PROCEEDINGS OF SCIENCE

Searches for vector-like quarks with the ATLAS detector at the LHC

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The naturalness argument for theories beyond the Standard Model supports the presence of fermionic top/bottom quark partners, usually referred to as vector-like quarks. Searches for vector-like quarks have been performed in various final states with leptons, jets and missing transverse momentum at the ATLAS experiment. This writeup summarises recent vector-like quarks searches at ATLAS with 20 fb^{-1} LHC Run 1 data.

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1. Introduction

While the Standard Model (SM) is considered a complete and confirmed model, there are still some open questions such as matter-antimatter asymmetry in the Universe, the hierarchy problem, the candidate for dark matter and so on. Many beyond the Standard Model (BSM) models such as Grand Unification Theories (GUTs) [1], little Higgs [2], composite Higgs [3] predict the existence of vector-like quarks (VLQs) as a solution for naturalness and hierarchy problems, since the quadratically divergent virtual contribution to the Higgs mass from the top quark can be cancelled by a VLQ. Moreover, they can provide an explanation for the matter-antimatter asymmetry in the Universe by addressing the *CP* violation [4]. VLQs are fermionic top/bottom quark partners and they can be singlet, doublet or triplet. Left and right-handed components of VLQs transform identically under SU(2) x U(1) gauge transformations. They can carry electroweak charges and decay the same way as SM quarks. However, unlike chiral quarks, they can also decay via the Flavor Changing Neutral Currents (FCNC) channels at tree level to a W , Z, or H boson plus an SM quark, as indicated in Table 1.

Table 1: Charge and decay modes of vector-like quarks for singlet SU(2) and doublet scenarios [5].

	Charge	Decay Mode	
T singlet	+2/3	$T \to W^+b, Zt, Ht$	
B singlet	-1/3	$B \to W^-t, Zb, Hb$	
(T,B) doublet	(+2/3,-1/3)	$T \to W^+b, Zt, Ht$	$B \to W^-t, Zb, Hb$
(X,T) doublet	(+5/3,+2/3)	$X \to W^+t$	$T \to Zt, Ht$
(B,Y) doublet	(-1/3,-4/3)	$B \to Zb, Hb$	$Y \to W^-b$

Vector-like quarks can be produced either singly or in pairs (See Figure 1). Up to VLQ masses of 1 TeV, the dominant production mechanism is in pairs via strong interaction. However, single production mediated by the electroweak interaction can enhance the sensitivity significantly.

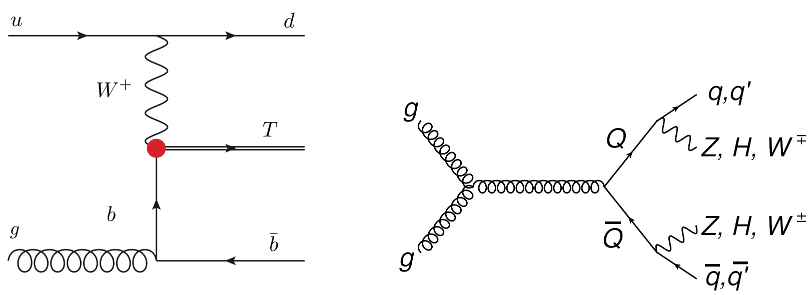

Figure 1: Single (left) and pair (right) production of VLQs.

2. ATLAS Run 1 Vector-Like Quarks Searches

In Run 1, the ATLAS Collaboration has performed many VLQ searches with *pp* collision data at centre of mass energies of 7 TeV and 8 TeV. To be able to consider different branching ratios (BR) and derive a limit accordingly, recent studies have followed a general search strategy to consider all three decay modes from Table 1 concurrently so that possible signal contaminations are avoided. In Figure 2, BR for different decay modes can be seen for the SU(2) singlet and doublet models. Many searches have been performed assuming that VLQs couple preferentially to third-generation SM quarks, but their couplings to the light generations are also possible and not excluded. However, one recent ATLAS search has studied also the case where VLQs couple to the light generations [6].

