Z’ Searches with New Heavy Fermions

by

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Abstract

A number of new physics models suggest that a heavy $Z'$ or $W'$ particle may decay through heavy fermions. In some such models, decays with intermediate new particles may have a higher branching ratio than decays to standard model particles. These new models are not currently excluded by experimental searches, resulting in a gap in the coverage of new physics models with heavy bosons.

A search for $Z' \rightarrow t\bar{t}'$, restricted to decays with a single highly energetic lepton, is outlined. Data from proton-proton collisions at the CMS detector, with a center of mass energy of 13 TeV, and corresponding to an integrated luminosity of 2.6 fb$^{-1}$ are analyzed. A new background estimate relying on recent developments in jet substructure is detailed and expected limits are presented.

Primary Reader: Petar Maksimovic

Secondary Reader: Morris Swartz
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Chapter 1

Introduction

Figure 1.1: Photograph of a cloud chamber from 1933: the vertical line is the path of an positron curving in a magnetic field.

The first hints that there were particles smaller than the atom came in 1869 when Johann Wilhelm Hittorf discovered Cathode Rays \[^{2}\]. It would take a further 42 years before these were indubitably identified as electrons (and photographed, see Figure \[^{1.1}\]). This was the world’s first subatomic particle. The proton came soon after (1917) and the neutron a little later (1935).
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However, as quantum mechanics developed, a number of new particles came onto the scene. Some were “needed” for models to make sense and others appeared uninvited. Before long, there were hundreds of subatomic particles and an entire branch of physics dedicated to their study. The Particle Data Group now publishes a textbook sized reference listing the masses, lifetimes, charges, spins, strangenesses, isospins, charms, and couplings of the $\psi$, $\Delta^-$, $\pi^+$, $\mu$, $\Omega_{c \bar{c}}^{++}$ and hundreds of other particles. Fortunately, all of these fit within a mathematical framework called The Standard Model.

1.1 The Standard Model

The Standard Model is sometimes called a “Theory of Almost Everything”. It describes the hundreds of particles discovered and explains everything about them and how they interact with a single formula (shown in Figure 1.2). Amazingly, this formula can be boiled down to a simple list of particles and mediating forces usually represented by the diagram in Figure 1.3.

---

1 the pion for example
2 such as the muon, whose discovery in 1937 prompted the famous quip “who ordered that?”
3 This is extremely inaccurate...
Figure 1.2: The Lagrangian of the Standard Model.
CHAPTER 1. INTRODUCTION

Figure 1.3: The Standard Model. Image taken from CERN \[1\].
1.1.1 The Leptons

The electron retains its status as a truly fundamental particle. It is joined by two heavy versions of itself: the muon ($\mu$) and the tau ($\tau$), roughly 200 and 4,000 times as massive as the electron. Each is negatively charged.$^4$

These particles are each paired with a neutrino of a given flavor, for example, the electron neutrino is partnered with the electron; they are denoted $\nu_e$, $\nu_\mu$ and $\nu_\tau$. The neutrinos are chargeless and massless.$^5$

Each of these particles has an anti-particle, with opposite charge (denoted by a bar, or by specifying the charge: $\overline{e}$, $\overline{\mu}$, $\overline{\tau}$ or $e^+$, $\mu^+$, $\tau^+$). Neutrinos, while they are chargeless, also have antiparticles: the anti-neutrinos ($\overline{\nu}_e$, $\overline{\nu}_\mu$ and $\overline{\nu}_\tau$).

There is another property we must mention: the spin. Spin is the intrinsic angular momentum of the particle. The electron is a point particle, and there is therefore nothing actually revolving. Just as in the macro-world, there are two directions something can spin around an axis, which we denote as positive or negative spins. The spin is a vector quantity. The leptons all have spin $\frac{1}{2}$ (or $-\frac{1}{2}$), which means they are fermions.

The spin of a particle allows us to define one more property: the helicity (also called handedness). The helicity is defined as the sign of the projection of the particle’s spin vector onto its momentum vector. We usually refer to negative helicity as left-

---

$^4$We say an electron has charge -1: which corresponds to $-1.602 \times 10^{-19}$ Coulombs

$^5$This is not true: While the Standard Model neutrino has no mass, various experiments have shown that this is not the case. An explanation for neutrino mass must lie outside of the Standard Model.
handedness and positive helicity as right-handedness. Handedness might seem like a trivial quantity but it plays an important part in the actual calculations that are part of the Standard Model: left and right handed particles can behave differently. Indeed, while the massive leptons can be either left or right handed, it appears that all neutrinos are left-handed, and all anti-neutrinos are right handed. There is currently no explanation for this strange fact.

1.1.2 The Hadrons

The Standard Model constructs the myriad particles found in the last century (excluding of course the leptons) out of just six particles, called the quarks. Like the leptons they exist in three separate groups (called “generations”). They are: the up ($u$) and down ($d$) quarks, the strange ($s$) and charm ($c$) quarks, and the bottom ($b$) and top ($t$) quarks.

The $u$, $c$ and $t$ quarks have charge $+\frac{2}{3}$ and the $d$, $s$ and $b$ quarks have charge $-\frac{1}{3}$. Each has its own mass, and like the leptons they have antiparticles ($\bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}$ and $\bar{t}$), and spin. Like the leptons they have spin $\frac{1}{2}$ (or $-\frac{1}{2}$) and are therefore also fermions.

Unlike the leptons however, the quarks are colored\textsuperscript{6}. While there are two “kinds” of electric charge: positive and negative, color is a bit more complicated: quarks can be red, green or blue. Anti-quarks meanwhile can be anti-red, anti-green or anti-blue.

The electric charge can be detected directly, color cannot. Because of the par-

\textsuperscript{6}this is just a different kind of charge, it has nothing to do with the colors we experience visually
ticularities of the force governing colored particles, the quarks always come bound
together in color neutral combinations, either by combining all three colors (which
count as neutral) or by combining a color and its anticolor. For example, the proton
is the combination of two $d$ and one $u$ quarks. Each of these caries one of the distinct
colors and the combination is neutral. The pion ($\pi^{\mp}$) is a combination of a $u$ and a
$\bar{d}$ where the up quark would carry some color and the (anti-)down would carry that
same anti-color. All the particles discovered in the 1900s were just combinations of
the six quarks. The fractional charges of the quarks can never be directly detected
as there are no colour neutral combinations which do not result in unit charge.

1.1.3 The Forces

Without some forces to hold all these pieces together, the universe would be a
soup of quarks and leptons. In the Standard Model, forces are not “Actions at a
Distance”, but rather, the exchange of force mediating particles.

Consider the most basic of particle interactions: two electrons are shot towards
each other. Since they are both negatively charged, they repel each other. If we con-
sider that the system starts in some state $i$ and ends in some state $f$, the probability
of the transition $i \rightarrow j$ happening is related to the infinite sum:

$$S_{fi} = \sum_{n=0}^{\infty} S^n$$

(1.1)
CHAPTER 1. INTRODUCTION

The sum is over orders of perturbation\footnote{Quantum Mechanics uses perturbation theory to move from a simple approximate solution to a more precise one.}, where the first order $n = 1$ state is the case where the electrons do not interact at all. The next (and first interesting) term of $S$ is:

$$S^{(2)} = \pm |^{(n)}\bar{\psi}(x)ie\gamma^\mu \psi(x)\bar{\psi}(x')ie\gamma^\nu \psi(x') \int \frac{d^4k}{(2\pi)^4} \frac{-g_{\mu\nu}}{k^2 - i0} e^{-ik(x-x')} \quad (1.2)$$

where the integral is over all the possible momenta of the incoming and outgoing electrons. This is just the first non-trivial term of the sum. Fortunately it is the dominant term. Unfortunately, a clear description of the process is hidden by the opaqueness of the mathematics. Enter the Feynman diagram. Each term in the expression for $S^{(2)}$ can be encoded in as a pictoral element of a Feynman Diagram (as shown in Figure 1.4). With the Feynman Diagram, we can explicitly refer to physical processes with an (exact) visual description. There is no loss of generality or rigor!
CHAPTER 1. INTRODUCTION

Returning to the specifics of our example; two electrons interacting: the entire (first order) interaction is encoded in the Feynman Diagram in Figure 1.5. The effect of the electromagnetic force is just the exchange of a photon. The Standard Model however doesn’t just describe how particles interact. Indeed, the interaction we’ve just described could be described without any particle physics or even quantum mechanics. What the Standard Model allows us to do that previous formulations did not was account for the fact that particles can be created or destroyed. Consider for example the diagram in Figure 1.6. Here, an electron ($e^-$) and an anti-electron ($e^+$) are shot at each other. They annihilate, which is to say: they become (or merge into) a photon. Some time later, the photon decays into a new set of positrons and

\footnote{This model is of course, only valid on the very small scales (both in time and space) of particle physics. If we were to really shoot two electrons together in a laboratory, they would exchange a great many photons, not just one.}
Figure 1.6: A Feynman Diagram depicting the annihilation of a positron and an electron.

electrons. During this interaction charge was conserved, since the photon is chargeless and the electron/positron pair combined has $1 + (-1) = 0$ charge.

These two processes are essentially equivalent. They are just different arrangements of the same vertex. A vertex is a point interaction between particles. In the case of electron-positron annihilation or electron-electron repulsion, the vertex is the same, and is shown in Figure 1.7. With just this vertex, we can construct a huge num-

Figure 1.7: Simple electromagnetic vertex describing the interaction of two electrons and a photon.
CHAPTER 1. INTRODUCTION

A number of possible electromagnetic interactions. In the diagrams, electrons and positrons are the same: a positron moving backward in time (in the negative time direction on the axis, so to the left in our diagrams) is the same as an electron moving forward in time. In the case of the photon, similar vertexes exist for any charged particle and its (opposite sign) anti-particle. For example, muons can be produced via the process $e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-$, whose Feynman diagram is shown in Figure 1.8. Now that we are armed with the Feynman Diagram, each force can be thought of as some mediator particles with some rules governing which vertexes may be constructed. We will allow the Feynman Diagrams to obfuscate the computations, and focus on a qualitative description of these processes.

1.1.4 The Electromagnetic Force:

The field theory description of the Electromagnetic Force is called quantum electrodynamics, often abbreviated as QED. It describes how charges interact. QED with its carrier particle, the photon ($\gamma$), is the simplest of the fundamental forces described by the Standard Model. In fact, we’ve already described it fully, as the only vertex

![Figure 1.8: Annihilation of an electron and a positron to create a muon and anti-muon. Backwards going arrows are often used in lieu of charges to denote anti-particles.](image-url)
CHAPTER 1. INTRODUCTION

included is that in Figure 1.7. The photon is massless, and moves at the speed of light.

QED has been rigorously tested by a variety of experiments, with very little deviation from the behavior expected from the Standard Model.

1.1.5 The Strong Force:

Quantum Chromodynamics (abbreviated to QCD) is the field theory of colored interactions. The force carrier is the gluon (g). The photon is chargeless, so it cannot couple to itself. The gluon however carries color; which means that there is more than one vertex in QCD. These vertexes are shown in Figure 1.9.

Each quark carries one color (and each anti-quark carries one anti-color). Color is conserved, so for the diagrams in Figure 1.9 to work, the gluons must carry both a color and an anti-color. There is no r\(r\) (red + anti-red) gluon. Instead, we must delve a little bit into the behavior of the strong force.

While the protons and the neutrons (called nucleons) are confined to nuclei by the strong force, they are not colored the way the quarks are. This might seem like a contradiction, but it is not: the gluon is not the carrier particle which binds the nucleons together. Instead, the nucleons exchange mesons (two-quark bound states) in the same way that two electrons might exchange photons. This is sometimes called

\[9\]very little deviation here means truly miniscule deviations: differences on the order of \(10^{-11}\) of the predicted values, and well within the expected uncertainties of such measurements.
CHAPTER 1. INTRODUCTION

Figure 1.9: Three vertexes arising from QCD interactions. The curly line represents gluons. Note that gluons, which are colored, may interact with themselves.

the residual strong force, it’s an emergent property of complex systems of colored particles. While the gluon is massless (and therefore, like the photon, not limited in range) the mesons are not, limiting the range over which this interaction can take place, and explaining why the strong force can’t be felt the same way as the electric force.

The leptons are truly “colorless”, but while the protons and the neutrons behave similarly, they are a color singlet. The color singlet is the superposition\textsuperscript{10} of the

\textsuperscript{10}In quantum mechanics, the results of measurements can be a superposition of states: for example, the color state \((r\bar{b} + b\bar{r})/\sqrt{2}\) corresponds to a gluon which is equally likely to be in the state red +
quantum states:

$$r\tau + b\bar{b} + g\bar{g}$$

Singlets may interact with each other (this is what’s happening when a pion travels between two nucleons). Since singlets may interact with each other, and there is no mass to limit the range of the gluon, we can be sure (empirically) that no gluons carry the singlet color state.

Gluons can take any of the remaining color combinations. Instead of writing them all down, we represent them with a linearly independent set from which all of them can be constructed:

$$
\begin{align*}
\frac{r\bar{b} + b\tau}{\sqrt{2}} & & \frac{r\bar{g} + g\tau}{\sqrt{2}} & & \frac{b\bar{g} + g\bar{b}}{\sqrt{2}} & & \frac{r\tau - b\bar{b}}{\sqrt{2}} \\
-\frac{i(r\bar{b} - b\tau)}{\sqrt{2}} & & -\frac{i(r\bar{g} - g\tau)}{\sqrt{2}} & & -\frac{i(b\bar{g} - g\bar{b})}{\sqrt{2}} & & \frac{r\tau + b\bar{b} - 2g\bar{g}}{\sqrt{6}}
\end{align*}
$$

These are the color octet. It is not the only such set possible, but there are no combinations which are less complex. The octet must be constructed in such a way that it is impossible to get the singlet state.

What does happen if we try to forcibly separate a singlet state? For example, let’s say that we smash an electron into a proton with sufficient force to temporarily overcome the strong force and one of its quarks is ejected?

The shards of the proton coming out of this collision all carry color, and are therefore able to interact with each other. If they only felt electric charges, they anti-blue or blue + anti-red. The square root of two is a normalizing term to make the quantum mechanical calculations return probabilities less than one.
would simply exchange photons. Not so with the strong force: as the quarks drift away form each other, the carrier gluons, which can interact with each other) form a web between the them. We call this object a color tube. The tube containing a jumble of self-interacting gluons. These tubes exert approximately constant force when stretched, increasing the energy in the tube until\textsuperscript{11} it becomes more energetically favorable to create a new pair of quarks out of the vacuum (through the top left vertex shown in Figure 1.9).

The result is that the quark that was drifting away, abhorrently not contained in a singlet state, suddenly finds itself paired with a new quark. If there isn’t too much energy, these now stay bound and have become a meson. If the quark is still too energetic to be contained, then the process will repeat itself, chipping away at the energy of the original quark until every colored particle is collected in a singlet state. This property is called containment, and the process by which new quarks are produced to enforce it is called hadronization.

