-leptonic $t\bar{t}$ decay.

4.1 Objects and event selection criteria

4.1.1 Objects selection

The reconstruction of $t\bar{t}$ events in the semi-leptonic channel makes use of reconstructed electrons, muons and jets, as well as of the missing transverse energy $E_T$, which is sensitive to the momentum imbalance in the transverse plane, indicating the presence of escaping neutrinos. The following criteria are used to define the selected objects in an event.

Electrons

Each electron is required to pass the tight cuts described in Section 3 in order to be considered as a good electron for the analysis. A minimum $E_T$ is also required, depending on the considered data: for the 2010 data analysis the electron is required to have $E_T > 20$ GeV, while for the 2011 data analysis, the threshold is raised to 25 GeV, mainly due to the use of a higher threshold single electron trigger (see Section 4.1.2).
Electrons are reconstructed in the central region of the detector, where both the calorimeter and the tracker system are fully operational. They are required to have $|\eta_{\text{cluster}}| < 2.47$, where $\eta_{\text{cluster}}$ is the pseudorapidity of the calorimeter energy cluster associated with the electron candidate. The calorimeter crack region at $1.37 < |\eta_{\text{cluster}}| < 1.52$ is excluded.

To reduce the background from electrons coming from hadron decays, (i.e. from heavy flavour decays inside jets), the electron has to be isolated, and a cut on the variable $etcone20$ is applied. This variable is built summing the $E_T$ deposited in the calorimeter towers in a cone of radius $\Delta R = 0.2$ in $\eta$-$\phi$ space around the electron position. The $E_T$ due to the electron ($E_T^e$) is subtracted. For the 2010 data analysis the cut $etcone20 < 4 \text{ GeV}$ is applied. For the 2011 one, due to the increased pile-up rate affecting the isolation variable, a pile-up correction is added to the isolation variable, and the cut on it is tightened to $etcone20 < 3.5 \text{ GeV}$.

**Muons**

For both the 2010 and the 2011 data analyses combined muons reconstructed with the algorithm MuId are used. Muons are required to have a minimum $p_T$ of 20 GeV and to be in the detector central region ($|\eta| < 2.5$). Quality cuts are applied to the Inner Detector track associated to each muon.

As for electrons, an isolation cut is used considering both the $etcone30$ variable (similar to the $etcone20$ one, but where the $E_T$ deposited in the calorimeter towers is summed in a cone of 0.3) and the $ptcone30$ variable (the analogous of $etcone30$ but summing the $p_T$ of the tracks in the Inner Detector around the muon track). It is then imposed that $etcone30 < 4 \text{ GeV}$ and $ptcone30 < 4 \text{ GeV}$.

Additionally, muons are required to have a distance $\Delta R > 0.4$ from any jet with $p_T > 20 \text{ GeV}$, to further suppress muons from heavy flavour decays inside jets.

**Jets**

The anti-$k_T$ algorithm with $\Delta R = 0.4$ is used to reconstruct the jets. Jets are required to have $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$.

Since reconstructed electrons might also be reconstructed as jets in the calorimeter, any jet overlapping with a selected electron within a cone of $\Delta R < 0.2$ is removed from the list of jets.

Jet quality criteria are applied to identify those jets not associated to in-time real energy deposits in the calorimeters due to various sources as hardware problems in the calorimeter, the LHC beam conditions, and the atmospheric muon-ray induced showers (bad jets).

**B-quark jets**

Jets satisfying the above requirements, can be classified as jets coming from the fragmentation of a $b$-quark if they are identified by a chosen $b$-tagging algorithm. The different $b$-tagging algorithms used to identify $tt$ candidate events are described in Section 3.4.
For the 2010 analysis, the $b$-tagging algorithm is the SV0 tagger. A working point defined by $w > 5.85$ is chosen, corresponding to a 50% tagging efficiency for $b$-quark jets. The choice of the tagger and of the working point is made in order to maximize the expected significance of a $t\bar{t}$ signal when requiring $\geq 1$ $b$-tagged jet with the first 2.9 pb$^{-1}$ of data (see [29]).

For 2011 data, the higher performance tagger JetFitterCombinedNN is used. The chosen working point ($w > 0.35$) corresponds to a 70% $b$-tagging efficiency. This choice is made in order to minimize the effect of the $b$-tagging efficiency uncertainty on the $t\bar{t}$ cross-section measurement (see Section 5.2).

### Missing Transverse Energy

A threshold on the $E_T$ variable, calibrated with the RefFinal scheme, is applied for the analyses described in this thesis. This threshold is channel-dependent, as will be shown in Section 4.1.4.

### $W$ Transverse Mass

In single lepton events, when the lepton is originated from the decay of a $W$-boson (i.e. in most of the signal events, as well as in $W$+jet and single top events), the $E_T$ is originated by the neutrino produced in association with the lepton. The invariant mass of the $\ell+\nu$ system should match the $W$-boson mass for the events of interest. While the full system cannot be reconstructed due to the missing information of the neutrino longitudinal momentum, a variable $m_T(W)$ can be defined as:

$$m_T(W) = \sqrt{2p_T^{\ell}p_T^{\nu}(1 - \cos(\phi^{\ell} - \phi^{\nu}))},$$

(4.1)

and can be measured by assuming $p_T^{\nu} = E_T$ and $\phi^{\nu} = \tan(\theta_{y}/\theta_{x})$ (the direction of the missing energy in the transverse plane).

The $W$-boson transverse mass variable is used together with the $E_T$ to define selection cuts aimed to suppress the fake lepton background, as described in Section 4.1.4. In Figure 4.1, the 2-dimensional distribution of $E_T$ v.s. $m_T(W)$ is shown, for $t\bar{t}$ and QCD fake lepton background events in the $e$+jet and $\mu$+jet channels. The channel-specific $E_T$ and $m_T(W)$ cuts are shown.

### 4.1.2 Trigger selection

Since all the events to be selected are supposed to have in the final state exactly one high $p_T$ and isolated electron or muon, all the events are required to fire a single electron or single muon trigger.

The detailed trigger requirements varied through the data-taking period due to the rapidly increasing LHC luminosity and the commissioning of the trigger system, as described below.

The thresholds have always been set low enough to ensure that leptons with $p_T > 20$ GeV (or 25 GeV for the 2011 analysis in the electron channel) lie in the efficiency plateau.
Figure 4.1. $E_T$ v.s. $m_T(W)$ distribution for $t\bar{t}$ (left) and QCD (right) events in the $e$+jets (top) and $\mu$+jets (bottom) channels. The $t\bar{t}$ events distribution is taken from MC simulation, while the QCD is extracted from data using the method described in Section 6.1.5 and 6.1.6. The applied cuts on these variables are also shown.

The electron selection requires a L1 electromagnetic cluster with $p_T > 10$ GeV. A more refined electromagnetic cluster selection is required in the L2 trigger. Subsequently, a match between the selected calorimeter electromagnetic cluster and an Inner Detector track is required in the EF. Muons are selected requiring a $p_T > 10$ GeV momentum threshold muon trigger chamber track at L1, matched by a muon reconstructed in the precision chambers at the EF.

All the events are also required to have the single selected electron or muon matching the corresponding trigger object within a $\Delta R$ of 0.15.
4.1.3 Event quality cuts

After the trigger selections, the following event quality cuts are applied to reject those events which are not properly reconstructed:

- events must have at least one offline-reconstructed primary vertex with at least five tracks, to reject non-collision background events;
- any event is discarded if a selected electron is also reconstructed as a muon;
- events with a bad jet (see Section 4.1.1) above a $p_T$ threshold are rejected;
- events where some of the objects are reconstructed within problematic regions of the detector are rejected.

4.1.4 Event selection cuts

The event selection for the $t\bar{t}$ single-lepton analysis consists of a series of requirements on the reconstructed objects as defined in Section 4.1.1. For the $e$+jets and $\mu$+jets channels, different event selections are applied. Here follow the selection criteria for the final states:

- the appropriate single-electron or single-muon trigger is fired;
- the event quality cuts are applied;
- the event contains exactly one reconstructed lepton (electron or muon, depending on the channel), matching the corresponding high-level trigger object;
- in the $e$+jets channel: $E_T > 35$ GeV and $m_T(W) > 25$ GeV;
- in the $\mu$+jets channel: $E_T > 20$ GeV and $E_T + m_T(W) > 60$ GeV;
- the event must have at least one jet.

Events are then classified according to the number of jets (we will refer to this classification in the following as “jet multiplicity”), being either one, two, three, four, at least four or at least five. This defines the so called “pretag” selection, which consists in pretag samples depending on the jet multiplicity in the event. Subsets of these samples are then defined with the additional requirement that at least one of the jets is tagged as a $b$-quark jet (“tagged” or “$b$-tag” samples). As an example, the “pretag 2-jets” sample contains all the events with exactly two jets, while the “$b$-tag ≥ 4-jets” sample contains all the events with at least four jets and at least one $b$-tagged jet.

$t\bar{t}$ signal events are expected to be reconstructed mainly in the ≥ 4-jet pretag and $b$-tag samples (the so called “signal region”), while the lower jet multiplicity samples (the “control region”) are used to check the data-driven background estimation methods described in Section 6.
4.2 Data samples

Only data for which all the subsystems described in Section 2.2 are fully operational are used in the analysis. Applying these requirements to $\sqrt{s} = 7$ TeV $pp$ collision data taken in stable beam conditions during the 2010 LHC run, results in a data sample of $35 \text{ pb}^{-1}$. The 2011 data selected with the same requirements, considering only the data collected up to August used in the analysis, correspond to an integrated luminosity of $2.05 \text{ fb}^{-1}$. The luminosity is determined from proton scattering measurements and Van der Meer scans, with a relative uncertainty of 3.4% for 2010 data [73] and of 3.7% for 2011 data [74].

Data samples are divided in several data-taking periods and sub-periods, presenting different beam and detector conditions. Figure 4.2 and 4.3 show the number of selected events in 2010 and 2011 data respectively, as a function of the data-taking sub-periods considered for the analysis, divided by the integrated luminosity. These plots are useful to check the stability of the event selection efficiency and its dependence on the different beam and detector conditions.
4.3 Monte Carlo simulation

MC simulation samples are used to develop and validate the analysis procedures, to calculate the acceptance for $t\bar{t}$ events and to evaluate the contributions from several background processes.

For the $t\bar{t}$ signal and the single top background, the NLO generator MC@NLO v3.41 [75] is used, assuming a top-quark mass of 172.5 GeV and with the NLO parton density function (PDF) set CTEQ66 [76]. For single top, the “diagram removal scheme” [77] is used, to remove overlaps between the single top and the $t\bar{t}$ final states.

For the main non-top backgrounds, consisting of $W/Z$ boson production in association with multiple jets, ALPGEN v2.13 [78] is used, which implements the exact LO matrix elements for final states with up to six partons. Using the LO PDF set CTEQ6L1 [80], the following backgrounds are generated: $W+$jet events with up to five partons and $Z/\gamma+$jet events with up to five partons and with the dilepton invariant mass $m_{\ell\ell} > 40$ GeV. The “MLM” matching scheme of the ALPGEN generator [79] is used to remove overlaps between the $n$ and $n+1$ parton samples. For all the processes, separate samples are generated that include $b$- and $c$-quark pair production at the matrix element level. In addition, for the $W+$jets process, a separate sample containing $W+c+$jet events is produced.

Diboson $WW+$jet, $WZ+$jet and $ZZ+$jet events are produced using HERWIG v6.510 [81]. The background cross-sections are normalized to the highest order calculations available for the different processes. Approximate NNLO predictions are used for $t\bar{t}$ [25], single top [37] [38] [39], and $W/Z+$jets [82], while for dibosons, NLO predictions [83] are available.

The parton shower and the underlying event are added using the HERWIG and JIMMY [84] generators with the AUET1 tune [85] to the ATLAS data. The ATLAS detector response is simulated using GEANT4 [86] and the standard ATLAS reconstruction software is used [87]. For the pile-up simulation PYTHIA6 [88] minimum bias events are used and variable pile-up rates are assumed.

4.4 Systematic uncertainties

The use of a MC simulation to predict the $t\bar{t}$ selection efficiency, as well as to predict part of the backgrounds, introduces a number of systematic uncertainties on the $t\bar{t}$ cross-section measurement.

Some of the systematic uncertainties are related to the object identification, reconstruction and energy measurement, while other systematics are related to the event generation, the theoretical knowledge of the production cross-section and the PDFs. Uncertainties specific for the different data-driven methods used to estimate the QCD fake and $W+$jet backgrounds are not listed here, and are instead discussed in Section 6.

Here follow the main sources of systematics:

Jet reconstruction uncertainties

The jet reconstruction performances and their uncertainties are derived by combining information from test-beam data, collision data and simulation [89] [90], and are parametrized
as a function of jet properties.

- The Jet Energy Scale (JES) uncertainty is evaluated by shifting up and down the energy of all the jets in the simulated samples by a $p_T$- and $\eta$-dependent fraction, which varies from 4 to 10%. The dependence on the gluon and quark content of the simulated samples is taken into account, as well as the distance between the jets. The energy scale for $b$-jets is different from the energy scale for light jets, and this is correctly taken into account scaling the $b$-jet energy independently. The effect of a higher pile-up level in the 2011 data is taken into account by assigning a higher uncertainty to the low-$p_T$ jets.

- The Jet Energy Resolution (JER) uncertainty is taken into account by performing a jet $p_T$ smearing to reflect the resolution for the jet energy observed in data, considering the difference with the un-smeared MC as a systematic uncertainty.

- The jet reconstruction efficiency (JRE) is measured in data by looking at jets identified using the ID. The effect of the $\sim 2\%$ lower JRE measured in data with respect to the MC simulation is evaluated by randomly dropping jets from events with a probability of about 2%. The resulting difference with respect to the nominal case is symmetrized and quoted as systematic uncertainty.

Lepton reconstruction uncertainty

The MC modelling of the lepton trigger and reconstruction performances is checked using $Z \to \ell\ell$ data events, selected asking for two same-flavour leptons with an invariant mass in a $Z$-boson mass window. The “Tag & Probe” technique is used to measure the efficiency of the single electron (muon) triggers and of the $e$ ($\mu$) reconstruction and identification. The energy (momentum) scale and resolution of selected electrons (muons) are measured looking at the $Z$-boson mass peak position and resolution. The uncertainties on the measurement of these quantities are considered as systematic uncertainties.

Missing Energy uncertainty

The $E_T$ is calculated taking into account the contributions of jets, electrons and muons in the event. Any shift applied as a systematic uncertainty on the energy of these objects is propagated to the $E_T$ calculation. In addition, the uncertainty contribution from soft jets and the unclustered energy is considered as an additional explicit $E_T$ uncertainty.

