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Searches for Leptoquarks with the ATLAS detector

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Leptoquarks are hypothetical particles that appear in many theoretical extensions of the Standard Model. They are predicted to mediate interactions between quarks and leptons, bridging the gap between the two fundamental classes of particles. Other theoretical models such as supersymmetry, introduce a link between bosons and fermions, predicting also additional particles such as stops. Both extensions offer a compelling avenue for exploring new physics beyond the Standard Model and have the potential to explain a variety of experimental observations. Decays of supersymmetric particles and leptoquarks decays to neutrinos lead to a characteristic shared signature of missing energy, allowing for an easy interpretation of searches in both models. The ATLAS experiment at the Large Hadron Collider is conducting a comprehensive program of searches for leptoquarks and supersymmetric particles, targeting interactions with particles from all three generations. This talk will present the most recent results from the ATLAS collaboration's search for leptoquarks and stops in various experimental signatures, including flavour-diagonal and cross-generational final states.

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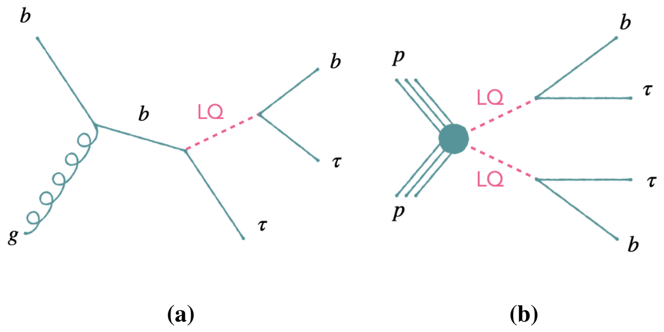
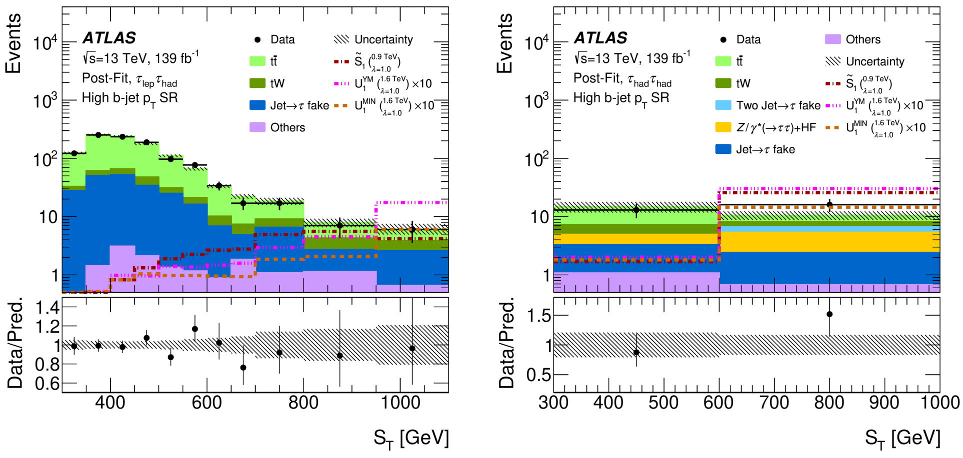


Figure 1: Feynman diagrams of the leptoquark (LQ) production in (a) a single and (b) a pair of third-generation leptoquarks decaying into a bottom quark and a τ lepton.

1. Introduction

The similarities in the Standard Model (SM) between the lepton and quark sectors give rise to the possibility of a new underlying symmetry in particle physics. Leptoquarks (LQs) could form a connection between the lepton and the quark sector, as those hypothetical particles couple to both leptons and quarks. LQs can be scalar or vector bosons. LQs have non-zero baryon and lepton numbers and a fractional electric charge. Several extensions to the SM that try to unify the fundamental interactions predict the existence of LQs, such as technicolour, composite models, and grand unification. Furthermore, LQs may explain hints of lepton universality violation in flavour experiments, such as those recently reported by BaBar [1], Belle [2], and LHCb [3, 4] in B-meson decays. The 4.2σ deviation from the SM in the muon anomalous magnetic moment measurement [5] could be caused by LQ contributions to the magnetic moment [6], although significantly reduced by lattice QCD calculations [7].

