Search for a light charged Higgs boson in the decay channel
\[ H^+ \rightarrow c\bar{s} \] using the ATLAS detector

A thesis submitted to the University of Manchester for the degree of Doctor of Philosophy in the Faculty of Engineering and Physical Sciences

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**Copyright**

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Abstract

A search for a light charged Higgs boson ($H^\pm$) decaying into two jets ($c\bar{s}$) using $pp$ collisions at $\sqrt{s} = 7$ TeV is presented. A data sample corresponding to an integrated luminosity of 4.7 fb$^{-1}$ recorded by the ATLAS detector in 2011 has been analysed. The search is performed in the semi-leptonic $t\bar{t}$ channel, where one of the top quarks decays via $t \to bH^\pm$. The other top quark decays to $bW$, where the $W$ boson decays to a lepton ($e/\mu$) and a neutrino. The search is based on the invariant mass distribution of the two light jets in the final state as the discriminating variable. With no observation of an $H^\pm$ signal, 95% confidence level (CL) upper limits are set on the decay branching ratio of top quarks to charged Higgs bosons. These limits are between 5% and 1% for charged Higgs boson masses between 90 and 150 GeV, and can be considered as model-independent limits on the decay branching ratio of top quarks to any charged boson beyond the Standard Model.
Declaration

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Chapter 1

Introduction

One of the most successful theories that physicists have developed in the 20th century is the Standard Model (SM) of particle physics. This theory explains three of the four fundamental forces in nature and describes the elementary particles and their interactions. Predictions of the SM have been experimentally tested and proved over the years. The theory gained further credence with the discovery of the bottom and top quarks and the tau neutrino. More recently, and after decades of experimental research, a particle consistent with the characteristics of the SM Higgs boson has been discovered by both the ATLAS and CMS collaborations [1][2]. Despite successful explanations for elementary particle interactions, the SM fails to address several important issues. For instance, the asymmetry between matter and anti-matter leading to a matter-dominated universe, the origin of dark matter hypothesized by observational cosmology and the hierarchy problem are not explained in the theory. Gravity is also not included in the theory.

Many hypotheses have been proposed over the years to resolve the problems that are not accounted for in the SM. The analysis presented in this thesis concentrates on models that contain an extended Higgs sector compared with the SM. This extension gives rise to five physical Higgs bosons, three of which are neutral ($h^0, H^0$ and $A^0$) and two are charged ($H^+$ and $H^-$). The boson that has recently been discovered is compatible with many of these models as well as the SM. Therefore, it is necessary to study its nature to understand the mechanism of Electroweak Symmetry Breaking (EWSB). On the other hand, the discovery of a charged Higgs boson would be direct evidence of physics beyond the SM.

Searches for a charged Higgs boson have been performed at particle physics facilities such as LEP and the Tevatron. No evidence for a signal has been observed, and therefore limits are set on its mass. With a much larger centre
of mass energy and luminosity, the LHC provides an opportunity to search for a charged Higgs boson in an extended mass window. The cross section of $t\bar{t}$ pair production at the LHC is much larger than that at the Tevatron, and searches have considered the production of charged Higgs boson in association with a top quark. Two decay channels for the charged Higgs boson have been explored; the hadronic and leptonic decay channels.

This thesis presents a search for a charged Higgs boson using 4.7 fb$^{-1}$ of $pp$ collisions recorded by the ATLAS detector at the LHC in 2011. The charged Higgs boson is assumed to be produced in the decay of a top quark, and therefore has a mass $m_{H^+} < m_{\text{top}} - m_b$. The search is performed using semi-leptonic $t\bar{t}$ events in the decay channel $t \rightarrow bH^+$ with a branching ratio $\mathcal{B}(H^+ \rightarrow c\bar{s}) = 1$. This decay implies the replacement of one $W$ boson in the SM decay $t \rightarrow bW^+$ with a charged Higgs boson, $H^+$. A paper describing this analysis and the obtained results has recently been published in EPJC [3]. Charge conjugation of processes is assumed throughout this thesis.

The following structure is used for this thesis. The theoretical background, including a description of the signal and main background processes, is presented in Chapter 2. Chapter 3 describes the experimental apparatus, the Large Hadron Collider and the ATLAS detector. In Chapter 4, the techniques used for the reconstruction of physics objects from detector information are presented. A Monte Carlo (MC) simulation is used to model the signal and background processes and to study many systematic effects. This is explained in Chapter 5. The techniques used in the analysis, including the event selection requirements, background estimation and event reconstruction techniques, are discussed in Chapter 6. The analysis is affected by many systematic uncertainties, which are described in Chapter 7. The procedures followed to test the level of agreement between the data and MC expectations are presented in Chapter 8. The results obtained from this analysis and the conclusions drawn from them are given in Chapters 9 and 10 respectively.
Chapter 2

Theory and Motivation

The theoretical background needed to understand the search presented in this thesis will be given in this chapter. The Standard Model (SM) is widely accepted as the current theory of particle physics. This theory is described in detail elsewhere, for example [4]. Only a summary of the fundamental particles in nature and their interactions as described by the SM will be given in Section 2.1. Section 2.2 gives some reasons why searches are extended beyond the SM, where a charged Higgs boson can be produced. Then, the decay channel probed in the analysis presented in this thesis and the major background processes, as well as limits from previous searches, will be presented in Sections 2.3 and 2.4.

2.1 Fundamental Particles and Interactions in The Standard Model

The Standard Model is a quantum field theory developed to describe the elementary particles and the interactions between them. Three of the four fundamental forces observed in nature are successfully described by the SM. The strong, electromagnetic and weak interactions are explained via the exchange (emission or absorption) of gauge bosons (particles with integer spin) between the fermions (particles with $\frac{1}{2}$ integer spin), which form matter. Twelve fermions are considered to be fundamental particles comprising six leptons and six quarks. Each set or “family” of fermions is further divided into three generations, as shown in Table 2.1. Interactions between fermions are mediated by the gauge bosons shown in Table 2.2.

Each generation of leptons contains an electrically charged lepton and its corresponding neutral neutrino. Lepton number is a quantum number assigned to
Leptons

<table>
<thead>
<tr>
<th>Generation</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle</td>
<td>Electron</td>
<td>Muon</td>
<td>Tau</td>
</tr>
<tr>
<td>Symbol</td>
<td>$e$</td>
<td>$\mu$</td>
<td>$\tau$</td>
</tr>
<tr>
<td>Mass [MeV]</td>
<td>0.511</td>
<td>105.7</td>
<td>1777</td>
</tr>
<tr>
<td>Electric charge [e]</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>Particle</td>
<td>Electron neutrino</td>
<td>Muon neutrino</td>
<td>Tau neutrino</td>
</tr>
<tr>
<td>Symbol</td>
<td>$\nu_e$</td>
<td>$\nu_\mu$</td>
<td>$\nu_\tau$</td>
</tr>
<tr>
<td>Mass [MeV]</td>
<td>$&lt; 2 \times 10^{-6}$</td>
<td>&lt; 0.19</td>
<td>&lt; 18.2</td>
</tr>
<tr>
<td>Electric charge [e]</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Quarks

<table>
<thead>
<tr>
<th>Generation</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle</td>
<td>Up</td>
<td>Charm</td>
<td>Top</td>
</tr>
<tr>
<td>Symbol</td>
<td>$u$</td>
<td>$c$</td>
<td>$t$</td>
</tr>
<tr>
<td>Mass [GeV]</td>
<td>$(2.3^{+0.7}_{-0.5}) \times 10^{-3}$</td>
<td>$1.275 \pm 0.025$</td>
<td>$173.5 \pm 0.6 \pm 0.8$</td>
</tr>
<tr>
<td>Electric charge [e]</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{2}{3}$</td>
</tr>
<tr>
<td>Particle</td>
<td>Down</td>
<td>Strange</td>
<td>Bottom</td>
</tr>
<tr>
<td>Symbol</td>
<td>$d$</td>
<td>$s$</td>
<td>$b$</td>
</tr>
<tr>
<td>Mass [GeV]</td>
<td>$(4.8^{+0.7}_{-0.3}) \times 10^{-3}$</td>
<td>$(95 \pm 5) \times 10^{-3}$</td>
<td>$4.18 \pm 0.03$</td>
</tr>
<tr>
<td>Electric charge [e]</td>
<td>$-\frac{1}{3}$</td>
<td>$-\frac{1}{3}$</td>
<td>$-\frac{1}{3}$</td>
</tr>
</tbody>
</table>

Table 2.1: Fundamental fermions present in the SM [5].

Gauge Bosons

<table>
<thead>
<tr>
<th>Interaction</th>
<th>EM</th>
<th>Weak</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle</td>
<td>Photon</td>
<td>W-boson</td>
<td>Z-boson</td>
</tr>
<tr>
<td>Symbol</td>
<td>$\gamma$</td>
<td>$W^\pm$</td>
<td>$Z$</td>
</tr>
<tr>
<td>Mass [GeV]</td>
<td>0</td>
<td>$80.385 \pm 0.015$</td>
<td>$91.1876 \pm 0.0021$</td>
</tr>
<tr>
<td>Electric charge [e]</td>
<td>0</td>
<td>$\pm 1$</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.2: The gauge bosons present in the SM [5].

each lepton and the overall lepton number is conserved in any interaction, such as $\beta$ decay;

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$L_e: 0 = 0 + 1 - 1$$

where a neutron decays to a proton, electron and electron anti-neutrino. It should be noted that for each particle there is an anti-particle with the same mass and spin, but with opposite non-zero internal quantum numbers. Charged leptons interact via both the electromagnetic and weak interactions, whereas neutrinos
interact only via the weak interaction, and therefore they cannot be directly tracked by detectors. Instead, the neutrino momentum can be deduced from the total transverse momenta of all other particles in an event, which is known as “missing transverse momentum or energy”.

Each generation of quarks contains an up-type quark and a down-type quark. Quarks carry fractional electric charge, \( +\frac{2}{3} \) for the up-type quarks and \( -\frac{1}{3} \) for the down-type quarks. A baryon quantum number of \( B = \frac{1}{3} \) is assigned to each quark. This number is also conserved in the interactions. In addition, quarks carry a colour charge which allows them to interact via the strong interaction. A quark can be in any of the three colour states labeled as red (\( R \)), blue (\( B \)) or green (\( G \)) and an anti-quark in one of the anti-colour states (\( \bar{R}, \bar{B}, \bar{G} \)). Colour charge is also a conserved quantity in interactions.

Due to the fact that all observed particles are colour-neutral, an additional requirement is imposed leading to the concept of colour confinement. Therefore, quarks can only exist in colourless bound states called hadrons. Hadrons can be composed of either a quark-antiquark pair in colour and anti-colour states called mesons or three quarks/anti-quarks each of a colour or anti-colour state called baryons. Because a gluon carries a colour charge, it can interact with a quark or another gluon. Quarks and gluons interact with each other via the strong force. Due to these interactions and the colour confinement, jets of hadronic particles are observed in the detector as a result of quark production or gluon emission.

The electromagnetic, weak and strong interactions between particles are mediated by the gauge bosons shown in Table 2.2. The photon is a massless particle which acts as the mediator of the electromagnetic force between electrically charged particles. It does not carry electric charge, whereas the gluon, the mediator of the strong force between coloured particles, is a massless particle which carries a colour charge and therefore can interact with other gluons. The unification of the electromagnetic and the weak forces results in the electroweak force. This force is mediated by four gauge bosons, the \( W^+, W^- \) and \( Z \) bosons and the photon (\( \gamma \)). These particles are expected to be massless, however three of them, the \( W^+, W^- \) and \( Z \) bosons, are observed to have non-zero masses. The mechanism by which these particles acquire masses in the SM is known as spontaneous Electroweak Symmetry Breaking (EWSB) or the Higgs mechanism, although it was proposed by several physicists \[6, 7, 8\]. This mechanism is described elsewhere, for example in \[9\]. The Higgs mechanism requires an additional neutral particle, the Higgs boson. Intensive searches have been performed over the last decades to detect the Higgs boson. Recently, a particle consistent with the char-
acteristics of the SM Higgs boson was discovered by both the ATLAS and CMS collaborations [1, 2].

2.2 Beyond The Standard Model

Although the Higgs boson is the last particle predicted by the SM, its discovery does not end particle physics or the search for new particles. The SM itself cannot be considered as a complete theory, because there are several problems that it does not resolve. The gravitational interaction between massive objects is not explained within the SM. Despite the fact that the Higgs mechanism explains how particles acquire masses within the SM, several parameters are not predicted by the theory, and more importantly the disparity between the masses of fermions is not explained. Other issues which are not resolved by the SM include the matter-anti-matter asymmetry and the dark matter present in the Universe. The matter-anti-matter asymmetry has resulted in a matter-dominated Universe that cannot be explained by the CP-violation included in the SM. The dark matter is predicted by cosmological observations. It acquired its name because it cannot be seen as it does not interact electromagnetically. However, it has gravitational effects that cannot be explained by the visible masses of the galaxies alone. Within the SM, neutrinos are the only particles that could be a dark matter candidate, but they are excluded as their mass and density do not satisfy the dark matter requirements [10]. Therefore, the SM does not provide a satisfactory dark matter candidate. These unsolved problems suggest some underlying physics processes beyond the SM.

Many extensions to the Standard Model have been theorised to address some or all of these unanswered questions. Two Higgs Doublet Models (2HDMs), such as the Minimal Supersymmetric Standard Model (MSSM), are the simplest models with an extended Higgs sector. In the 2HDMs, the Higgs sector responsible for the spontaneous EWSB has two Higgs doublets, and therefore two vacuum expectation values ($v_1$ and $v_2$), instead of the one in the SM (with a vacuum expectation value, $v_{SM}$). This results in five physical Higgs boson states, two of which are charged scalar bosons ($H^\pm$) and the others are two neutral scalars ($h, H$), and one pseudoscalar ($A$). An important parameter in studying 2HDMs is $\tan \beta$, which is defined as;

$$\tan \beta \equiv \frac{v_2}{v_1}, \quad (2.3)$$
where \( v_1^2 + v_2^2 = v_{SM}^2 \). Many studies of 2HDMs have focused on the \( H^\pm \) boson as it can never decay “invisibly”, therefore its discovery would be a definite signal for new physics beyond the SM. The 2HDMs are discussed in detail in [11].

The searches for a charged Higgs boson have gained a sufficiently great interest that a series of conferences, CHarged 2006, CHarged 2008, CHarged 2010 and CHarged 2012, have been held to discuss the theory and phenomenology of charged Higgs bosons [12, 13, 14, 15]. If the mass of the charged Higgs boson is less than the mass of the top quark minus the mass of the bottom quark \( (m_{H^\pm} < m_t - m_b) \), then the decay \( t \to bH^+ \) is kinematically allowed, and thus an \( H^+ \) signal could exist in the decay of \( t \bar{t} \) pairs. The charged Higgs boson decay branching ratios depend on the chosen model and \( \tan \beta \). For example, in the MSSM model the decay mode \( (H^+ \to c\bar{s}) \) dominates at low \( \tan \beta \), while the decay mode \( (H^+ \to \tau\bar{\nu}) \) dominates at higher \( \tan \beta \). This analysis is focused on a light charged Higgs boson in the \( H^+ \to c\bar{s} \) decay channel.

**2.3 Signal and Background Processes**

For the \( m_{H^+} < m_t - m_b \) scenario, the decay \( t \to bH^+ \) is kinematically allowed, and therefore the signal is expected to be embedded in the SM \( t \bar{t} \) events. For this analysis, it is necessary to understand the kinematics of the \( t \bar{t} \) system to extract signal events if a strong enough signal exists. The production of SM \( t \bar{t} \) events at the LHC centre of mass energy of \( \sqrt{s} = 7 \) TeV is dominated by gluon-gluon fusion \((\approx 80\%)\), with a smaller contribution \((\approx 20\%)\) from quark-antiquark annihilation. The leading order production modes are shown in Figure 2.1. The theoretical cross section of \( t \bar{t} \) events in \( pp \) collisions at a centre of mass energy of \( \sqrt{s} = 7 \) TeV calculated using a next-to-next-to-leading order approximation for a top quark mass of 172.5 GeV is \( \sigma_{t\bar{t}} = 167^{+17}_{-18} \) pb [16]. With this production cross section, a large number of \( t \bar{t} \) events is expected to be present in the data-set recorded by ATLAS in 2011.

**2.3.1 The SM \( t \bar{t} \) System**

The lifetime of the top quark is \( \approx 5 \times 10^{-25} \) s, thus it decays before forming hadrons. The leading pair-production process has the following three final states;

1. All-jets: \( t \bar{t} \to W^+bW^-\bar{b} \to q\bar{q}'bq''\bar{q}'''\bar{b}, \) (45.7%)

2. Lepton+jets \((l+\text{jets})\): \( t \bar{t} \to W^+bW^-\bar{b} \to q\bar{q}'bl^-\bar{\nu}(or)l^+\nu bq''\bar{q}'''\bar{b}, \) (43.8%)
3. Dilepton ($ll$): $t\bar{t} \to W^+bW^-\bar{b} \to l\nu_l b l'\bar{\nu}_{l'} \bar{b}$, (10.5%) 

The relative contribution of each decay channel is given assuming lepton universality \cite{5}. Here, lepton ($l$) refers to an electron ($e$), a muon ($\mu$) or a tau ($\tau$). The quarks in the final states of the decay channels, 1, 2 and 3, hadronise producing hadronic jets in the detector. In addition, the quarks and gluons in the initial and final state can radiate gluons increasing the number of detected jets in the event. The branching fractions for all decay channels of the $t\bar{t}$ pair are shown in Figure 2.2.

A Feynman diagram illustrating the all-jets decay channel, which has the largest branching fraction, is shown in Figure 2.3. This channel has at least six jets in the final state leading to the difficulty of the correct jet-parton assignment in the event reconstruction. An additional challenge is to distinguish $t\bar{t}$ events from the large QCD multi-jet background produced in $pp$ collisions, which has a similar detector signature with mainly $b$-jets present in $t\bar{t}$ events.

The dilepton channel is not sensitive to the QCD multi-jet background. It has the smallest branching fraction of 10.5%, but a clean signal characterised by two $b$-jets and two isolated leptons in the final state. This channel does not contribute to this analysis due to the assumption that $B(H^+ \to c\bar{s}) = 100\%$, which implies four hadronic jets in the final state.

The lepton+jets or semi-leptonic decay channel shown in Figure 2.4 accounts for 43.8\% of $t\bar{t}$ events. One of the $W$ bosons from the top pair decays leptonically, producing a high $p_T$ lepton and large missing transverse energy due to the undetected neutrino, while the other $W$ boson decays hadronically producing two jets in addition to the two $b$-jets from the top pair decay. As shown in Figure 2.2, the lepton+jets channel includes the $\tau$+jets decay mode. The $\tau$ lep-
ton can decay hadronically producing two additional jets. Therefore, the $\tau$ decay mode is excluded from the semi-leptonic decay channel used for this analysis, and only the electron and muon modes are considered. The kinematics distinguish the semi-leptonic $t\bar{t}$ decays from the QCD multi-jet background. The transverse momentum of the neutrino in the final state can be calculated using the known mass of the $W$ boson, and the event can be fully reconstructed [17]. The low jet multiplicity, typically four jets, reduces the number of jet configurations in the event reconstruction. This lepton+jets decay channel, shown in Figure 2.4, will be referred to as the SM $t\bar{t}$ background or SM $t\bar{t}$ events.

2.3.2 The Signal Process

For a light charged Higgs boson, $m_{H^+} < m_t - m_b$, the decay $t \rightarrow H^+b$ is kinematically possible. The analysis presented here assumes that $\mathcal{B}(H^+ \rightarrow c\bar{s}) = 100\%$ and aims to measure or set limits on the branching ratio $\mathcal{B}(t \rightarrow H^+b)$. The $t \rightarrow H^+b$ decay mode, if it exists, can alter the processes discussed in Section 2.3.1 adding the following decay modes:

1. Fully hadronic ($H^+W^-$), $t\bar{t} \rightarrow H^+bW^−\bar{b} \rightarrow q\bar{q}'bq''\bar{q}''\bar{b}$,
or \((H^+ H^-)\),  
\[ t\bar{t} \rightarrow H^+ b H^- \bar{b} \rightarrow q\bar{q}' b q'' \bar{q}'' b. \]

2. Semi-leptonic, \( t\bar{t} \rightarrow H^+ b W^- \bar{b} \rightarrow q\bar{q}' b l^- \bar{\nu} b. \)

The fully hadronic decay has the same kinematics as that shown in Figure 2.3, where at least one \(W\) boson from the \(t\bar{t}\) decay is replaced by an \(H^+\), and therefore this channel suffers from large QCD multi-jet background. In the semi-leptonic channel, one of the \(W\) bosons in the event decays leptonically, while the other \(W\) is replaced by an \(H^+\) as shown in Figure 2.5, and hence this channel is distinguishable from QCD multi-jet background. Additionally, this channel has the advantage of a relatively large branching fraction and it is, therefore, the decay channel chosen for this analysis. The kinematics of this channel allows the reconstruction of \(t\bar{t}\) events, from which a mass distribution of the dijet assigned to
the decaying boson can be formed. This distribution is expected to peak at $m_W$, however, it will gain a secondary peak at $m_{H^+}$ if a signal is present.

![Feynman diagram](image)

Figure 2.5: Feynman diagram showing the semi-leptonic $t \bar{t}$ decay channel with $t \rightarrow bH^+$ and $H^+ \rightarrow c \bar{s}$. This is the charged Higgs boson signal searched for in this analysis.