Hadronization plays a very important part in the experiment this Thesis will describe. It’s relationship with particle detection is described in detail in Chapter 3.

1.1.6 The Weak Force:

In this very distant past, the Weak force and the Electromagnetic force were one. They were called the Electroweak Interaction, and there were four carrier particles,\textsuperscript{11} at distances of about $10^{-15}$, incidentally the roughly the radius of an atomic nucleus.
CHAPTER 1. INTRODUCTION

\( W_1, W_2, W_3 \) and \( B \). All four of these were massless, and had unit spins (as such, they were \textit{bosons}). While temperatures were high enough, these bosons were able to ignore the effects of the Higgs field, which we discuss in the next section.

As the universe cools down, the four bosons begin to interact with this field. The fermions now no longer interact directly with the \( W_1, W_2, W_3 \) and \( B \), but rather, with superpositions of them. Where previously there were a \( B \) and a \( W_3 \) Boson, we now have, \( \gamma \) and \( Z \). This superposition is simple to write:

\[
\begin{pmatrix}
\gamma \\
Z
\end{pmatrix}
= 
\begin{pmatrix}
cos \theta_W & \sin \theta_W \\
-\sin \theta_W & \cos \theta_W
\end{pmatrix}
\begin{pmatrix}
B \\
W_3
\end{pmatrix}
\tag{1.4}
\]

Where \( \theta_W \) called the Mixing Angle or Weinberg Angle, is a parameter of the Standard Model. The photons of the Electromagnetic force are just a particular combination of the \( B \) and \( W_3 \). The \( Z \) Boson is one of the carrier particles of the Weak Force. Similarly, the \( W_1 \) and \( W_2 \) bosons combine via the superposition

\[
W^\pm = \frac{(W_1 \mp iW_2)}{\sqrt{2}}
\tag{1.5}
\]

to form two new Bosons, the \( W^+ \) and \( W^- \).

We’ve already talked about the behavior of the photon, so we just need to detail the vertexes involving the \( W \) and \( Z \) bosons for a full description of the Weak Force. These vertexes are shown in Figure 1.10. The \( Z \) Boson is not massless, it has mass...
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Figure 1.10: Vertexes arising from weak interactions. The wavy lines represent the Bosons. The straight lines represent any particle where the appropriate quantities are conserved (details in the text).

91.2 GeV/c\(^2\) Z bosons couples particles to their anti-particles. For example, the process \(Z \to e^-e^+\) is allowed but the process \(Z \to \mu^+\mu^-\) is not. Similarly, \(Z \to b\bar{b}\) is allowed but \(Z \to b\bar{u}\) is not. In this regard, it behaves like a heavy version of the photon, except that it can couple to neutral particles (for example, \(Z \to \nu_e\bar{\nu}_e\)).

The W boson (with a mass of 80.4 GeV/c\(^2\)) also couples pairs of fermions, except that it links the flavors within a generation. For example, a W boson might decay to two quarks (\(W \to u\bar{d}\)) or to a lepton and its neutrino (\(W \to \mu\nu_\mu\)). It is charged, so the process \(\gamma \to W^+W^-\) is allowed. The decay \(Z \to W^+W^-\) is also allowed.

The W boson is a fascinating object to study. As we’ve already mentioned in passing: The weak interaction only acts on left-handed particles and right-handed anti-particles.\(^{13}\)

\(^{12}\)The unit GeV/c\(^2\) is a unit of mass. One eV/c\(^2\) is equal to \(1.78 \times 10^{-36}\) kg. An electron has mass \(\sim 0.5\) MeV/c\(^2\) and a proton \(\sim 1\) GeV/c\(^2\).

\(^{13}\)This causes considerable complications because neutrinos have mass. It is therefore possible to define a reference frame in which the neutrino is moving backwards with relation to the W it decayed.
The decay $\gamma \rightarrow \mu^+ e^-$ is a perfectly plausible decay, seeing as charge is conserved. However, it never occurs. Similarly, the Z boson might be allowed to decay to different generation quarks (this wouldn’t violate charge or color), but it simply does not happen. These decays are called flavor changing neutral currents. Flavor changing charged currents on the other hand, do exist. Specifically, Ws can decay to quark pairs outside of their generation. For example, we might see $W \rightarrow s\bar{u}$. The probability of a W decaying to different generations is encoded in the CKM Matrix, an empirically measured set of values. Here is that matrix:

$$
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} =
\begin{pmatrix}
0.974 & 0.225 & 0.004 \\
0.225 & 0.973 & 0.041 \\
0.009 & 0.040 & 0.999
\end{pmatrix}
$$

where $|V_{ij}|^2$ is the probability that a quark $i$ decays to a quark $j$ through the emission of a W.

It is then because of the W and the W only that our world seems to be composed of only up and down quarks and electrons. All other particles will eventually decay (through a W) to something lighter. The other leptons (the muons and the taus) will eventually decay by emitting a neutrino and a W, with the W decaying to an electron and a neutrino. All the various particles discovered in the last century eventually decayed to protons and neutrons because the higher order quarks embedded in them from, thus flipping its helicity...
CHAPTER 1. INTRODUCTION

decayed (again, through a W) back to the first generation.

1.1.7 Mass and the Higgs Boson

The Higgs Boson is the most recent addition to the Standard Model to be discovered. It is responsible for giving the other particles their mass\textsuperscript{14} As we already mentioned, this does not happen at very high energies. To understand this, we should consider the Higgs Potential. For the purpose of illustration we can simplify it to the form $\sim (\phi^2 - \eta^2)^2$, where $\phi$ is the Higgs Field, which we plot in Figure 1.1\textsuperscript{15}. The potential in question is symmetric (about the y-axis, which in the case of the actual Higgs potential would have units of energy). In the high-temperature early universe, the energies of particles was such that the ”bump” at the bottom of the potential played no part. As the universe cools, however, things must settle into either of the two valleys. It’s not the case that the equations of of the Standard Model aren’t symmetric, it’s that practically, at the energies in question, they cause behavior which is not. This is called spontaneous symmetry breaking.

This asymmetry causes the Higgs field in the low temperature universe to take on a vacuum expectation value (roughly speaking: its average value in empty space) which is non-zero (it’s 246 GeV). We usually abbreviate this as just the VEV. The VEV couples to the electroweak interactions, creating the photon and the weak force

\textsuperscript{14} except the neutrinos, which by now you must have noticed, are devious...

\textsuperscript{15} This shape is sometimes called the “mexican hat” or “champagne bottle” potential, depending on the level of cultural sensitivity required.
CHAPTER 1. INTRODUCTION

Figure 1.11: Sketch of the Higgs Potential. Notice that while the over-all shape is symmetric about the y-axis, the function is not symmetric about the minima.

bosons as we experience them.

Through a similar but not identical process, this spontaneously broken Higgs field also couples to the weak bosons, quarks, electron, muon and tau, giving them mass where without it they were massless. The neutrinos do not couple, and are therefore massless in the standard model.

So far we’ve been talking about the Higgs field, but as you may have heard, there is also a Higgs Boson. This particle is just an excitation of the Higgs Field the way we think of a photon as being an excitation of the electromagnetic field. It was discovered in 2012 at the Large Hadron Collider after a 40 year long search. This
CHAPTER 1. INTRODUCTION

Higgs has no charge, has no spin, and has a mass of 126 GeV. It couples to anything with mass, which means it couples to itself. The Higgs Vertex is the very last piece of the Standard Model, and is shown in Figure 1.12.

![Figure 1.12: The Higgs Vertex. The dashed line is the Higgs Boson and the straight lines represent any massive particle (including the Higgs).](image)

1.2 Rounding Up the Standard Model Particles

So to recap, there are, once we count all the colors and anti-particles, 61 particles in the standard model. We know they interact, and we can pictorially express a number of complex interactions using the Feynman diagram. For example, consider the diagram in Figure 1.13. This is an important physics process\[16\] found in high energy colliders, and we’ll discuss it in much more detail later on. For now, it serves as a useful example of the kind of processes we can construct with our Feynman\[16\] incidentally, the primary background of this Thesis’ analysis
Figure 1.13: Collider Example: two quarks collide and form a gluon, which decays to two top quarks.

diagrams: two protons collide and quarks inside of them annihilate into a gluon. That gluon propagates some distance before it decays back to quarks, this time to a pair of top quarks. Each of these decays through Weak interactions to a b and a W (this is almost always the case, see Equation 1.6). One W decays to a lepton and a neutrino, and the other to a pair of quarks. This diagram then contains five distinct vertexes.

Indeed, we can make these diagrams as complicated as we want. Some of them become quite silly. See Figure 1.14 for some more entertaining examples.

We’ve given a mostly qualitative description of the model, without differentiating between facts gleaned from experiments and facts that come from calculations within the model itself. Fortunately, the Standard Model is extremely self-consistent and despite there being 61 particles, 4 forces and 1 Higgs field, there are only 19 “free

\[17\text{ See Chapter 3 for a more formal description of what’s happening there} \]
parameters” which have to be determined experimentally. Most of them are masses.

The Higgs Boson is the reason that the particles have mass, but it doesn’t specify what those masses should be. What was the question “why does a particle have this mass” now becomes “why is this particle’s coupling to the Higgs what it is”.

The CKM Matrix’s nine entries can be interrelated with just four parameters. The remaining parameters have to do with the Higgs field or the couplings of the forces.
1.2.1 The top quark

No discussion of the standard model is complete unless it mentions how strange the top quark is\(^\text{18}\). The top quark’s mass is 174 GeV/c\(^2\). The next heaviest quark barely makes it to the 5 GeV/c\(^2\) mark, with all other fermions being lighter than it.

This might just be a curiosity, as there is nothing inherently “wrong” with a very heavy top, but it does lead to some strange behavior. The top quark is the only quark that can exist outside of a color singlet. This is because the color tubes we mentioned before never form: due to its very large mass, the top decays immediately (in \(5 \times 10^{-25}\) seconds) through the Weak force to a bottom quark (or very rarely, a c or a d) and a W Boson.

This does not mean that the top quark can only interact weakly, just that it decays that way. The top quark plays an important role in Higgs production (since the Higgs couples so strongly to it), as shown in Figure 1.15. As we will see, the top quark is a frequent player in searches for new physics as new theories often couple preferentially to massive objects.

1.3 A Few Open Questions

For a supposed Theory of Everything, the Standard Model could use some improvement. It only covers a slim 4.6% of the content of the known universe. Dark

\(^{18}\text{even though it has strangeness 0.}\)
CHAPTER 1. INTRODUCTION

Matter, something completely outside the Standard Model, accounts for a further 24%, with the rest being mysterious Dark Energy. Both these Dark Entities loom as considerable proof that while the Standard Model does a good job of describing that little 4.6% we call Baryonic Matter, it is far from a complete description of the world.

Actually, the Standard Model isn’t even a complete description of Baryonic Matter. The obvious problem being of course, that it fails to explain, or in any way even include, the most obvious of forces: Gravity. Gravity is not included in the Standard Model. It’s easy to just say that gravity just doesn’t matter at the very small distances the Standard Model applies to, but the addition of some massless force-carrying Graviton would certainly be welcome.

Of course, there’s also these pesky neutrinos and their unwarranted masses to directly (experimentally) challenge our model. These are not the only hints that we’re missing something. One obvious observation is that while the Standard Model treats positrons and electrons (and quarks and anti-quarks) symmetrically, the universe’s Baryonic Matter is overwhelmingly composed of electrons and quarks. What
happened to all the anti-particles?

And what are these insanely energetic cosmic rays we detect from time to time? The Standard Model puts limits on the energy a cosmic ray can attain before it is slowed down by interactions in space... and yet, we have detected particles some orders of magnitude above that limits.

One of the great strengths of the Standard Model is that it is incredibly self-consistent. Indeed, it has been tested and re-tested, with no obvious internal flaw. Now however, as we start to seek the answer to new questions, this strength becomes a flaw as there is no way to modify the model without un-hinging some other internal aspect. To answer the questions of modern physics then, we must venture into new territory Beyond The Standard Model!
Chapter 2

Beyond The Standard Model

There are a large number of possible “new physics” models which add particles to the standard model\footnote{Or maybe it’s better to say, which propose that there are particles outside of the standard model}. Unfortunately for theorists however, the standard model (and all the data we have collected in the last century) already imposes some constraints on most simple theories.

2.1 Can there be a fourth generation of fermions?

The vast majority of the matter we observe in the universe is composed of 1st generation matter. The second generation came as a complete surprise. Even with this precedent set, the third generation was also a surprise. Why then do we believe
CHAPTER 2. BEYOND THE STANDARD MODEL

that we should stop there? After all, the $\tau$ is an order of magnitude heavier than the $\mu$, shouldn’t we look for some new lepton with mass an order of magnitude above the $\tau$?

Now that we do have a working Standard Model, it turns out that it explains things very well: even things that might seem to have absolutely nothing to do with particle physics. For example, we have made very accurate measurements of the Cosmic Microwave Background (usually abbreviated “CMB”, see Figure 2.1) and these measurements are sensitive to the number of neutrinos. That limit is “3 or 4”: if there were five generations of leptons, we would be surprised by the CMB we see. This is a roundabout limit to obtain, but it is illustrative of how tightly

![Figure 2.1: The Cosmic Microwave Background: This is an image of the sky in the microwave wavelength, revealing a snapshot of the universe almost 14 Billion years ago when the average matter in the universe was no longer energetic enough to absorb that wavelength.](image)

constrained our model is: Precision measurements at particle colliders impose very tight bounds on the number of generations. If the new leptons come with Standard Model like neutrinos (a fourth generation neutrino), the $Z$-boson would have no reason
not to decay to these. Measurements of Z-boson decays reject this hypothesis with 99.99999% certainty.

The quarks are similarly limited in their number by precision measurements. Some of these come from detailed study of the values of the CKM matrix, others from more recent measurement of the newly discovered Higgs Boson. The measurements stemming from measuring the properties of the Higgs Boson limit the mass of a fourth generation of quarks to under 300 GeV/c²: a bound already covered by experimental searches.

But, as previously noted, it’s clear that there is something beyond the Standard Model... how can we put new particles on the table if the Standard Model is so restricting?

2.2 New Forces and their Mediators

An electron and a positron casually colliding at low energy will not produce a Z boson because energy must be conserved and the Z-boson is quite massive (90 GeV/c² to the electron’s 0.0005). Similarly, some new particle, let’s call it Z' for now, with some enormous mass might very well exist, but without natural processes to produce it, we would never notice its presence.

Unlike new fermions which must be inserted carefully into the Standard Model, new forces and their carriers are easier to introduce. Furthermore, the existence of
some new heavy bosons is predicted or at least motivated by a number of theories:

### 2.2.1 The Kaluza-Klein Theory

The Kaluza-Klein Theory [4, 5] is an excellent example of a new physics model which naturally introduces new particles. The theory is quite old, with Kaluza’s paper being published in 1921, and in fact, was not initially developed to solve any problems in particle physics [2]. The theory is simple: what if our four-dimensional world (newly described by Einstein’s General Relativity) is embedded in a fifth dimension?

