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Searches for Vector-like Quarks, $t\bar{t}$ and tb resonances with the ATLAS Detector

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Abstract

Various extensions of the Standard Model predict the existence of new types of quarks or bosons. We report on searches for vector-like quarks decaying to a Z boson and a top quark or bottom quark and new resonances decaying to a top-antitop pair and a top-antibottom pair. Several of these searches include the use of boosted top quark reconstruction techniques. These searches use the data sample recorded in 2012 at $\sqrt{s}$=8 TeV centre-of-mass energy by the ATLAS experiment at CERN's Large Hadron Collider. In these searches no evidence for new physics is observed.

Keywords: ATLAS, Exotics, Beyond the Standard Model, vector-like quarks, top-antitop, top-antibottom, boosted

1. Introduction

The Standard Model (SM) of particle physics is one of the most thoroughly tested theories ever and provides a successful description of high-energy physics experimental data. To date there have been no significant discrepancies between SM predictions and the data collected by the ATLAS experiment [1] at the LHC [2]. However, there are several outstanding features of the universe that remain beyond explanation in the SM, among them the existence of dark matter and dark energy, the number of particle generations and the hierarchy problem. These features motivate new, Beyond the SM (BSM) theories that incorporate solutions to one or more of these questions. For experimentalists BSM theories become particularly interesting when they predict potentially observable phenomena at the TeV scale, within the reach of the ATLAS experiment.

In this review we present an overview of several searches for BSM physics involving the decay of new, heavy particles to top and bottom quarks, either alone or with a boson. Models that predict such decays include those with vector-like quarks (VLQs) that mix preferentially with the 3rd generation, as well as Topcolor, Composite Higgs and Randall-Sundrum models which predict new vector bosons (Z', W') or Kaluza-Klein gluons (g_{kk}) that may couple to the third generation.

2. Vector-like Quarks

The first set of analyses discussed are searches for VLQs. The addition of fourth generation quarks with SM-like chiral couplings is strongly disfavored by the recent Higgs boson observation. However VLQs, where the left- and right-handed components of these new fermions characteristically have identical electroweak gauge transformations, are allowed. For example, Little Higgs and Composite Higgs models (in which the Higgs boson emerges as a pseudo-Nambu-Goldstone boson) predict new, heavy partners of the top and bottom quarks with charges +2/3 and −1/3, respectively. These models are particularly interesting as the top partner may have a role in regulating the Higgs mass divergence. In these models pair production through the strong interaction dominates at low mass (< 1 TeV), as shown in Fig. 1. The only tunable input is m_Q, the mass of the new, heavy quark. Single production (through the electroweak interaction) becomes more important at higher masses. However, the rate of single production depends on both m_Q and a model dependent coupling parameter. The VLQ can decay through a variety of channels through $Q \rightarrow Vq$ where Q is the VLQ, V is a Z, W

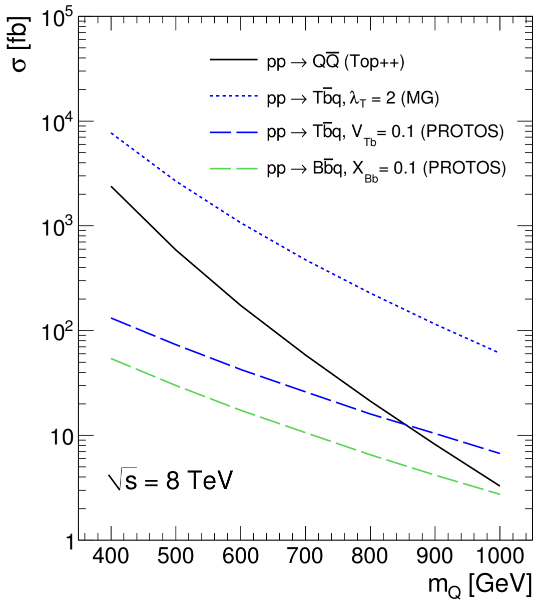

Figure 1: The $\sqrt{s}$ = 8 TeV LHC cross section versus quark mass for pair production, denoted by the solid line, as well as for the Tbq and Bbq single production processes, denoted by dashed lines. The pair production cross section has been calculated with Top++. The single production cross sections were calculated with Protos and Madgraph.

