SEARCHES FOR NEW HEAVY QUARKS IN ATLAS

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A search for new heavy quarks focusing on recent vector-like quark searches with the ATLAS detector at the CERN Large Hadron Collider is presented. Two recent searches targeting the pair production of type vector-like quarks are described. The first search is sensitive to vector-like up-type quark (T) decays to a t quark and either a Standard Model Higgs boson or a Z boson. The second search is primarily sensitive to T decays to W boson and a b quark. Additionally, the results can be interpreted for alternative VLQ decays.

1 Introduction

Although appealing, a straightforward addition of a fourth generation of Standard Model (SM) quarks is excluded by experimental observation; such an addition would contribute to the SM Higgs boson production via fermion loops and would not be compatible with the observed [1,2] Higgs boson production cross-section. For this reason and others, latest searches for new heavy quarks in ATLAS [3] have targeted Vector-Like Quarks (VLQs). VLQs are proposed in various models [12,13,14,15] of new physics beyond the SM. They are coloured spin-1/2 fermions of which the left- and right-handed components transform the same way under gauge transformations [4,5]. VLQs evade limitations imposed on chiral quark extensions of the SM, however they can mix with their SM quark counterparts and regulate the Higgs boson mass-squared divergence. They therefore provide an attractive mechanism to solve the hierarchy problem.

VLQs can have charges analogous to their SM quark counterparts, such as the T and B VLQs with charge $q = 2/3e$ and $-1/3e$, respectively, or more exotic charges, such as in the case of the X and Y VLQs, with charge $q = 5/3e$ and $-4/3e$, respectively, where e is the charge of the electron. The various VLQs can be arranged in $SU(2)$ singlets or multiplets. The VLQs can decay to the W, Z, and Higgs (H) bosons with branching ratios which depend on the model and, in general, decays to third generation SM quarks are favoured. As a consequence, it is usually assumed in searches that the VLQs couple exclusively to the t and b quarks.

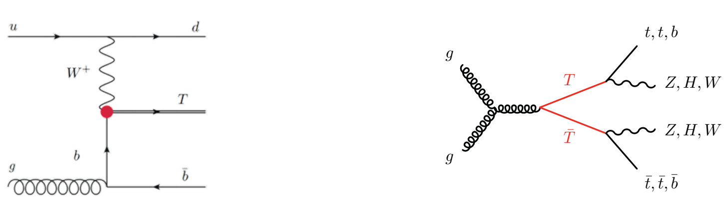

Figure 1 – Example Feynman diagrams for single VLQ production (left) and pair-production (right)

The new quarks could be produced either singly or in pairs. The single production mechanism dominates for high VLQ masses [6]. For single production, the production cross-sections depend strongly on the model, since the mechanism requires the mediation of a gauge boson, as shown on the left of Figure 1. Conversely, the pair-production mechanism, proceeding via gluon-splitting as shown on the right of Figure 1, is generally considered model-independent and dominates up to VLQ masses of the order of 800 GeV. As a consequence, the recent ATLAS searches presented in these proceedings have focused on VLQ pair-production. Two searches are discussed in the following sections: a search for the pair production of up-type VLQs in events with multiple b-jets [7] and a search for the pair production of VLQs decaying to a high-p_{T} W-boson and a b-quark in events with leptons and jets [8]. Both analyses are using the 36.1 fb^{-1} of proton-proton collisions delivered by the LHC at $\sqrt{s} = 13$ TeV in 2015 and 2016 and recorded by the ATLAS detector.

2 Search for pair production of up-type vector-like quarks and for four-top-quark events in final states with multiple b-jets with the ATLAS detector ($T\bar{T} \to Ht+X$)

The search targets $T\bar{T}$ pair production where at least one of the VL T decays to a H boson or a Z boson with the boson decaying to either to a pair of b quarks ($T \to H(\to b\bar{b})t$) or a pair of neutrinos ($T \to Z(\to \nu\bar{\nu})t$), respectively. Additionally, the search investigates anomalous four-top-quark production in the context of an effective field theory model and in a universal extra dimensions model, however this analysis is not discussed in these proceedings.

