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1 Introduction

The remarkable similarities between quarks and leptons in the Standard Model (SM) lead to the supposition that there could be a fundamental relationship between them at a sufficiently high energy scale, manifested by the existence of leptoquarks (LQ) [1]. LQs are hypothetical particles which carry both baryon and lepton number and have fractional electrical charge. The present search is performed within the minimal Buchmüller-Rückl-Wyler model [2], where LQs are restricted to couple to quarks and leptons of one generation. In this model, LQs are required to have pure chiral couplings to SM fermions in order to avoid inducing four-fermion interactions that would cause flavour-changing neutral currents and lepton family-number violations. At the Large Hadron Collider (LHC), scalar LQs can be produced either in pairs or singly. Single LQ production involves the unknown $\lambda_{LQ-\ell-q}$ coupling, while pair production of scalar LQs occurs mostly via gluon-gluon fusion, dominant for $m_{\mathrm{LQ}} \lesssim 1$ TeV, and $q\overline{q}$-annihilation, dominant at larger masses. Both pair-production modes involve only the strong coupling constant, and therefore all model dependence is contained in the assumed LQ mass m_{LQ} and the branching ratio β for LQ decay to a charged lepton and a quark [1]. LQs can also decay to a neutrino and a quark; in this case, the branching ratio is $1-\beta$. Pair production of scalar LQs at the LHC has been calculated at next-to-leading order (NLO) [4].

The results presented in this paper are an update of the previous ATLAS search for second generation LQs [5] and extend the bounds arising from previous direct searches performed by CMS [6], ATLAS [5], D0 [7] and OPAL [8]. A total integrated luminosity of 1.03 fb^{-1} of proton-proton collision data at a centre of mass energy $\sqrt{s} = 7$ TeV, collected with the ATLAS detector from March through July 2011, is used for the search. The final states arising from leptoquark pairs decaying into two muons and two quarks ($\mu\mu jj$), or into a muon, a neutrino and two quarks ($\mu\nu jj$), are considered. These result in experimental signatures of either two high transverse momentum (p_{T}) muons and two high p_{T} jets, or one high p_{T} muon, missing transverse momentum, and two high p_{T} jets.

Analyses for both dimuon and single muon final states start with the selection of event samples with

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[1] The $\lambda_{LQ-\ell-q}$ coupling determines the LQ lifetime and width [3]. For LQ masses considered here, 200 GeV$\leq m_{\mathrm{LQ}} \leq$700 GeV, couplings greater than $e \times 10^{-6}$, with $e = \sqrt{4\pi\alpha}$ the electron charge, and $\alpha(M_{\mathrm{Z}}) = 1/128$, correspond to decay lengths less than roughly 1 mm. In addition, to be insensitive to the coupling, the width cannot be larger than the experimental resolution of a few GeV. This sets the approximate sensitivity to the unknown coupling strength.

large signal acceptance. Since background cross sections are several orders of magnitude larger than the signal cross sections, these samples are dominated by the major backgrounds: Z+jets and $t\bar{t}$ in the $\mu\mu jj$ case, and W+jets and $t\bar{t}$ for the $\mu\nu jj$ case. Further selection requirements are then applied to these samples to define control regions used to determine the normalization of the aforementioned backgrounds. The determination of the multi-jet background is performed in a fully data-driven approach, and the smaller diboson and single top-quark backgrounds are estimated using Monte Carlo (MC) simulations.

After all background contributions are determined, variables selected to enhance the discrimination between signal and background are combined into a log likelihood ratio, which is used to search for an excess of events over the SM background prediction. The searches are performed independently for each final state. The results are then combined and interpreted as lower bounds on the LQ mass for different β hypotheses.

2 The ATLAS detector

The ATLAS detector [9] is a multi-purpose detector with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle [2].

The three major sub-components of ATLAS are the tracking detectors, the calorimeters and the muon spectrometer. Charged particle tracks and vertices are reconstructed with silicon-based tracking detectors that cover $|\eta| < 2.5$ and a transition radiation tracker extending to $|\eta| < 2.0$. The inner tracking system is immersed in a homogeneous 2 T axial magnetic field provided by a solenoid. Electron, photon, and jet energies are measured in the calorimeters. The calorimeter system is segmented into a central barrel and two endcaps, collectively covering the pseudorapidity range of $|\eta| < 4.9$. A liquid-argon (LAr) electromagnetic calorimeter covers the range $|\eta| < 3.2$ and an iron-scintillator tile hadronic calorimeter covers the range $|\eta| < 1.7$. Endcap and forward LAr calorimeters provide both electromagnetic and hadronic measurements and cover the region $1.5 < |\eta| < 4.9$.

Surrounding the calorimeters, a muon spectrometer [9] with air-core toroids, a system of precision tracking chambers, and detectors with triggering capabilities provides muon identification and precise momentum measurements. The muon spectrometer is based on three large superconducting toroids with coils arranged in an eight-fold symmetry around the calorimeters, covering a range of $|\eta| < 2.7$. Over most of the η range, precision measurements of the track coordinates in the principal bending direction of the magnetic field are provided by Monitored Drift Tubes (MDTs). At large pseudorapidities ($2.0 < |\eta| < 2.7$), Cathode Strip Chambers (CSCs) with higher granularity are used in the innermost station.

