Hadronic $W$ Reconstruction in the Search for a Fourth-Generation Down-type Quark

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Abstract

This paper explores an alternative means of hadronic $W$ reconstruction in the search for a fourth-generation down-type quark. Whereas previous methods of reconstruction used anti-$K_t$-4 dijets, proposed reconstruction involves single anti-$K_t$-4 jets as well as dijets. This new means of hadronic $W$ reconstruction improves expected limit-setting by 40 GeV and raises the possibility of further improvements through a different binning system.
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1 Introduction

1.1 The Standard Model


Of the four fundamental forces in the Universe (the strong force, the weak force, the electromagnetic force and gravity), it is known that the first three result from the exchange of force-carrying particles called bosons. The strong force is carried by the gluon, the weak force by the W and Z bosons, and the electromagnetic force by the photon. The fifth boson is the recently-discovered Higgs boson, which accounts for the origin of particle mass. Gravity is not included in the Standard Model, since physicists have been unable to reconcile quantum physics and general relativity, and thus there is no theory of quantum gravity.

The twelve matter particles, the fermions, are divided into two categories: quarks and leptons. There are 6 quarks and 6 leptons in the Standard Model, and both are sorted into three generations, each with two particles. The lightest and most stable particles are in the first generation, while the second and third generations consist of heavier, less stable particles. Each fermion also has its corresponding antiparticle.

Quarks are matter particles that carry charge and color charge, and flavor and thus interact via the electromagnetic, strong and weak forces. They bind
together in triplets (called baryons) or pair (called mesons) such that the composite particle has neutral color charge - if a quark is isolated, a new quark/anti-quark pair forms to maintain color-neutrality. The six known quarks include the up, down, strange, charm, top and bottom quarks. Each generation (up/down, strange/charm, top/bottom) consists of an up-type quark with charge $\frac{2}{3}$ and a down-type quark with charge $-\frac{1}{3}$. [?]  

1.2 Motivation for Research

The standard model currently includes three generations of quark, but there is no reason why there might not be a fourth. A fourth generation of quarks would be a natural extension to the Standard Model - it would not break any symmetries, not introduce any new ones. Furthermore, the addition of a fourth generation of quark might lead to additional CP symmetry violation, which would help explain the particle-antiparticle asymmetry of the universe. [?]  

1.3 Decay Channel

Assuming that $b'$ is chiral and has a mass greater than that of $m_t + m_W$, it will decay primarily as $b' \rightarrow Wt \rightarrow WWb$. Pair-production of $b'$ then yields four $W$ bosons and two $b$-quarks. 

Each $W$ boson can decay leptonically into a lepton and corresponding neutrino, or hadronically into two jets. Though hadronic decay has a higher branching ratio than leptonic decay, hadronic decay does not stand out from background events. For this reason, this analysis examines the channel where one $W$ boson decays leptonically, and the other three decay hadronically. 

The main source of background for this decay channel comes from $t\bar{t}$ production with additional jets. Other sources of background include $W$+jets, $Z$+jets
where a lepton is missed, and multi-jet background in which a jet is misidentified as a lepton.

2 The Experiment

2.1 The LHC

The Large Hadron Collider is the world’s largest and most powerful particle collider, hosted by the European Organization for Nuclear Research (CERN), and forms a 27-km ring buried about 100m beneath France and Switzerland. The LHC collides two beams of protons or heavy ions which are guided by superconducting magnets. It was designed to operate at a center of mass energy $\sqrt{s} = 14$ TeV, and has been running since 2010 at 3.5 TeV per beam, or a center of mass energy of 7 TeV. [?]

2.2 ATLAS

ATLAS (A Toroidal LHC ApparatuS) is one of four main LHC experiments. ATLAS is a general-purpose multi-layer detector, 46m long, consisting of 4 major components: the inner detector, calorimeter, muon spectrometer and magnet system. [?] ATLAS uses a right-handed cylindrical coordinate system, with the z-axis along the beam-pipe. $\theta$ is defined as the angle measured from the z-axis, and pseudorapidity as $\eta = -\log(tan(\frac{\theta}{2}))$. This measurement will be referred to throughout this paper.

3 Current Analysis

The current analysis considers the scenario where each $b'$ decays exclusively to a top-quark and a $W$ boson, yielding $t\bar{t}W^+W^-$. The detector signature is expected to resemble $t\bar{t}$ with additional jets from the additional $W$ bosons, so recommendations from the ATLAS Top Group’s study of lepton + jets decays of $t\bar{t}$ have been applied. The largest background is $t\bar{t}$ with additional jets.

In the lepton + jets decay channel of $b'\bar{b}'$, expected results of decay include one lepton, missing transverse energy ($E_T^{miss}$) from the undetected neutrino, and a peak at six energetic jets (as shown in Figure 2).

