SEARCH FOR A CHARGED HIGGS BOSON IN PROTON-PROTON COLLISIONS AT THE LHC USING THE ATLAS DETECTOR

BY

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DISSERTATION

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Abstract

This thesis documents several searches for charged Higgs bosons ($H^\pm$) in the decay $H^\pm \rightarrow \tau_{\text{had}} \nu$, which are performed using data recorded in 2011 and 2012 by the ATLAS detector at the LHC. The $H^\pm$ bosons are predicted by some extensions of the Standard Model (SM) that include multiple Higgs doublet fields, such as the Minimal Supersymmetric Standard Model. None of these searches has found evidence for the existence of $H^\pm$, and exclusion limits are set on $B(t \rightarrow H^+b) \times B(H^+ \rightarrow \tau \nu)$ and $\sigma_{H^\pm} \times B(H^+ \rightarrow \tau \nu)$.

For the 2011 ATLAS dataset, searches are performed for light $H^\pm$, defined by $m_{H^\pm} < m_{t\bar{t}}$, on a data sample corresponding to an integrated luminosity of 4.6 fb$^{-1}$ proton-proton collisions with $\sqrt{s} = 7$ TeV. These searches are conducted using the decay channel $t\bar{t} \rightarrow WbH^\pm b$, with $H^\pm \rightarrow \tau_{\text{had}} \nu$ and the $W$ boson decaying hadronically ($\tau$+jets channel) or leptonically ($\tau$+lepton). The combination of the channels in this search excludes at 95% confidence level (CL) a branching fraction of $B(t \rightarrow H^+b) \times B(H^+ \rightarrow \tau \nu) = 1 - 5\%$ for the mass range $m_{H^\pm} = 90 - 160$ GeV.

An additional search, with the aim of observing $H^\pm$ through apparent violation of lepton universality in a ratio of yields, is also performed on this dataset. In this search, the $t\bar{t} \rightarrow t\nu b\tau\nu b\bar{t}$ event yield is compared to that of $t\bar{t} \rightarrow t\nu b\ell\nu b\bar{t}$. The signal would contribute to these yields through $H^\pm$ replacing the $W$ boson in the SM $t\bar{t}$ decay and preferentially decaying to $\tau \nu$. Combining this search with the $\tau$+jets channel results in an improved 95% CL exclusion on the branching fraction of $B(t \rightarrow H^+b) \times B(H^+ \rightarrow \tau \nu) = 0.8 - 3.4\%$ for the mass range $m_{H^\pm} = 90 - 160$ GeV.

For the 2012 ATLAS dataset, searches for an extended mass range of $H^\pm$ are performed on a data sample corresponding to an integrated luminosity of 19.5 fb$^{-1}$ proton-proton collisions at $\sqrt{s} = 8$ TeV. These $H^\pm$ searches are for final states involving a hadronic $\tau$ and jets, both in $t\bar{t}$ decays and top-associated production. For $H^\pm$ with $m_{H^\pm} < m_{t\bar{t}}$, 95% CL limits are set on $B(t \rightarrow H^+b) \times B(H^+ \rightarrow \tau \nu)$ of 0.3 - 2.4\% in a mass range of $m_{H^\pm} = 90 - 160$ GeV. For $H^\pm$ with $m_{H^\pm} > m_{t\bar{t}}$, 95% CL limits are set on $\sigma_{H^\pm} \times B(H^+ \rightarrow \tau \nu)$ of 0.03 - 0.8 pb, for a mass range of $m_{H^\pm} = 180 - 600$ GeV.
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B.2 Distributions of a selection of identification variables for background di-jet events selected from 2011 data and simulated $Z \to \tau\tau$ and $W \to \tau\nu$ signal events. The distribution are scaled to unity.
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<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>2HDM</td>
<td>Two Higgs Doublet Model</td>
</tr>
<tr>
<td>4FS</td>
<td>Four-Flavor Scheme</td>
</tr>
<tr>
<td>5FS</td>
<td>Five-Flavor Scheme</td>
</tr>
<tr>
<td>ALICE</td>
<td>A Large Ion Collider Experiment</td>
</tr>
<tr>
<td>AM</td>
<td>Associative Memory</td>
</tr>
<tr>
<td>ATLAS</td>
<td>A Toroidal LHC Apparatus</td>
</tr>
<tr>
<td>BDT</td>
<td>Boosted Decision Tree</td>
</tr>
<tr>
<td>CERN</td>
<td>Originally “Conseil Européen pour la Recherche Nucléaire”, now generally referred to as “The European Organization for Nuclear Research”</td>
</tr>
<tr>
<td>CL</td>
<td>Confidence Level</td>
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<tr>
<td>CMS</td>
<td>Compact Muon Solenoid</td>
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<tr>
<td>CR</td>
<td>Control Region</td>
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<td>FastTracker</td>
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<tr>
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<td>Inner Detector</td>
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<tr>
<td>JVF</td>
<td>Jet Vertex Fraction</td>
</tr>
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<td>LEP</td>
<td>Large Electron-Positron Collider</td>
</tr>
<tr>
<td>LINAC2</td>
<td>Linear Accelerator 2</td>
</tr>
<tr>
<td>LHCb</td>
<td>Large Hadron Collider beauty experiment</td>
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<tr>
<td>LHC</td>
<td>Large Hadron Collider</td>
</tr>
<tr>
<td>MSSM</td>
<td>Minimal Supersymmetric Standard Model</td>
</tr>
<tr>
<td>OS</td>
<td>Opposite Sign</td>
</tr>
<tr>
<td>PS</td>
<td>Proton Synchrotron</td>
</tr>
<tr>
<td>ROB</td>
<td>ReadOut Buffer</td>
</tr>
<tr>
<td>ROD</td>
<td>ReadOut Driver</td>
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<td>SCT</td>
<td>Semiconducter Tracker</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>SM</td>
<td>Standard Model of particle physics</td>
</tr>
<tr>
<td>SPS</td>
<td>Super Proton Synchrotron</td>
</tr>
<tr>
<td>SS</td>
<td>Same sign</td>
</tr>
<tr>
<td>TRT</td>
<td>Transition Radiation Tracker</td>
</tr>
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</table>
List of Symbols

\( \hbar c \)  Natural units, where this \( = 1 \) and is not explicitly shown, are used in this thesis.

\( \tau \)  The third-generation lepton, decaying into hadrons for the scope of this thesis. Any reference to leptonically decaying \( \tau \) leptons will explicitly noted.

\( H^\pm \)  Charged Higgs boson.

\( p_T \)  Transverse momentum.

\( m_T \)  Transverse mass.

\( \eta \)  Pseudorapidity.

\( \phi \)  Azimuthal angle.

\( \Delta R \)  Spatial separation in \( \eta-\phi \) space.

\( E_T^{\text{miss}} \)  Missing transverse energy.
Chapter 1

Introduction

The Standard Model (SM) of particle physics has been extensively tested in the past decades, through analysis of data collected at many experiments. Though the SM has been very successful at predicting experimental data, there are still some questions that it does not resolve. In order to resolve a number of these open questions, one can consider models with extended Higgs sectors. The simplest extension of the SM Higgs sector is a Two Higgs Doublet Model (2HDM), which describes the Higgs sector of the Minimal Supersymmetric Standard Model (MSSM). In this model, there are five Higgs bosons, three of which are neutral and 2 of which are charged. This thesis details several searches for a charged Higgs boson ($H^\pm$) decaying into a hadronically-decaying $\tau$ lepton and neutrino using the ATLAS detector at the LHC.

The theoretical framework and motivation for the search for $H^\pm$ is described in more detail in Chapter 2. Chapter 3 describes the LHC and the ATLAS detector, as well as describing in detail the trigger system of the ATLAS detector and a proposed update called the FastTracKer (FTK). The data and simulation used for $H^\pm$ searches, in addition to object selection and some event preselection, are described in Chapter 4. The searches for $H^\pm$ decaying to a $\tau$ and neutrino are described in Chapter 5. The data-driven techniques used to estimate many background contributions are detailed in Chapter 6. Systematic uncertainties and comparisons between results predicted for the Standard Model and those observed in data are shown in Chapter 7, and analysis limit techniques are addressed in more detail in Chapter 8. A summary of the final conclusions are stated in Chapter 9, along with some discussion of the future prospects of the channel.

This thesis documents analyses that can be found in two publications, as well as a current analysis on the full 2012 ATLAS dataset. The first publication is for a light ($m_{H^\pm} < m_{top}$) $H^\pm$, with 4.6 fb$^{-1}$ of total integrated luminosity, and it can be found in the Journal of High Energy Physics[12]. The second publication, which uses 4.6 fb$^{-1}$ of total integrated luminosity to search for a light $H^\pm$ through apparent violation of lepton universality, can also be found in the Journal of High Energy Physics[13]. The final analysis, which searches for $H^\pm$ with $m_{H^\pm}$ both greater than and less than $m_{top}$, uses the full 2012 dataset of 19.5 fb$^{-1}$. This thesis also draws from several ATLAS internal notes [11, 8, 10, 9].
The field of particle physics is always striving to improve the understanding of the universe through the study of elementary particles and their interactions. The Standard Model (SM) represents our current best understanding of particle physics. The SM predictions of particle properties and interactions have been tested and validated to high precision across a wide range of energies by many experiments. However, there are still many questions in particle physics that have yet to be satisfactorily resolved, and many models have been suggested to modify the SM in a way to explain these issues. Therefore, an important part of experimental particle physics involves probing areas that might indicate the existence of processes beyond the SM.

This chapter provides an outline of the SM and points to questions that are, as of yet, unresolved. Also included are descriptions of an extended Higgs sector model known as a Two Higgs Doublet Model (2HDM) and a common extension of the SM that includes a 2HDM Higgs sector, called the Minimal Supersymmetric Standard Model (MSSM). The charged Higgs boson \( H^\pm \) and hadronically decaying \( \tau \) leptons, which are a dominant decay mode of \( H^\pm \) in many scenarios, are then discussed. Lastly, the results from previous experiments are summarized, and the implications for \( H^\pm \) from the recent discovery of a boson with a mass of 126 GeV are considered.

2.1 Standard Model

The SM is a quantum field theory that has very successfully described all elementary particles as well as three of the four fundamental forces (electromagnetic, strong, and weak) that govern their interactions [14]. The fourth fundamental force, gravity, is much weaker (by approximately 40 orders of magnitude, relative to the strong force), and is not expected to contribute in a meaningful way to any of the physical processes described in this thesis.

The SM is based in the gauge symmetry group \( G_{SM} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \). The gauge group \( SU(3)_C \) corresponds to the strong interaction, in which color charge (C) is conserved. The gauge group
<table>
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Table 2.1: Observed properties of the fermions and gauge bosons of the SM [1].

$SU(2)_L \otimes U(1)_Y$ corresponds to the electroweak symmetry, where the subscripts refer to the weak (L)eft-handed isospin $T$ (or more accurately, its third component, $T_3$) and the hypercharge $Y$. These quantities are related to the electric charge $Q$, which is also conserved, through the Gell-Mann–Nishijima relation:

$$Q = \frac{Y}{2} + T_3.$$

The elementary particles are representations of the symmetry group $G_{SM}$, and they are separated into fermions, which constitute matter, and bosons, which mediate interactions. Fermions have half-integer spin and obey Fermi-Dirac statistics, while bosons have integer spin and obey Bose-Einstein statistics. There are twelve fundamental fermions—six leptons and six quarks—and each has a corresponding anti-particle of opposite charge. The leptons interact through the electroweak force, while the quarks can interact through both the electroweak and strong force. The fermions and gauge bosons are listed in Tab. 2.1, with their masses, charge, and the forces by which they interact.

In weak isospin $SU(2)_L$ transformations of fermions, particles that exist as a chirality eigenstate with eigenvalue of $-1$ (left-handed particles) are doublets of the group, and particles that exist as a chirality eigenstate with eigenvalue of $+1$ (right-handed particles) are singlets. However, neutrinos with positive chirality eigenvalues have not been observed experimentally [15], so they are listed here only within left-handed doublets of $SU(2)_L$. Leptons and quarks exist in three generations, shown here grouped in left-handed weak isospin doublets:

$$
\begin{pmatrix}
\nu_e \\
e
\end{pmatrix}_L,
\begin{pmatrix}
\nu_\mu \\
\mu
\end{pmatrix}_L,
\begin{pmatrix}
\nu_\tau \\
\tau
\end{pmatrix}_L
$$

(2.1)
The right-handed singlets appear as \((e)_R, (\mu)_R, (\tau)_R\) for the leptons, and \((u)_R, (d)_R, (c)_R, (s)_R, (t)_R, (b)_R\) for the quarks.

In addition to electric charge, quarks also have a property called color charge, and their anti-particles carry a corresponding anti-color property. Quarks are confined to composite colorless states called hadrons, which include mesons (quark-antiquark states) and baryons (three quark states). An interesting exception to this is the top quark, which can only be produced at the high energies found in particle accelerators or the upper atmosphere. Due to the extremely high mass of the top quark, its lifetime is very short \((5 \times 10^{-25}\) s), so it does not have time to form hadrons before decaying via the weak force. In the SM, the top quark decays almost always into a \(W^\pm\) boson and a \(b\) quark.

Spin 1 elementary particles called gauge bosons are the mediators of the fundamental interactions. The photon \((\gamma)\) and three vector bosons \((W^\pm\) and \(Z)\) are mediators of the electromagnetic and weak forces, respectively, while gluons \((g)\) are mediators of the strong force. The coupling of leptons to the weak gauge bosons \((W^\pm\) and \(Z)\) are flavor-independent, so the weak gauge bosons have lepton universality, meaning the bosons’ branching fractions to each of the three flavors of leptons are equal.

### 2.2 The Higgs Mechanism

The gauge invariance of \(SU(2)_L \otimes U(1)_Y\) requires that the weak bosons and fermions are massless, but it is known experimentally that weak bosons are massive (see Tab. 2.1). The simplest solution to this problem, which is the mechanism in the SM, is known as the Higgs mechanism [16].

Consider a complex scalar boson \(\phi\) and massless gauge boson \(A^\mu\). The Lagrangian density will have the form

\[
\mathcal{L}_\phi = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + (D^\mu \phi)^* D^\mu \phi - V(\phi).
\]

Here \(F^{\mu\nu}\) is the antisymmetric tensor of the gauge boson field \(F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu\), and \(D^\mu\) is the covariant derivative, \(D^\mu = \partial^\mu - ig A^\mu\), where \(g\) is a coupling constant. The potential \(V(\phi)\) is defined as

\[
V(\phi) = -\mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2.
\]
This theory is invariant under a local gauge transformation, defined as

\[ \phi \rightarrow \phi' = e^{ig\chi(x)} \phi \]

and then

\[ A^\mu \rightarrow A'^\mu = A^\mu - \partial^\mu \chi(x). \]

The potential has a minimum for \( \phi = \sqrt{\mu^2/2\lambda} \equiv v/\sqrt{2} \). If one expands \( \phi \) around this non-zero vacuum expectation value as follows,

\[ \phi = [v + h(x)]/\sqrt{2}, \]

with \( h(x) \) as a real field, one obtains

\[ \mathcal{L}_\phi = \frac{1}{2} \left[ D_\mu(v + h(x)) D^\mu(v + h(x)) \right] + \frac{1}{2} \mu^2(v + h(x))^2 - \frac{1}{4} \lambda (v + h(x))^4 - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}. \]

While the original Lagrangian is symmetric around \( \phi = 0 \), the expansion around the vacuum expectation value no longer shares this symmetry. This is known as spontaneous symmetry breaking, and the following manipulation of the Lagrangian shows the mass terms for the gauge boson and the scalar boson of the theory.

\[ \mathcal{L}_\phi = \frac{1}{2} (\partial_\mu - igA_\mu)(v + h(x))(\partial^\mu + igA^\mu)(v + h(x)) + \frac{1}{2} \mu^2(v + h(x))^2 - \frac{1}{4} \lambda (v + h(x))^4 - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \]

\[ = \frac{1}{2} (\partial_\mu h(x))^2 + \frac{g^2 v^2}{2} A_\mu A^\mu - \lambda v^2 (h(x))^2 - \frac{1}{4} \lambda (h(x))^4 - \lambda v (h(x))^4 + \frac{1}{4} \lambda v^4 - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \]  

(2.3)

In this Lagrangian, the term \( \frac{g^2 v^2}{2} A_\mu A^\mu \) can be interpreted as a mass term for the gauge boson, and \( \lambda v^2 (h(x))^2 \) can be interpreted as the mass term for the scalar boson. Through the non-zero vacuum expectation value, this theory with a complex scalar boson and a massless gauge boson has been reinterpreted as a theory with a real scalar boson and a massive gauge boson.

In the case of the SM, the gauge fields and the coupling constants of the group \( SU(2)_L \otimes U(1)_Y \) are \( W_\mu^i \), \( B_\mu \), and \( g, g' \), respectively. The electroweak Lagrangian (\( \mathcal{L}_{EW} \)) can be written as:

\[ \mathcal{L}_{EW} = -\frac{1}{4} W_{\mu\nu} W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \bar{\psi} i \gamma^\mu D_\mu \psi \]

(2.4)

where the Yang–Mills and Maxwell tensors are

\[ W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu - g W_\mu \times W_\nu \quad \text{and} \quad B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \]
and the covariant derivative is defined, in this case, as

$$D_\mu = \partial_\mu + ig W_\mu T + \frac{1}{2} ig' B_\mu Y.$$  

Here \( Y \) is the generator of the \( U(1)_Y \) group and \( T \) are the generators of the \( SU(2)_L \) group, which are equivalent to half of the non-commuting 2 \( \times \) 2 Pauli matrices. The complex scalar field of the theory is an \( SU(2) \) doublet of the form

$$\phi = \begin{pmatrix} \phi^0 \\ \phi^1 \end{pmatrix}$$

with a weak hypercharge \( Y = +1 \). This doublet field can be introduced into the electroweak Lagrangian as

$$\mathcal{L}_{\text{scalar}} = (D_\mu \phi)^\dagger D^\mu \phi + \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2.$$  

Minimizing the Lagrangian as in the previous case, there is a non-zero vacuum expectation value for the scalar field of

$$\langle \phi \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix},$$

where \( v = \sqrt{-\mu^2/2|\lambda|} \). Expanding around the minimum of the potential of the electroweak Lagrangian results in three massive gauge bosons (\( W^\pm, Z \)) and one massive Higgs boson. The mass of the Higgs boson relies on both \( v \) and \( \lambda \). While \( v \) is determined by the \( W \) boson mass, there is no way to determine \( \lambda \) without experimental information. Thus, the Higgs sector is a highly important area of experimental research, to either confirm the SM prediction or discover new physics.

### 2.3 Beyond the SM

While the SM has been very successful at describing most experimental data, there are indications that it may not be the whole story. The weaknesses of the SM become apparent through various unresolved issues. These include the fact that the basic SM does not incorporate neutrino masses, incorporate the gravitational force, nor explain the pattern of fermion masses. It also has three problems that require new physics: the gauge coupling problem, the lack of a dark matter candidate, and the fine tuning problem [17]. These last three issues will now be considered in more detail.

As discussed previously, the SM is based on a \( SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \) gauge symmetry, which is a product of three different groups with different coupling constants. Since this is not a complete unification,
it seems that there should be a more fundamental symmetry, such as SU(5) or SO(10), which would describe the three forces within a single gauge group with one coupling constant [18]. However, the strengths of the coupling constants in the SM fail to meet at a common point as energy increases [19], so there is not a clear way to achieve this unification.

Dark matter is also unexplained by the SM. In 1932, astrophysicists observed that $\sim 4\%$ of the total energy density of the universe consisted of baryonic matter [20]. Now, it appears that nearly $25\%$ of the energy density is due to dark matter, and the remainder is referred to as dark energy. One possible explanation for the lack of observation of dark matter is that it is composed of a stable or long-lived cold [21] particle that does not interact through strong or electromagnetic forces. However, this particle does not correspond to any particle in the SM, so it requires some kind of extension of the model.

The fine-tuning problem is related to the hierarchy problem, and the large difference between the electroweak and Planck energy scales. At the electroweak scale, the SM Higgs boson mass is expected to be on the same order of magnitude as the $W$ and $Z$ bosons. However, a calculation of the first-order correction to the Higgs boson mass squared gives a quadratically divergent expression arising from the quantum loop corrections. Therefore, if one sets the cut-off, beyond which the theory is no longer valid, at the Planck energy scale, this quadratically divergent term will cause the Higgs boson to take on a mass close to the Planck scale, rather than the electroweak scale. To prevent this, an unnatural fine adjustment of parameters must be performed, so that these divergent terms will cancel. While this can be accomplished mathematically, it would be preferable to have a physical motivation for the cancellation.

Many extensions to the SM have been proposed in an attempt to solve these and other problems. This thesis will focus on a specific extension of the Higgs sector known as the 2HDM [22] and a particular extension of the SM that utilizes this form of Higgs sector, the MSSM [23].

### 2.4 Two Higgs Doublet Models and the Minimal Supersymmetric Standard Model

The simplest extension of the SM Higgs sector is a 2HDM, in which the Higgs sector contains one additional scalar doublet field. In 2HDMs, the Higgs fields can be written with $i = 1, 2$ as

$$
\phi_i = \begin{pmatrix} \phi_i^0 \\ \phi_i^\dagger \end{pmatrix}.
$$
The 2HDM is predicted in multiple beyond SM scenarios, including Little Higgs [24] and the MSSM, so it is desirable for searches for 2HDM observables to present results in a way that is not dependent on a specific model. In this thesis, the results of the search will be stated both in a relatively model independent way, and in terms of the parameter space of an MSSM scenario.

The most general $SU(2)_L \otimes U(1)_Y$ invariant Lagrangian for a 2HDM can be written in the form

$$\mathcal{L}_{2HDM} = \mathcal{L}_\phi + \mathcal{L}_{SM} + \mathcal{L}_{Yukawa}.$$ 

Here $\mathcal{L}_{SM}$ describes the SM interactions of fermions and gauge bosons, and $\mathcal{L}_{Yukawa}$ describes the Yukawa interactions of fermions with Higgs scalars. The 2HDM Higgs Lagrangian is $\mathcal{L}_\phi$, which takes the usual form

$$\mathcal{L}_\phi = \sum_{i=1,2} (D_\mu \phi_i) (D^\mu \phi_i^\dagger) - V(\phi_1, \phi_2).$$

In this case, the covariant derivative is defined as in the SM in Equation 2.2. Because the Higgs fields are weak isodoublets with hypercharge $Y = \pm 1$, the model satisfies $\rho = \frac{m_W}{m_W^2/m_Z^2} = 1$ at tree level, which is an experimentally determined quantity [25]. To discuss the general properties of a 2HDM, two Higgs doublet fields of $Y = +1$ will now be considered. The most general Higgs potential for this 2HDM is written as:

$$V(\phi_1, \phi_2) = \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 + \frac{1}{2} \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2)$$

$$+ \frac{1}{2} \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \frac{1}{2}[\lambda_5 (\phi_1^\dagger \phi_1)^2 + h.c.]$$

$$+ \{[\lambda_6 (\phi_1^\dagger \phi_1) + \lambda_7 (\phi_2^\dagger \phi_2)](\phi_1^\dagger \phi_2) + h.c.]$$

$$- \frac{1}{2} \{m_{11}^2 (\phi_1^\dagger \phi_1) + m_{12}^2 (\phi_1^\dagger \phi_2) + h.c.] + m_{22}^2 (\phi_2^\dagger \phi_2)\}$$

(2.5)

where $\lambda_1, \lambda_2, \lambda_3, \lambda_4, m_{22}^2$, and $m_{11}^2$ are real parameters, while $\lambda_5, \lambda_6, \lambda_7$, and $m_{12}^2$ can be complex parameters, making a total of 14 free parameters.

This potential is responsible for the electroweak symmetry breaking of the model, which proceeds similarly to the case for the SM. The symmetry breaking provides the masses of the gauge bosons, but it also provides the masses of five physical Higgs bosons. In the charged sector, there are two bosons $H^\pm$; in the CP-odd sector, there is a neutral boson $A^0$; in the CP-even sector, there are two additional neutral bosons $H^0$ and $h^0$. In addition to predicting five Higgs bosons instead of the one expected by the SM, the 2HDM potential is not unique. For example, different sets of parameters in the potential can produce different mass eigenstates, interactions, and Feynman rules. For this reason, it is often useful to define a particular version of the 2HDM.
One case of a 2HDM that is of particular interest in this thesis is the Higgs sector of the MSSM. Supersymmetric models, such as the MSSM, predict the existence of a superpartner for every known particle, differing by $1/2$ unit of spin. In order for the superpartners to be of high enough mass to have not yet been observed, supersymmetry has to be a broken symmetry.

Supersymmetric extensions of the SM are especially attractive due to their resolution of many of the remaining problems in the SM. Supersymmetry changes the slope of the coupling constants’ dependence on energy, so that the different coupling constants converge at an energy of around $10^{16}$ GeV [26]. In supersymmetry, the quadratic divergence on the Higgs mass corrections is naturally canceled by related loop graphs involving the superpartners of SM particles [27]. Furthermore, supersymmetric models include possible candidates for dark matter particles, such as the lightest supersymmetric particle [28].

The simplest supersymmetric extension of the SM is the MSSM. The MSSM utilizes a specific kind of 2HDM known as a type-II 2HDM, which has two fields of opposite hypercharge ($Y$). In the Higgs potential of Equation 2.5, the MSSM requires $\lambda_1 = \lambda_2 = -2\lambda_3$ and $\lambda_5 = \lambda_6 = \lambda_7 = 0$. In a type-II 2HDM, up-type leptons and quarks couple with the $Y=1$ doublet, while down-type leptons and quarks couple with the $Y=-1$ doublet. This coupling of up- and down-type fermions to separate doublets is necessary to preserve the suppression of flavor changing neutral currents, which have not been observed experimentally [29].

The MSSM has a large number of unknown parameters, so it is generally necessary to impose a number of constraints and consider specific scenarios that are of interest. Specifically, benchmark scenarios are constrained to the point that the Higgs sector can be fully described by two parameters, one of the Higgs boson masses (taken to be $m_{H^\pm}$ for the searches in this thesis) and the parameter $\tan \beta = v_2/v_1$, defined as the ratio of the vacuum expectation values of the two Higgs doublet fields. The standard benchmark scenario for ATLAS searches has been the $m_h$-max scenario of the MSSM. In the $m_h$-max scenario, the parameters of the MSSM are set so that the mass of $h^0$ takes on its maximal value as a function of $\tan \beta$. 

Figure 2.1: Example of leading-order Feynman diagrams for the production of $H^\pm$ at masses below (the left diagram) and above (the two right diagrams) the top quark mass.
Figure 2.2: Theoretical production cross sections for light $H^\pm$ from $t\bar{t}$ decays, as a function of $m_{H^\pm}$ [2].

### 2.5 Production and Decay of Charged Higgs Bosons ($H^\pm$)

The production and decay properties of $H^\pm$ depend on its mass. Two separate cases are defined: a light $H^\pm$, with $m_{H^\pm} < m_{top}$, and a heavy $H^\pm$, with $m_{H^\pm} > m_{top}$. The Feynman diagrams of the dominant production modes of both the light and heavy $H^\pm$ at the LHC are shown in Fig. 2.1. The heavy $H^\pm$ can also be produced through a quark-antiquark production mode, but this mode is negligible in comparison with $gg$ and $gb$.

The light $H^\pm$ is dominantly produced through $t\bar{t}$ decays, where a top quark decays into a $H^\pm$ and $b$ quark instead of the $W$ boson and $b$ quark expected in the SM. As a result, the expected production cross section of $t\bar{t}$ decaying via SM processes is reduced by the presence of $H^\pm$ production.

The heavy $H^\pm$ is dominantly produced in association with a top quark. The two diagrams shown for heavy $H^\pm$ are not truly independent, but they represent two different ways of ordering perturbation theory. The two schemes for calculating the production are called the 4-flavor scheme (4FS) and the 5-flavor scheme (5FS). In the 4FS, one does not consider $b$ quarks as partons in the proton, so the lowest order process is $gg(q\bar{q}) \rightarrow tH^\pm b$. In the 5FS, $b$ quarks are considered as partons in the proton for the calculation. The cross sections of the two processes are combined using a method called Santander matching, which is described in [30].

The theoretical production cross sections are shown in Fig. 2.2 for the light $H^\pm$ production through $t\bar{t}$, which increases with increasing $\tan\beta$ [2]. In Fig. 2.3, the theoretical production cross sections are shown for the top-associated production of the heavy $H^\pm$. The cross sections shown in Fig. 2.3 are both split by flavor scheme and combined.
Theoretical production cross sections for the heavy $H^\pm$ produced with an associated top quark, as a function of $m_{H^\pm}$, in collisions with $\sqrt{s} = 8$ TeV. This plot is an updated version of those found in [2].

Figure 2.4: Decay modes of $H^\pm$, as a function of $m_{H^\pm}$, in the $m_h$-max scenario of the MSSM. Shown are the branching ratios for $\tan \beta = 1$ (left) and $\tan \beta = 35$ (right) [2].

The branching fractions for $H^\pm$ decay as a function of $m_{H^\pm}$ are shown in Fig. 2.4 for two different values of $\tan \beta$ (1 and 35) in the $m_h$-max scenario of the MSSM. At high $\tan \beta$, $H^\pm$ continues to have a sizable branching ratio to a $\tau$ lepton and neutrino, even at masses higher than a top quark. In this thesis, the focus is exclusively on the decay of $H^\pm$ to a $\tau$ lepton and neutrino, where the $\tau$ lepton decays hadronically. As the hadronically-decaying $\tau$ lepton is central to the searches described in this thesis, the particle will now be considered in more detail.

2.5.1 Hadronic Decays of $\tau$ Leptons

With a mass of $1776.82 \pm 0.16$ MeV, the third-generation $\tau$ lepton is the only lepton that can decay into both hadrons or another lepton and neutrinos. Approximately 35% of the time, the $\tau$ lepton decays into an
electron or muon, and it decays into charged mesons (usually π mesons) the rest of the time. The branching ratios are shown in Fig. 2.5.

The hadronic decays of τ leptons can be classified based on the number of charged hadrons that are produced in the decay. Hadronically-decaying τ leptons typically decay into one or three charged hadrons, which are referred to as 1-prong and 3-prong decays, respectively. Additional neutral π⁰ particles may also be present in the decay. This decay signature is quite similar to that of jets of hadrons, as is shown in Fig. 2.6. The extremely large production cross section of multi-jet events at the ATLAS detector make these jets a major background for searches involving hadronically-decaying τ leptons.

In trigger and offline algorithms, low track multiplicity and collimated, isolated energy deposits in the calorimeters are used to separate hadronically-decaying τ leptons from hadronic jets. Electrons, or even muons with mis-attributed calorimeter energy deposits, can also look quite similar to hadronically-decaying τ leptons with single charged tracks. A major focus of the analyses contained within this thesis is the challenge of distinguishing hadronic τ lepton decays from their backgrounds.

2.6 Current Constraints on $H^\pm$

2.6.1 Direct Collider Searches

Before the limits on $H^\pm$ production from experiments at the LHC, the leading direct exclusion limits were from LEP and the Tevatron. For a type-II 2HDM with the assumption of $\text{BR}(H^+ \to \tau \nu) = 1$, the combined LEP lower limit for the $H^\pm$ mass is about 94 GeV [31]. At the Tevatron, no evidence was found for $H^\pm$ production in $p\bar{p}$ collisions, and the Tevatron experiments placed upper limits in the 15–20% range on $\text{BR}(t \rightarrow bH^\pm)$ for light $H^\pm$ production [32, 33]. The D0 experiment at the Tevatron $p\bar{p}$ collider has
also conducted a search for a heavy $H^\pm$ with mass from 180-300 GeV in the $H^+ \rightarrow tb$ decay channel and interpreted this result in various 2HDM [34].

Searches for light $H^\pm$ have been conducted at the LHC by both CMS [35] (2fb$^{-1}$, $\sqrt{s} = 7$ TeV) and ATLAS [12, 13] (4.7fb$^{-1}$, $\sqrt{s} = 7$ TeV) Collaborations using the $\tau\nu$ final state. Neither experiment found evidence for a light $H^\pm$ in their data samples. Upper limits on $B(t \rightarrow H^+ b) \times B(H^+ \rightarrow \tau\nu)$ were set at 95% confidence level (CL) at the level of 0.8-3.4% for masses between 90 – 160 GeV. The two searches referenced from ATLAS are, in fact, the topic of this thesis, as well as a search for a light or heavy $H^\pm$ in $\sqrt{s} = 8$ TeV data collisions, in ATLAS. A search in the $H^\pm \rightarrow c\bar{s}$ channel has also been performed (4.7 fb$^{-1}$, $\sqrt{s} = 7$ TeV), and an upper limit was set on $B(t \rightarrow H^\pm b) \times B(H^\pm \rightarrow c\bar{s})$ of 1-5 %, for masses of 90-150 GeV. [36]

2.6.2 Indirect Constraints

Indirect limits have also been published by studies in cosmology and $b$-physics, though these limits are model-dependent and may be circumvented by beyond SM effects. Results from $b$ flavor physics have now placed a limit of $m_{H^\pm} > 316$ GeV for a type-II 2HDM, irrespective of tan$\beta$ [37]. This result combines leptonic and semileptonic tree-level flavor-changing decays, as well as loop processes ($b \rightarrow s\gamma$, $B\bar{B}$ mixing or $Z \rightarrow b\bar{b}$). From cosmology, constraints from the CDMS-II and XENON100 dark matter direct detection searches rule out large areas of parameter space for some MSSM scenarios [38].