A three-level trigger system selects events to be recorded for offline analysis. The muon trigger detectors consist of Resistive Plate Chambers (RPCs) in the barrel ($|\eta| < 1.05$) and Thin Gap Chambers (TGCs) in the end-cap regions ($1.05 < |\eta| < 2.4$), with a small overlap in the $|\eta| = 1.05$ region. The data considered in this analysis are selected from events containing at least one muon with the transverse momentum determined by the trigger system satisfying $p_{\mathrm{T}} > 18$ GeV.

3 Simulated samples

Simulated event samples are used to determine all signal and some of the background yields. Signal samples for LQ masses between 200 GeV and 1000 GeV are simulated with PYTHIA 6.4.25 [10]. NLO cross sections as determined in Ref. [4], using CTEQ6.6 [11] parton distribution functions (PDFs), are used to normalize the samples at each mass point.

Samples of W and $Z/\gamma^{\star}$ production in association with n partons (where n can be 0, 1, 2, 3, 4 and 5 or more) are simulated with the ALPGEN [12] generator interfaced to HERWIG [13] and JIMMY [14] to model parton showers and multiple parton interactions, respectively. The MLM [12] parton-shower matching scheme is used to form inclusive W/Z+jets samples. MC@NLO [15] is used to estimate the production of single top quarks and top quark pairs. A top quark mass of 172.5 GeV is used in the simulation. Diboson events are generated using HERWIG, and the cross sections are scaled to NLO calculations [15,16].

All simulated events are passed through a full detector simulation based on GEANT4 [17] and then reconstructed with the same software chain as the data [18]. During the data-taking period considered in this search, the mean number of primary proton-proton interactions per bunch crossing was approximately six. The effect of this pile-up is taken into account in the analysis by overlaying simulated minimum bias events onto the simulated hard-scattering events. The MC samples are then reweighted such that the average number of pile-up interactions matches that seen in the data.

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[2] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point and the z-axis along the beam pipe. Cylindrical coordinates (r,ϕ) are used in the transverse plane, with ϕ the azimuthal angle around the beam pipe. The pseudorapidity η is defined in terms of the polar angle θ by $\eta = -\ln\tan(\theta/2)$.

4 Object and Event selection

Collision events are identified by requiring at least one reconstructed primary vertex candidate with at least three associated tracks with $p_{\mathrm{T,track}} > 0.4$ GeV. If two or more such vertices are found, the one with the largest sum of $p^2_{\mathrm{T,track}}$ is taken to be the primary vertex. Muons are reconstructed by matching tracks in the inner detector to track segments in the muon spectrometers, as described in Ref. [19]. In addition to the track quality requirements imposed for identification, the muon tracks must also satisfy $|d_0| < 0.1$ mm and $|z_0| < 5$ mm, where d_0 and z_0 are the transverse and longitudinal impact parameters measured with respect to the primary vertex. All selected muons must have $p_{\mathrm{T}} > 30$ GeV and are restricted to be within $|\eta| < 2.4$. Muon candidates must pass the isolation requirement $p_{\mathrm{T}}^{\mathrm{cone20}}/p_{\mathrm{T}} < 0.2$, where $p_{\mathrm{T}}^{\mathrm{cone20}}$ is the sum of the p_{T} of the tracks within $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta^2)} < 0.2$ of the muon track, excluding the muon p_{T} contribution. Selected events must have at least one muon identified by the trigger system within a cone $\Delta R < 0.1$ centered on a selected muon.

Jets are reconstructed from calorimeter energy clusters using the anti-k_t algorithm [21] with a radius parameter $R = 0.4$. Corrections are applied in order to account for the effects of the non-compensating calorimeter, upstream material and other effects, by using p_{T} and η-dependent correction factors derived from simulation and validated with test-beam [22] and collision data studies [23]. After applying quality requirements based on shower shape and signal timing with respect to the beam crossing, the selected jets must satisfy $p_{\mathrm{T}} > 30$ GeV, $|\eta| < 2.8$ and must be separated from the selected candidate muons by $\Delta R \geqslant 0.4$. The presence of neutrinos is inferred from the missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$, defined as the magnitude of the negative vector sum of the transverse momenta of reconstructed electrons, muons and jets, as well as calorimeter energy deposits not associated to reconstructed objects.

Corrections to the muon trigger and reconstruction efficiencies and to the momentum resolution are applied to the simulated events so that their kinematic distributions match those observed in data, with an impact on the predicted number of events of less than 2%. These corrections are derived from samples of $Z \to \mu\mu$ and $W \to \mu\nu$ decays [19], taking into account the effects of multiple scattering and the intrinsic resolution of the muon spectrometer [20]. In order to validate the corrections at high p_{T}, the alignment of the muon spectrometer, which dominates the momentum resolution for p_{T} larger than approximately 200 GeV, is derived from a sample of straight track data taken in special runs with the toroids turned off, resulting in agreement within the considered systematic uncertainties.