$b$-tagging uncertainties

The performances of the tagging algorithms in identifying or mis-identifying $b$-, $c$- and light-jets are measured in data [70] [71] [72], and the MC events are corrected accordingly. The uncertainties on these calibrations are propagated to the analyses. The $b$- and the $c$-tagging efficiencies are considered as correlated between them and uncorrelated with the light-tagging efficiency.
MC event generator uncertainties

As discussed in Section 4.3, different event generators with possible different settings are compared to check the dependence of the analysis on the specific event simulation. The following sources are considered as systematic uncertainties in the $tt$ sample generation:

- the effect of using different NLO MC generators is considered comparing the standard sample generated with MC@NLO, with a sample generated with POWHEG \[^1\];
- the effect of different showering models is taken into account by comparing the results using POWHEG+HERWIG and POWHEG+PYTHIA;
- in order to take into account the uncertainty on the amount of simulated initial and final state QCD radiation (ISR and FSR), which can introduce additional gluon jets in the observed events, a set of dedicated samples generated with the AcerMC \[^2\] LO event generator by varying the ISR and FSR parameters inside the parton shower (PYTHIA) is used, quoting as systematic uncertainty the maximum discrepancy observed from the default AcerMC sample. \[^2\]

For $W$+jets, the MC samples generated with ALPGEN are compared with samples generated with SHERPA \[^3\].

Parton Distribution Functions (PDF)

The parton distribution functions (PDFs) to model the incoming partons to the hard scattering process are used as input by the MC generators. These PDFs were measured from data (i.e. in deep inelastic scattering experiments) and have therefore associated uncertainties. These uncertainties are propagated to the analysis by assigning different weight to each simulated event depending on the properties of the incoming partons, for each of a number of variations. The variations in the resulting pseudo-samples are then taken into account to extract a systematic uncertainty on the PDFs. In the presented analysis, the PDF uncertainty is considered for $tt$ and $W$+jet events.

Theoretical cross-section uncertainties

For the $Z$+jet, single top and diboson backgrounds, for which the expected number of events is taken from the MC simulation normalized by the theoretical cross-section (see Section 4.3), an uncertainty on this theoretical cross-section is considered. For the $Z$+jets background the theory uncertainty is taken to be 4% (which is the theoretical uncertainty on the inclusive $Z$+jets production), but an additional 24% uncertainty per additional jet in the event is added in quadrature (according to the results of different parameter variations in the MC generator). For single top and diboson production, only overall

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[^1]: In this case the same parton shower HERWIG is used for both the NLO MC event generators.
[^2]: The parameters controlling the ISR/FSR branching probabilities are variated in order to separately minimize or maximize the ISR and FSR effects. The variation ranges are comparable to the ones used in \[^3\].
normalization uncertainties are considered and these are taken to be 11% and 5%, respectively.

Pile-up

The amount of pile-up in data is measured looking at the average number of interactions per bunch crossing $\langle \mu \rangle$. The MC simulated samples are produced together with a certain amount of pile-up, with a certain $\langle \mu \rangle$ distribution which is in principle different to the $\langle \mu \rangle$ distribution in data. Depending on the data period the MC simulation has to be compared with, the MC can be re-weighted according to the bin-by-bin ratio of the respective $\langle \mu \rangle$ distributions. For the 2010 data analysis, re-weighted MC samples are compared with the un-weighted default MC to quote an uncertainty coming from pile-up. For the 2011 data analysis, this MC re-weighting is applied by default and the effect of the pile-up uncertainty is evaluated applying larger energy scale variations to the low-$p_T$ jets and to the un-clustered energy in the calorimeter.
Chapter 5

Result: cross-section measurement

The selection cuts described in Section 4.1 are designed to isolate $t\bar{t}$ events with semi-leptonic final states. However, events coming from a number of different processes are expected to survive the event selection, and their contribution to the final sample has to be taken into account.

The $t\bar{t}$ cross-section is extracted using a simple counting method. The signal yield $N_{t\bar{t}}$ after the event selection is obtained subtracting the estimated background yield $N_{bkg}$ from the number of observed events $N_{data}$. The $\sigma_{t\bar{t}}$ is derived dividing by the considered integrated luminosity $\int L dt$ and the signal selection efficiency $\epsilon_{t\bar{t}}$:

$$\sigma_{t\bar{t}} = \frac{N_{t\bar{t}}}{\int L dt \cdot \epsilon_{t\bar{t}}} \approx \frac{N_{data} - N_{bkg}}{\int L dt \cdot \epsilon_{t\bar{t}}}.$$  \hspace{1cm} (5.1)

Here $\epsilon_{t\bar{t}}$ is evaluated from MC simulation and includes the branching ratio for the considered channel ($e$+jets or $\mu$+jets), the angular acceptance and the efficiency of the kinematical cuts.

$N_{bkg}$ is the sum of the contributions from the different backgrounds. The two main background sources, QCD and $W$+jets, are evaluated with data-driven methods, explained in detail in Section 4. The other backgrounds (single top, $Z$+jets and diboson) are taken from MC simulation.

For a given integrated luminosity, the statistical uncertainty depends on both $\epsilon_{t\bar{t}}$ and $N_{bkg}$. Also the uncertainty on the knowledge of $N_{bkg}$ contributes to the total uncertainty, depending on the purity of the selected signal sample. A compromise between a high efficiency and a high purity event selection is therefore needed. This point is especially important for the 2010 data analysis, where the integrated luminosity is smaller.

In addition, the event selection has to be as less sensitive as possible to the systematic uncertainties affecting $\epsilon_{t\bar{t}}$, especially the Jet Energy Scale (JES) and the $b$-tagging efficiency uncertainty. This point becomes more important for the 2011 data, where both the statistical and the background estimation uncertainties are considerably smaller than for the 2010 data analysis, thanks to the higher integrated luminosity.
5.1 Cross-section measurement with the 2010 data

In the 2010 data analysis, the measurement is performed in the $\geq$4-jets pretag and $b$-tag samples. The results are reported in [95] and [96].

![Graphs showing jet multiplicity distribution](image)

Figure 5.1. Distribution of jet multiplicity in the $\geq$1-jet pretag and $b$-tag samples, for the $e$+jet and $\mu$+jet channels.

To estimate the QCD background, two different methods are used for the two channels. In the $e$+jets channel a template fit on the $E_T$ variable is performed, taking the shape for the QCD background from a data sample orthogonal to the signal one, obtained by inverting some of the selection cuts for the electron. In the $\mu$+jets channel, the so called Matrix Method is used: the number of data events are counted using a looser muon selection (i.e. dropping the muon isolation cut) and is compared with the number of data events with the standard selection. By knowing the probabilities for QCD events and for “real lepton” events which pass the looser selection to survive the standard selection...
as well, the number of QCD events in the standard selected sample is extracted. Both methods are described in details in Section 6.1.

![Graph](image)

Figure 5.2. Number of b-tagged jets in the ≥4-jet pretag sample, for the e+jet and μ+jet channels.

The W+jets background in the pretag sample is extracted using the W/Z Ratio method, based on counting the number of Z+jet events after a selection requiring two leptons instead of one lepton and $E_T$, and multiplying by the ratio of W+jet over Z+jet events extracted from a low jet multiplicity control region. Other two methods are used to cross-check the results, and the W/Z Ratio method is chosen since it gives the smallest uncertainty. The number of W+jet background events in the b-tag sample is extracted multiplying the pretag yield by a tagging fraction obtained from a low jet multiplicity control region and corrected using MC simulation. For the details of the W+jets background estimation, see Section 6.2.

The $\sigma_{t \bar{t}}$ is extracted separately for e+jets and μ+jets and in the two selection samples pretag and b-tag ≥4-jets. The numbers of selected signal, background and data events are reported in Tables 5.1 and 5.2 including the lower jet multiplicity bins used as control regions. The same information is also reported in Figure 5.1 which shows the jet multiplicity distribution plots. Figure 5.2 shows the number of b-tagged jets in the pretag ≥4-jets sample: the sum of the two right-most bins corresponds to the b-tag selection. Figure 5.3 shows the distribution of the hadronic top candidate invariant mass for events passing the pretag and the b-tag ≥4-jets selection, where the hadronic top candidate is defined as the three-jet combination with the highest total transverse momentum ($m_{jjj}$).

The results of the measurement in the two channels and for the two selection samples are shown in Table 5.3, including the number of selected data events, the total estimated background yield and the extracted number of signal events.

The two e+jet and μ+jet channels are then combined using a Bayesian approach (see for an introduction to Bayesian analysis). This allows a straightforward treatment of the systematic uncertainties and their correlation between the two channels.
### Table 5.1

Number of events in the (a) pretag and (b) b-tag samples with different jet multiplicities in the e+jets channel. The observed number of events are shown, together with the MC simulation prediction for $t\bar{t}$, $W$+jet, $Z$+jet and single-top events, normalised to the integrated luminosity of 35 pb$^{-1}$. The data-driven estimates for the QCD fake background (see Section 6.1) are also shown.

#### (a)

<table>
<thead>
<tr>
<th>Pretag e+jets</th>
<th>1-jet</th>
<th>2-jet</th>
<th>3-jet</th>
<th>$\geq$4-jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>$14 \pm 3$</td>
<td>$61 \pm 9$</td>
<td>$116 \pm 13$</td>
<td>$193 \pm 27$</td>
</tr>
<tr>
<td>QCD</td>
<td>$287 \pm 143$</td>
<td>$123 \pm 61$</td>
<td>$62 \pm 31$</td>
<td>$22 \pm 11$</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>$9005 \pm 1892$</td>
<td>$2337 \pm 748$</td>
<td>$584 \pm 251$</td>
<td>$183 \pm 115$</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>$65 \pm 14$</td>
<td>$62 \pm 20$</td>
<td>$32 \pm 14$</td>
<td>$18 \pm 11$</td>
</tr>
<tr>
<td>single top</td>
<td>$36 \pm 4$</td>
<td>$42 \pm 5$</td>
<td>$22 \pm 4$</td>
<td>$11 \pm 3$</td>
</tr>
<tr>
<td>diboson</td>
<td>$35 \pm 3$</td>
<td>$30 \pm 2$</td>
<td>$9 \pm 2$</td>
<td>$3 \pm 1$</td>
</tr>
<tr>
<td>Total background</td>
<td>$9429 \pm 1897$</td>
<td>$2595 \pm 751$</td>
<td>$709 \pm 253$</td>
<td>$236 \pm 116$</td>
</tr>
<tr>
<td>Total expected</td>
<td>$9443 \pm 1897$</td>
<td>$2656 \pm 751$</td>
<td>$823 \pm 254$</td>
<td>$430 \pm 119$</td>
</tr>
<tr>
<td>Observed</td>
<td>$9481$</td>
<td>$2552$</td>
<td>$781$</td>
<td>$400$</td>
</tr>
</tbody>
</table>

#### (b)

<table>
<thead>
<tr>
<th>b-tag e+jets</th>
<th>1-jet</th>
<th>2-jet</th>
<th>3-jet</th>
<th>$\geq$4-jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>$5 \pm 1$</td>
<td>$33 \pm 6$</td>
<td>$75 \pm 11$</td>
<td>$135 \pm 23$</td>
</tr>
<tr>
<td>QCD</td>
<td>$14 \pm 7$</td>
<td>$15 \pm 8$</td>
<td>$11 \pm 9$</td>
<td>$9 \pm 9$</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>$105 \pm 39$</td>
<td>$77 \pm 35$</td>
<td>$32 \pm 18$</td>
<td>$16 \pm 12$</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>$0.3 \pm 0.1$</td>
<td>$1.5 \pm 0.5$</td>
<td>$1.1 \pm 0.5$</td>
<td>$1.5 \pm 1.0$</td>
</tr>
<tr>
<td>single top</td>
<td>$13 \pm 2$</td>
<td>$20 \pm 3$</td>
<td>$12 \pm 3$</td>
<td>$7 \pm 2$</td>
</tr>
<tr>
<td>diboson</td>
<td>$1.1 \pm 0.2$</td>
<td>$1.8 \pm 0.3$</td>
<td>$0.7 \pm 0.2$</td>
<td>$0.2 \pm 0.1$</td>
</tr>
<tr>
<td>Total background</td>
<td>$133 \pm 39$</td>
<td>$116 \pm 36$</td>
<td>$56 \pm 20$</td>
<td>$33 \pm 16$</td>
</tr>
<tr>
<td>Total expected</td>
<td>$138 \pm 40$</td>
<td>$149 \pm 36$</td>
<td>$131 \pm 23$</td>
<td>$168 \pm 28$</td>
</tr>
<tr>
<td>Observed</td>
<td>$147$</td>
<td>$133$</td>
<td>$173$</td>
<td>$156$</td>
</tr>
</tbody>
</table>
Table 5.2. Number of events in the (a) pretag and (b) $b$-tag samples with different jet multiplicities in the $\mu$+jets channel. The observed number of events are shown, together with the MC simulation prediction for $t\bar{t}$, $W$+jet, $Z$+jet and single-top events, normalised to the integrated luminosity of 35 pb$^{-1}$. The data-driven estimates for the QCD fake background (see Section 6.1) are also shown.
Figure 5.3. Distribution of the invariant mass of the three-jet combination with highest \( p_T \) in the \( \geq 4 \)-jet pretag and \( b \)-tag samples, for the \( e^+ \)jet and \( \mu^+ \)jet channels.

Table 5.4 provides a detailed breakdown of the total systematic uncertainties on the cross-section for the different channels and selection samples.

The method is based on the extraction of a posterior probability density function (pdf) for the parameter of interest (in this case the combined \( \sigma_{t\bar{t}} \)) as the product of its prior probability times a likelihood (built as the product of two Poisson likelihoods for the two considered channels), following Bayes theorem. The effect of each systematic uncertainty is accounted for by including in the likelihood the dependence of the combined cross-section from a number of nuisance parameters and multiplying by their prior probabilities. The posterior pdf of \( \sigma_{t\bar{t}} \) is then obtained by integrating out the dependence on the nuisance parameters (marginalization) and solving the Bayes formula.

The marginalization over the uncertainties is performed using the Markov Chain Monte Carlo (MCMC) technique as implemented in the Bayesian Analysis Toolkit [98]. A flat
### 2010 data pretag $e$+jets | pretag $\mu$+jets | $b$-tag $e$+jets | $b$-tag $\mu$+jets
---|---|---|---
$N_{\text{data}}$ | 400 | 653 | 156 | 246
$N_{\text{bkg}}$ | $208 \pm 41$ | $401 \pm 64$ | $29 \pm 9$ | $64 \pm 14$
$\epsilon_{t\bar{t}}$ | $0.033 \pm 0.005$ | $0.047 \pm 0.007$ | $0.0224 \pm 0.004$ | $0.0319 \pm 0.006$

### $\sigma_{t\bar{t}}$ [pb]
| 2010 data pretag $e$+jets | pretag $\mu$+jets | $b$-tag $e$+jets | $b$-tag $\mu$+jets |
---|---|---|---|
| $164 \pm 17$ & $152 \pm 15$ & $155 \pm 15$ & $157 \pm 13$ |

Table 5.3. Number of observed events, total estimated background and signal selection efficiency, in the $\geq 4$-jets pretag and $b$-tag samples for the $e$+jet and $\mu$+jet channels. The reported numbers are used, together with the integrated luminosity $\int L \, dt = 35.3 \pm 1.2 \, \text{pb}^{-1}$, to extract the measured values for $\sigma_{t\bar{t}}$ in each of the samples. The three quoted uncertainties correspond to the statistical, the systematic and the luminosity contributions.