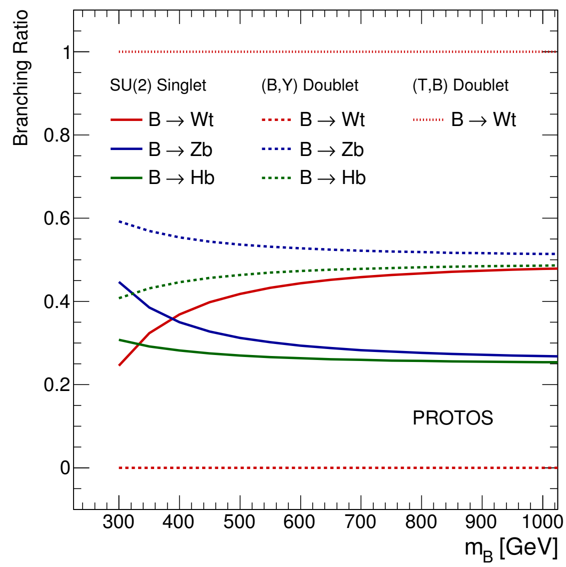

Figure 2: Vector-like T quark branching ratios to the Wb, Zt, and Ht decay modes versus the T quark mass, computed with Protos for an $SU(2)$ singlet and two types of doublets. The X quark in an (X,T) doublet has charge +5/3.

or Higgs boson, and q is a SM (here assumed to be a third generation) quark. As an example, the branching ratios for T decay are shown in Fig. 2. The many decay channels provide diverse final states for analyses.

The most recent VLQ results from the ATLAS collaboration use a multi-lepton signature to search for both the pair and single production of vector-like heavy top and bottom quark partners T and B, where $T \to Zt$ and $B \to Zb$ [4]. Events with a Z boson candidate are selected by requiring at least one pair of same flavor leptons (electrons or muons) with opposite electric charge. Z boson candidates are reconstructed if the invariant mass of a same-flavor opposite-charge lepton pair differs from the Z boson mass by less than 10 GeV. Additionally, all events are required to have at least two central jets ($|\eta| < 2.5$) and the Z boson must have a transverse momentum greater than 150 GeV.

The events are split into dilepton or trilepton channels based on the presence of a third electron or muon. For dilepton events at least two of the jets in the event must be tagged as a b quark. To reduce the background in the search for pair produced top-partners the scalar sum of the transverse momentum of the jets in the event, H_T(jets), is required to be greater than 600 GeV. Separately, in the search for single production one forward jet ($2.5 < |\eta| < 4.5$) is required. The final discriminant is the $m(Zb)$ spectrum, shown with the SM background and signal hypotheses in Fig. 3 for the search targeting the pair production mechanism. The data are in good agreement with the SM predictions and 95% CL limits[1] are set on the production of VLQs as a function of mass and branching fraction in Figs. 4 and 5.

For trilepton events ($\geq$ 3 electrons/muons) at least one of the jets in the event must be tagged as a b quark. Again, in the search for single production one forward jet is required, while in the pair production search no additional selection is made. The final discriminant is the scalar sum of the transverse momentum of the leptons and the jets, H_T(leptons + jets). This profits from the discriminating power of the extra lepton in the event to reduce the background. The H_T(leptons + jets) spectrum is shown with the SM background and signal hypotheses in Fig. 6 for the search targeting the single production mechanism. The data are again in good agreement with the SM predictions and limits are set on the single production of VLQs, shown in Figs. 7 and 8. Combinations of the above results with existing searches, along with summary plots for this and other

[1] All limits are quoted at the 95% CL.

