Searching for $\boldsymbol{W'}$ bosons at LHC with single top production

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One of the strengths of the LHC is its capacity for the discovery of new physics. As a consequence of many BSM theories, W' bosons make an ideal particle to search for to constrain many models. One mode in particular has relatively low background: Single top quark production mediated by a W' boson. For W' masses less than 1500 GeV, all the decay products of the top quark are visible, and the strongest channel is the top's decay into an electron or muon, with the associated neutrino and a bottom jet. As the W' mass increases, the decay products from the highly boosted top and bottom quarks from the W' appear as fat jets; boosted top tagging algorithms abound, and we propose a boosted bottom tag to set an exclusion limit of 2750 GeV for standard model-like couplings with existing 8 TeV data.

1. Introduction

The Large Hadron Collider is the best tool for discovering new particle resonances in existence today. Resonance searches can be used as a powerful tool for constraining many new theories; few are as powerful as the W' particle. A model independent search for the W' can reveal restrict many theories, from $SU(3)_L$ x $SU(3)_R$ to extra dimensions. A W' search through the top-bottom decay channel is accessible for all unexcluded masses, most theoretical couplings, and both chirailties (the lepton-neutrino channel cannot detect right-handed W's without right-handed neutrinos). For our analyses, we use the general Lagrangian [1, 2]:

$$\mathcal{L} = \frac{g'}{2\sqrt{2}} V'_{ij} W'_{\mu} \bar{f}^i \gamma^{\mu} (1 \pm \gamma_5) f^j + \text{H.c.}\,, \qquad (1)$$

When analyzing decays including top quarks, there are two important regimes to be studied. In a non-boosted regime with relatively low-mass W's ($m_{W'} < 1.5$ TeV), the most efficient method is to look at the leptonic decay channel of the top quark, discussed thoroughly in Ref. [3]. For more highly boosted channels ($m_{W'} > 1.5$ TeV), leptons fail isolation cuts, and using a boosted top tagging algorithm is better (Ref. [4]). For optimal signal to background, an additional cut must be placed to restrict the dijet background. A b-tag is normally the best way to reduce a light jet background, but for high-mass W's the traditional secondary vertex tagger will fail due to highly suppressed decay angle. To combat this, we propose to use a "boosted bottom tag" to suppress the light jet background. The most effective way to do this is restricting the $\Delta R_{\mu,\mathrm{jet}}$ and the muon p_T.

We use the MadGraph and MadEvent [5] programs for event simulations. For our non-boosted regime analysis, we also used the PYTHIA program [6] for showering and PGS [7] for detector simulation. A MCFM [8] analysis was also done to calculate K-factors at next leading order. For the boosted regime, we use top and bottom tags on the MadEvent output. The top tag simulates the CMS top tagger [9] algorithm, looking for three subjets in a R=1 Cambridge-Aachen jet. The boosted b tag was developed by analyzing b decays through PYTHIA and PGS. We propose using bbj data to extract the tagging efficiencies in situ.

2. Non-boosted Regime

To analyze the non-boosted regime for W' decay, we choose to look at the $bblv$ final state. The final state in the detector from the top decay should be an electron or muon, a b tagged jet, and missing energy; there should also be a highly energetic recoiling jet, which may or may not be b-tagged with a traditional b tag. The best way to reduce background is to reconstruct the top quark; using the known W mass, missing energy, and the lepton four-vector to reconstruct the W, then adding the tagged b jet to reconstruct the top quark.

There are strong differences in shape between both positive and negative W's, as well as between left- and right-handed W's. The jet from the top-decay tends to have a larger E_T when coming from the left-handed decay. The differences between positive and negative W's are twofold. The recoiling high energy jet will tend to be more central in a W'^- decay, whereas the W'^+ has a double-peaked structure in pseudorapidity. Conversely, the leptons from W'^- top decays tends to be more central than those from W'^+.

The cuts used include transverse energy (E_T) cuts on the primary and secondary jets, as well as cuts on the lepton and missing energy. The lead jet, assumed to be the recoiling b, is required to have $E_T > 0.2 m_{W'}$. The secondary jet is required to be b-tagged and have $E_T > 20$ GeV. The lepton is required to pass isolation cuts and have $p_T > 20$ GeV, and the missing transverse energy (MET) greater than 20 GeV. Finally, all jets and leptons used must have a pseudorapidity (η) less than 2.5 ($|\eta| < 2.5$). Using the missing energy and the lepton four-momentum, if we assume the W to be produced on-shell, we can reconstruct the neutrino four-momentum up to a twofold ambiguity. Choosing the smallest rapidity solution for the neutrino, we can then fully reconstruct the 'top quark'; we apply an upper cut on $M_{l\nu b} < 200$ GeV. Finally we fit to a mass window of $0.75 m_{W'} < M_{l\nu bj} < 1.1 m_{W'}$. With all the cuts in place, the maximum detectable mass would be at approximately 1800 GeV, which agrees with the results of the CMS [10] and ATLAS [11] collaborations.

