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A Search for Leptoquark Bosons in $e^- p$ Collisions at HERA

H1 Collaboration

Abstract

A search for scalar and vector leptoquarks coupling to first generation fermions is performed in the H1 experiment at the ep collider HERA. The analysis uses $e^- p$ data collected in 1998 and 1999 at a centre-of-mass energy of 320 GeV, corresponding to an integrated luminosity of ~ 15 pb^{-1}. No evidence for the direct production of such particles is found in a data sample with a large transverse momentum final state electron or with large missing transverse momentum, and constraints on leptoquark models are established. For a Yukawa coupling of electromagnetic strength leptoquarks are excluded for masses up to ~ 290 GeV. This analysis complements the leptoquark searches performed previously using data collected whilst HERA was operating with positrons instead of electrons.

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The ep collider HERA offers the unique possibility to search for resonant production of new particles which couple to lepton-parton pairs. Examples are leptoquarks (LQs), colour triplet bosons which appear naturally in various unifying theories beyond the Standard Model (SM). At HERA, leptoquarks could be singly produced by the fusion of the initial state lepton of energy 27.5 GeV with a quark from the incoming proton of 920 GeV, with masses up to the centre-of-mass energy $\sqrt{s_{ep}}$ of 320 GeV.

This analysis presents a search for LQs coupling to first generation fermions using e^-p data collected in 1998 and 1999. Collisions between *electrons* and protons provide a high sensitivity to LQs with fermion number $F = 2$ (i.e. LQs coupling to e^- and a *valence quark*) while the production of such LQs is largely suppressed in e^+p collisions where the interaction involves an *antiquark*[1]. Thus this analysis complements the searches for LQs in e^+p data [1, 2]. This search considers the decays $\mathrm{LQ} \to eq$ and $\mathrm{LQ} \to \nu q$ which lead to final states similar to those of deep-inelastic scattering (DIS) neutral current (NC) and charged current (CC) interactions at very high squared momentum transfer Q^2. The integrated luminosity amounts to 15 pb^{-1}, an increase in statistics by a factor of about 35 compared to previous LQ searches [3, 4] in e^-p collisions.

The phenomenology of LQs at HERA was discussed in detail in [1]. 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. The amplitudes for both these processes interfere with those from DIS. We shall consider here the mass domain where the resonant s-channel contributions largely dominate the LQ signal cross-section.

In the s-channel, a LQ is produced at a mass $M = \sqrt{s_{ep}x}$ where x is the momentum fraction of the proton carried by the interacting quark. When the LQ decays into an electron and a quark, the mass is reconstructed from the measured kinematics of the scattered electron, and is henceforth labelled M_e. Similarly when the LQ decays into a neutrino and a quark, the mass is labelled M_h as it is reconstructed from the hadronic final state alone [1].

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 angular range[2] $4° < \theta < 154°$, and the inner tracking detectors which measure the angles and momenta of charged particles over the range $7° < \theta < 165°$. A full description of the detector can be found in [5].

This search relies essentially on inclusive NC and CC DIS selections. The selection of NC-like events is identical to that presented in [1]. It requires an identified electron with transverse energy above 15 GeV and considers the kinematic domain defined by $Q^2 > 2500$ GeV^2 and $0.1 < y < 0.9$, where $y = Q^2/M^2$. The inelasticity variable y is related to the polar angle θ^* of the lepton in the centre-of-mass frame of the hard subprocess by $y = \frac{1}{2}(1 + \cos\theta^*)$. Since the angular distribution of the electron coming from the decay of a scalar (vector) resonance is markedly (slightly) different from that of the scattered lepton in NC DIS [1], a mass dependent cut $y > y_{\mathrm{cut}}$ allows the signal significance to be optimized. The measured mass spectrum is compared in Fig. 1 with the NC SM prediction, obtained using a Monte-Carlo calculation [6] and the MRST parametrization [7] for the parton densities. The distributions are shown before

[1] A fusion between an e^+ and a valence quark would lead to a LQ with $F = 0$.

