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Leptoquark searches with electrons and muons in the final state

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Leptoquarks (LQ), introduced in several Beyond the Standard Model (BSM) theories, can provide a possible explanation of potential violations of lepton flavour universality in measurements of B-meson decays ("B-anomalies"), and of the $g-2$ anomaly measured at Fermilab. Recent results from the ATLAS Collaboration on scalar and vector leptoquark pair production and decay in third generation quarks and first- or second-generation leptons (LQ_{mix}) are presented. The analyses have been performed on a dataset corresponding to 139 fb^{-1}, recorded at the LHC at a centre of mass energy of $\sqrt{s}$ = 13 TeV. No evidence of new physics has been found, and lower limits on the mixed-generation leptoquark LQ_{mix} mass have been set, both scalar and vector, up/down type, and assuming different coupling scenarios for vector leptoquarks: Yang-Mills (vLQ_{YM}) or minimal coupling (vLQ_{min}).

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1. Introduction

Leptoquarks, introduced in several BSM theories [1]-[7], are hypothetical bosonic particles that carry fractional electric charge and non-zero baryon and lepton quantum numbers. They interact with both quarks and leptons, and they can mediate processes that violate lepton-flavour universality. They can have either spin 0 (scalar LQ) or spin 1 (vector LQ) and are produced at the LHC [10] via pair, single, or non-resonant production. Most searches by the ATLAS [8] and CMS [9] experiments at the LHC have targeted the scenario where LQs only interact with leptons and quarks of the same generation, however the possibility of flavour-off-diagonal couplings is also explored as part of a broad and exhaustive LQ search programme. The different ATLAS search results are presented as a function of m_{LQ} and the branching ratio into a quark and a charged lepton ($\mathcal{B}$). Up-type scalar LQs interacting with mixed quark and lepton generation, $\mathrm{LQ}^{\mathrm{u}}_{\mathrm{mix}}$, have electric charges of $+2/3e$ and decay to $b\ell^+$ or $t\bar{\nu}$, with $\ell = e, \mu$. Down-type scalar $\mathrm{LQ}^{\mathrm{d}}_{\mathrm{mix}}$ have electric charges of $-1/3e$ and decay to $t\ell^-$ or $b\nu$. In the case of vector LQ searches: the iso-singlet LQ U_1 carrying electric charge $+2/3e$ and with two different coupling scenarios, U_1^{YM} and U_1^{min}, and the iso-singlet vector LQ $\tilde{U}_1$ with electric charge $+5/3e$ and a right-handed coupling to a top quark and a charged lepton, are considered. The analyses presented in these proceedings focus on the searches for scalar and vector leptoquark pair production and decay in third generation quarks and first- or second-generation leptons, in final states with multiple leptons or with exactly one lepton plus missing transverse momentum. Finally, the results of a combination of these searches are reported.

2. Search in final states with multiple leptons

Down-type leptoquark pair production has been searched [11] looking for the processes described in Figure 1, in $t\bar{t}\ell\ell$ final states. Since the W boson from the top quark can decay leptonically, a multi-lepton final state can be generated.

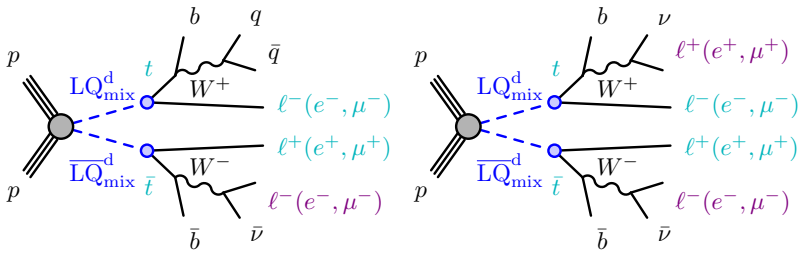
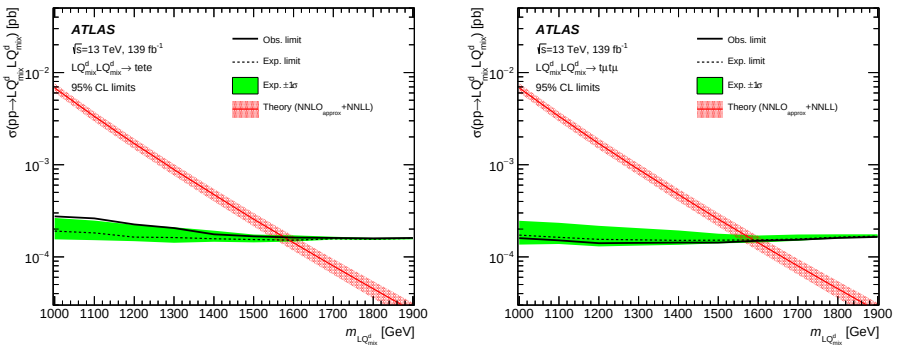