These proceedings summarise two recent searches using the full LHC Run2 dataset with an integrated luminosity of 139 fb^{-1} pp collision data at a centre of mass energy of 13 TeV for LQs using the ATLAS detector [8]. The first search for singly-produced LQs [9] is outlined in section 2, and the second search for pair-produced LQs [10] and is outlined in section 3. Example Feynman diagrams for both production modes are shown in Figure 1. Both searches consider third-generation LQs that couple solely to third-generation quarks and leptons. The LQs decay into a bottom quark and a τ lepton. The bottom quarks are reconstructed in the ATLAS detector as flavour (b) tagged jets. The τ leptons can decay leptonically via a W boson into a muon or electron and two neutrinos or hadronically into a neutrino and a set of visible decay products, also referred to as τ_{had}. The visible decay products, referred to as $\tau_{\text{had-vis}}$, comprise one or three charged pions and up to two neutral pions. The $\tau_{\text{had-vis}}$ reconstruction is seeded by jets, and reconstructed pion tracks are matched to the $\tau_{\text{had-vis}}$ object. Multivariate discriminant techniques are used in the track-matching process, and a recurring neural network separates $\tau_{\text{had-vis}}$ objects from jets initiated by other quarks or gluons using information from the reconstructed tracks and calorimeter energy clusters. There are two analysis channels defined by both searches: $\tau_{\text{lep}}\tau_{\text{had}}$ if one of the τ leptons decays leptonically and the other hadronically, and $\tau_{\text{had}}\tau_{\text{had}}$ if both τ leptons in the event decay hadronically. No signal is observed, and limits are set on the cross-section times branching fraction of the LQ decay into a



(a) **(b)**

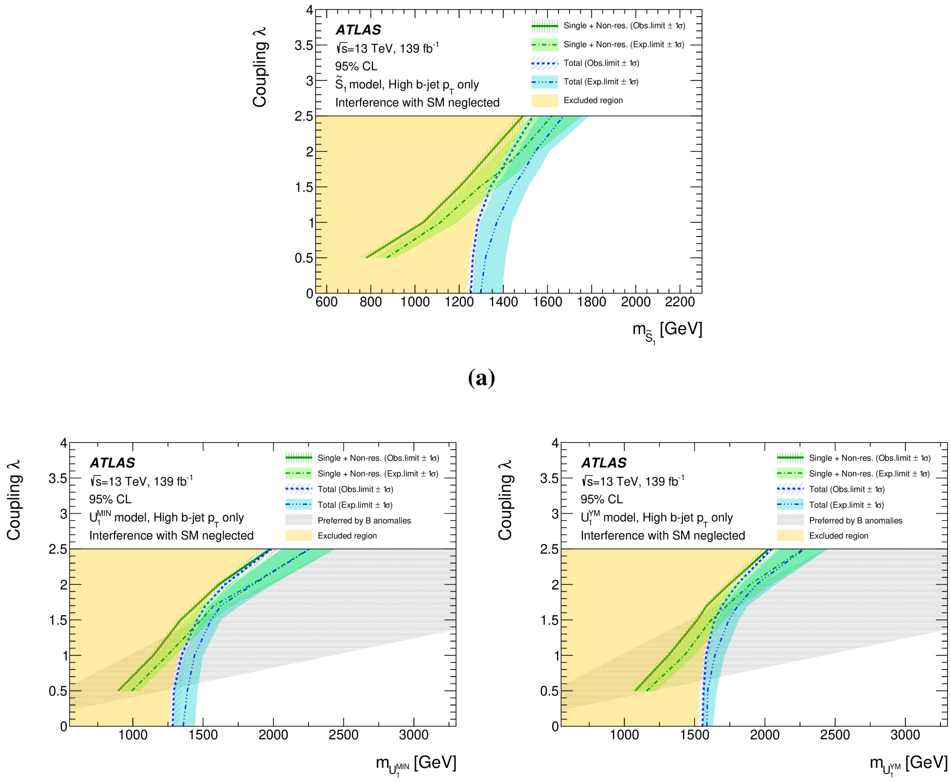
Figure 2: Post-fit distributions of the discriminating variable S_T in the high b-jet p_T signal region for the (a) $\tau_{\text{lep}}\tau_{\text{had}}$ and (b) $\tau_{\text{had}}\tau_{\text{had}}$ channels. The two channels are fit simultaneously, considering the background-only hypothesis. The lower panels show the ratio of the data to the predictions, where the uncertainty band includes both statistical and systematic post-fit errors. Entries with values above the plotted S_T range are included in the last bin of each distribution. For illustrative purposes, the dotted lines show the expectation from the three singly-produced scalar and vector LQ signals. Figures and caption taken from ref. [9].

