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Search for Lepton Flavour Violation in $e^- p$ Collisions at HERA II

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Abstract

A search for scalar and vector leptoquarks coupling to first and second generation fermions and thus mediating lepton flavour violation is presented. This search uses all HERA II $e^- p$ data collected by the H1 experiment, which corresponds to a total integrated luminosity of $158\,\mathrm{pb}^{-1}$. Especially the sensitivity to leptoquarks with fermion number $F = 2$ is increased with respect to the previous H1 results. No evidence for the direct or indirect production of such particles is found in data samples with a large transverse momentum final state muon. The results of the present analysis are used to set new constraints on lepton flavour violating leptoquark couplings, assuming $\lambda_{eq} = \lambda_{\mu q} = \lambda$ and $\lambda_{\tau q} = 0$. For a coupling of $\lambda = 0.3$, $F = 2$ leptoquarks with masses up to $433\,\mathrm{GeV}$ are ruled out.

1 Introduction

The ep collider HERA offers the unique possibility to search for the resonant production of new particles which couple directly to a lepton and a parton. Leptoquarks (LQs), colour triplet bosons, which appear naturally in various unifying theories beyond the Standard Model (SM) are such an example. At HERA, leptoquarks could be singly produced by the fusion of the initial state lepton of energy 27.6 GeV with a quark from the incoming proton of energy up to 920 GeV.

The phenomenology of LFV at HERA is discussed in detail in [1]. The effective Lagrangian considered there conserves lepton and baryon number, obeys the symmetries of the SM gauge groups $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$ and includes both scalar and vector LQs. Dimensionless couplings λ_{eq}, $\lambda_{\mu q}$ and $\lambda_{\tau q}$ define the coupling at the e-q-LQ, μ-q-LQ and τ-q-LQ vertex, respectively. At HERA, LQs can be resonantly produced in the s-channel or exchanged in the u-channel between the incoming lepton and a quark coming from the proton. In both cases, the production requires a non-zero λ_{eq}. The leptoquark can then decay either lepton flavour conserving via the same coupling, or via one of the lepton flavour violating couplings $\lambda_{\mu q}$ or $\lambda_{\tau q}$ into final states with a jet and a muon or τ-lepton with high transverse momentum.

Although particle interactions in the SM conserve lepton flavour, experimental evidence for lepton flavour violation (LFV) has been obtained in neutrino physics [2, 3]. While experimental upper bounds on neutrino masses imply very small LFV in the charged lepton sector, an observation of such effects would clearly indicate new phenomena beyond the SM.

This note presents a search for LQs coupling to first and second generation fermions with fermion number[1] $F = 2$ in scattering of longitudinally polarised electrons on protons at a center-of-mass energy of $\sqrt{s_{ep}} \approx 320$ GeV. For the lefthanded[2] running phase with an average polarisation of -26 %, the integrated luminosity amounts to 105 pb^{-1}, whereas for the righthanded running phase with an average polarisation of 32 %, 54 pb^{-1} of data are analysed. The results of this search are combined with the HERA I results [1], which correspond to an integrated luminosity of 14 pb^{-1} for e^-p and 67 pb^{-1} for e^+p running.

Due to the more favourable quark-densities of quarks with respect to anti-quarks at high x, the e^-p data sets are mostly sensitive to LQs with fermion number $F = 2$. The search reported here considers only decays into LQ $\rightarrow \mu q$. These LQ decays lead to unique final states with a jet and a muon with high transverse momenta.

2 Experimental Conditions

The H1 detector components most relevant to this analysis are the liquid argon calorimeter, which measures the positions and energies of charged and neutral particles over the polar angle[3]

[1]The fermion number F is given by $F = |3B + L|$, with B and L being the baryon and lepton number respectively.

[2]The names 'lefthanded' and 'righthanded' refer to the longitudinal polarisation of the electrons in the beam

[3]The polar angle θ is defined with respect to the incident proton momentum vector (the positive z axis).

range of $4^\circ < \theta < 154^\circ$, the inner tracking detectors which measure the angles and momenta of charged particles over the range $7^\circ < \theta < 165^\circ$ and the instrumented iron return yoke which allows muon identification in the polar angle range of $5^\circ < \theta < 175^\circ$. A full description of the H1 detector can be found in [4].