2.6.3 New Boson Discovery

In 2012, the ATLAS and CMS Collaborations announced the discovery of a particle with properties that resemble those of a SM Higgs boson and a mass close to 126 GeV [39, 40]. This discovery opens the question of whether or not this particle is part of an extended Higgs sector. Such a particle is predicted in many extensions of the SM Higgs sector, such as the 2HDM, of which the MSSM as a particular example. In fact, the observed particle can be compatible with the MSSM under the assumption that it is identified with one
Figure 2.7: The $m_{H^\pm}$-$\tan\beta$ plane in the $m_{h}\text{-max}$ scenario, with excluded regions from direct Higgs searches at LEP (blue), and the LHC (solid red); the dotted (lighter) red region is excluded by LHC searches for a SM-like Higgs boson. The two green shades correspond to the parameters for which $M_h = 125.5 \pm 2(3)$ GeV [3].

of the neutral MSSM Higgs bosons [41]. For the $m_{h}\text{-max}$ scenario of the MSSM, there is still an accessible region within which the existence of a heavy $H^\pm$ remains a possibility, when the new boson is identified with the lightest neutral Higgs. This available parameter space is shown in the green band of Fig. 2.7 [3].
Chapter 3

Experimental Apparatus

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is a proton-proton collider at the CERN laboratory, and it is currently the world’s highest energy particle accelerator. Since the first CERN particle accelerator was started up over fifty years ago, a number of accelerators have been constructed at CERN. Some of these accelerators are now being used to provide particle beams for the Large Hadron Collider (LHC). Many experiments and accelerators at CERN, and the paths of particles moving between them, are shown in Figure 3.1, along with the date of construction and circumference, where applicable. Protons are initially accelerated by the LINAC2, from which they move through the Proton Synchrotron Booster, the Proton Synchrotron (PS), the Super Proton Synchrotron (SPS), and finally arrive at the LHC ring. The underground LHC tunnel has a circumference of 27 km, and straddles the border between Switzerland and France. It is composed of eight straight sections of tunnel, which are the access points and collision points for detectors, and eight curved sections.

The LHC first saw beam on September 10th, 2008, but was subsequently shut down for technical intervention until November 2009. First collisions arrived at March 30th, 2010, but the rest of the 2010 run was mainly for commissioning purposes. During 2011, an integrated luminosity of 5.61 fb\(^{-1}\) at an energy of \(\sqrt{s} = 7\) TeV was produced for physics analyses. A run at the higher center-of-mass energy of 8 TeV was completed during the year of 2012, delivering an integrated luminosity of 23.3 fb\(^{-1}\). At the end of 2012, the LHC reached the design specified bunch spacing of 25 ns, and it is expected to reach the design specification of 14 TeV center-of-mass energy after the long technical shutdown that began in 2013.

There are four large experiments at the LHC: ATLAS, CMS, LHCb and ALICE. ATLAS and CMS are general purpose detectors, LHCb studies \(b\)-physics and probes CP-violation, and ALICE is focused on studying quark-gluon plasma through heavy ion collisions. The analyses for this thesis were conducted using collisions recorded by the ATLAS detector.
Figure 3.1: Particle accelerators and experiments at CERN. The dates correspond to the date of construction, and the circumferences are also marked for ring accelerators (Image courtesy of CERN).
3.2 The ATLAS Detector

ATLAS stands for **A** **T**oroidal **L**HC **A**pparatus. The ATLAS experiment is a global collaboration of approximately 3,000 scientists and engineers from 174 institutions located in 38 countries. The ATLAS detector (described in [42]) is located in an underground cavern at the LHC. It is 46 meters long, 25 meters high, 25 meters wide, and weighs 7,000 tonnes. It is a general purpose detector, so it is designed to be able to detect as broad of a range of signals as possible. The detector (shown in Fig. 3.2) can be broken down into three basic subdetector systems: the inner detector, the calorimeters (electromagnetic and hadronic), and the muon spectrometer.

The ATLAS superconducting magnet system consists of a central solenoid and a toroidal system that has both barrel and end-cap components. The central solenoid provides a magnetic field of 2 tesla to curve the paths of charged particles in the inner detector. The toroidal system consists of 8 superconducting barrel loops and two end-caps, which are located in between the calorimeters and the muon spectrometer. It provides a magnetic field of 4 tesla, which curves the paths of charged particles in the muon spectrometer.

Fig. 3.3 shows how these different subsystems contribute to the detection of different elementary particles. Charged particles are detected by the inner detector, where the curve imparted by the magnetic field to their tracks provides information about the particles’ momentum. Electrons and photons are expected to be completely absorbed in the electromagnetic calorimeter, while only a fraction of the energy of other charged particles is absorbed. Hadrons are absorbed by the hadronic calorimeter, and muons are the only detectable particles that pass through to the muon spectrometer. Neutrinos are not detected by ATLAS, and are
inferred through the missing energy in the event, calculated through energy conservation in the transverse plane relative to the beamline.

An understanding of the ATLAS coordinate system is required for discussion of the detector and relevant physics analyses. In this coordinate system, the proton beams travel along the z-axis, and the x-y plane is transverse to the beam direction. The positive x-axis points towards the center of the LHC ring, and the positive y-axis points upwards. The azimuthal angle $\phi$ is measured around the beam axis, while the polar angle $\theta$ is measured from the beam axis. Two quantities measured from these coordinates are often used in descriptions; the pseudorapidity $\eta = -\ln(\tan(\theta/2))$ and the distance in pseudorapidity-azimuthal angle space, $\Delta R = \sqrt{\phi^2 + \eta^2}$.

### 3.2.1 Inner Detector

The inner detector consists of three subdetectors that cover a range of $|\eta| < 2.5$. The innermost subdetector consists of three layers of pixel detectors. This subdetector is designed to give very high-granularity, high-precision measurements close to the interaction point. Due to its usefulness in finding short-lived particles, such as $b$-hadrons, the innermost pixel layer is referred to as the “B-layer”. The second subdetector is the SemiConductor Tracker (SCT), which consists of eight layers of silicon microstrip detectors. The SCT con-
tributes to measurement of momentum, impact parameter, and vertex position. The outermost subdetector of the inner detector is the Transition Radiation Tracker (TRT). This subdetector consists of straws that contain xenon gas isolating a sense wire, which detect transition-radiation photons.

### 3.2.2 The Calorimeters

The ATLAS calorimeters, located outside of the inner detector and solenoidal magnet, provide coverage up to $|\eta| < 4.9$. The calorimeters can be discussed in terms of the inner electromagnetic (EM) calorimeters and the outer hadronic calorimeters, with specially designed forward calorimeters to handle particles at very high values of $|\eta|$. The EM calorimeter system absorbs energy from charged particles and photons, which interact through the EM force. The calorimeter consists of lead and liquid argon, with accordion-shaped Kapton electrodes. The lead in the calorimeter is the energy-absorbing material, and liquid argon is the sampling material. The accordion geometry allows the calorimeter to cover the complete azimuthal range without cracks. However, at the boundary between the barrel and end-cap electromagnetic calorimeters, the thickness of material in front of the calorimeter results in lower performance. As a result, the region from $1.37 < |\eta| < 1.52$ is not used for physics measurements involving photons. Beyond this lower performance region, the electromagnetic calorimeter provides coverage up to $|\eta| < 3.2$.

The hadronic calorimeter system absorbs energy from particles that have passed through the EM calorimeter, and interact through the strong force. The main hadronic calorimeter is the tile calorimeter, which provides coverage for $|\eta| < 1.7$. This calorimeter uses steel as an absorbing material and scintillating plastic tiles as the sampling material. In the range $1.5 < |\eta| < 3.2$, a calorimeter with copper as the absorbing material and liquid argon as the sampling material is used. For $|\eta| = 3.2 - 4.9$, coverage is provided by a high density forward calorimeter, which is designed with the ability to withstand a high level of radiation. The forward calorimeter consists of three sections, one with copper as the absorbing material and two with tungsten. Each section is a metal matrix with longitudinal channels filled with concentric rods and tubes. The rods are at a high positive voltage, while the tubes and matrix are grounded. In the gaps is liquid argon, which serves as the the sampling material.

### 3.2.3 Muon Spectrometer

The muon spectrometer surrounds the calorimeter and detects muons, the only detectable particles that are not absorbed completely by the calorimeters. The strength of the muon spectrometer is that it uses high quality tracking and the strong toroidal magnetic field to provide an accurate muon momentum measurement.
3.2.4 Trigger System

The ATLAS trigger system (shown in Fig. 3.4) uses information from these subdetectors at three levels of increasing refinement, in order to reduce the flow of events from the order of 40 MHz to the order of hundreds of hertz for recording. This is a very important system, as it must maintain high efficiencies for accepting interesting physics events while suppressing the enormous background from quantum chromodynamic (QCD) multi-jet events.

The first step of the system is the Level-1 trigger, which makes a decision based on reduced-granularity
information from a subset of the detectors. The dedicated chambers of the muon spectrometer are used in identifying high-\(p_T\) Level-1 muons, and reduced granularity calorimeter information is used for the trigger decisions of many other objects (electrons, photons, jets, \(\tau\) leptons, missing transverse energy). The Level-1 trigger decision is made by dedicated hardware processors. Events selected at Level-1 are read out from the detectors’ front-end electronics systems into readout drivers (RODs) and then readout buffers (ROBs). This information is stored in ROBs until the next level trigger decision is made.

The next step is the Level-2 trigger, which makes its decisions based on regions-of-interest provided by the Level-1 trigger. For these small identified regions of the detector, the full information of the event is retrieved. For muons, this level tightens the selection by raising the \(p_T\) and applying isolation requirements. For electrons and \(\tau\) leptons, a greater rejection is achieved using the full-granularity calorimeter and tracking information.

The final step is the Event Filter (EF), which uses the full event information and utilizes more complex algorithms, which are similar to offline methods. The Level-2 and the EF stages are collectively known as the High-Level Trigger, and they both use software algorithms run on a computer farm.

### 3.2.5 FTK Trigger Upgrade

Tracking at Level-2 is very important for many objects, including hadronically-decaying \(\tau\) leptons. The presence of highly collimated, low multiplicity tracks are one primary way to distinguish between \(\tau\) leptons and hadronic jet backgrounds. In the trigger, hadronically-decaying \(\tau\) leptons are seeded by related energy deposits in the electromagnetic and hadronic calorimeters at Level-1. At Level-2, a combination of calorimeter and tracking information are utilized to further classify hadronically-decaying \(\tau\) leptons.

At the EF level, a full reconstruction of the \(\tau\) lepton object is performed, using algorithms similar to those used in offline reconstruction. At this point, a multivariate technique (Boosted Decision Tree or Log Likelihood) is used to accept \(\tau\) leptons and reject a portion of the enormous background of hadronic jets. The selections are optimized for an efficiency of 85% for 1-prong and 80% for 3-prong \(\tau\) leptons. At this step, the background rejection is not very high, and most of the discrimination against background jets is achieved through offline identification algorithms.

A proposed trigger upgrade called the FastTracKer (FTK), described in [5], is intended to provide high-quality tracking information for the full inner detector at the beginning of Level-2 processing. The near-offline-quality tracks and increased available execution time provided by the upgrade will allow the use of improved downstream trigger algorithms.

The FTK algorithm contains two steps. The first is the pattern recognition step, where an Associative
Figure 3.5: Comparison of FTK (red) and offline (black) helix parameter resolutions in the barrel region: (a) curvature, (b) $d_0$, (c) $z_0$, (d) $\phi_0$, and (e) $\eta$. The resolution is calculated as the reconstructed (RECO) quantity minus the generated (TRUTH) value [5].
Memory (AM) matches track candidates to collections of SCT hits in coarse-resolution roads. As the silicon data passes through FTK, the AM uses massive parallelism to process hundreds of millions of roads nearly simultaneously, saving time on what is usually the most computation-intensive aspect of tracking. If the road has hits on all but one of the silicon layers, the next step occurs. At this point, full resolution hits in the road are fit to reconstruct the helix parameters, and the goodness of fit is found (using $\chi^2$). Tracks that pass the goodness of fit requirements are sent to the Level-2 processors.

The resolution of helix parameters is shown for both FTK and the offline reconstruction in Fig. 3.5. The figure shows that the performance is only slightly degraded in the use of FTK tracking with respect to offline tracking. In the figure, $d_0$ is the transverse impact parameter, defined as the point of closest approach to the $z$-axis of the detector. The longitudinal track parameter $z_0$ is defined as the $z$ value at this point of closest approach, and $\phi_0$ is momentum angle $\phi$ at this point. The curvature of the track is used to determine the
momentum of a particle, and $\eta$ is the pseudorapidity.

Since tracking is important for selecting $\tau$ leptons at Level-2 of the trigger system, the FTK system can be especially useful in this case. The FTK tracking is nearly offline in quality, so it can be used at Level-2 to rapidly reject a large amount of the hadronic jet background of the hadronically-decaying $\tau$ lepton. To check the efficiency of reconstructing the tracks of a hadronically-decaying $\tau$ lepton at Level-2, tracks were considered that had $p_T > 1.5$ GeV and were within a cone of $\Delta R = 0.35$ from a Level-1 $\tau$ calorimetric cluster. A signal cone was defined as a cone of $\Delta R = 0.13$ around a track with $p_T > 6$ GeV, and a wider isolation cone was defined with $\Delta R = 0.26$. For a properly reconstructed $\tau$ lepton, there must be one or three tracks found within the signal cone, and none within the isolation cone.

Efficiencies were measured from simulated Higgs events provided by the vector boson fusion process, with the Higgs decaying into two hadronically-decaying $\tau$ leptons. The denominator consists of generated hadronically-decaying $\tau$ leptons that are matched to a Level-1 $\tau$ calorimetric cluster. The resulting efficiencies for 1- and 3-prong hadronically-decaying $\tau$ leptons are shown in Fig. 3.6. The efficiencies are shown as a function of the $p_T$ and $|\eta|$ of the generated $\tau$ lepton, for both the design luminosity ($1 \times 10^{34} cm^{-2} s^{-1}$) and a higher luminosity ($3 \times 10^{34} cm^{-2} s^{-1}$). The efficiencies are similar for the offline and FTK track reconstruction algorithms. A small proto-FTK, called a “vertical slice”, is now located at CERN. It is being used to show FTK capabilities on a small scale and commission the FTK with real data.
Chapter 4

Experimental Methods

4.1 Data Set

The analyses in this thesis are performed using the 2011 and 2012 datasets. The ATLAS detector recorded 5.25 fb\(^{-1}\) of integrated luminosity in 2011, and 21.7 fb\(^{-1}\) in 2012, as shown in Fig. 4.1. The measurement of this luminosity \([43, 44]\) is determined by the equation

\[
\mathcal{L} = \frac{R_{\text{inel}}}{\sigma_{\text{inel}}} \quad (4.1)
\]

where \(R_{\text{inel}}\) is the rate of inelastic collisions and \(\sigma_{\text{inel}}\) is the \(pp\) inelastic cross section. In terms of what ATLAS measures, the luminosity can also be written as:

\[
\mathcal{L} = \frac{\mu_{\text{vis}} n_b f_r}{\sigma_{\text{vis}}} \quad (4.2)
\]

where \(f_r\) is the revolution frequency of the ring, and \(n_b\) is the number of bunch pairs colliding per revolution. Then, \(\mu_{\text{vis}}\) is the observed interaction rate per crossing, which is measured independently by several detectors.

Figure 4.1: Integrated luminosity delivered by the LHC and recorded by the ATLAS detector in 2011 (left) and 2012 (right) (Figure courtesy of ATLAS Collaboration Luminosity Working Group).
Monte Carlo (MC) simulated samples are used to develop and validate analysis methods, calculate the signal selection efficiency, and evaluate systematic uncertainties. The MC tuning and generation is nearly the same for the simulated datasets produced with center-of-mass energy $\sqrt{s} = 7$ TeV, for the analysis of 2011 data, and $\sqrt{s} = 8$ TeV, for the analysis of 2012 data. Thus, the details given here are valid for both the 2011 and 2012 MC production, though the 2012 production uses updated versions of software with respect to the 2011 production.

For the $t\bar{t}$ cross section, the theoretical prediction and uncertainties are used. The $t\bar{t}$ cross section for $pp$ collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV is $\sigma_{t\bar{t}} = 167^{+17}_{-18}$ pb for a top quark mass of 172.5 GeV. For $pp$ collisions at a center-of-mass energy of $\sqrt{s} = 8$ TeV, the $t\bar{t}$ cross section is $\sigma_{t\bar{t}} = 238^{+22}_{-24}$ pb. These cross sections have been calculated at approximate NNLO in QCD with HATHOR 1.2 [45] using the MSTW2008 90% NNLO PDF sets [46] incorporating PDF+$\alpha_S$ uncertainties, according to the MSTW prescription [47], added in quadrature to the scale uncertainty and cross checked with the NLO+NNLL calculation of Cacciari et al. [48] as implemented in Top++ 1.0 [49].

The modeling of $t\bar{t}$ and single top quark events is performed with MC@NLO [50], except for the $t$-channel of the single top quark production, which is modeled with ACERMC [51]. The top quark mass is set to 172.5 GeV and the parton density function is CT10 [52]. For events generated with MC@NLO, the parton shower and underlying event are added using HERWIG [53] and JIMMY [54], while PYTHIA [55] is used for events generated with ACERMC.

Single vector boson production is simulated using ALPGEN interfaced to HERWIG/JIMMY for the underlying event model. The parton density function CTEQ6.1 [56] is used for the matrix element calculations and parton shower evolution. The MLM matching scheme [57] is used to match partons to their respective jets. It is applied inclusively for the production of $W$ $(5$ partons$)$, a $2 \rightarrow 7$ process, and exclusively for the lower multiplicity sub-samples.

Vector boson $(V = W/Z)$ production with additional heavy flavor partons $(V + c, V + c\bar{c}, V + b\bar{b})$ is simulated separately with ALPGEN. The inclusive $W$ and $Z/\gamma^*$ production samples are formed by adding the corresponding parton multiplicity sub-samples. The $V+$jets samples with light and heavy flavor are combined with their relevant cross sections, and the overlap between the samples are removed. Smaller backgrounds,
<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>Cross section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ with at least one lepton $\ell$</td>
<td>MC@NLO</td>
<td>91</td>
</tr>
<tr>
<td>$t\bar{t}$ with no lepton</td>
<td>MC@NLO</td>
<td>76.2</td>
</tr>
<tr>
<td>Single top quark $t$ (with $\ell$)</td>
<td>ACERMC</td>
<td>20.9</td>
</tr>
<tr>
<td>Single top quark $s$ (with $\ell$)</td>
<td>MC@NLO</td>
<td>1.5</td>
</tr>
<tr>
<td>Single top quark $Wt$ (inclusive)</td>
<td>MC@NLO</td>
<td>15.7</td>
</tr>
<tr>
<td>$W(t\bar{t}) + \text{jets}$</td>
<td>ALPGEN</td>
<td>$3.1 \times 10^4$</td>
</tr>
<tr>
<td>$Wb + \text{jets}$</td>
<td>ALPGEN</td>
<td>$1.3 \times 10^2$</td>
</tr>
<tr>
<td>$Wc + \text{jets}$</td>
<td>ALPGEN</td>
<td>$3.6 \times 10^2$</td>
</tr>
<tr>
<td>$Wc + \text{jets}$</td>
<td>ALPGEN</td>
<td>$1.1 \times 10^3$</td>
</tr>
<tr>
<td>$Z/\gamma^{*}(t\bar{t}) + \text{jets}$, $m(t\bar{t}) &gt; 10$ GeV</td>
<td>ALPGEN</td>
<td>$1.5 \times 10^4$</td>
</tr>
<tr>
<td>$Z/\gamma^{*}(t\bar{t})b\bar{b} + \text{jets}$, $m(t\bar{t}) &gt; 30$ GeV</td>
<td>ALPGEN</td>
<td>38.7</td>
</tr>
<tr>
<td>$WW$</td>
<td>HERWIG</td>
<td>17.0</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>HERWIG</td>
<td>1.3</td>
</tr>
<tr>
<td>$WZ$</td>
<td>HERWIG</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Table 4.1: Cross sections for the main SM MC samples at $\sqrt{s} = 7$ TeV. In this table, $\ell$ refers to the three lepton families $e$, $\mu$ and $\tau$.

arising from diboson events ($WW$, $WZ$, and $ZZ$) are generated and hadronized using HERWIG.

Three types of signal samples are produced with PYTHIA for $m_{H^\pm}$ between 90 and 160 GeV: $t\bar{t} \to b\bar{b}H^+W^-$, $t\bar{t} \to b\bar{b}H^-W^+$, and $t\bar{t} \to b\bar{b}H^+H^-$, with $H^\pm \to \tau\nu$ and inclusive $W$ decays. For the signal samples between 180 and 600 GeV, samples for top-associated $H^+$ production are produced with POWHEG interfaced with PYTHIA, for $H^+ \to \tau\nu$ and inclusive top decays. These samples contain both the combination of both the 4FS and 5FS diagrams of heavy $H^\pm$ production described in Section 2.5.

The event generators are tuned to describe the ATLAS data, using the parameter sets AUET2B [58] and AUET2 [59] for events hadronised with PYTHIA and HERWIG/JIMMY, respectively. The simulated events are propagated through a detailed GEANT4 simulation [60] of the ATLAS detector, and reconstructed using the same algorithms as the data. MC events are overlaid with additional minimum bias events generated with PYTHIA to simulate the effect of pile-up interactions. TAUOLA [61] is used for the hadronic decays of $\tau$ leptons, and PHOTOS [62] is used for photon radiation from charged leptons. The processes, generators, and cross sections of the background samples used are displayed in Table 4.1 for the 2011 production, and Table 4.2 for the 2012 production.

### 4.3 Physics Objects and Calibrations

#### 4.3.1 Electrons

Electrons are reconstructed by matching energy deposits in the EM calorimeter to reconstructed tracks in the inner detector. In addition, they must have $E_T > 20$ GeV for the 2011 and $E_T > 25$ GeV for the
<table>
<thead>
<tr>
<th>Process</th>
<th>Generator</th>
<th>Cross section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ with at least one lepton $\ell$</td>
<td>MC@NLO</td>
<td>129</td>
</tr>
<tr>
<td>Single top quark $t$ (with $\ell$)</td>
<td>ACRMC</td>
<td>28.4</td>
</tr>
<tr>
<td>Single top quark $s$ (with $\ell$)</td>
<td>MC@NLO</td>
<td>1.8</td>
</tr>
<tr>
<td>Single top quark $Wt$ (inclusive)</td>
<td>MC@NLO</td>
<td>22.4</td>
</tr>
<tr>
<td>$W(t\bar{t}) + \text{jets}$</td>
<td>ALPGEN</td>
<td>$3.6 \times 10^4$</td>
</tr>
<tr>
<td>$Wb + \text{jets}$</td>
<td>ALPGEN</td>
<td>$1.6 \times 10^2$</td>
</tr>
<tr>
<td>$Wc + \text{jets}$</td>
<td>ALPGEN</td>
<td>452.8</td>
</tr>
<tr>
<td>$Wc + \text{jets}$</td>
<td>ALPGEN</td>
<td>1779.1</td>
</tr>
<tr>
<td>$Z/\gamma^* (t\bar{t}) + \text{jets}, m(\ell\ell) &gt; 10 \text{ GeV}$</td>
<td>ALPGEN</td>
<td>$1.7 \times 10^4$</td>
</tr>
<tr>
<td>$Z/\gamma^* (t\bar{t})b\bar{b} + \text{jets}, m(\ell\ell) &gt; 30 \text{ GeV}$</td>
<td>ALPGEN</td>
<td>49.2</td>
</tr>
<tr>
<td>$WW$</td>
<td>HERWIG</td>
<td>20.9</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>HERWIG</td>
<td>1.5</td>
</tr>
<tr>
<td>$WZ$</td>
<td>HERWIG</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Table 4.2: Cross sections for the main SM Monte Carlo background simulation samples at $\sqrt{s} = 8 \text{ TeV}$. In this table, $\ell$ refers to the three lepton families $e$, $\mu$ and $\tau$.

2012 analyses, where $E_T$ is calculated from $E_{\text{cluster}}/\cos |\eta_{\text{track}}|$. The $|\eta|$ range of the electron is limited to $|\eta| < 2.47$, and the transition region between the barrel and end-cap calorimeters, $1.37 < |\eta| < 1.52$, is also removed. A cut-based selection for electron identification is used for electrons within the $|\eta|$ range of interest [63]. This selection uses shower shape variables of the EM calorimeter, hadronic leakage variables, track quality requirements, track-cluster matching, $E/p$, TRT information, B-layer hit requirements, and information about reconstructed conversion vertices. Within the $E_T$ and $|\eta|$ range of interest, the electron identification has an efficiency in the range of 70–80%. The cut-based selection of the electron identification has been updated for the 2011 and 2012 dataset. In addition to these selections, the electrons are also required to be isolated, using a collection of $E_T$ and $|\eta|$ independent calorimeter (tracking) requirements on a cone of $\Delta R = 0.2(0.3)$ around the electron, excluding the electron object itself. The isolation requirements of the electron are optimized for a true electron cut efficiency of 90%.

4.3.2 Muons

Muons are required to have matching good quality tracks in the inner detector and in the muon spectrometer. The muon reconstruction efficiency is measured in [64], and shown to agree well with simulated events. The muons for these analyses must also have $p_T > 15 \text{ GeV}$ for the 2011 and $p_T > 25 \text{ GeV}$ for the 2012 analyses. The 2011 muon isolation depends upon both tracking and information from the calorimeters. For a cone around the muon of radius $\Delta R = 0.2$, excluding the muon object, the transverse energy in the calorimeters must be less than 4 GeV. For a similar cone of $\Delta R = 0.3$, the transverse momentum of the inner detector tracks must be less than 2.5 GeV. In 2012, a “mini-Isolation” is used, which uses a cone size that is reduced
as the $p_T$ of the muon increases. The transverse energy in this cone is required to be less than 5% of the muon’s $p_T$, and the max cone size is $\Delta R = 0.4$.

### 4.3.3 Jets

In analyses on the 2011 dataset, jets are reconstructed using an anti-$k_t$ algorithm [65, 66]. This is a sequential clustering algorithm which has the benefit of being stable with respect to collinear splitting and soft emissions, as well as insensitive to pile-up interactions and the underlying event. In general, the algorithm looks at topological clusters within an area with a size parameter of $\Delta R = 0.4$, and calculates the distances between the particles, as well as between each particle and the beam. If the smallest measured distance is between two particles, they are combined, and if the smallest difference is between a particle and the beam, the particle is removed and labeled as a jet. Jets are reconstructed at the electromagnetic scale appropriate for the energy deposited by electrons or photons. They are then calibrated with MC based $p_T$- and $\eta$-dependent correction factors to restore the full hadronic energy scale after passing through the non-compensating calorimeters [67].

A quantity called the Jet Vertex Fraction (JVF) [68] uses tracking and vertexing information to identify and select jets originating from the hard-scatter interaction. By combining the tracks and their primary vertices with calorimeter jets, a discriminant can be defined to measure the probability that a jet originated from a particular vertex. Jet selection based on this discriminant is insensitive to the contributions from simultaneous uncorrelated soft collisions that occur due to pile-up interactions. JVF cuts are used in some overlap removal steps, as well as in final jet requirements during the event selections.

For analyses that use the 2012 dataset, the jets are also reconstructed using the anti-$k_t$ algorithm and a size parameter of $\Delta R = 0.4$, but first the clusters are calibrated using a local calibration [69]. The local calibration method classifies calorimeter clusters as either electromagnetic or hadronic, through considering properties such as the cluster’s energy density, isolation and depth in the calorimeter. Based on this classification, the energy is then corrected using weights derived from single pion MC simulation. Energy corrections are derived to account for the effects of non-compensation, signal losses due to noise thresholds effects, and energy lost in non-instrumented regions.

For tagging jets as $b$ quarks, a high-performance $b$-tagging algorithm [70] is used for both 2011 and 2012 analyses. This tagger combines impact-parameter information with the explicit determination of an inclusive secondary vertex. Since it relies on inner detector tracking, the $b$-tagger enforces a cut of $|\eta| < 2.5$ on the jet selection. A cut value on the discriminant produced by this algorithm that has a $b$-tagging efficiency of 70% is used to select $b$-tagged jets.
4.3.4 \( \tau \) Leptons

Unless it is explicitly stated otherwise, any reference to \( \tau \) leptons in this thesis is intended to refer to \( \tau \) leptons that decay hadronically. As discussed in chapter 1, hadronically-decaying \( \tau \) leptons are characterized by the presence of one or three charged tracks, accompanied by a neutrino and possibly neutral pions. This results in a collimated shower profile in the calorimeter with only a few nearby tracks. Before the object selection and identification techniques, \( \tau \) leptons that decay hadronically are seeded by jets.

At the first step in the reconstruction of hadronically-decaying \( \tau \) leptons [6], the candidates are seeded by anti-\( k_t \) jets of size parameter \( \Delta R = 0.4 \), calibrated using local hadron calibration. Each jet depositing at least \( E_T > 10 \) GeV in the calorimeters and having \( |\eta| < 2.5 \) is considered as a possible \( \tau \) lepton. The jets are then re-calibrated at the \( \tau \) energy scale, and \( \tau \)-specific variables are calculated. Tracks are associated with the \( \tau \) lepton if they pass the following quality requirements:

- \( p_T > 1 \) GeV
- number of pixel hits \( \geq 2 \)
- number of pixel hits + SCT hits \( \geq 7 \)
- \( |d_0| < 1.0 \) mm
- \( |z_0 \sin \theta| < 1.5 \) mm

Tracks within \( \Delta R = 0.2 \) of the reconstructed \( \tau \) lepton axis are considered to be associated with the \( \tau \) lepton, while tracks found within \( 0.2 < \Delta R < 0.4 \) are saved as tracks in the isolation cone. For this analysis, \( \tau \) leptons are required to have exactly one or three associated tracks, corresponding to the 1- and 3-prong hadronic decay signatures of the \( \tau \) lepton. The \( \tau \) leptons are also required to have a visible \( p_T > 20 \) GeV and \( |\eta| < 2.3 \).

Multivariate and cut-based methods are used to discriminate between true \( \tau \) leptons and \( \tau \) leptons that are reconstructed from jets, electrons, or muons [6]. Electrons and muons have a single, isolated charged track, so they can have a similar detector signature to 1-prong \( \tau \) leptons. The dedicated algorithms for rejecting electrons and muons that are misidentified as 1-prong \( \tau \) leptons are highly effective, leaving only a very small background from these sources. The jet background to the hadronically-decaying \( \tau \) lepton is more difficult to reduce to a manageable level. Even when one uses multivariate techniques specifically designed to discriminate against jets, events with jets misidentified as \( \tau \) leptons make a significant contribution to the analyses considered in this thesis. The input variables used for the algorithms that distinguish true \( \tau \)
To discriminate between 1-prong $\tau$ leptons and electrons, a Boosted Decision Tree (BDT) is used. While electrons and 1-prong hadronically-decaying $\tau$ leptons have similar detector signatures, there are properties that can be used to distinguish well between them. For instance, $\tau$ leptons tend to have longer and wider showers in the electromagnetic calorimeter than electrons. The BDT is optimized using simulated $Z \rightarrow \tau \tau$ events as signal and simulated $Z \rightarrow ee$ events as background. The BDT score distribution for 2011 simulation, shown in Fig. 4.2, discriminates very well between electrons and $\tau$ leptons. The signal and inverse background efficiency for this BDT distribution is shown for 2011 simulation in Fig. 4.3, split into two bins in $|\eta|$. An equivalent electron veto, optimized for the 2012 dataset, is used in the 2012 $H^\pm$ searches.

Muons are less likely to be misidentified as $\tau$ leptons, since they deposit little energy in the calorimeters. A cut-based veto is used to discriminate against this small background. There are two cases that result in...
in muons being misidentified as \( \tau \) leptons. The first is when the muon leaves anomalously large energy deposits in the calorimeter, and the second is when energy deposits in the calorimeter from other sources are associated with the muon. A cut-based veto is optimized to reject this background for a \( \tau \) efficiency of 96%. This rejects approximately 55% of the muon background.

To discriminate against the large background of jets misidentified as \( \tau \) leptons, two different multivariate identification algorithms are developed. These two identification algorithms are based on BDT and Likelihood discriminants, and provide similar rejection power and efficiency. For the development of the 2011 BDT and Likelihood discriminants, the signal samples used for optimizing the jet rejection are a combination of \textsc{Pythia} \( W \rightarrow \tau \nu \), \( Z \rightarrow \tau \tau \), and \( Z' \rightarrow \tau \tau \) simulated samples. The background used for optimization is a QCD multi-jet sample taken from a selection of di-jet events in ATLAS data.

The signal \( \tau \) leptons are required to be truth-matched to a hadronically decaying \( \tau \) lepton. For the background samples, the di-jet selection includes events that pass a Level-1 jet trigger and have at least two reconstructed \( \tau \) leptons. The leading reconstructed \( \tau \) lepton must have \( p_T > 30 \) GeV and the sub-leading reconstructed \( \tau \) lepton must have \( p_T > 15 \) GeV. The two reconstructed \( \tau \) leptons must be separated by \( \Delta \phi > 2.7 \). The leading reconstructed \( \tau \) lepton is required to have fired the trigger, and the sub-leading reconstructed \( \tau \) lepton is used for identification and efficiency calculations. The optimization of the performances of the BDT and Likelihood \( \tau \) identifications are also updated for the 2012 ATLAS dataset, using similar regions.

