Search for Lepton Flavour Violation at HERA

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Abstract.
A search for second and third generation scalar and vector leptoquarks produced in $e^{\pm}p$ collisions via the lepton flavour violating processes $ep \to \mu X$ and $ep \to \tau X$ is performed by the H1 experiment at HERA. The full H1 $e^{\pm}p$ data sample taken at a centre-of-mass energy $\sqrt{s} = 319$ GeV is used for the analysis. No evidence for the production of such leptoquarks is observed in the H1 data. Leptoquarks produced in $e^{\pm}p$ collisions with a coupling strength of $\lambda = 0.3$ and decaying with the same coupling strength to a muon-quark pair or a tau-quark pair are excluded at 95% confidence level up to leptoquark masses of 712 GeV and 479 GeV, respectively.

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LEPTOQUARK PRODUCTION AT HERA

The $e^{\pm}p$ collisions at HERA provide a unique possibility to search for new particles coupling directly to a lepton and a quark. Leptoquarks (LQs), colour triplet bosons that do just that, are an example of such particles and appear in many theories attempting to unify the quark and lepton sectors of the Standard Model (SM).

A discussion of the phenomenology of LQs at HERA can be found elsewhere [1]. In the framework of the Buchmüller-Rückl-Wyler (BRW) effective model [2], LQs are classified into 14 types with respect to the quantum numbers spin J, weak isospin I and chirality C, resulting in seven scalar ($J = 0$) and seven vector ($J = 1$) LQs. Some LQs may decay to a neutrino-quark pair and in such cases the branching fraction for decays into charged leptons is assumed within the BRW model to be $\beta_\ell = \Gamma_{\ell q}/(\Gamma_{\ell q} + \Gamma_{\nu_\ell q}) = 0.5$.

Leptoquarks carry both lepton (L) and baryon (B) quantum numbers, and the fermion number $F = L + 3B$ is assumed to be conserved. Leptoquark processes proceed at HERA directly via s-channel resonant LQ production or indirectly via u-channel virtual LQ exchange. A dimensionless parameter λ defines the coupling at the lepton-quark-LQ vertex. For LQ masses well below the centre-of-mass energy $\sqrt{s} = 319$ GeV, the s-channel production of $F = 2$ ($F = 0$) LQs in e^-p (e^+p) collisions dominates. However, for LQ masses above $\sqrt{s}$, both the s and u-channel processes are important such that both e^-p and e^+p collisions have similar sensitivity to all LQs types.

Assuming a LQ produced at HERA observes flavour conservation, which is implicit in the BRW model, then such a particle would decay exclusively into a quark and a first generation lepton, $ep \to eX$ or $ep \to \nu X$. Dedicated searches have been performed by H1 for such *first generation* LQs, where the SM expectation is dominated by neutral

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current (NC) and charged current (CC) deep inelastic scattering (DIS) background [3, 4]. A search for first generation leptoquarks was recently completed using the complete H1 data set, where for a coupling of electromagnetic strength $\lambda = \sqrt{4\pi\alpha_{\rm em}} = 0.3$, first generation LQs are excluded at 95% confidence level (CL) up to leptoquark masses of 800 GeV, depending on the leptoquark type [4].

SEARCH FOR LEPTON FLAVOUR VIOLATING LEPTOQUARKS

A more general extension of the BRW model allows for the decay of LQs to final states containing a quark and a lepton of a different flavour, i.e. a muon or tau lepton. Non-zero couplings λ_{eq_i} to an electron-quark pair and $\lambda_{\mu q_j}$ ($\lambda_{\tau q_j}$) to a muon(tau)-quark pair are therefore assumed. The indices i and j represent quark generation indices, such that λ_{eq_i} denotes the coupling of an electron to a quark of generation i, and $\lambda_{\ell q_j}$ is the coupling of the outgoing lepton (where $\ell = \mu$ or τ) to a quark of generation j. An overview of this extended model for the LQ coupling to u and d quarks is provided elsewhere [5].

The introduction of lepton flavour violation (LFV) to leptoquark models would mean the processes $ep \to \mu X$ or $ep \to \tau X$, mediated by the exchange of a *second* or *third generation* leptoquark, would be observable at HERA with final states containing a muon or the decay products of a tau lepton back-to-back with a hadronic system X. The main SM background contribution to this topology is from photoproduction events, in which a hadron is wrongly identified as a muon or a narrow hadronic jet fakes the signature of the hadronic tau decay. Similarly, the scattered electron in NC DIS events may also be misinterpreted as the one-prong hadronic tau decay jet. Smaller SM background contributions arise from events exhibiting intrinsic missing transverse momentum (for example CC DIS), events containing high P_T leptons (such as lepton pair production, particularly inelastic muon-pair events if one muon is unidentified) or events with both of these features (real W production with leptonic decay).