2.3.3 Other SM Background Processes

In $pp$ collision data, all kinematically allowed processes are expected to occur and interesting events need to be selected above a huge background. The major background processes are those with kinematics similar to those of the semi-leptonic $t \bar{t}$ events. These backgrounds include $W$+jets, $Z$+jets and diboson events. The contributions of these backgrounds are minimised via event selection techniques which will be discussed in detail in Chapter 6. Events with a single top quark are expected to have cross sections smaller than that of $t \bar{t}$ \cite{5}. The single top events are not considered in the search for charged Higgs signals and are treated as background events. Four Feynman diagrams describing single top production in the SM are shown in Figure 2.6

2.4 Previous Searches and Limits

As mentioned in Section 2.2, the search for charged Higgs bosons has attracted the attention of many physics experiments. Searches at the LEP experiments gave lower limits on $m_{H^+}$ at about 80 GeV \cite{18, 19, 20, 21, 22}. The Tevatron experiments extended the search for $H^+$ to the range above the mass of the $W$ boson using $p\bar{p}$ collisions. No evidence for a charged Higgs boson was found
Figure 2.6: Feynman diagrams showing single-top producton channels; (a) the s-channel $tb$, (b) the t-channel $tbq$ and (c) the $Wt$ channel.

and the CDF and D0 experiments extracted upper limits on the branching ratio, $\mathcal{B}(t \to H^+ b)$, for a light charged Higgs boson, $m_{H^+} < m_t - m_b$ \cite{23, 24}. These limits, shown in Figure 2.7, are between 10% and 30% depending on $m_{H^+}$ and were obtained assuming $\mathcal{B}(H^+ \to cs) = 100\%$.

With a much higher centre of mass energy, the LHC has joined the hunt for charged Higgs bosons. At $\sqrt{s} = 7$ TeV a significant increase in the production cross section of $t\bar{t}$ pairs is achieved. A search for a light charged Higgs boson decaying to $cs$ using semi-leptonic $t\bar{t}$ pair events has been performed with 35.3 pb$^{-1}$ of integrated luminosity \cite{25}. No charged Higgs boson signal is observed, and therefore 95% confidence upper limits were set on the $\mathcal{B}(t \to H^+ b)$ at 25% for $m_{H^+} = 90$ GeV, 15% for $m_{H^+} = 110$ GeV and 14% for $m_{H^+} = 130$ GeV. These limits are comparable to limits from the Tevatron as shown in Figure 2.8.

With a significantly larger data-set recorded by the ATLAS experiment in 2011, the search presented in this thesis aims to observe a charged Higgs boson signal as a secondary peak in the reconstructed dijet mass distribution obtained from semi-leptonic $t\bar{t}$ candidate events, or to set limits on the branching ratio $\mathcal{B}(t \to H^+ b)$. With a data-set of 4.7 fb$^{-1}$, the effect of systematic uncertainties is expected to be a major challenge for this analysis.
Figure 2.7: The 95% confidence level upper limits on the branching ratio $B(t \to bH^+)$ versus $m_{H^+}$ assuming $B(H^+ \to c\bar{s}) = 1$ for the charged Higgs boson (left:CDF, right:D0). The CDF study [23] used a 2.2 fb$^{-1}$ data-set while the D0 study [24] used a 1 fb$^{-1}$ data-set.

Figure 2.8: The extracted 95% C.L. upper limits on $B(t \to bH^+)$ from the ATLAS early data of 35 pb$^{-1}$ compared with the limits from the Tevatron [25].
Chapter 3

Experimental Apparatus

The Large Hadron Collider (LHC) is the largest and the highest energy hadron accelerator and collider in the world. It is the most recent addition to the CERN’s accelerator complex located near Geneva. The LHC inherited the existing 26.7 km circumference tunnel that was constructed for the LEP machine. The new machine is designed to operate six experiments, ATLAS, ALICE, CMS, LHCb, TOTEM and LHCf, each with its unique particle detector. The existing civil engineering structures were modified and additional work was also needed both over and underground. The ALICE and LHCb experiments used the infrastructure at Points 2 and 8 respectively, while the new additions include the excavation of the two large caverns for the ATLAS and CMS detectors. Figure 3.1 shows schematically the changes to the underground structure of LEP needed to install the LHC machine. More details can be found in Ref. [26].

This chapter describes, briefly, the LHC and its performance. The ATLAS detector is then presented in more detail.

3.1 The Large Hadron Collider (LHC)

The main purpose of the LHC is to accelerate proton beams to the highest possible energy. Its initial design was to collide proton beams at $\sqrt{s} = 14$ TeV, with a design luminosity of $10^{-34}$ cm$^{-2}$s$^{-1}$. This centre of mass energy and luminosity provide a powerful tool to probe an energy regime much higher than that covered by the Tevatron. The LHC is also capable of accelerating heavy ions, predominantly for the ALICE experiment. The machine is supplied with protons via an accelerator chain, shown in Figure 3.2. The injection chain was upgraded substantially to satisfy the requirements of the LHC [26]. Protons from an ion source are accelerated by LINAC 2 to 50 MeV and injected into the Proton...
Synchrotron Booster. The Proton Synchrotron (PS) receives protons from the Booster at 1.4 GeV and accelerates them up to 26 GeV to feed the Super Proton Synchrotron (SPS). The SPS increases the energy of protons up to 450 GeV before injecting them into the LHC. The LHC consists of two beampipes to accelerate two counter-rotating proton beams. Each beampipe has its own Radio Frequency (RF) cavities. At the experimental detectors, the two beams share the same beam pipe. Protons are filled into the LHC in up to 2808 bunches, each with a population of the order $10^{11}$ protons, with a nominal bunch spacing of 25 ns. After the injection of the clockwise and anti-clockwise beams, the acceleration process is started. The magnetic fields of the dipole magnets are simultaneously...
ramped up to bend the beam around the LHC ring. At the end of the acceleration phase the beams are squeezed in size and collided at the interaction points of the experiments.

3.2 LHC Performance

The instantaneous luminosity and the centre of mass energy are important parameters for the LHC. The number of events per second, $N_{\text{event}}$, for a particular physics process is given by:

$$N_{\text{event}} = L\sigma_{\text{event}},$$

where $\sigma_{\text{event}}$ is the cross section of the physics process and $L$ is the instantaneous luminosity of the machine which is given by:

$$L = \frac{f n_1 n_2}{4\pi \varepsilon \beta^*},$$

where $f$ is the collision frequency, $n_1$ and $n_2$ are the numbers of particles per bunch, $\varepsilon$ is the transverse emittance and $\beta^*$ is the amplitude function.

The LHC performance has improved significantly since its first operation in November 2009. This improvement can be seen in Figures 3.3 and 3.4 [27]. Beam energies were ramped up early in 2010 and on the 30th of March the LHC achieved 3.5 TeV per beam. Between March and November 2010 the LHC collided proton
beams at $\sqrt{s} = 7$ TeV delivering $48.1 \text{ pb}^{-1}$ of integrated luminosity to the physics experiments at an instantaneous luminosity of the order of $10^{32}\text{ cm}^{-2}\text{s}^{-1}$.

In 2011 the LHC continued to run at $\sqrt{s} = 7$ TeV. The machine started proton-proton collisions in March 2011 and by the end of June the delivered luminosity exceeded 1 fb$^{-1}$. By increasing the number of colliding bunches, the instantaneous luminosity has increased reaching a peak of $3.65 \times 10^{33}\text{ cm}^{-2}\text{s}^{-1}$. It was possible to deliver 5.61 fb$^{-1}$ of integrated luminosity to the experiments by the end of October 2011. However, as a consequence of the increase in instantaneous luminosity the number of simultaneous interactions in the bunch crossing, known as pile-up, has increased. Figures 3.3 and 3.4 show the total delivered luminosity, number of colliding bunches in ATLAS, the peak instantaneous luminosity delivered to ATLAS and the maximum mean number of events per beam crossing recorded by ATLAS in 2010, 2011 and 2012. With an efficiency of over 93% the ATLAS experiment has recorded 5.25 fb$^{-1}$ of physics data. This data-set was used for the analysis presented in this thesis.

In 2012 it was decided to run the LHC at 4 TeV per beam. The LHC delivered over 23 fb$^{-1}$ of integrated luminosity by the end of the 2012 run. With the same efficiency as in 2011, ATLAS recorded over 21.5 fb$^{-1}$ of physics data during the 2012 run. The instantaneous luminosity has increased, reaching a peak of $7.73 \times 10^{33}\text{ cm}^{-2}\text{s}^{-1}$. The pile-up has also increased significantly compared with the 2010 and 2011 runs. These changes can be seen in Figures 3.3 and 3.4.

![Figure 3.3: Delivered Luminosity versus time for 2010, 2011 and 2012](27)
Figure 3.4: [Top] the number of colliding bunches in ATLAS versus time, [Middle] the peak instantaneous luminosity delivered to ATLAS per day versus time and [Bottom] the maximum mean number of events per beam crossing versus day during the $p$-$p$ runs of 2010, 2011 and 2012 [27].

### 3.3 The ATLAS Detector

ATLAS is a general purpose detector situated at Point 1 on the LHC ring, approximately 100 m underground. It is the largest detector at the LHC with a length of about 44 m, a diameter of approximately 25 m and a total weight of almost 7000 tons [28]. Figure 3.5 shows the ATLAS detector and its main components. The detector is designed to test the Standard Model predictions, including the existence of the SM Higgs boson, and to search for new physics phenomena beyond the SM. These searches require accurate particle identification and precise measurements close to the interaction point. The physics goals and the high energy and luminosity of the LHC can be expressed in the following...
general requirements:

1. The high energy and flux radiation environment requires the use of fast and radiation-hard electronics and sensors. In addition, a high sub-detector granularity is crucial to handle the high particle multiplicity and to cope with the pile-up arising from high luminosity.

2. An almost full coverage in the polar, $\theta$, and azimuthal, $\phi$, angles is required to contain the entire collision event to enable the calculation of the missing transverse energy of the undetected particles.

3. Very good charged-particle momentum resolution and high track reconstruction efficiency in the inner detector are essential for precise measurements close to the interaction point. These measurements are vital to identify $\tau$-leptons and heavy meson decays. It is necessary to reduce the energy loss of particles before the calorimeters by using the minimum possible material.

4. Very good electromagnetic calorimetry to identify and measure the energy of electrons and photons is needed.

5. Good hadronic calorimetry with full coverage is required to measure the jet energy and calculate the missing transverse energy with good energy resolution.
6. Muon identification and the ability to measure momentum with good resolution over a wide range of momenta are necessary.

7. Stable magnetic fields with strong bending power are fundamental for momentum measurements of charged particles in the inner detector and muon spectrometer.

8. High efficiency triggering is needed to achieve a high and stable data taking rate with sufficient background rejection.

ATLAS satisfies, to a large extent, these requirements. Its extended length provides a large acceptance in pseudorapidity and the high granularity of the inner detector allows an efficient track reconstruction. Both the electromagnetic and hadronic calorimeters provide good energy resolution. The ATLAS muon spectrometer yields a good muon identification and the trigger system has a very high efficiency. The ATLAS coordinate system, magnet system, sub-detectors and trigger system will be described in some detail in the following sections. Full details can be found in the technical design report [28].

3.3.1 ATLAS Coordinate System

The coordinate system defined here is used to describe tracks of particles in the ATLAS detector. The origin of this coordinate system is defined to be at the interaction point (IP), where the collision occurs. The positive $x$-axis points from the IP towards the centre of the LHC ring, while the $y$-axis points upwards from the IP. The beam direction, which is transverse to the $x$-$y$ plane, defines the $z$-axis with the positive direction pointing towards LHCb. Since ATLAS is cylindrical shaped, it is also convenient to define a cylindrical coordinate system. In this system the polar angle $\theta$ is measured between the $z$-axis and the $x$-$y$ plane and the azimuthal angle $\phi$ is measured from the $x$-axis around the beam in the $x$-$y$ plane. The pseudorapidity variable $\eta$ defined by Equation 3.3, is used to describe the object’s trajectory in the detector.

$$\eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right).$$  \hspace{1cm} (3.3)

It depends only on the angle $\theta$, but it can also be defined in terms of the particle’s momentum as:

$$\eta = \frac{1}{2} \ln \left( \frac{|p| + p_z}{|p| - p_z} \right).$$  \hspace{1cm} (3.4)
It should be noted that the rapidity of a particle is defined as:

\[ y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right). \]  

(3.5)

The angular distance \( \Delta R \) between two objects in the detector is usually defined in the \( \eta-\phi \) space as:

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

(3.6)

The transverse momentum, \( p_T \), is defined in the \( x-y \) plane as:

\[ p_T = |p| \sin(\theta). \]  

(3.7)

The transverse energy \( E_T \) and the missing transverse energy \( E_T^{\text{miss}} \) are defined in an analogous way.

### 3.3.2 ATLAS Magnet System

The ATLAS magnet system has two main components, the central solenoid (CS) and the air-core toroids. The CS provides the inner detector (ID) with a 2 T magnetic field to bend the tracks of charged particles. It is a superconducting magnet located between the ID and the electromagnetic calorimeter with minimum radiative thickness. The CS is kept at 4.5 K by a liquid helium cooling system. The toroid system consists of a barrel toroid and two end-cap toroids. It generates magnetic fields necessary to bend muon tracks in the muon spectrometer. The barrel toroid consists of 8 superconducting coils each 25 metres long and 5 metres wide, generating about 0.5 T and covering a pseudorapidity range \( 0 < |\eta| < 1.6 \). The end-cap toroids are housed in two cryostats each containing 8 superconducting coils producing a 1 T magnetic field. The end-cap coils are positioned inside the barrel toroid at both sides and are rotated by 22.5 degrees with respect to the barrel toroids to enhance the bending power at the overlap regions. The end-cap toroids extend the covered pseudorapidity to \( |\eta| < 2.7 \) with an overlap region \( 1.4 < |\eta| < 1.6 \).

### 3.3.3 Inner Detector

The inner detector (ID) is designed to provide precise track measurements. These measurements are vital to identify primary and secondary vertices. The momentum of charged particles can be calculated with high resolution from the curvature
of tracks in the magnetic field. The nominal $p_T$ threshold for these measurements is 0.5 GeV within the pseudorapidity range $|\eta| < 2.5$. The ID, shown in Figure 3.6, comprises three complementary components; the pixel detector, the silicon microstrip tracker (SCT) and the transition radiation tracker (TRT). Each of these sub-detectors consists of a central barrel section and two endcaps to extend the pseudorapidity coverage.

![ID components](image)

**Figure 3.6: The ATLAS Inner detector [28].**

The ID is exposed to a high flux of energetic particles emerging from the interaction point, therefore stringent conditions are imposed on its sensors. It is also required to use the minimum material to reduce the energy lost by particles before the calorimeters. A typical charged particle leaves on average 47 hits in the ID. These hits are used to calculate the momentum of the particle. Monte Carlo studies have been performed to model the resolution of the inverse momentum of the track, $1/p_T$, in the region $0.25 < |\eta| < 0.5$ of the barrel with the following formula:

$$
\sigma_{1/p_T} = \sigma_\infty \left( 1 + \frac{44}{p_T} \right)
$$

where $\sigma_\infty = 0.34$ TeV$^{-1}$ and $p_T$ is given in units of GeV. The second term in
Equation 3.8 is the multiple scattering component, which is small for high $p_T$ tracks \cite{29}.

Silicon Detector

The silicon detector is the innermost sub-detector system in ATLAS. It uses silicon technology for both the pixel detector and the Semi-Conductor Tracker (SCT) and consists of barrel and end-cap regions. The silicon detector provides large acceptance in pseudorapidity up to $|\eta| < 2.5$. It is operated at temperatures between -5 and -10 °C maintained by the cooling system.

The pixel detector is composed of three layers at radii of 50.5, 88.5 and 122.5 mm in the barrel region. The closest layer to the beam pipe is known as the vertexing layer or the $b$-layer. In the end-cap regions, there are three flanges extending radially from 88.8 to 149.6 mm on each side, as shown in Figure 3.6.

The pixel detector has high granularity to provide precise track information with typically three hits per track passing through it. It mainly contributes to the reconstruction of vertices and to the measurement of impact parameters of charged particles. This information is used to tag $\tau$-leptons and jets from heavy-flavour quarks. There are 1744 pixel sensors each containing 47232 pixels. About 90% of pixels are 50x400 $\mu$m$^2$ and the remaining pixels are 50x600 $\mu$m$^2$. The number of readout channels per module is 46080 taking the total number of the pixel detector channels to over 80 million.

The SCT uses the same semi-conductor technology, but it is made of silicon strips instead of pixels to reduce detector cost and to maintain reliability. It is constructed from four strip layers of radii between 299 mm and 514 mm in the barrel region and nine discs at different distances in the end-cap regions. Pairs of identical silicon micro-strip sensors are attached together back-to-back, with a 40 mrad stereo angle on a mechanical core to form a strip layer because a silicon micro-strip sensor provides position measurement only in one direction. The core is made of thermal pyrolitic graphite to transfer the heat generated by the sensors and readout electronics to the cooling pipe \cite{28}. The SCT consists of 15912 sensors with a typical thickness of 285 $\mu$m. It contributes four spatial measurements per track in the barrel and up to nine measurements in the end-caps for precise momentum calculation.

Transition Radiation Tracker

The TRT detector employs drift tube technology instead of semi-conducting material. Straws of 4 mm diameter and special electrical and mechanical properties
are developed for this purpose. These thin-walled drift tubes are 144 cm long in the barrel and 37 cm long in the end-cap regions. The tube anode is made of 31 μm thick tungsten wire coated with gold. The tubes are filled with a mixture of 70% Xe, 27% CO₂ and 3% O₂. Straws are arranged parallel to the beam pipe in the barrel and radially in the end-cap parts. This orientation enhances the number of space points measured per track to ease pattern recognition. Charged particles crossing the tubes emit transition radiation photons. The xenon gas mixture absorbs these photons efficiently and the resulting ionisation produces detectable signals. The quality of the TRT gas mixture is monitored by a recirculating gas system. The TRT is operated at room temperature with an envelope of a CO₂ cooling system.

3.3.4 ATLAS Calorimetry

In contrast to the inner detector, the calorimetry system is required to absorb the energy of the incident particles to provide energy and position measurements. The ATLAS calorimeter system, shown in Figure 3.7, has two main components, the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL).

They provide almost hermetic coverage in pseudorapidity up to |η| < 4.9. Both calorimeters use sampling techniques based on alternate layers of absorber
and active material. Showers produced by the incident particles in the absorber are measured by the active detector. A large amount of material is required to contain the shower and minimise punch-through into the muon spectrometer. Fine granularity of the ECAL is needed in the \( \eta \) range matched to the ID to measure the energy of electrons and photons precisely. The hermetic coverage of the system and the large thickness of the absorber material ensure good missing transverse energy measurements \[28\].

**Electromagnetic Calorimeter**

The function of the ECAL is to measure the energy of photons and electrons. This includes the measurement of the neutral component of \( \tau \)-lepton decays and hadronic jets by measuring the energy from the decay \( \pi^0 \rightarrow \gamma\gamma \). The ECAL comprises lead absorber plates and liquid argon (LAr) sampling layers in an accordion shape. This geometry optimises the \( \phi \) coverage and enhances the signal extraction. Electromagnetic showers are produced when electrons and photons interact with the absorber. Secondary electrons emit bremsstrahlung radiation and photons undergo pair production. The cascade passes many layers losing energy and causing ionisation in the LAr sampling layers. The resulting charge is collected by electrodes producing a signal proportional to the energy of the incident particle.

The ECAL is mechanically divided into a barrel and two end-cap regions, each in a separate cryostat covering \( |\eta| < 1.475 \) and \( 1.375 < |\eta| < 3.2 \) respectively. In the barrel region the ECAL is made of two identical half-barrels with a total thickness of \( > 22 \) radiation lengths \( (X_0) \) separated by a gap of \( 4 \) mm. In each end-cap region, the ECAL consists of two coaxial disks of total thickness of \( > 24 \) \( X_0 \). Particles passing through material from the interaction point to the ECAL may lose energy. Therefore a pre-sampler layer of LAr is installed to correct for the energy loss before the ECAL. Figure \[3.8\] shows the segmentation of the ECAL into calorimeter cells in \( \eta-\phi \) space.

The energy of the incident particle is deposited in several neighbouring cells and is calculated from the cluster energy. The resolution on this energy is parametrised by:

\[
\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} + b, \tag{3.9}
\]

where \( a \) is a sampling term given in \( \sqrt{\text{GeV}} \) units and \( b \) is a constant term describing non-linearities in the calorimeter response. Test-beam studies of the barrel
modules with electron beams found that $a = 0.1$ and $b = 0.17\%$. The energy resolution can vary as a function of $\eta$.

**Hadronic Calorimeter**

The purpose of the hadronic calorimeter is to measure the position and energy of hadronic jets. Hadronic jets are narrow cones of protons, neutrons, mesons and other particles produced by the fragmentation and hadronization of quarks and gluons. These jets pass through the ID and ECAL without significant loss of energy. The HCAL is situated outside of the ECAL and comprises a barrel and two end-cap regions.