The Likelihood function for signal and background, \( L_{S(B)} \), is defined as the product of the one-dimensional probability density functions \( p^{S(B)}_i(x_i) \), of each identification variable, \( x_i \):

\[
L_{S(B)} = \prod_{i=1}^{N} p^{S(B)}_i(x_i) \tag{4.3}
\]

The discriminant is defined as the log-likelihood ratio between signal and background:

\[
d = \ln \left( \frac{L_S}{L_B} \right) = \sum_{i=1}^{N} \ln \left( \frac{p^{S}_i(x_i)}{p^{B}_i(x_i)} \right) \tag{4.4}
\]

Each \( p^{S(B)}_i(x_i) \) is calculated as the fraction of events per bin in a histogram of the \( x_i \) distribution, and the \( x_i \) histograms are split into categories that are designed to maximize discrimination power. These categories separate \( \tau \) leptons with one and three tracks, and also separate \( \tau \) leptons based on three regions of \( p_T \) and the number of reconstructed vertices in the event. Any variable that contributes less than a few percent to the overall performance is removed, leaving eight total input variables. The 2011 Likelihood score for 1-prong and 3-prong \( \tau \) leptons is shown in Fig. 4.4.

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Figure 4.4: Log-likelihood ratio score for 1-prong (left) and 3-prong (right) hadronically-decaying $\tau$ leptons. True $\tau$ leptons are taken from simulation, and jets are taken from ATLAS data [7].

Figure 4.5: BDT score for 1-prong (left) and 3-prong (right) hadronically-decaying $\tau$ leptons. True $\tau$ leptons are taken from simulation, and jets are taken from ATLAS data [7].

The 2011 BDT identification is trained separately for $\tau$ leptons with one and three tracks, as well as for categories defined by the number of reconstructed primary vertices in the event. The dependence of the BDT score on $p_T$ is taken into account through defining $p_T$-dependent cuts on the working points used for analyses. The final BDT scores for the 1-prong and multi-prong cases are shown in Fig. 4.5.

The performances of both BDT and Likelihood identification are shown in Fig. 4.6, in terms of signal efficiency and inverse background efficiency. A cut-based $\tau$ identification is also displayed on the plots, showing the dramatic improvement achieved by using multivariate techniques.

For the 2011 analyses, a “tight” working point of the Likelihood identification is used that corresponds to a true $\tau$ efficiency of around 30%, and a rejection factor of 100-1000 against jets, depending on the $\eta$, $p_T$, and number of associated tracks of the $\tau$ lepton. In the 2012 analysis, a similar “tight” working point is used with the BDT identification.

In this thesis, $\tau$ candidates will be considered as objects that pass the basic $\tau$ lepton object selection and lepton vetoes, but which have no requirement on the multivariate identification designed to discriminate
against jets. The τ candidates are used in several data-driven background estimation methods that will be described in this thesis. It has been observed that some τ variables tend to be poorly modeled in simulated events with jets that are misidentified as τ leptons. Two of these poorly modeled τ variables can be seen in Fig. 4.7, which shows a selection of τ candidates arising from jets in W+jets simulated events, and an identical selection of W+jets events in data, with simulated true τ contributions subtracted. Since this mis-modeling of variables gives rise to a mis-modeling of the resulting identification score, the data-driven techniques that will be described in this thesis rely on data to model the performance of the τ identification for jets.

4.3.5 Missing Transverse Energy

For analyses of 2011 data, the $E_T^{\text{miss}}$ is calculated from topological clusters calibrated at the electromagnetic scale (EM) and corrected according to the energy scale of the associated objects. The topological clusters are associated to electrons, high-$p_T$ jets and low-$p_T$ jets. The ordering of these objects indicates the order of association of the clusters to the objects, where the clusters are associated with the first object used. Muons are also considered in the calculation, and any remaining calorimeter energy not associated with
these objects is calibrated to the EM scale. In 2012, the main difference in the MET definition is that jets included in the calculation use a local calibration, as described in the object selection for 2012 jets.

4.3.6 Overlap Removals

With these defined objects, the following overlap removal is applied for 2011 analyses. First, if any selected muons share a track with selected electrons, the event is vetoed. Next, selected muons are rejected if they are within $\Delta R = 0.4$ of a jet that passes a JVF cut of 0.75 and has $p_T > 25$ GeV. Then, selected $\tau$ leptons are rejected if they are within $\Delta R = 0.2$ of a selected muon or electron. Jets are then rejected if they are within $\Delta R = 0.2$ of a selected $\tau$ lepton or electron.

In the 2012 analysis, there are several changes in the overlap removal procedure. As in 2011, the event is vetoed if any muons and electrons share a track. Selected muons are also rejected if they are within $\Delta R = 0.4$ of a jet that passes a JVF cut of 0.5 and has $p_T > 25$ GeV. Then, the nearest jet to each selected electron (in $\Delta R$) is rejected. Electrons are rejected if they are within $\Delta R = 0.4$ of a remaining jet that has $p_T > 25$ GeV. Finally, $\tau$ leptons are rejected if they are within $\Delta R = 0.2$ of a selected muon or electron, and jets are then rejected if they are within $\Delta R = 0.2$ of a selected $\tau$ lepton.

4.3.7 Scale Factors and Calibrations

While the MC simulation performs well overall, it is necessary to study the level of mis-modeling in the various physics objects and apply corrections where needed. Performance groups in ATLAS determine the
scale factors, energy calibrations, and momentum smearing that are needed for both data and simulation. The effects of these scale factors and calibrations are generally small, but they enable a closer modeling of data using simulated events.

Scale factors are generally calculated from a ratio of efficiencies in data and simulation. For muons and electrons, trigger, reconstruction, and identification scale factors are applied to simulated events. For \( \tau \) leptons, scale factors are applied for the identification efficiency, and these are applied only for simulated true \( \tau \) leptons. In addition, reconstructed \( \tau \) lepton scale factors are defined based on the electron BDT veto efficiency, and these are applied only to simulated electrons that are misidentified as \( \tau \) leptons. Furthermore, scale factors are calculated for the efficiency of the \( \tau + E_T^{miss} \) trigger that is used in analysis channels containing only \( \tau \) leptons, jets, and \( E_T^{miss} \). The efficiency or misidentification efficiency of the \( b \)-tagging algorithm also has an associated scale factor. Finally, some scale factors are required by specific analyses only, and these will be considered within the discussion of the analyses in question.

The corrections to particle energies are generally designed to achieve agreement with data in energy scale and resolution. For muons, the simulated \( p_T \) is smeared in such a way that the resolution of the mass peak from \( Z \rightarrow \mu\mu \) matches for simulation and data. For electrons, an energy correction is applied in data, and energy is smeared in simulation. In data events with electrons, the electromagnetic cluster energy is corrected by applying the energy scales obtained from resonances such as \( Z \rightarrow ee, J/\psi \rightarrow ee \), or \( E/p \) studies using isolated electrons from \( W \rightarrow e\nu \). The electron energy smearing in simulated events matches the energy resolution to that observed in data. For jets, several corrections are applied to both simulation and data. First, a pile-up correction is applied, which is based on the number of vertices in the event and the number of interactions. An origin correction is then applied, which corrects the jet direction to point to the primary vertex of the event. The jet energy and \( |\eta| \) are then corrected at the jet energy scale, and a final in-situ calibration is applied only to data. All energy corrections and smearing are propagated to the calculation of the \( E_T^{miss} \) of the event.

### 4.4 Event Preselection

The \( H^\pm \) search analyses use a wide variety of physics objects (jets, electrons, taus, muons, \( b \)-jets, \( E_T^{miss} \)), so only events recorded with all of the ATLAS subsystems operational are considered. The 2011 dataset used for the analyses of this thesis consists of a total integrated luminosity of \( 4.6 \pm 0.2 \text{ fb}^{-1} \) at \( \sqrt{s} = 7 \text{ TeV} \), and the 2012 dataset consists of a total integrated luminosity of \( 19.5 \pm 0.5 \text{ fb}^{-1} \) at \( \sqrt{s} = 8 \text{ TeV} \).

Several weights are applied to simulated events, in order to ensure the simulation accurately represents
Figure 4.8: Normalised distribution of the number of vertices with five or more tracks, in data and in a \( t\bar{t} \) MC sample, before and after pile-up reweighting of the simulated events, for 2011(left) and 2012(right) [8, 9].

data conditions. As shown in Fig 4.8 for 2011 and 2012, weights are included to match the level of pile-up interactions in simulation and data. In 2012, a small weight is also included to correct the vertex position of simulated events.

A group of preselections are defined to further remove problematic events from data. Events are vetoed if they contain any jets that are consistent with having originated from instrumental effects, such as large noise signals in one or several channels of the hadronic end-cap calorimeter, coherent noise in the electromagnetic calorimeter, or non-collision backgrounds. In addition, events are discarded if the reconstructed vertex with the largest sum of squared track momenta has fewer than five associated tracks with a transverse momentum \( p_T > 400 \) MeV.

Events are also vetoed if there is a noise burst in the liquid argon calorimeter. In addition to this veto, a region of the the liquid argon calorimeter suffered a loss of information in a fraction of the 2011 data. Therefore, an event veto was applied in data and simulation for events in the relevant data runs with electrons or jets that fell into this region. In the 2012 analysis, events are also rejected if they are incompletely recorded or there is data corruption in the tile calorimeter.

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Chapter 5

$H^{\pm}$ Search Strategies

This thesis documents searches for $H^{\pm} \rightarrow \tau \nu$ that are conducted on both the 2011 and 2012 ATLAS datasets, on integrated luminosities of 4.6 fb$^{-1}$ and 19.5 fb$^{-1}$, respectively. The 2011 searches are exclusively for light $H^{\pm}$, and they have resulted in two publications [12, 13]. Each of the papers represents a different strategy for differentiating the hypothetical signal from the large SM background. In the first, a direct search for the $H^{\pm}$ is conducted in several channels, utilizing variables which differentiate signal and background through the use of kinematical information. In the second, a ratio of yields is used to detect the possible presence of $H^{\pm}$ through apparent violation of lepton universality, which would arise from preferential decay of the $H^{\pm}$ to $\tau \nu$. On the 2012 dataset, direct searches are conducted in a single channel, again using a variable that is able to differentiate between signal and background through kinematical information. For these searches, results for both light and heavy $H^{\pm}$ are included.

During the development of these analyses, the signal region is “blinded”, meaning the analyzers do not look into the signal region until the analysis event selections and methods are finalized. The data-driven background methods are validated in control regions, simulation, and early signal region, and event selection is optimized with simulated events. This is to prevent any unintentional bias in the choice of event selections or background methods.

5.1 Light $H^{\pm}$ Strategy

For the light $H^{\pm}$ searches conducted on the 2011 and 2012 ATLAS datasets, two channels with $H^{\pm} \rightarrow \tau \nu$ are of interest. Both channels are produced through $t\bar{t}$ decays, where $t \rightarrow H^{\pm}b$ and $H^{\pm} \rightarrow \tau \nu$, as shown in the left diagram in Fig. 2.1. The two decay channels are:

- $\tau$+jets: $t\bar{t} \rightarrow bbWH \rightarrow bb(q\bar{q})(\tau \nu)$, i.e. $W$ and $\tau$ both decay hadronically;
- $\tau$+lepton: $t\bar{t} \rightarrow bbWH \rightarrow bb(\ell \nu)(\tau \nu)$, i.e. $W$ decays leptonically ($\ell = e, \mu$) and $\tau$ decays hadronically;
Since $H^\pm$ decays to a $\tau$ and neutrino, its presence would be indicated by an excess of events with $\tau$ final states, relative to SM expectations. Direct searches are performed for the two channels with the 4.6 fb$^{-1}$ 2011 dataset, and the results are combined with a third channel, which corresponds to $\tau$+jets with a leptonically-decaying $\tau$ lepton, and is described in the published paper [12]. A different approach to the $\tau$+lepton channel, relying on a ratio of yields to check apparent violation of lepton universality, has also been performed using the 2011 dataset. The results from this strategy are combined with the limits in the $\tau$+jets channel. The result for light $H^\pm$ in the $\tau$+jets channel is also updated using the 19.5 fb$^{-1}$ 2012 dataset.

5.1.1 $\tau$+Jets Channel

2011 $\tau$+Jets Analysis

The 2011 $\tau$+jets channel uses a $\tau+E_T^{miss}$ trigger [71, 71] with a threshold of 29 GeV for the $\tau$ lepton and 35 GeV on calorimeter-based $E_T^{miss}$ for the earlier periods of 2011 data. For later periods of 2011 data, a trigger is used that has the same $p_T$ and $E_T^{miss}$ thresholds, but additionally requires three Level-1 jets with a minimum $p_T$ of 10 GeV. The average efficiency of these triggers, as measured in signal simulation after all selection criteria, is 70%. The efficiencies with respect to $p_T^{\tau}$ and $E_T^{miss}$ for these two triggers, as measured in a simulated signal sample of $m_{H^\pm} = 130$ GeV, are shown in Fig. 5.1.

The $\tau$+jets channel also includes scale factors and uncertainties that are derived in a data-driven way from the comparison of $\tau+E_T^{miss}$ trigger efficiencies in data and simulated events. In order to make this comparison, events are selected that are consistent with $t\bar{t}$ decays in the $\mu + \tau$ final state, where the muon and $\tau$ lepton are expected to come from the two $W$ decays. The resulting sample of events is expected to have a relationship between the $\tau$ lepton and $E_T^{miss}$ that is very similar to that of events in the $\tau$+jets signal region. The $\mu + \tau$ region events are used in a tag-and-probe method, where the event is triggered by the presence of the muon, and the $\tau$ + $E_T^{miss}$ trigger is then applied to study the comparison of its efficiency in data and simulation.

The events in the $\mu + \tau$ region used for studying the trigger efficiency must pass basic event cleaning cuts (described in Section 4.4), and contain exactly one muon of $p_T > 15$ GeV. The event must fire a muon trigger with a $p_T$ threshold 18 GeV, and contain at least two jets, with at least one of them tagged as a $b$-jet. The event must also contain an identified $\tau$ lepton.

The expected composition of events for this region is shown in Fig. 5.2. The data excess at low $p_T^\tau$ and low $E_T^{miss}$ is due to QCD multi-jet backgrounds, which are not represented in the stacked simulated samples. In the regions of interest for this analysis, $p_T^\tau > 40$ GeV and $E_T^{miss} > 65$ GeV, there is a high purity of $t\bar{t}$.
Figure 5.1: The efficiencies of the two $\tau + E_T^{\text{miss}}$ triggers used for the first 2011 data period (left) and the second 2011 data period (right). Efficiencies are shown with respect to $p_T^\tau$ and $E_T^{\text{miss}}$ for a simulated signal sample of $m_{H^\pm} = 130$ GeV [8].

<table>
<thead>
<tr>
<th>$E_T^{\text{miss}}$</th>
<th>$p_T^\tau = [40, 70]$ GeV</th>
<th>$p_T^\tau = [70, 500]$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[65, 100]$ GeV</td>
<td>$0.76 \pm 0.09$</td>
<td>$0.86 \pm 0.13$</td>
</tr>
<tr>
<td>$[100, 500]$ GeV</td>
<td>$1.10 \pm 0.12$</td>
<td>$0.91 \pm 0.14$</td>
</tr>
</tbody>
</table>

Table 5.1: Trigger scale factors determined from a $\mu$-triggered control sample. These factors correspond to the ratio of efficiencies in each $p_T^\tau$ and $E_T^{\text{miss}}$ bin, and are applied as a correction to simulated events.

The data is separated into four $E_T^{\text{miss}}$ and $p_T^\tau$ bins. The $p_T^\tau$ bins are $40 \text{ GeV} \leq p_T^\tau < 70 \text{ GeV}$ and $70 \text{ GeV} \leq p_T^\tau < 500 \text{ GeV}$. The $E_T^{\text{miss}}$ bins are $65 \text{ GeV} \leq E_T^{\text{miss}} < 100 \text{ GeV}$ and $100 \text{ GeV} \leq E_T^{\text{miss}} < 500 \text{ GeV}$. The scale factors for each bin, and their statistical uncertainties, are shown in Table 5.1.

In addition to passing the event preselection (described in Section 4.4) and trigger requirements, events for the signal region of the $\tau+$jets channel must also meet the following requirements:

1. At least 4 jets with $p_T > 20 \text{ GeV}$, $|JVF| > 0.75$, and $|\eta| < 2.4$.

2. Exactly one $\tau$ lepton with $p_T > 20 \text{ GeV}$.

3. The selected $\tau$ lepton has to match a $\tau$ trigger object (in $\Delta R < 0.1$) and have $p_T > 40 \text{ GeV}$.
Figure 5.2: Comparisons of $E^\text{miss}_T$ (top) and $p^\tau_T$ (bottom) for data and simulated events in the $\mu+\tau$ region used for the calculation of trigger scale factors and uncertainties, before the application of the $\tau+E^\text{miss}_T$ trigger [8].

Figure 5.3: The left plot shows the $p^\tau_T$ of the highest energy $\tau$ candidate, just before the $\tau$ selection cut, and the right plot shows the $E^\text{miss}_T$, just before the $E^\text{miss}_T$ cut. The disagreement, arising from events with low $E^\text{miss}_T$, is expected to arise from QCD multi-jet events, which contribute at a high level in the early cut flow. These plots also contain simulated signal contributions, shown with $m_{H^\pm} = 130$ GeV and $B(t \rightarrow H^+ b) = 0.05$ [8].
4. No identified electrons and muons.

5. $E_T^{miss} > 65$ GeV

6. A cut is placed on a quantity defined as the $E_T^{miss}$ significance, $\frac{E_T^{miss}}{0.5\sqrt{\sum p_T^{track}}}$ > 13 GeV^{-1/2}, where $p_T^{track}$ is the transverse momentum of a track originating from the primary vertex. This variable is chosen for robustness against pile-up interactions.

7. At least one $b$-tagged jet.

8. The $jjb$ candidate with the highest $p_T^{jjb}$ value must satisfy $m(jj) \in [120, 240]$ GeV. The $jjb$ candidates are built by combining a $b$-tagged jet with jets that fail the $b$-tagging cut.

In Fig. 5.3 plots of $p_T^\tau$ and $E_T^{miss}$ are shown, at a point in the cut flow just before the cuts are applied to each quantity. For the $p_T^\tau$ plot in Fig. 5.3, the bin at zero corresponds to the case where there is no $\tau$ candidate in the event. In Fig. 5.4, $E_T^{miss}$ significance and $m_{jjb}$ are shown just before their respective cuts are applied. In all distributions, a hypothetical contribution from a signal with $m_{H^\pm} = 130$ GeV and $B(t \rightarrow H^+b) = 0.05$ is also shown in gray. The signal distribution corresponds to the expected signal stacked with the SM contribution, taking into account the reduction of the SM process $B(t \rightarrow W^\pm b)$ resulting from the presence of a signal with $B(t \rightarrow H^+b) = 0.05$. Early in the cut flow, a large contribution is expected from QCD multi-jet events, a background which must be estimated using data-driven techniques.

A cut flow table for MC and data is also shown in Table 5.2, which shows the expected contributions from different SM processes, from a possible signal with $m_{H^\pm} = 130$ GeV and $B(t \rightarrow H^+b) = 0.05$, and the number of data events observed. QCD multi-jet backgrounds are not included in the table, since there
Table 5.2: Selection cut flow for data and simulation. The signal is the possible contribution from $H^\pm$ with $m_{H^\pm} = 130$ GeV and $B(t \rightarrow bH^+) = 0.05$. The errors in parentheses are statistical only.

<table>
<thead>
<tr>
<th>$H^\pm$ mass [GeV]</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$+jets (2011)</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>0.17</td>
</tr>
<tr>
<td>100</td>
<td>0.19</td>
</tr>
<tr>
<td>110</td>
<td>0.23</td>
</tr>
<tr>
<td>120</td>
<td>0.27</td>
</tr>
<tr>
<td>130</td>
<td>0.30</td>
</tr>
<tr>
<td>140</td>
<td>0.31</td>
</tr>
<tr>
<td>150</td>
<td>0.33</td>
</tr>
<tr>
<td>160</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 5.3: Signal efficiency determined from simulation, for events passing the full cut flow of the 2011 light $H^\pm$ search in the $\tau$+jets channel.

The discriminating variable at the end of the cut flow is $m_T$, which is defined as:

$$m_T = \sqrt{2p_T^\tau E_T^{miss}(1 - \cos \Delta\phi_{\tau,miss})}$$

where $\Delta\phi_{\tau,miss}$ is the azimuthal angle between the $\tau$ lepton and the $E_T^{miss}$ direction. The $m_T$ variable is related to the $W$ boson mass in the case of the SM background, and to the $H^\pm$ mass for the signal hypothesis.

The discriminating variable $m_T$ is shown in Fig. 5.5, which shows the discrimination power of the variable to distinguish between a signal with $B(t \rightarrow bH^+) = 0.05$ and the SM background.

**2012 $\tau$+Jets Analysis**

The 2012 $\tau$+jets analysis is very similar to the 2011 analysis, though a few small changes to various cuts have been incorporated. Three different $E_T^{miss}+\tau$ triggers [71, 71] are used for different periods in the data. For the early data period, a trigger with a $p_T^{\tau}$ threshold of 29 GeV and a $E_T^{miss}$ threshold of 40 GeV is used. For second data period, the $E_T^{miss}$ threshold is raised to 50 GeV and the EF $E_T^{miss}$ algorithm is moved to
Figure 5.5: The discriminating variable at the end of the cut flow, comparing data and simulation. The simulated signal contribution is shown with $m_{H^\pm} = 130$ GeV and $B(t \rightarrow H^+ b) = 0.05$. This comparison is done before including data-driven estimations, and with no estimate of QCD multi-jet backgrounds [8].

![Graph showing events vs. m_t](image)

This comparison is done before including data-driven estimations, and with no estimate of QCD multi-jet backgrounds [8].

### Table 5.4: Trigger scale factors determined from a $\mu$-triggered control sample used for measuring the $\tau+E_T^{miss}$ trigger efficiencies in data and simulated events. These factors correspond to the ratio of efficiencies in each $p_T^{\tau}$ and $E_T^{miss}$ bin, and are applied as a correction to simulated events.

<table>
<thead>
<tr>
<th>$E_T^{miss}$</th>
<th>$p_T^{\tau}$ = [40, 70] GeV</th>
<th>$p_T^{\tau}$ = [80, 500] GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>[65, 80] GeV</td>
<td>0.98 ± 0.17</td>
<td>0.91 ± 0.14</td>
</tr>
<tr>
<td>[80, 100] GeV</td>
<td>0.99 ± 0.12</td>
<td>1.00 ± 0.15</td>
</tr>
<tr>
<td>[100, 500] GeV</td>
<td>0.91 ± 0.091</td>
<td>0.94 ± 0.1</td>
</tr>
</tbody>
</table>

The events that pass this selection are used in a tag-and-probe method, where the event is triggered by an approach based on topological clustering. For the later data period, the $\tau$ trigger is improved, reducing the $p_T$ threshold to 27 GeV. The expected average efficiency of these triggers in signal simulation is 76-88%, depending on $m_{H^\pm}$.

The scale factors and systematic uncertainties associated with the use of the $E_T^{miss}+\tau$ trigger are measured as in the 2011 $\tau$+jets analysis, using a muon-triggered control region to measure the trigger efficiency in data and simulated events. The muon trigger required in the 2012 analysis has a $p_T$ threshold of 24 GeV, and the cut on the muon $p_T$ is 65 GeV. The muon $p_T$ cut is chosen to achieve good agreement between the $E_T^{miss}$ distributions from the $\mu+\tau$ region in data and the signal region in simulation, before the application of the $\tau+E_T^{miss}$ trigger. The rest of the event selection of this control region is unchanged from the 2011 analysis.

The $\mu+\tau$ region used for the trigger efficiency measurement is observed to have a high purity of $t\bar{t}$ events. The $E_T^{miss}$ distributions for this region are shown in Fig. 5.6 and the $p_T$ distributions are shown in Fig. 5.7. From these distributions, it can be seen that there is very little expected contamination in these distributions from QCD multi-jet events.
the presence of the muon, and the $\tau + E_T^{miss}$ trigger is then applied in order to investigate differences in the trigger efficiency between data and simulation. The bins are $[40,70]$ and $[70,500]$ GeV in $p_T^{\tau}$ and $[65,80]$, $[80,100]$, and $[100,500]$ GeV in $E_T^{miss}$. The final scale factors are shown in Table 5.4, where the errors are statistical only.

In addition to passing the event preselection (described in Section 4.4), and trigger requirements, events in the 2012 $\tau +$jets analysis must fulfill the following criteria:

1. At least 4 jets with $p_T > 25$ GeV.

   (a) Jets with $p_T < 50$ GeV and $|\eta| < 2.4$ must also satisfy $|JVF| > 0.5$.

   (b) Jets are also accepted without a $JVF$ cut if they satisfy $p_T < 50$ GeV and $|\eta| = (2.4 - 2.5)$ or $p_T > 50$ GeV and $|\eta| < 2.5$.

2. Exactly one $\tau$ lepton with $p_T > 20$ GeV.

3. Selected $\tau$ lepton has to match the trigger $\tau$ object (in $\Delta R < 0.1$) and have $p_T > 40$ GeV.

4. No identified electrons and muons.

5. $E_T^{miss} > 65$ GeV
Figure 5.8: The left plot shows the $p_T^\tau$ of the selected $\tau$ and the right plot shows the $E_T^{miss}$. Both are shown just after the cut requiring no electrons or muons in the event. These plots also contain simulated signal contributions, shown with $m_{H^{\pm}} = 130$ GeV and $B(t \rightarrow H^{\pm}b) = 0.01$.

![Plot showing $p_T^\tau$ and $E_T^{miss}$ distributions](image1)

Figure 5.9: The left plot shows the $E_T^{miss}$ significance, and the right plot shows $m_{jjb}$. Both plots are just before the respective cuts on the variables are applied. These plots also contain simulated signal contributions, shown with $m_{H^{\pm}} = 130$ GeV and $B(t \rightarrow H^{\pm}b) = 0.01$.

![Plot showing $E_T^{miss}$ significance and $m_{jjb}$ distributions](image2)

6. $\frac{E_{T^{miss}}}{\sqrt{\sum p_T^{trk}}} > 13$ GeV$^{1/2}$.

7. At least one $b$-tagged jet.

8. The $jjb$ candidate with the highest $p_T^{jjb}$ value must satisfy $m(jjb) \in [120, 240]$ GeV.

Fig. 5.8 shows the distributions of $p_T^\tau$ and $E_T^{miss}$, at a point in the cut flow just after the requirement that there be no electrons or muons in the event. In Fig. 5.9, $E_T^{miss}$ significance and $m_{jjb}$ are shown just before their respective cuts are applied. In all distributions, the contribution from a hypothetical signal with $m_{H^{\pm}} = 130$ GeV and $B(t \rightarrow H^{\pm}b) = 0.01$, shown in blue, is stacked on top of the SM backgrounds. The SM $t\bar{t}$ cross section is reduced in these distributions, in accordance with the hypothetical signal shown. The discrepancies early in the cut flow are expected to arise from QCD multi-jet backgrounds, which are not simulated. The cuts on $E_T^{miss}$ and $E_T^{miss}$ significance are designed to discriminate against this large
Table 5.5: The yield of background events in 19.4 fb$^{-1}$, with various MC samples and for the light $H^+$ simulation, with $m_{H^\pm} = 130$ GeV and $B(t \to H^+ b) = 0.01$. The yields are reported from MC simulation and data, with no QCD multi-jet backgrounds included. The statistical uncertainties are in parentheses.

<table>
<thead>
<tr>
<th>Selection Criteria</th>
<th>Signal</th>
<th>tt</th>
<th>Single top</th>
<th>W+jets</th>
<th>Z+jets</th>
<th>Diboson</th>
<th>BG Sum</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td>event preselection</td>
<td>6624 (46)</td>
<td>157569 (280)</td>
<td>9656 (98)</td>
<td>94658 (820)</td>
<td>1206 (74)</td>
<td>15 (2)</td>
<td>15131 (216)</td>
<td>35594 (189)</td>
</tr>
<tr>
<td>$\tau$ requirement</td>
<td>1302 (20)</td>
<td>7672 (61)</td>
<td>351 (17)</td>
<td>5887 (193)</td>
<td>2158 (24)</td>
<td>27277 (895)</td>
<td>1673422 (1294)</td>
<td></td>
</tr>
<tr>
<td>lepton veto</td>
<td>1237 (20)</td>
<td>7944 (58)</td>
<td>334 (16)</td>
<td>5816 (191)</td>
<td>1080 (70)</td>
<td>12 (2)</td>
<td>14286 (212)</td>
<td>34848 (187)</td>
</tr>
<tr>
<td>$E_T^{miss}$ selection</td>
<td>636 (14)</td>
<td>4135 (44)</td>
<td>203 (12)</td>
<td>5424 (143)</td>
<td>6 (1)</td>
<td>8194 (156)</td>
<td>8099 (90)</td>
<td></td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>315 (12)</td>
<td>3490 (39)</td>
<td>150 (10)</td>
<td>535 (60)</td>
<td>62 (15)</td>
<td>3 (1)</td>
<td>4200 (74)</td>
<td>4152 (64)</td>
</tr>
<tr>
<td>$m_{jjb}$</td>
<td>294 (9)</td>
<td>1962 (26)</td>
<td>53 (5)</td>
<td>130 (29)</td>
<td>13 (7)</td>
<td>1.1 (0.5)</td>
<td>2059 (41)</td>
<td>2039 (45)</td>
</tr>
</tbody>
</table>

Table 5.6: Signal efficiency determined from simulation, for events passing the full cut flow of the 2012 light $H^\pm$ search in the $\tau$+jets channel.

<table>
<thead>
<tr>
<th>$H^\pm$ mass [GeV]</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$+jets (2012)</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>0.201</td>
</tr>
<tr>
<td>100</td>
<td>0.227</td>
</tr>
<tr>
<td>110</td>
<td>0.262</td>
</tr>
<tr>
<td>120</td>
<td>0.275</td>
</tr>
<tr>
<td>130</td>
<td>0.323</td>
</tr>
<tr>
<td>140</td>
<td>0.325</td>
</tr>
<tr>
<td>150</td>
<td>0.356</td>
</tr>
<tr>
<td>160</td>
<td>0.338</td>
</tr>
</tbody>
</table>

A cut flow table for MC and data is also shown in Table 5.5, showing the expected contributions from different SM processes, a possible signal at $m_{H^\pm} = 130$ GeV and $B(t \to H^+ b) = 0.01$, and the observed data. The table contains no contribution from QCD multi-jet events, which will be estimated using data-driven methods. The efficiencies for signal simulation passing the full cut flow are shown in Table 5.6, as a function of $m_{H^\pm}$.

The discriminating variable of the analysis is the $m_T$ of the $\tau$ lepton and $E_T^{miss}$, which is defined in Equation 5.1. The variable $m_T$ is shown for data and simulation in Fig. 5.10, with a possible signal point of $m_{H^\pm} = 130$ GeV and $B(t \to H^+ b) = 0.01$ stacked on top of the SM contributions.

Control regions (CRs) are regions in data that are designed to enrich certain classes of background events, so that the agreement between data and simulation can be assessed. A major CR for the light $H^\pm$ search is the the QCD CR, which is selected by applying the nominal selection except with an inverted cut on $E_T^{miss}$ and exactly zero $b$-tagged jets. This region has a very small contribution from $H^\pm$ signal events. The inverted $E_T^{miss}$ cut and requirement of zero $b$-tagged jets enrich the data in events containing primarily gluon-initiated jets and falsely reconstructed $E_T^{miss}$. This sample is not expected to be well-described by the sum of the $t\bar{t}$, single top, and $W$+jets MC samples and is used for testing our ability to assess QCD multi-jet background.
Figure 5.10: The discriminating variable at the end of the cut flow, comparing data and simulation. The simulated signal contribution is shown with $m_{H^\pm} = 130$ GeV and $B(t \rightarrow H^+b) = 0.01$. This comparison is done before including data-driven estimations, and with no estimate of QCD multi-jet backgrounds.

5.1.2 $\tau$+Lepton Channel

The $\tau$+lepton channel uses events from the 2011 dataset that pass a single lepton trigger [72, 73]. The electron trigger has an $E_T$ threshold of 20-22 GeV, depending on data period, and the muon trigger has a $p_T$ threshold of 18 GeV. The electrons and muons selected are in the plateau region of their respective triggers’ efficiency curves. In addition to passing the event preselection (described in Section 4.4) and the trigger requirements, events in this channel must pass the following selections:

1. Exactly one lepton, which has $E_T > 25$ GeV (electron) or $p_T > 20$ GeV (muon), and which is matched to its trigger object.

2. Exactly one $\tau$ lepton having $p_T > 20$ GeV and an electric charge opposite to that of the lepton.

3. At least two jets with $p_T > 20$ GeV, $|JVF| > 0.75$ and $|\eta| < 2.4$, with at least one $b$-tagged jet.

4. $\sum p_T^{PV \text{ trk}} > 100$ GeV, where $\sum p_T^{PV \text{ trk}}$ is defined as in the $\tau$+jets event selection.