3. Interference

When modeling left-handed W's, the effect of interference should not be ignored. Depending on the model, the interference can be constructive or destructive. To retain generality, we present left-handed results as a band in the mass-coupling parameter space. We show that the effects of interference are predominantly just a rescaling of the shape of the cross-section curve at low masses if a search is done, but shrinks considerably if a narrow resonance search is done. At high masses the interference effects and the large widths produce small changes in the exclusion limits for left-handed W', with the destructive interference with the standard model process slightly reducing the significance for the corresponding signal (the only reason interference has an effect is that at high coupling, the peak is wide enough to interfere with the relatively low-mass SM W peak). For low to moderate mass W's ($m_{W'} < 2500$ GeV) however, the effect of interference is negligible, to the order of a few percent change on the resultant cross-section.

4. Boosted Regime

As the W' mass increases, the lepton is forced closer to the jet. This will prevent the lepton from being properly reconstructed due to failing isolation criteria. If instead we analyze top decays, it is possible to use jet substructure to tag the boosted top as a whole, instead of looking at the individual final state objects. This will unfortunately introduce a massive dijet background, which needs to be reduced through other methods even after using the top tagging algorithm on it. Commonly ignored backgrounds for top tagging algorithms are the Wjj and Zjj backgrounds; if one of the jets falls within the large jet radius of the tagging algorithm, all that remains is to pass a loose top mass cut for the jet to be accepted as a boosted-top jet.

When analyzing the Wjj and Zjj backgrounds to top tags, NLO radiation could significantly affect the amount of radiation near the vector boson (see Fig. 1). To model this effect, Wjj and $Wjjj$ events were compared in MCFM; they are found to be very different, with NLO effects being similar

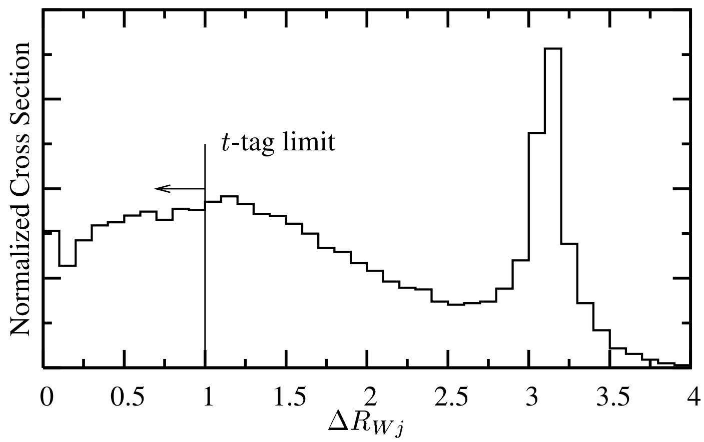

Fig. 1. The distance between the W and the nearest jet in Wjj events. Anytime the $\Delta R < 1$, the Wj combination has a chance of passing a top tag.

magnitude to leading order effects. This background will need to be carefully studied in experiment to accurately account for backgrounds to most single top-production processes.

A boosted top tagging algorithm to tag top jets is by itself very useful. This tag combined with a simple mass cut on the 'resonance' is enough to match the results from the non-boosted regime as described above. To truly gain an advantage over the non-boosted analysis, however, a cut must be placed on the recoil jet, which will be a b quark upwards of 99% of the time. Since a traditional b tagging algorithm relies heavily on vertex tagging, its effectiveness is greatly reduced as the energy of the jet increases. As the jet energy approaches 1000 GeV, it is unlikely the secondary vertex will be seen due to angle suppression of the decay products from the initial meson. This can be an advantage, however, when we look at the particulars of the B decay. While most of the decay products of the B will be quark matter, approximately 20% of B quarks will decay directly, or through an intermediate D meson, to a muon with additional quark radiation. Since muons are produced only rarely in light jet decays, the characteristics of this muon can be a large boon to salvaging a boosted-b tag.

