A Search for Z’ Gauge Bosons Decaying to Tau-Antitau Pairs in Proton-Proton Collisions with the ATLAS Detector

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Abstract

A Search for Z’ Gauge Bosons Decaying to Tau-Antitau Pairs in Proton-Proton Collisions with the ATLAS Detector

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Many Beyond-the-Standard-Model theories predict the existence of one or more additional neutral gauge bosons, or Z’ bosons, with masses at the TeV scale or higher. A search for resonances of Z’ bosons decaying to $\tau^+\tau^-$ pairs in $\sqrt{s} = 8$ TeV $pp$ collisions from the LHC is presented. The data was collected by the ATLAS detector and corresponds to an integrated luminosity of 19.5-20.3 fb$^{-1}$. The search is performed in ditau decay channels in which at least one tau decays hadronically. In each channel, the numbers of ditau events in high-mass regions of data are counted and compared to the expected numbers from Standard Model backgrounds and Z’ signals. No statistically significant excess above the Standard Model expectation is observed in any channel. Bayesian 95% credibility upper limits are placed on the Z’ production cross section times Z’ $\rightarrow \tau\tau$ branching ratio as functions of the Z’ resonance mass for each channel and for a combination of the channels. Sequential Standard Model Z’ bosons with masses below 2.02 TeV are excluded at 95% credibility. The impacts on the cross section limits from varying the $Z'_{SSM}$ decay width and couplings to fermions are evaluated. Limits are also placed on the cross section times branching ratio of Non-Universal $G(221)$ Z’ bosons with enhanced couplings to third-generation fermions. These are evaluated as functions of the $Z'_{NU}$ mass and another free parameter. Z’ $_{NU}$ bosons with masses below 1.3-2.1 TeV are excluded at 95% credibility.
Acknowledgements

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<td>TMVA</td>
<td>Tool for MultiVariate Data Analysis</td>
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</tr>
<tr>
<td>VEV</td>
<td>Vacuum Expectation Value</td>
</tr>
<tr>
<td>WLCG</td>
<td>Worldwide LHC Computing Grid</td>
</tr>
<tr>
<td>WNC</td>
<td>Weak Neutral Current</td>
</tr>
</tbody>
</table>
Physical Constants

Speed of Light \( c \ = \ 1 \)

\( \hbar \quad h \ = \ 1 \)
For my family
“New knowledge is the most valuable commodity on earth. The more truth we have to work with, the richer we become.”

-Kurt Vonnegut
Introduction

The collection of theoretical models predicting $Z'$ gauge bosons has been described as “one of the best motivated extensions of the Standard Model” [1]. In this thesis, a search for resonances from such a boson is presented. In this particular search, the $Z'$ would be produced from proton collisions and would decay to a tau-antitau pair. This dissertation comprises five chapters which detail the analysis or present relevant background information.

The first two chapters present the physics theory relevant to the $Z'$ search. In chapter 1, the Standard Model describing the experimentally-verified theories of fundamental particles is discussed. This includes details of the particles it models, the interactions between them, and several phenomena that it fails to explain. In chapter 2, theories beyond the scope of the Standard Model are presented, with particular emphasis on theories that include $Z'$ bosons. The basic physics behind $Z'$ interactions is presented as well as examples of models with one or more $Z'$ bosons. Previous searches for $Z'$ bosons and their results are also summarized.

The last three chapters present the experimental information relevant to the analysis. Chapter 3 describes the functionality of the experimental hardware: the accelerator used to accelerate and collide the protons and the ATLAS detector used to observe events from proton collisions. It also describes how data from ATLAS is collected, cleaned for defect removal, and sent to computer centers throughout the world to be used in multiple simultaneous analyses. Chapter 4 details the processes used at ATLAS to reconstruct tau lepton decays and discriminate taus from various backgrounds. The methods used to select events with taus in data are also discussed, as well as how the information
from tau candidates can be used to find defects within data. The details of the $Z' \to \tau\tau$ search are finally presented in chapter 5. These include details of the procedure as well as the results and conclusions. Although all search channels are covered, extra supporting material is included for the two $\tau_{\text{lep}}\tau_{\text{had}}$ channels, the search channels on which I primarily worked. This material is found in the appendices.
Chapter 1

The Standard Model

The Standard Model (SM) is a gauge theory describing the most fundamental known particles and forces and the nature of their interactions [2–5]. This theory was developed during the 1960’s and 1970’s and has since been supported by experimental discoveries and measurements consistent with its predictions. The Standard Model comprises 17 particles: 12 fermion matter particles, 4 force-carrying gauge bosons, and one Higgs boson.

1.1 Fermions

The fermions of the Standard Model are spin-$\frac{1}{2}$ particles that obey the Pauli Exclusion Principle. They are divided into three families (or generations) numbered I, II, and III; each containing four particles: two quarks and two leptons. Each family’s fermions have the same respective charges as the corresponding fermions in the other families, although the respective masses increase with each generation\(^1\). The first generation fermions, being the least massive, do not decay. The massive fermions of the other generations, however, can decay to lighter particles according to the rules of the Standard Model interactions.

\(^1\)While this is certainly true for heavier fermions, the neutrino masses are not yet understood well enough to conclusively declare this for them.
1.1. **FERMIONS**

### 1.1.1 Quarks

Each generation of fermions contains two particles known as quarks. Quarks are fermions that have color charge (red, blue, or green), and thus interact with each other via the strong force. They also interact with each other and other particles through the electromagnetic (EM) and weak forces. One quark in each family has an electric charge of $+\frac{2}{3}$. In order of generation, these are the up quark ($\text{mass} = 2.3 \text{ MeV}$), charm quark ($1.275 \text{ GeV}$), and top quark ($173.21 \text{ GeV}$). The other quarks have a charge of $-\frac{1}{3}$. These are the down ($4.8 \text{ MeV}$), strange ($95 \text{ MeV}$), and bottom ($4.18 \text{ GeV}$) quarks. Due to the nature of the strong force, quarks have not been observed as stand-alone particles. They are held together by gluons into composite, colorless particles known as hadrons. These are divided into baryons, consisting of three valence quarks of different colors, and mesons, which are made from a valence quark and a valence antiquark with matching color-anticolor pair. Quarks have a conservation number associated with them called baryon number. This equals $+\frac{1}{3}$ for quarks, $-\frac{1}{3}$ for antiquarks, and 0 for other fundamental particles. The baryon number of hadrons equals the sum of its constituents’ baryon numbers [6].

### 1.1.2 Leptons

The other six fermions of the Standard Model are known as leptons. Each generation has one massive lepton with electric charge $-1$ and a neutral lepton known as a neutrino, which is treated as massless. In ascending order of generation, the charged leptons are the electron ($\text{mass} = 0.51 \text{ MeV}$), muon ($105.7 \text{ MeV}$), and tau ($1.777 \text{ GeV}$). The corresponding neutrinos are simply called the electron neutrino, muon neutrino, and tau neutrino. The charged leptons interact through both the electromagnetic and weak forces, whereas neutrinos only interact via the weak force. Furthermore, only left-handed neutrinos have been observed. Each lepton flavor has its own conservation number that must be conserved during decays and collisions (i.e. an electron, muon, or tau number). This

---

2 Although it is the valence quarks and/or antiquarks that determine the quantum numbers of hadrons, each hadron may have an indefinite number of virtual (or “sea”) quarks, antiquarks, and gluons.
1.2. GAUGE BOSONS

lepton number equals +1 (−1) for lepton particles (anti-particles) of the appropriate generation and 0 for all other particles.

1.1.3 Antimatter

For each charged matter particle in the Standard Model there is a corresponding antimatter particle, or antiparticle. These antiparticles have the same mass and spin statistics as their partner matter particle but are oppositely charged. When corresponding matter and antimatter particles interact, they annihilate into neutral bosons. Although neutrinos are neutral fundamental leptons, there are also antineutrinos with helicity opposite to that of neutrinos (i.e. right-handed instead of left-handed). However, there are theories that declare neutrinos to be their own antiparticles [7].

1.2 Gauge Bosons

The Standard Model also features four spin-1 gauge bosons that mediate fundamental forces between fermions.

1.2.1 Photons

The chargeless, massless photon (γ) mediates the electromagnetic interaction. This interaction occurs between all electrically charged particles and has essentially infinite range. The rules of the electromagnetic force are governed by Quantum Electrodynamics (section 1.5).

1.2.2 Gluons

The strong interaction is mediated by the chargeless, massless gluon (g). This interaction occurs between all particles with color charge and has a range of ~10^{−15} m (about the size of a nucleon). As its name suggests, it is stronger than the other fundamental forces, particularly at low energy scales. There are eight types of gluons, corresponding to the eight orthogonal eigenstates of the gluon color octet [5]. The strong force obeys the rules of Quantum Chromodynamics (section 1.6).
1.3 HIGGS BOSON

1.2.3 W and Z

The weak force consists of two types of interactions: a charged and a neutral interaction. The charged weak current is mediated by the $W^+$ and $W^-$ bosons (charge of +1 and -1 respectively), while the neutral weak current is mediated by the electrically neutral $Z^0$ boson. Unlike the massless photon and gluons, the $W$ and $Z$ have masses of 80.4 GeV and 91.2 GeV respectively [6]. This is due to the spontaneous breaking of the electroweak (EW) symmetry (section 1.8). Because of these large masses, the weak range is very small ($\sim 10^{-18}$ m), particularly with respect to other fundamental forces. The charged weak interaction occurs between all left-handed fermions of the Standard Model, while the neutral weak interaction encompasses all SM fermions except right-handed neutrinos.

1.3 Higgs Boson

The electroweak symmetry breaking, which accounts for the non-zero $W$ and $Z$ masses, requires the presence of an additional scalar (spin-0) boson called the Higgs boson. This particle was discovered experimentally by the ATLAS and CMS experiments at the European Organization for Nuclear Research (CERN), where its discovery was announced in 2012 [8, 9]. The Higgs boson has a mass of $\approx 125.7$ GeV [6]. Although not all of its decay modes have been experimentally verified, it is believed to have couplings to all fundamental SM particles (except possibly neutrinos).

1.4 Quantum Field Theories

The nature of the interactions between fundamental particles is determined from Quantum Field Theories (QFT) [11]. According to QFT, each type of fundamental particle has a corresponding field occupying all of space. This field is characterized by a wave function over space and time (e.g. $\phi(x,t)$). Any given field has corresponding creation and annihilation operators, similar to the raising and lowering operators of the harmonic oscillator in non-relativistic quantum mechanics. When acting on a field, these creation (annihilation) operators raise (lower) the field to states with
more (fewer) particles. In this framework, the “existence” of a certain particle corresponds to its field occupying a state that is excited with respect to the lowest-energy (vacuum) state \( |0\rangle \). In this sense, particle interactions are actually interactions between their underlying fields. QFT also accounts for relativistic, in addition to quantum, phenomena.

The behavior of a wave function of a free (non-interacting) field can be derived from its Lagrangian density\(^3\), \( \mathcal{L} \), using the Euler-Lagrange equations:

\[
\partial_\mu \left( \frac{\partial \mathcal{L}}{\partial (\partial_\mu \phi)} \right) - \frac{\partial \mathcal{L}}{\partial \phi} = 0, \quad \mu = 0, 1, 2, 3 \tag{1.1}
\]

where \( \partial_\mu = \frac{\partial}{\partial x^\mu} \).\(^4\) Different Lagrangians are used for scalar, spin-\(\frac{1}{2}\) fermion, and higher-order fields. One important property of the Lagrangians for Standard Model processes is that they are gauge theories: they are invariant under certain local transformations applied to the fields. In order to maintain gauge invariance, some additional terms that involve interactions between different fields

\(^3\)For the remainder of the text, Lagrangian density will be referred to as Lagrangian for short, not to be confused with the proper Lagrangian \( L = \int d^4x \mathcal{L} \).

\(^4\)\(x^\mu\) is the relativistic four-vector for space-time: \((x^0, x^1, x^2, x^3) = (t, \mathbf{x})\).
must be included in the Lagrangian. These terms dictate the type of interactions that are allowed to take place. If the interaction terms’ coefficients (also called couplings) are small, then the interaction strengths are low. These interactions can then be treated as perturbations of the free field theory. In this framework, the cross sections of particle interactions and particle decay rates can be determined by evaluating the Feynman diagrams of the possible configurations of the interaction (more details on this in appendix A).

1.5 Quantum Electrodynamics (QED)

The quantum field theory describing interactions between photons and charged fermions is called Quantum Electrodynamics (QED). The laws of these interactions are derived from the QED Lagrangian:

\[
\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}(x)(i\gamma^{\mu} D_{\mu} - m)\psi(x)
\]

\[
= -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}(x)(i\gamma^{\mu}(\partial_{\mu} + iqA_{\mu}) - m)\psi(x)
\]

\[
= -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}(x)(i\gamma^{\mu}\partial_{\mu} - m)\psi(x) - q\bar{\psi}\gamma^{\mu}\psi A_{\mu}
\]

\[
= \mathcal{L}_{\text{Maxwell}} + \mathcal{L}_{\text{Dirac}} - q\bar{\psi}\gamma^{\mu}\psi A_{\mu}
\]

(1.2)

Here, \( q = Qe \) is the coupling term as well as the fermion particle’s charge (\( e \) being the positron charge). \( \mathcal{L}_{\text{Maxwell}} \) and \( \mathcal{L}_{\text{Dirac}} \) are the free Lagrangians for photon (\( A^\mu \))\(^5\) and charged fermion (\( \bar{\psi} \) or \( \psi \)) fields respectively. With the additional interaction term \( \mathcal{L}_{\text{Int.}} = -q\bar{\psi}\gamma^{\mu}\psi A_{\mu} \) included, the Lagrangian is invariant under the local field transformations

\[
\psi(x) \rightarrow \psi'(x) = e^{-iq\alpha(x)}\psi(x) \quad \text{and} \quad A_{\mu}(x) \rightarrow A'_{\mu}(x) = A_{\mu}(x) + \partial_{\mu}\alpha(x)
\]

(1.3)

making this a gauge theory with \( U(1) \) symmetry. This term may also be written as

\[
\mathcal{L}_{\text{int}} = -qj^{\mu}A_{\mu} = -eJ_{Q}^{\mu}A_{\mu}
\]

(1.4)

\(^5\)In the kinetic term, \( F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu \).
1.5. QUANTUM ELECTRODYNAMICS (QED)

where \( j^\mu \equiv \bar{\psi} \gamma^\mu \psi \) is the conserved Noether current of the free Dirac field Lagrangian\(^6\). The presence of this term allows for interactions between the photon and charged fermion fields. In particular, each interaction must have one incoming fermion (or outgoing antifermion), one outgoing fermion (or incoming antifermion), and one photon. Such an interaction is represented by the following Feynman vertex:

\[
-\imath q \gamma^\mu
\]

Several physical processes with this QED vertex are shown in figure 1.2.

\[\text{Figure 1.2: Several processes involving QED interactions, including (a) electron-electron (Møller) scattering, (b) electron-positron (Bhabha) scattering, (c) electron-photon (Compton) scattering, (d) pair annihilation, and (e) pair production. Time propagates from left to right in these diagrams.}\]

One important feature of QED is its behavior from loop corrections to Feynman diagrams. Following the Feynman rules for loops, the loop momentum must be integrated to infinity (or some large cutoff scale \( \Lambda \) where the theory breaks down). These corrections diverge logarithmically with \( \Lambda \).

\(^6qj^\mu \) is also the electromagnetic four-current \((\rho, j)\)
1.6. QUANTUM CHROMODYNAMICS (QCD)

However, this divergence can be absorbed into the coupling term by a process called renormalization. This will yield the coupling measured in the laboratory. There is still a finite correction term (a function of $Q^2 \propto |p|^2$, the incoming fermion’s momentum squared) from the loop diagrams. This can also be absorbed into the coupling, creating the running coupling term, $q(Q^2)$. In the example of the vacuum polarization\footnote{For QED, this refers to corrections from single-\check f \bar f loops bisecting photon propagators.} with $Q^2 \gg m^2$, the running fine structure constant is given by

$$
\alpha(Q^2) = \frac{q^2(Q^2)}{4\pi} = \frac{\alpha(0)}{1 - \frac{\alpha(0)}{4\pi} \ln \frac{Q^2}{m^2}}
$$

with $\alpha(0) = \frac{q^2(0)}{4\pi} \approx \frac{1}{137}$ for electrons. Since $\alpha(0)$ is very small, most QED processes can be characterized accurately by lower-order diagrams, particularly at low energies. Even at the scale of the $Z$ mass ($\sim 90 \text{ GeV}$), $\alpha(M_Z^2) \approx \frac{1}{129}$, which is only about 6\% larger than $\alpha(0)$. However small the perturbation may be, it is important to note that the coupling, and thus the charge $q$, always increases at shorter distances (higher energies), with a well-defined lower limit as $r \to \infty$.

1.6 Quantum Chromodynamics (QCD)

Quantum Chromodynamics (QCD) is the gauge theory governing interactions between particles that have the property of color. Color has three states: red, blue, and green. These color eigenstates can be represented by three linearly independent three-component vectors. Gluons, the carriers of the strong force, each have a color and anti-color state. There are eight states of gluons, corresponding to eight possible gluon states from the gluon octet\footnote{There is a ninth state called the gluon singlet. This state is colorless and can not mediate interactions between colored particles.}. Each gluon state has a corresponding $3 \times 3$ matrix, one of the eight Gell-Mann $\lambda$ matrices. These matrices are the generators for $SU(3)$, which is the symmetry of color interactions in the Standard Model.
1.6. QUANTUM CHROMODYNAMICS (QCD)

The QCD Lagrangian takes the form:

\[
\mathcal{L} = \sum_f \bar{q}_f(x) (i \gamma^\mu \partial_\mu - m_f) q_f(x) - \frac{1}{4} G^a_{\mu \nu} G^{a \mu \nu} - \frac{g_s}{2} \langle \bar{q}_\lambda \gamma^\mu \lambda_a q \rangle G^a_\mu \\
= \mathcal{L}_{\text{Dirac}} \text{(quarks)} + \mathcal{L}_{Yang-Mills} + \mathcal{L}_{\text{Quark-Gluon-Int}} \tag{1.5}
\]

This Lagrangian is invariant under the following transformations to the quark and gluon fields:

\[
q \rightarrow q' = (1 + i \alpha_a \lambda^a) q \quad \text{and} \quad G^a_\mu \rightarrow G'^a_\mu = G^a_\mu - \frac{1}{g_s} \partial_\mu \alpha_a - f_{abc} \alpha_b G^c_\mu
\]

where \( f_{abc} = \text{Tr} \left[ \lambda^a, \lambda^b \right] \lambda^c / 4i \). This invariance defines the SU(3) symmetry for this gauge theory.

The QCD Lagrangian bares some resemblance to the QED Lagrangian, but with several key distinctions. First, the quark-gluon interaction term is summed over the eight states of \( \lambda \) matrices and gluons. This allows for eight different Feynman vertices with the following pattern:

These vertices equate to 0 unless color and quark flavor are conserved. Another distinctive feature of the QCD Lagrangian is the Yang-Mills component. QCD is a non-abelian gauge theory, meaning the gluon field terms don’t commute, so even though the Yang-Mills Lagrangian resembles the Maxwell Lagrangian, each \( G^a_\mu \) has an extra term

\[
G^a_\mu = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g f_{abc} G^b_\mu G^c_\nu
\]

which, given the expanded Lagrangian, allows for 3-gluon and 4-gluon interaction terms:
When calculating loop corrections, virtual gluon bubbles with these types of vertices must be
counted in addition to quark-antiquark loops. A running coupling constant can be defined similarly
to QED. For vacuum polarization\(^9\) with \(Q^2 \gg \Lambda^2 (\Lambda \sim 200-300 \text{ GeV})\), the strong running coupling
constant is
\[
\alpha_s(Q^2) = \frac{\alpha_s(Q^2)}{4\pi} = \frac{\alpha_s(\mu)}{1 + \frac{\alpha_s(\mu^2)}{12\pi} (33 - 2f) \ln \frac{Q^2}{\mu^2}} = \frac{12\pi}{(33 - 2f) \ln \frac{Q^2}{\mu^2}}
\]
where \(f\) is the number of quark flavors. Since this does not exceed \(\frac{33}{2}\), \(\alpha_s(Q^2)\) is actually smaller
at larger energy scales. This property is called asymptotic freedom. Since there is no convenient
minimum around which to perform this perturbation as in QED, it must be done at some arbitrary
scale \(\mu^2\) (or \(\Lambda^2\))\(^10\) large enough to make the perturbation valid. At high enough energies, quarks
and gluons will interact very weakly and exist as a quark-gluon plasma\(^12\).

To accompany asymptotic freedom, QCD has a related property called confinement. This means
that as the interaction distances goes to infinity, the strong potential increases rather than disappears.
Although there is no analytical explanation for this, it has been observed that colored particles
don’t exist freely in nature and are confined within colorless baryons and mesons. This has made
it impossible thus far to observe free quarks and gluons, or partons. However, due to asymptotic
freedom, the partons confined within hadrons can be modeled as very weakly interacting. This has
made it possible to model the behavior of hadrons and their constituent partons.

1.7 Weak Interactions

Since weak interaction theories include massive bosons, they are neither gauge invariant nor renor-
malizable. Although the electroweak Lagrangian introduces additional terms that solve these issues,
\(^9\)For QCD, this refers to corrections from single-\(q\bar{q}\) OR single-\(gg\) loops bisecting gluon propagators.
\(^{10}\)\(\Lambda \equiv \mu \exp \left(\frac{6\pi}{33 - 2f} \frac{\mu^2}{\mu_0^2}\right)\)
1.7. WEAK INTERACTIONS

the standalone weak Lagrangians are still viable for tree-level diagrams with low-momentum boson propagators.

1.7.1 Charged Current Interaction

The interaction of the $W^+$ and $W^-$ with fermions is derived from the interaction Lagrangian:

$$\mathcal{L} = -\frac{g_w}{2\sqrt{2}} \left( J_W^{\mu} W_{\mu}^- + J_W^{\dagger \mu} W_{\mu}^+ \right)$$ (1.6)

where $J_W^{\mu}$ is the charge-raising current, given by

$$J_W^{\mu} = \left( \bar{e}_{\nu} \gamma_{\mu}^{\nu} \gamma^\mu \left( 1 - \gamma^5 \right) \left( \begin{array}{c} e \\ \mu \\ \tau \end{array} \right) + \left( \bar{\nu} \gamma_{\tau} \right) \gamma^\mu \left( 1 - \gamma^5 \right) V_{\text{CKM}} \left( \begin{array}{c} d \\ s \\ b \end{array} \right) \right)$$ (1.7)

and $J_W^{\dagger \mu}$ is its hermitian conjugate, the charge-lowering operator. Here, $g_w = \sqrt{4\pi\alpha_w}$ is the weak coupling. $V_{\text{CKM}}$ is the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix which rotates the quark mass eigenstates $d$, $s$, and $b$ to weak eigenstates states $d'$, $s'$, and $b'$. The factor of $\frac{1-\gamma^5}{2}$, the left-handed projection operator, gives the current a $V-A$ (vector minus axial-vector) form, which means it maximally violates parity $P$ and charge conjugation $C$ (although $CP$ is conserved). It also means that $W^\pm$ only mediate interactions between fermions with left-handed chirality, $\psi_L$.

As photons and gluons respectively mediate interactions between fermions with electric charge and color charge, the weak-current bosons mediate interactions between fermions with a characteristic called weak isospin, a chiral $SU(2)$ property modeled similarly to spin. This will be discussed further under electroweak unification, but for now it suffices to say that only left-handed fermions and right-handed antifermions have non-zero weak isospins. The z-components of fermion weak isospins ($I_3$) are detailed in table 1.1.

At each charged weak vertex,
1.7. WEAK INTERACTIONS

<table>
<thead>
<tr>
<th>Fermion Type</th>
<th>Weak Isospin ($I_3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u, c, t$</td>
<td>$+1/2$</td>
</tr>
<tr>
<td>$d, s, b$</td>
<td>$-1/2$</td>
</tr>
<tr>
<td>$\nu_e, \nu_\mu, \nu_\tau$</td>
<td>$+1/2$</td>
</tr>
<tr>
<td>$e, \mu, \tau$</td>
<td>$-1/2$</td>
</tr>
</tbody>
</table>

Table 1.1: Weak Isospins of left-handed fermions. Right-handed antifermions have the opposite weak isospin as their left-handed fermion partners. Right-handed fermions and left-handed antifermions have weak isospin of 0.

The weak isospin must be conserved, but also flipped from the incoming to outgoing fermion. This gives $W^\pm$ a weak isospin of $\pm 1$. As the charged current Lagrangian dictates, each incoming (outgoing) charged lepton must share a vertex with an outgoing (incoming) neutrino of the same flavor and the appropriately charged $W$. As for quark interactions, a positively-charged quark can share a vertex with a negatively charged quark from any generation, although the vertex gains a factor of the appropriate element from the CKM matrix.

Experimental measurements have determined that at low energy, $\alpha_w \approx 29.5^{-1}$, which is larger than the electromagnetic fine structure constant. However, because the $W^\pm$ has non-zero mass, each vertex gains a factor of $\sim M_W^{-1}$, which is why the interaction is so weak. In fact, under the low momentum scenario ($|Q|^2 \ll M_W^2$), the $W^\pm$ exchange is effectively a four-fermion interaction characterized by

$$-\frac{g_w}{2\sqrt{2}} \gamma^\mu \left(1 - \gamma^5\right)$$

where the coupling term $\frac{G_F}{\sqrt{2}} = \frac{g_w^2}{8M_W^2}$. Here, the fermi constant $G_F = 1.166367 \times 10^{-5}$ GeV$^{-2}$. 

$$-L_{CC}^{\mu} = \frac{G_F}{\sqrt{2}} J_W^\mu J_W^\mu$$

(1.8)
1.7. WEAK INTERACTIONS

1.7.2 Neutral Current Interaction

The neutral weak mediator $Z$ interacts with fermions according the weak neutral current (WNC) interaction:

$$\mathcal{L} = -\frac{g_Z}{2} J^\mu_Z Z_\mu$$  \hspace{1cm} (1.9)

where $g_Z$ is the WNC coupling term and the current $J^\mu_Z$ is given by

$$J^\mu_Z = \bar{u}_L \gamma^\mu u_L - \bar{d}_L \gamma^\mu d_L + \bar{\nu}_L \gamma^\mu \nu_L - \bar{\tau}_L \gamma^\mu \tau_L - 2 \sin^2(\theta_W) J^\mu_Q$$  \hspace{1cm} (1.10)

In this current, $\theta_W$ is called the Weinberg angle ($\sin^2 \theta_W = 1 - \frac{M_Z^2}{M_W^2} = 0.2314$) and $J^\mu_Q$ is the electromagnetic current mentioned in eq. 1.4:

$$J^\mu_Q = \frac{2}{3} \bar{u} \gamma^\mu u - \frac{1}{3} \bar{d} \gamma^\mu d - \bar{\nu} \gamma^\mu \nu$$  \hspace{1cm} (1.11)

Because the WNC contains both V–A terms and pure vector terms, parity is violated, but not maximally. This means that the neutral weak vertex takes the modified form

$$-i \frac{g_Z}{2} \gamma^\mu (c_V - c_A \gamma^5)$$

where the coefficients $c_V$ and $c_A$ are summarized in table 1.2.

<table>
<thead>
<tr>
<th>fermion</th>
<th>$c_V$</th>
<th>$c_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$, $\nu_\mu$, $\nu_\tau$</td>
<td>$\frac{1}{2}$</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>$e$, $\mu$, $\tau$</td>
<td>$-\frac{1}{2} + 2 \sin^2 \theta_W$</td>
<td>$-\frac{1}{2}$</td>
</tr>
<tr>
<td>$u$, $c$, $t$</td>
<td>$\frac{1}{2} - \frac{4}{3} \sin^2 \theta_W$</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>$d$, $s$, $b$</td>
<td>$-\frac{1}{2} + \frac{2}{3} \sin^2 \theta_W$</td>
<td>$-\frac{1}{2}$</td>
</tr>
</tbody>
</table>

Table 1.2: Vector and Axial Coefficients for the Neutral Weak Vertex
1.8. **ELECTROWEAK UNIFICATION**

Similarly to the photon in QED, the $Z$ does not carry electric charge $Q$ or weak isospin $I_3$, so the incoming fermion must be the same type as the outgoing fermion at each vertex. Like the charged weak interaction, the strength of the interaction is limited not by the coupling $g_Z$, but by the mass of the boson. Under the low momentum scenario, the $Z$-exchange also becomes an effective four-fermion interaction

$$-\mathcal{L}_{\text{eff}}^{NC} = \frac{G_F}{\sqrt{2}} J_{Z\mu} J^\mu_{Z}$$

with the same effective coupling as the low-momentum charged current: $G_F = \frac{g^2}{8M_W^2} = \frac{g^2}{8M_Z^2}$.

### 1.8 Electroweak Unification

Although weak theory holds at tree level in low momentum cases, fundamental masses for $W^\pm$ and $Z$ bosons violate gauge invariance and lead to non-renormalizable divergences in loop corrections, which makes the theory meaningless in the general case. This problem has been solved by unifying electromagnetism and weak interactions into a gauge-invariant theory called the Glashow-Weinberg-Salam model. Glashow first developed a gauge theory with $SU(2) \times U(1)$ symmetry including four massless gauge bosons and massless fermions [13]. Weinberg and Salam then independently showed that through the processes of spontaneous symmetry breaking (SSB) and the Higgs Mechanism, these states would mix and three boson states would acquire effective mass terms along with the fermion states [14, 15]. It was later shown by ’t Hooft that this electroweak theory is renormalizable, and thus valid for modeling electromagnetic and weak interactions [16].

#### 1.8.1 Glashow-Weinberg-Salam Model

The unified electroweak theory is based on the gauge group $SU(2)_L \times U(1)_Y$. $SU(2)_L$ is the symmetry for weak isospin $I$, briefly mentioned in section 1.7.1. This symmetry has generators $T^i = \frac{1}{2} \tau^i$ ($i = 1,2,3$), where $\tau^i$ are the three Pauli matrices. The gauge fields for this symmetry are $W^i_{\mu}$ ($i = 1,2,3$). This is a chiral symmetry which only applies to left-handed fermions. These fermions have $I = 1/2$,
with eigenvalues for the z-component $I_3$ listed in table 1.1. The $U(1)_Y$ refers to the symmetry of weak hypercharge $Y = 2(Q - I_3)$, which yields different eigenvalues for left- and right-handed fermions. The corresponding gauge field is $B_\mu$.

Due to the chiral nature of the electroweak theory and transformations under $SU(2)_L$, left- and right-handed fermions are represented differently. Left-handed fermion states are represented as $SU(2)$ doublets:

$$ q^0_{mL} = \begin{pmatrix} u^0_m \\ d^0_m \end{pmatrix}_L, \quad \nu^0_{mL} = \begin{pmatrix} \nu^0_m \\ \epsilon^0_m \end{pmatrix}_L$$ (1.13)

while right-handed fermions are given the singlet representation:

$$ u^0_mR, \quad d^0_mR, \quad \nu^0_mR, \quad \epsilon^0_mR $$ (1.14)

In this notation, $m$ is the family index ($m = 1, 2, 3$) and the $0$ superscript refers to these states being the weak eigenstates.

In order to utilize spontaneous symmetry breaking, a scalar field $\phi(x)$, also called the Higgs field, is included. This takes the form of a complex scalar $SU(2)$ doublet:

$$ \phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}, \quad \phi_{1,2,3,4} \text{ real} $$ (1.15)

with $Y = 1$ ($Q = +1$ for the top element, 0 for the bottom).

The $SU(2)_L \times U(1)_Y$ symmetry calls for invariance under the following gauge transformations:

$$ \phi \to e^{i\alpha(x)}e^{\frac{i}{2} + i\beta(x)Y}\phi, \quad \psi_L \to e^{i\alpha(x)}e^{\frac{i}{2} + i\beta(x)Y}\psi_L, \quad \psi_R \to e^{i\beta(x)Y}\psi_R, $$

$$ W^i_\mu \to W^i_\mu - \frac{1}{g} \partial_\mu \alpha_i - \epsilon_{ijk} \alpha^j W^k_\mu, \quad B_\mu \to B_\mu - \frac{1}{g} \partial_\mu \beta $$ (1.16)
where \( g \) (\( g' \)) is the weak isospin (hypercharge) coupling and \( \epsilon_{ijk} \) is the antisymmetric Levi-Civita tensor. The Electroweak Lagrangian satisfying this invariance can be broken up into four terms:

\[
\mathcal{L} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_f + \mathcal{L}_\phi + \mathcal{L}_{\text{Yuk}}
\]

The first is the gauge term given by

\[
\mathcal{L}_{\text{gauge}} = -\frac{1}{4} W_{\mu i} W^{\mu i} - \frac{1}{4} B_{\mu \nu} B^{\mu \nu}
\]

Here, the field strength tensors are

\[
W_{\mu i} = \partial_\mu W^i - \partial_i W_\mu - g\epsilon_{ijk} W^j W^k
\]

\[
B_{\mu \nu} = \partial_\mu B_\nu - \partial_\nu B_\mu
\]

The next term is the fermion Lagrangian given by

\[
\mathcal{L}_f = \sum_m \left( \tau^0 \bar{l}_m L^0 + \tau^0 \bar{d}_m D^0 + \tau^0 \bar{u}_m u^0 + \bar{\tau}^0 \bar{e}_m e^0 \right)
\]

The gauge covariant derivative \( D_\mu \) expands to

\[
D_\mu \psi^L_R = \begin{cases} 
\left( \partial_\mu + i \frac{g}{2} \tau^i W^i_\mu + i \frac{g'}{2} Y B_\mu \right) \psi^L_R \\
\left( \partial_\mu + i \frac{g'}{2} Y B_\mu \right) \psi^R
\end{cases}
\]

The third term is the scalar part of the Lagrangian

\[
\mathcal{L}_\phi = \left( D^\mu \phi \right)^\dagger D_\mu \phi - V(\phi)
\]
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The gauge covariant derivative is

\[ D_\mu \phi = \left( \partial_\mu + i \frac{g}{2} \tau^i W^i_\mu + i \frac{g'}{2} B_\mu \right) \phi \]  \hspace{1cm} (1.23)

and the Higgs potential \( V(\phi) \) is limited to the form

\[ V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad \lambda > 0 \]  \hspace{1cm} (1.24)

due to gauge invariance, renormalizability, and vacuum stability requirements.

The final Lagrangian term is the Yukawa interaction

\[
\mathcal{L}_{\text{Yuk}} = -\sum_{m,n} \left[ \Gamma^u_{mn} \overline{U}^0 \Gamma^\dagger (i\tau_2 \phi^\dagger) u^0_{nR} + \Gamma^d_{mn} \overline{U}^0 \phi^0_{nR} + \Gamma^e_{mn} \overline{U}^0 \phi^0_{nR} \right] + h.c.
\]  \hspace{1cm} (1.25)

which couples the Higgs to fermions. This is added to account for fermion masses, since fundamental fermion masses would break gauge invariance. The \( 3 \times 3 \) \( \Gamma \) matrices determine the eventual fermion masses and mixings of fermion states.

1.8.2 Spontaneous Symmetry Breaking and Higgs Mechanism

The scalar Higgs field is bound by the potential given by equation 1.24. Using the representation defined in equation 1.15, this potential can be expressed as

\[ V(\phi) = \frac{\mu^2}{2} \left( \sum_{i=1}^{4} \phi_i^2 \right) + \frac{\lambda}{4} \left( \sum_{i=1}^{4} \phi_i^2 \right)^2 \]  \hspace{1cm} (1.26)

The orientation of the fields \( \phi_i \) can be selected so that without loss of generality, \( \langle 0 | \phi_i | 0 \rangle = \nu \geq 0 \) for \( i = 3 \) and 0 for all other \( i \). This gives \( \phi \) a vacuum expectation value (VEV) of \( \nu = \frac{1}{\sqrt{2}} \left( \begin{array}{c} 0 \\ \nu \end{array} \right) \)
where $\nu$ minimizes the potential

$$V(\nu) = \frac{1}{2} \mu^2 \nu^2 + \frac{1}{4} \lambda \nu^4 \quad (1.27)$$

In the case of $\mu^2 < 0$, the solution is $\nu^2 = -\frac{\mu^2}{\lambda} \neq 0^{12}$. Since $V$ becomes unstable at $\phi = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$, the fields $\phi_i$ become perturbations around $\nu$ when energy is sufficiently low:

$$\phi_3(x) = \nu + H(x), \quad \phi_{i \neq 3}(x) = \xi_i(x) \quad (1.28)$$

Using the Higgs mechanism, a gauge transformation is chosen that removes the massless Goldstone boson fields $\xi_i^{13}$, so the Higgs field takes the form

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + H \end{pmatrix} \quad (1.29)$$

Because $I_i \nu \neq 0$ and $Y \nu \neq 0$, the field is no longer invariant under $1.16$ and the $SU(2)_L \times U(1)_Y$ symmetry is spontaneously broken. However, since $Q \nu = 0$, the $U(1)_Q$ symmetry of QED remains intact and the associated photon field $A_\mu$ acquires no mass.