In the $\tau$+lepton channel, roughly half of the total SM background is expected to arise from events with jets misidentified as hadronically-decaying $\tau$ leptons. The requirement of a well-defined lepton greatly reduces the contribution from QCD multi-jet events, so most of the events with jets misidentified as $\tau$ leptons arise from $t\bar{t}$, $W$+jets, single top, and diboson events. Since $\tau$ properties reconstructed from jets are mis-modeled in simulation, it is not expected that there will be good agreement between simulation and data. Data-driven estimates of backgrounds from jets misidentified as $\tau$ leptons are therefore crucial to the analysis. The signal efficiencies for the $e+\tau$ and $\mu+\tau$ channels from simulation, at the end of their respective event selections, are shown in Table 5.7 as a function of the mass of the generated $m_{H^\pm}$. 

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Table 5.7: Signal efficiency determined from simulation, as a function of $m_{H^\pm}$.

<table>
<thead>
<tr>
<th>$H^\pm$ mass [GeV]</th>
<th>$\tau$+lepton (µ-channel)</th>
<th>$\tau$+lepton ($e$-channel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>0.40</td>
<td>0.32</td>
</tr>
<tr>
<td>100</td>
<td>0.42</td>
<td>0.31</td>
</tr>
<tr>
<td>110</td>
<td>0.42</td>
<td>0.32</td>
</tr>
<tr>
<td>120</td>
<td>0.43</td>
<td>0.31</td>
</tr>
<tr>
<td>130</td>
<td>0.40</td>
<td>0.29</td>
</tr>
<tr>
<td>140</td>
<td>0.35</td>
<td>0.27</td>
</tr>
<tr>
<td>150</td>
<td>0.29</td>
<td>0.23</td>
</tr>
<tr>
<td>160</td>
<td>0.23</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Figure 5.11: A comparison of MC and data in $E_T^{miss}$ for the $\mu+$τ channel (left) and the $e+$τ channel (right) at the end of the cut flow [10].

A comparison of data and simulation is shown in Fig. 5.11, taken from the end of the cut flow. All events with correctly reconstructed electrons and muons are taken from simulation, and the expected QCD multi-jet background is the contribution labeled “Fake Leptons.” This background is predicted using a method that will be described in Chapter 6.

The additional $E_T^{miss}$ contribution in this channel complicates the reconstruction of masses in this system. In the $\tau$+jets channel, the only neutrinos present in the signal decay arise from $H^\pm \to \tau \nu$ and the neutrino from the hadronic decay of the $\tau$ lepton. In the $\tau$+lepton channel, the $E_T^{miss}$ also has a component from the $W \to l\nu$ decay. Due to the effect of this additional $E_T^{miss}$, the variable $m_T(\tau, E_T^{miss})$ has little power to discriminate between signal and background. Therefore, $E_T^{miss}$ is used as the discriminating variable, where its power to separate signal and background is based on the likelihood of events with top quark decays mediated by $H^\pm$ to have more highly energetic neutrinos.
$\Delta B(\tau \nu_{\ell} + X) = \Delta B(\tau \nu_{\ell} + \nu_{\ell}) = \Delta B(\tau \nu_{\ell} + \ell \nu_{\ell})$

Figure 5.12: Relative increase with respect to the SM values of the branching ratios for $t\bar{t}$ events (left), in a $\tau$+lepton or dilepton final state, and of the ratio $R_\ell$ between these branching ratios (right), as a function of $B(t \rightarrow bH^+)$. In both plots, $X = \bar{b}b +$ neutrinos [11].

### 5.1.3 Ratio Method

The Ratio Method search is designed to detect an apparent violation of lepton universality in a ratio of event yields from top quark pair decays. The leptonic decay of the $W^\pm$ is expected by the SM to have equal branching fractions for each flavor of lepton. If $H^\pm$, which decays preferentially into $\tau$ leptons, replaces a $W$ boson in a fraction of $t\bar{t}$ decays, the effect would be to increase the total yield of events with $\tau$ final states. This would appear to violate the lepton universality of the $W$ decay, though the apparent violation would actually be evidence for the existence of a new particle. The ratio of yields is defined as:

$$R_\ell = \frac{B(t\bar{t} \rightarrow b\bar{b} + \ell \nu_{\ell} + N\nu)}{B(t\bar{t} \rightarrow b\bar{b} + \ell' \nu_{\ell} + N\nu)}$$

where $\ell = e, \mu$, and the denominator case has two leptons of different flavor. The presence of a $H^\pm$ signal would affect both the numerator and denominator. Fig. 5.12 shows the expected relative shifts in theoretical branching fraction for both $\tau$+lepton and dilepton events as a function of $B(t \rightarrow bH^+)$, as well as the relative shift in the ratio of the two branching fractions. For these plots, a mass point of $m_{H^\pm} = 130$ GeV is used as an example of the hypothetical signal. The presence of $H^\pm$ mediating the top quark decay would result in a higher fraction of total $\tau$ leptons, which can decay leptonically or hadronically. Therefore, the $H^\pm$ signal can contribute to the denominator definition through a leptonically-decaying $\tau$ lepton.

The motivation for using a ratio of yields is to increase sensitivity by reducing the total systematic uncertainty of the analysis. In the ratio, uncertainties from luminosity determination and trigger efficiencies, as well as those associated with reconstruction, identification, and energy scales of leptons and jets, are
expected to equivalently affect the numerator and denominator. The main remaining source of uncertainty
are the those associated with the $\tau$, which affect only the numerator, and the uncertainties of data-driven
methods.

The analysis relies on a single lepton trigger, with the same $p_T$ thresholds as the $\tau$+lepton search of
the previous analysis. One change is introduced in this analysis with respect to the usual overlap removal
described in Section 4.3.6. Instead of discarding all jets that overlap with selected $\tau$ leptons, only jets that
are not $b$-tagged are discarded. If a reconstructed jet is $b$-tagged, the overlapping $\tau$ lepton is discarded
instead. This is done to both reduce the possible background from $b$-jets misidentified as $\tau$ leptons, as well
as to increase the acceptance of $b$-tagged jets. In addition to passing the event preselection, described in
section 4.4, this modified overlap removal, and the trigger requirements, events in this channel must pass
the following selections:

- One charged lepton $\ell(e, \mu)$ with $E_T(p_T) > 25$ GeV for electron (muon), matched to a trigger object
- At least 2 jets with $p_T > 20$ GeV and $|\eta| < 2.4$ and $|JVF| > 0.75$, with exactly 2 $b$-tagged jets
- Either exactly one $\tau$ or one lepton $(e, \mu)$ of a different flavor than the lepton that is matched to a
  trigger object, with $E_T$ (electron) or $p_T$ ($\tau$, muon) greater than 25 GeV.
- $E_T^{miss} > 40$ GeV

At this point, the events are are separated into two categories, based on the flavor of the lepton that is
matched to a trigger object. The electron category contains $e + \tau$ and $e + \mu$ events, and the muon category
contains $\mu + \tau$ and $\mu + e$ events. Events that fire both an electron and muon trigger are assigned to both
categories, and this overlap is taken into account in limit setting. These two categories form two ratios that
are combined for the final limits, defined as:

$$R_e = \frac{N(e + \tau)}{N(e + \mu)} \quad \text{and} \quad R_\mu = \frac{N(\mu + \tau)}{N(\mu + e)} \quad (5.3)$$

In addition to deriving results from the yield ratios, a new mass variable with possible discriminating
power is considered. This variable is the generalized transverse mass variable, $M_{T2}^H$, which gives an event-
by-event lower bound on the mass of the charged boson ($W$ or Higgs) produced in the top quark decay
[74].

For the definition of $M_{T2}$, one must look at the under-constrained system of equations that arises from
$t\bar{t}$ events that decay in the $\tau$+lepton channel.
\[(p^{H\pm} + p^b)^2 = m_{top}^2\] (5.4)

\[(p^\ell + p^{\bar{\nu}_e})^2 = m_W^2\] (5.5)

\[(p^\ell + p^{\bar{\nu}_e} + p^b)^2 = m_{top}^2\] (5.6)

\[(p^{\bar{\nu}_e})^2 = 0\] (5.7)

\[(p^{H^+} - p^{\tau^+_\text{had}} + p^{\bar{\nu}_e} - p^b)^2 = \not{p}_T^{miss}\] (5.8)

The variables \(p^{H\pm}\) and \(p^{\bar{\nu}_e}\) are the unknown quantities, as more than one neutrino accounts for the \(E_T^{miss}\).

These constraints leave two free parameters, over which the \(H^\pm\) mass is maximized in order to compute \(M_{T2}^H\). With one of the free parameters as the \(z\)-component of \(p^{H^+}\), the maximization is performed as follows:

\[M_{T2}^H = \max_{\text{constraints}} [m_T^H(\not{p}_T^{H^+})]\] (5.9)

with \(m_T^H(\not{p}_T^{H^+})\) as:

\[(m_T^H(\not{p}_T^{H^+}))^2 = (\sqrt{m_{top}^2 + (\not{p}_T^{H^\pm} + \not{p}_T^b)^2 - \not{p}_T^b})^2 - (\not{p}_T^{H^+})^2\] (5.10)

The maximization of the second free parameter is performed numerically. Thus, in the signal case, the mass would be greater than the actual \(m_{H^\pm}\) but less than \(m_{top}\). The use of \(M_{T2}^H\) is the motivation behind requiring exactly 2 \(b\)-tagged jets, as these jets are needed for the calculation.

In order to calculate this mass, it is necessary to define two sides of the event, an “\(H^+\)-side” and a “\(W\)-side”. The two sides of the event are defined by assigning the \(b\)-jets to the other visible decay of their respective top quarks. The mass \(M_{T2}^H\) is then calculated using the objects on the “\(H^+\)-side” of the event.

In \(\tau+\text{lepton}\) events, the \(b\)-jet assignment is chosen as the combination that minimizes the \(\Delta R\) between each \(b\)-jet and their assigned \(\tau\) or lepton \((\Delta R(b_1, \ell) + \Delta R(b_2, \tau))\). According to simulation studies, this assignment method has an efficiency of about 70\%. After this assignment, the side of the event with a \(\tau\) lepton and \(b\)-jet is defined as the “\(H^+\)-side” of the event, where \(M_{T2}^H\) is calculated, and the other pair of lepton and \(b\)-jet is defined as the “\(W\)-side” of the event.

In dilepton events, the \(b\)-jets are assigned to the two charged leptons in the same way, and the efficiency for matching the \(b\)-jets successfully is about 76\%. In these events, the side with the lepton that has fired the trigger is defined as the “\(W\)-side”, and the other side of the event is used to calculate \(M_{T2}^H\). Events in both the \(\tau+\text{lepton}\) and dilepton channels with a \(M_{T2}^H\) of zero arise from incorrect pairings of \(b\)-jets and the
leptons (e, µ, τ) of the event, and so these events are discarded.

5.2 Heavy $H^{\pm}$ Strategy

The 2012 search for a heavy $H^{\pm}$ decaying to a $\tau$ lepton and neutrino is conducted on a dataset of 19.5 ±0.5 fb$^{-1}$ at $\sqrt{s} = 8$ TeV. While the heavy $H^{\pm}$ ($m_{H^{\pm}} > m_{t_{\text{top}}}$) is not produced in a top quark decay, the final state remains rather similar to that of the $\tau$+jets channel in the light $H^{\pm}$ searches. This specific final states that are included in this search are of the topology:

\begin{align}
    gb & \rightarrow [t] \; [H^+] \rightarrow [(jj)b] \; [(\tau^+_\text{had} + E_T^{\text{miss}})] \\
    gg & \rightarrow [tb] \; [H^+] \rightarrow [(jj)bb] \; [(\tau^+_\text{had} + E_T^{\text{miss}})]
\end{align}

where the top quark decays to a $W$ boson and $b$ quark, and both the $W$ boson and the $\tau$ lepton decay hadronically. These channels correspond to the right two diagrams shown in Fig. 2.1. This topology has several advantages: the fact that the $H^+$ candidate can be reconstructed in the transverse plane, that the top mass can be reconstructed, and that there is a large branching fraction for $W$ decaying into hadrons.

For the heavy $H^{\pm}$ signal reference points in this thesis, $B(H^{\pm} \rightarrow \tau \nu) = 100\%$ is assumed for quoted yields. The reference point for signal given throughout this thesis is for $m_{H^{\pm}} = 250$ GeV and $\tan \beta = 30$, which actually has a corresponding branching fraction in the $m_h$-max scenario of the MSSM of $B(H^{\pm} \rightarrow \tau \nu) \approx 39\%$. However, the reference point for signal is intended primarily to show cut efficiencies and shape differences, which is unaffected by this inflation of the overall normalization. Furthermore, the final results will be quoted in terms of $\sigma_{H^+} \times B(H^{\pm} \rightarrow \tau \nu)$, with no assumption on branching fractions or specific MSSM models.

This channel uses the same triggers as described in the 2012 light $H^{\pm}$ search, as well as the same trigger scale factors and uncertainties. The trigger efficiencies, as measured in a simulated signal sample of $m_{H^{\pm}} = 250$ GeV, are shown in Fig. 5.13. In addition to passing the event preselection (described in Section 4.4) and the trigger requirements, the event selection consists of the following requirements:

1. At least 3 jets with $p_T > 25$ GeV.
   
   (a) Jets with $p_T < 50$ GeV and $|\eta| < 2.4$ must also satisfy $|JVF| > 0.5$.
   
   (b) Jets are also accepted without a $JVF$ cut if they satisfy $p_T < 50$ GeV and $|\eta| = 2.4 - 2.5$ or $p_T > 50$ GeV and $|\eta| < 2.5$.

2. Exactly one $\tau$ lepton with $p_T > 20$ GeV.
Figure 5.13: The efficiencies of the three $\tau + E_T^{miss}$ triggers used for in 2012 data. The first data period is on the left, the second is in the middle, and the third is on the right. Efficiencies are shown with respect to $p_T^\tau$ and $E_T^{miss}$ [9].

3. Selected $\tau$ lepton has to match the trigger $\tau$ object (in $\Delta R < 0.1$) and have $p_T > 40$ GeV.

4. No identified electrons and muons.

5. $E_T^{miss} > 80$ GeV.

6. $E_T^{miss} > 80$ GeV.

7. At least one $b$-tagged jet.

8. The $jjb$ candidate with the highest $p_T^{jjb}$ value must satisfy $m(jj b) \in [120, 240]$ GeV.

The distributions for $p_T^\tau$ and $E_T^{miss}$ are shown in Fig. 5.14, at the point in the cut flow just after the requirement for the event to have no electrons or muons. In Fig. 5.15, the $E_T^{miss}$ significance and $m_{jjb}$ are shown just before the respective cuts on those variables are applied. In all distributions, the contribution from a signal with $m_{H^\pm} = 250$ GeV and ten times the cross section at $\tan \beta = 30$ in the $m_h$-max scenario of the MSSM, shown in blue, is stacked on top of the expected SM backgrounds. As in the light $H^\pm$ search, a large contribution is expected from QCD multi-jet backgrounds early in the cut flow, and this background is not included in these plots. The cuts on $E_T^{miss}$ and $E_T^{miss}$ significance are primarily designed to discriminate against this large background.

The expected cut flow is shown in Table 5.8, with contributions from a signal with $m_{H^\pm} = 250$ GeV and the $m_h$-max scenario cross section at $\tan \beta = 30$, simulated SM backgrounds, data, and no estimation of
Figure 5.14: The left plot shows the $p_T^{\tau}$ of the selected $\tau$ and the right plot shows the $E_T^{miss}$, just after the cut requiring no electrons or muons in the event. These plots also contain simulated signal contributions, shown with $m_{H^\pm} = 250$ GeV and shown with the production cross section of the $m_h$-max scenario of the MSSM at $\tan(\beta) = 30$, scaled by a factor of 10.

Figure 5.15: The left plot shows the $E_T^{miss}$ significance, just before the cut is applied, and the right plot shows $m_{jjb}$ just before the cut window is applied. These plots also contain simulated signal contributions, shown with $m_{H^\pm} = 250$ GeV and shown with the production cross section of the $m_h$-max scenario of the MSSM at $\tan(\beta) = 30$, scaled by a factor of 10.
Table 5.8: The yield of background events in 19.4 fb$^{-1}$ for various MC samples passing the heavy $H^\pm$ event selection, in the signal MC sample ($m_{H^\pm} = 250$ GeV), and in the data (19.5 fb$^{-1}$). The signal MC has been normalized to the MSSM $m_h - max$ production cross-section and the branching fraction to $B(H^\pm \to \tau \nu)$ is set to 100%. The yields are reported from MC simulation and data with statistical uncertainties in parentheses.

<table>
<thead>
<tr>
<th>Selection Criteria</th>
<th>Signal</th>
<th>tt</th>
<th>Single top</th>
<th>W+jets</th>
<th>Z+jets</th>
<th>Diboson</th>
<th>BG Sum</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td>event preselection</td>
<td>966 (9)</td>
<td>240347 (343)</td>
<td>21850 (149)</td>
<td>290894 (11450)</td>
<td>21533 (319)</td>
<td>8112 (46)</td>
<td>582736 (1532)</td>
<td>4493688 (2120)</td>
</tr>
<tr>
<td>$\tau$ requirement</td>
<td>254 (5)</td>
<td>12991 (78)</td>
<td>859 (27)</td>
<td>19137 (374)</td>
<td>3483 (127)</td>
<td>73 (4)</td>
<td>36544 (404)</td>
<td>103720 (322)</td>
</tr>
<tr>
<td>lepton veto</td>
<td>43 (5)</td>
<td>11335 (73)</td>
<td>819 (26)</td>
<td>18933 (372)</td>
<td>3138 (120)</td>
<td>57 (4)</td>
<td>34284 (404)</td>
<td>101783 (319)</td>
</tr>
<tr>
<td>$E_T^{miss}$ selection</td>
<td>183 (4)</td>
<td>7098 (57)</td>
<td>521 (20)</td>
<td>11911 (306)</td>
<td>1385 (79)</td>
<td>3483 (127)</td>
<td>73 (4)</td>
<td>34282 (398)</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>119 (3)</td>
<td>5127 (50)</td>
<td>361 (16)</td>
<td>1008 (179)</td>
<td>118 (7)</td>
<td>616 (158)</td>
<td>46 (15)</td>
<td>3457 (162)</td>
</tr>
</tbody>
</table>

QCD multi-jet events. The dominant background in the channel, at the end of the cut flow, arises from $t\bar{t}$ events. The total signal efficiency of the event selection, as determined from simulation, is given in Table 5.9 as a function of the generated $m_{H^\pm}$.

In order to illustrate the shape differences between $H^\pm$ and backgrounds, some cut variables are shown in Fig 5.17, Fig 5.18, and Fig 5.19. These plots follow the heavy $H^\pm$ cut selection, and show an overlay of three $H^\pm$ masses: 130 GeV, 250 GeV, and 500 GeV. Shown in Fig 5.17, the $p_T^{\tau}$ appears to increase, on average, as a function of increasing $m_{H^\pm}$. However, the cut at $p_T > 40$ GeV is motivated more by the $\tau$ trigger’s $p_T$ threshold than by discrimination against backgrounds. In the $E_T^{miss}$ distribution, shown in Fig 5.17, there is a tendency towards higher $E_T^{miss}$ with increasing $m_{H^\pm}$. This, along with the stronger discrimination against QCD multi-jet backgrounds, is why the $E_T^{miss}$ cut is raised to 80 GeV for the heavy $H^\pm$. A similar trend is seen with $E_T^{miss}$ significance, shown in Fig 5.18.

The number of $b$-tagged jets, shown in Fig 5.18, illustrates that the light $H^\pm$, which occurs in $t\bar{t}$ decays, tends to have 2 $b$-tagged jets, while the top-associated production of $H^\pm$ is more likely to have 1 $b$-tagged jet. The reconstructed top mass $m_{jjb}$, shown in Fig. 5.19, is used to remove some of the remaining non-$t\bar{t}$ backgrounds.

The final discriminating variable is $m_T(\tau, E_T^{miss})$, as in the light $H^\pm$ search in the $\tau$+jets channel. The $m_T$ variable is defined in Equation 5.1, and is shown in Fig. 5.16 at the end of the cut flow of the heavy $H^\pm$ search. The $m_T$ distribution displays data, a signal sample of $m_{H^\pm} = 250$ GeV, and backgrounds from

Table 5.9: The signal efficiency, as determined from simulation, as a function of $m_{H^\pm}$.

<table>
<thead>
<tr>
<th>$H^\pm$ mass [GeV]</th>
<th>Efficiency (%)</th>
<th>$H^\pm$ mass [GeV]</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>1.094</td>
<td>350</td>
<td>2.145</td>
</tr>
<tr>
<td>190</td>
<td>1.137</td>
<td>400</td>
<td>2.442</td>
</tr>
<tr>
<td>200</td>
<td>1.214</td>
<td>450</td>
<td>2.481</td>
</tr>
<tr>
<td>225</td>
<td>1.417</td>
<td>500</td>
<td>2.633</td>
</tr>
<tr>
<td>250</td>
<td>1.643</td>
<td>550</td>
<td>2.875</td>
</tr>
<tr>
<td>275</td>
<td>1.742</td>
<td>600</td>
<td>2.841</td>
</tr>
<tr>
<td>300</td>
<td>1.933</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

56
Figure 5.16: The discriminating variable at the end of the cut flow, comparing data and simulation. The simulated signal contribution is shown with $m_{H^{\pm}} = 250$ GeV and shown with the production cross section of the $m_{h}$-max scenario of the MSSM at $\tan \beta = 30$, scaled by a factor of 10. This comparison is done before including data-driven estimations, and with no estimate of QCD multi-jet backgrounds.

Figure 5.17: Comparison of MC electroweak backgrounds (non-multijet backgrounds) and a few signal simulation samples (with $m_{H^{\pm}} = 130, 250, 500$ GeV). Shown are (left) the $\tau$ candidate’s $p_{T}$ after event preselection and trigger requirements, (right) the $E_{T}^{miss}$ after $\tau$ selection. The signal MC samples are normalized to have the same integral as the sum of the non-signal MC samples, so that a direct shape comparison can be made [9].

The heavy $H^{\pm}$ search uses the same QCD CR as the 2012 light $H^{\pm}$ search, but it also makes use of a top quark dominated control region, called the Top CR. This region is selected by requiring the nominal selection, but with the $b$-jet requirement tightened to exactly two $b$-tagged jets and an additional cut of $m_{T} < 60$ GeV. This is designed to enrich the data in events consistent with the $t\bar{t}$ topology, while leaving only a small fraction of possible signal from heavy $H^{\pm}$. The requirement of exactly two $b$-tagged jets also has a lower efficiency on heavy $H^{\pm}$ events than on $t\bar{t}$ events, due to the fact that the heavy $H^{\pm}$ events either have no second $b$-jet or have a second $b$-jet whose $p_{T}$ is low enough that $b$-tagging is much less efficient.
Figure 5.18: Comparison of simulated backgrounds and a few signal simulation samples (with $m_{H^+} = 130, 250, 500$ GeV). Shown are (left) the $E_T^{\text{miss}}$ significance after $\tau$ lepton selection, and (right) the number of tagged $b$-jets after $E_T^{\text{miss}}$ and $E_T^{\text{miss}}$ significance selection. The signal MC samples are normalized to have the same integral as the sum of the non-signal MC samples, so that a direct shape comparison can be made [9].

Figure 5.19: Comparison of simulated backgrounds and a few signal simulation samples (with $m_{H^+} = 130, 250, 500$ GeV). Shown are (left) the reconstructed hadronic top decay mass after requiring at least one $b$-tagged jet and (right) the transverse mass of the $\tau$ lepton and $E_T^{\text{miss}}$ after windowing on the top mass. The signal MC samples are normalized to have the same integral as the sum of the non-signal MC samples, so that a direct shape comparison can be made [9].

Since the background to this analysis is dominated by $t\bar{t}$ events, this control region is used to check the $t\bar{t}$ shape modeling and normalization. In Fig. 5.20, the distributions with data and simulation are shown for $m_{jjb}$, $E_T^{\text{miss}}$, and $p_T^{\tau}$. The shape and normalization appear to agree reasonably well in this region. A closer look is taken at the mass peak in the distribution of $m_{jjb}$, where the data and simulation appear to have some disagreement.
Figure 5.20: Comparison of simulated backgrounds and data in the Top CR. These are “N-1” plots, where the variable shown has no control region selection applied to it but the remaining variables do have the control region selection applied [9].
Chapter 6

Background Estimation

6.1 Background Categorization

In this chapter, the background estimation methods used for each analysis will be described. The hadronically-decaying $\tau$ lepton is central to this analysis, and the background estimation techniques differ based on the object from which the reconstructed $\tau$ lepton originates. For this reason, the backgrounds in these analyses are separated corresponding to which object is reconstructed as a $\tau$ lepton, rather than by SM process. Electrons, muons, and various types of jets can be misidentified as a hadronically-decaying $\tau$ lepton. Major SM backgrounds also arise from events with a correctly reconstructed hadronically-decaying $\tau$ lepton. A description of the different categories of backgrounds, as well as the SM processes that contribute to them, now follows.

6.1.1 True $\tau$ Lepton Backgrounds

Events with correctly reconstructed hadronically-decaying $\tau$ leptons are a major SM background in all of the $H^{\pm}$ searches. These are primarily $t\bar{t}$ events, but some significant contributions can also arise from $W \rightarrow \tau\nu$+jets or single top events. The portion from $t\bar{t}$ events events generally shares a physical final state with the signal, so it is very difficult to reduce this background in the cut selection. The main source of discrimination between these $t\bar{t}$ backgrounds and signal processes is seen in the discriminating variables that are used to generate results.

The background from correctly reconstructed $\tau$ leptons can be taken from simulation, though this requires taking into account all simulation-related systematic uncertainties. These include the uncertainties on centrally provided scale factors, as well as those corresponding to the energy scales of physics objects, theory cross section and generator-related uncertainties. In the 2011 $\tau$+jets analysis, this background is estimated using a data-driven method called ‘embedding’, where simulated hadronically-decaying $\tau$ leptons are embedded into data events. The systematic uncertainties are reduced by using this method, since the entire event is taken directly from data, with the exception of the simulated $\tau$ lepton.
6.1.2 Lepton → τ Backgrounds

Due to the rejection power of the multivariate muon and electron vetos, backgrounds with leptons misidentified as hadronically-decaying τ leptons make up a very small part of the total background (< 5% in all cases, and sometimes much smaller). The remaining background, which can arise from t\bar{t}, single top, or W/Z+jets, is taken from simulation. For events with a 1-prong reconstructed τ lepton truth-matched to an electron, the simulated expectation is modified with centrally provided scale factors, which are based the ratio of the electron veto efficiency in data and simulation.

6.1.3 Jet → τ Backgrounds

The background contribution arising from events with jets that are misidentified as τ leptons is particularly challenging to evaluate. These jet → τ events consist primarily of QCD multi-jet, t\bar{t} and W+jets events, and each process has a different jet composition for τ candidates. QCD multi-jet events tend to be dominated by gluon initiated jets, W+jets are typically dominated by light quark initiated jets, and t\bar{t} events are a mixture of the two, in addition to having a non-negligible contribution of b-jets. For the terminology of the description of this background, light quarks will be considered to correspond to all first and second generation quarks (u, d, c, s).

These differences in composition are especially challenging, since gluons, light quarks, and b-jets each have a different probability of being reconstructed as a τ lepton. The expected misidentification probabilities of the three main sources of jets can be seen in Fig. 6.1 for the 2011 τ Likelihood identification and Fig. 6.2 for the τ BDT identification used in 2012. These probabilities are measured from simulated t\bar{t} events, for τ candidates truth-matched to light quarks, gluons or b-jets. While the absolute misidentification probability measured in simulation is unreliable, it is useful to see the relative differences in the probabilities for jets originating from different particles. In general, light quarks have the highest misidentification probability, gluons have the lowest, and b-jets are between the two.

Other sources of difficulty in the evaluation of this background are the lack of simulated events in adequate statistics, and the mis-modeling of the simulated τ identification. For QCD multi-jet events, simulated samples with statistics sufficient for creating variable distributions do not exist. Due to the large production cross section of these events at the LHC, and the very small probability for events to pass the final event selections of the analyses described in this thesis, creation of a sufficiently large simulated dataset is not feasible. Furthermore, the τ identification response is mis-modeled for jets in simulated events, so it is also not advisable to use simulation for jet → τ backgrounds arising from t\bar{t} or W+jets events. Therefore, it is necessary to estimate the jet → τ backgrounds in a data-driven way. Finding a way to accurately and
Figure 6.1: Probabilities for jets to be misidentified as $\tau$ leptons, as a function of $p_T$ for 1-track (left) or 3-track (right) $\tau$ candidates, for the use of the 2011 $\tau$ Likelihood identification. The probabilities shown are measured from light quark jets (full circles), $b$ jets (open circles), and gluon jets (triangles) in simulated $t\bar{t}$ events.

Figure 6.2: Probabilities for jets to be misidentified as $\tau$ leptons, as a function of $p_T$ for 1-track (left) or 3-track (right) $\tau$ candidates, for the use of the 2012 $\tau$ BDT identification. The probabilities shown are measured from light quark jets (full circles), $b$ jets (open circles), and gluon jets (triangles) in simulated $t\bar{t}$ events.

precisely estimate this background is a major challenge of all channels that contain hadronically-decaying $\tau$ leptons.

For the 2011 searches, the contributions from jets misidentified as $\tau$ leptons are separated into QCD multi-jet events and non-QCD events, and different data-driven techniques are used to estimate each contribution. For the QCD multi-jet events, the methods used to predict the background involve template
fitting or a matrix method based on lepton misidentification. The non-QCD jet events are estimated using \( \tau \) identification efficiencies measured in data applied to simulated \( \tau \) candidates. In the 2012 searches, a data-driven method is developed to estimate both the QCD and non-QCD jet background together, with no reliance on simulated jets. This method uses binned weights calculated from true \( \tau \) lepton efficiencies and jet misidentification probabilities. These weights are then applied to \( \tau \) candidates in the data signal region, constructing the distributions for the total expected contribution of the jet \( \to \tau \) background.

### 6.2 Light \( H^\pm \)

#### 6.2.1 \( \tau + \)Jets Channel

In the \( \tau + \)jets channel, the dominant SM background is composed of events with correctly reconstructed \( \tau \) leptons. Other backgrounds consist of QCD multi-jet events, non-QCD jet \( \to \tau \) events, and lepton \( \to \tau \) events. The jet \( \to \tau \) contributions are expected to have a peak above 100 GeV in \( m_T \), which is the region with a higher fraction of hypothetical signal. This shape is sculpted purely by kinematic cuts on \( p_T \) and \( E_T^{\text{miss}} \), as well as the reliance of \( m_T \) on \( \Delta \phi(\tau, E_T^{\text{miss}}) \). While jet \( \to \tau \) events make up a smaller fraction of the total SM background, this expected shape in the final discriminating variable makes it especially important to have an accurate and precise prediction of the shape and yield of the jet \( \to \tau \) background.

In the 2011 analysis, both true \( \tau \) and jet \( \to \tau \) backgrounds are estimated using data-driven methods. In the 2012 analysis, different data-driven techniques are used to estimate the total jet \( \to \tau \) background, and the true \( \tau \) lepton background is taken from simulation. In both searches, the small contribution from lepton \( \to \tau \) is taken from simulation, and standard scale factors are applied.

**Non-QCD Jet \( \to \tau \) (2011)**

For the non-QCD jet \( \to \tau \) background in the 2011 analysis, the idea behind the data-driven method is to replace the \( \tau \) identification response in simulated events with a misidentification probability that is measured in data.

The misidentification probability is measured in a \( W + \)jets region in a data sample corresponding to an integrated luminosity of 4.6 fb\(^{-1}\). This region contains a relatively pure sample of jets misidentified as \( \tau \) candidates, with a jet composition dominated by light quarks. For this region, an event selection is applied that requires:

1. Event preselection (described in Section 4.4), and the firing of one of the single lepton triggers required by the \( \tau + \)lepton channel (described in Section 5.1.2).
2. One electron or muon, with $E_T > 25$ GeV (electron) or $p_T > 20$ GeV (muon), which must also be matched to a trigger object.

3. Number of $b$-tagged jets = 0.

4. At least one $\tau$ candidate with $p_T > 20$ GeV

The $\tau$ candidates are the denominator of the misidentification probability, $m_{\tau,j}$, and numerator objects are the subset of $\tau$ candidates that also pass the $\tau$ identification requirement:

$$m_{\tau,j} = \frac{\text{number of } \tau \text{ candidates passing object selection and } \tau \text{ ID}}{\text{number of } \tau \text{ candidates passing object selection}}$$

The misidentification probability is measured per jet, and binned in the $p_T$, $|\eta|$, and number of associated jets.

Figure 6.3: Probabilities for jets to be misidentified as $\tau$ leptons, as functions of $p_T$ (top) and $|\eta|$ (bottom), for 1-track (left) or 3-track (right) $\tau$ candidates. The probabilities shown are measured in ATLAS data (full circles) and Monte Carlo simulation (open circles) [12].
charged tracks (one or three) of the reconstructed $\tau$ lepton. The misidentification probabilities are shown in Fig. 6.3, measured both in the 2011 dataset and in simulated events. For $\eta$, the three bins are $|\eta| < 1.37$, $1.37 < |\eta| < 1.52$, and $|\eta| > 1.52$, which corresponds to the barrel, transition region, and end-cap regions of the detector. The transition region is the section where the thickness of material in front of the electromagnetic calorimeter results in a lower performance. As expected, there are some discrepancies in the measurement of misidentification probabilities between data and simulation.

One concern in the estimation of jet→$\tau$ backgrounds is that the jet composition in $t\bar{t}$ may not be similar to that found in the $W+$jets region, where the misidentification probability is measured. Table 6.1 and Table 6.2 show the composition of $\tau$ candidates not matched to true hadronically-decaying $\tau$ leptons in the signal and $W+$jets regions, for 1- and 3-prong $\tau$ candidates, respectively.

