PROCEEDINGS OF SCIENCE

Searches for Vector-Like Quarks at 13 TeV at the ATLAS Experiment

Olaf Nackenhorst[*][†]
University of Geneva, now at Technical University of Dortmund
E-mail: olaf.nackenhorst@cern.ch

Vector like quarks appear in many theories beyond the Standard Model as a way to solve the hierarchy problem of the Higgs boson. The current status of the ATLAS searches for the production of vector like quarks will be reviewed for proton-proton collisions at 13 TeV. This presentation will address the analysis techniques, in particular the selection criteria, the background modeling and the related experimental uncertainties.

EPS-HEP 2017, European Physical Society conference on High Energy Physics
5-12 July 2017
Venice, Italy

[*]Speaker.
[†]on behalf of the ATLAS collaboration

 https://pos.sissa.it/

PoS(EPS-HEP2017)320

1. Introduction

The discovery of the Higgs boson by the two LHC [1] experiments ATLAS [2] and CMS in 2012 is a major milestone in particle physics [3, 4]. All measurements of its couplings and properties performed since then are consistent with the Standard Model (SM). Although we now understand that elementary particles acquire their masses by spontaneous breaking of the electroweak symmetry, we do not understand the underlying nature of this symmetry-breaking yet. Quantum loop corrections in the Higgs boson propagator, which contribute to the mass of the Higgs boson, diverge quadratically with the energy scale. In order to avoid an unnatural fine-tuning, these loop contributions need to be canceled by some new mechanism to preserve the Higgs boson mass at the electroweak scale. The most prominent candidates for such particles are super-symmetric particles, however no hint for super-symmetry has been found yet. Another more straightforward solution is the inclusion of a fourth generation of quarks which could account for these cancellations. While a fourth generation of chiral quarks is highly disfavored, since the Higgs boson discovery [5], vector-like quarks (VLQs) could still exist and are predicted in extensions to the SM like Little Higgs [6, 7], Composite Higgs [8, 9] or warped extra dimensions [10]. VLQs are hypothetical spin-1/2 colored particles, whose left- and right-handed chiral representations transform in the same way under the electroweak gauge group and hence their masses are not generated by the coupling to the Higgs boson. Since the mixing with SM quarks is expected to be proportional to the quark mass, they couple preferably to top and bottom quarks. In most models VLQs can decay either via charged or via flavour-changing neutral current conserving the electric charge. As a result the vector-like partner of the SM top quark, usually referred to as T (2/3e) or Y (-4/3e) can decay into Wb/Zt/Ht or Wb, while the bottom quark partner, referred to as B (-1/3e) or X (5/3e), can decay into Wt/Zb/Hb or Wt. The branching ratios of these decays depend on VLQ masses and on the realization as singlets, doublets or triplets. In the high mass limit above 1 TeV the branching ratios of a vector-like T (B) are roughly 2:1:1 for Wb:Zt:Ht (Wt:Zb:Hb) as a singlet and 1:1 for Zt:Ht (Zb:Hb) as a doublet. Electroweak precision measurements require the mass difference between the VLQs to be small, hence cascade decays like $T \rightarrow Wb$ are kinematically suppressed. Below a mass of 1 TeV VLQs are mainly produced in pairs via the strong interaction, while for higher masses the single production via electroweak interaction becomes more important. The ATLAS collaboration has searched for T and B production at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV covering almost all production and decay channels [11–18]. The results of the searches performed by the ATLAS collaboration at $\sqrt{s} = 13$ TeV will be briefly summarized in the following.