Events selected for this search are required to contain either exactly two muons and at least two jets for the $\mu\mu jj$ final state, or exactly one muon, at least two jets and $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV for the $\mu\nu jj$ final state. In the $\mu\mu jj$ channel, only events with $m_{\mu\mu} > 40$ GeV are considered. In the $\mu\nu jj$ channel, events are required to have $m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\mu}E_{\mathrm{T}}^{\mathrm{miss}}(1 - \cos(\Delta\phi))} > 40$ GeV, where $\Delta\phi$ is the angle between the muon and the $E_{\mathrm{T}}^{\mathrm{miss}}$ direction in the plane perpendicular to the beam. Events with identified electrons as defined in Ref. [24], with $p_{\mathrm{T}} > 30$ GeV, and $|\eta| < 2.47$ are rejected. After all the selection criteria are applied the acceptance times efficiency ranges from about 60% (55%) for a LQ signal of $m_{\mathrm{LQ}} = 300$ GeV to 65% (60%) for a LQ signal of $m_{\mathrm{LQ}} = 600$ GeV for the $\mu\mu jj$ ($\mu\nu jj$) channel.

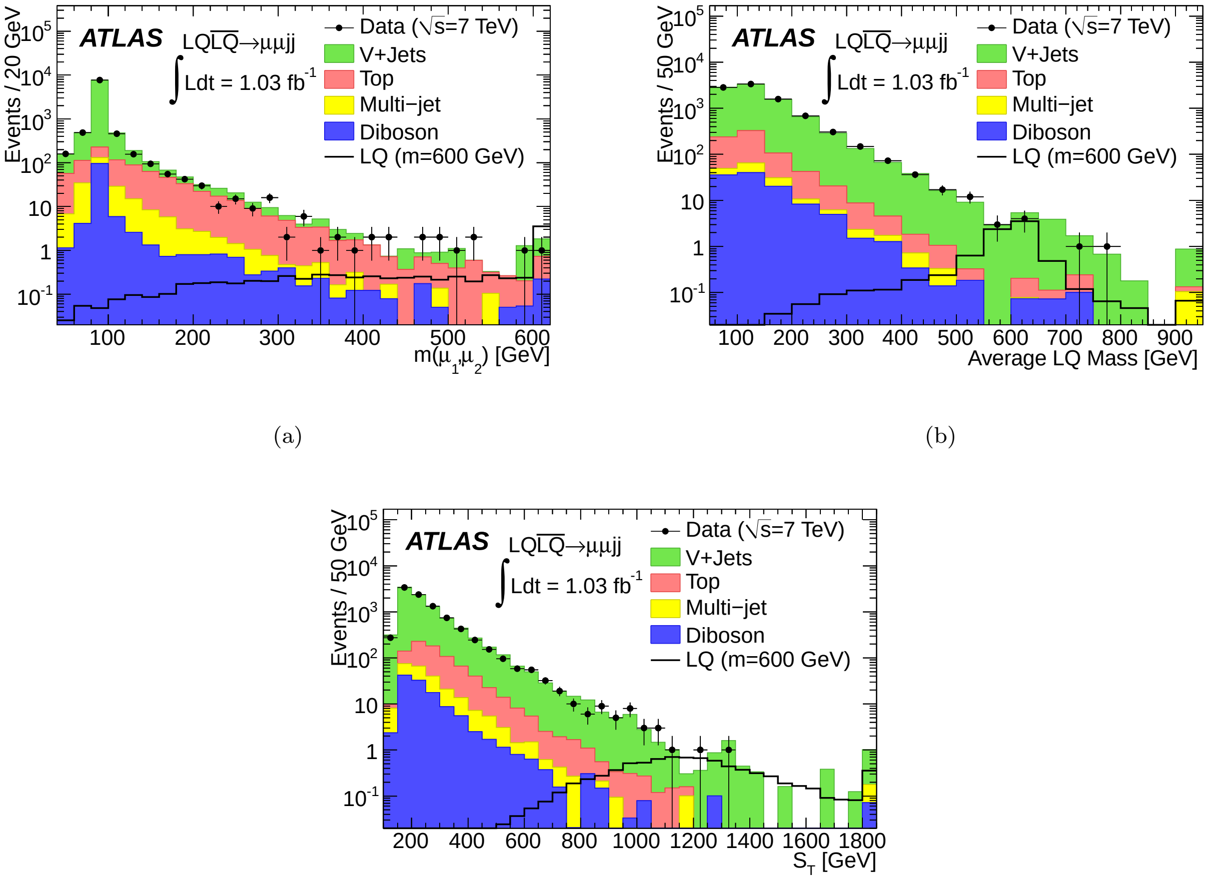
5 Background determination

Major backgrounds in this search arise from V+jets ($V = W, Z$) and $t\bar{t}$ processes. The kinematic distributions of these are determined using MC samples, and their absolute normalization is evaluated from data using control regions, which are subsets of the selected sample, designed to enhance either the V+jets or the top quark contribution. The multi-jet background is obtained directly from data and prior to the estimation of the normalization for the two main backgrounds, while the determination of the remaining backgrounds (diboson and single top quark production) relies entirely on MC simulations.