3.1 Selection

3.1.1 Object Selection

The object selection defined by the ATLAS Top Group’s study of the lepton + jets decay of $t\bar{t}$ is applied. A detailed description of the cuts is available in the most recent $t\bar{t}$ documentation.
Electrons: Electrons are found by a colorimeter-seeded reconstruction algorithm. They are required to satisfy \( E_{\text{cluster}}/\cosh(\eta_{\text{track}}) > 25 \text{ GeV} \) in a pseudorapidity range \( |\eta_{\text{cluster}}| < 2.47 \) but excluding a crack region of \( 1.37 < |\eta_{\text{cluster}}| < 1.52 \). Electrons must also satisfy calorimeter isolation \( I_{\text{cal}} < 3.5 \text{ GeV} \) in an \( \eta - \phi \) cone of 0.2. A corrected isolation provided by the CaloIsoCorrection tool contained in egammaAnalysisUtils-00-02-34 is used, which corrects for pileup and electron \( p_T \) leakage. The electron quality requirements match the definition for Tight with a matching track as defined by the electron performance group [?]. Additional electron reconstruction details can be found in [?].

Jets: Jets are reconstructed from topological calorimeter clusters [?] using the \( R = 0.4 \) anti-\( k_T \) algorithm [?]. These jets are then calibrated to the hadronic energy scale using jet \( p_T \) and \( \eta \) dependent correction factors obtained from simulation [?]. They are required to satisfy jet \( p_T < 25 \text{ GeV} \) and \( |\eta| < 2.5 \). The closest jet to an electron in an \( \eta - \phi \) cone of 0.2 is removed, but only electrons that match all other selection requirements are checked. The electron calorimeter cluster \( \eta \) and \( \phi \) are used for this calculation. Additional jet reconstruction details can be found in [?].

Muons: Muons are found with the Muid [?] Combined algorithm, which requires that objects detected in the muon spectrometer and reconstructed with the Muid algorithm also have a matched track in the ATLAS inner detector. A loose cosmic reduction is applied by removing all muon pairs satisfying \( |d_0| > 0.5 \text{ mm}, \Delta\phi > 3.1, \) and opposite sign \( d_0; d_0 \) is the transverse impact parameter with respect to the beam spot. Muon candidates must satisfy \( p_T^\mu > 20 \text{ GeV} \) and \( |\eta| < 2.5 \). Numerous track requirements are also imposed; more details can be found in the supporting note. [?]. Finally, all muons within a \( \eta - \phi \) cone of 0.4 of any jet with \( p_T^\mu > 20 \text{ GeV} \) are removed. Additional muon reconstruction details can be found in [?].
• Missing transverse energy: The algorithm used to reconstruct $E_T^{\text{miss}}$ was provided by the Jet/$E_T^{\text{miss}}$ Working group:

"The $E_T^{\text{miss}}$ is constructed from the vector sum of topological calorimeter cluster deposits, resolved into the transverse plane. Deposits not associated with a jet or electron are included at the EM scale. Deposits associated with jets are taken at the corrected energy scale that was used for jets, while the contribution from deposits associated with electrons are substituted by the calibrated transverse energy of the electron, taking away the correction for out-of-cluster effects to avoid double cell energy counting. Finally, the contribution from muons are included after an adjustment for muon contribution to calorimeter energy deposits" [?]

3.1.2 Event Selection

The event selection is also defined by the Top Group lepton + jets selection for decays of $t\bar{t}$. A detailed description of the cuts is available in the most recent $t\bar{t}$ documentation.

• The event must have a primary vertex with at least 5 tracks.
• The event must pass data quality and event cleaning cuts.
• Exactly one lepton ($e$ or $\mu$) must pass selection from Section 3.1.1.
• The event must pass trigger requirements and must have a trigger-matched lepton within an $\eta - \phi$ cone of 0.15. The trigger matched lepton must pass the selection criteria defined in Section 3.1.1. No trigger matching is done for muons in either data or Monte Carlo.
• At least one jet in the event must pass selection from Section 3.1.1
• To reduce QCD background, the following cuts used by the Top-group have been implemented, known as the "triangle cut":
  - $e$-channel: $E_T^{\text{miss}} > 35$ GeV and $m_W > 25$ GeV
  - $\mu$-channel: $E_T^{\text{miss}} > 30$ GeV and $E_T^{\text{miss}} + m_W > 60$ GeV

3.2 Event Reconstruction

The $b'$ signal is distinguished from the background by having many jets with larger $E_T$ than those produced from gluon radiation (see Figure 3). These additional jets come from the hadronic decays of $W$ bosons, which themselves have significantly more $p_T$ than $W$'s produced from backgrounds, as can be seen in Figure ???. Leptons originating from the $W$ boson produced by the $b'$ decay (rather than the subsequent $W$ from top decay) will also have larger transverse momentum than that expected from top quark pair production.
For each event, two quantities are calculated that help distinguish the $b'$ signal from the background:

- Jet multiplicity: the number of reconstructed jets in the event
- The number of reconstructed $W$ bosons, discussed below.