bottom quark and a τ lepton. The search for singly-produced LQs sets additional exclusion limits in the LQ coupling vs mass ($\lambda - m_{\text{LQ}}$) plane, as shown in this proceedings.

2. Search for singly-produced leptoquarks decaying into the $b\tau$ final state

The event selection for the $\tau_{\text{lep}}\tau_{\text{had}}$ and the $\tau_{\text{had}}\tau_{\text{had}}$ channels requires at least one b-tagged jet, one lepton, and a $\tau_{\text{had-vis}}$ object or two $\tau_{\text{had-vis}}$ objects, respectively. The leading b-jet p_T is required to be above 200 GeV. The variable used in the final maximum likelihood fit to discriminate between the LQ signal and background is the sum of the transverse momenta S_T of all reconstructed LQ decay products. Those channel-dependent decay products are the reconstructed $\tau_{\text{had-vis}}$ object, the muon or electron, and the b-tagged jet in the event. The post-fit distributions for the discriminating variable S_T for both analysis channels $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ are shown in Figure 2. Dominating backgrounds in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel arise from $t\bar{t}$ and single top (tW) processes that involve t quarks that can produce τ leptons or jets that can be misidentified as τ_{had}. The Jet$\rightarrow\tau$ fake background describes events where a lepton is produced in association with a jet misidentified as τ_{had}. Backgrounds such as $t\bar{t}$, tW and $Z/\gamma^* \rightarrow \tau_{\text{had}}\tau_{\text{had}}$ dominate in the $\tau_{\text{had}}\tau_{\text{had}}$ channel. Current simulations of the $t\bar{t}$ process overestimate the upper tail of the top-quark p_T spectrum. Those inaccuracies are corrected using a scale factor derived from a dedicated control region.

Figure 3 shows the two-dimensional exclusion limits in the LQ coupling to b quarks (λ) vs mass plane for the scalar, Minimal coupling, and Yang-Mills LQ model. Those exclusion limits include the single LQ production, the non-resonant LQ production, and the LQ pair production.



(a)