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

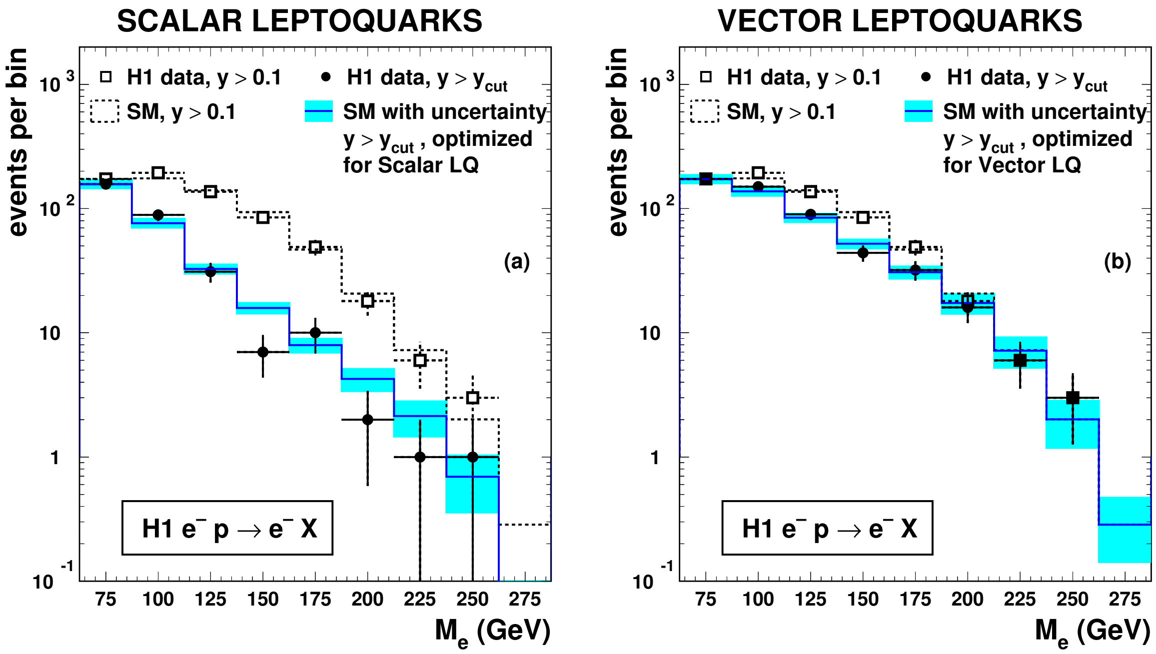

Figure 1: Mass spectra of the events from the inclusive NC DIS selection for data (symbols) and DIS expectation (histograms). The data is shown before (open squares, dashed-line histogram) and after (filled dots, full-line histogram) a y cut designed to maximize the significance of (a) a scalar and (b) a vector leptoquark (LQ) signal. The grey boxes indicate the $\pm 1\sigma$ uncertainty due to the systematic errors on the NC DIS expectation.

and after applying the mass dependent lower y cut designed to maximize the significance of a scalar (Fig. 1a) or vector (Fig. 1b) LQ. For scalar (vector) LQs, $y_{\rm cut}$ continuously decreases from ~ 0.45 (~ 0.25) at 100 GeV to ~ 0.35 (~ 0.15) at 200 GeV, reaching 0.1 (0.1) at 290 GeV. In the mass range $M_e > 62.5$ GeV and after applying the y cut optimized for scalar (vector) LQ searches, 298 (514) events are observed in good agreement with the SM expectation of 297 ± 22 (504 ± 38) events.

The selection of CC-like events follows closely that presented in [8]. In addition, a missing transverse momentum exceeding 25 GeV and $Q^2 > 2500$ GeV^2 are required. The domain at high y where the resolution on the mass M_h degrades is removed by requiring $y < 0.9$. For $M_h > 65$ GeV, 345 events are observed, in good agreement with the CC SM expectation of 350 ± 28 events. The observed and expected mass spectra are shown in Fig. 2.