### 2010 data pretag $e$+jets | pretag $\mu$+jets | $b$-tag $e$+jets | $b$-tag $\mu$+jets
---|---|---|---
| Statistical error | $\pm 10.4$ | $\pm 10.2$ | $\pm 9.8$ | $\pm 8.6$ |

**Object selection**

| Lepton Reco & Trigger | $\pm 3.6$ | $\pm 1.0$ | $\pm 3.6$ | $\pm 1.0$ |
| $b$-tagging | n/a | n/a | $+14.2$/$-9.3$ | $+14.7$/$-9.5$ |

**Background rate**

| QCD norm | $\pm 4.4$ | $\pm 6.1$ | $\pm 6.2$ | $\pm 0.7$ |
| $W$+jets norm | $\pm 19.5$ | $\pm 23.4$ | $\pm 3.7$ | $\pm 7.5$ |
| Other bkg norm | $\pm 5.7$ | $\pm 6.1$ | $\pm 0.7$ | $\pm 0.7$ |

**Signal simulation**

| ISR/FSR | $+10.6$/$-6.5$ | $+10.3$/$-4.6$ | $+8.9$/$-6.7$ | $+8.3$/$-5.9$ |
| PDF | $\pm 1.7$ | $\pm 1.4$ | $\pm 1.9$ | $\pm 1.6$ |
| Parton Shower | $\pm 4.6$ | $\pm 3.8$ | $\pm 4.6$ | $\pm 3.8$ |
| NLO generator | $+7.1$/$-6.2$ | $\pm 5.0$ | $+7.0$/$-6.1$ | $\pm 2.7$ |
| Pile-up | $\pm 1.2$ | $\pm 1.2$ | $\pm 0.6$ | $\pm 0.8$ |

**Sum systematics**

| $\pm 27.5$ | $\pm 30.2$ | $+23.6$/$-18.7$ | $+21.7$/$-16.7$ |

| Integrated Luminosity | $\pm 3.7$ | $\pm 3.7$ | $\pm 3.4$ | $\pm 3.4$ |

Table 5.4. Summary of the individual systematic uncertainty contributions to the $\sigma_{t\bar{t}}$ determination. All numbers are relative errors expressed as percentage. For a detailed description of the individual systematic uncertainties, consult Section 4.4.
prior for \( \sigma_{tt} \) is assumed. The posterior pdf for \( \sigma_{tt} \) obtained in this way fully includes the sources of systematic uncertainties and their correlations.

The most probable value and the central 68\% probability interval of the posterior can be taken as a representative value for the combined cross section and its uncertainty, and it turns out to be:

\[
\sigma_{tt} = 154^{+50}_{-45} \text{ pb} \quad (5.2)
\]

for the pretag selection and:

\[
\sigma_{tt} = 156^{+36}_{-30} \text{ pb} \quad (5.3)
\]

for the \( b \)-tag selection.

The results of the single-channel cross-section measurements and of the combinations for pretag and \( b \)-tag selection are shown in Figure 5.4 compared with the theoretical prediction.

---

**Figure 5.4.** Summary of the \( \sigma_{tt} \) measurements with 2010 data, in the single lepton channel using the counting method, including errors bars for both statistical uncertainties only (blue) and all systematics (red). The approximate NNLO prediction is shown as a vertical dotted line with its yellow error band.
5.2 Cross-section measurement with the 2011 data

The measurement described in Section 5.1 is repeated with the 2011 data, with some improvements in order to reduce the systematic uncertainty.

Instead of performing the measurement in the $\geq 4$-jets, the exclusive 4-jets bin is used. This choice is made in order to reduce the JES uncertainty on the measurement, while keeping a good signal purity in the selected sample. Other systematics as well are significantly reduced, like the effect of the ISR/FSR and of the NLO generator uncertainty. This choice of the signal region is not optimal for the pretag selection, where the signal over background ratio is too small and consequently the $W$+jets background uncertainty dominates the measurement. The systematic uncertainty on the measurement in the pretag sample is even higher than those for the 2010 data analysis, but in the $b$-tag sample the total uncertainty is significantly reduced. The numbers for the pretag selection are reported anyway for reference. Also, it is important to note that, as reported in Section 4.1 for the 2011 data analysis, a different tagger is used to define the $b$-jets. This has two
important advantages for the cross-section analysis.

- The $b$-tagging efficiency is increased from 50% to 70% on average for the jets selected in the analysis. The efficiency of the $b$-tag cut for the signal (given that $t\bar{t}$ events have two $b$-jets in the final state) is therefore increased from $\sim70\%$ to $\sim90\%$. Also the tagging efficiency for a light jet is higher, providing a higher $W+$light flavour background rate. This reflects in a worse signal to background rate, but on the other hand the higher available statistics of $W+$jet background events in the signal region allows a lower statistical uncertainty on its estimation.

- The effect of the $b$-tagging uncertainty on the signal efficiency $\epsilon_{t\bar{t}}$ is reduced. This is due to both the choice of the tagging algorithm and of the higher efficiency working point.

Figure 5.6. Distribution of the invariant mass of the three-jet combination with highest $p_T$ in the 4-jet pretag and $b$-tag samples, for the $e$+jet and $\mu$+jet channels.
Figure 5.7. Distribution of the $W$ transverse mass in the 4-jet pretag and $b$-tag samples, for the $e$+jet and $\mu$+jet channels.

The QCD background is estimated using the Matrix Method (the same method used in the $\mu$+jets channel for the 2010 data analysis) in both the $e$+jet and $\mu$+jet channels, as shown in Section 6.1. In the $e$+jets channel, the looser electron definition needed by the method is obtained by loosening both the isolation cut and the electron identification criteria. The $W$+jets background is estimated in two steps, getting the pretag estimate with the Charge Asymmetry method (as shown in Section 6.2.3) and multiplying it by a tagging rate evaluated in the same way as for the 2010 data analysis. The Charge Asymmetry method, based on counting the difference between positively and negatively charged lepton events in data, is preferred to the other methods giving the lowest uncertainty, thanks to the high available statistics.
### Table 5.5. Number of events in the (a) pretag and (b) \( b \)-tag samples with different jet multiplicities in the \( e^+ \)jets channel. The observed number of events are shown, together with the MC simulation prediction for \( t\bar{t} \), \( Z \) + jet and single-top events, normalised to the integrated luminosity of 2.05 fb\(^{-1}\). The data-driven estimates for \( W \) + jets and QCD fake backgrounds (see Section 6.2 and 6.1) are also shown.

<table>
<thead>
<tr>
<th></th>
<th>1-jet</th>
<th>2-jets</th>
<th>3-jets</th>
<th>4-jets</th>
<th>( \geq )5-jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pretag</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( t\bar{t} )</td>
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<tr>
<td>QCD</td>
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<td>4641</td>
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<td>528</td>
</tr>
<tr>
<td>( W ) + jets</td>
<td>468401</td>
<td>127010</td>
<td>33108</td>
<td>8637</td>
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</tr>
<tr>
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<td>8057</td>
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<td>511</td>
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<td>1740</td>
<td>2183</td>
<td>1210</td>
<td>485</td>
<td>210</td>
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<tr>
<td>diboson</td>
<td>1773</td>
<td>1624</td>
<td>542</td>
<td>142</td>
<td>36</td>
</tr>
<tr>
<td>Total background</td>
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<td>42879</td>
<td>11890</td>
<td>4130</td>
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<tr>
<td>Total expected</td>
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<td>48791</td>
<td>17698</td>
<td>8689</td>
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<tr>
<td>Observed</td>
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<td>162416</td>
<td>49275</td>
<td>17335</td>
<td>9032</td>
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</tbody>
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<table>
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<tr>
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<th>2-jets</th>
<th>3-jets</th>
<th>4-jets</th>
<th>( \geq )5-jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b )-tag</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( t\bar{t} )</td>
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<td>2201</td>
<td>4874</td>
<td>5057</td>
<td>4069</td>
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<td>680</td>
<td>230</td>
<td>73</td>
</tr>
<tr>
<td>( W ) + jets</td>
<td>12838</td>
<td>8332</td>
<td>3567</td>
<td>1294</td>
<td>536</td>
</tr>
<tr>
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<td>275</td>
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<td>89</td>
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<tr>
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<td>901</td>
<td>380</td>
<td>173</td>
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<tr>
<td>diboson</td>
<td>95</td>
<td>179</td>
<td>76</td>
<td>25</td>
<td>6</td>
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<tr>
<td>Total background</td>
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<td>12008</td>
<td>5499</td>
<td>2070</td>
<td>877</td>
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<tr>
<td>Total expected</td>
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<td>4946</td>
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<td>Observed</td>
<td>18491</td>
<td>14716</td>
<td>10615</td>
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<td>5335</td>
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</tbody>
</table>

(a)

(b)
<table>
<thead>
<tr>
<th>Pretag</th>
<th>1-jet</th>
<th>2-jets</th>
<th>3-jets</th>
<th>4-jets</th>
<th>≥5-jets</th>
</tr>
</thead>
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<td>( t\bar{t} )</td>
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<td>9526</td>
<td>2532</td>
<td>858</td>
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<td>( W^+)jets</td>
<td>1150367</td>
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<td>63331</td>
<td>15166</td>
<td>4150</td>
</tr>
<tr>
<td>( Z^+)jets</td>
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<td>17470</td>
<td>5168</td>
<td>1492</td>
<td>552</td>
</tr>
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<td>80855</td>
<td>20105</td>
<td>5896</td>
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<tr>
<td>Total expected</td>
<td>1297903</td>
<td>350075</td>
<td>89229</td>
<td>28590</td>
<td>12460</td>
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<tr>
<td>Observed</td>
<td>1319326</td>
<td>346575</td>
<td>90806</td>
<td>28695</td>
<td>13517</td>
</tr>
</tbody>
</table>

(b) | b-tag | 1-jet | 2-jets | 3-jets | 4-jets | ≥5-jets |
<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t} )</td>
<td>467</td>
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<td>7401</td>
<td>5869</td>
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<td>QCD</td>
<td>8076</td>
<td>5711</td>
<td>2087</td>
<td>684</td>
<td>295</td>
</tr>
<tr>
<td>( W^+)jets</td>
<td>31951</td>
<td>19227</td>
<td>6880</td>
<td>2231</td>
<td>805</td>
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<td>( Z^+)jets</td>
<td>1249</td>
<td>983</td>
<td>486</td>
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<td>97</td>
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<td>1402</td>
<td>540</td>
<td>228</td>
</tr>
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<td>diboson</td>
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<td>134</td>
<td>35</td>
<td>11</td>
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<tr>
<td>Total background</td>
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<td>28582</td>
<td>10973</td>
<td>3675</td>
<td>1433</td>
</tr>
<tr>
<td>Total expected</td>
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<td>31572</td>
<td>17880</td>
<td>11075</td>
<td>7301</td>
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<td>Observed</td>
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<td>31338</td>
<td>18246</td>
<td>11261</td>
<td>7959</td>
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</table>

Table 5.6. Number of events in the (a) pretag and (b) b-tag samples with different jet multiplicities in the \( \mu^+\)jets channel. The observed number of events are shown, together with the MC simulation prediction for \( t\bar{t} \), \( Z^+\)jet and single-top events, normalised to the integrated luminosity of 2.05 fb\(^{-1}\). The data-driven estimates for \( W^+\)jets and QCD fake backgrounds (see Section 6.2 and 6.1) are also shown.
Figure 5.8. Distribution of the transverse momentum of the lepton (e or $\mu$) in the 4-jet pretag and $b$-tag samples, for the $e$+jet and $\mu$+jet channels.

Tables 5.5 and 5.6 show the number of expected events in the various jet multiplicity samples compared with the events observed in data, for both the pretag and $b$-tag selection, in the $e$+jet and $\mu$+jet channels respectively. The same information is also reported in the plots in Figure 5.5. Figures 5.6, 5.7, 5.9 and 5.8 show the comparison between data and expectation for some kinematical distributions in the signal region. The agreement is good within the background uncertainty, indicated by the shaded area on top of the expectation histogram.

The results of the measurement in the two channels and for the two selection samples are shown in Table 5.7.
## Table 5.7

<table>
<thead>
<tr>
<th>2011 Data</th>
<th>Pretag $e$+jets</th>
<th>Pretag $\mu$+jets</th>
<th>$b$-Tag $e$+jets</th>
<th>$b$-Tag $\mu$+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{data}$</td>
<td>17335</td>
<td>28695</td>
<td>7085</td>
<td>11261</td>
</tr>
<tr>
<td>$N_{bkg}$</td>
<td>11890 $\pm$ 1338</td>
<td>20105 $\pm$ 2404</td>
<td>2070 $\pm$ 268</td>
<td>3675 $\pm$ 561</td>
</tr>
<tr>
<td>$\epsilon_t$</td>
<td>0.0171 $^{+0.0017}_{-0.0014}$</td>
<td>0.0251 $^{+0.0018}_{-0.0028}$</td>
<td>0.0149 $^{+0.0018}_{-0.0015}$</td>
<td>0.0219 $^{+0.0020}_{-0.0029}$</td>
</tr>
<tr>
<td>$\sigma_{t\bar{t}}$ [pb]</td>
<td>155 $\pm$ 4 $^{+39}_{-40}$ $\pm$ 8</td>
<td>167 $\pm$ 3 $^{+52}_{-49}$ $\pm$ 8</td>
<td>164 $\pm$ 3 $^{+19}_{-21}$ $\pm$ 7</td>
<td>169 $\pm$ 2 $^{+28}_{-20}$ $\pm$ 7</td>
</tr>
</tbody>
</table>

The reported numbers are used, together with the integrated luminosity $\int L dt = 2.045 \pm 0.076$ pb$^{-1}$, to extract the measured values for $\sigma_{t\bar{t}}$ in each of the samples. The three quoted uncertainties correspond to the statistical, the systematic and the luminosity contributions.

## Table 5.8

<table>
<thead>
<tr>
<th>2011 Data</th>
<th>Pretag $e$+jets</th>
<th>Pretag $\mu$+jets</th>
<th>$b$-Tag $e$+jets</th>
<th>$b$-Tag $\mu$+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical error</td>
<td>$\pm$ 2.4</td>
<td>$\pm$ 2.0</td>
<td>$\pm$ 1.7</td>
<td>$\pm$ 1.4</td>
</tr>
<tr>
<td><strong>Object selection</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lepton Reco &amp; Trigger</td>
<td>$\pm$ 2.6</td>
<td>$\pm$ 5.9/1.6</td>
<td>$\pm$ 2.6</td>
<td>$\pm$ 5.9/1.6</td>
</tr>
<tr>
<td>Jet Reco, $E_T$ &amp; Pile-up</td>
<td>$\pm$ 4.4</td>
<td>$\pm$ 9.8/8.7</td>
<td>$\pm$ 7.5</td>
<td>$\pm$ 8.7/7.7</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>n/a</td>
<td>n/a</td>
<td>$\pm$5.7/4.3</td>
<td>$\pm$5.8/4.4</td>
</tr>
<tr>
<td><strong>Background rate</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QCD norm</td>
<td>$\pm$ 8.0</td>
<td>$\pm$ 8.8</td>
<td>$\pm$ 1.4</td>
<td>$\pm$ 2.7</td>
</tr>
<tr>
<td>$W$+jets norm</td>
<td>$\pm$ 18.8</td>
<td>$\pm$ 24.1</td>
<td>$\pm$ 4.7</td>
<td>$\pm$ 6.4</td>
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<tr>
<td>Other bkg norm</td>
<td>$\pm$ 12.9</td>
<td>$\pm$ 10.4</td>
<td>$\pm$ 1.9</td>
<td>$\pm$ 1.7</td>
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<tr>
<td><strong>Signal simulation</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>$\pm$ 3.2</td>
<td>$\pm$6.8/1.0</td>
<td>$\pm$ 4.2</td>
<td>$\pm$ 7.9/1.6</td>
</tr>
<tr>
<td>PDF</td>
<td>$\pm$ 1.7</td>
<td>$\pm$ 1.5</td>
<td>$\pm$ 1.7</td>
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</tr>
<tr>
<td>Parton Shower</td>
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<td>$\pm$ 1.1</td>
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<td>NLO generator</td>
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<td>Sum systematics</td>
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<td>$\pm$ 12.1</td>
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<td>Integrated Luminosity</td>
<td>$\pm$ 4.9</td>
<td>$\pm$ 4.7</td>
<td>$\pm$ 4.1</td>
<td>$\pm$ 4.1</td>
</tr>
</tbody>
</table>

Table 5.8. Summary of the individual systematic uncertainty contributions to the $\sigma_{t\bar{t}}$ determination. All numbers are relative errors expressed as percentage. For a detailed description of the individual systematic uncertainties, consult Section 4.3.
Figure 5.9. Distribution of the transverse momentum of the leading jet in the event in the 4-jet pretag and b-tag samples, for the e+jet and µ+jet channels.