### 1.8.3 Final Electroweak Lagrangian

After spontaneous symmetry breaking, the covariant kinetic scalar Lagrangian becomes

$$(D^\mu \phi)^\dagger D_\mu \phi = \frac{1}{2} (0 \nu) \left[ \frac{g^2}{2} \tau^I W^I_\mu + \frac{g}{2} B_\mu \right]^2 \begin{pmatrix} 0 \\ \nu \end{pmatrix} + H \text{ terms} \quad (1.30)$$

The charged $W^\pm_\mu$ fields are expressed as linear combinations of $W^1_\mu$ and $W^2_\mu$:

$$W^\pm_\mu = \frac{W^1_\mu \mp iW^2_\mu}{\sqrt{2}} \quad (1.31)$$

---

12 Experiments have determined that $\nu \approx 246$ GeV.

13 In actuality, the degrees of freedom from the Goldstone bosons translate to the longitudinal degrees of freedom of the now-massive gauge fields.
while \( Z_\mu \) and \( A_\mu \) are a rotation of \( W_3^\mu \) and \( B_\mu \) by \( \theta_W \equiv \tan^{-1} \frac{e_9'}{g} \):

\[
\begin{pmatrix}
Z_\mu \\
A_\mu
\end{pmatrix} = \begin{pmatrix}
\cos \theta_W & -\sin \theta_W \\
\sin \theta_W & \cos \theta_W
\end{pmatrix}
\begin{pmatrix}
W_3^\mu \\
B_\mu
\end{pmatrix}
\]  

(1.32)

Ignoring the Higgs terms, this Lagrangian component becomes the mass terms for \( W^\pm \) and \( Z \):

\[
M_W^2 W^\pm_\mu W^-_\mu + \frac{M_Z^2}{2} Z_\mu Z_\mu
\]

(1.33)

When paired with the new representation of \( \mathcal{L}_{\text{gauge}} \),

\[
-\frac{1}{2} W^+_\mu W^-_{\mu \nu\rho} - \frac{1}{4} Z_{\mu \nu} Z^{\mu \nu} - \frac{1}{4} A_{\mu \nu} A^{\mu \nu}
\]

(1.34)

there are now three massive and one massless gauge boson. The rest of \( \mathcal{L}_\phi \) yields terms for the physical Higgs \( H \) with a mass \( m_H = \sqrt{-2\mu} \):

\[
\frac{1}{2} (\partial_\mu H)^2 + \mu^2 H^2 + \text{self-couplings} + \text{couplings to } W, Z + \text{constant}
\]

(1.35)

Similarly, the Yukawa interaction, now written as

\[
\mathcal{L}_{\text{Yuk}} = -\left[ \bar{\psi} \Gamma^\mu \left( \frac{\nu + H}{\sqrt{2}} \right) u_R + \text{h.c.} \right] + \mathcal{L}_{\text{Yuk}}(d) + \mathcal{L}_{\text{Yuk}}(\nu) + \mathcal{L}_{\text{Yuk}}(e)
\]

(1.36)

yields mass terms for fermions. Unitary transformations from fermion weak eigenstates \( \psi^0 \) to mass eigenstates \( \psi \) will diagonalize the matrices \( \frac{\nu^0}{\sqrt{2}} \) to yield the fermion mass eigenvalues, which (within a factor of \( \nu^{-1} \)) are also the couplings of fermions to \( H \). When the fermion mass terms are combined with \( \mathcal{L}_f \), this yields the Dirac Lagrangian \( \mathcal{L}_{\text{Dirac}} \) plus the fermion-gauge interaction terms:

\[
-\frac{g}{\sqrt{2}} \left( J^\mu_W W^-_\mu + J^\mu_W W^+_\mu \right) - g \sin \theta_W J_Q^\mu A_\mu - \frac{g}{2 \cos \theta_W} J^\mu_Z Z_\mu.
\]

(1.37)
When compared to equations 1.4, 1.6, and 1.9, it is clear that $g_w = g$, $e = g \sin \theta_W$, and $g_Z = \frac{g}{\cos \theta_W}$.

The SM Lagrangian terms not explicitly written are interactions of the gauge and Higgs fields with themselves and each other. The interactions made possible by these terms are listed in table 1.3.

<table>
<thead>
<tr>
<th>Higgs-Gauge</th>
<th>$W^+ W^- H$, $ZZH$, $W^+ W^\mp H^2$, $ZZH^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higgs-self</td>
<td>$H^3$, $H^4$</td>
</tr>
<tr>
<td>Gauge-self</td>
<td>$W^+ \gamma W^-$, $W^+ Z W^-$, $W^+ W^- W^-$, $W^+ \gamma Z W^-$, $W^+ \gamma \gamma W^-$, $W^+ Z Z W^-$</td>
</tr>
</tbody>
</table>

Table 1.3: Possible Standard Model Interactions Involving the Gauge and/or Higgs Fields

### 1.9 Shortcomings of the Standard Model

The electroweak unification successfully incorporates weak and EM interactions under a single gauge-invariant, renormalizable model. When quark states are distinguished by color and gluon gauge and gluon-quark interaction terms are added to the electroweak model, this yields the full Standard Model Lagrangian with $SU(3)_c \times SU(2)_L \times U(1)_Y$ symmetry. This theory has been highly successful with experimental predictions and is almost certainly the correct description of elementary particles down to $\sim 10^{-18}$ m. However, the Standard Model has several arbitrary factors without explanations. This may be an implication that it is not the final model of fundamental physics. Such issues include, but are not limited to:

**Unification and Gauge Symmetry Problems** The Standard Model consists of three distinct symmetries with distinct couplings. If a single, overarching symmetry exists, it would be expected that the running couplings converge at some scale where these three symmetries become embedded into one. However, measurements have shown that no such convergence point exists [17]. Furthermore, there is no explanation for imbalances such as the $P$ and $C$ violation in weak interactions.
1.9. SHORTCOMINGS OF THE STANDARD MODEL

Hierarchy Problem The Higgs mass squared has been experimentally determined to be $m_H^2 \approx (125.7 \text{ GeV})^2$. However, loop corrections to the theoretical tree-level (or bare) $m_H^2$ diverge quadratically with the cutoff scale $\Lambda (\sim 10^{16} \text{ GeV} \text{ for Grand Unification Theories})$. This would mean that $m_{H,\text{bare}}^2 \sim 10^{32} \text{ GeV}^2$ and the correction provides a finely tuned cancellation. Many theorists find such a correction to be a contrived explanation and evidence of an incomplete theory.

Fermion Problem The Standard Model provides no explanation as to why fermions are arranged in at least three families and why the later families are heavier copies of the first. There is also no prediction of the fermion masses, which span over five orders of magnitude.

There are also several observed physical phenomena that are absent from the Standard Model altogether, such as:

Gravity This is the only known fundamental force not incorporated into the Standard Model. The effects of gravity at the electroweak scale $\nu$ are practically negligible, but are expected to become significant at the Planck Scale ($\sim 10^{19} \text{ GeV}$).

Neutrino Masses Neutrinos have been observed to oscillate in flavor, which requires mixing with non-zero mass states. Observations have established that indeed, $m_\nu \sim 0.1 \text{ eV}$. This contradicts the Standard Model which treats neutrinos as massless [18].

Baryon Asymmetry The Standard model does not fully account for the observed imbalance of baryons and anti-baryons in the universe.

Dark Matter and Dark Energy Matter described by the Standard Model is called baryonic matter. Observations of cosmological phenomena such as the expanding universe, the cosmic microwave background radiation, and gravitation effects of galaxies have determined that this only accounts for 5% of the energy in the universe, the rest being dark matter (27%) and dark energy (68%) [19].
Chapter 2

Z’ Physics and Theories Beyond the Standard Model

Although the Standard Model has been successful in many respects, it falls short in several areas (section 1.9). Many theoretical models that extend beyond the Standard Model’s reach have been developed to address these issues. Several of these models contain one or more additional neutral gauge bosons, also known as Z’ bosons. Several direct and indirect Z’ searches have been performed using various methods. Although none of them have found evidence of Z’ bosons, they have been able to place constraints on the parameters of multiple Z’ models, thereby constraining possible “new physics” scenarios.

2.1 Physics Beyond the Standard Model

Many categories of theories attempting to describe new physics have been developed. Some of these Beyond-the-Standard-Model (BSM) theories simply expand upon the SM in order to address one or more specific issues. These include models such as supersymmetry, extended Higgs sectors, warped extra dimensions, or extended gauge groups. Other models, such as Grand Unification
and superstring theories, aim to achieve a more fundamental understanding of the unified forces of nature. Some of the more popular categories of BSM theories are presented here.

### 2.1.1 Supersymmetry

Supersymmetry (SUSY) is a theory characterized by a symmetry between bosons and fermions. According to SUSY, each SM particle \( s \) has a “superpartner” (or “sparticle”) \( \tilde{s} \) with a spin differing by \( \frac{1}{2} \). These include spin-0 lepton superpartners (sleptons) and spin-\( \frac{1}{2} \) superpartners to gauge bosons (gauginos). These sparticles have the same \( SU(3) \times SU(2) \times U(1) \) symmetry as their partner particles. Some supersymmetric models also introduce a superpartner to the spin-2 graviton: the spin-\( \frac{3}{2} \) gravitino.

Supersymmetric theories require an expansion of the Higgs sector. Although a single Higgs doublet \( \phi \) is permitted in the SM, this would lead to gauge anomalies with supersymmetric models. In the Minimal Supersymmetric Standard Model (MSSM), one of the simplest supersymmetric models, two Higgs fields are predicted:

\[
\begin{align*}
\begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix} \quad \text{and} \quad
\begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix}
\end{align*}
\]  

(2.1)

which couple to the up/neutrino and down/charged-lepton families respectively. Each of these also has a corresponding spin-\( \frac{1}{2} \) superpartner, or Higgsino. The Higgsinos are able to mix with the winos \( (\tilde{W}^i) \) and bino \( (\tilde{B}) \) to form two chargino states \( (\tilde{\chi}_{1,2}^\pm) \) and four neutralino states \( (\tilde{\chi}_{1,2,3,4}^0) \).

Supersymmetry is particularly motivated by attempts to unify gravity with other forces, but it is appealing for many other reasons as well. The loop corrections to the Higgs mass from sparticles cancel out the quadratic divergences from SM loop corrections, solving this part of the hierarchy problem. Under supersymmetry, gauge coupling unification is much more successful than the SM at high energy scales. In SUSY models that require \( R \)-parity (even number of sparticles at each

\footnote{There are actually multiple SUSY theories. The specific details of these theories vary but they all have the common theme of superpartners.}
vertex), the lightest particle is completely stable and a candidate for dark matter. SUSY also provides mechanisms for generating neutrino masses.

Although supersymmetry solves many issues with the Standard Model, it is not without its own complications. No SUSY particles have been observed, so supersymmetry must be broken at or above the 100-GeV scale, if it exists at all. Although supersymmetry provides a solution to the hierarchy problem, it introduces a tree-level version called the $\mu$ problem, in which the phenomenologically allowed range of the bare Higgs mass contradicts the range expected from cutoff-scale and extra-symmetry considerations. Furthermore, a number of conditions must be met in order to avoid reintroducing the original hierarchy problem with supersymmetry breaking. Several of these conditions require further extension of SUSY theories [20].

### 2.1.2 Grand Unification

Grand Unification Theories (GUT’s) predict that the SM symmetry $SU(3) \times SU(2) \times U(1)$ becomes embedded into a single symmetry $G$ at some large energy scale ($\sim 10^{16}$ GeV). Within this symmetry, quarks and leptons are combined in the same multiplets and the gauge interactions are unified with a single coupling. The first theory providing full SM unification was developed by Georgi and Glashow [21]. This model, which predicted that the SM symmetry was part of a larger $SU(5)$ symmetry, was eventually excluded because it predicted a proton lifetime much lower than the experimental lower limit [22]. However, many extensions to this theory are still being considered, including several models with supersymmetric extensions.

### 2.1.3 Extra Dimensions and Superstrings

Several theories introduce extra space-time dimensions in order to unify gravity with the other fundamental forces. Some of the earliest theories were developed by Kaluza and Klein, who introduced an additional, compactified spatial dimension to unify gravity with electromagnetism [23]. Although this theory ultimately failed, its basic ideas were later used to develop string theory, which predicts
2.2. STANDARD MODEL EXTENSIONS WITH Z' BOSONS

even more spacial dimensions. String theory introduces one-dimensional “strings” as the most fundamental unit of matter. Particles would then be representations of the vibrational modes. The exact number of dimensions predicted by string theory has varied over its development, but Superstring theory, which incorporates supersymmetry and includes both bosons and fermions, predicts 10 dimensions total [24].

One drawback to superstring theories is that they predict the extra dimensions to be compactified near the Planck scale, well above the energy scale currently accessible to experimentation. However, alternative theories predict extra dimensions that are testable at much lower energy scales. Some of these models predict that the weak effect of gravity is due to extra compactified dimensions in which only gravity can propagate\(^2\). These include the Arkani-Hamed, Dimopoulos, and Dvali (ADD) [25] and Universal Extra Dimensions (UED) [26] models. Other models, such as the Randall and Sundrum (RS) model [27], predict extra dimensions with warped curvatures that make them difficult to escape, particularly for gravity. Under all these theories, SM particles only experience a fraction of the gravitational force because of its propagation through the extra dimensions. Under these conditions, gravity may unify with the electroweak force at a scale as low as the TeV scale. In addition to making gravitational theories more experimentally accessible, this has the added benefit of reducing the SM cutoff scale \(\Lambda\), effectively solving the hierarchy problem. Another appealing feature of extra-dimensional theories are the excitations of the Kaluza-Klein modes: massive states resulting from the propagation of SM fields in the extra dimensions. The lightest of these states is stable and considered a candidate for dark matter [6].

2.2 Standard Model Extensions with Z' Bosons

Extensions to the Standard Model often require additional fermions and/or bosons. Several models include one or more additional neutral gauge bosons (Z'). Depending on the model, they could be massless, extremely heavy, or somewhere in between, though experimental mass limits suggest that

\(^2\)It was later shown that SM fields could propagate in these dimensions as well.
2.2. STANDARD MODEL EXTENSIONS WITH Z' BOSONS

$M_{Z'} \gtrsim 1$ TeV for any existing $Z'$. The couplings of these $Z'$ bosons to fermions enter into gauge theories via extensions to the SM electroweak neutral current (NC) Lagrangian:

$$-\mathcal{L}_{NC}^S = g J_{\mu}^W W_\mu^3 + g' J_Y^B B_\mu = e J_{\mu}^Q A_\mu + g_1 J_{\mu}^Z Z^0_{1\mu}$$  \hspace{1cm} (2.2)

where $g_1 \equiv g_Z$, $Z^0 \equiv Z$, and $J_{\mu}^Z = J_{Z'}_{\mu}/2$. The initial currents here take the general form

$$J_{\mu}^\alpha = \sum_i \bar{f}_i \gamma^\mu [Q_L^\alpha(i) P_L + Q_R^\alpha(i) P_R] f_i$$  \hspace{1cm} (2.3)

where $Q_{L(R)}(i)$ is the respective $\alpha$ charge of left-handed (right-handed) fermion $i$ and $P_{L,R}$ are the left- and right-chiral projections $(1 \mp \gamma^5)/2$. The final currents are given by equations 1.11 and 1.10, with 1.10 simplified as

$$J_{\mu}^Z = \sum_i \bar{f}_i \gamma^\mu \left[ \epsilon_{L}^1(i) P_L + \epsilon_{R}^1(i) P_R \right] f_i$$  \hspace{1cm} (2.4)

where $\epsilon_{L,R} = (c_V \pm c_A)/2$ ($c_V$ and $c_A$ are given in table 1.2). The extensions to this Lagrangian contain extra $Z$-like terms as well as their respective currents and coupling constants. These expanded Lagrangians are used to derive the properties of $Z'$ bosons as well as their couplings to other SM or BSM particles [1, 3]. The SM extensions in the following sections yield $Z'$ bosons with couplings to SM fermions.

2.2.1 SU(2) × U(1) × U(1)’

One of the simplest SM extensions containing $Z'$ is a model with a $SU(2) \times U(1) \times U(1)'$ symmetry. The extra $U(1)'$ symmetry adds an additional neutral gauge boson, expanding the NC Lagrangian in equation 2.2 to

$$-\mathcal{L}_{NC} = g J_{\mu}^W W_\mu^3 + g' J_Y^B B_\mu + g_2 J_{\mu}^Z Z^0_2 = e J_{\mu}^Q A_\mu + g_1 J_{\mu}^Z Z^0_{1\mu} + g_2 J_{\mu}^Z Z^0_{2\mu}$$  \hspace{1cm} (2.5)

$^3$In the case of mixing between $Z^0_1$ and $Z^0_2$ in $\mathcal{L}_{gauge}$ (kinetic mixing), a correction term of $-g_1 \chi J_{\mu}^Z Z^0_{2\mu}$ ($\chi$ small) is applied.
2.2. STANDARD MODEL EXTENSIONS WITH Z' BOSONS

where $Z_0^{0\mu}$ is the $Z'$ boson and the currents $J_{\mu}^{i}$ generalize to

$$J_{\alpha}^{\mu} = \sum_i \bar{f}_i \gamma^{\mu} [\epsilon_L^{\alpha}(i) P_L + \epsilon_R^{\alpha}(i) P_R] f_i = \sum_i \bar{f}_i \gamma^{\mu} [Q_{\alpha i} P_L - Q_{\alpha' i} P_R] f_i$$  \hspace{1cm} (2.6)

where $\epsilon_L^{\alpha}(i)$ is the same as in eq. 2.4 and $\epsilon_R^{\alpha}(i)$ depends on the particular $Z'$ model. The NC part of the covariant derivative for a complex $SU(2)$ Higgs scalar would become

$$D_\mu \phi_i = \left( \partial_\mu + ieQ_\mu A_\mu + i \sum_{\alpha = 1}^{2} g_\alpha Q_{\alpha i} Z_0^{0\mu} \right) \phi_i$$  \hspace{1cm} (2.7)

where $Q_\alpha$ is the charge associated with $J_{\alpha}^{\mu}$ ($Q_1 = Q_Z/2$ and $Q_2$ is the same for all members of the $SU(2)$ multiplet). When multiple Higgs scalars acquire VEV’s, the photon remains massless (assuming $Q = 0$ for each non-zero $\langle \phi_i \rangle$) and the $Z_0^{0\mu}$ acquire a mass-squared matrix:

$$M^2_{Z-Z'} = 2 \begin{pmatrix} g_1^2 \sum_i Q_1^2_i |\langle \phi_i \rangle|^2 & g_1 g_2 \sum_i Q_1_i Q_{2i} |\langle \phi_i \rangle|^2 \\ g_1 g_2 \sum_i Q_{1i} Q_{2i} |\langle \phi_i \rangle|^2 & g_2^2 \sum_i Q_2^2_i |\langle \phi_i \rangle|^2 \end{pmatrix} = \begin{pmatrix} M^2_{Z0} & \Delta^2 \\ \Delta^2 & M^2_{Z'} \end{pmatrix}$$  \hspace{1cm} (2.8)

where $M^2_{Z0}$ is the mixing-free $Z$ mass from eq 1.3. Its mass eigenvalues are

$$M^2_{1,2} = \frac{1}{2} \left[ M^2_{Z0} + M^2_{Z'} \mp \sqrt{(M^2_{Z0} - M^2_{Z'})^2 + 4\Delta^4} \right]$$  \hspace{1cm} (2.9)

and the corresponding mass eigenstates $Z_{1,2}$ are rotated from $Z_0^{0\mu}$ though the $Z-Z'$ mixing angle

$$\theta_M = \frac{1}{2} \tan^{-1} \left( \frac{2\Delta^2}{M^2_{Z'} - M^2_{Z0}} \right).$$  \hspace{1cm} (2.10)

$^4$ $Q_{\alpha'i}$ is the charge associated to $f_i^c$, the charge conjugate to left-handed fermion field $f_i$.

$^5$ After SSB, $Q_1$ simplifies to $I_3$ assuming that $Q_{E,M} = 0$ for $\langle \phi_i \rangle \neq 0$.

$^6$ The SM Higgs field alone is not sufficient to account for the degrees of freedom introduced by additional massive gauge bosons.

$^7$ Technically, this value only holds if the Higgs fields are $SU(2)$ doublets or singlets ($I_3 = \pm 1/2$ or 0). Otherwise, a correction factor $1/\rho_0(I_1, I_3, \langle \phi_i \rangle)$ is applied (calculated from nonzero $\langle \phi_i \rangle$).
Since $Z'$ bosons have not been observed, it is expected that $M_{Z'} \gg M_{Z^0}, |\Delta|^8$. In this case, the masses approximate to

$$M_1^2 \approx M_{Z^0}^2 - \frac{\Delta^4}{M_{Z'}^2} \ll M_2^2, \quad M_2^2 \approx M_{Z'}^2. \tag{2.11}$$

This downward shift in the $Z$ mass affects the value of $\theta_W$ determined from $Z$-pole measurements. The $Z-Z'$ mixing also implies corrections to the weak four-fermion interaction (eq. 1.12) as well as the vector and axial couplings of $Z_1$ to fermions (table 1.2) [1, 3].

In some cases, models may predict more than one $U(1)'$ coupled to the SM $SU(2)_L \times U(1)_Y$ symmetry. In the general case of a $SU(2) \times U(1)^N$ symmetry, the Lagrangian in eq. 2.5 generalizes to

$$- \mathcal{L}_{NC} = e J^\mu_Q A_\mu + \sum_{\alpha=1}^N g_\alpha J^\mu_\alpha Z^0_{\alpha \mu} \tag{2.12}$$

and $\alpha$ runs from 1 through $N$ in equations 2.6 and 2.7. The mass-squared matrix will be an $N \times N$ matrix with each term given by [1]:

$$M_{\alpha \beta}^2 = 2g_\alpha g_\beta \sum_i Q_{\alpha i} Q_{\beta i} |\langle \phi_i \rangle|^2. \tag{2.13}$$

### 2.2.2 $SU(N) \times SU(N)$

Several BSM models involve extensions of a Standard Model $SU(N)$ to $SU(N) \times SU(N)$, where one set of fermion fields transforms under one $SU(N)$ and a different set transforms under the other. One important feature of an $SU(N)$ symmetry is that it can be broken by a VEV of an $N \times N$ Higgs representation $\Phi$, given by

$$\Phi = \sum_{i=1}^{N^2-1} \phi_i L_i \tag{2.14}$$

where $\phi_i$ are real and $L_i$ are the fundamental $N \times N$ representation matrices, $N-1$ of which are diagonal. $\langle \Phi \rangle$ can always be diagonalized by an $SU(N)$ transformation, ensuring that the $N-1$ diagonal generators remain unbroken. This means that the unbroken subgroup will always be at

\footnote{This is also the case in theories with an $SU(2)$ singlet Higgs field with VEV $\gg \nu$ that only couples to $Z'$.}
least\(^9\) \(U(1)^{N-1}\). When the \(SU(N) \times SU(N)\) symmetry breaks to the SM \(SU(N)\), up to \(N - 1\) \(Z'\) bosons will be present. In some GUT cases, the SM symmetry will be part of an even higher symmetry, including \(SU(N)\) with \(N \geq 4\). Extending this would lead to multiple extra gauge bosons, both neutral and charged [1].

The simplest model if this type has a \(SU(2) \times SU(2)\) symmetry. In the electroweak case, \(SU(2)_1 \times SU(2)_2 \times U(1)\) breaks to \(SU(2)_L \times U(1)_Y\) through either \(SU(2) \times U(1) \rightarrow U(1)_Y\) (e.g. Left-Right Model from section 2.3.3) or \(SU(2)_1 \times SU(2)_2 \rightarrow SU(2)_L\) (e.g. Non-Universal Model from section 2.3.4). Since \(SU(2)\) has three generators, charged \(W'\) bosons are introduced in addition to a \(Z'\). Models with the \(SU(2)_1 \times SU(2)_2 \times U(1)\) gauge structure belong to a model class called \(G(221)\) [28]. This class contains several well-motivated models, some of which will be discussed in detail in the next section.

### 2.3 Examples of \(Z'\) Models

Many well-motivated BSM models contain SM extensions like those described in sections 2.2.1 and 2.2.2. These include both models with extensions that address specific SM and BSM issues (e.g. the SUSY \(\mu\) problem) and models that aim to unify fundamental forces (GUT’s). Not all \(Z'\) models will be discussed in this dissertation, but the following sections present several representative examples.

#### 2.3.1 Sequential Standard Model

The Sequential Standard Model (SSM) includes one \(Z'\) with the same couplings to fermions as the SM \(Z\). This is not a gauge invariant model, but it serves as a good basis for comparison in searches for \(Z'\) from well-motivated models. The \(Z'_{SSM}\) is the benchmark model used for the \(Z' \rightarrow \tau\tau\) search at ATLAS [1, 29].

\(^9\)The subgroup may be larger if multiple diagonal entries are equal
2.3. EXAMPLES OF $Z'$ MODELS

2.3.2 Grand Unification Theories

Although Georgi and Glashow’s $SU(5)$ theory has been excluded, other GUT’s expanding on this are still under consideration, several of them containing $Z'$ bosons. The most popular of these models (and some of the overall most popular $Z'$ models) are based on the $SO(10)$ and $E_6$ symmetries \cite{30}.

The simpler of these two symmetries is $SO(10)$, which breaks according to

$$SO(10) \rightarrow SU(5) \times U(1)'_\chi \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'_\chi$$ \hspace{1cm} (2.15)

where the $U(1)'_\chi$ symmetry indicates a single extra gauge boson $Z'_\chi$. The larger symmetry, $E_6$, is found in some superstring theories. It predicts a fundamental 27-member multiplet containing all the left-handed fermion fields, including some exotic varieties. $E_6$ breaks according to

$$E_6 \rightarrow SO(10) \times U(1)'_\psi \rightarrow SU(5) \times U(1)'_\chi \times U(1)'_\psi.$$ \hspace{1cm} (2.16)

which means that two $Z'$ states are included: $Z'_\chi$ and $Z'_\psi$, which will mix by some angle $\beta$. Of the two resulting states, the one given by

$$Z' (\beta) = Z'_\chi \cos \beta + Z'_\psi \sin \beta$$ \hspace{1cm} (2.17)

is assumed to be light (TeV scale), while the orthogonal state will likely be beyond the range of direct detection with any current experiment. Some special cases of the lighter state include $\beta = 0$ (pure $SO(10)$ $Z'_\chi$), $\beta = \frac{\pi}{2}$ (pure $E_6$ $Z'_\psi$), and $\beta = -\tan^{-1} \sqrt{\frac{2}{3}}$ ($Z'_\psi$, found in some heterotic string theories). For all $E_6$ and $SO(10)$ models, the charges of left-handed quarks and leptons (and their charge conjugates) associated with $Z'_\chi$ and $Z'_\psi$ are

$$Q^q, u^e, \bar{e} = -\frac{1}{3} Q^l_{l'}, \quad \frac{1}{5} Q^e_{e'}, \quad -\frac{1}{\sqrt{40}} \quad \text{and} \quad Q^q, q^e, \bar{e} = \frac{1}{\sqrt{24}}.$$ \hspace{1cm} (2.18)
and the coupling parameter $g_2 = \sqrt{\frac{2}{3}} g_1 \sin \theta_W$\textsuperscript{10} at the GUT scale [31, 32].

2.3.3 Symmetric Left-Right Model

One of the other most popular $Z'$ models besides the $SO(10)$ and $E_6$ GUT’s is the Symmetric Left-Right Model (LRM) [33] from the $G(221)$ class. This appears in the context of several theories, including GUT’s\textsuperscript{11} and extra-dimensional models. The electroweak component of this model has symmetry $SU(2)_L \times SU(2)_R \times U(1)_{BL}$. The $SU(2)_R$ generators $T^i_R$ are associated with right-handed weak isospins, $I^i_R$, and only yield non-zero values for right-handed fermion fields, which now transform under $SU(2)$ doublets analogous to eq. 1.13. The charge associated to $U(1)_{BL}$ is $Q_{BL} = 2(Q - I^3_L - I^3_R) = B - L$, the baryon number minus lepton number.

The NC Lagrangian in this model can be expressed as

$$- \mathcal{L}_{NC} = g J^\mu_{3L} W^3_{L\mu} + g_R J^\mu_{3R} W^3_{R\mu} + g_{BL} J^\mu_{BL} W_{BL\mu}.$$  \hspace{1cm} (2.19)

At a scale $M_{Z'}$ (assumed $\gg M_{Z''}$), $SU(2)_L \times SU(2)_R \times U(1)_{BL}$ breaks to $SU(2)_L \times U(1)_Y$ when a Higgs multiplet\textsuperscript{12} with right-handed couplings and non-zero $Q_{BL}$ acquires a VEV. The $W_{BL}$ and $W_R$ states the mix by angle $\gamma = \tan^{-1}(g_R/g_{BL})$ to the SM $B$ state (whose coupling $g'$ is given as $g_R \cos \gamma$) and a $Z_2^0$ state with charge

$$Q_{LR} = \sqrt{\frac{3}{5}} \left( \alpha I^3_{3R} - \frac{1}{2\alpha} Q_{BL} \right)$$  \hspace{1cm} (2.20)

where

$$\alpha = \frac{g_R}{g_{BL}} = \sqrt{\frac{g_R^2}{g^2} \cot^2 \theta_W - 1}.$$  \hspace{1cm} (2.21)

\textsuperscript{10}Below the GUT scale, a coefficient of $\lambda_y^{1/2}$ is applied ($2/3 \lesssim \lambda_y \lesssim 1$).

\textsuperscript{11}This is actually an intermediate symmetry of some $SO(10)$ models, which break under $SO(10) \rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{BL}$.

\textsuperscript{12}Most models use either a doublet $\delta_R$ or triplet $\Delta_R$. In either case, only the electrically neutral component acquires a nonzero VEV ($v_{\delta_R}$ or $v_{\Delta_R}$). Each has a corresponding left-hand field, $\delta_L$ or $\Delta_L$, with a much smaller VEV.
2.3. EXAMPLES OF Z’ MODELS

The associated coupling is \( g_2 = \sqrt{3/5} g_Z \sin \theta_W \sim 0.46 \). The \( \alpha \) parameter depends largely on the \( SU(2)_L \times SU(2)_R \times U(1) \) breaking scale. In versions of the LRM where this symmetry survives to the TeV scale, \( g_R \approx g \) so \( \alpha \sim 1.58 \). In GUT scenarios, the higher breaking scales would suggest \( \alpha \sim 0.7 - 0.9 \) \( (\alpha = \sqrt{4/3} \) coincides with \( Z'_0 \)) [34].

The gauge bosons acquire mass when the electroweak symmetry is broken. In this case, a pair of Higgs doublets acquire VEV’s \( \kappa \) and \( \kappa' \) \( (|\kappa|^2 + |\kappa'|^2 = \nu^2/2 \sim (246 \text{ GeV})^2/2) \) \(^{13}\) in their electrically neutral components. The photon remains massless, but the \( Z \) and \( Z'_0 \) acquire a mass-squared matrix as in eq. 2.8, with values of

\[
M_{Z'_0}^2 = \frac{1}{4} g_2^2 \nu_L^2, \quad M_{Z'_0}^2 = \frac{1}{4} (g_R^2 + g_{BL}^2) \nu_R^2, \quad \Delta^2 = -\frac{g_R^2}{2} \alpha \left(|\kappa|^2 + |\kappa'|^2\right)
\]

where \( \nu_{L,R}^2 = 2 \left(|\kappa|^2 + |\kappa'|^2 + |v_{\delta L,R}|^2 + 4 |v_{\Delta L,R}|^2\right) \). This symmetry breaking also yields \( W_{R}^{\pm} \) which couple only to right-handed fermions. These mix with \( W_L^{\pm} \) to form mass states \( W_1^{\pm} \) and \( W_2^{\pm} \) with the heavier mass determined by

\[
\frac{M_{Z'_0}^2}{M_{W_2}^2} \approx \left(1 + \frac{1}{\alpha^2}\right) \frac{|v_{\delta R}|^2 + 4 |v_{\Delta R}|^2}{|v_{\delta R}|^2 + 2 |v_{\Delta R}|^2}
\]

for \( \nu_R \gg \nu_L \) [3, 32].

2.3.4 Models with Enhanced Couplings to Third-Generation Fermions

Several \( Z' \) models without Grand Unification motivations involve extra gauge bosons with stronger couplings to the third-generation fermions. These models involve extensions to the SM symmetry where one symmetry group applies only to heavy (third-generation) fermions and another applies to light (first- and second-generation) fermions. One such group is the Non-Universal (NU) subset of \( G(221) \) models [35, 36] where the \( SU(2)_L \) symmetry is extended to separate symmetries for light and heavy fermion flavors. These models are particularly motivated by the heavy mass of the top

\(^{13}\)In models with Higgs doublets \( \delta_R \) and \( \delta_L \), the electroweak scale is determined by \( |v_{\delta L}|^2 + |\kappa|^2 + |\kappa'|^2 = \nu^2/2 \).
2.3. EXAMPLES OF Z' MODELS

quark, which suggests different dynamical behavior for the third generation. Examples of these models include Non-Commuting Extended Technicolor (NCETC) [37] and Topflavor [38].

In the NU $G(221)$ models, the initial NC Lagrangian is given by

$$-\mathcal{L}_{NC} = g_h J^{h}_{3h} W^3_{h\mu} + g_l J^{l}_{3l} W^3_{l\mu} + g' J^{l}_{Y} B_{\mu}$$

(2.24)

where $g_l = g_h \tan \phi = \frac{g}{\cos \phi}$ ($\phi$ being the $h$-$l$ mixing angle) and $J^{l}_{3l,h}$ are the z-component weak isospin currents for light and heavy flavors respectively. The $G(221)$ symmetry breaks to the electroweak symmetry at some scale $u > \nu$, which then breaks to the EM symmetry as usual at $\nu$:

$$SU(2)_h \times SU(2)_l \times U(1)_Y \xrightarrow{u>\nu} SU(2)_{t+h} \times U(1)_Y \xrightarrow{\nu>\nu} U(1)_{EM}.$$ 

(2.25)

The final gauge fields $A, Z,$ and $Z'$ are expressed in terms of initial fields $W^3_h, W^3_l,$ and $B$ through $\theta_W$ and $\phi$:

$$\begin{pmatrix} A_{\mu} \\ Z_{\mu} \\ Z'_{\mu} \end{pmatrix} = \begin{pmatrix} \sin \theta_W \sin \phi & \sin \theta_W \cos \phi & \cos \theta_W \\ \cos \theta_W \sin \phi & \cos \theta_W \cos \phi & -\sin \theta_W \\ \cos \phi & -\sin \phi & 0 \end{pmatrix} \begin{pmatrix} W^{3}_{h\mu} \\ W^{3}_{l\mu} \\ B_{\mu} \end{pmatrix}$$

(2.26)

Diagonalizing the mass matrix leads to mass eigenstates

$$Z_1 = Z + \frac{\sin^3 \phi \cos \phi}{x \cos \theta_W} Z'$$
and
$$Z_2 = Z' - \frac{\sin^3 \phi \cos \phi}{x \cos \theta_W} Z$$

(2.27)

(up to leading order in $x^{-1} \equiv \nu/u$) corresponding to masses of

$$M^2_{Z_1} = \frac{M^2_0 \cos^2 \theta_W}{\cos^2 \phi} \left( 1 - \frac{\sin^4 \phi}{x} \right) = \frac{M^2_{W_1}}{\cos^2 \theta_W}$$

$$M^2_{Z_2} = \frac{M^2_0 \cos^2 \phi}{\sin^2 \phi + \sin^2 \phi} = M^2_{W_2}.$$ 

(2.28)
where $M_0 = \frac{g}{Z} = M_{W}^{SM}$. The heavy $Z_2$ field couples to left- and right-handed fermion fields with couplings (times charges, i.e. $g_2Q_2$) of

\begin{align}
g_L &= g \left( \frac{\cos \phi}{\sin \phi} I_{3h} - \frac{\sin \phi}{\cos \phi} I_{3l} - \frac{\sin^3 \phi \cos \phi}{x \cos^2 \theta_W} (I_{3h} + I_{3l} - Q \sin \theta_W) \right) \\
g_R &= -gQ \sin^2 \theta_W \left( \frac{\sin^3 \phi \cos \phi}{x \cos^2 \theta_W} \right).
\end{align}

Since the experimental $Z'$ mass exclusion is fairly high ($>1$ TeV) it is expected that $u \gg \nu$. In this limit the $x^{-1}$ terms effectively vanish, which leads to several consequences. There is no mass mixing, so $Z' = Z_2$. The right-handed couplings disappear, leaving a strictly left-handed $Z'$. Since the terms with $Q$ disappear, the couplings are the same for all fermions within the light-flavor family or within the heavy-flavor family (though they differ between these two families). The removal of the $x^{-1}$ terms also eliminates any mass dependence in the couplings.

Other models containing $Z'$ with enhanced third-generation couplings involve an extension of the hypercharge symmetry. One such model is Topcolor Assisted Technicolor (TC2) [37], which provides an alternate mechanism to explain the top quark mass. This model is based on the symmetry

$$SU(3)_1 \times SU(3)_2 \times SU(2) \times U(1)_{Y1} \times U(1)_{Y2}$$

where $SU(3)_{1(2)} \times U(1)_{Y1(2)}$ couples preferentially to the heavy-(light-)flavor fermions. The $SU(3)_1 \times SU(3)_2 \rightarrow SU(3)_c$ breaking leads to an octet of massive colored bosons with preferential couplings to top and bottom quarks$^{14}$. The $U(1)_{Y1} \times U(1)_{Y2} \rightarrow U(1)_Y$ breaking, which yields a $Z'$, provides a mechanism to generate a top mass much larger than the bottom mass. The resulting neutral gauge boson $Z'_1$ couples to fermions according to

$$g_t = \frac{g'}{2} (\cot \phi_h Y_1 - \tan \phi_h Y_2)$$

$^{14}$This initial breaking leads to a top mass of $\sim 600$ GeV, which is brought down to the observed top scale by mixing with exotic fermions.
where $\phi_h$ is the $Y_1$-$Y_2$ mixing angle. This differs from the NU $G(221)$ couplings in eq. 2.29-2.30 in that the TC2 couplings are set at order of hypercharge rather than weak isospin and the $Z'_1$ couples to both left- and right-handed particles at leading order.

### 2.3.5 Other $Z'$ Models

There are currently hundreds of $Z'$ models being considered. Many of these models predict $Z'$ bosons with masses beyond the current experimental reach. Others include $Z'$ bosons at the TeV scale that could potentially be discovered at current experiments. Among the latter are the Little Higgs models [29, 39], a set of non-GUT models in which the Higgs is a pseudo-Goldstone boson of an approximate global symmetry. These models include various types of extended symmetries which lead to extra gauge bosons, fermions$^{15}$, and Higgs bosons that remove the quadratic divergences from the SM Higgs mass. The $Z'$ would couple to fermions like $\frac{2}{3}I_3\cot\theta_H$, with $\theta_H$ being another mixing angle. A similar theory is the Twin Higgs model [40], which cancels the Higgs quadratic divergences via particles from a hidden sector that mirrors the SM and interacts mainly through an extended Higgs sector. The gauge bosons from this extended sector could potentially decouple from SM particles and may or may not have mass. The $G(221)$ class also includes some additional models predicting TeV-scale $Z'$ bosons. One notable model from this class is the Ununified Model (UUM) [41], which predicts separate $SU(2)$ couplings for quarks and leptons. The $Z'$ here is expected to couple to leptons and quarks like $g(\cot\phi_{UUM}I_{3q} - \tan\phi_{UUM}I_{3l})$ (where $\phi_{UUM}$ is the $q$-$l$ mixing angle) and have mass $M_{Z'_{UUM}} > 2$ TeV.

