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Search for third generation scalar leptoquarks in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

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Contents

1 Introduction

Leptoquarks (LQ) are colour-triplet bosons that carry both lepton and baryon numbers and have a fractional electric charge. They are predicted by many extensions of the Standard Model (SM) [1–7] and may provide unification between the quark and lepton sectors. In accordance with experimental results on lepton-number violation, flavour-changing neutral currents and proton decay, it is assumed that individual leptoquarks do not couple to particles from different generations [8, 9], thus leading to three generations of leptoquarks. The most recent limit on pair-produced third generation scalar leptoquarks (LQ_3) decaying to $\tau b \tau b$ comes from the CMS experiment, in which scalar leptoquarks with masses below 525 GeV are excluded at the 95% confidence level (CL)[10]. Limits have also been set by the D0 [11] and CDF [12] experiments at the Tevatron, which have excluded third generation scalar leptoquarks with masses up to 210 GeV and 153 GeV respectively. First and second generation scalar leptoquarks have been excluded up to 830 GeV and 840

GeV respectively [13–15]. The results presented here are based on a total integrated luminosity of $4.7\,\text{fb}^{-1}$ of proton-proton collision data at a centre-of-mass energy of $\sqrt{s} = 7$ TeV, collected by the ATLAS detector at the LHC during 2011. The final states investigated arise from the decay of both leptoquarks into a tau lepton and a b-quark, leading to a $\tau b \tau b$ final state. The branching fraction of LQ_3 decays to τb is assumed to be equal to 100%.

Tau leptons can decay either leptonically (to an electron or muon plus two neutrinos), or hadronically (typically to one or three charged hadrons, plus one neutrino, and zero to four neutral hadrons). Since the final state includes two taus, this leads to three possible sub-categories of events: di-lepton, lepton–hadron and hadron–hadron. Of these, the lepton–hadron category has the largest branching fraction (45.6%), and the presence of one charged light lepton ($\ell = e, \mu$) in the event is useful for event triggering and provides better rejection of the multi-jets background. Only the lepton–hadron decay mode is considered in this analysis, resulting in either an $e\tau_{\text{had-vis}}bb + 3\nu$ or $\mu\tau_{\text{had-vis}}bb + 3\nu$ final state, where $\tau_{\text{had-vis}}$ refers to the visible (non-neutrino) components of the hadronic tau decay.

Selected events are therefore required to have one electron or muon with large transverse momentum (p_{T}), one high-p_{T} hadronically decaying tau, missing transverse energy from the tau decays, and two high-p_{T} jets. Searches are performed independently for the electron and muon channels. The results are subsequently combined and interpreted as lower bounds on the LQ_3 mass.

2 The ATLAS detector

The ATLAS detector [16] is a multi-purpose detector with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse (x, y) plane, with ϕ being the azimuthal angle around the beam pipe. The pseudorapidity η is defined in terms of the polar angle θ by $\eta = -\ln(\tan(\theta/2))$. The three major sub-components of ATLAS are the tracking detector, the calorimeter and the muon spectrometer.

Charged particle tracks and vertices are reconstructed using silicon pixel and microstrip detectors covering the range $|\eta| < 2.5$, and by a straw tube tracker that covers $|\eta| < 2.0$. Electron identification capability is added by employing Xenon gas to detect transition radiation photons created in a radiator between the straws. The inner tracking system is immersed in a homogeneous 2 T magnetic field provided by a solenoid.

Electron, jet and tau energies are measured in the calorimeter. The ATLAS calorimeter system covers a pseudorapidity range of $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and end-cap high-granularity lead/liquid argon (LAr) electromagnetic (EM) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$, to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by a steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic end-cap calorimeters. The forward region ($3.1 < |\eta| < 4.9$) is instrumented by a LAr calorimeter with copper (EM) and tungsten (hadronic) absorbers.

Surrounding the calorimeters, a muon spectrometer with air-core toroids, a system of precision tracking chambers providing coverage over $|\eta| < 2.7$, and detectors with triggering capabilities over $|\eta| < 2.4$ to provide precise muon identification and momentum measurements.

A three-level event-triggering system selects inclusive electron and muon candidates to be recorded for offline analysis.

3 Monte Carlo simulations

Simulated signal events are produced using the PYTHIA 6.425 [17] event generator with underlying-event Tune D6 [18] and CTEQ6L1 [19] parton distribution functions (PDFs). The coupling $\lambda_{LQ \to lq}$ which determines the LQ lifetime and width [20] is set to $0.01 \times 4\pi\alpha$, where α is the fine-structure constant. This value is widely used in leptoquark searches and gives the leptoquark a full width of less than 1 MeV and a decay length of less than 1 mm. The signal process is normalised using next-to-leading-order (NLO) cross-sections for scalar leptoquark pair production [21]. The signal production cross-section for a leptoquark mass of 500 GeV is 46.2 fb.

Background processes considered in this analysis are the production of W+jets, Z/γ^*+jets, $t\bar{t}$, single top quarks, boson pairs, and multi-jets. The W- and Z-boson processes are simulated using the ALPGEN 2.13 generator [22] with the technique described in ref. [23] to match the hard process (calculated with a leading-order (LO) matrix element for up to five partons) to the parton shower of HERWIG 6.510 [24], and uses JIMMY 4.31 [25] to model the underlying event. Wherever available, dedicated ALPGEN 2.13 samples with massive charm and bottom partons were used for the W+jets and Z/γ^*+jets processes. All samples listed above are generated using the CTEQ6L1 PDFs. Di-boson processes (WW, WZ, and ZZ) are modelled with HERWIG 6.510 using the MRST [26] LO PDFs. Samples of top-quark pair production and associated production of single top quark (Wt) events are produced using the MC@NLO 4.01 [27–30] generator interfaced with HERWIG 6.510 for parton showering, and JIMMY 4.31 to model the underlying event. The CT10 [31] PDFs are used. Single-top s- and t-channel processes are modelled with AcerMC 3.8 [32] using the MRST LO PDFs. The top-quark mass is taken as 172.5 GeV. In all simulated samples TAUOLA [33] and PHOTOS [34] are used to model τ-lepton decays and additional photon radiation from charged leptons, respectively. The W+jets and Z+jets samples are normalised to the inclusive NNLO cross-sections in the proportions predicted by NLO calculations for exclusive n-parton production. The most precise available calculation (nearly NNLO) is used to normalise $t\bar{t}$ production [35]. All other sources of background are normalised using the cross-sections calculated at NLO.

Signal and background events are processed through a detailed detector simulation [36] based on GEANT4 [37]. The data used in this paper are affected by multiple pp collisions occurring in the same or neighbouring bunch crossings (pile-up) and have an average of ten interactions per bunch crossing. The effects of pile-up are taken into account by overlaying simulated minimum-bias events onto the simulated hard-scattering events. The Monte Carlo (MC) samples are then re-weighted such that the average number of pile-up interactions matches that seen in the data.