The combined e+jet and µ+jet channels σ_{t\bar{t}} is estimated using a different method than the one used for the 2010 data analysis: instead of a Bayesian approach, a frequentist approach is used. The method is based on the profile likelihood ratio.

A likelihood \( L(\sigma_{t\bar{t}}, \alpha_j) \) is built, including the parameter of interest \( \sigma_{t\bar{t}} \) and all the nuisance parameters \( \alpha_j \) associated to the systematic uncertainties. This likelihood is written as the product of two Poisson likelihoods (\( P \)) for the two considered channels and a number of Gamma or Gaussian (\( G_j \)) distributed constraints for the nuisance parameters:

\[
L(\sigma_{t\bar{t}}, \alpha_j) = \prod_{i=e,\mu} P(\bar{N}_i^{\text{obs}} | N_i^{\text{exp}}(\sigma_{t\bar{t}}, \alpha_j)) \prod_{j \in \text{syst}} G_j(\alpha_j),
\]

where \( N_i^{\text{obs}} \) indicates the number of observed events and \( N_i^{\text{exp}}(\sigma_{t\bar{t}}, \alpha_j) \) the number of expected events in the channel \( i \).

Then the profile likelihood ratio is written as:

\[
\lambda(\sigma_{t\bar{t}}) = \frac{L(\sigma_{t\bar{t}}, \hat{\alpha}_j)}{L(\hat{\sigma}_{t\bar{t}}, \hat{\alpha}_j)},
\]

64
where \( \hat{\sigma}_{t\bar{t}} \) and \( \hat{\alpha}_j \) denote the maximum likelihood estimates of all the parameters and \( \hat{\alpha}_j \) represents the conditional maximum likelihood estimates of \( \alpha_j \) holding \( \sigma_{t\bar{t}} \) fixed. The best fit value of the cross-section is simply \( \hat{\sigma}_{t\bar{t}} \) and the 68% confidence interval is derived from the values of \( \sigma_{t\bar{t}} \) which give \(-2 \log \lambda(\sigma_{t\bar{t}}) = 1\). All the correlations between channels and systematic uncertainties are included with this procedure.

This method (based on the RooFit/RooStats software package [99]), is the same as the one used for the combination of the dilepton channels [100] [101] and of the dilepton and single lepton channels together [29] [30] for the \( t\bar{t} \) cross-section measurement in ATLAS (see Section 5.3). It has been proved to give consistent results with the Bayesian one in [29], and is therefore chosen for this analysis being more widely used inside ATLAS.

The fitted value with its uncertainty, taken as the combined \( \sigma_{t\bar{t}} \) measurement, is:

\[
\sigma_{t\bar{t}} = 155^{+41}_{-38} \text{ pb} \quad (5.6)
\]

for the pretag selection and:

\[
\sigma_{t\bar{t}} = 164^{+20}_{-17} \text{ pb} \quad (5.7)
\]

for the \( b \)-tag selection.

The results of the single-channel \( \sigma_{t\bar{t}} \) measurements and of the combinations for pretag and \( b \)-tag selection are shown in Figure 5.10 compared with the theoretical prediction.

![Figure 5.10](data:image/png;base64,iVBORw0KGgoAAAANSUhEUgAAAIwAAADcCAYAAAAiwM9hAAAABGd vegetarian.jpg)
5.3 Other $t\bar{t}$ cross-section measurements in ATLAS

Beside the measurements reported in Section 5.1 and 5.2, several other $t\bar{t}$ cross-section measurements, in different channels and with different methods, have been performed in ATLAS with the full 2010 data set and part of the 2011 one.

The different channels include the $ee$, $e\mu$ and $\mu\mu$ dilepton channels [100] [101], the $\mu\tau$ channel [102] and the all hadronic channel [103].

![Figure 5.11](image)

Figure 5.11. Plots of the measured $\sigma_{t\bar{t}}$ using several analyses in various decay channels, including errors bars for the only statistical uncertainty (blue) and for all the systematics (red). The combined result is based on the lepton+jets $b$-tag multivariate and the dilepton counting analyses. The approximate NNLO prediction is shown as a vertical dotted line with its yellow error band.
In the single lepton channel, more sophisticated measurements are performed by fitting kinematical variable distributions and combining different jet multiplicity bins \([95 \) \(96\). The most precise results are obtained using a multivariate technique to build a likelihood function based on different kinematical variables sensitive to discriminate \(t\bar{t}\) events from background events. Different jet multiplicity samples are combined and a profile likelihood fit, able to constrain the main sources of systematic uncertainties, is applied \([104\).

![Figure 5.12](image)

Figure 5.12. Plots of measured \(\sigma_{t\bar{t}}\) using several analyses in each decay channel, including errors bars for the only statistical uncertainty (blue) and for all the systematics (red). The approximate NNLO prediction is shown as a vertical dotted line with its yellow error band.

The best results in the different channels are reported in Figure 5.11 and 5.12 (for the 2010 and 2011 data respectively) and are compared with the best results obtained with the counting method in \(\ell+jets\) reported in this thesis. In Figure 5.11 the combination of the best results in the single lepton and the dilepton channels \([30\) is also shown.

The results obtained by ATLAS are also in good agreement with the ones from CMS, both using the 2010 \([105\) \([106\) \([107\) and the 2011 \([32\) datasets.
5.4 Top mass indirect determination

Direct measurements of $m_{\text{top}}$ at hadron colliders rely on the reconstruction of a kinematic observable that is sensitive to this variable (such an observable is often the invariant mass of the decay products of the top quark candidates, see [108]). These direct measurements depend on the MC simulation either to fit the chosen kinematic observable [108] or to calibrate the measurement [109], [110]. The interpretation of such direct measurements has become a subject of intense discussion in terms of its renormalization scheme [111].

In this Section, $m_{\text{top}}$ is instead extracted from the measured $t\bar{t}$ cross-section, following the same procedure used in [112] and in [113]. The inclusive $t\bar{t}$ production cross-section described in Section 5.2 is compared with an approximate NNLO computation, where the top quark mass parameter is un-ambiguously defined as the pole mass ($m_{\text{top}}^{\text{pole}}$). The extraction of $m_{\text{top}}^{\text{pole}}$ from the measured $t\bar{t}$ cross-section provides complementary information, with different sensitivity to theoretical and experimental uncertainties, compared to direct methods that rely explicitly on the details of the kinematic mass reconstruction. This method also tests the internal consistency of perturbative QCD calculations for $\sigma_{t\bar{t}}(m_{\text{top}}^{\text{pole}})$ that are calculated in a well-defined renormalization scheme.

![Figure 5.13](Figure 5.13. Comparison of the predicted cross-section $\sigma(m_{\text{top}}^{\text{pole}})$, and the experimentally measured cross-section as a function of $m_{\text{top}}^{MC}$.)

\[ \int L \, dt = 2.05 \text{ fb}^{-1} \]

\[ \text{approx. NNLO} \]

\[ \text{scale + PDF unc.} \]

\[ \text{Measurement} \]
Figure 5.13 shows the theoretical approximated NNLO prediction of the $t\bar{t}$ cross-section as a function of $m_{\text{pole}}^{\text{top}}$ obtained using the HATOR code, together with the measured cross-section as a function of the top mass parameter in the MC generator ($m_{\text{top}}^{\text{MC}}$). This mass-dependent measured cross-section is obtained repeating the measurement shown in Section 5.2 using different MC samples for $t\bar{t}$ events to get the selection efficiency $\epsilon_{t\bar{t}}$, generated at various $m_{\text{top}}^{\text{MC}}$. The experimental points are then fitted with a third order polynomial. The uncertainty stemming from identifying $m_{\text{pole}}^{\text{top}} \equiv m_{\text{top}}^{\text{MC}}$ in the experimental inputs is evaluated by shifting $m_{\text{top}}^{\text{MC}}$ by $\pm 1$ GeV.

To extract the top quark mass, a combined uncorrelated theoretical (th) and experimental (exp) likelihood based on the above description is constructed as:

$$f(m_{\text{top}}) \propto \int f_{\text{th}}(\sigma|m_{\text{top}}) \cdot f_{\text{exp}}(\sigma|m_{\text{top}}) d\sigma,$$

where $f_{\text{th}}(\sigma|m_{\text{top}})$ ($f_{\text{exp}}(\sigma|m_{\text{top}})$) is the theoretical (experimental) probability density function constructed using a Gaussian likelihood function centered on the theoretical prediction (measured value) and having as width the total theoretical (experimental) uncertainty.

The value maximizing the likelihood and the 68% area around that value are taken as the measured top quark mass value and its uncertainty:

$$m_{\text{top}}^{\text{pole}} = 173.3^{+6.3}_{-6.0} \text{ GeV}, \quad (5.9)$$

in perfect agreement with the world average experimental value

$$m_{\text{top}} = 173.2 \pm 0.9 \text{ GeV}. \quad (5.10)$$

The result is also in agreement, within the uncertainty, with other analogous measurements performed by the DØ Collaboration [113]:

$$m_{\text{top}}^{\text{pole}} = 167.5^{+5.2}_{-4.7} \text{ GeV}, \quad (5.11)$$

and by the ATLAS Collaboration, using 2010 data [112]:

$$m_{\text{top}}^{\text{pole}} = 166.4^{+7.8}_{-7.3} \text{ GeV}. \quad (5.12)$$
Chapter 6

Background processes to the $t\bar{t}$ single lepton channel

In this Chapter, the methods to evaluate the various sources of background for the $t\bar{t}$ cross-section measurement in the single lepton channel, already introduced in Section 5, are described in more detail.

In general, two basic categories of background processes can be defined: physics backgrounds and instrumental backgrounds. Physics backgrounds are those processes that share the same final state as the signal events. Instrumental backgrounds are those instead which mimic the signal final state due to a detector effect, resulting in a mis-identification of some of the final state objects. Although the mis-identification rates are typically very small, < 1%, instrumental backgrounds can still significantly contribute to the final selected samples due to the very large production cross-sections.

Usually, instrumental backgrounds are estimated using control data samples, while physics backgrounds are estimated using MC simulations, re-normalized using high order theoretical calculations (as explained in Section 4.3) or data-driven methods. Examples of instrumental backgrounds for the $t\bar{t}$ signal in the single lepton channel are the QCD multi-jet and $W$+jet processes (which might be also physics background, see the following discussion). Section 6 describes in detail the data-driven methods used to extract the backgrounds.

The inclusive QCD process $pp \rightarrow$jets has a production cross-section which is about nine orders of magnitude larger than the $t\bar{t}$ ones. The jets originate predominantly from light quarks ($u$, $d$, $s$-quarks) or gluons: $b$-quark jets are produced in a few percent of these events. For semi-leptonic final states, the QCD background is sometimes referred to as the “non-$W$” or “fake lepton” background. It is a consequence of the mis-identification of a jet as an isolated high energy lepton and of a mis-measurement of the $E_T$ which makes the event fall into the selected sample. If $b$-quark jet identification is required, a further mis-identification of one of the light quark or gluon jets is also necessary in order for the event to survive all selection criteria. The methods used to estimate from data both the normalization and the distribution shapes for this background are described in Section 4.3.
The $W$+jets process has a production cross-section about three orders of magnitude greater than the $tt$ process and is the most important background for the $tt$ semileptonic final state. When the $W$ decays leptonically, there are a genuine high energy lepton and $\not{E}_T$ in the event. In a sample selected without requiring a $b$-jet, this background appears as physics background, while after a $b$-tag selection, $W$+jet events can contribute both as instrumental background, when the $W$ is produced in association with light jets only (and therefore to pass the selection cuts one of the jets has to be mis-identified as $b$-jet), and as physics background, when at least one of the jets is originated from a heavy $b$- or $c$-quark (the so called “$W$+heavy flavour” production). The shapes of the distributions for $W$+jet events is taken from MC simulation, while their normalization is extracted from the data (as shown in Section 6.2) since there are large theoretical uncertainties involved. These uncertainties arise since complete calculations of the $W$+3 jet and $W$+4 jet cross-sections, including heavy flavour contributions, are unavailable and current estimates rely on a mixture of partial calculations at lower orders and part on shower MC models to extrapolate to larger jet multiplicities.

A related background, $Z$+jets, has a production cross-section roughly a factor of ten smaller than the $W$+jets background. It can contribute to the selected sample if the $Z$ decays to $e^+e^−$ or $\mu^+\mu^−$ and one of the leptons escapes undetected giving rise to fake $\not{E}_T$. This effect is dominated by the limited geometric acceptance of the detector and is estimated using MC simulation. Moreover, $Z \rightarrow \tau^+\tau^−$ events, when one of the $\tau$ leptons decays leptonically and the second one hadronically, can have a very signal-like final state. Once the relevant branching fractions are included, this turns out to be a small background and is estimated from MC.

The production of a single top quark via electroweak interaction, has a production cross-section about a factor of two smaller than the $tt$ cross-section. These single top events have usually final states with a smaller number of jets than $tt$ events, and therefore their contribution to the high jet multiplicity samples is small. On the contrary, in the low jet multiplicity control samples their contribution is important, especially after the $b$-tag requirement. The single top background is estimated using MC simulation and normalized using the theory predicted cross-section.

The diboson processes $pp \rightarrow WW$, $WZ$, $ZZ$ have small cross-sections and usually don’t contribute significantly to the high jet multiplicity samples, but their contribution is still taken into account using MC simulation normalized by using the theoretical predictions.

In the following two sections, the data-driven methods used to extract the QCD and the $W$+jet backgrounds are described.

The candidate has been personally working on the QCD fake background estimation in the 2011 data set (Section 6.1.5 and Section 6.1.6), on the Charge Asymmetry method to estimate the $W$+jets background in pretag sample (Section 6.2.3) and on the $W$+jets background extrapolation from pretag to $b$-tag sample. The results of the QCD estimation in the $e$+jets channel and of the $W$+jets estimation have been used by other analyses in ATLAS as well, in particular for the currently most precise $\sigma_{tt}$ measurement [104].
6.1 QCD background determination

Semi-leptonic $t\bar{t}$ decays are “tagged” through their high $p_T$ leptons in the final state. While electroweak processes can produce real electrons or muons (prompt leptons from $W$ and $Z$ decays) passing these selections, there remains an additional component from mis-identified leptons or “fake leptons”, called QCD background.