We show that for high energy b jets, optimal cuts can be placed with the minimum muon $p_T > 20$ GeV, and a maximum $\Delta R_{\mu,j}$ of 0.1. This gives an ultimate b tagging rate of approximately 20% for high energy b jets, with lower tagging efficiencies for lower energy jets, as shown in Table 1. It can be shown through simple kinematic arguments that for a 20 GeV muon, the maximum radius of decay from a B meson is approximately 0.12

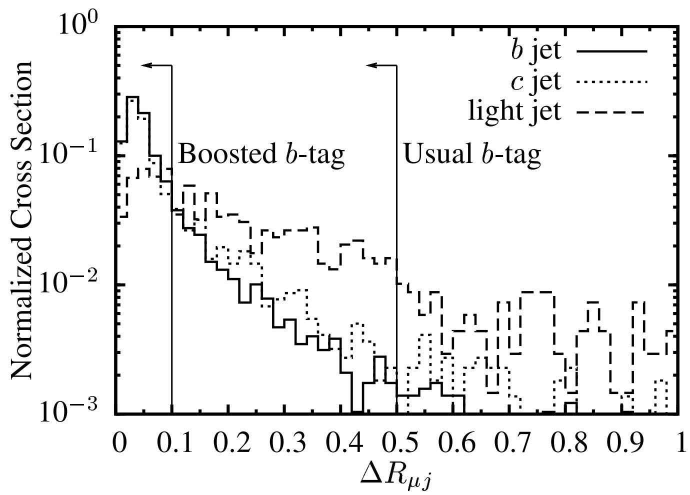

Fig. 2. The distance between muon energy and jet energy for b jets, charm jets, and light jets. Muons from heavy jets have a much higher chance of being central than light-quark initiated jets.

radians (shown in Fig. 2). The implications of this are that these cuts are synergistic with each other, and only occasionally will a muon with the specified criteria appear inside a light jet with these properties. Ultimately, although the acceptance rate is considerably lower, the tag to mistag ratio is comparable if not better than the standard secondary vertex tag, as long as the b is boosted enough.

Table 1. Boosted-bottom jet efficiencies using a muon tag with $p_{T\mu} > 20$ GeV and $\Delta R_{\mu j} < 0.1$ for b jets, c jets, and light jets j as a function of jet E_T.

Type	$E_{Tj} = 100$ GeV	400 GeV	1000 GeV
b	4.8%	11.8%	15.0%
c	2.1%	5.5%	7.5%
j	0.1%	0.4%	0.6%

With both the boosted top and boosted bottom tags in effect, the boosted object analysis can reach up to 750 GeV higher in mass than looking at isolated decay products. The ultimate limit of this method comes not from lack of signal or cut inefficiency, but from the characteristics of the signal itself. For W' masses above 2500 GeV (which require large couplings to identify), the width of the resonance becomes very large, approaching the mass. By g'/g=5 ($m_{W'}$=3 TeV), the width of the resonance required for detection is approximately 1000 GeV; the effect of this broadening means that

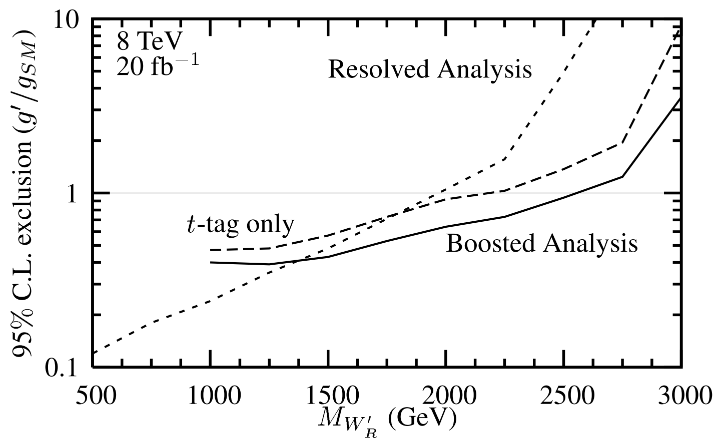

Fig. 3. 95% C.L. limit on the effective coupling g'_R relative to g_{SM} as a function of right-handed W'_R mass. Curves show the reach from current resolved-top quark analysis (dashed), the boosted-top analysis (dotted), and after adding a boosted-bottom tag (solid).

a simple peak search will fail due to the significantly more of the signal falling outside of the 'peak' region. The alternative, widening the search window, will introduce more background than signal for a broad peak, worsening the significance. Finally, the initial state parton luminosity falls rapidly for $m_{W'} > 3$ TeV, setting this as an approximate limit on any $m_{W'}$ search regardless of method, due to loss of signal.