Events passing event selection with more than 6 jets are binned into nine different categories based on their jet multiplicity and number of reconstructed $W$s: events can have 6 jets, 7 jets or 8+ jets, and 0, 1 or 2+ hadronic $W$s. These nine categories are then used for limit setting. Details regarding systematics and statistics for this analysis can be found in the supporting note [?].

### 3.2.1 Hadronic W Reconstruction

In the lepton + jets channel each $b'$ decay produces three hadronic $W$ bosons in addition to the leptonically decaying $W$. To reconstruct the $W$ masses in the high-multiplicity environment, jets are selected which fall within $\Delta R < 1.0$ of each other. Each unique jet pair with an invariant mass in the $W$-mass window, 70-100 GeV, is counted as a reconstructed $W$. Note that any jet may only be part of one jet pair.

### 4 Modified Hadronic W Reconstruction

#### 4.1 Motivation

So far, studies from ATLAS in the $b\bar{b}' \rightarrow lepton + jets$ channel with $1 \text{ fb}^{-1}$ of data have excluded $b'$ for masses lower than 480 GeV with 95% certainty,
Figure 5: These plots are normalized to 1, in order to compare their shapes. The $\Delta R$ peak at 0.4, the point at which jets are as close together as possible, increases with mass. This shows that, at higher $b'$ masses, jets become more highly boosted and closer to each other, to the point of overlapping.

and studies from CMS in the same sign di-lepton and tri-lepton channel with 4.9 $fb^{-1}$ have excluded $b'$ for masses lower than 611 GeV with 95% certainty. With these limits, studies on $b'$ are looking at very massive particles. When a very massive particle decays, it imparts a lot of energy to its decay products, giving them a higher transverse momentum: they are 'boosted'. If the two jets emerging from the decay of the hadronic $W$s are boosted, they do not fall into two distinct areas when they hit the detector. Depending on how boosted they are, the jets overlap a little, or even fall on top of each other entirely. Yet the current method of hadronic $W$ reconstruction, which looks for a dijet pair, misses these highly energetic hadronic $W$s.

The current analysis reconstructs hadronic $W$s by searching for a pair of jets reconstructed with the anti-\(K_t\) algorithm with $R = 0.4$ that are very close to each other, with $\Delta R <= 1.0$. But in the case where the two jets from the hadronic $w$ decay begin to overlap, a single jet with a wider radius might perform better. If the jets are so highly boosted that they overlap completely, a single jet with the $R = 0.4$ might also yield hadronic $W$s. For this reason, single jets with $R = 1.0$ (anti-$K_t$-10 jets) were compared with single jets with $R = 0.4$ (anti-$K_t$-4 jets) and with dijets with $R = 0.4$ (anti-$K_t$-4 dijets) in terms of hadronic $W$ reconstruction.

4.2 Selection of Jet Types

As can be seen in figure ?? The mass of anti-$K_t$-4 jets, anti-$K_t$-10 jets and anti-$K_t$-4 dijets with a $\Delta R$ cut of 1.0 all show a peak around 80 GeV - the mass of a $W$ boson - which increases for higher $b'$ mass.

These peaks also become even more distinct when higher $p_T$ cuts are applied, as can be seen in Figure ???. From this, it can be concluded that these peaks contain jets that correspond to hadronic $W$s.
Figure 6: These plots are normalized to 100,000 events before selection. Each of the three candidate jet-types for hadronic W reconstruction - single ant-$K_t$-4 jets, anti-$K_t$-4 dijets, and single anti-$K_t$-10 jets - show a mass peak around 80 GeV
Figure 7: These plots are normalized to 100,000 events before selection. The 80-GeV mass peaks for the three types of jets survive a $p_T$ cut of 250 GeV.

Figure 8: This plot contains the masses of different jet-type candidates for hadronic W reconstruction for signal with a mass of 800 GeV. They are normalized to 100,000 events before selection.
A comparison of the mass plots for the three different means of hadronic W reconstruction (Figure ??) shows that the anti-$K_{T}$-4 peaks are much more well-defined than that of the anti-$K_{T}$-10 peak. This means that the peaks for the anti-$K_{T}$-4 jets and dijets have a higher ratio of hadronic Ws to other jets. Furthermore, combining anti-$K_{T}$-10 jet hadronic W reconstruction with reconstruction from anti-$K_{T}$-4 jets would involve a complicated procedure to remove overlap between the two jet types.