In the barrel region the HCAL uses steel layers as an absorber and plastic scintillator sampling sheets, called tiles, as an active material. The barrel itself is divided into a central section which covers $|\eta| < 1$ and two extended barrels covering $0.8 < |\eta| < 1.7$. The tile calorimeter extends radially from 2.28 m to
4.25 m making a total thickness of 9.7 interaction lengths (λ) at η = 0. Hadrons interact with absorber nuclei producing a shower of particles. Light is emitted when the shower particles pass through the scintillator. Fibres at the end of each tile collect this light and carry it to photomultiplier tubes which convert it into an electric signal. This signal is used to determine the energy of the incident particles.

The Hadronic End-cap Calorimeter (HEC) uses the same LAr technology as the ECAL, but with copper plates as an absorber. Each end-cap region consists of two wheels fixed behind the end-cap ECAL. With a small overlap with the tile calorimeter, the HEC covers 1.5 < |η| < 3.2.

Equation 3.9 can be used to parametrise the energy resolution of the HCAL. The sampling term a and the constant term b are found from test-beam studies using charged pions to be 56.4% and 5.5% respectively. These values can vary with η due to the variation in the effective depth of the calorimeter material.

**Forward Calorimeter**

The Forward Calorimeter (FCAL) is designed to provide a robust measurement of the missing transverse energy by measuring particle energies up to |η| < 4.9. Another advantage of the FCAL is to reduce the radiation background in the muon system in the forward regions. The thickness of the FCAL is about 10 interaction lengths; it comprises three sub-calorimeters in each end-cap. The first (FCAL1) is an electromagnetic calorimeter with copper absorber, while the other two (FCAL2 and FCAL3) use tungsten absorbers and perform hadronic calorimetry. The sensitive medium in these calorimeters is LAr. The forward calorimeters are exposed to high particle fluxes, therefore the electrodes are made of copper rods and the LAr gaps are smaller than those in the ECAL and HCAL to avoid problems due to the build-up of charge and to reduce the signal collection time. The energy resolution of the FCAL for hadrons is given by Equation 3.9.

Test-beam studies using pions result in a sampling term of a = 94% and a constant term b = 7.5%.

### 3.3.5 Muon Spectrometer

Muons pass through ATLAS leaving tracks in the inner detector and losing little energy in the calorimeters. The Muon Spectrometer (MS) shown in Figure 3.9 is the outermost part of ATLAS. It uses the radius of curvature of tracks to measure the momentum and charge sign of muons. The MS consists of a barrel section to
cover \(|\eta| < 1.0\) and two end-cap regions extending the coverage to \(|\eta| < 2.7\). The barrel toroids produce an inhomogeneous magnetic field of approximately 0.5 T in the \(|\eta| < 1.4\) region, while the end-cap toroids provide the \(1.6 < |\eta| < 2.7\) region with a non-uniform magnetic field of about 1 T. As mentioned in Section 3.3.2, the magnetic fields of the barrel and end-cap toroids overlap in the region \(1.4 < |\eta| < 1.6\) which is known as the transition region. The MS uses two different technologies for muon momentum measurements, the Monitored Drift Tubes (MDTs) and the Cathode Strip Chambers (CSCs).

The vast majority of precision momentum measurements are provided by MDTs, which cover the barrel region and most of the end-cap regions. The CSCs are used only in the innermost part of the end-cap to cover the forward region \(2 < |\eta| < 2.7\). The MS barrel section consists of three cylindrical shells around the beam pipe at radii of 5 m, 7.5 m and 10 m. Each shell is made of between 3 and 8 MDT layers. Each end-cap section is made of four stations at 7.4 m, 10.8 m, 14 m and 21.5 m, each of which contains between 6 and 8 layers of MDTs. The MDTs are 15 mm radius aluminium drift tubes filled with a pressurised Ar/CO\(_2\) gas mixture with a 50 \(\mu\)m W/Re gold plated wire centred in each tube as an anode. Muons passing through the MDTs cause ionisation in the gas, and electric charges are collected to provide drift time measurements.
In the region $2 < |\eta| < 2.7$ precision measurements are made by the CSCs, which are multiwire proportional chambers. In this region huge background is expected and higher granularity is needed in the innermost part of the MS. The CSCs are made of anode wires perpendicular to the beam direction, surrounded by an Ar/CO$_2$ gas mixture. A set of cathode strips run perpendicular to the anode wires.

Due to the limited time available for the Level 1 muon trigger system to make a decision, it is impossible for it to use tracking algorithms. For this reason, it employs Resistive Plate Chambers (RPCs) in the barrel region, $|\eta| < 1.05$, and Thin Gap Chambers (TGCs) in the end-cap regions $1.05 < |\eta| < 2.4$. This means that the muon trigger system does not cover the region $2.4 < |\eta| < 2.7$ of the muon spectrometer. The trigger chambers are used to measure the coordinates of the muon tracks in the $(\eta)$ and $(\phi)$ planes. There are two reconstruction modes of the muon tracks, the standalone and the combined modes. In the standalone mode only the MS information is used, while in the combined mode, tracks in the MS are matched with hits in the ID. The latter provides precise momentum measurements and fake muon rejection.

3.3.6 ATLAS Trigger System

The event rate at the design luminosity of the LHC is 40 MHz. With an average event size of 1.3 Mb, the data storage system cannot record all interaction events [28]. In addition, the majority of these events are soft interactions containing no interesting physics. Therefore, the trigger system is vital to reduce the event rate sent to the storage system by selecting events which pass certain criteria. The ATLAS trigger system, shown in Figure 3.10, consists of three sequential levels, Level 1 (L1) trigger, Level 2 (L2) trigger and event filter (EF). The L1 trigger is a hardware-based system, while the L2 and EF are based on software and are collectively known as the High Level Trigger (HLT). The trigger system is designed to cope with the change in the event rate due to changes in luminosity. At high luminosity the event rates exceed the bandwidth, therefore prescaling is necessary to reduce the rates associated with certain triggers. Prescale factors can be defined and applied at any level and on any trigger item.

Level 1 Trigger

The L1 trigger uses radiation-hard specialised hardware processors situated near the detectors. It is designed to handle a high event rate in the IP of up to 100 kHz.
At such a high rate it has only 2.5 $\mu$s to make a decision about each event. It searches for high $p_T$ detector objects such as muons, electrons, photons, $\tau$-leptons decaying into hadrons, jets and large missing transverse energy. The L1 trigger uses only information from the muon spectrometer and reduced granularity of the calorimeters. The ID output cannot be used on this timescale. Muons are selected by the L1 muon trigger using signals from the muon trigger chambers. The RPCs in the barrel region and the TGCs in the end-cap regions provide hits in the MS stations. The L1 muon trigger searches for patterns which satisfy a certain $p_T$ threshold. Calorimeter objects are selected by the L1 trigger based on energy deposited in the calorimeter clusters. Electromagnetic calorimeter clusters are used to identify electrons and photons and isolation can be required on these objects. Jets and hadronically decayed taus are triggered using HCAL clusters. The $E_T^{\text{miss}}$ is triggered by using information from the calorimeter up to $|\eta| < 4.9$.

The decision of the L1 trigger is made by the central trigger processor (CTP) based on the total triggered objects in the event. Trigger menus that can be programmed with up to 256 items are used to make this decision. For each event that passes the L1 trigger, the items that caused the trigger to fire and their geographical coordinates in $\eta$ and $\phi$, known as regions of interest (RoI), are sent to the HLT.
**High Level Trigger**

The High Level Trigger has two software-based components. The first component is the L2 trigger which is fed by the output of the L1 trigger. It uses dedicated computing farms to run fast algorithms. Within a time scale of about 40 ms per event, it aims to reduce the event rate to approximately 3.5 kHz. This can be achieved by using the information about the RoI from the L1 trigger to seed the search process. In this stage, the full detector granularity and precision are used. The L2 trigger makes decisions based on lists of trigger signatures which must be satisfied. It runs only on the RoI defined by the L1 trigger and stops any chain that fails to select interesting events. Selected events are passed to the event filter.

The event filter is the final stage of the ATLAS trigger system. It uses the offline reconstruction algorithms to reduce the event rate to about 200 Hz within a few seconds per event. Events which pass the EF are recorded with all the relevant trigger information. These events are then processed and distributed for analysis by the data distribution system.
Chapter 4

Physics Object Reconstruction

This analysis searches for a non-Standard Model decay of the $t\bar{t}$ pair in the semi-leptonic channel. A charged Higgs boson is assumed to replace the $W$ boson in the hadronic side of the event. This mechanism, however, does not alter the characteristics of the final state of the event. Therefore, the signal and the SM semi-leptonic $t\bar{t}$ events have the same final state signature. These events are characterized by a high $p_T$ lepton (electron or muon), a large missing transverse energy due to the undetected neutrino, and four hadronic jets, two of which originated from $b$-quarks from the $t\bar{t}$ decay. The identification and reconstruction of these objects with very good energy resolution are crucial to this analysis. This chapter provides a description of the triggering and reconstruction of these objects from the detector information.

4.1 Tracks

Charged particles traveling through the ID leave hits in each sub-detector. These hits are used to track the particles and measure their momenta. Track reconstruction in ATLAS is done via specialized software, which allows for track extrapolation, track and vertex fitting and corrections for detector material \[29\]. The track reconstruction process in the ID is done in three sequential stages.

- Hits in the pixel and SCT detectors are formed into clusters of space points using information from both sides of the SCT modules. The timing information from the TRT is used in this pre-processing stage to build drift circles.

- In the track-finding stage, combinations of the space-points in the three layers of the pixel detector and the first SCT layer are used as seeds to form
track segments. These segments are extended through the rest of the SCT and fitted with the clusters to resolve any ambiguity and reject fake tracks by applying track quality cuts. Tracks are then extrapolated into the TRT and associated with the drift circles to resolve the left-right ambiguities. Full ID information is used to refit the extended tracks to improve track resolution. The last step of the track finding is known as back-tracking, in which any remaining segments in the TRT are extrapolated towards the IP. This strategy improves the tracking efficiency for tracks resulting from secondary or displaced vertices and converted photons.

- In the last stage, a dedicated algorithm called the vertex finder uses tracks to reconstruct the primary vertices in the event. Secondary vertices and photon conversions are reconstructed after that using other algorithms.

4.2 Electrons

Tracks of electrons are characterized by hits in the inner detector and electromagnetic showers in the ECAL. The energy of the incident electron is deposited into many neighbouring calorimeter cells called clusters. This energy must be summed and corrected for detector effects to obtain the total energy of the electron.

The ATLAS electron reconstruction algorithm [31] uses the ID and ECAL information to reconstruct electrons allowing an optimum identification efficiency and background rejection. The reconstruction starts with initiating primary seed clusters from calorimeter cells by a sliding window algorithm. These seed clusters are required to have energies above $E_T^{\text{threshold}}$. An electron candidate is defined if a reconstructed track in the ID ($|\eta| < 2.5$) is matched with a seed cluster. If more than one track is matched to the same cluster, the closest track in $\Delta R$ is chosen giving priority to tracks with hits in the silicon layers. Tracks without silicon hits are considered to be more likely due to photon conversion electrons. However, converted photons undergo pair production before reaching the ECAL and can have hits in the ID. Therefore, hits in the $b$-layer can be required to discriminate against photon conversions.

Several corrections are applied to the reconstructed cluster energy to account for various effects. These corrections include energy loss outside the cluster due to Bremsstrahlung radiation, $\eta$-$\phi$ dependence of the detector material traversed by the particle and the finite granularity of the calorimeter.

Monte Carlo truth information is used to optimise sets of cuts to improve the electron identification efficiency. Electron candidates are classified into four
categories based on their origin using MC truth information. These categories are:

- Isolated electron, if it is matched with a true electron from a $W$ or $Z$ boson.
- Non-isolated electron, if it is matched with a true electron from a $B$ (or $C$) hadron.
- Hadron fake, if it does not match with a true electron, muon or tau.
- Background electron, if it is matched with a true electron which originated from a photon or a Dalitz decay.

ATLAS uses three sets of cuts to separate isolated electrons and fake electrons. Discriminating variables used in the selection cuts include information from the tracker and calorimeter. These selection cuts are loose, medium and tight with, increasing rejection power and can be applied independently. Table 4.1 shows the definitions of variables used in the these cuts.

The tight electron selection cuts, which by definition include the loose and medium cuts, are used for this analysis. In addition, selected electrons are required to have a $p_T > 25$ GeV. Selected electrons are also required to be found within the central region of the detector, $|\eta| < 2.5$, excluding the transition region between the barrel and the end-cap regions. The Electromagnetic (EM) energy scale accounts for the energy of the EM shower deposited in the ECAL. It is calibrated using MC $Z \rightarrow e^+e^-$ events and is known to a precision of the order of 0.5%.

### 4.3 Muons

In contrast to electrons, muons do not shower in the calorimeter after leaving tracks in the ID. They lose little energy as they pass through the calorimeter system and leave hits in the Muon Spectrometer (MS). These hits are used to reconstruct muon candidates and measure their $p_T$ in the presence of the magnetic field. As mentioned earlier, muon candidates are classified into combined and stand-alone muons.

Stand-alone muons are reconstructed by forming track segments from the hits in the MS. These segments are then combined and the information from the muon trigger chambers is used to make muon candidates. Corrections are applied to account for the energy loss in the detector and Coulomb scattering.
<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Variable name</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Loose cuts</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceptance of the detector</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Hadronic leakage</td>
<td>Ratio of $E_T$ in the first layer of the HCAL to $E_T$ of EM cluster (used over the range $</td>
<td>\eta</td>
</tr>
<tr>
<td>Second layer of the ECAL</td>
<td>Ratio in $\eta$ of cell energies in $3 \times 7$ versus $7 \times 7$ cells. Lateral width of the shower.</td>
<td>$R_\eta$, $\omega_\eta_2$</td>
</tr>
<tr>
<td><strong>Medium cuts (includes loose)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First layer of ECAL</td>
<td>Total shower width. Ratio of the energy difference associated with the largest and second largest energy deposit over the sum of these energies.</td>
<td>$\omega_{\text{stat}}$, $E_{\text{ratio}}$</td>
</tr>
<tr>
<td>Track quality</td>
<td>Number of hits in the pixel detector ($\geq 1$). Number of hits in the pixels and SCT ($\geq 7$). Transverse impact parameter ($&lt; 5\text{mm}$).</td>
<td>$d_0$</td>
</tr>
<tr>
<td>Track matching</td>
<td>$\Delta \eta$ between the cluster and the track ($&lt; 0.01$).</td>
<td>$\Delta \eta_1$</td>
</tr>
<tr>
<td><strong>Tight cuts (includes Medium)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b$-layer</td>
<td>Number of hits in the $b$-layer ($\geq 1$).</td>
<td></td>
</tr>
<tr>
<td>Track matching</td>
<td>$\Delta \phi$ between the cluster and the track ($&lt; 0.02$). Ratio of the cluster energy to the track momentum. Trigger $\Delta \eta$ cut ($&lt; 0.005$).</td>
<td>$\Delta \phi_2$, $E/p$, $\Delta \eta_1$</td>
</tr>
<tr>
<td>Track quality</td>
<td>Trigger transverse impact parameter cut ($&lt; 1\text{mm}$).</td>
<td>$d_0$</td>
</tr>
<tr>
<td>TRT</td>
<td>Total number of hits in the TRT. Ratio of the number of high-threshold hits to the total number of hits in the TRT.</td>
<td></td>
</tr>
<tr>
<td>Conversions</td>
<td>Electron candidates matching to reconstructed photon conversions are rejected.</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: Definition of variables used for selection cuts, loose, medium and tight for the central region of the detector [31].

These corrections depend on the track $p_T$ and $\eta$. The MS covers the range up to $|\eta| < 2.7$.

Muon reconstruction algorithms use tracks in the MS as an input and extrapolate them towards the interaction point. The ID hit information is used and a
fit is performed using all the track hits. The reconstructed track is accepted as a combined muon candidate if the segments in the MS are matched with ID hits with a satisfactory fit. Corrections are applied to account for any energy loss.

As in the case of the electron identification, tight cut requirements are applied to combined muon candidates to select only high-quality muons. These requirements include:

- At least one hit in the pixel detector, six hits in the SCT and hits in the TRT.
- Muon $p_T$ must be greater than 20 GeV and pseudorapidity $|\eta| < 2.5$.
- An isolation cut is applied to reduce fake muons. The transverse energy inside a cone of radius 0.2 in $\eta$-$\phi$ space must be less than 4 GeV.
- The scalar sum of the $p_T$ of additional tracks in a cone of $R = 0.3$ is required to be < 2.5 GeV.
- The number of muons originating from heavy meson decays is reduced by removing from the event any muon with $p_T > 25$ GeV within $\Delta R < 0.4$ of a considered jet.

### 4.4 Hadronic Jets

The semi-leptonic decay of a $t\bar{t}$ pair produces four hadronic jets in the final state. Two jets correspond to the two $b$-quarks from the top (anti-top) decay, and two light jets originate from the hadronic decay of the $W$-boson (or charged Higgs signal if it exists). However, $t\bar{t}$ events are expected to have more than 4 jets on average due to processes such as initial and final state radiation (ISR/FSR). The reconstruction of these jets and measurement of their kinematic properties such as $p_T$, $\eta$ and $\phi$ are vital for this analysis.

#### 4.4.1 Jet Reconstruction

Partons produced in the hard scatter cannot be directly measured in the detector. They undergo fragmentation producing jets of particles which interact with the detector material leaving measurable signatures. This is shown schematically in Figure 4.1. Jet reconstruction algorithms are used to search for these signatures and cluster together particles that are likely to belong to the same parton to
form a jet. The kinematic properties of the jet are corrected and associated to the original parton.

There are several jet reconstruction algorithms in use. Jets used in this analysis are reconstructed using the \( \text{anti} - k_t \) jet-clustering algorithm with a radius parameter of 0.4 \cite{32}. This algorithm is based on the \( k_t \) and Cambridge-Aachen sequential jet finding algorithms. It has the advantages of being infra-red safe and collinear safe. Infra-red safe means that the radiation of a soft gluon between two partons should not affect the clustering result, while collinear safe means that the outcome of jet clustering should not be affected by the splitting of a parton into near-collinear partons.

Sequential jet finding algorithms start with forming a list of topological clusters of energy deposit by particles in the calorimeter. Two distances, \( d_{ij} \) between particles or pseudo-jets and \( d_{iB} \) between entry \( i \) and the beam are defined by:

\[
d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta^2_{ij}}{R^2},
\]

\[
d_{iB} = k_{ti}^{2p},
\]

where \( \Delta^2_{ij} = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 \), while \( k_{ti}, y_i, \phi_i \) and \( R \) are respectively the transverse momentum, rapidity, azimuth of particle \( i \) and the radius parameter. The parameter \( p \), which governs the relative power of the energy versus the geometrical \( (\Delta_{ij}) \) scales, also determines the type of the algorithm. The \( p = 0 \) value returns the Cambridge-Aachen algorithm, \( p = 1 \) corresponds to the \( k_t \) algorithm and \( p = -1 \) gives the \( \text{anti} - k_t \) jet algorithm. More details can be found in \cite{32}.  

Figure 4.1: Schematic diagram of the jet evolution.
The algorithm loops over that list and compares the distances $d_{ij}$ and $d_{iB}$. If $d_{ij}$ is smaller than $d_{iB}$, the objects $i$ and $j$ are combined into one cluster on the list. If, however, the distance $d_{iB}$ is smaller, the cluster $i$ is considered to be a jet and removed from the list. In this way, a topological cluster can only be used in one jet, making the algorithm infra-red safe. Collinear safety arises due to the fact that no seeds are used to define the jet centre.

Corrections are applied to the measured energy in the calorimeter to recover the actual energy of the hadronic shower. The electromagnetic (EM) energy scale is applied to the jets to account for the detector response to hadronic jets. On top of that, the jet energy scale (JES) is applied. It aims to correct the reconstructed jets for several effects such as detector, instrumental and pile-up effects and any inefficiencies in the clustering and reconstruction algorithms.

Pre-selection cuts are applied to the reconstructed and corrected jets before they are used as input jets in this analysis. Jets are required to be found in the central region of the detector within $|\eta| < 2.5$ and to have $p_T > 25$ GeV. A cut which uses the vertex and tracking information, known as the Jet Vertex Fraction (JVF), is used to select jets originating from the hard scatter interactions. A cut of $|JVF| < 0.75$ is applied to remove any jet that is likely to have originated from pile-up interactions. The optimisation of the JVF cut based on the average jet multiplicity will be presented in Section 6.2.3. More details about the Jet Vertex Fraction can be found in [33]. In addition, the closest jet to an electron candidate within $\Delta R < 0.2$ is removed to avoid double-counting of electron candidates as jets.

### 4.4.2 $b$-Jets

As mentioned in Section 4.4, the decay of the $t\bar{t}$ pair results in two jets known as $b$-jets, which originate from the two $b$-quarks. These jets are very likely to have secondary vertices, as shown in Figure 4.2, because $B$-hadrons have lifetimes long enough to travel measurable distances in the detector before they decay. These secondary vertices can be used, with other detector information, to distinguish $b$-jets from light-quark jets. The identification of the $b$-jets could help to reduce the non-$t\bar{t}$ background and improve the reconstruction efficiency of the $t\bar{t}$ events. Specialised algorithms are used to “tag” $b$-jets. There are several $b$-tagging algorithms in use such as the SV0 $b$-tagging algorithm [34] used for early ATLAS data, the IP3D, SV1, JetFitterCombNN and MV1 $b$-tagging algorithms [35].