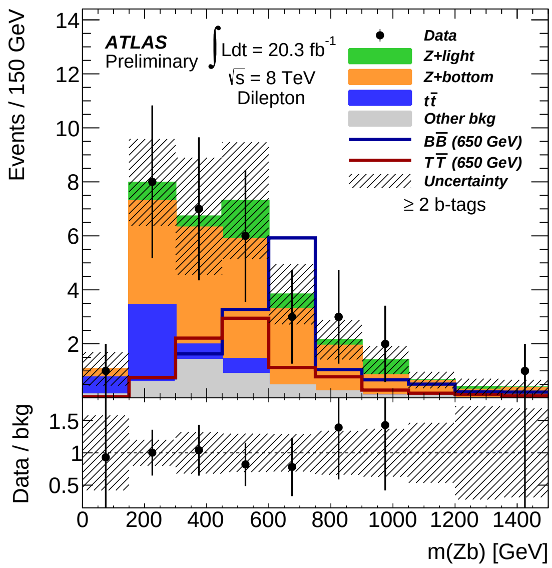

Figure 3: The final $m(Zb)$ distribution after requiring $p_T(Z) > 150$ GeV and H_T(jets) > 600 GeV in events with $N_{tag} \geq 2$.

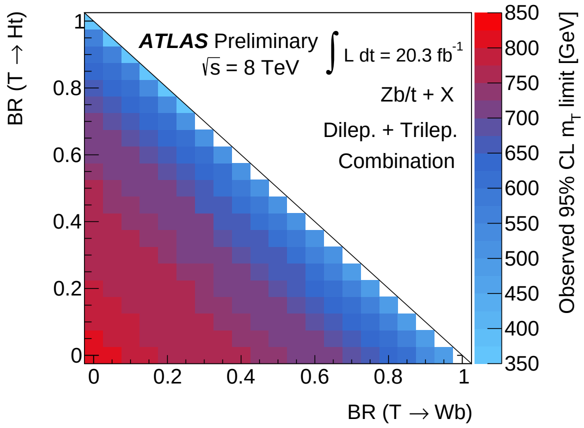

Figure 4: Observed limit (95% CL) on the mass of the T quark assuming the pair production hypothesis and presented in the (Wb, Ht) branching ratio plane.

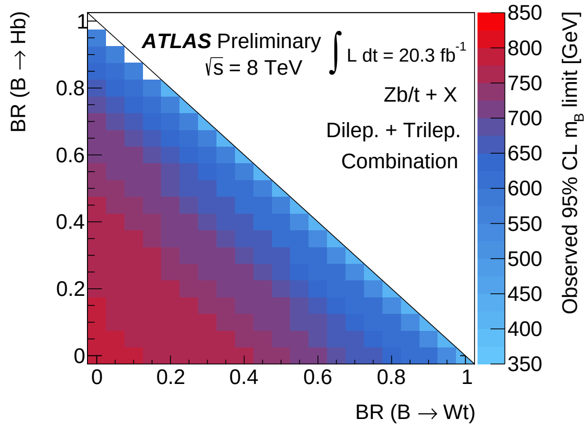

Figure 5: Observed limit (95% CL) on the mass of the B quark assuming the pair production hypothesis and presented in the (Wt, Hb) branching ratio plane.

analyses, are available on the ATLAS website [3].

3. $t\bar{t}$ Resonances

The next analysis discussed is the search for a heavy, spin-1, neutral particle decaying into top quark pairs [7]. Among the models that predict this type of particle are Topcolor models with a lepto-phobic Z' or Randall-Sundrum models with Kaluza-Klein gluons. ATLAS uses a single lepton signature to search for $t\bar{t}$ resonances. The analysis is separated into a “resolved” channel, where the decay products of the top quark are distinct in the detector, and a “boosted” channel, where the top quark is produced with a large momentum resulting in collimated decay products that are observed as just one jet in the detector. The resolved case has greater power at lower $m(t\bar{t})$, and the boosted case at higher masses. In both cases the leptonically decaying top quark candidate is reconstructed from an electron or muon, the missing transverse energy in the event, and a jet. In the boosted channel the hadronically decaying top quark candidate is reconstructed as a radius 1.0 jet by the anti-k_T algorithm with a trimming algorithm applied. To be selected the jet is required to have a transverse momentum greater than 300 GeV, mass greater than 100 GeV, and pass jet substructure requirements. The resolved channel includes all events that did not pass the boosted selection. Here the hadronically decaying top candidate is reconstructed with two or three radius 0.4, anti-k_T jets.