The dominant sources of these fake leptons are from:

- semi-leptonic $b$-jet decays,
- long lived weakly decaying states such as $\pi^{\pm}$ or $K$ mesons,
- $\pi^0$ shower reconstructed as an electron,
- electrons from photons conversions or direct photons.

While the probability of a multi-jet event passing the selection is very low, the production cross-section for multi-jet events is orders of magnitude above that of $t\bar{t}$ production. These background sources are also highly detector dependent. Therefore, data-driven methods are the most appropriate to estimate the rate of fake leptons in an analysis.

6.1.1 Matrix Method

The Matrix Method (MM), extensively used at the Tevatron [114], is based on selecting two categories of events using “loose” and “tight” lepton selection requirements. This method is in principle valid for every event selection based on single-lepton identification and can be extended to di-lepton selections (as shown in [29], [100] and [101]) as well.

The tight lepton selection is usually the standard lepton selection used in the analysis, while the loose one is obtained reducing some of the lepton identification requirements. In this way, all the leptons passing the tight selection (“tight leptons”) are also passing the loose lepton selection (they are “loose leptons” as well).

Based on these loose and tight lepton selections, one can distinguish between a loose and a tight event selection, differing only in the lepton identification criteria.\footnote{It is important to note that, even if the tight lepton selection is actually a subset of the loose one, this is not necessarily the case for the corresponding event selection. Indeed, if the event selection includes a lepton veto (i.e. a requirement of the form “exactly N lepton” or “no more than N leptons”), it might happen that some events are passing the tight selection without passing the loose one. This is the case when, i.e. for the $e+\text{jets}$ selection, there are two electrons in the event, one passing the tight selection, and the other one passing the loose selection but not the tight one; this event has exactly one tight electron, and is therefore passing the tight event selection, but on the other hand it has two loose electrons, which means that it’s not passing the loose event selection, which is requiring “exactly one” loose electron.}
The number of selected events in each sample \((N_{\text{loose}}\) and \(N_{\text{tight}}\)) can be expressed as a linear combination of the numbers of events with real and fake leptons, in such a way that the following system of equations can be defined:

\[
N_{\text{loose}} = N_{\text{loose, real}} + N_{\text{loose, fake}}, \tag{6.1}
\]

\[
N_{\text{tight}} = N_{\text{tight, real}} + N_{\text{tight, fake}}, \tag{6.2}
\]

where \(N_{\text{loose, real}}\) and \(N_{\text{tight, real}}\) indicate the number of events passing the tight and the loose lepton selection requirements respectively, containing a real (fake) lepton.

The ratio between \(N_{\text{tight, real}}\) and \(N_{\text{loose, real}}\) can be expressed as an “efficiency”, which differs for the real and fake lepton components. One can then relate \(N_{\text{tight, real}}\) and \(N_{\text{tight, fake}}\) to the corresponding number of loose events introducing the two efficiencies \(\varepsilon_{\text{real}}\) and \(\varepsilon_{\text{fake}}\):

\[
N_{\text{tight, real}} = \varepsilon_{\text{real}} \cdot N_{\text{loose, real}}, \tag{6.3}
\]

\[
N_{\text{tight, fake}} = \varepsilon_{\text{fake}} \cdot N_{\text{loose, fake}}, \tag{6.4}
\]

and Formula 6.2 can be re-written as

\[
N_{\text{tight}} = \varepsilon_{\text{real}} \cdot N_{\text{loose, real}} + \varepsilon_{\text{fake}} \cdot N_{\text{loose, fake}}. \tag{6.5}
\]

Knowing the values of \(\varepsilon_{\text{real}}\) and \(\varepsilon_{\text{fake}}\) (usually measured in data, as described below) and counting \(N_{\text{loose}}\) and \(N_{\text{tight}}\), the system composed by the equations shown in Formula 6.1 and 6.5 can be solved, since it contains two equations and two unknowns.

In particular, the number of tight events coming from fake leptons can be expressed as:

\[
N_{\text{fake}} = \frac{\varepsilon_{\text{fake}}}{\varepsilon_{\text{real}} - \varepsilon_{\text{fake}}} \cdot (\varepsilon_{\text{real}} \cdot N_{\text{loose}} - N_{\text{tight}}). \tag{6.6}
\]

Usually, both \(\varepsilon_{\text{real}}\) and \(\varepsilon_{\text{fake}}\) are strongly dependent on the lepton \(\eta\). Not only the number of expected events coming from fake lepton background has to be predicted but also the shape of the relevant kinematical distributions. For these purposes, the previous formula can be generalized in order to obtain a weight \(w_i\) to be applied to each data event \(i\) passing the loose or the tight selection:

\[
w_i = \frac{\varepsilon_{\text{fake}}}{\varepsilon_{\text{real}} - \varepsilon_{\text{fake}}} \cdot (\varepsilon_{\text{real}} \cdot \text{isLoose}(i) - \text{isTight}(i)), \tag{6.7}
\]

where \(\text{isLoose}(i)\) (\(\text{isTight}(i)\)) is equal to 1 if the event \(i\) passes the loose (tight) event selection and 0 otherwise, and \(\varepsilon_{\text{real}}\) and \(\varepsilon_{\text{fake}}\) may depend on the properties of the event \(i\) (i.e. the lepton \(\eta\)). These weights are built is such a way that the sum over all the data events gives Formula 6.6:

\[
\sum_{i \in \text{data}} w_i = N_{\text{fake}}. \tag{6.8}
\]
Real efficiency determination

The real efficiency \( \epsilon_{\text{real}} \) can be measured in data applying an event selection with a minimum contamination from fake lepton events and counting the fraction of loose events passing the tight selection. While by definition the loose selection in the \( \ell + \text{jets} \) channel is enriched by fake lepton events, this is not the case for events with two same-flavour leptons, one of the two identified as tight lepton, where \( Z \rightarrow \ell^+ \ell^- \) events are dominating.

This method is called “tag-and-probe”, and is based on the identification of a tight lepton (the tag lepton) and a loose one (the probe lepton) in events selected to come from a Z-boson leptonic decay (i.e. requiring the two leptons to be opposite-signed, including a cut on their invariant mass to be close to the Z-boson mass and asking a low \( E_T \) in the event). The fraction of those events where also the probe lepton is identified as tight gives a good estimation of \( \epsilon_{\text{real}} \).

Fake efficiency determination

To measure in data the fake efficiency \( \epsilon_{\text{fake}} \), one needs to isolate a sample of events enriched in fake leptons both after the loose and the tight event selection.

This can be obtained by inverting the \( E_T \) or the \( m_T(W) \) cut, to reduce the number of real lepton events entering the selection. It has to be noted that, in order to keep the measured \( \epsilon_{\text{fake}} \) in this “fake control region” (\( CR_{\text{fake}} \)) the same as the \( \epsilon_{\text{fake}} \) in the signal region, most of the other cuts have to be the same for the two regions (i.e. the b-tagging cut, the lepton \( p_T \) and \( |\eta| \) cut, the event quality cuts, etc...).

After a \( CR_{\text{fake}} \) is chosen, \( \epsilon_{\text{fake}} \) can be simply determined as the ratio between the number of tight and loose events in this region. Since usually the contribution of real lepton events in the \( CR_{\text{fake}} \) is not negligible, it has to be subtracted from both the loose and tight samples:

\[
\epsilon_{\text{fake}} = \frac{N_{\text{tight}}^{\text{fake}}}{N_{\text{loose}}^{\text{fake}}}_{CR_{\text{fake}}} = \frac{N_{\text{tight}} - N_{\text{tight}}^{\text{real}}}{N_{\text{loose}} - N_{\text{loose}}^{\text{real}}}_{CR_{\text{fake}}},
\]

(6.9)

where \( N_{\text{tight}}^{\text{real}} \) and \( N_{\text{loose}}^{\text{real}} \) are the real lepton contributions to the tight and loose samples in the fake control region. These numbers can be evaluated from MC simulation or with an iterative procedure (explained in [29]). In case a MC simulation is used, a specific systematic uncertainty is introduced in the measurement of \( \epsilon_{\text{fake}} \), due to the uncertainty on the normalization of the real lepton events contribution.

Efficiency parametrization

In general, both \( \epsilon_{\text{fake}} \) and \( \epsilon_{\text{real}} \) depend on the lepton \( \eta \). For this reason, in the MM implementations described below, they are taken as \( \eta \)-dependent \( (\epsilon_{\text{fake}}(\eta) \) and \( \epsilon_{\text{real}}(\eta) \)) by measuring the \( \epsilon_{\text{fake}} \) or \( \epsilon_{\text{real}} \) for each \( \eta \) bin\(^2\).

\(^2\)The size of the bins depends on the available statistics.
In case it shows a significant dependence on them, $\epsilon_{\text{fake}}$ can be parametrized as a function of additional variables. Let’s consider for example a second parametrization variable $x$. The additional parametrization can be done considering a multi-dimensional histogram and extracting $\epsilon_{\text{fake}}$ for each $(\eta, x)$ bin. In alternative, in order to reduce the statistical uncertainty on the efficiency determination, the dependence of $\epsilon_{\text{fake}}$ on $x$ can be considered as uncorrelated with $\eta$ (and eventually with the other parametrization variables) and the second parametrization can be done introducing a function $f(x)$ describing the dependence of $\epsilon_{\text{fake}}$ on the variable $x$:

$$\epsilon_{\text{fake}} = \epsilon_{\text{fake}}(\eta) \cdot \frac{f(x)}{<\epsilon_{\text{fake}}>}.$$  \hspace{1cm} (6.10)

In case of more than one additional parametrization variable, the procedure can be iterated. The same procedure can be eventually applied to $\epsilon_{\text{real}}$.

The MM is used to estimate the QCD fake background in the $\mu$+jets channel for the 2010 data analysis (as described in Section 6.1.4) and in both the $e$+jet and $\mu$+jet channels for the 2011 data analysis (see Section 6.1.5 and 6.1.6).

### 6.1.2 Fitting Method

An alternative way to estimate the number of expected QCD events after a single-lepton event selection is the so-called Fitting Method. This method was used in the $e$+jets channel for the 2010 data analysis (see Section 6.1.3) and is used as cross-check method for the 2011 data. In principle it is applicable to the $\mu$+jets channel as well.

The method is based on the choice of a fitting variable which discriminates well between QCD fake and real lepton processes, and the definition of a model, i.e. a particular lepton selection (and a corresponding event selection) to build the shape of the fitting variable.

The best fitting variables have been found to be:

- the $E_T$, used for the 2010 data analysis, with the fit performed only in the region below the $E_T$ cut defining the signal region;

- the lepton isolation, used for one of the two cross-check methods applied to the 2011 data, with the fit performed only in the region above the signal lepton isolation cut.

The QCD fake model is built selecting events with:

- either a lepton failing some of the identification criteria (the so called “anti-electron” or “anti-muon” model)

- or, in case of the electron channel, a jet very close to the definition of an electron (the so called “jet-electron” model),

instead of the single good lepton requirement for the signal selection.

---

3To perform a fit in this region, the lepton definition is loosened by removing the isolation cut. After the fit, the cut is applied to extrapolate the number of QCD events surviving the signal region selection.
A binned likelihood template fit is performed on the fitting variable after all the selection cuts (including jet multiplicity and eventually the $b$-tagging selection) except the one on the fitting variable. Some of the cuts which might reduce too much the fraction of QCD fake events are not applied at this point, and their effect is instead estimated via extrapolation, using the shape obtained from the model.

The data are fitted to a sum of a number of templates describing the fitting variable distribution of QCD and of the other signal and background components: $W$+jets, $Z$+jets, single top and $t\bar{t}$. The QCD template is extracted from the data according to the chosen QCD model, while the templates for the other processes are taken from a MC simulation. The fraction of QCD events in the signal region ($\rho_{QCD}$) is then calculated by extrapolating the fitted fraction of events to the signal region using the template shape. $\rho_{QCD}$ is then multiplied by the observed number of events to get the estimated number of QCD fake events in the specific sample.

### 6.1.3 QCD fakes in the electron channel for the 2010 data analysis

The fitting method, using the anti-electron model together with the jet-electron model, was used to estimate the QCD background in the $e$+jets channel of the analysis which first observed the top quark in the ATLAS experiment [29]. For the full 2010 data analysis, only the anti-electron model was used. To build the anti-electron model, the method selects events with the same electron trigger used for the signal event selection and applies the usual electron identification requirements except for the so-called “hadronic leakage” requirement. This choice of the control sample definition gives a good agreement with data and, at the same time, provides a high statistics sample.

The $E_T$ distribution is the most sensitive one to evaluate the electron fakes contribution and it is used to perform the fit in each of the jet multiplicity pretag and $b$-tag samples, in the $E_T < 35$ GeV region (the sideband not used in the analysis). Model distributions to perform the fit in the $b$-tag samples are obtained from the corresponding tagged control samples.

<table>
<thead>
<tr>
<th></th>
<th>1-jet</th>
<th>2-jets</th>
<th>3-jets</th>
<th>4-jets</th>
<th>$\geq$5-jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>pretag</td>
<td>287 ±144</td>
<td>123 ±62</td>
<td>62 ±31</td>
<td>13.1 ±6.6</td>
<td>7.6 ±3.8</td>
</tr>
<tr>
<td>$b$-tag</td>
<td>14.4 ±7.2</td>
<td>15.2 ±7.6</td>
<td>10.8 ±8.6</td>
<td>5.5 ±6.0</td>
<td>3.1 ±3.5</td>
</tr>
</tbody>
</table>

Table 6.1. Number of estimated QCD fake events in the various jet multiplicity pretag and $b$-tag samples, using the anti-electron Fitting Method in the $e$+jets channel in the 2010 data (35 pb$^{-1}$).

---

4One of the requirements used to define an electron in this analysis is the energy deposit in the hadronic calorimeter being below a certain threshold. Anti-electrons are defined asking instead this energy deposit to be above the threshold.
Alternative models were used to cross check the fitted fractions. They all suffer from a lack of statistics but provide consistent results with the default model within its uncertainty (the statistical uncertainty plus a 50% systematic uncertainty, set by the level of agreement between the different models in low jet multiplicity samples, where the statistical uncertainty is small). In Table 6.1 the expected numbers of QCD events are reported, together with the associated uncertainties in each considered sample, while Figure 6.1 (left) shows the QCD fake fraction as a function of the jet multiplicity for the pretag and b-tag selection.

6.1.4 Matrix Method in the muon channel for the 2010 data analysis

In the muon channel, the fake lepton background is basically only coming from heavy hadron decays inside a jet, since the probability of having a non-muon object (a jet, a photon or an electron) faking a muon in the spectrometer is close to zero. Therefore, loosening the muon definition and allowing non-isolated muons to be accepted as good muons, results in a perfect loose muon definition for the MM to work.

The loose $\mu$+jets event selection is the same as the baseline $\mu$+jets selection, but it requires exactly one loose muon instead of exactly one tight muon, where a loose muon is defined in the same way as a normal muon but removing the cuts $\etacone_{30} < 4$ GeV and $p_{tcone_{30}} < 4$ GeV.