The $b$-jets used in this analysis are tagged by the MV1 algorithm, which is based on a neural network. This algorithm uses the output weights from
the IP3D, SV1 and JetFitterCombNN $b$-taggers as inputs [36]. Each $b$-tagging algorithm provides a weight $w$ as output. These weights are used to discriminate between $b$-jets and non-$b$-jets. The higher values of $w$ reflect the purity of $b$-jets. Each $b$-tagger is calibrated for several operating points each corresponding to a certain value of $w$. The MV1 $b$-tagger, used for this analysis, is calibrated using an inclusive sample of MC $t\bar{t}$ events [36] and an operation point corresponding to a $b$-tagging efficiency of 70% is chosen. The $b$-tagging efficiency of the MV1 tagger as a function of jet $p_T$ at this working point is measured using simulated $t\bar{t}$ events and compared to data. Figure 4.3 shows the expected and measured $b$-tagging efficiency of the MV1 algorithm using the kinematic selection calibration method. The resulting scale factor is also shown. More details can be found in [36].

![Figure 4.2: Primary and secondary vertices and the track impact parameter used to tag $b$-jets.](image)

![Figure 4.3: The expected (MC) and measured (data) $b$-tagging efficiency of the MV1 algorithm in the single lepton $t\bar{t}$ events using the kinematic selection calibration method; the statistical (error bars) and total uncertainty (green band) are shown [36].](image)
4.5 Missing Transverse Energy

The neutrinos produced in the semi-leptonic decay of $t\bar{t}$ pairs cannot be directly detected as they do not leave any tracks in the detector. However, they usually carry large transverse momenta, which can be used as a trigger. Since the total transverse momentum of the colliding partons is zero, any net momentum in the transverse direction indicates the existence of undetected particle(s) in the event. The missing transverse energy, $E_T^{\text{miss}}$, is calculated from the negative transverse vector sum of the momenta of all calorimeter clusters and other reconstructed objects in the event such as electrons, photons, muons and jets. All the corrections applied to the energies or momenta of the event objects are considered in the $E_T^{\text{miss}}$ calculation.

Any inefficiency in the detector, such as dead and crack regions due to the support structures, contributes into the $E_T^{\text{miss}}$ calculation. These detector effects on the $E_T^{\text{miss}}$ measurements are studied in [29]. To improve the resolution of the $E_T^{\text{miss}}$ the final detector objects with their calibrations are used instead of using the energies of the individual calorimeter cells. In addition, a cut of $E_T^{\text{miss}} > 20(30)$ GeV is applied to the muon (electron) channels to suppress backgrounds from QCD multi-jet events.

4.6 Scale Factors

Several correction factors have been applied to correct differences between the MC models and data. These differences include the lepton reconstruction, trigger and ID tracking efficiencies, which are accounted for by applying lepton scale factors. The Muon Combined Performance (MCP) group estimated the muon reconstruction efficiency using the tag-and-probe method in $Z \rightarrow \mu^+\mu^-$ samples [37]. The same method is used to estimate the electron reconstruction efficiency in $Z \rightarrow e^+e^-$ events. Since the data were taken in different periods, the correction factors are evaluated for these periods separately to correct the MC to match the data. The lepton trigger efficiencies are measured in the data and MC using the same method.

The efficiency with which a jet is tagged to have originated from a $b$-quark or $c$-quark and the mis-tag rate are corrected by applying scale factors. The mis-tag rate is defined as the rate of mistakenly tagging a jet of light-flavour (gluon, $u$, $d$ or $s$-quark). These correction factors are obtained and applied as functions of $p_T$. Additionally, the rates of $W$+jets and $W$+heavy-flavour jets between data and MC are corrected by applying scale factors [37].
The muon, egamma, flavour tagging and $W$+jets performance groups have centrally derived these scale factors. These scale factors have been implemented in centerally produced tools. In this analysis all these scale factors are applied using these tools.
Chapter 5

Monte Carlo and Data Samples

Monte Carlo (MC) generators are powerful tools used to model the expected signal and background processes. Simulated event samples must be able to reproduce the yields and kinematic distributions expected in the data. Another advantage of the MC events is the possibility of generating high statistics samples to completely cover the phase space of the process of interest. For this analysis, MC samples were generated for the charged Higgs signal and the relevant backgrounds.

The data samples used in this analysis were recorded by the ATLAS detector in the 2011 run. The data was split into the electron and muon channels and the results were combined at the end of the analysis.

The production of the MC samples is discussed in this chapter. The signal samples, the SM $t\bar{t}$ background and the non-$t\bar{t}$ background samples are presented. The data sets and the lepton triggers associated with each data period are then discussed.

5.1 Monte Carlo Samples

Monte Carlo simulation is used to produce signal and background samples. The MC generators employ the theoretical knowledge of the SM processes to create simulated events of the process of interest. The Parton Distribution Functions (PDFs) have the form $f_i(x, Q^2)$, and give the probability of finding a parton of flavour $i$ in the proton with a momentum fraction $x$ of the proton’s momentum, where $Q$ is the energy scale of the hard interaction [38]. The proton PDFs are extracted mainly from fits to data in Deep Inelastic Scattering (DIS) results obtained by the HERA and Tevatron experiments.

The simulation includes the generation of the tree level process, which is the leading order Feynman diagram where no loops are included, and the modeling
of the parton shower. There are several MC generators in use and the choice depends on the process of interest. A few steps are followed in producing the MC samples.

- Event generation: MC events are generated randomly based on theoretical distributions using specialised software. All the relevant subprocesses such as the hard scatter processes, initial-state radiation, final-state radiation, underlying event and parton shower evolution are simulated in this stage.

- Simulation: In this stage the interactions of the produced particles with the detector material is simulated. The GEANT4 toolkit [39] is used to model the response of the ATLAS subdetectors to the particles produced in the event.

- Digitisation: The signals representing the energy deposited in the detector are converted into Raw Data Objects (RDOs). These RDOs correspond to the proton-proton collision data recorded by ATLAS.

- Reconstruction: In this stage the raw data is prepared for analysis. The Event Summary Data (ESDs) and the Analysis Object Data (AODs) are created. They contain all the necessary information about the event ingredients to support the physics analysis.

The MC samples used in this analysis are further reduced in size by converting the AODs to “ntuples”. The ntuples are files that are much smaller in size, but contain all the necessary information to perform the analysis.

The signal samples and the SM $t\bar{t}$ background samples are presented in the following sub-sections. Other non-$t\bar{t}$ backgrounds are also discussed.

5.1.1 The Signal Samples

At the LHC, a light charged Higgs boson, if it does exist, is expected to be predominantly produced via the decay of the top quark, $t \rightarrow H^+b$. This analysis considers the decay mode $H^+ \rightarrow c\bar{s}$ and uses the semi-leptonic $t\bar{t}$ decay channel. Therefore, the signal has $H^+bW^−\bar{b}$ final states from $t\bar{t}$ events, as shown in Figure 2.5. This signal is modeled by the leading order MC generator PYTHIA 6.425 [40]. Seven high statistics signal samples have been produced. These samples cover the $H^+$ mass range from 90 GeV to 150 GeV. The branching ratio $\mathcal{B}(t \rightarrow bH^+) = 0.1$, which is close to the limits obtained by the Tevatron, is used for the signal cross-sections. In the signal samples the top quark is required to
decay as $t \rightarrow b H^+$ with an $H^+$ decay branching ratio $B(H^+ \rightarrow c \bar{s}) = 100\%$. The anti-top quark is forced to decay leptonically, $\bar{t} \rightarrow \bar{b} W^-$, where the $W^-$ decays into a lepton ($e$ or $\mu$). The cross-section, including correction factors ($K$-factors) for missing higher orders, MC generator and the number of events produced in each signal sample are listed in Table 5.1.

<table>
<thead>
<tr>
<th>Process ($H^+$ mass)</th>
<th>$\sigma$ [pb]</th>
<th>Generator</th>
<th>$N_{MC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H^+ \rightarrow c \bar{s}$, 90 GeV</td>
<td>10.8</td>
<td>PYTHIA</td>
<td>100k</td>
</tr>
<tr>
<td>$H^+ \rightarrow c \bar{s}$, 100 GeV</td>
<td>10.8</td>
<td>PYTHIA</td>
<td>200k</td>
</tr>
<tr>
<td>$H^+ \rightarrow c \bar{s}$, 110 GeV</td>
<td>10.8</td>
<td>PYTHIA</td>
<td>100k</td>
</tr>
<tr>
<td>$H^+ \rightarrow c \bar{s}$, 120 GeV</td>
<td>10.8</td>
<td>PYTHIA</td>
<td>200k</td>
</tr>
<tr>
<td>$H^+ \rightarrow c \bar{s}$, 130 GeV</td>
<td>10.8</td>
<td>PYTHIA</td>
<td>200k</td>
</tr>
<tr>
<td>$H^+ \rightarrow c \bar{s}$, 140 GeV</td>
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<td>PYTHIA</td>
<td>100k</td>
</tr>
<tr>
<td>$H^+ \rightarrow c \bar{s}$, 150 GeV</td>
<td>10.8</td>
<td>PYTHIA</td>
<td>100k</td>
</tr>
</tbody>
</table>

Table 5.1: Signal Monte Carlo samples are shown with the cross-section including branching ratios and $K$-factors. The branching ratio $B(t \rightarrow b H^+) = 0.1$, which is close to the Tevatron limit, is assumed.

5.1.2 The Standard Model $t \bar{t}$ Background Samples

Since the semi-leptonic decay channels of the signal and SM $t \bar{t}$ events have the same kinematics, the SM $t \bar{t}$ events contribute the largest irreducible background. To model this background, a large sample (15 million events) was generated using the NLO CT10 PDF and the next-to-leading order MC generator MC@NLO [41] version 4.01. The parton shower was modeled by HERWIG [42] version 6.520 and the underlying event was modeled by JIMMY version 4.31 [43]. The fully hadronic channel was filtered out from this sample. The detector response was simulated using GEANT4. The signal process, $H^+ \rightarrow c \bar{s}$, was not included as a hard-scatter process in the MC@NLO MC generator and was generated using the PYTHIA MC generator. Therefore, an additional systematic uncertainty is introduced to account for this effect. This uncertainty is discussed in Chapter 7.

In addition to the SM $t \bar{t}$ control sample, a set of MC $t \bar{t}$ samples has been produced to study the effect of various systematic uncertainties. These samples are summarised in Table 5.2. The NLO POWHEG [44] version 1.0 MC generator was used to study the systematic effects of the parton shower and hadronization. In one sample HERWIG was used for parton shower and hadronization, while in the second sample the PYTHIA MC was used. These samples have been used to study the effect of using different MC generators and to estimate the resulting

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systematic uncertainty. Another two MC samples were generated to study the effect of the initial and final state radiation (ISR/FSR). The ISR is defined as the radiation emitted by the incoming partons prior to the hard scatter, while the FSR is that emitted by the outgoing partons after the hard scatter. These samples have two different levels of ISR/FSR and were generated using the leading order ACER MC generator. These samples are used to study the effect and estimate the uncertainty due to the ISR/FSR.

5.1.3 Other non-$t\bar{t}$ Background Samples

In addition to the irreducible SM $t\bar{t}$ background, there are other SM non-$t\bar{t}$ backgrounds that need to be taken into account. Some of these backgrounds can mimic the signal and the semi-leptonic decay of the SM $t\bar{t}$. MC samples have been produced to study the contributions to the signal and the shapes of these backgrounds. Selection cuts have been developed to reduce their effect.

**Single Top Samples**

The three single top production channels shown in Figure 2.6 can produce a similar signature to the signal and SM $t\bar{t}$ data when the event has additional high-$p_T$ jets due to ISR/FSR and the top quark decays leptonically. To model this background, the electron, muon and tau decay channels are generated for each single top decay channel. The MC@NLO MC generator was used to create the $t$-channel and the $s$-channel, while the ACERMC MC generator was used to obtain the $t$-channel samples. Table 5.3 shows the MC generator, number of generated events and cross-section including $K$-factors.

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$ [pb]</th>
<th>Generator</th>
<th>$N_{MC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>90.6</td>
<td>MC@NLO+HERWIG</td>
<td>15M</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>90.6</td>
<td>POWHEG+HERWIG</td>
<td>10M</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>90.6</td>
<td>POWHEG+PYTHIA</td>
<td>10M</td>
</tr>
<tr>
<td>$t\bar{t}$ ISR/FSR More</td>
<td>90.6</td>
<td>ACERMC+PYTHIA</td>
<td>12M</td>
</tr>
<tr>
<td>$t\bar{t}$ ISR/FSR Less</td>
<td>90.6</td>
<td>ACERMC+PYTHIA</td>
<td>10M</td>
</tr>
</tbody>
</table>

Table 5.2: The SM $t\bar{t}$ Monte Carlo samples are shown with the MC generator, number of generated events and cross-section including $K$-factors.
<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$ [pb]</th>
<th>Generator</th>
<th>$N_{MC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single top $Wt$-channel all decays</td>
<td>15.74</td>
<td>MC@NLO+HERWIG</td>
<td>797k</td>
</tr>
<tr>
<td>Single top $t$-channel ($\mu$+jets)</td>
<td>6.97</td>
<td>ACERMC+PYTHIA</td>
<td>507k</td>
</tr>
<tr>
<td>Single top $t$-channel ($e$+jets)</td>
<td>6.97</td>
<td>ACERMC+PYTHIA</td>
<td>1,097k</td>
</tr>
<tr>
<td>Single top $t$-channel ($\tau$+jets)</td>
<td>6.97</td>
<td>ACERMC+PYTHIA</td>
<td>254k</td>
</tr>
<tr>
<td>Single top $s$-channel (lepton+jets)</td>
<td>0.50</td>
<td>MC@NLO+HERWIG</td>
<td>253k</td>
</tr>
</tbody>
</table>

Table 5.3: The single top Monte Carlo samples (different channels) are shown with the MC generator, number of generated events and cross-section including $K$-factors.

**$W+$jets Samples**

The $W+$jets events with $W \rightarrow e\nu/\mu\nu$ decay can have similar final states to that of the signal events. Some of these channels have large cross sections at the LHC energy. For these processes, cross sections including $K$-factors are shown in Table 5.4. The $W+$jets background includes the $W+$heavy flavoured (HF) jets and the $W+$light jets components. The HF jets are defined as jets originating from a heavy-type quark, ($c$ or $b$), whereas the light flavoured jets (LF) are jets originating from a light quark ($u,d,s$) or a gluon. To model the $W+$jets background, the ALPGEN MC generator was used with HERWIG to model the parton shower and JIMMY for the underlying event.

Two sets of MC samples were generated for the $W+$light jets. In the first set, $W \rightarrow \mu\nu+\text{additional partons (0 to 5)}$ events have been generated to study the contribution to the muon channel. A similar set of samples has been generated for the electron channel. These samples are listed in Table 5.4. A double $b$-tagging selection cut can significantly reduce the contribution of the $W+$light jets.

The $W+$HF jets components have lower cross sections, but higher probability to pass the $b$-tagging selection cut. Several samples have been generated to study the contribution of the $W+$HF jets. These samples include, $W + b\bar{b}+(0$ to $3)$ partons, $W + c\bar{c}+(0$ to $3)$ partons and $W + c+(0$ to $4)$ partons. A list of these samples is also given in Table 5.4.

**$Z+$jets and Di-boson Samples**

The $Z+$jets background is similar to the $W+$jets background, but with smaller cross section. This background was also modeled by the ALPGEN+HERWIG MC generator. Samples for $Z(\rightarrow ll)+b\bar{b}+(0$ to $3)$ partons were created for the electron and muon channels. The contribution of this background can be reduced by the selection cuts due to the presence of two leptons and the lack of a neutrino.
<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$ [pb]</th>
<th>Generator</th>
<th>$N_{MC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow \mu\nu + 0$ partons</td>
<td>8.303</td>
<td>ALPGEN+HERWIG</td>
<td>3,463k</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu + 1$ parton</td>
<td>1.565</td>
<td>ALPGEN+HERWIG</td>
<td>4,997k</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu + 2$ partons</td>
<td>453</td>
<td>ALPGEN+HERWIG</td>
<td>3,768k</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu + 3$ partons</td>
<td>122</td>
<td>ALPGEN+HERWIG</td>
<td>1,008k</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu + 4$ partons</td>
<td>31</td>
<td>ALPGEN+HERWIG</td>
<td>255k</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu + 5$ partons</td>
<td>8.5</td>
<td>ALPGEN+HERWIG</td>
<td>70k</td>
</tr>
<tr>
<td>$W \rightarrow e\nu + 0$ partons</td>
<td>8.306</td>
<td>ALPGEN+HERWIG</td>
<td>1,600k</td>
</tr>
<tr>
<td>$W \rightarrow e\nu + 1$ parton</td>
<td>1.565</td>
<td>ALPGEN+HERWIG</td>
<td>1,314k</td>
</tr>
<tr>
<td>$W \rightarrow e\nu + 2$ partons</td>
<td>454</td>
<td>ALPGEN+HERWIG</td>
<td>2,045k</td>
</tr>
<tr>
<td>$W \rightarrow e\nu + 3$ partons</td>
<td>122</td>
<td>ALPGEN+HERWIG</td>
<td>564k</td>
</tr>
<tr>
<td>$W \rightarrow e\nu + 4$ partons</td>
<td>31</td>
<td>ALPGEN+HERWIG</td>
<td>142k</td>
</tr>
<tr>
<td>$W \rightarrow e\nu + 5$ partons</td>
<td>8.4</td>
<td>ALPGEN+HERWIG</td>
<td>40k</td>
</tr>
<tr>
<td>$W + b\bar{b} + 0$ partons</td>
<td>56.78</td>
<td>ALPGEN+HERWIG</td>
<td>475k</td>
</tr>
<tr>
<td>$W + b\bar{b} + 1$ parton</td>
<td>42.92</td>
<td>ALPGEN+HERWIG</td>
<td>505k</td>
</tr>
<tr>
<td>$W + b\bar{b} + 2$ partons</td>
<td>20.8</td>
<td>ALPGEN+HERWIG</td>
<td>175k</td>
</tr>
<tr>
<td>$W + b\bar{b} + 3$ partons</td>
<td>7.95</td>
<td>ALPGEN+HERWIG</td>
<td>70k</td>
</tr>
<tr>
<td>$W + c\bar{c} + 0$ partons</td>
<td>153.03</td>
<td>ALPGEN+HERWIG</td>
<td>1,275k</td>
</tr>
<tr>
<td>$W + c\bar{c} + 1$ parton</td>
<td>125.61</td>
<td>ALPGEN+HERWIG</td>
<td>1,050k</td>
</tr>
<tr>
<td>$W + c\bar{c} + 2$ partons</td>
<td>62.49</td>
<td>ALPGEN+HERWIG</td>
<td>525k</td>
</tr>
<tr>
<td>$W + c\bar{c} + 3$ partons</td>
<td>20.35</td>
<td>ALPGEN+HERWIG</td>
<td>170k</td>
</tr>
<tr>
<td>$W + c + 0$ partons</td>
<td>773.28</td>
<td>ALPGEN+HERWIG</td>
<td>6,499k</td>
</tr>
<tr>
<td>$W + c + 1$ parton</td>
<td>246</td>
<td>ALPGEN+HERWIG</td>
<td>2,070k</td>
</tr>
<tr>
<td>$W + c + 2$ partons</td>
<td>60.96</td>
<td>ALPGEN+HERWIG</td>
<td>520k</td>
</tr>
<tr>
<td>$W + c + 3$ partons</td>
<td>13.68</td>
<td>ALPGEN+HERWIG</td>
<td>115k</td>
</tr>
<tr>
<td>$W + c + 4$ partons</td>
<td>3.36</td>
<td>ALPGEN+HERWIG</td>
<td>30k</td>
</tr>
<tr>
<td>$WW$</td>
<td>17.0</td>
<td>HERWIG</td>
<td>2.5M</td>
</tr>
<tr>
<td>$WZ$</td>
<td>5.54</td>
<td>HERWIG</td>
<td>1M</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>1.26</td>
<td>HERWIG</td>
<td>250k</td>
</tr>
<tr>
<td>$Z(ee) + bb + 0$ partons</td>
<td>8.21</td>
<td>ALPGEN+HERWIG</td>
<td>150k</td>
</tr>
<tr>
<td>$Z(ee) + bb + 1$ parton</td>
<td>3.10</td>
<td>ALPGEN+HERWIG</td>
<td>100k</td>
</tr>
<tr>
<td>$Z(ee) + bb + 2$ partons</td>
<td>1.11</td>
<td>ALPGEN+HERWIG</td>
<td>40k</td>
</tr>
<tr>
<td>$Z(ee) + bb + 3$ partons</td>
<td>0.48</td>
<td>ALPGEN+HERWIG</td>
<td>10k</td>
</tr>
<tr>
<td>$Z(\mu\mu) + bb + 0$ partons</td>
<td>8.2</td>
<td>ALPGEN+HERWIG</td>
<td>150k</td>
</tr>
<tr>
<td>$Z(\mu\mu) + bb + 1$ parton</td>
<td>3.08</td>
<td>ALPGEN+HERWIG</td>
<td>100k</td>
</tr>
<tr>
<td>$Z(\mu\mu) + bb + 2$ partons</td>
<td>1.11</td>
<td>ALPGEN+HERWIG</td>
<td>40k</td>
</tr>
<tr>
<td>$Z(\mu\mu) + bb + 3$ partons</td>
<td>0.48</td>
<td>ALPGEN+HERWIG</td>
<td>10k</td>
</tr>
</tbody>
</table>

Table 5.4: MC samples of other Standard Model backgrounds are shown with the MC generator, number of generated events and cross-section including $K$-factors.
in the final state.