The analysis takes advantage of the presence of multiple jets, b-tagged jets, t-tagged jets, H-tagged jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$. Jets are reconstructed using the anti-k_t algorithm [10] with a radius parameter $R = 0.4$. Jets containing b hadrons are tagged using a working point with 77% efficiency measured in simulated $t\bar{t}$ events. Large-radius jets are obtained by reclustering [11] the $R = 0.4$ jets using the anti-k_t algorithm with a radius parameter $R = 1.0$. By "t-tagged" and "H-tagged" jets we refer to large-radius jets identified with decaying t quark or H boson candidates by making requirements on their transverse momentum, mass, and number of constituents.

The analysis is split into two channels, with initial preselection criteria as shown in Table 1, taking advantage of the event characteristics of the two targeted signatures. The "1-lepton (1L) channel" requires exactly one isolated electron or muon and has a modest requirement on $E_{\mathrm{T}}^{\mathrm{miss}}$, while the "0-lepton (0L) channel" requires the absence of any isolated electrons or muons and $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV.

Table 1: Summary of preselection requirements for the 1-lepton and 0-lepton channels in the $Ht + X$ analysis [7]. Here m_{T}^{W} is the transverse mass of the lepton and the $E_{\mathrm{T}}^{\mathrm{miss}}$, and $\Delta\phi_{\mathrm{min}}^{4\mathrm{j}}$ is the minimum azimuthal separation between the $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ vector and each of the four highest-p_{T} jets.

Preselection requirement		
Requirement	1-lepton channel	0-lepton channel
Trigger	Single-lepton trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
Leptons	$= 1$ isolated e or μ	$= 0$ isolated e or μ
Jets	≥ 5 jets	≥ 6 jets
b-tagging	≥ 2 b-tagged jets	≥ 2 b-tagged jets
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV
Other $E_{\mathrm{T}}^{\mathrm{miss}}$-related	$E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W}$	$\Delta\phi_{\mathrm{min}}^{4\mathrm{j}} > 0.4$

The two channels are further divided into search regions according to the number of b-, t-, and H-tagged jets in the event as well as the overall jet multiplicity. In addition, for the 0L channel, the regions are categorized in "high-mass" (HM) and "low-mass" (LM) regions depending on whether the selected events satisfy (HM) or fail (LM) the requirement $m_{\mathrm{T,min}}^{b} > 160$ GeV, where $m_{\mathrm{T,min}}^{b}$ is the minimum transverse mass formed with the $E_{\mathrm{T}}^{\mathrm{miss}}$ and any of the 2 (or 3) b-jets. In total, 12 (22) search regions are defined for the 1L (0L) channel.

The final discriminant is the effective mass (m_{eff}), defined as the scalar sum of the p_{T} of the lepton, jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$ present in the events. As can be seen in Figure 2, the background is

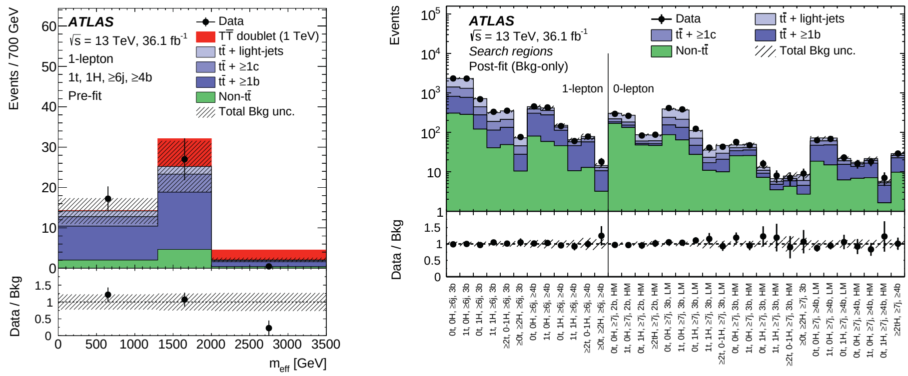

Figure 2 – Left: Distribution of the final discriminant for data, expected background, and a signal model with $m_T = 1$ TeV in an example search region before the background-only fit for the $Ht + X$ analysis [7]. Right: Compatibility of the background expectation with the data in the search regions after the background-only fit in the $Ht + X$ analysis [7].