### 2.4 Searches for $Z'$

Several experiments searching for evidence of $Z'$ bosons from various models have been performed. These include both indirect searches from precision measurements of SM parameters and direct searches for $Z'$ resonances performed using particle collisions. As of early 2015, no $Z'$ bosons have

$^{15}$The lightest of these, if stable, could be a dark matter candidate.
been discovered. Although previous experiments have not resulted in a discovery, they have been able to place tighter limits on the allowed masses of $Z'$ bosons from multiple models (set at a given confidence level, or $\text{CL}^{16}$, usually 95%), as well as constraints on other parameters. The highest current $Z'$ mass lower limits for several popular models are summarized in table 2.1.

<table>
<thead>
<tr>
<th>Model</th>
<th>Indirect (EW)</th>
<th>Indirect ($e^+e^- \rightarrow f \bar{f}$)</th>
<th>Direct ($p\bar{p}$ or $pp$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'_{SSM}$</td>
<td>1500</td>
<td>1305</td>
<td>2900</td>
</tr>
<tr>
<td>$Z'_{LR}$</td>
<td>1162</td>
<td>600</td>
<td>630</td>
</tr>
<tr>
<td>$Z'_{X}$</td>
<td>1141</td>
<td>781</td>
<td>2620</td>
</tr>
<tr>
<td>$Z'_{\psi}$</td>
<td>476</td>
<td>475</td>
<td>2570</td>
</tr>
<tr>
<td>$Z'_{\eta}$</td>
<td>619</td>
<td>515</td>
<td>2440</td>
</tr>
</tbody>
</table>

Table 2.1: 95% CL lower limits on the masses of $Z'$ from various models (in GeV). These include high-precision measurements from electroweak data, measurements of interference effects in the $e^+e^- \rightarrow f \bar{f}$ process at LEP, and results from direct searches at the Tevatron and LHC. All direct searches listed are from search channels with final states of $e^+e^-$ and $\mu^+\mu^-$ [6, 42–44].

### 2.4.1 Indirect Searches

Since the mass eigenstates of neutral gauge bosons result from the mixing of weak eigenstates, the existence of $Z'$ bosons would lead to corrections in several SM parameters$^{17}$. For a given $Z'$-sensitive observable parameter $O_i$, the presence of a $Z'$ is more likely when its deviation $\Delta Z' O_i$ from the expected SM value $O_i(SM)$ is larger than the experimental error $\Delta O_i$. To determine whether a $Z'$ hypothesis can be rejected, a $\chi^2$ statistic can be calculated:

$$\chi^2 = \sum_i \left( \frac{O_i - O_i(SM + Z')}{\Delta O_i} \right)^2 \quad (2.33)$$

where the errors include both statistical and systematic components: $\Delta O_i = \sqrt{(\Delta O_i^{\text{stat}})^2 + (\Delta O_i^{\text{syst}})^2}$, and are assumed to have Gaussian distributions when there are many events. The $Z'$ hypothesis is rejected when $\chi - \chi_{min} > \chi_{cl}$, where $\chi_{min}$ is the minimum value of $\chi$ obtained by optimizing the

---

$^{16}$This assumes that the Frequentist interpretation of probability is used. When Bayesian methods are used, “CL” refers to the credibility level.

$^{17}$Even in the absence of $Z$-$Z'$ mixing, a $Z'$ would lead to higher-order corrections for several SM parameters through radiative corrections, etc...
free parameters and \( \chi_{CL} \) is the threshold for rejection based on the chosen confidence level \([32, 45]\).

The variables can be calculated from both precision measurements of electroweak data and cross section measurements from lepton colliders. Different center-of-mass energies \((\sqrt{s})\) provide varied levels of sensitivity for different observables.

### 2.4.1.1 Electroweak Precision Measurements

Some of the SM corrections due to massive \( Z' \) bosons and/or \( Z-Z' \) mixing can be seen at the electroweak scale. One energy region with high sensitivity to the mixing is the \( Z' \)-pole: the peak in the \( \sigma(e^+e^- \rightarrow f \bar{f}) \) distribution at \( s = M_{Z'}^2 \) (figure 2.1). This peak follows a modified Breit-Wigner \([46]\) form whose parameters, particularly \( M_{Z'} \) and \( \Gamma_{Z'} \) (the peak width), depend on \( Z'-related \) parameters. The shift in \( M_{Z'} \) is given in equation 2.9 and approximated at the large \( M_{Z'} \) limit in eq. 2.11. The shift in \( \Gamma_{Z'} \) is related to the shift in the \( Z' \) couplings (table 1.2), which now become:

\[
c_{V,A}^1(f_i) \rightarrow \cos \theta_M c_{V,A}^1(f_i) + \frac{g_2}{g_1} \sin \theta_M c_{V,A}^2(f_i) \sim c_{V,A}^1(f_i) + \frac{g_2}{g_1} \theta_M c_{V,A}^2(f_i). \tag{2.34}
\]

The \( Z' \)-pole observables are not sensitive to \( Z' \) exchange (due to dominant \( Z \)-exchange) and therefore lack \( M_{Z'} \) sensitivity. They are, however, quite sensitive to \( \theta_M \) and are mainly used to constrain its range \([1]\).

Precision measurements can also be performed at energies below the \( Z \)-pole. At this scale, the effective WNC interaction (eq. 1.12) becomes valid and is corrected for \( Z-Z' \) mixing to:

\[
-L_{NC}^{eff} = \frac{4G_F}{\sqrt{2}} \frac{M_W^2}{\cos^2 \theta_W} \left[ \left( \frac{\cos^2 \theta_M}{M_1^2} + \frac{\sin^2 \theta_M}{M_2^2} \right) J_1^2 + \frac{2}{g_1} \left( \frac{g_2}{g_1} \cos \theta_M \sin \theta_M \left( \frac{1}{M_1^2} - \frac{1}{M_2^2} \right) J_1 J_2 + \left( \frac{g_2}{g_1} \right)^2 \left( \frac{\sin^2 \theta_M}{M_1^2} + \cos^2 \theta_M \frac{M_W^2}{M_2^2 \cos^2 \theta_W} \right) J_2^2 \right] \right. \\
\left. \approx \frac{4G_F}{\sqrt{2}} \left( \frac{M_W^2}{M_1^2 \cos^2 \theta_W} J_1^2 + 2 \left( \frac{g_2}{g_1} \right) \theta_M J_1 J_2 + \left( \frac{g_2}{g_1} \right)^2 \frac{M_W^2}{M_2^2 \cos^2 \theta_W} J_2^2 \right) \right) \tag{2.35}.
\]
where the approximation holds for small $\theta_M$ and $M_Z^2$. Scattering via this process involves (virtual) $Z'$-exchange, and experiments like coupling measurements in $\nu$-$e$ or $\nu$-hadron scattering are more sensitive to the $Z'$ mass than $Z$-pole measurements [1]. Another low-energy experiment called the E-158 Polarized Møller scattering experiment [29] measures polarization which is sensitive to

$$
\sin^2 \theta_W \sim \sin^2 \theta_W - \frac{g^2}{\sqrt{2G_F M_Z^2}} c_V(e) c_A(e).
$$

On a larger size scale, Atomic Parity Violation (APV) from the exchange of gauge bosons with axial couplings in heavy atoms is sensitive to $Z'$ parameters. APV is experimentally parameterized by the weak charge

$$
Q_W = -4 \sum_i \frac{M_Z^2}{M_Z^2} c_V(e) \left[ c_V^i(u) (2P + N) + c_V^i(d) (2N + P) \right] + \text{mixing}
$$

where $P(N)$ is the number of protons (neutrons) in the atom. Deviations from the SM prediction are less sensitive to $\theta_M$ than $Z$-pole experiments, but are much more sensitive to $M_1/M_2$ [29, 32].

Various other $Z'$-sensitive SM measurements can be made below and/or above the $Z$-pole. These include measurements from CKM unitarity, the Muon Anomalous Magnetic Moment, mass measurements for the top quark and $W^{\pm}$, and various asymmetries [48]. Measurements above the $Z$-pole are typically made with data from lepton-lepton, lepton-hadron, and hadron-hadron collisions. In some cases, cosmological measurements such as the number of left- and right-handed neutrinos interacting
with the Z and energy released from stellar collapse can lead to constraints on \( M_{Z'} \).\(^\text{18}\) Non-Z-pole measurements generally can’t compete with Z-pole \( \theta_M \) constraints, but they are typically more sensitive to the \( Z' \) mass. Each type of measurement has different sensitivities to the \( Z' \) mass and \( Z-Z' \) mixing\(^\text{19}\), so the best results are usually obtained by combining multiple measurements [49].

The highest 95% CL lower limits on \( Z' \) masses from electroweak precision data are presented in column 1 of table 2.1 for several \( Z' \) models.

### 2.4.1.2 Searches at Lepton Colliders

In the energy range of \( s > M_{Z'}^2 \), measurements are usually made at high-energy colliders. Lepton colliders are useful in that they provide very low backgrounds. Direct detection of \( Z' \) resonances is theoretically possible if \( s \approx M_{Z'}^2 \). However, as of 2015, the highest collision energy from a lepton collider was 209 GeV at the Large Electron-Positron (LEP) Collider [50], well below the lower limits on \( M_{Z'} \) from most models. Indirect measurements are therefore required when searching for evidence of \( Z' \) bosons in lepton collisions.

The LEP collider utilized collisions of electrons and positrons to search for new resonances and make precision measurements. The LEP process most sensitive to \( Z' \)-exchange is fermion pair-production \((e^+e^- \to f\bar{f})\). The Born-level differential cross section for this (in the limit of negligible fermion masses) is given by [31]:

\[
\frac{d\sigma (e^+e^- \to f\bar{f})}{d\cos \theta} = \frac{1}{128\pi s} \left[ \left( |C_{LL}|^2 + |C_{RR}|^2 \right) (1 + \cos \theta)^2 \\
+ \left( |C_{LR}|^2 + |C_{RL}|^2 \right) (1 - \cos \theta)^2 \right]
\]  

\[ (2.37) \]

where

\[
C_{ij} = \sum_{X=\gamma,Z,Z'} g_{X,i}(e)g_{X,j}(f) \frac{s}{s - M_X^2 + i\Gamma_X M_X}
\]  

\[ (2.38) \]

\(^{\text{18}}\)The cosmological limits on \( M_{Z'} \) are stronger than collider limits in some cases where the \( Z' \) couples to right-handed neutrinos. However, these limits are based on more model assumptions than collider limits.

\(^{\text{19}}\)Since deviances from SM values can be very small, it is important to take radiative corrections into account.
(g_{X,L(R)}(f_i)) is the coupling of X to left-(right-)handed f_i. The Z' term in C_{ij} provides interference\textsuperscript{20} to the SM calculation, which only includes γ and Z terms. This means that the following measurements can be used for exclusion limits:

- total cross section, \( \sigma_T = \int d \cos \theta \frac{d\sigma}{d \cos \theta} \),

- Forward-Backward asymmetry:

\[
A_{FB}^f = \frac{\left[f_0^1 - f_{-1}^0\right] d \cos \theta \frac{d\sigma}{d \cos \theta}}{\left[f_0^1 + f_{-1}^0\right] d \cos \theta \frac{d\sigma}{d \cos \theta}}. \tag{2.39}
\]

This can be calculated fairly easily for \( f = \text{leptons} \), though heavier quarks with a sufficiently efficient tagging algorithm can be used too.

- Left-Right asymmetry:

\[
A_{LR}^f = \frac{\sigma(e_R^R) - \sigma(e_L^-)}{\sigma(e_R^R) + \sigma(e_L^-)}. \tag{2.40}
\]

This can be measured when the electron beam is polarized. If the beam is only partially polarized (fraction \( P \)), the value \( A_{LR}^f(P) = PA_{LR}^f(1) \) is used. Hadronic final states have the largest cross sections and thus provide the best statistics for this.

- Polarization asymmetry:

\[
A_{pol}^f = \frac{\sigma(f_R^R) - \sigma(f_L^-)}{\sigma(f_R^R) + \sigma(f_L^-)}. \tag{2.41}
\]

This is most easily calculated with taus due to their well-understood branching ratios and decay patterns (chapter 4). For other final-state fermions, polarization can be determined from \( A_{FB} \) for specific initial electron polarizations.

When the final state fermions are not an electron-positron pair, only the s-channel\textsuperscript{21} \( \gamma/Z/Z' \) exchange occurs at tree level and the cross section in eq. 2.37 is valid. For Bhabha scattering, the t-channel exchange must be included as well in the cross section calculation. This process has a much

\textsuperscript{20} In the s \( \ll M_2^2 \) limit, the Z_2 exchange is an effective four-fermion interaction similar to eq. 2.35 but with the \( M_1^{-2} \) terms removed.

\textsuperscript{21} The \( x \)-channel exchange (\( x = s, t, \) or \( u \), one of the Mandelstam variables (appendix A)) is when \( [p^\mu(Z/Z'/\gamma^*)]^2 = x \).
larger event rate than fermion pair production and thus provides better statistics for measurements.

In the case of $e^-e^-$ collisions, Møller scattering occurs. Its cross section is calculated from the $t$- and $u$-channel exchanges and has a high event rate within electron collisions. For both Bhabha and Møller scattering, having two (or at least one) polarized beams allows for precision measurements of left-right asymmetries. This also enables measurements of transverse asymmetries (Bhabha) and multiple angular distributions (Møller). Constraints on $M_{Z'}$ from the angular distributions are weaker than those from pair production, though constraints on the vector and axial couplings are comparable [32].

The $e^+e^- \to W^+W^-$ process can also be sensitive to $Z'$ bosons in the case of $Z$-$Z'$ mixing. Without this mixing, the interference terms in the $s$-channel scattering amplitude approximately cancel\(^{22}\) for large values of $s$. Mixing changes the $W$ couplings so that the cancelation is destroyed and unitarity is not restored until $s \gg M_Z^2$. The couplings to the $W$ pairs change to $g_{WW\gamma} = e(1+\delta_{\gamma})$ and $g_{WWZ} = e(\cot \theta_W + \delta_Z)$, where $\delta_{\gamma,Z}$ are sensitive to $M_{Z'}$, $c_{V,A}(f)$, and $\theta_M$. Present limits are not yet comparable to those of $e^+e^- \to f\bar{f}$ processes [29, 32].

The highest 95% CL lower limits on the $Z'$ mass from LEP measurements are presented in column 2 of table 2.1 for several models. If lepton colliders with higher center-of-mass energies were constructed, the sensitivity to $Z'$ bosons could be increased. At $s \approx M_Z^2$, a real (not virtual) $Z'$ could be directly produced and its resonance could be observed. This energy region also provides the best precision measurements (similar to $Z$ measurements at the $Z$-pole) and the best exclusion limits on $\theta_M$. The $s > M_Z^2$ region would be less sensitive to $Z'$ parameters, though it could lead to constraints on models with weaker fermion couplings than in most GUT’s [32]. In practice, it is difficult to achieve high enough energies in lepton colliders due to limited accelerating distance in linear colliders and synchrotron radiation [51] in circular colliders. High levels of power consumption is another factor that limits the highest achievable energies for all lepton colliders.

\(^{22}\)Technically, they scale like $\ln s/s$. 

2.4. SEARCHES FOR $Z'$

2.4.2 Direct Searches at Hadron Colliders

The best possibilities for direct production and observation of $Z'$ resonances come from hadron colliders ($pp$ or $p\bar{p}$), which offer several advantages over lepton colliders. Since hadrons are composite particles, the constituent partons have a broad energy range. Collisions from the partons can therefore have a broad invariant mass spectrum, allowing direct production of $Z'$ for $M_{Z'}^2 < s$\footnote{Realistically, the mass range for direct production is closer to $M_{Z'}^2 < \frac{s}{4}$ since the hadron’s energy is spread across its constituent partons.}. This advantage is complemented by the higher energy range of hadron colliders, which is in part due to the reduced synchrotron radiation from the higher mass of protons (relative to leptons). The highest energy achieved by a hadron collider is $\sqrt{s} = 8$ TeV at the Large Hadron Collider (section 3.1). Hadron colliders are not without their disadvantages though. In particular, the large backgrounds from QCD processes make it difficult to identify signals and calculate several observables. There are also higher uncertainties on collision parameters due to uncertainties on the hadrons’ constituent partons \footnote{This is defined as $x_{a,b} \equiv \frac{\sqrt{\Delta T}}{E_y}$, where $y$ is the rapidity, $\frac{1}{2} \ln \frac{E + p_y}{E - p_y}$.}.

2.4.2.1 $Z'$ Production Process

The dominant process for $Z'$ production is the Drell-Yan (DY) \footnote{\cite{52}} process in which a quark and anti-quark from different initial hadrons annihilate to a gauge boson which then decays to a $l^+l^-$ pair (figure 2.2). The Born-level cross section for this process is

$$
\frac{d\sigma}{d\cos\theta} \left( pp \rightarrow Z/Z'/\gamma^* \rightarrow l^+l^- \right) = \sum_q \int dx_a dx_b \left[ f_q(x_a, Q^2) f_{\bar{q}}(x_b, Q^2) \frac{d\sigma(\theta)}{d\cos\theta} 
+ f_{\bar{q}}(x_a, Q^2) f_q(x_b, Q^2) \frac{d\sigma(\pi - \theta)}{d\cos\theta} \right] \tag{2.42}
$$

where the * superscript refers to an off-shell resonance, $q$ is the quark flavor, $f_q(x_{a,b},Q^2)$ are the parton distribution functions (PDF’s) \footnote{\cite{53}} describing the probability distributions of longitudinal momentum fractions $x_{a,b}$\footnote{This is defined as $x_{a,b} \equiv \sqrt{\Delta T}$, where $y$ is the rapidity, $\frac{1}{2} \ln \frac{E + p_y}{E - p_y}$.} at scale $Q^2$, and $\frac{d\sigma(\theta)}{d\cos\theta}$ is the differential cross section for the individual
2.4. SEARCHES FOR Z’

q\bar{q} processes (same as equations 2.37 and 2.38 except with \(e^- (e^+) \rightarrow q(\bar{q})\)\cite{25} and \(f(\bar{f}) \rightarrow l^- (l^+)\)) \cite{41].

Coefficients called K-factors \((K(Q^2), \text{usually } \sim 1-2)\) \cite{54} can also be applied to account for higher-order QCD and EW corrections. The spectrum of \(\sigma(DY)\) should form a peak at \(M_{inv}^{26} = M_{Z'}\) which would facilitate decent signal-background separation and the measurement of \(M_{Z'}\). Rare, higher-order processes such as \(Z' \rightarrow f\bar{f}X\) and \(pp \rightarrow Z'X\) grow logarithmically with \(s\) and may yield complimentary information at \(s \gg M_{Z'}^2\) \cite{32].

\[
\Gamma \left( Z' \rightarrow f_i\bar{f}_i \right) = \frac{M_{Z'} C_f}{24\pi} \left( g_{Z',L}(f_i)^2 + g_{Z',R}(f_i)^2 \right)
\]

where \(C_f\) is the color factor (3 for \(q\), 1 for \(l\)) \cite{1}. Since decays to gauge bosons are rare, the total decay width \(\Gamma_{Z'}\) is determined by adding the partial decay widths from fermion final states\footnote{When individual quark colors are considered, a factor of \(\frac{1}{3}\) is applied to the cross section to account for the average of initial states.}. The

\footnote{This is the invariant mass \((\sqrt{Q^2})\)

\footnote{If the \(Z'\) couples to exotic particles, these will also contribute to \(\Gamma_{Z'}\).}
branching ratios are then determined by the fractions of the partial and full decay widths \([31]\):

\[
BR(Z' \to f_i \bar{f}_i) = \frac{\Gamma(Z' \to f_i \bar{f}_i)}{\Gamma_{Z'}}.
\]

(2.44)

The most probable non-exotic \(Z'\) decays occur in the following channels:

\(Z' \to l^- l^+ (e^- e^+ \text{ or } \mu^- \mu^+)\) These channels (collectively referred to as the dilepton channels) have the smallest backgrounds and are potentially the most sensitive to \(Z'\) signals, yielding the highest mass limits. The mass resolution \(\frac{\Delta M}{M}\) should be sensitive to the \(Z'\) peak and could even measure the peak width if small enough \((\frac{\Delta M}{M} \lesssim \frac{\Gamma_{Z'}}{M_{Z'}})\). \(A_{FB}\) could also reveal information on fermion couplings if enough on-peak data was collected \([29, 41]\).

\(Z' \to \tau^- \tau^+\) The ditau channel has a much larger background from QCD processes and is thus less sensitive to most \(Z'\) models than the dilepton channels. However, the information from tau decays can be used to calculate polarization on or near the \(Z'\) peak \([29]\). This channel is also useful in searches for \(Z'\) with enhanced third-generation couplings.

\(Z' \to q_i \bar{q}_i (t \bar{t} \text{ or } b \bar{b})\) Although these channels could possibly be used to measure \(A_{FB}\) for heavy quark final states to assist with the measurement of individual quark couplings \([41]\), the background is so large that this channel will probably not reveal any new information except in special cases.

\(Z' \to q_i \bar{q}_i\) The QCD background is far too high to observe any \(Z'\) signals decaying to \(u\bar{u}, d\bar{d}, c\bar{c}\), or \(s\bar{s}\) in the current generation of experiments \([29]\).

### 2.4.2.3 Results from Direct \(Z'\) Searches

Direct searches at colliders have placed limits on \(M_{Z'}\) through measurements of the total cross section \(\sigma\) (times branching ratio \(BR\)). When no resonance peak occurs for a given \(Z'\) mass hypothesis, statistical and systematic errors are used to calculate upper limits on \(\sigma \times BR\). When this limit lies below the theoretical cross section, that mass hypothesis is excluded. Exclusion capabilities weaken
for higher masses due to limited statistics. The highest 95% CL lower limits on $M_{Z'}$ from direct searches are presented in column three of table 2.1. The highest limit on the $Z'_{LR}$ mass was obtained by the CDF [55] experiment using $p\bar{p}$ collisions at the Tevatron [56], while the other limits were determined by the ATLAS and/or CMS collaborations using $pp$ collisions at the LHC. All limits were obtained through searches in the dilepton channels.

2.4.2.4 $Z'$ Searches in the $\tau^+\tau^-$ Decay Channel

Although the ditau channel is less sensitive to most $Z'$ resonances than the dilepton channels, searches in this channel have been performed using both $p\bar{p}$ and $pp$ collisions. These searches have mostly been limited to $Z'_{SSM}$, with the exception of one $Z'_{\psi}$ search at CMS. The $M_{Z'}$ exclusion limits from these searches are summarized in table 2.2. These do not include the results presented in chapter 5, which improve upon previous limits and include additional models.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Collisions</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>Integrated Luminosity (fb$^{-1}$)</th>
<th>$M_{Z'_{SSM}}$ Lower Limit (TeV)</th>
<th>$M_{Z'_{\psi}}$ Lower Limit (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>$p\bar{p}$</td>
<td>1.96</td>
<td>0.2</td>
<td>$\sim 0.4$</td>
<td>$-$</td>
</tr>
<tr>
<td>CMS</td>
<td>$pp$</td>
<td>7</td>
<td>4.9</td>
<td>1.4</td>
<td>1.1</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$pp$</td>
<td>7</td>
<td>4.6</td>
<td>1.4</td>
<td>$-$</td>
</tr>
</tbody>
</table>

Table 2.2: Previous 95% CL exclusion limits on the mass of $Z'$ from searches in the ditau channel [57–59].
One of the major challenges with searching for fundamental particles is that most are not commonly found in nature due to their low stability and short lifetimes. It typically requires large amounts of energy to produce these particles in physical interactions. In order to generate enough energy to produce these high-mass particles, accelerators have been built which accelerate hadrons or leptons to high energies and then collide them to initiate high-energy interactions. The largest and most energetic man-made particle accelerator (as of 2015) is the Large Hadron Collider, which accelerates protons to 4 TeV in high-intensity beams and collides them at $\sqrt{s} = 8$ TeV. The search for $Z' \rightarrow \tau\tau$ discussed in this dissertation is performed using data from proton collisions produced using this collider. The products of these collisions are then detected and analyzed using several detectors built at the collision points of the Large Hadron Collider's beams. The detector of interest for this dissertation is ATLAS, a detector with a broad range of physics goals.
3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [60, 61] is a high-energy proton-proton\(^1\) (pp) collider at CERN, located just outside Geneva, Switzerland. As of 2015, it is the largest experimental facility ever built and produces the highest-energy man-made collisions on record [62]. It is a circular synchrotron collider, 26.7-km in circumference, that lies 45-170 m underground beneath the Franco-Swiss border in the tunnel that originally housed the LEP electron-positron collider (figure 3.1). It consists of two concentric tunnels, separated by 195 mm, in which protons are accelerated in opposite directions using superconducting magnets and accelerating cavities. These rings intersect at four different locations where protons collide with a center-of-mass energy (\(\sqrt{s}\)) of 8 TeV\(^2\). Detectors with various physics goals are built around these collision points to observe events from collisions.

\[\text{Figure 3.1: The LHC lies 45-170 m underground near Geneva, Switzerland. The accelerator is 26.7 km in circumference and passes underneath the border between France and Switzerland [63].}\]

3.1.1 Proton Acceleration Chain

The protons accelerated by the LHC originate from hydrogen gas, H\(_2\), which is injected into a Duo-plasmatron [64] proton source. This proton source uses an electric field to separate the constituent protons and electrons. It then uses a radio frequency (RF) quadrupole [65] to accelerate the protons.

\(^{1}\)The LHC is also used to collide lead ions. These Pb-Pb and p-Pb collisions are used for a small subset of studies and will not be discussed extensively in this document.

\(^{2}\)The original design included \(\sqrt{s} = 14\) TeV collisions. This was reduced after an accident occurred which destroyed several magnets in 2008. Collisions with \(\sqrt{s} = 7\) TeV were used in 2010-2011 before increasing to 8 TeV in 2012.
3.1. THE LARGE HADRON COLLIDER

into a 750-keV\(^3\) beam, focus the beam, and spread the protons into discrete clusters called bunches. These protons are used as inputs to the linear accelerator LINAC 2. This 33-m-long accelerator consists of multiple RF cavities. The electric field at each end of these cavities oscillates at a rate optimized to accelerate each proton bunch as it passes through. Protons exit the LINAC 2 at 50 MeV and are directed by a series of magnets to the circular Proton Synchrotron Booster (PSB). Due to its circular shape, protons are able to pass through this 157-m-circumference accelerator multiple times, increasing their energy with each lap. When they reach an energy of 1.4 GeV, protons are injected into the Proton Synchrotron (PS) circular accelerator (628-m circumference), where they are accelerated to 25 GeV. They then travel to an even larger (6.9-km circumference) circular accelerator called the Super Proton Synchrotron (SPS), which accelerates them to 450 GeV. Finally, proton bunches are directed to either the clockwise or counter-clockwise ring of the LHC, each of which accelerates protons to their terminal 4-TeV energy \(^{[60]}\). The full acceleration chain is depicted in figure 3.2.

![CERN Accelerator Complex Diagram](image)

**Figure 3.2:** The proton acceleration chain begins at the LINAC 2 and passes through multiple circular accelerators before protons reach their peak energy at the LHC. The Pb ion acceleration chain is also shown. This begins at an alternate linear accelerator called LINAC 3 and the circular Low Energy Ion Ring before these ions are accelerated at the PS and beyond \(^{[66]}\).

\(^3\)Proton energies in this chapter refer to the kinetic energies of the proton. For reference, the proton rest energy is 938 MeV.
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3.1.2 **LHC Layout and Systems**

The LHC consists of eight 2.46-km-long arcs and eight 528-m-long insertion sections alternating in order. Each arc contains 154 superconducting dipole magnets used to steer the proton beam, as well as other types of magnets with a variety of purposes. The insertions each consist of a long straight section with a dispersion-suppressing (DS) transition region on either end. The layout of each straight section depends on whether it is used for acceleration, collisions, proton injections, beam dumping, or beam cleaning [60].

The LHC can be divided into either eight sectors or eight octants. A sector is defined as the region between two insertion points and is considered a working unit of the LHC. Magnet installation, hardware commission, and powering occurs sector-by-sector. All dipoles in a sector are connected in series and are part of the same, continuous cryostat. An octant starts in the middle of one arc and ends in the middle of the next arc. This division is more practical when discussing how magnets manipulate the beams for a particular straight section [61].

3.1.2.1 **Magnet Systems**

The LHC uses a total of 9593 magnets. These include dipoles, quadrupoles, sextupoles, octupoles, decapoles, and magnets with poles of even higher order. Each type of magnet controls and optimizes the beam in a different way. The largest of these magnets are the 1232 main dipoles located in the arcs and DS regions (figure 3.3). These dipoles are 14.3 m long and use niobium-titanium (NbTi) cables which become superconducting at the temperature of operation (1.9 K). At this temperature, the current in these cables creates a magnetic field up to 8.3 T, which is able to steer the trajectory of the high-energy proton beam. The dipole is cooled with superfluid helium, and the cooled components are contained within a single iron yoke called the cold mass. These are twin-aperture magnets, meaning that each dipole contains both beamlines within its cold mass [60].

The LHC also contains 392 main quadrupole magnets within the arcs. These twin-aperture
3.1. THE LARGE HADRON COLLIDER

Figure 3.3: The LHC contains 1232 main dipole magnets used to steer the beams in circular trajectories around the accelerator. These dipoles operate at 1.9 K, where a superconducting state allows the magnetic field to rise as high as 8.3 T and steer protons with energies up to 7 TeV [67].

Magnets are used to maintain the beams’ focus. In addition to these, special single- and twin-aperture quadruples are used at the collision points to focus each beam to its smallest possible size. Other magnets within the accelerator are called correction magnets. These include both single- and twin-aperture magnets with various orders of multipoles. Correction magnets are typically embedded in the cold masses of the main dipoles and quadrupoles [60, 61].

Most of the magnets are contained within the arcs. Each arc consists of 23 106.9-m-long units called cells, which are bisected into two half-cells. Each half-cell contains three main dipoles and a smaller segment called the short straight section (SSS). Each SSS contains a main quadrupole, an orbit-correcting dipole, a lattice-correction unit, and either a lattice- or skew-sextupole. Magnets in each insertion section are arranged in a unique configuration to accommodate the needs of that particular section [60].

3.1.2.2 LHC Insertion Sections

The insertion points are arranged in the middle of each octant, starting with Point 1 at the southernmost octant and advancing clockwise. Each insertion point is designed to meet a specific goal
3.1. THE LARGE HADRON COLLIDER

of the LHC (figure 3.4). At four of these points (1, 2, 5, and 8), the beams intersect for collisions and alternate positions (inner and outer). The other four points are used to manipulate the proton beams for optimal collisions at the intersection points and protect the accelerator from beam-related damage.

Figure 3.4: The LHC is divided into eight octants, each centered around an insertion point. Points 1, 2, 5, and 8 are used for collisions and house the detectors that reconstruct the resulting events. The other points are used to either accelerate the beams (Point 4) or prevent the beams from damaging the accelerator (Points 3, 6, and 7) [68].

Points 1 and 5 are the respective locations for the ATLAS (A Toroidal LHC ApparatuS) [69] and CMS (Compact Muon Solenoid) [70] detectors. These detectors both have a wide range of physics goals, including searches for undiscovered particles and measurements with known existing particles. To accommodate these needs, specialized quadrupole triplets are used to focus the beam for high-luminosity interactions. Luminosity\(^5\) \((\mathcal{L})\) refers to the number of collisions per unit area per unit time:

\[
\mathcal{L} = f_{coll} \frac{n_1 n_2}{4\pi \sigma_x \sigma_y}
\]

where \(f_{coll}\) is the bunch-crossing frequency, \(n_1(2)\) is the number of protons in bunch 1(2) and \(\sigma_{x,y}\)

\(^4\)These points also host the detectors for the LHCf [71] (point 1) and TOTEM [72] (point 5) collaborations. These detectors are much smaller and are located further from the interaction points.

\(^5\)The beam performance for an entire run is often parameterized by integrated luminosity \(L\), defined as \(\int \mathcal{L} \, dt\).
3.1. **THE LARGE HADRON COLLIDER**

characterize the standard deviations of the beam size in the transverse directions. The high luminosities allow these detectors to observe a large number of events $N$, according to

$$N_{\text{int}} = \int \mathcal{L} \times \sigma_{\text{int}} \, dt$$  \hspace{1cm} (3.2)

where the “int” subscript refers to a particular interaction and $\sigma_{\text{int}}$ is the cross section for that interaction. The LHC is designed to achieve luminosities up to $10^{34} \text{cm}^{-2}\text{s}^{-1}$ at these points [60].

Point 2 houses the ALICE (A Large Ion Collider Experiment) [73] detector, which uses lead ion collisions to study strongly-interacting matter. This is a designated “medium luminosity” ($10^{27} \text{cm}^{-2}\text{s}^{-1}$) experiment and does not require bunches to be packed as tightly as ATLAS and CMS, though it uses a similar quadrupole triplet arrangement to focus the beam. Point 2 also serves as the injection point for the clockwise ring (Ring-1) [60].

The final collision point at Point 8 is where the LHCb (LHC-beauty) [74] detector is located. This is a highly-specialized detector which studies $B$-hadrons to learn more about $CP$ violation and the matter-antimatter imbalance. It uses quadrupole triplets to engineer medium-luminosity ($10^{32} \text{cm}^{-2}\text{s}^{-1}$) interactions. Point 8 is also the injection point for the counterclockwise ring (Ring-2) [60].

Points 3 and 7 are designated for beam “cleaning”. Protons that stray from the core of the beam are energetic enough that a small number may cause the superconducting magnets to quench (return to their non-superconducting state) if they hit the same spot on the superconducting coils. Quenching would cause these magnets to release their stored energy, which would raise their temperature by over 970 K in less than one second, severely damaging the magnet (and likely several surrounding magnets) [76]. Points 3 and 7 contain collimators respectively designed to scatter particles with high momentum offsets and high betatron amplitudes. Secondary collimators are used to absorb and refocus these particles in both cases [60].

---

6If an experiment performed a search for a particular interaction through a specific decay mode, this would be multiplied by the branching ratio $BR$ of that decay mode. The signal acceptance and efficiency (discussed in chapter 5) would also have to be taken into account when determining what fraction of interactions were actually observed.

7The MoEDAL experiment [75], which aims to observe the magnetic monopole, is also housed here.
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Point 4 contains the superconducting RF cavities used for beam acceleration and focusing. Each beam uses 8 cavities (in 2 groups of 4, called cryomodules), which deliver 2 MV at 400 MHz. To allow enough space for these cavities, dipoles are used to increase the beam separation from 195 mm to 420 mm. This insertion point also contains the transverse damping and feedback system, which is used to damp transverse injection errors, prevent transverse coupled-bunch instabilities, and excite transverse oscillations for beam measurements [60].

Point 6 is where the beam abort system, or “beam dump”, is located. When it is time for the beams to shut down, kicker magnets divert them to a series of septum magnets, which deflect each beam vertically. The deflected beam then passes through a 700-m-long vacuum, where dilution kicker magnets are used to dilute the beam. Finally, the beam is deposited in the beam dump proper: an 8-m-long, 1-m-diameter graphite cylinder encased in steel and concrete shielding. Kicker magnets are used to sweep the beam in an “e” shape across the face of this cylinder in order to spread out the beam deposits and prevent damage. This beam dump proper (or “dumping block”) is the only component of the LHC able to withstand the full impact of the beam. Each beam has its own separate beam dump cavern, both of which are based at Point 6 [60, 76].

3.1.2.3 Vacuum Systems

The LHC has three vacuum systems: the insulation vacua for the cryomagnets and helium distribution and the beam vacuum. The beam vacuum has the strictest requirements of the three. At cryogenic temperatures, the pressure (normalized to hydrogen) must be below $10^{15} \text{ H}_2 \text{ m}^{-3}$ to meet the required beam lifetime of 100 hours. The insulation vacua will stabilize at about $10^{-6} \text{ mbar}$ at cryogenic temperatures. The largest volume required to be pumped is the insulation vacuum for the cryomagnets ($\approx 9000 \text{ m}^3$) [60, 61].
3.1.3 Proton Beam Parameters

Once the beams are fully accelerated to 4 TeV, they each contain up to 1380 bunches of $\sim 10^{11}$ protons with 50-ns spacing between each bunch\textsuperscript{8} \cite{77}. These protons reach a speed of 0.999999972 times the speed of light\textsuperscript{9}. The beam is designed to achieve a peak luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$, at which it will produce 600 million collisions per second \cite{61}.

3.2 ATLAS

One of the detectors used to detect the products of proton collisions at the LHC is ATLAS. ATLAS is one of two multipurpose detectors (along with CMS) that was intended for a broad range of physics goals, including searches for undiscovered particles (Higgs boson, SUSY particles) and precision measurements for SM particles ($W$ and $Z$ bosons, top quark). The LHC proton beams used with ATLAS deliver collisions at high luminosity to generate enough data to adequately perform these analyses. ATLAS uses multiple components with various technologies to detect and reconstruct physical objects from the final states of these proton collisions. A dedicated trigger system is used to select interesting events in data to be recorded for further study. ATLAS also has a dedicated software framework and working group to ensure that all data used for physics analyses is free of defects. Once data from ATLAS has been recorded, it is accessed by over 3000 scientists throughout the world. These scientists perform various analyses that collectively intend to accomplish the many physics goals of the ATLAS collaboration.

3.2.1 ATLAS Geometry

The ATLAS detector is cylindrical in shape, with the central axis overlapping with the LHC beamline. It is 46 m long, 25 m in diameter, and weighs 7000 tonnes. Two spacial coordinates are used to parameterize physical directions in ATLAS. The first is the azimuthal angle, $\phi$ (with $\phi = 0$ pointing

\textsuperscript{8}The LHC was originally designed to have 2808 bunches with 25-ns spacing. This was changed due to energy and pile-up considerations.