Two control regions are used in the $\mu\mu jj$ channel. (I) Z+jets: formed by events within a narrow dimuon invariant mass $m_{\mu\mu}$ window around the Z boson mass, defined by $81 < m_{\mu\mu} < 101$ GeV, and at least two jets, and (II) $t\bar{t}$: one of the muons is replaced by an electron resulting in events with a muon and an electron, and at least two jets.

Three control regions are used in the $\mu\nu jj$ channel. (I) W+ 2 jets: events in the vicinity of the W boson Jacobian peak, selected by requiring $40 < m_{\mathrm{T}} < 120$ GeV, exactly two jets and $S_{\mathrm{T}} < 225$ GeV, where S_{T} is the scalar summed transverse energy S_{T}, defined as $S_{\mathrm{T}} = p_{\mathrm{T}}^{\mu} + E_{\mathrm{T}}^{\mathrm{miss}} + p_{\mathrm{T}}^{\mathrm{jet1}} + p_{\mathrm{T}}^{\mathrm{jet2}}$, (II) W+ 3 jets: events passing the $40 < m_{\mathrm{T}} < 120$ GeV requirement, with at least three jets and $S_{\mathrm{T}} < 225$ GeV, and (III) $t\bar{t}$: events with at least four jets, with $p_{\mathrm{T}}^{\mathrm{jet1}} > 50$ GeV and $p_{\mathrm{T}}^{\mathrm{jet2}} > 40$ GeV. In all of the control regions the expected signal yields are negligible.

The normalizations of the V+jets and $t\bar{t}$ backgrounds are obtained by comparing data and MC yields in the



(a)

(b)

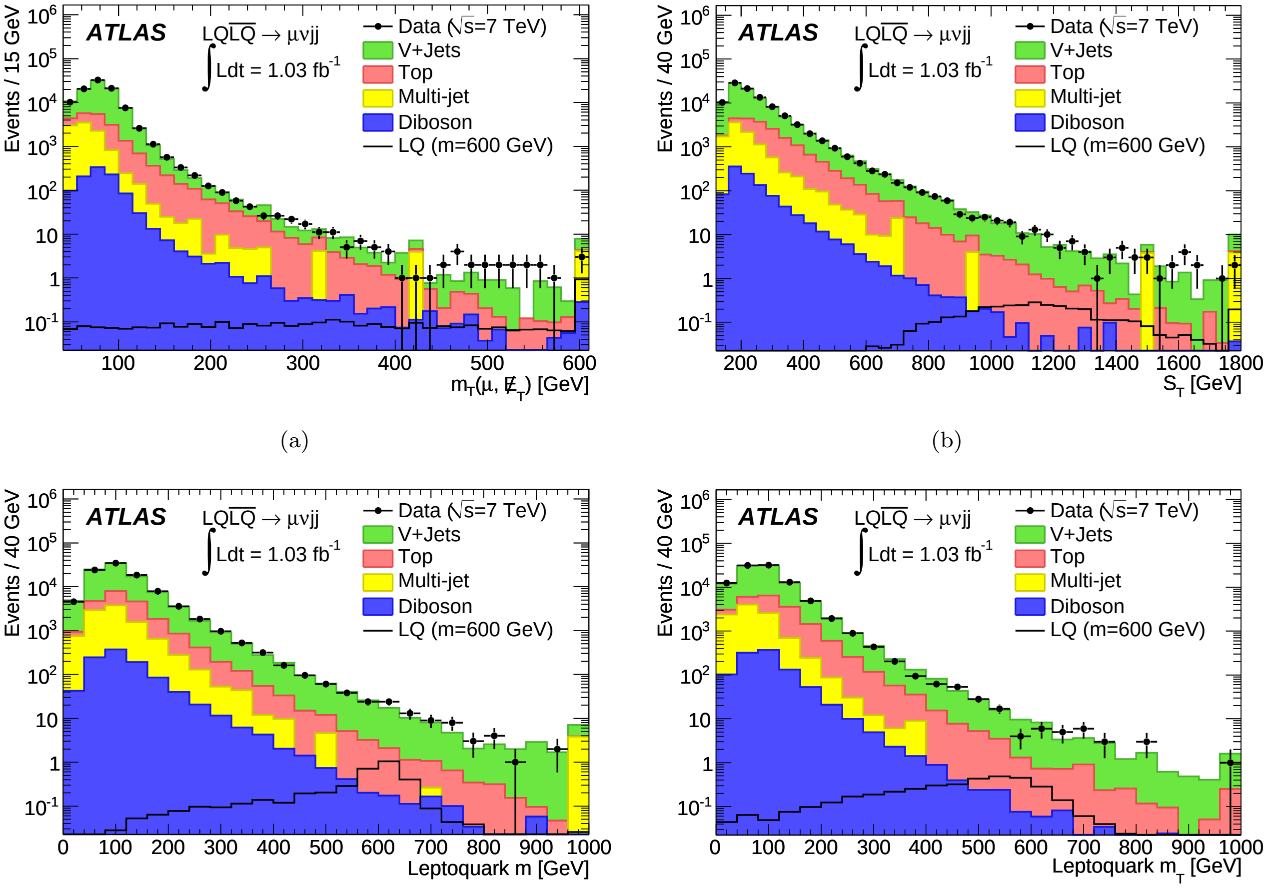
(c)

