PROCEEDINGS OF SCIENCE

The LHC as Lepton–Proton Collider: Search for the Resonant Production of Leptoquarks

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Searches for leptoquarks are a key component of the Large Hadron Collider program probing physics beyond the Standard Model. These hypothetical particles couple to a lepton and a quark and are predicted by many extensions of the Standard Model such as Grand Unified Theories. The existing leptoquark searches at the Large Hadron Collider currently consider mostly production modes via quark and/or gluon interactions. However, the small but non-zero lepton content of the proton allows to also study the significantly less explored *s*-channel, resonant leptoquark production. This production mode gives rise to lepton-plus-jet signatures. Thus, leptoquarks would emerge as distinctive peaks over the smoothly falling Standard Model background in the invariant mass spectrum of the lepton-plus-jet system. The poster will give an overview of the first ATLAS analysis searching for this new process in four separate final states involving light leptons plus either jets originating from light quarks or from bottom quarks. It will especially focus on the details of the search for the electron-plus-jet signature. The general analysis strategy and the results of this search will be discussed. Probing the resonant, *s*-channel production shows competitive and complementary sensitivity to existing searches for e.g. the pair production of leptoquarks, particularly for leptoquarks with a high coupling to fermions. To maximise the sensitivity reach, the full ATLAS Run 2 dataset, collected between 2015 and 2018, is combined with the partial Run 3 dataset collected in 2022 and 2023.

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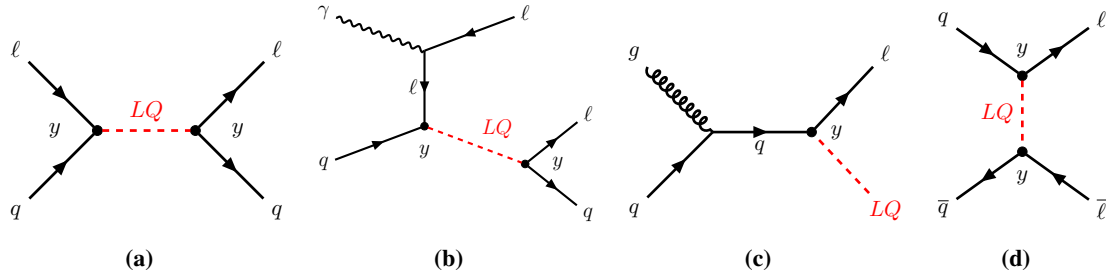


Figure 1: Example Feynman diagrams for the (a) leading-order and (b) next-to-leading-order resonant as well as the (c) single and (d) Drell–Yan LQ production modes. The symbol y marks interactions mediated by a LQ Yukawa coupling to quarks and leptons. All shown LQ production modes are considered for the interpretation of the analysis results. Diagrams and caption adapted from Ref. [1].

1. Introduction

The Standard Model of particle physics (SM) shows intriguing similarities between the quark and lepton sectors that hint towards a larger symmetry beyond the SM. Such a symmetry connecting the two sectors gives rise to new particles called Leptoquarks (LQs). LQs are colour-charged, vector or scalar bosons with a fractional electric charge that decay into a lepton-quark pair. The coupling pattern to the different lepton and quark flavours is not known a priori and depends on the particular LQ model considered.

This proceedings summarises a recently published search for LQs [1] that targets the s-channel, resonant production mode of LQs. The analysis utilises data taken at the ATLAS experiment [2, 3]. The full Large Hadron Collider (LHC) Run 2 dataset with an integrated luminosity of 140 fb^{-1} of proton–proton collision data at a centre-of-mass energy of 13 TeV is used. In addition, to maximise the sensitivity, the first two years of the Run 3 dataset with 55 fb^{-1} of proton–proton collision data at 13.6 TeV is considered in this search. The resonant production of LQs, mediated via an s-channel, shown in figure 1 (a) and (b), is a novel production mechanism in the context of LHC searches as it involves the lepton content of the proton. Precise calculations of the lepton parton distribution function (PDF) of the proton [4][1] suggest that this production mode can yield competitive sensitivity with respect to previously explored LQ search strategies at the LHC [5].