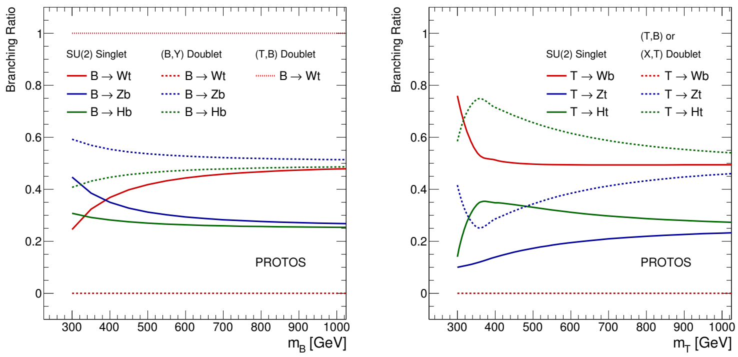

Figure 2: Branching ratios for the different decay modes as a function of vector-like B and T quark mass for SU(2) singlet and doublet scenarios [8].

In this section, four different analysis will be introduced briefly by emphasising their strongest aspects and different approaches.

2.1 Same Sign Dilepton Analysis

The same sign dilepton analysis has been performed with the full data sample of pp collisions at $\sqrt{s}$ = 8 TeV, corresponding to an integrated luminosity of 20.3 fb^{-1} to look for pair produced T and B quarks [7]. The analysis requires pairs of isolated high-p_{T} (transverse momentum) leptons (electron or muon) with the same electric charge together with sizeable (missing transverse momentum) $E_{\mathrm{T}}^{\mathrm{miss}}$ and at least two jets, where at least one of the jets is b-tagged. Events with additional leptons beyond the same-sign pair are also accepted ($T\bar{T}/B\bar{B} \to l^{\pm}l^{\pm}(l)+b+X$).

The analysis has been performed as a signature-based search and it is sensitive to eleven signal regions with separate final selection criteria and optimisations. While the SM contribution is relatively small, estimating fake backgrounds which are caused by either a misidentification of a jet as an isolated lepton or mismeasurement of the lepton charge become more significant.

After the final selection, an excess is observed in data over the SM prediction for some of the signal regions with a significance of up to 2.5σ. Exclusion limits have been set. Data constrained the SU(2) masses of B and T quarks to 0.62 TeV and 0.59 TeV at the 95% CL, respectively (Figure 3).

2.2 Zb/t+X

ATLAS Collaboration has performed another search with a complete 8 TeV Run 1 dataset corresponding to 20.3 fb^{-1} of pp collisions to look for for the production of charge +2/3 (T) and

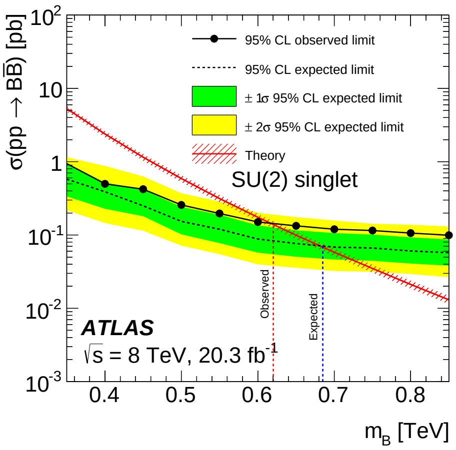

Figure 3: Observed limits on the pair production cross section as a function of mass of the B quark [7].

-1/3 (B) VLQs that decay to a Z boson and a third-generation quark by considering both the pair production ($T\bar{T}/B\bar{B} \rightarrow Zt/Zb+X$) and the single production modes ($Tbq/Bbq \rightarrow Zt/Zb+bq$) [8]. A pair of oppositely charged same flavour leptons (electrons or muons) are required for the reconstruction of Z boson candidate. For final event selection, two different channels are studied depending on the presence of a third lepton; dilepton and trilepton channels.

To be able to enhance sensitivity, two channels are analyzed separately by using both a common set of event selection criteria and additional specific requirements for each channel. For both channel, a Z boson candidate with at least p_T of 150 GeV and at least 2 central jets are required. Specifically for the dilepton channel, event selection is done by requiring exactly two leptons and at least two b-jets. If the VLQs are pair produced, a 600 GeV cut is applied on the H_T variable for the jets in the event. If the analyzed quark produced singly, then at least one forward jet is required in the final state. On the other side, for the trilepton channel, at least three leptons and at least one b-tagged jet are required. If the process is single production, then again at least one forward jet is required in the event.

As a final discriminant, dilepton channel uses the invariant mass of the VLQ and trilepton channel uses H_T variable for jets and leptons in the final state. In Figure 4, the final discriminants for both channels are presented. Analysed data are found to be consistent with the background-only hypotheses in each of the final distributions and limits are derived according to the CLs prescription.