\textsuperscript{9}If each beam is driven up to its original design energy of 7 TeV, this will increase to 0.999999991 times the speed of light, equivalent to 11245 laps per second around the LHC.
3.2. ATLAS

towards the center of the LHC rings). The second is the pseudorapidity, \( \eta \), defined by:

\[
\eta = -\ln \left( \tan \frac{\theta}{2} \right)
\]

where \( \theta \) is the polar angle from the spherical coordinate system. This is configured so that \( \eta = +\infty \) \((-\infty)\) is aligned (anti-aligned) with the forward direction along the counter-clockwise beamline.

ATLAS consists of several layered subdetectors, each of which plays a different role in reconstructing particles and events (figure 3.5). These layers are centered around the collision point, though the exact shape and configuration of these layers depend on \( \eta \). For \(|\eta| \lesssim 1.3\) (the barrel region)\(^{10}\), layers form concentric cylinders that wrap around the beamline. For \(|\eta| \gtrsim 1.7\) (the endcap)\(^{10}\), each sublayer consists of flat, circular disks perpendicular to the beamline. The region in between (the crack) is where these planes intersect (and often overlap). These layers are arranged like this to align the planes approximately perpendicular to the particle trajectory in order to maximize the detector sensitivity for all possible particle directions [69].

### 3.2.2 ATLAS Components

The ATLAS detector consists of several subdetectors arranged in concentric cylinders (as described in section 3.2.1). Each subdetector is dedicated to measuring different properties of final-state particles from proton collisions. These properties are then used to identify and characterize the detected particles. The inner-most layer is the Inner Detector, which measures the charges and momenta of charged particles and aids with electron identification. The layer surrounding this is the Calorimeter system, which uses the sizes and shapes of energy deposits to identify particles and characterize the processes which produced them. The outermost layer is the Muon Spectrometer, which identifies muons and measures their momenta with high precision. ATLAS also contains an intricate set of superconducting magnets used to bend the trajectories of charged particles in the Inner Detector and Muon Spectrometer.

\(^{10}\)The exact boundaries of the barrel and endcaps vary for each system and subsystem in ATLAS.
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Figure 3.5: The different subdetectors of ATLAS form concentric cylinders around the collision point. From interior to exterior, these include the Inner Detector layers (Pixel, SCT, TRT), the Calorimeters (LAr, Tile), and the Muon Spectrometer. Superconducting solenoid and toroid magnets are used to steer the trajectories of charged particles [60].

3.2.2.1 Inner Detector

The subdetector system closest to the beamline is the Inner Detector. The full Inner Detector is a 6.2-m-long cylinder with a 2.2-m diameter (figure 3.6). It is encased in a superconducting solenoid magnet (section 3.2.2.4) that generates a 2-T magnetic field along the direction of the beamline [78]. This magnetic field bends the transverse trajectories of charged particles within the Inner Detector. The Inner Detector uses various technologies to measure the $\eta$ and/or $\phi$ positions of charged particles at select distances from the beamline. These are used to reconstruct the tracks of charged particles. The charge and momentum of each particle are respectively determined from the direction and curvature of its track(s). The Inner Detector consists of three sections (figure 3.7): the Pixel Detector, the Semi-Conductor Tracker (SCT), and the Transition Radiation Tracker (TRT). Each has its own unique advantages to contribute to the overall performance of track reconstruction and particle identification [69].

The Inner Detector section closest to the beamline is the Pixel Detector. This 1.3-m-long section
Figure 3.6: The ATLAS Inner Detector reconstructs tracks to determine the charges and momenta of charged particles. The inner layers use silicon sensors for precision measurements. The outer TRT layer specializes in measuring transition radiation to identify electrons [60].

Figure 3.7: A sample section of the Inner Detector in the barrel region. After particles pass through the beryllium beam pipe, they cross three layers of the pixel detector, four layers of the SCT, and \(\sim 35-40\) straw tubes of the TRT [60].
covers the radii of 50.5-122.5 mm from the beamline in the barrel (and up to 149.6 mm in the endcap). The Pixel Detector consists of three cylindrical layers in the barrel and three disks on either side of the endcap. It is made up of 1744 identical units called modules, each measuring $19 \times 63$ mm$^2$. Each module contains 46080 250-µm-thick silicon pixel sensors. Each pixel is assigned to an electrical readout channel which receives a signal when the pixel is hit by a charged particle with transverse momentum $p_T \gtrsim 0.5$ GeV. These pixels are each $50 \times 400$ µm$^2$, though the intrinsic accuracy for measuring charged particle positions is $10 \times 115$ µm$^2$. This resolution is the sharpest of all the Inner Detector systems, which is important due to the Pixel Detector’s proximity to the beamline. This proximity also requires the Pixel Detector components to be radiation hardened for prolonged operation. The Pixel Detector is particularly important for identifying secondary vertices for heavy particle decays (e.g. bottom, tau), which occur within millimeters (if not micrometers) of the beamline [69].

The next layer of the Inner Detector is the SCT, which covers the radii of 299-514 mm from the beamline in the barrel (up to 560 mm in the endcap) and is 544 mm in length. It consists of four layers in the barrel and nine disks on either endcap. The SCT uses silicon sensors similar to those of the Pixel Detector. However, larger sensors with less precise resolution are used for material-density- and cost-related reasons, though this is acceptable due to the increased distance from the beamline. Each silicon sensor strip is 285 µm thick, 80 µm wide, and ~12 cm long, lying parallel to the beamline in the barrel and outward radially in the endcaps. The sensors are arranged similarly across 4088 two-sided modules, with one side rotated by 40 mrad to provide sensitivity in $\eta$. The SCT contains a total of ~6.3 million readout channels and has an intrinsic accuracy of $17 \times 580$ µm$^2$. Although this is not as precise as the Pixel Detector, it has the best $\phi$ resolution per point with respect to radial distance of all three Inner Detector sections [69].

The outermost layer of the Inner Detector, covering 563-1066 mm from the beamline, is the TRT. This subdetector utilizes 4-mm-wide polyimide drift tubes (straws) with 31-µm-thick tungsten wires

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$^{11}$This is the momentum component in the transverse plane (perpendicular to the detector’s central axis).

$^{12}$Although there are more layers in the endcap than in the barrel, the inner and outer radii of these endcap disks are designed so that a particle traveling at a given $|\eta| (< 2.5)$ will only hit four layers.
3.2. ATLAS

in the center. These straws are filled with a gas consisting of 70% Xe, 27% CO$_2$, and 3% O$_2$. The barrel contains 52,544 144-cm-long straws arranged in 73 layers with each straw oriented parallel to the beamline. The combined endcaps contain 245,760 37-cm-long straws arranged in 160 planes with straws oriented radially [79]. About 351,000 readout channels are used for the TRT. When a charged particle with $p_T > 0.5$ GeV passes through a straw, the gas becomes ionized and excites the tungsten wire. This sends an electrical signal that yields a $\phi$ measurement for the hit. The TRT falls short of the silicon detectors in several respects: it yields no $\eta$ measurement, only covers $|\eta| < 2.0$, and has the poorest intrinsic accuracy per measurement ($130$ $\mu$m) of all the Inner Detector systems. The TRT has several advantages over the other Inner Detector systems though. The relatively poor resolution is compensated by the number of measurements taken ($\sim$35-40) and the extended measured track length. The TRT can also take advantage of transition radiation to contribute to particle identification. When highly relativistic particles pass through the Xe gas, they deposit more energy from transition radiation than particles with lower speeds. Different energy thresholds are therefore utilized to identify the signatures of these high-speed particles (i.e. electrons) [69].

3.2.2.2 Calorimeter

The layer of ATLAS surrounding the central solenoid is the Calorimeter system (figure 3.8). The calorimeters are used to absorb (and thus measure) the energies of particles that pass through them. The calorimeters of ATLAS are sampling calorimeters which use alternating layers of dense, absorbing material which absorbs the particle energy and sampling material which measures the shape of the resulting particle shower. They cover the detector region of $|\eta| < 4.9$. The Calorimeter system consists of two subsystems. The subsystem closest to the interaction point is the Electromagnetic (EM) Calorimeter, whose finer granularity is suited for precision measurements of electrons and photons. The outer system is the Hadronic (HAD) Calorimeter, which is less precise, but sufficient for measuring the energies of hadrons. These two subsystems function similarly but use different materials and configurations to meet their particular design goals [69].
Figure 3.8: The Calorimeter uses dense absorbing material to absorb particle energy and sampling material to characterize the resulting shower and measure the energy. The inner (EM) layer is for measuring photon and electron energy, while the outer (Hadronic) layer measures the energies of hadrons [60].

The EM Calorimeter is divided into barrel ($|\eta| < 1.475$, 6.4 m long) and endcap ($1.375 < |\eta| < 3.2$, 2.1-m radius) segments, 53-cm and 63-cm thick respectively. This thickness is designed to contain the energy of electrons and photons but allow hadrons and muons to “punch through” to other layers. The absorbing material used is steel-coated lead (\(\eta\)-dependent thickness between 1.13-2.2 mm) and the sampling material is liquid argon (LAr). The lead-liquid argon electrodes are configured with a zig-zagged “accordion” geometry which provides full coverage (no gaps) in \(\phi\) (figure 3.9). These electrodes are arranged across three radial layers\(^{13}\) with decreasing \(\eta\) granularities, which correspond to a total of 22-33 radiation lengths (\(X_0\)) depending on \(\eta\). In the $|\eta| < 1.8$ region, a layer of liquid argon\(^{14}\) called the presampler is used at the innermost radius to correct for electron and photon energy lost before the calorimeter. The EM calorimeter is designed to measure \(\eta\) and \(\phi\) as precise as $0.025 \times 0.025$ radians\(^2\) [69].

The HAD Calorimeter consists of three smaller calorimeters which cover different \(\eta\) regions and

\[^{13}\text{This drops to 2 layers for } |\eta| > 2.5.]^{14}\text{11-mm thick in the barrel, 5-mm in the endcap}\]
Figure 3.9: The electrodes of the EM Calorimeter are arranged in an accordion geometry to provide full coverage in $\phi$. They are divided into three radial layers with different granularities in $\eta$. The trigger tower is the smallest unit of angular resolution available to the L1 trigger [60].

use different materials for absorbing and sampling. Each of these systems is designed to contain the energy of hadrons, but allow muons to punch through to the Muon Spectrometer. The section covering $|\eta| < 1.7$ is called the Tile Calorimeter. This section consists entirely of barrel-like layers which extend from an inner radius of 2.28 m to an outer radius of 4.35 m, for a total of 7.4 interactions lengths ($\lambda$). This includes a primary barrel 5.8 m in length and two 2.6-m-long barrel extensions which cover the endcap calorimeter disks. The absorber material in the Tile Calorimeter is steel, while the sampling material is scintillating tile, which is read out through wavelength-shifting fibers and photomultiplier tubes. The peak $\Delta \eta \times \Delta \phi$ resolution is about $0.1 \times 0.1$ radians$^2$. The section covering $1.5 < |\eta| < 3.2$ is the Hadronic Endcap Calorimeter (HEC). These endcap disks have inner radii of either 372 mm or 475 mm$^{15}$ and outer radii of 2.03 m. The total thickness is 1.8 m in each endcap. The absorbing material is copper with thickness between 25-50 mm and the sampling material is liquid argon. The angular resolution in the HEC is the same as the Tile Calorimeter. The final calorimeter pieces are the Forward Calorimeters (FCal) which cover $3.1 < |\eta| < 4.9$. Each FCal consists of three stacked 45-cm-thick modules which fit within the wider inner radius of the

$^{15}$Each end of the HEC comprises 7 disks. The innermost disk has the smaller radius, while the other 6 all have the larger.
HEC. The first module of each FCal is used as an EM Calorimeter and uses copper absorbers with liquid argon as the sampling material. The second and third modules are intended as Hadronic Calorimeters and use tungsten absorbers with liquid argon samplers [69].

### 3.2.2.3 Muon Spectrometer

The layers of ATLAS outside the Calorimeter compose the Muon Spectrometer (figure 3.10), or MS, which is used for the identification and high-precision tracking of muons. The trajectories of muons are bent in the longitudinal-radial plane using one or more of ATLAS’ large toroidal magnets (section 3.2.2.4). Three cylindrical layers in the barrel (radii of 5, 7.5, and 10 m) and four layers of endcap disks\(^\text{16}\) (\(|z| = 7.4, 10.8, 14, \text{and} 25\) m) are used to reconstruct the tracks of these muons and measure their momenta based on the curvatures of their tracks. Muon momenta near 1 TeV are measured with about 10% resolution, though resolution improves as \(p_T\) decreases so that momenta of ~3 GeV may be measured by the MS alone. Each MS layer, which covers \(|\eta| < 2.7\) (or \(|\eta| < 2.0\) in the innermost layer), uses Monitored Drift Tube chambers (MDT’s) to track muons in the bending plane (the plane containing the beam axis). Each aluminum drift tube is 29.97 mm thick and contains a 50-\(\mu\)m-thick tungsten anode wire and Ar/CO\(_2\) (93:7) gas. As muons pass through the tubes, they ionize the gas. This sends a signal through the wire which registers the \(\eta\) coordinate. Each MS layer consists of two sublayers of chambers, each with 3-4 layers of drift tubes, and yields a resolution as sharp as 35 \(\mu\)m along the bending plane. In the region of \(2.0 < |\eta| < 2.7\) where particle fluxes and muon-track densities are the highest, the inner layer uses Cathode Strip Chambers (CSC’s) instead of MDT’s due to their higher rate capability and time resolution. Each of these chambers contains radially-oriented anode wires and cathode strips which run both parallel and perpendicular to the anodes. Each muon crosses four CSC layers and thus yields four measurements each for \(\eta\) and \(\phi\). The combined resolutions are 40 \(\mu\)m in the bending plane and 5 mm in the transverse plane [69].

In addition to tracking muons, the MS has the added function of triggering on muon tracks for \(|\eta| < 2.4\). This is performed with fast trigger chambers which are located on specific MS layers.

\(^{16}\)Although there are four disks in the endcap, their inner and outer radii are set so that a given muon will most likely only hit three disks.
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Figure 3.10: One quadrant of the Muon Spectrometer used to track and identify muons. MDT’s are used for precision tracking in the barrel and endcap, while RPC’s and TGC’s are used to trigger on muons in the barrel and endcap respectively. CSC’s are used to track muons on the innermost layer for \(2.0 < |\eta| < 2.7\) [80].

These chambers deliver signals in 15-25 ns, thus making them available for L1 trigger decisions (section 3.2.3). Two \(\eta\)-dependent technologies are used for these chambers. The barrel (\(|\eta| < 1.05\)) is equipped with Resistive Plate Chambers (RPC’s) on both sides of layer 2 and one side of layer 3, while the endcap (\(1.05 < |\eta| < 2.4\)) utilizes Thin Gap Chambers (TGC’s) on the inside of layer 1 and both sides of layer 3\(^{17}\). These technologies are chosen for their respective regions because TGC’s have a higher rate capability to deal with the high rate of endcap muons, while RPC’s have better spacial resolution which is important for measuring the track curvature in the barrel. Both types of trigger chambers are responsible for providing bunch-crossing information and well-defined \(p_T\) thresholds. An additional function of the trigger chambers is that they are able to measure coordinates in both the bending plane (within 2-10 mm) and transverse plane (within 3-10 mm). The bending-plane coordinate is used to match triggered muon tracks with those of the precision trackers, and the

\(^{17}\)A double layer of TGC’s (with < 1-m separation) is placed on the outside of endcap layer 3.
transverse coordinate is assigned to the track as a second coordinate (since precision trackers do not measure this for $|\eta| < 2.0$) [69].

3.2.2.4 Magnet System

In order to bend charged particles to measure their momenta in the Inner Detector and/or Muon Spectrometer, ATLAS uses a system of four superconducting magnets (figure 3.11). The first of these magnets is the inner solenoid. This 1154-turn solenoid is 5.8 m long, 2.51 m in diameter, and covers the Inner Detector. It generates a magnetic field within its interior that is aligned with the beamline and bends charged particles in the transverse plane. This magnetic field is 1.998 T at the interaction point and is uniform throughout most of the cavity, dropping by $\sim 10\%$ at $|z| \approx 1.7$ m and steeply dropping to $\sim 0.9$ T at the cavity’s edge. This field is strong enough to allow high-resolution momentum measurements, but weak enough that particles with $p_T > 0.4$ GeV will move straight enough to be detected [69].

![Figure 3.11: The ATLAS magnet system. A central solenoid (blue) is used to bend charged particles in the transverse plane within the Inner Detector. The barrel toroid (red) and endcap toroids (green) are embedded in the Muon Spectrometer and are used to bend muon trajectories within the plane containing the beam axis [81].](image)

The other magnets are toroids embedded within the Muon Spectrometer. These include a central barrel toroid and two endcap toroids. Each toroid consists of eight\(^{18}\) rectangular loops separated by 45 degrees in $\phi$. The loops of the barrel toroid have inner radius of 4.7 m, outer radius of 10 m,\(^{18}\)Each of these loops contain 116-120 turns.

\(^{18}\)Each of these loops contain 116-120 turns.
and are 25.3 m long. They generate a magnetic field within the center of these loops oriented in the azimuthal ($\hat{\phi}$) direction. This bends muons in the MS along the plane that overlaps with the beamline. The magnetic field is not uniform, as that would require many more loops in the toroid. It varies from 0.15 T to 2.5 T, with an average of 0.5 T, within $|\eta| < 1.4$. The endcap toroid loops each have inner radius of 82.5 cm, outer radius of 5.35 m, and are 5 m long. They are displaced from the interaction point along $z$ by $\sim 10.5$ m in either direction. In order to fit in alongside the barrel toroid, the endcap toroids are rotated by 22.5 degrees along $\phi$ with respect to the barrel toroid. The magnetic field generated by the endcap toroids varies between 0.2 T and 3.5 T in the range of $1.6 < |\eta| < 2.7$. The $|\eta|$ range between 1.4 and 1.6 is where the fringe field from one magnet largely cancels the field from the other [69].

3.2.3 Trigger and Data Acquisition

Collisions at ATLAS occur at a rate of up to 40 million bunch crossings per second (40 MHz).\textsuperscript{19} As of 2015, computing standards have not reached a point where all of this data can reasonably be stored. Given that in many collisions the interacting partons only contain a small fraction of the proton energy, only a small fraction of events will be of interest anyway. A dedicated trigger and data acquisition system (TDAQ) has been developed at ATLAS to carefully select and record relevant data (figure 3.12). This successfully reduces the amount of data by $\sim 5$ orders of magnitude. The TDAQ records 320 Mbytes per second, which amounts to $\sim 3$ Pbytes per year.

The trigger filters data in 3 steps: Level 1 (L1), Level 2 (L2), and the Event Filter (EF). The L1 trigger is implemented using hardware components from the Calorimeter trigger towers as well as RPCs and TGCs in the Muon Spectrometer. Special-purpose processors use reduced-granularity information from these systems to select events with signatures of high-$p_T$ muons, electrons, photons, jets, and taus, as well as events with large missing transverse energy ($E_T^{\text{miss}}$) or large total transverse energy. The L1 trigger decision must reach the read-out electronics within 2.5 $\mu$s of bunch crossings. The L1 trigger outputs collision data at a maximum rate of 100 kHz. This data is collected by the

\textsuperscript{19}This corresponds to the LHC’s initial design of 25-ns bunch separation.
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Figure 3.12: The ATLAS trigger chain. The L1 trigger uses detector hardware components to filter events using reduced-granularity information. The L2 trigger and event filter then use full-granularity data with computer clusters to reduce the event rate to 200-1000 Hz. The full trigger chain reduces the event rate by a factor of $\sim 10^5$ [82].

data acquisition system (DAQ) and transmitted to the L2 and EF triggers through point-to-point readout links.

The L2 trigger and EF constitute the high level trigger (HLT), which uses computer clusters and software to filter data. The HLT selects events using the full-granularity information from the Calorimeter and MS, as well as information from the Inner Detector. The L2 trigger, which comprises about 500 processors, seeds its selection by regions of interest (ROI’s). or regions of $\eta$ and $\phi$ where the L1-triggered objects were located. It uses the full-granularity information from ROI’s to make decisions which limit the amount of data transferred from the detector readout. The L2 trigger selection cuts the event rate to 3.5 kHz. Its average processing time per event is 40 ms. The final trigger level, the EF, is composed of 1800 processors. It uses offline procedures (incorporating alignments, calibrations, etc...) to select fully-built events. The EF reduces the event rate to $\sim$200-1000 Hz and processes events with an average time of 4 s. The full chain of HLT processes is controlled by the DAQ, which also controls and monitors the ATLAS detector during data taking [69].
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3.2.4 Computing

Raw data from ATLAS is recorded after passing the full trigger chain. As stated in section 3.2.3, this amounts to \( \sim 3 \) Pbytes of data (or \( \sim 1 \) billion events) per year. Once events are reconstructed, this adds another \( \sim 2 \) Pbytes per year. In order to study this data on a reasonable time scale, it is vital to divide it up for large-scale parallel processing. In order to make this data widely accessible and enable many simultaneous analyses with it, the ATLAS collaboration takes advantage of the Worldwide LHC Computing Grid (WLCG), a network of computer centers responsible for storing and processing data from LHC experiments [83].

The raw data from ATLAS and the other LHC detectors is collected at Tier 0, the computing center at CERN. This is also where the first pass at reconstruction occurs. The raw and reconstructed data from Tier 0 is divided up and evenly distributed to 13 academic/research institutions called Tier 1 centers, which are scattered throughout North America, Europe, and Asia. These centers access Tier 0 data through dedicated optical fiber links\(^{20}\) at 10 Gbit/s. In addition to storing and reprocessing data, Tier 1 centers provide support for the Grid at all times. Much of the data sent to Tier 1 institutions is further divided up and sent to \( \sim 150 \) Tier 2 sites, which mainly include universities and scientific institutes. These centers store and process data for specific analysis tasks and connect to Tier 1 centers through national research and education networks. As processed data is produced at Tier 2 sites, it is sent up to Tier 1 sites for storage. Finally, individuals access the Grid through Tier 3 resources (university or personal computers). These are used for personal data storage/analysis and do not formally engage with any of the WLCG systems. Much of the research presented in this dissertation was performed at the ATLAS Tier 3 site at Yale University [83].

3.2.5 Data Quality

In order to ensure that the various systems of ATLAS are functioning properly, ATLAS has a dedicated Data Quality (DQ) group for monitoring the performance of ATLAS. This group includes

\(^{20}\)These constitute the LHC Optical Private Network (LHCOPN).
representatives from each of the ATLAS subsystems (Inner Detector subsystems, Calorimeter systems, etc . . . ) as well as the combined performance (CP) groups who oversee the reconstruction and identification of physics objects (electrons, jets, muons, etc . . . ). Data Quality Monitoring (DQM) at ATLAS has both an online (during data taking) and offline (after data taking) components. Both rely on the same Data Quality Monitoring Framework (DQMF) to collect and evaluate data [84].

Online DQM is performed by designated shifters working in the ATLAS control room at the time of data collection. The DQMF interacts with the TDAQ to produce histograms which characterize the information collected in the three Inner Detector subsystems, the LAr and Tile calorimeters, and the tracking and trigger systems of the MS. These are mostly basic histograms which map out the hits or energy collected in the different spatial regions of these components. Histograms can cover either a single event, a luminosity block\(^2\), or an entire collision run. Each histogram has a set of automated checks which measure specified statistical parameters. Thresholds are set on these parameters to indicate whether a deviation has occurred from the subdetector’s expected behavior. When no issues are present, a histogram will be marked as green. If one or more statistical parameters from an automated check fall outside the acceptable range, the histogram will be flagged as yellow (possible issue) or red (definite issue) and the shifter will be alerted. The shifter can then access the histograms and automated check results through the Data Quality Monitoring Display (DQMD), which allows the shifter to quickly diagnose issues. These issues include such problems as misaligned components, broken modules, or high levels of background noise. Once the shifter diagnoses an issue, he/she can either fix the issue on the spot (for issues such as noisy channels) or flag the issue to be recovered in offline DQM [85].

Offline DQM uses a similar system of evaluating histograms for defects. However, these histograms are from events which have been reconstructed at Tier 0. After the Tier 0 processing, shifters who represent the ATLAS subsystems are responsible for checking histograms using the

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\(^2\)This is a small time interval (~ 1 minute) where the instantaneous luminosity remains constant. It is also the time subinterval used to integrate instantaneous luminosities in order to calculate integrated luminosity.
results of automated checks. Shifters representing the combined performance groups must also mon-
itor histograms as a cross-check to make sure that the distributions of variables used for object 
reconstruction and identification have not been impacted by defects within the data. Once defects 
have been flagged, the data is reprocessed using calibrations which either remove or compensate for 
the defect. The shifters from the ATLAS subsystems and CP groups then check these reprocessed 
histograms for any remaining defects. Any collision runs still afflicted with defects are flagged for 
removal from physics analyses. The remaining runs are added to the Good Run List (GRL), which 
is used by physics analyses to select data which has been approved by DQM [86].

3.2.6 Data Taking in 2012

During the 2012 8-TeV collision period, the LHC delivered 308 runs of proton collisions with a 
maximum luminosity of $7.73 \times 10^{33}$ cm$^{-2}$s$^{-1}$ to ATLAS. The total integrated luminosity from these 
collisions was 22.8 fb$^{-1}$. 21.3 fb$^{-1}$ of data was recorded by ATLAS, and 20.3 fb$^{-1}$ was included 
in the GRL (figure 3.13) [87]. This data is divided across 10 periods (A-E, G-I, and L) which use 
slightly varied calibrations, trigger configurations, and reconstruction methods.

![Figure 3.13: Integrated Luminosity vs time for data delivered by LHC, recorded by ATLAS, and approved by ATLAS DQM.](image-url)
Chapter 4

Physics with Taus at ATLAS

The tau lepton is the heaviest of the known leptons and the only known lepton massive enough to decay into one or more hadrons. The proper decay length of the tau is $87 \, \mu m$ [6], which means that taus from LHC collisions decay before even reaching the ATLAS Pixel Detector. Because of this, taus in events recorded by ATLAS must be reconstructed from their visible decay products. Tau decays can be divided into hadronic and leptonic decays. The hadronic decays involve the tau decaying into one or more hadrons\(^1\) and a tau neutrino. These are the most common types of tau decays (64.8% branching ratio). The other 35.2% of tau decays involve the decay into a lighter charged lepton and the appropriately flavored neutrino-antineutrino pair. Table 4.1 provides more details on tau branching ratios. Because their individual decay products can be studied, taus can yield more information about parent particles than other charged leptons (e.g. polarization). Their couplings to parent bosons also allow them be used as probes in searches for the SM Higgs boson and particles from multiple BSM theories.

Because leptons from leptonically decaying taus ($\tau_{lep}$) are very difficult to distinguish from other leptons, ATLAS focuses on reconstructing and identifying hadronically-decaying tau candidates ($\tau_{had}$). Furthermore, neutrinos do not interact in the ATLAS detector, so they are not taken into account when reconstructing $\tau_{had}$. The hadronic decay products of $\tau_{had}$ are first reconstructed as jets:

\(^1\)most commonly pions ($\pi$), though rare decays to kaons ($K$) or $\rho$ mesons occur
4.1. TAU RECONSTRUCTION

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Branching Ratio (%)</th>
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<td>total leptonic decays</td>
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<tr>
<td>$e^-\nu_e\nu_\tau$</td>
<td>17.83</td>
</tr>
<tr>
<td>$\mu^-\nu_\mu\nu_\tau$</td>
<td>17.41</td>
</tr>
<tr>
<td>total hadronic decays</td>
<td>64.76</td>
</tr>
<tr>
<td>$h^-\nu_\tau +$</td>
<td>49.75</td>
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<tr>
<td>neutr. (1-prong)</td>
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</tr>
<tr>
<td>$h^-h^+\nu_\tau +$</td>
<td>14.57</td>
</tr>
<tr>
<td>neutr. (3-prong)</td>
<td></td>
</tr>
<tr>
<td>5 or more prongs</td>
<td>&lt; 1.0</td>
</tr>
</tbody>
</table>

Table 4.1: Branching ratios for the $\tau^-$. The ”neutr.” label is used to signify zero or more electrically neutral hadrons. The branching fractions for $\tau^+$ are determined by flipping the charge signs of decay products (or swapping a neutrino for an antineutrino and vice-versa).

Narrow cones of hadrons produced from high-energy physics processes, typically the hadronization of gluons or quarks. Reconstructed taus are difficult to distinguish from quark- and gluon-initiated jets\(^2\). To be considered for physics analyses they must first pass tau identification, which utilizes tau characteristics such as their distinct 1- or 3-prong track signature and narrow shower shape to discriminate between taus and jets. Electrons and muons can also be misidentified as one-prong taus, so $\tau_{\text{had}}$ are subjected to algorithms for lepton rejection as well \([88]\).

4.1 Tau Reconstruction

The reconstruction of $\tau_{\text{had}}$ is seeded from jet objects reconstructed using an anti-$k_t$ algorithm with distance parameter $R = 0.4$ \([89]\). Topological clusters (clusters of calorimeter cells with high signal-to-noise ratio \([90]\)) originating from these jets are used as inputs for the reconstruction algorithm. All jet objects with $p_T > 10$ GeV and $|\eta| < 2.5$ are considered. The vertex of the $\tau_{\text{had}}$ decay is selected using the Tau Jet Vertex Association (TJVA) algorithm, which assigns scores for each vertex candidate based on the total $p_T$ of tracks matched to that vertex from a given $\tau_{\text{had}}$ \([91]\).

The four-momentum\(^3\) of each $\tau_{\text{had}}$ is defined with three degrees of freedom: $p_T\(^4\), $\eta$, and $\phi$. A barycenter is calculated from the four-vectors of the topological clusters. The detector axis for the $\tau_{\text{had}}$ is then calculated from clusters within $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.2$ of this barycenter. These

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\(^2\) Unless otherwise stated, “jets” will refer to quark- and gluon-initiated jets for the remainder of this document.

\(^3\) This is the relativistic four-vector for energy and momentum: $p^\mu = (E, p)$.\(^4\)

\(^4\) The invariant mass of each $\tau_{\text{had}}$ is defined as 0, so $E_T (= E \sin \theta) = p_T$ for $\tau_{\text{had}}$ objects.
4.1. TAU RECONSTRUCTION

clusters are then recalibrated with the tau vertex coordinate system. The sum of these vectors is called the intermediate axis and is used to define the direction \((\eta, \phi)\) of the \(\tau_{\text{had}}\).

The initial topological clusters are calibrated using the Local Hadron Calibration (LC) [92]. However, this does not account for energy lost before the calorimeter, underlying event and pile-up\(^5\) contributions, and out-of-cone effects, all of which are needed to restore the true tau momentum/energy scale (TES). Using simulated samples of \(W \to \tau \nu, \ Z \to \tau \tau\), and \(Z^0_{SSM} \to \tau \tau\) events, weights are derived in bins of LC-calibrated energy, \(\eta\), and number of tracks \((N_{\text{track}})\) which restore the tau momentum to the true TES (figure 4.1). The contribution of pile-up to \(E_T\) is also calculated and subtracted out. Lastly, small (~1\%) corrections which account for poor instrumentation between the barrel and endcap are applied to \(\eta\) [93].

![Figure 4.1](image.png)

**Figure 4.1:** Weights are derived for different LC-calibrated energy \((E^{\tau}_{LC})\) and \(\eta\) ranges for 1-prong (left) and multi-prong (right) \(\tau_{\text{had}}\) to account for energy losses.

Tracks are associated to the \(\tau_{\text{had}}\) if they lie within the core cone \((\Delta R < 0.2\) of the intermediate axis) and pass several quality criteria from the inner detector (table 4.2). \(\tau_{\text{had}}\) are classified as one-prong (multi-prong) if they have only one (more than one) track within the core cone. Tracks within the isolation annulus \((0.2 < \Delta R < 0.4\) of the intermediate axis) are not associated to the \(\tau_{\text{had}}\), but they are used to calculate variables for tau identification and must also pass the quality criteria in table 4.2.

Neutral pions \((\pi^0)\) from hadronic tau decays are also reconstructed. The \(\pi^0\) reconstruction algorithm first counts the number of \(\pi^0\) candidates \((N_{\pi^0})\) within the core region using global tau features

\(^5\)This is a condition in which multiple pp interactions occur within the same (or adjacent) bunch crossing(s).
4.2. TAU IDENTIFICATION

<table>
<thead>
<tr>
<th>Quality Criteria for Track Reconstruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_T &gt; 1 \text{ GeV} )</td>
</tr>
<tr>
<td>( N(\text{pixel}) \geq 2 )</td>
</tr>
<tr>
<td>( N(\text{pixel}) + N(\text{SCT}) \geq 7 )</td>
</tr>
<tr>
<td>(</td>
</tr>
<tr>
<td>(</td>
</tr>
</tbody>
</table>

Table 4.2: Quality criteria required for tracks to be associated to reconstructed \( \tau_{\text{had}} \). \( N(x) \) is the number of hits in the \( x \) layer (maximum of 3 for pixel or 8 for SCT). \( d_0 \) (\( z_0 \)) is the distance of closest approach, or impact parameter, in the transverse (longitudinal) plane.

from the calorimeter and track momenta as inputs to boosted decision trees (section 4.2.1.1). The calorimeter clusters most likely associated with \( \pi^0 \)'s are then selected (2 clusters per \( \pi^0 \) candidate) based on a \( \pi^0 \) likeness score. The energy in these clusters is corrected for contributions from pile-up and electronic noise before finally being associated to the \( \tau_{\text{had}} \) [94].

4.2 Tau Identification

The algorithm used to reconstruct \( \tau_{\text{had}} \) provides very little rejection against the background from quark- and gluon-initiated jets. Contributions from light leptons falsely identified as taus are also present. In order to reduce these backgrounds, cut-based and multivariate algorithms are used to identify taus. These algorithms use variables calculated from the Calorimeter and Inner Detector during reconstruction. These identification variables describe the track characteristics and shower shape in the core and isolation regions. The definitions of these variables can be found in table 4.3, while the variables used in each algorithm are listed in table 4.4.

4.2.1 Discrimination against Jets

The largest background contribution for processes involving taus comes from jets\(^6\), largely because jets have a high production rate and similar signatures to taus [88]. In order to differentiate jets from taus, a set of multivariate algorithms called the tau ID has been developed. These algorithms

\(^6\)Jets misidentified as taus are said to “fake” taus.
### Table 4.3: Definitions of variables used in tau identification algorithms.

Several of these variables characterize the number of tracks, the width of the \( \Delta R \) cone, or vertex placement of \( \tau_{\text{had}} \). These help differentiate taus from jets, since taus have exactly 1 or 3 tracks, a comparatively narrow cone, and a displaced secondary vertex. Other variables characterize the length of the Calorimeter showers or the levels of transition radiation deposited in the TRT. These differentiate 1-prong taus from electrons, since electrons deposit higher levels of transition radiation and have shorter shower lengths in the Calorimeter.

<table>
<thead>
<tr>
<th>Identification Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{\text{vtx}} )</td>
<td>( \text{N(pile-up vertices w/} \geq 2 \text{tracks)} + \text{Primary Vertex (w/} \geq 4 \text{tracks)} )</td>
</tr>
<tr>
<td>( f_{\text{cent}} )</td>
<td>Fraction of core ( E_T ) in central region (( \Delta R &lt; 0.1 ))</td>
</tr>
<tr>
<td>( f_{\text{cent}}^\text{corr} )</td>
<td>( f_{\text{cent}} + 0.003 \times N_{\text{vtx}} ) for ( p_T &gt; 80 \text{ GeV}, f_{\text{cent}} ) otherwise</td>
</tr>
<tr>
<td>( f_{\text{track}} )</td>
<td>Ratio of ( p_T ) from leading track (track w/ highest ( p_T )) to core ( E_T )</td>
</tr>
<tr>
<td>( f_{\text{track}}^\text{corr} )</td>
<td>( f_{\text{track}} + 0.003 \times N_{\text{vtx}} )</td>
</tr>
<tr>
<td>( R_{\text{track}} )</td>
<td>Weighted (by track ( p_T )) average ( \Delta R ) of tracks in core + isolation</td>
</tr>
<tr>
<td>( S_{\text{lead track}} )</td>
<td>( d_0 ) significance of ( \tau_{\text{had}} ) leading track in core (( d_0/\delta d_0 ))</td>
</tr>
<tr>
<td>( N_{\text{track}}^{\text{iso}} )</td>
<td>Number of tracks in isolation region</td>
</tr>
<tr>
<td>( \Delta R_{\text{max}} )</td>
<td>Maximum ( \Delta R ) between intermediate axis and ( \tau_{\text{had}} ) track within core</td>
</tr>
<tr>
<td>( S_T^{\text{flight}} )</td>
<td>Decay length significance of secondary vertex for multi-prong ( \tau_{\text{had}} ) in transverse plane (( L_T^{\text{flight}}/\delta L_T^{\text{flight}} ))</td>
</tr>
<tr>
<td>( m_{\text{tracks}} )</td>
<td>Invariant mass of the track system (core + isolation)</td>
</tr>
<tr>
<td>( m_{\pi^0+\text{tracks}} )</td>
<td>Invariant mass of the track system and ( \pi^0 ) clusters</td>
</tr>
<tr>
<td>( N_{\pi^0} )</td>
<td>Number of ( \pi^0 ) associated to the ( \tau_{\text{had}} )</td>
</tr>
<tr>
<td>( p_T^{\pi^0+\text{track}}/E_T )</td>
<td>Ratio of ( p_T ) estimate from tracks and ( \pi^0 ) information to calorimeter-only measurement</td>
</tr>
<tr>
<td>( f_{\text{EM}} )</td>
<td>Fraction of ( E_T ) deposited in EM calorimeter</td>
</tr>
<tr>
<td>( f_{\text{HT}} )</td>
<td>Ratio of high-threshold to low-threshold TRT hits from the lead track</td>
</tr>
<tr>
<td>( E_{\text{T,max}} )</td>
<td>Maximum ( E_T ) deposited in a cell in strip layer of EM calorimeter, excluding cells associated to the lead track</td>
</tr>
<tr>
<td>( f_{\text{lead track HCAL}} )</td>
<td>Ratio of ( E_T ) from Hadronic Calorimeter to ( p_T ) of leading track</td>
</tr>
<tr>
<td>( f_{\text{lead track ECAL}} )</td>
<td>Ratio of ( E_T ) from EM Calorimeter to ( p_T ) of leading track</td>
</tr>
<tr>
<td>( f_{\text{PS}} )</td>
<td>Fraction of ( E_T ) in presampler layer of calorimeter</td>
</tr>
<tr>
<td>( f_{\text{EM}}^{\pi^\pm} )</td>
<td>Fraction of ( E_T ) in EM calorimeter that comes from ( \pi^\pm )</td>
</tr>
<tr>
<td>( f_{\text{iso}} )</td>
<td>( 1 - f_{\text{cent}} )</td>
</tr>
<tr>
<td>( R_{\text{Had}} )</td>
<td>( E_T )-weighted ( \Delta R ) in hadronic calorimeter</td>
</tr>
</tbody>
</table>
are trained using samples of taus and jets and are optimized to discriminate between them based on variables from tables 4.3 and 4.4, particularly those characterizing the width of the shower (figure 4.2) and placements of tracks and vertices.