dominated by $t\bar{t}$+jets events after preselection. Small contributions arise from single-top-quark, W/Z+jets, multijet and WW, WZ, ZZ production, as well as from the associated production of a vector boson V ($V = W, Z$) or a H boson and a $t\bar{t}$ pair ($t\bar{t}V$ and $t\bar{t}H$). All backgrounds are estimated using samples of simulated events and initially normalized to their theoretical cross sections, with the exception of the multijet background, which is estimated using data-driven methods. A combined maximum likelihood fit of the m_{eff} distribution is performed to the data in all search regions to determine the normalization of the backgrounds. As can be seen in Figure 2, the background expectation has a very good agreement with the data in all search regions, after the background-only fit. The background modelling is further checked in 10 (16) additional validation regions made orthogonal by requiring exactly 5 (6) jets in for the 1L (0L) channel. The main systematic uncertainties, which vary by search region, are the modelling of the $t\bar{t}$ background, flavor tagging uncertainties, and background normalization uncertainties.

Given the compatibility of the data and the background expectation, 95% CL limits are set on the pair production of VL T separately for the two channels, as well as combined. The excluded VL T masses depend on the branching ratios assumed by the model under investigation. For example, as shown in Figure 3, VL T masses up to 1.3 TeV are excluded for the SU(2) doublet model which assumes $BR(T \to Ht) \approx BR(T \to Zt) \approx 0.5$. For a model assuming a VL T exclusively decaying to Ht ($BR(T \to Ht) = 1$) masses up to 1.4 TeV are excluded.

However, a more general interpretation of the results can be performed by reweighting the signal samples to other BR compositions to obtain two-dimensional limits on the BR plane, as shown on the right of Figure 3. Under the assumption $BR(T \to Ht) + BR(T \to Wb) + BR(T \to Zt) = 1$, each point on the plane indicates a model with a given BR composition. The colour scale indicates the highest excluded mass at the given BR composition. As can be seen, the highest excluded masses are near point $(0, 1)$ where $BR(T \to Ht) = 1$ which is expected given the optimization of the search for the $T \to Ht$ and Zt decays.

3 Search for pair production of heavy vector-like quarks decaying to high-p_{T} W bosons and b quarks in the lepton-plus-jets final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector ($Q\bar{Q} \to Wb + X$)

The second search primarily targets $T\bar{T}$ production where at least one of the VL T decays via $T \to Wb$. Events are initially required to have exactly one lepton (either an electron or a muon), to have at least three jets of which at least one is required to be b-tagged, and to have

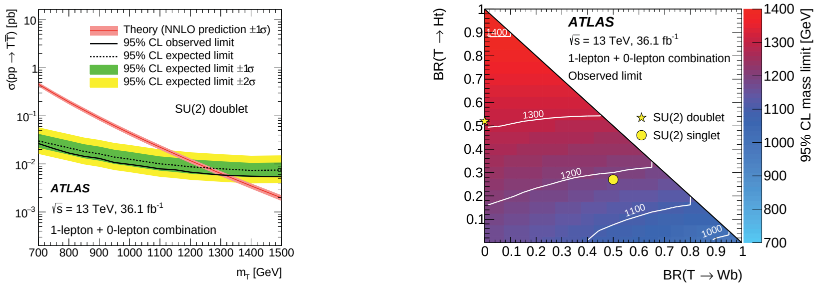

Figure 3 – Combined expected and observed limits as a function of VL T mass for an example BR scenario (left) and combined observed mass limits in the two-dimensional BR plane (right) for the $Ht+X$ analysis [7].

$E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV. The events are further required to have at least one high-p_{T} W candidate which decays hadronically, labelled W_{had}. The selection is therefore optimized for the decay $T\bar{T} \to W_{\mathrm{had}} W_{\mathrm{lep}} bb$, where W_{lep} denotes a W decaying leptonically. The four-momentum of the neutrino is analytically determined using the missing transverse momentum vector $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ and constraints of the lepton-neutrino system from the mass of the W boson.

The final discriminant used in the analysis is the reconstructed mass of the semi-leptonically decaying VL T (m_T^{lep}). The analysis attempts to reconstruct two T candidates in each event by making all combinations of the hadronic and leptonic W candidates with the jets in the event and selecting the combination that minimizes the quantity $|m_T^{\mathrm{had}} - m_T^{\mathrm{lep}}|$, where m_T^{had} is the reconstructed mass of the fully hadronically decaying VL T. Shown in the left of Figure 4 are the unit-normalized m_T^{lep} distributions for the dominant $t\bar{t}$ background and for signal, generated under various assumptions of VL T mass for a model assuming $BR(T \to Wb) = 1$. As can be seen, m_T^{lep} provides an excellent separation power against background. The same procedure can be applied to a search for VL $B \to Wt$ without need for further optimization. As shown on the right of Figure 4 the m_T^{lep} still has a very good separation power against the background when used for signal with a model assuming $BR(B \to Wt) = 1$.

