Search for vector-like quarks with the ATLAS detector

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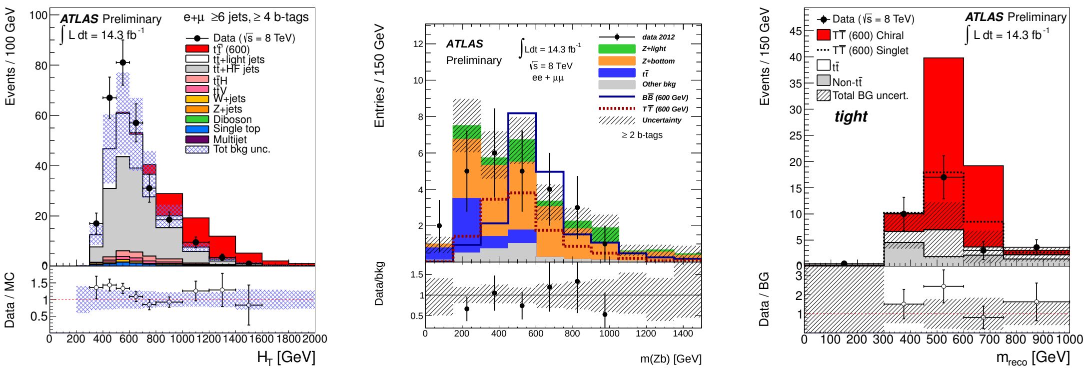
A cornerstone of the Standard Model (SM) is the formulation of the electroweak interactions as arising from a spontaneously broken gauge symmetry, which has been confirmed during the past four decades. However, the SM cannot be considered as a complete description of nature since there are several open questions that still need to be solved. For example, there is no explanation for the number of fermions and there are quadratic divergences in the Higgs boson mass terms. There are several beyond the SM models which try to answer these questions and in some of them the existence of new vector-like quarks, which are defined as quarks for which both chiralities have the same transformation properties under the gauge symmetry group, is a feature.

In the present note, four analyses ($Ht + X$, same-sign leptons, $Zt/b + X$ and $Wb + X$) targeting the pair production of vector-like quarks with different decay modes are presented. These analyses use a dataset corresponding to 14.3 fb^{-1} of pp colisions at a center of mass energy of 8 TeV recorded in 2012 with the ATLAS detector [1] at the CERN Large Hadron Collider. Two vector-like quark models (singlet and doublet [2]) and flavors (T and B with electric charges of $2/3|e|$ and $-1/3|e|$ respectively) have been studied, testing them for different vector-like quark masses ranging from 350 GeV up to 850 GeV in 50 GeV steps.

In the Ht+X [3] analysis ($T\bar{T} \to Ht$+X), final states with one lepton and a high multiplicity of jets (≥ 6) and b-tagged jets (≥ 2) are compatible with signal hypothesis. The backgrounds for this analysis are primarily $t\bar{t}$+jets, W+jets (for which the normalization is derived from data) and multijet processes (derived using data-driven techniques). Small contributions arise from single-top, Z+jets, diboson (WW, ZZ, WZ) and $t\bar{t} + V$ ($V = W, Z$) production.

The final selection is defined as those events in which there are ≥ 6 jets, ≥ 2 b-tagged jets, missing tranverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) above 20 GeV and $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}} > 60$ GeV, where $m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}}(1 - \cos\Delta\Phi)}$, p_{T}^{ℓ} being the transverse momentum of the lepton and $\Delta\Phi$ the azimuthal angular separation between the lepton and the direction of the missing transverse momentum. The sample is divided in three regions based on the b-tagged jet multiplicity: 2, 3 and ≥ 4 b-tagged jets. The higher signal to background ratio is found in the last region and therefore it is the one which drives the sensitivity of the analysis. The regions with 2 and 3 b-tagged jets, that have low signal contamination, are used to better estimate the $t\bar{t}$ background and constrain the systematic uncertainties.

