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Letter

Combination of searches for pair-produced leptoquarks at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration ⋆

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ABSTRACT

A statistical combination of various searches for pair-produced leptoquarks is presented, using the full LHC Run 2 (2015–2018) data set of 139 fb^{-1} collected with the ATLAS detector from proton–proton collisions 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 are investigated. Since no significant deviations from the Standard Model expectation are observed in any of the individual analyses, combined exclusion limits are set on the production cross-sections for scalar and vector leptoquarks. The resulting lower bounds on leptoquark masses exceed those from the individual analyses by up to 100 GeV, depending on the signal hypothesis.

Contents

1. Introduction

Leptoquarks (LQs) are hypothetical particles that carry both baryon and lepton quantum numbers ($B \neq 0,\ L \neq 0$). They are either scalar (spin zero) or vector (spin one) particles, carry colour and have a fractional electric charge. LQs therefore couple simultaneously to both quarks and leptons, providing a connection between the lepton and quark sectors, which appear to have similar structures. As such, LQs have already been discussed for many decades not only in unified theories [1–3] but also in technicolour [4–6] or composite models [7–9].

In the past decade, there has been renewed interest in LQs because of anomalies in various measurements of B-meson decays. While a recent reanalysis of data from the LHCb Collaboration has yielded results in agreement with lepton-flavour universality [10,11], other anomalies such as in the $b \to s\mu\mu$ angular distribution or in charged-current $b \to c\ell\nu$ transitions remain [12–20].

This Letter combines searches from the ATLAS experiment for pair production of LQs that decay into a charged or neutral lepton and either a top or bottom quark. All analyses use the full Run 2 data set with an integrated luminosity of 139 fb^{-1}. This dataset was recorded between 2015 and 2018 with the ATLAS detector [21], when the Large Hadron Collider (LHC) collided protons at $\sqrt{s} = 13$ TeV.

LQs decay into a quark and lepton of the same or of different generations [22]. Third-generation scalar LQs have a charge of either $\pm 1/3$ ($\mathrm{LQ}_3^{\mathrm{d}}$) with decays into $\bar{b}\bar{\nu}_\tau$ or $\bar{t}\tau^+$ (and charge conjugate decays) or $\pm 2/3$ ($\mathrm{LQ}_3^{\mathrm{u}}$) with decays into $b\tau^+$ or $t\bar{\nu}_\tau$ (and charge conjugate decays). Mixed-generation scalar LQs can decay into a first- or second-generation lepton and a third-generation quark. Similarly to LQ_3, they can have

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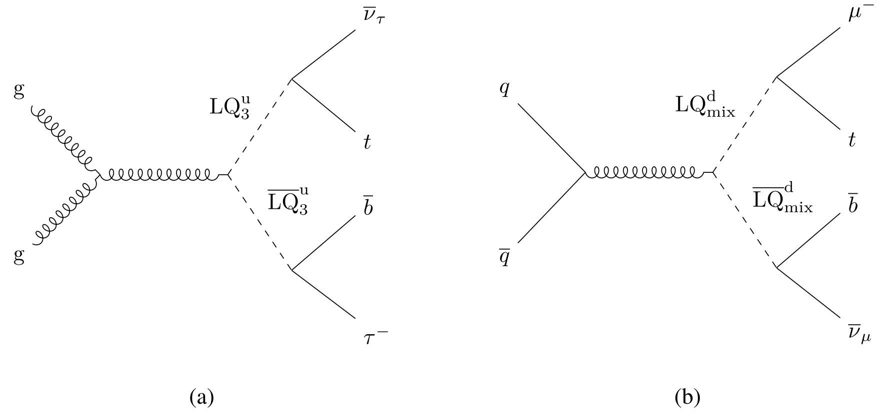


Fig. 1. Pair production of (a) up-type LQs of the third generation via gluon–gluon fusion with decays into a top quark and a neutrino or into a bottom quark and a τ-lepton, and of (b) down-type mixed LQs via quark–antiquark annihilation with decays into a top quark and a muon or into a bottom quark and a neutrino.

charge $\pm 1/3$ (LQ_{mix}^d) or $\pm 2/3$ (LQ_{mix}^u). Pairs of LQs would be produced at the LHC mainly via gluon–gluon fusion or quark–antiquark annihilation. These mechanisms are shown in Fig. 1, together with some example decays. The pair-production cross-section for scalar LQs depends only on the LQ mass (m_{LQ}).

This Letter considers nine independent searches that between them are sensitive to all decays into a bottom or top quark and any one of the charged or neutral leptons of all three generations. Sets of these analyses are combined to produce two-dimensional exclusion limits for both third-generation and mixed scalar LQs, as a function of m_{LQ} and branching ratio ($\mathcal{B}$) to the charged lepton in order to obtain limits that are more stringent than those from the individual analyses. A limited set of searches is also interpreted in vector LQ models [23]. The pair-production cross-section for vector LQs depends not only on m_{LQ} but also on the coupling to gluons. An additional coupling of Yang–Mills type to gluons is either present or absent ("minimal coupling") [24].

It should be noted that because the ATLAS analyses included here do not have any requirements on the LQ charge, the results for decays to a charged lepton are also valid for LQs with charge $\pm 4/3$, e.g. with decays into $\bar{b}\tau^+$, or charge $\pm 5/3$, e.g. with decays into $t\tau^+$.

