Search for Single Production of Vector-like Quarks Coupling to Light Generations in 4.64 fb\(^{-1}\) of ATLAS Data at \(\sqrt{s} = 7\) TeV

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Abstract. This analysis presents a search for singly-produced vector-like quarks (VLQs) coupling to light quark generations in events with a \(W\) or \(Z\) boson produced in association with two or more high transverse momentum jets. The vector boson produced in the VLQ decay is reconstructed in the \(W \to \ell \nu\) or \(Z \to \ell \ell\) modes, where \(\ell\) is an electron or a muon. No evidence of VLQs is observed above the expected background in 4.64 fb\(^{-1}\) of data taken in 2011 by the ATLAS experiment at the LHC at a centre-of-mass energy of 7 TeV. A fit to the distribution of the invariant mass of the system composed of the vector boson and the highest transverse momentum jet is used to set limits on the heavy quark production cross section times branching ratio, and mass bounds are obtained for three flavors of VLQs.

1. Introduction
Many extensions of the Standard Model (SM) predict the existence of vector-like quarks (VLQs) in Refs. [1,2], defined as spin 1/2 quarks for which both chiralities have the same transformation properties under \(SU(2) \times U(1)\). Notably, VLQs are often introduced as a top partner to cancel quadratic divergence of the top loop in the Higgs propagator. Although VLQs are generally assumed to mix primarily with third-generation SM quarks in order to satisfy constraints from electroweak (EWK) precision measurements and flavor observables, mixing to first generations is not excluded. In some scenarios, including the benchmark model considered in this search from Ref. [3], corrections to the quark mixings can cancel and relax these constraints, thus producing sizeable cross sections for the production of multiple new VLQs at the LHC in which single production is found to be the most likely channel for discovery.

Searches for single production of VLQs, in these channels have previously been reported by ATLAS [4], CDF [5] and D0 [6]. This search, more fully documented in Ref. [7], is performed for three flavors of VLQs, one up-type \(U\) quark of charge \(+2/3\), one down-type \(D\) quark of charge \(-1/3\), and one \(X\) quark of charge \(+5/3\) in which the decays are assumed to contain \(W\) and \(Z\) bosons 100% of the time. In this analysis, performed using data collected with the ATLAS detector [8] at \(\sqrt{s} = 7\) TeV, these VLQs are searched for in events with a \(W\) or \(Z\) boson produced in association with at least two jets, and in which the vector boson decays leptonically with electrons or muons in the final state.
2. Selection and Optimization

The VLQs searched for in this analysis are assumed to decay to a W or Z boson, referred to as CC charged current or NC neutral current channels respectively, and a light quark. Thus, this new physics signal can be detected as an excess in the rate of production of W/Z in association with a jet. This excess will manifest itself as a resonance near the VLQ mass, and so the sensitivity of this search is increased and it is made model-independent by “bump-hunting” for W/Z+jet resonant signals. However, background processes producing a W or Z boson and a high-transverse momentum (high-p_T) jet, whether fake or irreducible, are large and so a set of selection criteria are applied to select a subset of signal-like events used for the search. This selection is optimized by using Monte Carlo simulation of the primary standard model backgrounds (W/Z+jets, tt, single top, and diboson) and proceeds in two stages. First, an initial baseline preselection is made to ensure that well understood events are being used in the search. Then, a multivariate optimization procedure is implemented to exploit kinematic features of the signal to define a set of selection criteria that increase the sensitivity to the VLQ signal.

The initial baseline event selection is performed by selecting events using a set of preselection criteria that ensure events to have been recorded during data-taking periods during which all subsystems of the detector are operational. Events in both data and Monte Carlo are then required to pass a high-p_T lepton trigger fired by one of the leptons used to reconstruct the leptonic W/Z boson decay. In each event, selection criteria are applied to all the physics objects necessary to reconstruct the full topology of the production and decay of the VLQ. Electrons are reconstructed using an algorithm to select high quality, well isolated leptons with E_T > 25 GeV and |η| < 2.47^1 (but vetoing electrons reconstructed in the transition region of 1.37 < |η| < 1.52). Muons are reconstructed using an algorithm to veto muons coming from heavy flavor decay and cosmic rays, and are required to be well-isolated and have p_T > 25 GeV and |η| < 2.7. Jet candidates are reconstructed using the anti-kt algorithm [10] with a radius parameter of 0.4, using topological calorimeter clusters as constituents. These jets are required to pass a set of selection criteria defined to suppress jets coming from pileup or problematic detector regions and are further required to have p_T > 25 GeV and |η| < 4.5. Lastly, the missing transverse energy (E_T^{miss}), used as the candidate object for the neutrino in CC channel events, is calculated as the negative vector sum of the transverse momenta of all reconstructed objects in an event within |η| < 4.5.

The four-vector of the VLQ is then reconstructed in the CC (NC) channel as the sum of the four vectors from the W (Z) boson and the highest p_T jet in the event. In the CC channel, the W boson is reconstructed in events with exactly one lepton and E_T^{miss} > 50 GeV and is required to have a transverse mass greater than 40 GeV. Furthermore, for full reconstruction of the VLQ in the CC channel the longitudinal momentum of the neutrino candidate is determined using a W mass constraint with the lepton and E_T^{miss}. In the NC channel, events with a Z boson are selected as having two oppositely charged leptons of the same flavor whose combined invariant mass is between 66 GeV and 116 GeV.