The di-boson background includes $WW$, $WZ$ and $ZZ$ events. This background, especially $WW$ events, can, in the presence of additional jets due to ISR/FSR, produce a similar final state to the SM $t\bar{t}$, but with smaller cross sections. Three samples have been generated using HERWIG MC generator to model these events. The $Z$+jets and the di-boson MC samples are also included in Table 5.4.

**The QCD multi-jet Background**

The QCD multi-jet background contributes a considerable fraction to the total backgrounds. However, this background is not modeled using MC generated samples. The normalisation of this background was instead obtained from a data-driven method described in [45]. The QCD multi-jet contribution will be discussed in Section 6.3.2.

### 5.2 The Data Sets and Lepton Triggers

Unlike the MC generated events, the data contain all kinematically allowed processes. Events of interest need to be selected from large backgrounds. Semi-leptonic $t\bar{t}$ events are not an exception. These events are characterised by a high $p_T$ lepton, a large $E_T^{\text{miss}}$ and multiple high $p_T$ jets. Lepton triggers are used to select $t\bar{t}$ candidates and reject multijet background events such as QCD. Although QCD events tend not to have isolated leptons, they can contaminate semi-leptonic $t\bar{t}$ samples via high $p_T$ non-prompt or fake leptons.

#### 5.2.1 Lepton Triggers

The ATLAS trigger system, described in Section 3.3.6, is used to select semi-leptonic $t\bar{t}$ candidates. Two single-lepton triggers, an electron trigger and a muon trigger, are used. For the electron channel, three increasing $p_T$ threshold triggers were used for different data periods due to the increase in the instantaneous luminosity. Each trigger covers a set of data taking periods. These triggers, as well as the data sets they are used for, are shown in Table 5.5. For the muon channel, two muon triggers, EF$_{\mu18}$ for periods B-I and EF$_{\mu18}$ medium for periods J-M are used. These triggers use the combined mode in which muon tracks in the MS are matched with hits in the ID to form combined muons. The difference between these two triggers comes from the L1 trigger seed. The L1$_{\mu10}$ is
used for the EF\textsubscript{mu18}, while the EF\textsubscript{mu18\_medium} is seeded by L1\textsubscript{mu11}. Both L1\textsubscript{mu10} and L1\textsubscript{mu11} are hardware-based triggers with a threshold of 10 GeV. They differ in the number of required hits in the muon stations. The former requires only two stations, whereas the latter requires at least three stations in the MS to fire. Muon triggers and the data sets associated with each are shown in Table 5.5.

<table>
<thead>
<tr>
<th>Data period</th>
<th>Electron Trigger</th>
<th>Muon Trigger</th>
<th>Run Range</th>
<th>Luminosity [pb\textsuperscript{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-D</td>
<td>e20_medium</td>
<td>mu 18</td>
<td>177986-180481</td>
<td>178.388</td>
</tr>
<tr>
<td>E-H</td>
<td>e20_medium</td>
<td>mu 18</td>
<td>180614-184169</td>
<td>948.666</td>
</tr>
<tr>
<td>I</td>
<td>e20_medium</td>
<td>mu 18</td>
<td>185353-186493</td>
<td>337.543</td>
</tr>
<tr>
<td>J</td>
<td>e20_medium</td>
<td>mu 18_medium</td>
<td>186516-186755</td>
<td>226.392</td>
</tr>
<tr>
<td>K</td>
<td>e22_medium</td>
<td>mu 18_medium</td>
<td>186873-187815</td>
<td>590.363</td>
</tr>
<tr>
<td>L-M</td>
<td>e22_vh_medium</td>
<td>mu 18_medium</td>
<td>188902-191933</td>
<td>2431.74</td>
</tr>
</tbody>
</table>

Table 5.5: Lepton triggers used for the different data periods.

5.2.2 The Data Sample

This analysis uses proton-proton collision data recorded by the ATLAS experiment in 2011 (periods B-M). This dataset corresponds to an integrated luminosity of 4.7 fb\textsuperscript{-1} and a centre of mass energy of $\sqrt{s} = 7$ TeV. This is more than 200 times larger than the data set recorded by ATLAS in 2010. Recorded events are triggered by the single lepton triggers (shown in Table 5.5) and filtered using a Good Run List (GRL). The GRL is a dedicated list of runs and luminosity blocks recorded under certain requirements, such as stable beams and detector conditions, to ensure good data quality. The stable beams condition means that the beams in the LHC are at full energy and circulating steadily. The data quality requirements for all detector systems are vital to the physics object identification and the $E_T^{\text{miss}}$ calculations. The GRL can be used to reject data periods from individual luminosity blocks or runs to avoid any data with known problems. The data periods, their run range and the corresponding integrated luminosity are shown in Table 5.5.
Chapter 6

Analysis

The analysis presented in this thesis describes the searches for charged Higgs bosons in semi-leptonic $t\bar{t}$ events. It is assumed that one of the top quarks decays via $t \rightarrow bH^+$ with the charged Higgs boson subsequently decaying into two jets ($cs$). The $W$ boson from the other quark decays into a lepton ($e/\mu$) and a neutrino. The search is made using the full dataset collected by ATLAS in 2011. The final-state objects include two $b$-jets, two light-jets, one lepton ($e/\mu$) and a large $E_T^{\text{miss}}$ due to the undetected neutrino. Event selection criteria are essential to reject background events whilst selecting semi-leptonic $t\bar{t}$ events. Selected events are then used to reconstruct the invariant mass of the $W/H^+$ boson from the final-state objects.

This chapter concentrates on the experimental method used to select semi-leptonic $t\bar{t}$ candidates, reconstruct the signal and estimate backgrounds. It begins with the event selection criteria optimised for this purpose. After that the event reconstruction is discussed. This includes the reconstruction of the di-jet mass system using a kinematic fitter. The estimation of various backgrounds is then presented. In the last section of this chapter, a comparison between the data and MC predictions is presented and the reconstructed di-jet mass distribution is used to search for any evidence of a signal of mass $m_{H^+}$ different from the SM $m_W$.

6.1 Event Selection

A set of kinematic event selection cuts and cleaning requirements is used to select semi-leptonic $t\bar{t}$ events and simultaneously reject the non-$t\bar{t}$ backgrounds. These selection cuts have been developed and applied within ATLAS analyses that use the semi-leptonic $t\bar{t}$ events. By doing this, many of the same tools and
systematic uncertainties can be shared. Events reaching this stage of the analysis have already passed the physics objects pre-selection requirements described in Chapter 4. The final event selection cuts used for this analysis are explained below:

1. Events are required to pass the Good Run List (GRL) requirement and the relevant single lepton trigger. Data is required to pass the GRL requirement and the high-transverse momentum single-lepton triggers shown in Table 5.5 are applied to the data and MC events.

2. Events are required to have a primary vertex with $N_{\text{tracks}} > 4$. This cut is applied to remove non-collision backgrounds such as cosmic-ray and beam-gas events. These events tend to have vertices with low number of tracks, whereas collision events tend to have vertices with multiple tracks.

3. There is a requirement for exactly one electron with $E_T > 25$ GeV and $|\eta| < 2.47$, excluding the crack region ($1.37 < |\eta| < 1.52$), or exactly one muon with $p_T > 20$ GeV within $|\eta| < 2.5$. This requirement ensures selecting events with a single high $p_T$ lepton, which is reconstructed within a well instrumented region of the detector. This cut aims to reduce the SM background events having multiple, fake or low $p_T$ leptons as the signal whilst SM semi-leptonic $t\bar{t}$ events are expected to have a single high $p_T$ lepton.

4. The selected lepton is required to match the triggered object. After applying the single lepton cut, the selected lepton is required to match the triggered object within $\Delta R < 0.2$.

5. Events are removed if an electron shares the same inner detector track with a non-isolated muon. By applying this cut, in addition to cuts 3 and 4 above, the analysis is split into two independent channels, the electron channel and the muon channel. This separation allows different treatment of each channel as demonstrated in cuts 8 and 9 below.

6. An event-cleaning cut is applied. In this cut, an event is rejected if it contains a poorly reconstructed jet with a $p_T > 20$ GeV.

7. Events are required to have at least four jets with $E_T > 25$ GeV and $|\eta| < 2.5$. This cut is chosen because a typical semi-leptonic $t\bar{t}$ event contains at least four high $p_T$ jets; two $b$-jets from the decay of the $t\bar{t}$ system and two jets from the hadronically decaying $W$ (or charged Higgs) boson. This
cut has a high efficiency at removing several backgrounds, particularly the $W$+jets contribution. Additional jets in this background originating from gluon emissions from the hard scatter tend to have lower $p_T$. Jets found in the central region of the detector, $|\eta| < 2.5$, are generally reconstructed with good energy resolution. This cut is important since the discrimination between the signal and background is very sensitive to the Jet Energy Scale (JES) uncertainty.

8. The missing transverse energy is required to be $E_T^{\text{miss}} > 30$ GeV for the electron channel, or $E_T^{\text{miss}} > 20$ GeV for the muon channel. The asymmetry between the electron and muon channels in the thresholds of the $E_T^{\text{miss}}$ and $M_T(W)$ selection cuts arises from optimisation of the cuts in the electron channel in order to improve the rejection of the QCD multi-jet background. Semi-leptonic $t\bar{t}$ events are expected to have large $E_T^{\text{miss}}$ due to the presence of the undetected neutrinos. This cut reduces the contribution of QCD multi-jet events, where the $E_T^{\text{miss}}$ occurs mainly from the mismeasurement of the jet energy in the detector. Therefore, the calculated $E_T^{\text{miss}}$ is expected to be low. This cut also reduces the contribution of the $Zb\bar{b}+\text{jets}$ background.

9. The transverse $W$ mass is required to be $M_T(W) > 30$ GeV for the electron channel, or $(E_T^{\text{miss}} + M_T(W)) > 60$ GeV for the muon channel. The $M_T(W)$ is defined as:

$$M_T(W) = \sqrt{2 \times p_T^{\text{lepton}} E_T^{\text{miss}} \times (1 - \cos \Delta \phi)}, \quad (6.1)$$

where $p_T^{\text{lepton}}$ is taken to be equivalent to $E_T^{\text{miss}}$. On the leptonic side of the semi-leptonic $t\bar{t}$ event, the $M_T(W)$ distribution is expected to peak around the mass of the $W$ boson, whereas in QCD multi-jet events there is no preferred peak position.

10. Events are required to have at least two jets to be tagged as $b$-jets (with a $b$-tagging MV1 weight larger than 0.601713). The definition of the $b$-tagged jets is based on secondary vertex requirements as discussed in Chapter 4. The chosen weight corresponds to a $b$-tagging efficiency of 70%. The $t\bar{t}$ system has typically two $b$-jets, therefore this cut is applied to further reduce the non-$t\bar{t}$ backgrounds.

This set of cuts is very efficient in non-$t\bar{t}$ background rejection and results in an almost pure sample of semi-leptonic $t\bar{t}$ events. Therefore, events that pass this
selection criteria can be considered as semi-leptonic $t\bar{t}$ candidates and used for the analysis. Each event contains a high $p_T$ lepton and a large $E_{T}^{\text{miss}}$, which are used to reconstruct the $W$ boson on the leptonic side of the event. In addition, the event contains at least two $b$-tagged jets and two un-tagged (light) jets from which the signal or the hadronically decaying $W$ is reconstructed.

The effects of these cuts on the data and MC signal and background samples for the electron and muon channels are shown in Tables 6.1 and 6.2 respectively. The final cut on the $\chi^2$ value will be discussed in the following section.

6.2 Event Reconstruction

The aim of this analysis is to search in semi-leptonic $t\bar{t}$ events for a charged Higgs boson decaying into two jets. The presence of this signal will change the shape and normalization of the dijet mass ($W/H^+$) reconstructed from the $t\bar{t}$ system. In terms of the shape of the reconstructed dijet mass system, the $H^+$ signal will form a secondary peak around $m_{H^+}$. The presence of an $H^+$ signal decaying exclusively into two jets will reduce the observed number of semi-leptonic $t\bar{t}$ events in data due to the decay of both top quarks into charged Higgs bosons, which in turn decay hadronically to produce fully hadronic $t\bar{t}$ events.

It might be suggested that the two light jets in the selected events can be used to reconstruct the invariant mass of the $H^+$ or $W$ boson. This is, however, not always the case. The semi-leptonic $t\bar{t}$ candidates contain on average more than four high $p_T$ jets due to the addition of jets from both initial and final state radiation, and it is not necessary that the two jets from the $H^+$ or $W$ boson decay have the highest $p_T$ among the untagged jets in the event. The number of jets with a $p_T > 25$ GeV and $|\eta| < 2.5$ per event is shown in Figure 6.1.

In order to discriminate between the signal and background, the invariant mass of the dijet system needs to be reconstructed correctly. This requires the identification of the jets originating from the $H^+$ or $W$ boson. Alternatively, the knowledge of $m_W$ and $m_{\text{top}}$ can be used to fully reconstruct the $t\bar{t}$ system. By doing so, the invariant mass of the dijet system can be improved. This analysis employs a Kinematic $\chi^2$ Fitter [23] to optimise the discriminating power of the reconstructed dijet mass.

6.2.1 The $\chi^2$ Kinematic Fitter

The two untagged leading jets can be used to reconstruct the dijet mass of the $H^+$ or the hadronically decaying $W$ boson in semi-leptonic $t\bar{t}$ events. The resulting
<table>
<thead>
<tr>
<th>Process</th>
<th>Number of events after</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>no cut</td>
<td>trigger</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>164×10⁶</td>
<td>1278×10⁵</td>
</tr>
<tr>
<td>$H^+ \rightarrow cs$, 90 GeV</td>
<td>50331</td>
<td>11818</td>
</tr>
<tr>
<td>$H^+ \rightarrow c\bar{s}$, 100 GeV</td>
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<tr>
<td>$H^+ \rightarrow cs$, 110 GeV</td>
<td>50331</td>
<td>11852</td>
</tr>
<tr>
<td>$H^+ \rightarrow c\bar{s}$, 120 GeV</td>
<td>50331</td>
<td>11874</td>
</tr>
<tr>
<td>$H^+ \rightarrow c\bar{s}$, 130 GeV</td>
<td>50331</td>
<td>11775</td>
</tr>
<tr>
<td>$H^+ \rightarrow c\bar{s}$, 140 GeV</td>
<td>50331</td>
<td>11843</td>
</tr>
<tr>
<td>$H^+ \rightarrow c\bar{s}$, 150 GeV</td>
<td>50331</td>
<td>11838</td>
</tr>
<tr>
<td>SM $tt$, not all hadronic</td>
<td>421876</td>
<td>111644</td>
</tr>
<tr>
<td>Single top, $Wt$-channel</td>
<td>73295</td>
<td>11140</td>
</tr>
<tr>
<td>Single top, $t$-channel</td>
<td>64913</td>
<td>20814</td>
</tr>
<tr>
<td>Single top, $s$-channel</td>
<td>4656</td>
<td>1442</td>
</tr>
<tr>
<td>$Wc\bar{c} +$ jets</td>
<td>598234</td>
<td>108384</td>
</tr>
<tr>
<td>$Wc +$ jets</td>
<td>1683552</td>
<td>294819</td>
</tr>
<tr>
<td>$Wc +$ jets</td>
<td>4121936</td>
<td>1011610</td>
</tr>
<tr>
<td>$W +$ jets</td>
<td>4882×10⁴</td>
<td>2958×10⁴</td>
</tr>
<tr>
<td>$Zb\bar{b} +$ jets</td>
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<td>46047</td>
</tr>
<tr>
<td>Dibosons</td>
<td>110952</td>
<td>36020</td>
</tr>
<tr>
<td>QCD(e)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total SM background</strong></td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6.1: Cut flow table for the charged Higgs boson signal with $B(t \rightarrow bH^+) = 10\%$, and for the main SM backgrounds in the electron channel. The integrated luminosity is 4.7 fb⁻¹.
### Table 6.2: Cut flow table for the charged Higgs boson signal with $B(t \rightarrow bH^+) = 10\%$, and for the main SM backgrounds in the muon channel. The integrated luminosity is 4.7 fb$^{-1}$. 

<table>
<thead>
<tr>
<th>Process</th>
<th>muon channel</th>
<th>Number of events after</th>
<th>$E_T^{miss}$</th>
<th>2 b-tag</th>
<th>$\chi^2$</th>
</tr>
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<td>trigger</td>
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<td>4 jets</td>
<td>$\chi^2$</td>
</tr>
<tr>
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<tr>
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<td>13066</td>
<td>9224</td>
<td>4952</td>
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<tr>
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<tr>
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<td>12785</td>
<td>9158</td>
<td>4704</td>
<td>4019</td>
</tr>
<tr>
<td>H$^+ \rightarrow c\bar{s}$, 140 GeV</td>
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<td>9224</td>
<td>4528</td>
<td>3885</td>
</tr>
<tr>
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<td>9207</td>
<td>3985</td>
<td>3396</td>
</tr>
<tr>
<td>SM $t\bar{t}$, not all hadronic</td>
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<td>29561</td>
</tr>
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<td>12095</td>
<td>7912</td>
<td>1410</td>
<td>1197</td>
</tr>
<tr>
<td>Single top, $t$-channel</td>
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<td>21906</td>
<td>17888</td>
<td>1265</td>
<td>1089</td>
</tr>
<tr>
<td>Single top, $s$-channel</td>
<td>4656</td>
<td>1587</td>
<td>1262</td>
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<td>51</td>
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<td>$Wb\bar{b} +$ jets</td>
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<td>99096</td>
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<td>1659</td>
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<td>$Wc\bar{c} +$ jets</td>
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<td>314579</td>
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<td>2789</td>
</tr>
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<td>$Wc +$ jets</td>
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<td>38689×10$^3$</td>
<td>34489×10$^3$</td>
<td>49454</td>
<td>41658</td>
</tr>
<tr>
<td>$Zb\bar{b} +$ jets</td>
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<td>QCD($\mu$)</td>
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<tr>
<td>Total SM background</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
distribution is shown in Figure 6.2(a). The large width of these distributions presents a problem in separating a small $H^+$ signal from the SM $t\bar{t}$ background, since the signal peak will be on top of a large background. In addition, the differentiation between the signal and SM $t\bar{t}$ background becomes increasingly difficult as $m_{H^+}$ approaches $m_W$. For these reasons, a kinematic fitter ("dijet mass fitter") that fully reconstructs $t\bar{t}$ events from the reconstructed lepton, leading four jets, and $E_T^{\text{miss}}$ is used. This requires the correct assignment of the jets from the top quark decays to the four original partons. Since the two jets from the same charged boson are interchangeable, the event kinematics are independent of these jet assignments. The two $b$-jets can be assigned only to the $b$-quarks and, as there are two possible assignments, there are two possible jet configurations for events with two $b$-tagged and two light jets. The aim of the fitter is to reduce the widths and tails of the dijet mass distribution.

The reconstruction of the leptonically decaying $W$-boson requires the knowledge of the neutrino momentum. The transverse momentum of the neutrino, $p_T(\nu)$, is inferred from $E_T^{\text{miss}}$. Then, the mass of the leptonically decaying $W$-boson is constrained to be 80.4 GeV [46], allowing the longitudinal momentum
of the neutrino, $p_L(\nu)$, to be expressed in terms of two measurable quantities: $p_T(\nu)$ and the lepton momentum $p_l$. The resulting quadratic equation in $p_L(\nu)$ provides two solutions for each permutation of jet assignment.

For each combination, an additional top-specific transfer function \cite{17} is applied to convert, on average, the measured jet energy to a partonic level energy. The $p_T$-dependent top-specific corrections and their resolution functions are derived using a sample of MC@NLO $t\bar{t}$ events. These events are selected where all four leading jets are matched to the truth partons within $\Delta R < 0.2$. The true parton $p_T$ is then compared with the reconstructed jet $p_T$, and a transfer function is derived as a function of the jet $p_T$. This method additionally provides an estimate of the parton-jet $p_T$ resolution $\sigma_{jet}$ as a function of $p_T$. Since the top-specific corrections and their resolution functions are derived independently for $b$-jets and light jets, these corrections are applied in the fitter based on whether or not the jet is assigned to a $b$-quark. The top-specific transfer functions and resolution functions are shown in Figure 6.3.

6.2.2 The Fit

The dijet mass fitter is applied with the following motivation: it selects the combination of jets for which it is most likely that the jet assignment is correct and it leads to an improved resolution of the dijet mass distribution. In the fitting process, the MINUIT algorithm \cite{47} is used to minimise the following $\chi^2$ function:
Figure 6.3: Top specific transfer functions (left) and resolution functions (right) for $b$-jets and light quark jets. The response function is defined as $R = \frac{p_T^{\text{parton}} - p_T^{\text{jet}}}{p_T^{\text{jet}}}$. The correction applied to the jet $p_T$ is then $(1+R)$ \cite{17}.

$$
\chi^2 = \sum_{i=\text{lepton,4jets}} \frac{(p_{T,i}^{\text{fit}} - p_{T,i}^{\text{meas}})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_{j}^{\text{SEJ,fit}} - p_{j}^{\text{SEJ,meas}})^2}{\sigma_j^2} + \sum_{k=jjb,bl\nu} \frac{(M_k - M_{\text{top}})^2}{\sigma_{\text{top}}^2} + \frac{(M_{\nu} - M_W)^2}{\sigma_W^2}
$$

where $\sigma_W$ and $\sigma_{\text{top}}$ are the widths of the $W$-boson (2.12 GeV) and the top quark (1.5 GeV), respectively \cite{18}. The $W$ boson width is set to its measured value \cite{16} and the top quark width is set to the value predicted from theory. The top quark and $W$ boson masses are fixed to be $M_{\text{top}} = 172.5$ GeV and $M_W = 80.4$ GeV \cite{18}. The sum of extra jet energy SEJ is defined as a quantity absorbing all jet $E_T$ not associated with the primary lepton or the four leading jets. It is used to correct $E_T^{\text{miss}}$ which is an input in the calculation of the neutrino four-vector.