For the 2010 data analysis, two control regions $CR_{fake}^1$ and $CR_{fake}^2$ are used to extract the fake efficiency $\epsilon_{fake}$, both selecting events with one lepton and at least one jet. Additionally:

- $CR_{fake}^1$ is selected by requiring a low $W$-boson transverse mass $m_T(W) < 20$ GeV and applying a reversed triangular cut $E_T + m_T(W) < 60$ GeV;
- $CR_{fake}^2$ is obtained by requiring a low missing transverse energy $E_T < 10$ GeV.

In this last case, an iterative procedure to subtract the real leptons contribution is applied, while in the first one this contribution is subtracted using the MC simulation.

The real efficiency $\epsilon_{real}$ is measured using the tag & probe method in $Z \rightarrow \mu\mu$ data events. Both $\epsilon_{fake}$ and $\epsilon_{real}$ are binned in the $\eta$ variable.

To predict the QCD contribution in the $b$-tag samples, the method is applied to the tagged sample and $\epsilon_{fake}$ is measured in the tagged control sample. The results of the application of the MM to the 2010 data are presented in Table 6.2 and in Figure 6.1 (right).

<table>
<thead>
<tr>
<th></th>
<th>1-jet</th>
<th>2-jets</th>
<th>3-jets</th>
<th>4-jets</th>
<th>$\geq$5-jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>pretag</td>
<td>521.6 ±157.5</td>
<td>287.4 ±87.2</td>
<td>121.4 ±37.4</td>
<td>31.7 ±10.5</td>
<td>19.6 ±6.8</td>
</tr>
<tr>
<td>b-tag</td>
<td>33.1 ±10.6</td>
<td>41.4 ±13.1</td>
<td>24.2 ±8.0</td>
<td>8.7 ±3.3</td>
<td>4.3 ±1.9</td>
</tr>
</tbody>
</table>

Table 6.2. Number of estimated QCD fake events in the various jet multiplicity pretag and b-tag samples, using the Matrix Method in the $\mu$+jets channel in the 2010 data (35 pb$^{-1}$).
Given that the QCD fake estimates obtained using different control regions for the $\epsilon_{\text{fake}}$ measurement are in excellent agreement with each other, a conservative 30% uncertainty on the QCD rate is assigned, based on the results of the closure test applied to the MC simulation samples.

6.1.5 Matrix Method in the electron channel for the 2011 data analysis

In the electron channel, fake lepton events are coming from all the sources listed in the introduction of this section. Since each of these components can present different kinematical distribution shapes (in particular, different $E_T$ and $m_T(W)$ distributions), the choice of the loose electron selection is important. It has to be chosen in such a way that the relative contributions of the different fake components are similar for the loose and for the tight event selection. For this reason, several modifications of the electron identification requirements have been investigated, including:

Figure 6.2. Real efficiency in the $e+$jets 2011 data sample, as a function of the electron $\eta$ and $p_T$. 

Figure 6.1. Fractions of QCD events found in the 2010 data, estimated applying the anti-electron model Fitting Method for $e+$jet events (left) and the Matrix Method for $\mu+$jet events (right).
the electron cuts medium or tight\footnote{The loose one has not been considered here since it is incompatible with the trigger-level selection, which is already requiring the electron to be medium.}.

- the electron isolation,

- the presence of a hit in the innermost layer of the ID (the so called Pixel B-layer), in order to reduce the contribution from photon conversions\footnote{The $b$-layer hit requirement is included in the tight electron cuts.}.

Figure 6.3. Fake efficiency in the $e$+jets 2011 data sample, as a function of: the electron $\eta$, the sum of the $E_T$ of all the jets and electrons in the event, the electron $p_T$, the $\Delta\phi$ between the electron and the $E_T$, the minimum $\Delta R$ between the electron and the jets.
The best combination, in terms of data-expectation agreement for the most important variable shapes in the low jet multiplicities and relaxed cuts control regions (see Figure 6.4 and 6.5) and in terms of independence of $\epsilon_{fake}$ on variables other than the electron $\eta$, has been found to be the following. A “loose electron” is defined as an usual electron (see Section 4.1) but:

- the medium cuts are required instead of the tight ones;
- a B-layer hit is required in addition to the medium cuts;
- the isolation is loosened, requiring $etcone < 6$ GeV.

Note that, for the loose electron events, the $E_T$ definition is different from that used for the tight events. It is calibrated considering as electrons all the medium electrons and not only the tight ones (see Section 3 and Section 4.1.1).

Both $\epsilon_{fake}$ and $\epsilon_{real}$ are parametrized as a function of the electron $\eta$, as shown in Figure 6.3 and 6.2. To estimate $\epsilon_{fake}$, a low $E_T$ region is used, requiring $5 \text{ GeV} < E_T < 20$ GeV and applying no cuts on $m_T(W)$. $\epsilon_{fake}$ is evaluated for pretag and $b$-tag selection independently and is parametrized as a function of the electron $\eta$ and of four additional variables: $\sum E_T$, $p_T(e)$, $\Delta\phi(e - E_T)$ and $\Delta R(e - jet)_{min}$ (see Figure 6.3 where the dependence of $\epsilon_{fake}$ on these variables is shown). The real lepton contribution in $CR_{fake}$ is subtracted using the MC simulation. The real efficiency $\epsilon_{real}$ is measured selecting data events from $Z \to ee$ decay and asking for two opposite-signed electrons with an invariant mass within 10 GeV from the $Z$ boson mass ($80 \text{ GeV} < m_{ee} < 100$ GeV), and the $t\bar{t}$ MC simulation is used to check its dependence on the different variables shown in Figure 6.2.

To check its validity, the method is applied to the different jet multiplicity bin selections relaxing the $E_T$ and $m_T(W)$ cuts, in order to enrich the samples in QCD events and to check the shape of the distributions. Figure 6.4 shows the $E_T$ distribution for a selection without any $E_T$ or $m_T(W)$ cuts, while Figure 6.5 shows the $m_T(W)$ distribution after applying a relaxed cut of $E_T > 20$ GeV and no cuts on $m_T(W)$.

<table>
<thead>
<tr>
<th></th>
<th>1-jet</th>
<th>2-jets</th>
<th>3-jets</th>
<th>4-jets</th>
<th>$\geq 5$-jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>pretag</td>
<td>2.5649 ± 0.7695</td>
<td>12.820 ± 0.3846</td>
<td>46.41 ± 1.392</td>
<td>145.9 ± 4.39</td>
<td>528 ± 161</td>
</tr>
<tr>
<td>b-tag</td>
<td>2.440 ± 0.732</td>
<td>16.76 ± 0.504</td>
<td>68.0 ± 0.205</td>
<td>230 ± 0.71</td>
<td>73 ± 0.26</td>
</tr>
</tbody>
</table>

Table 6.3. Number of estimated QCD fake events in the various jet multiplicity pretag and $b$-tag samples, using the Matrix Method in the $e+$jets channel for the 2011 data analysis (2.05 fb$^{-1}$).

The expected number of QCD events are reported in Table 6.3 and the QCD event fraction is shown in Figure 6.10 for different jet multiplicities and for the pretag and $b$-tag selections for the different taggers and working points.

---

7The 5 GeV minimum cut is chosen to minimize the effect of pile-up and to exclude events with a too low $E_T$ which are expected to have different properties from the high $E_T$ events in the signal region.

8The variable $\sum E_T$ is built summing the contributions of all the reconstructed objects in the same way as the $E_T$.  

Figure 6.4. Missing transverse energy distribution, in the 2-jet, 3-jet and ≥ 4-jet bins for the pretag and b-tag selections. No cuts on $E_T$ and $m_T(W)$ are applied.

To evaluate the systematic uncertainty of the method, different variations have been tried:

- an alternative control region for $\epsilon_{fake}$ has been used, requiring $m_T(W) < 20$ GeV
Figure 6.5. $W$ transverse mass distribution, in the 2-jet, 3-jet and $\geq 4$-jet bins for the pretag and $b$-tag selections. A relaxed $\slashed{E}_T$ cut ($\slashed{E}_T > 20 \text{ GeV}$) and no cuts on $m_T(W)$ are applied.

and no cuts on $\slashed{E}_T$:

- the additional parametrizations v.s. $\sum E_T, p_T(e), \Delta \phi(e - \slashed{E}_T)$ and $\Delta R(e - \text{jet})_{\text{min}}$
have been dropped;

- the real lepton contribution in CRfake has been scaled by ±25%;
- \( \epsilon_{\text{real}} \) has been taken from the MC simulation and not from data (see Figure 6.2).

For each of these variations, the estimate has been redone, and the difference with the default estimate has been taken as uncertainty.

### 6.1.6 Matrix Method in the muon channel for the 2011 data analysis

For the 2011 data analysis, the same loose muon definition as for the 2010 data is used.

The fake efficiency \( \epsilon_{\text{fake}} \) is measured in a low \( E_T \) CRfake defined by 5 GeV < \( E_T \) < 15 GeV. The real lepton contribution is subtracted according to the MC simulation. The efficiency is binned as a function of the muon \( \eta \), and is additionally parametrized as a function of the \( p_T \) of the leading jet in the event, of the \( \Delta \phi(\mu - E_T) \) and of the \( \Delta R(\mu - \text{jet})_{\text{min}} \), using Formula 6.10. As can be seen in Figure 6.7, the dependence of \( \epsilon_{\text{fake}} \) from these variables is important, and these variables are highly correlated with the number of jets in the event.

To estimate \( \epsilon_{\text{real}} \), a \( Z \rightarrow \mu\mu \) sample is selected, requiring two opposite signed muons with 80 GeV < \( m_{\mu\mu} \) < 100 GeV and low \( E_T \). As can be seen in Figure 6.6, \( \epsilon_{\text{real}} \) shows a negligible dependence on the muon \( \eta \).

Like in the e+jets channel (see Section 6.1.5), the \( E_T \) and \( m_T(W) \) distributions with relaxed cuts are shown in Figure 6.8 and 6.9.

The estimated numbers of QCD events in the 2011 data, for the various jet multiplicity and \( b \)-tag bins, are reported in Table 6.4, while the QCD fake event fraction is shown in Figure 6.10 (right).

---

**Figure 6.6.** Real efficiency \( \epsilon_{\text{real}} \) in the 2011 data set in the \( \mu+jets \) channel, as a function of the muon \( \eta \) and \( p_T \).
Figure 6.7. Fake efficiency $\epsilon_{\text{fake}}$ in the 2011 data set in the $\mu$+jets channel, as a function of different variables in the event: the muon $\eta$, the $p_T$ of the leading jet in the event, the $\Delta\phi$ between the muon and the missing energy, the minimum $\Delta R$ between the muon and the jets.

<table>
<thead>
<tr>
<th></th>
<th>1-jet</th>
<th>2-jets</th>
<th>3-jets</th>
<th>4-jets</th>
<th>$\geq$5-jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>pretag</td>
<td>86530±25959</td>
<td>35228±10568</td>
<td>9526±2858</td>
<td>2532±760</td>
<td>858±259</td>
</tr>
<tr>
<td>b-tag</td>
<td>8076±2423</td>
<td>5711±1713</td>
<td>2087±626</td>
<td>684±206</td>
<td>295±90</td>
</tr>
</tbody>
</table>

Table 6.4. Number of estimated QCD fake events in the various jet multiplicity pretag and b-tag samples, using the Matrix Method in the $\mu$+jets channel for the 2011 data analysis (2.05 fb$^{-1}$).
Figure 6.8. Missing transverse energy distribution, in the 2-jet, 3-jet and ≥ 4-jet bins for the pretag and b-tag selections. No cuts on $E_T$ and $m_T(W)$ are applied.
Figure 6.9. $W$ transverse mass distribution, in the 2-jet, 3-jet and $\geq 4$-jet bins for the pretag and $b$-tag selection. A relaxed $E_T$ cut ($E_T > 20$ GeV) and no cuts on $m_T(W)$ are applied.
To evaluate the systematic uncertainty of the method, different variations have been tried:

- an alternative $CR_{fake}$ for $\epsilon_{fake}$ has been used, requiring low $m_T(W)$ and applying an inverted triangular cut, like for the 2010 data analysis;
- the additional parametrizations v.s. $p_T$(leading jet), $\Delta\phi(\mu-\not{E}_T)$ and $\Delta R(\mu-jet)_{min}$ have been dropped;
- the real lepton contribution in $CR_{fake}$ has been scaled by $\pm 25\%$;
- $\epsilon_{real}$ has been taken from the MC simulation and not from data.

Figure 6.10. Fractions of QCD fake events found in the 2011 data, estimated applying the Matrix Method for the $e$+jet events (left) and for the $\mu$+jet events (right).
6.2 $W+$jets background determination

Since the theoretical uncertainties on the estimate of the $W+$jets background for high jet multiplicities (especially after $b$-tag selection) are large, data-driven methods that combine measurements from several control sample are used.

The approach described here, and applied for both the 2010 and 2011 data analyses, consists in two steps. The first step is to get an estimate of the number of $W+$jet events after a specific selection without including any $b$-tagging requirement ($W_{\text{Nj pretag}}$) with one of the methods described in Sections 6.2.1, 6.2.2 and 6.2.3. As a second step, needed for the $W+$jet background estimation in a $b$-tag sample, the pretag estimate is extrapolated to the corresponding $b$-tag selection ($W_{\text{Nj tagged}}$) by multiplying by an appropriate factor $f_{\text{tag}}^{Nj}$ ("$W$-tagging-rate"). In such a way, one can write:

$$W_{\text{Nj tagged}} = W_{\text{Nj pretag}} \cdot f_{\text{tag}}^{Nj}.$$  \hspace{1cm} (6.11)

The way $f_{\text{tag}}^{Nj}$ is evaluated combining the MC information with a data-driven method is described in Section 6.2.5.

Which one of the three pretag estimation methods is preferred for the analysis, depends on the integrated luminosity, being each method dominated by statistical or systematic uncertainties in different ways. Figure 6.11 shows the total uncertainty on the $W+$jets pretag estimation for the three methods as a function of the integrated luminosity.

![Figure 6.11](image)

Figure 6.11. Total uncertainty on the $W+$jets background estimation in the pretag $\geq 4$-jets sample, depending on the integrated luminosity. The extrapolation is made considering a fixed systematic uncertainty and a luminosity dependent statistical uncertainty. The input numbers are an average between the $e+$jet and $\mu+$jet channel uncertainties on the 2010 data analysis.

In the following, the used methods for the pretag and the $b$-tag estimates are presented, together with the results obtained applying them to the 2010 and 2011 data analyses.
6.2.1 Berend’s Scaling method

The first approach, used for the analysis which first observed a top quark signal in the ATLAS experiment [29], exploits the fact that the ratio of $W+n$ jets to $W+n+1$ jets is expected to be approximately constant as a function of $n$ (Berend’s Scaling) [115] [116]. The method is used in the 2010 data analysis as a cross-check measurement. The number of $W$ events in the $N$-jet pretag sample (with $N > 2$) can be estimated as:

$$W^{Nj} = W^{2j} \cdot \left( \frac{W^{2j}}{W^{1j}} \right)^{N-2},$$

(6.12)

and for an inclusive jet multiplicity sample, as the $\geq 4$-jets one, one can write:

$$W^{\geq 4j} = W^{2j} \cdot \sum_{i=2}^{\infty} \left( \frac{W^{2j}}{W^{1j}} \right)^{i}.$$

(6.13)

The number of $W$ events in the 1- and 2-jet bins can be extracted from the data by simply counting the data events after the selection and subtracting the non-$W$ backgrounds (mainly QCD), since the $t\bar{t}$ contribution is negligible.