However, the single anti-$K_{T}$-4 jet and anti-$K_{T}$-4 dijet methods of hadronic W reconstruction can be easily combined by forming Ws first from single anti-$K_{T}$-4 jets and then from dijet pairs amongst the remaining jets. This is an easily-implemented means of improving hadronic reconstruction W.

### 4.3 Cuts

To optimize hadronic W reconstruction, cuts were made upon the $p_{T}$ and mass window of the single-jet reconstructed hadronic Ws, and upon the $\Delta R$ and mass window of the dijet-reconstructed hadronic Ws.

To do this, a technique involving truth-jet matching was used. Jets were considered 'matched' to jets from truth Ws if they fell within $\Delta R < 0.05$ and mass window 60-100 GeV. These matched jets represented what the products of Ws look like after being run though detector. By plotting the value of $p_{T}$ and $\Delta R$ for these jets, it was possible to get a general range for cuts to isolate the hadronic Ws. Within those ranges, the combination of cuts that resulted in the highest $\sqrt{\text{signal}/\text{background}}$ ratio was chosen.

For single-jet reconstructed hadronic Ws, a $p_{T}$-cut range of 250-250 GeV was chosen based upon truth matching. From within this range, a final $p_{T}$ cut of 250 GeV and a mass window of 60-100 GeV was chosen. The plots prompting these cuts can be seen in Figure ??

For dijet-reconstructed hadronic Ws, a $p_{T}$ cut range of 0-200 GeV and a $\Delta R$ range of 0.6 - 1.0 were chosen. After plotting $\sqrt{\text{signal}/\text{background}}$ for all possible combination of $p_{T}$ cut, $\Delta R$ cut and various mass ranges, a final $\Delta R$ cut of 0.8, no $p_{T}$ cut and mass range of 70-100 GeV was chosen. The plots prompting these cuts can be seen in Figure ??

To summarize, the new proposal for hadronic W reconstruction involves accepting anti-$K_{T}$-4 jets that pass a $p_{T}$ cut of 250 GeV and are within a mass range of 70-100 GeV as single-jet reconstructed hadronic Ws. From the remaining jets, any dijet pairs that are within $\Delta R < 0.8$ of each other and a mass window of 70-100 GeV are accepted as dijet-reconstructed hadronic Ws. The total number of hadronic Ws is the sum of these two varieties.
Figure 9: Based upon the truth-matching plot, a $p_T$ cut range of 250-350 GeV was chosen. After plotting $\frac{\text{signal}}{\sqrt{\text{background}}}$ for all possible combinations of $p_T$ cut and various mass ranges, a final $p_T$ cut of 250 GeV and mass range of 70-100 GeV was chosen.
Figure 10: Based upon the truth-matching plots, a $p_T$ cut range of 0-200 GeV was chosen, as was a $\Delta R$ range of 0.6-1.0. After plotting $\frac{\text{signal}}{\sqrt{\text{background}}}$ for all possible combination of $p_T$ cut, $\Delta R$ cut and various mass ranges, no $p_T$ cut, a final $\Delta R$ cut of 0.8 and a mass range of 70-100 GeV were chosen.
4.4 Impact upon Analysis

Applying the proposed method of hadronic $W$ reconstruction improves the expected limit setting for the analysis. If no signal exists, an analysis with the previous reconstruction method could exclude $b'$ quarks with a mass below 650 GeV with a 95% confidence level. The proposed method of reconstruction, however, increases that limit to 690 GeV, as can be seen in Figure ??.

Furthermore, distinguishing between hadronic $W$s reconstructed from single jets and hadronic $W$s reconstructed from dijets opens the possibility of using more bins for the analysis. Since hadronic $W$s reconstructed from single jets are very highly boosted, they are likely a better discriminant between signal and background than dijet-reconstructed hadronic $W$s, particularly at high masses for $b'$. A new set of bins, grouped by number of jets, number of single-reconstructed hadronic $W$s and number of dijet-reconstructed hadronic $W$s might well improve limit-setting even further.

5 Conclusion

The proposed means of hadronic $W$ reconstruction improves expected limit setting, and will be incorporated into the progressing analysis. It is predicted that the new method will be particularly helpful when the LHC begins to run at 8 TeV. There is further potential to improve limit-setting by exploring different means of binning that differentiate between hadronic $W$s reconstructed from single jets and those reconstructed from dijets. Additionally, it would be worthwhile to reinvestigate using anti-$K_{T}$-10 jet for hadronic $W$ reconstruction for 8 TeV.
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References