The discriminant variable for the $Ht + X$ analysis is H_{T}, shown in Figure 1a, which is defined as the scalar sum of the transverse momenta of the jets, the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$. In the absence of evidence for signal, limits are set assuming a branching ratio corresponding to the single (doublet) model, excluding a vector-like T quark with mass lower than 790 (640) GeV at a 95% confidence level.



(a) (b) (c)

Figure 1: Discriminant variables for (a) the $Ht+X$, (b) $Zt/b+X$ and (c) $Wb+X$ analyses are shown. As illustration a signal distribution is shown for a vector-like quark with a mass of 600 GeV.

The same-sign lepton analysis [4] is not only intended to look for pair production of vector-like quarks but it has a broader scope in which the interesting final states are those with a pair of same-sign leptons. There are several processes in which this signature is expected, such as chiral b' quark pair production, vector-like quark pair production, SM production of four top quarks or two positively charged top quarks. In the case of vector-like quarks this search is sensitive to both B and T quarks, being more sensitive to the W and Higgs boson decay modes in the case of vector-like B and T quarks respectively.

The selected events are those in which there is a pair of same-sign leptons (ee, $\mu\mu$ or $e\mu$), ≥ 2 jets, ≥ 1 b-tagged jet, $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV and $H_{\mathrm{T}} > 500$ GeV, where H_{T} is defined as the scalar sum of the transverse momenta of the selected leptons and jets. Two requirements in the mass of the leptons are also applied when they have the same flavor: $m_{\ell\ell} > 15$ GeV and $|m_{\ell\ell} - m_Z| > 10$ GeV to reduce the contribution from resonances in which one lepton's charge was mismeasured.

There are two main sources of background for the same-sign analysis: processes with real same-sign leptons in the final state and processes in which one of the leptons has been misidentified or misreconstructed. Processes with same-sign leptons in the final state include diboson production with a heavy flavor jet and $t\bar{t}$ pair production with an associated vector boson. The contribution of these processes is evaluated through Monte Carlo simulation. Background contributions from misidentified leptons are derived using data-driven techniques and can be separated in two categories: events in which a jet is misidentified as a lepton and opposite sign leptons in which the charge of a lepton is mismeasured, which is estimated using a $Z \to ee$ sample. The latter background is negligible for muons.

After the final selection 2.7 ± 0.5, 4.4 ± 0.9 and 2.3 ± 1.2 background events are expected and 3, 10 and 2 events are observed for the ee, $e\mu$ and $\mu\mu$ channels respectively. The signal efficiency ranges from 0.01% for B pair production with a mass of 350 GeV in the ee channel to 0.34% for T pair production with a mass of 850 GeV in the $e\mu$ channel. In the absence of evidence for signal, 95% confidence level limits are set assuming branching ratios corresponding to the singlet model and masses below 0.59 (0.54) TeV are excluded for pair production of vector-like B (T) quark.

The $Zt/b + X$ analysis [5] (searching for $Q\bar{Q} \to Zq + X$, with $Q = T, B$ and $q = t, b$ respectively) is sensitive to high branching ratio to the Z boson decay channel which is a phase-space region not covered by any of the previous analyses.

The main background in this analysis is Z+jets, with some contribution from $t\bar{t}$+jets and a small contribution from $t\bar{t} + V(V = W, Z)$ production, single top, diboson and W+jets production. Two corrections are applied to the Z+jets background. The first one aims to correct the b-tagged jet multiplicity, defining a control region with a Z boson candidate with $p_{\mathrm{T}} < 100$ GeV and ≥ 2 jets. The second one corrects the $p_{\mathrm{T}}(Z)$ distribution, which is derived in a control region with a Z boson candidate, ≥ 2 jets and 1 b-tagged jet.

