PROCEEDINGS OF SCIENCE

ATLAS Searches for Leptoquarks and Vector-like Quarks

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The Standard Model of particle physics explains many natural phenomena yet remains incomplete. Leptoquarks are hypothetical particles predicted to mediate interactions between quarks and leptons, bridging the gap between the two fundamental classes of particles. Vector-like quarks lie at the heart of many extensions seeking to address the hierarchy problem, as they can naturally cancel the mass divergence for the Higgs boson. These proceedings present the new results from leptoquarks and Vector-like quarks searches with the ATLAS detector using the Run-2 dataset.

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1. Introduction

Leptoquarks (LQs) are hypothetical particles that carry color and a fractional electric charge, decay into quark-lepton pairs, and appear in several models such as a part of the Grand Unification Theory. Hints of lepton flavour universality violation are observed in charged and neutral current processes in B-physics experiments, and the size of the anomalies suggests a tree-level mediator such as a leptoquark. Leptoquarks can be scalar or vector particles, the latter includes two scenarios that depend on anomalous couplings with gluons, one of these scenarios sets the LQ as a fundamental gauge boson (Yang-Mills (YM) coupling scenario), and the other scenario sets the LQs to be composite particles (minimal coupling scenario). Leptoquarks can be produced in pairs, singly, or non-resonantly, and searches for single- and pair- produced LQ resonant production are presented here. Decays can occur into all possible lepton and quark combinations.

Vector-like Quarks (VLQs) are color-triplet, spin-$1/2$ fermionic partners of Standard Model (SM) quarks that appear in many models such as composite Higgs, little Higgs, extra dimensions, all of which mitigate divergences to the Higgs mass. Vector-like quarks could appear as different types of multiplets: SU(2) singlets, doublets, or triplets of T, B, X and Y. The T and B have the same electric charges as the SM t- and b-quarks, while X and Y have $5/3$ and $-4/3$, respectively. Pair-production dominates at low mass and single production dominates at high mass and high coupling. Preferential coupling to third generation SM quarks is assumed to cancel out the Higgs boson mass divergence from top-quark loops. The cross section limits are typically set as a function of the mass of the T/B quark (M_T, M_B), the global electro-weak coupling parameter (κ), the relative couplings to W, Z, and H bosons respectively ($\xi W, \xi Z, \xi H$), and the relative width ($\Gamma/M \sim \kappa^2 M^2$).

Several results from the searches for LQs and VLQs are presented using the full LHC Run-2 data sample with an integrated luminosity of 139 fb^{-1} collected with the ATLAS detector in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV.

2. Searches for Leptoquarks

2.1 Pair production in the $\mathrm{b}\tau\mathrm{b}\tau$ final state

A search is performed for the channel in which LQs are produced in pairs and decay into the $\mathrm{b}\tau\mathrm{b}\tau$ final state [1]. Full-hadronic $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ and semi-leptonic $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ (lep = e, μ) channels are considered. The high-energy phase space which is sensitive to high-mass signal events is selected based on $\mathrm{p_T}$, $\mathrm{E_T^{miss}}$, and scalar sum of $\mathrm{p_T}$ ($\mathrm{s_T}$). The $\mathrm{s_T}$ of single- and pair- top quark events is reweighted to correct the known mis-modeling of the transverse momentum distribution for top quarks, and the background from multi-jets is estimated by using a data-driven method. A parametric neural network (PNN) is used to separate signal and background, and is used as the final discriminant variable.

A binned profile likelihood fit is performed on the PNN score distribution. No significant excess over the SM expectation is observed and 95% confidence-level (CL) upper limits are set. Figure 1 shows examples of limits for cross section versus mass, and for branching ratio versus mass for scalar LQs.

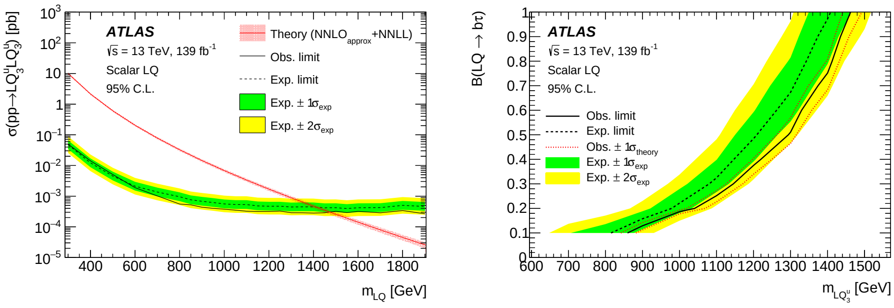

Figure 1: 95% CL upper limits for cross section versus mass (left) and branching ratio versus mass (right). [1]