Fig. 1 Distributions of the input LLR variables for the $\mu\mu jj$ channel for data and the SM backgrounds. (a) Invariant mass of the two muons in the event, (b) Average LQ mass resulting from the best muon-jet combinations in each event, and (c) S_{T}. The stacked distributions show the various background contributions, and data are indicated by the points with error bars. The 600 GeV LQ signal is also shown for $\beta = 1.0$. In all figures, the last bin contains the sum of all entries equal to and above the bin lower boundary.

control samples defined above. In the $\mu\mu jj$ channel, each correction factor is obtained independently for each background, on account of the high purity of the two different control regions. In the $\mu\nu jj$ channel, there is significant cross-region contamination and therefore the number of V+jets and $t\bar{t}$ events is determined by simultaneously minimizing the χ^2 formed by the differences between the observed and predicted SM yields in the three control regions. The resulting scale factors are of the order of 10% in the low S_{T} region.

The multi-jet background in the selected sample and in each control sample is obtained from a fit to the $m_{\mu\mu}$ and $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in the $\mu\mu jj$ and $\mu\nu jj$ channels, respectively. In these fits, the relative fraction of the multi-jet background is a free parameter, and the sum of the total predicted events is constrained to be equal to the total observed number of events. The V+jets and $t\bar{t}$ normalizations are not fixed. Multi-jet background arises predominantly from muons from secondary decays. Therefore, templates for the multi-jet background distributions are constructed from multi-jet enhanced samples of data events in which the muons fail the requirement on the transverse impact parameter or the isolation selection requirements described in Section 4. In the $\mu\mu jj$ channel, the W+jets contribution is estimated together with the multi-jet background. During this procedure, the V+jets and $t\bar{t}$ normalizations are fitted as well, providing an independent estimate. The resulting values agree with those obtained from the control regions, which are the ones used in the analysis.

After analyzing 1.03 fb^{-1} of data and applying the analysis requirements described in Section 4, good agree-



(a) (b)

(c) (d)

Fig. 2 Distributions of the input LLR variables for the $\mu\nu jj$ channel for data and the SM backgrounds. (a) Transverse mass of the muon and the $E_{\mathrm{T}}^{\mathrm{miss}}$ in the event, (b) S_{T}, (c) LQ mass, and (d) LQ transverse mass. The stacked distributions show the various background contributions, and data are indicated by the points with error bars. The expected signal for a 600 GeV LQ signal is also shown for $\beta = 0.5$. In all figures, the last bin contains the sum of all entries equal to and above the bin lower boundary.

ment is observed between the data and the SM expectation. The observed and expected yields in the selected sample are 9254 and 9300 ± 1700 for the $\mu\mu jj$ channel, and 97113 and 97000 ± 19000 for the $\mu\nu jj$ channel. For a LQ mass of 600 GeV, 8.2 ± 0.4 and 3.9 ± 0.2 events are expected for the $\mu\mu jj$ and the $\mu\nu jj$ final states, respectively. The aforementioned uncertainites fully account for (the dominant) systematic and statistical uncertainties.

6 Likelihood analysis

Several kinematic variables, selected to provide the best discrimination between LQ events and SM backgrounds, are combined in a log likelihood ratio in order to search for a LQ signal. In the $\mu\mu jj$ channel, $m_{\mu\mu}$, $S_{\mathrm{T}} = p_{\mathrm{T}}^{\mu1} + p_{\mathrm{T}}^{\mu2} + p_{\mathrm{T}}^{\mathrm{jet1}} + p_{\mathrm{T}}^{\mathrm{jet2}}$ and the average reconstructed leptoquark mass $\bar{m}_{\mathrm{LQ}}$ are used. In the $\mu\nu jj$ channel, S_{T}, m_{T}, the transverse leptoquark mass $m_{\mathrm{T}}^{\mathrm{LQ}}$ and the leptoquark mass m_{LQ} are used. The distributions of these input variables are shown in Fig. 1 and Fig. 2 for the $\mu\mu jj$ and the $\mu\nu jj$ final states, respectively.

