Search for pair produced new heavy quarks in proton-proton collisions with the ATLAS detector at the LHC

by

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DEDICATION

To the loving memory of my father and to mom, who advised me to quit fooling around and submit my thesis four years ago. Here it is.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLES</td>
<td></td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td></td>
<td>ix</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td></td>
<td>xiv</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td></td>
<td>xv</td>
</tr>
<tr>
<td>CHAPTER 1. Introduction</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>CHAPTER 2. Theory: The Standard Model and Beyond</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>2.1</td>
<td>The Standard Model</td>
<td>3</td>
</tr>
<tr>
<td>2.1.1</td>
<td>The Fundamental Forces</td>
<td>3</td>
</tr>
<tr>
<td>2.1.2</td>
<td>Leptons</td>
<td>4</td>
</tr>
<tr>
<td>2.1.3</td>
<td>Quarks</td>
<td>6</td>
</tr>
<tr>
<td>2.1.4</td>
<td>Gauge Bosons</td>
<td>7</td>
</tr>
<tr>
<td>2.1.5</td>
<td>The Higgs Boson</td>
<td>7</td>
</tr>
<tr>
<td>2.1.6</td>
<td>Hadrons</td>
<td>8</td>
</tr>
<tr>
<td>2.2</td>
<td>Beyond the Standard Model</td>
<td>8</td>
</tr>
<tr>
<td>2.2.1</td>
<td>Vector-Like Quarks</td>
<td>10</td>
</tr>
<tr>
<td>2.2.2</td>
<td>E6 Isosinglet Quarks</td>
<td>10</td>
</tr>
<tr>
<td>2.2.3</td>
<td>Mirror Quarks</td>
<td>11</td>
</tr>
<tr>
<td>2.2.4</td>
<td>General Search for New Heavy Quarks at the Large Hadron Collider</td>
<td>11</td>
</tr>
<tr>
<td>CHAPTER 3. Experimental Setup</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>3.1</td>
<td>Introduction</td>
<td>13</td>
</tr>
<tr>
<td>3.2</td>
<td>The Large Hadron Collider</td>
<td>13</td>
</tr>
</tbody>
</table>
3.3 The ATLAS Experiment ............................................. 16
3.4 Detector Coordinates .................................................. 17
3.5 Inner Detector .......................................................... 18
  3.5.1 Pixel Detector ...................................................... 20
  3.5.2 Semi Conductor Tracker .......................................... 21
  3.5.3 Transition Radiation Tracker ................................. 22
3.6 Calorimeter System .................................................... 23
  3.6.1 The Electromagnetic Calorimeter .......................... 24
  3.6.2 The Hadronic Calorimeter ..................................... 25
3.7 Muon Spectrometer ................................................... 27
3.8 Magnets ................................................................. 29
  3.8.1 Solenoid ............................................................ 30
  3.8.2 Toroid .............................................................. 30
3.9 Trigger and Data Acquisition System .......................... 31
  3.9.1 L1 Trigger .......................................................... 32
  3.9.2 L2 Trigger .......................................................... 33
  3.9.3 L3 Trigger .......................................................... 34

CHAPTER 4. Reconstruction of Physics Objects ...................... 35
4.1 Introduction ............................................................. 35
4.2 Tracks ................................................................. 35
4.3 Primary Vertex ........................................................ 36
4.4 Electrons .............................................................. 37
  4.4.1 Electron Trigger .................................................. 37
  4.4.2 Electron Offline Selection ..................................... 39
4.5 Muons ................................................................. 39
  4.5.1 Muon Trigger ...................................................... 40
  4.5.2 Muon Offline Selection .......................................... 41
4.6 Jets ................................................................. 42
  4.6.1 Jet calibration .................................................... 42
4.6.2 B-tagging ................................................................. 44
4.7 $E_T^{\text{miss}}$ ................................................................. 45

CHAPTER 5. Expected Signal and Background Processes .............. 47
  5.1 Introduction .......................................................... 47
  5.2 Heavy Quark Production ............................................. 47
  5.3 Heavy Quark Decay .................................................. 48
  5.4 Signal Signature in the Detector ................................... 49
  5.5 Background Processes .............................................. 50
  5.6 Modeling of Signal and Background Processes .................. 52
  5.7 Signal Samples ....................................................... 52
  5.8 Background Samples ............................................... 53

CHAPTER 6. Event Pre-selection ........................................... 58
  6.1 Introduction .......................................................... 58
  6.2 Good Runs Lists ..................................................... 58
  6.3 Pileup Reweighting ................................................ 58
  6.4 Pre-selection ......................................................... 59
  6.5 Analysis Strategies After Pre-selection ......................... 60

CHAPTER 7. Kinematic Fitting ............................................. 63
  7.1 Introduction .......................................................... 63
  7.2 Kinematic Fitting of $t\bar{t}$ Semi-leptonic Decay ............... 63
  7.3 Log Likelihood Ratio Discriminant ................................ 66
  7.4 Monte Carlo Samples .............................................. 67
  7.5 Object Definition and Event Selection ......................... 67
  7.6 Truth Matching of Objects ....................................... 68
  7.7 Derivation of Resolution Functions ............................ 68
  7.8 Results ............................................................... 70
    7.8.1 $t\bar{t}$ Reconstruction ....................................... 71
    7.8.2 $t\bar{t}$ Reconstruction Efficiency .......................... 71
**LIST OF TABLES**

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Heavy quark pair-production cross section at $\sqrt{s} = 8$ TeV</td>
<td>49</td>
</tr>
<tr>
<td>5.2</td>
<td>Cross sections for the main SM backgrounds at $\sqrt{s} = 8$ TeV</td>
<td>57</td>
</tr>
<tr>
<td>6.1</td>
<td>Event yields at pre-selection</td>
<td>61</td>
</tr>
<tr>
<td>7.1</td>
<td>Reconstruction efficiency for events with exactly 4 jets</td>
<td>72</td>
</tr>
<tr>
<td>7.2</td>
<td>Reconstruction efficiency for events with exactly 5 jets</td>
<td>73</td>
</tr>
<tr>
<td>7.3</td>
<td>Reconstruction efficiency for events with exactly 5 jets</td>
<td>74</td>
</tr>
<tr>
<td>8.1</td>
<td>Yields in the control region CR1: $m_{\text{reco}} &lt; 350$ GeV</td>
<td>91</td>
</tr>
<tr>
<td>8.2</td>
<td>Yields in the control region CR2: $H_T &lt; 800$ GeV</td>
<td>92</td>
</tr>
<tr>
<td>8.3</td>
<td>Yields after the LOOSE selection requirements</td>
<td>97</td>
</tr>
<tr>
<td>8.4</td>
<td>Yields after the TIGHT selection requirements</td>
<td>97</td>
</tr>
<tr>
<td>9.1</td>
<td>List of systematic uncertainties in the electron channel</td>
<td>103</td>
</tr>
<tr>
<td>9.2</td>
<td>List of systematic uncertainties in the muon channel</td>
<td>104</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<p>| Figure 2.1 | The particles and the force carriers of the Standard Model | 5 |
| Figure 3.1 | The LHC and its four main experiments | 14 |
| Figure 3.2 | CERN accelerator complex | 16 |
| Figure 3.3 | The ATLAS detector | 18 |
| Figure 3.4 | The Inner Detector schematic | 19 |
| Figure 3.5 | The Pixel Detector | 21 |
| Figure 3.6 | The SCT Detector | 22 |
| Figure 3.7 | The Transition Radiation Tracker | 23 |
| Figure 3.8 | Accordion shape of the Barrel EM Calorimeter | 25 |
| Figure 3.9 | The Calorimeter | 26 |
| Figure 3.10 | The Muon Spectrometer | 28 |
| Figure 3.11 | Thin Gap Chamber | 29 |
| Figure 3.12 | Spatial arrangements of the magnets | 30 |
| Figure 3.13 | Barrel Toroid | 31 |
| Figure 3.14 | ATLAS Trigger System | 33 |
| Figure 4.1 | Event display of a Higgs → 4e candidate | 38 |
| Figure 4.2 | Candidate for Z → μμ decay | 40 |
| Figure 4.3 | Quarks and Gluons | 43 |
| Figure 4.4 | High mass dijet event | 44 |
| Figure 4.5 | Secondary Vertex | 45 |
| Figure 5.1 | Predicted pair production cross section for T quark | 48 |</p>
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2</td>
<td>Pair Production of $T$ quark and its subsequent decay</td>
</tr>
<tr>
<td>5.3</td>
<td>$t\bar{t}$ background</td>
</tr>
<tr>
<td>5.4</td>
<td>$W$+jets background</td>
</tr>
<tr>
<td>7.1</td>
<td>logL for various permutations in a single $t\bar{t}$ event</td>
</tr>
<tr>
<td>7.2</td>
<td>Resolution of $b$-jet $p_T$ for $</td>
</tr>
<tr>
<td>7.3</td>
<td>Resolution of light jet $p_T$ for $</td>
</tr>
<tr>
<td>7.4</td>
<td>$m_{reco}$ distribution for $TT$ and $t\bar{t}$</td>
</tr>
<tr>
<td>7.5</td>
<td>Reconstructed $T$ quark mass</td>
</tr>
<tr>
<td>7.6</td>
<td>Log Likelihood Ratio Performance</td>
</tr>
<tr>
<td>7.7</td>
<td>Signal efficiency vs. background rejection for LLR</td>
</tr>
<tr>
<td>8.1</td>
<td>$\Delta R$ between the 2 quarks resulting from $W$ boson decay</td>
</tr>
<tr>
<td>8.2</td>
<td>$\Delta R$ between charged lepton and neutrino</td>
</tr>
<tr>
<td>8.3</td>
<td>$H_T$ distribution after pre-selection</td>
</tr>
<tr>
<td>8.4</td>
<td>$p_T$ distribution of $q$-quarks</td>
</tr>
<tr>
<td>8.5</td>
<td>Splitting variable distribution</td>
</tr>
<tr>
<td>8.6</td>
<td>Distribution of the invariant mass of di-jet combinations</td>
</tr>
<tr>
<td>8.7</td>
<td>$p_T$ distribution of the di-jet combinations</td>
</tr>
<tr>
<td>8.8</td>
<td>Distribution of the number of $W$-jet candidates</td>
</tr>
<tr>
<td>8.9</td>
<td>Distribution of the splitting variable</td>
</tr>
<tr>
<td>8.10</td>
<td>$m_{reco}$ after Cut1</td>
</tr>
<tr>
<td>8.11</td>
<td>Distribution of the 2nd leading jet $p_T$ after cut1</td>
</tr>
<tr>
<td>8.12</td>
<td>$H_T$ distribution after cut1</td>
</tr>
<tr>
<td>8.13</td>
<td>$\Delta R$ between the leptonic and hadronic heavy quarks after cut1</td>
</tr>
<tr>
<td>8.14</td>
<td>Splitting variable after Cut7</td>
</tr>
<tr>
<td>8.15</td>
<td>$m_{reco}$ after LOOSE selection</td>
</tr>
<tr>
<td>9.1</td>
<td>Final discriminant</td>
</tr>
<tr>
<td>9.2</td>
<td>Limits for LOOSE selection</td>
</tr>
</tbody>
</table>
Figure 9.3  Limits for combined $e - \mu$ channel .......................... 108
Figure 9.4  Final discriminant ................................................. 109
Figure 9.5  Expected Limit for TIGHT selection ......................... 110

A.1  Resolutions of $b$-jet $p_T$ binned in $p_T$ for $|\eta| < 0.80.$ ............... 111
A.2  Resolutions of $b$-jet $p_T$ binned in $p_T$ for $0.80 < |\eta| < 1.37.$ ........... 112
A.3  Resolutions of $b$-jet $p_T$ binned in $p_T$ for $1.37 < |\eta| < 1.52.$ ........... 112
A.4  Resolutions of $b$-jet $p_T$ binned in $p_T$ for $1.52 < |\eta| < 2.50.$ ........... 113
A.5  Resolutions of light-jet $p_T$ binned in $p_T$ for $|\eta| < 0.80.$ ............... 113
A.6  Resolutions of light-jet $p_T$ binned in $p_T$ for $0.80 < |\eta| < 1.37.$ ........... 114
A.7  Resolutions of light-jet $p_T$ binned in $p_T$ for $1.37 < |\eta| < 1.53.$ ........... 115
A.8  Resolutions of light-jet $p_T$ binned in $p_T$ for $1.52 < |\eta| < 2.50.$ ........... 116
A.9  Resolutions of unclustered energy. ........................................ 116

B.1  Jet Multiplicity at pre-selection ........................................... 117
B.2  $H_T$ at pre-selection ....................................................... 118
B.3  Leading jet $p_T$ at pre-selection ........................................ 118
B.4  2nd Leading jet $p_T$ at pre-selection .................................... 119
B.5  3rd leading jet $p_T$ at pre-selection ..................................... 119
B.6  4th Leading jet $p_T$ at pre-selection .................................... 120
B.7  Leading jet $\eta$ at pre-selection .......................................... 120
B.8  2nd Leading jet $\eta$ at pre-selection ..................................... 121
B.9  3rd leading jet $\eta$ at pre-selection ..................................... 121
B.10 4th Leading jet $\eta$ at pre-selection .................................... 122
B.11  Lepton $p_T$ at pre-selection .............................................. 122
B.12  Lepton $\eta$ at pre-selection .............................................. 122
B.13  $E_{miss}^T$ at pre-selection ................................................. 123
B.14  $E_{miss}^T + M_T(W)$ at pre-selection .................................... 124
B.15  Jet Multiplicity in CR1 ...................................................... 125
B.16  $H_T$ in CR1 ................................................................. 126
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.17</td>
<td>Leading jet $p_T$ in CR1</td>
<td>126</td>
</tr>
<tr>
<td>B.18</td>
<td>2nd Leading jet $p_T$ in CR1</td>
<td>127</td>
</tr>
<tr>
<td>B.19</td>
<td>Lepton $p_T$ in CR1</td>
<td>127</td>
</tr>
<tr>
<td>B.20</td>
<td>$\Delta R$(lepton,$\nu$) in CR1</td>
<td>128</td>
</tr>
<tr>
<td>B.21</td>
<td>Mass difference between leptonic and hadronic heavy quark</td>
<td>128</td>
</tr>
<tr>
<td>B.22</td>
<td>$\Delta R$ between leptonic and hadronic heavy quark</td>
<td>129</td>
</tr>
<tr>
<td>B.23</td>
<td>Splitting variable in CR1</td>
<td>129</td>
</tr>
<tr>
<td>B.24</td>
<td>$\Delta R$(Whad,Qhad) in CR1</td>
<td>130</td>
</tr>
<tr>
<td>B.25</td>
<td>$\Delta R$(Wlep,Qlep) in CR1</td>
<td>130</td>
</tr>
<tr>
<td>B.26</td>
<td>min $\Delta R$(Whad,Qs) in CR1</td>
<td>131</td>
</tr>
<tr>
<td>B.27</td>
<td>min $\Delta R$(Wlep,Qs) in CR1</td>
<td>131</td>
</tr>
<tr>
<td>B.28</td>
<td>$m_{reco}$ after cut1</td>
<td>132</td>
</tr>
<tr>
<td>B.29</td>
<td>Jet Multiplicity in CR2</td>
<td>133</td>
</tr>
<tr>
<td>B.30</td>
<td>$H_T$ in CR2</td>
<td>133</td>
</tr>
<tr>
<td>B.31</td>
<td>Leading jet $p_T$ in CR2</td>
<td>134</td>
</tr>
<tr>
<td>B.32</td>
<td>2nd Leading jet $p_T$ in CR2</td>
<td>134</td>
</tr>
<tr>
<td>B.33</td>
<td>Lepton $p_T$ in CR2</td>
<td>135</td>
</tr>
<tr>
<td>B.34</td>
<td>$\Delta R$(lepton,$\nu$) in CR2</td>
<td>135</td>
</tr>
<tr>
<td>B.35</td>
<td>Mass difference between leptonic and hadronic heavy quark</td>
<td>136</td>
</tr>
<tr>
<td>B.36</td>
<td>$\Delta R$ between leptonic and hadronic heavy quark</td>
<td>136</td>
</tr>
<tr>
<td>B.37</td>
<td>Splitting variable in CR2</td>
<td>137</td>
</tr>
<tr>
<td>B.38</td>
<td>$\Delta R$(Whad,Qhad) in CR2</td>
<td>137</td>
</tr>
<tr>
<td>B.39</td>
<td>$\Delta R$(Wlep,Qlep) in CR2</td>
<td>138</td>
</tr>
<tr>
<td>B.40</td>
<td>min $\Delta R$(Whad,Qs) in CR2</td>
<td>138</td>
</tr>
<tr>
<td>B.41</td>
<td>min $\Delta R$(Wlep,Q) in CR2</td>
<td>139</td>
</tr>
<tr>
<td>B.42</td>
<td>$m_{reco}$ after cut2</td>
<td>140</td>
</tr>
<tr>
<td>B.43</td>
<td>$m_{reco}$ after cut3</td>
<td>141</td>
</tr>
<tr>
<td>B.44</td>
<td>$m_{reco}$ after cut4</td>
<td>141</td>
</tr>
<tr>
<td>B.45</td>
<td>$m_{reco}$ after cut5</td>
<td>142</td>
</tr>
<tr>
<td>B.46</td>
<td>$m_{\text{reco}}$ after cut6</td>
<td>142</td>
</tr>
<tr>
<td>-------</td>
<td>-------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>B.47</td>
<td>$m_{\text{reco}}$ after cut7</td>
<td>143</td>
</tr>
</tbody>
</table>
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A search is presented for the pair production of a new heavy quark, $T$, assuming that it has a significant branching ratio to decay into a $W$ boson and a light-flavor quark, $q$. The search is based on the 20 fb$^{-1}$ of proton-proton collision data at $\sqrt{s} = 8$ TeV recorded in 2012-2013 with the ATLAS detector at the Large Hadron Collider. Data are analyzed in the lepton+jets channel, which is characterized by a high transverse momentum electron or muon, large missing transverse momentum, and at least four jets. The analysis strategy relies on the substantial momentum transferred to all of the decay products of the heavy quark. No significant excess above the Standard Model expectation is observed and 95% confidence level upper limits are derived on the cross section times the branching ratio of $T$ quark in the lepton+jets channel.
CHAPTER 1. Introduction

All natural phenomena can be described by one of the four fundamental interactions - gravitational, electromagnetic, weak, and strong. The last three of these four interactions together make up the theoretical framework of elementary particles called the Standard Model.

In spite of a series of its predictions and verifications, there are strong reasons to believe that the Standard Model (SM) is not the final theory of nature. The SM has no mechanism to explain the observed matter anti-matter asymmetry. The nature of dark matter still remains mysterious. Additionally, there are several phenomena not explained within the Standard Model. The generational structure of the fundamental fermions and the mass hierarchy among those generations are not explained by the SM. There also exists a mixing between these generations which are parametrized by but not explained by the SM. Thus, the SM is not considered a complete theory but is instead regarded as a low energy approximation of a more fundamental theory.

To address the shortcomings of the SM, many new theoretical models have been proposed. A feature common to several of these models is the existence of new, heavy quarks, which could possibly be pair produced at the LHC and could then be detected as they decay into the SM gauge bosons and quarks.

The work presented in this thesis comprises a search for pair production of such new, heavy quarks. The thesis is organized as follows. Chapter 2 gives a brief introduction to the Standard Model, its merits and demerits, and the reasons to look for theories beyond the Standard Model. It also provides a brief theoretical overview of new quarks and a brief phenomenology of potential searches at the Large Hadron Collider. Chapter 3 describes the experimental setup including the Large Hadron Collider and the ATLAS detector. Chapter 4 introduces the process of reconstruction of physics objects from the debris of proton-proton collisions.
Chapter 5 describes the expected background and signal processes. Chapter 6 provides the motivation for and introduction to the event selection. Chapter 7 describes the technique of kinematic fitting. Chapter 8 describes the boosted analysis technique and introduces the final event selection. Chapter 9 describes the statistical analysis and the treatment of systematic uncertainties. It also presents the results of the search and conclusion. Some technical details have been moved to the appendix to maintain the flow of the main physics interest.
CHAPTER 2. Theory: The Standard Model and Beyond

2.1 The Standard Model

What is matter made of? How do the building blocks of matter interact with each other? Elementary particle physics seeks answers to these questions. The current understanding of the constituents of matter and their interactions is established in a theoretical framework that is called the Standard Model (SM). According to the SM, matter is composed of fundamental constituents called quarks and leptons, and the forces between them are carried by other particles, the fundamental bosons. Additionally, there is the Higgs boson, which is a massive elementary particle responsible for giving mass to other elementary particles (see 2.1.5. These particles are elementary in the sense that they are treated like point particles and assumed to have no internal structure or excited states. Each of these particles has an anti-particle with the same mass as the particle in question but opposite charge. The description of the elementary particles and the fundamental forces described in the next sections is loosely based on Chapters 1 and 2 of [1] and Chapters 2 and 3 of [2].

2.1.1 The Fundamental Forces

The fundamental forces most familiar to people are gravity and electromagnetism. However, they are not the only forces that have been identified. There are two additional less familiar forces.

To think about the third force, consider the atomic nucleus. Due to the electromagnetic force the positively charged protons should repel each other. But the nuclei of atoms somehow hold together, which is evidence for some stronger force that causes these particles to stay put. This force, which overcomes the electromagnetic repulsion and allows atomic nuclei to
remain stable, is prosaically called the “strong force”. Just as electric charge is an intrinsic property of particles subject to the electromagnetic force, the intrinsic property of particles which renders them subject to the strong force is called “color”, or sometimes “color charge”. The color-charged particles and their interactions are described by a theory called “Quantum Chromodynamics”, or QCD. According to QCD, the force between the color-charged particles is mediated by massless particles called “gluons”.

The fourth force is responsible for certain types of radioactive decays; for example, permitting a neutron to turn into a proton. It is called the “weak force”. In the 1960s, Sheldon Glashow, Abdus Salam, and Steven Weinberg independently developed a theory that unified the electromagnetic and weak forces. At sufficiently high energies the difference between these two separate forces is negligible and they instead act together as the “electroweak force”. At lower energy scales, the symmetry between the electromagnetic force and the weak force is broken and we observe two different forces with different properties.

Electroweak theory predicts four force-carrier particles. The force mediating particle for electromagnetism is the neutral, massless photon (usually represented by the Greek letter \( \gamma \)). And the mediators for the weak force are the massive \( W^+ \) (with +1 proton charge), \( W^- \) (with −1 proton charge) and \( Z^0 \) (electrically neutral) bosons.