The leptoquark signal is generated with the LEGO [5] event generator using the CTEQ5D [6] parametrisation of the parton distributions. The main characteristic of the signal events is an isolated muon with large transverse momentum which is back-to-back in the transverse plane with the hadronic final state. To avoid the simulation of signal events for each leptoquark mass and coupling, the LEGO sample is generated with a flat mass distribution and the same reweighting technique as used in [1] is applied to calculate the selection efficiencies for arbitrary masses and couplings. This procedure provides an exact leading order prediction over the full range of LQ parameters.

The LQ kinematics are reconstructed using the double angle method [7]. The direction of the detected lepton and jet are used to reconstruct the Bjørken scaling variable x and therefore the LQ mass $m_{\rm LQ}^{\rm rec} = \sqrt{xs}$.

The SM background to this search includes the following processes: The most important background to the final selection is lepton pair production, which has been generated with GRAPE [8]. It can mimic the signal topology either if one of the muons is lost into the beam pipe or if one of the muons happens to be close to the hadronic final state. Additional muons in jets are not rejected because in a LFV leptoquark decay semileptonically decaying heavy quarks should not be excluded. Further backgrounds are real W boson production generated with EPVEC [9], photoproduction generated with PYTHIA [10] and neutral current (NC) and charged current (CC) deep-inelastic scattering (DIS) generated by RAPGAP [11] and DJANGO [12], respectively.

All signal and SM samples are passed through a detailed simulation of the H1 detector response based on the GEANT program [13] and the same reconstruction and analysis algorithms as used for the data.

3 The $e^-p \rightarrow \mu X$ Selection

The event selection requires an isolated muon and at least one jet. The muon should have a transverse momentum $p_t > 8$ GeV and a polar angle in the range $10^\circ < \theta < 140^\circ$ and has to be identified in the instrumented return yoke. The isolation criterion requires that the minimal angular distance of the muon candidate to any other track $D = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ has to be larger than 0.5. Only exactly one muon fulfilling this isolation criterion is allowed in order to reject di-muon events. The fact that a high energetic muon only leaves a minimal energy deposit in the calorimeter leads to a high net transverse momentum reconstructed from all clusters recorded in the LAr calorimeter, $p_T^{\rm calo}$, which is required to be larger than 25 GeV. Two cuts are employed to further exploit the event topology in the transverse plane. The azimuthal angle between the jet and the muon has to be larger than 170° and $V_{ap}/V_p < 0.2$ is required, where V_{ap}/V_p is defined as the ratio of the anti-parallel to parallel projections of all energy deposits in the calorimeter with respect to the direction of $\vec{p}_T^{\rm calo}$ [14]. In order to reject any remaining NC background events with an isolated electron candidate are vetoed. With these cuts, a high signal efficiency of 45% to 70% is obtained over a broad range of masses for all LQ types starting at about 75 GeV up to the contact interaction limit. Two candidate events are found in the data, compared to a total SM background expectation of 2.2 ± 0.6 events, dominated by lepton pair production, which contributes 1.4 ± 0.4 events.

The following experimental systematic uncertainties are applied to the SM background expectation as well as to the signal: The reconstructed polar angle of the jet is varied by 10 mrad in the central region of the detector and by 5 mrad in the forward region, where as the polar angle of the muon is assumed to be measured with a precision of 3 mrad. The azimuthal angle of both the muon and the jet are varied within 1 mrad each. The muon identification efficiency is assumed to be known to 15% in the forward region and to 5% in the central part of the detector and the reconstructed transverse momentum of the muon is varied by 5%.

Further uncertainties of 4% for the luminosity measurement, 3% for the polarisation measurement and a 30% theoretical uncertainty on the modelling of lepton pair production as the main background source and 50% on the photoproduction background are taken into account. The uncertainties originating from the parton densities, which are the main uncertainty on the signal expectation have been treated in the same way as in [1].

The leptoquark mass spectra obtained after the final selection are shown in figure 1. Two candidate events are observed in the data. Both events are consistent with lepton pair production, where one muon is too close to the hadronic final state to be recognized as a second isolated muon, which would lead to a rejection of the event.

Since no evidence for LQ production is observed, the data are used to set constraints on LQs coupling to first and second generation fermions. The results of this analysis are combined with the results of the HERA I data published in [1].