2. Signal models

Simulated events with pair-produced scalar up-type and down-type LQs were generated at next-to-leading order (NLO) in quantum chromodynamics (QCD) with MadGraph5_aMC@NLO 2.6.0 [25]. The method described in Ref. [26] is used, in which fixed-order NLO QCD calculations [27,28] are interfaced to Pythia 8.230 [29] for the parton shower (PS) and hadronisation. Parton luminosities were provided by the five-flavour scheme NNPDF3.0nlo [30] parton distribution functions with $\alpha_s = 0.118$, and the underlying event (UE) was modelled with the A14 set of tuned parameters [31]. MadSpin [32] was used for the decay of the LQ. The branching ratio of LQ decays to a charged lepton is controlled by the model parameter β, so for $\beta = 0$ there are only decays into a neutrino and a quark, and for $\beta = 1$ there are only decays into a charged lepton and a quark. However, for equal couplings to charged and neutral leptons, i.e. $\beta = 0.5$, $\mathcal{B}$ differs from 0.5 due to the sizeable top-quark mass [33]. Signal samples were mostly produced for a model parameter of $\beta = 0.5$, and target branching fractions $\mathcal{B}$ were obtained by reweighting the samples using generator-level information, as described in Ref [33]. The coupling strength parameter λ was set to 0.3, resulting in a LQ width of about 0.2 % of its mass [22,34].

Signal cross-sections for scalar LQs were obtained from a calculation of the pair production of scalar coloured particles, e.g. the supersymmetric partner of the top quark. Such particles have the same production modes (except lepton t-channel contributions) and their pair-production cross-section depends only on their mass. These cross-sections are computed at approximate next-to-next-to-leading order (NNLO) in QCD with resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms [35–38]. Lepton t-channel contributions are neglected and may lead to corrections at the percent level [39].

In addition to scalar LQs, two models of vector LQs are investigated. Simulated events with pair-produced U_1 and $\tilde{U}_1$ LQs were generated at leading order (LO) in QCD with MadGraph5_aMC@NLO, handling PDFs and the UE in the same way as for scalar LQs. For U_1 LQs, a simplified model [23] is used, neglecting further degrees of freedom relevant for the ultraviolet (UV) completion of the model. The samples were produced with a coupling strength parameter of $g_U = 3.0$, leading to a signal width of approximately 11 % [40]. The large value of g_U is motivated by a suppression of the production cross-section for additional mediators in an UV-complete model, which might otherwise be in tension with existing LHC Z' limits [24]. The coupling to gluons is determined through the chosen value of the model parameter κ, where $\kappa = 0$ corresponds to the Yang–Mills coupling scenario (U_1^{YM}) and $\kappa = 1$ to the minimal coupling scenario (U_1^{MC}). The coupling strength to left- and right-handed quarks and leptons of the various generations is determined by the model parameters $\beta_{L/R}$. While right-handed couplings are assumed to vanish in this analysis, β_L is set to unity, resulting in equal coupling strengths of U_1 LQs to top quarks and neutrinos or bottom quarks and charged leptons of a certain generation. Conversely, $\tilde{U}_1$ LQs [24,41] carry an electric charge of $\pm 5/3$, and thus only decays into a top quark and τ-lepton are allowed. Couplings of $\tilde{U}_1$ to the Standard Model gluon are governed by the model parameter κ_t. Additional couplings of $\tilde{U}_1$ to the heavy gluon g', required for the UV completion of the model, depend on the model parameter κ_s. The choice of $\kappa_t = \kappa_s = 0$ corresponds to the Yang–Mills scenario ($\tilde{U}_1^{YM}$), whereas $\kappa_t = \kappa_s = -1$ gives the minimal coupling scenario ($\tilde{U}_1^{MC}$). Since production via an intermediate g' contributes only in quark-initiated processes, which are subdominant compared to gluon–gluon fusion, the pair-production cross-section of $\tilde{U}_1$ LQs depends only very slightly on the heavy-gluon mass, which is assumed to vanish in this analysis. No higher-order cross-section computations are available for the U_1 and $\tilde{U}_1$ models. Therefore, the cross-sections computed at LO by MadGraph5_aMC@NLO are used in the analysis.

Additional details of the Monte Carlo simulation and the estimation of background processes in the individual analyses can be found in the respective publications.

3. Experimental signatures

In the following, each of the analyses contributing to the combined results is described briefly, with further details available in the references. The final state in all analyses is reconstructed from electrons [42], muons [43], hadronically decaying τ-leptons (τ_{had}) [44], jets and missing transverse momentum (with magnitude E_T^{miss}) [45].

Different quality criteria, isolation requirements and transverse momentum (p_T) thresholds are applied in each analysis because of the different backgrounds present. No attempt is made to distinguish between a leptonically decaying τ-lepton and a prompt electron or muon (ℓ). Jets are reconstructed from energy deposits in the calorimeter system [46] or from particle-flow objects [47,48], using the anti-k_t algorithm [49,50] with a radius parameter of 0.4 by default. Jets can be categorised as b-tagged (i.e. as "b-jets") if they satisfy the requirements of a multivariate algorithm [51–53]. In order to better reconstruct high-p_T top quarks, jets with a larger radius-parameter value are used in some analyses, with the top-quark decay products reconstructed from jet substructure information.

In most of the analyses, one or both LQs have a neutrino in the final state, so they cannot be fully reconstructed. Various methods are employed to separate background from signal, such as the usage of event-level variables designed to identify one or more missing particles, or multivariate techniques that combine several final-state variables in an optimised way. In addition to signal-enriched regions, also called signal regions (SRs), control regions (CRs) are defined for the purpose of constraining major background processes. CRs and SRs are designed to be mutually exclusive.