The electromagnetic, weak, and strong forces described above, together with the fundamental particles, constitute what is called the Standard Model of Particle Physics.

2.1.2 Leptons

Leptons are spin-1/2 fermions\(^1\) that interact via electromagnetic(only charged leptons), weak, and gravitational forces. They do not interact through the strong force because they do not carry color charge. There are three charged leptons, grouped into three different generations based on their masses. The electron is the lightest of the charged leptons. The muon and the tau are exactly similar to an electron except they are heavier. There are also three neutral leptons, called neutrinos (“little neutral one”), one type for each of the charged leptons: the electron neutrino, the muon neutrino, and the tau neutrino. Neutrinos do not carry electric

\(^1\text{Fermions are particles with half-integer spin obeying Fermi-Dirac statistics.}\)
charge, so they are not affected by the electromagnetic forces. Therefore a typical neutrino passes through normal matter almost unimpeded. Neutrinos are created as a result of certain types of radioactive decay, or nuclear reactions such as those that take place in the Sun, in nuclear reactors, or in the decay of one of the force carrying particles such as $W$ or $Z$ bosons, or in the decay of muon or tau lepton.

Fig. 2.1 shows the leptons classified into three generations and some of their physical properties, along with the quarks and bosons\(^2\), which will be described in subsequent sections.

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\(^2\)https://cdsweb.cern.ch/record/1473657/
2.1.3 Quarks

Experiments have established that protons are composed of elementary particles called “quarks”. Through further experiments it has been found that there are six flavors of quarks, grouped into three generations, even though only the first generation makes up ordinary matter. The first generation contains the up and down quarks, the second generation contains the more massive charm and strange quarks, and the third generation contains the even more massive top and bottom quarks. Fig. 2.1 shows the quarks classified into three generations and some of their physical properties, along with the leptons and bosons. As can be seen, the quarks with charge $+2/3$ are all in the upper row while the quarks with charge $-1/3$ are all in the lower row. The upper row (lower row quarks) are sometimes collectively referred to as up-type (down-type) quarks.

Quarks are subject to the strong force due to the color-charge they carry. It is found that there are three different types of colors: (arbitrarily defined as) red, green, and blue. Quarks are grouped together to make composite particles that are colorless. The notion of color quantum number to the quark model was introduced to explain how two quarks, in otherwise identical quantum state, could co-exist in a composite particle without violating the exclusion principle.

Quarks, in addition to possessing the color-charge, have an interesting feature that they are never found in isolation, but always inside of a composite particle. This phenomenon is called “confinement”. The strong force increases in strength as two colored particles are pulled away from each other, just like when the ends of a piece of elastic are pulled apart. If the separation distance between the two quarks reaches a certain threshold, sufficient potential energy is built up and it can be converted to matter, creating a quark-antiquark pair. The pair will separate and the resulting particles will recombine with the original quarks. On the other hand, as two quarks get closer together, the strong force between them becomes weaker until the quarks move around freely. This phenomenon is a called “asymptotic freedom”.

Quarks also interact with other particles via the weak force. Weak force is the only force that can cause a change of flavor of quarks. When this happens, a quark either turns into a heavier quark by absorbing a $W$ boson, or it emits a $W$ boson and thereby decays to a lighter
quark. Consider beta decay, a radioactive process in which a neutron turns into a proton, an electron and a neutrino. One of the down quarks in the neutron decays to a lighter up quark by emitting a $W^-$ boson. Physical quantities such as electric charge, total momentum, energy, quark number, and lepton number are conserved in the process. The neutron, which had one up and two down quarks, now has one down and two up quarks, which is the composition of a proton. The electron and antineutrino are created from the decay of the $W^-$ boson.

2.1.4 Gauge Bosons

In the mathematical formulation of quantum field theory, the Lagrangian can be made invariant under a local gauge transformation by the addition of a vector field called a “gauge field” (Chapter 11, [1]). The quantum of the gauge field is a type of particle, which is called a “gauge boson”. There are three types of gauge bosons described by the Standard Model. They are the photon, which carries the electromagnetic force, the $W$ and $Z$ bosons, which carry the weak force, and the gluons which carry the strong force. Each of these bosons has been experimentally verified. Experiments have demonstrated that the gluons have eight different color states and that, because they interact via the strong force, they have properties similar to quarks, such as confinement. Fig. 2.1 shows the bosons and some of their physical properties, along with the quarks and leptons.

2.1.5 The Higgs Boson

The Higgs boson is the only Standard Model boson that is not a gauge boson. It is the quantum of the scalar Higgs field. At a seminar held on 4 July 2012, the ATLAS and CMS experiments at the LHC announced that they had observed a new particle: a boson consistent with the Higgs boson. In March 2013, in the light of the updated ATLAS and CMS results, CERN announced that the new particle was indeed a Higgs boson.

This newly discovered boson provides support for the existence of the proposed Higgs field, which explains how some particles come to have mass and others have not. For example, the $W$ and $Z$ bosons are very massive, whereas the photon is massless. Experiments have been able to confirm the existence of all the elements of the SM. The Higgs boson, however, had
eluded detection until recently, prompting speculation that the theory could be incorrect. The new measurements suggest a Higgs boson compatible with the Standard Model.

### 2.1.6 Hadrons

Hadrons are bound state of quarks. They can be either fermions or bosons, depending on the number of constituent quarks. An odd number of bound quarks create a spin-1/2 or spin-3/2 hadron, which is called a baryon, and an even number of quarks create spin-0 or spin-1 hadrons, called mesons. The terms baryon and meson often refer to just three or two bound quarks, respectively.

The most well-known examples of baryons are protons and neutrons. Protons are made of two up quarks and one down quark, or $|uud\rangle$, and neutrons are made of two down quarks and one up quark, or $|udd\rangle$. Mesons are made of a quark and an antiquark pair, though not necessarily of the same generation. Examples include $\pi^+ |ud\rangle$ and $K^+ |us\rangle$.

The numerous possible combinations of six quarks put into a three-quark or two-quark hadron is one of the reasons for the zoo of particles discovered in the past century. Each of these combinations can be a different quantum mechanical state, and hence can possess different properties. For example, a $K^+$ contains an up quark and an anti-strange quark. A $K^0$ contains a down quark and an anti-strange quark. A rho meson $\rho$ has the same combination of quarks as a pion $\pi$, but the $\rho$ is spin-1 whereas the pion is spin-0.

### 2.2 Beyond the Standard Model

In spite of the confirmation of all elements of the SM, there are strong reasons to believe that the SM is only a low energy approximation of a more fundamental theory. There are several phenomena not explained by the SM.

- **Neutrino Oscillations**

  A neutrino changes lepton flavor as it travels. For example, we can take a measurement and observe an electron neutrino, even though it was known to have been created as a muon neutrino. These oscillations of flavor can only occur if neutrinos have mass
(even very small mass), so the fact that the SM currently predicts them to be massless demonstrates that either there are some parameters in the theory that need to be adjusted or a new theory is needed [3].

- **Matter Anti-Matter Asymmetry**
  The universe is made up of mostly matter. However, the SM predicts that matter and anti-matter should have been created in almost equal amounts. Yet, the SM has no mechanism to explain the observed asymmetry [4].

- **Gravity**
  Gravitational interaction is not included in the SM at all. From the experimental point of view, gravity is weaker than the weak force, so its exclusion from the SM doesn’t make any measurable difference in the properties of elementary particles. However, from the point of view of the completeness of a theory, the failure of the SM to include or explain gravity is still a source of discomfort, to say the least.

- **Dark Matter**
  Cosmological observations tell us that the SM explains about 4% of the matter-energy present in the universe. Of the missing 96%, about 27% should be dark matter. Yet, the SM does not contain any fundamental particles that are good dark matter candidates [5].

- **Hierarchy Problem**
  The SM introduces particle masses through a process known as spontaneous symmetry breaking caused by the Higgs field. Within the SM, the mass of the Higgs gets very large quantum corrections due to the presence of virtual particles (mostly virtual top quarks). These corrections are much larger than the actual mass of the Higgs. This means that the bare mass parameter of the Higgs in the SM must be fine tuned in such a way that almost completely cancels the quantum corrections. This level of fine tuning is deemed unnatural by many theorists [6].

  All these shortcomings of the SM have led theorists to look for theories beyond the SM (BSM). Some of the BSM theories that motivate the search presented in this dissertation are
briefly described in the following sections.

2.2.1 Vector-Like Quarks

Vector-like quarks are hypothetical spin-1/2 particles that transform as triplets under the color gauge group and whose left- and right-handed components have the same color and electroweak quantum numbers [7]. Vector-like quarks do not receive their masses from Yukawa couplings to a Higgs doublet, and are consistent with existing Higgs data. They can also mix with the SM quarks and thereby modify the couplings of the SM quarks to the $Z$, $W$ and Higgs boson. The addition of vector-like quarks to the SM is the simplest way of breaking the Glashow-Iliopoulos-Maiani [8] mechanism, giving rise to tree-level flavor-changing neutral currents [9, 10] and potentially striking new effects in low energy physics. In this respect, new vector-like quarks also introduce new sources of CP violation [11, 12, 13, 14]. Finally, vector-like quarks at the TeV scale are strongly motivated by two main theoretical ideas: they are required if the Higgs is a pseudo-Goldstone boson\(^3\) to induce electroweak symmetry breaking and explain the observed mass of the Higgs [15, 16, 17], and they emerge as fermion resonances in the partial-compositeness theory of flavor [18, 19]. Vector-like quarks arise in Little Higgs [20, 21], Top SeeSaw Models [22, 23, 24] and in any model with quarks propagating in the bulk of extra dimensions and in grand unified and string theories based on the group $E_6$ [25].

2.2.2 E6 Isosinglet Quarks

The grand unified theories (GUTs) aim to address some of the open questions in the SM by imposing a fundamental symmetry between all known fermions of the same family. This symmetry, manifesting itself at high energies, is expected to reduce the number of free parameters in the SM. The experimental implication of extending the existing $SU_C(3) \times SU_W(2) \times U_Y(1)$ group structure of the SM to a single gauge group with a large fundamental representation is the prediction of new particles. The exceptional Lie group $E_6$ has been long considered as one of the favorite candidates for such a GUT gauge symmetry group [26, 25]. The new colored

\(^3\)Goldstone or Nambu-Goldstone bosons are massless, spin-0 particles that necessarily appear in models requiring spontaneous symmetry breaking of a continuous global symmetry. (Chapter 11, [1]).
particles predicted by $E_6$ are isosinglet quarks, leptoquarks and diquarks depending on model variations. Some of these particles would be accessible at the LHC experiments. The LHC will cover the region up to mass of new quark up to 1 TeV for the pair production channel [27] at its design capacity. In [28], the possible impact of the mixing between the $E_6$ isosinglet quark and the SM down type quarks is considered and the potential searches at the LHC are described.

2.2.3 Mirror Quarks

The idea of left-right symmetry with mirror fermions is very appealing from the symmetry point of view. In this picture the symmetry is not only left-right, but each left handed fermion multiplet is accompanied by a new right- handed fermion multiplet. In Ref. [29] a gauge symmetry, $SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{Y'}$, supplemented by a discrete $Z_2$ symmetry is considered. Instead of having a right-handed multiplet for each left-handed multiplet of the same fermions as in the usual left-right model, the mirror model include right-handed doublets involving new fermions (called mirrors), and similarly for each right-handed singlet, there are corresponding mirror singlets. Thus the gauge anomaly is naturally absent in this model and the model also provides a solution for the strong CP problem because of parity conservation. The first stage of symmetry breaking is achieved by a doublet mirror Higgs with a vacuum expectation value $\simeq 10^7$ GeV. The mirror fermions can mix with the ordinary fermions via a scalar which is singlet under the gauge symmetry. In this model, only light mirror particles having masses in a few hundred GeV range, are allowed. They can be pair produced at the LHC, and can be detected as resonances. The signals of these mirror fermions at the LHC has been discussed in detail in Ref. [29], and it has been found that the reach at the LHC can be as large as $m_{\tilde{q}} \simeq 800$ GeV.

2.2.4 General Search for New Heavy Quarks at the Large Hadron Collider

New heavy quarks can be pair-produced at hadron colliders through their gauge couplings to gluons, with a strength given by the strong coupling constant, $g_s$. They subsequently decay into SM particles, namely ordinary quarks plus a Higgs or a gauge boson, with branching ratios that are mostly determined by their gauge quantum numbers [7]. These decays occur through
the mixing of the new quarks with the SM ones. The pair-production and subsequent decays of new quarks are described in 5.2 and 5.3. Even though there are several labels in the literature, one for each model, to represent the new quarks \((Q, T, T', t', \hat{q} \text{ etc.)},\) we will use a generic \(T\) for all models.

In the searches performed so far, one key assumption has been that the new quarks mix only with third generation SM quarks. While in some models it has theoretical motivation, this assumption still needs to be experimentally verified. There have been only a few searches where the mixing with the lighter generation quarks was considered [30]. The current limit on the new quark mass for non-zero mixing with lighter quarks comes from the ATLAS search [31] in the two-lepton channel. This search excludes \(T\) quark with mass less than 350 GeV, assuming a 100% branching ratio to \(Wq\), where \(q = u, d, c, s, b\) quark.

In the present search, we assume 100% mixing with the lighter quarks (first or second generation quarks). This search complements the searches that assume 100% mixing with third generation quarks. In the absence of discovery, the combined results from these complementary searches could put the most stringent limit on the described theoretical models. More importantly, in the E6 Isosinglet Quark Model and Mirror Fermions Model discussed above, only mixing with lighter quarks is allowed. In the Mirror Fermion Model, only pair-production of the new quark is possible due to the imposed \(Z_2\) symmetry. Motivated by these, in this dissertation a search is presented for \(T\bar{T}\) production and subsequent decay into a \(W\) boson and a light quark using 20 fb\(^{-1}\) of \(pp\) collision data at \(\sqrt{s} = 8\) TeV collected with the ATLAS detector.
CHAPTER 3. Experimental Setup

3.1 Introduction

The analysis presented in this thesis makes use of the proton-proton collision data collected by the ATLAS detector at the Large Hadron Collider (LHC) at CERN near Geneva, Switzerland. This chapter describes the setup of the LHC and the ATLAS detector.

3.2 The Large Hadron Collider

The Large Hadron Collider is expected to address some of the unsolved questions of physics, advancing human understanding of physical laws. It was built in collaboration with over 10,000 scientists and engineers from over 100 countries, as well as hundreds of universities and laboratories. The LHC is currently the most powerful particle accelerator in the world. Managed by the European Council for Nuclear Research (Conseil Européen pour la Recherche Nucléaire, CERN), the accelerator complex is inside a 27 km circular tunnel, which is 100-120 meters underground on both sides of the French-Swiss border. Fig. 3.1 shows the LHC accelerator and the four experiments at the four collision points. Mont Blanc and the Alps appear in the background.

According to the de Broglie relation in quantum mechanics, the wavelength of a particle is inversely proportional to the momentum (or energy) of the particle. This implies that the deeper we want to probe into the heart of matter, the higher the energy (smaller wavelength) of the probing particles must be. For the case of a circular collider, the maximum obtainable energy is a function of the radius of the machine and the strength of the dipole magnetic field that keeps particles in their orbits. For a given magnetic field, the larger the collider, the more energy of the colliding particles. A collider with two counter-circulating beams has an
advantage over other kinds of accelerators where the beam collides with a stationary target. When two beams collide, the centre-of-mass energy of the collision is the sum of the energies of the two beams. A beam of the same energy that hits a fixed target would produce a collision of much less energy. The circumference of the tunnel, the strength of the magnets, and other essential elements of the machine, represent the main constraints that determine the design energy of 7 TeV per proton beam.

![LHC and its four main experiments](image)

Figure 3.1 The LHC and its four main experiments

The LHC is designed to provide proton-proton (and ion) collisions at a center of mass energy up to $\sqrt{s} = 14$ TeV (for proton-proton collision) to the four main experiments: two general-purpose detectors, ATLAS and CMS, to a detector focused on studies of $b$-physics, LHCb, and to ALICE, which is focused on studies of heavy ion collisions.

The accelerator complex is a succession of machines with increasingly higher energies. Each
machine injects the beam into the next one, which takes over to bring the beam to an even higher energy. In the LHC, the last element of this chain, each particle beam would be accelerated to an energy of 7 TeV. The accelerator chain with the LHC as the final destination for the protons is shown in Fig. 3.2.

Linear accelerator 2 (LINAC 2) is the starting point for the protons used in experiments at CERN. Hydrogen is passed through an electric field to strip off its electrons, leaving only protons to enter the accelerator. Accelerated to 50 MeV by LINAC2, the protons are transferred to the Proton Synchrotron BOOSTER and further accelerated to 1.4 GeV. Then, in the Proton Synchrotron (PS), they reach an energy of 25 GeV. They continue their journey into the Super Proton Synchrotron (SPS)\(^1\), where they are accelerated to the LHC injection energy of 450 GeV in a ring of 7 km in circumference. From the SPS, two transfer lines inject proton beams into the two beam pipes of the LHC. Both proton beams are accelerated simultaneously in the Large Hadron Collider and are brought to collision at four interaction points after reaching their final energies. The designed energy of each beam is 7 TeV, but the data analyzed in this analysis use the beam accelerated up to 4 TeV. The four big LHC experiments, ALICE, ATLAS, CMS, and LHCb are built around the four collision points. The data analyzed in this thesis were delivered by the LHC and recorded by the ATLAS detector which is described next.

\(^1\)A major highlight for the SPS, after it was switched on in 1976, came in 1983 with the Nobel-prize-winning discovery of W and Z particles, with the SPS running as a proton-antiproton collider.
With unprecedented collision energy and luminosity, the LHC opens a new frontier in particle physics. The ATLAS experiment has been optimized to best exploit this new territory in physics. As has been mentioned earlier, the goals of the LHC and its experiments were the discovery of the Higgs boson, supersymmetric particles and extra dimension while also maintaining the capability to measure known processes such as heavy quarks and gauge bosons.
Hence, ATLAS has been developed as one of the two general purpose detectors at the LHC to fully cover the rich potential of LHC physics, to discover new and perhaps unanticipated phenomena.

The basic design criteria that ATLAS has adhered to can be summarized as follows:

- excellent tracking at high luminosity for high-$p_T$ lepton-momentum measurement to distinguish between electrically charged particles and neutral ones;
- excellent electromagnetic calorimetry for electron and photon identification and measurement complemented by full-coverage hadronic calorimetry for accurate jet and missing transverse energy measurements;
- high precision muon momentum measurements;
- detection capability over the full solid angle, including along the beam direction;
- triggering and measurements of charged particles at low-$p_T$ thresholds, providing high efficiency for most physics processes of interest;

The detector, shown in Fig. 3.3 is cylindrical in shape, 44 meters in length, and 25 meters in diameter and is built around one of the accelerator collision points. It consists of layers of sub-detectors - the inner tracking detector surrounded by a superconducting solenoid magnet, the electromagnetic and hadronic calorimeters, and the muon spectrometer. The description of the detector components presented here is loosely based on [32].

### 3.4 Detector Coordinates

The ATLAS detector employs a coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam line. Observables labeled as transverse are projected onto the $x-y$ plane. The $x$-axis points from the IP to the centre of the LHC ring while the $y$-axis points upwards. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane. The azimuthal angle $\phi$ is measured from the $x$-axis, around the beam. The pseudorapidity is defined in terms of the polar angle $\theta$ as: $\eta = -\ln \tan(\theta/2)$. $\theta$ is defined
as the angle from the positive $z$-axis. The $\Delta R$ distance is defined as $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$.

Transverse momentum is defined as $p_T = \sqrt{(p_x)^2 + (p_y)^2}$.

Figure 3.3 The ATLAS detector

3.5 Inner Detector

Thousands of particles emerge from the collision point every 25 ns, which creates a very large track density in the detector. In order to achieve the momentum and vertex resolution required to observe the known physics processes, precise measurements must be made along the trajectories of the particles thus requiring fine detector granularity. The inner detector (ID) is designed to provide precision measurement of the trajectory that charged particles take as they leave the central interaction point. The layout of the inner detector is shown in Fig. 3.4.
Figure 3.4 The Inner Detector schematic
The inner detector and its associated services are immersed in a 2 T solenoidal magnetic field. There are three main components of the inner detector: a pixel detector, the Semiconductor Tracker or SCT, and the Transition Radiation Tracker or TRT. The Pixel Detector and SCT rely on fine granularity silicon technology to provide high-precision measurements of track parameters closest to the interaction point. The TRT has a coarser inherent granularity but it benefits from a much larger volume over which to make its measurement. All end-cap tracking elements are located in planes perpendicular to the beam direction.

In general, each detector element registers hits as charged particles traverse them. Track-finding algorithms take these hits and form tracks. It is known that charged particles follow helical trajectories in the presence of a magnetic field, so these tracks, in general, will be curved according to: \[ \mathbf{p} = BQr \], where \( p \) is the momentum of the particle, \( Q \) is the charge, \( B \) is the magnetic field, and \( r \) is the radius of curvature. An accurate measurement of the track (and thus the radius of curvature) is thus a measure of the particle’s momentum.

### 3.5.1 Pixel Detector

The Pixel Detector uses silicon pixels and provides a very precise measurement of the charged particle position closest to the interaction point. It gives three precision measurements over the full acceptance and is the major contributor to the impact parameter resolution and the ability of the Inner Detector to find short lived particles such as \( B \)-hadrons. Fig. 3.5 shows a 3-D model of the pixel detector and its framework.

The pixel detector occupies the radius between 50 and 122.5 mm from the beamline and is arranged in a central barrel module (parallel to the beam axis) with two end-cap modules (perpendicular to the beam axis). All pixel sensors are identical and have a minimum pixel size of \( 50 \times 400 \mu m^2 \). There are 1744 individual sensors, each with 46080 readout channels, resulting in a total readout of approximately 80.4 million channels. The barrel consists of three concentric layers and each end-cap contains three wheels. As charged particles traverse the sensor element, they create free electrons which are read out by electrodes in the chip. Once enough charge is accumulated, a hit is registered. Pixel technology is more expensive to construct and operate than other designs, but it offers resolutions much better than other
types of tracking systems.

![The Pixel Detector](image)

**Figure 3.5** The Pixel Detector

### 3.5.2 Semi Conductor Tracker

The Semi Conductor Tracker (SCT) system, shown in Fig. 3.6, is designed to provide eight precision measurements per track in the intermediate radial range \((299 < r < 514\text{mm})\), contributing to the measurement of momentum, impact parameter, and vertex position. The SCT operates on principles similar to that of the pixel detector. There is a central barrel region with four layers of concentric modules (2112 in total) giving a coverage of \(|\eta| < 1.1\) to 1.4, and two sets of end-cap wheels (with a total of 1976 modules) with a coverage of 1.1 < \(|\eta| < 2.5\.