As quantum mechanics and quantum field theory were developed, and to make such a fifth dimension fit with measurements of relativity in the canonical four dimension, Klein and others re-worked the model into a true field theory which only worked if the fifth dimension was **compact**. A compact dimension, unlike the $xyz$-axes we are used to, is not infinite, and in particular is periodic [3].

KK-theory may not seem to have anything to do with particle physics, but the periodicity of this new dimension means that it would behave like the orbitals of an atom: SM particles with the right energies could enter an excited state (in the fifth dimension) while those without the right energy would behave as if there were only four dimensions [4]. If the first allowed excitation is at a high energy, then we may

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2. The proton had just been discovered.

3. In a periodic dimension, if you too far in one direction and you’ll find yourself back where you started. Imagine an ant living on a cylinder of infinite length: it may travel arbitrarily far along the cylinder, but if it travels along the curve it will eventually come back to where is started.

4. Think of it this way: for wave to exist on a circle, it must have the same value at 0 as it does at $2\pi$. This limits the allowed waves to those with frequencies that allow an integer number of
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not have produced them in experiments. In our four-dimensional laboratory, such an excited particle would look like a much more massive version of the SM particle.

There are quite a few versions of the KK-theory, but many of them predict that the excited state of the gluon would have the largest coupling to the SM. This state, which we’ll call $G^*$ would behave like a very heavy gluon. Like any gluon, this $G^*$ could decay to quarks, in particular to $t\bar{t}$-pairs.

2.2.2 The Hierarchy Problem

Another common generator for new particles is a new symmetry which attempts to resolve the Hierarchy problem. To understand the Hierarchy problem, consider the diagram in Figure 2.2. This is the most basic Feynman Diagram with a Higgs as the

![Figure 2.2: A very basic higgs diagram. Two particles, 1 and 2 interact, producing a higgs which decays to two new particles, 3 and 4.](image)

wavelengths to fit on the circle.

$^5$of course, there is a $G^{**}$ and a $G^{***}$ etc in the theory which correspond to the next allowed KK excitation.

$^6$It turns out that this decay is strongly favored.
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internal leg. It is called a tree level diagram. Let’s say that we wanted to measure the mass of the Higgs and that we designed an experiment with the goal of producing this diagram. We know with certainty what particles 1 and 2 are, and we can measure particles 3 and 4 exactly. The internal higgs leg however we cannot directly measure, all our information about it comes from the behaviors of particles 1, 2, 3 and 4.

Now consider the diagrams in Figure 2.3. These diagrams have loops, and are perfectly valid processes. There is furthermore no way of knowing if we measure particles 1, 2, 3 and 4 which of the three diagrams actually represents what happened. And as long as we obey the Feynman rules, we can add any number of diagrams to the list.

From a mathematical perspective, the equations governing the standard model
have some mass term, $m_H^{\text{bare}}$: the \textit{bare mass} of the higgs, which governs how a single higgs propagates. This term is the only one that appears in the tree level diagram. However if we happened to measure a process with a loop, then the mass would be different. The loop represents a \textit{quantum correction} to the higgs mass. As such, experimentally we can only ever measure:

$$m_H = m_H^{\text{bare}} \times \left( 1 + \sum_{\text{all loops}} \text{corrective terms} \right). \quad (2.1)$$

Herein lies the Hierarchy Problem. Because the higgs is a scalar (spin 0)\textsuperscript{7}, these corrective terms add up very quickly to very large values, so that it would seem that the dominant term in the measured higgs mass is from quantum corrections.

This \textit{fine tuning} is considered by many to be unsatisfactory, especially when there are many extensions of the standard model which force the corrective terms down to more manageable levels. One of the leading theories (or rather, class of theories) is called \textit{Supersymmetry}. In a supersymmetric model, particles don’t just have antiparticles, they have superpartners\textsuperscript{8} which would cancel terms in the higgs mass corrections. This might seem like an arbitrary fix, but it turns out that these supersymmetric particles also provide useful candidates for dark matter.

\textsuperscript{7}Having no spin dooms the higgs to have no polarizations. Other particles’ infinite sum of diagrams contain different terms for each possible polarization, which (at least partially) cancel each other out, so that the bare mass is the dominant term.

\textsuperscript{8}I’m not making these words up
the SM which stops these corrections from taking over. Conveniently, we do know
of another field: gravity... but it is much too weak to play a part. The Hierarchy
Problem is sometimes stated in terms of force couplings: i.e. why is the Weak force
so much stronger than gravity. What if, instead of gravity, there is some other
field. Depending on how we construct this field and what symmetries we demand
be imposed by it we can recover the cancellations we need to keep the higgs mass
corrections from dominating.

One such model, the Little Higgs model [{7,9}], introduces a number of new fields
with behavior similar to the Weak force. Like the Weak force, this new field would
have one or more force carrying bosons, in particular, some heavy version of the $Z$
boson, which we might call $Z'$. $Z'$s would be quite massive\(^9\) and therefore, unlike the
regular $Z$ boson, would be allowed to decay to $t\bar{t}$ pairs, giving us a way of detecting
them.

\section{2.3 The $Z' \rightarrow t\bar{t}$ Channel}

For convenience, let’s refer to both the excited gluons ($G^*$) of a KK theory and
the new $Z$-like bosons of a little higgs theory with the same symbol: $Z'$ where really
we just mean “something which behaves like a heavy version of the $Z$”\(^{10}\). There are a
lot of other theories, which include combinations of new symmetries, new fields, and

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\(^9\)a weaker force has a heavier force carrier
\(^{10}\)and \textit{really}, we just mean “something which decays to two tops”
new dimensions which can produce a $Z'$, but as experimentalists, we don’t attempt to distinguish between them. Instead, we simply search for some arbitrary $Z'$ by trying to detect one of its more interesting signatures: the process $Z' \rightarrow t\bar{t}$.

A $Z'$ could decay to a number of final states (the particles we attempt to detect directly), but the $t\bar{t}$ final state is especially interesting. Every version of a $Z'$ theory comes with some parameters: the mass of the $Z'$ and it’s couplings. The couplings are the vertices, one for every possible $Z'$ decay (so for example, $Z' \rightarrow t\bar{t}$, $Z' \rightarrow \nu_\mu\bar{\nu}_\mu$, etc). The mass is usually a free parameter, but the coupling constants are not, they depend on how the new particle interacts with the standard model. In many models, the couplings are stronger to heavy particles, and since the top quark is (by far) the heaviest thing around, we focus on this decay\textsuperscript{11} Searches for this decay have been performed since the top itself was discovered. So far no $Z'$ has been found (in any channel, not just ours). Since there are so many possible $Z'$ models, we cannot simply state that we have excluded the $Z'$, or even that we’ve excluded it up to a certain mass. There may be a $Z'$ with mass not far from the regular $Z$ but with couplings so weak that we’ll never produce it\textsuperscript{12}. Instead we must set limits on the cross-section of a $Z'$ at a particular mass. The cross-section has units of area and represents the “size” of a possible signal at a given mass. The latest limits on a $Z'$ are shown in Figure\textsuperscript{2.4} \cite{10}. Currently, most common $Z'$ models are excluded for masses below 2.5 TeV.

\textsuperscript{11}there are of course many other experiments which search for $Z'$ through other final states.
\textsuperscript{12}fortunately there is no theoretical motivation for such a scenario
Figure 2.4: Current limits from the CMS collaboration on $Z' \rightarrow t\bar{t}$. The horizontal axis shows the mass of a theoretical $Z'$. The vertical axis has units of cross-section. The dashed red line represents the cross-section of a particular (generic) new physics model. The solid black line represents (with 95% confidence) the largest signal that we would be unable to detect. When the black line is lower than the red line, the $Z'$ would be too large to remain hidden, and the analysis would have seen it.

2.3.0.1 cross-sections

We usually measure the size of a coupling with a cross-section (usually represented by the greek letter $\sigma$)? Recall the example we gave for the higgs mass measurement: in it, particles 1 and 2 are accelerated towards each other and we measure the outcome, particles 3 and 4. The cross-section tells us the probability of a particular outcome
happening once we’ve fired off 1 and 2. The outcome is not restricted to just two new particles, and complicated decay chains might be measured. The cross-section is conditional on the initial conditions of the experiment (what were particles 1 and 2? what energy did they carry? did they have some specific polarization?).

The unit we use is the \textit{barn}, with $1\, \text{barn} = 100\, \text{fm}^2 = 10^{-28}\, \text{m}^2$. Like any area, cross-sections are additive, so we can add up different decays of the higgs, and get the total cross-section for higgs production. We can also specify the energies of decay products, and quote the cross-section of different energy ranges. It may seem strange that we use a unit of area to denote this, but in the early days, particle experiments were literally trying to measure the area of the nucleus and the only outcome was whether or not a collision took place. In such a simple experiment the probability of the outcome was easily converted to the apparent size of that nucleus. The convention has stuck.

With all this in mind, we can look back at Figure 2.4 and see that the $Z'$ doesn’t appear to exist at the masses and cross-sections predicted by theories.

### 2.3.1 Vector-Like Quarks

Historically, new particles don’t come one at a time, and the “simplest” models are often wrong. In fact, some of the models we’ve already considered (particularly the KK model and little Higgs model) predict quite a few new particles, amongst

\footnote{because hitting a gold nucleus is about as easy as hitting the side of a barn... this really is where the term comes from}
them, the *Vector-Like Quark* (VLQs) \[11\]. We mentioned earlier that there can be no new Standard Model like quarks, but a Vector-Like Quark isn’t Standard Model like. The six quarks we know about have couplings that depend on their handedness.

All the constraints on any new generations melt away if we remove this requirement.

Searches have been performed for such objects, in particular partners of the bottom and top quark (the $B'$ and $T'$ particles). These searches have not found anything, so if these partners exist, they are quite heavy (current limits place their masses above 500 GeV). If they did exist, at some very large mass, then the top quark would no longer be the heaviest particle around and the $Z'$ might decay preferentially to $T$ or $B$. In other words, the cross-section for $Z' \to t\bar{t}$ might be much smaller than for $Z' \to T'T'$!

No such searches have been explicitly performed, however, many of the models which posit the existence of a VLQ see them produced in pairs. Searches for pair produced VLQs should be sensitive to their existence.

There is one more option however, which nobody has explored: what if the $Z'$ is quite heavy, and the $T'$ is also quite heavy: so heavy that the difference between their masses is much less than the mass of the $T'$. In such a scenario, the $Z'$ would be unable to decay to $T'T'$, not because such a coupling isn’t present in the theory, but because there is insufficient energy in in the mass of the $Z'$. \[14\] The only remaining options for our $Z'$ is to decay to one regular quark and one VLQ. This is precisely the model

\[14\] remember, $E = mc^2$, so unless the $Z'$ is very energetic, there isn’t enough juice to create two $T'$ masses.
That model envisions a fixed VLQ mass (generically called $\chi$) and determines the decay rates of a $G^*$ to either two regular quarks ($\psi$), two VLQs, or one of each. There is a regime where the $\psi\chi$ state dominates. In this Thesis we will investigate decays of a massive $Z^0$ to a top and a top-like VLQ. This channel hasn't been covered by any experiment and covers a selection of models which may have “hidden” the $Z'$ and new physics from us.
Chapter 3

Particle Detection

While particle physics has come a long way in the last century, the basic discovery mechanism hasn’t changed: to get a new particle, smash known particles together. In the early days, this was achieved by simply waiting for cosmic rays\(^1\) to enter our detectors.

For example, a positron might be accelerate by the Sun’s tumultuous electromagnetic fields to very high energy and it might collide with an atom in our atmosphere. The positron might annihilate with one of the electrons in that atom (through the process in Figure 1.7). Even if the electron was at rest, the positron carried sufficient energy that the resulting photon could decay into something heavier than the electron: a pair of muons for example. This is exactly how muons are produced in the atmosphere, and in fact, at sea level every square meter is showered with about

\(^1\)Charged particles ejected from the sun which strike our atmosphere
CHAPTER 3. PARTICLE DETECTION

a hundred muons per second.

Other particles should be accessible this way, but as can be seen in Figure 3.1, their rates are considerably lower than the muon. We would need to wait a very long time to have enough $W$s pass through our detector to have any hope of making a reasonable measurement. The muon is relatively long-lived, while the bosons and heavier quarks would decay in flight. The muon only makes it to our detectors because it is moving near the speed of light and benefits from the effects of time dilation$^2$.

Clearly then we need to force positron and electrons to collide on our terms, preferably at very high energies.

The most basic collider is a long, straight tunnel which fires a beam of electrons at a beam of positrons. Most of the positron and electrons will pass by each other, with only a few actually interacting. Because of this, it makes more sense to build circular rings spinning the particles in opposite directions. This way a bunch$^3$ of electrons isn’t wasted if it doesn’t produce any interesting interactions with the positrons: it’ll whip around the ring for a second pass, and a third, until it’s depleted.

The Large Electron-Positron Collider at CERN was precisely such a machine, and was able to produce collisions with a center of mass energy of 206 GeV. More than enough energy to produce $Z$ and $W$ bosons (then the heaviest particles around). There are however some drawbacks to electron-positron colliders: charged particles radiate energy when they are bent by an electro-magnetic field, according to the following

\begin{itemize}
\item $^2$The faster something goes, the slower time runs for it
\item $^3$this is a technical term, as we’ll discuss later
\end{itemize}
Figure 3.1: Fluxes of common particles created in the atmosphere by cosmic rays. Note that muons are the most common charged particles produced in these interactions.
formula:

\[ P = \frac{e^4}{6\pi^2m^4c^5}E^2B^2 \]  

(3.1)

For the E (electric) and B (magnetic) fields at the LEP collider, this was equivalent to \( P \approx 0.2 \text{mW per electron} \). This may not seem like much, but even before LEP was operating at its full potential the total synchrotron radiation output measured around thirteen megawatts.\(^4\) Such losses can quickly become overwhelming, especially if we plan on detecting particles several orders of magnitude heavier than the Z boson.

Fortunately, the radiated power depends not just on the E and B fields, but on the mass of the particles being accelerated: from Equation 3.1 we can see that this dependence is \( \sim 1/m^4 \). If we accelerated protons instead of electrons, we decrease the radiated power by a factor of \( 10^{13} \).

### 3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) \(^1\) is the premier proton collider in the world. It is the largest machine ever built, and has produced more particle data than all other experiments combined.\(^5\) It is where we look for new particles.