Third-generation quarks and leptons

$t\nu b\tau$ [54]: The main selection requirements for this search are one τ_{had}, two b-jets, and large E_T^{miss}, allowing searches in the $LQ_3^u \to t\nu$ or $b\tau$ and $LQ_3^d \to t\tau$ or $b\nu$ channels. The p_T of the τ_{had} is used as the discriminant. This channel is also interpreted in the U_1^{YM} and U_1^{MC} models.

$b\tau b\tau$ [55]: This search targets the $LQ_3^u \to b\tau$ channel by selecting events with either two or one τ_{had} and one light charged lepton (arising from a leptonic τ decay), together with one or more b-jets. The discriminant is the output of a parameterised neural network [56], which uses as input various kinematic variables including the partially reconstructed LQ masses. This channel is also interpreted in the U_1^{YM} and U_1^{MC} models.

$t\tau t\tau$ [57]: The search targets the $LQ_3^d \to t\tau$ channel. Events are selected by requiring between one and three light charged leptons, at least one τ_{had} and two or more jets, one of which is b-tagged. The phase space of interest is divided into seven mutually exclusive SRs, based on the light charged-lepton and τ_{had} multiplicities. In each SR, the effective mass, m_{eff}, defined as the scalar sum of E_T^{miss} and the transverse momenta of all reconstructed leptons and jets is used as the discriminant. This channel is also reinterpreted in the $\tilde{U}_1^{YM}$ and $\tilde{U}_1^{MC}$ models.

Third-generation quarks and first- or second-generation leptons

$t\nu b\ell$ [40]: The strategy of this search is to select events with one light charged lepton, large E_T^{miss} and four or more jets, of which at least one must be b-tagged. It is therefore sensitive to the $LQ_{mix}^u \to t\nu$, be or $b\mu$ and $LQ_{mix}^d \to b\nu$, te or $t\mu$ channels. The discriminant is the output of a neural network with kinematic variables as input. This channel is also interpreted in the U_1^{YM} and U_1^{MC} models.

$b\ell b\ell$ [58]: This analysis targets either the $LQ_{mix}^u \to be$ or $b\mu$ channels. Events are required to contain exactly two electrons or two muons with opposite electric charges and at least two jets. Events are then categorised according to the multiplicity of the b-tagged jets. LQ candidates are identified by choosing the combination of leptons and jets resulting in the smallest difference between the two lepton–jet invariant masses. The average mass of the two LQ candidates serves as the discriminant.

$t\ell t\ell$ (2ℓ) [59]: The search targets the $LQ_{mix}^d \to te$ or $t\mu$ channels. The analysis is optimised for signal events with both top quarks decaying hadronically by requiring exactly two opposite-sign same-flavour leptons and two $R = 1.0$ jets containing the top decay products. A boosted decision tree classifier (BDT) is trained to separate signal events from background events. In addition to variables calculated from the p_T of leptons and jets as well as E_T^{miss}, observables obtained using recursive jigsaw reconstruction techniques [60] serve as input to the BDT. The BDT output score is used as the discriminant in the SRs.

$t\ell t\ell$ ($\geq 3\ell$) [61]: Complementing the $t\ell t\ell$ (2ℓ) analysis, this search targets the same signal hypotheses in final states with at least three light charged leptons. In addition, events are required to have at least two reconstructed jets, at least one of which must be b-tagged. The SR is split on the basis of lepton multiplicity, and m_{eff} is used as the discriminant.

Third-generation quarks and neutrinos

$t\nu t\nu$ [62]: The search for pair-produced scalar partners of the top quark in final states consisting of two hadronically decaying top quarks and large E_T^{miss} is also interpreted as a search for pair-produced LQs, primarily targeting the $LQ_3^u \to t\nu$ channel. The main selection requirements in the SR are four jets, two of which are b-tagged, no charged leptons, and large E_T^{miss}. Top candidates are reconstructed using jets with $R = 1.2$. Two such top candidates are required, and the SR is subdivided according to both the mass of the top candidate with lower transverse momentum and the kinematic variable m_{T2,χ^2} [63], which is a transverse mass suited to the case where there are two missing particles. For this publication, this channel is also reinterpreted in the LQ_{mix}^u, U_1^{YM} and U_1^{MC} models.

$b\nu b\nu$ [64]: The search for scalar partners of the bottom quark in events with no light charged leptons, two b-tagged jets and large E_T^{miss} also targets pair-produced LQs in the $LQ_3^d \to b\nu$ channel. However, since there is neither a requirement on additional jets nor explicit τ reconstruction the search also has sensitivity to the $LQ_3^d \to t\tau$ channel. A cut-based approach is used for high values of a specific mass reconstructed in the presence of neutrinos, m_{CT} [65]. The SR is subdivided into regions depending on m_{CT} and m_{eff}. At lower values of m_{CT} a BDT is used as the discriminant, with input variables based on the kinematics of the final-state jets and E_T^{miss}. For this publication, this channel is also reinterpreted in the LQ_{mix}^d models.

A summary of the channels considered in this Letter, together with which interpretations are made and the main selection requirements, is given in Table 1.