![Figure 4.2: Distributions of \( f_{\text{cent}} \) and \( R_{\text{track}} \), used for discrimination against jets. Taus and jets are represented by red and black dots respectively. Both distributions indicate that jets from taus tend to be narrower than quark- and gluon-initiated jets.](image)

The signal taus used to train the tau ID come from simulated \( W \rightarrow \tau \nu \), \( Z \rightarrow \tau \tau \), and \( Z'_{\text{SSM}} \rightarrow \tau \tau \tau \) samples. Both reconstructed and true\(^7\) taus must pass quality criteria to be considered. Reconstructed \( \tau_{\text{had}} \) must satisfy \(|\eta| < 2.3 \) and \( p_T > 15 \text{ GeV} \), in addition to being truth-matched (\( \Delta R < 0.2 \) between the \( \tau_{\text{had}} \)'s reconstructed axis and the axis of a true tau determined from truth variables). The truth variables from visible tau decay products must satisfy \(|\eta^{\text{truth}}| < 2.3\), \( p_T^{\text{truth}} > 10 \text{ GeV} \), and \( N_{\text{track}}^{\text{truth}} = 1 \) or 3. The background jets used for training come from jet-enriched data and must also satisfy \(|\eta| < 2.3 \) and \( p_T > 15 \text{ GeV} \). The tau ID is trained separately for 1- and multi-prong (2- or 3-prong) \( \tau_{\text{had}} \).

The performance of each algorithm is measured by the signal and background efficiencies defined as:

\[
\varepsilon_{\text{sig}} = \frac{N_{\text{pass \tau-ID}}^{\text{truth-matched \tau_{\text{had}}}}}{N_{\text{true taus}}} \quad \varepsilon_{\text{bkg}} = \frac{N_{\text{pass \tau-ID \ background \ \tau_{\text{had}}}}}{N_{\text{background \ \tau_{\text{had}}}}} \tag{4.1}
\]

where \( N_X^Y \) denotes the number of \( X \) satisfying \( Y \) (or total number of \( X \) for the denominators).

Efficiencies are measured separately for 1-prong and multi-prong \( \tau_{\text{had}} \). For each algorithm, three

\(^7\)\( m_{Z^{\prime}} = 250, 500, 750, 1000, \) and 1250 GeV. These are mainly to enhance the number of high-\( p_T \) taus.

\(^8\)These are created and flagged as actual taus by Monte Carlo generators. Their “truth” kinematic variables are determined at the point of generation, as opposed to reconstructed variables which are determined by simulating reconstruction with ATLAS.
4.2. TAU IDENTIFICATION

thresholds (loose, medium, and tight) are set based on different target signal efficiencies. These provide different balances between high signal efficiency and high background rejection in order to accommodate different physics analyses. The target $\varepsilon_{\text{sig}}$ for loose, medium, and tight 1-prong $\tau_{\text{had}}$ are 70%, 60%, and 40% respectively. The target $\varepsilon_{\text{sig}}$ for multi-prong $\tau_{\text{had}}$ are each 15-20% less than the corresponding 1-prong value.

Two types of multivariate algorithms are used for the tau ID. One uses boosted decision trees (BDT’s), while the other uses a projective likelihood (LLH) algorithm. To account for differences between data and simulation, scale factors are calculated by measuring efficiency in data from 2012. These are then applied as weights to simulated events in physics analyses (see section 4.2.1.3 for more details).

4.2.1.1 Boosted Decision Tree ID

The BDT algorithm [95] uses decision trees [96] in order to select taus and reject jets. A decision tree consists of a branching structure of nodes, each representing a cut on an identification variable. Using an entire training set (or sample collection of truth objects) as input, a cut is optimized\(^9\) for the initial node to provide the maximum discrimination between background jets and signal taus. $\tau_{\text{had}}$ that fail this cut are passed down the tree to a new node while events that pass are sent downstream to an alternate new node. For each of these nodes, a new cut is then optimized to yield the maximum discrimination among its own inputs. This continues recursively until a stopping condition is reached (minimum number of input $\tau_{\text{had}}$ for this particular case [97]). At each of these terminal nodes, or leaf nodes, the purity\(^10\) of true taus among its inputs is assigned to that node as a decision tree score. Once the decision tree is trained, individual $\tau_{\text{had}}$ are then fed to the input node and are passed down the tree according to which cuts they pass or fail. They are then assigned the decision tree score of the leaf node at which they arrive.

---

\(^9\)This optimization includes both the variable selection and the choice of threshold.  
\(^{10}\)defined as $\frac{N_{\text{signal}}}{N_{\text{signal}} + N_{\text{background}}}$
4.2. TA hips Identification

A boosted decision tree utilizes multiple decision trees and weights their decision tree scores into a final boosted decision tree score ranging from 0 (background-like) to 1 (signal-like) \[97\]. These decision trees are trained in series, each assigning larger weights to objects misclassified\[11\] by the previous iteration \[98\]. For the tau ID, BDT score thresholds are set as functions of true visible \(p_T\) and \(N_{track}\) for loose, medium, and tight working points to yield the target signal efficiencies as flat distributions across \(p_T\). The ROOT [99] Toolkit for Multivariate Data Analysis (TMVA) [100] is used to train two boosted decision trees: one for 1-prong \(\tau_{had}\) and the other for 3-prong \(\tau_{had}\). Although the latter is trained with only 3-prong \(\tau_{had}\), it is used to classify all multi-prong \(\tau_{had}\). The tau ID BDT uses a small number of variables (5-6) in order to reduce dependence on pile-up conditions. The performance of the BDT tau ID is shown in figure 4.3.

![Signal Efficiency vs. Inverse Background Efficiency](image)

> **Figure 4.3:** \((\varepsilon_{bkg})^{-1}\) as functions of \(\varepsilon_{sig}\) for low (left) and high (right) \(p_T\) ranges. The loose, medium, and tight working points are marked in red.

4.2.1.2 Projective Likelihood Method

The projective likelihood method evaluates the relative probability of a \(\tau_{had}\) belonging to the signal or background using the log likelihood discriminant:

\[
d_{LLH} = \ln \left( \frac{L_S}{L_B} \right) = \sum_{i=1}^{N} \ln \left( \frac{p_S(x_i)}{p_B(x_i)} \right)
\]

\[\text{(4.2)}\]

\[11\] Objects are classified as taus if the decision tree score lies above a set threshold (usually 0.5). Otherwise they are classified as jets.
where \( p_i^{S(B)}(x_i) \) is the probability distribution of the variable \( x_i \) for the signal (background) \([101]\).

These distributions are evaluated from the fraction of taus (or jets) per bin in a one-dimensional histogram of \( x_i \). These histograms are produced separately for 1-prong and 3-prong \( \tau_{\text{had}} \), as well as for three different \( p_T \) ranges (< 45 GeV, 45-100 GeV, and > 100 GeV). To avoid discontinuities in \( p_T \), a linear interpolation of \( d_{LLH} \) is used for \( \tau_{\text{had}} \) within \( \pm 10 \) GeV of the 45-GeV \( p_T \) boundary or \([-30, +60]\) GeV of the 100-GeV boundary. Loose, medium, and tight thresholds on \( d_{LLH} \) are selected as functions of true visible \( p_T \) for 1-prong and 3-prong \( \tau_{\text{had}} \) in order to achieve the target signal efficiencies as flat distributions with respect to true \( p_T^{\text{vis}} \).

### 4.2.1.3 Tau ID Efficiency Scale Factors

The tau ID has been tuned to achieve specific signal efficiencies in simulation. The tau ID signal efficiencies must also be measured in data to make sure that the tau ID performs comparably.

The signal efficiencies from data are used to calculate tau ID scale factors which are used in physics analyses to account for any discrepancies between data and simulation due to differences in modeling of the input variables.

The efficiencies in data are evaluated using a procedure called the tag-and-probe method \([88]\): signal events in data with real leptons are selected and efficiencies are estimated by counting the number of \( \tau_{\text{had}} \) before and after each variation of tau ID is applied. These efficiency measurements are repeated for different physics processes with hadronic taus in the final states. The main measurement is conducted using a \( Z \rightarrow \tau_{\text{lep}} \tau_{\text{had}} \) signal which has low background and covers the 20 GeV < \( p_T < 50 \) GeV region. \( W \rightarrow \tau_{\text{had}}\nu_T \) events are used to cross-check this measurement. A \( t\bar{t} \rightarrow \tau_{\text{had}} + \text{jets} \) signal is used for measuring efficiency in a higher \( p_T \) regime (40 GeV < \( p_T < 100 \) GeV).

Since it is impossible to obtain a pure sample of signal events from data, the signal and background contributions are estimated using a variable that provides good discrimination between the two. The variable chosen for this is the extended track multiplicity, or the number of tracks within \( \Delta R < 0.6 \) of the \( \tau_{\text{had}} \) axis that are \( p_T \)-correlated to a track within the core cone\(^{12}\) \([88, 91]\). Expected

\(^{12}\)This correlation is satisfied if \( \frac{p_{T\text{inner}}}{p_{T\text{outer}}} \times \Delta R(\text{inner, outer}) < 0.4 \).
4.2. TAU IDENTIFICATION

Distributions\(^{13}\) (templates) of this variable from signal and backgrounds are then fit to data to obtain an estimate of the signal (figure 4.4), which is then used for counting \(\tau_{\text{had}}\). This fit to data is performed both before and after the tau ID is applied.

\[ SF = \frac{\varepsilon_{\text{data}}}{\varepsilon_{\text{simulation}}} \]  

(4.3)

where \(\varepsilon_{\text{simulation}}\) is the \(p_T\)-inclusive signal efficiency from simulation. Both \(\eta\)-inclusive and barrel- and endcap-specific scale factors are measured. Systematic uncertainties on the scale factors are obtained by propagating uncertainties on the signal efficiency, which are in turn calculated by varying the templates used to estimate the signal to account for various systematic effects\(^{[88]}\). Scale factors account for subtle changes and evaluate close to unity, rising up to \(\sim 10\%\) for some tight working points (figure 4.5).

\(^{13}\)These templates are derived from simulation for true leptons and taus and from data-driven estimates for jets.
4.2. TAU IDENTIFICATION

<table>
<thead>
<tr>
<th>Identification Variable</th>
<th>Tau ID (BDT or LLH) 1-prong</th>
<th>3-prong</th>
<th>Electron Veto 1-prong</th>
<th>Muon Veto 1-prong</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{corr}$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$f_{cent}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f_{track}$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$S_{lead\ track}$</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{track}^{iso}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta R_{max}$</td>
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<td></td>
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<td>$S_{T}^{flight}$</td>
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</tr>
<tr>
<td>$m_{tracks}$</td>
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<td>$N_{\pi^{0}}$</td>
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<td>$p_T^{\pi^{0}+\ track}/E_T$</td>
<td>✓</td>
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<tr>
<td>$f_{EM}$</td>
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<tr>
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</tr>
<tr>
<td>$f_{EM}^{\pi^{0}}$</td>
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<tr>
<td>$f_{iso}$</td>
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<td>✓</td>
<td></td>
</tr>
<tr>
<td>$R_{Had}$</td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4: Identification variables and the algorithms that use them. A check mark denotes that the variable for that row is used by the algorithm for that column. The * symbol denotes a tau ID variable used for offline identification but not for the trigger-level identification.

Figure 4.5: Tau ID Scale Factors and their uncertainties. Results for different $\tau_{lep}$ decays and $\eta$ ranges are shown as well as inclusive results.
4.2. TAU IDENTIFICATION

4.2.2 Discrimination against Electrons

Electrons are capable of leaving a signature very similar to that of 1-prong taus\textsuperscript{14}. After the suppression of jet backgrounds, this leaves a significant electron background. However, electrons can be differentiated from taus by several characteristics, such as their transition radiation emissions in the TRT and their short, narrow shower shape. These and other variables (see table 4.4) are used to optimize a BDT for rejecting electron backgrounds, also known as the electron veto. As is the case with the tau ID, scale factors are measured to compensate for the difference between the electron veto’s performance in simulation and in data.

4.2.2.1 Boosted Decision Tree Electron Veto

The electron veto BDT is trained using the TMVA. The training set consists of simulated $Z \rightarrow \tau\tau$ events for the signal and $Z \rightarrow ee$ events for the background. $\tau_{\text{had}}$ and electrons must be truth-matched to true 1-prong taus and true electrons respectively. All objects must have $p_T > 20$ GeV and pass the loose BDT tau ID. Taus overlapping ($\Delta R < 0.2$) with electrons are excluded. Five BDT’s were trained; each covers a different $\eta$ range\textsuperscript{15} ($|\eta| < 0.8$, $0.8 \leq |\eta| < 1.37$, $1.37 \leq |\eta| < 1.52$, $1.52 \leq |\eta| < 2.0$, and $2.0 \leq |\eta| < 2.47$) and uses a slightly different set of variables. Loose, medium, and tight working points are established for the electron veto with respective target signal efficiencies of 95\%, 85\%, and 75\%. For each working point, thresholds are placed on the BDT score as a function of reconstructed $p_T$ to achieve the target signal efficiency as a flat distribution across $p_T$. The performance of the BDT electron veto is shown in figure 4.6.

4.2.2.2 Electron Veto Efficiency Scale Factors

To measure the performance of the electron veto in data, identification efficiencies are calculated in data from $Z \rightarrow ee$ events. These efficiencies are determined from a tag-and-probe analysis in which events with real electrons in their final states are selected and the number of $\tau_{\text{had}}$ are counted before

\textsuperscript{14}Electrons can also mimic three prong taus, but studies on this matter transcend the scope of this analysis.

\textsuperscript{15}This is largely because the TRT and its associated variables only cover $|\eta| < 2.0$. 
and after the electron veto, tau ID, and overlap removal are applied. Efficiency measurements are repeated using multiple levels of tau ID, electron veto, and electron overlap removal and are compared to the efficiencies from simulated $Z\rightarrow ee$. Scale factors are calculated in bins of $\eta(\tau_{\text{had}})$ according to equation 4.3 to account for discrepancies between simulation and data.

Before $\tau_{\text{had}}$ can be counted, backgrounds from multijets, $W\rightarrow e\nu$, $Z\rightarrow \tau\tau$, and $t\bar{t}$ must be estimated and subtracted. The shape and normalization of the multijet background is estimated from a control region characterized by the electron and $\tau_{\text{had}}$ having the same electric charge. The shapes of the other three backgrounds are taken from simulation, but the normalizations are each derived from a control region designated for that background in data.

Systematic uncertainties are evaluated by varying the tag electron’s $p_T$ and calorimeter isolation requirements as well as the background normalization. Scale factors evaluate close to unity with uncertainties that are small for the loose working point but increase for the medium and tight working points (largely due to statistical uncertainties). Comparisons between data and simulation for the loose working point are shown in figure 4.7.

### 4.2.3 Discrimination against Muons

Although muons are unlikely to deposit enough energy in the Calorimeter to be reconstructed as a $\tau_{\text{had}}$, they are sometimes misidentified as such if a sufficiently energetic cluster is associated with a
muon track. This is largely alleviated by rejecting $\tau_{\text{had}}$ which overlap with muon candidates, though some muons which fail muon reconstruction remain. A dedicated cut-based algorithm is used to reject these remaining muons faking taus.

Muon reconstruction sometimes fails because enough energy is deposited in the Calorimeter to skew the muon track in the Muon Spectrometer. These muons typically deposit most of their energy in the HAD Calorimeter (low $f_{EM}$) and have higher track $p_T$ than calorimeter energy (high $f_{track}$). Other muons fail reconstruction due to low energy which causes them to stop in the Calorimeter. They are characterized by high $f_{EM}$ and low $f_{track}$. Using true muons from simulated $Z \rightarrow \mu\mu$ and true taus from simulated $Z \rightarrow \tau\tau$, regions of high and low $f_{EM}$ are defined with a different $f_{track}$ cut applied in each. This cut-based algorithm retains over 96% of the signal taus and rejects $\sim 40\%$ of muons faking taus [88].

4.3 Triggering on Taus

In order to use hadronic taus for trigger decisions, $\tau_{\text{had}}$ reconstruction and/or tau identification is performed at all three trigger levels. However, due to the technical limitations of the trigger, changes to the reconstruction methods must be made at each level to accommodate the capabilities of that trigger. At L1, no Inner Detector information is available and the Calorimeter granularity is reduced.
4.3. TRIGGERING ON TAUS

to trigger towers ($\Delta \eta \times \Delta \phi = 0.1 \times 0.1$). The core region is defined as a $2 \times 2$ square of trigger towers ($\eta \times \phi = 0.2 \times 0.2$). The $\tau_{\text{had}}$'s $E_T$ is defined as the $E_T$ sum of the two most energetic neighboring towers in the EM and HAD calorimeters, while the EM isolation $E_T$ is the sum of the $E_T$ deposits in the annulus between $0.2 \times 0.2$ and $0.4 \times 0.4$ in the EM calorimeter. These $E_T$ values are used to establish various thresholds for different $\tau_{\text{had}}$ triggers. To suppress backgrounds and reduce the trigger rate, EM isolation $E_T < 4$ GeV is required for the lowest $E_T$ threshold.

The HLT is able to use full-granularity information, but latency issues at L2 require reduced reconstruction performance. Instead of using the Topocluster algorithm, $E_T$ is simply calculated and corrected for pile-up and electronic noise in the ROI from L1. The $\tau_{\text{had}}$ axis is taken as the $E_T$-weighted barycenter of cells within $\Delta R < 0.4$ of the L1 seed, though the $E_T$ assigned to the $\tau_{\text{had}}$ is calculated in the usual core region. The tracking variables are calculated using only Pixel and SCT information within $\Delta R < 0.3$ of the $\tau_{\text{had}}$ axis for tracks with $p_T > 1.5$ GeV. Since no vertex information is available, a cut of $|\Delta z_0| < 2$ mm between the candidate track and highest-$p_T$ track in the ROI is used as alternative method of pile-up removal. To reduce jet backgrounds and suppress the trigger rate, variables from tables 4.3 and 4.4 are calculated and cuts are optimized to provide background efficiencies of $\sim 10\%$ while maximizing signal efficiency.

$\tau_{\text{had}}$ reconstruction with the EF is very similar to that used by offline $\tau_{\text{had}}$ reconstruction. The primary differences are that $\pi^0$s are not reconstructed and impact parameter cuts of $\Delta z_0 < 1.5$ mm and $\Delta d_0 < 2$ mm with respect to the ROI leading track are used instead of the offline pile-up removal. To further reject jet backgrounds, BDTs are trained using table 4.4 variables to provide signal efficiency working points of $85\%$ and $80\%$ with respect to the medium offline candidates for one-prong and multi-prong $\tau_{\text{had}}$ respectively.

At all trigger levels, different trigger options are used to select events containing at least one $\tau_{\text{had}}$, two $\tau_{\text{had}}$, one $\tau_{\text{had}}$ and one electron or muon, or one $\tau_{\text{had}}$ and high $E_{\text{Tmiss}}$. Different $p_T$ (or $E_{\text{Tmiss}}$) thresholds are chosen based on the particular signal event for which the trigger is optimized to search. At a luminosity of $7.3 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, each L1 tau trigger outputs 3.5-12.5 kHz. This is reduced
4.4. DATA QUALITY WITH TAUS

to 2-18 Hz by the EF tau triggers operating at the same luminosity (figure 4.8). Signal efficiencies from the full trigger chain are calculated in data through a tag-and-probe analysis ($Z \rightarrow \tau\tau$ events) and scale factors are calculated by comparing these with efficiencies in simulation (figure 4.9) [94].

![Figure 4.8: L1 (left) and EF (right) trigger rates for various $\tau_{\text{had}}$ triggers as functions of luminosity.](image1)

![Figure 4.9: Signal efficiencies of the 20-GeV $\tau_{\text{had}}$ trigger in data and simulation in bins of offline $p_T$. These are used to calculate scale factors which are used in physics analyses.](image2)

4.4 Data Quality with Taus

The Tau Combined Performance group is one of the combined performance groups responsible for monitoring histograms as a part of ATLAS Offline DQM. Various kinematic distributions of $\tau_{\text{had}}$ (as well as events containing them) are used to determine whether defects in the detector are affecting $\tau_{\text{had}}$ reconstruction or tau identification. Depending on the particular defects observed, this information can be used to help the DQM groups monitoring the subsystems diagnose issues.
and determine which runs or luminosity blocks are affected. Since $\tau_{\text{had}}$ are reconstructed using information from the Inner Detector and Calorimeter systems, Tau Data Quality (Tau DQ) monitors histograms of both Inner Detector- and Calorimeter-related variables. Tau DQ histograms are particularly sensitive to Calorimeter issues since $\tau_{\text{had}}$ reconstruction is seeded from Calorimeter clusters. The issue that most commonly affects Tau DQ histograms is hot spots, or noisy regions of the Calorimeter. These can be diagnosed by monitoring the energy deposits in different $\eta$ and $\phi$ regions of the calorimeters. More complicated Calorimeter issues can be identified by monitoring the other Calorimeter-related variables from table 4.3. Tau DQ histograms are also sensitive to Inner Detector issues such as misalignment, so Inner Detector variables such as the number of hits in each layer are monitored to help diagnose these defects. As a broader check of detector performance, the results of the various tau ID algorithms are monitored for each run. Although this does not point to specific issues, large deviations from the expected performance help determine which runs contain defects that interfere with tau reconstruction and identification. Examples of histograms used for Tau DQ are shown in figure 4.10.
Figure 4.10: Examples of Tau DQ plots used to diagnose issues with the Calorimeter (top left), Inner Detector (top right), and overall tau identification (bottom). These are overlaid with normalized reference histograms (grey) which come from runs that are unanimously approved as good-quality runs by all DQ subgroups.
Chapter 5

$Z' \rightarrow \tau\tau$ Search at ATLAS

This chapter details the search for neutral high-mass resonances decaying to $\tau^+\tau^-$ pairs in $\sqrt{s} = 8$ TeV $pp$ collisions from the LHC using ATLAS [102]. The data was recorded during the 2012 LHC run period and corresponds to an integrated luminosity of 19.5-20.3 fb$^{-1}$. The search is performed across three decay channels, each distinguished by the tau decay products: $\tau_{\text{had}}\tau_{\text{had}}$ (42% branching ratio), $\tau_{e}\tau_{\text{had}}$ (23%), and $\tau_{\mu}\tau_{\text{had}}$ (23%). Because these channels have different dominant backgrounds and signal sensitivities, they are analyzed separately and then statistically combined to maximize the overall sensitivity. The $Z'_{SSM}$ signal is used to optimize the event selection in each channel. Upper limits on the $Z'_{SSM}$ production cross section ($\sigma$) times ditau branching ratio ($BR$) are measured for each signal mass hypothesis. The effects on the signal acceptance and $\sigma \times BR$ from adjusting the $Z'$-fermion couplings and $Z'$ decay widths are evaluated and additional limits are placed on the Non-Universal $G(221)$ $Z'$ model which predicts enhanced couplings to third-generation fermions.

For all signal hypotheses, limits are determined by counting events from data passing high-mass thresholds in each search channel and comparing to the expected numbers of signal and background events.
5.1 Data and Simulated Samples

5.1.1 Data

The data used in this analysis comes from $\sqrt{s} = 8$ TeV proton-proton collisions recorded by ATLAS in 2012. This data was reconstructed using the ATLAS Athena framework (release 17) [103]. Multiple event cleaning requirements were used to ensure high quality data (see section 5.2.2). The $\tau_{\text{had}}\tau_{\text{had}}$ channel uses 19.5 fb$^{-1}$ of integrated luminosity, while the two $\tau_{\text{lep}}\tau_{\text{had}}$ channels use the full 20.3 fb$^{-1}$. The specifics of the data requirements in each channel are discussed in sections 5.3.1 and 5.4.1.

5.1.2 Simulated Backgrounds

With the exception of some data-driven backgrounds (sections 5.3.3, 5.4.3), background processes are estimated using Monte Carlo (MC) simulation. The backgrounds generated are as follows:

$Z/\gamma^{*} \rightarrow \tau\tau$ This background is generated from PYTHIA 8.165 [104]. The Drell-Yan mass ranges for these samples include 180-250 GeV, 250-400 GeV, 400-1000 GeV (in blocks of 200 GeV), and 1-3 TeV (in blocks of 250 GeV). Cross sections for these samples are calculated at next-to-next-to-leading order (NNLO) with FEWZ 2.0 [105] using MSTW2008 NNLO PDF’s [106]. Mass-dependent $K$-factors are derived from these NNLO cross sections and are applied to leading order cross sections of $Z/\gamma^{*} \rightarrow \tau\tau$ and $Z' \rightarrow \tau\tau$.

$Z/\gamma^{*} \rightarrow ll ( + \text{jets})$ These samples are generated with POWHEG r1556 [107–109]. This generator is interfaced with PYTHIA 8 to simulate parton showering (radiation from QCD processes) and hadronization. The mass ranges chosen are the same as for $Z/\gamma^{*} \rightarrow \tau\tau$. $K$-factors are derived using the same technique as for $Z/\gamma^{*} \rightarrow \tau\tau$ and are applied to NLO cross sections of $Z/\gamma^{*} \rightarrow ll ( + \text{jets})$ [110].

$W(\rightarrow \mu\nu \text{ or } \tau\nu) + \text{jets}$ These samples, which are only used with the $\tau_{\text{had}}\tau_{\text{had}}$ channel, are generated with Sherpa 1.4.1 [111]. Cross sections are calculated at NNLO with FEWZ 2.0.
5.1. DATA AND SIMULATED SAMPLES

**tt\bar{t}, Wt, s-channel single top** The samples for these backgrounds are generated with MC@NLO 4.01 [112–114]. The parton showering and hadronization is performed with HERWIG 6.520 [115], which is interfaced to JIMMY 4.31 [116] for multiple-parton interactions. The cross sections are calculated at approximate NNLO for tt\bar{t} and Wt [117] and at next-to-next-to-leading-logarithm for s-channel top [118].

**t-channel single top** This top sample is generated using AcerMC 3.8 [119]. The parton showering and hadronization is done by PYTHIA 6.421 [120]. Cross sections are calculated at approximate NNLO [121].

**diboson (WW, WZ, ZZ)** Diboson samples are generated with HERWIG. The cross sections are calculated at NLO with MCFM [122].

The Parton Distribution Functions [123, 124] and MC Tune [125] are chosen based on the choice of generator. The choice of photon radiation [126] and/or tau-lepton decay simulators [127] are also generator-dependent. These choices are summarized in table 5.1.

<table>
<thead>
<tr>
<th>Generator</th>
<th>PDF’s</th>
<th>MC Tune</th>
<th>Photon Radiation</th>
<th>Tau-lepton Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>AcerMC</td>
<td>CTEQ6L1</td>
<td>AUET2B</td>
<td>PHOTOS</td>
<td>TAUOLA</td>
</tr>
<tr>
<td>HERWIG</td>
<td>CTEQ6L1</td>
<td>AUET2</td>
<td>PHOTOS</td>
<td>TAUOLA</td>
</tr>
<tr>
<td>MC@NLO</td>
<td>CT10</td>
<td>AUET2</td>
<td>PHOTOS</td>
<td>TAUOLA</td>
</tr>
<tr>
<td>POWHEG</td>
<td>CT10</td>
<td>AU2</td>
<td>PHOTOS</td>
<td>–</td>
</tr>
<tr>
<td>PYTHIA</td>
<td>CTEQ6L1</td>
<td>AU2</td>
<td>PHOTOS</td>
<td>–</td>
</tr>
<tr>
<td>Sherpa</td>
<td>CT10</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

*Table 5.1:* PDF’s, MC Tune, Photon radiation, and Tau-lepton decay are chosen based on the generator used. Dashes indicate that a particular tool was not needed by a particular generator for the chosen samples.

The response of the detector to each MC sample is simulated using a GEANT4 simulation of the ATLAS detector [128]. This is complicated by the fact that the detector response is very sensitive to pile-up. To account for this, minimum-bias interactions\(^1\) are overlaid with the generated MC events.

\(^1\)This refers to the expected events observed by the detector using a trigger that simply requires evidence of an interaction using detectors along the beamline.
5.2. PRESELECTION

These events are then reweighted so that the number of minimum-bias events per bunch crossing matches that of the data.

5.1.3 Signals

The various $Z' \rightarrow \tau \tau$ signal samples are created by reweighting the $Z/\gamma^* \rightarrow \tau \tau$ samples. This is performed using the TauSpinner algorithm [129], which is able to account for spin effects in tau decays. The details of the reweighing, the models used, and the rationale for using them are discussed in section 5.6. The names of the models are:

- $Z'_{SSM}$: Sequential Standard Model $Z'$
- $Z'_L$: Left-handed $Z'$
- $Z'_R$: Right-handed $Z'$
- $Z'_{\text{narrow}}$: $Z'$ with narrow decay width
- $Z'_{\text{wide}}$: $Z'$ with wide decay width
- $Z'_{NU}$: Non-Universal $G(221)$ $Z'$ (actually several signals with varying mixing angles)

Each signal model includes 17 mass hypotheses from 500-2500 GeV, in increments of 125 GeV.

5.2 Preselection

Before the analysis is broken into separate channels, a process called preselection is applied to all objects and events. This is a minimal set of criteria used to ensure good-quality objects in all search channels. It is based on object-selection and event-cleaning recommendations from various ATLAS Combined Performance groups and is intended for multiple analyses. Establishing a preselection for the analysis allows for data vs simulated signal + background comparisons to be made before looking at data in signal-sensitive regions.
5.2. **PRESELECTION**

5.2.1 **Object Reconstruction and Preselection**

Objects are reconstructed by common prescriptions across the ATLAS experiment. While some corrections and calibrations are applied during reconstruction, other preselection requirements must be implemented afterwards. The criteria for object preselection are chosen based on the type of object.

**Muons** Muons are reconstructed by matching tracks in the Muon Spectrometer to tracks in the Inner Detector [130]. The preselection requirements for muons are mostly recommended by the ATLAS Muon Combined Performance group [131], with some additional requirements on $p_T$ and $|\eta|$. These requirements are listed in table 5.2.

<table>
<thead>
<tr>
<th>Muon Preselection Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstructed as “Staco muon” (tracks are statistical average of Inner Detector and Muon Spectrometer tracks)</td>
</tr>
<tr>
<td>$p_T &gt; 10$ GeV</td>
</tr>
<tr>
<td>$</td>
</tr>
<tr>
<td>Pass “loose” Staco muon identification requirement</td>
</tr>
<tr>
<td>Require a B-layer hit (innermost Pixel layer) if expected</td>
</tr>
<tr>
<td>$N$(pixel hits) + $N$(dead pixel sensors) $\geq 1$</td>
</tr>
<tr>
<td>$N$(SCT hits) + $N$(dead SCT sensors) $\geq 5$</td>
</tr>
<tr>
<td>$N$(pixel holes) + $N$(SCT holes) $\leq 2$</td>
</tr>
<tr>
<td>if $0.1 &lt;</td>
</tr>
</tbody>
</table>

Table 5.2: Muon Preselection Requirements

**Electrons** Electrons are reconstructed by matching Inner Detector tracks to clusters in the EM Calorimeter [130]. Using a provided hypothesis for these tracks, they are refitted using a Gaussian-Sum-Filter (GSF) Fitter [132]. The electron identification algorithm used is the “Loose++” electron ID, which selects electrons with about 95% efficiency [133–135]. The full list of electron preselection requirements is found in table 5.3.

**Hadronic Taus** The reconstruction and identification of hadronic taus are described in detail in sections 4.1 and 4.2 respectively. The criteria for preselection are listed in table 5.4.
5.2. PRESELECTION

Electron Preselection Requirements

\[ p_T > 15 \text{ GeV} \]
\[ |\eta| < 1.37 \text{ or } 1.52 < |\eta| < 2.47 \]
\[ \text{el}\_\text{author} = 1 \text{ or } 3 \text{ (Reconstruction algorithm name)} \]
\[ \text{el}\_\text{QQ}\&1446 = 0 \text{ (quality map from ATLAS Egamma Working Group)} \]
Passes “Loose++” electron identification
Require at least one B-layer hit if expected
No overlap (\(\Delta R < 0.2\)) with preselected muons

<table>
<thead>
<tr>
<th>Table 5.3: Electron Preselection Requirements</th>
</tr>
</thead>
</table>

Hadronic Tau Preselection Requirements

\[ p_T > 20 \text{ GeV} \]
\[ |\eta| < 1.37 \text{ or } 1.52 < |\eta| < 2.47 \]
Passes Loose BDT electron veto
1 or 3 tracks reconstructed from charged decay products
Charge = \(\pm 1\)
No overlap (\(\Delta R < 0.2\)) with preselected muons or electrons

<table>
<thead>
<tr>
<th>Table 5.4: Hadronic Tau Preselection Requirements</th>
</tr>
</thead>
</table>

Jets Although quark- and gluon-initiated jet objects are not directly selected in this analysis, they are used in the calculation of missing transverse momentum (\(E_T^{\text{miss}}\)), so they must still pass some quality criteria. Jets are reconstructed with the anti-\(k_t\) algorithm (\(R = 0.4\)) [89, 136] using three-dimensional topological energy clusters [90] from the calorimeter as inputs. The clusters are corrected for dead calorimeter material and energy losses [137]. The Jet Energy Scale is calibrated using the Local Hadron Calibration scheme [138].

Missing Transverse Momentum The missing transverse momentum (\(E_T^{\text{miss}}\)) refers to the transverse momentum from neutrinos, which can not be detected by ATLAS [139]. Since \(E_T = 0\) before the proton collision, \(E_T^{\text{miss}}\) can be determined by calculating the total \(E_T\) and \(\phi\) of other objects in a given event. Energy deposits in the calorimeter are associated with reconstructed physics objects\(^2\) and are then calibrated based on the respective objects. Energy deposits not associated to objects (called “soft” contributions) are also taken into account, as well the \(p_T\) of

\(^2\)If a calorimeter deposit can be associated with more than one object type, priority is given to electrons, photons, \(\tau_{\text{had}}\), jets, and muons, in that order.
reconstructed muons. As a measure to suppress pile-up, jets with $p_T < 50$ GeV and $|\eta| < 2.4$ are weighted with the JetVertex Fraction (JVF), which measures the probability that a jet came from a particular vertex [140]. Energy clusters not associated to physics objects are weighted using the soft term vertex fraction (STVF)$^3$ [139].

In the $\tau_{lep}\tau_{had}$ search channels, the $E_T^{\text{miss}}$ calculation is modified when estimating the background from jets faking taus. $\tau_{had}$ which fail the medium BDT tau ID are normally treated as jets (cone size of 0.4) in the $E_T^{\text{miss}}$ calculation. In order to properly model the $E_T^{\text{miss}}$-related variables in the jet-faking-tau background, they must be treated as taus (cone size = 0.2) so that the fake factor method works properly (section 5.4.3.2). Following this, a residual over-estimation in the $E_T^{\text{miss}} \approx 60$-100 GeV range is corrected by reweighing anti-tau events based on the value of $E_T^{\text{miss}}$ (projected along the $\tau_{had}$) / $p_T$.

### 5.2.2 Event Preselection and Cleaning

The event preselection is used to ensure that there is no overlap in events used for the three different channels. This is done by imposing orthogonal requirements on the required number of preselected muons and electrons in events. These requirements are listed in table 5.5.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Required Muons</th>
<th>Required Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{had}\tau_{had}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\tau_{e}\tau_{had}$</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$\tau_{\mu}\tau_{had}$</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.5: Event Preselection, used to ensure orthogonal event selection across channels. Muons and electrons must pass object-level preselection.

In addition, events must pass the following event cleaning and data quality requirements:

**Good Run List** All events must pass data quality requirements and be included in the GRL, as described in sections 3.2.5 and 4.4. The GRL file

$$STVF^3 = \frac{\sum_{track} p_T(\text{track unmatched to physics objects, associated to primary vertex})}{\sum_{track} p_T(\text{track unmatched to physics objects, associated to any vertex})}$$
5.2. PRESELECTION

data12_8TeV.periodAllYear_DetStatus-v61-pro14-02_DQDefects-00-01-00_PHYS_StandardGRL_All_Good.xml

was used with the following tool:

atlasoff/DataQuality/GoodRunsLists/tags/GoodRunsLists-00-01-09.

**Vertex Requirement** At least one primary vertex with a minimum of four tracks is required to be constructed to make sure that the event is a good collision event.

**Jet Cleaning** To ensure that jets (and thus $E_T^{miss}$) are properly reconstructed, additional cuts which reject events with mis-reconstructed jets are applied. These cuts were prescribed by the JetEtMiss Combined Performance group and supported by the Tau Combined Performance group [141].

**Incomplete Events** In 2012 a Timing, Trigger, and Control (TTC) restart was developed in order to recover certain detector systems without restarting a run. However, some of the events in the following luminosity block were incomplete. These events were removed from this analysis through a dedicated flag [142].

**LAr/Tile Error** Events with integrity errors in either calorimeter are removed based on bitsets provided by the LAr community [142]. Events affected by Tile Calorimeter high-voltage trips are also rejected as per the recommendations of the data preparation group [143].

**Hot Tile Veto** During data periods B1 and B2, a hot calorimeter cell was not masked during reconstruction and impacted the data. Events from these periods are removed when a jet points towards these regions [144].