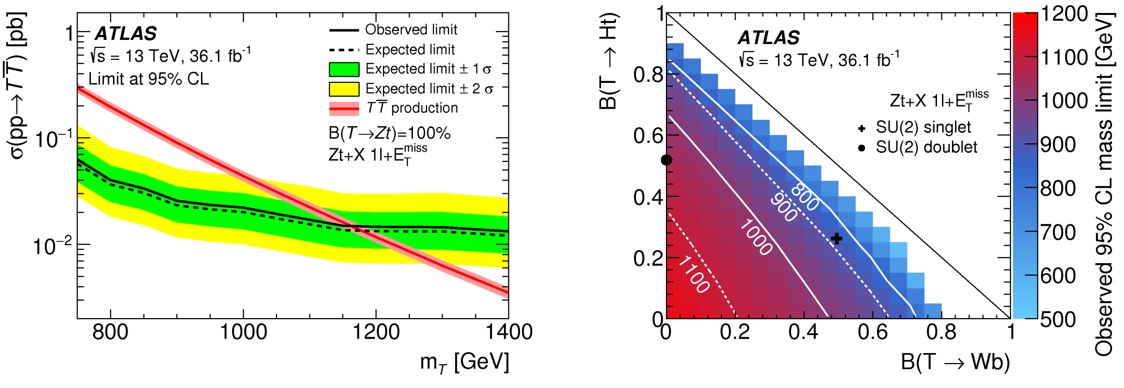
2. Searches for vector-like quark pair production at $\sqrt{s} = 13$ TeV

2.1 Search for $T\bar{T}$ (Zt+X)

The search for $T\bar{T}$ (Zt+X) [11] uses the full 2015 and 2016 dataset of 36.1 fb^{-1} and is optimized for final states, in which one vector-like top quark decays into Zt with the Z decaying subsequently into two neutrinos ($T \rightarrow tZ(\nu\nu)$). The other vector-like T is allowed to decay arbitrarily. The event selection requires exactly one high p_T lepton, at least four high p_T small-R jets, at least two large-R jets and large $E\!\!\!/_T$. The analysis follows then a cut & count approach defining one signal enriched region and two control regions, which are dominated by the main background

PoS(EPS-HEP2017)320

processes $t\bar{t}$ and W+jets. The regions are defined by applying different cuts on the transverse W mass m_T, a generalized version of the transverse mass am_{T2}, the significance of vectorial sum of all jets and lepton transverse momentum $H_{T,sig}^{miss}$ and the number of b-jets. The predictions of the number of $t\bar{t}$ and W+jets events are improved by fitting the estimates obtained from simulation to data in the control regions. The improved predictions are validated in three separate regions purified in $t\bar{t}$, W+jets and single top events, which are made orthogonal to the control and signal regions by requiring exactly one large-R jet. No significant excess above the background only prediction is observed and lower limits on the vector-like top quark mass are set for different benchmark scenarios. Assuming that the vector-like T decays exclusively into Zt the observed (expected) lower mass limit is 1160 (1170) GeV, as shown in Figure 1 a). In Figure 1 b) the lower limits of the T quark



(a) (b)

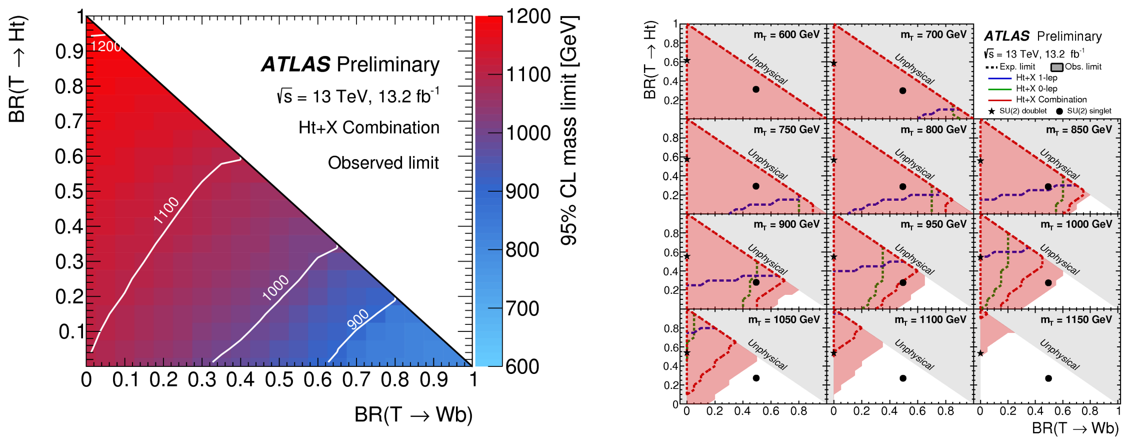
Figure 1: a) Observed and expected 95% CL upper limit on the cross-section times branching ratio for VLT pair production as a function of the T mass for B($T \to Zt$) = 100%. b) Observed 95% CL lower limit on the T quark mass as a function of the decay branching ratios into Wb and Ht [11].