The final discriminant is the invariant mass spectrum of the $t\bar{t}$ pairs. This is shown for the combined boosted

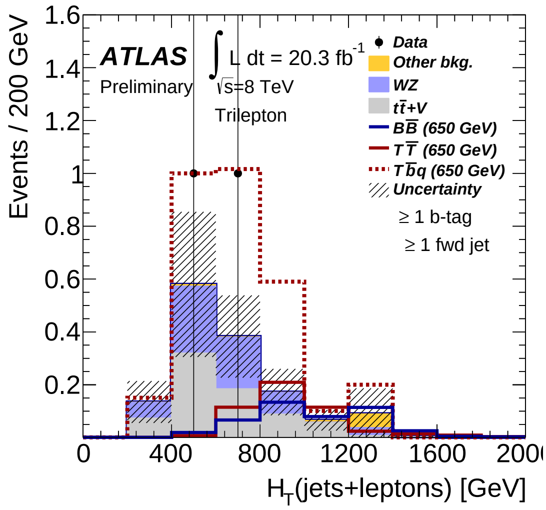

Figure 6: The H_T(leptons + jets) distribution following the requirement of at least one forward jet in trilepton channel events. The predicted Tbq signal assumes a mixing parameter value of $\lambda_T = 2$.

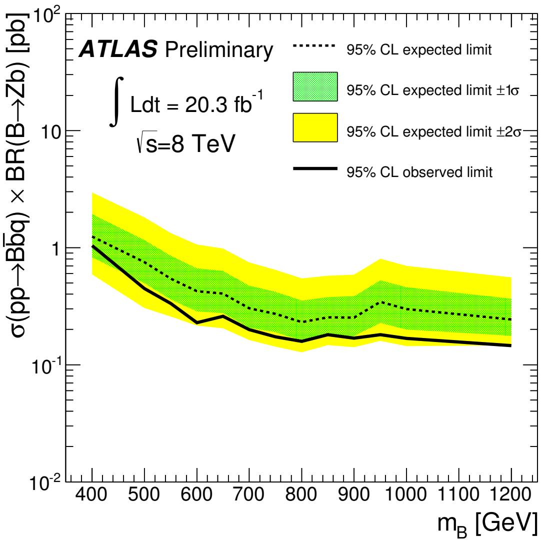

Figure 7: Upper limit (95% CL) on the single production cross section times branching ratio versus heavy quark mass: $\sigma(pp \to B\bar{b}q) \times \mathrm{BR}(B \to Zb)$.

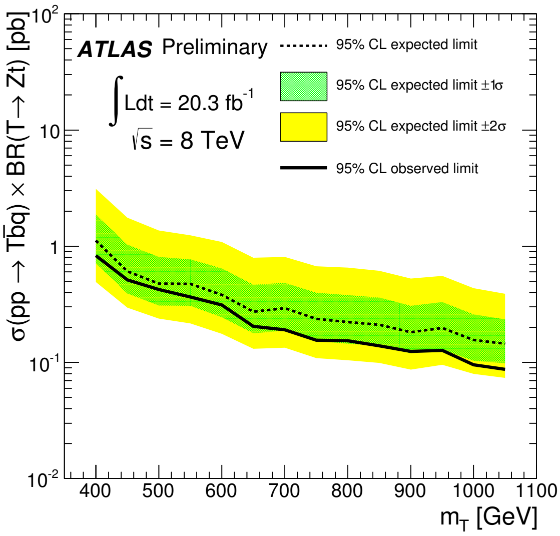

Figure 8: Upper limit (95% CL) on the single production cross section times branching ratio versus heavy quark mass: $\sigma(pp \to T\bar{b}q) \times \mathrm{BR}(T \to Zt)$.

and resolved channels in Fig. 9. The data and backgrounds are in good agreement. 95% CL limits are determined first for a narrow width resonance ($\Gamma/m = 1.2\%$) found in Topcolor models (lepto-phobic Z') of 1.8 (1.9) TeV, obs. (exp.) (shown in Fig. 10), and second for a wide width resonance ($\Gamma/m = 15.3\%$) found in Randall-Sundrum models (Kaluza-Klein gluon) of 2.0 (2.1) TeV, obs. (exp.) (shown in Fig. 11).