No evidence for LQ production is observed in either data sample. Hence the data are used to set constraints on LQs which couple to first generation fermions. We use the numbers of observed and expected events within a variable mass bin, adapted to the experimental mass distribution for a given true LQ mass $M_{\rm LQ}$, and which slides over the accessible mass range. As an example, candidate events with M_e within the interval from 187 GeV to 206 GeV are used to constrain a 200 GeV LQ decaying into electrons. For LQs decaying into νq, the mass window is enlarged (to about 40 GeV for a 200 GeV LQ) to account for the mass resolution when relying on the hadronic final state. The final signal efficiencies, including the mass bin

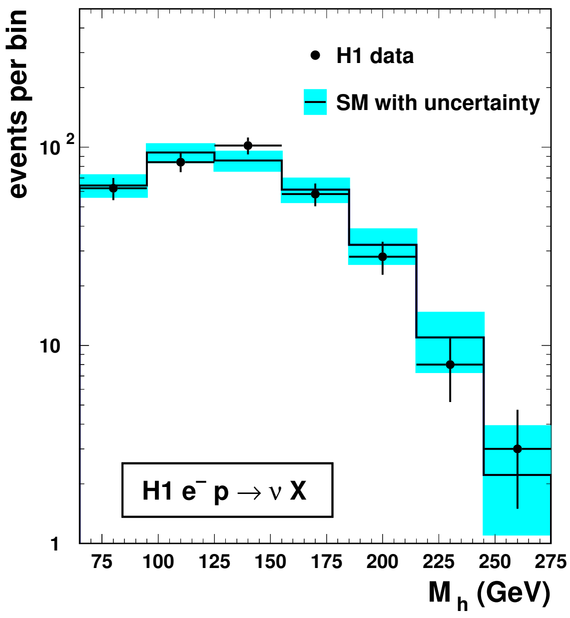

Figure 2: Mass spectra of the events from the inclusive CC DIS selection for data (symbols) and DIS expectation (histogram). The grey boxes indicate the $\pm1\sigma$ uncertainty due to the systematic errors on the CC DIS expectation.

requirement, vary with the LQ mass between 35% (20%) and 52% (45%) for scalar (vector) LQs decaying into eq, and between 20% and 52% for LQs decaying into νq.

Assuming Poisson distributions for the SM background expectations and for the signal, an upper limit on the number of events coming from LQ production is obtained using a standard Bayesian prescription. This limit on the number of signal events is then translated into an upper bound on the LQ cross-section, which in turn leads to constraints on LQ models. The signal cross-section is obtained from the leading-order LQ amplitudes given in [9], corrected by multiplicative K-factors [10] to account for next-to-leading order QCD corrections. These corrections can enhance the LQ cross-section by $\mathcal{O}(10\%)$.

The procedure which folds in the statistical and systematic errors is described in detail in [3]. The main source of experimental systematic error is the uncertainty on the electromagnetic energy scale (between 0.7% and 3%) for the NC analysis, and the uncertainty on the hadronic energy scale (2%) for the CC analysis. Furthermore, an error of $\pm7\%$ on the DIS expectations is attributed to the limited knowledge of proton structure. An additional systematic error arises from the theoretical uncertainty on the signal cross-section, originating mainly from the uncertainties on the parton densities. This uncertainty is 7% for LQs coupling to e^-u, and varies between 7% at low LQ masses up to 50% around 290 GeV for LQs coupling to e^-d. Moreover, choosing alternatively Q^2 or the square of the transverse momentum of the final state lepton instead of $M_{\rm LQ}^2$ as the hard scale at which the parton distributions are estimated yields an additional uncertainty of $\pm7\%$ on the signal cross-section.