mass are shown as a function of the decay branching ratios into Wb and Ht, which demonstrates that the search is most sensitive to the Zt decay. The search sensitivity is currently limited by the statistical uncertainty, with the main systematic uncertainties arising from $t\bar{t}$ and single top quark modeling.

2.2 Search for $T\bar{T}$ (Ht+X)

The search for $T\bar{T}$ (Ht+X) [12] uses 13.2 fb^{-1} of the $\sqrt{s} = 13$ TeV data and targets subsequent $T \to tH(bb)$ decays. The event selection requires either one lepton or zero leptons and high $\not{E}_T$ in order to suppress multi-jet background events. In addition, at least five jets of which at least two are b-tagged and one large-R jet with high mass are required. The events are then classified into 20 signal and 15 validation regions defined by the number of jets, b-jets, high mass large-R jets and high and low reconstructed $m_{bb}^{\mathrm{min}\Delta\mathrm{R}}$ (1 lepton) or $m_{T,\mathrm{min}}^{b}$ (0 leptons). In order to improve the modeling of the background predictions containing mainly $t\bar{t}$ events, a simultaneous profile likelihood fit of all signal regions is performed using as discriminating variable the effective mass m_{eff}, which is the scalar sum of all jet and lepton p_T plus $\not{E}_T$. After this fit, the background predictions agree considerably better with data and the systematic uncertainties are significantly constrained.

The most important systematic uncertainties arise from the modeling of $t\bar{t}$+jets background events. Because no significant excess above the background expectations is observed, lower limits on the vector-like T quark mass are set. Since the analysis is most sensitive to the Ht decay (Fig. 2 (a)), the best lower mass limit of $m_T > 1200$ GeV is obtained assuming BR($T \to Ht$) = 100%. However, due to the inclusion of the 0-lepton channel (Fig. 2 (b)), the analysis is also quite sensitive to Zt decays, where a limit of $m_T > 1100$ GeV is obtained assuming exclusive Zt decays.

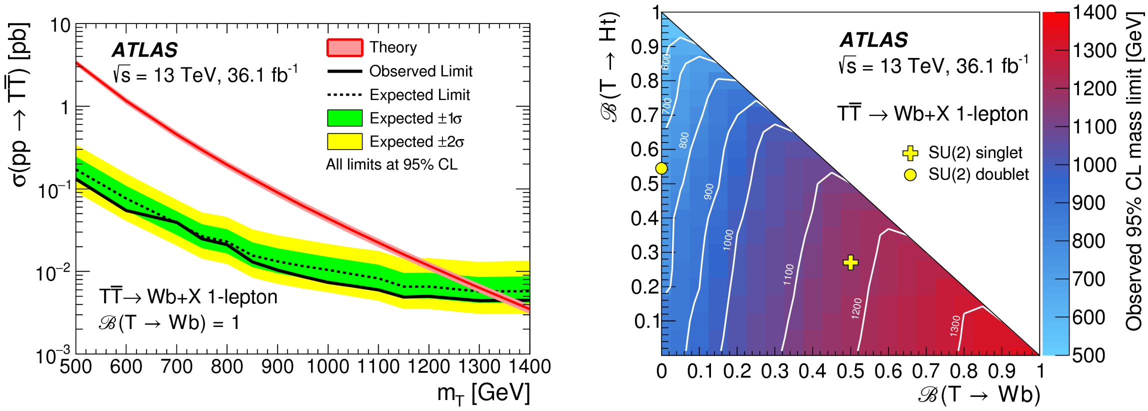


(a) (b)