4. *tb* Resonances

The ATLAS collaboration has also searched for a W' boson decaying to top and bottom pairs. The top quark is allowed to decay either leptonically [6] or hadronically [7]. For leptonic decay the top quark candidate is reconstructed from an electron or muon, the missing transverse energy, and a jet. Additionally, the event must have either two or three jets in total, at least one of which is tagged as a b quark. The hadronically decaying top quark candidate is required to be boosted. The boosted candidate is reconstructed as a radius 1.0 jet by the anti-k_T algorithm, with a trimming algorithm applied. To be selected the jet is required to have a transverse momentum greater than 350 GeV and pass jet substructure requirements to reduce the QCD-multijet background. The hadronic decay channel is further categorized into events with one additional jet tagged as a b quark and those with two or more jets tagged as

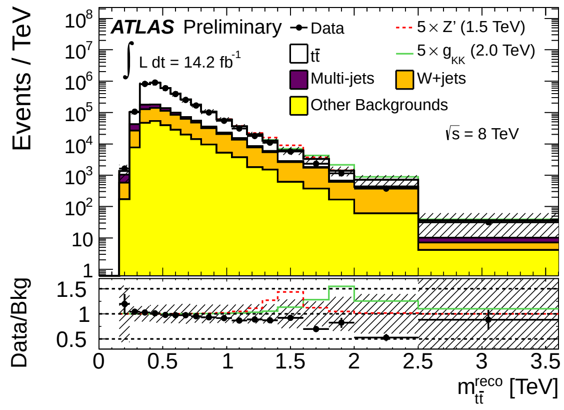

Figure 9: The $t\bar{t}$ invariant mass spectrum, summing the spectra from the two selection methods. The shaded areas indicate the total systematic uncertainties. Two benchmark signals are indicated on top of the background, a Z' with $m = 1.5$ TeV and a g_{KK} with m=2.0 TeV.

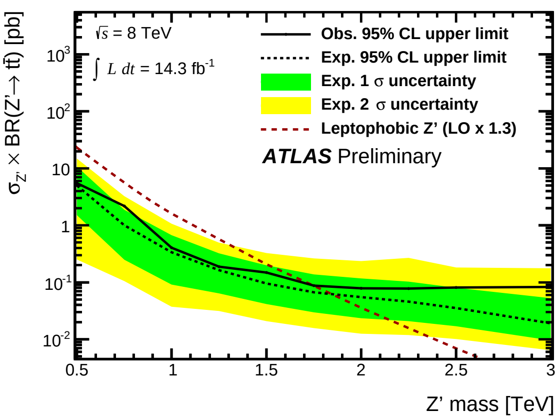

Figure 10: Observed and expected upper cross section limits times the $t\bar{t}$ branching ratio on Z' bosons. The resolved and the boosted selections have been combined in the estimation of the limits. Both systematic and statistical uncertainties are included.

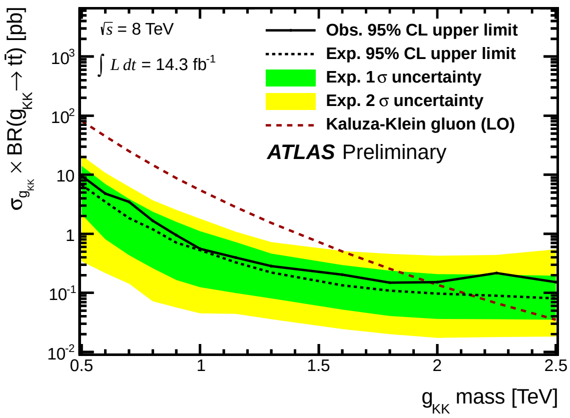

Figure 11: Observed and expected upper cross section limits times the $t\bar{t}$ branching ratio on Kaluza-Klein gluons. The resolved and the boosted selections have been combined in the estimation of the limits. Both systematic and statistical uncertainties are included.

b quarks. Additionally, one of the b quark candidates must be opposite to the selected top quark candidate ($\Delta R > 2.0$). The invariant mass spectrum of the reconstructed top and bottom quark candidates in events with two b tags is shown in Fig. 12. The data is in good agreement with the background-only fit (the solid blue line).