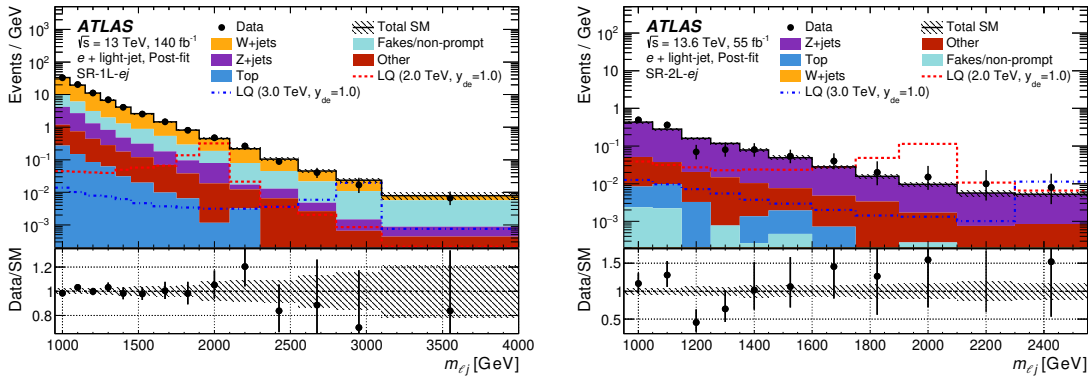
The search presented utilises a simple scalar LQ benchmark model, denoted as $\tilde{S}_1$. This particular type of LQ has an electric charge of $4/3e$ and exclusively decays into a charged lepton and a down-type quark. Its free parameters are the LQ mass and the coupling strength to different flavour combinations. The LQ production and decay is simulated using a state-of-the art event generation setup with next-to-leading order (NLO) precision [6]. Four different signal scenarios are considered where each corresponds to setting all coupling parameters of the LQ to zero except for one targeted flavour combination: y_{de}, $y_{s\mu}$, y_{be} and $y_{b\mu}$. Accordingly, the search defines four channels targeting mutually exclusive detector signatures: e + light-jet, μ + light-jet, e + b-jet and μ + b-jet. Here, light-jet describes a jet that is not tagged to contain a b-hadron decay. Each of the channels target both the lepton-plus-jet signature – as evident from Figure 1 (a) – and the 2-lepton-plus-jet signature – as

[1] The calculation in Ref. [4] shows a lepton-lepton parton luminosity suppressed by a factor of $8 \cdot 10^3$ compared to the lepton-up-quark luminosity. This suggests a suppression factor on the order of 10^4 for lepton PDFs compared to those of quarks.

evident from Figure 1 (b) – of the resonant LQ production. Although diagrams with an additional lepton as in Figure 1 (b) are at NLO, their contribution is enhanced due to the dependence on the photon PDF instead of the lepton PDF. Hence, the 2-lepton final state is also relevant to the analysis. Due to the consideration of this additional signature, the analysis is sensitive to further LQ production modes, the single resonant, see Figure 1 (c), and the non-resonant Drell-Yan production, see Figure 1 (d). Correspondingly, the contribution of these additional diagrams [7] is considered in the interpretation of the results.
This proceeding focuses on the analysis in the e + light-jet channel, i.e. the search for the $\tilde{S}_1$ of mass m decaying into an electron and a down quark with coupling y_{de}.

2. Analysis Strategy

The analysis is based on individually optimised, lepton-enriched signal regions: single-lepton (SR-1L) and dilepton (SR-2L) regions. In each, the invariant mass of the leading transverse momentum (p_{T}) lepton–jet system, $m_{\ell j}$, is used as the main discriminating observable between the LQ signal and any SM background. The $m_{\ell j}$ distribution of the signal displays a characteristic peak around the mass of the LQ considered while the background shows a continuously falling distribution. In order to be sensitive to these peaks, both the SR-1L and the SR-2L are binned in $m_{\ell j}$ where the bin width is increased with $m_{\ell j}$ to take the worsening detector resolution into account. The last $m_{\ell j}$ bin is defined inclusive so that at least one SM background event is expected per bin. The post-fit $m_{\ell j}$ distributions in the SR-1L and SR-2L are shown in Figure 2.



(a) **(b)**

Figure 2: Data (dots) and post-fit SM distribution (histograms) of $m_{\ell j}$ in (a) SR-1L-ej (Run 2) and (b) SR-2L-ej (Run 3) of the e + light-jet channel obtained by a CR+SR background-only fit. The lower panel shows the ratio of observed data to the total post-fit SM prediction. The last bin includes the overflow. Uncertainties in the background estimates include both the statistical and systematic uncertainties, with correlations between uncertainties taken into account. The dashed lines show the predicted yields for two benchmark signal models corresponding to $\tilde{S}_1(m, y_{de}) = (2.0\ \mathrm{TeV}, 1.0)$ and $\tilde{S}_1(m, y_{de}) = (3.0\ \mathrm{TeV}, 1.0)$, respectively. Figures and caption adapted from Ref. [1].

3. Background Estimation

The main SM backgrounds in the SR-1L are W boson production in association with jets (W+jets) and processes where the reconstructed electron is not an actual, prompt electron but misidentified from different detector signatures such as jets, fake or non-prompt (FNP). In the SR-2L, the background is dominated by Z boson production in association with jets (Z+jets). W+jets and Z+jets are estimated from MC simulations that are normalised to data in dedicated control regions (CRs). The resulting *normalisation factors* (NFs) derived for both processes are extrapolated into the SRs after being validated in kinematically close validation regions (VRs). The FNP background is estimated in a data-driven way using the *fake factor* (FF) technique. In dedicated estimation regions enriched in FNP processes, fake factors are measured to estimate the rate at which detector signatures like jets are mistakenly reconstructed as electrons.
Other background processes, including those from top-quark interactions, are estimated from MC simulation.