The composition is similar between the signal and background regions for 1-prong $\tau$ leptons, but significantly different for the 3-prong case. The majority of the background arises from 1-prong $\tau$ leptons, so the effect of the difference in composition is taken as a systematic uncertainty. To calculate this systematic uncertainty, the separate fake rates for gluons, light quarks, and $b$ quarks are measured in simulation, and the prediction of jet composition in the $W+$jets and signal regions is also taken from simulation. Then, the fake rates measured for gluons, light quarks, and $b$-jets are combined in the expected ratios for each region, and the bin-by-bin difference in misidentification probabilities is taken as the variation between regions due to differing jet composition.

In order to apply the misidentification probability to the signal region, a modified event selection is initially applied. This requires events to pass most of the event selection, with the exception of the $\tau$ lepton requirements, jet-related requirements, or the overlap removal between $\tau$ leptons and jets in the event. At

<table>
<thead>
<tr>
<th>Truth particle</th>
<th>$W + $ Jets</th>
<th>Signal Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light quarks</td>
<td>79 %</td>
<td>74 %</td>
</tr>
<tr>
<td>$b$ quarks</td>
<td>&lt; 2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Gluons</td>
<td>19 %</td>
<td>24 %</td>
</tr>
<tr>
<td>Leptons</td>
<td>&lt; 2 %</td>
<td>&lt; 0.1 %</td>
</tr>
</tbody>
</table>

Table 6.1: Composition of 1-track $\tau$ candidates not matched to true $\tau$ leptons in simulated events.

<table>
<thead>
<tr>
<th>Truth particle</th>
<th>$W + $ Jets</th>
<th>Signal Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light quarks</td>
<td>72 %</td>
<td>47 %</td>
</tr>
<tr>
<td>$b$ quarks</td>
<td>&lt; 1 %</td>
<td>16 %</td>
</tr>
<tr>
<td>Gluons</td>
<td>17 %</td>
<td>37 %</td>
</tr>
<tr>
<td>Leptons</td>
<td>&lt; 1 %</td>
<td>&lt; 0.1 %</td>
</tr>
</tbody>
</table>

Table 6.2: Composition of 3-track $\tau$ candidates not matched to true $\tau$ leptons in simulated events.
least one $\tau$ candidate is then required, and a method is applied to determine whether each $\tau$ candidate has a possibility of contributing to the background.

To evaluate whether the $\tau$ candidate could possibly contribute to the background, the event is considered with each $\tau$ candidate separately promoted to a selected $\tau$ lepton. The identified jet that corresponds to the $\tau$ candidate is removed from the event, and this is propagated through the determination of the number of reconstructed jets, $b$-tagged jets, and the calculation of $m_{jjb}$. If the event still passes the baseline selection, then that $\tau$ candidate is kept as a possible identified $\tau$ lepton. If the event does not pass the selection, the $\tau$ candidate is discarded.

The remaining $\tau$ candidates are then weighted by the misidentification probability corresponding to their reconstructed $p_T$, $|\eta|$, and number of associated charged tracks. For the case of multiple $\tau$ candidates in a single event, the weight must also take into account that the baseline selection accepts only events with exactly one $\tau$ lepton. Therefore, the misidentification probability for each $\tau$ must be modified by the probability that the other $\tau$ candidates will not be identified as a $\tau$ lepton. The weight for each $\tau$ candidate takes the form:

$$p_{\text{total},i} = p_i \prod_{j \neq i} (1 - p_j)$$

where $i$ denotes the $\tau$ candidate in question, and the product is over all other $\tau$ candidates. Distributions that rely on $\tau$ properties, such as the discriminating variable $M_{T}(\tau, E_{T}^{\text{miss}})$, are calculated using the $\tau$ candidate and its misidentification weight.

Before applying the misidentification probability in the signal region, the method is tested in a control
Figure 6.5: Predicted distribution and uncertainty from the data-driven method of estimating backgrounds with jets misidentified as $\tau$ leptons in the 2011 $\tau$+jets channel.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>$33 \pm 1$ (stat)</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>$2.5 \pm 0.1$ (stat)</td>
</tr>
<tr>
<td>Single top</td>
<td>$1.3 \pm 0.1$ (stat)</td>
</tr>
</tbody>
</table>

Table 6.3: Yields, separated by physics sample, for the data-driven estimation of the non-QCD background from jets misidentified as $\tau$ leptons, for the 2011 $\tau$+jets channel.

QCD Jet $\rightarrow \tau$ (2011)

The remaining jet $\rightarrow \tau$ background in the 2011 $\tau$+jets channel search is composed of QCD multi-jet events, and it is estimated using a data-driven method that uses template fitting techniques. In this method, a template for the distribution shape of $E_T^{\text{miss}}$ from QCD multi-jet events in the signal region is taken from a QCD-rich region in data. This template is fitted to the signal region data in the baseline selection, along
Figure 6.6: Comparison of the shape of $E_T^{\text{miss}}$ in a control region of the data and using the baseline selection. The baseline distribution is shown after subtracting the expectation from $t\bar{t}$ events, $W$+jets, and single top quark processes, as estimated from simulation. The distributions are compared early in the cut flow, just before the $E_T^{\text{miss}}$ distribution [12].

with the shape of simulated non-QCD events. The control region for the QCD multi-jet template is defined by a selection that is orthogonal to the signal region. It requires the following:

1. One $\tau$ candidate passing a looser requirement on the $\tau$ Likelihood identification, but not the tighter requirement of the baseline selection.

2. Exactly zero $b$-tagged jets.

3. Since there are no $b$-tagged jets, the requirement on the reconstructed $m_{bjj}$ is removed.

In order for the $E_T^{\text{miss}}$ shape of the control region to be an acceptable template for the QCD multi-jet background in the signal region, it must be shown that their shapes are sufficiently similar. To check this, the distributions are compared very early in the event selection, after event cleaning, trigger requirements, $\tau$ selection, and the requirement that there are no additional leptons in the event. Contributions from $t\bar{t}$, $W$+jets, and single top quark processes are subtracted from both regions using simulated events. At this point, the control region consists of 99.4% QCD multi-jet events.

The comparison of the two regions is shown in Fig 6.6. The template fitting relies on the assumption that the distributions will still agree, within uncertainty, after the full event selection is applied. The discrepancies that are observed in this early shape comparison are taken into account as systematic uncertainties.

At this point, the final QCD multi-jet template is obtaining by applying the full event selection to the control region sample. As before, simulation is used to subtract the contributions from $t\bar{t}$, $W$+jets and single top events from the distribution. This QCD multi-jet template and the sum of all contributions from $t\bar{t}$, $W$+jets, and single top, as predicted by simulation, are then fitted to the signal region data. The overall normalization and the QCD fraction are the free parameters of the fit, and the individual bins in the $E_T^{\text{miss}}$
template shapes are fixed.

The result of the fit in the $E_T^{\text{miss}}$ distribution is shown in Fig. 6.7. The QCD fraction is determined to be $(20.7 \pm 6.4)\%$, where the error includes only statistical effects. The systematic uncertainties of the method are evaluated in the following ways:

- The uncertainty on the $t\bar{t}$ cross section dominates the uncertainty on shape and normalization in simulated $t\bar{t}$ and $W+\text{jets}$, and this leads to an absolute uncertainty on the QCD fraction of $^{+0.03\%}_{-0.02\%}$.

- Varying the range of the fit between 250 GeV and 350 GeV gives an absolute uncertainty of $^{+0.7\%}_{-0.0\%}$ due to the fit range.

- Varying the bin sizes between 20, 30 and 40 GeV bins gives an absolute uncertainty of $^{+6.7\%}_{-0.0\%}$, from the binning of the fit.

- The discrepancies in the plot from early in the event selection (Fig. 6.6) are taken into account by rescaling the bins such that the control region distribution matches the signal region distribution. This
gives an absolute uncertainty of $\pm 4.6\%$.

The QCD fraction is $20.7^{+10.4}_{-6.5}\%$, with both statistical and systematic uncertainties included. The expected contribution from QCD multi-jet events in the $m_T(\tau, E_T^{\text{miss}})$ distribution of the final event selection is shown in Fig. 6.8.

**Jet $\to \tau$ (2012)**

In the 2012 search, the background from events with jets misidentified as hadronically-decaying $\tau$ leptons is predicted in a different way than in the previous analysis. This new method is used in the search for both the light and the heavy $H^\pm$. Rather than replacing the simulated $\tau$ identification with a probability measured in data, the 2012 method aims to estimate the jet$\to\tau$ background without any reliance on simulated jets reconstructed as $\tau$ candidates. To do this, a matrix method is developed, which defines matrix weights that are applied to $\tau$ candidates passing or failing the baseline $\tau$ BDT identification in signal region data. Since there is no reliance on simulated events, it is impossible to break this background down into QCD multi-jet events and events from $t\bar{t}$, $W+$jets, and single top processes. Therefore, this method is designed to predict the entirety of the jet$\to\tau$ background.

The weights for the matrix method are determined based on several relations. First, “loose” and “tight” $\tau$ selections are defined. The loose selection requires that the $\tau$ lepton pass the basic object selection and trigger-matching, but places no requirement on the $\tau$ BDT identification. The tight $\tau$ selection requires the object to pass both the loose selection and the baseline $\tau$ BDT identification requirement.

In the 2012 analysis, it became possible to match $\tau$ leptons to the trigger objects of specific $\tau$ triggers. Therefore, while the 2011 analysis simply required that the $\tau$ lepton be matched to any $\tau$ trigger object, the 2012 search is able to require a tighter matching. The $\tau$ trigger for this search includes a cut on a BDT algorithm in the EF level of the trigger system. This algorithm has a much higher efficiency and lower rejection than the offline $\tau$ BDT identification, but trigger-matching to these $\tau$ objects is still seen to have a large effect on the probability for jets to be misidentified as $\tau$ leptons.

In order to keep the same denominator objects in the control region where the fake rate is measured and the signal region where it is applied, this tight trigger-matching is always required for the loose $\tau$ definition. Since the denominator is significantly tighter than in the 2011 analysis, the measured misidentification probabilities will appear to be higher. This is solely due to the redefinition of numerator and denominator, and is no reflection on the performance of the $\tau$ identification algorithm. In fact, the 2012 re-optimized $\tau$ identification represents an improvement in rejection of jets.

The collections of loose and tight $\tau$ leptons both contain real and misidentified objects, so the total
number of events can be expressed as:

\[ N^L = N^L_m + N^L_r \]

\[ N^T = N^T_m + N^T_r \]

where \( N_m \) refers to the number of misidentified \( \tau \) leptons in each case and \( N_r \) refers to the number of real \( \tau \) leptons. Two probabilities are also defined: the probability for a real \( \tau \) lepton passing the loose criteria to also pass the tight, and the probability for a misidentified \( \tau \) lepton passing the loose criteria to also pass the tight. These can be defined as:

\[ p_m = \frac{N^T_m}{N^L_m} \]

\[ p_r = \frac{N^T_r}{N^L_r} \]

Using these two sets of equations, one can solve for the total number of misidentified tight \( \tau \) leptons as a function of \( p_r \), \( p_m \), and the total numbers of loose and tight taus, as follows:

\[ N^T_m = \frac{p_m}{(p_r - p_m)} (p_r N^L_m - N^T) \]

The final weights will be applied to events with loose \( \tau \) leptons, with a different weight for the loose \( \tau \) leptons that pass or fail the tight requirements. Since the tight \( \tau \) leptons are a subset of the loose \( \tau \) leptons, the two labels can be redefined as \( N^L = N(\text{Loose, not tight}) + N(\text{Loose and Tight}) \) and \( N^T = N(\text{Loose and Tight}) \).

The weights applied to these categories of \( \tau \) leptons are:

\[ N(\text{Loose, not Tight}) = \frac{p_m p_r}{(p_r - p_m)} \]

\[ N(\text{Loose and Tight}) = \frac{p_m (p_r - 1)}{(p_r - p_m)} \]

The probability \( p_m \) is measured in a \( W + \text{jets} \) control region in data. In order to enable \( \tau \) trigger matching, the region must fire a combined trigger that requires either an electron or muon and a hadronically-decaying \( \tau \) lepton. The \( \tau \) portion of both electron and muon combination triggers has a \( p_T \) threshold of 20 GeV, the muon trigger has a \( p_T \) threshold of 15 GeV, and the electron trigger has an \( E_T \) threshold of 18 GeV. This \( W + \text{jets} \) region is selected using the same event cleaning cuts as the baseline selection, and further requiring:

- exactly one muon or electron,
- zero $b$-tagged jets,
- at least one loose $\tau$,
- $m_T(\ell, E_T^{miss}) > 50$ GeV.

This region has a contamination from true $\tau$ leptons, electrons, and muons of approximately 15%, and this contamination is subtracted using the simulated expectation. After this subtraction, the jet composition of loose $\tau$ leptons in this region is dominated by light quarks. A systematic uncertainty on this subtraction is determined using the systematic variation on the background subtraction that has the largest effect on the measured rate.

The probability $p_r$ is determined using truth-matched hadronically-decaying $\tau$ leptons in simulated $t\bar{t}$ events. The baseline $\tau+E_T^{miss}$ triggers are required, but no additional event selection. Systematics associated with the simulated true $\tau$ leptons are taken into account, with the only non-negligible account arising from the uncertainty on the $\tau$ identification scale factors.

The probabilities $p_m$ and $p_r$ are binned in number of associated $\tau$ tracks, number of isolation tracks, $p_T^{\tau}$, and $|\eta^{\tau}|$. The measured rates binned in these variables are shown in Fig. 6.9 for $p_m$ and Fig. 6.10 for $p_r$. The parameterization of the variables is applied by calculating $\varepsilon_i$. Here $i$ = one or three associated tracks, $\varepsilon$ corresponds to $p_m$ or $p_r$, and $<\varepsilon>$ is the average of $p_m$ or $p_r$. The total rate is defined as:

$$\varepsilon_i = \varepsilon(p_T^{\tau}) \times \frac{\varepsilon(|\eta^{\tau}|)}{<\varepsilon>} \times \frac{\varepsilon(N_{\text{track}}^{\text{iso}})}{<\varepsilon>}$$

The $W+$jets region is expected to have a loose, misidentified $\tau$ lepton composition dominated by light quarks, which is not identical to the expected composition of the signal region. In the signal region, the background from jets misidentified as $\tau$ leptons arises from QCD multi-jet events, which are gluon-dominated, as well as from $t\bar{t}$ or $W+$jets events, which contain a mixture of light quark jets, $b$-jets, and gluons. To take into account this possible difference in jet composition, a systematic uncertainty is calculated for both shape and normalization.

This systematic is derived using the QCD CR, which is described in Chapter 5. This region gives a very pure selection of jet events, which come primarily from QCD multi-jet events. The loose $\tau$ leptons that make up the denominator of $p_m$ have a level of contamination from non-jet sources of 4%. This small contamination arises from correctly reconstructed $\tau$ leptons and electrons or muons mis-reconstructed as $\tau$ leptons. Simulation is used to subtract this contamination from the misidentification probability.

As shown in Fig. 6.2, light quarks have the highest probability of being misidentified as a $\tau$ lepton, and gluons have the lowest. Therefore, the difference in jet composition between the $W+$jets region and the
QCD CR is expected to be greater than the difference between either control region and the signal region. As a result, the binned difference between the misidentification probabilities in the QCD CR and $W+$jets region define a safely conservative systematic uncertainty on the effect of the difference in jet composition between control and signal regions.

It is useful to check the comparison of the $\tau$ identification response for jets misidentified as $\tau$ leptons in data as compared with simulated events, to see the level of mis-modeling one would expect from simulation. The rates are shown as a function of $p_T^\tau$ in Fig. 6.11 for 1- and 3-prong $\tau$ leptons, where it is clear that the mis-modeling effects observed in 2011 simulation are still present.

Figure 6.9: The probability $p_m$ as a function of the parameterizing variables $p_T$, $|\eta|$, and $N_{\text{iso\_track}}$, shown separately for 1 and 3 track $\tau$ leptons. The probability $p_m$ is measured in a $W+$jets control region in data [9].
Figure 6.10: The probability $p_r$ as a function of the parameterizing variables $p_T$, $|\eta|$, and $N_{\text{track}}^{\text{iso}}$, shown separately for 1 and 3 track $\tau$ leptons. The probability $p_r$ is measured in simulated $t\bar{t}$ events [9].

Possible differences in $p_m$ arising from the three different trigger periods in data are also evaluated. The trigger period binning results are shown in Fig. 6.12, where one can see the only deviation from average is the first period bin for 3-prong $\tau$ leptons. This bin contains only 2% of the $W$+jets region data, and the deviation corresponds to a $2\sigma$ statistical fluctuation. Therefore, it was concluded that binning in period would only add complexity without increasing the performance or reducing the systematic uncertainty of this method. Evaluating this additional effect as a systematic results in a shift of the yield of less than 1 event, so the effect is considered negligible.

This method is validated in the QCD CR and the early signal region. The $m_T$ variable for the QCD control region is shown in Fig. 6.13, with $p_m$ measured from the QCD CR (left) and the $W$+jets region
Figure 6.11: The probability $p_m$ as a function of $p_T$, shown separately for 1 and 3 track $\tau$ leptons in data and simulation. The probability $p_m$ was measured in a $W$+jets region in data.

Figure 6.12: The probability $p_m$ as a function of the trigger period, shown separately for one and three track $\tau$ leptons. The probability $p_m$ was measured in a $W$+jets region in data [9].

(right). In Fig. 6.13, all uncertainties are shown except for the uncertainty corresponding to the difference in jet composition between the QCD CR and $W$+jets region. Therefore, the left distribution shows the performance of the method, when there is no difference in jet composition between the region where $p_m$ is derived and where it is applied. The discrepancy illustrated in the right distribution defines the systematic uncertainty in shape and normalization that corresponds to the difference in jet composition between the two regions.

The method is then validated in the signal region, just after the requirement in the cut flow that there
are no muons or electrons. At this point, only 3 jets are required, so the final signal regions for both heavy and light $H^\pm$ are a subset of this region. These plots are therefore also validation plots for the heavy $H^\pm$ case.

Figure 6.13: This plot shows the $m_T$ distribution of the QCD CR, where the backgrounds where the identified $\tau$ originates from true $\tau$ leptons, electrons, or muons are predicted by simulation, and the contribution from jets misidentified as $\tau$ leptons is predicted by the matrix method. Relevant systematic and statistical uncertainties are shown added in quadrature [9].

Figure 6.14: Distributions of $E_T^{miss}$ (left) and $\Delta\phi(\tau, E_T^{miss})$ (right), early in the signal region cut flow (just after the cut requiring no muon or electron). Multi-jet backgrounds are predicted by the matrix method, data points correspond to data of an integrated luminosity of 19.5 fb$^{-1}$, and the remaining backgrounds are taken from simulated events. All uncertainties are shown, added in quadrature [9].

The distributions shown are $E_T^{miss}$ and $\Delta\phi(\tau, E_T^{miss})$. The final discriminating variable, $m_T$, is calculated from these two variables and $p_T$, in which the misidentification probability is parameterized. Good agreement is found between the sum of the backgrounds in these two distributions and the observed events in data. Table 6.4 shows the expected contribution from background events with a jet misidentified as a $\tau$ lepton for the latter part of the cutflow. The final expected contribution at the end of the cut flow is shown in Fig. 6.15.

The following are considered as sources of systematic uncertainties on the method:

- **Event Environment/Jet Composition ($p_T$):** This evaluated by taking the bin-by-bin difference in the
Figure 6.15: The predicted $\tau \to \text{Jet}$ contribution to the signal region at the end of the cut flow. Systematic and statistical uncertainties are shown.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton veto</td>
<td>$19101 \pm 1361(stat.)$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ selection</td>
<td>$1280 \pm 85(stat.)$</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>$492 \pm 33(stat.)$</td>
</tr>
<tr>
<td>$m_{jjb}$</td>
<td>$242 \pm 17(stat.)$</td>
</tr>
</tbody>
</table>

Table 6.4: The results of applying the matrix method to 2012 data through the later part of the cut flow for the heavy charged Higgs selection. The event yields shown correspond to the total predicted background of events with a jet misidentified as a $\tau$ (QCD multi-jet events, $t\bar{t}$ events, $W$+jets events, and others).

fake rate measured in the $W$+jets and QCD control regions. The final effect is a 8.6-9.2% shift in the yield.

- **Tau Contamination ($p_m$):** The true $\tau$ contamination in $p_m$ is subtracted using simulation. This subtraction is varied according to the uncertainty on the $\tau$ identification scale factors. The difference is taken as the systematic uncertainty (2.0-2.1% on the yield).

- **Lepton Contamination ($p_m$):** The true lepton contamination in $p_m$ is subtracted using simulation. The effect of the variation on the subtraction due to uncertainty on the $\tau$ e-veto is taken as the systematic uncertainty (1.7-2.0% on the yield).

- **Simulation Uncertainties ($p_r$):** Object-related systematics have a negligible effect on the measurement of the ratio, $p_r$. The dominant systematic on the measurement of $p_r$ arises from the uncertainty on the $\tau$ identification scale factors (11.5-13.5 % on the yield).

The largest possible signal contamination to the $W$+jets control region where $p_m$ is measured is negligible. Since this would only manifest as an additional $\tau$ contamination of a negligible size compared with that of SM processes, the effect on the method is negligible. A systematic uncertainty due to the differences in trigger period are also considered. Since the resulting shift in yield is less than one event (0.1%) in the signal regions, this source of uncertainty is considered negligible.
**True \( \tau \) Leptons (2011/2012)**

In the 2012 analysis, backgrounds with true \( \tau \) leptons are taken from simulation, and all relevant systematic uncertainties are applied. In the 2011 analysis, backgrounds with true \( \tau \) leptons are estimated in a data-driven way, using a technique known as embedding [12].

To use the embedding method, first a sample of \( t\bar{t} \), single top, and \( W + \)jets events with muons in the final state are selected in data. The detector signature of the muon in the event is then replaced with a simulated \( \tau \) lepton, and the new hybrid event is run through reconstruction again. The resulting events with embedded \( \tau \) leptons are then used instead of simulation for the estimation of the background with true \( \tau \) leptons. The advantage of using this method is that the entire event, except for the simulated \( \tau \) lepton, is taken directly from data. This includes the underlying event, pile-up interactions, \( E_T^{\text{miss}} \), \( b \)-jets and light quark jets.

In previous studies [75], this method is shown to model the \( t\bar{t} \) background within a 10\% error margin. However, in the referenced study, the \( \tau \) lepton is merged with the \( t\bar{t} \) event at the reconstructed-object level. Since the \( \tau \) lepton is reconstructed in a clean environment, it can introduce a bias, and the \( E_T^{\text{miss}} \) of the event would need to be recalculated after the merging of the \( \tau \) lepton into the event.

Since then, embedding tools have been developed to allow the \( \tau \) lepton to be replaced at the detector level. This corresponds to replacing the tracks and calorimeter depositions of the \( \tau \) lepton. These tools have been studied for the \( Z \rightarrow \tau\tau \) background to \( H/A/h \rightarrow \tau\tau \) searches [76], and they have been adapted for a \( t\bar{t} \)-like environment where only one muon is replaced with a \( \tau \) lepton [77]. The method has also been validated in \( \tau + \)jets events using early ATLAS data [78].

For embedding, it is necessary to select a region that is similar to the signal region, but with a muon instead of a \( \tau \) lepton. The event selection applied to define this \( \mu + \)jets region requires:

1. Event preselection (described in Section 4.4)
2. A single muon trigger with a \( p_T \) threshold of 18 GeV at the event-filter level,
3. Exactly one isolated muon with \( p_T > 25 \) GeV,
4. Zero isolated electrons with \( p_T > 20 \) GeV,
5. At least four jets with \( p_T > 20 \) GeV,
6. At least one \( b \)-tagged jet,
7. \( E_T^{\text{miss}} > 35 \) GeV.
Table 6.5: Expected and observed event yields for the event selection defining the region used for embedding. The uncertainty is statistical only, and no estimation is made of the QCD multi-jet background.

<table>
<thead>
<tr>
<th></th>
<th>$t\bar{t}$</th>
<th>Single Top</th>
<th>$W +$ Jets</th>
<th>Total</th>
<th>Observed(data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events</td>
<td>25500 ± 90</td>
<td>2120 ± 30</td>
<td>6500 ± 400</td>
<td>34120 ± 410</td>
<td>37275</td>
</tr>
</tbody>
</table>

This selection is looser than the baseline selection, so that a bias will not be included in the control region. For technical reasons, the $\tau$ trigger can’t be simulated for embedded events. Therefore, the events are corrected by parameterizing the trigger efficiency as a function of $p_T^\tau$ and $E_T^{miss}$, and using this efficiency as a part of the calculation of the final normalization. The number of expected events in this region from simulation and those observed in data are shown in Table 6.5.

From simulation studies, there is expected to be a 10% impurity from muons produced in leptonic $\tau$ decays and from non-isolated muons (primarily from $b\bar{b}$ and $c\bar{c}$ events). This introduces a bias, since there is no physical correspondence for these events when the muon is replaced with a $\tau$ lepton. This bias is reduced in the final result, since few of these events pass the full signal region event selection.

The embedding method is then applied to this control region. The muon’s vertex position and momentum are extracted, and the momentum is rescaled to account for the higher $\tau$ mass, using:

$$p_\tau = \frac{\sqrt{E_\mu^2 - m_\tau}}{\sqrt{\vec{p}_\mu \cdot \vec{p}_\mu}} \vec{p}_\mu$$ (6.4)

This momentum is fed into TAUOLA [61], which produces the $\tau$ decay products and generates the final state radiation. The result is then propagated through the ATLAS detector simulation, and the tracks, calorimeter depositions, and segments in the muon spectrometer in the vicinity of the muon are replaced with the $\tau$ decay products. The reconstruction algorithms are then run on this hybrid event, reconstructing $\tau$ leptons, other leptons, $E_T^{miss}$, and other high-level physics objects.

The shape of the $m_T$ distribution for the backgrounds with true $\tau$ leptons is taken from the distribution obtained using these embedded events, after applying the full $\tau+$jets event selection. The normalization is derived from the embedded events, using the relation:

$$N_\tau = N_{\text{embedded}} \cdot (1 - c_{\tau \rightarrow \mu}) \frac{\varepsilon_{\tau + E_T^{miss}}^{\text{trigger}}}{\varepsilon_{\mu-ID,\text{trigger}}} \cdot B(\tau \rightarrow \text{hadrons} + \nu)$$ (6.5)

where

- $N_\tau$ is the number of events with correctly reconstructed $\tau$ leptons (determined from simulation),

- $N_{\text{embedded}}$ is the number of embedded events in the signal region,
Figure 6.16: Comparison of the $m_T$ distribution for correctly reconstructed $\tau$ leptons, predicted by the embedding method and simulation. The uncertainties shown combine both statistical and systematic [12].

- $c_{\tau \rightarrow \mu}$ is the fraction of events with a selected muon that is a decay product of a $\tau$ lepton (determined from simulation),
- $\varepsilon_{\tau+E_T^{\text{miss}}-\text{trigger}}$ is the $\tau+E_T^{\text{miss}}$ trigger efficiency (as a function of $p_T^\tau$ and $E_T^{\text{miss}}$, derived from data),
- $\varepsilon^{\mu-ID,\text{trigger}}$ is the muon trigger and identification efficiency (as a function of $p_T^\mu$ and $\eta$, derived from data),
- $B(\tau \rightarrow \text{hadrons} + \nu)$ is the branching fraction of the hadronic decay of the $\tau$ lepton.

The resulting $m_T$ distribution for the background containing correctly reconstructed $\tau$ leptons, as predicted by the embedding method, is shown in comparison to simulation in Fig. 6.16.

**Lepton $\rightarrow \tau$ (2011/2012)**

A very small portion of the background in both the 2011 and 2012 searches arises from events with leptons that are misidentified as 1-prong hadronically-decaying $\tau$ leptons. The $\tau$ BDT identification is optimized solely against jets, but a dedicated BDT electron veto and a cut-based muon veto are also used in this analysis. The vetoes eliminate most of the background from events with leptons misidentified as $\tau$ leptons, but the remainder of the $e \rightarrow \tau$ background is corrected using centrally provided scale factors that are derived from a tag-and-probe method [7].

In 2011, a tag and probe method with $Z \rightarrow ee$ events is used to calculate electron veto efficiencies and scale factors. The process $Z \rightarrow ee$ enables the selection of an unbiased and clean data sample of electrons. The tag electron passes the electron object selection, is matched to an electron trigger object, and has $E_T >$
Table 6.6: Scale factors applied in the 2011 analysis, for 1-prong identified $\tau$ leptons that are truth-matched to an electron. Combined statistical and systematic uncertainties are quoted.

| $|\eta_{\text{track}}|$ | Range | Scale Factor |
|-----------------|-------|-------------|
| $\leq 1.37$     |       | $1.28 \pm 0.52$ |
| 1.37-1.52      |       | $1.00 \pm 1.00$ |
| 1.52-2.00      |       | $0.54 \pm 0.36$ |
| $\geq 2.00$    |       | $2.76 \pm 1.29$ |

Table 6.7: Scale factors applied in the 2012 analysis, for 1-prong identified $\tau$ leptons that are truth-matched to an electron. Combined statistical and systematic uncertainties are quoted.

| $|\eta_{\text{track}}|$ | Range | Scale factor |
|-----------------|-------|-------------|
| $\leq 0.05$     |       | $0.775 \pm 0.357$ |
| 0.05–0.80       |       | $1.394 \pm 0.322$ |
| 0.80–1.37       |       | $1.388 \pm 0.268$ |
| 1.37–1.52       |       | $0.877 \pm 0.229$ |
| 1.52–2.00       |       | $1.515 \pm 1.305$ |
| $\geq 2.00$     |       | $1.440 \pm 0.547$ |

25 GeV. The probe object is considered if it is reconstructed as a $\tau$ candidate, and has $p_T > 20$ GeV, $|\eta| < 2.5$ and one associated track. The $e - \tau$ pair with the highest scalar sum of transverse energies, separated by $\Delta R > 0.4$, is then chosen. The tag and probe objects must have opposite sign charge, and events with $E_T^{\text{miss}} > 20$ GeV are rejected, in order to reduce the contamination from $W \rightarrow e\nu$ decays. The invariant mass of the pair are also required to be between 80 and 100 GeV. From Monte Carlo simulation, it is expected that this selection results in probe objects that are 99% composed of electrons.

At this point, mis-identification probabilities $m \text{ID}_e$ are computed for the $\tau$ candidates that fulfill the above selection criteria, in the following way:

$$m \text{ID}_e = \frac{\tau \text{ candidates passing object selection, } \tau \text{ ID and electron veto}}{\tau \text{ candidates passing object selection}}$$ (6.6)

These misidentification probabilities are measured both in simulated events and data, and scale factors are calculated from the ratio. These scale factors are applied to simulated events with a 1-prong $\tau$ lepton that is truth-matched to an electron. The scale factors are parameterized in $|\eta_{\text{track}}|$, and the values used for the 2011 analysis are shown in Table 6.6. For the 2012 analysis, a similar method is used to calculate $\eta$-dependent scale factors for the full 2012 dataset. These factors are shown in Table 6.7.
Figure 6.17: Predicted distribution and uncertainty from the data-driven method of estimating backgrounds with jets misidentified as $\tau$ leptons in the $\tau$+lepton channel. Shown are the $e+\tau$ channel (left) and $\mu+\tau$ channel (right).

6.2.2 $\tau$+Lepton Channel

The $\tau$+lepton channel has the same backgrounds as the $\tau$+jets channel, but the fraction of the background arising from each source is significantly different. The main sources of background in the $\tau$+lepton channel are non-QCD multi-jet events with jets misidentified as $\tau$ leptons, and events with true $\tau$ leptons. Each of these backgrounds is expected to contribute roughly half of the total background. Smaller remaining backgrounds include QCD multi-jet events and events with leptons misidentified as hadronically-decaying $\tau$ leptons.

In this channel, the non-QCD backgrounds with jets misidentified as $\tau$ leptons are estimated in the same way as the $\tau$+jets channel. The small QCD multi-jet contribution is estimated using a matrix method that relies on the lepton identification of the ATLAS detector, and the true $\tau$ contribution is taken from simulation.

**Non-QCD Jet $\rightarrow \tau$**

The non-QCD jet $\rightarrow \tau$ background for the $\tau$+lepton channel is estimated using the same method as the 2011 $\tau$+jets channel, which is described in more detail in Section 6.2.1. A misidentification probability, binned in $|\eta|$, $p_T$, and number of charged tracks associated with the $\tau$ lepton, is measured in a $W$+jets control region. For simulated jet $\rightarrow \tau$ events in the signal region, the probability is applied to $\tau$ candidates in place of the simulated $\tau$ identification. The contribution from different SM processes is detailed in Table 6.8, and the final jet $\rightarrow \tau$ contributions are shown in Fig. 6.17 for the $e+\tau$ and $\mu+\tau$ channels.
### Table 6.8: Yields, separated by physics sample, for the data-driven estimation of the non-QCD background from jets misidentified as τ leptons, for the τ+lepton channel.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>t(\bar{t})</td>
<td>901 ± 15 (stat)</td>
</tr>
<tr>
<td>W+jets</td>
<td>150 ± 3 (stat)</td>
</tr>
<tr>
<td>Single top</td>
<td>81 ± 1 (stat)</td>
</tr>
<tr>
<td>Z+jets</td>
<td>44 ± 1 (stat)</td>
</tr>
</tbody>
</table>

Table 6.8: Yields, separated by physics sample, for the data-driven estimation of the non-QCD background from jets misidentified as τ leptons, for the τ+lepton channel.