The LHC is built in the same tunnel as the LEP, which it replaced, and turned on in 2007, initially colliding protons with a center of mass energy of 7 TeV. This energy

\(^4\)For reference, a modern locomotive produced about 6MW of power

\(^5\)To the tune of 300 gigabytes of data a second, necessitating the largest computing grid in the world to handle. During its entire lifetime, LEP produced 400 TB of data. The LHC has already produced 130 PB.
CHAPTER 3. PARTICLE DETECTION

was upgraded to 8 TeV in 2012, and it now operates with a center of mass energy of 13 TeV. A schematic of the LHC is shown in Figure 3.2. Protons are accelerated in stages, initially in a linear accelerator and then through a series of increasingly large circular synchrotrons until they can be injected into the LHC’s main rings. The two proton beams are identical other than the direction they travel in. The main rings are outfitted with 1,232 dipole magnets\(^6\) which keep the protons moving along the beam direction (and accelerate them) and 392 quadrupole magnets (which are used to focus the beam, see Figure 3.3). The enormous 7 Tesla magnetic fields necessary to handle these ultra-high-energy protons can only be achieved with superconducting magnets which must be cooled to below 2 Kelvin. The LHC requires almost 100 tonnes of superfluid liquid helium to remain operational. At its current collision energy, the protons reach a top speed of 99.99999999\% the speed of light\(^7\). The beams are not

\(^6\)A bar magnet is an example of a dipole magnet
\(^7\)Which is significantly faster than a Ferrari
Figure 3.3: Quadrupole magnetic field, with the direction of the force felt by a charged particle in the field shown in blue. Alternating the N and S faces of the magnets allows the fields to focus a particle beam in both the vertical and horizontal directions.

continuous, but rather are composed of *bunches* of protons, each bunch containing roughly 115 billion protons.

The beams are made to cross at four experiments along the ring (see Figure 3.2). The spacing between bunches leaves 25 nanoseconds between crossings, equivalent to
a collision rate of 40 MHz.

### 3.1.1 A proton-proton Collision

Collision between electrons and positrons are easy to describe because both are point particles. Protons on the other hand, are composite. We usually talk about protons (and other hadrons like the neutron) as being composed of three quarks. This however is not strictly true: when we say that the proton is made up of two up and one down quarks, we are naming the *valence* quarks of the proton. The proton is actually a complicated, ongoing interaction between those three quarks. The interaction is mediated by a web of gluons whose energy makes up the majority of the mass of the proton. And it’s not one gluon per quark pair: the gluons interact with each other, spontaneously produce pairs of quarks from every generation, which decay back to gluons. As such, when we do smash two protons together with as much energy as the LHC provides, we aren’t colliding protons, but rather, quarks or gluons (collectively called *partons*).

This can make measurements particularly difficult, as it’s almost impossible to know what actually collided. Instead, we rely on the *Parton Distribution Function* (usually abbreviated as PDF) for a statistical understanding of what to expect. While we can never know, collision per collision, what actually interacted with what, we can simulate the collisions and create good models of what we expect

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8 which makes google searches for them very difficult
CHAPTER 3. PARTICLE DETECTION

to see.

Two example PDFs at different collision energies are shown in Figure 3.4. The 10 TeV collision PDF is representative of what we might see at the LHC. The plots are read as follows: each curve represents a particle parton in a proton, and tells us the probability density\(^{10}\) of finding that parton carrying momentum fraction \(x\). The momentum fraction is the fraction of the (longitudinal) momentum of the proton carried by that parton, so at the LHC \(x = 1\) would mean that parton with energy 6.5 TeV, \(x = 0.1\) would be a parton with energy 0.65 TeV, and so forth\(^{11}\). We are usually interested in events in which a large fraction of the total available energy is involved in the collision (At least, this is where we are most likely to find new physics). Each proton is governed by the PDFs, so in a collision between two protons we combine the probabilities. For example, from the Figure we see that at a low energy collider, if most of the energy of the protons is involved, there is a much higher chance of seeing a collision between two up quarks. This makes sense, as there are two up valence quarks in a proton. If we could somehow build a neutron-neutron collider, we would expect the down quark interactions to dominate. At higher energies, notice that the PDF for the gluon moves forward in \(x\): at higher energies, we expect to see many more events with high energy that came from quark-gluon and gluon-gluon collisions.

Having correct PDFs is incredibly important for predicting the size of new physics signals at the LHC since many models have new particles which are only produced

\(^9\) currently operating at 13 TeV

\(^{10}\) a quantum mechanical quantity easily converted to a probability

\(^{11}\) the beams at the LHC have combined energy of 13 TeV, so 6.5 TeV per beam.
in specific interactions (our $Z'$ for example is not created by gluon-quark interactions). Unfortunately, the PDFs are extraordinarily difficult to compute, so partial models are combined with large number of measurements at fixed target and collider experiments to hone in on their true values. Since these are inexact, we must assign systematic uncertainties to our simulations based on the variance between sets of “plausible” PDFs. This will be discussed in more detail in Section 9.

In two protons there are all the ingredients to create any particle in the standard model, as well as enough energy to access a lot of new physics. Even if the new physics is only accessible through the collisions of two bottom quarks, we can see
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from the PDFs that we expect bottom-bottom collisions carrying as high as 1.2 TeV of energy, easily high enough to probe new physics models. Such events would be a small signal compared to other collisions, but with a good detector, we should be able to sort them out from the backgrounds.

Figure 3.5: The Compact Muon Solenoid.

3.2 The Compact Muon Solenoid

The LHC collides protons at four experiments, each one-hundred meters below ground. Our analysis is performed on data collected by the Compact Muon Solenoid
CMS [17]. Weighing in at 14,000 tons and run by a crew of almost 4,000 scientists, CMS may not seem compact, but it is the smaller (in volume) of the two main detectors on the LHC ring. A full description of its operation would easily fill an encyclopedia sized book, so we will just give a cursory overview: enough to understand how our analysis reconstructs collisions.

A slice of the detector is sketched in Figure 3.6.

3.3 Coordinates

The CMS detector is essentially a large cylinder with concentric layers of detectors. The ends of the cylinder are also covered (we call these parts of the detector the endcaps). We define directions in the detector using two angles as in a modified spherical coordinate system: $\eta$ and $\phi$, where $\phi$ is the angle which sweeps our the circular component of the cylinder (and is therefore always perpendicular to the beam). $\eta$, the pseudorapidity is defined as:

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

(3.2)

Where $\theta$ is the angle usually used alongside $\phi$ in spherical coordinates. $\eta = 0$ points straight out of the detector, while $\eta = \infty$ points directly along the beamline (see Figure 3.7). We use $\eta$ instead of $\theta$ because differences in rapidity are Lorenz Invariant.\footnote{A Lorenz Invariant quantity is independent of the reference frame it is measured in.}
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Figure 3.6: Schematic view of the CMS detector. Each portion is described in the text.
with the pseudorapidity being approximately so. This is very useful property, for while the protons in each beam have the same energy, and are therefore symmetric in the laboratory rest frame, the partons which actually collide likely do not.

When we measure a particle in the CMS detector, we report three values: its radial angle, $\phi$, pseudorapidity $\eta$ and transverse momentum $p_T$. The transverse momentum is the momentum perpendicular to the walls of the cylinder. We rarely have cause to leave these coordinates, but we could recover Cartesian coordinates through the following transformations:

$$p_X = p_T \cos \phi, \quad p_Y = p_T \sin \phi, \quad p_Z = p_T \cosh \eta$$

(3.3)

The central axis (where the protons are in flight before the collision) is referred to as the beam.
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3.3.1 The Subdetectors

3.3.1.1 The Tracker

The innermost layer of the detector is the Silicon Tracker. This sub-detector accurately measures the paths of charged particles as they zip through it. It is composed of 13 layers (14 in the endcaps). The first four layers are composed of silicon pixels, 66 million in total, each 100×150μm in area. The remaining layers are a cross-hatch of longer strips (180μm by 10 cm or 25 cm, depending on where they are). Taken all together this represents over 200 square meters of silicon sensors which enable us to measure the paths of particles by reconstructing series of “hits” in the pixels and strips. These tracks are determined with accuracies around 10μm.

Only charged particles interact with the silicon. The tracker is immersed in a magnetic field (described below) which causes charged particles to curve. This curvature allows us to measure the charge and energy of particles. Unlike the calorimeters, the Silicon Tracker doesn’t try to stop the charged particles, but rather, simply measures their momenta as they fly through it. It is our best tool for measuring the paths taken by the particles.

3.3.1.2 The Calorimeters

There are two Calorimeters: the Electromagnetic Calorimeter and the Hadron Calorimeter. Each operates on the same principle. They try to stop the majority of
a particular kind of radiation, and measure the energy deposited. This allows us to measure the energy of the particles.

The Electromagnetic Calorimeter (ECAL) is composed of almost 80,000 lead-tungstate (PbWO$_4$) crystals. These crystals are a type of scintillator: a material which emit light when a particle deposits energy in it. Lead-Tungstate scintillates when a light charged particle (especially electrons) impact them. This light is proportional to the energy of the particle, and is collected to get a measure of the energy deposited. While photons have no charge, they can either pair produce electron-positron pairs, or directly interact with an electron in the crystal. For both electrons and photon processes, the initial radiation from the collision is typically energetic enough to interact several times in the crystal, producing a shower of electrons and light as byproducts of the initial interaction also cause scintillation. Heavier particles punch through these crystals leaving little energy. They are instead measured by the Hadronic Calorimeter.

The Hadronic Calorimeter (HCAL) (shown in Figure 3.8) consists of stacks of brass plates interlayed with plastic scintillator. The brass stops the hadrons, causing showers of secondary radiation which are detected by the scintillators. It is the only detector at CMS which can stop neutral particles (such as neutrons and many types of mesons), making it crucial for reconstructing events with hadronic activity.
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Figure 3.8: The Hadronic Calorimeter, composed of 600 tons of brass, mostly recycled from WW2 naval shells.

3.3.1.3 The Solenoid

All three of these detectors are contained within a large solenoid\textsuperscript{13} This provides a field of 3.8 Tesla\textsuperscript{14} This field causes charged particle tracks to bend. The degree of this effect is dependent on the particle energy, which allows us to use the silicon tracker to measure the momentum of particles. The field is powerful enough to shift the alignment of the detector, an effect which must be properly accounted for. Brass is non-magnetic, explaining the choice to use it in the HCAL.

\textsuperscript{13}basically a really big electromagnet
\textsuperscript{14}this is a powerful field! A bar magnet usually has strength measured in millitesla.
3.3.1.4 The Muon Chambers

The final detector layers are the Muon Chambers. Muons are too heavy to be stopped by the ECAL but not heavy enough to be stopped by the HCAL. Special detectors are instead used to detect them. There are three kinds of muon chambers, all of which operate on the same principle: as the muon traverses them, it knocks electrons off of gas atoms. These electrons are collected by the detector to measure the energy: the more electrons, the more energetic the muon.

3.3.2 The Particle Flow Algorithm

All the information from these subdetectors is collected and analyzed by the Particle Flow Algorithm (PFAlgorithm, or just PF) \[18\]. This allows us to reconstruct events with a high level of certainty. The PF Algorithm leads to a gain especially in energy resolution for compound object, as can be seen in Figure 3.9. The PF is crucial for our ability to reconstruct jets which are described below.

Figure 3.9: Energy resolution gain from combining all information in the detector using the PF algorithm compared to that achievable with just the hadronic calorimeter.

3.3.3 Jets

In Chapter \[1\] we mentioned that colored particles cannot exist outside of a color-singlet state. When bare quarks are produced in proton-proton collisions they im-
immediately begin the process of hadronization: creating new colored particles out of
the vacuum until no color-states remain. Similarly, gluons created in proton-proton
collisions must eventually decay to quarks, which in turn hadronize.

As a result of this, the LHC is unable to measure individual quarks, but instead,
sees a shower of hadrons in the direction the original quark (or gluon) was moving.
These showers, shown in Figure 3.10 are called jets. Jets are composed of constituents

Figure 3.10: Typical CMS event with large number of hadrons (shown by the green
lines). These hadrons are collected into jets (shown by yellow triangles). The PF al-
gorithm combines information from the trackers and calorimeters to properly measure
the total momentum of the jet.

which are created by combining all the information available to the PF Algorithm
mentioned above. Charged hadrons (such as \( \pi^+ \), \( K^+ \), etc) leave tracks in the sili-
CHAPTER 3. PARTICLE DETECTION

con tracker and deposite energy in the hadronic calorimeter. Neutral hadrons (such as neutrons, \( \pi^0 \), etc) do not leave tracks but deposite their energy in the hadronic calorimeter. Other particles may appear from decays of the hadrons: for example charged pions decay most commonly to \( \mu \nu \) pairs and neutral pions usually decay to two high energy photons. These particles are measured by the muon chambers and electromagnetic calorimeter respectively and retained as constituents of the jet. Neutrinos don’t interact with anything and their energy is therefore irrevocably lost.

Most events of interest at CMS produce more than one bare quark, and it is therefore not trivial to cluster the many possible consituents into the “correct” jets which faithfully reflect the underlying interaction. A number of algorithms exist. Four of the more common ones are shown in Figure 3.11. We exclusively use the Anti-\( K_T \) algorithm. The algorithm runs iteratively in the following fashion: Every \textit{PF Candidate} (individual reconstructed particles) is considered against every other candidate and the distance-like parameter:

\[
d_{ij} = \min(p_{T,i}^{-2}, p_{T,j}^{-2}) \left( y_i - y_j \right)^2 + \left( \phi_i - \phi_j \right)^2 \right) \right) / R^2 \tag{3.4}
\]

is measured. Here \( R \) is a distance parameter which sets the size of the jet. The two closest constituents are paired together and become a new constituent. This pairing continues, adding new constituents to this and other pseudo-jets until \( d_i B \) (where \( B \) is the beam) is equal to \( 1/p_T^2 \) of a pseudo-jet. When this is the case, that pseudo-jet
Figure 3.11: Four different clustering algorithms, each run on the same event. We use the Anti-$K_T$ algorithm, described further in the text.

is classified as a jet and it is removed from consideration. The algorithm continues for remaining constituents and pseudo-jets until no constituents remain.

The Anti-$K_T$ algorithm is notable for creating “conical” jets with smooth, rounded edges (see again Figure 3.11) although this is not an exact statement, especially when two jets are near each other. We will refer to jets created with this algorithm as AK$R$ jets, where $R$ is the distance parameter used. We use two different kinds of jets in our analysis: AK8 and AK4, with $R$ respectively 0.8 and 0.4. While it is impossible to reconstruct the small masses of most quarks, the energies and momentums of the
CHAPTER 3. PARTICLE DETECTION

jet can be used to measure their kinematic properties. More massive particles such as the Higgs or W bosons and the very heavy top quark yield jets whose mass can be measured with some degree of accuracy. We use AK8 jets to reconstruct heavier objects.

3.3.4 Triggers

The detector output for each bunch-crossing would take approximately a megabyte to store. The crossing rate is forty megahertz, a rate well above what any modern computing system can handle. Because of this, the majority of collisions at CMS are discarded. The trigger system is responsible for pruning this output of uninteresting events.