The majority of the background has a p_T^{calo} of less than 45 GeV, whereas a large fraction of the leptoquark signal is expected to have $p_T^{\mathrm{calo}} > 45$ GeV. Thus signal and background expectation as well as the data are divided into two bins in p_T^{calo}, one with between 25 and 45 GeV and one bin above 45 GeV. Both are combined with a procedure designed to fully exploit the sensitivity to the signal. The statistical method has been described in detail in [15].

4 Limit Results

In the following we will show limits derived within the phenomenological model proposed by Buchmüller, Rückl and Wyler (BRW) [16].

The BRW model describes 7 LQs with $F = 0$ and 7 LQs with $F = 2$ coupling to eq. We use here the nomenclature of [17] to label the various scalar $S_{I,L}$ ($\overset{(\sim)}{S}_{I,R}$) or vector $\overset{(\sim)}{V}_{I,L}$ ($V_{I,R}$) LQ types of weak isospin I, which couple to a left-handed (right-handed) electron. The tilde is used to distinguish LQs which differ only by their hypercharge. Table 1 lists the 7 LQ types with fermion number $F = 2$ described by the BRW model.

$F=2$	Prod./Decay	$\beta_{e,\nu}$
Scalar Leptoquarks		
$S_{0,L}$	$e^-_L u_L \to e^- u$	$1/2$
	$\to \nu d$	$1/2$
$S_{0,R}$	$e^-_R u_R \to e^- u$	1
$\tilde{S}_{0,R}$	$e^-_R d_R \to e^- d$	1
$S_{1,L}$	$e^-_L d_L \to e^- d$	1
	$e^-_L u_L \to e^- u$	$1/2$
	$\to \nu d$	$1/2$
Vector Leptoquarks		
$V_{1/2,R}$	$e^-_R d_L \to e^- d$	1
	$e^-_R u_L \to e^- u$	1
$V_{1/2,L}$	$e^-_L d_R \to e^- d$	1
$\tilde{V}_{1/2,L}$	$e^-_L u_R \to e^- u$	1

Table 1: Leptoquark isospin families with $F = 2$ in the Buchmüller-Rückl-Wyler model. For each leptoquark, the subscript denotes its weak isospin and the chirality of the incoming electron which could mediate their production in e^-p collisions. $\beta_{e,\nu}$ indicates the assumed branching fraction into electrons or neutrinos if both channels are allowed.

Since here only leptoquarks coupling to first and second generation fermions are under consideration, the number of free parameters is reduced by choosing $\lambda_{eq} = \lambda_{\mu q} = \lambda$ and $\lambda_{\tau q} = 0$. All results in this sections are obtained with this choice of the couplings.

The resulting constraints are shown in figure 2a for the four scalar and in figure 2b for the three vector LQs with $F = 2$. The areas above the curves are excluded at 95% confidence level. The strongest constraints on the coupling λ can be set for LQ masses below the kinematic limit of the s-channel. At higher masses the production is not resonant anymore but contact interaction–like and the cross–sections scale approximately with $(\lambda/M_{LQ})^4$. For a coupling of electromagnetic strength $\alpha_{\rm em}$ ($\lambda = \sqrt{4\pi\alpha_{\rm em}} = 0.3$) this analysis rules out LQ masses below 291 to 433 GeV, depending on the LQ type.

Figure 3 summarises the constraints on the $S_{0,L}$ leptoquark obtained by H1 and by the D0 experiment at the Tevatron [18]. The limits from the Tevatron are independent of the coupling λ as they were derived from the dominant pair production processes. However they assume leptoquarks coupling to only one generation, whereas at HERA the first generation coupling is needed for production even if the decay into second generation fermions is searched for. Therefore the most stringent mass constraints from the Tevatron experiments corresponding to the HERA scenario can be derived from the $e\nu qq$ channel. The published H1 results [1] from the HERA I phase (mainly e^+p running) are shown for comparison.

5 Summary

In summary, a search for leptoquarks with fermion number $F = 2$ coupling to first and second generation fermions has been performed using the complete e^-p data set from the HERA II running phase. No signal has been observed and constraints on leptoquarks have been set in combination with the full HERA I data published in [1]. The new limits extend beyond the domains excluded previously by H1. For a coupling of electromagnetic strength, leptoquark masses below $291 - 433$ GeV can be ruled out, depending on the leptoquark type.

