Search for vector-like quarks *

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Vector-like quarks (VLQ) are predicted by many extensions of the Standard Model. If the Higgs sector is not changed the VLQs can be isospin singlets, doublets or triplets, and can decay via charged (W) or neutral currents (H, Z). A search for pair-production of vector-like quarks T and B with a leptonically decaying Z boson is presented, with 36.1 fb$^{-1}$ of data collected by the ATLAS detector at the Large Hadron Collider at $\sqrt{s} = 13$ TeV. This search targets events that contain a pair of opposite-sign same-flavour leptons, and at least a third generation quark, which would arise from the VLQ decay. The lepton pair is selected to form a Z candidate, with the boosted topology being explored in order to target high VLQ masses.

1. Introduction

1.1. Motivation for Vector-like Quarks

The Standard Model of particle physics (SM) does not predict the number of fermion families. Direct searches for an extra chiral family have upper mass limits of about 600 GeV [1]. The precise measurement of the $H \rightarrow \gamma \gamma$ cross section [2] disfavours the existence of a sequential fourth generation of quarks, since these heavy chiral quarks would enter the virtual loops and affect the production cross section by about an order of magnitude [3, 4, 5]. Vector-like quarks (VLQs) however have the same left- and right- handed SU(2) quantum numbers. Consequently they do not need the Higgs mechanism to acquire mass and the constraints from the Higgs sector are therefore relaxed. VLQs are naturally predicted in many beyond the SM theories that try to tackle the naturalness problem such as Composite Higgs models [6, 7].

1.2. VLQ phenomenology

Different mechanisms to produce VLQs are illustrated in Figure 1. Pair-production of VLQs occurs via Quantum Chromodynamics (QCD) interac-
tions. It is the more model independent mechanism and dominates for lower VLQ masses, as can be seen in Figure 2. On the other hand, as VLQ masses increase, phase-space restrictions become more severe and VLQ single-production starts to dominate. It is mediated via electroweak (EW) bosons, therefore its cross section has a direct dependence on the assumed coupling to the EW boson. This creates a stronger model dependency when compared to pair-production.

![Feynman diagrams for (left) single-produced vector-like T, (center) single-produced vector-like B, (right) pair-produced VLQ. From Ref. [8].](image1)

VLQs can have SM-like electric charges of $\frac{2}{3}|e|$ (T) and $-\frac{1}{3}|e|$ (B) and exotic charges of $-\frac{4}{3}|e|$ (X) and $\frac{5}{3}|e|$ (Y). In the current analysis only T and B are considered.

2. Search for VLQ

2.1. Analysis description

This analysis uses data collected by the ATLAS experiment [10] in 2015 and 2016 at $\sqrt{s} = 13$ TeV, which amounts to an integrated luminosity of 36.1 fb$^{-1}$. In this search events compatible with a leptonic decay of a Z boson are selected. It assumes that there are only VLQ decays to third-generation quarks (i.e. $W/Z/H + t/b$) and that singlet and doublets have negligible kinematic differences.

![Cross section as a function of the mass of the VLQ for the different production mechanisms. From Ref. [9].](image2)
The analysis is split into pair- and single-production [11]. Both are divided into dilepton (exactly 2 leptons) and trilepton (at least 3 leptons) channels. The pair-production dilepton search is further divided into a semi-boosted channel (events with 0 or 1 large radius jets) and a boosted channel (events with at least 2 large radius jets). In order to improve the signal to background ratio a selection is applied that relies on the fact that, since VLQs are expected to be massive, the final state objects coming from VLQ decays have a harder energy spectrum. Each analysis uses an optimized selection in order to fully profit from the particular features of its phase space. In the end the different channels are fitted simultaneously.

2.2. Results

![Fig. 3. VLQ pair-production discriminant variables in (left) semi-boosted dilepton analysis, (center) boosted dilepton analysis, (right) trilepton analysis. From Ref. [11].](image)

As can be seen in Figure 3, no significant deviation from the SM expectation was found. Therefore upper limits on the production cross section as a function of mass were derived at 95% Confidence Level (CL). Figure 4 shows the limits for the case where the Branching Ratio of the VLQ decays to $Z$ is 100%. In this scenario masses up to around 1.2 to 1.3 TeV are excluded.

For single-production the cross section is dependent of the coupling itself so Figure 4 shows limits for a specific coupling of the VLQ to the $W$ boson as is shown in Figure 1, as well as coupling limits as a function of the VLQ mass.
Fig. 4. Upper limits on the VLQ pair (up) and single (down) production cross section at 95% CL. From Ref. [11].

3. Pair-production combination

All ATLAS searches for pair-produced VLQs were combined [12]. The results of this combination can be seen in Figure 5, which shows the exclusion of each mass across the Branching Ratio plane. It can be seen that each analysis brings sensitivity to different phase space regions. The analysis described in this document is represented in purple \((Z(l\ell)t/b + X)\).

4. Conclusions

A search for VLQs decaying via a leptonic Z boson was performed. Since no deviations from the SM expectation were found upper limits on the production cross section were derived. This analysis was combined with all other pair-production searches. The results were significantly improved and show the complementary between searches.

An update of the analysis using the full dataset collected by the ATLAS collaboration in the second run is planned. It amounts to an integrated luminosity of about 139 fb\(^{-1}\) which represents a factor 4 improvement from the 2015+2016 dataset. The main challenge for this iteration will be to fully profit from the increase in statistics, e.g. by improving the treatment of boosted topologies and introducing machine learning techniques.

Fig. 5. Observed (filled area) and expected (dashed lines) exclusion plane for different masses of vector-like $T$ (top) and vector-like $B$ (bottom) at 95% CL. From Ref. [12].
REFERENCES