This method cannot be applied after the $b$-tag selection, since in this case the Berend’s Scaling assumption is not any more valid, mainly because of the different contributions from $Wc$, $Wc\bar{c}$ and $Wb\bar{b}$ components in the various jet multiplicity bins (as shown in Section 6.2.4).

Also, the fraction of $W \rightarrow \tau\nu$ entering the $\ell+jets$ selection (due to a $\tau \rightarrow e/\mu\nu\bar{\nu}$ decay) is not behaving like the rest of the selected $W+jet$ events (i.e. the events where the $e/\mu$ is coming directly from the $W$ decay) in terms of Berend’s Scaling. For this reasons, the $W \rightarrow \tau\nu$ contribution has to be subtracted from the $W^{2j}$ and $W^{1j}$ counted in the data and added again to the $W^{Nj}$ estimation, by multiplying the fraction of $W \rightarrow \tau\nu$ in MC simulation ($\sim 5\%$ in $e+jets$ and $\sim 7\%$ in $\mu+jets$) by the estimated $W^{Nj}$.

<table>
<thead>
<tr>
<th>2010 data (35 pb$^{-1}$)</th>
<th>$e+$jets</th>
<th>$\mu+$jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainty</td>
<td>5%</td>
<td>6%</td>
</tr>
<tr>
<td>Purity of control samples</td>
<td>18%</td>
<td>9%</td>
</tr>
<tr>
<td>Validity of the extrapolation</td>
<td>22%</td>
<td>19%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>2%</td>
<td>2%</td>
</tr>
</tbody>
</table>

| Predicted $W^{\geq 4j}_{pretag}$ (MC) | 183 | 314 |
| Estimated $W^{\geq 4j}_{pretag}$ (Berend’s Scaling) | 180 ± 47 | 321 ± 68 |

Table 6.5. Number of $W$+jet background events estimated using the Berend’s Scaling method, in the $\geq 4$-jets pretag sample, for the 2010 data analysis. The main source of uncertainties are listed in the form of relative uncertainty, and the total uncertainty on the estimate is reported together with the final estimate. The expected number of events from the MC simulation is also reported for comparison.

The following sources of systematic uncertainty are considered.

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The purity of the $W+$jets control sample, considering the uncertainties on the MC-estimated single top, $Z+$jets and di-bosons, and on the data-driven QCD fake background estimation (see Sections 4.3 and 6.1).

The assumption that the $W+n+1$-jets / $W+n$-jets ratio is constant is checked using the ALPGEN samples with different generator parameters. The spread around unity of the value of $(W^{2j}/W^{\geq 4j}) \cdot \sum_{i=2}^{\infty} (W^{2j}/W^{1j})^i$, found to be of the order of 20%, is used as systematic uncertainty. The PDF uncertainty effect on the same quantity is found to be 3%. The sum of these two contributions in quadrature is considered as the total theoretical uncertainty in the validity of the extrapolation.

The effect of the experimental uncertainties on the assumption that the $W+(n+1)$-jets / $W+n$-jets ratio is constant is also considered. The only significant contribution comes from the jet energy scale uncertainty and it is found to be 2%.

Given the abundance of $W+$jet events in the 1 and 2-jet bins, the method gives the smallest uncertainty for low integrated luminosity, where the other methods are statistically limited, as shown in Figure 6.11.

In Table 6.5 the results of this method applied to the full 2010 data analysis are reported.

### 6.2.2 $W/Z$ ratio method

The second approach uses the fact that the $W/Z$ ratio is better known than the inclusive $W+$jet rates, and it is approximately constant with the jet multiplicity. The number of $W$ events in the $N$-jet pretag sample can thus be estimated as:

$$W^{Nj} = Z^{Nj} \cdot \left( \frac{W^{1j}}{Z^{1j}} \right)_{data} \cdot C_{MC}, \quad C_{MC} = \frac{(W^{Nj}/W^{1j})_{MC}}{(Z^{Nj}/Z^{1j})_{MC}}. \quad (6.14)$$

While $W^{1j}$ is measured in the data as with the Berend’s Scaling method, the number of $Z$ events in the data ($Z^{Nj}$ and $Z^{1j}$) is counted using a particular event selection built in order to keep the ratio $C_{MC}$ as close to one as possible. In particular, the $W/Z$ ratio method requires the kinematical selection on the leptons from the $Z$ to match the one applied to the charged lepton and the neutrino on the $W$ and $t\bar{t}$ signal candidates. Two different selections for the $Z$ candidates are applied (“selection A” and “B” in the following), for the electron and the muon channel:

- the same trigger and general event requirement for the $\ell+$jets selection are applied;
- exactly two good electrons or two good muons are required, with opposite charge and with an invariant mass between 80 GeV and 100 GeV;
- to apply the estimate in the electron channel (“selection A”), the $p_T$ of the negatively charged lepton is required to be $> 35$ GeV (to mimic the $E_T$ cut tighter than the minimum $p_T$ cut on the electron) and the transverse mass of the $\ell^+\ell^-$ system is required to be $> 25$ GeV (to mimic the $m_T(W)$ cut);
• to apply the estimate in the muon channel (“selection B”), the sum of the $p_T$ of the negatively charged lepton with the transverse mass of the $\ell^+\ell^-$ system is required to be $> 60$ GeV (to mimic the “triangular” cut);

• no cuts on the $E_T$ and on the $m_T(W)$ are applied.

The $ee$ and $\mu\mu$ selections are actually combined in order to minimize the statistical uncertainty of the background estimation in the $e$+jet and $\mu$+jet channels separately, but the two estimates are statistically correlated. This is properly taken into account when combining the two $\ell$+jet channels for the $t\bar{t}$ cross-section measurement.

As in the case of the Berend’s Scaling method, the $W\rightarrow\tau\nu$ events are subtracted from the 1-jet bin and added again for the final estimate using the MC-based fraction.

<table>
<thead>
<tr>
<th></th>
<th>2010 data (35 pb$^{-1}$)</th>
<th>$e$+jets</th>
<th>$\mu$+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainty</td>
<td>21%</td>
<td>19%</td>
<td></td>
</tr>
<tr>
<td>Purity of control samples</td>
<td>3%</td>
<td>2%</td>
<td></td>
</tr>
<tr>
<td>Theoretical uncertainties</td>
<td>12%</td>
<td>9%</td>
<td></td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>3%</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>PDFs</td>
<td>3%</td>
<td>3%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Predicted $W_{\geq4j}^{\text{pretag}}$ (MC)</th>
<th>Estimated $W_{\geq4j}^{\text{pretag}}$ (W/Z Ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>183</td>
<td>314</td>
</tr>
<tr>
<td></td>
<td>$157 \pm 38$</td>
<td>$309 \pm 61$</td>
</tr>
</tbody>
</table>

Table 6.6. Number of $W$+jet background events estimated using the $W/Z$ ratio method, in the $\geq 4$-jets pretag sample, for the 2010 data analysis. The main source of uncertainties are listed in the form of relative uncertainty, and the total uncertainty on the estimate is reported together with the final estimate. The expected number of events from the MC simulation is also reported for comparison.

The following systematic uncertainties are considered:

• The purity of the $W^{1j}$ and $Z^{1j}$ data samples. The uncertainties on QCD, $Z(W)$+jets and single top are taken into account in the $W^{1j}$ ($Z^{1j}$) sample. The uncertainty coming from the purity of the $W^{1j}$ sample is the largest one.

• The uncertainty on the $C_{MC}$ factor, from the choice of the ALPGEN generator parameters, the difference between ALPGEN and SHERPA samples, and the PDFs set. The first component is evaluated using the ALPGEN samples with varying parameters. The event selection of the $W$ and $Z$ control samples is applied on the MC objects and the corresponding value of $C_{MC}$ is evaluated for each ALPGEN sample. Since the variations are within the uncertainty, due to the limited MC statistics of the samples, the RMS of the values is taken as systematic uncertainty, and added in quadrature to the difference between the nominal ALPGEN and SHERPA values. This gives a total theoretical uncertainty of around 10%. The PDF uncertainty is found to be $\sim 3\%$. 

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The uncertainties due to the detector reconstruction are evaluated; out of these, the most important one is associated to the jet energy scale, and is about 3%.

The advantages of the $W/Z$ ratio method with respect to the Berend’s Scaling are the following:

- the $Z$ event selection is less sensitive to the presence of other backgrounds like QCD;
- the uncertainty on the $W/Z$ ratio measured in the 1-jet bin control region is propagated linearly to the signal region ($\geq 4$-jet), while in the Berend’s Scaling method the uncertainty on the measured $W+n+1/W+n$ jets ratio is increased by the $> 1$ power relation in Formula 6.12 and 6.13.

On the other hand, the method is statistically limited by the relatively small number of leptonically decaying $Z+\geq 4$-jets events. For this reason it is not used for the measurement performed with 2.9 pb$^{-1}$ [29].

In Table 6.6 the results of this method obtained with the full 2010 data are shown. They have been used as default $W$+jets background estimation for the 2010 cross-section measurement described in Section 5.1.

### 6.2.3 Charge Asymmetry method

The third approach is based on the fact that, in $pp$ collisions, while the $t\bar{t}$ production results in the same number of positive and negative lepton candidates (is “charge-symmetric”), the $W$+jet production results in an excess of the former (is “charge-asymmetric”). Indeed, positively charged $W$-bosons can be produced from parton level processes such as $u\bar{d} \rightarrow W^+$ or $c\bar{s} \rightarrow W^+$ and depend upon products of PDFs such as $u(x_1)\bar{d}(x_2)$. On the other hand, the production of negatively charged $W$-bosons from, e.g., $d\bar{u} \rightarrow W^-$ depends upon the $d(x_1)\bar{u}(x_2)$ PDF product. The PDFs of up and down valence quarks are different in a proton, hence there is a charge asymmetry.

The cross-section ratio, $R = \sigma(pp \rightarrow W^+)/\sigma(pp \rightarrow W^-)$ is relatively well understood [117]. In fact, the main theoretical uncertainty on $R$ is due to the PDF uncertainties, so that $R$ is predicted to within a few percent at LHC energies, i.e. better than the prediction of the cross-section for $W$-bosons produced in association with three or more jets. One can therefore use the theoretical prediction for $R$ to measure the $W$+jets background to $t\bar{t}$ production in the $\ell$+jets channel.

The amount of $W$-bosons in a given sample can be estimated as:

$$W^+ + W^- = \left( \frac{W^+ + W^-}{W^+ - W^-} \right)_{MC} \cdot (D^+ - D^-) = \frac{R + 1}{R - 1} \cdot (D^+ - D^-)$$

(6.15)

where $D^+$ ($D^-$) are the data events with a positively (negatively) charged lepton, and $R$ is evaluated for the particular kinematical selection from MC simulation.
In particular, $R$ depends on the jet multiplicity and is different in the electron and muon channel, as shown in Figure 6.13 (left). The increase of $R$ with the number of jets is due to the fact that higher jet multiplicities probe larger values of the parton momentum fraction $x$, where the difference between the up and down valence quark PDFs is larger. The difference between the channels is a combination of two factors: firstly, the $E_T$ and $m_T(W)$ cuts are different in the two channels, and secondly electron and muon reconstruction efficiencies have a different $\eta$ dependence (electron efficiency is lower for higher values of $|\eta|$) which, combined with the different $\eta$ distribution of $\ell^+$ and $\ell^-$ in $W$ events shown in Figure 6.12, gives rise to different $R$ values.

Figure 6.13. $R$ value as a function of the jet multiplicity. Left: $e$+jet and $\mu$+jet channels and pretag and $b$-tag selection (using the JetFitterCombinedNN tagger with 70% working point) are compared. Right: The values for the different $W$+jet flavour components are reported, taking an average between the $e$+jet and $\mu$+jet channels, for pretag selection.
The formula is valid due to the fact that the processes $t\bar{t}$, QCD, $Z$+jets are charge-symmetric, so that $W^+ - W^- \simeq D^+ - D^-$ to a very good approximation. However, other important processes like single top and diboson production are charge-asymmetric as well. Therefore, they have to be taken into account and subtracted from $D^+$ and $D^-$, according to the sign of the reconstructed lepton. Table 6.7 shows the expected charge asymmetry for all the non-$W$ relevant processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>$e$+jets</th>
<th>$\mu$+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>0.988 ± 0.010</td>
<td>1.001 ± 0.009</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>1.03 ± 0.03</td>
<td>1.06 ± 0.03</td>
</tr>
<tr>
<td>single top</td>
<td>1.18 ± 0.03</td>
<td>1.22 ± 0.02</td>
</tr>
<tr>
<td>diboson</td>
<td>1.01 ± 0.07</td>
<td>1.28 ± 0.06</td>
</tr>
</tbody>
</table>

Table 6.7. Values of the ratio $R$ in the pretag $\geq$4-jets sample, for different non-$W$ processes. The uncertainty due to the limited MC statistic is reported.

The Charge Asymmetry method, which has also been considered by the CMS Collaboration [118], becomes the most precise method to estimate the $W$+jets background in $t\bar{t}$ signal region for high integrated luminosities, as seen in Figure 6.11. In particular, the method does not suffer from any extrapolation uncertainty, as the measurement is done exclusively after the specific event selection of interest, and the large QCD uncertainty does not enter in the estimate. However, due to the relatively large statistical uncertainty, this method was only used as a cross-check measurement of the $W$+jets background in the 2010 data analysis. The results of the measurement in the $\geq$4-jet pretag sample are shown in Table 6.8. For the 2011 data analysis, due to the large available statistics, the Charge Asymmetry is the standard method to normalize from data the $W$+jets background, not only in the $t\bar{t}$ signal region but also in the lower jet multiplicity bins. The results of the measurement applied to the 2011 data set in the various jet multiplicity bins are shown in Table 6.9. Figure 6.14 shows the normalization factors (or “scale factors”, $SF$s) that have to be applied to the MC $W$+jets prediction in order to agree with the measured yields (simply $SF = N(W+ jets)_{data}/N(W+ jets)_{MC}$).

The following systematic uncertainties have been considered. Some of the systematics are properly calculated and applied to the 2011 data only, where the $W$+jets estimate with this method is actually used for the $t\bar{t}$ cross-section measurement.

- To investigate the MC modelling effects on the value of $R$, two different MC generators, SHERPA and ALPGEN, were used to calculate $R$ as a function of the jet multiplicity. The relative difference is considered as an uncertainty associated to the MC generator.

- The effect of charge mis-identification was studied by selecting $Z \rightarrow \ell\ell$ events in data (which are supposed to always have in the final state two oppositely charged leptons) and looking at the probability of finding two same-signed leptons. The probability was found to be negligible (0-0.003%) for muons and between 0.2% and
Table 6.8. Number of $W + \text{jet}$ background events estimated using the Charge Asymmetry method, in the $\geq 4$-jets pretag sample, for 2010 data analysis. The main source of uncertainties are listed in the form of relative uncertainty, and the total uncertainty on the estimate is reported together with the final estimate. The expected number of events from the MC simulation is also reported for comparison.