4. Statistical interpretation

The statistical combination of the different searches follows the same formalism as the individual analyses. Simultaneous binned profile-likelihood fits to CRs and SRs, steered by the `cabinetry` library [66,67], are performed, and a modified frequentist method, the CL_s method [68] as implemented in `pyhf` [69,70], is used to set exclusion limits on various signal hypotheses. Systematic uncertainties are accounted for by including them in the fits via nuisance parameters (NPs). The binned likelihood function $\mathcal{L}(\mu, \theta)$ is constructed as the product of Poisson probability terms over all bins considered in the analysis and a number of Gaussian or log-normal priors for the NPs associated with systematic uncertainties. It depends on the signal strength parameter, μ, a multiplicative factor applied to the theoretical signal production cross-section, and on θ, a set of NPs including a number of unconstrained multiplicative factors for the major background processes as well as those entering the Gaussian and log-normal priors, which adjust the expectations for signal and background according to the corresponding systematic uncertainties.

Table 1
Overview of the individual analyses, together with the models used to interpret them and the main object selections in the signal region: number of electrons or muons (N_ℓ), number of hadronically decaying τ-leptons ($N_{\tau_{\text{had}}}$) and number of b-jets ($N_{b\text{jets}}$). All analyses interpreted in the same model are combined except for U_1 in the $t\nu b\ell$ final state, where no other channels are available for combination.

Interpretation										
Search		Scalar				Vector		Signal Region		
Final State	Citation	LQ_3^{u}	LQ_3^{d}	$\text{LQ}_{\text{mix}}^{\text{u}}$	$\text{LQ}_{\text{mix}}^{\text{d}}$	$U_1^{\text{YM/MC}}$	$\tilde{U}_1^{\text{YM/MC}}$	N_ℓ	$N_{\tau_{\text{had}}}$	$N_{b\text{jets}}$
$t\nu b\tau$	[54]	✓	✓	–	–	✓	–	0	1	≥ 2
$b\tau b\tau$	[55]	✓	–	–	–	✓	–	$\{0,1\}$	$\{1,2\}$	$\{1,2\}$
$t\tau t\tau$	[57]	–	✓	–	–	–	✓	$\{1,2,3\}$	≥ 1	≥ 1
$t\nu b\ell$	[40]	–	–	✓	✓	✓	–	1	–	≥ 1
$b\ell b\ell$	[58]	–	–	✓	–	–	–	2	–	$\{0,1,2\}$
$t\ell t\ell$ (2ℓ)	[59]	–	–	–	✓	–	–	2	–	–
$t\ell t\ell$ ($\geq 3\ell$)	[61]	–	–	–	✓	–	–	$\{3,4\}$	–	≥ 2
$t\nu t\nu$	[62]	✓	–	✓	–	✓	–	0	0	≥ 2
$b\nu b\nu$	[64]	–	✓	–	✓	–	–	0	–	≥ 2

The test statistic used to determine the exclusion limits is based on the profile likelihood ratio

$$t_\mu = -2\ln\frac{\mathcal{L}(\mu,\hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu},\hat{\theta})},$$

where $\hat{\mu}$ and $\hat{\theta}$ are the values of the parameters that maximise the likelihood function, and $\hat{\hat{\theta}}$ are the values of the NPs that maximise the likelihood function for a given value of μ. Upper limits on the signal production cross-section are derived for each of the signal scenarios considered in this analysis. For a given signal scenario, values of the production cross-section (parameterised by μ) yielding $\text{CL}_\text{s} < 0.05$, where CL_s is computed using the asymptotic approximation [71], are excluded at $\geq 95\,\%$ confidence level (CL).

The sensitivity of each individual analysis entering the combination is limited primarily by statistical uncertainties. As such, systematic uncertainties do not have a major impact in the combined analysis, and therefore assumptions about their correlation across the different analyses do not affect the results significantly. Detector-related uncertainties are assumed to be correlated across analyses, unless that is not valid because of different approaches to event reconstruction or a different choice of correlation model in individual analyses. Similarly, uncertainties in the modelling of the signal process are only assumed to be correlated when parameterised in the same way in individual analyses. However, treating these uncertainties as fully uncorrelated yields a difference of at most 5% on the cross-section limit. Uncertainties in the modelling and normalisation of background processes are assumed to be uncorrelated between analyses, since the phase spaces of interest and background estimation techniques can differ significantly. As is standard in ATLAS searches, theory uncertainties affecting the signal acceptance are considered when setting exclusion limits, but those affecting the production cross-section are not.

In each combination, the SRs and CRs defined for the individual searches are generally statistically independent between the various analyses, due to the selection requirements on the multiplicity and flavour of the charged leptons. Additional criteria are used in the one-lepton CRs in the (otherwise zero-lepton) $t\nu t\nu$ channel, such as the requirement that the lepton p_T is below the threshold used in the SRs and CRs of the other channels. Residual overlaps caused by the use of different lepton identification criteria were found to be negligible in all cases except between one of the six SRs of the $t\nu t\nu$ analysis and the SR of the $t\nu b\tau$ analysis. Since this SR in the $t\nu t\nu$ analysis does not significantly affect the sensitivity for LQ signal processes, it is removed from the combination. Other overlaps between SRs of different analyses do not exceed $7\,\%$ ($2\,\%$), as estimated with Monte Carlo signal samples (data), and have negligible impact on the results presented in this Letter. Similarly, statistical overlaps between CRs in one analysis and SRs or CRs in other analyses have negligible impact on the results and are therefore ignored.