Searches for such signatures have been previously performed by H1 [1, 5] and the latest analysis [6] is performed using the complete $e^{\pm}p$ H1 collision data taken at a centre-of-mass energy $\sqrt{s} = 319$ GeV, which was recorded during the years 1998-2007. The corresponding integrated luminosity of 245 pb^{-1} for e^+p collisions and 166 pb^{-1} for e^-p collisions represents an increase in size of the data sample with respect to the previous publication by a factor of 3 and 12, respectively.

Leptoquarks with couplings to first and second generation leptons may decay to a muon and a quark. Event topologies with an isolated, high transverse momentum P_T muon back-to-back to a hadronic system in the transverse plane are therefore selected. Several additional cuts based on the transverse and longitudinal event balance are employed to remove the SM background [6].

Leptoquarks with couplings to first and third generation leptons may decay to a tau and a quark. Tau leptons are identified using the muonic and one-prong hadronic decays of the tau. The analysis of the muonic decay channel employs the same selection as in the second generation LQ search. The tau decay results in missing transverse momentum in the event due to the escaping neutrinos and this is exploited in the analysis of the hadronic decay channel, which also uses the track multiplicity of narrow jets to identify candidate one-prong tau decay jets. Full details of the event selection can be found in

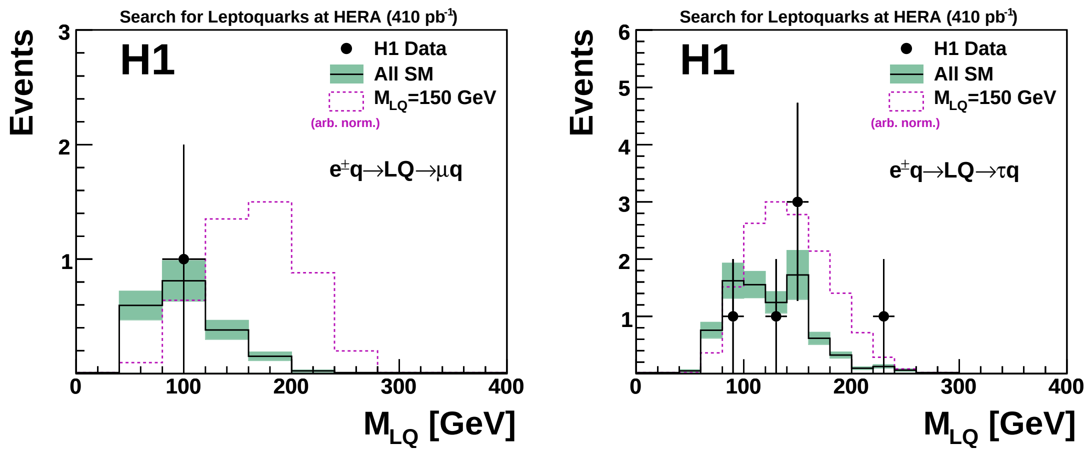

FIGURE 1. The reconstructed leptoquark mass in the search for $ep \to \mu X$ (left) and $ep \to \tau X$ (right) events. The data are the points and the total uncertainty on the SM expectation (open histogram) is given by the shaded band. The dashed histogram indicates the LQ signal with arbitrary normalisation for a leptoquark mass of 150 GeV.

the H1 publication [6].

After all selection cuts, the observed number of events is in agreement with the SM prediction and therefore no evidence for LFV is found. The reconstructed leptoquark mass in the search for $ep \to \mu X$ and $ep \to \tau X$ events is shown in figure 1, compared to the SM prediction and an example LQ signal with arbitrary normalisation.

SECOND AND THIRD GENERATION LEPTOQUARK LIMITS

In the absence of a signal, the results of the search are interpreted in terms of exclusion limits on the mass and the coupling of LQs mediating LFV using a modified frequentist method with a likelihood ratio as the test statistic. The LQ production mechanism at HERA involves non-zero coupling to the first generation fermions $\lambda_{eq_i} > 0$. For the LFV leptoquark decay, it is assumed that only one of the couplings $\lambda_{\mu q_j}$ and $\lambda_{\tau q_j}$ is non-zero and that $\lambda_{eq_i} = \lambda_{\mu q_j}(\lambda_{\tau q_j})$.