**BCH Cleaning** Certain modules of the HAD calorimeter were masked throughout the 2012 data-taking period for multiple reasons. However, the corrections used for masked modules were not able to handle completely dead modules correctly. This resulted in problems with energy and position resolution, particularly with the highly collimated high-$p_T$ jets. To reject events in data where a jet falls into a masked region, and to perform the appropriate corrections in MC, the BCH cleaning tool provided by the JetEtMiss performance group is used [145]:

5.3 Search in the $\tau_{\text{had}}\tau_{\text{had}}$ Channel

The $Z' \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ channel has the largest branching fraction of the ditau decay modes and yields the largest contribution to the overall signal sensitivity at high $Z'$ masses. When searching for resonances at lower mass values, this advantage can not be utilized due to the strict requirements for tau identification needed to suppress the large multijet background. In the mass range for this analysis, however, the multijet background is sufficiently suppressed with loose tau identification and appropriate kinematic selection. Due to the low background in this channel’s signal region, the systematic uncertainties from the backgrounds have little effect on the signal sensitivity, which is mainly impacted by statistical fluctuations in data and systematic uncertainties of the signal.

5.3.1 Trigger

This channel uses the single-tau EF-level trigger EF\_tau125\_medium1, which requires events to have at least one reconstructed $\tau_{\text{had}}$ with $E_T > 125$ GeV that passes the EF BDT tau ID.

The conditions of this trigger changed over the course of the 2012 data-taking period. In data period B, the selection based on longitudinal impact parameter $\Delta z_0$ was applied to reduce the effect of pile-up. A bug was found in this feature which affected the selection of 1-prong $\tau_{\text{had}}$ candidates. A corrected version was applied to periods C-L. A reoptimized version of the tau BDT was also implemented from periods B-L. Period A (794.02 pb$^{-1}$) had to be discarded because the information required to recalculate the trigger decision for the BDT reoptimization was not available without the $\Delta z_0$ selection.

\footnote{The effect of the buggy $\Delta z_0$ requirement on period B is very small and is covered by the trigger uncertainty.}
5.3. SEARCH IN THE $\tau_{\text{HAD}}\tau_{\text{HAD}}$ CHANNEL

5.3.2 Selection

5.3.2.1 Object Selection

Since $\tau_{\text{had}}$ are the only visible objects utilized for this channel, only they must undergo further selection requirements. In addition to the preselection requirements, all $\tau_{\text{had}}$ are required to have $p_T > 50$ GeV and must pass the loose BDT tau ID.

5.3.2.2 Event Selection

In addition to the preselection and trigger requirements, $\tau_{\text{had}}\tau_{\text{had}}$ events must possess the following criteria:

- Events must have at least 2 selected hadronic taus. In the event that there are more, only the two with the highest $p_T$ are considered.
- The $\tau_{\text{had}}$ with the highest $p_T$ (the leading $\tau_{\text{had}}$) must also have $p_T > 150$ GeV and overlap ($\Delta R < 0.2$) with a trigger candidate.
- The two selected $\tau_{\text{had}}$ must have opposite electric charges ($q(\tau_1) = -q(\tau_2)$).
- The $\tau_{\text{had}}$ must be back-to-back in the transverse plane ($\Delta \phi (\tau_1, \tau_2) > 2.7$). This requirement mainly suppresses the $Z$+jets background.

5.3.2.3 Final Selection

The final requirement on event selection is a lower bound on the total transverse mass $m_T^{\text{tot}}$ (the invariant mass of the two $\tau_{\text{had}}$ and $E_T^{\text{miss}}$ in the transverse plane):

$$m_T^{\text{tot}}(\tau_1, \tau_2, E_T^{\text{miss}}) = \sqrt{[E_T(\tau_1) + E_T(\tau_2) + E_T^{\text{miss}}]^2 - [p_T(\tau_1) + p_T(\tau_2) + E_T^{\text{miss}}]^2}$$  \hspace{1cm} (5.1)

Since the $Z'$ cross section peaks at a much higher invariant mass than each background contribution, this criterion establishes a region in which the number of signal events should be notably higher than the number of background events. The transverse mass is chosen because ATLAS has the highest
resolution in the transverse direction. For each $Z'$ mass hypothesis, the $m^{\text{tot}}_T$ threshold is optimized to yield the best expected 95% CL upper limit on the cross section times branching ratio (using a 50-GeV step size). These thresholds are given in table 5.6. The full $m^{\text{tot}}_T$ distribution for this channel after the application of the full analysis selection is shown in figure 5.1.

<table>
<thead>
<tr>
<th>$Z'$ Mass</th>
<th>500</th>
<th>625</th>
<th>750</th>
<th>875</th>
<th>1000</th>
<th>1125</th>
<th>1250</th>
<th>1375</th>
<th>$\geq$ 1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m^{\text{tot}}_T$ lower bound</td>
<td>400</td>
<td>450</td>
<td>500</td>
<td>550</td>
<td>600</td>
<td>700</td>
<td>750</td>
<td>800</td>
<td>850</td>
</tr>
</tbody>
</table>

**Table 5.6**: $m^{\text{tot}}_T$ lower bound thresholds used for each $Z'$ signal mass. All values are given in GeV.

![Figure 5.1: The $m^{\text{tot}}_T$ distribution in the $\tau_\text{had}\tau_\text{had}$ channel after the event selection. Standard Model backgrounds are stacked. $Z'_{SSM}$ signals with $m_{Z'} = 750$, 1250, and 1750 GeV are stacked on top of the total background. Events from data are overlaid. Statistical and systematic uncertainties on the estimated background are included. The last bin also includes overflow.](image)

### 5.3.3 Background Estimation

Backgrounds for this channel come from two types of sources: other resonances decaying to taus and processes with jets that fake taus. Monte Carlo is sufficient for modeling the former, but the latter type requires some sort of data-driven estimate to accurately model.
5.3. SEARCH IN THE $\tau_{\text{had}}\tau_{\text{had}}$ CHANNEL

5.3.3.1 Backgrounds from Taus

Backgrounds featuring correctly identified taus are estimated directly from simulation. This includes the largest background for this channel: the SM Drell-Yan Process ($Z/\gamma^* \rightarrow \tau\tau$). Because $Z'$ signals are produced from the Drell-Yan process, this background is irreducible. At sufficiently high masses, however, the SM contribution becomes small compared to the $Z'$ contribution. Since the top quark is so massive, it can sometimes decay with one or more taus in the final state. Therefore, top processes (single top, $t\bar{t}$, or $t$ produced alongside a $W$) also contribute to the overall background for this channel. The final background process featuring real taus is diboson production ($WW$, $WZ$, or $ZZ$), which may result in the decay to multiple leptons (electrons, muons, or taus). The top and diboson backgrounds are both very minor backgrounds that quickly become negligible above $m_{T\tau} \approx 400$ GeV.

5.3.3.2 Multijets

The multijet background is the largest background for processes involving jets faking taus. It consists of events with two or more jets in the final state, but no final-state leptons from $W$ or $Z/\gamma^*$ decays. Because jets are typically wider\(^5\) in data than in MC, the jet-to-tau fake rate is overestimated using MC. In order to model the fake rate correctly, data-driven methods must be used to estimate backgrounds from jets. The multijet background is estimated using a procedure called the fake factor method, which consists of two phases.

In the first phase of the fake factor method, the jet-to-tau fake rate for multijet events is measured in data. This measurement is performed in a region that is pure in dijet (2 jets) events. This dijet control region is the same as the signal region of the $\tau_{\text{had}}\tau_{\text{had}}$ channel except for the following alterations:

- No tau ID is applied.
- Single jet triggers are used instead of single tau triggers to improve statistics at high $p_T$.

\(^5\)i.e. the Calorimeter clusters are wider and/or the tracks are spread further apart.
5.3. SEARCH IN THE $\tau_{\text{HAD}}\tau_{\text{HAD}}$ CHANNEL

- A requirement of $p_T(\text{sub-leading }\tau_{\text{had}}) > 0.4 \times p_T(\text{leading }\tau_{\text{had}})$ is imposed\(^6\).
- Same-sign charges are also accepted to minimize errors due to low statistics.

Within bins of $p_T$ and number of tracks, the ratio of events where the sub-leading $\tau_{\text{had}}$ passes loose tau ID to events where the sub-leading $\tau_{\text{had}}$ fails tau ID is measured\(^7\):

$$f_{\tau-\text{ID}}(p_T, N_{\text{track}}) = \frac{N_{\text{pass } \tau-\text{ID}}(p_T, N_{\text{track}})}{N_{\text{fail } \tau-\text{ID}}(p_T, N_{\text{track}})}_{\text{dijet}}$$

This is known as the fake factor. The fake factors for 1-prong and 3-prong $\tau_{\text{had}}$ are shown in figure 5.2.

![Figure 5.2: Tau-ID fake factors for 1-prong (left) and 3-prong (right) $\tau_{\text{had}}$, measured in the dijet control region of data. Statistical and systematic uncertainties are included.](image)

The second phase of the method is where the multijet background is estimated. Events are chosen in an anti-tau control region, which is identical to the signal region with the exception that the sub-leading $\tau_{\text{had}}$ must fail loose tau ID instead of pass. These events are then weighted by the

\(^6\)At lower values of $p_T(\text{sub-leading }\tau_{\text{had}})$, the fake factors become much higher. It is assumed that this is caused by contamination from other backgrounds.

\(^7\)The sub-leading $\tau_{\text{had}}$ is chosen because the trigger-matching requirement on the leading $\tau_{\text{had}}$ would strongly bias the fake rate.
appropriate fake factor:

\[
N_{\text{multijet}}(p_T, N_{\text{track}}, x) = f_{\tau-ID}(p_T, N_{\text{track}}) \times \left( N_{\text{data}}^{\tau-ID}(p_T, N_{\text{track}}, x) \right)
\]  

(5.3)

where \(x\) is any kinematic variable(s) besides \(p_T\) and \(N_{\text{track}}\). This approximates the shape and size of the distribution for multijet events in which a jet somehow passes the tau ID. The fake factor method has the additional benefit over MC of improved statistical precision, particularly in the high-mass tail, since more events fail the tau ID than pass.

The validity of the fake factor method relies on the presumption that the fake factors don’t vary with the variables used to distinguish the signal and multijet control regions. The systematic uncertainty of the fake factors is thus derived by varying the requirements on the \(p_T\) balance and charge product of the two taus, as well as the tau ID BDT score threshold on the leading (tag) tau (see figure 5.2). The contamination of MC backgrounds in the anti-tau control region is considered negligible and covered by the statistical uncertainty of the estimation.

5.3.3.3 \textit{W+}jets and Other Fake Tau Backgrounds Besides Multijets

Backgrounds involving jets faking taus other than multijets are estimated directly from simulation. These mainly consist of \(W+\)jets events (one leptonic \(W\) decay and at least one jet), with smaller contributions from \(Z/\gamma^*+\)jets, top, and other backgrounds. Since the jet-to-tau fake rate is mis-modeled in MC, the actual fake rates are calculated in a region of data with high \(W(\rightarrow \mu\nu)+\)jets purity. They are then applied to the MC as weights in lieu of the tau ID.

The \(W(\rightarrow \mu\nu)+\)jets purity region used for the fake rate calculation consists of events in data which pass the following criteria:

- Included in GRL and pass event cleaning.
- Pass either of the single muon triggers (section 5.4.1): \texttt{EF\_mu24i\_tight} or \texttt{EF\_mu36\_tight}. 
5.3. SEARCH IN THE $\tau_{\text{HAD}}\tau_{\text{HAD}}$ CHANNEL

- Exactly one trigger-matched preselected muon which passes medium muon identification and has $p_T > 40$ GeV and $\text{etcone20} < 0.06 \times p_T^8$.
- No preselected electrons or additional preselected muons.
- At least one tau candidate.
- $E_{T}^{\text{miss}}$ must point between the selected leptons: $\cos (\Delta \phi (\mu, E_{T}^{\text{miss}})) + \cos (\Delta \phi (\tau_{\text{had}}, E_{T}^{\text{miss}})) < -0.15$ (used mainly to remove multijet contamination).

The fake rate measurement is performed using the leading $\tau_{\text{had}}$, also known as the probe $\tau_{\text{had}}$. The fake rate is defined as the ratio of number of probe $\tau_{\text{had}}$ passing a given level of tau ID to the total number of probe $\tau_{\text{had}}$, binned by $p_T$ and number of tracks of the probe $\tau_{\text{had}}$:

$$f_{\text{rate}}(p_T, N_{\text{track}}) = \frac{N_{\text{pass \ tau\ ID}}(p_T, N_{\text{track}})}{N_{\text{total}}(p_T, N_{\text{track}})}_{W+jets} (5.4)$$

The fake rate measurement is performed separately for events with oppositely charged (OS) muon-$\tau_{\text{had}}$ pairs (main measurement) and events with same-sign (SS) pairs (for uncertainty calculation), since the OS fake rates are much higher than the SS fake rates. A likely cause of this is the higher concentration of quark-initiated jets (as opposed to gluon-initiated jets) in OS events, though there are likely other reasons. Fake rates are also calculated separately depending on whether the probe $\tau_{\text{had}}$ must pass a single tau trigger in addition to the loose tau ID. This trigger requirement reduces the fake rates by a factor $\sim 2-4$ because it requires a tighter level of identification than the loose tau ID. Otherwise, similar behavior is produced.

Two uncertainties are taken into account with applying the fake rates to jets in MC. The first is the statistical uncertainty due to the limited size of the $W(\rightarrow \mu \nu)+$jets control region. The second accounts for the differences in quark/gluon-initiated jet compositions between the $W(\rightarrow \mu \nu)+$jets control region and various MC samples. For the latter, a 60% uncertainty is assumed based on the fake rate difference between OS and SS events. The fake rates and their uncertainties (without the tau trigger requirement) are shown in figure 5.3.

$^8$pt(\text{etconeX}) \equiv \text{the total } p_T(E_T) \text{ within } \Delta R < X/100 \text{ of the track (energy cluster), excluding the track (energy cluster) itself}$
5.4. SEARCH IN THE $\tau_{\text{lep}}\tau_{\text{had}}$ CHANNELS

The $\tau_{\text{e}}\tau_{\text{had}}$ and $\tau_{\mu}\tau_{\text{had}}$ channels each have the second-largest branching fraction and thus provide the second-largest contributions to the overall signal sensitivity. Although the selection for the $\tau_{\text{lep}}\tau_{\text{had}}$ channels parallels that of the $\tau_{\text{had}}\tau_{\text{had}}$ channel in several ways, the presence of a light lepton impacts the choice of trigger as well as the simulated and data-driven backgrounds for these channels.

5.4.1 Trigger

The $\tau_{\text{lep}}\tau_{\text{had}}$ channels use single-lepton triggers ($e$ or $\mu$), taking advantage of the presence of a light lepton in the signal’s final state. In the $\tau_{\text{e}}\tau_{\text{had}}$ channel, events are accepted if they pass either the EF$_{e24\text{vhi}}$ medium1 or EF$_{e60}$ medium1 EF trigger. The former requires at least one electron with $p_T > 24$ GeV and isolation within $\Delta R < 0.2$ of the track$^9$. The inclusion of the latter waives the isolation requirement for $p_T > 60$ GeV in order to improve efficiency in the high-$p_T$ regime. Both require the electron to pass the medium++ electron ID.

$^9$For this trigger, the $p_T$ requirement varies slightly with $\eta$. A hadronic-leakage veto is also applied.
5.4. SEARCH IN THE $\tau_{\text{lep}}\tau_{\text{had}}$ CHANNELS

In the $\tau_{\text{lep}}\tau_{\text{had}}$ channel, events must pass either the $\text{EF}_{\mu 24i}\text{tight}$ or $\text{EF}_{\mu 36i}\text{tight}$ EF trigger. The first of these requires at least one muon with $p_T > 24$ GeV that passes isolation. The inclusion of other trigger discards the isolation requirement for muons with $p_T > 36$ GeV to improve the efficiency for high-$p_T$ muons.

5.4.2 Selection

5.4.2.1 Object Selection

In addition to preselection, additional requirements are placed on $\tau_{\text{had}}$, muons, and electrons.

**Hadronic taus** For preselected $\tau_{\text{had}}$ to pass final selection, they must have $p_T > 30$ GeV and pass both the medium BDT tau ID\(^\text{10}\) and a channel-dependent algorithm for lepton rejection (medium BDT electron veto for $\tau_e\tau_{\text{had}}$, cut-based muon veto for $\tau_{\mu}\tau_{\text{had}}$). $\tau_{\text{had}}$ are also rejected if the lead track falls within $|\eta| < 0.05$, since the rate of electrons faking taus is extremely high in this region. Variations on these selections were considered for the $\tau_e\tau_{\text{had}}$ channel. These studies are described in appendix C.

**Electrons** In order to pass final selection, preselected electrons must have $p_T > 30$ GeV, pass the tight++ electron ID (the tightest level of identification recommended by the Electron Combined Performance group), and pass the following isolation requirements:

- $\text{etcone20} < 5 \text{ GeV} + 0.007 \times p_T$
- $\text{ptcone30} < 0.05 \times p_T$

Studies on variations to the electron ID are described in appendix C.

**Muons** Selected muons must pass preselection, have $p_T > 30$ GeV, pass the $\text{isCombinedMuon}$ test (which signifies a good track reconstructed in both the Inner Detector and Muon Spectrometer), and pass an isolation requirement of $\text{ptcone30} < 0.05 \times p_T$. Additional requirements were considered to improve the selection of high-$p_T$ muons, but these were abandoned due to

\(^{10}\)The medium threshold is chosen mainly to improve the statistics in the anti-tau region used to estimate the large $W$+jets background.
negative impacts on the signal sensitivity. The studies that were performed to determine the
impact of the high-$p_T$ muon selection criteria are detailed in appendix B.

5.4.2.2 Event Selection

In addition to preselection and trigger requirements, events in the $\tau_{\text{lep}}\tau_{\text{had}}$ channels must pass the following requirements:

- There must be exactly one selected lepton (electron for $\tau_{\text{e}}\tau_{\text{had}}$, muon for $\tau_{\mu}\tau_{\text{had}}$).
- There must be at least one selected hadronic tau. If there is more than one, only the $\tau_{\text{had}}$ with the highest $p_T$ is considered.
- The selected $\tau_{\text{had}}$ and lepton must have opposite electric charges ($q(\tau_{\text{had}}) = -q(\text{lep})$).
- The $\tau_{\text{had}}$ and lepton must be back-to-back in the transverse plane ($\Delta\phi(\tau_{\text{had}}, \text{lep}) > 2.7$). This mainly suppresses $Z/W$+jets.
- The event must have low transverse mass between the lepton and missing transverse momentum $m_T(\text{lep}, E_T^{\text{miss}}) \equiv \sqrt{2p_T^{\text{lep}}|E_T^{\text{miss}}| (1 - \cos \Delta\phi(\text{lep}, E_T^{\text{miss}}))} < 50$ GeV. This helps to suppress the $W$+jets background.

5.4.2.3 Final Selection

As with the $\tau_{\text{had}}\tau_{\text{had}}$ channel, the final requirement is a lower bound on $m_T^{\text{tot}}$, optimized for each $Z'$ mass hypothesis to yield the best 95% CL upper limit on the cross section times branching ratio. The results are the same as for the $\tau_{\text{had}}\tau_{\text{had}}$ channel (table 5.6). The $m_T^{\text{tot}}$ distribution for the sum of the $\tau_{\text{e}}\tau_{\text{had}}$ and $\tau_{\mu}\tau_{\text{had}}$ channels after the full analysis selection is shown in figure 5.4.

5.4.3 Background Estimation

In addition to the backgrounds featuring real taus and jets faking taus, the $\tau_{\text{lep}}\tau_{\text{had}}$ channels contain background processes involving light leptons faking taus. The real tau and lepton-faking-tau
5.4. SEARCH IN THE $\tau_{\text{lep}}\tau_{\text{had}}$ CHANNELS

Figure 5.4: The combined $m_{T}^{\text{tot}}$ distribution for the two $\tau_{\text{lep}}\tau_{\text{had}}$ channels after the event selection. All Standard Model backgrounds are stacked. $Z_{\text{SSM}}$ signals with $m_{Z'} = 750, 1250, \text{and} 1750$ GeV are stacked on top of the total background. Events from data are overlaid. Statistical and systematic uncertainties on the estimated background are included. The last bin also includes overflow.

Backgrounds are modeled from MC. The backgrounds from jets faking taus are modeled using data-driven estimates, as is done in the $\tau_{\text{had}}\tau_{\text{had}}$ channel, though they are now dominated by $W+\text{jets}$ events instead of multijets.

5.4.3.1 Backgrounds from Taus and Leptons

Backgrounds involving properly identified taus and leptons faking taus are estimated directly from MC. The backgrounds from real taus include the irreducible $Z/\gamma^{*} \rightarrow \tau\tau$ (the largest background above $m_{T}^{\text{tot}} \approx 300$ GeV) as well as the top and diboson backgrounds (which quickly become negligible above $m_{T}^{\text{tot}} \approx 400$ GeV). The backgrounds from leptons faking taus each include one lepton that fakes a hadronic tau and one properly identified lepton. They consist of events with $Z/\gamma^{*} \rightarrow \mu\mu$ ($\tau_{\mu}\tau_{\text{had}}$ only) or $Z/\gamma^{*} \rightarrow ee$ ($\tau_{e}\tau_{\text{had}}$ only). These dilepton background have notable contributions near $m_{T}^{\text{tot}} \approx 100$ GeV but diminish quickly at higher $m_{T}^{\text{tot}}$ ranges.
5.4. SEARCH IN THE $\tau_{\text{lep}}\tau_{\text{had}}$ CHANNELS

5.4.3.2 Backgrounds from Jets Faking Taus

As is the case in the $\tau_{\text{had}}\tau_{\text{had}}$ channel, the jet-to-tau fake rate is poorly modeled in MC, so backgrounds involving jets faking taus are estimated using data-driven methods. In the $\tau_{\text{lep}}\tau_{\text{had}}$ channels, the largest such background (and largest overall background for $m_T^{\text{tot}} \approx 100-300$ GeV) is $W/Z+\text{jets}$.

Multijet events also provide a small background at low $m_T^{\text{tot}}$. The full jet background is modeled using a modified version of the fake factor method (section 5.3.3.2).

Fake factors are measured in a region of data heavily concentrated with $W+\text{jets}$ events. The events in this $W+\text{jets}$ control region must pass the following criteria:

- Exactly one selected electron (for $\tau_e\tau_{\text{had}}$) or muon (for $\tau_{\mu}\tau_{\text{had}}$) that passes the corresponding isolation requirement(s).
- No additional preselected muons or electrons.
- At least one preselected $\tau_{\text{had}}$ (though only the highest-$p_T\tau_{\text{had}}$ is used).
- $70$ GeV $< m_T(\text{lep},E_T^{\text{miss}}) < 200$ GeV. This reduces the contamination from $Z/\gamma^* \rightarrow \tau\tau$ events and ensures that there is no overlap with the signal region.

In these channels the fake factor measures the ratio of events passing the medium BDT tau ID to those failing in bins of $p_T$ and $\eta$:

$$f_{\tau-ID}(p_T, \eta) = \frac{N_{\text{pass \tau-ID}}(p_T, \eta)}{N_{\text{fail \tau-ID}}(p_T, \eta)} \bigg|_{W+\text{jets}}$$ (5.5)

The events in which the leading $\tau_{\text{had}}$ fails the tau ID (also called “denominator events”) must also satisfy the requirement of $\text{BDTJetScore} > 0.7 \times \text{BDTJetScoreLoose}$, where $\text{BDTJetScoreLoose}$ is the minimum $\text{BDTJetScore}$ required to pass the loose tau ID. This helps reduce the dependence of the fake factors on the sample, since the lower-scoring jets tend to be gluon-initiated, unlike the quark-initiated jets which dominate $W+\text{jets}$ events. When calculating the number of numerator (pass tau ID) and denominator events in the $W+\text{jets}$ control region, contamination from other MC processes is subtracted out. Fake factors for the $\tau_e\tau_{\text{had}}$ and $\tau_{\mu}\tau_{\text{had}}$ channels are shown in figure 5.5.
Figure 5.5: $\tau$-inclusive tau ID fake factors measured in the $\tau_{\mu}\tau_{\text{had}}$ (top) and $\tau_{\tau}\tau_{\text{had}}$ (bottom) channels for 1-prong (left) and 3-prong (right) $\tau_{\text{had}}$. Statistical and systematic uncertainties are included. Fake factors from the alternate multijet control region are overlaid.

The fake factors are then applied as weights to events in the anti-tau control region. This has the same criteria as the signal region except that the requirement for the $\tau_{\text{had}}$ to pass tau ID is replaced with the requirement to fail (plus the additional denominator requirement). The contaminations from other MC backgrounds in this region are subtracted away:

$$N_{W+\text{jet}}(p_T, \eta, x) = f_{\tau-ID}(p_T, \eta) \times \left(N_{\text{data}}^{\tau-ID}(p_T, \eta, x) - N_{\text{MC}}^{\tau-ID}(p_T, \eta, x)\right)$$  \hspace{1cm} (5.6)
This initial estimation poorly models distributions involving $E_T^{\text{miss}}$ because of inconsistencies between the treatments of taus and jets during $E_T^{\text{miss}}$ calculation. This is corrected using the procedure described in section 5.2.1.

The estimation from the fake factor method is only useful when the fake factors do not depend on the variables that differentiate the signal region from the $W+\text{jets}$ control region, namely the cut on $m_T(\text{lep},E_T^{\text{miss}})$. By measuring the fake factors in different regions of $m_T(\text{lep},E_T^{\text{miss}})$, it is shown that the fake factors do not vary significantly with this variable (see appendix D.1).

The estimation also assumes that the background from fake taus is dominated by $W+\text{jets}$. This assumption is verified by using an additional fake factor on lepton isolation to model the multijet background separately, thus showing that $W+\text{jets}$ accounts for $\approx 98\%$ of fake taus (see appendix D.2). Since the fake factors could still vary based on the balance of quark- and gluon-initiated jets, additional fake factors are measured in a gluon-enriched multijet control region and are used to motivate a systematic uncertainty on the fake estimate. This multijet control region is defined by the following criteria:

- Exactly one selected electron (for $\tau_\ell\tau_{\text{had}}$) or muon (for $\tau_\mu\tau_{\text{had}}$), except it must fail the isolation requirement.
- No additional preselected muons or electrons.
- At least one preselected $\tau_{\text{had}}$ (choose the highest $p_T$ candidate).
- $m_T(\text{lep},E_T^{\text{miss}}) < 30$ GeV.
- $E_T^{\text{miss}} < 30$ GeV.

The fake factors from this region are generally lower than in the $W+\text{jets}$ control region because the gluon-initiated jets are wider and less likely to pass the tau ID. Based on the comparison between the fake factors, a conservative 30% systematic uncertainty is applied to cover the difference in extremes between the two regions (figure 5.5).
5.5 Systematic Uncertainties

The following sections describe the sources of systematic uncertainties, both theoretical and experimental, on the final event yield in this analysis. The uncertainties in section 5.5.1 are for attributes of individual objects: taus, jets, and $E_{\text{miss}}^T$. These are evaluated by shifting the quantity in question by one standard deviation (based on the distribution from the attribute’s calculation) in each event and measuring the impact on the final event yield. The uncertainties in section 5.5.2 are evaluated on the total normalization of the final event count.

5.5.1 Object-Level Uncertainties

5.5.1.1 Identification Efficiency for $\tau_{\text{had}}$

The uncertainty on the efficiency of hadronic tau identification is measured using a $Z \rightarrow \tau\tau$ tag-and-probe analysis \[88\]. It evaluates to $\sim 2-7\%$, depending on $\eta$ and $N_{\text{track}}$. However, due to the kinematic distribution of $Z \rightarrow \tau\tau$, this only applies to $\tau_{\text{had}}$ with $p_T \lesssim 60$ GeV. It is unclear whether this measurement applies to $\tau_{\text{had}}$ in the entire kinematic region of the $Z' \rightarrow \tau\tau$ search ($p_T \lesssim 1$ TeV). Since the sources of high-$p_T$ taus were very limited, a measurement could not be made directly. It was then a matter of whether or not the $p_T$ range had any notable effects on the modeling of the tau decay or detector response. Since the tau decay has good data-MC agreement at low $p_T$ and should be insensitive to the $p_T$ range, the detector response should be the only main source of degradation (if any) in the tau ID performance at high $p_T$.

In order to show that the detector response performs well for $\tau_{\text{had}}$ at high $p_T$, the mean and root mean square (rms) from BDT distributions are examined in dijet events in data and MC. The variances are used to smear the BDT scores of signal taus in MC. The differences in loose BDT efficiency don’t yield any large trend with $p_T$. This smearing is then repeated multiple times, each time after varying a smearing input variable within its uncertainty. To quantify any trend of decreasing performance, the ratio of unsmeared to smeared loose BDT efficiencies are fit to a line for each iteration of smearing. Deviations from 0 in the slope are used to motivate an increase in
uncertainty for 1- and 3-prong $\tau_{\text{had}}$:

\[
\Delta \varepsilon_{1p} (p_T \geq 100 \text{ GeV}) = \sqrt{\left(\Delta \varepsilon_{1p}^{\text{low} \ p_T}\right)^2 + \left(13.7\% \times \frac{(p_T - 100 \text{ GeV})}{\text{TeV}}\right)^2}
\]

\[
\Delta \varepsilon_{3p} (p_T \geq 100 \text{ GeV}) = \sqrt{\left(\Delta \varepsilon_{3p}^{\text{low} \ p_T}\right)^2 + \left(7.83\% \times \frac{(p_T - 100 \text{ GeV})}{\text{TeV}}\right)^2}
\]

5.5.1.2 Reconstruction Efficiency of high-$p_T$ 3-prong $\tau_{\text{had}}$

At higher $p_T$, 3-prong taus become more collimated and are more likely to be reconstructed with only 2 tracks (figure 5.6). This leads to lower reconstruction efficiencies for 3-prong $\tau_{\text{had}}$ at high $p_T$. In general, the modeling of this track merging in MC agrees with the data. Since the uncertainty on tracking-efficiency loss can not be measured directly, a conservative 50% uncertainty is assumed.

This is used to derive a systematic uncertainty on the 3-prong $\tau_{\text{had}}$ reconstruction efficiency for this analysis. It is observed that for $p_T \geq 150 \text{ GeV}$, the 3-prong reconstruction efficiency drops by $\approx 10\%$ every 100 GeV. Taking 50% of this leads to

\[
\Delta \varepsilon_{3p} = \left(\frac{p_T}{\text{GeV}} - 150\right) \times 5\%
\]

for $\tau_{\text{had}}$ with $p_T \geq 150 \text{ GeV}$.

5.5.1.3 $\tau_{\text{had}}$ Trigger Efficiency

Tau trigger scale factors for data/MC are measured using a $Z \rightarrow \tau \tau$ tag and probe analysis for low-$p_T$ taus. These are useful for correcting MC efficiency in low-mass analyses, but are unfortunately not applicable for the tau $p_T$ range of this analysis. Instead, the uncertainty due to mismodeling in MC is derived from an envelope around the discrepancies between data and MC at low $p_T$. Deviations are consistent within a 10% band, so a 10% uncertainty is used. No additional uncertainty is needed for $\tau_{\text{had}}$ with high $p_T$ since this is covered by the inflated tau ID uncertainty.
5.5. SYSTEMATIC UNCERTAINTIES

Figure 5.6: Efficiencies for 3-prong taus to be reconstructed with 2, 3, or 4 tracks as functions of $p_T$.

5.5.1.4 $\tau_{\text{had}}$ Momentum/Energy Scale

The uncertainty on the number of signal events due to the TES uncertainty is derived by shifting the $\tau_{\text{had}}$ energy based on uncertainties from this tool:

\texttt{atlasoff/PhysicsAnalysis/TauID/TauCorrUncert/tags/TauCorrUncert-00-00-16}

The uncertainties provided by this tool are binned in $\eta$ and $p_T$ and are determined separately for truth-matched and non-truth-matched $\tau_{\text{had}}$. The tool was provided by the ATLAS Tau Combined Performance group [93].

5.5.1.5 Jet Energy Scale

The uncertainty on the final event yield due to the uncertainty on the jet energy scale is calculated by shifting the energy of each jet based on its uncertainty. The jet energy uncertainties are provided by this tool from the ATLAS JetEtMiss Combined Performance group:

\texttt{atlasoff/Reconstruction/Jet/JetUncertainties/tags/JetUncertainties-00-08-07}
5.5. SYSTEMATIC UNCERTAINTIES

5.5.1.6 BCH Cleaning

The use of the BCH cleaning tool is described in section 5.2.2. The associated systematic uncertainties are evaluated by treating the jets in each sample as entirely quark- or gluon-initiated [145].

5.5.1.7 Missing Transverse Momentum

The systematic uncertainties related to $E_T^{\text{miss}}$ are evaluated from both hard objects and soft terms. For hard objects, the uncertainties on the energies and/or momenta of these objects are propagated to the $E_T^{\text{miss}}$ calculation. The uncertainties from soft terms are evaluated from measurements of multiple observables in data and simulation [139]. These include uncertainties on the soft $E_T^{\text{miss}}$ resolution and scale. The uncertainties on the soft $E_T^{\text{miss}}$ are provided by the following tool:

atlasoff/Reconstruction/MissingETUtility/tags/MissingETUtility-01-02-08

5.5.1.8 Charge Misidentification

The uncertainty due to the misidentification of the charge of $\tau_{\text{had}}$ decay products is obtained by measuring the negative-momentum probability from the $p_T$ resolution of muons in the inner detector. Muons are chosen because their mass is similar to that of pions. Although the misidentification rate increases as a function of $p_T$ ($P(\text{misidentification}) > 10\%$ for $p_T \gtrsim 1$ TeV), the average $p_T$ of the leading track is only about 400 GeV. This brings the total charge misidentification rate down to $\sim 1\%$ [146].

5.5.2 Event-Level Uncertainties

5.5.2.1 Luminosity

The luminosity uncertainty is calculated from a calibration of the luminosity scale which was measured in 2012 from beam separation scans [147]. It is evaluated to be 2.8%. 

5.6. SIGNAL MODELS

5.5.2.2 Simulation Cross Sections

Using the same justification as the ATLAS $H \rightarrow \tau\tau$ search\textsuperscript{11} [148, 149], the uncertainties assigned to the cross sections of the single top, $t\bar{t}$, and diboson backgrounds are 13%, 10%, and 5% respectively. The uncertainties on the $Z$ background are evaluated by varying the PDF and $\alpha_S$. Combined with the electroweak corrections to the cross section, the uncertainties for this background amount to $< 10\%$ for each mass range. For the $W+$jets uncertainty in the $\tau_{\text{had}}\tau_{\text{had}}$ channel, a 6% uncertainty is derived from the data/MC comparison in the $W+$jets control region.

5.5.2.3 Signal Acceptance

The uncertainty from the PDF on the signal acceptance was found to be negligible in a previous $Z' \rightarrow \tau\tau$ search which used $\sqrt{s} = 7$ TeV collisions at ATLAS [58, 146]. This was not reevaluated for this analysis.

5.6 Signal Models

$Z' \rightarrow \tau\tau$ signals are generated by reweighting $Z/\gamma^* \rightarrow \tau\tau$. The $Z'_{\text{SSM}}$ signals are used to optimize the event selection for the analysis. In addition to $Z'_{\text{SSM}}$, variations with altered fermion couplings and decay widths are used to study the impact on signal acceptance and $\sigma \times BR$. An additional signal motivated by the Non-Universal $G(221)$ model featuring $Z'$ with enhanced couplings to third-generation fermions is also studied.

5.6.1 Reweighting

All $Z'$ samples in this analysis are generated by reweighting $Z/\gamma^* \rightarrow \tau\tau$ events using the TauSpinner algorithm [129]. This algorithm can create samples with tau polarizations that are different from the initial sample. It relies on a leading-order approximation where spin density matrices for hard 2→2 Born-level processes are calculated from spin amplitudes and is constrained to only the

\textsuperscript{11} These total uncertainties include uncertainties due to scale, PDF choice, and differences between MC generators.
longitudinal degrees of the tau spin. Polarimetric vectors are determined from the four-momenta of
the taus and initial $Z/\gamma^*$, while helicities are assigned randomly using a probability function
$p_Z^\tau (\theta, s, g_X(q), g_X(\tau))^{12}$. The algorithm does not rely on the initial quark states, but instead cal-
culates a weighted average over all possible initial quark configurations (including allowed color-
anticolor combinations).

The final weight $w$ used to reweight $Z/\gamma^*$ to $Z'$ is given by

$$ w = \frac{w_{SM}^{spin} w_\sigma}{w_{BSM}^{spin}} \tag{5.8} $$

where $w_\sigma$ is the cross section reweighting factor and $w_{SM,BSM}^{spin}$ are the spin weights for SM $Z/\gamma^*$
and the new resonance respectively [150]. These spin weights are defined as

$$ w_{spin} = R_{ij} h^i h^j \tag{5.9} $$

where $R_{ij}$ is a matrix describing the spin states of the taus and their correlation, and $h^{i,j}$ are the
polarimetric vectors of the taus.