Detector elements in the SCT are single-sided 6 cm-long wafers, glued together on opposite sides of a module. Each module has 768 readout channels per side, for a total of over 6.3 million. Hits are registered when free electrons, created by charged particles as they pass through the detector element, are readout by an electrode. The resolution of the SCT is approximately 17 \(\mu\text{m}\).
3.5.3 Transition Radiation Tracker

The Transition Radiation Tracker (TRT), shown in Fig. 3.7, is based on the use of straw tube detectors, which can operate at the expected high rates due to the small diameter of the tubes and the isolation of the sense wires within individual gas volumes.

A large number of hits, typically 36 per track, along the particle trajectory can be provided by the 4-mm diameter straw tubes of the TRT. It can follow tracks up to $|\eta| = 2.0$. The TRT consists of thousands of “straws”, each straw being a cylindrical chamber filled with gas, with an anode wire in the center, and the straw wall acting as cathode. Charged particles and photons traversing through the straw ionize the gas and produce a current. Relativistic electrons interact with the gas-solid interface and produce transition radiation photons, which are subsequently detected by ionization of the TRT gas mixture of 70% Xe, 27% CO$_2$, and 3% O$_2$. The TRT has a barrel region with 96 modules arranged in three concentric layers, covering a radial distance of 554 - 1082 mm and two sets of 40 end-cap wheels. In total, the TRT has 351,000 readout channels, and is capable of a tracking resolution on the order of 130 $\mu$m per
straw.

Figure 3.7 The Transition Radiation Tracker

The combination of precision trackers at small radii and the TRT at a larger radius gives very robust pattern recognition and high precision in all detection directions. Although the straw detectors have lower precision per point compared to the silicon detector, the signal from the TRT at the outer radii contributes significantly to the momentum measurement because the TRT has the advantage of providing a large number of measurements at longer track length.

3.6 Calorimeter System

The ATLAS calorimeter system is intended to measure the energy of charged and neutral particles, and to measure the $E_\text{miss}^1$ of an event. To achieve these measurements, the calorimeter employs two sampling calorimeter systems: an electromagnetic calorimeter and a hadronic calorimeter. Sampling calorimeters function by placing alternating layers of absorber and active material enabling measurement of ionization energy as charged particles traverse them. Upon interaction with the absorber, the particle passing through creates a shower of charged particles which are measured by the active material. The number of secondary particles produced in
the shower is proportional to the energy of the incoming particle. To accurately measure the incoming particle’s energy, it is important that it loses all of its energy within the calorimeter. This is also important to prevent the punch through of any particle, except muons, into the muon spectrometer. Thicker calorimeters reduce the punch-through effects of the detector but this has to be balanced against the additional weight and cost of the device. This is quantified by two parameters: the radiation length ($X_0$), defined as the average distance traveled by an electron before encountering an electromagnetic interaction inside the calorimeter; and the interaction length ($\lambda$), defined as the average distance for a hadron to undergo a hadronic interaction. The electromagnetic calorimeter provides 24 radiation lengths in the barrel region and 26 in the end-cap region, while contributing about 10 interaction lengths. The electromagnetic calorimeter is placed closer to the interaction point and is surrounded by the hadronic calorimeter; both are depicted in Fig. 3.9.

3.6.1 The Electromagnetic Calorimeter

The inner section of the ATLAS calorimeter is designed for the measurement of the energy of electro-magnetically interacting particles out to $|\eta| < 4.9$. It is divided into a barrel part and two end-cap components, each contained in its own cryostat. The EM calorimeter is a lead/liquid-argon detector and has accordion-shaped electrodes and lead absorber plates over its full coverage, Fig. 3.8. The accordion geometry provides complete azimuthal coverage without cracks. The lead thickness in the absorber plates has been optimized as a function of $|\eta|$ for the energy resolution capabilities of the EM calorimeter. Precision measurements are made using three sampling layers in the central-most region of the detector ($|\eta| < 2.5$). Two sampling layers are used in the more forward region ($2.5 < |\eta| < 3.2$), which contains the overlap between the barrel and end-cap EM components, as well as the end-cap hadronic component. The forward calorimeter is responsible for the most forward region ($3.1 < |\eta| < 4.9$).
3.6.2 The Hadronic Calorimeter

There are two main functions of the hadronic calorimeters. First, they measure the energies and directions of clusters of particles that result from the ejection from the collision point. These clusters are called “jets”. Second, the hadronic calorimeters can also be used to infer
the presence of one or more neutral, undetectable particles such as neutrinos by monitoring the total transverse momentum. There are three types of hadronic calorimeter built in the ATLAS detector: the tile calorimeter, the hadronic end-cap calorimeter, and the forward calorimeter.

![The Calorimeter](image)

Figure 3.9  The Calorimeter

The tile calorimeter is located outside the liquid argon calorimeter and is specialized in the detection of the energy of hadronic particles for $|\eta| < 1.7$. The active medium for the tile calorimeter is scintillating tile and the absorber is steel-plate. The hadronic-end-cap calorimeter is made up of two wheels per end-cap and is directly forward of the EM calorimeter with coverage $1.5 < |\eta| < 3.2$. The forward calorimeter (FCAL) has coarser granularity than other calorimeters and covers the most forward range $3.1 < |\eta| < 4.9$. 
3.7 Muon Spectrometer

The muon spectrometer (MS) is a robust tracking system for muons, incorporating four separate technologies to deliver high precision tracking and fast triggering. It is based on the magnetic deflection of muon tracks in the large superconducting air-core toroid magnets, instrumented with separate trigger and high precision tracking chambers. The MS provides tracking using monitored drift tubes (MDT) and cathode strip chambers (CSC) in the range $|\eta| < 2.7$, with a resolution of 10% for a muon with momentum of 1 TeV. In order for ATLAS to trigger on events with high $p_T$ muons, the MS delivers fast triggering using resistive plate chambers (RPC) and thin gap chambers (TGC) for muons in the range $|\eta| < 2.4$. The MS is placed within toroidal magnetic fields where the barrel toroids provide a field for $|\eta| < 1.0$ and the end-cap magnets serve the region $1.4 < |\eta| < 2.7$. The fields produced by the toroids are orthogonal to the trajectories of the muons in most regions of the MS. The barrel region contains three cylindrical layers of chambers (MDT and RPC), meanwhile, the end-cap consists of four wheels on each side (MDT, TGC, and CSC). The muon spectrometer, depicted in Fig. 3.10, is the largest sub-detector in ATLAS, spanning 40 m in length and 20 m in height.

The monitored drift-tube chambers are a set of aluminum proportional wire drift tubes measuring 3 cm in diameter and containing a gaseous mixture. A single wire runs axially down the center of each tube. High voltage between the wire and the tube volume produces ionization electrons when muons pass through the tube volume, thus allowing their trajectories to be tracked. The barrel region of the detector consists of three concentric layers of chambers spaced by 2.5 m, covering the region $|\eta| < 1.1$. Meanwhile, the end-cap comprises three wheels of chambers spaced along $z$ in 7 m increments, where the two most outer wheels span the range $1.1 < |\eta| < 2.7$ and the innermost wheel covers the region of $|\eta| < 2.0$. At angles close to the beam line, 32 cathode strip chambers (CSC), which are multi-wire proportional chambers with the cathode wires segmented into two strips, with high granularity are used in the innermost plane over the range $2 < |\eta| < 2.7$. CSC’s effectiveness at the high rate of incident particles makes it suitable to be placed near the beamline.
The thin gap chambers provide fast triggering in the forward region of the detector, covering the range $1.05 < |\eta| < 2.4$. The TGC’s use multi-wire proportional chamber technology, similar to the CSC’s, but with a larger distance between anode wires than the distance from the anode wire to the cathode strip, enabling faster signals for triggering. Fig. 3.11 shows the TGC structure.
In the barrel portion of the detector, resistive plate chambers are used to trigger on muons in the region $|\eta| < 1.05$. They employ gaseous parallel electrode-plate technology and are placed in three concentric cylinders around the beam pipe.

### 3.8 Magnets

The momentum of a charged particle is determined by measuring the curvature of its trajectory through the detector. To achieve this, all tracking devices need to be placed in a magnetic field to bend the particle trajectories. The ATLAS detector contains a solenoid magnet to provide a magnetic field for the inner detector and barrel and end-cap toroidal systems of eight magnet coils to induce the magnetic field inside the muon system. Both magnet systems consist of superconducting magnets operating at a temperature of about 4.5 K. The spatial arrangement of the coil windings is shown in Fig. 3.12.
3.8.1 Solenoid

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

3.8.2 Toroid

Three independent air-core toroid systems, each consisting of eight coils, are used in the barrel region and end-cap regions on each side. The magnetic field provided in the central part is 3.9 T and grows to 4.1 T in the forward region. While each of the eight coils in the barrel
region is housed inside its own cryostat, the full end-cap toroid system shares one cryostat on each side. Fig. 3.13 shows the barrel toroid as installed in the underground cavern.

Figure 3.13 Barrel toroid as installed in the underground cavern. The scale is indicated by the person standing in between the two bottom coils.

3.9 Trigger and Data Acquisition System

The LHC produces $pp$ collisions at a rate of 40 MHz when operated at design specifications. At this rate, ATLAS would need to store 60 TB of data per second which is not practical due to bandwidth and data storage limitations. To reduce the rate of event storage to a manageable frequency, while ensuring that interesting physics is not lost, ATLAS implements a three tiered trigger system: the level one trigger (L1), level two trigger (L2), and event filter trigger (EF). Each trigger level refines the decisions made at the previous level and applies
additional conditional criteria if necessary. The data acquisition system receives and buffers the event data from the detector-specific readout electronics. The L1 trigger is hardware based trigger that determines, from the total detector information, if an event’s data should be passed on to the software based L2 trigger. The high level triggers (HLT), L2 and EF triggers, perform complex calculations to determine whether or not an event is recorded. Interesting physical processes typically contain any of these characteristics: high $p_T$ jets or leptons, events with large $E_T^{\text{miss}}$, or events with a large sum of transverse energy. The triggers are configured to quickly detect such characteristics, maximizing the number of events recorded. Due to limited bandwidth, some triggers are pre-scaled, meaning that only a fraction of the events passing that trigger are stored and then the events are scaled to agree with expectation. Pre-scaling occurs at all three trigger levels.

3.9.1 L1 Trigger

The L1 trigger searches for high $p_T$ muons, electrons, photons, jets, and tau-leptons decaying into hadrons as well as for large missing transverse energy and total transverse energy. High $p_T$ muons are identified using trigger chambers in the barrel and end-cap regions of the Muon Spectrometer. Calorimeter selections are based on reduced-granularity information from all the calorimeters. In addition to reducing the rate of events to 75 kHz, the L1 trigger defines regions of interest (RoI), i.e. the geographical coordinates of those regions within the detector where the selection process has identified interesting features. The RoI data include information on the type of feature identified and the criteria satisfied such as a particular threshold. That is, the RoI contains the $\eta$, $\phi$, and $p_T$ measurements of the trigger towers that determined the selection of the event.
3.9.2 L2 Trigger

The L2 selection is thus “seeded” by the RoI information provided by the L1 trigger. The L2 trigger relies upon software based algorithms to determine if an event is passed along to the EF trigger. It has access to information from the sub-detectors located in the RoI, as well as information from the Inner Detector. On average, the L2 takes about 40 ms to perform a basic reconstruction of the trigger object, reducing the rate of events to approximately 3 kHz.
3.9.3 L3 Trigger

The L3 (Event Filter) trigger carries out the final stage of the event selection. It is the most sophisticated of the three, employing parallel processors to perform a robust reconstruction using the offline-analysis algorithms. It utilizes $p_T$ thresholds, as well as object quality requirements (e.g. isolation requirements), to reduce the event rate to approximately 200 Hz from the 3 kHz event rate. Having passed the EF trigger, an event can be recorded into one (or more) of four different data streams: muon, electron/photon, jet/tau/$E_T^{\text{miss}}$, and minimum bias. The minimum bias stream, having the largest pre-scaled trigger, randomly selects events with a low total $p_T$ threshold.
CHAPTER 4. Reconstruction of Physics Objects

4.1 Introduction

In this dissertation we focus on the search performed in the lepton+jets channel, characterized by one high $p_T$ charged lepton, one neutrino, and four or more light quarks. Therefore, our physics objects of interest are electron ($e$), muon ($\mu$), missing transverse energy ($E_T^{\text{miss}}$), light jets, and $b$-jets (so as to veto them). Each of these physics objects must be reconstructed from the energy deposits in the calorimeters, hits in the trackers, and muon chambers. Tracks must be matched to the energy deposits in the calorimeters. This chapter describes how these physics objects are reconstructed and identified.

4.2 Tracks

As charged particles pass through the inner tracker, they deposit small amounts of energy. This energy is reconstructed into hits in each layer of the detector at the location of the particle. The trajectory of the particle can then be determined via pattern recognition algorithm and fitting a track from these hits. Tracks are used in this analysis to identify charged particles and to distinguish them from neutral particles. The tracks in the inner detector also form the basis to distinguish jets originating from $b$-hadrons from other jets and also for the reconstruction of the primary vertex.

To reconstruct tracks, the raw data from the pixel and semiconductor trackers are converted into clusters and the TRT raw timing information is turned into calibrated drift circles [32]. The default tracking exploits the high granularity of the pixel and SCT detectors to find prompt tracks originating from the vicinity of the interaction region. Track seeds are formed from a combination of hits, also called space-points, in the three pixel layers and the first SCT layer.
These seeds are then extended throughout the SCT to form track candidates. After applying additional quality cuts, the selected tracks are extended into the TRT to associate drift-circle information in a road around the extrapolation and to resolve the left-right ambiguities. Finally, the extended tracks are refitted with the full information of all three detectors and the quality of the refitted tracks.

Extensive validation of the tracking algorithms’ performance and their modeling in Monte Carlo simulation has been done using tracks from cosmic rays incident on the detector, $pp$ collisions, and heavy ion collisions, under a variety of conditions [33, 34].

### 4.3 Primary Vertex

The primary vertex is the location of the hard collision between $pp$ pair and is the origin of the particles produced in this collision. In ATLAS the location of the primary vertex is close to the center of the detector in the $(x, y)$-plane. The challenge of locating the primary vertex stems from multiple tracks and their actual origins. A dedicated vertex finder is used to reconstruct primary vertices. This is followed by algorithms dedicated to the reconstruction of photon conversions and secondary vertices.

Vertexing tools constitute an important component of the higher-level tracking algorithms. Primary vertex is reconstructed using an iterative vertex finding algorithm [35]. Vertex seeds are obtained from the $z$-position at the beamline of the reconstructed tracks. An iterative $\chi^2$ fit is made using the seed and nearby tracks. Each track carries a weight which is a measure of its compatibility with the fitted vertex depending on the goodness of the fit. Tracks that are displaced by more than $7\sigma$ from the vertex are used to seed a new vertex and the procedure is repeated until no additional vertices are found. During reconstruction, vertices are required to have at least two tracks. For this analysis, we require at least one primary vertex with at least four reconstructed tracks.
4.4 Electrons

Electrons leave tracks when passing through the inner detector and also deposit energy in the electromagnetic calorimeter because they are charged particles. Fig. 4.1 shows an event with four electron candidates. Electrons are reconstructed using an algorithm seeded by clusters in the electromagnetic calorimeter.

The clusterization in the calorimeter is based on a sliding window algorithm, in which a fixed cone in $\Delta \eta \times \Delta \phi$ is moved over the calorimeter cells and the position which yields the maximum energy deposition within the cone is chosen as the seed. These seeds are then used to build clusters by iterating over the calorimeter layers to define the energy and position of the cluster [36]. The results from this method are used for electron reconstruction. Matching the clusters to an inner detector track and shower shape distributions typical for electron-induced showers are used to distinguish electrons from photons. In addition, information from the TRT detector based on the transition radiation is used to separate electrons from hadrons. Depending on a set of cuts on the shower shapes, the track matching and the existence of a hit in the innermost pixel layer, good quality electrons are distinguished from looser electron candidates.

4.4.1 Electron Trigger

Single electron trigger chains are used to pre-select events in the electron+jets channel. Electron objects are required to match the lowest unprescaled single electron trigger in 2012 data-taking, $EF_{e24vhi\_medium1}$, representing the full trigger (L1-L3) chain $L1\_EM18VH \rightarrow L2\_vh\_medium1 \rightarrow EF_{e24vhi\_medium1}$. The $V$ component in the L1 name stands for varied threshold (small $v$ in the HLT name) and is effectively a coarse dead material correction applied on a single L1 EM trigger threshold. The $H$ stands for the hadronic core isolation in L1. This cut leads to inefficiencies in selecting very high $E_T$ electron objects (i.e. $E_T \gg 200$ GeV) with respect to offline selection cuts, so it is ORed with the single electron trigger $EF_{e60\_medium1}$ to mitigate the problem. The $EF_{e60\_medium1}$ also recovers some efficiency loss for $E_T > 80$ GeV by removing the cut on the EM calorimeter back energy frac-
Figure 4.1 Event display of a Higgs → 4e candidate event with $m(4l) = 124.5$ (124.6) GeV without (with) Z mass constraint. The masses of the lepton pairs are 70.6 GeV and 44.7 GeV. The event was recorded by ATLAS on 18-May-2012, 20:28:11 CEST in run number 203602 as event number 82614360. The tracks of the two electron pairs are colored red, the clusters in the LAr calorimeter are colored dark green.
tion (F3). It should be noted that in the EF.e24vhi_medium1 trigger a loose track isolation, PtCone20/$E_T < 0.1$, is applied.

4.4.2 Electron Offline Selection

Electron objects are reconstructed in the central region with energy deposits (clusters) in the EM calorimeter associated to reconstructed tracks in the Inner Detector. The candidates are selected with $|\eta_{cl}| < 2.47$, excluding the transition region of $1.37 < |\eta_{cl}| < 1.52$, in the EM calorimeter. Low $|\eta_{cl}|$ is required so the electron candidates fall inside the fiducial acceptance of the calorimeters. The candidates are required to have transverse energy $E_T > 25$ GeV ($E_T = E/\cosh(\eta)$, where the energy is taken from the cluster, $E_{cl}$, and the direction from the associated track, $\eta_{track}$). High transverse energy is required to select electrons on the stable plateau of the electron trigger efficiency curve. Electrons are required to satisfy the Tight++ criteria, which use various calorimeter and track measureables to identify electrons and reject the background from charged hadrons, as described in [37]. Specifically, tight $p_T$ and $\eta$-dependent cuts are made on the shower-shape variables as measured in the strips and second compartment of the EM calorimeter. Track quality is enforced by requiring at least 1 hit in the Pixel detector and 7 hits in the pixel or SCT detectors. The calorimeter deposit and track are required to match within an $\eta$ of 0.05, and the candidate must have an impact parameter less than 5.0 mm. The isolation cuts are derived from $Z \rightarrow ee$ tag-and-probe data based on the full 2012 dataset. The EM calorimeter isolation variables are corrected for energy leakage into the isolation cone and for energy deposit from pile-up events. Jets within $\Delta R < 0.2$ of the selected electron are removed from events. If an additional jet is found within $\Delta R < 0.4$ and with $p_T > 25$ GeV and $|JVF| > 0.5$, then the electron is discarded.

4.5 Muons

Muons leave tracks through both the inner tracker and the layers of the muon system and may also deposit traces of energy in the calorimeters. Though the instrumental part in the identification and reconstruction of muons is the muon system of the ATLAS detector, information from all detector parts can be used to reconstruct the track of a muon in the
detector and to determine its transverse momentum. Fig. 4.2 illustrates an event with a $Z$ boson decaying to 2 muons.

![ATLAS Experiment](image)

$$Z \rightarrow \mu^- \mu^+ + 3 \text{ jets}$$

**Run Number 158466, Event Number 4174272**
**Date: 2010-07-02 17:49:13 CEST**

Figure 4.2 Candidate for $Z \rightarrow \mu\mu$ decay, with the $Z$ produced in association with three jets, collected on 10 May 2010. In the x-y projection, the muon candidates are shown as solid blue lines. The harder muon candidate has left a significant energy deposit (see lego-plot projection), presumably through bremsstrahlung.

In this analysis, the muon object is defined following the recommendations from the Muon Combined Performance (MCP) group.

### 4.5.1 Muon Trigger

The single muon triggers to be used with 2012 data are `EF_mu24i_tight` and `EF_mu36_tight`. These triggers differ by $p_T$ threshold and an isolation requirement, which is applied in the
EF\_mu24i\_tight trigger. The isolation requirement in EF\_mu24i\_tight is $p_{T,\mu}^{0.2}/p_T < 0.12$, i.e. the $p_T$ sum of the tracks in a cone of size 0.2 around the muon is required to be less than 12% of the $p_T$ of the muon. The mini-isolation requirement to be applied offline is tighter than this, thus analyses are not affected by the isolation applied at the trigger level. No isolation requirement is made in the EF\_mu36\_tight trigger.

4.5.2 Muon Offline Selection

Muon candidates are reconstructed from track segments in the various layers of the muon spectrometer and matched with tracks found in the inner detector. The final candidates are refitted using the complete track information from both detector systems. A cut of $p_T > 25$ GeV is set to be on the plateau of the single muon trigger efficiency. To be within the detector acceptance, muon candidates are required to have $|\eta| < 2.5$. They must also satisfy the inner detector track quality cuts. Combined muon tracks are required to be associated with at least one hit in the pixel detector, at least five hits in the SCT, and to have no more than three missing hits in the SCT and the pixel detector. Muon tracks within $0.1 < |\eta| < 1.9$ are required to have at least five TRT hits and/or outliers, with an outlier fraction less than 0.9. Additionally, muons are required to be separated by $\Delta R > 0.4$ from any accepted jet (See Isolation below). Muons are also required to satisfy a $p_T$-dependent track-based isolation requirement that has good performance even under high pileup conditions. The muon is required to pass the mini-isolation requirement described below. Further, muons are required to have a hit pattern in the inner detector consistent with a well-reconstructed track. Similar to the electrons, the muon track longitudinal impact parameter with respect to the primary vertex, $z_0$, is required to be less than 2 mm.

4.5.2.1 Muon Isolation Efficiency

The efficiency of the isolation requirement is measured using the tag-and-probe method in $Z$ events. Events are selected using a dilepton selection, requiring two muons that have opposite charge, an invariant mass between 80 and 100 GeV, a $p_T$ of at least 25 GeV, and a distance $\Delta R$ of at least 0.4 to the closest jet. At least one muon has to pass the isolation requirement;
this muon is then the ‘tag’ muon, and the isolation efficiency is measured by determining if the
other muon (the ‘probe’) also passes the isolation requirement.