The trigger operates in two main stages: the Level 1 trigger is a hardware trigger. Detector output is stored in a buffer and analyzed by custom built FPGA circuits. This analysis looks for key markers of “interesting” physics such as a high energy muon, or very large deposits of energy in the HCAL or ECAL. This stage allows us to reject all but about 0.1% of collisions. The buffered data is released to the next stage, at a rate of around fifty kilohertz.

The High Level trigger takes the output of the Level 1 trigger and analyzes it further, separating interesting events for further study and rejecting all others. A large number of triggers are available, and there are further sorted into Datasets sharing a common characteristic. For example, the SingleMuon dataset consists of a
large logical or of possible

High Level Trigger Paths. Example of such paths include $HLT_{Mu50}$ (an event with a 50 GeV muon), $HLT_{Mu45Eta2p1}$ (an event with a 45 GeV muon in with $|\eta| < 2.1$) and others. Most triggers used in analysis attempt to keep all possible events, but prescale Trigger are also kept, with only a fraction of triggering events allowed through. These triggers are used to measure the efficiency of the un-prescaled analysis triggers.

The resulting rate is about one kilohertz. There are the events which Physics Analyses are performed on. Our search for $Z'$ will use two triggers: the $Mu45\_eta2p1$ trigger which collects events with one high energy (45 GeV) muon in the barrel of the detector, and the $El45\_PFJet200\_PFJet50$ trigger, which collects events with one high energy electron (45 GeV) and at least two jets, one with energy at least 200 GeV and the other with energy at least 50 GeV.

Modeling the trigger is a crucial component of good simulations of the detector, especially when modeling new physics signals. Uncertainties in the overall efficiency of these triggers is an important systematics uncertainty of the analysis and will be further discussed.

### 3.3.5 Pileup

An event in CMS, ideally, is the outcome of a particular proton-proton collision. Most events do not yield any new physics or even “interesting” physics and the goal
CHAPTER 3. PARTICLE DETECTION

of our analysis will be to reduce the number of events in consideration to as small a set as possible.

Unfortunately, this ideal picture is not representative of the actual output of the detector because in each bunch-crossing there can be multiple proton-proton interactions. An event may therefore consist of up to forty individual interactions. It is therefore necessary to define a primary vertex: a vertex is a point along the beam from which a large number of particle flow objects originate. The primary vertex is selected as the vertex with the highest value for the sum of the square of the transverse momenta of tracks and candidates associated with it.

Pileup can greatly affect the jet algorithms as particles produced in a vertex separate from the one we consider may be clustered into jets from the primary vertex. These pileup contributions smear out the measurements of jet mass and momentum and must be accounted for in the analysis. Specialized variables described in the next section can reduce these effects and better identify the mass of a jet. The choice of the AK4 and AK8 jet clustering algorithms is in part predicated on the resistance of that algorithm to effects from soft constituents (i.e. constituents from other vertices). This effect is shown in Figure 3.12
Figure 3.12: Resolution of $R = 1.0$ jets from different algorithms. The $Anti - K_T$ Algorithm performs best.
Chapter 4

Tagging Interesting Jets

Our analysis will attempt to isolate $Z' \rightarrow tT'$ decays by reconstructing the decays of the top and the VLQ. The $T'$ is constrained in our analysis to always decay to a $b$ quark and a W boson. Tops, bs and Ws may all decay to jets. These jets have particular properties due to the nature of their parent particle which allow them to be identified with high degrees of accuracy.

4.1 The Soft-Drop Mass Algorithm

Tops and Ws have large masses (170 and 90 GeV respectively). Heavy particles tend to hadronize into wider cones. To see why this is the case, consider a W boson at rest. Ws decaying hadronically do so through a pair of quarks. These quarks, in the rest frame of the W, are emitted back to back and travel away from each other.
CHAPTER 4. TAGGING INTERESTING JETS

In the frame of the detector, the angle between the two quarks is dependent only on the velocity the W had. Low energy Ws will produce two separate quark-jets, while high energy ones (which we call boosted) will have their decay products merged into single jets.

To maximize our chance of collecting all the decay products in a single jet, we use the wider AK8 jets to reconstruct Ws (and tops). Ws with transverse momentum above 200 GeV and tops above 400 GeV have sufficient energy to collimate their decay products into a single AK8 jet. Our analysis restricts itself to finding these boosted Ws and tops, as the large masses of the $Z'$ and $T'$ lend themselves to high energies for their decay products.

The mass of an AK8 jet is found by summing the momentum vectors of all its constituent particles into one combined object. The mass of a jet from a top or from a W should be large compared to the average light flavor jet. However, due to the pileup at CMS, jets from background QCD processes may appear to have large masses as well. Several grooming algorithms exist to better define the mass of a jet. We use on in particular: the Soft-Drop Mass Algorithm \cite{20}.

The algorithm works by unclustering the jet, following the reverse order of the algorithm used to create it (in our case, the AK algorithm). At each stage the two pseudo-jets (labeled 1 and 2 in the following equation) are evaluated in the condition:

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z$$  \hspace{1cm} (4.1)
where $z$ determines the strength of the cut. We use $z = 0.1$ in our analysis. If the condition is met, then the jet is kept as is. Otherwise the lower energy subjet is discarded and the procedure continues. The condition is meant to emulate the behavior of a jet arising from real decays from a heavy particle, rather than the scattered constituents of a background jet. The effect of applying this algorithm to jets can be seen in Figure 4.1. We will use the Soft Drop mass as a tagging variable.

![Figure 4.1](image.png)

Figure 4.1: The mass of ungroomed jets (left) is a poor choice for differentiating jets from real top decays. The Soft Drop algorithm (right) allows the W and top peaks to be identified and reduces the mass of most background jets. The peak around 100 GeV is the W, while the peak around 200 is the top.

to identify W and top jets.
CHAPTER 4. TAGGING INTERESTING JETS

4.2 The N-subjetiness Algorithm

Despite the gains of a grooming algorithm for jet mass, the large cross-sections of background processes compared to our signal oblige us to use further tagging requirements for our jets. For top-tagging, we use a variable called the \textit{n-subjetiness} \cite{21,22}. The N-subjetiness algorithm defines variables $\tau_N$, where $N$ is the number of subjet axes, as follows:

$$
\tau_N = \frac{1}{d_0} \sum_i p_T i \times \min(\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{N,i})
$$

Where $\Delta R_{j,i}$ is the distance between the subjet axis $j$ and the PF candidate $i$. $d_0$ is a normalizing term which takes $p_T$ into account, with $d_0 = \sum p_T R_0$. The quantity $\tau_3/\tau_2$ is indicative of how likely a jet is to originate from a top (with three subjets). This variable is shown for top jets and background jets in Figure 4.2.

4.2.1 Mass and Parton Dependence of $\tau_3/\tau_2$

The N-subjetiness and Soft Drop Masses are both useful tools which exploit the jet \textit{substructure}. Perhaps unsurprisingly, there is a correlation between the Soft Drop Mass variable and the N-subjetiness variable. This correlation is shown in Figure 4.3. Notice also that there is also a dependence on the underlying parton, with the behavior of light partons being different than that of gluons. This behavior is further evident if we consider the combined efficiency of both cuts: for example, a cut on the
CHAPTER 4. TAGGING INTERESTING JETS

Figure 4.2: N-subjetiness variable $\tau_3/\tau_2$ for top jets and background jets. A cut can be made that keeps only jets with low values of $\tau_3/\tau_2$, thus reducing the background.

Soft Drop Mass in a window consistent with the top (we use $[110,210]$ GeV) and a maximum on the $\tau_3/\tau_2$ variable (we use 0.5). The efficiency for such a cut is shown in Figure 4.4. These small differences are not trivial. As will be described in section 7, a concise measurement of the top-tagging rate is needed to properly estimate the background to our signal. However, this measurement must be performed on a sample similar in content to the signal region distribution it estimates. From Figure 4.4, we can see that the difference between the gluon and quark tagging rates are a factor of two. Figure 4.5 shows the content of a QCD background sample at two energy ranges. The difference in gluon and quark content is noticeable, and the top tagging
4.3 The CSV Algorithm

The N-subjetiness can also be used to identify $W$ jets using the ratio $\tau_2/\tau_1$, however, we forgo this in our analysis. The $\tau_2/\tau_1$ has a dependence not just on mass, but on the momentum of the jet, which complicates its use in background estimation.
CHAPTER 4. TAGGING INTERESTING JETS

Figure 4.4: Dependence of top-tagging rate on parton species.

Figure 4.5: Parton Fractions in two different background samples, one at low (left) and one at high (right) energies.
In addition, the separation between signal and background is not as strong. We will only use the soft-drop mass to tag Ws.

We will complement this relatively weak requirement with a tag on potential b jets. b quarks are an order of magnitude lighter than the W, and therefore cannot be identified by their mass. Instead, we rely on a different property: the long decay time of the B-meson.

If we recall the CKM Matrix (equation 1.6), we note that the decay rates from $b$ to $u/c$ are smaller than the rates for the other quarks (excluding of course the top). This means that B-mesons (two-quark pairs which contain a b-quark) have a longer decay time than most other constituents (about 1.5ps, enough time to travel hundreds of $\mu$m). When this meson eventually decays, it creates a new vertex (called the secondary vertex) which is significantly displaced from the primary vertex.

The CSV Algorithm is a multi-variate measurement of jets with a displaced vertex, which takes into account a number of kinematic factors of the jet constituents and the displacement of the vertex to compute a discriminant variable which is in turn a function of the likelihoods of the jet originating from a b, c or other parton. This discriminator is shown in Figure 4.6 as can be seen in the figure, the CSV discriminator separates the b jets from background jets.
Figure 4.6: CSV (version 2) discriminator for jets from a light (dashed line), charm (dotted line) and b (solid line) partons. The discriminator peaks sharply at 1 for jets originating from a b parton.
Chapter 5

$Z' \rightarrow tT'$ Analysis Strategy

We investigate the productions of heavy $Z'$ bosons, considering the decay $Z' \rightarrow tT'$, where the top partner $T'$ also has large mass. Both the top and $T'$ are constrained to decay to a bottom quark and a W boson, with a further requirement that exactly one of the W bosons decay to a lepton and a neutrino (the so-called *semileptonic channel*).

Our signal samples were created using the Monte Carlo\(^1\) generator MadGraph\(^2\) and further hadronized using Pythia8\(^3\). Interactions with the detector are simulated using Geant4. Each samples has a specific mass for the $Z'$ and $T'$. The samples and masses are listed in Table 5.1. We focus our search on combinations of $Z'$ and $T'$ masses where the $T'$ mass is more than half the $Z'$ mass. When this is not true, the $Z'$ may decay preferentially to $T'$ pairs and escape our signal region.

---

\(^1\)A Monte Carlo, or MC, is a computer generated set of events obtained by repeated random sampling.
CHAPTER 5. \( Z' \to TT' \) ANALYSIS STRATEGY

Nonetheless, we cut loosely on \( T' \) mass and resonant decays with \( T' \) masses as low as 600 GeV should be visible. We normalize all signal samples to 5 pb for plotting and limit setting.

The main irreducible background in this search is standard model production of \( t\bar{t} \) pairs which have the same decay products as our signal: in particular real top quark decays. We estimate this background with a data-driven template morphing technique described in Chapter 6. Other sources of real top backgrounds are minor in comparison to the \( t\bar{t} \) contribution and are taken directly from simulations (see Table 5.2).

Backgrounds from QCD processes are naturally suppressed by the requirements on the leptonic leg of the decay, with the surviving non-top backgrounds consisting mostly of events where a \( W \) produced along with jets decays by \( W \to \ell \nu \). We do not attempt to distinguish between non-top background events with a real \( W \) (\( W+\text{jets} \)) and events from QCD with a fake lepton. QCD processes may produce leptons which we refer to as fake because they do not originate from a real \( W \), but rather, through an off-shell \( W \) as part of the decay of a hadron. Muons from B-mesons are especially prevalent, as the B-meson decays to a muon and muon neutrino 98% of the time.

Both non-top backgrounds are estimated as one part from measurements in sidebands, as described in Chapter 7.

The methods described in this note draw from preliminary work done on the Run 1 dataset (19.7\( fb^{-1} \)) with \( \sqrt{s} = 8 \) TeV, the results of which are shown in Appendix
Table 5.1: Signal Samples

<table>
<thead>
<tr>
<th>Signal Sample</th>
<th>$Z'$ mass</th>
<th>$T'$ mass</th>
<th>of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZprimeToTprimeT_TprimeToWB_MZp-1500Nar_MTp-700Nar</td>
<td>1.5 TeV</td>
<td>700 GeV</td>
<td>232,956</td>
</tr>
<tr>
<td>ZprimeToTprimeT_TprimeToWB_MZp-1500Nar_MTp-900Nar</td>
<td>1.5 TeV</td>
<td>900 GeV</td>
<td>232,731</td>
</tr>
<tr>
<td>ZprimeToTprimeT_TprimeToWB_MZp-1500Nar_MTp-1200Nar</td>
<td>1.5 TeV</td>
<td>1200 GeV</td>
<td>232,087</td>
</tr>
<tr>
<td>ZprimeToTprimeT_TprimeToWB_MZp-2000Nar_MTp-900Nar</td>
<td>2 TeV</td>
<td>900 GeV</td>
<td>229,857</td>
</tr>
<tr>
<td>ZprimeToTprimeT_TprimeToWB_MZp-2000Nar_MTp-1200Nar</td>
<td>2 TeV</td>
<td>1200 GeV</td>
<td>196,598</td>
</tr>
<tr>
<td>ZprimeToTprimeT_TprimeToWB_MZp-2000Nar_MTp-1500Nar</td>
<td>2 TeV</td>
<td>1500 GeV</td>
<td>229,497</td>
</tr>
<tr>
<td>ZprimeToTprimeT_TprimeToWB_MZp-2500Nar_MTp-1200Nar</td>
<td>2.5 TeV</td>
<td>1200 GeV</td>
<td>226,913</td>
</tr>
<tr>
<td>ZprimeToTprimeT_TprimeToWB_MZp-2500Nar_MTp-1500Nar</td>
<td>2.5 TeV</td>
<td>1500 GeV</td>
<td>227,926</td>
</tr>
</tbody>
</table>
### Table 5.2: MC Samples and Datasets

<table>
<thead>
<tr>
<th>Process</th>
<th>Dataset</th>
<th>$\sigma$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>t$t$ (s-channel)</td>
<td>ST_s-channel_4f_fLeptonDecays</td>
<td>831.8</td>
</tr>
<tr>
<td>single top (s-channel)</td>
<td>ST_s-channel_4f_fInclusiveDecays</td>
<td>3.34</td>
</tr>
<tr>
<td>single top (t-channel)</td>
<td>ST_t-channel_4f_fInclusiveDecays</td>
<td>136.02</td>
</tr>
<tr>
<td>single top (tW-channel)</td>
<td>ST_tW_top_5f_fInclusiveDecays</td>
<td>23.2</td>
</tr>
<tr>
<td>single top (tW-channel)</td>
<td>ST_tW_antitop_5f_fInclusiveDecays</td>
<td>23.2</td>
</tr>
<tr>
<td>Muon Events</td>
<td>SingleMuon_Run2015DCD</td>
<td>2630</td>
</tr>
<tr>
<td>Electron Events</td>
<td>SingleElectron_Run2015DCD</td>
<td>2630</td>
</tr>
</tbody>
</table>


5.1 **Type 1 Channel**

The powerful top-tagging techniques described in Chapter 4 lend themselves well
to this analysis, especially when the top-quark is sufficiently boosted to merge into
a single jet. We call this scenario the *Type 1 Channel*. A sketch of this channel is
shown in Figure 5.1. In the Type 1 Channel, the W coming from the $T'$ decays to a
lepton and a neutrino. The top-tagging scheme is powerful enough that other than

Figure 5.1: Decay of the $Z'$ in the Type 1 Channel. A merged top jet recoils against a
$T'$ decaying to a $b$ and a W. The W decays to a lepton ($mu$ or $e$ only) and a neutrino.
We use top-tagging on the top jet but do not attempt to tag the b jet.

leptonic requirements, no other tagging is necessary and we can increase our signal
efficiency\footnote{how much of the signal we keep in the analysis} by avoiding the use of b-tagging cuts.