4 Physics object identification

Collision events are required to have at least one reconstructed vertex with at least four associated tracks with $p_{\mathrm{T}} > 0.4\,\mathrm{GeV}$. In events where more than one vertex is found, the primary vertex is defined as the one with the highest $\sum p_{\mathrm{T}}^2$ of the associated tracks. For the final state of interest described below, this choice of primary vertex is correct in 98.9% (98.4%) of the cases in the electron (muon) channel for the luminosity range considered here.

Electron candidates are reconstructed from clusters of cells in the electromagnetic calorimeter and from tracks in the inner detector. They are required to pass a set of electron identification cuts, based on information about the transverse shower shape, the longitudinal leakage into the hadronic calorimeter, transition radiation, and the requirement that a good-quality track with a hit in the innermost pixel layer points to the calorimeter cluster [38]. A tight working point corresponding to a selection efficiency of approximately 80% for true electrons in simulation is chosen. Electrons are required to have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.47$, excluding the transition region between the barrel and the end-cap calorimeters, *i.e.* $1.37 < |\eta| < 1.52$. Isolation requirements are placed on the electron candidates by demanding that the calorimeter transverse energy in a cone of radius $\Delta R = 0.2$ around the electron (not including the electron cluster) must be less than 20% of the electron p_{T}, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. In addition, track isolation is imposed by requiring that the p_{T} sum of additional tracks (not including the electron track) in a cone of radius $\Delta R = 0.2$ is less than 20% of the electron track p_{T}.

Muon tracks are reconstructed independently in the inner detector and in the muon spectrometer. Tracks are required to have a minimum number of hits in each, and must be compatible in terms of geometrical and momentum matching. The information from both systems is then used in a combined fit to refine the measurement of the momentum of each muon. Muon candidates are required to have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.5$. The average muon reconstruction efficiency is approximately 90%, except for small regions in pseudorapidity where it drops to 80% [39]. Isolation requirements are imposed by demanding that the transverse energy (E_{T}) deposited in the calorimeter in a cone of radius $\Delta R = 0.2$ around the muon (not including the cells crossed by the muon) is less than 20% of the muon p_{T}. Furthermore, track isolation is imposed by requiring that the p_{T} sum of additional tracks (not including the muon track) in a cone of radius $\Delta R = 0.2$ be less than 20% of the muon p_{T}.

Jets are reconstructed using the anti-k_t [40] algorithm with a radius parameter $R = 0.4$. The jet algorithm is run on calibrated topological clusters of calorimeter cells [41]. Additional p_{T}- and η-dependent corrections are applied to jets to bring them to the final calibrated energy scale [42]. Selected jets must have $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $|\eta| < 2.8$.

The identification of jets originating from b-quarks is performed using a neural-network-based tagger [43] that uses the output weights of several likelihood-based algorithms as inputs. The track transverse and longitudinal impact parameters with respect to the primary vertex are examples of variables used by these algorithms. A working point corresponding to an identification efficiency of approximately 70% for true b-jets in simulation is chosen. For jets initiated by gluons or light quarks, the rejection factor (1/fraction that pass the b-tagging ID) is of order 100.

The reconstruction of hadronically decaying tau leptons is seeded by jets which are reconstructed within the acceptance of the inner detector. Only clusters in a cone with radius $\Delta R = 0.2$

are used to define the visible tau energy and direction because the products of hadronic tau decays are more collimated than those from multi-jet processes. Additional corrections depending on the p_{T}, η and number of tracks are applied to bring the reconstructed tau candidates to the correct energy scale [44]. The energy deposition in the calorimeter is required to be matched to either one or three tracks in the inner detector. Hadronically decaying taus are required to have visible $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.5$ and unit charge, and are identified using a Boosted Decision Tree (BDT)[1] [45] which uses both calorimeter and tracking-based variables such as shower width and track multiplicity. A working point with an identification efficiency for true hadronic tau decays in simulation of $\sim 50\%$ is chosen. The rejection factor for jets ranges from 50 to 100 depending on the number of tracks matching the jet candidate.

The missing transverse momentum is a two-dimensional vector defined as the negative vector sum of the transverse momenta of reconstructed electrons, muons, tau leptons and jets, and also of calorimeter energy deposits not associated with reconstructed objects.[2] The magnitude of the missing transverse momentum vector is referred to as the missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$).

5 Event selection

Events are required to be identified by the trigger system as containing at least one electron or one muon. In order to control the data-taking bandwidth, the trigger system imposed a minimum transverse energy threshold on electrons of 20 GeV or 22 GeV (depending on the data-taking period), and a minimum p_{T} threshold on muons of 18 GeV. For the highest luminosities towards the end of the data-taking period, the muon trigger is required to be accompanied by a jet that passes the first-level trigger p_{T} threshold of 10 GeV. All data events are required to be recorded during stable LHC running conditions and with all relevant sub-detectors functioning normally. Events are cleaned for instrumental effects, such as sporadic noise bursts [46].

Events are required to have exactly one reconstructed electron (muon) with $p_{\mathrm{T}} > 25$ (20) GeV. This suppresses background processes such as $Z/\gamma^* \to \ell\ell$ and $t\bar{t}$ which have a higher average lepton multiplicity. Exactly one identified hadronic tau decay candidate with $p_{\mathrm{T}} > 30$ GeV and opposite-sign charge to the lepton is required. The $E_{\mathrm{T}}^{\mathrm{miss}}$ is required to be larger than 20 GeV in order to further reject multi-jet and $Z/\gamma^* \to \ell\ell$ processes. In addition, at least two reconstructed jets are required, with the leading jet having $p_{\mathrm{T}} > 50$ GeV and the sub-leading jet having $p_{\mathrm{T}} > 25$ GeV.

The signal-to-background ratio is improved by requiring that either the leading or sub-leading jet passes the b-tagging requirements. After requiring that events must have one of these two jets passing the b-tagging requirements, the dominant background process is $t\bar{t}$. Since both the signal and $t\bar{t}$ processes contain two b-jets in the final state, no further improvement in sensitivity is obtained by requiring that a second jet in the event also pass the b-tagging requirements.

The visible mass ($m_{\tau_{\text{had-vis}}-\text{jet}}$) of the tau candidate and the closest jet in $\eta - \phi$ space (minimum ΔR) is required to be larger than 90 GeV. Only jets with $p_{\mathrm{T}} > 40$ GeV are considered. This cut

[1] A BDT is a multivariate analysis technique where the selection is based on a majority vote on the result of several decision trees, each of which is derived from the same training sample by supplying different event weights during the training.

[2] Energy deposits in the calorimeters are expressed as four-vectors $(E, \mathbf{p})$, where the direction is determined from the position of the calorimeter cluster and the position of the primary vertex.

is chosen to reject semi-leptonic $t\bar{t}$ events where the tau candidate is faked by jets from $W \to q\bar{q}$ decays.