**QCD Jet → τ (2011)**

The QCD multi-jet contribution to the background of the τ+lepton channel is expected to be quite small. This is because it requires not only a jet to be misidentified as a τ lepton, but for another jet to be simultaneously misidentified as the lepton(\(e, \mu\)) of the channel. While τ leptons have a large jet background, electrons and muons at the ATLAS detector have much higher rejection power against jets. In fact, the excellent lepton identification of the ATLAS detector is a major strength of the τ+lepton channel. The isolated lepton identification gives a very pure sample of leptons, and the single lepton triggers perform well at high efficiency [72, 73].

However, there is still some contamination from non-isolated leptons. This contamination can arise from the semileptonic decay of a c or b quark, or from the decay-in-flight of a \(\pi^\pm\) or K meson. For misidentified electrons, it can also arise from \(\pi^0\) reconstruction, photon conversions, or shower fluctuations. In order to estimate this background, a method is developed that relies on the difference in lepton identification between real (isolated) leptons and misidentified (non-isolated) leptons.

For the method, two data samples are defined with the same kinematic selection on the lepton, but differing in the lepton identification criteria. The first sample contains mostly events with real leptons, and it is referred to as the tight sample. The second one contains mostly events with misidentified leptons and is referred to as the loose sample.

The tight requirements for leptons are the same as the object selections of Section 4.3. For electrons, the loose requirements move the isolation requirement from a 90% to a 98% electron efficiency working point, and loosen the cuts in the quality selection [63]. For muons, the only change in the selection for the loose requirements is the omission of the isolation cuts on energy and total track transverse momentum in a cone around the muon.

Letting \(N^L_m\) and \(N^L_r\) (\(N^T_m\) and \(N^T_r\)) stand for the number of events containing misidentified and real leptons that pass the loose (tight) requirements, the total number of events with loose or tight leptons can be expressed as:

\[
N^L = N^L_m + N^L_r
\]

(6.7)
\[ N_T = N_T^m + N_T^r \]  
\[ p_m = \frac{N_T^m}{N_T} \]  
\[ p_r = \frac{N_T^r}{N_T} \]

The probability that a misidentified or real loose lepton will also pass the tight requirement can then be expressed as:

\[ p_m = N_T^m / N_T \] \hspace{1cm} (6.9)
\[ p_r = N_T^r / N_T \] \hspace{1cm} (6.10)

Using these four relations, the total number of misidentified leptons passing the tight requirement can be rewritten as:

\[ N_T^m = \frac{p_m}{p_r} \left( p_r N_L^m - N_T^r \right) \] \hspace{1cm} (6.11)

From this last equation, weights are determined to apply to events with loose and tight leptons in data. The weights are calculated from \( p_m \) and \( p_r \), which will be measured in data control regions, and any significant dependence of \( p_r \) and \( p_m \) on kinematic or topological variables will be taken into account in the parameterization of the rate.

For both electrons and muons, \( p_r \) is measured in a \( Z \to \ell \ell \) control region, using a tag and probe method. The events are required to have two oppositely charged leptons of the same flavor, with an invariant mass in the range of \([86, 96]\) GeV. The “tag” lepton passes the tight selection, and the “probe” lepton is required to pass the loose selection. \( p_r \) is measured from the rate at which the “probe” lepton passes the tight requirement. \( p_m \) is measured in a region dominated by QCD multi-jet events, which are defined by having one loose lepton and an \( E_T^{\text{miss}} \) in the range \([5, 20]\) GeV. Contributions from other SM processes are subtracted from this region using simulation.

\( p_m \) and \( p_r \) are determined to have a dependency on the \(|\eta|\) of the lepton, \( p_T \) of the leading jet in the event, and the distance between the lepton and nearest jet (in \( \Delta R \)). It was also found that the shape variations of the real and misidentified lepton probabilities are negligible from one data-taking period to another.

The dependencies of \( p_m \) and \( p_r \) on each variable are shown in Fig 6.18 for electrons and Fig 6.19 for muons. The final \( p_r \) and \( p_m \) are determined as follows (where \( \varepsilon \) denotes \( p_m \) or \( p_r \)):

\[ \varepsilon_\ell = \varepsilon(|\eta|_\ell) \times \frac{\varepsilon(p_T,j_1)}{<\varepsilon>} \times \frac{\varepsilon(N_b)}{<\varepsilon>} \times \frac{\varepsilon(N_T)}{<\varepsilon>} \] \hspace{1cm} (6.12)

The overall probabilities for \( p_r \) are 80% and 97% for electrons and muons, respectively, and the overall probabilities for \( p_m \) are 18% for electrons and 29% for muons.
Figure 6.18: Probability for a loose electron to be identified as a tight electron, measured in data, as functions of the $|\eta|$ of the electron, the distance $\Delta R$ between the electron and the nearest jet, the $p_T$ of the leading jet, the number of $b$-tagged jets and $\tau$ leptons. The total uncertainty is shown [12].

6.2.3 Ratio Method

The SM backgrounds that contribute to the Ratio Method analysis are separated in the same manner as the previous light $H^{\pm}$ search. The backgrounds for all 4 channels ($e + \tau$, $\mu + \tau$, $e + \mu$ and $\mu + e$) are largely composed of $t\bar{t}$ events. In the $e + \tau$ and $\mu + \tau$ channels, the backgrounds are primarily from events with correctly reconstructed $\tau$ leptons and jets misidentified as $\tau$ leptons. There are also small contributions from QCD multi-jet events and events with leptons misidentified as $\tau$ leptons. In the $e + \mu$ and $\mu + e$ channels, the only background that requires a data-driven estimate is from QCD multi-jet events. The remaining SM backgrounds arise from correctly reconstructed true leptons, and are taken from simulation.

Non-QCD Jet $\rightarrow \tau$

As in the other 2011 analyses, the estimation of this background relies on substituting the simulated $\tau$ identification with a misidentification probability measured in data. In the 2011 analyses of the $\tau$+jets and $\tau$+lepton channels, a dominant systematic uncertainty of the method corresponded to the difference in the jet composition of $\tau$ candidates between the control region, where the probability is measured, and the signal region, where it is applied. In the Ratio Method, an additional technique is employed to greatly reduce this
Figure 6.19: Probability for a loose muon to be identified as a tight muon, measured in data, as functions of the $|\eta|$ of the muon, the distance $\Delta R$ between the muon and the nearest jet, the $p_T$ of the leading jet, the number of $b$-tagged jets and $\tau$ leptons. The total uncertainty is shown [12].

difference in jet composition.

Events with one lepton ($e$, $\mu$) and one $\tau$ lepton can be separated into events where the $\tau$ and lepton are of the same sign (SS) charge, and events where they are of the opposite sign charge (OS). The signal, which arises from $t\bar{t}$ decays, only produces OS events, as long as the sign of the charge of the $\tau$ and lepton are accurately reconstructed. The charge reconstruction efficiency for true $\tau$ leptons is observed in simulation to be 99.5% (Fig. 6.20).

Events with light quarks reconstructed as $\tau$ candidates are biased towards OS events, while $b$-jets and gluons are charge symmetric with respect to OS and SS events. This occurs because gluons, being neutral, have an equal chance of being reconstructed as a positively or negatively charged $\tau$ candidate, and $b$-jets, produced in quark-antiquark pairs, have an equal chance of being reconstructed as a $\tau$ candidate. Contributions from QCD multi-jet events, where both the $\tau$ and the lepton are misidentified, also tend to be charge symmetric, since QCD multi-jet events tend to be dominated by gluon-initiated jets. Light quarks, however, often arise from a hadronic $W$ decay in the dominant $t\bar{t}$ background, and are therefore more likely to fake a $\tau$ lepton that is of the opposite sign charge to the lepton. As a result, when one subtracts SS events from OS events, one is left with a very pure misidentified $\tau$ candidate composition of light quark jets.
For this background estimate, the misidentification probability is measured in a $W$+jets control region. In this case, the $W$+jets region is defined similar to the baseline selection of the analysis, but with exactly zero $b$-tagged jets and at least one $\tau$ candidate. Events are required to have at least two jets in addition to a $\tau$ candidate, and a cut of 30 GeV is placed on $m_T(\ell, E_T^{\text{miss}})$ to remove contamination from true $\tau$ leptons and other leptons. The misidentification probability is defined as in the 2011 $\tau$+jets and $\tau$+lepton channels:

$$mID^j = \frac{\text{number of } \tau \text{ candidates passing object selection and } \tau \text{ ID}}{\text{number of } \tau \text{ candidates passing object selection}}$$

The control region and signal region are both separated into OS and SS events. The jet composition of OS and SS events is shown in Fig. 6.21 for the $W$+jets control region and in Fig. 6.22 for the $\tau$+lepton signal region. These plots are shown for all $\tau$ candidates in events that otherwise pass the $W$+jets or signal region selection. The OS events are shown above the axis, and SS events are shown below, to illustrate the symmetry of the gluon and $b$-jet contributions.

The misidentification probability is parameterized in the $p_T^\tau$, the number of charged associated tracks in the signal cone (1 or 3), and the number of tracks in the isolation cone. Tracks in the isolation cone are charged tracks that appear in a cone that extends from $\Delta R = 0.2$ from the center of the reconstructed $\tau$ lepton outward to the $\Delta R = 0.4$. Many $\tau$ candidates have tracks in the isolation cone, but few of those are identified as a $\tau$ lepton by the $\tau$ likelihood identification algorithm. The parameterized misidentification probabilities can be seen in Fig. 6.23.

Misidentification probabilities are measured by taking a bin-by-bin subtraction of SS events from OS. The binning of the probability is 3-dimensional parameterization, taking into account all possible correlations.
Figure 6.21: Composition of jets in events where the $\tau$ candidate is of the opposite sign charge to the lepton (OS) and of the same sign charge (SS). The composition is shown for $m_T(\ell, E_T^{miss})$ in the $W$+jets control region [13].

Figure 6.22: Composition of jets in events where the $\tau$ candidate is of the opposite sign charge to the lepton (OS) and of the same sign charge (SS). The composition is shown for the generalized transverse mass ($MT_{2H}$) in the signal region [11].
between the variables. The fake rates are applied as in the previous analysis, for each \( \tau \) candidate that can successfully be considered as a potential \( \tau \) lepton (i.e. if it is considered as an identified \( \tau \) lepton, and the overlapping jet is removed, the event would still pass the event selection). In this case, the rates are applied for both OS and SS events, but OS events are given a positive sign, and SS events are given a negative sign. This is equivalent to scaling an OS-SS distribution by the binned weights, but allows the application of the misidentification probability to be performed on a per-jet basis, rather than on an overall distribution.

In studies on the \( W+\text{jets} \) control region, a persistent discrepancy between data and simulation is observed in OS events, as shown in Fig. 6.21. This difference can be seen even more clearly after performing the subtraction of SS events from OS in the \( W+\text{jets} \) control region, seen in Fig. 6.24. Since this plot is of all \( \tau \) candidates, the discrepancy does not arise from the simulated \( \tau \) identification, but from something in the underlying selection. When the requirement of the presence of a \( \tau \) candidate is removed, as shown in Fig. 6.25, the discrepancy vanishes. Thus, it is clear that the discrepancy arises at some point in the \( \tau \) candidate selection, which is simply \( p_T > 25 \text{ GeV}, |\eta| < 2.3, 1 \text{ or } 3 \text{ tracks, and the lepton vetoes.} \)

Through investigation of the \( \tau \) candidate selection, it was found that the discrepancy is introduced by the requirement of one or three tracks. To check the modeling of this variable, the data and simulation track distributions are compared in the \( W+\text{jets} \) region, before the one or three track requirement and after removing non-jet contamination estimated by simulation. Fig. 6.26 clearly shows a discrepancy between data and simulated events for this variable. Specifically, simulated jets misidentified as \( \tau \) candidates are more likely to have lower multiplicities of tracks in the signal cone, so there are more \( \tau \) candidates with one
Figure 6.24: $m_T(\ell, E_T^{miss})$ after subtracting SS events from OS events, in the $W$+jets control region. This clearly shows the discrepancy between data and simulation that is observed in this region [13].

Figure 6.25: $m_T(\ell, E_T^{miss})$ in the $W$+jets control region, but with no requirement on the existence of a $\tau$ candidate. This shows that the data/MC discrepancy is a result of something in the $\tau$ candidate selection [11].

Figure 6.26: Distribution of the number of charged tracks associated with a $\tau$ candidate for the $W$+jets control region in data and simulation. Expected true $\tau$ lepton or other lepton contributions are subtracted from both distributions using simulation. The distributions are scaled to unity [11].
and three tracks in simulation than in data.

The relative difference between the data and simulated events in each track bin is used as a scale factor, resulting in $0.71 \pm 0.03$ for 1-prong $\tau$ candidates and $0.92 \pm 0.03$ for 3-prong $\tau$ candidates, where the uncertainties are statistical only. These scale factors are applied, before the OS-SS subtraction, to all simulated jets reconstructed as $\tau$ leptons. In order to estimate the systematic uncertainties associated with this scale factor, the number of jets in the $W$+jets control region is varied between 0 and $\geq 3$. The maximum fluctuations are found to be 3% for the 1-prong $\tau$ candidate scale factor, and 11% for the 3-prong $\tau$ candidate scale factor. The systematic uncertainty arising from the subtraction of $\tau$ and other leptons from the $W$+jets region is estimated by increasing and decreasing the total subtraction by 20%. The scale factors fluctuated by 4% for 1-prong $\tau$ candidates and are unchanged for 3-prong $\tau$ candidates. In order to be conservative, the total systematic uncertainty for the scale factors are chosen to be 7% for the 1-prong $\tau$ candidates and 11% for the 3-prong $\tau$ candidates.

**QCD Multi-jet Event Background**

QCD multi-jet events contribute a small background to $\tau + \ell$ and dilepton final states. This background is much smaller than in the previous analysis, due in large part to the requirement of two $b$-tagged jets. After the OS-SS subtraction, almost all of the QCD background is eliminated for $\tau + \ell$ final states, but there is still some contribution to the dileptonic events that make up the denominator of the ratio. The QCD multi-jet background is estimated using the same data-driven method as described in Section 6.2.2 for the previous $\tau$+lepton search.

For dileptonic events, one of the leptons is required to pass the tight requirement, while the other is required to pass the loose requirements. The total background contribution from dilepton events is written as:

$$N^{TT}_{m} = \frac{p_{m}}{p_{r}} (p_{r} N^{TL} - N^{TT})$$

(6.14)

Thus, the method is actually used to predict backgrounds with one or more misidentified leptons. For the dilepton case, this actually corresponds not only to QCD mult-jet events, but also $W \rightarrow \ell\nu$+jets events with one jet misidentified as a lepton.

To evaluate the systematic uncertainties of this method, the variation on the rates $p_{m}$ and $p_{r}$ is studied, the largest of which are discussed here. The largest contribution to the systematic uncertainties is from the difference in the jet composition of the region where the misidentification probability is measured and the signal region where it is applied. The misidentification probability is measured in a region dominated by
gluon-initiated events, as described in Section 6.2.2. In this case, the signal region has a larger fraction of quark-initiated events. The result of this difference on $p_m$ is estimated using simulation, and found to be 28% for electrons and 26% for muons. A much smaller systematic uncertainty results from uncertainty on the subtraction of simulated true lepton events from the region where the misidentification probability is measured, resulting in a change in the average $p_m$ of 1.8% for electrons and 2.5% for muons.

Due to large statistical fluctuations in the small final distributions, it is not straightforward to apply these systematic uncertainties on $p_r$ and $p_m$ to the event yield. Instead, a variation on the yield is calculated for each systematic uncertainty early in the event selection, and the total uncertainty is taken as the quadratic sum. The events are selected after requiring 1 trigger-matched lepton with $p_T(E_T) > 25$ GeV for muon(electron) and at least 2 jets with $p_T > 20$ GeV. At this point in the event selection, multi-jet events still make up a significant part of the background. These distributions and the total method-related systematic uncertainties are shown in Fig. 6.27.

**True $\tau$ Leptons and Lepton $\rightarrow \tau$**

For this analysis, SM backgrounds with electrons or muons misidentified as $\tau$ leptons or true $\tau$ leptons are taken from simulated events. For the case of events with electrons misidentified as $\tau$ leptons, the same scale factors are applied to the events as in the 2011 $\tau$+jets channel (see Table 6.6). Events with true $\tau$ leptons make up nearly half of the total SM background, whereas those from leptons misidentified as $\tau$ leptons make up less than 5% of the total background.
6.3 Heavy \(H^\pm\)

The 2012 search for the heavy \(H^\pm\) in the \(\tau+\text{jets}\) channel uses the same background estimation techniques as the 2012 light \(H^\pm\) search. The contribution from electrons and muons misidentified as \(\tau\) leptons is taken from simulation, using the 2012 scale factors for the \(e \rightarrow \tau\) contribution (Table 6.7), and the true \(\tau\) background is taken from simulation. The matrix method used to estimate the total jet \(\rightarrow \tau\) background can be applied to the high mass signal region in the same manner as it is for the light \(H^\pm\) search, since the only changes between the light and heavy \(H^\pm\) searches are the requirements on \(E_T^{\text{miss}}, E_T^{\text{miss}}\) significance, and number of jets.

![Graph showing events in \(m_b\) and \(E_T^{\text{miss}}\) distributions.](image)

**Figure 6.28:** A test of the method in the Top CR. As expected, the contribution from events with a jet misidentified as a \(\tau\) is very small. Only statistical uncertainties are shown here, as the systematic uncertainties will be dominated by the true \(\tau\) contribution [9].

The applications of the matrix method to the QCD CR and the early signal region in the 2012 light \(H^\pm\) search in the \(\tau+\text{jets}\) channel, described in Section 6.2.1, are also relevant for the validation of the method for the heavy \(H^\pm\) analysis. The QCD CR is also a control region of the heavy \(H^\pm\) search, and the early signal region is early enough in the cut flow to also contain the heavy signal region. These distributions are shown in Fig. 6.13, for the QCD CR, and Fig. 6.14, for the early signal region.

An additional control region used for the heavy search is the Top CR, which is dominated by \(t\bar{t}\) events. This region is expected to have a small contribution from jet\(\rightarrow\tau\) events, which is verified by the application...
Figure 6.29: The discriminating variable, $m_T$, in the Top CR. All systematic uncertainties are shown here, added in quadrature [9].

<table>
<thead>
<tr>
<th>Cut</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton veto</td>
<td>$66331 \pm 5442$ (stat.)</td>
</tr>
<tr>
<td>$E_T^{miss}$ selection</td>
<td>$3533 \pm 249$ (stat.)</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>$1082 \pm 75$ (stat.)</td>
</tr>
<tr>
<td>$m_{jjb}$</td>
<td>$480 \pm 31$ (stat.)</td>
</tr>
</tbody>
</table>

Table 6.9: The results of applying the matrix method to 2012 data through the later part of the cut flow for the heavy $H^\pm$ selection. The event yields shown correspond to the total predicted background of events with a jet misidentified as a $\tau$ lepton (QCD multi-jet events, $t\bar{t}$ events, $W$+jets events, etc.).

of the matrix method. Distributions for several Top CR variables are shown in Figure 6.28, and the discriminating variable of the analysis, $m_T$, is shown in Figure 6.29. The data is blinded above $m_T = 60$ GeV for the control region, but the full distribution is shown for simulation and the matrix method estimation. The uncertainties in this plot are dominated by $t\bar{t}$, and within these uncertainties, good agreement between data and the estimated background is seen.

The final distribution from the application of the method to the signal region is shown in Fig 6.30, and the expected contribution for the latter part of the event selection is shown in Table 6.9.
Chapter 7

Systematics and Results

7.1 Systematics

The systematic uncertainties on $H^{\pm}$ searches can be separated into three major sources. There are the systematic uncertainties that arise from detector simulation, additional uncertainties specific to $t\bar{t}$ events, and those that arise from the data-driven methods.

In addition to the uncertainty of 3.9% (3.8%) for 2011 (2012) on the measured integrated luminosity [43, 44], the main detector-related systematic uncertainties are on the trigger, reconstruction and identification efficiencies, as well as the resolution and scale of energy and momentum of the physics objects in the analysis. To assess the impact of most of these sources of systematic uncertainties, the selection cuts for each analysis are re-applied after shifting a parameter by its ±1 standard deviation uncertainty. All of the systematic uncertainties have been updated with the full 2011 dataset and the full 2012 dataset for the 2011 and 2012 analyses, respectively.

Systematic uncertainties of electrons and muons [63, 64, 79] include uncertainties on the trigger, reconstruction and identification efficiencies of the objects. There are also uncertainties on the energy scale and resolution of electrons, and momentum scale and resolution of muons. These uncertainties primarily affect the $\tau$+lepton analysis, since the $\tau$+jets analyses veto events with electrons or muons and these systematic uncertainties largely cancel in the Ratio Method.

The jet-related uncertainties [80] and the uncertainty on the $b$-tagging calibration [70] are applied for simulated backgrounds in all analyses. The jet uncertainties include the uncertainty on energy resolution, energy scale, reconstruction efficiency, and the JVF requirement. The uncertainty on the jet energy scale is taken as a single uncertainty in the 2011 analysis, but the 2012 analysis breaks down the effects into different sources, to more accurately handle correlations between them.

Simulated events must also take into account uncertainties of $\tau$ leptons [7]. These include uncertainties on the $\tau$ energy scale, the $\tau$ electron veto efficiency, and the $\tau$ identification efficiency. The standard $\tau$ identification efficiency scale factors and uncertainties are centrally provided. Another source of systematic
uncertainty is the reconstruction of $E_T^{\text{miss}}$ [81], which arises from pile-up interactions, object energy scale, and object energy resolution. The uncertainties on the energy and momentum of the physics objects are also propagated into the calculation of the $E_T^{\text{miss}}$. The $\tau$+jets channels also have an uncertainty from the $\tau+E_T^{\text{miss}}$ trigger efficiency measurement.

For all backgrounds using simulation for $t\bar{t}$, additional uncertainties must be taken into account. In order to estimate the systematic uncertainties arising from the $t\bar{t}$ generation and parton shower model, the acceptance is computed for $t\bar{t}$ events produced with MC@NLO interfaced to HERWIG/JIMMY and POWHEG interfaced to PYTHIA. There is no alternative generator available for the light $H^{\pm}$ signal samples, which are generated with PYTHIA and thus have no higher order corrections. Instead, the systematic uncertainty for the signal samples is set to the relative difference in acceptance between $t\bar{t}$ events from the different generators. For the heavy $H^{\pm}$, the generator uncertainties are evaluated by comparing event yields from the nominal sample generated by POWHEG interfaced to PYTHIA and the systematic sample of MC@NLO interfaced to HERWIG.

The systematic uncertainties arising from initial and final state radiation are computed using $t\bar{t}$ samples generated with ACERMC interfaced to PYTHIA, where initial and final state radiation parameters are set to a range of values not excluded by the experimental data [82]. The largest relative differences with respect to the reference sample after the full event selections are used as the systematic uncertainties. The same variation is used for the light $H^{\pm}$ samples, and the heavy $H^{\pm}$ uncertainty is taken from dedicated samples generated by POWHEG interfaced with PYTHIA.

Each of the channels also must also include the systematic uncertainties arising from the data-driven methods used to estimate the SM backgrounds. These uncertainties are specific to each search, and will be listed in their respective sections.

7.1.1 Light $H^{\pm}$ Search

The main detector-related systematic uncertainties for the 2011 $\tau$+jets and $\tau$+lepton channel light $H^{\pm}$ searches are shown in Table 7.1, along with a range of the effect on the relevant physics objects. For the 2012 analysis, the effect of uncertainties on the yield of $t\bar{t}$ events is shown in Table 7.1.1. The shift is shown for only $t\bar{t}$ events, which are the dominant background. This is done in order to give a clear idea of the relative sizes of the systematic uncertainties, without including possible fluctuations from backgrounds that are simulated with lower statistics.

In the $\tau$+lepton and $\tau$+jets channels, an additional source of uncertainty arises from the use of the theoretical $t\bar{t}$ cross section for events taken from simulation. This introduces a 6% uncertainty to 2011 and
Source of uncertainty | Treatment in analysis
---|---
Electron trigger efficiency | Up to 1.0%, depending on $p_T$, $\eta$ and data period.
Electron reco. efficiency | ± (0.6-1.1)%, depending on $\eta$.
Electron ID efficiency | ± (2.8-3.5)%, depending on $E_T$ and $\eta$.
Electron energy scale | ± (0.5-2.4)%, depending on $p_T$ and $\eta$.
Electron energy resolution | Up to 1.0%, depending on $E$ and $\eta$.
Muon trigger efficiency | ± (0.5-6.0)%, depending on $\phi$, $\eta$ and data period.
Muon reco. efficiency | ± (0.4-0.8)%, depending on $E$, $\phi$, and $\eta$.
Muon ID efficiency | ± (0.3-1.2)%, depending on the data period.
Muon momentum scale and resolution | Up to 1.0%, depending on $p_T$, $\eta$ and charge.
Jet energy resolution | ± (10-30)%%, depending on $p_T$ and $\eta$.
Jet energy scale (JES) | ± (2.5-14)%%, depending on $p_T$ and $\eta$ + pile-up term (2-7%) in quadrature.
Jet reconstruction efficiency | Randomly drop jets (2%) from the events and symmetrise.
$b$-tagging efficiency | ± (5-17)%, depending on $p_T$ and $\eta$.
$b$-tagging mistag rate | ± (12-23)%, depending on $p_T$ and $\eta$.
b-jet JES uncertainty | Up to 2.5%, depending on $p_T$, added to the standard JES.
$\tau$ ID efficiency | ± (4-7)%, depending on number of tracks.
$\tau$ energy scale | ± (2.5-5.0)%, depending on $p_T$, $\eta$ and the number of tracks.
$E_T^{\text{miss}}$ uncertainty | ± (4-7)%, Uncertainties from object scale and resolution, +6.6% flat pile-up contribution.

Table 7.1: Main systematic uncertainties arising from detector simulation for the light $H^{\pm}$ searches with 2011 data.

<table>
<thead>
<tr>
<th>Variation</th>
<th>Shift Up (%)</th>
<th>Shift Down (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$-jet (mis-)tag eff.</td>
<td>2.8</td>
<td>-3.2</td>
</tr>
<tr>
<td>JES: Baseline</td>
<td>6.0</td>
<td>-4.7</td>
</tr>
<tr>
<td>JES: Close By Jet</td>
<td>12.0</td>
<td>-13.2</td>
</tr>
<tr>
<td>JES: Flavour</td>
<td>4.4</td>
<td>-3.3</td>
</tr>
<tr>
<td>JES: Forward Jets</td>
<td>6.0</td>
<td>-4.7</td>
</tr>
<tr>
<td>JES: $b$-jet energy</td>
<td>1.5</td>
<td>-0.8</td>
</tr>
<tr>
<td>JES: Sum</td>
<td>15.4</td>
<td>-15.2</td>
</tr>
<tr>
<td>JVF Uncertainty</td>
<td>2.1</td>
<td>-2.1</td>
</tr>
<tr>
<td>MET Uncertainty</td>
<td>0.6</td>
<td>-0.5</td>
</tr>
<tr>
<td>$\tau$ e-Veto</td>
<td>0.3</td>
<td>-0.3</td>
</tr>
<tr>
<td>$\tau$ Energy Scale</td>
<td>4.0</td>
<td>-4.3</td>
</tr>
<tr>
<td>$\tau$ ID</td>
<td>5.6</td>
<td>-5.6</td>
</tr>
<tr>
<td>Pileup-related Uncertainty</td>
<td>3.2</td>
<td>-2.1</td>
</tr>
</tbody>
</table>

Table 7.2: The effect of each systematic uncertainty on the final event yield in $t\bar{t}$ events in the 2012 search for a light $H^{\pm}$ in the $\tau$+jets channel.

a 8% uncertainty to 2012 analyses, as a result of possible supersymmetric loop corrections [83].

$\tau$+Jets

The uncertainties in $t\bar{t}$ generation and initial and final state radiation for the $\tau$+jets channel are shown in Table 7.3 for the 2011 analysis and Table 7.4 for the 2012 analysis. There is an additional systematic uncertainty associated with the scale factors derived for the $\tau + E_T^{\text{miss}}$ trigger efficiencies. For the 2011 analysis, the systematic uncertainty on the trigger scale factors are determined by varying the QCD multi-jet contribution to the $\mu + \tau$ sample used for the derivation of the trigger scale factors. This contribution can be enriched or reduced by varying the muon isolation. The systematic uncertainty is determined by varying
the tracking and calorimeter muon isolation by 1 GeV around the nominal cut values. The systematic uncertainties for the 2011 search are shown in Table 7.5.

In 2012, systematic effects are evaluated by considering the variation of scale factors for 1- and 3-prong \( \tau \) leptons and different trigger periods, the effect of varying the muon \( p_T \) cut, and the effect of the expected contribution to the efficiency measurement region of events with misidentified \( \tau \) leptons. The systematic uncertainties for the 2012 analysis are not yet fully finalized with the full 2012 dataset.

The remaining systematic uncertainties of the 2011 and 2012 \( \tau + \text{jets} \) channels are those arising from data-driven methods. In the 2011 \( \tau + \text{jets} \) search, these uncertainties primarily arise from the template method, the \( \tau \) embedding method, and the method applying jet\( \rightarrow \tau \) misidentification rates to simulated events. The uncertainties of the data-driven methods are shown in Table 7.6.

The dominant method-related systematic uncertainties for the \( \tau + \text{jets} \) channel are shown in Table 7.6. In the template method, which is used to predict the QCD multi-jet background, the dominant systematic uncertainties are the statistical uncertainty of the fit due to the limited size of the data control sample and the uncertainties due to potential differences in the \( E_T^{\text{miss}} \) shape in signal and control regions.

In non-QCD events with jets reconstructed as \( \tau \) leptons, a misidentification probability is applied to simulated events. The largest uncertainty corresponding to the method resulted from the differing jet compositions in the control region where the misidentification probability was measured and the signal region where it was applied. However, the dominant uncertainty from this background arises from the detector-related systematic uncertainties of simulated objects in the events.

In the true \( \tau \) embedding method, the dominant uncertainty is from the determination of the normaliza-

---

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Normalization uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau + \text{jets} ): Generator and parton shower (( b\bar{b}W^\pm H^\pm ))</td>
<td>5%</td>
</tr>
<tr>
<td>( \tau + \text{jets} ): Generator and parton shower (( b\bar{b}W^+W^- ))</td>
<td>5%</td>
</tr>
<tr>
<td>Initial and final state radiation</td>
<td>19%</td>
</tr>
</tbody>
</table>

Table 7.3: Main systematic uncertainties arising from \( t\bar{t} \) modeling and from initial and final state radiation for the 2011 \( \tau + \text{jets} \) channels of the light \( H^\pm \) boson search.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Normalization uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau + \text{jets} ): Generator and parton shower (( b\bar{b}W^\pm H^\pm ))</td>
<td>6%</td>
</tr>
<tr>
<td>( \tau + \text{jets} ): Generator and parton shower (( b\bar{b}W^+W^- ))</td>
<td>6%</td>
</tr>
<tr>
<td>Initial and final state radiation</td>
<td>11%</td>
</tr>
</tbody>
</table>

Table 7.4: Main systematic uncertainties arising from \( t\bar{t} \) modeling and from initial and final state radiation for the 2012 \( \tau + \text{jets} \) channels of the light \( H^\pm \) search.
Table 7.5: Systematic uncertainties on the $\tau$+jets channel trigger scale factors for the 2011 light $H^\pm$ search in the $\tau$+jets channel. The numbers represent percent variation on the nominal scale factor.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Normalization uncertainty $\pm$</th>
<th>Shape uncertainty $\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$+jets: true $\tau$</td>
<td>$p_T^\tau = [40, 70)$ GeV $^{+13%}_{-13%}$</td>
<td>$p_T^\tau = [70, 500)$ GeV $^{+1%}_{-0%}$</td>
</tr>
<tr>
<td>$E_{T}^{miss} = [65, 100)$ GeV</td>
<td>$\pm 7%$</td>
<td>$\pm 0%$</td>
</tr>
<tr>
<td>$E_{T}^{miss} = [100, 500)$ GeV</td>
<td>$\pm 0%$</td>
<td>$\pm 3%$</td>
</tr>
</tbody>
</table>

Table 7.5: Systematic uncertainties on the $\tau$+jets channel trigger scale factors for the 2011 light $H^\pm$ search in the $\tau$+jets channel. The numbers represent percent variation on the nominal scale factor.