In the fitting process, both the $\eta$ and $\phi$ of the final state particles are fixed, while the magnitude of the measured momenta are permitted to vary within their experimental resolutions. It is this re-scaling of measured values that leads to the improvement of the dijet mass resolution. The effects of the re-scalings are propagated to the $E_T^{\text{miss}}$. The jet resolution, $\sigma_{\text{jet}}$, has been estimated as a function of $p_T$ during the derivation of the top-specific transfer functions, while the resolution of the sum of extra jet energy SEJ is estimated using the SM $t\bar{t}$ MC@NLO sample. In practice, the contribution to the total $\chi^2$ from the lepton and SEJ terms is small compared to that from the four leading jets. In each event, only the combination with the lowest $\chi^2$ value is used to extract the dijet mass. Figure 6.4 shows the $\chi^2$ distribution obtained from the SM $t\bar{t}$ sample for
the electron and muon channels. A cut is imposed requiring the lowest $\chi^2$ value to be less than 10 in order to achieve the best sensitivity in finding charged Higgs signals; otherwise, the event is rejected. In order to improve the $\chi^2$ cut efficiency and the resolution of the dijet mass distribution, the 5th jet is included as one of the four jets used in the dijet mass fitter. Thus, the 5th jet in the fitter can be exchanged with one of the two non-$b$-tagged jets. If a better $\chi^2$ is obtained, this new jet combination is used. This addition is motivated by the possibility of a high $p_T$ jet from ISR/FSR replacing a jet from the top decays in the list of the four leading jets. The overall selection efficiency with the inclusion of the fifth jet is 63% for the SM $t\bar{t}$ events. Figure 6.2 shows the improvement in the dijet mass distributions for the $H^+$ ($m_{H^+} = 120$ GeV) and $W$ bosons when the fitted energies of the jets and lepton with a cut of $\chi^2 < 10$ are used. Similar improvements for other mass points are obtained. Thus, the fitted dijet mass distributions as shown, for example, in Figure 6.2(b) are used in this analysis.

As the mass of the charged Higgs boson increases, the tails observed in the signal distributions increase in size due to larger combinatorial backgrounds. The $b$-jet $E_T$ distribution becomes softer as the mass of the $H^+$ approaches the mass of the top quark. For $m_{H^+} = 150$ GeV, a significant fraction of $b$-jets have $E_T < 25$ GeV. This leads to a decrease in tagging efficiency, causing a reduced acceptance from the two $b$-tag requirement. The final dijet mass distributions for $W$ boson from SM $t\bar{t}$ and seven $H^+$ signal samples ($m_{H^+} = 90, 100, 110, 120, 130, 140$ and 150 GeV), are shown in Figure 6.5. These distributions are used as templates in the fit to the data.
Figure 6.5: The dijet mass templates (electron and muon channels combined) for the reconstructed $W$ boson (SM $t\bar{t}$) and seven $H^+$ signal samples. The first and the last bins in each plot include the underflow and overflow entries. The $\chi^2 < 10$ cut has been applied.
6.2.3 Pile-up and Jet Vertex Fraction Cut

As a result of the increase in instantaneous luminosity of the LHC during the 2011 run, the number of simultaneous interactions in the bunch crossing, known as in-time pile-up events, increased. The maximum mean number of events per beam crossing versus day is shown in Figure 6.6. This plot shows the average value for all bunch crossings in a luminosity block. One of the effects of the pile-up is the increase in the number of reconstructed vertices in the event. The number of vertices in MC semi-leptonic $t\bar{t}$ events for the electron and muon channels are shown in Figure 6.7.

A study has been performed to investigate the effect of the pile-up on this analysis using the semi-leptonic $t\bar{t}$ MC sample. In these events, many extra jets are found to originate from in-time pile-up events. Figure 6.8 shows that the average jet multiplicity of MC@NLO $t\bar{t}$ events in the semi-leptonic channel is greatly increased as the number of reconstructed vertices increases. Therefore, a cut on the Jet Vertex Fraction (J VF) variable is used to remove jets originating from additional interactions. Figure 6.9 shows the effect of the various JVF cuts on the average jet multiplicities. An optimal value of the JVF is found to be 0.75. With $|\text{JVF}| \geq 0.75$, it is found that the average value of the jet multiplicity is constant as a function of the reconstructed vertices.

![Figure 6.6: The maximum mean number of events per beam crossing versus day. Plot shows the average value for all bunch crossings in a lumi-block.](image-url)
6.3 Backgrounds Estimation

As mentioned earlier, this analysis is sensitive to both the shape and normalisation of the invariant mass distribution of the dijet mass system. The presence of a charged Higgs boson decaying exclusively into two jets will reduce the number of semi-leptonic $t\bar{t}$ events observed in the data. Therefore, it is important to estimate the total number of events expected in data. The MC samples discussed in Chapter 5 are used to estimate the contribution of each background to the total number of expected events.
6.3.1 The SM $t\bar{t}$ Background

The dominant SM background is $t\bar{t}$ events where one $W$ decays to $e\nu$ (or $\mu\nu$) and the other $W$ decays to two light quarks. This background cannot be reduced because it has the same signature as the signal events. It contributes nearly 90% of the total expected events. The estimation of this background is performed using the MC@NLO sample with a cross section of 167 pb \cite{10}. The expected number of events for the electron and muon channels are shown in Tables 6.1 and 6.2 respectively. As mentioned in Section 6.2.2, the shape of the reconstructed dijet mass distribution for this background is shown in Figure 6.5 and used as a nominal template in the fit to data.

6.3.2 Other SM non-$t\bar{t}$ Backgrounds

Other backgrounds, labeled “non-$t\bar{t}$” backgrounds, consist of events from the production of single top quark, $W/Z+$light/heavy-jets, di-boson and QCD multi-jet events. The contributions of these backgrounds are estimated using the data and MC samples shown in Tables 5.3 and 5.4. The numbers of these background
events are significantly reduced by applying the event selection cuts described in Section 6.1. After applying the $\chi^2$ cut, the total contribution of these backgrounds is about 10% of the total expected number of background events. The estimation of the non-$t\bar{t}$ backgrounds is given below.

**Single-top Background**

The production of a single-top quark has a relatively small cross section (as shown in Tables 5.3), but a considerable contribution to the total non-$t\bar{t}$ background. This is due to the existence of a top quark in the event. The expected number of events from the production of a single top quark is estimated using MC@NLO samples, except for the $t$-channel where ACERMC is used, because the produced MC@NLO sample for $t$-channel had a bug in the sample. The 2 $b$-tag requirement and the $\chi^2$ cut are efficient in reducing this background as can be seen in Tables 6.1 and 6.2. The total contribution of the three components of the single-top background is about 3.7% of the total expected number of events. The resulting dijet mass distribution is shown in Figure 6.10. In this distribution, a peak can be seen around the $W$ mass. This is due to the fact that single-top events are expected to have a top quark which can be reconstructed by the fitter, unlike other non-$t\bar{t}$ background events.

**$W$+jets Background**

Various data-driven methods are available to estimate the amount of the expected $W$+jets events. However, these methods provide only the normalisation of this background, while the shape needs to be obtained from MC simulation. The overall normalisation of the $W$+jets background is estimated using the charge asymmetry method. Since the LHC is a proton-proton collider, the production of $W^+$ bosons has a higher cross section than the $W^-$ bosons due to the PDFs. The normalisation factors and their uncertainties are obtained for the $W$+jets samples using the ratio of the cross-sections of these two processes, $r_{MC}$. This ratio is well predicted by the MC. Normalisation factors specific to the flavour of the additional jets in the samples are used. The uncertainties on $W$+jets estimates are 26% for the electron channel and 28% for the muon channel. The total contribution of the $W$+jets background (including $W$+heavy flavour jets) is estimated to be about 3% in the electron channel and about 4% in the muon channel. The data driven method used to estimate the $W$+jets background is described in detail in [49]. The dijet mass distribution for all $W$+jets including heavy-flavour jets is shown in Figure 6.10.
QCD Multi-jet Background

As mentioned in Section 5.1.3, the contribution of the QCD multi-jet background is not modeled by MC samples. Instead, a data-driven method as described in [45] is used to estimate its contribution. The shape of the dijet mass distribution of the QCD contribution shown in Figure 6.10 is obtained from a control sample in which a control region, where leptons are required to be semi-isolated, is used. This semi-isolation requires that the sum of transverse momenta of the inner detector tracks (excluding the lepton) in a cone of radius $\Delta R = 0.3$ must satisfy $0.1 < \Sigma P_t(0.3)/P_t(e, \mu) < 0.3$. Leptons are also required to have an impact parameter of $0.2 \text{mm} < |d_0| < 2 \text{mm}$ and an impact parameter significance of $|d_0|/\sigma_d > 3$ in the control region. A large bias in the reconstruction of the top mass can be produced if an anti-isolation cut is used because a large fraction of the QCD multi-jet events will have very small opening angles between the lepton and jets. The contribution of this background is estimated to be about 2.7% of the total events. The uncertainty on the QCD multi-jet background is taken to be 50%.
Both the $Z$+jets and di-boson backgrounds have very small contributions to the expected total number of background events. These events are significantly reduced by the event selection cuts as can be seen in Tables 6.1 and 6.2. No shape template is made for this background, but it is included in the non-$t\bar{t}$ background in Figure 6.10.

### 6.4 Data Versus Monte Carlo predictions

The expected number of events for the charged Higgs signal, the semi-leptonic SM $t\bar{t}$ and other background processes at different stages of the event selection cuts are shown in Tables 6.1 and 6.2 in the electron and muon channels respectively. These numbers are compared with the observation in the data. The agreement between the expectation from the SM backgrounds and the observed number of events in the data gives no indication of a signal existence. The QCD multi-jet background is only defined for the 2 $b$-tag and $\chi^2$ cuts because it is estimated from data-driven methods for both channels. The numbers of events in all MC samples are scaled to the expected values for the integrated luminosity of 4.7 fb$^{-1}$. The scale factors described in Section 4.6 are applied to the events. Good agreement is seen between the number of data events observed and the predicted number of background events for both the electron and muon channels.

The expectation for the charged Higgs boson signals shown in the tables are given assuming that $\mathcal{B}(t \to bH^+) = 10\%$. From the tables, it can be noticed that the signal acceptance for the 2 $b$-tag requirement decreases as the mass of the signal increases. While the acceptance for $m_{H^+} = 90$ GeV is about 50\%, it decreases to about 30\% for $m_{H^+} = 150$ GeV. This is due to the decrease in the available energy to the $b$-jet in the hadronic side as the $H^+$ mass approaches the top quark mass.

The reconstructed di-jet mass distribution of the data is compared with the SM prediction with no charged Higgs boson signal. As can be seen in Figure 6.11, the data is well described by the MC prediction. The dijet mass distribution peaks at the $W$ mass as expected from SM semi-leptonic $t\bar{t}$ background. Other SM non-$t\bar{t}$ backgrounds added together, denoted in Figure 6.11 by “other bkg”, have a small constant contribution. It can be seen that the data is slightly higher than the SM prediction. This is due to the fact that the total number of events in data is slightly higher than the SM prediction as shown in Tables 6.1 and 6.2. However, it should be noted that systematic uncertainties are not included in Figure 6.11.
The sources of systematic uncertainty and their effects on this analysis will be discussed in detail in Chapter 7.

Figure 6.11: The reconstructed dijet mass distribution from data and the expectation from the SM. The semi-leptonic SM $t\bar{t}$ background is denoted by “ttbar” and all other SM non-$t\bar{t}$ backgrounds are added to give the “other bkg”. The first and the last bins in the plot include the underflow and overflow entries.
Chapter 7

Systematic Uncertainties

The full 4.7 fb$^{-1}$ data-set recorded by the ATLAS experiment in 2011 is used in this analysis. Although a 2 $b$-tag requirement is applied to the selected events, more than 15000 semi-leptonic $t\bar{t}$ candidates are observed in the electron and muon channels when combined. With this large number of events, systematic effects in the analysis become more important.

There are many sources of this systematic uncertainty that affect this analysis. These sources will be presented in the following section. The systematic uncertainties cause two overlapping effects. First, they can alter the selection acceptance for the signal and background events, and second they can perturb the shape of the dijet mass distribution. The systematic uncertainties that affect the shape and normalisation of the reconstructed dijet mass will be discussed in Section 7.2 while those that affect only the expected number of events will be presented in Section 7.3. The effect of systematic uncertainties on the reconstructed dijet mass distribution will be presented in Section 7.4.

7.1 Sources of Systematic Uncertainty

The full list of systematics and the definitions of $\pm 1\sigma$ are shown in Table 7.1. These systematic uncertainties include uncertainties on the jet energy scale (JES) for light-jets, charm-jets, and $b$-jets, the jet energy resolution (JER), the lepton identification and the mass of the top quark (Mtop). In addition, uncertainties on the tagging efficiency of $b$-jets ($b$Tag) and $c$-jets ($c$Tag), and mis-tagging of light jets as $b$-jets ($m$Tag) cause a large uncertainty on the acceptance for signal ($H^+$) and SM $t\bar{t}$ events. There are also systematics related to the MC generators used to model both the signal and background; the amount of initial and final state radiation (ISR/FSR) and the choice of Monte Carlo generator (Gen) and parton
<table>
<thead>
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<th>Systematic</th>
<th>Definition ±1σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale (JES)</td>
<td>MultijetJESUncertaintyProvider *</td>
</tr>
<tr>
<td>Jet energy resolution (JER)</td>
<td>JERProvider *</td>
</tr>
<tr>
<td>b-jet energy scale (bJES)</td>
<td>1 ~ 2.5%*</td>
</tr>
<tr>
<td>c-jet energy scale (cJES)</td>
<td>0.5 ~ 1.3%*</td>
</tr>
<tr>
<td>b-tagging efficiency on b-jets (bTag)</td>
<td>5 ~ 17%*</td>
</tr>
<tr>
<td>b-tagging efficiency on c-jets (cTag)</td>
<td>±2.4%</td>
</tr>
<tr>
<td>Mis b-tagging rate (mTag)</td>
<td>12 ~ 21%*</td>
</tr>
<tr>
<td>MC generator (Gen)</td>
<td>MC@NLO+HERWIG vs POWHEG +HERWIG +PYTHIA</td>
</tr>
<tr>
<td>Parton shower (PS)</td>
<td>ACER: (more - less)/2</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>δm_t = ±1.5 GeV</td>
</tr>
<tr>
<td>Top mass (Mtop)</td>
<td>up to 1%</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>±1%</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>up to 3.5%</td>
</tr>
<tr>
<td>Muon reconstruction &amp; identification</td>
<td>±1%</td>
</tr>
<tr>
<td>Electron trigger &amp; identification</td>
<td>±30%</td>
</tr>
<tr>
<td>Muon trigger &amp; identification</td>
<td>W+jets vs QCD</td>
</tr>
<tr>
<td>Non-tt cross-section</td>
<td>+10, −11%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>±3.9%</td>
</tr>
</tbody>
</table>

Table 7.1: Chosen definitions of ±1σ for each systematic uncertainty. Items marked by * depend upon the p_T and/or η of physics objects present in the event.
shower (PS) used in the event generation. There are additional uncertainties due to $t\bar{t}$ cross-section and non-$t\bar{t}$ background normalization. The $E_T^{\text{miss}}$ scale and resolution are accounted for by propagating the effect of the jet and lepton scales and resolutions to the $E_T^{\text{miss}}$ calculation.

The effect of these sources of systematic uncertainty on the efficiency to select $t\bar{t}$ background and signal events has been studied. The change in the acceptance of the SM $t\bar{t}$ background and the signal for $m_{H^+} = 110$ GeV due to the variation of these systematics as defined in Table 7.1 is shown in Table 7.2. The electron and muon identification and reconstruction efficiencies in Table 7.1 have been combined in Table 7.2 to give overall lepton efficiencies. It can be seen that some systematics, such as Jet Energy Scale, $b$-tagging efficiency on $b$-jets, ISR/FSR and $t\bar{t}$ cross-section, have a large effect, while other systematics have a smaller effect on the SM $t\bar{t}$ and signal acceptances.

<table>
<thead>
<tr>
<th>Systematic</th>
<th>$t\bar{t}$ background</th>
<th>Signal ($m_{H^+} = 110$ GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale</td>
<td>$+9.0, -9.5%$</td>
<td>$+9.3, -9.1%$</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>$\pm0.90%$</td>
<td>$\pm0.72%$</td>
</tr>
<tr>
<td>$b$-jet energy scale</td>
<td>$+0.3, -0.6%$</td>
<td>$+0.6, -1.5%$</td>
</tr>
<tr>
<td>$c$-jet energy scale</td>
<td>$+0.1, -0.3%$</td>
<td>$+0.1, -0.5%$</td>
</tr>
<tr>
<td>$b$-tagging efficiency on $b$-jets</td>
<td>$+11.0, -10.7%$</td>
<td>$+8.9, -8.8%$</td>
</tr>
<tr>
<td>$b$-tagging efficiency on $c$-jets</td>
<td>$\pm2.4%$</td>
<td>$\pm3.5%$</td>
</tr>
<tr>
<td>Mis $b$-tagging rate</td>
<td>$\pm1.8%$</td>
<td>$+4.4, -4.2%$</td>
</tr>
<tr>
<td>MC generator</td>
<td>$\pm4.3%$</td>
<td>$\pm4.3%$</td>
</tr>
<tr>
<td>Parton Shower</td>
<td>$\pm3.1%$</td>
<td>$\pm3.1%$</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>$\pm8.8%$</td>
<td>$\pm8.8%$</td>
</tr>
<tr>
<td>top mass</td>
<td>$+1.7, -1.9%$</td>
<td>$+1.7, -1.9%$</td>
</tr>
<tr>
<td>Lepton ($e/\mu$) identification</td>
<td>$\pm1.4%$</td>
<td>$+1.6, -1.2%$</td>
</tr>
<tr>
<td>Lepton ($e/\mu$) reconstruction</td>
<td>$\pm1.0%$</td>
<td>$+1.2, -0.7%$</td>
</tr>
<tr>
<td>$t\bar{t}$ cross-section</td>
<td>$+10, -11%$</td>
<td>$+10, -11%$</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$\pm3.9%$</td>
<td>$\pm3.9%$</td>
</tr>
</tbody>
</table>

Table 7.2: Effect of the systematic uncertainties on the efficiency of the $t\bar{t}$ background and signal event selection. The electron and muon identification and reconstruction efficiencies in Table 7.1 have been combined to give overall lepton efficiencies. Note some of the systematic uncertainties also affect the shape of the dijet mass distribution.
7.2 Shape Perturbing Systematics

7.2.1 Jet Energy Scale (JES) Uncertainty

The JES uncertainty is one of the largest systematic uncertainties that affect this analysis. This source of uncertainty affects both the shape and normalisation of the dijet mass distribution. It is the uncertainty on the JES correction factor which is applied to correct the response of the calorimeter to the energy of the jet back to the particle level. A detailed description of the JES components and their derivation using MC and collision data is given in [50]. These sources of uncertainty include:

1. **Uncertainty in the JES calibration method**
   For low $p_T$ jets, when comparing the energy of a MC simulated jet after calibration to its matched truth jet, a slight deviation from unity can be seen. This implies that the kinematics of the calibrated calorimeter jet are not fully reconstructed to that of the truth jet (non-closure). The main reason for this is the application of the same correction factor to the jet $p_T$ and energy. To account for the non-closure of the JES calibration, the larger deviation of the response from unity of either the jet energy or $p_T$ is taken as the systematic uncertainty.

2. **Uncertainty on the calorimeter response**
   The uncertainty on the calorimeter response to single particles contributes to the total JES uncertainty. In the simulation, it is possible to trace back the energy deposits in each calorimeter cell to the truth energy of the particle generated in the collision. Therefore, the uncertainty on the calorimeter response to jets can be obtained by propagating the uncertainty measured with single particle response [51].

3. **Uncertainties due to the detector simulation**
   Jets are constructed from topo-clusters of energy deposit in the calorimeter based on a signal-to-noise ratio [50]. The simulated noise differs from the real noise in data due to the fact that the noise can change over time in the data, while in simulation it is fixed for a simulated data set. This can alter the cluster shapes and produce fake topo-clusters. The jet reconstruction and calibration can be biased by these effects. The uncertainty on the jet energy measurement arising from the modelling of the calorimeter cell noise is estimated by modifying the noise thresholds in a MC sample and
comparing the response for jets with the same sample with the default noise thresholds.

4. **Uncertainties due to the event modelling in MC generators**
   This systematic uncertainty accounts for the effect of the choice of the MC generator used to model the fragmentation and the underlying event. Its contribution is estimated from the variation between samples from various MC generators.