For the calculation of the weights, the differential Born-level cross section of each process must be
provided. Since fermion masses are considered negligible, equation A.3 can be used. The invariant
matrix element $M_{fi}$ can be factored into an energy- and mass-dependent term and a spin-dependent
term $M_{fi}^{spin}$. For the SM processes, this is given by:

$$ |M_{SM}|^2 = |M_{Z/\gamma^*}|^2 = |M_\gamma + M_Z|^2 $$

$$ = |M_\gamma|^2 + |M_Z|^2 + 2 \Re (M_\gamma^* M_Z) $$

$$ = \frac{1}{12} |M_{\gamma}^{spin}|^2 + \frac{1}{12} \left( \frac{s^2}{M_Z^2 - s^2 + \Gamma_Z^2 M_Z^2} \right) |M_{Z}^{spin}|^2 + \text{interference} \tag{5.10} $$

$^{12}\theta$ is the scattering angle, $s$ is the center-of-mass energy squared, and $g_X(q)$ and $g_X(\tau)$ are the respective couplings
to the initial quarks and final taus (same notation as equation 2.38).
5.6. SIGNAL MODELS

where \( \mathcal{M}_X \equiv \mathcal{M}_{q\bar{q} \to X \to \tau^+\tau^-} \) and \( \text{Re}(Y) \) is the real component of \( Y \). Similarly, the matrix element for \( Z' \) production is:

\[
|\mathcal{M}_{Z'}|^2 = \frac{1}{12} \frac{s^2}{(M_{Z'}^2 - s)^2 + \Gamma_{Z'}^2 M_{Z'}^2} |\mathcal{M}_{Z'}^{\text{spin}}|^2
\]

(5.11)

For each of these processes, the spin-dependent component can be expanded as:

\[
|\mathcal{M}_X^{\text{spin}}|^2 = (\cos \theta + 1)^2 \left( |g_{X,L}(q) g_{X,L}(\tau)|^2 + |g_{X,R}(q) g_{X,R}(\tau)|^2 \right)
\]

\[\]

\[
+ (\cos \theta - 1)^2 \left( |g_{X,L}(q) g_{X,R}(\tau)|^2 + |g_{X,R}(q) g_{X,L}(\tau)|^2 \right)
\]

(5.12)

The couplings \( g_{X,L(R)}(f_i) \) are detailed in table 5.7

<table>
<thead>
<tr>
<th>fermion ( f_i )</th>
<th>( g_\gamma (f_i) / e )</th>
<th>( g_Z (f_i) / g_Z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_L )</td>
<td>( \frac{2}{3} )</td>
<td>( \frac{1}{3} - \frac{2}{3} \sin^2 \theta_W )</td>
</tr>
<tr>
<td>( u_R )</td>
<td>( \frac{2}{3} )</td>
<td>( -\frac{2}{3} \sin^2 \theta_W )</td>
</tr>
<tr>
<td>( d_L )</td>
<td>( -\frac{1}{3} )</td>
<td>( -\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W )</td>
</tr>
<tr>
<td>( d_R )</td>
<td>( -\frac{1}{3} )</td>
<td>( \frac{1}{3} \sin^2 \theta_W )</td>
</tr>
<tr>
<td>( \tau_L )</td>
<td>( -1 )</td>
<td>( -\frac{1}{2} + \sin^2 \theta_W )</td>
</tr>
<tr>
<td>( \tau_R )</td>
<td>( -1 )</td>
<td>( \sin^2 \theta_W )</td>
</tr>
</tbody>
</table>

Table 5.7: Coupling strengths of fermions to gauge bosons \( g_X (f_i) \). \( \theta_W \) is the Weinberg angle and the couplings \( e \) and \( g_Z \) are given in chapter 1. \( Z'_{SSM} \) has the same couplings as the SM \( Z \).

5.6.2 Signal Acceptance

Although the SSM serves as a good benchmark for setting limits on the \( Z' \) cross section and mass, it is useful to investigate how the couplings to fermions affect the signal acceptance \( A \): the fraction of true signal events that are actually observable due to detector limitations and/or constraints on the signal region\(^{13}\) (e.g. thresholds on \( \eta, p_T, m_{\text{tot}} \), etc . . . ). Understanding the relationship between fermion couplings and signal acceptance allows the \( Z'_{SSM} \) limits to be translated to other models.

The dependence of the signal acceptance on fermion couplings primarily arises from the differences in tau polarization and \( Z' \) decay width.

\(^{13}\)The ratio of reconstructed signal events in the signal region to total number of true signal events is called the acceptance \( \times \) efficiency \( (A \times \epsilon) \).
5.6. SIGNAL MODELS

5.6.2.1 Fermion Couplings: Tau Polarization

Changing the tau polarization leads to changes in the tau kinematic distributions. The analysis selections most affected by this are the thresholds on $p_T(\tau_{\text{had}})$ and $m_T^{\text{tot}}$. These distributions are affected by tau polarization mainly because the visible hadronic decay products from left-handed taus are usually softer than those from right-handed taus\(^\text{14}\) (figure 5.7). By changing the relative strengths of the $Z'$ couplings to left- and right-handed taus to the extreme values, the effect on the acceptance is found to have its largest impact at low mass, where the acceptance can change up to $-25\%$ and $+50\%$.

\[m_T^{\text{tot}}\] distribution for $Z'_{\text{SSM}}$ and variations of its couplings to purely left- and right-handed taus with $m_{Z'}=2$ TeV. The signal with purely right-handed (left-handed) couplings has a harder (softer) distribution due to the preferred kinematics of the tau decay.

The effect of changing the couplings to left- and -right-handed quarks is also investigated. By varying these couplings to the extreme values, the acceptance varies by $-2\%$ to $+20\%$\(^\text{15}\). However, once extreme values are chosen for the tau couplings, the quark couplings no longer impact the signal acceptance. Therefore, the following signals are defined to show the maximum impact of tau polarization on $Z'$ exclusion limits:

- $Z'_L$: $g_L(\tau) = -\frac{g_Z}{2}$, $g_R(\tau) = 0$, other couplings same as $Z'_{\text{SSM}}$
- $Z'_R$: $g_L(\tau) = 0$, $g_R(\tau) = \frac{g_Z}{2}$, other couplings same as $Z'_{\text{SSM}}$\(^\text{14}\) Since neutrinos are exclusively left-handed under the Standard Model, the neutrino momentum (w.r.t to the tau rest frame) is more likely to be aligned (anti-aligned) with a left-handed (right-handed) tau's lab frame momentum. This means that the hadronic tau decay products will be propelled backwards (forwards) relative to the left-handed (right-handed) tau’s rest frame. \(^\text{15}\)This asymmetry can be attributed to the $Z'_{\text{SSM}}$ having much stronger couplings to left-handed quarks than right-handed quarks.
5.6. SIGNAL MODELS

The impact on the signal acceptance as a function of signal mass is shown in figure 5.8.

![Figure 5.8: Ratios for the signal acceptances ($r_A$) of $Z'_L$, $Z'_R$, $Z'_{narrow}$, and $Z'_{wide}$ to that of $Z'_{SSM}$ as functions of $M_{Z'}$ for the $\tau_{had}$$\tau_{had}$ and combined $\tau_{lep}$$\tau_{had}$ channels.](image)

### 5.6.2.2 Decay Width

As the kinematic limit for high-mass $Z'$ production is approached, an increased fraction of low-mass off-shell signal events are produced: a phenomenon called the “parton luminosity tail”. This fraction increases further with a large decay width $\Gamma_{Z'}$ (figure 5.9), which is also dependent on fermion couplings. The ratio of signal acceptance to the SSM signal acceptance is studied as function of signal mass and relative decay width ($\Gamma_{Z'}/M_{Z'}$). The largest effects are found at higher masses, where the acceptance can drop as much as 45% for $\Gamma_{Z'}/M_{Z'} = 20\%$ and increase by up to 20% for $\Gamma_{Z'}/M_{Z'} = 1\%$. The effects of decay width on signal acceptance are summarized in figure 5.8. The signals with altered decay widths are defined as follows:

- $Z'_{narrow}$: $\Gamma_{Z'}/M_{Z'}$ is set to 1%.
- $Z'_{wide}$: $\Gamma_{Z'}/M_{Z'}$ is set to 20%.

For reference, $\Gamma_{Z'}/M_{Z'} \approx 3\%$ for the SSM.
5.6. SIGNAL MODELS

![Figure 5.9: Distributions of $M_{\text{inv}}$ and $m_T^{\text{tot}}$ ($M_{Z'} = 2$ TeV) for $Z_{SSM}^0$ and variations with wider and narrower decay widths. As the parton luminosity tail expands (contracts), a smaller (larger) fraction of events are found in high-$m_T^{\text{tot}}$ regions, thus reducing (increasing) the signal acceptance.](image)

5.6.2.3 Interference Effects

When calculating cross sections for the TauSpinner algorithm, the $Z-Z'$ and $\gamma-Z'$ interference terms are initially ignored so that the Drell-Yan process in the BSM $Z'$ theory has a squared scattering amplitude of

$$|M_{BSM}|^2 = |M_{SM}|^2 + \mu |M_{Z'}|^2$$  \hspace{1cm} (5.13)

where $\mu$ is the the signal strength parameter\textsuperscript{16}. This allows for separate simulated samples of SM processes and $Z'$, both of which have positive-definite cross sections in all regions. If the SM-BSM interference terms are included, the squared scattering amplitude becomes

$$|M_{BSM}|^2 = |M_{SM}|^2 + \mu |M_{Z'}|^2 + 2\sqrt{\mu} \text{ Re } (M_Z^* M_{Z'}) + 2\sqrt{\mu} \text{ Re } (M_Z^* M_{Z'}) .$$  \hspace{1cm} (5.14)

Depending on the given region, these effects may be small or large, constructive or destructive (figure 5.10). In the case of destructive interference, the total BSM cross section in some regions may be less than that of the SM, which would require a more complicated treatment of the signal simulation. The effects of the interference were studied for multiple signal mass hypotheses by

\textsuperscript{16}$\mu \geq 0$, $\mu = 0(1)$ corresponds to perfect agreement with the SM(BSM) theory.
measuring the fractional change in the $Z'$ expectation:

$$
\delta f_{int} (M_{Z'}) = \frac{N^\text{int}_{BSM} (M_{Z'}) - N^{no-int}_{BSM} (M_{Z'})}{N^\text{int}_{BSM} (M_{Z'}) - N_{SM} (M_{Z'})}
$$

(5.15)

where $N (M_{Z'})$ is the total number of events in the final signal region defined by $M_{Z'}$ (either for SM, BSM with interference, or BSM without interference). It was found that for $Z'_{SSM}$ with $M_{Z'} \leq 2$ TeV, the total contribution was reduced by $|\delta f_{int}| \leq 10\%$. The reduction was as high as 35% for the highest mass hypothesis. Effects on the $Z'_L$, $Z'_R$, and $Z'_{\text{narrow}}$ signals were found to be negligible for all masses. The effects on the $Z'_{\text{wide}}$ signal were found to be much more substantial, with $|\delta f_{int}| > 100\%$ for some mass hypotheses (though the exact effects depended strongly on the fermion couplings). A more exhaustive treatment of the effects of interference on the $Z'_{\text{wide}}$ was not carried out. It was noted that for future studies on $Z'$ with wide decay widths, interference effects should be considered in order to estimate the correct signal contributions.

![Figure 5.10: Effects of $Z$-$Z'$ and $\gamma$-$Z'$ interference on the $Z'_{SSM}$ invariant mass (left) and $m_{T'}^\text{tot}$ (right) distributions for $M_{Z'} = 2$ TeV. The signal acceptance is affected based on the $m_{T'}^\text{tot}$ distribution.](image)

### 5.6.3 Non-Universal $G(221)$ Model

In addition to the SSM and variations with altered fermion couplings and decay widths, a model with strong theoretical motivations is also chosen for this analysis: the Non-Universal $G(221)$ model (section 2.3.4). This model is selected because of its enhanced $Z'$ couplings to third-generation fermions.
fermions, as it may evade limits set by the dielectron and dimuon decay channels. Large mixing between muons and taus was considered as an additional feature of this model, but was ultimately excluded as this would lead to stronger limits in the more sensitive dilepton channels.

When the signal strength parameter $\mu$ is scaled for $Z'_SSM \rightarrow Z'_NU$, the NU-to-SSM ratio of the cross sections times branching ratios ($r_{sB}$, a function of $M_{Z'}$ and $\sin^2 \phi$, the $h\tau$ mixing angle) is used, as is the ratio for signal acceptance in the appropriate channel\(^{17}\), $r_A$ (figure 5.11). The relative cross section is stronger in much of the parameter space, peaking at intermediate values of $\sin^2 \phi$. It drops off at the extreme ends of the spectrum due to the suppression of $Z'$ production from light quarks ($\sin^2 \phi \sim 0$) or decay to taus ($\sin^2 \phi \sim 1$). The acceptance is generally lower than that of the SSM due to the dominantly left-handed couplings which lead to softer tau decays.. It is particularly low at the extreme values of $\sin^2 \phi$ due to an increased decay width which causes more off-shell signal production.

![Figure 5.11: Ratios of the production cross section times ditau branching fraction (left), signal acceptance in the $\tau_{had}\tau_{had}$ channel (middle), and signal acceptance in the $\tau_{lep}\tau_{had}$ channel (right) for $Z'_NU$ to $Z'_SSM$ as functions of $M_{Z'}$ and $\sin^2 \phi$.](image)

For this analysis, six different NU $G(221)$ signals samples were used, each with a different choice of $\sin^2 \phi$. Values for $\sin^2 \phi$ were selected from 0.1 to 0.5 in steps of 0.1, as well as 0.03.

\(^{17}\)In particular, the product of these ratios, $r_{sB} \times r_A$, is used to scale the signal strength parameter.
5.7 Results

5.7.1 $\tau_{\text{had}}\tau_{\text{had}}$

The total numbers of events expected from signal and background and observed in data after key selection stages are detailed in table 5.8. No events are observed in data above $m_{T}^{\text{tot}} = 850 \text{ GeV}$\(^{18}\), which is more consistent with the SM expectation of $1.32 \pm 0.24$ events than any $Z'$ model expectation. Since there are so few expected background events in the signal region, the uncertainties on the signal samples have the largest impact on the overall signal sensitivity. The largest of these uncertainties are on the efficiencies for the tau identification and tau trigger, which respectively contribute 10% and 12.1% to the 1.75-TeV signal mass. All the $\tau_{\text{had}}\tau_{\text{had}}$ uncertainties are detailed in table 5.9. Several key kinematic distributions for events passing the final event selection are shown in figure 5.12.

<table>
<thead>
<tr>
<th>Tau Selection</th>
<th>$Z/\gamma^{*} \rightarrow \tau\tau$</th>
<th>Multijet</th>
<th>$W/Z+$jets</th>
<th>Total SM</th>
<th>$Z_{\text{SSM}}^{\prime}(1750)$</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opposite Sign</td>
<td>$280 \pm 50$</td>
<td>$610 \pm 140$</td>
<td>$64 \pm 12$</td>
<td>$980 \pm 150$</td>
<td>$10.1 \pm 1.5$</td>
<td>$993$</td>
</tr>
<tr>
<td>$\Delta\phi(\tau_1, \tau_2)$</td>
<td>$117 \pm 18$</td>
<td>$210 \pm 40$</td>
<td>$35 \pm 6$</td>
<td>$370 \pm 50$</td>
<td>$9.2 \pm 1.4$</td>
<td>$363$</td>
</tr>
<tr>
<td>$m_3^{\text{tot}} &gt; 300 \text{ GeV}$</td>
<td>$107 \pm 16$</td>
<td>$99 \pm 14$</td>
<td>$28 \pm 5$</td>
<td>$241 \pm 24$</td>
<td>$9.2 \pm 1.4$</td>
<td>$234$</td>
</tr>
<tr>
<td>$m_3^{\text{tot}} &gt; 350 \text{ GeV}$</td>
<td>$64 \pm 10$</td>
<td>$43 \pm 5$</td>
<td>$17.8 \pm 3.4$</td>
<td>$130 \pm 14$</td>
<td>$9.0 \pm 1.4$</td>
<td>$119$</td>
</tr>
<tr>
<td>$m_3^{\text{tot}} &gt; 400 \text{ GeV}$</td>
<td>$38 \pm 6$</td>
<td>$19.3 \pm 2.2$</td>
<td>$10.1 \pm 2.0$</td>
<td>$70 \pm 8$</td>
<td>$8.8 \pm 1.3$</td>
<td>$56$</td>
</tr>
<tr>
<td>$m_3^{\text{tot}} &gt; 450 \text{ GeV}$</td>
<td>$24 \pm 4$</td>
<td>$9.2 \pm 1.1$</td>
<td>$5.9 \pm 1.2$</td>
<td>$40 \pm 5$</td>
<td>$8.5 \pm 1.3$</td>
<td>$30$</td>
</tr>
<tr>
<td>$m_3^{\text{tot}} &gt; 500 \text{ GeV}$</td>
<td>$15.4 \pm 2.6$</td>
<td>$4.6 \pm 0.6$</td>
<td>$3.4 \pm 0.7$</td>
<td>$24.0 \pm 2.9$</td>
<td>$8.1 \pm 1.3$</td>
<td>$18$</td>
</tr>
<tr>
<td>$m_3^{\text{tot}} &gt; 550 \text{ GeV}$</td>
<td>$9.7 \pm 1.7$</td>
<td>$2.6 \pm 0.4$</td>
<td>$1.9 \pm 0.4$</td>
<td>$14.6 \pm 2.0$</td>
<td>$7.8 \pm 1.2$</td>
<td>$11$</td>
</tr>
<tr>
<td>$m_3^{\text{tot}} &gt; 600 \text{ GeV}$</td>
<td>$6.3 \pm 1.2$</td>
<td>$1.80 \pm 0.34$</td>
<td>$1.19 \pm 0.25$</td>
<td>$9.4 \pm 1.3$</td>
<td>$7.4 \pm 1.2$</td>
<td>$4$</td>
</tr>
<tr>
<td>$m_3^{\text{tot}} &gt; 650 \text{ GeV}$</td>
<td>$4.2 \pm 0.8$</td>
<td>$0.90 \pm 0.24$</td>
<td>$0.73 \pm 0.15$</td>
<td>$5.8 \pm 0.9$</td>
<td>$7.0 \pm 1.1$</td>
<td>$3$</td>
</tr>
<tr>
<td>$m_3^{\text{tot}} &gt; 700 \text{ GeV}$</td>
<td>$2.9 \pm 0.5$</td>
<td>$0.54 \pm 0.18$</td>
<td>$0.53 \pm 0.11$</td>
<td>$4.0 \pm 0.6$</td>
<td>$6.6 \pm 1.1$</td>
<td>$0$</td>
</tr>
<tr>
<td>$m_3^{\text{tot}} &gt; 750 \text{ GeV}$</td>
<td>$2.0 \pm 0.4$</td>
<td>$0.44 \pm 0.16$</td>
<td>$0.32 \pm 0.07$</td>
<td>$2.8 \pm 0.5$</td>
<td>$6.2 \pm 1.0$</td>
<td>$0$</td>
</tr>
<tr>
<td>$m_3^{\text{tot}} &gt; 800 \text{ GeV}$</td>
<td>$1.41 \pm 0.28$</td>
<td>$0.26 \pm 0.12$</td>
<td>$0.22 \pm 0.05$</td>
<td>$1.93 \pm 0.32$</td>
<td>$5.8 \pm 1.0$</td>
<td>$0$</td>
</tr>
<tr>
<td>$m_3^{\text{tot}} &gt; 850 \text{ GeV}$</td>
<td>$1.00 \pm 0.21$</td>
<td>$0.12 \pm 0.07$</td>
<td>$0.19 \pm 0.04$</td>
<td>$1.32 \pm 0.24$</td>
<td>$5.4 \pm 0.9$</td>
<td>$0$</td>
</tr>
<tr>
<td>$m_3^{\text{tot}} &gt; 900 \text{ GeV}$</td>
<td>$0.71 \pm 0.16$</td>
<td>$0.10 \pm 0.07$</td>
<td>$0.14 \pm 0.04$</td>
<td>$0.95 \pm 0.18$</td>
<td>$5.1 \pm 0.9$</td>
<td>$0$</td>
</tr>
</tbody>
</table>

Table 5.8: Observed events and expected contributions from SM processes and the $Z_{\text{SSM}}^{\prime}$ signal ($M_{Z'} = 1750 \text{ GeV}$) in the $\tau_{\text{had}}\tau_{\text{had}}$ channel after various points in the event selection and after applying various $m_{T}^{\text{tot}}$ thresholds. The “tau selection” includes all selection criteria other than the OS, $\Delta\phi$, and $m_{T}^{\text{tot}}$ requirements. Diboson and $t\bar{t}$ contributions are omitted as they are negligible in the given regions. The total statistical plus systematic uncertainty is included.

---

\(^{18}\)This is the threshold for the 1.75-TeV SSM signal mass, the closest to the expected $Z'$ mass exclusion limit for this channel.
5.7. RESULTS

Figure 5.12: Key kinematic distributions in the $\tau_\text{had}$-$\tau_\text{had}$ channel for the leading (left) and sub-leading (right) $\tau_\text{had}$, and well as $E_{T}^{\text{miss}}$ (bottom). All Standard Model backgrounds are stacked. $Z_{\text{SSM}}$ signals with $m_{Z'} = 750, 1250$, and 1750 GeV are stacked on top of the total background. Events from data are overlaid. The statistical and systematic uncertainties on the estimated background are included. The last bins of the $p_T$ and $E_{T}^{\text{miss}}$ distributions also include overflow.
5.7. RESULTS

<table>
<thead>
<tr>
<th>Expected Events</th>
<th>$Z'_{SSM}(1750)$</th>
<th>$Z/\gamma^* \rightarrow \tau\tau$</th>
<th>Multijet</th>
<th>$W/Z+$jets</th>
<th>Total SM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Uncertainties (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Statistical</td>
<td>±2.4</td>
<td>±1.8</td>
<td>±59.0</td>
<td>±14.5</td>
<td>±6.0</td>
</tr>
<tr>
<td>Theo. Cross Sec.</td>
<td>±2.8</td>
<td>±2.8</td>
<td>±6.0</td>
<td>±5.8</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>±2.8</td>
<td>±2.8</td>
<td>±2.8</td>
<td>±2.5</td>
<td></td>
</tr>
<tr>
<td>$\tau$ ID Eff.</td>
<td>±12.1</td>
<td>±10.1</td>
<td>±3.5</td>
<td>±8.2</td>
<td></td>
</tr>
<tr>
<td>$\tau$ 3-prong Eff.</td>
<td>±4.4</td>
<td>±4.7</td>
<td>±6.6</td>
<td>±3.6</td>
<td></td>
</tr>
<tr>
<td>$\tau$ Trigger Eff.</td>
<td>±10.0</td>
<td>±10.0</td>
<td>±0.7</td>
<td>±7.6</td>
<td></td>
</tr>
<tr>
<td>TES (real)</td>
<td>±2.9</td>
<td>±12.6</td>
<td>±2.1</td>
<td>±9.8</td>
<td></td>
</tr>
<tr>
<td>TES (fake)</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>[-1.8, +7.2]</td>
<td>[-0.3, +1.0]</td>
<td></td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td></td>
</tr>
<tr>
<td>Soft $E_T^{miss}$ Res.</td>
<td>±0.1</td>
<td>[-0.1, +0.4]</td>
<td>[2.4, +0.0]</td>
<td>[0.2, +0.3]</td>
<td></td>
</tr>
<tr>
<td>Soft $E_T^{miss}$ Scale</td>
<td>±0.1</td>
<td>[+0.1, +0.2]</td>
<td>&lt; 0.1</td>
<td>[+0.0, +0.1]</td>
<td></td>
</tr>
<tr>
<td>Fake Factor</td>
<td>–</td>
<td>–</td>
<td>±8.8</td>
<td>±0.8</td>
<td></td>
</tr>
<tr>
<td>Fake Weight (stat.)</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>±16.2</td>
<td>±2.5</td>
<td></td>
</tr>
<tr>
<td>Fake Weight (comp.)</td>
<td>±0.2</td>
<td>±0.1</td>
<td>&lt; 0.1</td>
<td>±0.7</td>
<td></td>
</tr>
<tr>
<td>BCH Cleaning</td>
<td>±1.0</td>
<td>±0.4</td>
<td>[+1.2, -0.0]</td>
<td>±0.2</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.9: Total expected events and uncertainties for the $\tau_\text{had}\tau_\text{had}$ channel for $M_{Z'} = 1750$ GeV. Entries marked with – are non-applicable. Diboson and $t\bar{t}$ contributions are omitted as they are negligible in the signal region. The total SM uncertainty may be lower than the uncertainty from an individual background since each contribution is weighted by the expected number of events from that background.

5.7.2 $\tau_\text{lep}\tau_\text{had}$

The total numbers of events expected from signal and background and observed in data after key selection stages are detailed in tables 5.10 ($\tau_\text{e}\tau_\text{had}$) and 5.11 ($\tau_\mu\tau_\text{had}$). Between the two channels, only one event is observed in data above 850 GeV\textsuperscript{19}, which is consistent with the SM expectation of 0.96 ± 0.20 events. As is the case in the $\tau_\text{had}\tau_\text{had}$ channel, the expected number of background events is quite small, so the overall uncertainty is primarily rooted in the signal uncertainties, the largest of which are tau-related. These uncertainties are detailed in tables 5.12 ($\tau_\text{e}\tau_\text{had}$) and 5.13 ($\tau_\mu\tau_\text{had}$). Several key kinematic distributions for events passing the final event selection are shown in figure 5.13. These are the sums of the distributions for the individual channels.

\textsuperscript{19}This is the threshold for the 1.625-TeV SSM signal mass, the closest to the expected $Z'$ mass exclusion limit for each of these channels.
5.7. RESULTS

<table>
<thead>
<tr>
<th>Data</th>
<th>Total SM</th>
<th>$Z \to \tau\tau$</th>
<th>$W/Z + {\text{jets}}$</th>
<th>$Z \to \mu\mu$</th>
<th>$Z'_{SSM}(1625)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opposite Sign</td>
<td>97533</td>
<td>92229 ± 293</td>
<td>21118 ± 209</td>
<td>57166 ± 85</td>
<td>8165 ± 181</td>
</tr>
<tr>
<td>$\Delta\phi(e, \tau_{\text{had}})$</td>
<td>50663</td>
<td>48838 ± 247</td>
<td>14637 ± 173</td>
<td>25862 ± 61</td>
<td>6578 ± 163</td>
</tr>
<tr>
<td>$m_T(e, E_T^{\text{miss}})$</td>
<td>33804</td>
<td>32805 ± 232</td>
<td>13468 ± 167</td>
<td>13232 ± 48</td>
<td>5703 ± 153</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 100$ GeV</td>
<td>9259</td>
<td>9130 ± 114</td>
<td>1960 ± 56</td>
<td>4577 ± 28</td>
<td>2263 ± 95</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 200$ GeV</td>
<td>468</td>
<td>443 ± 8</td>
<td>148 ± 4</td>
<td>198 ± 4</td>
<td>15 ± 3</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 300$ GeV</td>
<td>76</td>
<td>93 ± 3</td>
<td>37 ± 1</td>
<td>32 ± 1</td>
<td>3 ± 7</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 400$ GeV</td>
<td>20</td>
<td>27 ± 1</td>
<td>12.8 ± 3</td>
<td>8.7 ± 7</td>
<td>1.5 ± 2</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 450$ GeV</td>
<td>11</td>
<td>16 ± 1</td>
<td>8.1 ± 0.2</td>
<td>4.4 ± 0.5</td>
<td>1.1 ± 0.2</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 500$ GeV</td>
<td>8</td>
<td>9.9 ± 0.8</td>
<td>5.1 ± 0.2</td>
<td>2.4 ± 0.4</td>
<td>0.7 ± 0.1</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 550$ GeV</td>
<td>5</td>
<td>6.6 ± 0.7</td>
<td>3.40 ± 0.09</td>
<td>1.7 ± 0.3</td>
<td>0.38 ± 0.07</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 600$ GeV</td>
<td>3</td>
<td>3.7 ± 0.4</td>
<td>2.22 ± 0.06</td>
<td>0.9 ± 0.2</td>
<td>0.21 ± 0.03</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 700$ GeV</td>
<td>1</td>
<td>1.5 ± 0.2</td>
<td>1.02 ± 0.03</td>
<td>0.3 ± 0.2</td>
<td>0.11 ± 0.01</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 750$ GeV</td>
<td>1</td>
<td>1.1 ± 0.2</td>
<td>0.70 ± 0.02</td>
<td>0.3 ± 0.2</td>
<td>0.08 ± 0.01</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 800$ GeV</td>
<td>1</td>
<td>0.8 ± 0.1</td>
<td>0.48 ± 0.01</td>
<td>0.2 ± 0.1</td>
<td>0.068 ± 0.009</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 850$ GeV</td>
<td>1</td>
<td>0.6 ± 0.1</td>
<td>0.35 ± 0.01</td>
<td>0.2 ± 0.1</td>
<td>0.056 ± 0.007</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 900$ GeV</td>
<td>1</td>
<td>0.5 ± 0.1</td>
<td>0.244 ± 0.007</td>
<td>0.2 ± 0.1</td>
<td>0.039 ± 0.005</td>
</tr>
</tbody>
</table>

Table 5.10: Observed events and expected contributions from SM processes and the $Z'_{SSM}$ signal ($M_{Z'} = 1625$ GeV) in the $\tau\nu_{\text{had}}$ channel after various points in the event selection and after applying various $m_T^{\text{tot}}$ thresholds. Diboson and $tt$ contributions are omitted as they disappear above $m_T^{\text{tot}} = 600$ GeV. The total statistical plus systematic uncertainty is included.

<table>
<thead>
<tr>
<th>Data</th>
<th>Total SM</th>
<th>$Z \to \tau\tau$</th>
<th>$W/Z + {\text{jets}}$</th>
<th>$Z \to \mu\mu$</th>
<th>$Z'_{SSM}(1625)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opposite Sign</td>
<td>96822</td>
<td>93388 ± 301</td>
<td>25219 ± 234</td>
<td>54103 ± 84</td>
<td>8013 ± 163</td>
</tr>
<tr>
<td>$\Delta\phi(\mu, \tau_{\text{had}})$</td>
<td>48846</td>
<td>47851 ± 253</td>
<td>17572 ± 194</td>
<td>21732 ± 56</td>
<td>6783 ± 151</td>
</tr>
<tr>
<td>$m_T(\mu, E_T^{\text{miss}})$</td>
<td>31839</td>
<td>31386 ± 235</td>
<td>16018 ± 186</td>
<td>9428 ± 41</td>
<td>5536 ± 137</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 100$ GeV</td>
<td>7941</td>
<td>7567 ± 92</td>
<td>2219 ± 61</td>
<td>3760 ± 24</td>
<td>1259 ± 64</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 200$ GeV</td>
<td>460</td>
<td>401 ± 8</td>
<td>144 ± 4</td>
<td>190 ± 4</td>
<td>2.8 ± 0.9</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 300$ GeV</td>
<td>93</td>
<td>87 ± 3</td>
<td>36 ± 1</td>
<td>36 ± 2</td>
<td>0.5 ± 0.2</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 400$ GeV</td>
<td>22</td>
<td>23 ± 2</td>
<td>11.7 ± 4</td>
<td>9 ± 1</td>
<td>0.2 ± 0.2</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 450$ GeV</td>
<td>12</td>
<td>13 ± 1</td>
<td>7.2 ± 0.2</td>
<td>5.6 ± 0.7</td>
<td>0.04 ± 0.03</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 500$ GeV</td>
<td>7</td>
<td>8.4 ± 0.7</td>
<td>4.4 ± 0.1</td>
<td>3.4 ± 0.6</td>
<td>0.04 ± 0.03</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 550$ GeV</td>
<td>5</td>
<td>4.6 ± 0.4</td>
<td>2.80 ± 0.08</td>
<td>1.8 ± 0.4</td>
<td>0.04 ± 0.03</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 600$ GeV</td>
<td>3</td>
<td>2.9 ± 0.3</td>
<td>1.86 ± 0.05</td>
<td>1.0 ± 0.3</td>
<td>0.0013 ± 0.0007</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 700$ GeV</td>
<td>1</td>
<td>1.00 ± 0.09</td>
<td>0.85 ± 0.03</td>
<td>0.15 ± 0.09</td>
<td>0.0012 ± 0.0006</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 750$ GeV</td>
<td>0.65 ± 0.07</td>
<td>0.57 ± 0.02</td>
<td>0.08 ± 0.07</td>
<td>0.0010 ± 0.0006</td>
<td>3.6 ± 0.2</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 800$ GeV</td>
<td>0.49 ± 0.07</td>
<td>0.41 ± 0.01</td>
<td>0.08 ± 0.07</td>
<td>0.0010 ± 0.0006</td>
<td>3.2 ± 0.1</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 850$ GeV</td>
<td>0.37 ± 0.07</td>
<td>0.281 ± 0.009</td>
<td>0.08 ± 0.07</td>
<td>0.0010 ± 0.0006</td>
<td>2.9 ± 0.1</td>
</tr>
<tr>
<td>$m_T^{\text{tot}} &gt; 900$ GeV</td>
<td>0.29 ± 0.07</td>
<td>0.198 ± 0.007</td>
<td>0.08 ± 0.07</td>
<td>0.0008 ± 0.0006</td>
<td>2.5 ± 0.1</td>
</tr>
</tbody>
</table>

Table 5.11: Observed events and expected contributions from SM processes and the $Z'_{SSM}$ signal ($M_{Z'} = 1625$ GeV) in the $\tau\nu_{\text{had}}$ channel after various points in the event selection and after applying various $m_T^{\text{tot}}$ thresholds. Diboson and $tt$ contributions are omitted as they disappear above $m_T^{\text{tot}} = 600$ GeV. The total statistical plus systematic uncertainty is included.
5.7. RESULTS

<table>
<thead>
<tr>
<th></th>
<th>$Z'_{SSM}(1625)$</th>
<th>Jet $\rightarrow \tau_{had}$ fakes</th>
<th>$Z \rightarrow \tau\tau$</th>
<th>$Z \rightarrow e\mu$</th>
<th>Total SM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected Events</strong></td>
<td>3.57</td>
<td>0.19</td>
<td>0.35</td>
<td>0.06</td>
<td>0.60</td>
</tr>
<tr>
<td><strong>Uncertainties (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Statistical</td>
<td>±3.7</td>
<td>[−71, +58]</td>
<td>±2.8</td>
<td>±12.4</td>
<td>±19.4</td>
</tr>
<tr>
<td>Theo. Cross Sec.</td>
<td>−</td>
<td>−</td>
<td>±7.8</td>
<td>±9.4</td>
<td>±5.5</td>
</tr>
<tr>
<td>Luminosity</td>
<td>±2.8</td>
<td>−</td>
<td>±2.8</td>
<td>±2.8</td>
<td>±1.9</td>
</tr>
<tr>
<td>$\tau$ ID Eff.</td>
<td>±6.9</td>
<td>−</td>
<td>±6.1</td>
<td>−</td>
<td>±3.6</td>
</tr>
<tr>
<td>$\tau$ 3-prong Eff.</td>
<td>±3.3</td>
<td>−</td>
<td>±3.7</td>
<td>−</td>
<td>±2.2</td>
</tr>
<tr>
<td>TES (real)</td>
<td>±4.6</td>
<td>−</td>
<td>±12.4</td>
<td>−</td>
<td>±7.2</td>
</tr>
<tr>
<td>TES (fake)</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td></td>
</tr>
<tr>
<td>$e \rightarrow \tau_{had}$ Fake</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>±21.0</td>
<td>±2.0</td>
</tr>
<tr>
<td>$e$ Energy Scale</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>±1.1</td>
<td>±0.1</td>
</tr>
<tr>
<td>Soft $E_T^{miss}$ Res.</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>±3.6</td>
<td>±0.3</td>
</tr>
<tr>
<td>Fake Factor</td>
<td>−</td>
<td>±46.4</td>
<td>−</td>
<td>−</td>
<td>±11.5</td>
</tr>
</tbody>
</table>

Table 5.12: Total expected events and uncertainties for the $\tau_{e/had}$ channel for $M_{Z'} = 1625$ GeV. Entries marked with − are non-applicable or < 1%. Diboson and $t\bar{t}$ contributions are omitted as they are negligible in the signal region. The total SM uncertainty may be lower than the uncertainty from an individual background since each contribution is weighted by the expected number of events from that background.

<table>
<thead>
<tr>
<th></th>
<th>$Z'_{SSM}(1625)$</th>
<th>Jet $\rightarrow \tau_{had}$ fakes</th>
<th>$Z \rightarrow \tau\tau$</th>
<th>Total SM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expected Events</strong></td>
<td>2.90</td>
<td>0.09</td>
<td>0.28</td>
<td>0.37</td>
</tr>
<tr>
<td><strong>Uncertainties (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Statistical</td>
<td>±4.9</td>
<td>[−100, +76]</td>
<td>±3.3</td>
<td>±18.4</td>
</tr>
<tr>
<td>Theo. Cross Sec.</td>
<td>−</td>
<td>−</td>
<td>±7.8</td>
<td>±6.0</td>
</tr>
<tr>
<td>Luminosity</td>
<td>±2.8</td>
<td>−</td>
<td>±2.8</td>
<td>±2.2</td>
</tr>
<tr>
<td>$\tau$ ID Eff.</td>
<td>±6.8</td>
<td>−</td>
<td>±6.1</td>
<td>±4.7</td>
</tr>
<tr>
<td>$\tau$ 3-prong Eff.</td>
<td>±3.7</td>
<td>−</td>
<td>±3.4</td>
<td>±2.6</td>
</tr>
<tr>
<td>TES (real)</td>
<td>±5.5</td>
<td>−</td>
<td>±13.9</td>
<td>±10.7</td>
</tr>
<tr>
<td>TES (fake)</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>$\mu \rightarrow \tau_{had}$ Fake</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>±15.0</td>
</tr>
<tr>
<td>$\mu$ Momentum Res. (MS)</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>±0.3</td>
</tr>
<tr>
<td>Soft $E_T^{miss}$ Res.</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Fake Factor</td>
<td>−</td>
<td>±46.7</td>
<td>−</td>
<td>±8.3</td>
</tr>
</tbody>
</table>

Table 5.13: Total expected events and uncertainties for the $\tau_{\mu/had}$ channel for $M_{Z'} = 1625$ GeV. Entries marked with − are non-applicable or < 1%. Diboson, $t\bar{t}$, and $Z \rightarrow \mu\mu$ contributions are omitted as they are negligible in the signal region. The total SM uncertainty may be lower than the uncertainty from an individual background since each contribution is weighted by the expected number of events from that background.
5.7. RESULTS

<table>
<thead>
<tr>
<th>Events</th>
<th>10^5</th>
<th>10^4</th>
<th>10^3</th>
<th>10^2</th>
<th>10^1</th>
<th>10^0</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>1</td>
<td>10</td>
<td>100</td>
<td>1000</td>
<td>10000</td>
<td>10000</td>
</tr>
</tbody>
</table>

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$ Data

$\tau^+\tau^-$, $Z'$ signals with $m_{Z'} = 750, 1250, 1750$ GeV are stacked on top of the total background. Events from data are overlaid. The statistical and systematic uncertainties on the estimated background are included. The last bins of the $p_T$ and $E_T^{miss}$ distributions also include overflow.

**Figure 5.13:** Key kinematic distributions for the lepton (top left), $E_T^{miss}$ (bottom left) and hadronic tau (right) in the sum of the $\tau_\ell\tau_{had}$ and $\tau_\mu\tau_{had}$ channels. All Standard Model backgrounds are stacked.