In this analysis events with ≥ 2 opposite-sign, same flavor leptons are selected (ee and $\mu\mu$) with $|m_{\ell\ell} - m_Z| < 15$ GeV to reconstruct the Z boson candidate. The events must have ≥ 2 jets and ≥ 2 b-tagged jets. Two control regions for 0 and 1 b-tagged jets are defined to better describe the main background of the analysis and derive systematic uncertainties associated with the Z+jets corrections. The Z boson candidate is required to have $p_{\mathrm{T}}(Z) > 150$ GeV to reduce the Z+jets background contribution. The scalar sum of the transverse momenta of the jets is required to be higher than 600 GeV.

The mass of the Zb system, shown in Figure 1b, is used as the discriminant variable. The b-tagged quark with highest transverse momentum is chosen to define the Zb system. In the absence of signal, limits are set and masses below 680 (725) GeV are excluded at a 95% confidence level for the T (B) quark.

In the $Wb + X$ analysis (searching for $TT \to WbWb$) the main background processes are very similar to the ones in the $Ht + X$ analysis: $t\bar{t}$+jets, W+jets and multijet events, with W+jets and multijets treated in the same way as in $Ht + X$. Small contributions arise from single-top, Z+jets and $t\bar{t} + V(V = W, Z)$ production. The high mass of the T quarks results in energetic W bosons and b quarks with large angular separation between them and small angular separation between the decay products of the boosted W boson. This is different from the signature of $t\bar{t}$ events in which the boost of the SM top quark translates into closer W boson and b quark than in the vector-like case.

Two selections, *loose* and *tight*, are defined. The *loose* selection is defined by requiring ≥ 4 jets, ≥ 1 hadronic W boson candidate and $H_{\mathrm{T}} > 800$ GeV, where H_{T} is defined as the scalar sum of $E_{\mathrm{T}}^{\mathrm{miss}}$, the transverse momentum of the lepton and the transverse momenta of the four highest-p_{T} jets. This loose selection is used to study background modeling. The *tight* selection adds the isolation requirements that allow better suppression of $t\bar{t}$ events: $\min\left[\Delta R(W_{had}, b_{1,2})\right] > 1.4$ and $\min\left[\Delta R(\ell, b_{1,2})\right] > 1.4$.

The discriminant variable used is the reconstructed mass of the vector-like T, reconstructed with a hadronic W boson and one of the 2 b-tagged jets as shown in Figure 1c. The $W - b$ pairing is chosen as the one giving the smallest difference between the mass obtained using the leptonic and hadronic W boson candidates.

Figure 2 summarizes the exclusion regions from the four analyses for vector-like T and B quarks respectively in the BR plane.

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References

[1] G. Aad *et al.* [ATLAS Collaboration], JINST **3** (2008) S08003.

[2] J. A. Aguilar-Saavedra, JHEP **0911** (2009) 030, arXiv:0907.3155 [hep-ph].