4.6 Jets

Jets are fairly complex objects reconstructed in the hadron collider detectors. Qualitatively,
quarks and gluons produced from the hard interaction that shower into a dense cluster of many
particles can be called a jet. Fig. 4.3 shows an illustration of the process of jet formation in \( pp \)
collisions \(^1\). Ideally, we would like the total momentum of all of the particles in the jet to be
close to that of the initial quark or gluon, even though that is not realistic given the detector
resolution, radiation etc. Jet reconstruction essentially defines which cells in the calorimeter
belong to a given jet. It is important when clustering the jet that the kinematic properties
of the original quark or gluon match as closely as possible to those of the reconstructed jet.
Fig. 4.4 shows a typical simulated di-jet event as seen by the ATLAS detector.

Jets in this analysis are reconstructed with the anti-\( k_t \) algorithm [38, 39] with a radius of 0.4
performed on topological clusters calibrated using the local cluster weighting (LCW) method,
which partially corrects the response and reduces fluctuations due to the non-compensating
nature of the ATLAS calorimeters [40, 41].

To avoid selecting jets from secondary \( p-p \) or other soft interactions, a selection on the
so-called “jet vertex fraction” (JVF) variable above 0.5 is applied. This is a requirement that
at least 50\% of the sum of the \( p_T \) of tracks with \( p_T > 1 \) \( \text{GeV} \) associated with a jet comes
from the tracks that originate from the primary vertex. If any of the jets lies within \( \Delta R \) of
0.2 of a selected electron, the single closest jet is discarded in order to avoid double counting
of electrons as jets. After this, electrons which are within \( \Delta R \) of 0.4 of a remaining jet are
removed so as to remove electrons coming from hadron decay.

4.6.1 Jet calibration

The reconstructed jets are calibrated, based on their \( \eta \) and \( p_T \), from the electromagnetic to
the hadronic scale to correct for energy losses due to the detector acceptance and non-active

\(^1\)http://www.quantumdiaries.org/wp-content/uploads/2010/10/jets.png
Figure 4.3  Quarks and gluons inside protons interact strongly during $pp$ collision. High energy quarks and gluons produced from such interactions radiate off other quarks and gluons, which all eventually hadronize into mesons or baryons. These hadrons deposit energy in calorimeters and leave tracks in the tracker (if they are charged), which we can measure.

parts of the sampling calorimeters. Corrections for additional proton-proton interactions, i.e. pile-up, and for the origin of a jet from a displaced vertex are applied additionally.

Jets are calibrated using Monte Carlo simulation-based $p_T$ and $\eta$ dependent correction factors, following the calibration scheme described in Section 8 of Ref. [41]. For the derivation of the calibration a Monte Carlo sample of MC12a Pythia inclusive QCD jet events was used. To remove the effect of additional $pp$ interactions (pile-up) from jets, a scheme based on the estimated jet area, $A$, and the event energy density, $\rho$, is employed: from the jet $p_T$ the product $\rho A$ is subtracted.

In addition, a residual correction is applied, parameterized according to the number of primary vertices in an event (NPV) and the number of average interactions in a luminosity
4.6.2 B-tagging

One of the most important selection criteria for the analysis of events containing top or top-like quarks is the identification of jets containing $b$-quarks. For the present analysis it is important to identify jets originating from $b$-hadrons and to veto events containing $b$-hadrons so as to suppress the $t\bar{t}$ background. The discrimination of $b$ jet from light-quark jets originates mainly in the relatively long lifetime of $b$-flavored hadrons, resulting in a significant flight path length $L$. This leads to measurable secondary vertices and impact parameters of the decay products. Fig. 4.5 shows a displaced secondary vertex for a $b$-jet.\textsuperscript{2}

\textsuperscript{2}http://www-d0.fnal.gov/Run2Physics/top/singletop_observation/b_tagging_graphic.png
Figure 4.5  Secondary vertex such as shown here is very useful to distinguish \( b \)-hadron jet from other jets which typically don’t have such displaced vertices.

specific information such as impact parameter or secondary vertex. Mass of the \( b \) hadrons can also be used for \( b \)-tagging, but this hasn’t yet been considered in the present algorithms.

Both the efficiency to correctly identify \( b \)-jets and the rate with which light jets are misidentified as \( b \)-jets, the mis-tag rate, have to be carefully measured in data and compared to the predictions in simulated events. This is typically done at one or more so-called working points of the algorithm. Working points are defined by a a desired for \( b \)-tagging efficiency and mis-tag rate. For MV1 algorithm, a working point of 70\% is chosen with 70\% \( b \)--tagging efficiency.

4.7  \( E_T^{\text{miss}} \)

All of the \( T \)-pair events considered in this analysis have a neutrino in the final state. As neutrinos pass through the detector without interacting, their presence can only be inferred. Before the \( pp \) collision, the momentum in the transverse plane is zero. By conservation of
momentum, the vector sum of the transverse momenta of all of the final state particles must also be zero. Therefore, the momentum of the neutrino is equal to the negative of this sum, denoted as $E_{T}^{\text{miss}}$.

In this analysis, an object based reconstruction algorithm is used to determine the amount of missing transverse energy from the energy imbalance of an event. In this approach, topological clusters in the calorimeter are used as a starting point. Clusters associated to the basic physics objects (electron, jets) with the same definitions as for usage in the final analyses, are included in the calculation of missing transverse energy at their corresponding energy scales, i.e. clusters associated to jets are calibrated to the hadronic scale as described above. The overall $E_{T}^{\text{miss}}$ is also corrected for the momenta of muons in the event.
CHAPTER 5. Expected Signal and Background Processes

5.1 Introduction

A proton-proton collision can result in several different physics processes. For example, a pair of top quarks can be produced in one $pp$ collision whereas in another $pp$ collision a Higgs boson. The challenge of any analysis is to distinguish the signal of interest from the several background processes that mimic the signal. In this chapter we review the expected signal from $T\bar{T}$ and the Standard Model background processes that can produce a signature similar to that of the signal.

5.2 Heavy Quark Production

At the LHC, new quarks are expected to be produced predominantly in pairs via the strong interaction for mass up to $O(1 \text{ TeV})$. At higher masses, single quark production mediated by electroweak interactions can possibly dominate, depending on the strength of the interaction between the new quarks and the weak gauge bosons. This search focuses on the pair production only and the predicted cross section is shown in Fig. 5.1 as a function of the new quark mass. The prediction is independent of the electroweak quantum numbers of the new quark. The cross section at centre-of-mass energy of 8 TeV ranges from approximately 5 pb for a 350 GeV quark to approximately 0.008 pb for a 900 GeV quark. The cross sections at centre-of-mass energy of 8 TeV are also listed in Table 5.1. The uncertainties on the signal samples are discussed in 9.2.10. The mass range of interest for this search is the region 350 GeV (5 pb) to 650 GeV (0.1 pb).
5.3 Heavy Quark Decay

The final state topology depends on the decay modes of the new quarks. Chiral quarks decay via charged-current at tree level due to the GIM suppression mechanism of the neutral-current mode. So a chiral quark will decay into a $W$ boson and a SM quark. Vector-like quarks (VLQ) can decay via either the charged- or neutral-current mode at tree level. A VLQ can decay to a $W, Z$, or $H$ boson plus a SM quark. The assumption in the searches performed so far is that these new heavy quarks couple preferentially to the third generation SM quarks. This analysis puts this assumption to test by performing a search in which the new quarks are assumed to couple to first or second generation quarks. Some models, such as the Left-Right Mirror Model [29], actually only allow decays to the first generation quarks, but we do not attempt in this search to distinguish between decays to first generation quarks from decays to second generation quarks.

![Graph showing predicted pair production cross section for $T$ as a function of mass. The lower panel shows the ratio of cross sections for 8 TeV vs. 7 TeV.](image)

Figure 5.1 The predicted pair production cross section for $T$ as a function of mass. The lower panel shows the ratio of cross sections for 8 TeV vs. 7 TeV.
Table 5.1 Heavy quark pair-production cross section at $\sqrt{s} = 8$ TeV with uncertainties.

<table>
<thead>
<tr>
<th>$m_T$ [GeV]</th>
<th>$\sigma_{Q\bar{Q}}$ [pb]</th>
<th>Scale Uncertainty</th>
<th>$PDF + \alpha_s$ Uncertainty</th>
<th>Total Uncert.</th>
</tr>
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<tr>
<td>350</td>
<td>5.32</td>
<td>$+0.12 - 0.13$</td>
<td>$\pm 0.43$</td>
<td>$\pm 0.45$</td>
</tr>
<tr>
<td>400</td>
<td>2.39</td>
<td>$+0.05 - 0.06$</td>
<td>$\pm 0.22$</td>
<td>$\pm 0.22$</td>
</tr>
<tr>
<td>450</td>
<td>1.15</td>
<td>$+0.025 - 0.026$</td>
<td>$\pm 0.113$</td>
<td>$\pm 0.116$</td>
</tr>
<tr>
<td>500</td>
<td>0.589</td>
<td>$+0.013 - 0.012$</td>
<td>$\pm 0.061$</td>
<td>$\pm 0.063$</td>
</tr>
<tr>
<td>550</td>
<td>0.315</td>
<td>$+0.007 - 0.006$</td>
<td>$\pm 0.034$</td>
<td>$\pm 0.035$</td>
</tr>
<tr>
<td>600</td>
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<td>$+0.0037 - 0.0034$</td>
<td>$\pm 0.0197$</td>
<td>$\pm 0.020$</td>
</tr>
<tr>
<td>650</td>
<td>0.0996</td>
<td>$+0.0021 - 0.0019$</td>
<td>$\pm 0.0116$</td>
<td>$\pm 0.0117$</td>
</tr>
<tr>
<td>700</td>
<td>0.0583</td>
<td>$+0.0012 - 0.0011$</td>
<td>$\pm 0.0069$</td>
<td>$\pm 0.0070$</td>
</tr>
<tr>
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<td>$+0.0007 - 0.0006$</td>
<td>$\pm 0.0042$</td>
<td>$\pm 0.0043$</td>
</tr>
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</tr>
<tr>
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<td>$\pm 0.00165$</td>
<td>$\pm 0.00167$</td>
</tr>
</tbody>
</table>

5.4 Signal Signature in the Detector

Assuming a 100% branching ratio for $T \to Wq\,(d,s)$, pair production of $T$ will have two $W$ bosons and two quarks from $TT\bar{T}$ decay. The $W$ bosons thus produced can decay to a charged lepton and its neutrino (leptonic decay) or into two light quarks (hadronic decay). If both $W$ bosons decay into two quarks, the channel is called hadronic. This channel has the highest branching ratio but it is challenging to reconstruct the event completely in this channel due to the high jet multiplicity and consequent combinatorics. If both $W$ bosons decay into leptons, the channel is called dileptonic. It has a very clean signature with two charged leptons but it has a very small branching ratio and it also poses a problem for complete event reconstruction since there are two neutrinos, and no lepton for trigger. This analysis is performed by requiring that one of the $W$ bosons decay hadronically while the other leptonically. This channel is called the single lepton channel (also lepton+jets or semi-leptonic channel) and provides a good balance between clean signature and high branching ratio. This channel is characterized by one charged lepton, one neutrino, and four quarks in the final state: $pp \to TT\bar{T} \to WqWq \to l\nuqqq$. The charged lepton (either an electron or a muon) produces a clean signature in the detector, the quarks are reconstructed as jets, and the missing transverse momentum in the event is attributed to the neutrino. Thus, our final state is an electron or muon, large missing transverse
momentum, and four or more jets.

Figure 5.2 Pair Production of $T$ quark and its subsequent decay into a $W$ boson and a light quark, $q$. In this analysis only those events are considered in which one of the $W$ bosons subsequently decays into two light quarks while the other $W$ boson decays into a charged lepton and a neutrino.

5.5 Background Processes

The SM background process that has the same final state as our signal is $t\bar{t}$. As shown in Fig. 5.3, $t\bar{t}$ has the same tree-level diagram as $T\bar{T}$. However, there is a very important difference between the two. Top quarks decay to a $W$ boson and a $b$ quark with almost 100% branching ratio. In the model we are testing, $T$ quarks decay to a $W$ boson and a light quark with 100% branching ratio. As explained in chapter 4, exploiting the long life and consequent longer decay length of $b$-quark hadron, we are able to distinguish between a $b$-jet and a light jet. Requiring a 0 $b$ jet in the final state suppresses the $t\bar{t}$ background and instead leaves $W+$jets the main background.

The dominant background to $T\bar{T}$ production in the lepton+jets channel with the above-described final state signature is the production of a $W$ boson in association with additional jets. The additional jets can either originate from light quarks or a mis-identified $b$-quark.
Other small background contributions result from the production of a $Z$ boson in association with additional jets. Our final state has exactly one charged lepton while a charged lepton from $Z$ boson decay usually results in either two charged leptons (quarks) or two neutral leptons. $Z+$jets is thus a small background. For the $Z+$jets events to pass one and only one charged lepton requirement, one of the charged leptons from the $Z$ decay has to be either lost or mis-identified as a jet. For example, in an event with $Z+4$ jets, the $Z$ can decay to an electron and a positron. However, we may lose the electron due to detector acceptance. This event then will have one charged lepton (the positron), missing transverse energy from the lost charged lepton, and 4 jets and hence pass the selection. The probability for a high $p_T$ lepton to be lost is very small, so $Z+$jets is one of our smaller backgrounds. Similar final state signatures may be produced by diboson or QCD multi-jet production. Feynman diagram for the $W$ boson produced with associated jets is shown in Fig. 5.4. Table 6.4 shows the expected number of
signal and background events at “pre-selection,” which will be described in the next chapter.

![Diagram](image)

(a) $W$+jets background

Figure 5.4 Production of $W$ boson in association with two jets.

### 5.6 Modeling of Signal and Background Processes

All of the signal and background processes are simulated using Monte Carlo event generators except the QCD multi-jet background. Such events were then passed through a GEANT4 simulation which simulates the particles’ interaction with the ATLAS detector. The same reconstruction methods for the physics objects are applied to data and simulated events and both are fed through the identical analysis chain.

### 5.7 Signal Samples

The signal samples are generated with PYTHIA8 [43] using the MSTW 2008 LO PDF set [44] for a range of masses, $m_T$, from 350 GeV to 900 GeV in steps of 50 GeV. All the samples were produced using fast simulation (ATLFAST2) except three mass points - 500 GeV, 800 GeV, and 900 GeV - which were produced using full simulation. Only the charged current decays of $T$ quarks via a $W$ boson are considered in this analysis. There is an ongoing effort by other groups in the ATLAS collaboration to study the neutral current decays via a $Z$ or Higgs boson. The signal events are generated by imposing branching fractions of $BF(T \rightarrow Wd) =$
\( BF(T \rightarrow Ws) = 0.25 \) and \( BF(T \rightarrow Wb) = 0.5 \). However, during the analysis, we filter out only the \( W_qW_q \) events, where \( q = d, \) or \( s \) quark based on truth information. We then weight these events to obtain the necessary branching fraction of 100\% for \( T \rightarrow Wq \). In order to maximize the number of MC signal events available for analysis, a single charged lepton filter at the truth level was used. This filter required the presence of at least one stable electron or muon with \( p_T > 10 \) GeV and \( |\eta| < 2.7 \) for each event. The production cross section of and theoretical uncertainties on the signals are described in Chapter 2.

### 5.8 Background Samples

The SM backgrounds in this analysis are estimated primarily with simulated with Monte Carlo (MC) methods using the same reconstruction and analysis chain as for collision data. Total cross sections of the MC samples are normalized to next-to-leading order (NLO) or higher calculations. The main SM backgrounds to the \( T\bar{T} \) signal are the production of a \( W \) boson in association with jets (\( W+\text{jets} \)) and \( t\bar{t} \) production. \( Z+\text{jets}, \) single top quark, diboson (\( WW, ZZ, WZ \)), and multi-jet production contribute to a lesser extent.

Simulated samples of \( t\bar{t} \) are generated using PowHeg+Pythia. The Powheg Matrix Element events are generated with CT10 (NLO) PDF [45] and the parton shower and hadronization is done with the P2011C tune. This tune uses the CTEQ6L1 (LO) PDF [46].

Single top background events (in the \( s \)-channel) are generated with MC@NLO v4.01 [[47], [48], [49]] using the CT10 set of PDFs [45]. For single-top production in the \( t \)-channel, ACERMC v3.8 leading-order (LO) generator [50] is used with the MRST LO** PDF set [51]. These samples were generated assuming a top quark mass of 172.5 GeV and are normalized to approximate NNLO theoretical cross sections [52]. The parton showering and fragmentation steps are performed by HERWIG v6.520 [53] in the case of MC@NLO and ALPGEN, and by PYTHIA 6.421 in the case of ACERMC. The total uncertainty results from the sum in quadrature of the scale and PDF+\( \alpha_s \) uncertainties according to the MSTW prescription [54].

Samples of \( W/Z+\text{jets} \) are generated with up to five additional partons using the ALPGEN v2.13 [55] LO generator and the CTEQ6L1 PDF set [46]. This is then interfaced to PYTHIA [43] for the parton showering and hadronization steps. The \( W+\text{jets} \) samples are gen-
generated separately for $W+$light jets, $Wb\bar{b}+$jets, $Wc\bar{c}+$jets, and $Wc+$jets. Heavy flavor quarks in the $W/Z+$jets sample can arise from a parton shower, while in the $W/Z + bb$, or $W/Z + cc$ samples can be produced directly from the matrix element.

When combining multiple Alpgen samples together, it is therefore necessary to veto certain classes of events in each of the samples to avoid double-counting. In case of $b$-quark production this double-counting can largely be avoided by choosing the $b\bar{b}$ phase space cuts identical to the MLM matching [56]. However, in case of $c$-quark jets the overlap will be even larger since the $W+Np$ samples contain massless charm quarks in the matrix element. Since the matrix element calculation gives the best results at large angles between quarks, while parton shower modeling is more accurate for collinear effects, the events are classified based on the distance between the jets, $R$. Events are removed from the $W+$light flavor sample if there are pairs of heavy flavor quarks with $R > 0.4$ added from the parton shower. Events from the $Wc+$jets samples are discarded, if the parton shower produces a heavy quark pair with $R > 0.4$ and $Wc\bar{c}+$jets are vetoed against if either the $c\bar{c}$ pair in the matrix element is simulated with $R < 0.4$ or if the parton shower adds a $b\bar{b}$ pair with $R > 0.4$. Finally, events are removed from the $Wb\bar{b}+$jets samples if the $b\bar{b}$ pair created in the matrix element fulfills $R < 0.4$. In order to produce the corresponding samples the HFOR Tool has been developed\(^1\), which we use to normalize the different $W+$heavy flavor samples.

The $Z+$jets samples are generated separately for $Z+$light jets, $Zb\bar{b}+$jets, and $Zc\bar{c}+$jets. The $Z+$jets background is normalized to the inclusive NNLO theoretical cross section [57].

After the final selection, $W+$jets is the dominant background. Therefore, a separate generator, SHERPA, was also employed to study this background. The SHERPA $W+$jets samples are produced using v1.4.1 with the CT10 [55] PDF set. These samples are divided into non-overlapping BFFilter, CFFilterBVeto, and CVetoBVeto samples, where the BFFilter requires any bottom hadron within $|\eta| < 4$ and CFFilter requires any charm hadron within $|\eta| < 3$ and jet $p_T > 15$ GeV. In addition to the dedicated flavor-filtered samples, the leading order SHERPA samples are further divided into intervals in $p_T(Z)$: inclusive, 70-140 GeV, 140-280 GeV, 280-500 GeV, and $> 500$ GeV. The samples in the first 3 slices are prepared with a fast detector

\(^1\)https://twiki.cern.ch/twiki/bin/view/AtlasProtected/HforTool
simulation while the remaining samples use the full detector simulation.

We will use ALPGEN prediction in this thesis for the Loose selection, described in 8.4.1. After the Tight selection described in 8.4, however, the statistical uncertainty in these samples are much larger than in the SHERPA samples. Therefore, there are ongoing efforts to use the SHERPA samples after the Tight selection. The expected sensitivity with the SHERPA samples will be described in Chapter 9.

The diboson samples are modeled using HERWIG with the CTEQ6L1 PDF set and is normalized to the NLO theoretical cross section [58].

The multi-jet contribution to the selected sample comes from the misidentification of a jet or a photon as an electron or the presence of a non-prompt lepton that passes the isolation requirement, e.g. from a semileptonic b or c hadron decay. QCD multi jet background events can pass the selection if a “fake” lepton and large $E_T^{\text{miss}}$ is present. Although the probability is fairly low for both these requirements to be satisfied, this is a significant background primarily because this analysis doesn’t require a heavy quark in the final state. Modeling this background would require a very large statistics and hence would be computationally intensive. Therefore, the corresponding yield is estimated via data-driven matrix methods [59].

The matrix method exploits differences in lepton identification-related properties between prompt, isolated leptons from W and Z boson decays (referred to as real leptons below) and those where the leptons are either non-isolated or result from the mis-identification of photons or jets. To this end, two samples are defined which differ only in the lepton identification criteria: a “tight” sample and a “loose” sample, the former being a subset of the latter. The tight selection employs the final lepton identification criteria used in the analysis. For the loose selection the lepton isolation requirements are omitted. The method assumes that the number of selected events in each sample ($N_{\text{Loose}}$ and $N_{\text{Tight}}$) can be expressed as a linear combination of the numbers of events with real and fake leptons, in such a way that the following system of equations holds:

\[
N_{\text{Loose}} = N_{\text{real}} + N_{\text{fake}} \\
N_{\text{Tight}} = \epsilon_{\text{real}} N_{\text{real}} + \epsilon_{\text{fake}} N_{\text{fake}}
\]
where $\epsilon_{\text{real}}$ ($\epsilon_{\text{fake}}$) represents the probability for a real (fake) lepton that satisfies the loose criteria to also satisfy the tight ones, and both are measured in data control samples. To measure $\epsilon_{\text{real}}$ samples enriched in real leptons from $W$ bosons decay are selected by requiring high $E_T^{\text{miss}}$. The average $\epsilon_{\text{real}}$ is approximately 0.75 (0.98) in the electron (muon) channel. To measure $\epsilon_{\text{fake}}$ samples enriched in multi-jet background are selected by requiring low $E_T^{\text{miss}}$ (electron channel) or high impact parameter significance for the lepton track (muon channel). The average $\epsilon_{\text{fake}}$ is approximately 0.35 (0.20) in the electron (muon) channel. Once $\epsilon_{\text{fake}}$ and $\epsilon_{\text{real}}$ are measured, the number of fake leptons passing the tight selection can be determined and translated into weights for loose muons to also be identified as tight muons.