5. **In-situ intercalibration using events with dijet topologies**
   Due to the different calorimeter technologies used in the central and endcap regions and to the amounts of material in front of the calorimeters, the calorimeter’s response to jets depends on the direction of jets. Therefore, a calibration is needed to account for this effect. This calibration is attained by applying correction factors derived from MC. The uncertainty on this calibration is obtained by comparing calibrated jets from the central and forward regions using dijet events. The uncertainty on the JES in the central region ($|\eta| < 0.8$) is obtained from the single particle response and systematic variations of the MC simulations, and the results from the dijet balance ($\eta$-intercalibration) method are used to transfer it to the forward regions.

6. **Uncertainties due to pile-up collisions**
   Studies of the jet response with respect to the $p_T$ of the jets as a function of the number of primary vertices are used to obtain the uncertainty due to pile-up corrections. This uncertainty is found to be dependent on the number of primary vertices and $\eta$, and needs to be added separately to the total JES uncertainty.

7. **The $t\bar{t}$ sample jet flavour and the close-by jet uncertainties**
   In addition to the previous JES uncertainties, which are derived from inclusive QCD dijet events to provide a clean detector environment and high statistics, there are two sources of uncertainty that are specific to the multi-jet environment of the $t\bar{t}$ events; the $t\bar{t}$ sample jet flavour and the close-by jet uncertainties. The ratio of jets originating from light quarks to those from gluons differs between the QCD dijet and $t\bar{t}$ environments. An uncertainty is therefore introduced to account for this difference.

The close-by jet uncertainty is needed due to the fact that in the QCD dijet events jets are fairly isolated from each other, while in the $t\bar{t}$ system there
Figure 7.1: On the left, the dijet mass distribution, muon channel, for the reconstructed $W$ bosons with JES $\pm \sigma$. On the right, the dijet mass distribution, muon channel, for $W$ bosons after the kinematic fit with JES $\pm \sigma$.

are multiple jets increasing the chance of overlap between the edges of the jets. This overlap can cause the assignment of energy to the incorrect jet.

The JES uncertainty is taken as the combination in quadrature of the contributions of all these sources of uncertainty, and it accounts for the uncertainty on the jet $p_T$ after applying the JES. It is estimated by varying the jet $p_T$ and $\eta$ by $\pm 1\sigma$, re-running the full analysis and reproducing the dijet mass templates. The effect of the $\pm 1\sigma$ change in the jets’ $p_T$ and $\eta$ is propagated into the $E_T^{miss}$ calculation. The JES uncertainties are provided by the MultijetJESUncertaintyProvider \[52\].

The two effects of the JES uncertainty on the dijet mass distribution of the reconstructed $W$ bosons from the SM $t\bar{t}$ events are shown before and after the kinematic fitter in Figure 7.1. First, the uncertainty changes the $t\bar{t}$ event selection efficiency via the change in the jet $p_T$ allowing more/less events to satisfy the four jet requirement. This effect cannot be corrected by the fitter, and the overall normalisation effect on the SM $t\bar{t}$ and $m_{H^+} = 110$ GeV signal sample is shown in Table 7.2. The second effect is the shift in the peak position of the reconstructed dijet mass distribution due to the change in the energy of the jets. This effect is partially corrected by the fitter due to a constraint on the mass of the top quark. A similar effect on the signal samples is expected and is seen as in Figure 7.2.

7.2.2 Jet Energy Resolution (JER) Uncertainty

The resolution of the jet energy affects the width of the reconstructed dijet mass system. Therefore, the Jet Energy Resolution (JER) needs to be correctly modelled in the MC to match that observed in the data. The JER is measured with
two methods based on jet $p_T$ using events with two or more jets. The MC is found to agree with the data within 14% for jets with $20 < p_T < 80$ GeV and $|y| < 2.8$ [53]. The systematic uncertainty on the JER is obtained by applying a Gaussian smearing (up to 16% to account for jets with $p_T > 80$ GeV) to the energy of each jet in the MC. The magnitude of this smearing depends on the position of the jet in the detector and increases with $|\eta|$. This method accounts for the case where the MC has a better resolution than the data. The reverse case is taken into account by symmeterizing the uncertainty about the nominal case. The normalisation effect of the JER uncertainty is given in Table 7.2 while its effect on the shape of the dijet mass before and after the fitter is shown in Figure 7.3. The effect of the JER uncertainty is found to be smaller than that of the JES uncertainty.

Figure 7.2: On the left, the dijet mass distribution, muon channel, for the reconstructed signal for $m_{H^+} = 110$ GeV with JES $\pm \sigma$. On the right, the dijet mass distribution, muon channel, for $H^+$ after the kinematic fit with JES $\pm \sigma$.

Figure 7.3: On the left, the dijet mass distribution for the reconstructed $W$ bosons with JER uncertainty applied. On the right, the dijet mass distribution for $W$ after the kinematic fit with JER uncertainty applied. Muon channel is used in both distributions.
7.2.3 Heavy-flavour Jet Energy Scale Uncertainty

The JES uncertainty described in Section 7.2.1 is derived using QCD jets events and $t\bar{t}$ events. In these events jets are assumed to have originated from either a quark or a gluon. The flavour of the jets was not taken into consideration. However, heavy-flavour jets have a different response to light-flavour jets due to differences in jet fragmentation functions and semi-leptonic decays of heavy quarks. Therefore, for heavy-flavour jets, additional systematic uncertainties are considered for the $b$-jet (bJES) and $c$-jet (cJES) energy scales. Figure 7.4 shows the jet energy responses to light-jets, $c$-jets, and $b$-jets. The ratio of $c$-jet energies to their parton energies is 3.1% lower than the light-jet response, but is 3.4% higher than the $b$-jet response. The uncertainty on the $c$-jet energy is taken to be 50% of the $b$-jet energy uncertainty as recommended by the ATLAS Top group [52]. Figure 7.5 shows the effect of the bJES and cJES uncertainties on the dijet mass distribution for the SM $t\bar{t}$ events. The uncertainty on the $b$-tagging efficiency for $b$-jets ($b$Tag) and $c$-jets ($c$Tag), as well as mis-tagging rate (mTag), is taken from the $b$-tagging group.

The effect of each component of these systematic uncertainties on the efficiency to select SM $t\bar{t}$ background events and signal events (for $m_{H^+} = 110$ GeV) is shown in Table 7.2. It is shown that the largest systematic effect comes from the $b$-tagging efficiency on $b$-jets. This reflects the importance of the $b$-tagging efficiency to reconstruct the $t\bar{t}$ system and the dijet mass distribution.

![Figure 7.4: Comparisons of the jet energy responses of the light jets [left], $c$-jets [left] and $b$-jets [right] with respect to the parton energies. The fitted mean values of the jet energy responses are 0.962, 0.995, and 1.026 for the $b$-jets, $c$-jets and light jets respectively.](image-url)
Figure 7.5: The dijet mass distribution for the reconstructed $W$ bosons after the kinematic fit: $b$-JES $\pm \sigma$ [left], $c$-JES $\pm \sigma$ [right]. Muon channel is used in both distributions.

### 7.2.4 Initial and Final State Radiation (ISR/FSR)

As mentioned earlier, $t\bar{t}$ events can contain more than four jets due to the presence of ISR/FSR contributions. A high $p_T$ jet produced by ISR can replace one of the leading jets used to reconstruct the $t\bar{t}$ system. On the other hand, a FSR gluon emitted at a wide angle outside the jet can form another jet and reduce the measured $p_T$ of the original parton, which is then, therefore, not considered in the fit. Both cases would cause the $t\bar{t}$ system to be mis-reconstructed. The modeling of the ISR/FSR in $t\bar{t}$ events has some uncertainty. This uncertainty is evaluated by using the ACER ISR/FSR more and less samples. In these samples, the amount of the ISR/FSR present in the $t\bar{t}$ events has been varied. These samples are used to calculate the effect on the acceptance and to estimate the effect on the dijet mass distribution. The half difference between the more and less samples is taken as the systematic uncertainty. The effect of the ISR/FSR uncertainty on the efficiency to select $t\bar{t}$ events is found to be 8.8%. Since the effect of the ISR/FSR on the signal and SM $t\bar{t}$ is expected to be similar, the SM $t\bar{t}$ was used for the signal samples as a normalisation systematic uncertainty. A comparison of the dijet mass distribution from the more/less ISR/FSR samples is shown in Figure 7.6. It can be seen from the figure that the variation of the ISR/FSR has a similar effect as the JES. It changes the efficiency of the cuts and shifts the peak position. This effect is reduced by the kinematic fitter due to the top mass constraint.
7.2.5 The Choice of the MC Generator and Parton Shower

Several Monte Carlo generators were used to model the signal and background processes used for this analysis, as discussed in Chapter 5. To account for differences between these MC generators, an additional systematic uncertainty is needed. The uncertainty due to the choice of MC generator is evaluated by comparing the results obtained by using the MC@NLO and POWHEG generators interfaced with HERWIG for the SM $t\bar{t}$ events. Both samples are simulated using ATLASFAST II simulation, in which the particle interactions in the inner detector and the muon tracks are fully simulated while running fast simulation for the calorimeters to reduce the CPU time needed. The full difference between the two samples is then transformed to the nominal MC@NLO sample and taken as the systematic uncertainty on the choice of MC generator.

The uncertainty due to the modelling of the parton shower is checked by comparing two different POWHEG samples where one sample is interfaced with the HERWIG parton shower model, and the other sample with PYTHIA. The difference between the two samples is large, as shown in Figure 7.7 [left]. However, it has been found that the current version of the ATLAS Pythia tune, AMBT1, is not in good agreement with the ATLAS jet data. The difference between the two samples could be an overestimate of the parton shower systematic uncertainty. The new POWHEG plus PYTHIA sample made with the Perugia 2011 C tune shows a small difference compared to the POWHEG plus HERWIG sample in the dijet mass distribution, shown in Figure 7.7 [right]. This full difference is taken as the systematic error due to parton shower. The effects of the choice of MC generator and parton shower uncertainties on the $t\bar{t}$ event selection efficiency are
shown in Table 7.2.

Figure 7.7: The dijet mass distributions for the reconstructed $W$ bosons after the kinematic fit are shown for two different parton shower models; [left] Powheg samples interfaced with Herwig and Pythia with the AMBT1 tune, [right] Powheg samples interfaced with Herwig and Pythia with the Perugia 2011 C tune, for the muon (mu) channel.

### 7.2.6 The Top Mass Uncertainty

The MC samples used to model the signal and background contributions were all generated at a top quark mass $M_{\text{top}} = 172.5$ GeV [16]. To account for the effect of the uncertainty in the top quark mass on the results of this analysis, three MC samples for the SM $t\bar{t}$ events were generated with the MC@NLO MC generator using ATLASFAST II simulation. From the combined measurement at the Tevatron [54], the uncertainty on $m_{\text{top}}$ is 0.9 GeV. However, a conservative value of 1.5 GeV is taken as a top mass uncertainty due to a possible bias in the lepton+jets channel from an $H^+$ signal. This value is consistent with the measurement of $m_{\text{top}}$ in the dilepton channel from the CMS experiment [55]. These samples were generated at a top quark mass of 170, 172.5 and 175 GeV. The difference between the nominal sample (172.5 GeV) and the other two samples (170 GeV and 175 GeV) is taken as the systematic uncertainty on the top quark mass. The effect of this uncertainty is also shown in Table 7.2.

### 7.2.7 The Shape Uncertainty in the Non-$t\bar{t}$ Background

In addition to the irreducible SM $t\bar{t}$ background, there are other SM non-$t\bar{t}$ backgrounds that contribute to the total expected events. The SM non-$t\bar{t}$ backgrounds contribute about 10% of the total number of events after all selection cuts. These
backgrounds are combined according to their contributions to form the SM non-$t\bar{t}$ background template shown in Figure 6.10.

Two samples are produced to evaluate the shape uncertainty in the non-$t\bar{t}$ backgrounds. In one sample, the shape of the QCD dijet events in the combined non-$t\bar{t}$ template is replaced by the $W$+jets shape. In the other sample, the shape of the $W$+jets events is replaced by the QCD shape. In both cases the shape exchange is performed whilst maintaining the nominal normalization. The difference between the two samples is taken as the non-$t\bar{t}$ shape systematic (Bkg,S).

7.3 Systematics Affecting the Normalisation

Not all systematic uncertainties affect the shape of the reconstructed dijet mass distribution. Some sources of systematic uncertainty affect only the normalisation of this distribution. The systematics that are taken as normalisation uncertainty include:

7.3.1 The Lepton Scale Factors

The lepton identification, trigger and reconstruction efficiencies and scale factors have some uncertainties associated with them. Uncertainties on lepton reconstruction and identification efficiency are determined using a tag and probe method in samples of $Z$ boson and $J/\psi$ decays [56]. The momentum resolution and scales are determined from fits to samples of $W$ boson, $Z$ boson, and $J/\psi$ decays [57, 58]. These uncertainties are found not to affect the shape of the dijet mass distribution. Due to the constraints on the masses of the $W$ boson and top quark in the fitter, their effect on the efficiency to select $t\bar{t}$ background and signal events is found to be small, as shown in Table 7.2.

7.3.2 The SM $t\bar{t}$ Cross-Section

The predicted SM $t\bar{t}$ cross-section for $pp$ collisions at $\sqrt{s} = 7$ TeV, obtained from approximate next-to-next-to-LO QCD calculations, is $\sigma_{t\bar{t}} = 167^{+17}_{-18}$ pb for a top quark mass of 172.5 GeV [10]. The uncertainty on the predicted value includes the uncertainty in the renormalization and factorization scales, parton density functions, and the strong coupling constant. An additional uncertainty on the $t\bar{t}$ cross-section (4.5%) is included due to the uncertainty on the top-quark mass. The systematic uncertainty on the SM $t\bar{t}$ cross-section has one of the largest
effects on the predicted numbers of events for the SM \(t\bar{t}\) and signals as shown in Table 7.2.

### 7.3.3 The Normalisation of the Non-\(t\bar{t}\) Background

For the non-\(t\bar{t}\) background, the normalization uncertainty on the \(W+\)jets background has been estimated to be 26\% (electron channel), 28\% (muon channel). The uncertainty on the data-driven QCD multi-jet background normalization is taken to be 50\%. For the single top and diboson production, the uncertainties were assumed to be 15\%. The \(Z+\)jets normalization uncertainties are assumed to be the same as the \(W+\)jets uncertainty. When combined, these estimates give an overall normalization uncertainty of 30\% on the non-\(t\bar{t}\) backgrounds (Bkg\(_N\)).

### 7.3.4 The Luminosity Uncertainty

The integrated luminosity used in this analysis of 4.7fb\(^{-1}\) has an uncertainty associated with it. This uncertainty does not affect the shape of the reconstructed dijet mass. The uncertainty on the luminosity has been constrained by various methods, such as performing Van de Meer scans and studies of the bunch currents. This uncertainty is taken to be 3.9\% [59].

### 7.4 Effect of Systematic Uncertainty on the Dijet Mass Distribution

In addition to the dijet mass distribution, various important kinematic variables in the event have been studied using MC samples and compared with data for both the electron and muon channels. These variables include the lepton \(p_T\) and \(\eta\), missing transverse energy \((E_T^{\text{miss}})\), the number of vertices per event, the \(p_T\) and \(\eta\) of the selected two \(b\)-jets and two light jets in the event. Comparisons of the data and the SM predicted backgrounds for these variables are shown in Figures 7.8, 7.9 and 7.10. The error bars represent the statistical uncertainty on the data. The uncertainty shown on the background estimate is the combination in quadrature of the all systematic uncertainties. A comparison of the \(\chi^2\) distribution in the data and the predicted backgrounds for the electron and muon channels is shown in Figure 7.11. All kinematic variables are found to be well described by the MC and agree with the data within uncertainty bands.

The reconstructed dijet mass distribution of the data is compared with the SM prediction with no charged Higgs boson signal. As can be seen in Figure 7.12.
the data is found to agree with the Standard Model expectation within the uncertainty band. This dijet mass distribution is used with the signal templates shown in Figure 6.5 to set upper limits on the branching ratio $B(t \to bH^+)$. The extraction of the upper limits on the branching ratio $B(t \to bH^+)$ is presented in Chapter 8.
Figure 7.8: Comparison of the data and predicted backgrounds for lepton $p_T$, lepton $\eta$, missing transverse energy, and the number of vertices; electron sample (left plots), muon sample (right plots).
Figure 7.9: Comparison of the data and predicted backgrounds for two $b$-jets (upper four plots: $b$-jets associated with the leptonic decay of $W$, lower four plots: $b$-jets associated with the hadronic decay of $W$) $p_T$ and $\eta$; electron sample (left plots), muon sample (right plots).
Figure 7.10: Comparison of the data and predicted backgrounds for $p_T$ and $\eta$, for the two light jets, 1 and 2, associated with the hadronic decay of the $W$; electron sample (left plots), muon sample (right plots).
Figure 7.11: Comparison of the $\chi^2$ distribution in data and the predicted backgrounds for the electron sample (left) and the muon sample (right).

Figure 7.12: The reconstructed dijet mass distribution from data and the expectation from the SM. The error bars represent the statistical uncertainty on the data. The uncertainty shown on the background estimate is the combination in quadrature of the $\pm 1\sigma$ systematic uncertainties, accounting for the constraint from the profile likelihood fit. The first and the last bins in the plot include the underflow and overflow entries.
Chapter 8

Setting of Limits

One of the major goals of particle physics experiments is to search for new particles or processes that have been predicted by theoretical models but not yet observed. A robust statistical framework is crucial to determine the significance of any new signal seen. This framework should also have the ability to exclude or constrain the expected signal based on the observed data.

A commonly used statistical framework in particle physics is the frequentist statistical test [60]. This framework can be used for discovering a new signal or for the purpose of setting limits. Two hypotheses are defined and tested against each other, the background only, $H_b$, and the signal plus background, $H_{s+b}$, hypotheses.

For the purpose of discovery, $H_b$ is tested against $H_{s+b}$, while for the case of setting limits the $H_{s+b}$ is tested against the $H_b$ hypothesis. In these tests, the level of agreement between the observed data and a given hypothesis is quantified by computing a $p$-value, which is defined as the probability of finding data of greater than or equal incompatibility with the hypothesis $H$. The number of observed events in regions of interest of certain distributions or the equivalent likelihood ratio for signal and background can be used to quantify the $p$-value. If the $p$-value is observed below a certain threshold, the hypothesis, $H$, can be excluded. In particle physics this threshold is often taken as 0.05 (a 95% Confidence Level). For a discovery, a conservative threshold of $p = 2.87 \times 10^{-7}$ (≡ a 5 standard deviation effect) is required.

The likelihood ratio is widely used as a test statistic to determine the statistical significance of an observed signal, in order to constrain or exclude its exis stance. The models describing the signal and background processes often contain, in addition to the cross section of signal and background, unknown nuisance parameters whose values must be fitted from the data.

In this analysis, the reconstructed di-jet mass distribution for the selected
data events is compared with the SM Monte Carlo predictions. Since no charged Higgs boson signal is seen in the data, upper limits are set on the branching ratio to charged Higgs bosons ($\mathcal{B}(t \rightarrow bH^+) )$ at 95% confidence level (CL) assuming that $\mathcal{B}(H^+ \rightarrow c\bar{s}) = 1$ using the frequentist procedure [60, 61].

8.1 Frequentist Exclusion Limits

The reconstructed dijet mass distribution for the data and the MC predictions for the SM background events, which is discussed in Section 6.4 and is shown in Figure 7.12, is used as the input to the limit setting procedure. All the systematic uncertainty sources discussed in Chapter 7 are included in the limit extraction procedure. The likelihood function used to define the profile likelihood ratio test statistic is given by Equation 8.1 [60]. This function depends on the branching ratio $\mathcal{B}(t \rightarrow bH^+)$ and the systematic uncertainties ($\alpha$). It describes the expected number of events in each bin of the distribution. The number of events in the SM background templates is scaled to that expected in $4.7 \text{ fb}^{-1}$, while the signal events are rescaled by the fitted value of $\mathcal{B}$.

$$L(\mathcal{B}, \alpha) = \prod_i \text{Pois}(n_i|\nu_i) \prod_j N(\alpha_j)$$

(8.1)

where $n_i$ is the number of observed events in bin $i$, $j$ labels the sources of systematic uncertainty, $N$ is the normal distribution and Pois is the Poissonian probability distribution function (pdf). The number of expected events, $\nu_i$ in each bin, is given by

$$\nu_i = 2\mathcal{B}(1 - \mathcal{B})\sigma_{tt} L \varepsilon_i^{H^+} \sigma_{1i}(\alpha) + (1 - \mathcal{B})^2 \sigma_{t\bar{t}} L \varepsilon_i^W \sigma_{2i}(\alpha) + n_i^b \sigma_{3i}(\alpha)$$

(8.2)

where $n_i^b$ is the expected number of non-$t\bar{t}$ background events, $\sigma_{tt}$ is the cross-section for top pair production, $L$ is the integrated luminosity, $\mathcal{B}$ is the branching ratio of $t \rightarrow H^+b$. The efficiencies to select the signal events ($t\bar{t} \rightarrow H^+bW^-\bar{b}$) and the SM $t\bar{t}$ background events ($t\bar{t} \rightarrow W^+bW^-\bar{b}$) are given by $\varepsilon_i^{H^+}$ and $\varepsilon_i^W$ respectively. The decay mode $t\bar{t} \rightarrow H^+bH^-\bar{b}$ does not contribute to the expectation because this mode does not produce an isolated lepton and hence has a negligible efficiency to pass the selection requirements. The first term of Equation 8.2 gives the expected number of semi-leptonic $t\bar{t}$ events containing an $H^+$ single, and the second term describes the number of SM $t\bar{t}$ background events. Both are dependant upon the branching ratio, $\mathcal{B}$. The third term, which is independent of $\mathcal{B}$, gives the expected number of non-$t\bar{t}$ events. The systematic uncertainties
described in Chapter 7 are included via the parameters $\sigma_{mi}$ and $\alpha$. The $\alpha_j$ parameters are defined such that $\alpha_i = \pm 1$ corresponds to the $\pm 1$ standard deviation variations for each systematic uncertainty. The $\sigma_{mi}$ parameters are defined as:

$$
\sigma_{mi}(\alpha) = \prod_j I(\alpha_j; \sigma^+_{mij}, \sigma^-_{mij})
$$

where

$$
I(\alpha; x^+, x^-) = \begin{cases} 
1 + \alpha x^+ & \text{if } \alpha > 0 \\
1 & \text{if } \alpha = 0 \\
1 - \alpha x^- & \text{if } \alpha < 0
\end{cases}
$$

where $\sigma^+_{mij}$ and $\sigma^-_{mij}$ represent the fractional effect of systematic $j$, in bin $i$ for process $m$. This enables asymmetric systematic uncertainties that affect the shape and normalization of the dijet mass distribution to be included in the limit calculation. Systematics are considered to be uncorrelated between different sources and each source is considered to be correlated between signal and the background.