In events containing leptoquark decays, large $E_{\mathrm{T}}^{\mathrm{miss}}$ arises from neutrinos accompanying the tau decays. Taus originating from leptoquarks typically have high momentum, thus the decay products are predominantly collinear and the $E_{\mathrm{T}}^{\mathrm{miss}}$ direction is correlated with the direction of the visible tau decay products. Two variables are defined in order to improve the separation of signal and background: the absolute difference in ϕ between the charged lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ ($|\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},\ell)|$), and the absolute difference in ϕ between the tau candidate and $E_{\mathrm{T}}^{\mathrm{miss}}$ ($|\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},\tau_{\text{had-vis}})|$). The relationship between these two variables for simulated signal (m_{LQ} = 500 GeV) and the dominant top background, after applying all the requirements described above is shown in figure 1. Events must satisfy the following requirement:

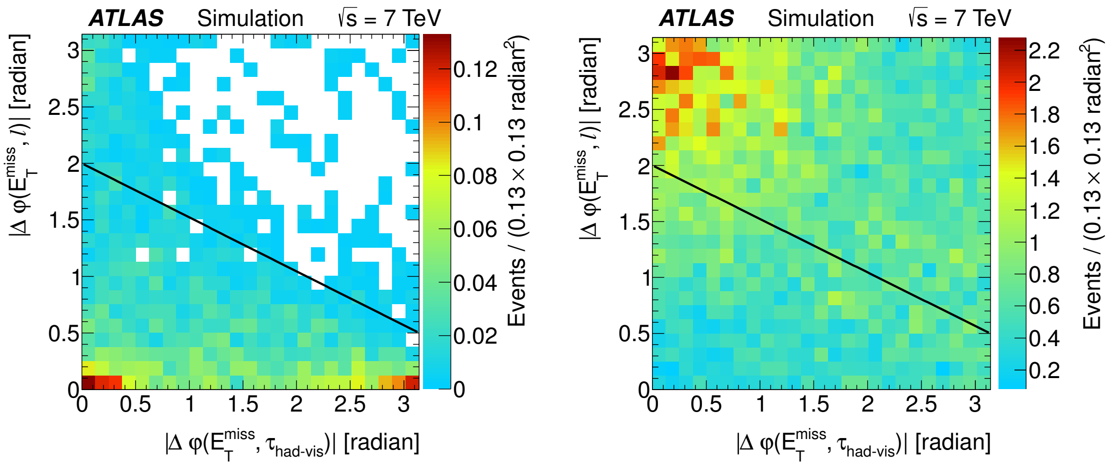
$$|\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},\ell)| \leq -\frac{1.5}{\pi}|\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},\tau_{\text{had-vis}})| + 2 \text{ (radians)}, \tag{5.1}$$

where $\ell = e, \mu$. This $E_{\mathrm{T}}^{\mathrm{miss}}$ angular requirement selects events below the solid line in figure 1. A leptonically decaying tau is accompanied by two neutrinos, whereas a hadronically decaying tau is accompanied by only one. In events with two true taus (as in the signal process), the $E_{\mathrm{T}}^{\mathrm{miss}}$ is therefore typically aligned with the leptonic tau decay and these events are preferentially selected by the $E_{\mathrm{T}}^{\mathrm{miss}}$ angular requirement. The signal efficiency is approximately 85%, independent of leptoquark mass. For $t\bar{t}$ events containing a real hadronic tau (produced from the W decay), the additional neutrinos from the tau decay cause the $E_{\mathrm{T}}^{\mathrm{miss}}$ to be preferentially aligned with the hadronic tau decay and these are rejected. In the subset of $t\bar{t}$ events where the tau is faked by a jet from W-decay, events are evenly distributed across the $|\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},\ell)|$-$|\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},\tau_{\text{had-vis}})|$ plane and a large proportion of these are also rejected. The overall efficiency for inclusive $t\bar{t}$ events is 31%.

6 Background estimation

Backgrounds considered in this analysis are the production of W+jets and Z/γ^*+jets (collectively referred to as V+jets), $t\bar{t}$, single top quarks, di-boson and multi-jets. Normalisation factors are applied to the MC predictions for V+jets and top backgrounds in background-enriched control regions, to predict as accurately as possible the background in the signal region, as described in more detail below. These control regions are constructed to be mutually exclusive of the signal region and the assumption is made that normalisation factors in the signal region are the same as in the background-enriched control regions. The contribution from multi-jets is estimated using fully data-driven techniques. The contribution from di-boson processes is taken directly from MC. The shapes of the distributions are taken from simulation in the signal region.

Different approaches are used to estimate the backgrounds in the electron and muon channels. Normalisation factors for the electron channel are calculated after applying the electron, tau, $E_{\mathrm{T}}^{\mathrm{miss}}$, charge-product cuts, and jet multiplicity and p_{T} requirements described in section 5 above. This approach minimises bias with respect to the signal region, but leads to limited statistics (for MC and data) in the control regions. Normalisation factors for the muon channel are calculated after applying only the muon, tau and charge-product requirements described in section 5.



(a) Signal, $m_{LQ} = 500$ GeV (b) Top-quark background

Figure 1. The absolute value of the angle $\Delta\phi$ between the reconstructed charged light lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$ as a function of $|\Delta\phi|$ between $\tau_{\text{had-vis}}$ and $E_{\mathrm{T}}^{\mathrm{miss}}$ for simulated (a) signal ($m_{\mathrm{LQ}} = 500$ GeV) and (b) top-quark background, after applying all selection cuts (see text) and normalising to the integrated luminosity of the data. The function corresponding to the solid line is defined in eq. 5.1.

6.1 Electron channel

The multi-jets background is estimated by defining a region in data with a tau candidate that fails the tau BDT identification used in the nominal selection but passes a looser identification working point, and has the same-sign charge as the electron. In addition, the events are required not to contain any taus that pass the nominal selection criteria. Contributions from W, Z/γ^*+jets, top-quark, and di-boson background processes estimated from MC simulations are subtracted to get the shape of the multi-jets distribution. The normalisation is determined by performing a two-component maximum likelihood fit to kinematic distributions of the sum of multi-jets and all other sources of background to data, with the multi-jets fraction being the fit parameter. The variable used for fitting is chosen to provide good discrimination between multi-jets and other sources of background. The method is used to calculate the multi-jets contribution in the signal region, where the transverse mass between the charged light lepton and the $E_{\mathrm{T}}^{\mathrm{miss}}$, defined to be:

$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell}E_{\mathrm{T}}^{\mathrm{miss}}(1-\cos(\Delta\phi))}, \tag{6.1}$$

is used as the fit variable. The multi-jets contribution is found to be $12^{+8}_{-16}\%$ of the total data yield in the signal region. The same method is also used in background control regions, fitting to the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in the W and $Z/\gamma^* \to \tau\tau$ control regions, and the electron E_{T} in the top control region. The validity of the method used to estimate the multi-jets background contribution is cross-checked by using events with same-sign charge electron–tau pairs as the control region and found to be compatible within statistical errors. Dependence on the choice of variable used is evaluated by fitting to other kinematic variables, and also found to be within statistical errors of the nominal value.