Table 5.2 lists the background processes along with their theoretical cross sections and the MC generators used to produce the samples.
Table 5.2 Cross sections and dataset numbers for the main SM background samples at $\sqrt{s} = 8$ TeV. In this table, $\ell$ refers to the three lepton families $e$, $\mu$, and $\tau$. All background cross sections are normalized to the NNLO predictions, except for diboson event production where the NLO prediction is used.

<table>
<thead>
<tr>
<th>Process</th>
<th>Generator &amp; parton shower</th>
<th>Dataset number(s)</th>
<th>Cross section (in pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ with at least one lepton $\ell$</td>
<td>Powheg &amp; Pythia</td>
<td>117050</td>
<td>137.2</td>
</tr>
<tr>
<td>Single top $t$-channel (with $\ell$)</td>
<td>AcerMC &amp; Pythia</td>
<td>110101</td>
<td>28.4</td>
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<tr>
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<td>MC@NLO</td>
<td>108343-45</td>
<td>1.8</td>
</tr>
<tr>
<td>Single top $Wt$-channel</td>
<td></td>
<td>108346</td>
<td>22.4</td>
</tr>
<tr>
<td>$W(\ell\nu) +$ jets</td>
<td>Alpgen &amp; Pythia</td>
<td>147025–30 (ee)</td>
<td>$3.6 \times 10^4$</td>
</tr>
<tr>
<td>$Wb\bar{b} +$ jets</td>
<td></td>
<td>147033–38 (\mu\nu)</td>
<td></td>
</tr>
<tr>
<td>$Wc\bar{c} +$ jets</td>
<td></td>
<td>147041–46 (\tau\nu)</td>
<td></td>
</tr>
<tr>
<td>$Wc +$ jets</td>
<td></td>
<td>110801–4</td>
<td>159.1</td>
</tr>
<tr>
<td>$Z/\gamma^* (\ell\ell) +$ jets, $m(\ell\ell) &gt; 60$ GeV</td>
<td>Alpgen &amp; Pythia</td>
<td>147105–10 (ee)</td>
<td>$2.9 \times 10^3$</td>
</tr>
<tr>
<td>$Z/\gamma^* (\ell\ell)$ b\bar{b} + jets, $m(\ell\ell) &gt; 30$ GeV</td>
<td></td>
<td>147113–18 (\mu\mu)</td>
<td></td>
</tr>
<tr>
<td>$Z/\gamma^* (\ell\ell)$ c\bar{c} + jets, $m(\ell\ell) &gt; 30$ GeV</td>
<td></td>
<td>147121–26 (\tau\tau)</td>
<td></td>
</tr>
<tr>
<td>$WW$</td>
<td>Herwig</td>
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<td>20.9</td>
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<tr>
<td>$ZZ$</td>
<td></td>
<td>105986</td>
<td>1.5</td>
</tr>
<tr>
<td>$WZ$</td>
<td></td>
<td>105987</td>
<td>7.0</td>
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CHAPTER 6. Event Pre-selection

6.1 Introduction

This chapter introduces the event selection for this analysis. The preliminary selection includes event level and global cuts common to all top-quark and top-like quark analyses. Motivation for each further selection cut will be explained. The gain in signal efficiency versus background rejection will be presented in subsequent chapters.

6.2 Good Runs Lists

Since the decay of a heavy quark pair gives rise to various particles that get reconstructed in all parts of the detector, only those data events can be considered for final analyses for which the full detector was functioning. Therefore, Good Runs Lists (GRLs) are used to define a set of data-taking runs and luminosity blocks for which the data was found to be of good enough quality for further analysis. A luminosity block is the unit of time for data-taking, and lasts about two minutes. A good run list is formed by applying data quality criteria to the list of all valid physics runs and luminosity blocks. Each physics group working group decides on a good run list configuration appropriate for its analysis. The GRLs for the presented analysis are globally defined for all top quark analyses within the ATLAS top quark working group.

6.3 Pileup Reweighting

In a high-luminosity collider such as the LHC, there is a non-negligible probability that one single bunch crossing may produce several separate events called pile-up events. While the Monte Carlo simulated events are generated assuming fixed beam conditions, the conditions vary during data-taking, resulting in a different amount of soft interactions coinciding with the
hard interaction. This results in different amount of pileup events in Monte Carlo compared to data. Therefore, the simulated events are re-weighted to account for different levels of pile-up. The re-weighting is based on the number of primary vertices in the event and is applied according to the conditions in the different run periods.

6.4 Pre-selection

Events in the data and the simulated samples are selected for the top quark and top-like quark analyses accounting for the basic topology of top quark events and are preselected by a single lepton trigger, which is described in Chapter 4. In order to ensure good data quality, similarity of the event to the signal of interest, and to pre-filter the dominant backgrounds, this analysis applies a set of selection cuts called “pre-selection”. For this analysis, pre-selection is defined by the following requirements:

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

- a single high-$p_T$ lepton trigger: In the lepton+jets channel considered in this analysis, a charged lepton originates from the decay of one of the $W$ bosons. Since charged leptons generally leave a very clean signature in the detector, we require that the event be triggered by a single high-$p_T$ lepton.

- exactly one lepton: Exactly one “good” muon (electron) is required in the event. A good muon (electron) is defined in Chapter 4.

- trigger matching: The selected charged lepton is required to be within a cone of $\Delta R = 0.15$ around the direction of the lepton reconstructed by the high level trigger.

- Second lepton veto: Event with second lepton is vetoed to ensure we are only studying single lepton channel.

- Overlap removal: Remove $e$ or $\mu$ within $\Delta R < 0.4$ of an accepted jet.
\( E_T^{\text{miss}} > 20 \text{ GeV} \) and \((E_T^{\text{miss}} + M_{T_W}^2) > 60 \text{ GeV}\): Optimized to suppress QCD multi-jet background. Here \( M_{T_W}^2 \) is the transverse mass of the W boson.

- At least 4 jets: At least 4 “good” jets are required corresponding to the final state of pair produced heavy quark decay in the lepton+jets channel. “Good” jets are defined in Chapter 4.

Detailed yields at pre-selection for the signal and background processes in both muon and electron channels can be found in Table 6.4. The number of observed data events is also shown, and is in good agreement with the total number of predicted events. We don’t expect any sensitivity at all on the heavy quark production at this stage since the highest expected signal yield in the electron (muon) channel is approximately 5000 (5500) events while the total background expectation is of approximately 94,000 (142,000) events.

In addition to these requirements, event kinematic information is used to select a signal enriched sample. The goal of the analysis is the best measurement - the smallest error or the best limits. It is typically achieved by reducing the background and keeping the signal. How to best keep the signal of interest while rejecting as much background as possible is an optimization problem. We refer to the optimization problem as “analysis strategy”.

### 6.5 Analysis Strategies After Pre-selection

There are two final states possible after pre-selection. We can require that all the selected jets be non-\( b \) jets to study the final state corresponding to the decay of the \( T \) quark into a \( W \) boson and a light quark only, or we can require that there be at least one \( b \)-jet to study the decay of the \( T \) quark into a \( W \) boson and a \( b \)-quark. In this thesis, we will consider both final states. I have studied both final states - the former by employing an analysis strategy that exploits the boosted properties of final state objects and the latter by using a kinematic fitting technique.

To illustrate the principle of kinematic fitting, which is a sophisticated but well-established technique for doing analysis in high energy physics, we will consider the topology with at least one \( b \) jet. I developed a kinematic fitting package, which is now available for public as a physics
### Event Yields at Pre-selection

<table>
<thead>
<tr>
<th>Background Processes</th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$+jets</td>
<td>$87,000 \pm 28,000$</td>
<td>$133,000 \pm 42,000$</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>$35,000 \pm 14000$</td>
<td>$17,900 \pm 7500$</td>
</tr>
<tr>
<td>$tt$</td>
<td>$25,900 \pm 2600$</td>
<td>$31,700 \pm 3200$</td>
</tr>
<tr>
<td>QCD multi-jet</td>
<td>$17,700 \pm 94$</td>
<td>$8670 \pm 90$</td>
</tr>
<tr>
<td>Single top</td>
<td>$3540 \pm 270$</td>
<td>$3430 \pm 270$</td>
</tr>
<tr>
<td>Dibosons</td>
<td>$1520 \pm 730$</td>
<td>$1720 \pm 830$</td>
</tr>
<tr>
<td><strong>Sum Backgrounds</strong></td>
<td><strong>$171,000 \pm 27,000$</strong></td>
<td><strong>$197,000 \pm 34,980$</strong></td>
</tr>
</tbody>
</table>

| Data                | 181242            | 205792        |

<table>
<thead>
<tr>
<th>Signal Sample</th>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_T = 350$ GeV</td>
<td>$5099 \pm 460$</td>
<td>$5560\pm500$</td>
</tr>
<tr>
<td>$m_T = 400$ GeV</td>
<td>$2557 \pm 250$</td>
<td>$2720\pm260$</td>
</tr>
<tr>
<td>$m_T = 450$ GeV</td>
<td>$1257 \pm 130$</td>
<td>$1280\pm130$</td>
</tr>
<tr>
<td>$m_T = 500$ GeV</td>
<td>$652.5 \pm 72$</td>
<td>$696.2\pm77$</td>
</tr>
<tr>
<td>$m_T = 550$ GeV</td>
<td>$370.4 \pm 43$</td>
<td>$362.5\pm42$</td>
</tr>
<tr>
<td>$m_T = 600$ GeV</td>
<td>$210.0 \pm 25$</td>
<td>$201.1\pm24$</td>
</tr>
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<td>$m_T = 650$ GeV</td>
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<td>$121.8\pm15$</td>
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<td>$m_T = 700$ GeV</td>
<td>$75.21 \pm 9.4$</td>
<td>$71.2\pm8.9$</td>
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<td>$m_T = 750$ GeV</td>
<td>$44.05 \pm 5.6$</td>
<td>$42.0\pm5.3$</td>
</tr>
<tr>
<td>$m_T = 800$ GeV</td>
<td>$26.35 \pm 3.3$</td>
<td>$25.4\pm3.2$</td>
</tr>
<tr>
<td>$m_T = 900$ GeV</td>
<td>$10.36 \pm 1.4$</td>
<td>$10.10\pm1.4$</td>
</tr>
</tbody>
</table>

Table 6.1  Event yields after pre-selection of events for various background and signal processes. The uncertainties include statistical and systematic uncertainties described in Chapter 9.
analysis tool in the ATLAS collaboration. For this study, I use 7 TeV data and simulated samples. This technique will be explained and its performance will be evaluated in Chapter 7.

The analysis on the 8 TeV data will be performed in the 0 $b$ jet final state. We found that the kinematic fitting I developed isn’t as powerful in this final state as in the final state with one or more $b$ jets. Therefore, we will employ a boosted analysis strategy, which is gaining much popularity in LHC new physics search because of the higher center-of-mass energy available compared to previous colliders. We will describe this strategy in chapter 8.
CHAPTER 7. Kinematic Fitting

7.1 Introduction

In several beyond the SM theories, the new heavy quarks such as $T$ are only allowed to mix with the third generation quarks. For example, a $T$ quark is only allowed to decay into a boson and a $b$-quark, and a $B$ quark is only allowed to decay into a boson and a top quark. In such models, then, in the semi-leptonic channel, the final state consists of 2 $b$-quarks (from 2 $T$ quarks), 2 light quarks (from one of the $W$ bosons) and 1 charged lepton and one neutrino (from the second $W$ boson). This is the same final state as $t\bar{t}$ in the lepton+jets channel. The main difference from the $t\bar{t}$ in the lepton+jets is the reconstructed mass of the top or $T$ quark. Whereas top quark has a mass of about 170 GeV, the $T$ quark is substantially heavier. This means that the reconstructed mass of the quark is a very powerful discriminating variable.

To improve the mass resolution of the top quark, I developed my own kinematic fitter, called ISUFitter. When validated, this fitter could also benefit a range of $t\bar{t}$ measurements which study essentially the same decay chain. This fitter was developed using 7 TeV data collected in 2011 in anticipation of 8 TeV data to be collected in 2012. For a number of reasons, it was agreed within the subgroups of the ATLAS collaboration to adopt a different technique for 2012 data analysis. Hence, the main objective of this chapter will be to illustrate the principle of kinematic fitting and to evaluate the performance of ISUFitter.

7.2 Kinematic Fitting of $t\bar{t}$ Semi-leptonic Decay

Kinematic fitting is a well established technique for improving the reconstructed event kinematics. By assuming a certain decay topology, we can over-constrain a system and hence improve the measurement.
Experiments in high energy physics generate data with various physical quantities measured by the detectors. These quantities such as $p_T$, $\eta$, $\phi$ vary on event-by-event basis and can be measured only within the resolution of the detector. Traditionally, these quantities are taken as measured at the detector level. One of the objectives of kinematic fitting is to improve the measured quantities by allowing them to float within their detector resolutions and finding the best fit value of the quantity for the assumed topology. In the case of semi-leptonic $t\bar{t}$ decay, the measured quantities don’t provide the information as to which jet originated at which quark. Consequently, another benefit of kinematic fitting is to use physical constraints and statistical tools to find the correct assignment between the detector level jets and the quarks they come from.

The kinematic fitter is based on likelihood approach. The likelihood is defined as a probability of observing a measured quantity given a hypothesis and its parameters. For semi-leptonic $t\bar{t}$ decay the final state objects are 1 charged lepton, 4 jets and $E_T^{\text{miss}}$. For a typical event we expect 4 or more jets. The discussion on whether to consider the 4 leading jets in $p_T$ or all the available jets can be found in Section 7.8. The measured quantities are:

- $p_T$, $\eta$, $\phi$ of jets, charged lepton
- $X$ and $Y$ component of $E_T^{\text{miss}}$

The directions of all objects ($\eta, \phi$) are assumed to be measured precisely because the resolutions are so tiny that the fitter has no chance of improving them and also because every additional fitted parameter decreases the stability and reliability of the fitter. $p_T$ is known only within the uncertainty given by the detector resolution. The transverse component of neutrino is inferred from the missing transverse energy in the detector since neutrinos don’t interact with the detector. Because $E_T^{\text{miss}}$ is correlated to other parameters we fit for, we have instead used the resolution of “unclustered energy”. We define unclustered energy as the energy clusters in the detector which do not get reconstructed as one of the final state objects. It is equal to the negative sum of $p_T$ of all the measured objects plus $E_T^{\text{miss}}$. These resolutions are described by analytical functions which give the likelihood of observing energy $X$ of detector level objects given the energy $Y$ of final state objects from the hard scattering. Details on the calculation...
of the resolution functions can be found in Section 7.7.

The calculation of the likelihood is based on the following assumptions:

1. the resolution functions of all quarks and charged lepton $p_T$ are known;
2. the resolution function of the unclustered energy is known;
3. the mass of the $W$ boson is taken as its pole mass, $M_W = 80.4$ GeV;
4. the mass of the top quark is taken as its pole mass of 172.5 GeV.

The parameters used in the fitting procedure are $p_T$ of the 4 jets and one charged lepton, $P_x$, $P_y$, and $P_z$ of neutrino. The top mass is either an additional free parameter or constrained to the top mass used in the generation of the Monte Carlo events. The parameter ranges are taken to be that of the detector limit. Because we don’t know a priori the correspondence between jets and quarks, all the possible permutations are taken into account. Given that 2 lights jets from W decay are interchangeable, there remain only 12 permutations if we consider only the 4 leading jets in the event. For each permutation we minimize the natural log of the likelihood function defined as:

$$
\log L = - \sum_{i=\ell,jets} R_i(P_T^{rec}, P_T^{fit}) - \sum_{j=x,y} R_j(P_T^{\nu,rec}, P_T^{\nu,fit}) - \frac{(m_{jj} - m_W)^2}{\Gamma_W^2} - \frac{(m_{b\nu} - m_W)^2}{\Gamma_W^2} - \frac{(m_{bjj} - m_{reco})^2}{\Gamma_t^2} - \frac{(m_{b\nu} - m_{reco})^2}{\Gamma_t^2}
$$

The invariant mass of the $W$ boson decay products ($m_{jj}$ and $m_{\ell\nu}$) are constrained to the mass of the $W$ boson. The top and anti-top masses ($m_{reco}$) are required to be the same and can be fixed to a certain value. The transverse component of the neutrino is constrained from the missing energy in the event, while the longitudinal component is calculated using the $W$ boson mass constraint. All measured quantities are allowed to float within their resolutions, $R$, in the fitter. The resolution functions for the angular parameters are available in the fitter package, but we fix these parameters to their measured values. Doing so reduces the number of parameters by 10, and increases the speed of minimization by 2 orders of magnitude. The minimization is performed using the Migrad algorithm of the Minuit package. The initial values
of the parameters are the measured values. For the z-component of neutrino, the initial value is given as 0. Of the two solutions for the z-component of neutrino, the one that minimizes the \(-\log L\) is kept. The fitter returns the best fitted parameters, the minimum \(\log L\) values for each permutation, and optionally the fitted top mass parameter. Fig. 7.1 shows various permutations for the jet-quark assignment and the corresponding \(\log L\) value. The lowest \(\log L\) value corresponds to permutation 5, which is kept as the best permutation by ISUFitter.

![Log likelihood vs mass](image)

Figure 7.1: \(\log L\) for various permutations in a single \(t\bar{t}\) event.

### 7.3 Log Likelihood Ratio Discriminant

Conventionally, analyses have used the fitted mass to discriminate the signal \(T\) quark from top quark, but there is more information that the fitter can provide. It can assign a likelihood \(L(m)\) to each mass, which we are using to define a new log-likelihood-ratio discriminant: \(\text{LLR} = \log L(m1) - \log L(m2)\). There are a couple of natural choices for \(m1\) and \(m2\), they can be the mass of the top quark or the assumed mass of the \(T\) quark or the best fitted mass. The advantage of \(\text{LLR}\) over \(m_{\text{reco}}\) is twofold:

- Due to its kinematics and topology each event has a different intrinsic mass resolution and \(L(m)\) represents our best knowledge of it. \(\text{LLR}\) automatically populates the signal
region with events that have a mass close to the $T$ quark and also have a good mass resolution.

- There is an ambiguity in how the four jets get mapped to the four quarks in the final state. Instead of only using the best match, LLR uses all permutations and populates the signal region with events that have a permutation that resembles a $T$ quark and that have no permutation that resembles a top.

For the LLR discriminant, the fitter is called twice once with top mass as a floating parameter and again with top mass fixed at a given value.

### 7.4 Monte Carlo Samples

The Monte Carlo samples used to develop the kinematic fitter and to evaluate its performance assume a center-of-mass energy of 7 TeV. However, the definition of reconstructed physics objects are very similar to those described in Chapter 4.

Monte Carlo samples of $t\bar{t}$ are generated using MC@NLO v3.41, assuming a top quark mass of 172.5 GeV, using the CTEQ6.6 set of parton distribution functions (PDF), and are normalized to the approximate next-to-next-to-leading-order (NNLO) theoretical cross sections. MC@NLO is interfaced to Herwig v6.5 to model the parton shower and fragmentation, while it is interfaced to Jimmy is used to simulate the underlying event. $T\bar{T}$ is modeled using Pythia 6.421 and are generated for a range of masses, $m_T$, from 350 to 600 GeV in steps of 50 GeV and are normalized to the approximate NNLO theoretical cross sections using the CTEQ6.6 PDF. The samples generated using Pythia use the MRST2007 LO* PDF set. All MC samples include multiple pp interactions and are processed through a full simulation of the detector geometry and response using Geant4. Simulated events are corrected to match the object identification efficiencies.

### 7.5 Object Definition and Event Selection

The object definitions used for this study are very similar to the objects defined in Chapter 4 with minor variation to account for the difference in center-of-mass energy. For example,
isolation requirement on the electron and the muon, described in Chapter 4, are required in 8 TeV data but this requirement had not been defined in 7 TeV data. This minor variation is negligible for the purpose of this study. The event selection in muon and electron channels for the two samples are the same as presented in Chapter 6.

7.6 Truth Matching of Objects

To compute the resolutions of the detector level objects, we need to ensure that the object has a corresponding matching parton level object. Therefore, when computing resolutions only those objects are kept which satisfy the geometric matching in the $\eta - \phi$ space to the partons. The distance in the $\eta - \phi$ space between a detector level object and a parton is defined as

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

Here $\Delta \eta$ and $\Delta \phi$ are the difference in $\eta$ and $\phi$ between the two selected objects. If this distance $\Delta R$ is less than 0.2, then the criterion is matched, and the resolution is computed between these two objects. It is also checked that the two quarks don’t get assigned to the same jet when making resolution.

7.7 Derivation of Resolution Functions

Each physical quantity that we measure has a detector resolution associated to it. Such resolutions can be modeled by analytical functions. We can then essentially vary the momenta of the observed particles within their resolutions to make the masses of intermediate particles agree with the masses of the assumed resonances (on shell particles). For $t\bar{t}$ it also has the added benefits of allowing to pick the best assignment of jets to quarks and constraining the neutrino $p_T$, which is not directly measured. The resolution functions are determined from Monte Carlo samples described above.

The resolution functions for the $p_T$ of the objects were found to be dependent on the type of objects, their $p_T$, and the $\eta$ region of the detector. The objects we distinguish are electron, muon, light jets, b-tagged jets, and $E_T^{\text{miss}}$. The $\eta$ regions considered are motivated by detector geometry:
(1) $|\eta| < 0.80$
(2) $0.80 < |\eta| < 1.37$
(3) $1.37 < |\eta| < 1.52$
(4) $1.52 < |\eta| < 2.50$

Resolution functions were calculated as functions of $p_T$ and $\eta$ for the jets. For charged leptons and unclustered, they have also been calculated by binning in $\eta$ and $\text{Sum}E_T$ respectively, but the results shown use the unbinned resolutions. Here $\text{Sum}E_T$ is defined as the total scalar sum of transverse energies of all the final state objects. Fits to the resolutions are derived from binned $\chi^2$ fit. Most of the fitted functions are double Gaussians, but a few are also single or triple Gaussians.

One essential feature of ISUFitter is that it takes the entire single or double Gaussian as its resolution. The main idea here is to fit a function to resolution that describes the peak as well as the tail. One significant difference in doing so compared to fitting around the peak is that the latter will do well for well-reconstructed events but may not do just as good for not so well-reconstructed events. If one knows where the peak sits and cares only about reconstructing a $T$ quark mass peak, then by definition one is mostly using events in the peak. There will be some events in the tail, but most of them are removed by the $\chi^2$ cut. One can still gain by having proper tails, but not as much.