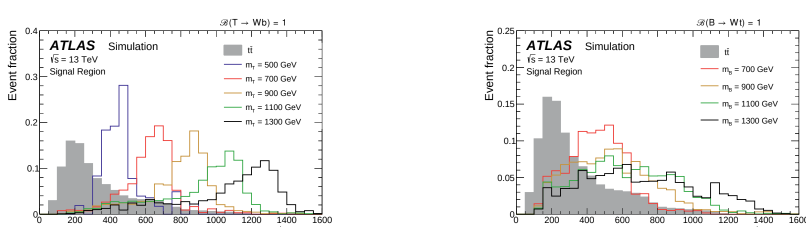

Figure 4 – The reconstructed leptonic VL T mass in the signal region of the $Wb+X$ analysis [8] is shown for the $t\bar{t}$ background and a few signal mass points, for signal models assuming $BR(T \to Wb) = 1$ (left) and for signal models assuming $BR(B \to Wt) = 1$ (right). In both figures, the distributions are normalized to unity for comparison of the relative shapes at each mass point.

The $t\bar{t}$ background is constrained by a dedicated control region (CR) and the search is performed in an orthogonal signal region (SR), by performing a likelihood fit of the background and signal contributions to the m_T^{lep} distribution observed in data. The SR and CR are defined using the scalar sum of the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the p_{T} of the lepton and jets (S_{T}) and the separation between the lepton and the neutrino ($\Delta R(lep, \nu)$). The definitions of the regions on the two-dimensional $\Delta R(lep, \nu)$ – S_{T} plane are shown in Figure 5 which shows the distribution expected for simulated $t\bar{t}$ background (left) and a signal model assuming $BR(T \to Wb) = 1$ and $m_T = 1.2$ TeV (right).

As can be seen, the CR and SR definitions allow for high signal efficiency in the SR and a large number of background events in the CR while being as close as possible to the SR. Sub-dominant backgrounds in this analysis include multijet events, estimated with the matrix method technique [9], and other SM backgrounds (W+jets, single t, Z+jets, $t\bar{t}V$) which are estimated with Monte Carlo.

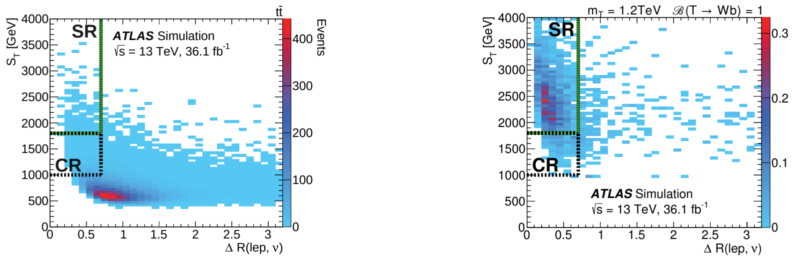

Figure 5 – The signal region (SR) and control region (CR) for the Wb+X analysis [8] are shown in a two-dimensional plane of S_{T} and $\Delta R(\mathrm{lep}, \nu)$, overlaying the distribution of the dominant $t\bar{t}$ background (left) and overlaying the expected signal distribution for $\mathcal{B}(T \to Wb) = 100\%$ and a mass of 1.2 TeV (right).

The dominant systematic uncertainties in this analysis are the single t and $t\bar{t}$ modelling uncertainties and the jet energy resolution. The m_T^{lep} distribution in the SR is shown in Figure 6 for background and for data before (left) and after (right) a background only fit. The expected signal distribution for a model with $BR(T \to Wb) = 1$ and $m_T = 1\ TeV$ is also shown in the pre-fit plot. After the fit, a very good agreement of the background expectation with the data is observed and therefore limits are set at 95% CL.