Table 7.6: Dominant systematic uncertainties from the data-driven estimates applied in the 2011 $\tau$+jets channel of the light $H^\pm$ search. The shape uncertainty given is the relative shift of the mean value of the final discriminant distribution.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Normalization uncertainty $\pm$</th>
<th>Shape uncertainty $\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$+jets: true $\tau$</td>
<td>$\pm 6%$</td>
<td>$\pm 3%$</td>
</tr>
<tr>
<td>Muon isolation</td>
<td>$\pm 7%$</td>
<td>$\pm 2%$</td>
</tr>
<tr>
<td>Parameters in normalization</td>
<td>$\pm 16%$</td>
<td>$\pm -%$</td>
</tr>
<tr>
<td>$\tau$ identification</td>
<td>$\pm 5%$</td>
<td>$\pm -%$</td>
</tr>
<tr>
<td>$\tau$ energy scale</td>
<td>$\pm 6%$</td>
<td>$\pm 1%$</td>
</tr>
<tr>
<td>$\tau$+jets: jet → $\tau$ misidentification</td>
<td>$\pm 2%$</td>
<td>$\pm -%$</td>
</tr>
<tr>
<td>Statistics in control region</td>
<td>$\pm 12%$</td>
<td>$\pm -%$</td>
</tr>
<tr>
<td>Purity in control region</td>
<td>$\pm 6%$</td>
<td>$\pm 1%$</td>
</tr>
<tr>
<td>Object-related systematic uncertainties</td>
<td>$\pm 21%$</td>
<td>$\pm 2%$</td>
</tr>
<tr>
<td>$E_{T}^{miss}$-shape in control region</td>
<td>$\pm 32%$</td>
<td>$\pm -%$</td>
</tr>
<tr>
<td>Fit-related uncertainties</td>
<td>$\pm 32%$</td>
<td>$\pm -%$</td>
</tr>
</tbody>
</table>

The dominant systematic uncertainties arising from the data-driven methods in the 2012 $\tau$+jets channel are shown in Table 7.7. These systematic uncertainties arise from the matrix method, which is used to predict the total jet→$\tau$ background of the analysis. The dominant systematic effect is from the expected difference in jet composition between the control region and the signal region, and from the uncertainty on the simulated true $\tau$ efficiency. Simulation is also used to subtract the small true $\tau$, electron, and muon contamination from the region where the misidentification probability is measured. The variation of the subtraction of true $\tau$ leptons, electrons, and muons results in an additional small uncertainty.

The method-related systematic uncertainties in this channel arise primarily from the application of the $t\bar{t}$ generator uncertainties for the 2011 light $H^\pm$ search in the $\tau$+lepton channel are shown in Table 7.8.

$\tau$+Lepton

The $t\bar{t}$ generator uncertainties for the 2011 light $H^\pm$ search in the $\tau$+lepton channel are shown in Table 7.8. The method-related systematic uncertainties in this channel arise primarily from the application of the $t\bar{t}$ generator uncertainties for the 2011 light $H^\pm$ search in the $\tau$+lepton channel.
jet→τ misidentification probability to simulated events, and from the estimation of the QCD multi-jet background using non-isolated leptons.

The method-related systematic uncertainties of the 2011 τ+lepton analysis are summarized on Table 7.9. The systematic uncertainties for events with jets misidentified as τ leptons come from the same sources as for the 2011 τ+jets channel. For events with misidentified leptons, the dominant systematic uncertainty is due to the difference in jet composition between the control region where the misidentification rate is measured and the signal region where it is applied. There is also a significant contribution from jet object systematic uncertainties on the simulation used to subtract events with true leptons from the control region where the misidentification rate is measured.

**Ratio Method**

The total systematic uncertainties of the analysis and their effects on \(R_e\) and \(R_\mu\) are shown in Table 7.10. The numbers shown are the relative shifts (in %) in the ratio when each systematic uncertainty is varied ±1 standard deviation in both the numerator and denominator.

One of the motivations of the Ratio Method is the expectation that many systematic uncertainties will approximately cancel in the final ratios. This expectation is based on the observation that any of the systematic uncertainties that arise from detector simulation affect the numerator and denominator of the ratio in the same manner, and thus have a limited impact on the final ratios (defined here as \(R_e\) and \(R_\mu\)). For instance, the systematic uncertainty on the integrated luminosity is the same for all simulated events.

### Table 7.7

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Effect on yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix Method: true τ contamination</td>
<td>2.0%</td>
</tr>
<tr>
<td>Matrix Method: jet composition</td>
<td>8.6%</td>
</tr>
<tr>
<td>Matrix Method: statistical uncertainties</td>
<td>6.0%</td>
</tr>
<tr>
<td>Matrix Method: electron veto uncertainties</td>
<td>1.7%</td>
</tr>
<tr>
<td>Matrix Method: τ ID SF uncertainties</td>
<td>13.5%</td>
</tr>
</tbody>
</table>

Table 7.7: Dominant systematic uncertainties associated with the data-driven matrix method, using to estimate the jet→τ background of the 2012 light \(H^\pm\) search in the τ+jets channel.

### Table 7.8

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Normalization uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ+lepton:</td>
<td></td>
</tr>
<tr>
<td>Generator and parton shower ((bbW^\pm H^\pm))</td>
<td>2%</td>
</tr>
<tr>
<td>Generator and parton shower ((b\bar{b}W^++W^-))</td>
<td>5%</td>
</tr>
<tr>
<td>Initial and final state radiation</td>
<td>13%</td>
</tr>
</tbody>
</table>

Table 7.8: Main systematic uncertainties arising from \(t\bar{t}\) modeling and from initial and final state radiation for the 2011 τ+lepton channel of the light \(H^\pm\) search.
<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Normalization uncertainty</th>
<th>Shape uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$+lepton: jet $\rightarrow \tau$ misidentification</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Statistics in control region</td>
<td>2%</td>
<td>-</td>
</tr>
<tr>
<td>Jet Composition</td>
<td>11%</td>
<td>-</td>
</tr>
<tr>
<td>Purity in control region</td>
<td>6%</td>
<td>1%</td>
</tr>
<tr>
<td>Object-related systematic uncertainties</td>
<td>23%</td>
<td>3%</td>
</tr>
<tr>
<td>$\tau$+lepton: lepton misidentification</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Choice of control region</td>
<td>4%</td>
<td>-</td>
</tr>
<tr>
<td>Z mass window</td>
<td>5%</td>
<td>-</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>14%</td>
<td>-</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>4%</td>
<td>-</td>
</tr>
<tr>
<td>Sample Composition</td>
<td>39%</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 7.9: Dominant systematic uncertainties on the data-driven estimates for the 2011 search for a light $H^{\pm}$ in the $\tau$+lepton channel. The shape uncertainty given is the relative shift of the mean value of the final discriminant distribution.

In addition, the systematic uncertainties pertaining to jets, triggered leptons, and $E_T^{\text{miss}}$ reconstruction are expected to affect the numerator and denominator equivalently. The remaining systematic uncertainties include those associated with the second lepton in the denominator and the $\tau$ of the numerator. In addition, there is still a minor contribution that is associated with the use of data-driven techniques.

When considering systematic uncertainties arising from generator and showering, or initial and final state radiation, large differences are observed between generators in the reconstruction of tracks associated with jets reconstructed as $\tau$ leptons. This tracking issue dominates the systematic uncertainty. This is not considered a meaningful uncertainty, since the nominal generator is already scaled to match the $N_{\text{track}}$ distribution of data. Uncertainties associated with this re-scaling of the track distribution have already been evaluated, and are included in the total uncertainty of the analysis. Furthermore, there is no reason to assume that the systematic generators are any more accurate than the nominal generator in their reconstruction of tracks. The systematic generators disagree with data in the distribution of tracks in the $\tau$ lepton isolation cone, while the nominal sample has agreement within statistical uncertainties.

In order to remove this tracking issue from the relevant systematic, $N_{\text{track}}$ and $N_{\text{iso track}}$ distributions of the systematic $t\bar{t}$ samples are re-scaled so that they match the distributions from data. Once this re-scaling is applied, the uncertainties on the $\tau$+lepton and dilepton event yields are 6-8% and 1-2% for the modelling of $t\bar{t}$ events and parton shower. For the initial and final state radiation, the uncertainties on the $\tau$+lepton and dilepton event yields are 11% and 8%.

The remaining systematic uncertainties are from data-driven background methods. For backgrounds with misidentified leptons, the systematic uncertainties arise from the same sources as the 2011 $\tau$+lepton channel. For the backgrounds with jets misidentified as $\tau$ leptons, the dominant uncertainties are those on
<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>$\Delta R_e$</th>
<th>$\Delta R_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Electron trigger efficiency</td>
<td>0.1%</td>
<td>N/A</td>
</tr>
<tr>
<td>Electron reco. and ID efficiency</td>
<td>0.2%</td>
<td>1.9%</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>0.1%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Electron energy resolution</td>
<td>0.1%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Muon trigger efficiency</td>
<td>N/A</td>
<td>0.1%</td>
</tr>
<tr>
<td>Muon reco. and ID efficiency</td>
<td>1.0%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Muon momentum resolution</td>
<td>&lt;0.1%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>0.1%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.4%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Jet vertex fraction</td>
<td>0.1%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Jet energy scale (JES)</td>
<td>0.7%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Jet reconstruction efficiency</td>
<td>0.1%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>1.9%</td>
<td>2.3%</td>
</tr>
<tr>
<td>$\tau$ ID efficiency</td>
<td>3.9%</td>
<td>3.9%</td>
</tr>
<tr>
<td>$\tau$ energy scale</td>
<td>2.9%</td>
<td>3.0%</td>
</tr>
<tr>
<td>$\tau$ mis-ID: number of associated tracks</td>
<td>2.1%</td>
<td>2.1%</td>
</tr>
<tr>
<td>$\tau$ mis-ID: true $\tau$ contamination</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>$\tau$ mis-ID: $H^+$ signal contamination</td>
<td>0.6%</td>
<td>0.6%</td>
</tr>
<tr>
<td>$\tau$ mis-ID: event environment</td>
<td>1.3%</td>
<td>1.2%</td>
</tr>
<tr>
<td>$\tau$ mis-ID: statistical uncertainties</td>
<td>3.3%</td>
<td>3.2%</td>
</tr>
<tr>
<td>$\tau$ mis-ID: electron veto uncertainties</td>
<td>0.6%</td>
<td>0.3%</td>
</tr>
<tr>
<td>$E_T^{miss}$ uncertainty</td>
<td>0.3%</td>
<td>0.1%</td>
</tr>
<tr>
<td>$t\bar{t}$: cross section</td>
<td>0.7%</td>
<td>0.6%</td>
</tr>
<tr>
<td>$t\bar{t}$: generator and parton shower</td>
<td>5.7%</td>
<td>4.4%</td>
</tr>
<tr>
<td>$t\bar{t}$: initial and final state radiation</td>
<td>3.6%</td>
<td>3.7%</td>
</tr>
<tr>
<td>Backgrounds with mis-ID leptons</td>
<td>3.5%</td>
<td>4.3%</td>
</tr>
<tr>
<td>Total (added in quadrature)</td>
<td>10.3%</td>
<td>10.1%</td>
</tr>
</tbody>
</table>

Table 7.10: Main systematic uncertainties in the Ratio Method search for the light $H^\pm$. The relative effect on the value of the ratio is shown for electron-triggered events (left) and muon-triggered events (right).

the tracking scale factors, the statistical uncertainties on the misidentification probability, and the difference in jet composition between control and signal regions. The jet composition uncertainty has been greatly reduced with respect to the other 2011 analyses. This is due to the OS-SS subtraction, which produces an approximately pure sample of light quarks in both the signal and control regions.

### 7.1.2 Heavy $H^\pm$ Search

Systematic uncertainties in the 2012 heavy $H^\pm$ search arise from the same sources as those listed for the 2012 light $H^\pm$ search, since the two analyses differ only by several basic selection cuts on $E_T^{miss}$, $E_T^{miss}$ significance, and number of jets. The uncertainty on $t\bar{t}$ events that arises from generator and parton shower, as well as initial and final state radiation, is the same as for the light $H^\pm$ search. The corresponding uncertainties for the heavy $H^\pm$ signal samples are shown in Table 7.11. The detector-related uncertainties and those arising
Source of uncertainty | Normalization uncertainty
--- | ---
\( \tau + \text{jets} \):
Generator and parton shower \((m_{H^\pm} \leq 200 \text{ GeV})\) | 15.2-16.2% 
Generator and parton shower \((m_{H^\pm} > 200 \text{ GeV})\) | 1.0-7.5% 
Initial and final state radiation | 4.6%

Table 7.11: Main systematic uncertainties arising from \( t\bar{t} \) modeling and from initial and final state radiation for the 2012 \( \tau + \text{jets} \) channels of the heavy \( H^\pm \) search. The uncertainties from \( t\bar{t} \) are given as ranges that are dependent on \( m_{H^\pm} \).

<table>
<thead>
<tr>
<th>Variation</th>
<th>Shift Up (%)</th>
<th>Shift Down (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b )-jet (mis-)tag eff.</td>
<td>2.1</td>
<td>-2.5</td>
</tr>
<tr>
<td>JES: Baseline</td>
<td>3.4</td>
<td>-3.7</td>
</tr>
<tr>
<td>JES: Close By Jet</td>
<td>13.8</td>
<td>-16.0</td>
</tr>
<tr>
<td>JES: Flavour</td>
<td>2.7</td>
<td>-2.6</td>
</tr>
<tr>
<td>JES: Forward Jets</td>
<td>3.4</td>
<td>-3.7</td>
</tr>
<tr>
<td>JES: ( b )-jet energy</td>
<td>0.4</td>
<td>-0.9</td>
</tr>
<tr>
<td>JES: Sum</td>
<td>14.8</td>
<td>-17.0</td>
</tr>
<tr>
<td>JVF Uncertainty</td>
<td>2.1</td>
<td>-2.0</td>
</tr>
<tr>
<td>MET Uncertainty</td>
<td>0.2</td>
<td>-0.5</td>
</tr>
<tr>
<td>( \tau ) e-Veto</td>
<td>0.3</td>
<td>-0.3</td>
</tr>
<tr>
<td>( \tau ) Energy Scale</td>
<td>4.2</td>
<td>-3.9</td>
</tr>
<tr>
<td>( \tau ) ID</td>
<td>3.8</td>
<td>-3.8</td>
</tr>
<tr>
<td>Pileup-related Uncertainty</td>
<td>1.6</td>
<td>-1.8</td>
</tr>
</tbody>
</table>

Table 7.12: The effect of each systematic uncertainty on the final event yield in \( t\bar{t} \) events in the 2012 search for a heavy \( H^\pm \) in the \( \tau + \text{jets} \) channel.

from the application of data driven techniques are shown in Table 7.12 and Table 7.13, respectively.

### 7.2 Results

In all of the analyses, good agreement is seen between observed data and the SM predictions. To demonstrate this agreement, event yields and distributions of discriminating variables are shown for the \( \tau + \text{jets} \) and \( \tau + \text{lepton} \) channels. For the Ratio Method, measured ratios are compared with those arising from the estimation of SM backgrounds, and \( M_{H_2}^T \) distributions are shown for the numerator and denominator events.

#### 7.2.1 Light Charged Higgs

For the light \( H^\pm \) searches, the \( H^\pm \) takes the place of a \( W \) boson in a \( t\bar{t} \) decay. Therefore, when giving a referential expected total signal+background event yield or distribution, the \( t\bar{t} \) cross-section is modified accordingly. Specifically, the cross sections of the different decays chains are modified as follows, with \( B = B(t \rightarrow bH^\pm) \):
Table 7.13: Dominant systematic uncertainties associated with the data-driven matrix method, using to estimate the jet → τ background of the 2012 heavy \( H^\pm \) search in the τ+jets channel.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Effect on yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix Method: true τ contamination</td>
<td>2.1%</td>
</tr>
<tr>
<td>Matrix Method: jet composition</td>
<td>9.2%</td>
</tr>
<tr>
<td>Matrix Method: statistical uncertainties</td>
<td>6.4%</td>
</tr>
<tr>
<td>Matrix Method: electron veto uncertainties</td>
<td>2.0%</td>
</tr>
<tr>
<td>Matrix Method: τ ID SF uncertainties</td>
<td>11.5%</td>
</tr>
</tbody>
</table>

Table 7.14: Number of expected events after all event selection in the τ+jets channel and number of events observed in 4.6fb\(^{-1}\) of ATLAS data. The values shown for \( H^+ \) correspond to \( B(t \to bH^+) = 5\% \) with \( m_{H^\mp} = 130 \) GeV.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Event yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>true τ</td>
<td>210 ± 10^{+43}_{-43}</td>
</tr>
<tr>
<td>jet → τ</td>
<td>36 ± 6^{+10}_{-10}</td>
</tr>
<tr>
<td>e → τ</td>
<td>3 ± 1^{+1}_{-1}</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>74 ± 3^{+43}_{-50}</td>
</tr>
<tr>
<td>(</td>
<td>\bar{\tau}S)M</td>
</tr>
<tr>
<td>Data</td>
<td>355</td>
</tr>
<tr>
<td>( t \to bH^+ )</td>
<td>220 ± 6^{+89}_{-62}</td>
</tr>
<tr>
<td>Signal+background</td>
<td>540 ± 13^{+80}_{-91}</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
t\bar{t} \to b\bar{b}W^+W^- : \sigma_{bbWW} &= \sigma_{\bar{\tau}t} \times (1 - B)^2 \\
t\bar{t} \to b\bar{b}H^\pm W^{\mp} : \sigma_{bbW} &= \sigma_{\bar{\tau}t} \times 2B(1 - B) \\
t\bar{t} \to b\bar{b}H^+H^- : \sigma_{bbWW} &= \sigma_{\bar{\tau}t} \times B^2
\end{align*}
\]

\( \tau + \text{Jets} \)

In the 2011 τ+jets channel analysis, all backgrounds are estimated using data-driven methods, as described in Chapter 6. The contribution of events with true hadronically-decaying τ leptons has been estimated using the embedding method. Events with jets misidentified as hadronically-decaying τ leptons have been estimated using misidentification probabilities measured in a \( W^+ \)+jets control region. Events with electrons misidentified as hadronically-decaying τ leptons have been corrected using scale factors measured in a \( Z \to ee \) control region. Events consistent with QCD multi-jet processes have been estimated using a fitting method with a control region template for the QCD shape.

The resulting yields from data and the application of data-driven methods to the signal region are shown in Table 7.14, along with a hypothetical signal with \( m_{H^\pm} = 130 \) GeV and \( B(t \to bH^+) = 5\% \). The \( m_T \)
Figure 7.1: The $m_T$ distribution for the 2011 $\tau$+jets channel at the end of the event selection. Shown are the observed events in 2011 ATLAS data, SM backgrounds estimated by data-driven methods, and a reference signal contribution from a $H^+$ with $t \rightarrow bH^+$ = 5% and $m_H^+ = 130$ GeV. The shaded area shows the systematic uncertainties added in quadrature [12].

<table>
<thead>
<tr>
<th>Light $H^+$</th>
<th>True $\tau$</th>
<th>$e \rightarrow \tau$ Misidentification</th>
<th>Multi-jet processes</th>
<th>$\sum$ SM</th>
<th>Data</th>
<th>$H^+$ (130 GeV)</th>
<th>Signal + background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1913 \pm 39_{-590}^{+613}$</td>
<td>$27 \pm 3_{-10}^{+19}$</td>
<td>$242 \pm 17_{-39}^{+30}$</td>
<td>$2182 \pm 44_{-591}^{+561}$</td>
<td>2076</td>
<td>$288 \pm 9_{-98}^{+80}$</td>
<td>$2436 \pm 45_{-599}^{+614}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.15: Number of expected events after all selections cuts in the $\tau$+jets channel and comparison with 19.5 fb$^{-1}$ of ATLAS data. The values shown for the $H^+$ signal correspond to $m_{H^+} = 130$ GeV and $B(t \rightarrow H^+b) = 1.0\%$. Both statistical and systematic uncertainties are shown, in that order.

distribution of these events is shown in Fig 7.1, along with the same hypothetical signal contribution. Results are shown with statistical and systematic uncertainties, and good agreement between estimated and observed events is achieved.

In the 2012 $\tau$+jets channel analysis, the number of events with true $\tau$ leptons has been estimated using simulation, the jet $\rightarrow \tau$ misidentification contribution has been estimated with the matrix method, and the $e \rightarrow \tau$ has been corrected using scale factors derived from data.

The resulting yields from data and the different sources of background contribution after the baseline selection are shown in Table 7.15. A hypothetical signal contribution with $m_{H^\pm} = 130$ GeV and $B(t \rightarrow H^+b) = 1.0\%$ is also shown for reference. The $m_T$ distribution is shown in Figure 7.2, with the same hypothetical signal contribution scaled by a factor of 10. Results are shown with statistical and systematic uncertainties, and a good agreement between estimated and observed events has been achieved.
Figure 7.2: The $m_T$ distribution at the end of the event selection, comparing the observation in collision data and the estimates from data-driven methods and simulation. The shaded area shows the size of the uncertainties on the expectation when adding them in quadrature. The distribution of the signal is given for a reference point in parameter space corresponding to $m_{H^+} = 130$ GeV and $B(t \rightarrow H^+b) = 1.0\%$, scaled by a factor of 10 [9].

$\tau+\text{Lepton}$

For the 2011 $\tau+\text{lepton}$ channel analysis, many backgrounds have been estimated using data-driven methods. Events with jets misidentified as hadronically-decaying $\tau$ leptons have been estimated using misidentification probabilities measured in a $W^{\pm}\text{jets}$ control region. Events with electrons misidentified as hadronically-decaying $\tau$ leptons are corrected using scale factors measured in a $Z \rightarrow ee$ control region. QCD multi-jets have been estimated using a method that relies on lepton efficiency and misidentification rates. Events with true hadronically-decaying $\tau$ leptons have been taken from simulation.

The resulting yields for the data and SM background events that pass the baseline selection are shown in Table 7.16, with a hypothetical signal of $m_{H^\pm} = 130$ and $B(t \rightarrow bH^+) = 5\%$, for reference. The $E_T^{\text{miss}}$ distributions of these events are shown in Fig 7.3, along with the same hypothetical signal contribution. Data and the total estimated SM background agree well within uncertainties.

Ratio Method

Though the shape is not used for the final limits, the generalized transverse mass described in section 5.1.3 is used to illustrate the improvement in limits when using the event yields in the form of the ratios. The $M_{T2}^H$ distributions for numerator and denominator events are shown in Fig. 7.4 for electron-triggered events and Fig. 7.5 for muon-triggered events.

The event yields for the 4 final states are obtained by integrating the $M_{T2}^H$ distributions shown in Fig. 7.4.
Figure 7.3: The $E_T^{\text{miss}}$ distribution for the $\tau+$lepton channels, $\tau + e$ (left) and $\tau + \mu$ (right), at the end of the event selection. Shown are the observed events in 2011 ATLAS data, SM backgrounds estimated by data-driven methods, and a reference signal contribution from $H^+$ with $B(t \to bH^+) = 5\%$ and $m_H = 130$ GeV. The shaded area shows the systematic uncertainties added in quadrature [12].

Figure 7.4: Distribution of $M_{T^2}$ in the electron-triggered signal region after the OS-SS subtraction. Ratio numerator $e + \tau$ events (left) and denominator $e + \mu$ events (right) are shown. The dashed line shows the SM-only hypothesis and the hatched area shows the total uncertainty for the SM backgrounds. “Others” refers to non-$t\bar{t}$ SM processes. The solid line shows the predicted distribution of signal+background with a $H^+$ of $m_{H^+} = 130$ GeV and $B(t \to bH^+) = 3\%$. The yellow shows the signal contribution, stacked on top of the SM backgrounds [13].
Table 7.16: Number of expected events after all event selection in the $\tau$+lepton channel and number of events observed in 4.6fb$^{-1}$ of ATLAS data. The values shown for $H^+$ correspond to $B(t \rightarrow bH^+) = 5\%$ with $m_{H^+} = 130$ GeV.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Event yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau + e$</td>
</tr>
<tr>
<td>true $\tau$</td>
<td>$429 \pm 14^{+34}_{-81}$</td>
</tr>
<tr>
<td>jet $\rightarrow \tau$</td>
<td>$512 \pm 23^{+63}_{-58}$</td>
</tr>
<tr>
<td>$e \rightarrow \tau$</td>
<td>$33 \pm 4^{+5}_{-5}$</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>$39 \pm 10^{+20}_{-29}$</td>
</tr>
<tr>
<td>$\Sigma$SM</td>
<td>$1013 \pm 29^{+103}_{-109}$</td>
</tr>
<tr>
<td>Data</td>
<td>$880$</td>
</tr>
<tr>
<td>$t \rightarrow bH^+$</td>
<td>$224 \pm 6^{+24}_{-31}$</td>
</tr>
<tr>
<td>Data+background</td>
<td>$1163 \pm 28^{+98}_{-104}$</td>
</tr>
</tbody>
</table>

and Fig. 7.5. The two ratios are defined as in Equation 5.3 in Chapter 5.

Each event yield ($N$) can be split into the contributions from $t\bar{t}$ (mediated by both $W$ and possibly $H^\pm$) and from all other SM processes. The $t\bar{t}$ contribution can be described as a function of the cross section, $\sigma_{t\bar{t}}$, the integrated luminosity $L$, the branching ratio $B = B(t \rightarrow bH^\pm)$, and the selection efficiencies. The selection efficiencies are defined as $\varepsilon_{W^+W^-,eH^+H^-}$, and $\varepsilon_{H^\pm+W^\pm}$ for $t\bar{t} \rightarrow b\bar{b}W^+W^-$, $t\bar{t} \rightarrow b\bar{b}H^+H^-$, and $t\bar{t} \rightarrow b\bar{b}H^\pm W^\pm$. Using these terms, the four yields can be written as:

$$N(e + \tau) = \sigma_{t\bar{t}} \times L \times [(1 - B)^2 \varepsilon_{W^+W^-}^{e+\tau} + B(1 - B)(\varepsilon_{H^+H^-}^{e+\tau} + \varepsilon_{W^+H^-}^{e+\tau}) + B^2 \varepsilon_{H^+H^-}^{e+\tau} + N_{\text{others}}(e + \tau)] (7.4)$$

$$N(e + \mu) = \sigma_{t\bar{t}} \times L \times [(1 - B)^2 \varepsilon_{W^+W^-}^{e+\mu} + B(1 - B)(\varepsilon_{H^+W^-}^{e+\mu} + \varepsilon_{W^+H^-}^{e+\mu}) + B^2 \varepsilon_{H^+H^-}^{e+\mu} + N_{\text{others}}(e + \mu)] (7.5)$$

$$N(\mu + \tau) = \sigma_{t\bar{t}} \times L \times [(1 - B)^2 \varepsilon_{W^+W^-}^{\mu+\tau} + B(1 - B)(\varepsilon_{H^+H^-}^{\mu+\tau} + \varepsilon_{W^+H^-}^{\mu+\tau}) + B^2 \varepsilon_{H^+H^-}^{\mu+\tau} + N_{\text{others}}(\mu + \tau)] (7.6)$$

$$N(\mu + e) = \sigma_{t\bar{t}} \times L \times [(1 - B)^2 \varepsilon_{W^+W^-}^{\mu+e} + B(1 - B)(\varepsilon_{H^+W^-}^{\mu+e} + \varepsilon_{W^+H^-}^{\mu+e}) + B^2 \varepsilon_{H^+H^-}^{\mu+e} + N_{\text{others}}(\mu + e)] (7.7)$$

As discussed in section 5.1.3, the sensitivity of the analysis to $H^+$ is determined by the slope of variation in the ratios $R_e$ and $R_\mu$ with an increasing branching ratio $B(t \rightarrow bH^+)$. This slope depends on the selection efficiencies and $m_{H^\pm}$. Fig. 7.6 shows the expected relative shift due to the presence of a $H^+$ with $m_{H^\pm} = 130$ GeV as a function of the branching ratio $B(t \rightarrow H^+b)$. The blue and green slopes show the shift in numerator and denominator yields, while the red shows the shift of the ratio. These plots are shown at the end of the event selection, for events that require an electron trigger and a muon trigger.

As expected, the contribution from $H^+$ causes an increase in the amount of $t\bar{t}$ events with a $\tau$+lepton final state. However, after the full event selection, the yield for dileptonic $t\bar{t}$ events decreases as a function of increasing $B(t \rightarrow bH^+)$, despite the fact that more events are expected at generator level in this channel.
Figure 7.5: Distribution of $M_{T2}^H$ in the muon-triggered signal region after the OS-SS subtraction. Ratio numerator $\mu + \tau$ events (left) and denominator $\mu + e$ events (right) are shown. The dashed line shows the SM-only hypothesis and the hatched area shows the total uncertainty for the SM backgrounds. “Others” refers to non-$t\bar{t}$ SM processes. The solid line shows the predicted distribution of signal+background with $H^+$ of $m_{H^+} = 130$ GeV and $B(t \rightarrow bH^+) = 3\%$. The yellow shows the signal contribution, stacked on top of the SM backgrounds [13].

Table 7.17: Variation of the slopes $s_e$ and $s_\mu$ with $m_{H^\pm}$ relative to the slopes of the ratios with a $H^+$ of mass 130 GeV. The low slope at 100 GeV mass in the channel triggered by an electron is a result of statistical fluctuation in the simulated signal sample.

<table>
<thead>
<tr>
<th>$m_{H^\pm}$ (GeV)</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_e/s_e^{130}$</td>
<td>1.12</td>
<td>0.96</td>
<td>1.15</td>
<td>1.06</td>
<td>1.00</td>
<td>0.81</td>
<td>0.52</td>
<td>0.22</td>
</tr>
<tr>
<td>$s_\mu/s_\mu^{130}$</td>
<td>1.04</td>
<td>1.04</td>
<td>1.06</td>
<td>1.04</td>
<td>1.00</td>
<td>0.81</td>
<td>0.47</td>
<td>0.16</td>
</tr>
</tbody>
</table>

(see Section 5.1.3). While there are a greater number of events due to the leptonic decays of the $\tau$ lepton, electrons and muons produced from a $\tau$ decay tend to be softer, and therefore less likely to pass the lepton object selections.

To examine the sensitivity as a function of mass, Table 7.17 shows the slope for the event ratios triggered by electrons and muons with $m_{H^\pm}$ in the range $90 - 160$ GeV. The slope for each value of $m_{H^+}$ is shown relative to the slope of the a signal with $m_{H^+} = 130$ GeV. The selection efficiencies are larger for $m_{H^\pm}$ values closer to $m_W$ than for those approaching $m_{top}$. This is due to the fact that the $b$-jet arising from $B(t \rightarrow bH^+)$ becomes softer as the difference between $m_{top}$ and $m_{H^\pm}$ becomes smaller, so signal events are less likely to pass the event selection.

The final event yields for the four channels are shown in Table 7.18. The predicted and observed values for the ratios are shown in Table 7.19, where the SM value is taken from simulated events and those predicted by data-driven methods, and the observed value is from signal region data. Both the measured yields and ratios agree, within uncertainties, with the SM prediction.
Figure 7.6: The effect of the presence of a $H^+$ signal with $m_{H^+} = 130$ GeV in the electron channel (left) and muon channel (right). The blue and green markers show the relative change as a function of $B(t \to bH^+)$ in the numerator and denominator yields, respectively. The red markers show the % increase in the resulting ratio \[13\].

### 7.2.2 Heavy $H^{\pm}$

In the 2012 search for a heavy $H^{\pm}$, the backgrounds are determined using the same methods described for the 2012 light $H^{\pm}$ search. The jet→τ backgrounds are predicted using the matrix method, $e \to \tau$ events are taken from simulation and corrected using data-driven scale factors, and events with true τ leptons are taken from simulation.