5. Results

After making use of the cuts for the resolved (non-boosted) analysis, a $m_{W'}$ limit can be set at approximately 1800 GeV for both left and right handed W's at SM-like coupling. While some models can support greater than larger than SM couplings, even those are certainly ruled out by 2500 GeV, where g'/g =5 for exclusion.

Using the boosted analysis has advantages and disadvantages compared to the resolved analysis. The most obvious is at low $m_{W'}$ ($m_{W'}$ <1500), the coupling limit in the boosted analysis is less effective due to the low tagging efficiencies of tops and bottoms at low energies. The primary advantage is the higher reach of the analysis ($m_{W'}$ >2750 GeV) for SM-like couplings. In the mid-range regime, both analyses are competitive with each other, but the boosted analysis is the more powerful of the two for most masses, as long as the boosted b algorithm is used, otherwise the boosted analysis is only more powerful for excluding theories that allow for $g'/g > 1$.

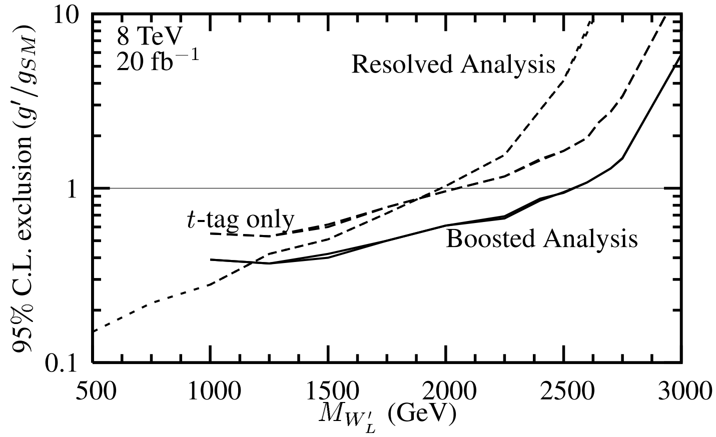

Fig. 4. 95% C.L. limit on the effective coupling g'_L relative to g_{SM} as a function of left-handed W'_L mass. Bands show the reach from current resolved-top quark analysis (dashed), the boosted-top analysis (dotted), and after adding a boosted-bottom tag (solid).

6. Outlook

By using the tb decay channel to its fullest extent, left handed W' bosons can approach the exclusion limits set by $W' > l\nu$ channel (the $l\nu$ final state will not appear for right-handed W's). The strength of the tb channel is twofold: Not only is it the only visible decay channel that will detect right-handed W's, but greater information could be gleaned about any potential signal due to the lack of missing energy in the boosted analysis, and the ability to fully reconstruct the mass resonance in the resolved analysis.

The boosted analysis will not be greatly affected by increases in pileup events, which is good for the LHC moving forward. The reason for this that high energy jets will be the least-effected by pileup (as opposed to light jets, which will suffer a larger percentage change in their energy due to pileup radiation). While large jet areas will suffer from more pileup than smaller jets, the jet substructure algorithms used in t tags will allow for significantly reduced excess energy in the 'fat' top jets. There is no reason this same analysis could not be used when the LHC turns back on at 14 TeV.

Acknowledgments

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References

[1] Zack Sullivan, Phys. Rev. D **66**, 075011 (2002).

[2] Yaofu Zhou and Zack Sullivan, "Modeling W' bosons for use with model independent studies," paper in production.

[3] Daniel Duffty and Zack Sullivan, Phys. Rev. D **86**, 075018 (2012).

[4] D. Duffty and Z. Sullivan, arXiv:1307.1820 [hep-ph].

[5] J. Alwall *et al.*, J. High Energy Phys. **09**, 028 (2007).

[6] T. Sjostrand, S. Mrenna, and P.Z. Skands, J. High Energy Phys. **05**, 026 (2006).

[7] J. Conway *et al.*, http://www.physics.ucdavis.edu/∼conway/research/software/pgs/pgs.html.

[8] J.M. Campbell and R.K. Ellis, Nucl. Phys. Proc. Suppl. **205-206**, 10 (2010).

[9] CMS Collaboration, CMS-PAS-JME-09-001.

[10] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Lett. B **718**, 1229 (2013).

[11] G. Aad *et al.* (ATLAS Collaboration), Phys. Rev. Lett. **109**, 081801 (2012).