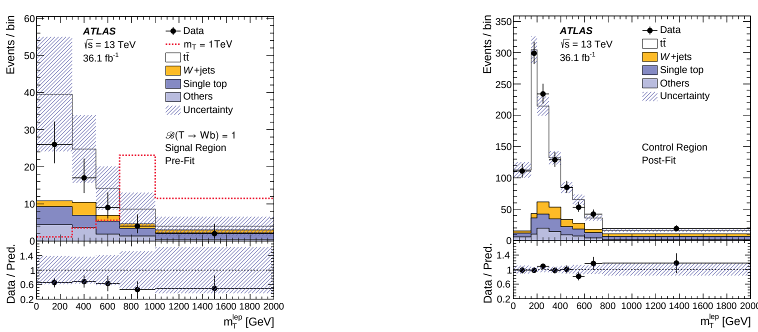

Figure 6 – Leptonic VLQ candidate mass distributions (m_T^{lep}) in the signal region of the $Wb + X$ analysis [8] before (left) and after a fit under the background-only hypothesis (right). The hatched area represents the total uncertainty in the background.

As in the first analysis, limits are set for particular benchmark models with specific BR assumptions as well as in the two-dimensional BR plane, using a similar signal reweighting procedure. Figure 7 (left) shows the highest excluded VL T mass for a given BR composition. The excluded masses are higher near point $(1, 0)$ indicating higher sensitivity to high $BR(T \to Wb)$. Masses up to 1350 GeV are excluded assuming $BR(T \to Wb) = 1$. For the SU(2) singlet scenario with BR to Wb, Zt, and Ht approximately equal to 0.5, 0.25, and 0.25, respectively, VL T masses up to 1170 GeV are excluded. The $BR(T \to Wb) = 1$ limits can be further applied to the VL Y quark with charge $q = -4/3e$ which decays exclusively to Wb, since no assumption on the VLQ charge is made. Pair production of VL Y quarks is therefore excluded up to 1350 GeV.

Furthermore, as discussed above, the same analysis can be used to determine limits on the pair production of VL B quarks and limits on the two-dimensional $BR(B \to Wt)$–$BR(B \to Hb)$

plane are shown in Figure 7 (right). Assuming $BR(B \to Wt) = 1$, VL B masses are excluded up to 1250 GeV, while masses up to 1080 GeV are excluded for a singlet scenario. The former limits are also applicable to the VL X with charge $q = 5/3e$ which decays exclusively to Wt and is therefore excluded for masses up to 1250 GeV.

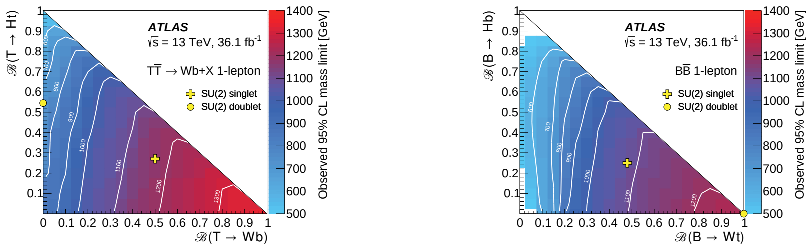

Figure 7 – Observed 95% CL lower limits on the mass of the T quark in the branching-ratio plane of $BR(T \to Wb)$ versus $BR(T \to Ht)$ (left) and observed 95% CL lower limits on the mass of the B quark in the branching-ratio plane of $BR(B \to Wt)$ versus $BR(B \to Hb)$ (right) for the $Wb{+}X$ analysis[8]. The markers indicate the branching ratios for the SU(2) singlet and doublet scenarios with masses above ≈ 0.8 TeV, where they are approximately independent of the VL T and B masses. The white region is due to the limit falling below 500 GeV, the lowest simulated signal mass.

4 Summary and conclusions

The latest ATLAS searches for new heavy quarks have focused on VLQs with a broad program targeting both pair and single production. Two recent searches for the pair production of VLQs performed by ATLAS and targeting decay modes via the W, Z, and H bosons have been presented. Assuming 100% BR to these decay modes, VL T masses up to between 1.17 TeV and 1.43 TeV are excluded at 95% CL. Additionally, VL B masses are excluded up to 1.25 TeV assuming 100% BR to Wt. Finally, exclusion limits are set for scenarios with intermediate BR compositions and interpretations in the two-dimensional BR plane for the highest excluded VLQ masses are provided.

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