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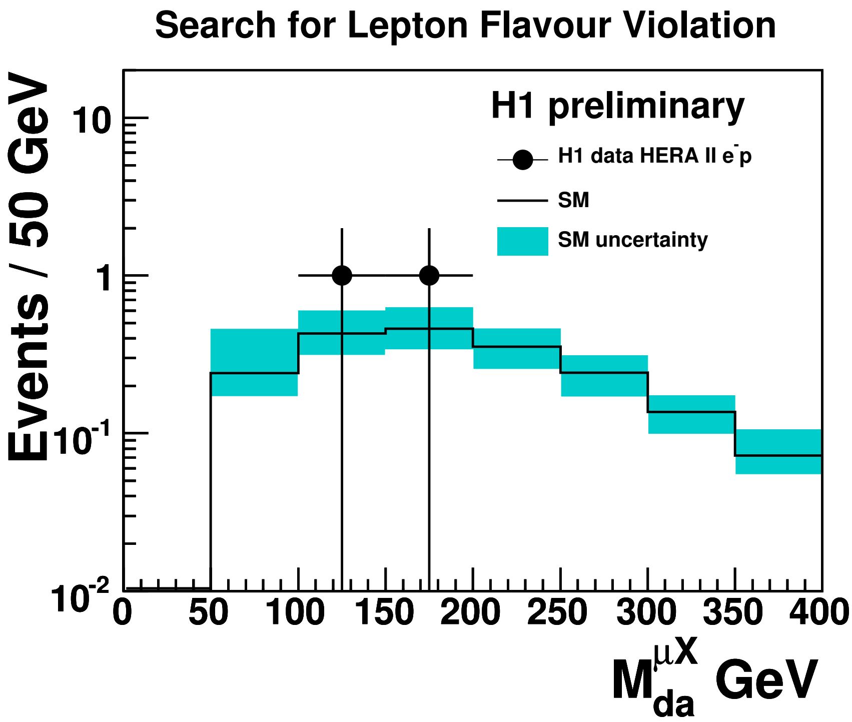

Figure 1: Leptoquark mass spectrum after the final selection, together with the corresponding SM expectations (histogram). The shaded bands indicate the $\pm 1\sigma$ uncertainty on the SM expectations.