The total number of events expected from the SM $t\bar{t}$ background and the charged Higgs boson signal as a function of the branching ratio, $B$, is shown in Figure 8.1. The number of non-$t\bar{t}$ background events expected is not shown, since this does not depend on this branching ratio. The expected number of SM $t\bar{t}$ events decreases following $(1 - B)^2$ as the branching ratio to signal events increases. The expected number of signal events follows $B(1 - B)$ and has a maximum at $B = 0.5$. This means that the analysis has a maximum sensitivity at this point. It should be noted that the total number of events expected to pass the event selection cuts decreases as the $B$ increases. This is because the analysis has almost no efficiency to select events where both top quarks decay into charged Higgs bosons. The selection acceptance of the fully hadronic SM $t\bar{t}$ channel, which has the same final state, is of the order of $10^{-6}$. This decay mode has no isolated leptons in the final state and as such does not enter into the analysis. Due to the assumption that signal events can only decay hadronically ($H^+ \rightarrow c\bar{s}$), the expected total number of events is correlated with $B$. This means that the analysis is not only sensitive to the shape of the reconstructed dijet mass, but also to the normalisation of the observed dijet mass distribution.

The limits are calculated using the test statistic, $q_B$, based on the profile
Figure 8.1: Number of expected events after all selection cuts from the $t\bar{t}$ background and the charged Higgs boson signal ($m_{H^+} = 110$ GeV) as a function of the branching ratio of top to charged Higgs. The number of non-$t\bar{t}$ background events expected is not shown, since this does not depend on this branching ratio.

likelihood ratio:

$$q_B = \begin{cases} 
-2\ln \frac{L(B, \hat{\alpha}(B))}{L(0, \hat{\alpha}(0))} & \text{if } \hat{B} < 0 \\
-2\ln \frac{L(B, \hat{\alpha}(B))}{L(B, B)} & \text{if } 0 < \hat{B} < B \\
0 & \text{if } \hat{B} > B
\end{cases}$$

where $\hat{\alpha}$ and $\hat{B}$ are the maximum likelihood estimators (MLE) for the systematics and the branching ratio for the signal, and $\hat{\alpha}(B)$ is the conditional MLE for the systematics for a given branching ratio $B$. The effect of systematic uncertainties can be constrained by information from the data when performing the MLE fits. From this definition of the test statistic $q_B$, the higher values of $q_B$ correspond to the lower compatibility of the data with the hypothesis. The pdfs of $q_B$ for branching ratio $B$ and background-only experiments, $f(q_B|B, \hat{\alpha}(B, obs))$ and $f(q_B|0, \hat{\alpha}(0, obs))$, can be constructed from toy Monte Carlo experiments. The $p$-value for a given branching ratio $B$ of the observation ($p_B$) is determined by integrating the pdf:

$$p_B = \int_{q_B, obs}^{\infty} f(q_B|B, \hat{\alpha}(B, obs))dq_B \quad (8.4)$$
The observed limit is determined by finding the value of $B$ for which $p_B = 0.05$. The quantity $(1 - p)$ is also known as the confidence level in the signal-plus-background hypothesis ($CL_{s+b}$). The expected limit can be found by calculating the median of the limit for a sufficiently large number ($\sim 1000$) of background-only toy experiments. The $\pm 1\sigma, \pm 2\sigma$ expected bands can also be derived from these toy experiments. The $p$-value of the observation for the background-only case is found by integrating the pdf obtained from the background-only toy experiments:

$$p_b = \int_{q_B,obs}^{\infty} f(q_B|0, \hat{\alpha}(0, obs)) dq_B$$

The pdfs can also be calculated by using the asymptotic formulae described in [62]. These formulae are applicable when the number of events is large, which is the case in this analysis. The toy MC approach gives limits consistent with the asymptotic formulae within $B = 0.01$, which is approximately the accuracy of the toy MC. This particular study was done in an analysis with 35 pb$^{-1}$ of data recorded by ATLAS in 2010 [63]. Therefore for computational ease, the results quoted here use the asymptotic formulae.

8.2 $CL_S$ Limits

The $CL_s$ limit setting technique [61] has been used amongst others by particle physics experiments at LEP and the Tevatron. This technique uses the same test statistic as described above, but instead of using the value of $CL_{s+b}$, it uses $CL_s$ which is defined as:

$$CL_s = \frac{CL_{s+b}}{CL_b}.$$  \hspace{1cm} (8.6)

The limit calculated by the $CL_s$ method is softened by the $CL_b$ contribution. This is due to the overlap between the pdfs of the two hypotheses. This effect increases as the two distributions become more indistinguishable, which means that the analysis becomes less efficient to distinguish between the two scenarios. Limits constructed from the $CL_s$ method are looser than those obtained from the $CL_{s+b}$ method. However they avoid excluding very small signal rates due to background-like fluctuations. The limits quoted in this analysis are calculated using the $CL_s$ method.
Chapter 9

Results

The data sample recorded by ATLAS and corresponding to an integrated luminosity of 4.7 fb$^{-1}$ has been analysed to search for a charged Higgs signal. The experimental method described in Chapter 6 is used to select semi-leptonic $t\bar{t}$ candidates, reconstruct events and estimate backgrounds. The procedures described in Chapter 8 are used to test the level of agreement between the data and a signal plus background hypothesis and a background only hypothesis. All systematic uncertainties discussed in Chapter 7 are included in the statistical treatment and limit extraction procedures as described in Chapter 8. In this chapter, the final results obtained from this analysis will be presented, discussed and compared with previous results in this channel.

9.1 Agreement of the Data with the Standard Model expectation

As shown in previous chapters, this analysis is sensitive to both the shape and the normalisation of the reconstructed dijet mass distribution. By comparing the reconstructed dijet mass spectrum obtained from the data and that from the SM expectation, it can be seen that the data agrees, within the uncertainty band, with the SM expectations, as shown in Figure 7.12. The presence of a signal would have appeared as a secondary peak on the reconstructed dijet mass distribution. The level of agreement between the data and the background-only model is tested by calculating the $CL_b$ for $B = 0$. The $p$-value was found to vary as a function of $m_{H^\pm}$ between 0.67 and 0.71. This means that the probability for the background to produce the dijet mass distribution observed in the data is between 67% and 71% indicating that the data is consistent with the background-only hypothesis.
9.2 Limits

Limits on the branching ratio $\mathcal{B}(t \to bH^+) \times \mathcal{B}(H^+ \to c\bar{s}) = 1$ have been extracted using the asymptotic formulae and the $CL_s$ method. The limits are set for the seven considered mass points of the charged Higgs boson (90, 100, 110, 120, 130, 140 and 150 GeV). The expected limits, using only statistical uncertainties, are shown with one-sigma and two-sigma bands in Figure 9.1. These limits are found to be in the range of 3% to 1% depending on the mass of charged Higgs boson.

![Figure 9.1: The expected 95% C.L. upper limits (for statistical uncertainties only) on $\mathcal{B}(t \to bH^+)$ using the $CL_s$ method.](image)

However, including the systematic uncertainties described in Chapter 7 loosens the expected limits to the range 8% to 2%. This shows that the limits are dominated by the effect of systematic uncertainties. The observed limits on the branching ratio are found to be between 5% to 1% depending on $m_{H^+}$. These results are shown in Table 9.1 and Figure 9.2. All systematic uncertainties discussed in Chapter 7 are included in the final procedure to set these limits. Following the expectation, the limits are tighter at high $m_{H^+}$ values and weaken as $m_{H^+}$ approaches $m_W$. This is due to the fact that the separation between the $m_{H^+}$ and $m_W$ peaks becomes more difficult. The observed limits are found to be tighter than the expected limits for most of the mass points. Most of the observed limits are found to be within the one-sigma uncertainty band of the expected limits as can be seen in Figure 9.2.

The expected number of events at the $m_W$ peak, Figure 7.12, would be reduced
in the presence of a signal as the branching ratio $B(t \to bH^+) \to$ increases due to
the signal events forming a secondary peak at $m_{H^+}$ and to the loss of events due
to both top quarks decaying to charged Higgs bosons.

The results presented here constitute a significant improvement compared to
the current limits on this decay channel from the Tevatron experiments \cite{23,24} and
the 2010 ATLAS data \cite{25}. The limits on the branching fraction $B(t \to bH^+)$
are improved by a factor of between 5 and 10. The extracted limits have recently
been published in EPJC \cite{3}. These limits are also comparable to those obtained
by the ATLAS and CMS experiments assuming an alternative decay channel
$H^\pm \to \tau \nu$ in $t\bar{t}$ events \cite{64,65}.

9.3 **Effect of the Systematics on the Limits**

The extracted limits on the branching ratio $B(t \to bH^+)$ are dominated by the
effect of the systematic uncertainties, as can be seen in Table \ref{tab:9.1}. Therefore,
the effect of these uncertainties and the correlation in the corresponding nuisance
parameters have been studied. Seventeen nuisance parameters, each correspond-
ing to a source of systematic uncertainty, are used in the fits to the dijet mass
distribution with the signal templates with $m_{H^+}$ in the range from 90 to 150 GeV.

Some nuisance parameters are found to have large correlations with other

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Figure 9.2: The extracted 95% CL upper limits on $B(t \to H^+ b)$ are shown in the
range of the charged Higgs mass from 90 GeV to 150 GeV. The limits shown are
calculated using the CLs limit-setting procedure.
Table 9.1: The expected branching ratio limits with and without systematics and the observed limits from the $CL_s$ method on the branching ratio of top decay to a charged Higgs boson and a $b$-quark.

<table>
<thead>
<tr>
<th>Higgs Mass (GeV)</th>
<th>Expected limit (Stat. only)</th>
<th>Expected limit (Stat.+Syst.)</th>
<th>Observed Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>0.027</td>
<td>0.080</td>
<td>0.051</td>
</tr>
<tr>
<td>100</td>
<td>0.015</td>
<td>0.034</td>
<td>0.034</td>
</tr>
<tr>
<td>110</td>
<td>0.012</td>
<td>0.026</td>
<td>0.025</td>
</tr>
<tr>
<td>120</td>
<td>0.011</td>
<td>0.021</td>
<td>0.018</td>
</tr>
<tr>
<td>130</td>
<td>0.011</td>
<td>0.023</td>
<td>0.014</td>
</tr>
<tr>
<td>140</td>
<td>0.010</td>
<td>0.020</td>
<td>0.013</td>
</tr>
<tr>
<td>150</td>
<td>0.010</td>
<td>0.015</td>
<td>0.012</td>
</tr>
</tbody>
</table>

nuisance parameters. The correlation matrices for the seventeen nuisance parameters used in the fit are shown in Tables 9.2, 9.3, and 9.4. The ISR/FSR parameter shows a large positive correlation with the Gen and PS parameters. As expected, the $\sigma_{tt}$ parameter shows a negative correlation with bTag, cTag, and Mtop nuisance parameters. The cross section, $\sigma_{tt}$, is constrained in the fit to be 167 pb with $+10\%/-11\%$ uncertainty. No change in the expected limits are found whene this constraint is removed as shown in Table 9.5.

The effect of the individual systematic uncertainties on the extracted limits has been investigated. Four representative cases ($m_{H^+} = 90, 100, 130$ and $150$ GeV) and ten major uncertainty sources, shown in Table 9.6, were considered in this check. One systematic effect from the entire list of systematics is removed in turn in the fit to extract the (N-1) limits. The resulting (N-1) limits are compared with the (N) limits where all systematics are included in the fit. The (N-1) limits are found to be close to the (N(STAT+SYST)) limits, as can be seen in Table 9.6. This can be explained by the correlation between several important nuisance parameters in the fit, as mentioned earlier.

In order to check the effect of the correlation between uncertainty sources on the calculated limits, a list of correlated systematic uncertainty sources in the fit is identified as a group (x) according to the correlation matrices shown in Table 9.2, 9.3, and 9.4. Each time, one group of correlated systematic items is removed from the fit for the limit calculation giving the (N-x) limits. The resulting (N-x) limits are compared with the (N(STAT+SYST)) limits and are shown in Table 9.7. In the (N-x) limits, the effect of the systematics can be clearly seen. At low Higgs mass (90 GeV) a group of the JES, bJES, and Mtop systematics is dominant. This can be understood as a decrease in sensitivity to distinguish between signal
and background at low Higgs mass due to JES and bJES uncertainties. At high Higgs mass, all systematic groups have similar effects on the limits due to the correlations among nuisance parameters.

Based on a few tests (N, N-1, N-x) on the limits, it is found that the extracted 95% CL limits are stable.
Table 9.2: The correlations among nuisance parameters from the fit of the $m_H = 90$ GeV case.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lumi</th>
<th>Bkg_N</th>
<th>bTag</th>
<th>cTag</th>
<th>Gen</th>
<th>I/FSR</th>
<th>JER</th>
<th>JES</th>
<th>LepES</th>
<th>LepId</th>
<th>mTag</th>
<th>PS</th>
<th>bJES</th>
<th>Bkg_S</th>
<th>cJES</th>
<th>Mtop</th>
<th>$\sigma_{t\bar{t}}$</th>
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</thead>
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<td>-0.08</td>
<td>-0.06</td>
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<td>-0.05</td>
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<td>-0.08</td>
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<tr>
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</tr>
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<td>0.10</td>
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</tr>
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<td>Parameter</td>
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<td>bTag</td>
<td>cTag</td>
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Table 9.3: The correlations among nuisance parameters from the fit of the $m_H = 110$ GeV case.
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Table 9.4: The correlations among nuisance parameters from the fit of the \( m_H = 150 \text{ GeV} \) case.
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Table 9.5: Expected limits on the branching ratio, $\mathcal{B}(t \to bH^+)$ without a constraint on $\sigma_{t\bar{t}}$. No difference is seen.

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<td>0.026</td>
<td>0.022</td>
<td>0.014</td>
</tr>
<tr>
<td>JER</td>
<td>0.076</td>
<td>0.026</td>
<td>0.022</td>
<td>0.014</td>
</tr>
<tr>
<td>MC</td>
<td>0.078</td>
<td>0.024</td>
<td>0.023</td>
<td>0.014</td>
</tr>
<tr>
<td>PS</td>
<td>0.079</td>
<td>0.026</td>
<td>0.022</td>
<td>0.014</td>
</tr>
<tr>
<td>I/FSR</td>
<td>0.080</td>
<td>0.026</td>
<td>0.023</td>
<td>0.015</td>
</tr>
<tr>
<td>bTag</td>
<td>0.073</td>
<td>0.023</td>
<td>0.021</td>
<td>0.014</td>
</tr>
<tr>
<td>Mtop</td>
<td>0.076</td>
<td>0.025</td>
<td>0.023</td>
<td>0.015</td>
</tr>
<tr>
<td>$\sigma(t\bar{t})$</td>
<td>0.079</td>
<td>0.026</td>
<td>0.022</td>
<td>0.015</td>
</tr>
<tr>
<td>Bkg N</td>
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<td>0.026</td>
<td>0.022</td>
<td>0.015</td>
</tr>
<tr>
<td>STAT</td>
<td>0.027</td>
<td>0.012</td>
<td>0.011</td>
<td>0.010</td>
</tr>
<tr>
<td>STAT+SYST</td>
<td>0.080</td>
<td>0.026</td>
<td>0.023</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Table 9.6: The (N-1) limits are shown, where each systematic item is removed in turn in the fits.

<table>
<thead>
<tr>
<th>Source</th>
<th>90</th>
<th>110</th>
<th>130</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES, bJES, Mtop</td>
<td>0.057</td>
<td>0.025</td>
<td>0.021</td>
<td>0.014</td>
</tr>
<tr>
<td>bTag, $\sigma(t\bar{t})$</td>
<td>0.069</td>
<td>0.024</td>
<td>0.021</td>
<td>0.014</td>
</tr>
<tr>
<td>MC, I/FSR, PS</td>
<td>0.078</td>
<td>0.023</td>
<td>0.022</td>
<td>0.014</td>
</tr>
<tr>
<td>MC, I/FSR, PS, JER</td>
<td>0.063</td>
<td>0.021</td>
<td>0.021</td>
<td>0.014</td>
</tr>
<tr>
<td>STAT</td>
<td>0.027</td>
<td>0.012</td>
<td>0.011</td>
<td>0.010</td>
</tr>
<tr>
<td>STAT+SYST</td>
<td>0.080</td>
<td>0.026</td>
<td>0.023</td>
<td>0.015</td>
</tr>
</tbody>
</table>

Table 9.7: The (N-x) limits are shown where the listed correlated systematic items (x) have been removed from the fits.
Chapter 10

Conclusions

A search for a light charged Higgs boson ($m_{H^+} < m_{top} - m_b$) has been performed using the semi-leptonic decay channel of $t\bar{t}$ events. The charged Higgs boson is assumed to decay hadronically, producing two jets in the detector. The full data set recorded by ATLAS in 2011, which corresponds to an integrated luminosity of 4.7 fb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 7$ TeV, was used in this analysis. No evidence for a charged Higgs boson signal is observed in the data. Therefore, upper limits are set on the branching fraction $\mathcal{B}(t \rightarrow bH^+)$, assuming $\mathcal{B}(H^+ \rightarrow c\bar{s}) = 1$, for Higgs masses of 90 GeV to 150 GeV in 10 GeV steps. The extracted 95% CL limits are between 5% and 1%, depending on $m_{H^+}$.

Semi-leptonic $t\bar{t}$ events, used for this analysis, are characterised by a high $p_T$ lepton (electron or muon), at least 4 jets and a large amount of missing transverse momentum. A set of kinematic event selection criteria is optimised and applied to select semi-leptonic $t\bar{t}$ candidates and reduce background contributions. The event selection criteria include a double $b$-tag requirement, in which at least two of the selected jets are identified to have originated from $b$-quarks. The analysis is also split into two lepton channels by requiring events to have exactly one electron or muon with $p_T > 20$ GeV. The two channels are then re-combined to test the level of agreement between the data and SM expectation.

Several Monte Carlo (MC) samples are used to model the signal and background events. The main background processes include single top production, $W/Z$ boson+jets and QCD multijet events, in addition to the irreducible SM $t\bar{t}$ events. Data-driven methods are used to estimate the QCD multijet background, while other backgrounds are modeled by the MC. Corrections are applied to account for differences between data and MC.

Selected $t\bar{t}$ candidates are fully reconstructed using a $\chi^2$ kinematic fitter to improve the mass resolution of the reconstructed dijet system. A cut of $\chi^2 < 10$
is applied to improve the shape of the dijet mass spectrum. It also reduces the contribution of major non-$t\bar{t}$ backgrounds.

The data is compared with the SM expectation via the reconstructed dijet mass distribution to search for a charged Higgs boson signal. After all cuts, the data contains 15803 double $b$-tagged $t\bar{t}$ candidates. This number agrees with the SM expectation. Furthermore, fits to the dijet mass distribution with templates of a charged Higgs mass from 90 to 150 GeV result in a null Higgs signal. Thus, upper limits are set on the branching ratio $B(t \to bH^+)$. The expected limits including only statistical uncertainties are found to be in the range of 3% to 1% for $m_{H^+}$ varying from 90 GeV to 150 GeV. Inclusion of the systematic uncertainties loosens these limits to the range 8% to 2%.

The extracted limits are dominated by the effect of systematic uncertainties. Studies of these systematic uncertainties have shown correlations between several sources. Due to this correlation the limits would not improve by reducing a single uncertainty.

The observed limits at 95% CL (5% to 1%) are within the two-sigma uncertainty band from the expected limits. These limits are the best limits to date and represent a significant improvement of a factor between 5 to 10, compared to the previous limits on this decay channel ($H^+ \to c\bar{s}$). Since no assumption has been made on the flavour of the quarks in the dijet system, these limits can be used directly for a generic scalar charged boson lighter than the top quark decaying to two jets, where the width of the formed resonance is less than the experimental mass resolution of 12 GeV. The extracted limits are also very similar to the limits obtained by the ATLAS and CMS experiments assuming an alternative 100% decay channel $H^\pm \to \tau\nu$ in $t\bar{t}$ events [64, 65].

A paper outlining the analysis and the corresponding limits on the branching ratio $B(t \to bH^+)$, which have been described in this thesis has recently been published in EPJC [3].
References


[arXiv:hep-ex/1204.2760].

[arXiv:hep-ex/1205.5736].