$Z/\gamma^* \to ee$+jets	Require one extra electron
$Z/\gamma^* \to \tau\tau$+jets	b-jet veto $40 < m_{e\tau_{\text{had-vis}}} < 80\,\text{GeV}$ $m_{\text{T}} < 60\,\text{GeV}$
W+jets	b-jet veto Fail $E_{\text{T}}^{\text{miss}}$ angular cut $60 < m_{\text{T}} < 120\,\text{GeV}$
Top-quark	b-jet requirement $m_{\tau_{\text{had-vis}}jet} > 90\,\text{GeV}$ Fail $E_{\text{T}}^{\text{miss}}$ angular cut $S_{\text{T}} < 350\,\text{GeV}$

Table 1. Control region definitions for the electron channel. The electron, tau, charge-product, $E_{\text{T}}^{\text{miss}}$, and jet multiplicity and p_{T} requirements are applied as described in section 5.

Separate control regions are defined for the $Z/\gamma^* \to ee$, $Z/\gamma^* \to \tau\tau$, W, and $t\bar{t}$ and single top-quark processes. They are defined by applying the electron, tau, charge-product, $E_{\text{T}}^{\text{miss}}$, and jet multiplicity and p_{T} requirements (as described in section 5, collectively referred to as the 'baseline' requirements), in addition to the cuts shown in table 1.

The control region for $Z/\gamma^* \to ee$ events is constructed by requiring an additional electron with $p_{\text{T}} > 20\,\text{GeV}$ and opposite-sign charge to the first one. The second electron is required to pass the same identification requirements as the first one.

The $Z/\gamma^* \to \tau\tau$ control region is defined by additionally requiring that the visible mass of the electron–tau pair is in the range $40 < m_{e\tau_{\text{had-vis}}} < 80\,\text{GeV}$ and that the transverse mass between the electron and the $E_{\text{T}}^{\text{miss}}$ is less than 60 GeV. A b-jet veto is also applied, using a looser working point (with a selection efficiency of 75%) compared to the working point used for signal selection. In this way contamination from top backgrounds is reduced.

The W+jets control region is constructed by applying in addition a b-jet veto (as described above), demanding that $60 < m_{\text{T}} < 120\,\text{GeV}$, and requiring that the event fail the $E_{\text{T}}^{\text{miss}}$ angular requirements cut (eq. 5.1).

The control region for top backgrounds is defined by additionally requiring that events pass the b-tagging requirements, have $m_{\tau_{\text{had-vis}}jet} > 90\,\text{GeV}$, fail the $E_{\text{T}}^{\text{miss}}$ angular requirements and have $S_{\text{T}} < 350\,\text{GeV}$, where S_{T} is defined as the scalar sum of the p_{T} of the charged light lepton, the tau, the two highest-p_{T} jets and the $E_{\text{T}}^{\text{miss}}$ in the event,

$$S_{\text{T}} = p_{\text{T}}^{e/\mu} + p_{\text{T}}^{\tau_{\text{had-vis}}} + p_{\text{T}}^{\text{jet1}} + p_{\text{T}}^{\text{jet2}} + E_{\text{T}}^{\text{miss}}. \tag{6.2}$$

Normalisation factors for V+jets and top backgrounds in the electron channel are calculated according to:

$$NF_{\text{BG}} = \frac{N^{\text{Data}} - N_{\text{OtherBG}}^{\text{MC}}}{N_{\text{BG}}^{\text{MC}}}, \tag{6.3}$$

where N^{Data} is the number of data events in the control region, $N_{\text{Other BG}}^{\text{MC}}$ is the expected number of events from other background processes, and $N_{\text{BG}}^{\text{MC}}$ is the contribution in the control region from the background process of interest.

To account for contamination from other background processes in the control regions, normalisation factors are found for each region in turn. At each stage the multi-jets contribution is re-estimated and all previously found normalisation factors are applied when estimating the contribution from other background processes.

The final background normalisation factors obtained are presented in table 3 and discussed together with the muon channel in section 6.3.

6.2 Muon channel

The multi-jets contribution to the control and signal regions are estimated in the muon channel from data using the ABCD method. Events are sorted into four regions using two observables assumed to be independent – the muon isolation and the sign of the charge product of the muon–tau pair. The regions are therefore defined as: isolated muon and opposite-sign muon–tau pair (A), isolated muon and same-sign muon–tau pair (B), as well as two regions with a non-isolated muon and opposite-sign or same-sign charge muon–tau pair (C and D respectively). Non-isolated muons are defined as those which fail at least one of the isolation requirements described in section 5. Contributions from other physics processes in regions B, C, and D are subtracted using the MC simulation. The shape of kinematic distributions for the multi-jets background is taken from region B, while the expected number of events in the signal region (A) is determined by taking the product of the number of events in region B with the ratio of the number of events in regions C and D (*i.e.* $N_A = N_B \times \frac{N_C}{N_D}$). The multi-jets contribution is estimated to be 15±4% of the total data yield in the signal region. The validity of the method is checked by varying both isolation cuts up and down from the nominal value of 0.2 by 0.05. Deviations in the ratio $\frac{N_C}{N_A}$ are included as an additional systematic uncertainty.

Control regions for V+jets and top-quark background processes are defined by applying the muon and tau requirements (including the charge-product requirement) as described in section 5. Additional selection criteria used for each control region are listed in table 2. Normalisation factors are calculated for each process by performing a maximum likelihood fit. The variable used for fitting is chosen in each case to provide good discrimination between the background process of interest, and other contributing physics processes in that control region. The contribution from multi-jets in each control region is estimated using the method described above, and this and contributions from other background processes are taken into account when performing the fits.

The control region for $Z/\gamma^* \rightarrow \mu\mu$ events is defined by requiring two oppositely charged muons and one hadronic tau decay. The second muon is required to pass the same requirements as the first. The normalisation factor for $Z/\gamma^* \rightarrow \mu\mu$ events in the signal region is then determined by fitting to the di-muon invariant mass distribution in the range $60 < m_{\mu\mu} < 120$ GeV.

The normalisation of $Z/\gamma^* \rightarrow \tau\tau$ events is obtained by selecting events with one muon, one hadronic tau decay and $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV. Additionally, events are required to fail the b-jet requirement. The fit is performed using the visible mass of the muon–tau pair in the range $45 < m_{\mu\tau_{\text{had-vis}}} < 80$ GeV.