On the other hand, the Type 1 channel suffers from a significant weakness for certain mass points. Figure 5.2 shows the masses and momentums of jets from a $t\bar{t}$ sample. Notice that it is comprised of three main regions of activity. The lowest in mass represents a multitude of jets not particularly associated with heavy objects (background jets, secondary radiations and the b jets). Then at roughly the mass of the W we see a second region of activity. These are real Ws merged into a single jet. This distribution is cut short at 400 GeV, where a second more massive distribution starts. These are real tops with enough energy to merge into a single jet (with the W and the b inside it). That energy is roughly 400 GeV.

This particularity makes the Type 1 Channel inappropriate for mass models where the difference between the $Z'$ mass and $T'$ mass is so small that there isn’t enough energy for the top to merge. Looking again at Table 5.1, two entries are especially ill suited for the Type 1 Channel: $(Z'_{1500} \to tT'_{1200})$ and $(Z'_{2000} \to tT'_{1500})$. It is still possible for an LHC collision to produce such a decay with enough energy to create a merged top: the $Z'$ must be produced with some initial momentum (if the partons colliding have different energies), however, such cases will be rare.

We therefore define a second channel to reconstruct these mass points (and lend statistical power to the other mass points).
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Figure 5.2: Mass and momentums of a $t\bar{t}$ sample. Note that the top jets only merge above a certain energy threshold (roughly 400 GeV).

5.2 Type 2 Channel

The Type 2 Channel is the complement in the Type 1 Channel: the W which decayed from the top goes to a lepton neutrino pair, aside a b jet. On the $T'$ side, the W decays to a single merged jet also along a b jet. Because of the large mass of the $T'$, there is no risk of the W not merging (even with our lightest $T'$ model, the mass splitting between the $T'$ and the W is 600 GeV... Even if the b jet takes a large
fraction of this energy, most Ws will have the 200 GeV necessary to merge into one jet). A sketch of this channel is shown in Figure 5.3. The Type 2 Channel has higher backgrounds than the Type 1 Channel (in large part because the high mass of the merged top jet in the Type 1 Channel is harder for light jets to fake). This weakness is offset by the fact that it treats all mass models equally.

5.3 Physics Objects

We define and use a number of Physics Objects for our analysis. These are for the most part compound objects, but we treat them each as single entities. In most cases, the MC simulation of these events is not a perfect reproduction of their partners in real data and corrective factors must be applied. These corrective factors come with
a slew of uncertainty which must be included in our final statistical evaluations. We will describe the objects in this section and any uncertainty in Chapter 9.

5.3.1 Primary Vertex Selection

We reconstruct the primary vertex in each event by clustering tracks using a deterministic annealing algorithm. Only vertices passing the following requirements are considered:

- $\sqrt{x^2 + y^2} < 2\text{ cm}$ and $|z| < 24\text{ cm}$,
- $N_{DOF} > 4$, where $N_{DOF}$ is the weighted number of tracks used to reconstruct that vertex.

The vertex with the highest $\sum_{tracks} p_T^2$ is selected as the primary vertex. All other vertices are discarded, except for those necessary for b-tagging. The total number of vertices is kept to make estimates of the pileup in each event.

5.3.2 Pileup

We re-weigh each MC event as a function of the Number of Primary Vertices so that the number of true pileup interactions in simulation matches the instantaneous luminosity profile measured in data. We assume the total cross-section of the proton-proton collisions to be 72mb. This value is measured during data-collection. This

\[\text{as mentioned in the previous section, these are offset from the beam}\]
cross-section is varied up and down by 5\% to obtain systematic uncertainties. The scale factor used in this correction, as well as its uncertainty, is plotted as a function of the number of primary vertices in Figure 5.4, along with the effect of this correction for the $Z'_2000, T'_900$ signal.

Figure 5.4: (left) Scale Factor applied to each event in MC samples as a function of the number of primary vertices in that event, shown here for the signal sample $Z'_2000 \rightarrow tT'_900$. This shape must be derived independently for each sample. (right) Change in the $Z'$ mass distribution in the type 1($\mu$) channel with and without the pileup correction.

5.3.3 Muon Reconstruction

We consider muons which pass the following requirements:

- The muon must be reconstructed as a Global Muon and a Particle Flow Muon: Such muons combine information from the tracker and muon systems. This is a very loose cut, only likely to remove muons from cosmic rays from consideration.

- The muon must hit at least two muon chambers, and one such hits must be used
to reconstruct the muon track (which means it is used to measure the positon, not just momentum of the muon). These requirements reduce the number of muons arising from decays in flight of hadrons (which may decay beyond the tracker).

- The muon must originate from within 5mm of the primary vertex along the beam line, and 2mm off the beamline. This requirement constrains the muon to be associated with the primary collision being considered and further reduces contributions from cosmic rays.

- Finally, the muon must have at least one hit in the pixel detector and at least five total hits in the tracker (pixel + track detectors). This further reduces the contribution from muons originating from secondary decays far from the primary vertex (especially, as mentioned previously, from B-meson decays).

These muons (called Tight ID Muons) are most likely to originate from real W decays rather than background sources. We keep the muons which fail these requirements for dedicated background studies described in Chapter 7.

5.3.4 Electron Reconstruction

We consider electrons which pass a similar set of requirements as the muons. Because the electrons do not have a dedicated system like the muon chambers to
measure them, more variables are used to identify them. An MVA\textsuperscript{4} is used along with a series of hard cuts. These electrons (called Tight ID Electrons)\textsuperscript{27,28} are most likely to originate from real W decays rather than background sources. We keep the electrons which fail these requirements for dedicated background studies described in Chapter 7.

5.3.5 Jet Reconstruction\textsuperscript{5}

The Particle Flow (PF) reconstruction algorithm is used to reconstruct all events in data and MC simulation samples. We use jets with Charge Hadron Subtraction. The PF candidates are clustered by the anti-$k_T$ algorithm into jets using an $R$ value of 0.4 for light jets (mass < 50 GeV) and 0.8 for heavier jets (mass > 50 GeV). We only consider AK8 jets which are separated from lighter jets by a $\Delta R$ of at least 0.8. We apply anti-$k_T$ jet energy corrections for all jets (data and MC). L1+L2+L3+residual corrections are applied, from the Global Tag Fall15_25nsV2_MC (MC) or Fall15_25nsV2_DATA (Data). The MC is corrected for the difference in these procedures. Uncertainties in this process (for MC) are kept as sources of systematic uncertainty for all MC derived quantities.

\textsuperscript{4}Multivariate Analysis: rather than hard cuts, all variables are considered and an overall measurement is made.

\textsuperscript{5}this section contains a lot of technical mumbo-jumbo intended for experts in jet reconstructions.
5.3.6 MET and W Reconstruction

The Missing Transverse Energy (MET) is computed as the negative of the vector sum of all PF Candidates. In each event we reconstruct a leptonic W candidate from the lepton and MET. We solve for the neutrino $\eta$, making the assumption that all the missing energy is due to this neutrino and that the lepton and neutrino have a reconstructed mass of exactly 80.4 GeV. The $\eta$ is given by:

$$\eta = \log \frac{m^2_W - m^2_{\text{MET}}}{m^2_{\text{MET}}} \pm \sqrt{\left(\frac{m^2_W - m^2_{\text{MET}}}{m^2_{\text{MET}}}\right)^2 - 4(p_\ell - p_\nu_s)(p_\ell - p_\nu_s)}$$

There are at most two solutions to this reconstruction. If more than one solution exists, the larger value is used. If the solution is imaginary, only the real component is used.

5.3.7 Top Tagging

We use the soft drop mass algorithm to calculate the mass of our taggable jets. In addition to mass requirements, we use the N-subjetiness algorithm to separate top jets from light flavor jets. The quantity $\tau_3/\tau_2$ is indicative of how likely a jet is to originate from a top (with three subjets). To correct for the fact that MC does not properly model the intricacies of the jet reconstruction and N-subjetiness algorithms, we apply data/MC scale factors to simulated events as an efficiency correction. We
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retain the error in these SF as a systematic uncertainty. We use the top tagging scale factor derived by Ivan Marchesini and Svenja Schumann. The result finds a scale factor for a top tag identical to our own measured in semileptonic events for top jet candidates with \( 400 < p_T < 550 \text{GeV} \) and \( p_T > 550 \text{GeV} \). Errors are also derived on each \( p_T \) bin to be used as a systematic uncertainty.

5.3.8 \( b \) tagging

We use \( b \)-jet tagging in the Type 2 channel. We use the loose working point of the CSVv2 algorithm (CSV > 0.605) \cite{29}. \( b \)-tagging scale factors are applied. A Scale Factor \cite{30} is applied as a function of \( p_T \), \( \eta \) and parton species to account for differences between the data and how the MC models \( b \), \( c \) and light quarks.

5.4 Event Selection

Both channels utilize a number of sidebands and control regions to perform a full estimate of all major backgrounds in the signal region. These regions are defined below, and shown in Figure \ref{fig:5.5}.
Figure 5.5: Phase space breakdown of the sidebands and control regions used in this analysis. The W+b sidebands (in red) are broken down into the low mass sideband and the mid mass sideband where the reconstructed top-like (b + W) objects have masses between [120, 250] and [250, 500] respectively. These sidebands are used to perform the t\bar{t} reweighting. The regions outlined in blue contain predominantly W+jets events and are used to estimate the non-top contribution to the background.

### 5.5 Event Preselection

Both channels and their sidebands only consider events which fulfill the following preselection requirements:

1. Total Event HLT must be greater than 800 GeV to be considered for the signal region. In the sidebands this requirement is relaxed to 500 GeV to include more background events with which to validate our methods.

2. Event must have exactly one AK8 jet with soft drop mass > 50 GeV for the Type 1 channel, > 40 GeV for the Type 2 channel, and $p_T > 200$ GeV. We will
often refer to this jet as the tag jet. It will be the top jet candidate for channel 1 and the W jet candidate for channel 2. The tag jet $p_T$ at preselection are shown in Figure 5.6 as obtained from our background estimation method. The soft drop mass is similarly plotted in Figure 5.7.

3. Event must have at least one AK4 jet with mass $< 50$ GeV and $p_T > 100$ GeV. The Type 2 channel must have two. Further, all AK4 jet axes must be minimum distance of $\Delta R > 0.6$ away from the AK8 jet. These jets’ $p_T$ in the preselection are plotted in Figure 5.8 as obtained from our background estimation method.

4. Event must have at least one $p_T > 50$ GeV lepton (muon or electron) in the (muons are further constrained to be in the eta region $|\eta| < 2.1$). We apply the Loose lepton ID requirement. This ID requirement is inverted to create a sideband in which to check our measurement of non-top backgrounds (see Section S:close). The lepton $p_T$ in the preselection is plotted in Figure 5.9 as obtained from our background estimation method.

5. The lepton must pass the MiniIsolation requirement $\text{miniIso} < 0.2$ for muons and $< 0.1$ for electrons. Where the miniIsolation is defined as $p_T^\ell/p_T^{\text{cone}}$ for a cone whose size is dependent on the lepton momentum as $R_{\text{iso}} = 15 \text{GeV}/p_T^\ell$. We also invert this requirement for events used in the closure test in Section S:close.

6. Events must have at least 25 GeV of MET, and the W reconstruction must have

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found a solution. The MET and W $p_T$ at preselection are shown in Figure 5.10 as obtained from our background estimation method.

![Figure 5.6: Distribution of the $p_T$ of the tag jet as reconstructed by both channels. (Only error in the non-top background is shown.)](image)
CHAPTER 5. \( Z' \rightarrow TT' \) ANALYSIS STRATEGY

Figure 5.7: Distribution of the mass of the tag jet as reconstructed by both channels. (Only error in the non-top background is shown.)
CHAPTER 5. $Z' \rightarrow TT'$ ANALYSIS STRATEGY

Figure 5.8: Distribution of the $p_T$ of the AK4 jets as reconstructed by both channels. (Only error in the non-top background is shown.)
Figure 5.9: Distribution of the $p_T$ of the lepton as reconstructed by both channels. (Only error in the non-top background is shown.)
Figure 5.10: Distribution of the $p_T$s of the W and the missing transverse energy, as reconstructed by both channels. (Only error in the non-top background is shown.)
5.6 Type 1 Channel

To be considered in the Type 1 Channel, events must pass the following requirements:

1. The tag jet must have soft drop mass $\in [110, 210]$ GeV and pass the N-subjetiness requirement $\frac{\tau_3}{\tau_2} < 0.51$. This is the top-tag. Events with masses $[70, 350]$ (excluding the top mass window) are reserved for measurements of backgrounds and correspond to the regions outlined in blue in Figure 5.5.

2. We define the leptonic top candidate as the four-vector sum: $T_{lep} = W_{lep} + \text{leading jet (excluding the tag jet)}$. Depending on its mass, the event can be placed in one of three regions as described below. When the mass of $T_{lep}$ is greater than 500 GeV we place this event in the signal region. This variable is plotted in Figure 5.11 as obtained from our background estimation method.

To estimate the $t\bar{t}$ contribution, and to provide a cross-check of our background estimate, we also define two control regions based on the mass of the leptonic top candidate, shown in Figure 5.5. The low mass region consists of events with $140 < M(T_{lep}) < 250$. These events are used to make a measurements of the SM $t\bar{t}$ distribution. The mid mass region consists of events with $250 < M(T_{lep}) < 500$. These events are between the signal and low mass region and serve as a further cross-check for our methods.
CHAPTER 5. $Z' \rightarrow TT'$ ANALYSIS STRATEGY

Figure 5.11: Reconstructed mass of the leptonic $T'$ candidate. (Only error in the non-top background is shown.)