The phenomenological model proposed by Buchmüller, Rückl and Wyler (BRW) [9] describes 14 LQs. We focus here on the 7 LQs with fermion number $F = 2$ since those with $F = 0$ are better constrained using e^+p data [1]. In the BRW model the branching ratios β_e (β_ν) for the LQ decays into eq (νq) are fixed and equal to 1 or 0.5 (0 or 0.5) depending on the LQ quantum numbers. The upper limits on the Yukawa coupling λ at the $e\,q$ LQ vertex obtained at 95% confidence level (CL) are shown as a function of the LQ mass in Figs. 3a and b, for scalar and vector LQs respectively. The nomenclature of [11] is used 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. For LQs decaying with an equal branching ratio into eq and νq, both the NC and CC channels were combined in the derivation of the limits. However, the CC channel offers much less sensitivity to the signal than the NC channel, and thus only marginally contributes to the resulting bounds. This is due to the fact that the mass windows are larger, and that no discriminating angular cut is applied in the CC channel. Both effects yield a much larger SM background in the CC channel than in the NC case[3]. For a Yukawa coupling of electromagnetic strength $\alpha_{\rm em}$ ($\lambda = \sqrt{4\pi\alpha_{\rm em}} \simeq 0.3$) this analysis rules out LQ masses below 275 to 290 GeV depending on the LQ type, at 95% CL. These are the most stringent direct bounds on LQs with $F = 2$.

Beyond the BRW ansatz, generic LQ models can also be considered, where other LQ decay modes are allowed such that the branching ratios β_e and β_ν are free parameters. The LQ production cross-section does not depend on the total LQ width Γ as long as Γ is not too large. Hence the signal cross-section observable in e.g. the NC channel depends only on the Yukawa coupling and on the branching ratio β_e, and mass dependent constraints on β_e can be set for a given value of λ. For a scalar LQ with $M_{\rm LQ} = 295$ GeV and $\lambda = 0.3$, this approach holds as long as $\Gamma \lesssim 2$ GeV, such that the LQ total width does not exceed about four times its partial decay width into eq. For a scalar LQ possessing the quantum numbers of the $\tilde{S}_{0,R}$, which couples to e^-d and thus cannot decay into νq, Fig. 4a shows the excluded part of the β_e-$M_{\rm LQ}$ plane for three values of the Yukawa coupling. The domain excluded by the D0 experiment at the Tevatron [12] is also shown. For a scalar LQ coupling to e^-u (possessing the quantum numbers of the $S_{0,L}$) and for $\lambda = 0.05$, the domain of the β_e-$M_{\rm LQ}$ (β_ν-$M_{\rm LQ}$) plane excluded by the NC (CC) analysis is shown in Fig. 4b. If the LQ decays into eq or νq only[4], the combination of both channels rules out the part of the plane on the left of the middle full curve, for $\lambda = 0.05$. The resulting combined bound is largely independent of the individual values of β_e and β_ν. Combined bounds are also shown for $\lambda = 0.03$ and $\lambda = 0.3$, for the same LQ type. For λ greater than ~ 0.03, these bounds extend considerably beyond the region excluded by the D0 experiment [12].

To summarize, a search for leptoquarks with fermion number $F = 2$ has been performed using the e^-p data collected by H1 in 1998 and 1999. No signal has been observed and constraints on such LQs have been set, which extend beyond the domains excluded by other experiments. For a Yukawa coupling of electromagnetic strength, LQ masses up to 290 GeV can be ruled out. This represents the most stringent direct bound on $F = 2$ leptoquarks.

[3]This is different from the e^+p case, where the CC channel significantly improves the sensitivity on the LQ production cross-section [1] due to the smaller CC DIS cross-section.

[4]It should be noted that $\beta_e + \beta_\nu = 1$ does not imply $\beta_e = \beta_\nu$ even when invariance under $SU(2)_L$ transformations is required. For example, when LQs belonging to a given isospin multiplet are not mass eigenstates, their mixing usually leads to different branching ratios in both channels for the physical LQ states.