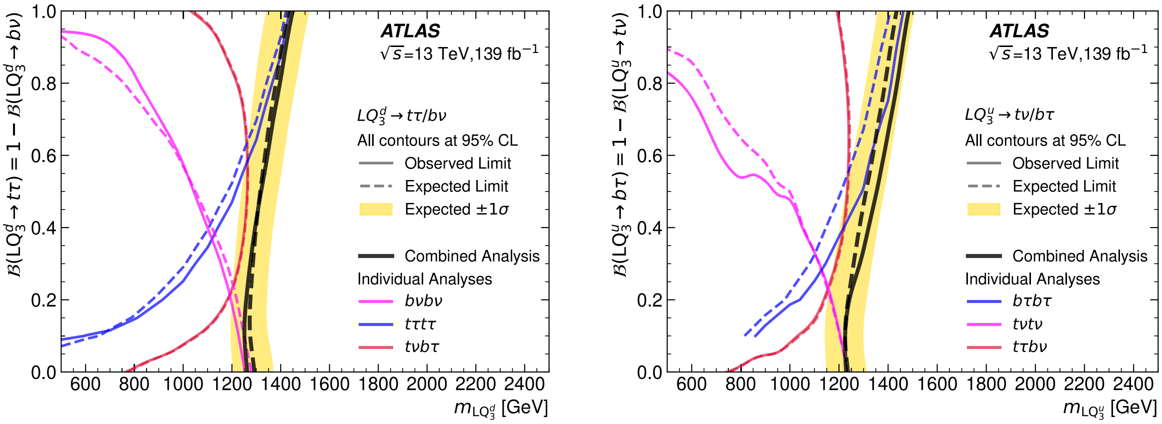
5. Results

No significant deviations from the Standard Model expectation are observed in any of the analysis channels considered in this Letter, and good agreement is also found in the combined background-only fits to data. Upper limits on the cross-sections for LQ pair production are calculated at $95\,\%$ CL using simultaneous signal-plus-background fits to the CRs and SRs, in which the background normalisations and possible signal contributions are determined. Such limits on the cross-sections are evaluated for a wide range of values for the branching ratio of LQs into charged leptons. Comparisons with theoretical cross-section predictions provide mass exclusion limits.

The exclusion limits for scalar third-generation up-type LQs obtained from the combined analysis are shown in Fig. 2(a) on top of an overlay of the limits from the three individual analyses. As discussed in Section 4 the limits are dominated by statistical uncertainties. As an example, at $\mathcal{B} = 0.4$ and a LQ mass of 1.3 TeV the dominating systematic uncertainties on the cross-section are due to background modelling (7%) and signal modelling (4%). Compared to the individual searches, the exclusion reach is improved by up to 100 GeV for intermediate values of $\mathcal{B}$, where more than one individual analysis provides sensitivity. Similar observations are made in the case of scalar third-generation down-type LQs, where the exclusion limits improve by up to 70 GeV as shown in Fig. 2(b).

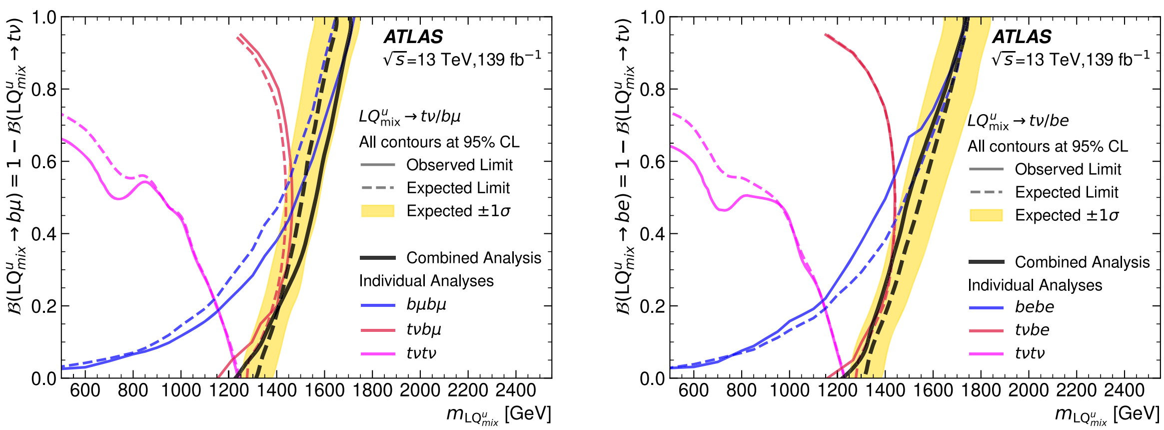
The combined exclusion limits also show improvement with respect to the three individual analyses sensitive to scalar up-type LQs decaying into a third-generation quark and a first- or second-generation lepton. This is especially true for low and intermediate values of $\mathcal{B}$. The corresponding exclusion contours are shown in Fig. 3 for decays to a muon (a) or an electron (b), with improvements in the observed exclusion limits of up to 80 GeV and 90 GeV, respectively.

In the case of scalar down-type LQs decaying into a third-generation quark and a first- or second-generation lepton, improvements in sensitivity are observed across the whole range of $\mathcal{B}$, since a total of four individual analysis channels are combined here, generally also resulting in higher exclusion limits when the LQ is assumed to decay exclusively into a top quark and a charged lepton. Corresponding results are shown in Fig. 4, with the combination improving the exclusion limits by up to 60 GeV for decays to a muon and by up to 80 GeV for decays to an electron. For LQs decaying into a top quark and a muon with $\mathcal{B} \approx 1$, the observed combined lower limit on the LQ mass is slightly weaker than the one observed in $t\mu t\mu$ ($\geq 3\ell$) since a worse-than-expected limit is observed in $t\mu t\mu$ (2ℓ).