5.7 Type 2 Channel

The two channels were constructed to be completely orthogonal, thanks to the tag jet mass windows considered. To be considered in the Type 2 Channel, events must pass the following requirements:

1. The tag jet must have soft drop mass $\in [70, 100]$ GeV. We do not apply an n-subjetiness requirement to the W jet. Instead we b-tag the jet on the leptonic side with a loose b-tag ($CSVv2 > 0.605$). Events with masses $[50, 120]$ (excluding the W mass window) are reserved for measurements of the backgrounds and correspond to the regions outlined in blue in Figure 5.5.

2. We define the hadronic top candidate as the four-vector sum: $T_{\text{had}} = \text{tag jet} + \text{remaining of the two leading jet (excluding the tag jet)}$. Depending on its mass, the event can be placed in one of three regions as described below. When the mass of $T_{\text{had}}$ is greater than 500 GeV we place this event in the signal.
region. This variable is plotted in Figure 5.12 as obtained from our background estimation method.

3. We define an object as the four-vector sum: $T_{lep} = W_{lep} + \text{closest of the two leading jets}$. This object must be consistent with a leptonically decaying top and have mass $\in [120, 270]$. This variable is plotted in Figure 5.13 as obtained from our background estimation method. It is unclear why the modeling here is so poor. The effect does not seem to be paralleled in other related variables (lepton $p_T$, jet $p_T$), nor does the effect seem to propagate into the control regions (see Section 6).

![Figure 5.12: Reconstructed mass of the hadronic $T'$ candidate. (Only error in the non-top background is shown.)](image-url)
CHAPTER 5. $Z' \rightarrow TT'$ ANALYSIS STRATEGY

Figure 5.13: Reconstructed mass of the leptonic top candidate. See note in text regarding discrepancy. (Only error in the non-top background is shown.)
CHAPTER 5. $Z' \to TT'$ ANALYSIS STRATEGY

As with the Type 1 channel, we also define a low mass region and mid mass region based on the hadronic top candidate mass, shown in Figure 5.5. The low mass region is defined as $120 < M(T_{had}) < 250$ and the mid mass region as $250 < M(T_{had}) < 500$. 
Chapter 6

$t\bar{t}$ Background Estimate

The $t\bar{t}$ contribution to the signal region is estimated using a data-driven template-morphing fit initially performed in the low mass control regions and extrapolated into the mid mass control regions as a test of closure. The estimate in the signal region uses both the low and mid control regions to perform the fit.

The template morphing procedure starts with shape and normalization of the $t\bar{t}$ distribution taken from simulation. This initial template is then allowed to morph by reweighing each simulated event according to a pre-defined analytic form. This form was derived by modifying the template morphing used by the TOP PAG to achieve agreement between MadGraph and data for events with a single low $p_T$ top. In their method, the following event weight is applied:

$$w_i(t^{mc}_{p_T}) = e^{N - \alpha t^{mc}_{p_T}} \quad (6.1)$$
CHAPTER 6. $T\bar{T}$ BACKGROUND ESTIMATE

We derive our functional form from a simple product of this weight to each of the two tops in the event:

$$w_t(t_{pT}^{mc}, \bar{t}_{pT}^{mc}) = \sqrt{e^{N' - \alpha t_{pT}^{mc}} e^{N' - \alpha \bar{t}_{pT}^{mc}}}$$ (6.2)

Which we simplify to:

$$w_{\bar{t}}(HT) = Ne^{-\alpha HT/2}$$ (6.3)

$HT\bar{t}$ is the scalar sum of the $p_T$s of the two tops in the MC event. $N$ and $\alpha$ are allowed to float in the template fit to data. The effect of the parameter $\alpha$ on the shape of the $t\bar{t}$ distribution is shown in Figure 6.1.

![Figure 6.1: Effect of the parameter $\alpha$ on the shape of the $t\bar{t}$ distribution (shown in the Type 1 Channel preselection, before cuts on the $T'$ mass).](image)

Because the parameter $\alpha$ depends only on the kinematic distribution of events in MC and in data, it is required to be constant between type 1 and type 2 channels, as well as in both the low and medium mass channels for any fit. The overall nor-
CHAPTER 6. $t\bar{t}$ BACKGROUND ESTIMATE

malization $N$ is forced to be the same between both channels. However, as the MC templates used as the base for the estimate suffer from mismodeling of the Nsub-jetiness and $b$ tags, we first apply the top and $b$ scale factors in order to factorize them from the normalization parameter $N$. All resulting uncertainties on the MC are corrected for by the fit. The non-top background in these distributions is estimated according to the method outlined in Section 7.

We measure the parameters using a binned likelihood fit in Theta, and find that $\alpha = 0.00064 \pm 0.00018$, with normalization $N = 0.93 \pm 0.06$. We show the results of the reweighting procedure in all channels in Figures 6.2 - 6.5.

Figure 6.2: Data and Estimate in the Type 1 low mass control region before (left) and after (right) the $t\bar{t}$ reweighting procedure (Only the non-top fit errors are shown).
Figure 6.3: Data and Estimate in the Type 1 mid mass control region before (left) and after (right) the $t\bar{t}$ reweighing procedure (Only the non-top fit errors are shown).
Figure 6.4: Data and Estimate in the Type 2 low mass control region before (left) and after (right) the $t\bar{t}$ reweighting procedure (Only the non-top fit errors are shown).
Figure 6.5: Data and Estimate in the Type 2 mid mass control region before (left) and after (right) the $t\bar{t}$ reweighting procedure (Only the non-top fit errors are shown).
Chapter 7

Non-top Multijet Background

Estimate

The dominant non-top contribution to background is from $W$+jets events. QCD processes are suppressed by the lepton and missing energy requirements, however, we do not attempt to make a distinction between these two sources of background. In the leptonic-inversion sideband used for a closure test in Section 7.3, QCD is a larger fraction of the background. Events without a true top will primarily enter the signal region when a jet has sufficiently high mass to be tagged as a top or a $W$ jet. The shape and normalization of these events can be extracted from data in sidebands of the jet mass and some tagging variable: $\tau_3/\tau_2$ of the tag jet for the type 1 channel and the $b$-tag discriminant for the type 2 channel. We define the pretag region to be all events passing the cuts in signal region except the jet mass and tagging requirement.
A schematic of the pretag region and its sub-regions is shown in Figure 7.1. If there is no correlation between the jet mass and the tagging variable, it would be sufficient to take the shape of the background from the anti-tag region and weigh it by the ratio of events passing and failing in the sidebands, as is done in the ABCD method. However, as can be seen in Figure , both tagging variables correlate with mass, so it is instead necessary to fit for that ratio, which we call the conversion factor as a function of mass.
Figure 7.2: (left:) Distribution of jet mass and nsubjetiness variable $\tau_3/\tau_2$. (right:) Distribution of jet mass and b tagging variable. The profiles are plotted in black on top of these distributions to showcase the linear behavior we will exploit in our background estimate. Contributions from real top events are subtracted from these events before any fitting is performed.
CHAPTER 7. NON-TOP MULTIJET BACKGROUND ESTIMATE

7.1 Type 1 estimate

We measure the conversion factor in sidebands of the top mass. Events which are neither in the antitag region nor the signal region are divided between events which pass or fail the N-subjetiness requirement. In each slice of jet mass, we calculate the fraction of events passing divided by the number of events failing the requirement. The resulting values represent masses above and below the signal region mass requirement, as shown in Figure 7.1. We fit a linear function to these values, interpolation for the number of passing event per failing event at any mass, including the signal and antitag regions. Such a function is motivated from considerations of the shape of the preselection region, see Appendix 11.3. This ratio is the conversation factor \( C_{\text{p/f}} = \frac{\text{# passing}}{\text{# failing}} \). Figure 7.3 shows the values obtained from data in the Type 1 channel, as well as the resulting fit. The contribution to the sidebands and antitag regions from real top events are subtracted out using the MC prediction (for minor backgrounds) and the distribution obtained from the \( t\bar{t} \) estimate. The error in the fit is used to obtain shape and normalization uncertainties for the non-top background estimate. Further systematics are assigned from the uncertainty in the distribution of true top sources, which are propagated through the interpolation to give separate systematic uncertainties. The full result of this background estimate in both the control region and \( t\bar{t} \) region can be seen in Chapter 6.
Figure 7.3: Fit for the mass dependence of the conversion factor $C_{p/f}$ in the $e$ (left) and $\mu$ (right) Type 1 Channel.
CHAPTER 7. NON-TOP MULTIJET BACKGROUND ESTIMATE

7.2 Type 2 estimate

The estimate initially attempted to use the tag jet mass and a cut on $\tau_2/\tau_1$ in exactly the same way as the type 1 channel. However, as detailed in Appendix 11.1, due to a pronounced interdependence between the nsubjettiness, the jet mass and the jet $p_T$, our method was not possible without modifications which greatly increased the error. In addition, while the cut on $\tau_3/\tau_2$ allows order 10% of non-top jets into the signal region while remaining sufficiently efficient for signal, similarly efficient $\tau_2/\tau_1$ cuts allow background to pass at a rate of almost 50%, meaning that our anti-tag region has no statistical advantage over the signal region.

Instead, the Type 2 channel uses the CSV score of the leptonic side jet as the discriminant, and measures the transfer factor in terms of the W-jet soft drop mass. Figure 11.3 shows the values obtained of the conversion factor from data in the mass sidebands in the Type 2 channel, as well as the resulting fit. As with the Type 1 channel, systematics are assigned from the uncertainty in the distribution of true top sources, which are propagated through the interpolation to give separate systematic uncertainties. The full result of this background estimate in both the control region and $t\bar{t}$ region can also be seen in Chapter 6.
CHAPTER 7. NON-TOP MULTIJET BACKGROUND ESTIMATE

Figure 7.4: Fit for the mass dependence of the conversion factor $C_{p/f}$ in the $e$ (left) and $\mu$ (right) Type 2 Channel.
7.3 Closure Tests in Sideband

We perform a closure test of our methods in data for a sideband of the signal region constructed to have similar kinematic behavior but an absence of signal. For this test, we use regions identical to our main analysis except that the lepton quality requirements are reversed. In addition, isolation requirements on these leptons are relaxed. The resulting distributions are naturally enhanced in non-top backgrounds and depleted of real tops. The fits and results for each channels’ equivalent sidebands can be seen in Figures 7.5 and 11.5. The true value of the conversion factor is plotted in blue, but was not used in fit.
CHAPTER 7. NON-TOPOLOGY MEASUREMENTS

Figure 7.5: Conversion factor fit for events in the leptonic closure sideband for the Type 2 Channel, which mimics the signal region except that the requirement that the lepton pass the Loose ID cut is inverted.
Figure 7.6: Prediction of events in the leptonic closure sideband for the Type 2 Channel, which mimics the signal region except that the requirement that the lepton pass the Loose ID cut is inverted.
Chapter 8

Full Background Estimate

The full background estimate is shown for channels 1 and 2 in Figures 8.1 and 8.2. This analysis is currently blinded so no data is plotted.

Figure 8.1: Background prediction in the type 1 channel for the full signal region. All signal points are normalized to 5 pb.
CHAPTER 8. FULL BACKGROUND ESTIMATE

Figure 8.2: Background prediction in the type 2 channel for the full signal region. All signal points are normalized to 5 pb.
Chapter 9

Statistical Interpretation

There are three main sources of uncertainty in the analysis: uncertainty in our modeling of the $t\bar{t}$ background, uncertainty from the fits and sidebands used to measure the non-top background and the uncertainty in the mis-modeling of the signal and MC derived backgrounds. Since the $t\bar{t}$ and non-top backgrounds are estimated from data-driven methods, we do not apply the MC uncertainties to them. Wherever possible we treat the uncertainty as a shape based effect. Table 9.1 shows all effects (and which distributions they affect), specifics for each systematic are detailed below.
Table 9.1: Summary of systematic uncertainties. Entries in a row are treated as correlated. The MCs refer to the single top background component and to the signal samples.

<table>
<thead>
<tr>
<th>Source</th>
<th>Type 1 non-top</th>
<th>Type 2 non-top</th>
<th>Type 1 (tt)</th>
<th>Type 2 (tt)</th>
<th>Type 1 MCs</th>
<th>Type 2 MCs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.7% norm.</td>
<td>2.7% norm.</td>
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<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>shape</td>
<td>shape</td>
</tr>
<tr>
<td>Jet Energy Res.</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>shape</td>
<td>shape</td>
</tr>
<tr>
<td>Pileup</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>shape</td>
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<tr>
<td>PDFs</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>shape</td>
<td>shape</td>
</tr>
<tr>
<td>(\bar{t}) (\alpha)-parameter</td>
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<td>shape</td>
<td>shape</td>
<td>shape</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(\bar{t}) normalization</td>
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<td>shape</td>
<td>6% norm.</td>
<td>6% norm.</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>shape</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>Type 2 non-top fit</td>
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<td>-</td>
<td>shape</td>
<td>shape</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(\mu) trigger</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>shape + 0.5% norm</td>
<td>shape + 0.5% norm</td>
</tr>
<tr>
<td>(\mu) ID</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>shape + 1% norm</td>
<td>shape + 1% norm</td>
</tr>
<tr>
<td>e trigger</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>shape + 1% norm</td>
<td>shape + 1% norm</td>
</tr>
<tr>
<td>e ID</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>shape + 0.5% norm</td>
<td>shape + 0.5% norm</td>
</tr>
<tr>
<td>t-Tagging SF</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>shape</td>
<td>-</td>
</tr>
<tr>
<td>b-Tagging SF</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>shape</td>
</tr>
</tbody>
</table>
9.1 $t\bar{t}$ background

The $t\bar{t}$ re-weighting procedure naturally provides us with the systematic uncertainty of the estimate. The errors in the fit parameters $N$ and $\alpha$ can be propagated through to the final estimate to provide us with shape based uncertainties. The shape based uncertainty in the parameter $\alpha$, compared to the nominal estimate, is shown in Figure 9.1.

![Figure 9.1: Uncertainty in $\alpha$ as it affects the $t\bar{t}$ background estimate shown for the type 1 channel’s $t\bar{t}$ control region (combining both lepton species).](image)

9.2 Non-top background

The main source of uncertainty for the non-top background is propagated directly from the error of the fit in mass-sidebands from which we have estimated the transfer factor. This uncertainty can be treated as a shape based uncertainty. While this uncertainty is the dominant uncertainty in the entire analysis, it is fully correlated between all bins of a particular estimate. We must further account for the statistical
uncertainty in the anti-tag region which is propagated to the signal region when the estimate is made. This uncertainty is small compared to the fit uncertainty, but is uncorrelated from bin to bin. Finally, the non-top estimate is performed after the contribution from $t\bar{t}$ and other sources of true top jets have been subtracted from the pre-tag region. We therefore retain the non-top estimate performed with the up and down systematics effects of the $t\bar{t}$ re-weighting as an additional systematic. All uncertainties are shown, compared to the nominal estimate, in Figure 9.2.