2.2 Combination of pair production searches

A statistical combination of various searches for pair-produced LQs is performed [2]. All possible decays of the LQs into quarks of the third generation and leptons of any generation are investigated. Overlap among regions and correlations among systematic uncertainties are carefully considered. Simultaneous binned profile-likelihood fits are performed. The resulting lower bounds on LQ masses exceed those from the individual analyses by up to 100 GeV, depending on the signal hypothesis. Figure 2 shows the 95% CL upper limits in the branching ratio versus mass plane for $\mathrm{LQ}_3^{\mathrm{u}} \to \mathrm{t}\nu/\mathrm{b}\tau$, $\mathrm{LQ}_3^{\mathrm{d}} \to \mathrm{t}\tau/\mathrm{b}\nu$, and $\mathrm{LQ}_{\mathrm{mix}}^{\mathrm{u}} \to \mathrm{t}\nu/\mathrm{b}\mu$. $\mathrm{LQ}_3^{\mathrm{u(d)}}$ is an up(down)-type LQ decaying to a quark and a lepton of the third generation, and $\mathrm{LQ}_{\mathrm{mix}}^{\mathrm{u}}$ is an up-type LQ decaying to mixed generations.

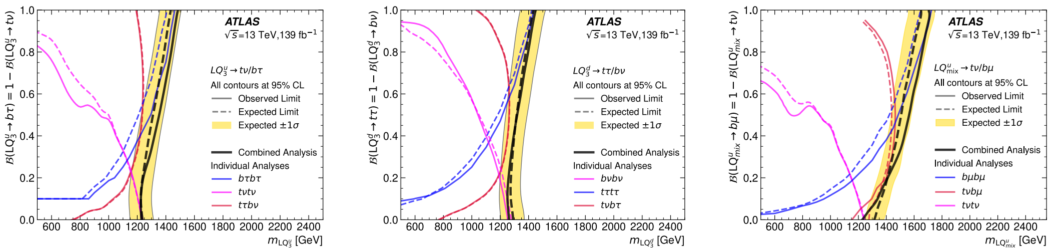

Figure 2: 95% CL upper limits for branching ratio versus mass for $\mathrm{LQ}_3^{\mathrm{u}} \to \mathrm{t}\nu/\mathrm{b}\tau$ (left), $\mathrm{LQ}_3^{\mathrm{d}} \to \mathrm{t}\tau/\mathrm{b}\nu$ (center), and $\mathrm{LQ}_{\mathrm{mix}}^{\mathrm{u}} \to \mathrm{t}\nu/\mathrm{b}\mu$ (right). [2]

2.3 Single production in the $\mathrm{b}\tau\tau$ final state

Single-LQ search offers the possibility to extend search region for higher mass range than pair production search does, depending on the coupling constant. A search for single-LQ production in the $\mathrm{b}\tau\tau$ final state is performed [3], where the event selection and background estimation is similar to the pair production analysis. The s_{T} is used as the final discriminant variable. No significant excess over the SM expectation is observed, and 95% CL upper limits are set. Figure 3 shows the 95% CL upper limits on the coupling λ as a function of the mass of the scalar LQ and vector LQ in the minimal coupling scenario and in the YM coupling scenario.

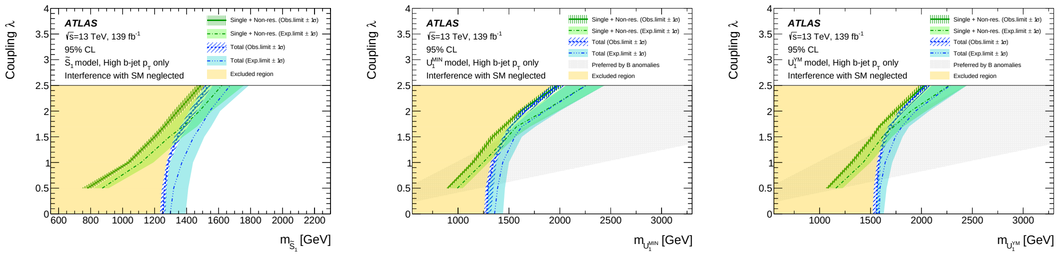

Figure 3: 95% CL upper limits on the coupling λ as a function of mass of the scalar LQ (left) and vector LQ in the minimal coupling scenario (center) and in the YM coupling scenario (right). [3]

3. Searches for Vector-like Quarks

3.1 Pair production in the final state with leptons, jets, and b-tagged jets

A search for pair production of VLQs with leptons, jets, and b-tagged jets in the final state is performed [4]. This analysis is optimized for the TT $\to$ WbWb channel with one W boson decaying leptonically and the other hadronically. A technique is employed that includes high-p_T hadronically decaying W bosons tagged as a single large-radius (large-R) jet. The T candidates are reconstructed such that the mass difference between the leptonically and hadronically decaying T candidates is minimized. The mass of the T candidate is the final discriminant variable.