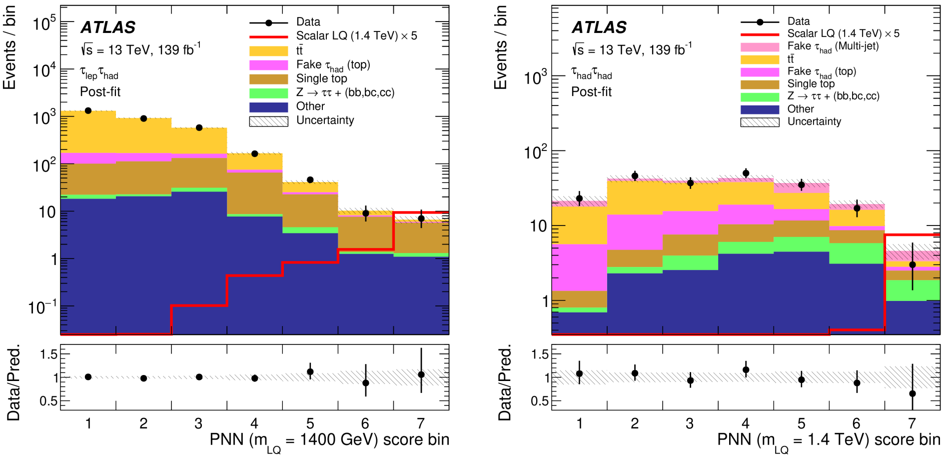
(b) **(c)**

Figure 3: The two-dimensional 95% CL exclusion limits in the $\lambda - m_{\mathrm{LQ}}$ plane for singly plus non-resonant produced LQ (green lines) and for the sum, referred to as total, of single plus nun-resonant plus pair LQ production (blue lines) for (a) scalar and (b, c) vector LQs in the Minimal coupling and Yang-Mills model. Regions to the left on the lines are excluded. The dotted areas in (b, c) show the preferred regions where the chosen LQ model can explain observed B anomalies. Figures and modified caption taken from ref. [9].

The observed limits obtained are less stringent than the expected limits, mainly driven by the higher data yields relative to the predicted yields in the highest S_T bin for the $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel. This is the first ATLAS result for the search of singly-produced LQs in the $b\tau\tau$ final state.

3. Search for pair-produced leptoquarks decaying into the $b\tau$ final state

This search targets LQs that couple to the third-generation of quarks and leptons, and for the specific benchmark model considered, the pair production cross-section is independent of the coupling parameter λ. Similar to the singly-produced LQ search in section 2, the event selection defines two analysis channels according to the nature of the τ lepton decay: $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ and $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$. An explicit electron or muon veto is imposed in the $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel to ensure orthogonality to the $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel. Among other selections, the sum of transverse momenta of the LQ decay products and the missing transverse energy S_T must be above 600 GeV. At least two jets are required for each event, and one or two must be b-tagged. The search uses a parameterised neural network (PNN) in terms of m_{LQ} to differentiate between the LQ signal and background. The input variables for the



(a) **(b)**

Figure 4: The PNN score post-fit distributions in the (a) $\tau_{\text{lep}}\tau_{\text{had}}$ and (b) $\tau_{\text{had}}\tau_{\text{had}}$ signal region for a m_{LQ} = 1.4 TeV signal and background predictions. The hatched bands indicate the combined statistical and systematic uncertainty in the total background predictions. The expected signals for scalar LQs with the corresponding masses, scaled by the indicated factors for visibility, are overlaid. Since the PNN score is not a physical quantity, it is represented solely by the bin number. Figures and modified caption taken from ref. [10].

PNN are several kinematic observables such as S_T, the invariant mass of $\tau_{\text{had-vis}}$ and the leading jet, and the angular separation between the leading $\tau_{\text{had-vis}}$ and the leading jet. The PNN binning is optimised for each LQ mass point. Figure 4 shows the simultaneous binned maximum-likelihood post-fit PNN score distributions for a scalar LQ signal with m_{LQ} =1.4 TeV. At the high PNN score bins, top quark backgrounds dominate the $\tau_{\text{lep}}\tau_{\text{had}}$ channel. For the $\tau_{\text{had}}\tau_{\text{had}}$ channel, we see a slight data deficit relative to the background prediction in the hightest PNN score bin. No significant excess above the SM prediction is observed. Figure 5 shows the 95% CL exclusion limits for the three LQ models (scalar, Minimal coupling, and Yang-Mills) on the LQ branching ratio to the $b\tau$ final state as a function of m_{LQ}. The observed limits are stronger than the expected limits due to the data deficit in the hightest PNN bin for the $\tau_{\text{had}}\tau_{\text{had}}$ channel. The difference between observed and expected limits increases for high m_{LQ} because the signal is more localised at high PNN scores.