Figure 9.2: Systematic uncertainties affecting the non-top background estimate shown for the type 1 channel’s $t\bar{t}$ control region (combining both lepton species).
CHAPTER 9. STATISTICAL INTERPRETATION

9.3 MC quantities

We consider the following systematic uncertainties on the background components estimated purely from MC, as well as the signal samples. The effect of all systematic uncertainties on the shape and normalization of a representative signal sample can be seen in Figures 9.3 through 9.6. To give an idea of the relative scales of these uncertainties, they are all plotted on the same axis in Figures 9.7.

1. **JEC**: We vary the $p_T$ of all jets in the analysis by the uncertainty in jet correction [33–35]. The uncertainty in the energy of each jet is a function of both $p_T$ and $\eta$. These uncertainties can increase or decrease the $p_T$ of a jet and move it into or out of our signal region.

2. **JER**: We smear the $p_T$ of all jets in the analysis up and down by the uncertainties in the jet energy resolution.

3. **Trigger ($\mu$)**: We apply up and down systematics to the Muon Trigger efficiency scale factor obtained from the Muon POG, as well as an additional 0.5% uncertainty, according to their recommendation [36].

4. **Lepton ID ($\mu$)**: We apply up and down systematics to the Muon ID efficiency scale factor obtained from the Muon POG, as well as an additional 1% uncertainty, according to their recommendation [36].

5. **Lepton Trigger/ID ($e$)**: We take the measurement of the electron SF and
associated uncertainties from the SUSY lepton SF measurement \[37\].

6. **Nsubjettiness Scale Factor:** We include uncertainty in the Nsubjettiness scale factor for top tagging. The top tagging scale factor, being applied in two bins of top $p_T$, is a shape based systematic. We use the top tagging scale factor derived by Ivan Marchesini and Svenja Schumann in the context of a (currently unpublished) AN for top-tagging.

7. **b-tagging Scale Factor:** We include uncertainty in the b-tagging scale factor which is evaluated for MC samples on a jet by jet basis as a function of $p_T$, $\eta$ and the generator parton flavor. We use the uncertainties provided by the BTV POG \[30\].

8. **Pileup:** We re-weigh each MC event as a function of the Number of Primary Vertices so that the number of true pileup interactions in simulation matches the instantaneous luminosity profile measured in data. We vary the minimum bias cross-section up and down by 5\% \[38\] to obtain a systematic uncertainty from this effect.

9. **PDFs:** The uncertainty in the PDFs is evaluated event by event by adding or subtracting the RMS of potential weights to the weight used by the MC generator. This yields a shape based effect.

10. **Luminosity:** The uncertainty in the total integrated luminosity of our data samples is 4.6\% \[39\]. This uncertainty is treated as an overall normalization
Figure 9.3: Effect of jet related systematic uncertainties from jet reconstruction in MC on a representative signal sample for the $Z_{2000}^\prime, T_{900}^\prime$ signal point (Signal is normalized to 5 pb.)
Figure 9.4: Effect of pileup systematic uncertainties on a representative signal sample for the $Z'_{2000}, T'_{900}$ signal point (Signal is normalized to 5 pb.)
Figure 9.5: Effect of top and b tagging uncertainties on a representative signal sample for the $Z'_{2000}, T'_{900}$ signal point (Signal is normalized to 5 pb. Note the dominating effect of the top-tagging scale factor uncertainty.)
Figure 9.6: Effect of lepton systematic uncertainties on a representative signal sample for the $Z'_{2000}, T'_{900}$ signal point (Signal is normalized to 5 pb).
Figure 9.7: Systematic Uncertainties plotted on the same scale for the $Z'_{2000}, T'_{900}$ signal point (Signal is normalized to 5 pb.)
CHAPTER 9. STATISTICAL INTERPRETATION

9.4 Limits

We set limits on the production of $Z'$ by comparing the observed and expected events in each of the four signal regions. The $Z'$ signal is normalized according to the following formula:

$$N_{\text{expected}} = \sigma_{Z' \rightarrow tbW} \times \varepsilon \times L$$  \hspace{1cm} (9.1)

Where $\sigma_{Z' \rightarrow tbW}$ is the cross section for $Z'$ production assuming a 100% branching ratio to the $tbW$ final state, $\varepsilon$ is the total efficiency (corrected by appropriate data/MC scale factors) and $L$ is the integrated luminosity of our dataset. After properly normalizing the signal, we perform a shape analysis using the $M_{tbW}$ distribution which compares the new physics hypothesis with the standard model expectation produced by our background estimates.

We use a Bayesian method to extract 95% CL upper limits on the production of $Z'$s. We use a Poisson model for each bin of each channel of the analysis, where in each bin $i$ the mean of the Poisson distribution is given by:

$$\mu_i = k \beta_k \times T_{k,i}$$  \hspace{1cm} (9.2)

where $k$ includes the signal and background models and $T$ represents the fraction of
events expected from each process $k$. Our likelihood function is then:

$$L(\beta_k) = \prod_{i}^{\text{bins}} \frac{\mu_i \times e^{-\mu_i}}{N_{\text{data}}^i}$$  \hspace{1cm} (9.3)$$

where $\mu_i$ is the mean of the Poisson distribution in each bin $i$, given in terms of $T$, the number of events expected from each process $k$.

We use the Theta package [40] to set limits, as well as to perform pseudoexperiments to calculate 68% and 95% upper bounds on the limit bands. The pseudoexperiments take into account the systematic effects as nuisance parameters. These nuisance parameters are varied within their uncertainties and the posterior is refit for each pseudoexperiment.

The resulting limits from the Type 1 channel, the Type 2 channel, and from the combination of both channels are shown in Figures 9.8 through 9.10.
Figure 9.8: Limits from the Type 1 Channel.
Figure 9.9: Limits from the Type 2 Channel.
Figure 9.10: Limits from the combination of both channels.
Chapter 10

Conclusion

We have presented an initial effort in the search for a heavy $Z'$ decaying through the previously untested channel $tT'$. This analysis is complemented by a similar analysis in the all hadronic channel which isolates one top jet, on b jet and one W jet to reconstruct the full $Z'$ decay. An eventual combination of the two channels, using the full dataset available as of Summer 2016 will greatly expand the discovery potential of $Z' \rightarrow tT'$ searches.

However, this channel is only part of the a richer landscape of new searches which should be undertaken. A number of new theoretical models are emerging which hide new heavy resonances behind VLQ or other heavy fermions. Of particular interest is a model which, along with a $G^*$ and a heavy $W'$, predicts the existence of up to four new fermions: $T'$, $B'$, $T^{5/3}$ and $B^{2/3}$. The branching ratios of this modeal are plotted in Figure [10.1]. Most of these decay modes have never been tested.
In addition to these new models, the $Z' \rightarrow bB'$ complement to our search has not been performed. All these searches share similar final states and backgrounds. The analysis techniques presented here, especially the data-driven estimates, lend themselves naturally to these channels.

Searches for simpler signatures such as $Z' \rightarrow t\bar{t}$ will continue to push to higher masses as new data accumulates, but the exclusion of a new $Z$-like boson is not complete until these composite channels have been checked.
Chapter 11

Appendix:

11.1 Dependence of $\tau_2/\tau_1$ on the jet $p_T$

A first attempt of the background estimate in the Type 2 region was performed similarly to the Type 1 region, but used the W mass and $\tau_2/\tau_1$ variables to define the signal, antitag and sideband regions. In addition, it was found that we must take into account the dependence on the tagging rate on event $HT$. As shown in Figure 11.1, there is a pronounced dependence in $\tau_2/\tau_1$ on the HT of the event and (equivalently) on the $p_T$ of the tagged jet. To account for this dependence, we compute the conversion factor in bins in HT of width 25 GeV spanning the range $HT \in [1000, 4000]$. The corrective effect of this modification can be seen in Figure 11.2, which shows the estimate performed in the preselection with just a W tag applied, with and without the HT binning. An example fit over all HT bins for the conversion
factor can be found in Figure[11.3]

Figure 11.1: Dependence of N-subjetiness variables on jet $p_T$ and event HT. A linear function is fit to the average value of the N-subjetiness variable as a function of $p_T$ and HT. Note the considerably steeper dependence of $\tau_2/\tau_1$ compared to $\tau_3/\tau_2$ requires us to bin the Type 2 Channel background estimate in HT.

As a consistency check, we apply the same procedure to $W + jets$ MC and check that the fit properly predicts the value of $C_{p/T}$ in the signal region. The result of this fit can be seen in Figure[11.4]. As a final consistency check, we apply the background estimate to a sideband region where the leptonic ID requirements have been inverted (see Figure[11.5]).
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Figure 11.2: Effect of HT binning on our estimate. The figure on the left shows an estimate of the preselection with just a W tag applied without taking into account the dependence of $\tau_3/\tau_1$ on the HT of the event. The figure on the right makes the same estimate but divides the preselection into a number of HT bins, computes the estimate in each bin, then adds the results for a final combined estimate. The pull plots in both figures represent only the statistical error in data, not the errors in the fits. Considerable improvement can be seen when switching to the second method.
Figure 11.3: Fit for the mass dependence of the conversion factor $C_{p/f}$ in the Type 2 Channel, for the all HT.
Figure 11.4: Consistency check of linear fit in W+jets MC for the Type 2 Channel. The red points are not used in the fit but represent the value of the conversion factor measured directly in the signal region.
Figure 11.5: Prediction of events in the leptonic closure sideband for the Type 2 Channel, which mimics the signal region except that the requirement that the lepton pass the Loose ID cut is inverted.
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11.2 Results in 2012 Data at 8 TeV

The full background estimate of the signal regions is shown in Figures 11.6 through 11.9. The systematic uncertainties in the and non-top are taken from their respective fits and need no further correction. The uncertainty in the single top distribution is taken as a flat 20% normalization uncertainty. The Type 2 channel at 8 TeV used the n-subjetiness variable $\tau_2/\tau_1$ for the background estimate, but did not correct for any $p_T$ dependence. Further, in both channels, the Pruned Mass was used in lieu of the Soft Drop Mass.

To estimate the sensitivity of our analysis to a heavy particle decaying to a top and a heavy top, we consider three signal samples obtained from FastSim in which a generic $G^*$ particle decays to $tT \rightarrow tb\ell\nu$. The mass of the $T$ is fixed to be two thirds that of the $G^*$. This signal is purely representative: the cross section is set to 0.1 pb for the purpose of setting expected limits. The limits are set using the Theta statistics package. We plot sensitivity for the analysis in Figures 11.10, 11.11 and 11.10.
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Figure 11.6: Full background estimate in the signal region for the hadronic top, muon channel. (Data from 2012 Run 1, at 8 TeV)
Figure 11.7: Full background estimate in the signal region for the hadronic top, electron channel. (Data from 2012 Run 1, at 8 TeV)
Figure 11.8: Full background estimate in the signal region for the leptonic top, muon channel. (Data from 2012 Run 1, at 8 TeV)
Figure 11.9: Full background estimate in the signal region for the leptonic top, electron channel. (Data from 2012 Run 1, at 8 TeV)
Figure 11.10: Sensitivity of the analysis to a $tT'$ signature (in pb), using only the Type 1 Channel. (Data from 2012 Run 1, at 8 TeV)
Figure 11.11: Sensitivity of the analysis to a $tT'$ signature (in pb), using only Type 2 Channel. (Data from 2012 Run 1, at 8 TeV)
Figure 11.12: Sensitivity of the analysis to a $tT'$ signature (in pb). (Data from 2012 Run 1, at 8 TeV)
11.3 Behavior of $\tau_N/\tau_{N-1}$ fitting function

We have found that a polynomial function is a good model for the pass-fail ratios of cuts on $\tau_N/\tau_{N-1}$. This is a useful and common approximation. Out of mathematical curiosity we investigate what behavior we expect should truly describe the distributions.

First, consider the example of $\tau_3/\tau_2$. The distribution in mass of this variable is shown in Figure 11.13. We have annotated the figure to show two values: the mean of the distribution in any slice of mass, which we will call $\mu(m)$ and the value of the cut which we are evaluating, which we call $c$. Each slice in mass has a roughly Gaussian distribution, as shown in Figure 11.14.
Figure 11.13: Definitions of $c$ and $\mu$ (which is a function of mass). Note that $\mu$ is roughly linear.
Figure 11.14: Roughly gaussian behavior of individual slices of $\tau_N/\tau_{N-1}$. 
Treating $\mu(m)$ as roughly linear and the distribution of the tagging variable in each slice as roughly Gaussian, we can sketch a diagram (Figure 11.15) from which we can obtain, exactly, the conversion factor. Regions A and B meet at $c$, and regions B and C meet at $\mu(m)$. Calling this Gaussian distribution $G$, the areas of parts A, B and C of the diagram are:

\[
\text{Area of A} = \int_{-\infty}^{c} G(x) \, dx \quad (11.1)
\]

\[
\text{Area of B} = \int_{c}^{\mu} G(x) \, dx \quad (11.2)
\]

\[
\text{Area of C} = \int_{\mu}^{\infty} G(x) \, dx = \sigma \sqrt{2\pi} \quad (11.3)
\]
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Where $\sigma$ is the width of the Gaussian (and a function of the mass slice $m$ which we are looking at). Here however we may exploit a symmetry of the distribution. Notice that:

$$\frac{A}{C + B} = \frac{C - B}{C + B} = C \times \frac{1 - B/C}{1 + B/C}$$

(11.4)

We know the area covered by $C$, it’s just half of the Gaussian. $B$ can be obtained from the $Erf$, so that:

$$\frac{N_{\text{pass}}}{N_{\text{fail}}} = \sigma \sqrt{2\pi} \left( \frac{1 - \frac{1}{2} Erf(\sigma (\mu - c) \sqrt{2})}{1 + \frac{1}{2} Erf(\sigma (\mu - c) \sqrt{2})} \right)$$

(11.5)

Erf is a tricky function, but we can expand it, substituting $z \equiv \sigma \times (\mu - c)$:

$$\frac{N_{\text{pass}}}{N_{\text{fail}}} = \sigma \sqrt{2\pi} \left( 1 - \sqrt{\frac{8}{\pi}} z + \frac{4}{\pi} z^2 + \frac{4\sqrt{2}(\pi - 3)}{3\pi^{3/2}} z^3 - O(z^4) \right)$$

(11.6)

A note on the value $z$: it is just $\sigma \times (\mu - c)$ which is the product of two numbers smaller than one. From Figure 11.14 $\sigma$ is around 0.2 and the difference between the average values and the cut is also around 0.2. The result is that $Z$ is order $10^{-2}$. If we permit ourselves to drop higher terms of $z$, we are left with a simple approximation:

$$\frac{N_{\text{pass}}}{N_{\text{fail}}} = \sigma(m) \sqrt{2\pi} - z(m) \sqrt{8/\pi}$$

(11.7)

This is not a particularly satisfying result, as the true functional form depends on the exact behavior of the width and mean of the N-subjetiness distribution on mass.
Nonetheless, since neither of these variables appears to exhibit behavior greatly deviating from linearity, we are left with a simple polynomial of $m$, the mass.
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