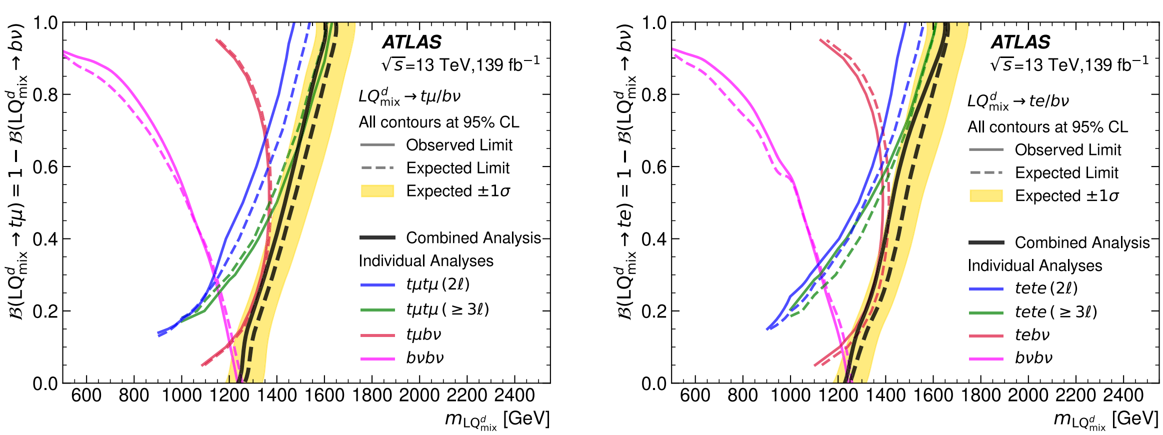
(a) (b)

Fig. 2. Expected and observed 95 % CL exclusion limits on the LQ mass as a function of the branching ratio to a charged lepton. Limits are presented for third-generation (a) up-type and (b) down-type LQs decaying into a third-generation quark and lepton. The full $\mathcal{B}$ parameter space is not evaluated for some analyses if they have limited sensitivity.



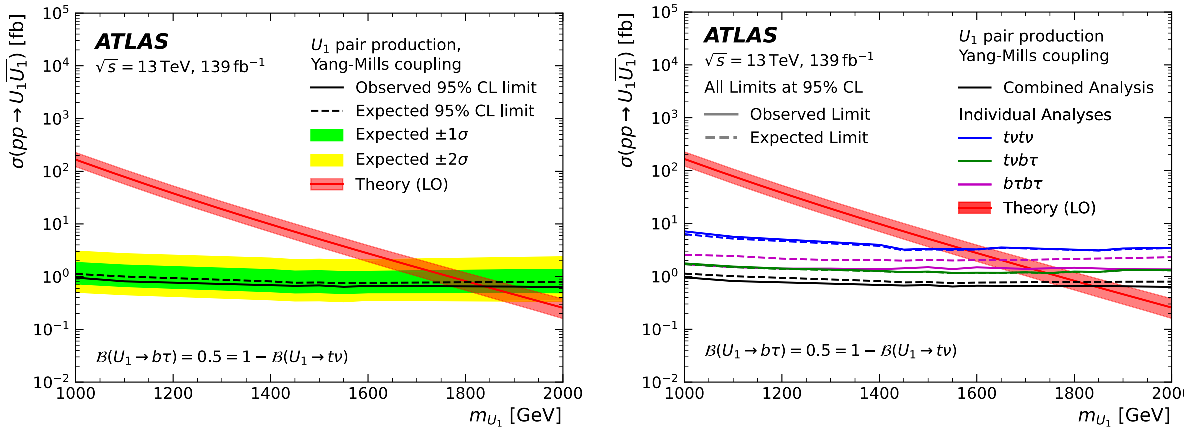
(a) (b)

Fig. 3. Expected and observed 95 % CL exclusion limits on the LQ mass as a function of the branching ratio to a charged lepton. Limits are presented for up-type scalar LQs 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.



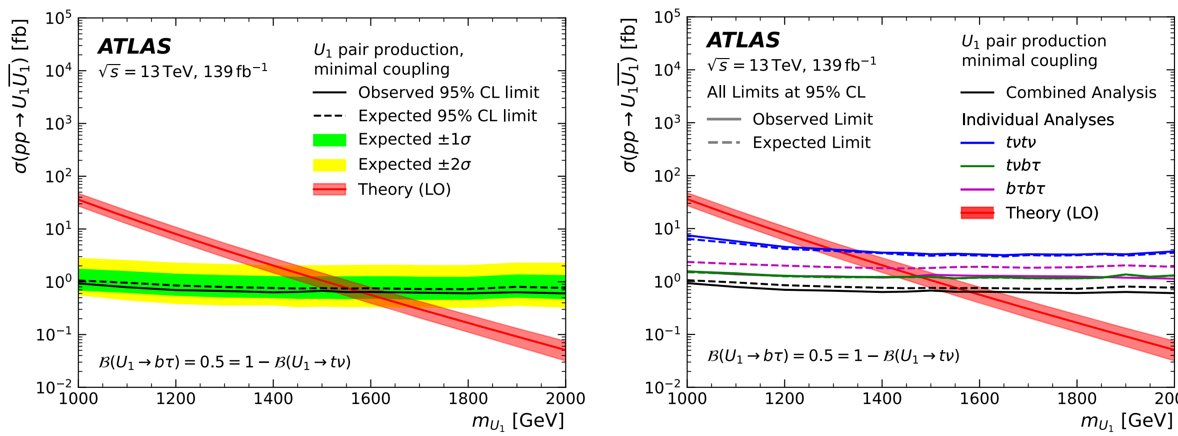
(a) (b)

Fig. 4. Expected and observed 95 % CL exclusion limits on the LQ mass as a function of the branching ratio to a charged lepton. Limits are presented for down-type scalar LQs 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.