However, we want to use the kinematic fitter and subsequently the LLR discriminant to distinguish between top and $T$ quarks, so just knowing the mass is only doing half the job. What we really want to know is whether the $T$ quark candidate came from the tail of the top mass peak. For example, we apply a quality cut on the LLR between the fit with floating mass and the fit fixed to the top mass. For the events of interest we want a large LLR, i.e. they will sit in the tail of our distribution. That means we need to get that tail correct. Therefore, we use the entire double Gaussian as our resolution function. Example of resolutions, the corresponding fits and their parameters appear in Fig. 7.2 and 7.3. Appendix B contains the rest of the resolution functions.
7.8 Results

This section described how well we reconstruct $\bar{t}t$ or $T\bar{T}$ events in the semi-leptonic channel using ISUFitter. We will focus on the reconstructed top mass, efficiency of reconstructing $\bar{t}t$ events as measured by matching with parton level top quarks, and finally show how well the LLR discriminant performs in rejecting $\bar{t}t$ background in search for the new heavy quarks.
7.8.1 $t\bar{t}$ Reconstruction

Reconstructed top mass is one of the measures of how well the fitter performs. For $t\bar{t}$ we know the mass has a peak at PDG top mass with a given distribution. Moreover, $m_{\text{reco}}$ itself can be used to distinguish between $t\bar{t}$ events and $T\bar{T}$ events provided that $T$ quark has a mass much higher than top’s mass. The quality of the top mass reconstruction is an important performance measure for our fitter. Two things are to be looked for here: That it reproduces the input top mass accurately and that it produces a narrow peak, corresponding to a small resolution. The peaks of the distribution do correspond directly to the masses of the input samples. Fig. 7.4 below show the floating top mass parameter corresponding to the highest likelihood in the fitter.

![Distribution of $m_{\text{reco}}$ in 400 GeV $T\bar{T}$ signal and in $t\bar{t}$.](image1)

(Left): Distribution of $m_{\text{reco}}$ in 400 GeV $T\bar{T}$ signal and in $t\bar{t}$.

![Distribution of $m_{\text{reco}}$ in 500 GeV $T\bar{T}$ signal and in $t\bar{t}$.](image2)

(Right): Distribution of $m_{\text{reco}}$ in 500 GeV $T\bar{T}$ signal and in $t\bar{t}$.

7.8.2 $t\bar{t}$ Reconstruction Efficiency

In order to evaluate the performance of the fitter we define overall efficiency, $\epsilon$, which is the fraction of events in which the highest likelihood permutation given by the fitter corresponds to the truth-matched permutation. However, there are events for which one-to-one matching doesn’t exist between detector level objects and the original patrons due to acceptance and other cuts. Therefore, it is first necessary to calculate the fraction of events where such a correspondence exists. To that end, we first define matching efficiency, $\epsilon_{m}$, as the number
of events in which one-to-one correspondence exists between all the final state objects and the partons divided by the total number of events. The former is labeled matched events. Note that if such a matching doesn’t exist, then the fitter has no way of finding the correct permutation. Then we define reconstruction efficiency, $\epsilon_r$, as the number of events in which the best permutation corresponds to the truth-matched permutation divided by the total number of matched events. The overall efficiency, $\epsilon$, then is simply the product of $\epsilon_m$ and $\epsilon_r$. This assumes that the jets come from $t\bar{t}$ ($T\bar{T}$) decay only.

Table 7.1  Events with exactly 4 jets and all of them are permutated. See the main text for details.

<table>
<thead>
<tr>
<th>sample</th>
<th>total</th>
<th>n_jet = 4</th>
<th>Matched</th>
<th>$\epsilon_m$</th>
<th>Fitted</th>
<th>$\epsilon_r$</th>
<th>$\epsilon$</th>
<th>forward q</th>
<th>merged q</th>
<th>q_pt &lt; 25</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttbar</td>
<td>64129</td>
<td>22765</td>
<td>6360</td>
<td>0.28</td>
<td>2317</td>
<td>0.36</td>
<td>0.10</td>
<td>2537</td>
<td>3571</td>
<td>8945</td>
</tr>
<tr>
<td>u4_350</td>
<td>11414</td>
<td>3915</td>
<td>1546</td>
<td>0.39</td>
<td>1094</td>
<td>0.71</td>
<td>0.28</td>
<td>322</td>
<td>700</td>
<td>796</td>
</tr>
<tr>
<td>u4_400</td>
<td>11374</td>
<td>3771</td>
<td>1581</td>
<td>0.42</td>
<td>1072</td>
<td>0.68</td>
<td>0.28</td>
<td>298</td>
<td>727</td>
<td>604</td>
</tr>
<tr>
<td>u4_450</td>
<td>11020</td>
<td>3545</td>
<td>1468</td>
<td>0.41</td>
<td>1027</td>
<td>0.70</td>
<td>0.29</td>
<td>266</td>
<td>742</td>
<td>548</td>
</tr>
<tr>
<td>u4_500</td>
<td>10954</td>
<td>3624</td>
<td>1590</td>
<td>0.44</td>
<td>1104</td>
<td>0.69</td>
<td>0.30</td>
<td>230</td>
<td>877</td>
<td>477</td>
</tr>
<tr>
<td>u4_550</td>
<td>11115</td>
<td>3681</td>
<td>1554</td>
<td>0.42</td>
<td>1067</td>
<td>0.69</td>
<td>0.29</td>
<td>263</td>
<td>981</td>
<td>414</td>
</tr>
<tr>
<td>u4_600</td>
<td>11085</td>
<td>3656</td>
<td>1480</td>
<td>0.40</td>
<td>979</td>
<td>0.66</td>
<td>0.27</td>
<td>235</td>
<td>1129</td>
<td>373</td>
</tr>
</tbody>
</table>

Table 7.1 shows the efficiencies for $t\bar{t}$ and $T\bar{T}$ samples. The first column shows the sample used - $t\bar{t}$ and various $T\bar{T}$ at various masses ranging from 350 GeV to 600 GeV. The second column shows the total number of events in the given sample after pre-selection cuts applied (see Chapter 6). The third column shows the total number of events with given number of jets. The fourth column shows the number of matched events as explained above. The fifth, seventh, and eighth columns show the matching, reconstruction, and overall efficiencies respectively. The sixth column shows the number of events in which the highest likelihood corresponds to the truth-matched event. The last 3 columns account for events which directly affect our matching efficiency since in any of these cases we don’t have a one-to-one matching. The 9th column
shows the number of events where one of the quarks has $|\eta| > 2.50$, beyond our acceptance. As expected, this decreases with the mass of top. The 10th column shows the number of events in which the two light quarks from one of the $W$ bosons get reconstructed as the same jet. Clearly, this increases with the mass of top as the $W$ from heavier top comes out more boosted. The last column shows the number of events in which one of the quarks fall below our $p_T$ acceptance of 25 GeV. Note: the reconstruction efficiency for $t\bar{t}$ goes up from 36 to 54 percent if the top mass is fixed to its PDG value of 172.5 GeV. This is useful for studying top quark’s properties other than its mass.

For events with 5 or more jets, there is a trade-off between matching efficiency and reconstruction efficiency depending on whether we permutate all the available jets or only the 4 leading jets in $p_T$. If all the available jets are considered for permutation, there is a greater chance of finding a match, and hence the matching efficiency increases as expected. It should be noted that as more jets are taken into account, the probability of matching with an incorrect jet also rises. However, since more jets are being permutated the chance of finding the correct permutation decreases. This can be seen in the events with 5 jets where either all 5 jets are permutated or only the 4 leading jets are permutated as shown in Tables 7.2 and 7.3.

![Table 7.2](image)
Table 7.3 Events with exactly 5 jets but only the leading four are permutated.

<table>
<thead>
<tr>
<th>sample</th>
<th>total</th>
<th>n_jet = 5</th>
<th>matched</th>
<th>$\varepsilon_{\text{m}}$</th>
<th>fitted</th>
<th>$\varepsilon$</th>
<th>$\epsilon$</th>
<th>forward q</th>
<th>merged q</th>
<th>$q_{pt} &lt; 25$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttbar</td>
<td>64129</td>
<td>10364</td>
<td>1335</td>
<td>0.13</td>
<td>500</td>
<td>0.37</td>
<td>0.05</td>
<td>741</td>
<td>938</td>
<td>3352</td>
</tr>
<tr>
<td>u4_350</td>
<td>11414</td>
<td>2936</td>
<td>742</td>
<td>0.25</td>
<td>545</td>
<td>0.73</td>
<td>0.19</td>
<td>196</td>
<td>325</td>
<td>471</td>
</tr>
<tr>
<td>u4_400</td>
<td>11374</td>
<td>2986</td>
<td>830</td>
<td>0.28</td>
<td>579</td>
<td>0.70</td>
<td>0.19</td>
<td>157</td>
<td>365</td>
<td>436</td>
</tr>
<tr>
<td>u4_450</td>
<td>11020</td>
<td>3033</td>
<td>878</td>
<td>0.29</td>
<td>604</td>
<td>0.69</td>
<td>0.20</td>
<td>186</td>
<td>407</td>
<td>352</td>
</tr>
<tr>
<td>u4_500</td>
<td>10954</td>
<td>2930</td>
<td>930</td>
<td>0.32</td>
<td>651</td>
<td>0.70</td>
<td>0.22</td>
<td>156</td>
<td>431</td>
<td>287</td>
</tr>
<tr>
<td>u4_550</td>
<td>11115</td>
<td>2951</td>
<td>874</td>
<td>0.30</td>
<td>608</td>
<td>0.70</td>
<td>0.21</td>
<td>177</td>
<td>523</td>
<td>299</td>
</tr>
<tr>
<td>u4_600</td>
<td>11085</td>
<td>2937</td>
<td>914</td>
<td>0.31</td>
<td>620</td>
<td>0.68</td>
<td>0.21</td>
<td>136</td>
<td>614</td>
<td>240</td>
</tr>
</tbody>
</table>

This trade-off further shows up in the reconstructed mass of the top quark as shown in Fig. 7.5. If all the available jets are permutated, then the resolution of reconstructed mass gets worse as opposed to the permutation of the only 4 leading jets. However, the discriminant under consideration, LLR, performs better at high background rejection region when all the available jets are permutated, Fig. 7.7. Currently, the fitter can be run with either all or only 4 leading jets.
Figure 7.5  Reconstructed $T$ quark mass for sample with generated mass 500 GeV. The more jets we consider for permutations, the worse the mass resolution gets.

### 7.8.3 Performance of LLR Discriminant

Since our LLR discriminant is meant as a replacement of the mass as the primary discriminant, the best test is to compare their relative performance. Fig. 7.6 shows the shape of the LLR distribution as well as the relative performance of the LLR and $m_{\text{reco}}$ in separating signal and background. It is immediately obvious that at high background rejection (where most of the sensitivity lies) our new discriminant does substantially better than the old mass based discriminant, and we hope that further work will improve on that. We have also studied the LLR by fixing the mass twice on the same event - once at top quark mass and again at generated mass for $T$ quark. The power curve shows this discriminant performs even better than the LLR with only one mass fixed.
Figure 7.6  (Left): Distribution of the log likelihood ratio for the $T\bar{T}$ signal and background from $t\bar{t}$.  (Right): Signal efficiency as a function of background rejection.

For events with more than 4 jets, LLR performs better if all the jets are considered for permutation, Fig. 7.7. However, we saw earlier that it degrades mass resolution. This trade-off needs to be further quantified and it is one of the improvements that ISUFitter can benefit from.

Figure 7.7  Signal efficiency as a function of background rejection for LLR in events with exactly 5 jets (left) and exactly 6 jets (right). At high background rejection, LLR seems to have better discriminating power if all the available jets are permuted instead of only 4 leading jets.
7.9 Outlook on Kinematic Fitting

The kinematic fitting package seems to reconstruct the $t\bar{t}$ events in the lepton+jets channel very well and also helps define a very powerful discriminant, the LLR. However, there are several significant improvements that it can benefit from.

I found that during the minimization of log likelihood, Minuit [60] can get stuck in a local minimum and never find the global minimum of the event. This would incorrectly reconstruct the event and consequently degrade mass resolution. This issue needs debugging.

Another improvement that can be implemented deals with events with more than four jets, which are very common. The main issue is that these have many more possible jet to quark assignments. Treating all of them equally yields worse results than using only the four highest energy jets. Since all jets not part of our final state must be from ISR, including an explicit ISR term for each unused jet in the fitter could benefit the fitter. This would also have the added benefit of letting those jets participate in our improved $E_T^{miss}$ resolution mechanism.

Another improvement is related to the boosted object. The basic idea is that for a heavy $T$ quark, the $W$ boson can be so boosted, that the two quarks it decays to end up in the same jet. Once a resolution function for these $W$ jets is determined, one could then go ahead and modify the fitter to take this particular event signature into account.

In 2012 data, our group was advised to study the 0 $b$-jet region. In this region, $W$+jets is the main background. While kinematic fitting and the LLR discriminants perform very well against $t\bar{t}$ background, we found that it doesn’t perform just as well against the $W$+jets background. There are also some issues and some improvements that the fitter can benefit from. However, given the time constraint for the searches with 8 TeV data, I switched to a different analysis technique, which will be described in the next chapter.
CHAPTER 8. Boosted Analysis

8.1 Introduction

In a search for new particles, the key is to isolate the signal from the background processes. In this analysis, we have to separate the heavy quark signal from the dominant backgrounds such as $W$+jets, $t\bar{t}$, and QCD multi-jet. This can be achieved by imposing selection cuts based on event kinematics and topology leading to a signal enriched sample with reduced backgrounds. Recent searches for new heavy quarks at the LHC [31, 61, 62, 63] have improved their strategy, taking into account the increased center-of-mass energy and high integrated luminosity. These analyses have focused on the region in which the $W$ (or $Z$) bosons stemming from the decay of the new heavy quarks have higher average transverse momentum compared to the backgrounds. In Refs. [64], [65], [66] and [67], it has been shown that the large boost that the $W$ or $Z$ bosons get from heavy quark decay can be exploited to separate signal from backgrounds.

8.2 Boosted Topology

8.2.1 Collimated Decay Products

When the transverse momentum $p_T$ of a particle becomes comparable to or higher than its mass, it is usually referred to as boosted and its decay products are collimated. That is, the higher the $p_T$ of the particle, the smaller the angle between its decay products. In Ref. [31], the mass of heavy quark candidates is reconstructed by assuming that the $W$ boson decay products (leptons) are nearly collinear in the lab frame. In Refs. [61, 62] and [63], $W$ boson candidates are reconstructed assuming that the $W$ boson decay products (jets) are close-by in $\Delta R$. The main advantages of such boosted topologies are a very high background rejection and a simplified combinatorics for the heavy quark mass reconstruction.
In the small angle approximation, the relation between the $W$ boson $p_T$ and the opening angle between its decay products is given as:

$$\Delta R = \frac{2 \times m_W}{p_W^T} \quad (8.1)$$

For our signal with mass $m_T = 400, 500, \text{ and } 600 \text{ GeV}$, the mean $p_T$ of the $W$ boson is 200, 240, and 290 GeV respectively. This implies that even from a relatively “lighter” heavy quark, the $W$ decay products are on average separated by an angular distance of $\Delta R \sim 0.8$.

This property is illustrated in Fig. 8.1 (Left), which shows, for the signal with $m_T = 600 \text{ GeV}$, the distribution of the truth-level $\Delta R$ between the 2 quarks coming from the decay of the $W$ boson. Fig. 8.1 (Right) shows the same distribution but as a function of $W$ boson $p_T$. The higher the $W$ boson $p_T$ is, the more collimated its decay products are. These distributions and all the following distributions in this section are derived from our Monte Carlo simulation in which we have followed the decay chain of all the partons resulting from the decay of the two heavy quarks.

Fig. 8.2 (Left) shows the same distribution as in Fig. 8.1 (Left), but for the lepton and the neutrino resulting from the decay of the $W$ boson. These distributions are almost identical, and show that the boost of the $W$ bosons can be exploited for both $T$ quark decays. For example, in $t\bar{t}$ events the mean $p_T$ of the $W$ boson is around 90 GeV, so the decay products are on average well separated.

We can classify three regions of the $W$ boson $p_T$ associated with distinct event topologies:

- “Non-boosted” topology: In the lowest-$p_T$ region, the separation angle between the $W$ boson decay products is not small, so the resulting jets from the hadronic $W$ boson cannot be easily distinguished from the other jets in the event. Consequently, reconstruction of the hadronic $W$ boson and the hadronic heavy quark becomes very challenging. Such topology suffers from substantial combinatorial background. We will not cover such topology in this analysis due to its relatively poor signal over background ratio compared to the following topologies. See kinematic fitting technique described in Chapter 7 which was developed to resolve such combinatorial problem.
Figure 8.1 Left: Distribution normalized to unit area of the true $\Delta R$ between the 2 quarks stemming from $W$ boson decay. Right: Distributions of the true $\Delta R$ between the 2 quarks stemming from the decay of the hadronic $W$ boson, as a function of the $W$ boson $p_T$ for the signal with $m_T = 600$ GeV.

- “Boosted-resolved” topology: In the intermediate-$p_T$ region, the $W$ boson decay products are relatively closer in $\Delta R$, which facilitates the identification of the hadronic $W$ boson. For example, di-jet combinations of close-by jets (e.g. within $\Delta R < 1.0$), can be studied to identify a di-jet system as a $W$ jet if its invariant mass lies around the $W$ mass. The heavy quark masses we are currently sensitive to fall in this region.

- “Boosted-unresolved” topology: In the highest-$p_T$ region, the decay products from the $W$ bosons are so collimated that they cannot be resolved as two jets using the jet algorithm and the definition of cone (anti-$k_T$ with $\Delta R = 0.4$), but are instead reconstructed as a single jet.

In practice, the distinction between these topologies depends on the cone size of the jet algorithm used. Ideally, one can include all three topologies using very large cone sizes, e.g. up to $\Delta R = 1.0$. Such large opening angles unfortunately contain many products of the pileup interactions or underlying-event, so additional filtering procedures have to be applied on such jet collections. Such procedures, together with the tagging algorithms that exploit the substructure properties of such highly-boosted jets, could have been applied for our search, but at the cost of large systematic uncertainty with little gain in signal over background.
The distribution of the true $\Delta R$ between the lepton and the neutrino stemming from the decay of the leptonic $W$ boson for the signal with $m_T = 600$ GeV is shown in the left panel of Fig. 8.2. The right panel shows the distribution of the true $\Delta R$ between the $W$ boson and its associated quark stemming from the decay of the heavy quark $T$ for the signal with $m_T = 600$ GeV.

Additionally, the most commonly used AntiKt4 jet collection in ATLAS, renders our signal events of interest a boosted-resolved topology. For a very high mass $m_T = 700$ GeV, $\sim 30\%$, $\sim 55\%$, and $\sim 15\%$ of the events falls in the non-boosted, boosted-resolved, and boosted-unresolved topologies respectively. For lower heavy quark masses, the fraction of boosted-unresolved events is always lower. For example, for a mass $m_T=500$ GeV, $\sim 7\%$, $\sim 48\%$, and $\sim 45\%$, of the events fall in the boosted-unresolved, boosted-resolved and non-boosted topologies respectively.

In this analysis, we will focus only on boosted-resolved topologies.

### 8.2.2 W boson and $q$-jet Separation

Another important property of the heavy $T$ quark decay is that the $W$ boson and its associated $q$-jet are more separated from each other than in the background processes. Fig. 8.2 shows the distribution normalized to unity of the truth-level $\Delta R$ between the $W$ bosons and their associated $q$-quark for the signal with $m_T = 600$ GeV. We will later exploit this property towards the end of our event selection to further suppress our background.
8.2.3 High $p_T$ Decay Products

Due to its high mass, the heavy $T$ quark decay products have higher transverse momenta compared to the ones from the top quark and other background processes. We will use a discriminating variable defined as the scalar $p_T$ sum of all objects in the final state. The variable is labeled $H_T$ and is given as:

$$H_T = E_{\text{miss}}^T + p_T^{\text{lepton}} + p_T^{W\text{-jet}} + p_T^{q\text{-jet} 1} + p_T^{q\text{-jet} 2}$$

Fig. 8.3 shows the $H_T$ distribution after requiring the presence of at least one hadronic $W$ boson as defined above. While the signal of interest ($m_T = 550$ GeV) peaks at around 1 TeV, the backgrounds peak much lower. Hence, requiring that $H_T > 1$ TeV gives a better signal over background.

![Figure 8.3](image)

Figure 8.3  Left: $H_T$ distribution after pre-selection in the electron channel. Right: $H_T$ distribution after pre-selection in the muon channel.

In order to reconstruct the $T$ quark 4-momentum, we must identify the $q$ quarks from the decay of the $T$ quark. In our studies, we found that at the truth level that the $q$ quarks are almost always two of the three highest-$p_T$ jets of the events, excluding the two jets that form the hadronic boosted $W$ boson candidates. This will be useful in the heavy quark mass reconstruction because this reduces the combinatorial problem in the assignment of the jets to
the \( q \) quarks. Fig. 8.4 shows the truth-level \( p_T \) of the highest-\( p_T \) and 2\(^{nd} \) highest \( p_T \) \( q \)-quarks.

![Distribution of the true \( p_T \) of the highest \( p_T \) \( q \)-quark](image1)

![Distribution of the true \( p_T \) of the 2\(^{nd} \) highest \( p_T \) \( q \)-quark](image2)

Figure 8.4  Left: Distribution normalized to unit are of the true \( p_T \) of the highest \( p_T \) \( q \)-quark stemming from the heavy quark pair-production for the signal with \( m_T = 600 \) GeV. Right: Distribution normalized to unity of the true \( p_T \) of the 2\(^{nd} \) highest \( p_T \) \( q \)-quark stemming from the heavy quark pair-production for the signal with \( m_T = 600 \) GeV.

### 8.2.4 Boson Tagging Improvements

The above selection criteria have been shown to be effective in enriching heavy quark signal in [61, 62, 63]. In these searches for heavy quarks coupling to a \( W \) or \( Z \) boson and a \( b \)-quark, the dominant background is \( t\bar{t} \) production. For such decay, the final state signature is exactly the same as the heavy quark decay signature, and the signal can be separated from this process almost only by exploiting kinematical differences between top and \( T \) quark decays.