Figure 1: Signal diagrams of the decay modes of pair-produced $\mathrm{LQ}^{\mathrm{d}}_{\mathrm{mix}}$ targeted in the search in final states with multiple leptons.

Events with at least two light leptons and at least two jets (at least one of them tagged as originated from a b-quark) have been selected, and four Signal Regions (SRs) have been defined: $3\ell SR - e$ and $3\ell SR - \mu$ to target events with one top decaying leptonically; $4\ell SR - e$ and $4\ell SR - \mu$ with both tops decaying leptonically. The dominant background contributions in this search arise from $t\bar{t}$ production in association with a vector boson and from diboson production. The effective mass variable m_{eff}, scalar sum of the transverse momenta of all selected leptons, the selected jets and the

missing transverse momentum, has been used as final discriminating variable, since higher values of this variable are expected for the signal compared to the background. Improved background estimates have been obtained defining “Control Regions" (CRs), and validated in “Validation Regions" (VRs). A total number of seven CRs have been defined exploiting 2ℓ same-sign lepton events, 3ℓ and 4ℓ event categories, each selected with suitable criteria in order to enhance the contributions of the corresponding background under study, and two VRs, close to the signal regions. No significant excess above the Standard Model expectation has been observed in any SR and, under the assumption of exclusive decays into te ($t\mu$), the corresponding lower exclusion limits at 95% confidence level (C.L.) on the scalar $\mathrm{LQ}^{\mathrm{d}}_{\mathrm{mix}}$ mass are at 1.58 (1.59) TeV (Figure 2), and on the vector leptoquark mass at 1.67 (1.67) TeV in the minimal coupling scenario and at 1.95 (1.95) TeV in the Yang-Mills scenario.



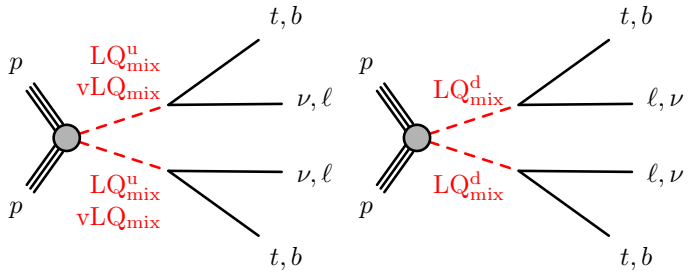
(a) **(b)**

Figure 2: Observed (solid line) and expected (dashed line) 95% C.L. upper limits on the $\mathrm{LQ}^{\mathrm{d}}_{\mathrm{mix}}$ pair production cross section as a function of $m_{\mathrm{LQ}^{\mathrm{d}}_{\mathrm{mix}}}$ for (a) $tete$ and (b) $t\mu t\mu$. The surrounding shaded band corresponds to the ±1 standard deviation around the combined expected limit. The red line and band show the theoretical prediction and its $\pm 1\sigma$ uncertainty.

3. Search in final states with exactly one lepton

Down-type and up-type (scalar and vector) leptoquark pair produced have been searched [12] looking for the processes described in Figure 3, where ℓ is an electron or a muon and the selected final state has a single light lepton, produced either by the leptoquark decay or by the top leptonic decay, together with missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$.