4. Results

By fitting the W+jets and Z+jets NFs – taking into account the systematic uncertainties – in the CRs and SRs, one arrives at the post-fit expected background yields. The observed data in the SRs agrees with the SM prediction within the post-fit uncertainties, as can be seen in Figure 2. Therefore, exclusion limits can be placed on the signal parameter space of the LQ model probed in the analysis. The exclusion limits on the $\tilde{S}_1$ model coupling to electrons and down-quarks from the e + light-jet channel analysis can be seen in Figure 3. The plot shows the previously strongest limit on the first-generation scalar LQ mass at 1.8 TeV from a pair production search by the ATLAS collaboration [8]. The LQ pair production is largely insensitive to the coupling parameter, so corresponding searches are sensitive up to a particular LQ mass for all coupling strengths. Meanwhile the resonant production cross section scales quadratically with the coupling strength [10], increasing the sensitivity of the presented search at higher y_{de}. The analysis shown improves on the previous limit for LQ couplings $y_{de} \gtrsim 0.25$ and excludes the minimal $\tilde{S}_1$ model considered with masses below 3.4 TeV at $y_{de} = 1$.
The analysis is predominantly constrained by statistical uncertainties due to the low event yield in the SR bins at large $m_{\ell j}$. The uncertainties derived on the FNP estimate make up the largest systematic in the SR-1L. In both SRs, significant contributions come from the jet energy scale and resolution as well as QCD scale variations and electroweak corrections on the W+jets and Z+jets backgrounds.
While this document reports mainly on the e + light-jet channel, Ref. [1] additionally analysed the μ + light-jet, e + b-jet and μ + b-jet channels. In these, masses below 4.3 TeV are excluded for $y_{s\mu} = 3.5$, below 3.1 TeV for $y_{be} = 3.5$ and below 2.8 TeV for $y_{b\mu} = 3.5$.

5. Conclusion

This proceeding presented the first ATLAS search for the resonant production of LQs, probing a process based on the scarce lepton content of the proton. These proceedings focused on the

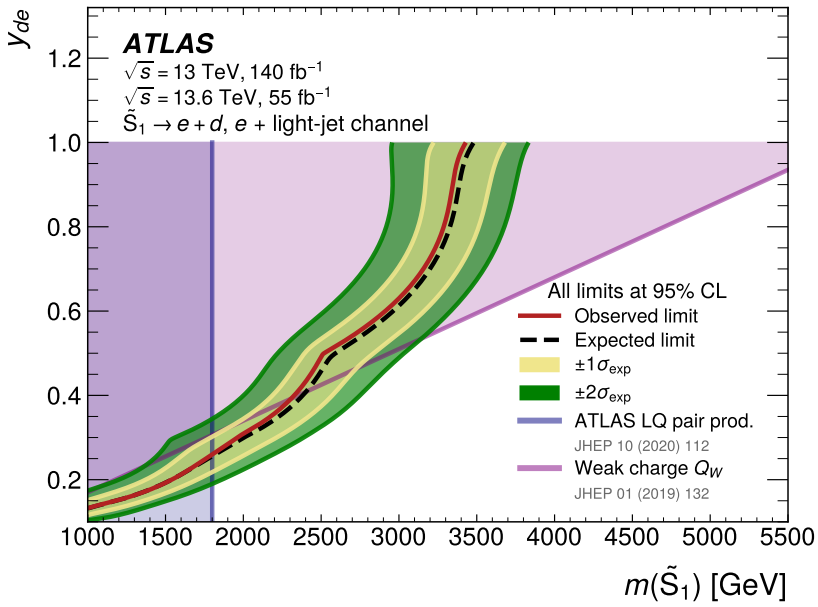


Figure 3: Exclusion limits for minimal models of $\tilde{S}_1$ production with only y_{de} being non-zero obtained from a simultaneous fit to SR-1L and SR-2L of the e + light-jet channel combining Run-2 and Run-3 data. All limits are computed at 95% CL and the observed (red solid lines) and expected (black dashed lines) exclusion limits are shown in the $m(\tilde{S}_1) - y_{de}$ plane. The observed exclusion should be interpreted as the region above the red line. The yellow inner (green outer) shaded band around the expected limits corresponds to the $\pm 1\,\sigma$ ($\pm 2\,\sigma$) variations of the expected limit, accounting for all uncertainties. The observed limit obtained from ATLAS searches for LQ pair production is also shown as dark blue line [8]. Constraints from weak charge measurements of protons and nuclei on y_{de} couplings derived by Ref. [9] are shown as light magenta line. Figures and caption taken from Ref. [1].

e + light-jet channel of the analysis published in Ref. [1]. It is one of the first ATLAS new physics searches making use of both the full LHC Run 2 and a partial Run 3 dataset to maximise its sensitivity. The LHC Run 3 is still ongoing with the latest years of data taking breaking records in recorded luminosity, making future searches increasingly sensitive to potential new physics phenomena like the LQ.

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