In our search, we will require a \( b \)-tagging veto, \( W+\)jets production becomes the dominant background. \( W+\)jets production cross section is higher than \( t\bar{t} \) production cross-section by almost three orders of magnitude. In recent years, there has been much progress in the domain of boson tagging and jet-substructure studies with large-\( \Delta R \) jets. An important variable, the studies have found, is the \( k_{\perp} \) splitting scale, which is defined by first re-clustering the constituents of a jet with the \( k_{\perp} \) algorithm [68, 69]. The final recombination step defines the splitting scale variable:

\[
\sqrt{d_{12}} = \min(\text{\( p_{Tj1} \), \( p_{Tj2} \)}) \times \Delta R(j_1,j_2)
\]  

(8.2)
where $j_1$ and $j_2$ are the two sub-jets combined at the final step of the $k_t$ algorithm, which often involves the two most widely separated and highest-$p_T$ sub-jet constituents. As a consequence, for a two-body heavy particle decay – such as a boosted $W$ boson – the final clustering step will usually be to combine those two decay products, and the parameter $\sqrt{d_{12}}$ can be used to distinguish:

- jets from two-prong decays, which tend to be symmetric. The expected value of $\sqrt{d_{12}}$ for a heavy particle decay is approximately $m/2$;

- QCD splittings, which tend to be largely asymmetric.

While we are not using large-R jets in our search, we want to exploit the above property to help distinguish boosted boson decays from QCD splittings involved in $W$+jets, $Z$+jets, and QCD multi-jet background processes. For that purpose, we define the following variable:

$$
splitting = \frac{\min(p_Tj_1, p_Tj_2)^2 \times \Delta R(j_1, j_2)^2}{m_{jj}^2}
$$

where $j_1$ and $j_2$ are the two AntiKt4 jets forming our boosted boson candidates, and $m_{jj}$ their invariant mass.

We require $m_{jj}$ to be within 30 GeV of the $W$ mass for selecting $W$ boson candidates. We will see that this variable is very efficient at rejecting the main background with a good signal efficiency. To our knowledge, this is the first time that such a variable – usually exploited in jet-substructure techniques – is used for a boosted-resolved search. Fig. 8.5 shows the splitting variable distribution. While the signal of interest ($m_T = 550$ GeV) peaks at around 0.25, the backgrounds peak much lower. Hence, a lower cut on splitting at 0.25 gives a better signal over background.
8.2.5 Leptonic $W$ boson

In order to reconstruct the leptonically decaying $W$ boson we reconstruct the neutrino 4-momentum using the $E_T^{miss}$ components in $X$ and $Y$ and $W$ boson mass constraint. For a two-body kinematic decay,

$$ P_W^2 = (P_l + P_\nu)^2 = M_W^2 $$ \hspace{1cm} (8.4)

Resolving the 4-momentum into its components and defining the following substitute variables,

$$ \alpha = \frac{1}{2}(M_W^2 - M_l^2) $$ \hspace{1cm} (8.5)

$$ \beta = \alpha + p_{X\nu}p_{Xl} + p_{Y\nu}p_{Yl} $$ \hspace{1cm} (8.6)

$$ \gamma = -\frac{\beta^2 - E_l^2(p_{X\nu}^2 + p_{Y\nu}^2)}{E_l^2 - p_{Zl}^2} $$ \hspace{1cm} (8.7)

$$ \lambda = \frac{2\beta}{E_l^2 - p_{Zl}^2} $$ \hspace{1cm} (8.8)

$$ \delta = \lambda^2 - 4\gamma $$ \hspace{1cm} (8.9)
we have two solutions for the $Z$ component of neutrino momentum.

$$p_{Z\nu} = \frac{\lambda \pm \sqrt{\delta}}{2}. \quad (8.10)$$

When no solution is found (negative discriminant), we make the approximation of setting $\delta = 0$.

Candidates for the leptonic $W$ boson are then defined adding the lepton 4-momentum and the 4-momenta of the neutrino candidates formed with the above $p_{Z\nu}$ solutions. If two candidates are found, only one of them will be chosen, as will be explained in Section 8.2.7.

### 8.2.6 Reconstruction of Hadronically Decaying Boosted $W$ boson

![Figure 8.6](image.png) Distribution of the invariant mass of di-jet combinations of jets within $\Delta R < 1.0$ at pre-selection. The signal cross-section has been multiplied by 500 in this plot to make the peak visible.

Fig. 8.6 shows the distribution of the invariant mass of all di-jet ($j_1, j_2$) combinations in the events selected after pre-selection. Only those near-by jets separated by an angular distance $\Delta R_{jj} < 1.0$ are considered. For the signal, which has been multiplied by 500 here, the distribution exhibits a clear peak at the $W$ boson mass.
Fig. 8.7 $p_T$ distribution of the di-jet combinations with an invariant mass $65 < m_{jj} < 100$ GeV and with $\Delta R_{jj} < 1.0$ in the events at pre-selection.

Fig. 8.7 shows the distribution of the $p_T$ of the di-jet combinations with an invariant mass $65 < m_{jj} < 100$ GeV and with $\Delta R(j_1,j_2) < 1$. We require the $W$ boson candidates to have $p_T$ greater than 200 GeV.

Formally, we define a $W$ boson candidate as di-jet combination $(j_1,j_2)$ satisfying:

- $65 < m_{jj} < 100$ GeV
- $p_{T_{jj}} > 200$ GeV
- $\Delta R_{jj} < 1.0$

Fig. 8.8 shows the number of such $W$-jet candidates at pre-selection.
Figure 8.8 Distribution of the number of $W$-jet candidates as defined in Section 8.2.6 at pre-selection.

Fig. 8.9 shows the splitting variable, as defined in Section 8.2.4 for such $W$-jet candidates (including events in which more than one candidate is reconstructed). The splitting variable is constructed from the two jets that form the $W$-jet candidate. One can see in this distribution that the splitting variable is fairly well modeled. When more than one $W$-jet candidate is found in an event, the one with the highest splitting is kept so as to increase our signal acceptance (see Cut8 in Section 8.4.1).
8.2.7 Heavy Quark Mass Reconstruction

After selecting a $W$ boson candidate, the three highest-$p_T$ jets among all the remaining jets (i.e. excluding the two jets used to form the $W$ boson) are considered as $q$-jet candidates. As explained above by $q$-jets, we mean the two jets resulting from the hadronization of the $q$-quarks after the $T \rightarrow Wq$ decay.

At this point, candidates for all the objects from the $TT$ decay have been identified: $q$-jets, solutions for the leptonic $W$ boson, and hadronic $W$ boson candidate. Assuming these objects have been correctly reconstructed, only the correct pairing the $q$-jets with the $W$ bosons is unknown. We consider all the 12 (or 6 in case there is only one leptonic $W$ boson solution) permutations that make:

- a hadronic $T$ quark $T_{had}$, i.e. the system formed by the $W$ jet and a $q$-jet
- a leptonic $T$ quark $T_{lep}$, i.e. the system formed by a leptonic $W$ boson candidate and another other $q$-jet.

Figure 8.9 Distribution of the splitting variable of the $W$-jet candidates per event as defined in Section 8.2.6 at pre-selection.
Then we take the permutation that minimizes the mass difference between the hadronic and leptonic $T$ quarks $|M(T_{\text{had}}) - M(T_{\text{lep}})|$. In the following, we will then use only the hadronic mass and refer to it as $m_{\text{reco}}$. Note that the best solution of the leptonic $W$ boson also corresponds to the solution of neutrino $p_Z$. Consequently, we are now able to construct the 4-momentum of the neutrino in the event and define another powerful variable for background rejection. The variable is the opening angle between the neutrino and the charged lepton, which tends to be much more collimated for signal than for backgrounds. Hence, an upper cut on this variable enhances signal over background.

Fig. 8.10 shows the $m_{\text{reco}}$ distribution after selecting a hadronic $W$-jet candidate. For the signal, which has been multiplied by 100 here, the distribution exhibits a clear peak at the heavy quark mass, with a resolution of 40 GeV.

Figure 8.10 $m_{\text{reco}}$ after the boosted selection requirements. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty. The signal cross-section has been multiplied by 100 in this plot to clearly show the signal peak above the backgrounds.
Table 8.1  Yields in the control region CR1: $m_{\text{reco}} < 350$ GeV.

<table>
<thead>
<tr>
<th>Source</th>
<th>Electron</th>
<th>Muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_4\bar{u}_4(550)$</td>
<td>47.5</td>
<td>44.3</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>3640 ± 1060</td>
<td>5500 ± 1500</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>1990 ± 210</td>
<td>2460 ± 260</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>1050 ± 430</td>
<td>630 ± 260</td>
</tr>
<tr>
<td>Single top</td>
<td>189 ± 19</td>
<td>181 ± 18</td>
</tr>
<tr>
<td>QCD</td>
<td>330 ± 12</td>
<td>135 ± 15</td>
</tr>
<tr>
<td>Dibosons</td>
<td>70 ± 34</td>
<td>83 ± 40</td>
</tr>
<tr>
<td>Total prediction</td>
<td>7270 ± 1160</td>
<td>9000 ± 1540</td>
</tr>
<tr>
<td>Data</td>
<td>7322</td>
<td>8223</td>
</tr>
</tbody>
</table>

8.3  Control Regions

After pre-selection it is possible to define control regions to validate the modeling of the backgrounds. These control regions have high statistics and are important to ensure that the backgrounds are well modeled.

The following two control regions are studied:

- CR1: $m_{\text{reco}} < 350$ GeV; In particular, this control region allows to validate the modeling of $H_T$.

- CR2: $H_T < 800$ GeV; In particular, this control region allows to validate the modeling of $m_{\text{reco}}$.

In these control regions, we study the modeling of the main discriminating variables. In general, good agreement between data and background prediction is found. Tables 8.1 and 8.2 show the yields in these two control regions. Appendix B shows the modeling of kinematic variables in the control regions.

8.4  Final Event Selection

8.4.1  Loose Selection

In order to further suppress background, we apply additional selection cuts that are motivated by the description of the truth-level kinematics of signal and background processes.
### Table 8.2  Yields in the control region CR2: $H_T < 800$ GeV.

<table>
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<th>Ele</th>
<th>Muon</th>
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</thead>
<tbody>
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<td>$u\bar{u}(550)$</td>
<td>16.8</td>
<td>16.7</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>$3800 \pm 1130$</td>
<td>$5600 \pm 1600$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$2030 \pm 220$</td>
<td>$2500 \pm 270$</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>$1150 \pm 460$</td>
<td>$680 \pm 290$</td>
</tr>
<tr>
<td>Single top</td>
<td>$193 \pm 19$</td>
<td>$184 \pm 18$</td>
</tr>
<tr>
<td>QCD</td>
<td>$388 \pm 13$</td>
<td>$170 \pm 16$</td>
</tr>
<tr>
<td>Dibosons</td>
<td>$83 \pm 40$</td>
<td>$95 \pm 46$</td>
</tr>
<tr>
<td>Total prediction</td>
<td>$7600 \pm 1180$</td>
<td>$9200 \pm 1645$</td>
</tr>
<tr>
<td>Data</td>
<td>7893</td>
<td>8833</td>
</tr>
</tbody>
</table>

- **Cut1**: We require that there be at least one hadronic $W$ boson as defined above in Section 8.2.6.

- **Cut2**: the mass difference between leptonic and hadronic heavy quarks reconstructed $|M(T_{had}) - M(T_{lep})|$ is required to be lower than 120 GeV. This cut is motivated by the signal resolution on $m_{reco}$, which is approximately 100 GeV.

- **Cut3**: the highest-$p_T$ $q$-jet of the event has to have $p_T > 160$ GeV. Generally, for a heavy $T$ quark, the decay products are more boosted than jets in $t\bar{t}$ or $W$+jets production. Hence, for signal the distribution peaks at a higher $p_T$ than for backgrounds. Fig. 8.4.1 show the $p_T$ distribution of the leading $q$-quark.

- **Cut4**: the 2$^{nd}$ highest-$p_T$ $q$-jet of the event is required to have $p_T > 80$ GeV for the same reason as for cut3. Fig. 8.11 show the distribution.

- **Cut5**: $H_T > 1$ TeV. As discussed above in Section 8.2.3, this is highly efficient at rejecting most of our backgrounds with a very high signal efficiency. For $m_T = 550$ GeV, this selection improves the signal-over-background ratio by a factor of $\sim 3.5$. See Fig. 8.12

- **Cut6**: $\Delta R$ between the lepton and the neutrino is required to be lower than 1.4. This cut is motivated by the discussion in Section 8.2.7 and the corresponding distribution shown in Fig. 8.2;
Figure 8.11  Distribution of the 2\textsuperscript{nd} leading jet $p_T$ after cut1.
• Cut7: $\Delta R$ between the reconstructed leptonic and hadronic heavy quarks has to be higher than 2.0 and lower than 4.2. This cut is motivated by the fact that the two heavy quarks are mainly produced back-to-back, so they are quite separated in $\Delta R$. However, because an extreme $\Delta R$ can also result from spurious background events, an upper cut is placed at $\Delta R = 4.2$. See Fig. 8.13;

• Cut8: splitting of the jets forming the $W$ boson has to be higher than 0.25. This cut is motivated by the discussion at the end of Section 8.2.4. Fig. 8.14 shows the splitting variable of the selected $W$ boson of the events after pre-selection and all the cuts through Cut7. It shows the high background rejection power of this variable. For $m_T = 550$ GeV, this cut improves the signal-over-background ratio by $\sim 67\%$.

We call this stage of our selection “LOOSE”, and corresponding distributions of the final discriminant, $m_{reco}$, can be seen in Fig. 8.15. Table 8.3 reports the signal and background yields at this stage of selection. A clear peak for the $T$ quark signal can be seen above a rather flat $W$+jets background.
8.4.2 Tight Selection

In addition to the Loose selection requirements, we apply 3 more cuts in order to improve sensitivity. The additional cuts define a Tight Selection. The additional cuts are as follows:

- **Cut9:** $\Delta R$ separation between the $W$ jet and each of the two $q$-jets has to be greater than 1.0. See Fig. 8.2.

- **Cut10:** $\Delta R$ separation between the leptonic $W$ and each of the two $q$-jets has to be greater than 1.0. See Fig. 8.2.

- **Cut11:** the 2$^{nd}$ highest-$p_T$ $q$-jet of the event has to have $p_T > 120$ GeV. This is just tightening of Cut4.

The first two cuts are intended to select isolated $W$ bosons, i.e. $W$ bosons that are more isolated from their associated $q$-jets: see explanations in Section 8.2.4 (Fig. 8.2 on page 81). We call this stage of our selection cuts “Tight selection”. Table 8.4 reports the yields.

There are ongoing efforts to improve sensitivity with these additional selection cuts. However, in this thesis, we will present results based on the Loose selection.
Figure 8.14 Splitting variable computed from the two jets forming the selected $W$ jet of the events after the Cut7. Left $e$ and right $\mu$ channel.

Figure 8.15 $m_{\text{reco}}$ after the LOOSE selection requirements. Left $e$ and right $\mu$ channel.
Table 8.3  Yields after the LOOSE selection requirements.

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<th></th>
<th>Ele</th>
<th>Muon</th>
</tr>
</thead>
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<tr>
<td>$TT(450)$</td>
<td>43.3</td>
<td>46.5</td>
</tr>
<tr>
<td>$TT(550)$</td>
<td>33.8</td>
<td>28.4</td>
</tr>
<tr>
<td>$TT(650)$</td>
<td>14.82</td>
<td>15.08</td>
</tr>
<tr>
<td>$W+$jets</td>
<td>$17.6 \pm 7.4$</td>
<td>$29 \pm 23$</td>
</tr>
<tr>
<td>$tt$</td>
<td>$7.8 \pm 2.0$</td>
<td>$11.9 \pm 2.6$</td>
</tr>
<tr>
<td>$Z+$jets</td>
<td>$1.59 \pm 0.89$</td>
<td>$1.79 \pm 1.15$</td>
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<tr>
<td>Single top</td>
<td>$0.17 \pm 0.14$</td>
<td>$0.16 \pm 0.13$</td>
</tr>
<tr>
<td>QCD</td>
<td>$0 \pm 0$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Dibosons</td>
<td>$0 \pm 0$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Total prediction</td>
<td>$27.1 \pm 8$</td>
<td>$42 \pm 24$</td>
</tr>
</tbody>
</table>

Table 8.4  Yields after the TIGHT selection requirements.

<table>
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<tr>
<th></th>
<th>Electron</th>
<th>Muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$TT(450)$</td>
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<td>$TT(550)$</td>
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<td>$TT(650)$</td>
<td>9.83</td>
<td>9.77</td>
</tr>
<tr>
<td>$W+$jets</td>
<td>$7.3 \pm 2.3$</td>
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<tr>
<td>$tt$</td>
<td>$1.19 \pm 0.52$</td>
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<tr>
<td>$Z+$jets</td>
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<td>$1.77 \pm 1.14$</td>
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<td>Single top</td>
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<tr>
<td>QCD</td>
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<td>$-0.291 \pm 0.102$</td>
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<td>Dibosons</td>
<td>$0 \pm 0$</td>
<td>$0 \pm 0$</td>
</tr>
<tr>
<td>Total prediction</td>
<td>$9.3 \pm 2.42$</td>
<td>$16.2 \pm 3.77$</td>
</tr>
</tbody>
</table>
CHAPTER 9. Statistical Analysis and Results

9.1 Introduction

In a search for new physics phenomena, there are several possible outcomes. Some of the outcomes are that we may find a sign of what we are looking for, we may find no sign of new physics, or, though it happens rarely, we may find something unexpected. Among the possible outcomes, the discovery certainly is very exciting. Nevertheless, an absence of discovery is not a null result and still carries substantial information about possible new physics. Even though new, heavy quarks are yet to be detected, results from the LHC have made significant progress and brought about large scale changes in the theoretical landscape in the past 5 years. Searches in several decay modes and under certain models have already excluded new, heavy quarks up to almost a TeV.

At this point, it is good to recall that the previous limit on the mass of new quarks that decay into a $W$ boson and a light quark is less than 350 GeV. In this chapter, the results from statistical analysis of our search will be presented. Statistical analysis of an experimental result allows us to test whether the signal hypothesis or the background-only hypothesis is correct. Once a background estimate has been made, it is possible to determine the exclusion or discovery significance of our model in the data. Before that, however, we have to understand the uncertainties of our measurement. The uncertainties of our measurements and theoretical uncertainties relevant to our search will be discussed in this chapter and the results will be presented.
9.2 Systematic Uncertainties

Systematic uncertainties represent uncertainties caused by imperfect models employed in our signal and background expectations. Unlike statistical uncertainties they don’t necessarily decrease with increased statistics of data set and have to be carefully evaluated in dedicated studies. To make meaningful measurement or to perform a rigorous search, a good understanding of the systematic uncertainties is crucial.

There are several sources of systematic uncertainties in this search. They can be split into two main subgroups. The first subgroup includes all the uncertainties due inaccurate modeling in the detector simulation and they apply to all Monte Carlo based, but not the data driven predictions. Uncertainties due to signal and background modeling constitute the second subgroup. The first subgroup accounts for uncertainties in jet energy scale (JES), jet energy resolution (JER), missing transverse energy, lepton trigger, lepton identification and reconstruction efficiency, lepton energy/momentum scales, b-tagging efficiency etc.. For the detector-related uncertainties, all variations are evaluated, as recommended by the ATLAS Top Group. Uncertainties related to the signal modeling are due to scale uncertainty and parton distribution functions (PDF)+\alpha_S uncertainty. Background modeling uncertainties include the W+jets modeling and normalization, and cross section uncertainties on other smaller backgrounds.

In this analysis individual sources of systematic uncertainty are considered uncorrelated. The effect of relevant systematic uncertainty is taken into account in the limits calculation by considering the normalization and shape effects on the \(m_{\text{reco}}\) distribution for each signal and background process. List of systematic uncertainties appear in Table 9.1 and Table 9.2.

9.2.1 Luminosity

Luminosity error is included as 2.8\% for all Monte Carlo based predictions. The uncertainty on the integrated luminosity is derived, following the same methodology as that detailed in Ref. [70], from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012.
9.2.2 Muon Trigger, Identification, and Reconstruction Efficiencies

The efficiency of the muon reconstruction requirements has been measured by the Muon Combined Performance group [71] and scale factors are used to bring the MC simulation in agreement with the data. Following Ref. [72] an overall conservative uncertainty of 2% is taken for muon trigger, identification, and reconstruction efficiency.

9.2.3 Muon Momentum Scale and Resolution

Muon momentum scale and resolution are varied within their $\pm 1\sigma$ uncertainties based on external studies of resolution and scale in $Z \rightarrow \mu\mu$ events. The smearing uncertainty is decomposed into different terms for the muon $p_T$ smearing in the muon spectrometer (MS) and the inner detector (ID).

9.2.4 Electron Trigger, Identification, and Reconstruction Efficiencies

All efficiencies and scale factors are derived by the $e - \gamma$ Combined Performance group using $Z \rightarrow ee$ samples. The systematic uncertainties on the scale factors are found to be typically below 0.5%. The uncertainties due to pile-up are also found to be below 0.5%. Following Ref. [72] an overall conservative uncertainty of 2% is taken for electron trigger, identification, and reconstruction efficiency.

9.2.5 Electron Energy Scale and Resolution

Uncertainties on the energy scale and resolution of the selected electron are estimated in dedicated studies using $Z \rightarrow ee$ events. In both cases separate templates for the $\pm 1\sigma$ variations are created with the electron energy scale and resolution correction raised and lowered by one sigma in order to estimate the shape change uncertainty.

9.2.6 Jet Energy Scale

Because of the high number of jets present in the selected events and because we are looking for a mass peak based on jet energies, a high sensitivity of the measurement to variations of the jet energy scale (JES) is expected. The jet energy scale uncertainty is effectively a combination
of several different sources of uncertainties, based on independent parts of the detector, Monte Carlo model assumptions made in the evaluation of the jet energy scale etc.. The jet energy scale and its uncertainty have been derived combining various studies from LHC collision data and simulation [73, 74].

For this analysis, we consider an envelope of all those sources of uncertainties as global jet energy scale uncertainty. Two additional samples are created with the JES correction raised and lowered by one sigma in order to estimate the shape change uncertainty. For the future studies, the jet energy scale uncertainty will be decomposed into its underlying uncertainties, which will then be treated as uncorrelated nuisance parameters in the final limit calculation.

9.2.7 Jet Reconstruction Efficiency

To account for differences in the reconstruction efficiency for jets between data and Monte Carlo simulated events, the efficiencies are measured in both samples. The resulting difference is propagated as uncertainty to the measurements by randomly dropping jets from the Monte Carlo simulated samples, based on their transverse momenta and pseudo-rapidities. This creates a one-sided uncertainty and the deviation from the nominal distribution is mirrored to create $\pm 1\sigma$ templates.