<table>
<thead>
<tr>
<th>Source</th>
<th>e+jets</th>
<th>$\mu$+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainty</td>
<td>33%</td>
<td>27%</td>
</tr>
<tr>
<td>MC generator</td>
<td>5%</td>
<td>3%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>PDFs</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Predicted $W_{\geq 4j}^{\text{pretag}}$ (MC)</td>
<td>183</td>
<td>314</td>
</tr>
<tr>
<td>Estimated $W_{\geq 4j}^{\text{pretag}}$ (Charge Asymmetry)</td>
<td>$242 \pm 83$</td>
<td>$379 \pm 106$</td>
</tr>
</tbody>
</table>

3% for electrons, depending on the electron $\eta$. The probability measured in data was found to agree well with that in the MC simulation and the uncertainty (mainly statistical) on the measurement is considered as a source of systematic uncertainty in the $e$+jets channel (for 2011 data analysis only).

- The value of $R$ is also depending on the $W$+jet heavy flavour fractions, which suffer from a relatively large theoretical uncertainty. Indeed, the production mechanisms for $Wb\bar{b}$, $Wc\bar{c}$, $Wc$ and $W$+light jets depend in different ways on the proton PDFs. Figure 6.13 (right) shows the different $R$ values for the different $W$+jet flavour components, as a function of the jet multiplicity. For both the 2010 and 2011 data sets, the heavy flavour fractions in $W$+jets are measured in data (see Section 6.2.4) and the measured values are used to correct the flavour composition of the $W$+jets MC sample used to evaluate $R$. The uncertainties on these fractions are propagated to the $W$+jets background estimate (in the 2011 data analysis only).

- Also the JES uncertainty has a non-negligible effect on the final uncertainty on $R$. This because $R$ depends on the jet multiplicity (as shown in Figure 6.13), and the jet multiplicity, which is the number of jets with $p_T > 25$ GeV in the event, depends on the energy scale correction applied to the jets.

- The uncertainty on the PDFs clearly has an effect on the predicted $R$. This uncertainty is evaluated as described in Section 4.4.
6 – Background processes to the $t\bar{t}$ single lepton channel

2011 data (2.05 fb$^{-1}$)

<table>
<thead>
<tr>
<th>Source</th>
<th>$e$+jets</th>
<th>$\mu$+jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainty</td>
<td>7.4%</td>
<td>4.7%</td>
</tr>
<tr>
<td>MC generator</td>
<td>4.0%</td>
<td>8.8%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>8.3%</td>
<td>2.0%</td>
</tr>
<tr>
<td>PDFs</td>
<td>5.5%</td>
<td>5.0%</td>
</tr>
<tr>
<td>Charge mis-id</td>
<td>2.2%</td>
<td>0%</td>
</tr>
<tr>
<td>HFF uncertainty</td>
<td>5.7%</td>
<td>7.8%</td>
</tr>
</tbody>
</table>

Predicted $W^{4j}_{\text{pretag}}$ (MC): 9607
Estimated $W^{4j}_{\text{pretag}}$ (Charge Asymmetry): 8637 ± 1250

Table 6.9. Number of $W$+jet background events estimated using the Charge Asymmetry method, in the 4-jets pretag sample, for the 2011 data analysis. The main sources of uncertainties are listed in the form of relative uncertainty, and the total uncertainty on the estimate is given together with the final estimate. The expected number of events from the MC simulation is also reported for comparison.

Figure 6.14. Ratio between the estimated (with Charge Asymmetry method) and predicted (via MC simulation) number of $W$+jet events in the various jet multiplicity pretag samples.
6.2.4 Determination of the $W$+jet flavour composition

Like the overall $W$+jets normalization, also its heavy flavour composition, i.e. the fraction of $Wb\bar{b}$, $Wc\bar{c}$ and $Wc$ events, suffers from a big uncertainty from MC simulation. Knowing these heavy flavour fractions (HFFs) in $W$+jets is essential to extract the $W$+jets background after a $b$-tag selection, as discussed in Section 6.2.5, but also for the Charge Asymmetry method for the pretag $W$+jets estimate (discussed in Section 6.2.3).

The determination of the $W$ HFF in the high jet multiplicity region is difficult due to the significant amount of $t\bar{t}$ contamination. A common solution to the problem is to measure the $W$ HFF in the 1- and 2-jet bins and extrapolate to the signal region using the MC simulation.

To determine the HFFs in the 1- and 2-jet bins in data, a “tag counting” method is used. Basically, it consists in a comparison of the pretag and $b$-tagged samples between data and MC. Counting the number of events in data and subtracting the number of expected non-$W$ background events ($t\bar{t}$, single top, $Z$+jets, diboson and QCD) in different jet multiplicity and $b$-tag bins, keeping from MC some constrain like the ratio between the HFFs in 1- and 2-jet bins, the ratio between $Wb\bar{b}$ and $Wc\bar{c}$ fractions and the tagging probability for each specific flavour type, a set of data-driven correction factors (or “scale factors”, SFs) for the different flavour fractions in the MC simulation can be extracted.
6 – Background processes to the $t\bar{t}$ single lepton channel

The systematic uncertainties related to this method are the following:

- cross-section uncertainties for $t\bar{t}$, single top, $Z$+jets and diboson,
- QCD normalization uncertainty,
- $b$- and light-tagging efficiency uncertainty,
- jet energy scale.

The second step consists in extrapolating the obtained HFF SFs from the 1- and 2-jet bin to higher jet multiplicity bins. The HFFs in MC are simply scaled by the same SFs, and an uncertainty obtained from MC is assigned. To assess the MC uncertainties associated with the HFF extrapolation, ALPGEN generator parameters are varied in both $W$+light and heavy flavour simultaneously, and the results are checked using NLO event generator.

This analysis is performed for both the 2010 and 2011 data sets, combining the $e$+jet and $\mu$+jet samples to reduce the statistical uncertainty. The SV0 tagging algorithm is used to define the tagged sample.

Results are summarized in Table 6.10. Note that the uncertainties in the extrapolation to higher jet multiplicity bins are treated slightly differently for the two analyses: for the 2010 one, the uncertainty is increasing with the jet multiplicity, while for the 2011 analysis the uncertainty is the same for every jet multiplicity bin higher than two.

<table>
<thead>
<tr>
<th></th>
<th>2010 (2.9 pb$^{-1}$)</th>
<th>2011 (0.7 fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{bb/cc}$</td>
<td>1.3 ± 0.7</td>
<td>1.63 ± 0.76</td>
</tr>
<tr>
<td>$k_c$</td>
<td>1.0 ± 0.4</td>
<td>1.11 ± 0.36</td>
</tr>
<tr>
<td>extrapolation</td>
<td>±20%*</td>
<td>±25%</td>
</tr>
</tbody>
</table>

* per jet multiplicity bin higher than 2, summed linearly: 20% in 3-jet bin, 40% in 4-jet bin etc.

Table 6.10. Scaling factors for $W$+jet HFFs resulting from tag counting measurement in the 2010 and 2011 data sets. The uncertainties reported on the number $k_{bb/cc}$ and $k_c$ are the combination of statistical and systematic uncertainty on the measurement. The extrapolation uncertainty has to be added to that uncertainty when considering the flavour fraction for a jet multiplicity higher than two.

In Figure 6.15 the HFFs in $W$+jets (already corrected according to the 2011 measurement) are shown for different jet multiplicity bins, in the $e$+jet and $\mu$+jet channels for both the pretag and $b$-tag selection (using the JetFitterCombinedNN tagger with a 70% efficiency working point). These uncertainties are obtained combining the uncertainty on the SFs and the extrapolation uncertainty for high jet multiplicity bins.

The reason for this difference is that, for 2011 data analysis, more accurate studies on the HFF in MC simulated $W$+jet events are available.
6.2.5 Estimate for $b$-tag selection

The methods described in Sections 6.2.1, 6.2.2 and 6.2.3, for different reasons, are not suitable for an estimation of the $W+$jets background after the $b$-tag selection. To get the expected number of $W+$jet events in a tagged sample, the strategy is to multiply the pretag estimate performed with one of the described methods by a “tag fraction”, defined as the ratio between the expected number of $W+$jet events after the $b$-tag selection and before any $b$-tag selection:

$$f_{\text{tag}} = \frac{W_{\text{tagged}}}{W_{\text{pretag}}}.$$  \hfill (6.16)

$f_{\text{tag}}$ depends on the event selection, and in particular on the number of jets required by the selection. It depends also on the $b$-tag and light-tag efficiencies, and on the $W+$jets HFF. Since these quantities have a relatively large uncertainty, the strategy is to measure $f_{\text{tag}}$ in data in a low jet multiplicity region, where the contribution from $t\bar{t}$ is negligible and $W+$jets is dominating. The chosen region is the 2-jet exclusive bin, which turns out to be a good compromise between the $t\bar{t}$ contamination and the difference in relative importance of the HFF in $W+$jets$^{10}$.

This measured $f_{\text{tag}}^{2j}$ can be used in the other jet multiplicity samples, but it has to be corrected according to the MC simulation:

$$f_{\text{tag}}^{N_j} = f_{\text{tag}}^{2j} \cdot W_{\text{pretag}}^{N_j}, \quad f_{\text{tag}}^{2j} = \left( \frac{f_{\text{tag}}^{N_j}}{f_{\text{tag}}^{2j}} \right)_{\text{MC}}.$$  \hfill (6.17)

For the determination of the uncertainty on $f_{\text{tag}}^{2j}$, the following sources are taken into account:

- the uncertainties on the HFF in $W+$jet MC samples (see Section 6.2.4);
- the $b$-tag and light-tag efficiency uncertainties (see Section 4.4);
- the JES (see Section 4.4).

The uncertainty on $f_{\text{tag}}$ in the signal region turns out to be smaller with this data-MC mixed approach than the one obtained using a pure MC approach. The reason is basically the cancellation of the systematics related to $b$- and light-tagging and HFF, which appear in the ratio $f_{\text{tag}}^{2j}$. 

On the other hand, the data-driven measurement of $f_{\text{tag}}^{2j}$ as the ratio of $W+$jet events in pretag and $b$-tag data samples, introduces new statistical and systematic uncertainties:

- the statistical uncertainty on the counted number of $W+$jet events in the 2-jet pretag and $b$-tag bins;

---

$^{10}$In fact, as shown in Figure 6.15, the $W+$jet HFF relative contributions depend on the number of jets in the event, and, to be able to reduce the uncertainty coming from them in the extrapolation factor $f_{\text{tag}}^{N_j \to N'}$, they should not be too different between the jet multiplicity $N$ and $N'$. 

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Table 6.11. Central values and uncertainties on $f_{\text{tag}}^{2j}$ and $f_{\text{tag}}^{2j \rightarrow Nj}$, and on the estimated number of $W + \geq 4$-jets events with the three different pretag methods, for the 2010 data analysis.

- the uncertainty on the expected number of QCD fake events obtained for both pretag and $b$-tag selection from data-driven methods (see Section 6.1);
- the uncertainties on the other (MC-based) background subtractions, dominated by the cross-section, the JES, and the $b$/light-tag efficiency uncertainties (see Section 4.4).

Table 6.12 reports the central values and uncertainties on $f_{\text{tag}}^{2j}$ and $f_{\text{tag}}^{2j \rightarrow Nj}$, with the specification of the main sources, expressed as relative uncertainties. The estimated number of $W + 4$-jet events using the Charge Asymmetry method is also reported, compared to the predicted number from MC simulation. All the numbers are for the 2011 data analysis.

The 2011 data analysis results are reported in Table 6.12, which shows the central values and the uncertainties on $f_{\text{tag}}^{2j}$ and $f_{\text{tag}}^{2j \rightarrow Nj}$ and the $W +$jets estimation for the 4-jets sample.
b-tag selection. Figure 6.16 shows the ratio between the estimated $W$+jets and the MC predicted one, for different jet multiplicity b-tag samples.

Note that, depending on the pretag estimation method, some of the systematics are affecting both the pretag estimation and the value of $f_{tag}$ and the proper correlation between the two effects needs to be considered.

Figure 6.16. Ratio between the estimated (with Charge Asymmetry method) and predicted (via MC simulation) number of $W$+jet events in the various jet multiplicity b-tag samples, for the 2011 data analysis (2.05 fb$^{-1}$). The reported statistical and systematic uncertainty combines the uncertainties on the pretag estimation and on the tagging fractions.
Conclusions

In this thesis, a counting method is used to measure the $t\bar{t}$ production cross-section in $pp$ collisions at $\sqrt{s} = 7$ TeV, with the data collected by ATLAS between August 2010 and August 2011. Events have been selected in the single lepton final state. The analysis developed in this thesis has been of fundamental importance for the first ATLAS publication on top quark physics, and is still useful to support the more sophisticated measurements performed in the same decay channel.

The candidate worked directly on the optimization of the selection cuts, on the extraction of the cross-section results, including the systematic uncertainty evaluation (for both the 2010 and 2011 data analysis), and on the data-driven determination of the main backgrounds (mainly for the 2011 data analysis).

The result of the performed measurements is the following:

$$\sigma_{t\bar{t}} = 156_{-30}^{+36} \text{ pb} \quad \text{with 2010 data},$$

$$\sigma_{t\bar{t}} = 164_{-17}^{+20} \text{ pb} \quad \text{with 2011 data}. $$

The total uncertainty on the measurement is $\sim 20\%$ ($\sim 10\%$) for the 2010 (2011) data analysis. Such a small uncertainty reached after such a short time from the start of the LHC operations, obtained without relying on any sophisticated statistical analysis method, probes the capability of the ATLAS detector to reconstruct and isolate signal events with complicated final states, involving at the same time high energy jets, jets coming from the hadronization of $b$-quarks, electrons, muons and missing transverse energy. This success provides an essential stepping stone for new physics searches involving similar final states.

The two measured cross-sections are in good agreement with both the theoretical predictions and the other $\sigma_{t\bar{t}}$ measurements performed by the ATLAS and CMS experiments. The agreement with the theoretical predictions in the framework of the SM, based on high order QCD calculations, supports their validity even at the highest available energies for a particle collider. The agreement within the experimental measurements of the same quantity, selecting different final states, can be used to set limits on new physics models which can modify the top quark production and decay mechanisms as predicted by the SM.

The result of the 2011 data analysis has been also used to extract an indirect measurement of the top mass, giving the result:

$$m_{\text{top}}^{\text{pole}} = 173.3_{-6.0}^{+6.3} \text{ GeV}/c^2,$$

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for a total relative uncertainty of 3.5%, in agreement with the world average value.

More sophisticated analyses in ATLAS, already showing a smaller relative uncertainty than the one obtained at the Tevatron experiments, are being updated with the presently collected data samples, and are foreseen to lower the total uncertainty on the measured $\sigma_{t\bar{t}}$ to $\sim 5\%$. The indirect determination of $m_{\text{top}}^{\text{pole}}$ from such a precisely measured $\sigma_{t\bar{t}}$, would allow to reach a precision of $\sim 2\%$ on the top mass determination. These sophisticated analyses are using the methods developed in this thesis to determine in a data-driven way the most important backgrounds to the $t\bar{t}$ production in the single lepton channel (i.e. the QCD and $W$+jet backgrounds). Beside the purpose of the $\sigma_{t\bar{t}}$ measurement, the improving precision of these methods with the increasing amount of accumulated data, will allow to significantly lower the uncertainties on other important top quark properties measurements.
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