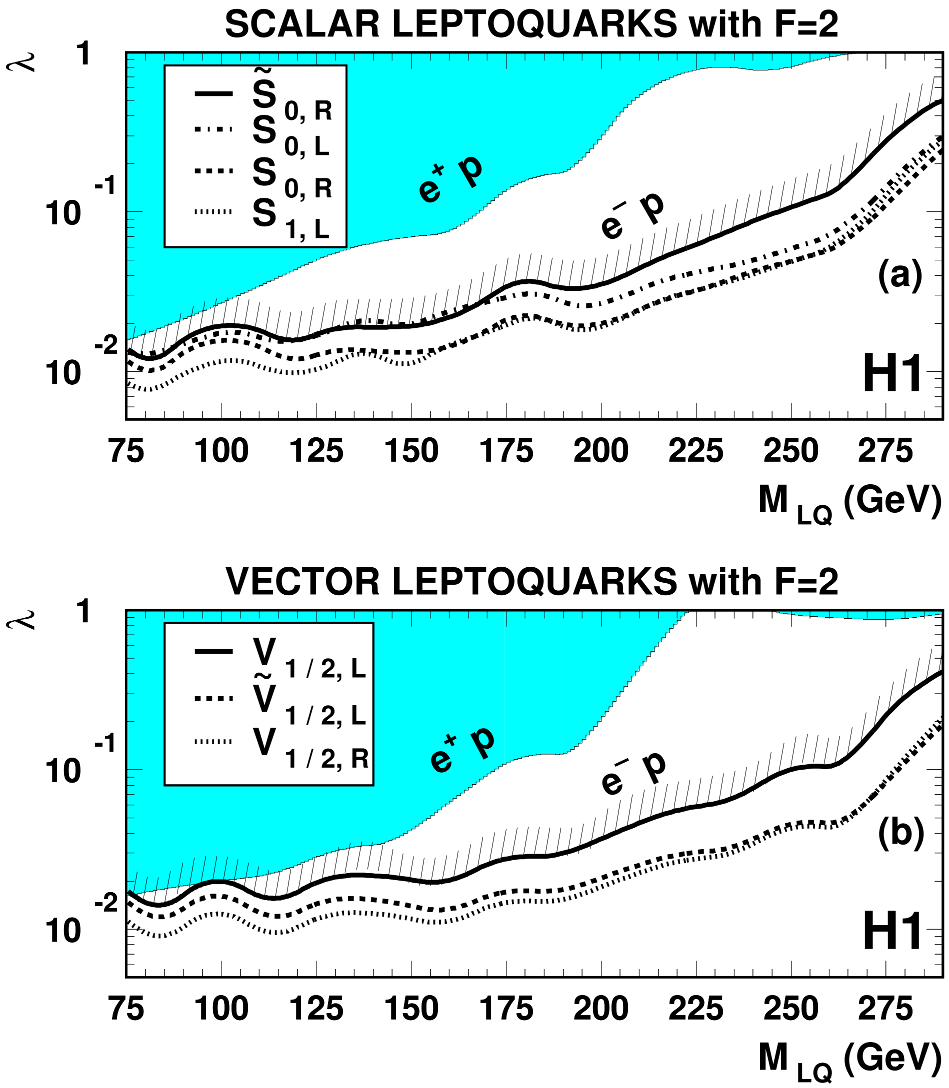

Figure 3: Exclusion limits at 95% CL on the Yukawa coupling λ as a function of the mass of (a) scalar and (b) vector leptoquarks (LQs) with fermion number $F = 2$ described by the BRW model. Domains above the curves are excluded by this analysis of the $e^- p$ data. The shaded area on each plot indicates the excluded region obtained from the $e^+ p$ data [1], less suited for constraining $F = 2$ LQs.