4. Conclusion

The ATLAS Collaboration explores the LHC Run-2 proton-proton collision dataset to search for LQs. The presented search for singly-produced LQs is the first search in ATLAS for the $b\tau\tau$ final state. The search for pair-produced LQs improved the exclusion limit on the branching ratio by 450 GeV compared to the partial LHC Run2 result [11]. Recent summary plots of exclusion limits set by ATLAS for various LQ scenarios are listed in ref. [12]. Additional searches for LQs, such as ref. [13], include cross-generational interactions. The LHC Run3 is ongoing, and the 13.6 TeV centre of mass energy pp collision dataset is expanding, so we can stay tuned for possible connections of the quark and the lepton sector that might turn out to be LQs.

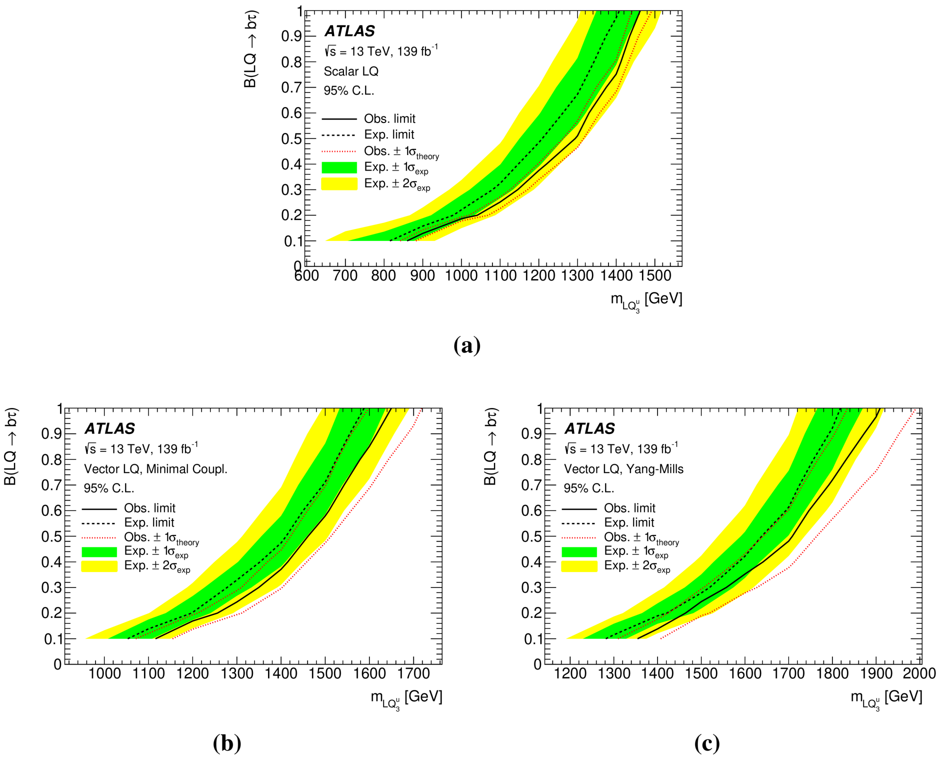


Figure 5: The observed (solid line) and expected (dashed line) 95% CL upper limits on the branching ratio into charged leptons as a function of m_{LQ} for (a) the scalar LQ case, (b) the vector LQ case in the minimal-coupling scenario, and (c) the vector LQs in the Yang-Mills scenario. The observed exclusion region is above the solid line, with the theoretical uncertainty in the model indicated by the red dotted lines. Figures and modified caption taken from ref. [10].

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