The control region for W+jets events is defined by selecting events with one muon, one hadronic tau decay and $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV, and which fail the b-jet requirement. The normalisa-

$Z/\gamma^* \to \mu\mu$+jets	Require one extra muon $60 < m_{\mu\mu} < 120\,\text{GeV}$
$Z/\gamma^* \to \tau\tau$+jets	$E_\text{T}^\text{miss} > 20\,\text{GeV}$ b-jet veto $45 < m_{\mu\tau_\text{had-vis}} < 80\,\text{GeV}$
W+jets	$E_\text{T}^\text{miss} > 20\,\text{GeV}$ b-jet veto $70 < m_\text{T} < 100\,\text{GeV}$
Top-quark	$E_\text{T}^\text{miss} > 20\,\text{GeV}$ $p_\text{T}^\text{jet1} > 50\,\text{GeV}$ b-jet requirement $m_{\tau_\text{had-vis}-\text{jet}} > 90\,\text{GeV}$ Fail E_T^miss angular cut $S_\text{T} < 350\,\text{GeV}$

Table 2. Control region definitions for the muon channel. The muon, tau and charge-product requirements are also applied as described in section 5.

Background	Electron channel	Muon channel
$Z/\gamma^* \to \ell\ell$+jets	0.54 ± 0.09	0.52 ± 0.02
$Z/\gamma^* \to \tau\tau$+jets	0.99 ± 0.08	1.00 ± 0.02
W+jets	0.63 ± 0.07	0.50 ± 0.01
$t\bar{t}$ and single-top	0.92 ± 0.08	0.93 ± 0.09

Table 3. Summary of background normalisation factors obtained using the control regions specified in tables 1 and 2. The errors include both the statistical and systematic (discussed in section 7.3) uncertainties.

tion is determined by fitting to the transverse mass of the charged light lepton and the E_T^miss in the range $70 < m_\text{T} < 100\,\text{GeV}$.

The control region for $t\bar{t}$ and single-top processes is defined by applying all selection criteria, with the exception of the E_T^miss angular requirement which is reversed. In addition, the S_T of the event is required to be less than 350 GeV. The normalisation factor is obtained by fitting to the S_T distribution up to 350 GeV.

6.3 Background summary

The background normalisation factors in the signal region determined from data for both channels are presented in table 3.

Uncertainties for normalisation factors are larger in the electron channel than the muon channel due to the tighter requirements placed on the control region definitions, namely the additional requirements on E_T^miss and jets which are not applied for the muon channel (unless explicitly stated).

As a cross-check, the electron channel method (detailed in section 6.1) is applied to the muon channel and the signal region normalisation factors determined in this way are found to be

$NF_{Z/\gamma\to\mu\mu} = 0.59 \pm 0.09$, $NF_{Z/\gamma\to\tau\tau} = 1.03 \pm 0.08$, $NF_W = 0.50 \pm 0.08$ and $NF_{\text{top}} = 0.93 \pm 0.09$. These figures agree within uncertainties with the factors determined using the method described in section 6.2 and shown in table 3.

The largest background contribution comes from $t\bar{t}$ events, with approximately 55% of these coming from events containing a real hadronic tau decay (from the W decay) after all selection cuts are applied. Approximately 40% come from events where the W boson decays hadronically, and the tau candidate is faked by one of the jets. In the remaining $\sim 5\%$ of events, the reconstructed hadronic tau decay is faked in equal proportions by electrons or b-jets. Normalisation factors for background processes in which the hadronic tau decay is faked by a jet are observed to be significantly smaller than unity. This is a known effect, caused by jets being narrower in simulation than in data and therefore being more likely to fake a hadronic tau decay [47].

In both methods used for background estimation, the control regions for V+jets background processes either make no requirements on b-tagging, or veto events containing one or more b-jets. Simulation tests have validated the assumption that the normalisation factors obtained in regions that require b-jets are the same as those in regions where b-jets are not explicitly required, or are vetoed.

7 Systematic uncertainties

In simulated samples all sources of uncertainty are varied individually within their errors and the impact on the results of the analysis is determined. Background normalisation factors and multi-jets contributions are recalculated for each source of systematic uncertainty. In this way the nominal simulation (comprising the current best estimates for physics object reconstruction corrections) and systematic variations are treated coherently, and the uncertainties are propagated through the analysis. The S_{T} distribution is used to test for the existence of leptoquarks, since this variable provides the best discrimination between signal and background (discussed further in section 8). The shape of the S_{T} distribution remains unchanged within the total shape uncertainty (see further discussion in section 8) when applying all the uncertainties detailed below and systematic variations are therefore treated as nuisance parameters affecting the overall scale. The relative changes in acceptance for signal and background are quoted for each systematic variation.

7.1 Object-level uncertainties

There are several sources of systematic uncertainty associated with the reconstruction, identification, and energy scale of physics objects, which can potentially affect the estimated shapes of kinematic distributions and the normalisation of various processes.

Uncertainties associated with the efficiency of single-lepton triggers are typically less than 1% [48, 49] and a $\pm 0.5\%$ ($\pm 3.3\%$) variation in the signal acceptance is observed when varying the electron (muon) trigger efficiency by $\pm 1\sigma$. The effect on background processes is negligible.

Varying the electron energy scale by $\pm\, 1\sigma$ results in a $\pm 0.8\%$ change in background acceptance compared to the nominal selection and has a negligible impact on the signal yields. The electron reconstruction and identification efficiency uncertainties are combined in quadrature and yield an overall change of less than 1.5% for both signal and background.

Varying the muon momentum scale by 1σ results in a 0.2% change in signal yields compared to the nominal selection. The impact of muon resolution uncertainties on signal and background acceptance is found to be negligible. A $\pm 1\sigma$ variation of muon reconstruction efficiency results in a $\pm 0.3\%$ change in signal acceptance.

The uncertainty on the tau energy scale is typically around 3%, depending on the p_{T} and η of the hadronically decaying tau candidate [50]. Varying the energy scale by $\pm 1\sigma$ changes the acceptance for background and low-mass signal ($m_{\mathrm{LQ}} = 200$ GeV) by approximately 2%, decreasing to 1.2% for $m_{LQ} = 500$ GeV. The uncertainty on the tau identification efficiency is 4% for taus with $p_{\mathrm{T}} < 100$ GeV. This increases linearly with p_{T} up to a maximum of 8% for three-prong taus with $p_{\mathrm{T}} > 350$ GeV. Varying the tau identification efficiency by this uncertainty results in an overall acceptance change for signal of approximately 6% (for a leptoquark of mass 500 GeV). The variation of background yields is found to be approximately 1% – significantly smaller than the change in the signal yield, because the effect is largely absorbed in the normalisation factor defined in the control region.

The jet energy resolution uncertainty is approximately 10% and affects the event yields by approximately 2% [42]. The jet energy scale uncertainty depends on p_{T} and η, and varies between 2% and 5%. It is modelled by 14 separate nuisance parameters, each of which is varied by $\pm 1\sigma$ independently from the others. The use of control regions does not significantly reduce the variations of the different background yields, and changes in acceptance of signal and background of up to $\pm 2\%$ are observed.