Limits are determined for both left- and right-handed W's assuming a SM-like coupling to fermions (g_{SM}). For right-handed couplings with $m(\nu_R) > m(W'_R)$ (i.e., the W' cannot decay to SM leptons) a limit of 1.8 (1.7) TeV, obs. (exp.) 95 % CL is found. For left-handed couplings (ignoring interference effects), or for right-handed couplings where $m(\nu_R) \ll m(W'_R)$, a limit of 1.7 (1.6) TeV, obs. (exp.) is found. These limits can be reinterpreted as limits on non-SM couplings, g' (the W' boson gauge coupling to fermions) in the $g'/g_{SM} - m(W')$ plane for left- and right-handed W' bosons. These limits are shown in Fig. 13 for the right-handed couplings.

5. Outlook

Searches for new physics that coupling preferentially to the third generation are motivated by a variety of models and the ATLAS collaboration has an active analysis program in this area. Presented here is only a selection of recent ATLAS analyses of 8 TeV data searching for vector-like quarks, $t\bar{t}$ and tb resonances. In all analyses the results are consistent with the SM and limits on new physics have been derived:

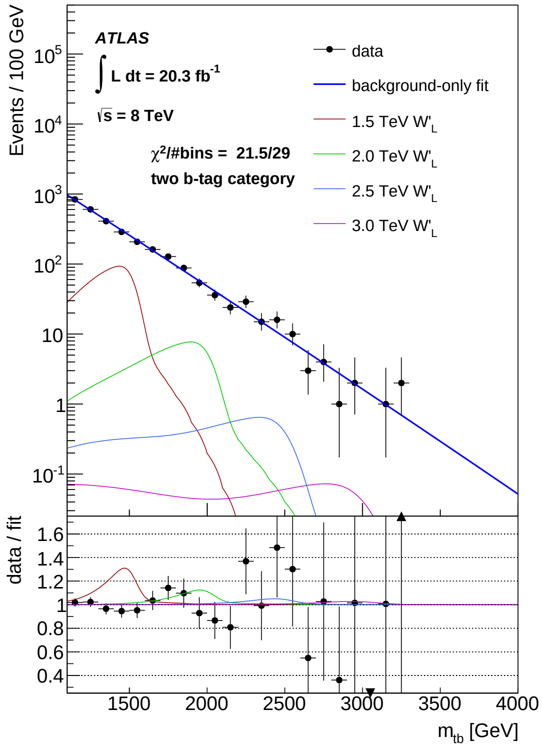

Figure 12: $m(tb)$ distributions in data in the two b-tag category. The background-only fit is shown, and the bottom plot shows the ratio of the data and the fit. Potential W'_L signal shapes in the hadronic top quark decay channel with $g' = g_{\rm SM}$ are also overlaid for resonance masses of 1.5, 2.0, 2.5 and 3.0 TeV.

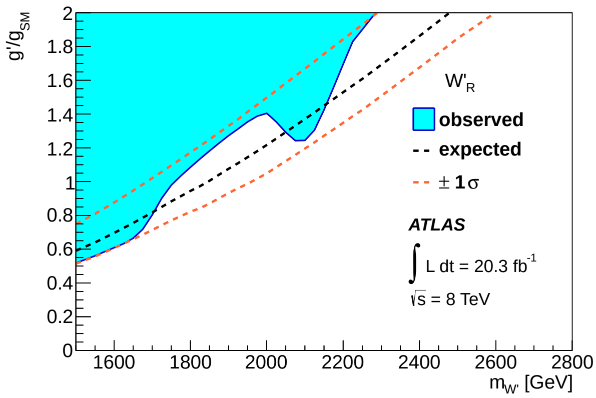

Figure 13: Observed and expected 95% CL limits on the ratio of coupling ($g'_R/g_{\rm SM}$) of the W'_R model as a function of the W' mass.

- Exclude (95% CL) vector-like top and bottom quarks with mass ≤ 700 GeV.
- Exclude (95% CL) $t\bar{t}$ resonances with mass ≤ 1.8 TeV for a narrow Z' resonances or ≤ 2.0 TeV for a wide g_{KK} resonances.
- Exclude (95% CL) tb resonances with mass ≤ 1.8 TeV.

These analyses have developed new techniques with boosted top quarks and jet substructure. This will be even more important as the search for high mass resonances resumes in the coming higher energy LHC run.

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