2.3 Wt+X

ATLAS Collaboration has performed Wt+X analysis [9] using an integrated luminosity of 20.3 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV to look for $B\bar{B}$ pair production process. Analysis aims for single lepton and multiple jets in its final state where one of the B quark subsequently decays to a boson and third generation quark ($B\bar{B} \rightarrow Wt/Zb/Hb+X$). In the final state of this analysis, exactly one isolated charged lepton (electron or muon) with high p_T, high value of E_T^{miss} and at least four jets with high p_T are required. Additionally, at least one of the jets should be b-tagged and at least one pair of jets should come from the hadronic decay of an electroweak boson.

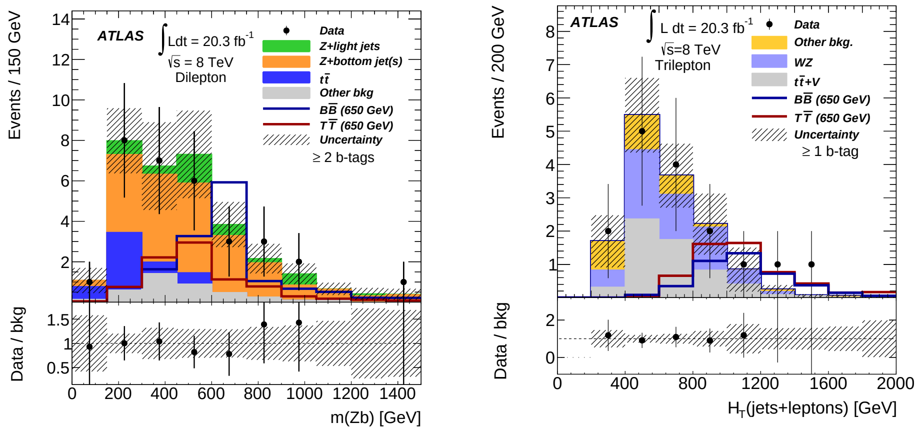

Figure 4: Final distributions for m(Zb) and H_{T}(jets+leptons) in dilepton and trilepton channels [8].

Analysis is optimised primarily for the signature $B\bar{B} \to WWtt \to WWWWbb$, but still it preserves the sensitivity for other VLQs. Therefore, dominant backgrounds for this study are $t\bar{t}$ and W+jets events. Search has been performed with two different analysis strategies; boosted decision trees (BDT) and cut based approaches. Final results are obtained with the BDT algorithm, while cut based algorithm results are used as cross-check study. For the BDT algorithm, information coming from 12 different variables are combined into a single discriminant value (see Figure 5) so that increased sensitivity is obtained.

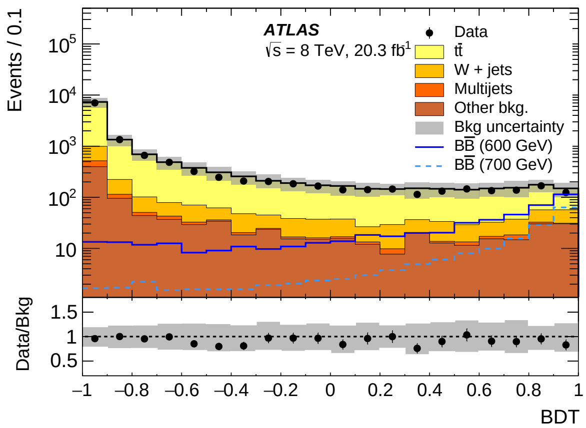

Figure 5: Distribution of the BDT discriminant for data in the signal region of the BDT analysis [9].

2.4 W/H+X

Based on the ATLAS pp collision data at $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 20.3 fb^{-1}, a search for pair produced vector-like T and B quarks has been done by considering W and H decay channels for three different processes separately [10]. In one channel, one T decays to W boson and a b quark ($T\bar{T} \to Wb + X$) with significant branching ratio and in the other two channel, both T and B quarks decay to a H boson and a third generation SM quark

($T\bar{T} \to Ht+X, B\bar{B} \to Hb+X$). For each of the decay channel exactly one reconstructed electron or muon and at least four jets are required in the final state.

In the search for $T\bar{T}$ events in W channel, events which have at least one b-tagged jet and at least one W boson candidate are accepted. Analysis optimised for two W boson where one of them is decays leptonically. Minimum 800 GeV H_T variable is required and further tight cuts are applied for identifying boosted W boson by using the information that its decay products should be almost collinear. Angular separation between W and b quarks are used for removing the $t\bar{t}$ background. For the singlet case, observed (expected) 95% CL limits are derived as 660 (670) GeV. $T\bar{T}$ events in Higgs channel are selected by requiring at least two b-tagged jets in their final state. After preselection, evaluating the jet multiplicity distributions, analysis selects events which have minimum five jets. Search in the H channel yields observed (expected) 95% CL limits of $m_T >$765 (720) GeV.