The uncertainty on the b-jet identification efficiency for the algorithm and operating point used in this analysis ranges from 5% to 18% depending on jet kinematics. The b-tagging efficiency and probability that a light jet is identified as a b-jet are anti-correlated and thus varied accordingly. A $\pm 1\sigma$ variation results in a $\pm 9\%$ ($\pm 15\%$) change in signal acceptance for leptoquarks with a mass of 200 (500) GeV. The use of control regions reduces the background yield variation to $\pm 3\%$ in both channels.

All energy scale and resolution corrections for electron, muon, tau and jet candidates are propagated consistently to the $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation. Additional uncertainties related to the energy scale and pile-up dependence of calorimeter clusters not associated with any high-p_{T} objects (electrons, taus, jets) are also considered in the $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation. These sources are varied independently within their uncertainties and the impact on signal and background yields is found to be negligible.

The uncertainty on the integrated luminosity for data taken during 2011 is $\pm 3.7\%$ as determined in ref. [51].

7.2 Theoretical uncertainties

QCD renormalisation and factorisation scales are varied by a factor of two to estimate the impact on the signal production cross-section. The variation is found to be $\pm 12\%$. A re-weighting technique is used to assess the sensitivity of the signal acceptance to the choice of parton distribution functions and the resulting uncertainty is estimated to be $\pm 12\%$. Varying the multi-parton interactions within experimental bounds has a negligible effect on the signal process.

The effect of the choice of event generator for the top-quark background is estimated by using PowHeg 1.0 [52, 53] (instead of MC@NLO 4.01) to model the hard process. The parton shower and hadronisation models, and the underlying event model (respectively HERWIG 6.510

and JIMMY 4.31 in the nominal sample) are replaced with those from PYTHIA 6.425. In addition, the CTEQ6L1 PDF set is used instead of CT10 which is used in the nominal $t\bar{t}$ sample. The total background yield is found to differ by 1.5% with respect to the nominal samples.

The uncertainty on the signal and the top-quark background due to initial-state radiation (ISR) and final-state radiation (FSR) is evaluated using the AcerMC generator interfaced to the PYTHIA 6.425 shower model with the parameters controlling ISR and FSR varied in a range consistent with experimental data [54]. The event yields are found to agree with nominal values within statistical uncertainties.

MC@NLO events with top-quark masses of 170 GeV and 175 GeV are used to assess the top-quark mass dependence, which is added in quadrature to the uncertainty related to the choice of event generator and PDF set. The resulting uncertainty (2.8%) is treated as a nuisance parameter affecting the background yield and is assumed to be fully correlated between the electron and muon channels.

Other background processes taken from simulation (W, Z/γ^*, di-boson) account for less than 20% of the total background. The W and Z/γ^* samples are simulated with the matching parameter (described in ref. [23]) set to 20 GeV. Event yields are found to agree with the nominal values within statistical uncertainties when this parameter is changed to 30 GeV.

The W and Z control regions are defined with either the application of a b-jet veto, or with no b-tagging requirements. The uncertainties on the production cross-sections of W or Z bosons in association with one or two b-jets are estimated using MCFM [55, 56]. The QCD renormalisation and factorisation scales are varied independently by a factor of two, and different PDF sets are considered. The total uncertainty is found to be 30% and the uncertainties on the normalisation factors for W and Z background processes are increased by this amount (*i.e.* to 2%).

7.3 Background uncertainties

For each channel, the systematic uncertainties on the normalisation factors in table 3 are evaluated by calculating the normalisation factor for a given background when normalisation factors for all other sources of background are varied up or down by their statistical error. The systematic uncertainty on the multi-jets background is evaluated by varying the normalisation factors of other backgrounds by $\pm 1\sigma$. The methods used to estimate the contributions from multi-jets processes are validated by modifying the control regions used, and in the case of the electron channel the variable used for fitting (see sections 6.1 and 6.2). Deviations from the nominal value are included as additional sources of systematic uncertainty.

Conservatively, all background normalisation factors are assumed to be fully correlated and the impact on the total background yield is $^{+16}_{-19}$% for the electron channel and ± 9% for the muon channel. The background estimation method used in the muon channel allows a more accurate determination of the normalisation factors compared to the event-counting method employed in the electron channel, and the normalisation factor uncertainty for the muon channel is correspondingly smaller than in the electron channel. For both channels, the limited number of data events in the top-quark control region is the main source of uncertainty on the top-quark normalisation factor, which in turn has the largest impact on the total yield uncertainty. Due to the tighter requirements on control regions for the electron channel background estimation, this method also suffers from a

	Background	LQ(m=500 GeV)
Luminosity	–	3.7
Theory	2.8	17
Normalisation factors	$+16/-19$	–
Trigger efficiency	< 0.2	0.5
Electron energy scale	0.8	0.4
Electron reconstruction and identification efficiency	1.5	1.5
Tau energy scale	2.6	1.2
Tau ID efficiency	1.2	5.7
Jet energy scale (nuisance parameter dependent)	$0.1-2.4$	< 0.2
Jet energy resolution	2.5	0.3
b-tagging efficiency	2.7	15

Table 4. The sources of systematic uncertainty in the electron channel and the relative change (in %) in the background and signal yields. The theory term includes uncertainties related to initial and final state radiation, PDFs, and multi-parton interactions.

limited number of events in data and simulation when estimating normalisation factors for V+jets background processes.

7.4 Summary of systematic uncertainties

The shape of the S_T distribution remains unchanged within statistical uncertainties when applying all the uncertainties mentioned above. The uncertainties for the electron and muon channels are summarised in tables 4 and 5 respectively. Uncertainties related to the background normalisation factors have the largest impact on the total background yield, while for the signal yield the largest sources of systematic uncertainty are due to theoretical uncertainties (comprising uncertainties related to PDFs, multi-parton interactions, and initial- and final-state radiation) and from b-jet identification.

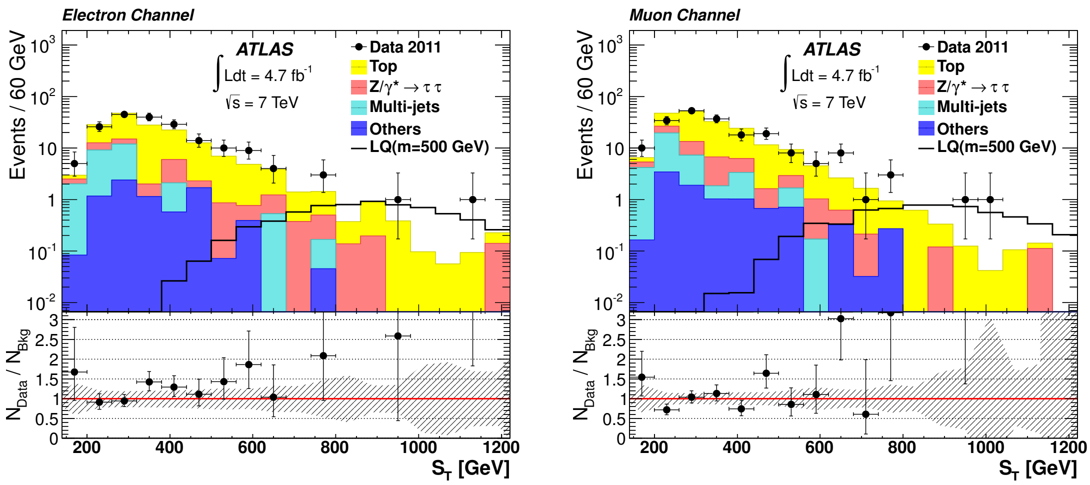
8 Results

The observed yields in data, as well as expected yields for the background processes and the signal for several leptoquark masses, after all selection cuts are applied, are shown in table 6. The S_T distribution is used to test for the existence of leptoquarks. Distributions for both channels are shown in figure 2.