In addition to these VLQ signature requirements, the signal to background ratio is enhanced by initially requiring events to have N_{jet} ≥ 2 in order to exploit the presence of the second light quark from the VLQ production, creating an “associated” forward jet. Then, an optimization of simple rectangular cuts is performed with five (six) angular separation variables as discriminating variables in the CC (NC) channel. The figure of merit S/\sqrt{S+B}, where B is the number of expected events according to the MC background estimate, and S is the number of expected events according to the 400 GeV VLQ Monte Carlo, is maximized using TMVA [9] to obtain

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1 ATLAS uses a right-handed coordinate system with the z-axis along the beam pipe. The x-axis points to the center of the LHC ring, and the y-axis points upward. The pseudorapidity is dened in terms of the polar angle \( \theta \) as \( \eta = \ln(\tan(\theta/2)) \)
the numerical values for the cuts placed on these variables, the quantitative details of which are provided in Ref. [7]. The sensitivity obtained for the spectrum of masses is not found to be greatly increased if the numerical values of these cuts are varied as a function of signal VLQ mass.

3. Search Results

After the optimization is performed using a Monte Carlo driven estimate of the background composition, the qualitative understanding of the background is confirmed by a comparison to data as in Figure 1(a) and Figure 1(b). However, the final background is parametrized by fitting the reconstructed invariant mass of the four-vector reconstructed from the $W$ or $Z$ boson and the highest $\eta$ jet, after the full selection. The functional form used to perform this fit is

$$f(m; p_{0,1,2,3}) = p_0 \cdot \frac{(1 - x)^{p_1}}{x^{p_2 + p_3 \ln(x)}},$$  (1)

where $x$ is the reconstructed VLQ mass $m_Q$ (in units of 7 TeV) and $p_{0,1,2,3}$ are four free parameters. This fit is performed on a binned distribution, where the binning is chosen to reflect the reconstructed width of the VLQ signal. This background estimation is used to initially perform search using the BUMP Hunter algorithm as described in Ref. [11] to search all mass windows for the largest excess in data above the smooth background hypothesis as in Figure 1(c) and Figure 1(d). In both channels, no significant deviation is found from the smooth background hypothesis, the most deviant region being illustrated in Figure 1(c) and Figure 1(d) by the vertical blue lines.

4. Interpretation of Results

Since these results are consistent with a background-only hypothesis, Bayesian limits are set on $\sigma(pp \rightarrow qQ) \times \text{BR}(Q \rightarrow W/Z + q)$ for the VLQ benchmark signal. These limits, shown in Figure 2, are generated for signal mass points between 400 GeV and 2 TeV using the fitted background estimation described above, with systematic uncertainties from the background fit and signal modelling integrated into the likelihood function with nuisance parameters for each. From this interpretation, the determined limits on cross section times branching ratio for the CC (NC) channel are found to range from 3 (1.9) pb at 400 GeV to 0.03 (0.07) pb at 2.0 TeV. For the nominal benchmark model considered here, the observed (expected) 95% confidence level lower limits on the VLQ mass are obtained at 1120 GeV (1160 GeV) and 1420 GeV (1570 GeV) for VLQs of charge $-1/3$ and $+5/3$ in the CC channel, and at 1080 GeV (1090 GeV) in the NC channel.

5. Conclusion

A search for heavy VLQs has been performed in $4.64 \text{ fb}^{-1}$ of $pp$ collision data taken in 2011 by the ATLAS experiment at a center-of-mass energy of 7 TeV. No evidence of VLQs is observed in the reconstructed VLQ candidate mass distributions, and limits are set on the production cross section for signal masses between 400 GeV and 2 TeV. For this benchmark model of VLQs with charge 2/3 and -1/3, these are the strongest limits to date and furthermore, for the charge +5/3 VLQ, which decays to a $W$ boson and a light quark, these are the first limits on such a model.

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Figure 1. From Ref. [7], figures (a) and (b) show the comparison of the Monte Carlo estimated backgrounds for the combined electron and muon channels for the CC (a) and NC (b) channel. A 1.1 TeV VLQ signal, normalized to the nominal cross section, is overlaid in each case. Figures (c) and (d) show the results from the search using the BumpHunter algorithm for combined electron and muon channels for the CC (c) and NC (d) channels showing the local deviation of the data from the smooth background hypothesis and the most significant deviation and corresponding region bounded by vertical blue lines.

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Figure 2. From Ref. [7], the expected and observed 95% C.L. upper limits on $\sigma(pp \rightarrow qQ) \times BR(Q \rightarrow Wq)$ where $Q$ is a $D$ or $X$ (a) and on $\sigma(pp \rightarrow qU) \times BR(U \rightarrow Zq)$ (b) calculated in the CC and NC channels, respectively. The nominal theoretical predictions are overlaid.