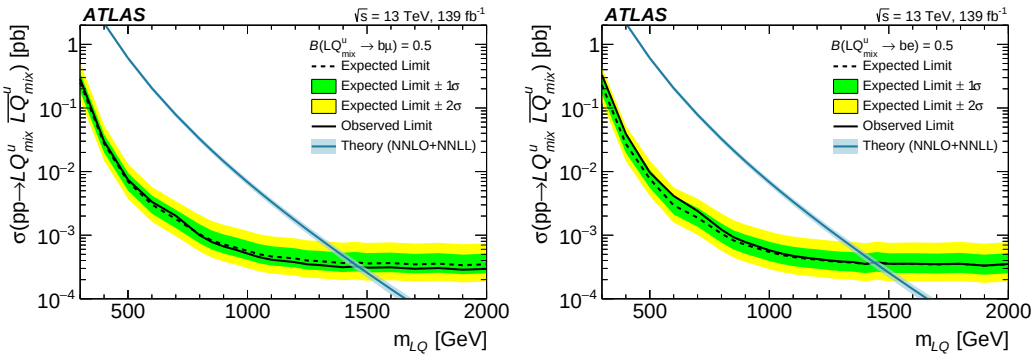
Events with exactly one light lepton, large missing transverse energy (> 250 GeV), at least four hadronic jets and at least one jet tagged as b-quark have been selected. The dominant background contributions in this search arise from $t\bar{t}$ production, W plus jets and single top production. Neural networks (NNs) have been trained separately for scalar and vector leptoquarks signal hypotheses, and their output ($\mathrm{NN}_{\mathrm{out}}$) has been used as signal against background final discriminant. The training region has been defined with requirements on the transverse mass $m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$ and the asymmetric transverse mass am_{T2} [13], while for the SRs $\mathrm{NN}_{\mathrm{out}} > 0.5$ has been required. In addition to $m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$ and am_{T2}, other variables, mainly kinematics-related, have been used as input in the NNs trainings. Three CRs have been defined, in order to normalise to the data the Monte



(a) **(b)**

Figure 3: Signal diagrams of the decay modes of pair-produced LQ^{u}_{mix} and LQ^{d}_{mix} targeted in the search in final states with exactly one lepton plus E_{T}^{miss}.

Carlo estimates of the three main backgrounds. A total of four NN trainings per lepton flavour at different values of $\mathcal{B}$ have been used for up-type scalar and vector leptoquarks, while in the case of down-type scalar leptoquarks only one NN has been trained per lepton flavour, assuming $\mathcal{B} = 0.5$. For each training, a separate fit to the NN_{out} has been performed. No significant excess above the Standard Model expectation has been observed in any SR and the lower limits at 95% C.L. on the leptoquark mass have been set separately for the $\mu(e)$ final state, assuming $\mathcal{B} = 0.5$: 1.46 (1.44) TeV for the scalar LQ^{u}_{mix} (Figure 4), 1.37 (1.39) TeV for the scalar LQ^{d}_{mix}, 1.71 (1.62) TeV for the vector leptoquark in the minimal coupling scenario, 1.98 (1.90) TeV for the vector leptoquark in the Yang-Mills scenario.