At very high S_T, the statistical uncertainties on the various background processes become very poor due to the limited number of MC and (in the case of the multi-jets) data events in the signal region. The sum of the background processes is fitted in the region 350 GeV $< S_T <$ 2000 GeV to an exponential function using a maximum likelihood fit. In this way the distribution is smoothed and a background expectation is provided throughout this S_T region. The fit parameters are varied within their uncertainties to obtain a shape uncertainty. The shape of the S_T distribution is checked for all systematic variations and the variation is found to be significantly smaller than the fit uncertainty in almost all cases. The only exception is for the variation in choice of generator used to model the

	Background	LQ(m=500 GeV)
Luminosity	–	3.7
Theory	2.8	17
Normalisation factors	9	–
Trigger efficiency	< 0.2	3.3
Muon momentum scale	0.1	0.2
Muon reconstruction efficiency	< 0.1	0.3
Tau energy scale	0.6	1.2
Tau ID efficiency	0.8	5.7
Jet energy scale (nuisance parameter dependent)	$0.1 - 2.0$	< 0.2
Jet energy resolution	1.5	0.5
b-tagging efficiency	2.7	15

Table 5. The sources of systematic uncertainty in the muon channel and the relative change (in %) in the background and signal yields. The theory term includes uncertainties related to initial- and final-state radiation, PDFs, and multi-parton interactions.



(a) Electron Channel (b) Muon Channel

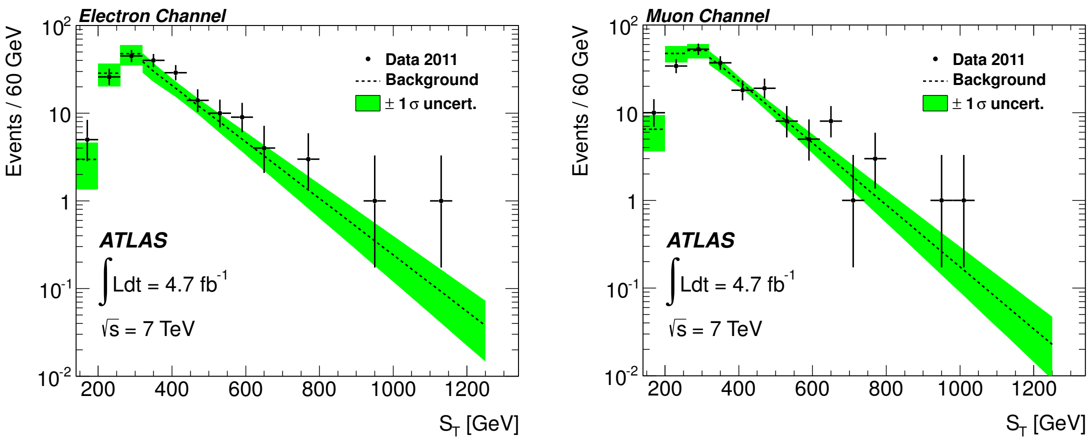
Figure 2. Data and MC comparisons of the S_T variable after applying all cuts in the (a) electron and (b) muon channels. The ratio $N_{\text{Data}}/N_{\text{Background}}$ is also shown, where the red line at unity and hashed band represent the Standard Model expectation and associated statistical and systematic uncertainties. No events with $S_T > 1.2$ TeV were observed in data.

$t\bar{t}$ background process, where the central value lies outside the nominal range (although covers the nominal value within its own statistical uncertainty). Conservatively, the difference between the nominal shape and the alternative shape is taken as a systematic uncertainty and added to the shape uncertainty determined from the nominal fit. The total shape uncertainty is treated as an additional nuisance parameter. Comparisons of the fitted distributions to data are shown in figure 3. Below S_T = 350 GeV the background shape is taken from the histogram.

Two alternative models are built to describe background-only and signal+background hypothe-

	Electron channel	Muon channel
$Z/\gamma^* \to \ell\ell$+jets	2.1 ± 0.9	1.1 ± 0.5
$Z/\gamma^* \to \tau\tau$+jets	21.4 ± 2.2	26.6 ± 2.2
W+jets	5.2 ± 1.2	7.1 ± 1.5
$t\bar{t}$ and single-top	119 ± 11	130 ± 11
Di-boson	1.1 ± 0.2	1.3 ± 0.2
Multi-jets	$20\,^{+13}_{-16}$	29 ± 8
Total background	$169\,^{+27}_{-32}$	195 ± 18
Data	187	198
$m_{\rm LQ} = 200\,\text{GeV}$	711 ± 22	839 ± 25
$m_{\rm LQ} = 300\,\text{GeV}$	131 ± 3	136 ± 3
$m_{\rm LQ} = 400\,\text{GeV}$	28.7 ± 0.6	28.6 ± 0.6
$m_{\rm LQ} = 500\,\text{GeV}$	7.53 ± 0.15	6.84 ± 0.15
$m_{\rm LQ} = 600\,\text{GeV}$	2.1 ± 0.04	1.87 ± 0.04

Table 6. Yields for data, background and several leptoquark masses in both channels after all cuts are applied. The errors include statistical uncertainties and systematic uncertainties on the background normalisation.