$Z_{SSM}^0$ signals with $m_{Z^0} = 750, 1250, 1750$ GeV are stacked on top of the total background. Events from data are overlaid. The statistical and systematic uncertainties on the estimated background are included. The last bins of the $p_T$ and $E_T^{miss}$ distributions also include overflow.
5.7.3 Statistical Combination

Since the number of observed events is consistent with the Standard Model expectations in all channels, exclusion limits on the $Z'$ cross section times ditau branching ratio are calculated. These are used to determine the limits on the $Z'$ mass. Bayesian Analysis is used to calculate the exclusion limits for each channel as well as the combination of the channels. This utilizes the calculation of the conditional probability distribution on the signal strength parameter $\mu$ given $N$ observed events using Bayes’ theorem:

$$p(\mu|N) = \frac{\int p(N|\mu, \theta) p(\mu, \theta) d\theta}{\int p(N|\mu', \theta) p(\mu', \theta) d\theta d\mu'}$$

(5.16)

where $\theta$ are the internal nuisance parameters which take the uncertainties into account [151, 152]. This equation takes the “prior” probability distribution of parameter $\mu$, $p(\mu)$, and uses the information of $N$ to update this to the more informed “posterior” probability distribution $p(\mu|N)$. The posterior distribution then yields insight into the absence or presence of a given signal.

5.7.3.1 Likelihood Model

In equation 5.16, the term $p(N|\mu, \theta)$ is called the likelihood function, and can also be written as $\mathcal{L}(N, \mu, \theta)$. This is a probability distribution on $N$ for a given $\mu$ and $\theta$. The overall likelihood $\mathcal{L}$ is the product of the individual channel likelihoods $\mathcal{L}_c \left( \mathcal{L} = \prod_c \mathcal{L}_c \right)$. The likelihood functions for individual channels are defined as:

$$\mathcal{L}_c = \text{Poisson} (N_c, \mu \times (s_c + \Delta s_c) + b_c + \Delta b_c) \prod_i \text{Gaussian} (\theta_i | 0, 1)$$

(5.17)

In this function, $s_c$ and $b_c$ respectively refer to the expected number of signal and background events in channel $c$. The deviations $\Delta s_c$ and $\Delta b_c$ represent the sums of the shifts in these values due to

$^{20}\text{Poisson}(n, \mu) \equiv \frac{e^{-\mu} \mu^n}{n!}$, $\text{Gaussian}(\theta|0, 1) \equiv \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2} \theta^2}$
5.7. RESULTS

Systematic uncertainties:

\[ \Delta s = \sum_i \theta_i \delta s_i \quad \text{and} \quad \Delta b = \sum_i \theta_i \delta b_i. \] (5.18)

The Gaussian-constrained nuisance parameters \( \theta_i \) are used to parameterize these uncertainties. These nuisance parameters take into account the correlation of uncertainties across channels.

5.7.3.2 Limit-Setting Procedure

Bayesian 95%-credibility upper limits are set on the cross section times branching ratio for a high-mass resonance decaying to a \( \tau^+ \tau^- \) pair as a function of the resonance mass. The upper limits on the signal strength parameter \( \mu_{up} \) are determined from the posterior distribution according to:

\[ 95\% = \int_0^{\mu_{up}} p(\mu'|N) \, d\mu' \] (5.19)

and translate to upper bounds on \( \sigma \)\(^{21} \) according to \( \sigma_{up} = \mu_{up} \times \sigma_{theory} \) (\( \sigma_{theory} \) being the theoretical \( Z' \) cross section). \( \mu_{up} \) is scaled from the SSM to other models (altered couplings or decay widths, \( Z'_{NU} \)) by

\[ \mu_{up,new} = \frac{\mu_{up,SSM}}{r_{ theory} \times r_A} \] (5.20)

in the case of individual channels. Each signal hypothesis is then excluded at mass points where \( \sigma_{up} < \sigma_{theory} \) (\( \mu_{up} < 1 \)) \[6, 151\]. The final limits are calculated with the Bayesian Analysis Toolkit \[153\] using uniform prior distributions and posterior distributions determined from Markov Chain Monte Carlo (MCMC) \[154, 155\].

5.7.3.3 Final Results

Based on the 95%-credibility upper limits on the signal strength for the combination of the channels, the resulting 95%-credibility lower limit on the mass of \( Z'_{SSM} \) decaying to \( \tau^+ \tau^- \) pairs is 2.02 TeV.

\(^{21}\)Technically, the bounds are placed on \( \sigma \times BR \), but this is shortened here for cleaner notation.
which is consistent with an expected limit of 1.95 TeV. The observed (expected) limits in the individual channels are 1.89 TeV (1.80 TeV) in $\tau_{\text{had}}\tau_{\text{had}}$, 1.59 TeV (1.59 TeV) in $\tau_\mu\tau_{\text{had}}$, and 1.55 TeV (1.65 TeV) in $\tau_\tau\tau_{\text{had}}$ (figure 5.14). The changes in signal acceptance from varying the fermion couplings or decay widths (section 5.6.2) translate linearly to the changes in the cross section limit (eq. 5.20). The total acceptance times efficiency is approximately 6% for $Z'_\text{SSM}$ masses $\geq 750$ GeV and drops down to 2.5% for $M_{Z'} = 500$ GeV. This is shown in figure 5.15, along with the contributions from the individual channels.

The impact of the choice of prior distribution on $\mu_{\text{up}}$ has been studied by changing the uniform prior to the reference prior [156], a prior distribution with less dependence on the choice of parameters. This improves the cross section limit by a maximum of 10%, which leads to a 20-GeV increase in the $Z'$ mass limit.

Limits are also calculated for the Non-Universal $G(221)$ model. In the range of $0.03 < \sin^2 \phi < 0.5$, $Z'_{\text{NU}}$ masses below 1.3-2.1 TeV are excluded at 95% CL. The exact mass limits for each choice of $\sin^2 \phi$ are shown in figure 5.16, overlaid with limits from multiple indirect searches. These are the
first direct $Z'_{NU}$ limits from the LHC. They do not surpass the leading results from indirect searches, but they are competitive in some regions of $\sin^2 \phi$.

Figure 5.16: 95%-CL exclusion limits of the Non-Universal $G(221)$ $Z'$ mass as a function of $\sin^2 \phi$. These limits are overlaid with indirect 95%-credibility exclusion results from Electroweak precision measurements (EWPT) \cite{157}, Lepton Flavor Violation (LFV) \cite{158}, CKM unitarity \cite{159}, and $Z$-pole data \cite{36}. 

Figure 5.15: $Z'_{SSM}$ Acceptance and Acceptance times Efficiency for each channel and the full analysis as functions of $M_{Z'}$. 
5.8 Conclusions

A search for heavy $Z'$ gauge bosons decaying to $\tau^+\tau^-$ was performed using 19.5-20.3 fb$^{-1}$ of data from the ATLAS detector collected during $\sqrt{s} = 8$ TeV $pp$ collisions at the Large Hadron Collider. The analysis was performed in the fully-hadronic and semi-hadronic ditau decay channels. The numbers of events in signal regions with high transverse mass were consistent with the expectations from the Standard Model. Bayesian 95%-CL upper limits were placed on the $Z'$ production cross section times ditau branching ratio for each signal hypothesis. $Z'$ from the Sequential Standard Model were excluded at 95% credibility for $M_{Z'} < 2.02$ TeV. The impact on the signal acceptance from changing the $Z'$ decay widths and couplings to fermions was investigated. Adjusting the decay width between 1-20% of $M_{Z'}$, while keeping the couplings constant changed the signal acceptance in the range $[-45\%, +20\%]$, with the largest deviations occurring for high $Z'$ masses. Altering the couplings to left- and -right-handed fermions changed the signal acceptance by as much as $[-25\%, +50\%]$, with the strongest impact at lower $Z'$ masses. The effects of $Z-Z'$ and $\gamma-Z'$ interference were found to be small for all models except those with wide decay widths. It was concluded that interference would need to be included to determine the correct behavior of these models in future studies. The Non-Universal $G(221)$ model was also investigated, resulting in 95%-CL lower mass limits of 1.3-2.1 TeV in the range of $0.03 < \sin^2 \phi < 0.5$ with no $\mu$-$\tau$ mixing.

Later in 2015, the LHC will be reactivated with upgraded capabilities and will produce $pp$ collisions with $\sqrt{s} = 13$ TeV. In this energy range, LHC experiments will become sensitive to $Z'$ signals with masses up to $\sim 4.5$ TeV [1]. In addition to repeating this and other past experiments at higher energy, other measures can be taken to improve results from $Z'$ searches. Since the largest uncertainties on the signal were related to the selection and identification of taus, the sensitivity to $Z' \to \tau\tau$ will improve as tau trigger and identification algorithms become more precise and sophisticated. Improvements to the algorithms used to identify top and bottom quarks could also improve the performance of $Z' \to t\bar{t}$ or $Z' \to b\bar{b}$ searches. In the absence of a $Z'$ discovery, exclusion limits could be improved by statistically combining results from multiple search channels. These currently
include the highly sensitive dilepton channels, but could also extend to $t\bar{t}$ or $b\bar{b}$ if the performance improved in these channels. In addition to combining results with other ATLAS searches, combining results with other experiments could lead to even stronger limits on the cross sections and masses of $Z'$ bosons. Future searches could also improve on previous ones by including even more varieties of $Z'$ signal models. In addition to incorporating popular models such as $Z'_X$ and $Z'_{L,R}$, more models featuring $Z'$ with strong third-generation couplings like TC2 could be included in future $Z'$ searches to yield more insight into the possibilities of new physics.
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Appendix A

Calculating Cross Sections and Decay Rates

A.1 Cross Sections

The cross section for a particular physical interaction is a value used to measure the likelihood for that type of event to occur. For an object traveling towards a fixed target, the cross section is the effective area within the transverse plane (perpendicular to the trajectory) over which a scattering interaction would take place. In the context of collisions between two sets of moving particles, the experimental cross section $\sigma$ for particles “$A$” and “$B$” colliding and scattering would be

$$\sigma = \frac{\text{Number of scattering events}}{l_\mathcal{A}l_\mathcal{B} \int d^2x \rho_\mathcal{A}(x)\rho_\mathcal{B}(x)}$$  \hspace{1cm} (A.1)$$

where $l_{\mathcal{A}(B)}$ is the longitudinal length of the cluster of $\mathcal{A}(B)$ and $\rho_{\mathcal{A}(B)}(x)$ is the number of $\mathcal{A}(B)$ per unit volume at spacial point $x$. At energy scales where QFT is required to model fundamental processes, the general form of the differential scattering cross section for two initial ($i$) particles
scattering to \( n \) final \( (f) \) particles is given by

\[
\frac{d\sigma}{d\cos \theta} = \frac{(2\pi)^4}{4E_{i,1}E_{i,2}} \prod_{k=1}^n \frac{d^3p_{f,k}}{(2\pi)^3} \frac{d^3p_{i,1}}{(2\pi)^3} \frac{d^3p_{i,2}}{(2\pi)^3} |M_{fi}|^2 
\]

where \( p_j \) is the four-vector momentum \((E_j, p_j)\), \( \beta_j \equiv p_j/E_j \), \( \delta^4(x) \) is the four-dimensional Dirac delta function, and \( M_{fi} \) is the invariant matrix element (also called transition amplitude or scattering amplitude) for final state \( f \) and initial state \( i \). In the special case of a 2-particle final state where the final masses match the initial masses (or all initial and final particles have negligible mass), this is given in the center-of-mass (CM) frame by

\[
\frac{d\sigma}{d\cos \theta} = \frac{|M_{fi}|^2}{32\pi s} 
\]

where \( \theta \) is the scattering angle between the initial and final trajectory lines and \( s \equiv (p_{i,1} + p_{i,2})^2 = E_{CM}^2 \). The scattering amplitude is calculated by setting \( i\mathcal{M} \) equal to the sum of the Feynman diagrams for the given process. These diagrams represent the possible unique configurations of the transition from the initial to final state and translate to amplitudes via the Feynman Rules (derived from interaction Lagrangians) [11]. The simplest diagrams (i.e. those with no loops) are called Born-level\(^2\) diagrams. As loops are added in higher-order\(^3\) diagrams, the number of vertices increases, each of which adds a factor of the coupling constant. If the coupling constant is sufficiently small, the scattering amplitude for a given process can be approximated at Born level.

As a practical example, consider the process \( q\bar{q} \to l^+l^- \) for arbitrary, but fixed, quark and lepton flavors. Based on the rules of the Standard Model (and some BSM theories), the quark-antiquark pair must annihilate into a neutral gauge boson before decaying to the lepton-antilepton state. This would include a photon and \( Z \) in the SM and would extend to \( Z' \) under certain BSM models. The

\(^1\)This is one of three Mandelstam variables, the others being \( t \equiv (p_{f,1} - p_{i,1})^2 \) and \( u \equiv (p_{f,2} - p_{i,1})^2 \).

\(^2\)These can alternatively be called “tree-level” or “leading-order” (LO) diagrams.

\(^3\)Diagrams with one loop are called “next-to-leading-order” (NLO). The subsequent orders are NNLO, etc...
amplitude for this is depicted in figure A.1. The contribution of each diagram can be expressed as

\[
\bar{v}_q(p_{i,3}) V^\mu u_q(p_{i,1}) \times P_{\mu\nu} (p_{i,1} + p_{i,2}) \times \bar{u}_{l^-} (p_{f,i}) V^{\nu} v_{l^+} (p_{f,2}) \quad (A.4)
\]

where \(u\) \((v)\) is the Dirac four-spinor for the given fermion \((\text{antifermion})\) and \(V_{\mu\nu}\) and \(P_{\mu\nu}\) are the diagram-specific vertex and propagator terms respectively (table A.1).

Since the \(u\) and \(v\) fields each have two eigenstates corresponding to the spin\(^4\) states, special consideration must be taken when calculating the cross section for states with particular polarizations. For completely unpolarized initial and final states, the total cross section is averaged over the initial states and summed over the final states. Since the initial fermions are quarks, the initial color-anticolor states must be averaged over as well:

\[
|M_{fi}|^2 = \frac{1}{4} \sum_{c=r,g,b} \sum_{i} \sum_{j} |M_{fi} (s^i_1, s^j_2, s^i_1, s^j_2)|^2 \quad (A.5)
\]

\(^4\)Alternatively, the basis with helicity eigenstates can be used.
A.2. DECAY RATES

The calculation of the final cross section can be performed using the four-spinor completeness relations

$$\sum_r u^r(p) \bar{u}^r(p) = \gamma^\mu p_\mu + m \quad \text{and} \quad \sum_r v^r(p) \bar{v}^r(p) = \gamma^\mu p_\mu - m \quad \text{(A.6)}$$

in conjunction with the $\gamma$-matrix trace identities [11].

A.2 Decay Rates

In cases where a single unstable particle decays into two or more particles, the rate of interaction is best parameterized by the decay rate (or decay width). For the initial particle $i$ to decay to a particular final state $f$, the partial decay rate $\Gamma_f$ is the probability per unit time for that decay to occur. In a laboratory setting, this would be a measurement of

$$\Gamma_f = \frac{\text{Decays of } i \rightarrow f \text{ per unit time}}{\text{Number of } i \text{ present}} \quad \text{(A.7)}$$

For fundamental processes, the differential partial decay rate to $n$ final particles is given by

$$d\Gamma_f = \frac{(2\pi)^4 \delta^4 \left((\sum_{k=1}^n p_{f,k}) - p_i\right)}{2m_i} \prod_{k=1}^n \frac{d^3p_{f,k}}{(2\pi)^3 2E_{f,k}} |M_{fi}|^2 \quad \text{(A.8)}$$

in the rest frame of the initial particle. A factor of $1/l!$ must be applied for each type of final particle, where $l$ is the number of that particle in the final state. The total decay rate $\Gamma$ for the initial particle is obtained by summing all the partial decay rates. This is equal to $1/\tau$, where $\tau$ is the particle’s lifetime.
Appendix B

High-$p_T$ Muon Studies for the $\tau_\mu \tau_\text{had}$ Channel

One of the difficulties with selecting muons with high momentum is that the $p_T$ resolution ($\delta p_T/p_T$) tends to increase for large $p_T$ values. More specifically, the tails of the resolution distributions become much larger as $p_T$ approaches the TeV scale (figure B.1). In order to suppress these tails, several muon selection requirements were recommended by the ATLAS Muon CP group. These are detailed in table B.1. One concern with these selection cuts was that they would reduce the selection efficiency (number of selected truth-matched muons / total number of true muons) enough to negatively impact the sensitivity to $Z'$ signals. In order to understand the impact of the high-$p_T$ selection, each cut was applied one-by-one to simulated high-mass muon samples. The selection efficiency was measured after each cut was applied (figure B.2).

The efficiency measurements showed that the new selection requirements had a significant impact on the selection efficiency. The 3-station (or 2-station) requirement had the most significant impact for $p_T \gtrsim 100$ GeV, though the impact parameter requirement had the largest impact at lower $p_T$ values. In order to determine which cuts were the most successful at reducing the resolution tails,
the resolution tail fraction (fraction of truth-matched muons with $p_T$ resolution $> 1.5$) was measured in bins of $p_T$ after each selection criterion was implemented (figure B.3).

The resolution tail fraction measurements determined that the two cuts with the most significant impact on the resolution tails were the 3-station (3- or 2-station) requirement and the ID-MS consistency requirement. The selection efficiency and resolution tail fractions were measured again using only these two criteria (figure B.4).

The selection efficiency and resolution tail fraction plots could not decisively indicate whether suppressing the resolution tail would compensate for the drop in selection efficiency. An estimate of the sensitivity in the signal region was made by measuring the parameter $S/\sqrt{S + B}$\(^1\) in the $m_T^{\text{jet}} > 600$ GeV signal region using the different levels of the high-$p_T$ muon selection (table B.2). This parameter was maximized when no high-$p_T$ requirements were implemented, so they were not used in the analysis.

\(^1\) $S(B)$ is the number of signal (background) events.
**APPENDIX B. HIGH-$p_T$ MUON STUDIES FOR THE $\tau_\mu^{\tau_{\text{had}}}$ CHANNEL**

### Table B.1: Proposed additional selections for muons. The 3-station (top) and 2-station (bottom) muon selections are independent sets of requirements. Cases where the muons pass the 3-station requirements or either set of requirements were considered.

<table>
<thead>
<tr>
<th>Cut Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3-station muon selections:</strong></td>
<td></td>
</tr>
<tr>
<td>IP</td>
<td>$</td>
</tr>
<tr>
<td>3-station req.</td>
<td>3 hits in each of three MS layers: either BI-BM-BO, EI-EE-EM, or EI-EM-EO (2 hits in CSC can replace the EI requirement for the third region)</td>
</tr>
<tr>
<td>MC Veto</td>
<td>No hits in the BIS7, BIS8, or BEE chambers</td>
</tr>
<tr>
<td>phi hit</td>
<td>At least one MS phi hit in two detector layers</td>
</tr>
<tr>
<td>ID-MS $p_T$-consistency</td>
<td>$</td>
</tr>
</tbody>
</table>

| **2-station muon selections:** | |
| IP | $|d_0| < 0.2$ and $|z_0| < 1.0$ w.r.t. the primary vertex |
| 2-station req. | $\geq 5$ hits each in BI and BO stations AND $\eta < 1.05$ AND No hits in the following regions: |
| | - phi sector 9 with $0.2 < |\eta| < 0.35$ |
| | - phi sector 4 or 6 with $|\eta| > 0.85$ |
| | - phi sector 13 with $0 < \eta < 0.2$ |
| MC Veto | No hits in the BIS7, BIS8, or BEE chambers |
| phi hit | At least one MS phi hit |
| ID-MS $p_T$-consistency | $|(q/p)_{ID} - (q/p)_{MS}|/\sigma_C < 3$ |

---

### Table B.2: The analysis was run using different combinations of the high-$p_T$ muon selection criteria. $S/\sqrt{S+B}$ was measured in the $m_T^{\mu\tau} > 600$ GeV signal region for the full SM backgrounds and the 1000-GeV and 1250-GeV $Z'$ signals to determine which selection combination would maximize sensitivity.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$N_{\text{Background}}$</th>
<th>$N_{Z'1000}$</th>
<th>$N_{Z'1250}$</th>
<th>$\frac{S}{\sqrt{S+B}}(Z'1000)$</th>
<th>$\frac{S}{\sqrt{S+B}}(Z'1250)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Selection</td>
<td>3</td>
<td>32</td>
<td>15</td>
<td>5.409</td>
<td>3.536</td>
</tr>
<tr>
<td>3-station added</td>
<td>2.5</td>
<td>29</td>
<td>13</td>
<td>5.167</td>
<td>3.302</td>
</tr>
<tr>
<td>3-station + ID-MS added</td>
<td>2.5</td>
<td>29</td>
<td>13</td>
<td>5.167</td>
<td>3.302</td>
</tr>
<tr>
<td>3or2-station added</td>
<td>2.5</td>
<td>29</td>
<td>13</td>
<td>5.167</td>
<td>3.302</td>
</tr>
<tr>
<td>3or2-station + ID-MS added</td>
<td>2.5</td>
<td>29</td>
<td>13</td>
<td>5.167</td>
<td>3.302</td>
</tr>
</tbody>
</table>
Figure B.1: The tails of muon resolution distributions grow larger as $p_T$ approaches the TeV scale. Different levels of the proposed high-$p_T$ selection are applied to study the effects on the tails.
APPENDIX B. HIGH-P_T MUON STUDIES FOR THE $\tau_{\mu}^{\text{HAD}}$ CHANNEL

Figure B.2: Selection efficiency was measured for the high-$p_T$ muon selection using simulated muons. These include selections with (left) and without (right) the impact parameter requirement. Different versions of the selection were applied for only 3-station muons (top), 3- or 2-station muons (middle), and 3-station muons without the 3-station requirement (bottom). The “new selection” label refers to the standard muon selection without the high-$p_T$ cuts (new relative to the 7-TeV analysis) and the “full high-$p_T$” label refers to the ID-MS $p_T$-consistency cut applied on top of the phi hit and previous cuts. The 3-station versions of phi hit and ID-MS $p_T$-consistency are used unless the muon fails the 3-station requirement but passes the 2-station requirement.
Appendix B. High-$p_T$Muon Studies for the $\tau_{\mu}^{HAD}$ Channel

Figure B.3: Resolution tail fraction was measured in bins of $p_T$ for the high-$p_T$ muon selection using simulated muons. These include selections with (left) and without (right) the impact parameter requirement. Different versions of the selection were applied for only 3-station muons (top), 3- or 2-station muons (middle), and 3-station muons without the 3-station requirement (bottom). The "2012 muon selection" label refers to the standard muon selection without the high-$p_T$ cuts and the "full high$p_T$" label refers to the ID-MS $p_T$-consistency cut applied on top of the phi hit and previous cuts. The 3-station versions of phi hit and ID-MS $p_T$-consistency are used unless the muon fails the 3-station requirement but passes the 2-station requirement.
APPENDIX B. HIGH-P_{T} MUON STUDIES FOR THE $\tau_{\mu,\text{HAD}}$ CHANNEL

Figure B.4: Muon selection efficiency (top) and resolution tail fraction (bottom) binned by $p_{T}$. Selection levels considered include no high-$p_{T}$ selection, 3-station requirement, 3- or 2-station requirement, 3-station requirement plus ID-MS $p_{T}$-consistency, and 3- or 2-station requirement plus ID-MS $p_{T}$-consistency. The 3-station version of ID-MS $p_{T}$-consistency is used unless the muon fails the 3-station requirement but passes the 2-station requirement.
Appendix C

Object Selection Studies for the \( \tau_e \tau_{\text{had}} \) Channel

Before the requirements of medium BDT tau ID, medium BDT electron veto, and tight++ electron ID were finalized for the \( \tau_e \tau_{\text{had}} \) channel, several alternative selections with looser requirements were considered. These selections are the same as the final selection, but with the following variations:

- loose BDT tau ID for variation 1
- loose BDT electron veto for variation 2
- medium++ electron ID for variation 3

Plots of \( m_T(e, E_T^{\text{miss}}) \) using these variations are presented in figure C.1. In the first variation, the loose BDT tau ID caused an inflation in the \( W + \text{jets} \) background, which would lead to reduced signal sensitivity. The loose BDT electron veto variation increased the \( Z \to ee \) background and caused poor modeling at low \( m_T(e, E_T^{\text{miss}}) \). The use of medium++ electron ID led to a large overestimation of the multijet background (as well as the fake-isolation subtraction from the \( W + \text{jets} \) background) which led to extremely poor modeling at low \( m_T(e, E_T^{\text{miss}}) \). The looser alternative selections were rejected in favor of the original selection.
Figure C.1: Distributions of $m_T(e, E_T^{\text{miss}})$ using the finalized analysis selection (top left) and variations using loose BDT tau ID (top right), loose BDT electron veto (bottom left), and medium++ electron ID (bottom right). These plots were produced using a cut on $f_{EM}$ of the electron and without the $E_T^{\text{miss}}$ reweighting, so some differences from the final analysis plots are present.
Appendix D

Fake Factor Studies for the $\tau_{\text{lep}}\tau_{\text{had}}$ Channels.

D.1 Fake Factor Stability

The fake factor method is only viable if the rate of jets passing the tau ID is the same in the signal region and the $W$+jets control region. In order to verify this, tau ID fake factors were measured using control regions with alternate $m_{\text{T}}(\text{lep}, E_{\text{T}}^{\text{miss}})$ requirements (since this is the primary variable distinguishing the two regions) in both the $\tau_{e}\tau_{\text{had}}$ and $\tau_{\mu}\tau_{\text{had}}$ channels (figure D.1). The fake factors are found to be quite stable, fluctuating within $\approx 10\%$ uncertainty (well below the $30\%$ systematic uncertainty on the $W$+jets background).

A $p_{\text{T}}$- and $\eta$-inclusive fake factor was also plotted in bins of $m_{\text{T}}(\text{lep}, E_{\text{T}}^{\text{miss}})$ for data and MC as well as opposite- and same-sign charges in both channels (figure D.2). These distributions are all fairly flat with fluctuations lying within the $30\%$ systematic uncertainty.
D.2 Single vs. Double Fake Factor

The fake factor method used for the $\tau_{lep}\tau_{had}$ channels models two backgrounds: $W$+jets and multijets. This is justified by the assumptions that the events with tau-ID fakes were dominantly $W$+jets and that the true fake factors for $W$+jets and multijets had little variation. The latter was mostly verified by the alternate tau-ID fake factors measured in the multijet control region (section 5.4.3.2). The former was verified using a more complicated fake factor method which estimates each of these backgrounds individually.

Jets from multijet events are generally less isolated than leptons in $W$+jet events, though multijet events may fake $W$+jets if a jet is well isolated. The multijet and $W$+jets backgrounds are therefore separated using lepton-isolation fake factors. These fake factors are calculated in the following dijet-pure region:

Figure D.1: Tau ID fake factors for 1-prong (left) and 3-prong (right) $\tau_{had}$ measured with varied $m_T(lep,E^{miss}_T)$ requirements for the $\tau_e\tau_{had}$ (top) and $\tau_\mu\tau_{had}$ (bottom) channels.
D.2. SINGLE VS. DOUBLE FAKE FACTOR

Figure D.2: Tau ID $\eta$- and $p_T$-inclusive fake factors for 1-prong (left) and 3-prong (right) $\tau_{\text{had}}$ in bins of $m_T(\text{lep}, E_T^{\text{miss}})$, for the $\tau_e \tau_{\text{had}}$ (top) and $\tau_\mu \tau_{\text{had}}$ (bottom) channels.

- exactly one lepton (electron for $\tau_e \tau_{\text{had}}$, muon for $\tau_\mu \tau_{\text{had}}$)
- no $\tau_{\text{had}}$
- $m_T(\text{lep}, E_T^{\text{miss}}) < 30$ GeV
- $E_T^{\text{miss}} < 30$ GeV
- $d_0(\text{lep}) > 0$ w.r.t the primary vertex

They are equal to

$$f_{iso} (p_T, \eta) = \frac{N_{\text{pass isolation}}(p_T, \eta)}{N_{\text{fail isolation}}(p_T, \eta)} \bigg|_{\text{dijet}}$$ (D.1)

and are applied as weights to events in a region in which the lepton fails isolation and the $\tau_{\text{had}}$ fails tau ID. These weighted events are subtracted from the pass-lepton-isolation/fail-tau-ID region and are then weighted by the multijet tau-ID fake factors to estimate the multijet background. The
remaining events in the pass-lepton-isolation/fail-tau-ID region are then weighted by the $W$+jets tau-ID fake factors to estimate the $W$+jets background.

Comparisons between kinematic distributions from the single and double fake factor methods are shown in figs. D.3 to D.8 and tables D.1 and D.2. The multijet background is negligible in comparison to the $W$+jets background and the full fake background is approximately the same between methods. This justified the use of the single fake factor method to model both backgrounds.

**Figure D.3:** Comparison between single (left) and double (right) fake factors in kinematic distributions in the $\tau\tau$ channel. The $E_{T}^{miss}$ reweighting is not applied.
### D.2. SINGLE VS. DOUBLE FAKE FACTOR

<table>
<thead>
<tr>
<th>Cutflow</th>
<th>total SM (Single)</th>
<th>total SM (Double)</th>
<th>fake taus (Single)</th>
<th>W/Z+jets (Double)</th>
<th>multijet (Double)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS $\mu$ and $\tau_{\text{had}}$</td>
<td>91803(289)</td>
<td>90105(290)</td>
<td>55656(84)</td>
<td>49902(86)</td>
<td>4055(10)</td>
</tr>
<tr>
<td>$</td>
<td>\Delta\phi(\mu, \tau_{\text{had}})</td>
<td>&gt; 2.7$</td>
<td>44953(240)</td>
<td>43952(240)</td>
<td>21149(54)</td>
</tr>
<tr>
<td>$m_{\text{T}}(\mu, E_{\text{T}}^{\text{miss}}) &lt; 50$ GeV</td>
<td>29084(223)</td>
<td>28416(223)</td>
<td>9005(38)</td>
<td>6643(39)</td>
<td>1694(7)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 100$ GeV</td>
<td>7485(89)</td>
<td>7268(90)</td>
<td>3831(22)</td>
<td>2918(23)</td>
<td>696(4)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 200$ GeV</td>
<td>412(8)</td>
<td>410(8)</td>
<td>196(4)</td>
<td>174(4)</td>
<td>20.4(4)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 300$ GeV</td>
<td>79(3)</td>
<td>79(3)</td>
<td>27(1)</td>
<td>25(1)</td>
<td>2.0(1)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 400$ GeV</td>
<td>20(1)</td>
<td>20(1)</td>
<td>6.9(7)</td>
<td>6.5(7)</td>
<td>0.38(5)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 500$ GeV</td>
<td>7.8(6)</td>
<td>7.8(6)</td>
<td>2.9(4)</td>
<td>2.8(4)</td>
<td>0.12(4)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 600$ GeV</td>
<td>2.7(2)</td>
<td>2.7(2)</td>
<td>0.9(2)</td>
<td>0.8(2)</td>
<td>0.02(1)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 700$ GeV</td>
<td>1.0(1)</td>
<td>1.0(1)</td>
<td>0.1(1)</td>
<td>0.1(1)</td>
<td>0.01(0)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 800$ GeV</td>
<td>0.5(1)</td>
<td>0.5(1)</td>
<td>0.1(1)</td>
<td>0.1(1)</td>
<td>0.004(3)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 900$ GeV</td>
<td>0.3(1)</td>
<td>0.3(1)</td>
<td>0.1(1)</td>
<td>0.1(1)</td>
<td>0.002(2)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 1000$ GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table D.1:** Comparison between the single and double fake factors for total and data-driven background events in the $\tau_{\text{e}}\tau_{\text{had}}$ channel. The parentheses contain the error on the least significant digit(s).

<table>
<thead>
<tr>
<th>Cutflow</th>
<th>total SM (Single)</th>
<th>total SM (Double)</th>
<th>fake taus (Single)</th>
<th>W/Z+jets (Double)</th>
<th>multijet (Double)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS $e$ and $\tau_{\text{had}}$</td>
<td>94644(299)</td>
<td>93358(300)</td>
<td>59962(90)</td>
<td>53548(90)</td>
<td>5128(8)</td>
</tr>
<tr>
<td>$</td>
<td>\Delta\phi(e, \tau_{\text{had}})</td>
<td>&gt; 2.7$</td>
<td>48960(252)</td>
<td>48113(253)</td>
<td>25856(63)</td>
</tr>
<tr>
<td>$m_{\text{T}}(e, E_{\text{T}}^{\text{miss}}) &lt; 50$ GeV</td>
<td>32822(237)</td>
<td>32111(237)</td>
<td>13111(50)</td>
<td>9526(50)</td>
<td>2873(6)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 100$ GeV</td>
<td>9648(120)</td>
<td>9429(120)</td>
<td>4866(32)</td>
<td>3597(32)</td>
<td>1051(3)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 200$ GeV</td>
<td>475(8)</td>
<td>478(8)</td>
<td>236(4)</td>
<td>200(4)</td>
<td>38.0(4)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 300$ GeV</td>
<td>96(3)</td>
<td>96(3)</td>
<td>36(2)</td>
<td>32(2)</td>
<td>4.7(1)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 400$ GeV</td>
<td>27(1)</td>
<td>27(1)</td>
<td>9.8(8)</td>
<td>8.8(8)</td>
<td>1.18(7)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 500$ GeV</td>
<td>9.8(8)</td>
<td>9.8(8)</td>
<td>2.6(4)</td>
<td>2.3(4)</td>
<td>0.37(4)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 600$ GeV</td>
<td>3.9(4)</td>
<td>3.9(4)</td>
<td>1.1(3)</td>
<td>1.0(3)</td>
<td>0.14(2)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 700$ GeV</td>
<td>1.6(2)</td>
<td>1.6(2)</td>
<td>0.4(2)</td>
<td>0.4(2)</td>
<td>0.07(2)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 800$ GeV</td>
<td>0.8(1)</td>
<td>0.8(1)</td>
<td>0.2(1)</td>
<td>0.2(1)</td>
<td>0.03(1)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 900$ GeV</td>
<td>0.5(1)</td>
<td>0.5(1)</td>
<td>0.2(1)</td>
<td>0.2(1)</td>
<td>0.014(7)</td>
</tr>
<tr>
<td>$m_{\text{T}} &gt; 1000$ GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table D.2:** Comparison between the single and double fake factors for total and data-driven background events in the $\tau_{\mu}\tau_{\text{had}}$ channel. The parentheses contain the error on the least significant digit(s).
D.3 Double Fake Factor Variations in the \( \tau_e \tau_{\text{had}} \) Channel

Modeling the multijet background in the \( \tau_\mu \tau_{\text{had}} \) channel is fairly straightforward since the jets that fake muons are almost exclusively from heavy-flavor particles. The \( \tau_e \tau_{\text{had}} \) channel is more complicated due to a more even blend of light- and heavy-flavor lepton fakes. The exact balance is not well known and may not even be the same across signal and control regions. As the \( d_0 \) requirement on the dijet control region for lepton-isolation fake factor calculation changes (thereby changing the light- and heavy-flavor balance), the lepton-isolation fake factors can change significantly, particularly at lower \( p_T \) (figure D.9).

The double fake factor models the jet backgrounds fairly well, but there is still some underestimation in the \( \tau_e \tau_{\text{had}} \) channel. It was assumed that this was related to different light- and heavy-flavor balances between the signal region and various control regions. Under this assumption, the \( d_0 \) requirement used for the isolation fake factor calculation could be varied so that the multijet background and anti-isolated subtraction from \( W+\text{jets} \) better reflect their true contributions. The multijet background and subtraction from \( W+\text{jets} \) now used independent lepton-isolation fake factors (with different \( d_0 \) requirements) because of the possibility of different heavy/light-flavor balances between the signal and anti-tau control regions.

To establish that the lepton-isolation fake factor \( d_0 \) requirement was the leading cause of the underestimated backgrounds, this requirement was changed for the multijets and the subtraction from \( W+\text{jets} \) to overestimate the overall jet backgrounds (figure D.10). The \( d_0 \) requirement was then adjusted for both backgrounds until the backgrounds were able to reproduce the data (figure D.11). The sensitivity to the \( d_0 \) requirement was then used to help motivate a systematic uncertainty for the data-driven backgrounds.
Figure D.4: Comparison between single (left) and double (right) fake factors in kinematic distributions in the $\tau_\text{e} \tau_\text{had}$ channel. The $E^\text{miss}_T$ reweighting is not applied.
D.3. DOUBLE FAKE FACTOR VARIATIONS IN THE $\tau_{e\tau_{had}}$ CHANNEL

Figure D.5: Comparison between single (left) and double (right) fake factors in the $m_{T}^{\text{tot}}$ distribution in the $\tau_{e\tau_{had}}$ channel. The $E_{T}^{\text{miss}}$ reweighting is not applied.
D.3. DOUBLE FAKE FACTOR VARIATIONS IN THE $\tau_\text{E} \tau_\text{HAD}$ CHANNEL

Figure D.6: Comparison between single (left) and double (right) fake factors in kinematic distributions in the $\tau_\text{E} \tau_\text{HAD}$ channel. The $E_T^{\text{miss}}$ reweighting is not applied.
Figure D.7: Comparison between single (left) and double (right) fake factors in kinematic distributions in the $\tau\tau_{\text{had}}$ channel. The $E_T^{\text{miss}}$ reweighting is not applied.
D.3. DOUBLE FAKE FACTOR VARIATIONS IN THE $\tau$\textsubscript{E\textsubscript{HAD}} CHANNEL

Figure D.8: Comparison between single (left) and double (right) fake factors in the $m_{T\mu}^{\text{tot}}$ distribution in the $\tau_{\mu}$\textsubscript{had} channel. The $E_{T}^{\text{miss}}$ reweighting is not applied.

Figure D.9: Lepton-isolation fake factors with various $d_{0}$ requirements the $\tau_{e}$\textsubscript{had} channel.
Figure D.10: Initial underestimations (left) and overestimations (right) of the data-driven jet backgrounds from the double fake factor method. The overestimation used a $|d_0| < 0.2$ requirement for the anti-isolated control region.
D.3. DOUBLE FAKE FACTOR VARIATIONS IN THE $\tau\tau$HAD CHANNEL

Figure D.11: Data-driven jet backgrounds optimized by choice of the $d_0$ requirement in the anti-isolated control region. No $d_0$ requirement is used for the multijet estimate, while $|d_0| > 0.4$ is used for the subtraction from $W$-jets.