In the $\mu\mu jj$ channel, an average LQ mass $\bar{m}_{\mathrm{LQ}}$ is defined for each event by reconstructing all possible combinations of lepton-jet pairs, using the two highest p_{T} jets in each event. Of the four possible combinations in each event, the pairing which provides the smallest difference between the LQ masses is chosen, and their average is used in the likelihood analysis. In the $\mu\nu jj$ final state, because the longitudinal component of the neutrino momentum is unknown, only one mass from the muon and a jet can be reconstructed, and the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the remaining jet are used to calculate the transverse mass of the other LQ. The two masses which provide the smallest absolute difference are used in the likeli-

Table 1 The predicted and observed yields and the expected yields for a LQ signal of $m_{\rm LQ} = 600$ GeV after requiring $LLR \geq 2$ for the $\mu\mu jj$ channel and $LLR \geq 7$ for the $\mu\nu jj$ channel. The $\mu\mu jj$ ($\mu\nu jj$) channel signal yields are computed assuming $\beta = 1.0$ (0.5). Statistical and systematic uncertainties as described in Section 7 are shown. These are calculated assuming a 100% correlation for the same source between the different backgrounds. These systematic uncertainties are computed as the sum of the absolute values of the systematic variation in each bin and are shown to indicate the scale. This is an approximation to the standard ensemble method used in the limit setting code.

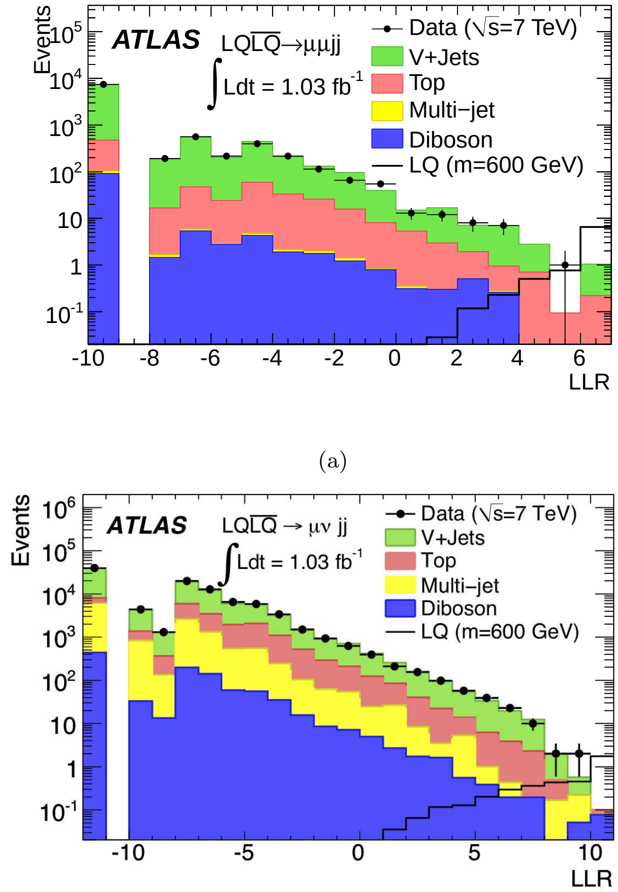
Source	$\mu\mu jj$ Channel	$\mu\nu jj$ Channel
V+jets	14.2 ± 6.4	12.9 ± 9.9
Top	3.0 ± 2.2	1.9 ± 1.2
Diboson	0.8 ± 0.6	0.3 ± 0.1
Multi-jet	< 0.1	< 0.1
Total	18 ± 8	15 ± 11
Data	16	14
LQ	8.2 ± 0.4	3.2 ± 0.2

hood analysis. With this algorithm, the probability of picking the correct pairing is of around 90% for both channels.

For each event, likelihoods are constructed for the background (L_B) and the various signal LQ hypothesis (L_S) as follows: $L_B \equiv \prod b_i(x_{ij})$, $L_S \equiv \prod s_i(x_{ij})$, where b_i, s_i are the probabilities of the i–th input variable from the normalized summed background and signal distributions, respectively, and x_{ij} is the value of that variable for the j–th event in a sample. The log likelihood ratio for each tested signal, $LLR = \log(L_S/L_B)$, is used as the final variable to search for the LQ signal.

7 Systematic uncertainties

Systematic uncertainties originating from several sources are considered. These include uncertainties in lepton momentum, jet energy and $E_{\rm T}^{\rm miss}$ scales and resolutions and their dependence on the number of pile-up events, the background estimations, and the LQ production cross section. For each source of uncertainty considered, the analysis is repeated with the relevant variable varied within its uncertainty, and a new LLR is built for the systematically varied sample, enabling the uncertainty in both the predicted yield and the kinematic distributions to be propagated to the final result. In this section, systematic uncertainties are described for each source of systematics, calculated assuming each source to be 100% correlated among the different backgrounds. Uncertainties are given for the region of $LLR \geq 2$ and $LLR \geq 7$ for the $\mu\mu jj$ and the $\mu\nu jj$ channels, respectively, although the full LLR distribution is used to search for the LQ signal.



(a)

(b)

Fig. 3 (a) LLR distributions for the $\mu\mu jj$ and (b) for the $\mu\nu jj$ final states for a LQ mass of 600 GeV. The data are indicated with the points and the filled histograms show the SM background. The multi-jet background is estimated from data, while the other background contributions are obtained from simulated samples as described in the text. The LQ signal corresponding to a LQ mass of 600 GeV is indicated by a solid line, and is normalized assuming $\beta = 1.0(0.5)$ in the $\mu\mu jj$ ($\mu\nu jj$) channel. The lowest bin corresponds to background events in regions of the phase space for which no signal events are expected.