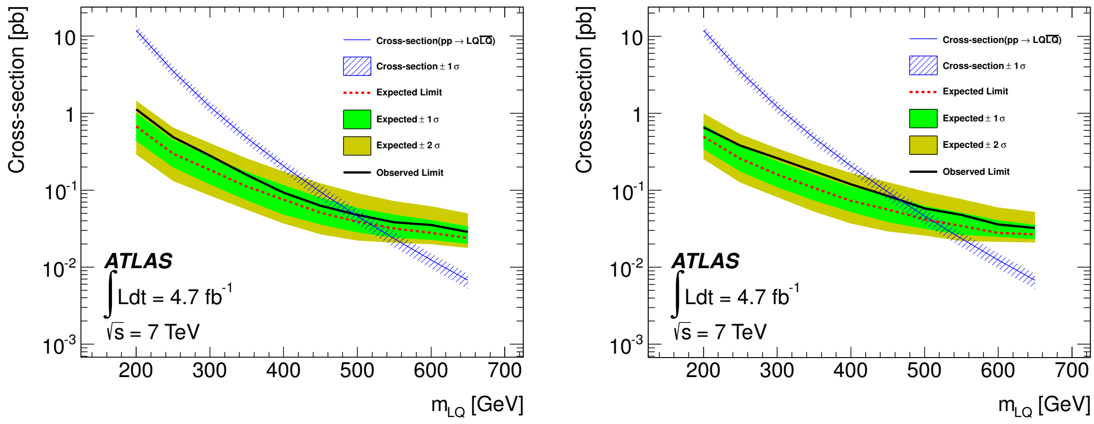


(a) Electron Channel

(b) Muon Channel

Figure 3. Comparison of the fitted $S_{\rm T}$ background shape to data in the (a) electron and (b) muon channels. The $\pm 1\sigma$ band represents the uncertainty on the shape of the $S_{\rm T}$ distribution, obtained by varying the fit parameters within their uncertainties and comparing with the shape of the $S_{\rm T}$ distribution obtained for each systematic variation. No events with $S_{\rm T} > 1.2\,\text{TeV}$ were observed in data.

ses. The signal component is calculated separately for each leptoquark mass, thus taking the mass dependence of the $S_{\rm T}$ distribution into account. For each mass hypothesis, a single 'signal strength' parameter (μ) multiplies the expected signal in each bin, where $\mu = 0$ corresponds to the absence of a signal and $\mu = 1$ corresponds to the presence of a signal with nominal strength. The model describes the expected number of signal (s_i) and background (b_i) events in each bin using a Poisson distribution. All systematic uncertainties described in section 7 are assumed to be distributed



(a) Electron Channel

(b) Muon Channel

Figure 4. The expected (dashed) and observed (solid) 95% credibility upper limits on the cross-section as a function of leptoquark mass, in the (a) electron and (b) muon channels. The 1(2) σ error bands on the expected limit represent all sources of systematic and statistical uncertainty. The expected NLO production cross-section for third generation scalar leptoquarks and its corresponding theoretical uncertainty (hashed band) are also included.

according to a Gaussian function and implemented as multiplicative constraint terms. The correlation of the systematic uncertainties across channels is taken into account. Statistical uncertainties in signal and background histogram bins are also treated as nuisance parameters and assumed to be distributed according to a Poisson function. The statistical analysis of the data employs a binned likelihood function $\mathscr{L}(\mu,\theta)$. The likelihood in each channel is a product over bins in the S_{T} distributions defined as

$$\mathscr{L}(\mu,\theta) = \prod_{i=\mathrm{bin}} \mathrm{Poisson}(N_i|\mu s_i + b_i), \tag{8.1}$$

where s_i and b_i are the expected number of signal and background events in bin i respectively, and N_i is the observed number of events. Both s_i and b_i depend on nuisance parameters $\boldsymbol{\theta}$. Pseudo-experiments are generated according to background-only and signal+background models to obtain distributions of the test statistic, $\log(\mathscr{L}(\mu,\theta)/\mathscr{L}(0,\theta))$. The CLs method [57] is used to calculate the p-values[3]. The signal strength parameter is varied iteratively to find the 95% confidence level.

The resulting cross-section limits as a function of leptoquark mass are calculated. It is assumed that $BR(LQ \to \tau b) = 1.0$. The 95% CL upper bounds on the NLO cross-section for scalar leptoquark pair production as a function of mass are shown for individual channels in figures 4(a) and 4(b). Error bands for the expected limits include all sources of uncertainty. Third generation scalar leptoquarks are observed (expected) to be excluded at 95% confidence level for masses below 498 (523) GeV and 473 (514) GeV in the electron and muon channels respectively by comparing the limits with theoretical predictions of cross-section versus m_{LQ}. The limit is taken using the nominal theoretical calculation for the leptoquark production cross-section at NLO. The uncertainty

[3]The p-value is the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true

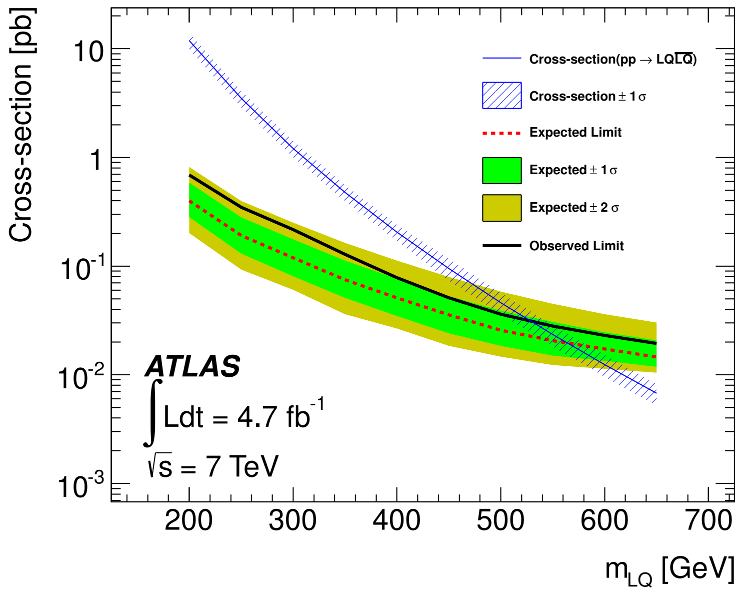


Figure 5. The expected (dashed) and observed (solid) 95% credibility upper limits on the cross-section as a function of leptoquark mass, for the combined result. The 1(2) σ error bands on the expected limit represent all sources of systematic and statistical uncertainty. The expected NLO production cross-section for third generation scalar leptoquarks and its corresponding theoretical uncertainty (hashed band) are also included.

on the cross-section is also shown. The result when both channels are combined is shown in figure 5. The likelihood for the combined model is defined as the product of likelihood terms for each channel. The data are found to be consistent with the background-only hypothesis and third generation scalar leptoquark production is excluded at 95% confidence level for leptoquark masses up to 534 GeV (the expected limit is 569 GeV).

9 Conclusions

A search for pair production of third generation scalar leptoquarks has been performed with the ATLAS detector at the LHC, using a data sample corresponding to an integrated luminosity of 4.7 fb^{-1}. No significant excess over the SM background expectation is observed in the data. The assumption is made that $BR(LQ \to \tau b) = 1.0$ and third generation scalar leptoquarks with masses up to $m_{\text{LQ}} < 534$ GeV are excluded at 95% CL. The cross-section for leptoquark pair-production increases with centre-of-mass collision energy. At $\sqrt{s} = 8$ TeV the production rate for leptoquarks with $m_{LQ} = 700$ GeV is enhanced by a factor of two, providing scope for setting stronger limits using data from the 2012 LHC run. Meanwhile, this result is the most stringent limit arising from direct searches for third generation scalar leptoquarks to-date.

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