Figure 2: a) Observed 95% CL lower limit on the T quark mass as a function of the decay branching ratios into Wb and Ht. b) Observed (red filled area) and expected (red dashed line) 95% CL exclusion in the plane of BR($T \to Wb$) versus BR($T \to Ht$), for different values of the vector-like T quark mass for the combination of the 1-lepton and 0-lepton searches [12].

2.3 Search for $T\bar{T}$ (Wb+X)

The search for $T\bar{T}$ (Wb+X) [13] uses the full 2015 and 2016 dataset of 36.1 fb^{-1} and targets final states, where one T decays into Wb and the other decays arbitrarily. The selection addresses events with exactly one lepton, large E_T^{miss} and at least three jets of which at least one is b-tagged. In addition, it is required that at least one large-R jet is tagged as a W boson and does not overlap with a b-jet. The events are categorized into one signal region and one $t\bar{t}$ control region, which are defined by the distance between the lepton and the neutrino, and the total scalar sum of the transverse momenta of all objects. A full event reconstruction of the $T\bar{T}$ system is performed by minimizing the absolute difference between the two reconstructed vector-like T quark masses. The transverse mass of the leptonically decaying T quark is then used in a profile likelihood fit in order to improve the background modeling. No excess in data above the background model is observed and lower mass limits on the vector-like T/Y and B/X masses are set for different benchmark scenarios. The search is most sensitive to $T/Y \to Wb$ and $B/X \to Wt$ decays and obtains limits of $m_{T/Y} > 1350$ GeV and $m_{B/X} > 1250$ GeV, respectively. The search is currently dominated by statistical uncertainties with the main systematic uncertainties arising from modeling of events with top quarks.



(a) (b)

Figure 3: a) Observed and expected 95% CL upper limit on the cross-section times branching ratio for VLT pair production as a function of the T mass for B($T \rightarrow Wb$) = 100%. b) Observed 95% CL lower limit on the T quark mass as a function of the decay branching ratios into Wb and Ht [13].

2.4 Search for pair VLQ production with same-sign leptons

The search for pair VLQ production with same-sign leptons [14] uses 3.2 fb^{-1} of data and addresses $T/B/X$ decays with at least two jets, exactly two same-sign leptons or at least three leptons including vetos on quarkonia and Z bosons. The events are classified and counted in eight signal regions depending on the number of b-jets, the scalar sum of all transverse momenta and $\not{E}_T$. The most dominant backgrounds in all signal regions are instrumental background events originating from misidentified non-prompt leptons and charge misidentification of the leptons. The search is most sensitive to $T \rightarrow Wb$ and $B \rightarrow Wt$ decays with the best limits of $m_T > 780$ GeV and $m_B > 830$ GeV assuming a singlet model.