The jet energy scale (JES) and resolution (JER) are varied up and down by 1σ [23] for all simulated events. Their impact is estimated independently, and the corresponding variations are propagated to the $E_{\rm T}^{\rm miss}$ in the case of the $\mu\nu jj$ channel. The resulting effect of the JES (JER) uncertainty is 9% (8%) and 15% (7%) for the backgrounds in the $\mu\mu jj$ and the $\mu\nu jj$ channels, respectively. For a LQ signal of $m_{\rm LQ} = 600$ GeV, both are 1% for the $\mu\mu jj$ channel, and 2.4% and 1% for the $\mu\nu jj$ channel.

The systematic uncertainties from the muon resolution and momentum scale are derived by comparing the $m_{\mu\mu}$ distribution in $Z \rightarrow \mu\mu$ control samples to

$Z \to \mu\mu$ MC samples and are approximately 1% [20]. These result in uncertainties of 12% and 3% for the total background prediction in the $\mu\mu jj$ and the $\mu\nu jj$ channels, respectively, and in uncertainties of 1.4% for a LQ signal of $m_{\mathrm{LQ}} = 600$ GeV for the $\mu\mu jj$ and the $\mu\nu jj$ channels.

Systematic uncertainties due to assumptions in the modelling of the V+jets background are estimated by using SHERPA [25] samples instead of the ALPGEN samples described in Section 3. The resulting uncertainty is 30% for the $\mu\mu jj$ channel and 60% for the $\mu\nu jj$ channel. Similarly, systematic uncertainties arising from the modelling of the $t\bar{t}$ process are obtained by using different parameter values to simulate alternative samples to the one described in Section 3. These include samples in which the top quark mass is varied up and down by 2.5 GeV, generated with MC@NLO, samples where the initial and final-state radiation (ISR and FSR) contributions are varied accordingly to their uncertainties, generated with ACER MC [26], and samples generated with POWHEG [27] interfaced to PYTHIA and JIMMY. These impact the total background yields by 12% (7%) for the $\mu\mu jj$ ($\mu\nu jj$) final state. For both V+jets and $t\bar{t}$ backgrounds, a 10% uncertainty on the scale factors is considered, covering the variation of the scale factors in the low and high p_{T} regions.

Systematic uncertainties in the multi-jet background in the $\mu\mu jj$ channel are determined by comparing results derived from fits to kinematic variables other than the nominal ones. These include the leading muon p_{T}, the leading jet p_{T}, the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the scalar sum of the transverse momenta of the two muons in the event. In the $\mu\nu jj$ channel, an alternative loose-tight matrix method [28] with two different multi-jet enhanced samples obtained by inverting the isolation and the $|d_0|$ requirements is used. Since the relevant phase space of the multi-jets in the two channels is very different, the different control regions have very different statistics which leads to a large difference in precision to which this background can be estimated. The resulting uncertainties are 90% in the $\mu\mu jj$ channel and 33% in the $\mu\nu jj$ channel.

A luminosity uncertainty of 3.7% [29] is assigned to the LQ signal yields and to the yields of background processes determined from simulation: diboson and single top quark production. Further systematic uncertainties considered arise from the finite number of events in the simulated samples, amounting to 4%–25% depending on the LQ mass being considered.

For the signal samples, additional systematic uncertainties originate from ISR and FSR effects, resulting in an uncertainty of 2% for both channels. The choice of the renormalization and factorization scales, which are varied from m_{LQ} to $2m_{\mathrm{LQ}}$ and $m_{\mathrm{LQ}}/2$, and the choice of the PDF, determined with the CTEQ eigenvectors errors and by using the MRST2007LO* PDF set [30], result in an uncertainty in the signal acceptance of 1%–6% for LQ masses between 300 GeV and 700 GeV.