9.2.8 Jet Energy Resolution

The jet energy resolution is fluctuated up and down by one sigma to create a pair of JER samples which are used to estimate the shape changing uncertainty.

9.2.9 $W+$jets Normalization

The estimate of the $W+$jets background is based on data for its normalization and on the simulation for its shape. In proton-proton collision, $W+$jets production is charge asymmetric. The total number of $W+$jets in data, $N_{WW} = N_{WW}^+ + N_{WW}^-$, can be estimated based on the difference between positively-charged and negatively-charged $W$ bosons, $N_{WW}^+ - N_{WW}^-$, and their

\cite{1See also: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissApproved2013JESUncertainty}
ratio, \( r_{MC} \), determined from simulation.

\[
N_W = \left[ \frac{(r_{MC}+1)}{(r_{MC}-1)} \right] (N_{W^+} - N_{W^-})_{\text{measured}}
\]

The overall yields of \( W \)-jets events are normalized by comparing the observed charge-asymmetry of \( W \) boson production from data \([75, 76]\) and the predicted charge-asymmetry from Monte Carlo using the above equation. Scale factors to correct the heavy flavor fraction of events are derived in \( W+2 \) jets events by comparing data and prediction. They are then extrapolated to the higher jet multiplicities. Since the total \( W \)-jets cross sections have to be preserved, the \( W \)-light flavor samples are assigned a scale factor as well, keeping the number of \( W \)-jets events conserved. Charge-symmetric contributions from \( t\bar{t}, Z+\text{jets} \) and multi-jet processes cancel in the difference. Slightly charge asymmetric contributions from the remaining backgrounds such as single top and dibosons are estimated using Monte Carlo simulation. This is again performed for different lepton flavors and jet multiplicity bins. The resulting normalization scale factors are consistent with unity within statistical and systematic uncertainties. Uncertainties on these scale factors vary from 13\% to 24\% depending on the channel (electron versus muon), jet multiplicity, and tagging. For this thesis, we consider a conservative uncertainty of 24\% across all bins.

### 9.2.10 Uncertainties from Signal Modeling

The \( T\bar{T} \) cross section for \( pp \) collisions at a centre-of-mass energy of \( \sqrt{s} = 8 \) TeV has been calculated at next-to-next-to leading order (NNLO) in QCD including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms with top++2.0 \([77, 78, 79, 80, 81, 82]\). The 8 TeV cross section values are also listed in Table 5.1. The uncertainties in the prediction stem from scale variations and the PDF+\( \alpha_S \) uncertainty and range from approximately 9\% at the low end to 14\% at the high end of mass scale \([83]\).
Table 9.1  List of all systematic uncertainties (in % of final event yield of each process) considered in the electron channel. The signal given here is a $T$ quark with mass 350 GeV.

<table>
<thead>
<tr>
<th></th>
<th>Electron Channel</th>
<th>Signal (350 GeV)</th>
<th>$W$+jets</th>
<th>Minor Bkg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Energy Resolution</td>
<td>–</td>
<td>+3.5/+5.3</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Electron Energy Scale</td>
<td>–</td>
<td>+9.7/-7.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Jet Reco. Eff.</td>
<td>–</td>
<td>+4.8/+0.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Jet Energy Resolution</td>
<td>–</td>
<td>+0.0/-21.2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>–</td>
<td>+13.8/-14.6</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Lepton ID, Trig., Reco. Eff.</td>
<td>+2.0/-2.0</td>
<td>+2.0/-2.0</td>
<td>+2.0/-2.0</td>
<td>+2.0/-2.0</td>
</tr>
<tr>
<td>Lumi.</td>
<td>+2.8/-2.8</td>
<td>–</td>
<td>+2.8/-2.8</td>
<td>–</td>
</tr>
<tr>
<td>Cross section $T350$</td>
<td>+10.0/-10.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Cross section Single top</td>
<td>–</td>
<td>–</td>
<td>+0.1/-0.1</td>
<td>–</td>
</tr>
<tr>
<td>Cross section $W$+jets</td>
<td>–</td>
<td>+24.0/-24.0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Cross section $Z$+jets</td>
<td>–</td>
<td>–</td>
<td>+8.1/-8.1</td>
<td>–</td>
</tr>
<tr>
<td>Cross section dibosons</td>
<td>–</td>
<td>–</td>
<td>+0.0/+0.0</td>
<td>–</td>
</tr>
<tr>
<td>Cross section $tt$</td>
<td>–</td>
<td>–</td>
<td>+8.2/-8.2</td>
<td>–</td>
</tr>
<tr>
<td>Total</td>
<td>+10.6/-10.6</td>
<td>+30.0/-36.3</td>
<td>+12.0/-12.0</td>
<td></td>
</tr>
</tbody>
</table>
Table 9.2  List of all systematic uncertainties (in % of final event yield of each process) considered in the muon channel. The signal given here is a $T$ quark with mass 350 GeV.

<table>
<thead>
<tr>
<th>Muon Channel</th>
<th>Signal (350 GeV)</th>
<th>W+jets</th>
<th>Minor Bkg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Reco. Eff.</td>
<td>–</td>
<td>+3.1/-0.0</td>
<td>–</td>
</tr>
<tr>
<td>Jet Energy Resolution</td>
<td>–</td>
<td>+0.0/-43.5</td>
<td>–</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>–</td>
<td>+1.5/-62.2</td>
<td>–</td>
</tr>
<tr>
<td>Lepton ID, Trig., Reco. Eff.</td>
<td>+2.0/-2.0</td>
<td>+2.0/-2.0</td>
<td>+2.1/-2.1</td>
</tr>
<tr>
<td>Lumi.</td>
<td>+2.8/-2.8</td>
<td>–</td>
<td>+2.9/-2.9</td>
</tr>
<tr>
<td>Muon Momentum Inner Det.</td>
<td>–</td>
<td>+3.1/+3.1</td>
<td>–</td>
</tr>
<tr>
<td>Muon Momentum MS</td>
<td>–</td>
<td>+3.1/+3.1</td>
<td>–</td>
</tr>
<tr>
<td>Muon Momentum Scale</td>
<td>–</td>
<td>+3.1/+3.1</td>
<td>–</td>
</tr>
<tr>
<td>Cross section $T350$</td>
<td>+8.4/-8.4</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Cross section Single top</td>
<td>–</td>
<td>–</td>
<td>+0.1/-0.1</td>
</tr>
<tr>
<td>Cross section $W$+jets</td>
<td>–</td>
<td>+24.0/-24.0</td>
<td>–</td>
</tr>
<tr>
<td>Cross section $Z$+jets</td>
<td>–</td>
<td>–</td>
<td>+6.4/-6.4</td>
</tr>
<tr>
<td>Cross section dibosons</td>
<td>–</td>
<td>–</td>
<td>+0.0/+0.0</td>
</tr>
<tr>
<td>Cross section $t\bar{t}$</td>
<td>–</td>
<td>–</td>
<td>+8.9/-8.9</td>
</tr>
<tr>
<td>Total</td>
<td>+9.1/-9.1</td>
<td>+24.9/-79.8</td>
<td>+11.5/-11.5</td>
</tr>
</tbody>
</table>
9.2.11 Theoretical Uncertainties on Small backgrounds

Contributions from small backgrounds, like $t\bar{t}$, $Z$+jets, single top quark production, and diboson production were estimated using their theoretical cross-sections. Uncertainties on these backgrounds are taken from the prescription from ATLAS Top Quark Group and are as follows. Uncertainty of 10% is assumed for the inclusive $t\bar{t}$ cross section and for single top cross section. The theoretical uncertainty of 4% on inclusive $Z$+jets production is propagated to the higher jet multiplicities based on the Berends scaling assumption [84] of a constant ratio of events in neighboring jet bins, describing the relative behavior of number of events with different jet multiplicities. The uncertainty on this assumption is studied and found to be 24% per additional jet. For the signal 4-jet bin this corresponds therefore to 48%. Such a large uncertainty on the main background would degrade the sensitivity of the search, but since $Z$+jets is not our main background, such a large uncertainty doesn’t affect our sensitivity just as adversely. Similarly, the theory uncertainty for inclusive diboson production is 4%. The additional uncertainty per additional jet is 24% to be added in quadrature, and for the signal 4-jet bin this corresponds therefore to 48%.

9.3 Additional Systematic Uncertainties

For technical reason, the following uncertainties are not included in the computation of limit for this thesis, but there are ongoing efforts within the ATLAS collaboration to include them in the future iteration of the analysis.

9.3.1 BTagging Scale Factor

The $b$-tagging scale factors are applied to correct the tagging efficiencies from MC to data. The uncertainties are obtained separately for each type of jets and treated as uncorrelated for $b$-jets, $c$-jets and light jets. The $b$, $c$ and light-jet tagging scale factors and corresponding systematic uncertainties are provided by the flavor tagging group.
9.3.2 Jet Vertex Fraction Efficiency

The jet vertex fraction (JVF) efficiency scale factors are used to match MC to data. The scale factor uncertainties are correspondingly applied to each jet, while the JVF efficiency and inefficiency are regarded as fully anti-correlated. The JVF uncertainty can change the selection efficiency, and eventually propagate to the cross-section measurement.

9.4 Statistical Analysis

In the absence of any significant data excess, the \( m_{\text{reco}} \) spectrum shown in Fig. 9.1 is used to derive 95\% CL upper limits on the \( T\bar{T} \) production cross section using the \( CL_s \) method [85, 86]. This method employs a log-likelihood ratio \( LLR = -2 \log(L_{s+b}/L_b) \) as test-statistic, where \( L_{s+b} (L_b) \) is a binned likelihood function (product of Poisson probabilities) to observe the data under the signal-plus-background (background-only) hypothesis.

Pseudo-experiments are generated for both hypotheses, taking into account per-bin statistical fluctuations of the total predictions according to Poisson statistics, as well as Gaussian fluctuations describing the effect of systematic uncertainties. The fraction of pseudo-experiments for the signal-plus-background (background-only) hypothesis with \( LLR \) that is
more signal-like than a given threshold defines $CL_{s+b}$ ($CL_b$). Such threshold is set to the observed (median) LLR for the observed (expected) limit. Signal cross sections for which $CL_s = CL_{s+b} / CL_b < 0.05$ are deemed to be excluded at 95% CL. Dividing by $CL_b$ avoids the possibility of mistakenly excluding a signal we are not sensitive to because of downward fluctuation of the background.

### 9.5 Results

From the statistical analysis, the resulting expected upper limits on the $T\bar{T}$ production cross section times branching fraction are shown in Fig. 9.2 as a function of $m_T$, and compared to the theoretical prediction for the benchmark scenario: a pair-produced new, heavy $T$ quark that decays into a $W$ boson and a light quark with a branching ratio of 100%. For such a $T$ quark, an observed (expected) 95% CL limit $m_T > 680$ (660) GeV is obtained in the $e$ channel for the central value of the theoretical cross section. Similarly, in the muon channel, an observed (expected) 95% CL limit $m_T > 660$ (640) GeV is obtained. Combining the two separate channels, an observed (expected) 95% CL limit $m_T > 690$ (710) GeV is obtained as shown in Fig. 9.3. The previous limit derived for a new, heavy quark that decays into a $W$ boson and a $q$ quark was $m_T > 350$ GeV [31], where $q = u, d, s, c, b$.

![Figure 9.2](image-url)  
Figure 9.2 Observed and Expected limits in the electron (left) and muon (right) channels for the **LOOSE** selection.
Figure 9.3 Observed and Expected limits in the combined $e - \mu$ channel for the LOOSE selection.

9.6 Conclusion

A search has been presented for the pair production of a new heavy quark, $T$, assuming that it has a significant branching ratio to decay into a $W$ boson and a light-flavor quark, $q$. The search is based on the 20 fb$^{-1}$ of proton-proton collision data at $\sqrt{s} = 8$ TeV recorded in 2012-2013 with the ATLAS detector at the Large Hadron Collider. Data were analyzed in the lepton+jets channel exploiting the substantial momentum transferred to all of the decay products of the heavy quark. No significant excess above the Standard Model expectation was observed and 95% confidence level upper limits have been derived on the cross section times the branching ratio of $T$ quark in the lepton+jets channel. Assuming a 100% branching ratio to $Wq$, where $q = u, d, c, s$, a new heavy quark with mass less than 690 GeV is excluded at the 95% confidence level in the combined $e - \mu$ channel.

9.7 Outlook

There are ongoing efforts to improve sensitivity by using the TIGHT selection. However, as mentioned in 5.5, the ALPGEN-generated $W+$jets background sample has large statistical
error after the Tight selection. Therefore, $W+$jets sample generated with SHERPA was used to test the sensitivity for the Tight selection. Using the $m_{\text{reco}}$ distributions shown in Fig. 9.4, we computed expected limits. For a $T$ quark, an expected 95\% CL limit $m_T > 740$ GeV is obtained in the combined electron-muon channel for the central value of the theoretical cross section. This improvement in sensitivity is highly welcome and will benefit the future iteration of the analysis.

Figure 9.4 $m_{\text{reco}}$ after Tight selection in the electron (left) and muon (right) channel. The entire distribution is used to compute limits.
Figure 9.5  Expected limit in the combined $e - \mu$ channel for the final TIGHT selection.
APPENDIX A. Resolution Functions

A.1 Resolutions for $b$-jet

Figure A.1 Resolutions of $b$-jet $p_T$ binned in $p_T$ for $|\eta| < 0.80$. 
Figure A.2  Resolutions of $b$-jet $p_T$ binned in $p_T$ for $0.80 < |\eta| < 1.37$.

Figure A.3  Resolutions of $b$-jet $p_T$ binned in $p_T$ for $1.37 < |\eta| < 1.52$. 
A.2 Resolutions for Light Jet

Figure A.4  Resolutions of $b$-jet $p_T$ binned in $p_T$ for $1.52 < |\eta| < 2.50$.

Figure A.5  Resolutions of light-jet $p_T$ binned in $p_T$ for $|\eta| < 0.80$. 
Figure A.6  Resolutions of light-jet $p_T$ binned in $p_T$ for $0.80 < |\eta| < 1.37$. 
Figure A.7  Resolutions of light-jet $p_T$ binned in $p_T$ for $1.37 < \eta < 1.53$. 
Figure A.8  Resolutions of light-jet $p_T$ binned in $p_T$ for $1.52 < |\eta| < 2.50$.

A.3  Resolutions for Unclustered Energy

Figure A.9  Resolutions of unclustered energy.
APPENDIX B. Data/Expectation Comparisons

B.1 Pre-Selection

The following section shows data over expected backgrounds at pre-selection for main kinematic variables. The agreement is good and within uncertainties. In all the plots the lower panel shows the significance of the disagreement between data and expectation in units of normal standard deviations as explained in [87].

Figure B.1  Jet multiplicity at pre-selection. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.
Figure B.2  \( H_T \) at pre-selection. Left \( e \) and right \( \mu \) channel. The total uncertainty shown is due to MC statistics and \( W+\)jets normalization uncertainty.

Figure B.3  Leading jet \( p_T \) at pre-selection. Left \( e \) and right \( \mu \) channel. The total uncertainty shown is due to MC statistics and \( W+\)jets normalization uncertainty.
Figure B.4 2nd Leading jet $p_T$ at pre-selection. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+$jets normalization uncertainty.

Figure B.5 3rd leading jet $p_T$ at pre-selection. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+$jets normalization uncertainty.
Figure B.6 4th Leading jet $p_T$ at pre-selection. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.

Figure B.7 Leading jet $\eta$ at pre-selection. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.
Figure B.8 2nd Leading jet $\eta$ at pre-selection. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+$jets normalization uncertainty.

Figure B.9 3rd leading jet $\eta$ at pre-selection. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+$jets normalization uncertainty.
Figure B.10 4th Leading jet $\eta$ at pre-selection. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.

Figure B.11 Lepton $p_T$ at pre-selection. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.
Figure B.12  Lepton $\eta$ at pre-selection. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+$jets normalization uncertainty.

Figure B.13  $E_{\text{miss}}^T$ at pre-selection. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+$jets normalization uncertainty.
Figure B.14 $E_T^{miss} + M_T(W)$ at pre-selection. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.
B.2 Control Region 1

The following section shows data over expected backgrounds in control region 1 defined as $m_{\text{reco}} < 350$ GeV. The agreement is good and within uncertainties. In all the plots the lower panel shows the significance of the disagreement between data and expectation in units of normal standard deviations as explained in [87].

Figure B.15  Jet multiplicity in CR1: $m_{\text{reco}} < 350$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.
Figure B.16  $H_T$ in CR1: $m_{\text{reco}} < 350$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.

Figure B.17  Leading jet $p_T$ in CR1: $m_{\text{reco}} < 350$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.
Figure B.18 2nd Leading jet $p_T$ in CR1: $m_{\text{reco}} < 350$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+\text{jets}$ normalization uncertainty.

Figure B.19 Lepton $p_T$ in CR1: $m_{\text{reco}} < 350$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+\text{jets}$ normalization uncertainty.
Figure B.20  $\Delta R(\text{lepton}, \nu)$ in CR1: $m_{\text{reco}} < 350$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.

Figure B.21  Mass difference between leptonic and hadronic heavy quark in CR1: $m_{\text{reco}} < 350$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.
Figure B.22 \( \Delta R \) between leptonic and hadronic heavy quark in CR1: \( m_{\text{reco}} < 350 \text{ GeV} \). Left \( e \) and right \( \mu \) channel. The total uncertainty shown is due to MC statistics and \( W+\text{jets} \) normalization uncertainty.

Figure B.23 Splitting variable in CR1: \( m_{\text{reco}} < 350 \text{ GeV} \). Left \( e \) and right \( \mu \) channel. The total uncertainty shown is due to MC statistics and \( W+\text{jets} \) normalization uncertainty.
Figure B.24 $\Delta R(\text{Whad}, \text{Qhad})$ in CR1: $m_{\text{reco}} < 350$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W^+\text{jets}$ normalization uncertainty.

Figure B.25 $\Delta R(\text{Wlep}, \text{Qlep})$ in CR1: $m_{\text{reco}} < 350$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W^+\text{jets}$ normalization uncertainty.
Figure B.26 Minimum $\Delta R$ between the hadronic W and the 2 q-jets in CR1: $m_{\text{reco}} < 350$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+\text{jets}$ normalization uncertainty.

Figure B.27 Minimum $\Delta R$ between the leptonic W and the 2 q-jets in CR1: $m_{\text{reco}} < 350$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+\text{jets}$ normalization uncertainty.
B.3  Control Region 2

The following section shows data over expected backgrounds in control region 2 defined as $H_T < 800$ GeV. The agreement is good and within uncertainties. In all the plots the lower panel shows the significance of the disagreement between data and expectation in units of normal standard deviations as explained in [87].

Figure B.28  $m_{\text{RECO}}$ after cut1. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.
Figure B.29  Jet multiplicity in CR2: $H_T < 800$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.

Figure B.30  $H_T$ in CR2: $H_T < 800$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.
Figure B.31  Leading jet $p_T$ in CR2: $H_T < 800$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+$jets normalization uncertainty.

Figure B.32  2nd Leading jet $p_T$ in CR2: $H_T < 800$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+$jets normalization uncertainty.
Figure B.33 Lepton $p_T$ in CR2: $H_T < 800$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.

Figure B.34 $\Delta R(\text{lepton},\nu)$ in CR2: $H_T < 800$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.
Figure B.35 Mass difference between leptonic and hadronic heavy quark in CR2: $H_T < 800$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+\text{jets}$ normalization uncertainty.

Figure B.36 $\Delta R$ between leptonic and hadronic heavy quark in CR2: $H_T < 800$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+\text{jets}$ normalization uncertainty.
Figure B.37 Splitting variable in CR2: $H_T < 800$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.

Figure B.38 $\Delta R(Whad,Qhad)$ in CR2: $H_T < 800$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.
Figure B.39 $\Delta R(W_{lep},Q_{lep})$ in CR2: $H_T < 800$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+\text{jets}$ normalization uncertainty.

Figure B.40 Minimum $\Delta R$ between the hadronic W and the 2 q-jets in CR2: $H_T < 800$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W+\text{jets}$ normalization uncertainty.
Figure B.41  Minimum $\Delta R$ between the leptonic W and the 2 q-jets in CR2: $H_T < 800$ GeV. Left $e$ and right $\mu$ channel. The total uncertainty shown is due to MC statistics and $W$+jets normalization uncertainty.
**B.4 $m_{\text{reco}}$ Distribution at Various Selection Level**

This section shows the final discriminant, $m_{\text{reco}}$, at various selection levels described in ??.

In all the plots the lower panel shows the significance of the disagreement between data and expectation in units of normal standard deviations as explained in [87].

Figure B.42 $m_{\text{reco}}$ after cut2. Left $e$ and right $\mu$ channel. THE DATA HISTOGRAM IS NOT FILLED IF $m_{\text{reco}} > 300$ GeV. The total uncertainty shown is due to MC statistics and $W+$jets normalization uncertainty.
Figure B.43  $m_{\text{reco}}$ after cut3. Left $e$ and right $\mu$ channel. THE DATA HISTOGRAM IS NOT FILLED IF $m_{\text{reco}} > 300$ GeV. The total uncertainty shown is due to MC statistics and $W+$jets normalization uncertainty.

Figure B.44  $m_{\text{reco}}$ after cut4. Left $e$ and right $\mu$ channel. THE DATA HISTOGRAM IS NOT FILLED IF $m_{\text{reco}} > 300$ GeV. The total uncertainty shown is due to MC statistics and $W+$jets normalization uncertainty.
Figure B.45 \( m_{\text{reco}} \) after cut5. Left \( e \) and right \( \mu \) channel. THE DATA HISTOGRAM IS NOT FILLED IF \( m_{\text{reco}} > 300 \) GeV. The total uncertainty shown is due to MC statistics and \( W + \text{jets} \) normalization uncertainty.

Figure B.46 \( m_{\text{reco}} \) after cut6. Left \( e \) and right \( \mu \) channel. THE DATA HISTOGRAM IS NOT FILLED IF \( m_{\text{reco}} > 300 \) GeV. The total uncertainty shown is due to MC statistics and \( W + \text{jets} \) normalization uncertainty.
Figure B.47 $m_{\text{reco}}$ after cut7. Left $e$ and right $\mu$ channel. THE DATA HISTOGRAM IS NOT FILLED IF $m_{\text{reco}} > 300$ GeV. The total uncertainty shown is due to MC statistics and $W+$jets normalization uncertainty.
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