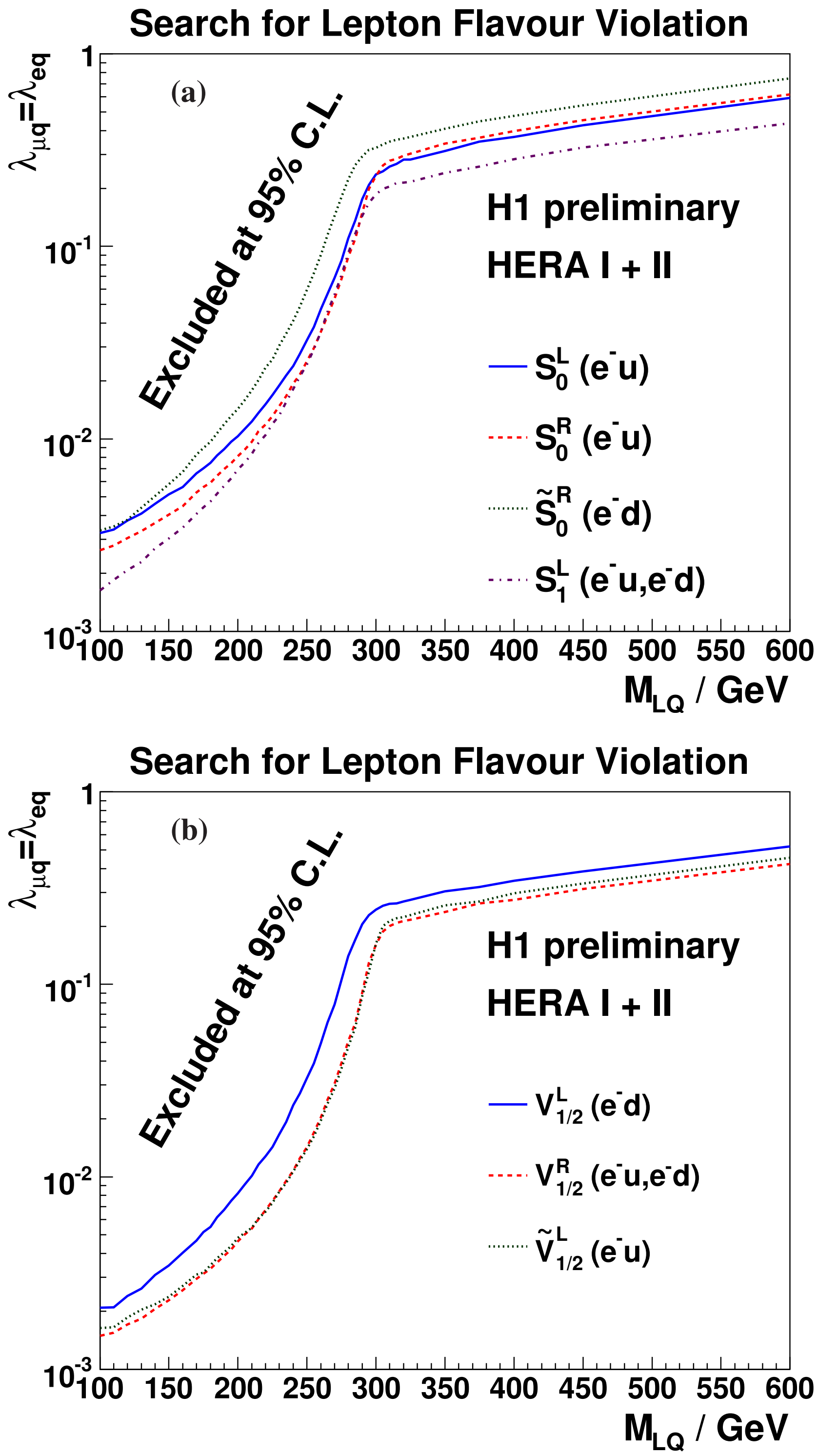

Figure 2: Exclusion limits for the 7 leptoquarks (LQs) with $F = 2$ described by the Buchmüller, Rückl and Wyler (BRW) model. The limits are expressed at 95% CL on the coupling $\lambda_{\mu q} = \lambda_{eq}$ as a function of the leptoquark mass for the (a) scalar LQs with $F = 2$, (b) vector LQs with $F = 2$. Domains above the curves are excluded. In the brackets, for each LQ type the pairs of Standard Model first generation fermions is indicated to which it couples.

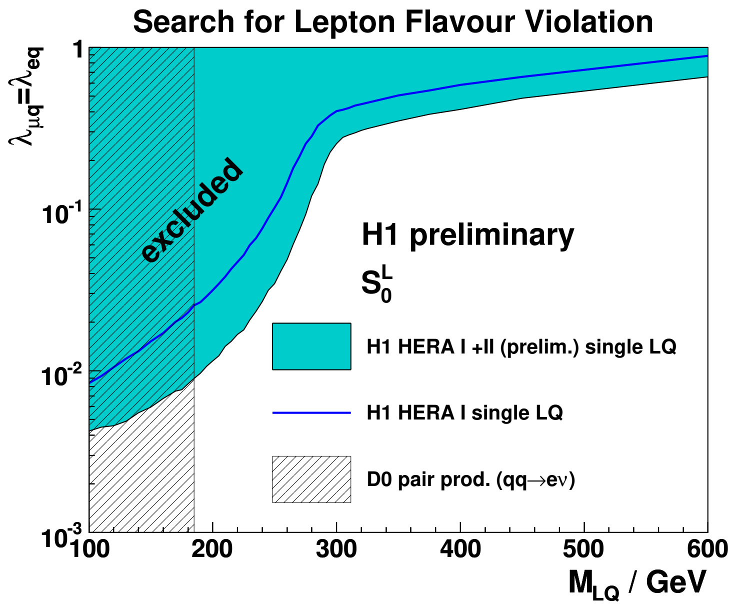

Figure 3: Exclusion limits at 95% CL on the coupling $\lambda_{\mu q} = \lambda_{eq}$ as a function of the leptoquark (LQ) mass for $S_{0,L}$ in the framework of the BRW model. The direct D0 limit obtained from leptoquark pair production is shown for comparison. In addition, the published H1 limit on $S_{0,L}$ from HERA I data is shown.