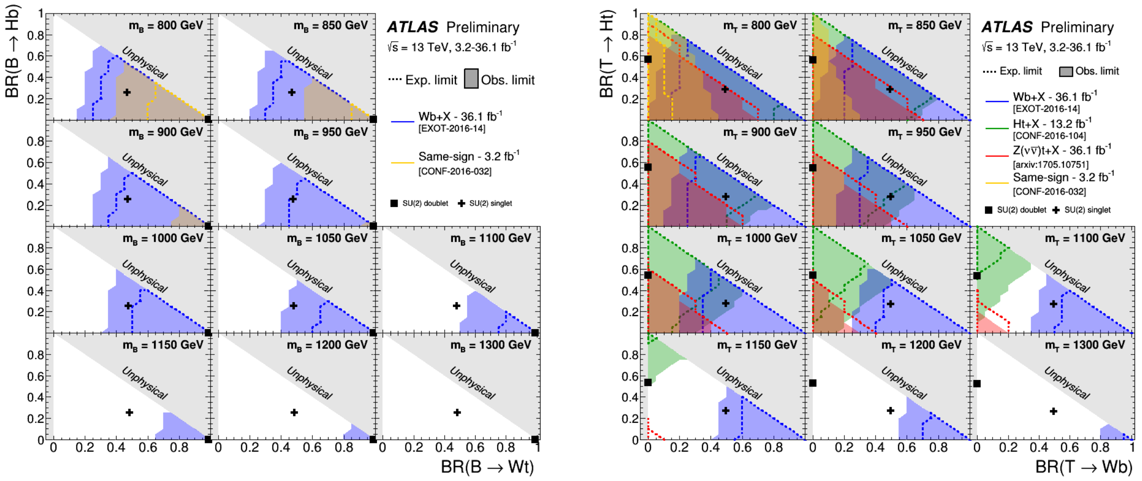
3. Searches for single production of vector-like quarks at $\sqrt{s} = 13$ TeV

3.1 Search for $T/Y \rightarrow Wb$

The search for single production of vector-like T/Y quarks decaying into Wb [19] uses 3.2 fb^{-1} of data. One signal region is defined by requiring exactly one lepton, large $\not{E}_T$, at least one high p_T jet and at least one forward jet in the event selection. In order to suppress $t\bar{t}$ background a veto on events with jets either close or in opposite direction to the leading b-jets is applied. In addition, one $t\bar{t}$ control region with inverted veto and one W+jets control region with zero b-jets are used in order to control the background predictions. The vector-like quark is reconstructed from the lepton, the $\not{E}_T$ and the b-jet, and its mass is then used in a profile likelihood fit. No significant excess over the SM expectations is observed and upper limits on the VLQ production cross section times the branching ratio are set as a function of the VLQ mass. Because of the production mechanism, lower limits on the vector-like quark mass depend on the assumed coupling strength. In addition, the results are also interpreted as limits on the coupling strength and the mixing angle with the SM sector.

4. Summary and conclusions

The ATLAS experiment has a broad search program for vector-like quarks at $\sqrt{s} = 13$ TeV. While all decay modes of the vector-like T quark are considered, the vector-like B decays are not fully covered (Fig. 4). So far, there is no evidence for new physics, but very competitive lower limits on the VLQ mass are set above the 1 TeV scale as summarized in Figure 4. The best limit



(a) (b)

Figure 4: a) Observed (filled area) and expected (dashed line) 95% CL exclusion in the plane of BR($B \to Hb$) versus BR($B \to Wt$) (a) and BR($T \to Ht$) versus BR($T \to Wb$) (b), for different values of the vector-like B and T quark mass for the Wb+X (blue), the Ht+X (green), the Zt+X (red) and the same-sign leptons (yellow) analyses [11–14].

of $m_{T/Y} > 1350$ GeV is currently achieved in the Wb+X analysis assuming exclusive Wb decays [13]. However, the full potential of the 2015 and 2016 data is not yet explored and many searches are currently being extended to the full dataset. Since all searches are limited by the integrated luminosity, the significant increase of data in 2017 is expected to improve the sensitivity of the searches considerably.

References

[1] L. Evans and P. Bryant, *LHC Machine*, JINST **3** (2008) S08001, ed. by L. Evans.

[2] *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003.

[3] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B **716** (2012) p. 1, arXiv: `1207.7214 [hep-ex]`.

[4] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. B **716** (2012) p. 30, arXiv: `1207.7235 [hep-ex]`.