The 95% CL upper limits are set on the cross section as a function of the mass. Figure 4 shows the 95% CL upper limits on the cross section as a function of the mass for B(T $\to$ Wb) = 1, and on the mass as a function of B(T $\to$ Ht) and B(T $\to$ Wb). The most stringent limits are set for the scenario in which B(T $\to$ Wb) = 1.

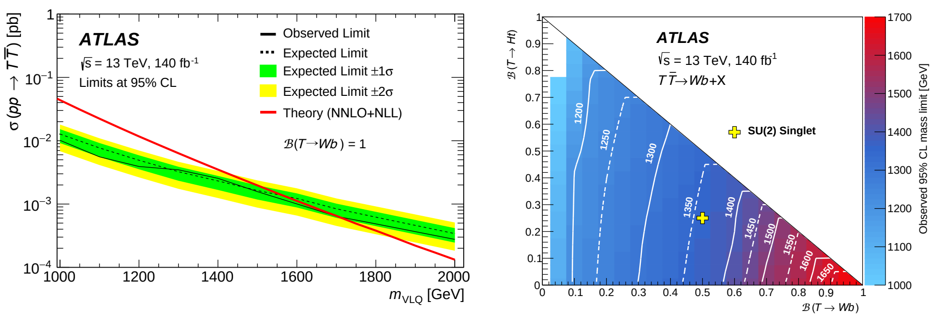

Figure 4: 95% CL upper limits on the cross section as a function of mass for B(T $\to$ Wb) = 1 (left), and on the mass as a function of B(T $\to$ Ht) and B(T $\to$ Wb) (right). [4]

3.2 Single production in the b-jets final state

An analysis focusing on single production of VLQ decaying into B $\to$ bH with H $\to$ bb is performed [5]. A technique is employed where a large-R jet with variable-radius (VR) track-jets is exploited to explore the presence of b-hadrons. Figure 5 shows the 95% CL upper limits on the electroweak coupling parameter κ as a function of the mass for the singlet scenario, and on the relative width as a function of the branching ratio of B → Wt. This is the first search for a single vector-like B quark in the bH(bb) final state in ATLAS, and this search provides the most stringent limits to date.

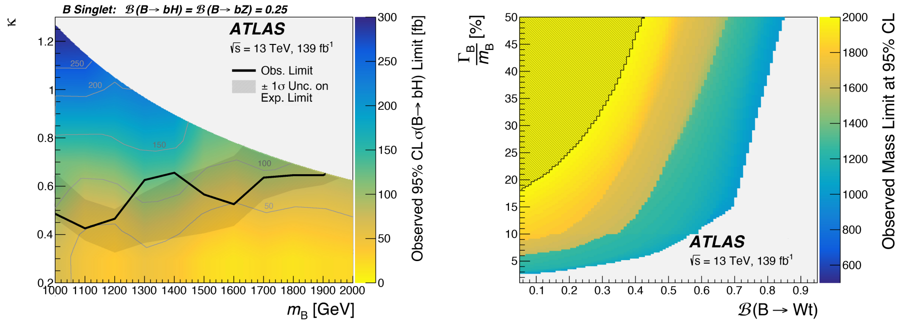

Figure 5: 95% CL upper limits on the electroweak coupling parameter κ as a function of mass for the singlet scenario (left), and on the relative width as a function of B → Wt (right). [5]

4. Summary

Searches for LQs and VLQs are performed using the full LHC Run-2 sample of 139 fb^{-1} collected with the ATLAS detector in proton-proton collisions at a center-of-mass energy of $\sqrt{s}$ = 13 TeV. No significant excess is found, thus the most stringent limits are set on several parameters. The improvements achieved are not only from the increase of the dataset, but also new analysis techniques such as machine learning technology for object reconstruction, identification and event selection contribute to these improvements. Brand-new analysis techniques, new channels, and new dataset from LHC Run-3 are being included which can further expand the scope of the searches.

References

[1] ATLAS Collaboration, *Search for pair production of third-generation leptoquarks decaying into a bottom quark and a τ-lepton with the ATLAS detector*, The European Physical Journal C **83** (2023) 1075.

[2] ATLAS Collaboration, *Combination of searches for pair-produced leptoquarks at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, Physics Letters B **854** (2024) 138736.

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[4] ATLAS Collaboration, *Search for pair-production of vector-like quarks in lepton+jets final states containing at least one b-tagged jet using the Run 2 data from the ATLAS experiment*, Physics Letters B **854** (2024) 138743.

[5] ATLAS Collaboration, *Search for single vector-like B quark production and decay via B → bH($b\bar{b}$) in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, Journal of High Energy Physics **11** (2023) 168.