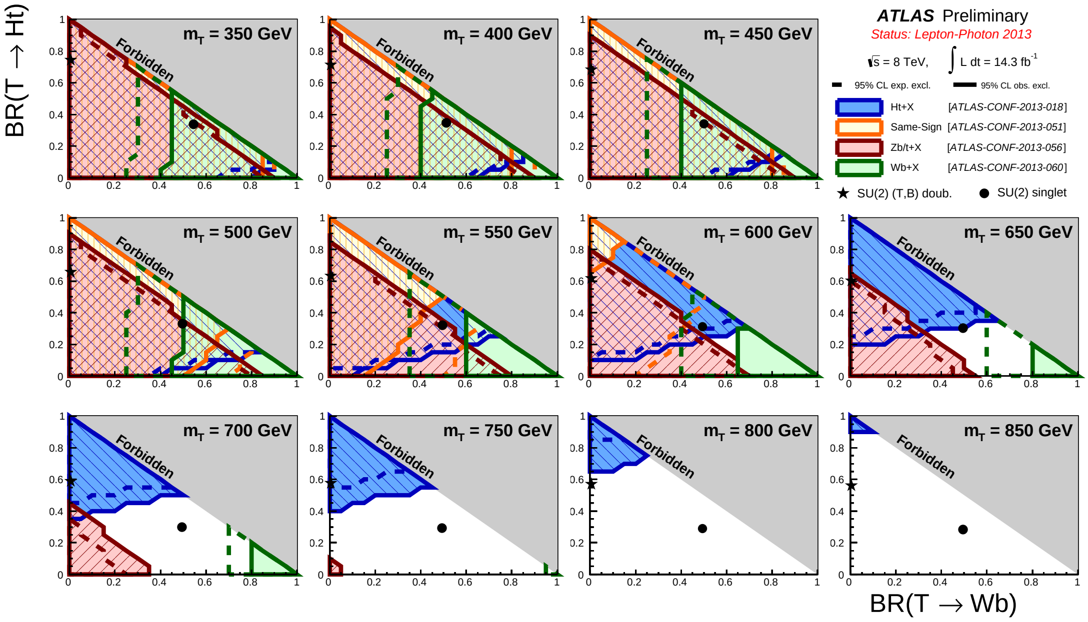
[3] ATLAS Collaboration, ATLAS-CONF-2013-018.

[4] ATLAS Collaboration, ATLAS-CONF-2013-051.

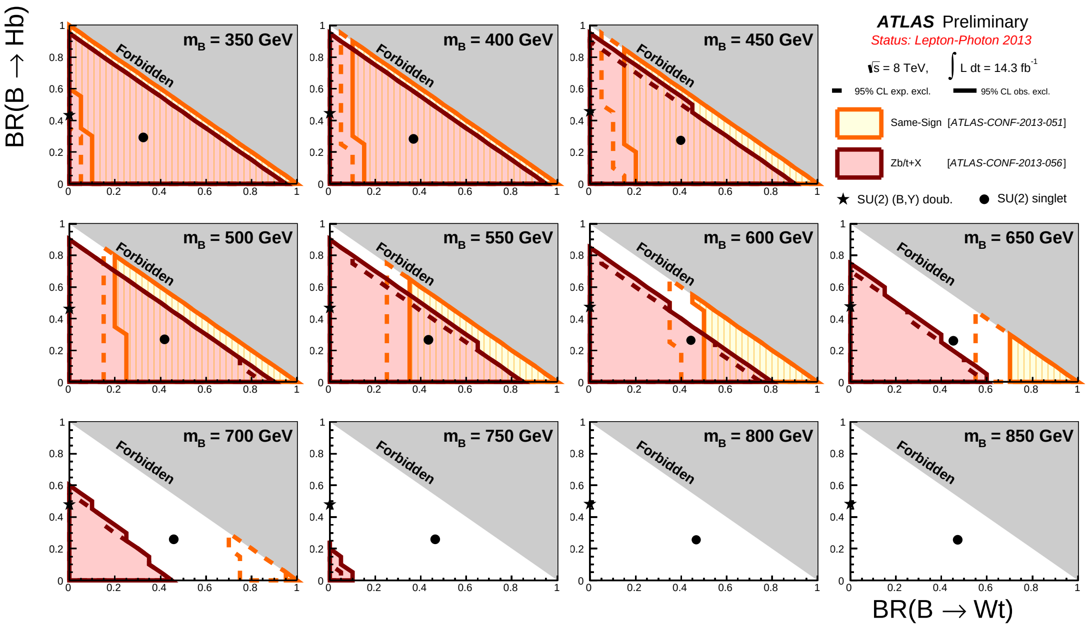
[5] ATLAS Collaboration, ATLAS-CONF-2013-056.

[6] ATLAS Collaboration, ATLAS-CONF-2013-060.

[7] ATLAS Collaboration, https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots#ExoticsVLQSummary.



(a)



(b)

Figure 2: A summary of the exclusion regions obtained by the different analyses is shown (a) for the vector-like T and (b) vector-like B [7].