(a) (b)

Fig. 5. Expected and observed 95 % CL exclusion limits on the U_1^{YM} production cross-section as a function of the LQ mass, with a branching ratio of 0.5 to a τ-lepton. The limits obtained from the combined analysis, including uncertainty bands, are presented in (a), whereas (b) shows the limits obtained from the individual analyses for comparison. The theoretical prediction and its $\pm 1\sigma$ uncertainty due to variations of the parton distribution functions, the strong coupling parameter and the renormalisation and factorisation scales are shown in red.



(a) (b)

Fig. 6. Expected and observed 95 % CL exclusion limits on the U_1^{MC} production cross-section as a function of the LQ mass with a branching ratio of 0.5 to a τ-lepton. The limits obtained from the combined analysis, including uncertainty bands, are presented in (a), whereas (b) shows the limits obtained from the individual analyses for comparison. The theoretical prediction and its $\pm 1\sigma$ uncertainty due to variations of the parton distribution functions, the strong coupling parameter and the renormalisation and factorisation scales are shown in red.

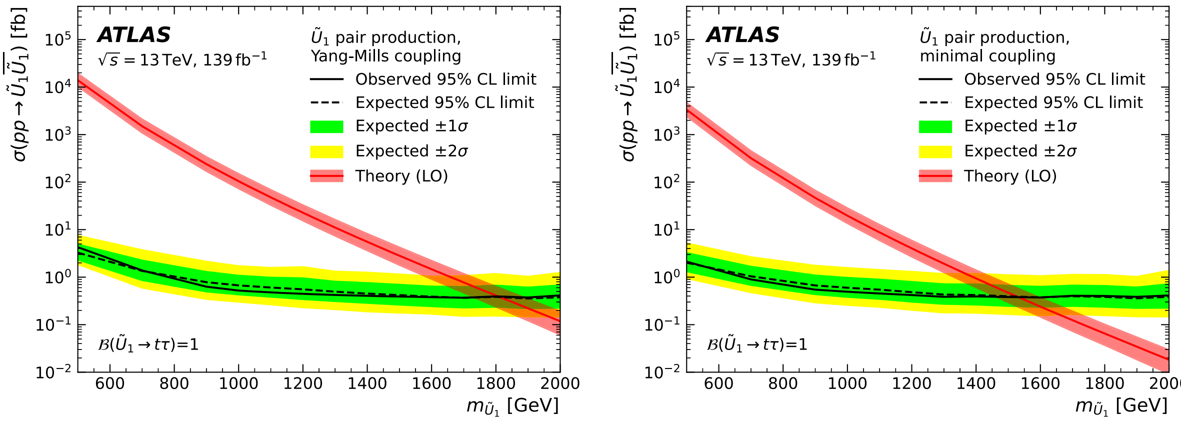
In addition to mass exclusion limits for scalar LQs, limits on the production cross-section of U_1 vector LQs decaying into a third-generation quark and lepton are provided, assuming $\mathcal{B} = 0.5$. The results of combining the three contributing analyses are shown in Fig. 5 and Fig. 6 for U_1^{YM} and U_1^{MC}, respectively. The observed (expected) lower limits on the U_1 mass are 1840 GeV (1810 GeV) for U_1^{YM} and 1580 GeV (1560 GeV) for U_1^{MC}. For these signal hypotheses, the combined expected limits are primarily driven by the searches in the $t\nu b\tau$ final state as expected. The combined observed limits are slightly higher than the expected ones, mainly due to the $b\tau b\tau$ channel showing similar behaviour, and are improved by 70 GeV (U_1^{YM}) and 80 GeV (U_1^{MC}) compared to the individual analyses.

Finally, the search in $\tau\tau\tau\tau$ final states is reinterpreted in the $\tilde{U}_1$ vector LQ model. Since $\tilde{U}_1$ carries an electric charge of $\pm 5/3$, it decays exclusively into a top quark and a τ-lepton. The resulting upper limits on the production cross-section are shown in Fig. 7, with observed (expected) lower limits on the $\tilde{U}_1$ mass of 1810 GeV (1810 GeV) and 1540 GeV (1530 GeV) for $\tilde{U}_1^{\mathrm{YM}}$ and $\tilde{U}_1^{\mathrm{MC}}$, respectively.

Table 2 summarises the lower limits on the LQ mass obtained in this analysis at $\mathcal{B} = 0.0, 0.5, 1.0$, including four additional limits [40] on U_1 vector LQs that decay into a third-generation quark and a first- or second-generation lepton, where no other channels are available for a combination. Since the analyses are not sensitive to the quark charge, the results shown for scalar LQs with $\mathcal{B} = 1$, i.e. the last column and first six rows of Table 2, are also valid for scalar LQs with charge $\pm 4/3$ and be, $b\mu$ or $b\tau$ decays or with charge $\pm 5/3$ and te, $t\mu$, or $t\tau$ decays.

A comparison to results from the CMS collaboration is not directly possible for results on vector LQs [72–74] due to the different models used by ATLAS and CMS. For the pair production of scalar LQs the individual limits are already better than the CMS limits [72–76][1] at $\mathcal{B} = 0.0, 0.5, 1.0$ for all decay channels. The limits shown in Figs. 2 to 4 therefore constitute the best limits to date for any value of $\mathcal{B}$.