Figure 2 shows the 95% CL upper limits on the couplings $\lambda_{\mu q_1}$ and $\lambda_{\tau q_1}$ for $F = 0$ LQs as a function of the mass of the LQ leading to LFV in $e^{\pm}p$ collisions. Similar limits are found for $F = 2$ LQs [6]. Only first generation quarks are considered here, limits involving other quark flavours can be found in the H1 publication [6]. Limits corresponding to LQs coupling to a u quark are more stringent than those corresponding to LQs coupling to the d quark only, as expected from the larger u quark density in the proton. Corresponding to the steeply falling parton density function for high values of x, the LQ production cross section decreases rapidly and exclusion limits are less stringent towards higher LQ masses. For LQ masses near the kinematic limit of 319 GeV, the limit corresponding to a resonantly produced LQ turns smoothly into a limit on the virtual effects of both an off-shell s-channel LQ process and a u-channel LQ exchange. For LQ masses $\gg \sqrt{s}$ the two processes contract to an effective four-fermion interaction.

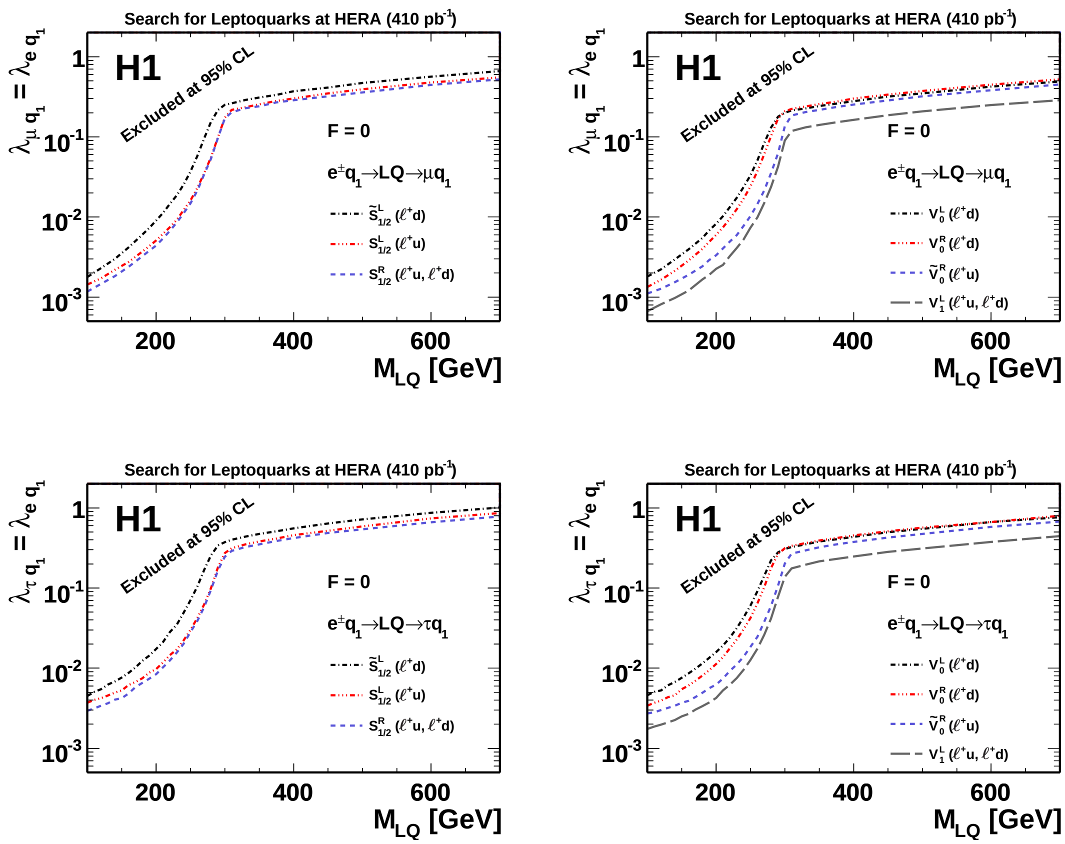

FIGURE 2. Exclusion limits on the coupling constants $\lambda_{\ell q_1} = \lambda_{eq_1}$ as a function of the leptoquark mass M_{LQ} for $F = 0$ leptoquarks. Top row: limits on second generation ($\ell = \mu$) scalar (left) vector (right) LQs; bottom row: limits on third generation ($\ell = \tau$) scalar (left) vector (right) LQs. Regions above the lines are excluded at 95% CL. The notation q_1 indicates that only processes involving first generation quarks are considered. The parentheses after the LQ name indicate the fermion pairs coupling to the LQ, where pairs involving anti-quarks are not shown.

For $\lambda = 0.3$, LFV leptoquarks produced in $e^{\pm}p$ collisions decaying to a muon-quark or a tau-quark pair are excluded at 95% CL up to leptoquark masses of 712 GeV and 479 GeV, respectively. The H1 limits at large couplings extend beyond those currently reported by the Tevatron and the LHC experiments, and also remain competitive with indirect limits from low-energy experiments.

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