[5] O. Eberhardt et al., *Impact of a Higgs boson at a mass of 126 GeV on the standard model with three and four fermion generations*, Phys. Rev. Lett. **109** (2012) p. 241802, arXiv: 1209.1101 [hep-ph].

[6] N. Arkani-Hamed, A. G. Cohen, E. Katz, and A. E. Nelson, *The Littlest Higgs*, JHEP **07** (2002) p. 034, arXiv: hep-ph/0206021 [hep-ph].

[7] M. Schmaltz and D. Tucker-Smith, *Little Higgs review*, Ann. Rev. Nucl. Part. Sci. **55** (2005) p. 229, arXiv: hep-ph/0502182 [hep-ph].

[8] D. B. Kaplan, H. Georgi, and S. Dimopoulos, *Composite Higgs scalars*, Phys. Lett. B **136** (1984) p. 187 .

[9] K. Agashe, R. Contino, and A. Pomarol, *The Minimal composite Higgs model*, Nucl. Phys. **B719** (2005) p. 165, arXiv: hep-ph/0412089 [hep-ph].

[10] L. Randall and R. Sundrum, *A Large mass hierarchy from a small extra dimension*, Phys. Rev. Lett. **83** (1999) p. 3370, arXiv: hep-ph/9905221 [hep-ph].

[11] ATLAS Collaboration, *Search for pair production of vector-like top quarks in events with one lepton, jets, and missing transverse momentum in* $\sqrt{s} = 13$ *TeV pp collisions with the ATLAS detector*, JHEP **08** (2017) p. 052, arXiv: 1705.10751 [hep-ex].

[12] ATLAS Collaboration, *Search for new phenomena in* $t\bar{t}$ *final states with additional heavy-flavour jets in* 3.2 fb^{-1} *of pp collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, ATLAS-CONF-2016-104, 2016, URL: https://cds.cern.ch/record/2220371.

[13] ATLAS Collaboration, *Search for pair production of heavy vector-like quarks decaying to high-*$p_{\rm T}$ *W bosons and b quarks in the lepton-plus-jets final state in pp collisions at* $\sqrt{s}$*=13 TeV with the ATLAS detector*, CERN-EP-2017-094, 2017, arXiv: 1707.03347 [hep-ex].

[14] ATLAS Collaboration, *Search for new phenomena using events with b-jets and a pair of same-charge leptons in* 3.2 fb^{-1} *of pp collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, ATLAS-CONF-2016-032, 2016, URL: https://cds.cern.ch/record/2161545.

[15] ATLAS collaboration, *Analysis of events with b-jets and a pair of leptons of the same charge in pp collisions at* $\sqrt{s} = 8$ *TeV with the ATLAS detector*, JHEP **10** (2015) p. 150, arXiv: 1504.04605 [hep-ex].

[16] ATLAS collaboration, *Search for pair and single production of new heavy quarks that decay to a Z boson and a third-generation quark in pp collisions at* $\sqrt{s} = 8$ *TeV with the ATLAS detector*, JHEP **11** (2014) p. 104, arXiv: 1409.5500 [hep-ex].

[17] ATLAS collaboration, *Search for production of vector-like quark pairs and of four top quarks in the lepton-plus-jets final state in pp collisions at* $\sqrt{s} = 8$ *TeV with the ATLAS detector*, JHEP **08** (2015) p. 105, arXiv: 1505.04306 [hep-ex].

[18] ATLAS collaboration, *Search for top squarks in final states with one isolated lepton, jets, and missing transverse momentum in* $\sqrt{s} = 13$ *TeV pp collisions with the ATLAS detector*, Phys. Rev. **D94** (2016) p. 052009, arXiv: 1606.03903 [hep-ex].

[19] ATLAS Collaboration, *Search for single production of vector-like quarks decaying into* Wb *in pp collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, ATLAS-CONF-2016-072, 2016, URL: https://cds.cern.ch/record/2206226.