Since these two channels of T quark have complementary sensitivity, they are combined in a single likelihood function taking into account the correlation of systematic uncertainties and one combined limit is derived for two decay modes yielding observed (expected) 95% CL limits of $m_T >$ 800 (755) GeV which can be seen in Figure 6.

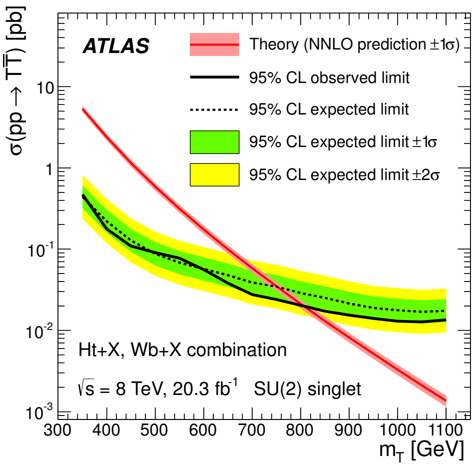

Figure 6: Observed (solid line) and expected (dashed line) 95% CL upper limits on the $T\bar{T}$ cross section as a function of the T quark mass under the assumption for a T quark singlet [10].

3. Limits for Branching Ratio Phase Space

The branching ratio phase space for the vector-like quarks is a triangle, considering the three different decay modes. Two of the decay modes can be seen in the x and y axis of the triangle and the last mode can be found easily from the normalised values.

In Run 1, the above ATLAS VLQ searches have been performed independently but using similar search strategies. No significant deviation from the Standard Model expectation is observed and lower limits on the masses of the vector-like T and B quark are derived as a function of branching ratio. Considering all these studies, separate regions in the BR triangle are excluded sequentially for each of the analyses rather than combined [10]. In Figure 7, the most restrictive observed limits for the B and T quarks can be seen.

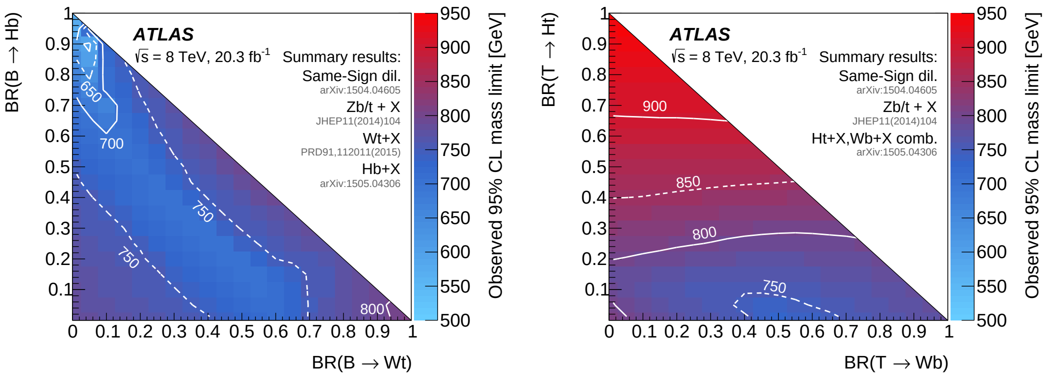

Figure 7: Summary of the most restrictive observed limit (95% CL) on the mass of the (a) B quark in the plane of BR($B \to Hb$) vs BR($B \to Wt$) and the (b) T quark in the plane of BR($T \to Ht$) vs BR($T \to Wb$) from all ATLAS searches for (a) $B\bar{B}$ production and (b) $T\bar{T}$ production. Contour lines are provided to guide the eye [10].

4. Conclusion

Searches for VLQs have been performed at ATLAS during Run 1, covering the entire T and B quark branching ratio phase space. No significant deviation from the SM expectation is observed, and lower limits on the masses of the vector-like T and B quark are derived as a function of branching ratio. The observed lower limits on the T (B) quark mass range between 730 GeV and 950 GeV (575 GeV and 813 GeV) for all possible values of the branching ratios into the three decay modes considered, while the corresponding range of expected lower limits is between 715 GeV and 885 GeV (615 GeV and 800 GeV). A further improvement in sensitivity is expected for Run 2.

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