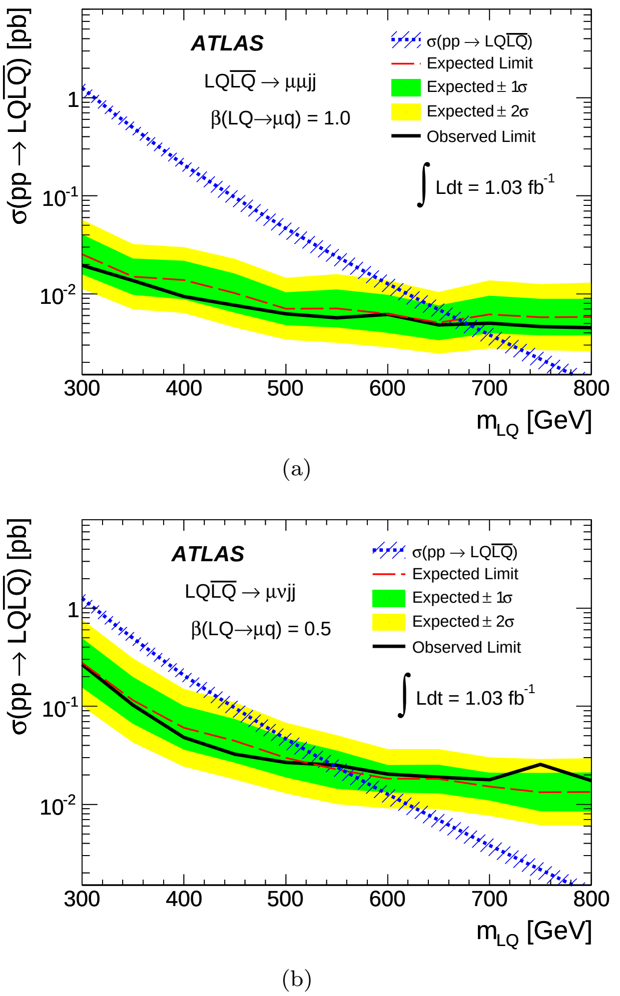
8 Results

Figure 3 shows the LLR for the data, the predicted backgrounds and a LQ signal of 600 GeV for the $\mu\mu jj$ and the $\mu\nu jj$ channels. To ensure sufficient background statistics, bins with a total background yield less than twice the statistical uncertainty in that bin are merged into a single bin. There is no significant excess in data observed at large LLR values where such a signal would appear, and the data are found to be consistent with the SM background expectations (see Table 1). Upper limits are derived at 95% confidence level (CL) for the scalar leptoquark production cross section using a modified frequentist CL_s approach [31,32]. The test statistic is defined as $-2\ln(Q) = -2\ln(L_{s+b}/L_b)$, where the likelihoods L_{s+b} and L_s follow a Poisson distribution and are calculated based on the corresponding LLR distributions. Systematic uncertainties as described in Section 7 are treated as nuisance parameters with a Gaussian probability density function.

The 95% CL upper bounds on the cross section for leptoquark pair production as a function of mass are shown in Fig. 4 for the $\mu\mu jj$ and the $\mu\nu jj$ channels at $\beta = 1.0$ and $\beta = 0.5$, respectively. The expected and observed limits for the combined channels are shown in the β vs. m_{LQ} plane in Fig. 5.

9 Conclusions

The results of a search for the pair production of second generation scalar leptoquarks using 1.03 fb^{-1} of proton-proton collision data produced by the LHC at $\sqrt{s} = 7$ TeV and recorded by the ATLAS detector are presented. The data are in good agreement with the expected SM background, and no evidence of LQ production is observed. Lower limits on leptoquark masses of $m_{\mathrm{LQ}} > 685$ GeV and $m_{\mathrm{LQ}} > 594$ GeV for $\beta = 1.0$ and $\beta = 0.5$ are obtained at 95% CL, whereas the expected limits are $m_{\mathrm{LQ}} > 671$ GeV and $m_{\mathrm{LQ}} > 605$ GeV, respectively. These are the most stringent limits to date arising from direct searches for second generation scalar leptoquarks.



(a)

(b)

Fig. 4 (a) 95% CL upper limit on the pair production cross section of second generation leptoquarks for the $\mu\mu jj$ channel at β =1.0 and (b) for the $\mu\nu jj$ channel at β =0.5. The solid lines indicate the individual observed limits, while the expected limits are indicated by the dashed lines. The theoretical prediction is indicated by the hatched band and includes the systematic uncertainties due to the choices of the PDF and the renormalization and factorization scales. The dark (green) and light (yellow) solid band contains 68% (95%), respectively, of possible outcomes from pseudo-experiments in which the yield is Poisson-fluctuated around the background-only expectation.

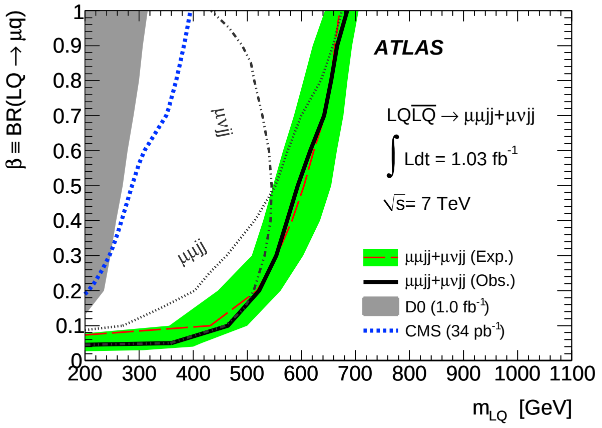


Fig. 5 95% CL exclusion region resulting from the combination of the $\mu\mu jj$ and the $\mu\nu jj$ channels shown in the β versus leptoquark mass plane. The shaded area at the left indicates the D0 exclusion limit [7] and the thick dotted line indicates the CMS exclusion region [6]. The dotted and dotted-dashed lines indicate the individual limits derived for the $\mu\mu jj$ and $\mu\nu jj$ channels, respectively. The combined observed limit is indicated by the solid black line. The combined expected limit is indicated by the dashed line, together with the solid band containing 68% of possible outcomes from pseudo-experiments in which the yield is Poisson-fluctuated around the background-only expectation.

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