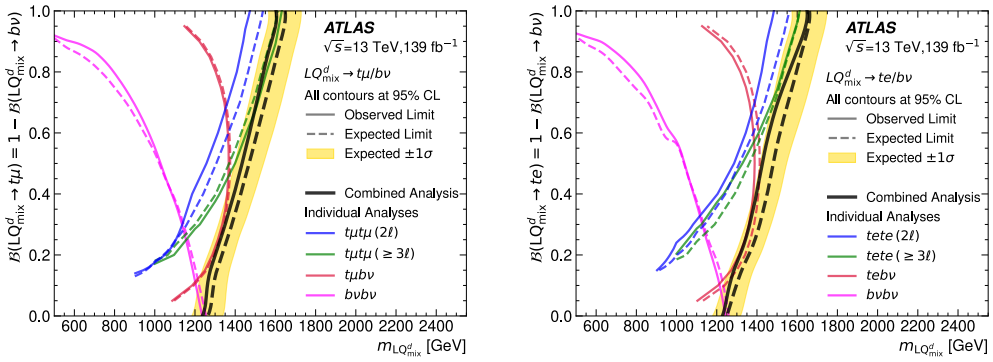
(a) **(b)**

Figure 4: Expected (dashed black) and observed (solid black) 95% C.L. upper limits on the scalar LQ^{u}_{mix} pair production cross section as a function of m_{LQ}, assuming $\mathcal{B} = 0.5$. The green (yellow) band shows the $\pm 1\sigma(\pm 2\sigma)$ uncertainty region around the expected limit. The theoretical prediction and its $\pm 1\sigma$ uncertainty band are shown in blue. Limits are presented for (a) LQ^{u}_{mix} decaying into muons, (b) LQ^{u}_{mix} decaying into electrons.

4. Combination of the leptoquark pair production searches

A statistical combination of nine independent searches for pair-produced leptoquarks [14] has been performed by using the data sample corresponding to 139 fb^{-1}, recorded at the LHC at a centre

of mass energy of $\sqrt{s}$ = 13 TeV. All possible decays of the leptoquarks into quarks of the third generation and charged or neutral leptons of any generation have been investigated. Statistical combination has used the same formalism as the individual, independent analyses. The overlaps among the different regions of the different analyses and the uncertainties correlations have been carefully treated. Improvements in the exclusion limits with respect to the individual analyses have been achieved: limits on the mass of the scalar LQ^{u}_{mix} decaying to muons (electrons) have been improved up to 80 (90) GeV by combining three analyses; limits on the mass of the scalar LQ^{d}_{mix} to muons (electrons) have been improved up to 60 (80) GeV by combining four analyses (Figure 5).



(a) **(b)**

Figure 5: Expected and observed 95% C.L. exclusion limits on m_{LQ} as a function of the branching ratio to a charged lepton. Limits are presented for scalar LQ^{d}_{mix} decaying into a third-generation quark and (a) a muon or (b) an electron. The full $\mathcal{B}$ parameter space is not evaluated for some analyses if they have limited sensitivity.

5. Conclusion

Several searches for leptoquarks with cross-generational couplings have been performed in ATLAS using data recorded at the LHC at a centre of mass energy of $\sqrt{s}$ = 13 TeV and corresponding to 139 fb^{-1}. No significant excess above the Standard Model predictions has been observed, and lower limits on the LQ_{mix} mass have been set in the context of several models and assumptions on the leptoquark spin, type and coupling.

References

[1] J. C. Pati and A. Salam, *Phys. Rev. D* **10** (1974) 275.

[2] H. Georgi and S. Glashow, *Phys. Rev. Lett.* **32** (1974) 438.

[3] S. K. Dimopoulos and L. Susskind, *Nucl. Phys. B* **155** (1979) 237.

[4] S. Dimopoulos, *Nucl. Phys. B* **168** (1980) 69.

[5] E. J. Eichten and K. Lane, *Phys. Lett. B* **90** (1980) 125.

[6] V. D. Angelopoulos, J. R. Ellis, H. Kowalski et al., *Nucl. Phys. B* **292** (1987) 59.

[7] W. Buchmüller and D. Wyler, *Phys. Lett. B* **177** (1986) 377.

[8] ATLAS Collaboration, *JINST* **3** (2008) S08003.

[9] CMS Collaboration, *JINST* **3** (2008) S08004.

[10] L. Evans and P. Bryant (editors) *2008 JINST* **3** S08001.

[11] ATLAS Collaboration, *Eur. Phys. J. C* **84** (2024) 818.

[12] ATLAS Collaboration, *JHEP* **06** (2023) 188.

[13] C. G. Lester and D. J. Summers, *Phys. Lett. B* **463** (1999) 99.

[14] ATLAS Collaboration, *Phys. Lett. B* **854** (2024) 138736.