The observed yields from data and the predicted SM backgrounds are shown in Table 7.20, along with a hypothetical signal contribution from $H^{\pm}$ with $m_{H^{\pm}} = 250$ GeV and $\tan \beta = 30$, in the \(m_{h^{\text{max}}}\) scenario of the MSSM. The \(m_T\) distribution of the remaining events is shown in Figure 7.7, where the signal contribution is scaled by a factor of 10. For this plot and table, the \(m_{h^{\text{max}}}\) branching fraction of $B(H^{\pm} \to \tau \nu) = 30\%$ is taken into account. Within uncertainties, a good agreement between estimated and observed events has been achieved.
Sample & OS-SS event yields \\
& $e + \tau$ & $e + \mu$ \\
\hline
Misidentified leptons & $-0.8 \pm 3.0 \pm 0.3$ & $94 \pm 9.0 \pm 36$ \\
$W/Z + \text{jets} \& \text{diboson}$ & $2.1 \pm 0.7 \pm 0.6$ & $0.7 \pm 0.3 \pm 0.2$ \\
Single top quark & $3.3 \pm 0.5 \pm 0.6$ & $24 \pm 2.0 \pm 4.0$ \\
tt & $111 \pm 2.0 \pm 25$ & $980 \pm 7.0 \pm 200$ \\
SM & $116 \pm 4.0 \pm 25$ & $1100 \pm 12 \pm 210$ \\
Data & 144 & 1247 \\
\hline
$tt$ with $B(t \rightarrow bH^+)$ (130 GeV) & 30 & 27 & 0.8 & 3.0 \\
Signal+background & 139 & 4.0 & 28 & 0.7 & 0.0 \\
\hline
Misidentified leptons & $0.2 \pm 1.0 \pm 0.1$ & $74 \pm 8.0 \pm 36$ \\
$W/Z + \text{jets} \& \text{diboson}$ & $2.6 \pm 1.2 \pm 1.0$ & $0.7 \pm 0.4 \pm 0.2$ \\
Single top quark & $4.6 \pm 0.6 \pm 0.7$ & $18 \pm 1.0 \pm 3.0$ \\
tt & $131 \pm 2.0 \pm 28$ & $740 \pm 6.0 \pm 150$ \\
SM & $138 \pm 3.0 \pm 29$ & $830 \pm 10 \pm 160$ \\
Data & 153 & 929 \\
\hline
$tt$ with $B(t \rightarrow bH^+)$ (130 GeV) & 35 & 20 & 1.0 & 3.0 \\
Signal+background & 166 & 3.0 & 32 & 0.7 & 0.6 \\
\hline
Table 7.18: Number of expected events and number of events observed in 4.6fb$^{-1}$ of ATLAS data, after all event selection and OS-SS subtraction, for the four final states used in the ratios. The values shown for $H^+$ correspond to $B(t \rightarrow bH^+) = 3\%$ with $m_{H^+} = 130$ GeV.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>$R_e$</th>
<th>$R_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM value</td>
<td>$0.105 \pm 0.004 ,(\text{stat}) \pm 0.011 ,(\text{syst})$</td>
<td>$0.166 \pm 0.004 ,(\text{stat}) \pm 0.017 ,(\text{syst})$</td>
</tr>
<tr>
<td>Measured value</td>
<td>$0.115 \pm 0.010 ,(\text{stat})$</td>
<td>$0.165 \pm 0.015 ,(\text{stat})$</td>
</tr>
</tbody>
</table>

Table 7.19: Predicted and measured values of the ratios $R_e$ and $R_\mu$.

| True $\tau$ | e$\rightarrow$\tau & Multi-jet processes & $\sum$ SM & Data | $H^+$ (250 GeV) & Signal + background |
|-------------|------------------|------------------|-----------|-------|--------------|-----------------|
| Heavy $H^+$ | $3022 \pm 61_{-34}^{+44}$ & $44 \pm 5_{-7}^{+9}$ & $480 \pm 31_{-72}^{+72}$ & $3545 \pm 69_{-805}^{+38}$ | $3325$ & $28 \pm 1_{-6}^{+3}$ & $3573 \pm 69_{-805}^{+38}$ |

Table 7.20: Number of expected events after all selection cuts in the 2012 $\tau$+jets channel and comparison with 19.5 fb$^{-1}$ of ATLAS data.== The values shown for the $H^+$ signal correspond to the $m_{h}$-max scenario cross section with $\tan \beta = 30$, with $B(H^+ \rightarrow \tau \nu) = 39\%$. Both statistical and systematic uncertainties are shown.
Figure 7.7: The $m_T$ distribution at the end of the event selection, comparing the observation in collision data and the estimates from data-driven methods. The error bars show the size of the data statistical uncertainties. The shaded area shows the size of the systematic uncertainties on the expectation when adding them in quadrature. The distribution of the $H^+$ signal is given for a reference point in parameter space corresponding to $m_{H^+} = 250$ GeV and a cross section of ten times the expected value for $\tan\beta = 30$ in the $m_{\tilde{A}}$-max scenario of the MSSM [9].
In the searches for light $H^\pm$ in the $\tau$+jets and $\tau$+lepton channels, the Ratio Method search for a light $H^\pm$, and the search for heavy $H^\pm$ in the $\tau$+jets channel, no statistically significant deviations from the SM predictions have been observed. Therefore, exclusion limits are set on the possible production of $H^+$ as a function of the $H^+$ mass. For the light $H^+$ case, where $H^+$ is produced in a $t\bar{t}$ decay, the limits will be derived for $B(t \rightarrow bH^+) \times B(H^+ \rightarrow \tau \nu)$. The 2011 limits will then be interpreted in terms of the $m_h$-max scenario of the MSSM, and shown in the $m_{H^+}$-$\tan \beta$ plane. The limits for the heavy $H^\pm$ case will be derived for $\sigma(H^+) \times B(H^+ \rightarrow \tau \nu)$.

All of the limits for these analyses are set following similar procedures. The limits make use of a profile likelihood ratio [84] with their discriminating variable(s) and they use a one-sided profile likelihood ratio, $\tilde{q}_\mu$, as a test statistic. Systematic uncertainties are incorporated via nuisance parameters, and they are considered in terms of both shape and normalization. The final limits are extracted at the 95% confidence level using the CL$_s$ procedure [85, 86]. These limits are based on the asymptotic distribution of the test statistic [84].

For setting limits on light $H^+$ in the MSSM $m_{h}$-max scenario, additional theoretical uncertainties on $B(t \rightarrow bH^+)$ are considered [87, 88]. The one-loop electroweak corrections missing in the calculations contribute 5%, missing two-loop QCD corrections contribute 2%, and $\Delta_b$-induced uncertainties contribute about 1% (depending on $\tan \beta$, where $\Delta_b$ is a correction factor to the running bottom quark mass). These uncertainties are added linearly, as recommended by the LHC Higgs cross section working group [88].

## 8.1 2011 Limits: Light $H^\pm$

For the 2011 light $H^\pm$ searches, limits are set on $B(t \rightarrow bH^+) \times B(H^+ \rightarrow \tau \nu)$ in the $\tau$+jets channel, the $\tau$+lepton channel, and the Ratio Method. In addition to the individual channel limits, there are also limits combining several of the channels. The $\tau$+jets and $\tau$+lepton, together with another channel arising from $\tau_{lep}$+jets [12], are combined into a single limit. The Ratio Method is also combined with the $\tau$+jets limit,
resulting in the strongest limit on light $H^+$ published with the 2011 dataset [13].

### 8.1.1 τ+jets

In the $\tau$+jets channel, the limits are extracted using a profile likelihood ratio with $m_T(\tau, E_T^{miss})$ as the discriminating variable. To describe the method in more detail, let $\mu$ and $n$ be the number of expected and observed events in the signal region at the end of the event selection. If $\varepsilon_W$ and $\varepsilon_H$ are the respective acceptances for $t\bar{t} \rightarrow b\bar{b}W^+W^-$ and $t\bar{t} \rightarrow b\bar{b}W^\pm H^\mp$ and $\mu_{\text{others}}$ is the number of expected events that are not from $t\bar{t}$ decays, the expected number of events is given by:

$$\mu = \mu_W\varepsilon_W + \mu_H\varepsilon_H + \mu_{\text{others}} = \mu_{t\bar{t}}[(1 - B^2)\varepsilon_W + 2B(1 - B)\varepsilon_H] + \mu_{\text{others}} \quad (8.1)$$

In the end, $t\bar{t} \rightarrow b\bar{b}H^+H^-$ events are excluded from the limits, due to problematic statistical effects arising from small simulated data samples. However, this contribution is expected to be very small, since $B(t \rightarrow bH^+)$ is expected to be less than 10%. The only effect of neglecting these events is that the limits will be slightly conservative. For the SM case, $\mu_W$ is the product of the theoretical $t\bar{t}$ cross section and the integrated luminosity. If a $H^\pm$ mediates a top quark decay, $\mu_W$ is reduced by a factor $(1 - B)^2$.

The simulated $m_T$ is then described using a probability density function $f_i(m_T)$. The expected and observed number of events in each bin $i$ are then $\mu_i = \mu f_i(E_T^{miss})$ and $n_i$, respectively. The resulting likelihood is given by:

$$L(B) = \prod_i \text{Poisson}(n_i|\mu_i) \prod_j p(\hat{\theta}_j|\theta_j) \quad (8.2)$$

where the index $i$ indicates the bin of the $m_T$ distribution. Nuisance parameters $\theta$ are used to describe the effect of systematic uncertainties, and $p(\hat{\theta}_j|\theta_j)$ are the Gaussian constraints relating each parameter to its nominal estimate $\hat{\theta}_j$. The profile likelihood statistical analysis is performed with $B$ as the single parameter of interest, and the test statistic is given by:

$$\hat{q}_B = -2 \log \frac{L(B, \hat{\theta}_B)}{L(\hat{B}, \hat{\theta})}, 0 \leq \hat{B} \leq B \quad (8.3)$$

where $\hat{\theta}_B$ are the maximum likelihood estimators (MLE) of the nuisance parameters for a fixed $B$, while $\hat{\theta}$ and $\hat{B}$ are the global MLE of $\theta$ and $B$, respectively. The limit is derived using a CL$_{s}$ criterion, based on a fully frequentist ensemble in which $n_i$ and $\hat{\theta}_j$ are randomized.

The compatibility with background is measured by $p_0$-values, which are summarized in Table 8.1. The
Table 8.1: Observed $p_{0}$-values as a function of $m_{H^\pm}$ in the $\tau$+jets channel.

<table>
<thead>
<tr>
<th>$m_{H^\pm}$ (GeV)</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{0}$-value</td>
<td>0.35</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Constant value of 50% for $p_{0}$ is a feature of the test statistic, which is defined as 50% when the unconditional fit returns an un-physical negative branching ratio. These $p_{0}$ values show that no indication of a $H^+$-like excess is found at any mass.

The upper limits on $B(t \rightarrow bH^+)$, with the assumption that $B(H^+ \rightarrow \tau\nu) = 100\%$, are shown on the left plot of Fig. 8.1. Branching ratios $B(t \rightarrow bH^+)$ < 0.01 − 0.06 have been excluded in the range of $m_{H^+} = 90 \text{−} 160$ GeV. A solid line in the figures is used to denote the observed 95% confidence levels, while a dashed line represents the expected exclusion limits. The outer edges of the green and yellow shadowed regions show the 1σ and 2σ error bands. The right plot of Fig. 8.1 shows the interpretation of this upper limit in the $m_{H^+}$-max scenario of the MSSM, in the $m_{H^+}$-tan β plane. In the interpretation, a region above approximately tan β = 10 − 22 can be excluded in the mass range 90 − 150 GeV.

### 8.1.2 $\tau$+Lepton

In the $\tau$+lepton channel, a profile likelihood ratio is used with the $E_{T}^{miss}$ distribution as the discriminating variable. The likelihood and test statistic are derived in a similar manner to what is described for the $\tau$+jets channel. As in the $\tau$+jets channel, $p_{0}$-values are calculated (Table 8.2), which show that there are
Table 8.2: Observed $p_0$-values as a function of the $m_{H^\pm}$ in the $\tau$+lepton channel.

<table>
<thead>
<tr>
<th>$m_{H^\pm}$ (GeV)</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_0$-value</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.15</td>
<td>0.24</td>
<td>0.20</td>
<td>0.50</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Figure 8.2: Expected and observed 95% CL exclusion limits from the $\tau$+lepton channel for $H^+$ production from top quark decays, as a function of $m_{H^+}$ (left), and as a function of $m_{H^+}$ and $\tan \beta$, within the MSSM scenario $m_h$-max (right). [12]

no indications of a $H^+$-like excess. As shown in the left plot of Fig. 8.2, the $\tau$+lepton channel sets an upper limit for $B(t \rightarrow bH^+)$ at $0.03 - 0.07$ for $m_{H^+}$ in the range of 90 – 160 GeV, with the assumption that $B(H^+ \rightarrow \tau \nu) = 100 \%$. The limits interpreted in the context of the $m_h$-max scenario of the MSSM are shown in the right plot of Fig. 8.2 for the $m_{H^+}$-$\tan \beta$ plane. In this context, the channel excludes values of $\tan \beta$ larger than 22 – 50 in the mass range 90 – 150 GeV.

8.1.3 Combination

The combined limit is derived from the product of the individual likelihoods of three completely orthogonal channels: $\tau$+lepton, $\tau$+jets and $\tau_{lep}$+jets. The last channel is a search for $H^\pm$ in a $\tau$+jets final state, but with a leptonically decaying $\tau$ lepton. More details on $\tau_{lep}$+jets are documented here [12]. The hadronically-decaying $\tau$+jets channel is observed to be the most sensitive of the three, which is a motivating factor in the use of this channel in the first 2012 $H^+$ limits.

The combined upper limits on $B(t \rightarrow bH^+)$, with the assumption that $B(H^+ \rightarrow \tau \nu) = 100 \%$, are shown in the left plot of Fig. 8.3. The combined upper limit for $B(t \rightarrow bH^+)$ is $0.01 - 0.05$ for $m_{H^+}$ in the range of 90 – 160 GeV. The limits interpreted in the context of the $m_h$-max scenario of the MSSM are shown in the
Figure 8.3: Expected and observed 95% CL exclusion limits for the combined channels $\tau$+jets, $\tau$+lepton, and $\tau_{lep}$+jets. Limits are shown for $H^+$ production from top quark decays as a function of $m_{H^+}$ (left), and as a function of $m_{H^+}$ and $\tan \beta$, within the MSSM scenario $m_h$-max. [12]

right plot of Fig. 8.3 for the $m_{H^+}$-$\tan \beta$ plane. In this context, the channel excludes values of $\tan \beta$ larger than 12 − 26, as well as between 1 and 2 − 6 in the mass range 90 − 140 GeV.

8.1.4 Ratio Method

No significant deviation from the SM expectation is observed for the event yield ratios $R_e$ and $R_\mu$. The limits are derived for $B(t \to bH^+)$, under the assumption that $B(H^+ \to \tau \nu) = 100\%$. This analysis uses a profile likelihood ratio [84] with first $M_{T2}^H$, and then $R_e$ and $R_\mu$, as the discriminating variables.

The purpose of first setting limits using $M_{T2}^H$ as a discriminating variable is as a reference point to assess the added sensitivity of using the ratio. The definition of the likelihood function and the fitting procedure on the discriminating variable $M_{T2}^H$ proceed according to the description given for the 2011 $\tau$+jets channel. Upper limits are set on $B(t \to bH^+)$ of 3.3 − 13% for the $e+\tau$ channel and 2.4 − 14% for the $\mu+\tau$ channel. These limits are shown in Fig. 8.4.

Limits are then calculated using the ratio of integrated event yields rather than the $M_{T2}^H$ distributions. This is expected to produce limits that are improved in sensitivity, due to the cancellation and reduction of many systematics. The assumed underlying probability density function of the measured variables must be known in order to perform a profile likelihood statistical analysis.

The measured event yield ratios $R_e$ and $R_\mu$ are the ratios of two Poisson variables, which have unknown probability density functions. However, the sampling variation of $N_{\ell\ell}$ is restricted to the subset $N_{\ell\tau} + N_{\ell\nu}$.
In other words, $0 < N_{\ell\ell'} < N_{\ell\tau} + N_{\ell\ell'}$. This relation implies that $N_{\ell\ell'}$ follows a binomial distribution, defined as:

$$
B_n(k, n, p) = \binom{n}{k} p^k (1 - p)^{n-k}
$$

where the parameters $k$, $n$, and $p$ are:

$$k = N_{\ell\ell'}$$

$$n = N_{\ell\tau} + N_{\ell\ell'}$$

$$p = \frac{N_{\ell\ell'}}{N_{\ell\tau} + N_{\ell\ell'}}$$

Such that $k = np$. The binomial parameter $p$ can then be re-written as a monotonic function of the ratio $R_{\ell\ell'}$:

$$p = \frac{1}{1 + R_{\ell\ell'}}$$

If both $np$ and $np(1 - p)$ are greater than 5, a good approximation to the binomial distribution $B_n(k, n, p)$ is given by the normal distribution:

$$\text{Gauss}(np, \sigma) = \sqrt{np(1 - p)}$$

Dividing by the parameter $n$ yields that $p$ is approximated by the normal distribution:

$$\text{Gauss}(p, \sigma) = \sqrt{\frac{p(1 - p)}{n}}$$
If $\rho$ and $R$ are defined as the expected and observed ratios, then the resulting likelihood function can be written as:

$$L(B) = \text{Gauss}(p(R_i)|p(\rho_i), \sigma(\rho_i, n_i)) \prod_j q(\tilde{\theta}_j | \theta_j)$$

where $\sigma$ stands for the second parameter of the normal distribution of $p$, and $i$ is either $e$ or $\mu$ (electron-triggered or muon-triggered event ratios). As before, nuisance parameters are used to describe the effects of systematic uncertainties, and $q(\tilde{\theta}_j | \theta_j)$ are the Gaussian constraints relating each parameter to its nominal estimate $\tilde{\theta}_j$.

Using the event yield ratios $R_e$ and $R_\mu$, upper limits are then placed on $B(t \to bH^+)$. For $m_{H^\pm}$ in the range of 90 – 140 GeV, limits of 4.5 – 6.3% are obtained using $R_e$, and 3.6 – 4.7% are obtained using $R_\mu$. These limits are shown in Fig. 8.5. As expected, these limits are a clear improvement for most $m_{H^\pm}$ over those obtained using the $M_{H^\pm}$ distribution (Fig. 8.4). The loss of sensitivity as $m_{H^\pm}$ approaches $m_{top}$, as predicted by Table 7.17, is also visible. The differences between the expected limits from $R_e$ and $R_\mu$ are small, since (from Table 7.10) the dominant systematic uncertainties in both cases arise from uncertainties related to the $\tau$ lepton, and those uncertainties are similar for both channels.

In order to obtain an upper limit using the combination of the two ratios, the same formalism is employed, using a global event yield ratio $R_{e+\mu}$, defined as:

$$R_{e+\mu} = \frac{N(e + \tau) + N(\mu + \tau)}{N(e + \mu) + N_{OR}(\mu + e)}$$

where $N_{OR}(\mu + e)$ corresponds to the event yield in the $\mu + e$ channel after removing the contribution from dileptonic events that are also categorized as $e + \mu$ events. The fraction of dileptonic events that are classified as both $e + \mu$ and $\mu + e$ is roughly 42% in data. Using this global event yield ratio, upper limits in the range of 3.2 – 4.4% can be placed on $B(t \to bH^+)$ for $m_{H^\pm}$ in the range 90 – 140 GeV. These limits are shown...
Figure 8.6: Upper limits on $tbH$ in the Ratio Method, derived from the global event yield ratio $R_{e+\mu}$ as a function of $m_{H^\pm}$ (left), and as a function of $m_{H^+}$. These limits are obtained using an integrated luminosity of 4.6$fb^{-1}$ with the assumption $B(H^+ \rightarrow \tau \nu) = 100\%$. [13]

Figure 8.7: Upper limits on $tbH$ in the Ratio Method, derived from the global event yield ratio $R_{e+\mu}$ as a function of $m_{H^+}$ and $\tan \beta$, within the MSSM scenario $m_{h_{\text{max}}}$. These limits are obtained using an integrated luminosity of 4.6$fb^{-1}$ with the assumption $B(H^+ \rightarrow \tau \nu) = 100\%$. [13]
Figure 8.8: Upper limits on $tbH$ derived from the combination of the 2011 $\tau$+jets channel and the global event yield ratio $R_{e+\mu}$, as a function of $m_{H^\pm}$. These limits are obtained using an integrated luminosity of 4.6fb$^{-1}$ with the assumption $B(H^+ \rightarrow \tau \nu) = 100\%$. [13]

Figure 8.9: Upper limits on $tbH$ derived from the combination of the 2011 $\tau$+jets channel and the global event yield ratio $R_{e+\mu}$ as a function of $m_{H^\pm}$ and $\tan \beta$, within the MSSM scenario $m_{h_{\text{max}}}$. These limits are obtained using an integrated luminosity of 4.6fb$^{-1}$ with the assumption $B(H^+ \rightarrow \tau \nu) = 100\%$. [13]
in Fig. 8.6. The limits are then interpreted in terms of the $m_h$-max scenario of the MSSM and shown in the $m_{H^\pm} - \tan \beta$ plane. The excluded regions in the $m_{H^\pm}$-$\tan \beta$ for limits derived using $R_{e+\mu}$ are shown in Fig. 8.7.

The Ratio Method limits are also combined with the 2011 search for a light $H^\pm$ in the $\tau$+jets channel. The event selection applied to the numerator and denominator events of the Ratio Method is orthogonal to the event selection of $\tau$+jets, so the combination is a straightforward multiplication of the profile likelihoods. A new set of combined upper limits on $B(t \rightarrow bH^\pm)$ are determined, using both the $m_T$ distribution in the $\tau$+jets channel and the global event yield ratio $R_{e+\mu}$. With this combination, $H^\pm$ can be excluded for a $B(t \rightarrow bH^\pm)$ of 0.8 $- 3.4\%$, for $m_{H^\pm}$ between 90-160 GeV, as seen in Fig. 8.8. The combined limit is also interpreted in terms of the $m_h$-max scenario of the MSSM in Fig. 8.9.

### 8.2 2012 Limits: Heavy and Light Charged Higgs

The limits for the 2012 analysis are determined using the same methods that have been described for the 2011 analyses. For both the heavy and light $H^\pm$ search, limits are extracted using a profile likelihood ratio with $m_T$ as the discriminating variable, and the process proceeds very similarly to what is described in the 2011 $\tau$+jets channel.

As in 2011, the light $H^\pm$ search, which looks for $H^\pm$ from $t\bar{t}$ decays, takes into account the effect of signal presence on the $t\bar{t}$ cross section in the limit-setting procedure. For the light $H^\pm$ analysis, new limits are set on the branching fraction $B(t \rightarrow bH^+) \times B(H^+ \rightarrow \tau\nu)$, which improve the 2011 $\tau$+jets 95% CL limit of 1.0 $- 6.0\%$ to a new range of 0.3 $- 2.4\%$, shown in the left plot of Fig. 8.10. The $\tau$+jets channel has historically been weakest at lower masses of $H^\pm$, due to the smaller shape separation and large systematic uncertainties corresponding to the background contributions at low $m_T$. This limit also corresponds to a significant improvement over the current best limits from 2011, $B(t \rightarrow bH^+) \times B(H^+ \rightarrow \tau\nu) < 0.8 - 3.4\%$.

The heavy $H^\pm$ is produced directly, so the 95% CL exclusion limit is set on $\sigma_{H^+} \times B(H^+ \rightarrow \tau\nu)$. The limits for a range of 180 $- 600$ GeV are shown in the right plot of Fig. 8.10, which correspond to an exclusion on $\sigma_{H^+} \times B(H^+ \rightarrow \tau\nu)$ of 0.03 $- 0.8$ pb, depending on the $H^\pm$ mass. This analysis represents the first limits from events recorded by the ATLAS detector on the production of a heavy $H^+$, and will likely also be the first direct limits on a heavy $H^+$ decaying to $\tau\nu$ worldwide.
Figure 8.10: Expected and observed 95% CL exclusion limits in the 2012 $\tau+\text{jets}$ channel. Shown are limits on $B(t \to bH^+) \times B(H^+ \to \tau \nu)$ of the light $H^+$ (left) and on $\sigma_{H^+} \times B(H^+ \to \tau \nu)$ of the heavy $H^+$ (right) as a function of $m_{H^\pm}$. 
Chapter 9

Conclusions

This thesis has described searches for a light and heavy $H^\pm$ in the decay $H^\pm \to \tau_{had}\nu$, performed using data recorded in 2011 and 2012 by the ATLAS detector at the LHC. No evidence for the observation of $H^\pm$ was found, and exclusion limits have been set for light $H^\pm$ on $B(t \to H^+b) \times B(H^+ \to \tau\nu)$, and for heavy $H^\pm$ on $\sigma_{H^+} \times B(H^+ \to \tau\nu)$. The relatively model-independent limits set by these analyses can be interpreted in the framework of any beyond SM scenario that utilizes a 2HDM.

The searches for $H^\pm \to \tau\nu$ in the $\tau$+jets, $\tau$+lepton, and Ratio Method analyses have placed strong limits on $H^\pm$. The 2011 searches for a light $H^\pm$ in ATLAS data with an integrated luminosity of 4.6 fb$^{-1}$ set a combined 95% CL limit of $B(t \to H^+b) \times B(H^+ \to \tau\nu) < 0.8 - 3.4\%$, depending on $m_{H^\pm}$, in a range of $m_{H^\pm} = 90 - 160$ GeV. The 2012 limits, in ATLAS data with an integrated luminosity of 19.5 fb$^{-1}$, strengthened the limit in the range of $m_{H^\pm} = 90 - 160$ GeV to 0.3 - 2.4%, and set 95% CL limits on the production of the heavy $H^+$, in a mass range of 180 - 600 GeV, of $\sigma_{H^+} \times B(H^+ \to \tau\nu) < 0.03 - 0.8$ pb as a function of the $H^\pm$ mass.

The 2012 limits on light $H^\pm$ significantly strengthen the 2011 result at higher masses, and together they represent the strongest limit from a direct search for light $H^\pm$. The limits on the heavy $H^\pm$ are not only the strongest limits from a direct search, but also the first for a heavy $H^\pm$ in the decay $H^\pm \to \tau\nu$.

In the future, these limits are intended to be combined with the results of searches for $H^\pm$ in the $\tau$+lepton channel and $H^\pm \to tb$, which are planned to be conducted on the 2012 ATLAS dataset. This combination will provide even more sensitivity for observation or exclusion of $H^\pm$ in models with a Higgs sector described by a 2HDM. As details of the Higgs sector continue to be probed at the LHC, in the 2012 dataset and in the future, searches for the $H^\pm$ will continue to represent a valuable channel for the possible discovery or exclusion of new physics.
Appendix A

Variables in Lepton\((e, \mu)\) Vetoes Used in \(\tau\) Lepton Object Selection

As described in section 4.3.4, dedicated algorithms are used to reject electron and muon backgrounds to 1-prong hadronically-decaying \(\tau\) reconstruction and identification. These algorithms reduce the background from events with leptons misidentified as \(\tau\) leptons to a nearly negligible level. The electron veto is based on a BDT score, while the muon veto is cut-based.

The variables that have been used in the 2011 optimization of the \(\tau\) lepton vetoes are described here, and some variable distributions are shown for signal and background. All of following variables were inputs for the BDT electron score, and \(f_{EM}\) and \(f_{track}\) are used by the muon cut-based algorithm.

Distributions for a selection of BDT electron veto variables are shown in Fig. A.1. For the cut-based muon veto, \(f_{EM}\) is shown in Fig. A.2, and \(f_{track}\) is shown in Fig. A.3, split for the case of high or low \(f_{EM}\).

- Track radius, \(R_{\text{track}}\) The \(p_T\)-weighted track width:

\[
R_{\text{track}} = \frac{\sum_{i}^{\Delta R_i < 0.4} p_{T,i} \Delta R_i}{\sum_{i}^{\Delta R_i < 0.4} p_{T,i}}
\]  

(A.1)

- Leading track momentum fraction, \(f_{\text{track}}\)

\[
f_{\text{track}} = \frac{p_{T,1}^{\text{track}}}{p_T}
\]

(A.2)

- Core energy fraction, \(f_{\text{core}}\)

\[
f_{\text{core}} = \frac{\sum_{i}^{\Delta R_i < 0.1} E_{T,i}}{\sum_{j}^{\Delta R_j (\text{all})} E_{T,j}}
\]

(A.3)

- Ring isolation, \(f_{\text{iso}}\)

\[
f_{\text{iso}} = \frac{\sum_{i}^{0.1 < \Delta R_i < 0.2} E_{T,i}}{\sum_{j}^{\text{all}} E_{T,j}}
\]

(A.4)

- Electromagnetic fraction, \(f_{EM}\)

\[
f_{EM} = \frac{\sum_{i}^{\Delta R_i < 0.4} E_{T,i}}{\sum_{j}^{\text{all}} E_{T,j}}
\]

(A.5)
Figure A.1: Distributions of a selection of identification variables for simulated $Z \rightarrow ee$ background events and $Z \rightarrow \tau\tau$ signal events [7]. The distributions are scaled to unity.

- TRT HT fraction, $f_{HT}$
  \[ f_{HT} = \frac{\text{High-threshold TRT hits}}{\text{Low-threshold TRT hits}} \]  
  \hspace{2cm} (A.6)

- Hadronic track fraction, $f_{track}^{Had}$
  \[ f_{track}^{Had} = \frac{\sum_{i < 0.4} E_{T,i}^\tau}{P_{T,1}^{track}} \]  
  \hspace{2cm} (A.7)

- Maximum strip $E_T$, $E_{T,\text{strip}}^{\tau,\text{max}}$: the maximum $E_T$ deposited in a cell in the pre-sampler layer of the EM calorimeter not associated with the leading track.

- Hadronic radius $R_{Had}$
  \[ R_{Had} = \frac{\sum_{i < 0.4} \Delta R_i < 0.4 E_{T,i} \Delta R_i}{\sum_{i < 0.4} (Had,EM3) E_{T,i}} \]  
  \hspace{2cm} (A.8)
Figure A.2: $f_{EM}$ for true hadronically-decaying $\tau$ leptons and muons from simulated events.[6].

Figure A.3: $f_{track}$ for true $\tau$ leptons and muons from simulated events, for the low $f_{EM} < 0.22$ region (left) and the high $f_{EM} > 0.81$ region (right).[6]
Appendix B

Variables of the Tau Jet Likelihood and Boosted Decision Tree

The $\tau$ identification algorithms, designed for discrimination between hadronically-decaying $\tau$ leptons and jets, are highly important for all $H^\pm \rightarrow \tau \nu$ searches. More information on the identification algorithms can be found in section 4.3.4, and especially in [7]. The $\tau$ likelihood identification is used in the 2011 searches of this thesis, while the BDT identification is used for the 2012 searches. A selection of discriminating variables are shown in Fig. B.1 and Fig. B.2, which are a subset of those used for building the BDT and likelihood-based discriminants. The specific variables used in the 2011 $\tau$ identification algorithms are described in the following two sections.

B.1 Tau Likelihood

The likelihood-based jet discriminant uses 8 variables in total, and the variables used for the 1- and 3-prong cases are not completely the same. Variables shown here are for the 2011 optimization of the $\tau$ identification. The $\tau$ identification has since been re-optimized for the 2012 dataset. Both 1- and 3-prong $\tau$ discriminants use:

- Track radius, $R_{\text{track}}$: The $p_T$-weighted track width:
  \[ R_{\text{track}} = \frac{\sum_{i}^{\Delta R_{i}<0.4} p_{T,i} \Delta R_{i}}{\sum_{i}^{\Delta R_{i}<0.4} p_{T,i}} \]  
  \[ (B.1) \]

- Core energy fraction, $f_{\text{core}}$:
  \[ f_{\text{core}} = \frac{\sum_{i}^{\Delta R_{i}<0.1} E_{T,i}}{\sum_{j}^{\Delta R_{j}<0.4} E_{T,j}} \]  
  \[ (B.2) \]

The 1-prong case further uses:

- $N_{\text{track}}^{\text{iso}}$: the number of tracks in the isolation cone $0.2 < \Delta R < 0.4$ of the $\tau$. 

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Figure B.1: Distributions of a selection of identification variables for background di-jet events selected from 2011 data and simulated $Z \rightarrow \tau \tau$ and $W \rightarrow \tau \nu$ signal events. The distributions are scaled to unity [7].

Figure B.2: Distributions of a selection of identification variables for background di-jet events selected from 2011 data and simulated $Z \rightarrow \tau \tau$ and $W \rightarrow \tau \nu$ signal events. The distributions are scaled to unity [7].
Calorimetric radius, $R_{\text{Cal}}$

$$R_{\text{Cal}} = \frac{\sum_{i \text{ (all)}} \Delta R_{i} < 0.4 \ E_{T,i} \Delta R_{i}}{\sum_{i \text{ (all)}} E_{T,i}}$$  \hspace{1cm} (B.3)

- $f_{2\text{leadclusters}}$: the ratio of the energy of the first two leading clusters over the total energy of all clusters associated with the $\tau$.

The 3-prong case further uses:

- Track mass, $m_{\text{tracks}}$

$$m_{\text{tracks}} = \sqrt{\left( \sum_{\text{tracks}} E \right)^2 - \left( \sum_{\text{tracks}} p \right)^2}$$  \hspace{1cm} (B.4)

- $S_{T}^{\text{flight}}$: the decay length significance of the secondary vertex in the transverse plane

$$S_{T}^{\text{flight}} = \frac{L_{T}^{\text{flight}}}{\delta L_{T}^{\text{flight}}}$$  \hspace{1cm} (B.5)

- $\Delta R_{\text{max}}$: The maximal $\Delta R$ between a core track and the $\tau$ candidate axis.

### B.2 Tau Boosted Decision Tree

The BDT jet discriminant uses 11 variables in total. Most are shared by 1- and 3-prong discriminants, but three are used solely for the multi-prong case. The BDT was re-optimized for the 2012 dataset. Both 1-prong and 3-prong discriminants use:

- Track radius, $R_{\text{track}}$ The $p_T$-weighted track width:

$$R_{\text{track}} = \frac{\sum_{i \text{ (all)}} \Delta R_{i} < 0.4 \ p_{T,i} \Delta R_{i}}{\sum_{i \text{ (all)}} p_{T,i}}$$  \hspace{1cm} (B.6)

- Leading track momentum fraction, $f_{\text{track}}$

$$f_{\text{track}} = \frac{p_{T,1}}{p_{T}}$$  \hspace{1cm} (B.7)

- Core energy fraction, $f_{\text{core}}$

$$f_{\text{core}} = \frac{\sum_{j \text{ (all)}} \Delta R_{j} < 0.4 \ E_{T,j}}{\sum_{j \text{ (all)}} E_{T,j}}$$  \hspace{1cm} (B.8)

- $N_{\text{iso}}$: the number of tracks in the isolation cone $0.2 < \Delta R < 0.4$ of the $\tau$. 

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• Calorimetric radius, $R_{Cal}$

\[ R_{Cal} = \frac{\sum_{i<0.4} \Delta R_{i} \Delta R_{i}}{\sum_{i<0.4} E_{T,i}} \]  

(B.9)

• $m_{eff,clusters}$: the invariant mass computed from the constituent clusters of the seed jet, calibrated at the LC energy scale.

• $S_{leadtrack}$: the impact parameter significance of the leading track of the $\tau$ candidate.

• $f_{leadclusters}$: the ratio of the energy of the first three leading clusters over the total energy of all clusters associated with the $\tau$.

The 3-prong case additionally uses:

• Track mass, $m_{tracks}$

\[ m_{tracks} = \sqrt{\left( \sum_{tracks} E \right)^2 - \left( \sum_{tracks} p \right)^2} \]  

(B.10)

• $S_{flight}$: the decay length significance of the secondary vertex in the transverse plane

\[ S_{flight} = \frac{L_{flight}}{\delta L_{flight}} \]  

(B.11)

• $\Delta R_{max}$: The maximal $\Delta R$ between a core track and the $\tau$ candidate axis.
References


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