[1] After submission of this paper a new result from the CMS Collaboration has been reported [77], yielding results on the search for scalar and vector LQs in the $b\mu b\mu$ final state.



(a) (b)

Fig. 7. Expected and observed 95 % CL exclusion limits on the $\tilde{U}_1$ production cross-section as a function of the LQ mass with a branching ratio of 1.0 to a τ-lepton. Limits are presented for (a) $\tilde{U}_1^{\mathrm{YM}}$ and (b) $\tilde{U}_1^{\mathrm{MC}}$. The theoretical prediction and its $\pm 1\sigma$ uncertainty due to variations of the parton distribution functions, the strong coupling parameter and the renormalisation and factorisation scales are shown in red.

Table 2

Expected and observed 95 % CL lower limits on the LQ mass at branching ratios to a charged lepton of $\mathcal{B} = 0.0, 0.5, 1.0$ for the signal hypotheses considered in this analysis, including four additional limits [40] on the U_1 vector LQs decaying into a third-generation quark and a first- or second-generation lepton, where no other channels are available for a combination.

	$\mathcal{B}=0.0$		$\mathcal{B}=0.5$		$\mathcal{B}=1.0$	
	95 % CL Limit [GeV]		95 % CL Limit [GeV]		95 % CL Limit [GeV]	
	Observed	Expected	Observed	Expected	Observed	Expected
$\mathrm{LQ}_3^{\mathrm{u}} \to t\nu/b\tau$	1240	1240^{+70}_{-90}	1340	1300^{+70}_{-80}	1480	1440^{+70}_{-80}
$\mathrm{LQ}_3^{\mathrm{d}} \to t\tau/b\nu$	1260	1260^{+80}_{-80}	1360	1340^{+60}_{-70}	1520	1470^{+70}_{-70}
$\mathrm{LQ}_{\mathrm{mix}}^{\mathrm{u}} \to t\nu/b\mu$	1230	1310^{+70}_{-70}	1570	1510^{+70}_{-70}	1710	1650^{+90}_{-90}
$\mathrm{LQ}_{\mathrm{mix}}^{\mathrm{u}} \to t\nu/be$	1230	1310^{+70}_{-70}	1510	1550^{+80}_{-80}	1730	1740^{+90}_{-100}
$\mathrm{LQ}_{\mathrm{mix}}^{\mathrm{d}} \to t\mu/b\nu$	1240	1260^{+70}_{-80}	1430	1470^{+70}_{-70}	1600	1650^{+80}_{-80}
$\mathrm{LQ}_{\mathrm{mix}}^{\mathrm{d}} \to te/b\nu$	1230	1250^{+70}_{-70}	1450	1500^{+70}_{-70}	1650	1660^{+90}_{-90}
$U_1^{\mathrm{YM}} \to t\nu/b\tau$	-	-	1840	1810^{+80}_{-90}	-	-
$U_1^{\mathrm{MC}} \to t\nu/b\tau$	-	-	1580	1560^{+70}_{-70}	-	-
$U_1^{\mathrm{YM}} \to t\nu/b\mu$	-	-	1980	1930^{+50}_{-60}	-	-
$U_1^{\mathrm{MC}} \to t\nu/b\mu$	-	-	1710	1660^{+50}_{-50}	-	-
$U_1^{\mathrm{YM}} \to t\nu/be$	-	-	1900	1930^{+50}_{-70}	-	-
$U_1^{\mathrm{MC}} \to t\nu/be$	-	-	1620	1650^{+50}_{-60}	-	-
$\tilde{U}_1^{\mathrm{YM}} \to t\tau$	-	-	-	-	1810	1810^{+80}_{-70}
$\tilde{U}_1^{\mathrm{MC}} \to t\tau$	-	-	-	-	1540	1530^{+90}_{-60}

6. Conclusion

A statistical combination of searches for pair-produced leptoquarks that decay into a third-generation quark (t or b) and any charged or neutral lepton is presented. The analysis exploits the full data sample recorded with the ATLAS detector in Run 2 of the LHC, corresponding to 139 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13$ TeV. No significant deviation from the Standard Model expectation is observed. At 95% CL the lower limits on the masses of scalar LQs are found to range from 1230 to 1730 GeV, depending on branching ratio, leptoquark charge and lepton flavour. The combined analyses extend the mass exclusion range by up to 100 GeV compared to the previous best individual analyses. For any combination of these parameters the ATLAS limits constitute the best limits to date.

Limits are also placed on some benchmark models of vector LQs. In the U_1^{MC} model, where the coupling to gluons is minimal, LQs are excluded in the mass range below 1580 to 1710 GeV for $\mathcal{B} = 0.5$, depending on LQ flavour. For the Yang–Mills model U_1^{YM}, LQs are excluded in the mass range below 1840 to 1980 GeV for $\mathcal{B} = 0.5$, depending on LQ flavour. The combined analysis extends the mass exclusion range by up to 80 GeV compared to the best individual analyses. Vector LQs with charge $\pm 5/3$ and $t\tau$ decays are excluded up to 1540 GeV for $\tilde{U}_1^{\mathrm{MC}}$ and up to 1810 GeV for $\tilde{U}_1^{\mathrm{YM}}$.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data for this manuscript are not available. The values in the plots and tables associated to this article are stored in HEPDATA (https://www.hepdata.net/).

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