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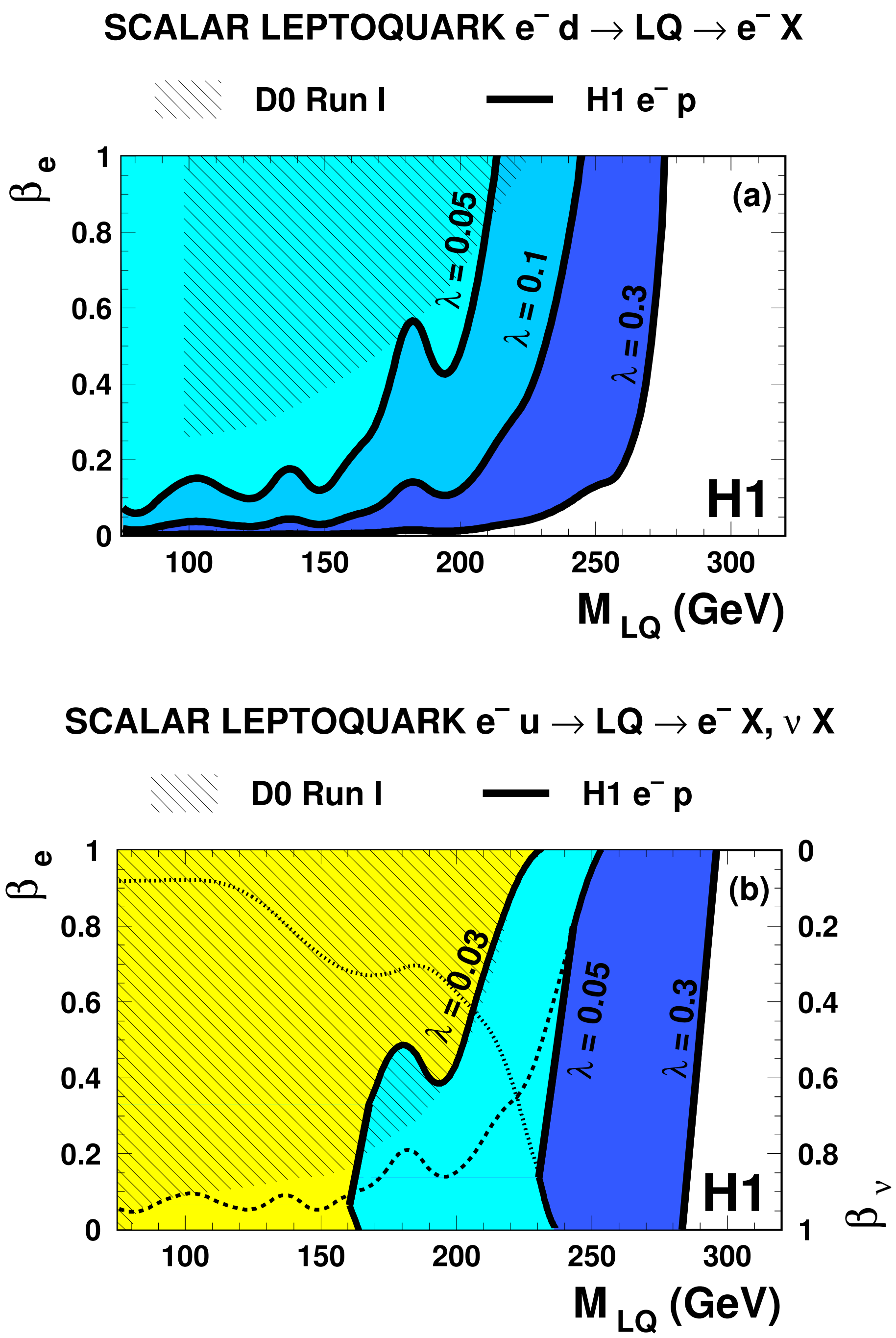

Figure 4: (a) Mass dependent exclusion limits at 95% CL on the branching ratio β_e of a scalar leptoquark (LQ) which couples to e^-d (with the quantum numbers of the $\tilde{S}_{0,R}$). (b) Domains ruled out by the combination of the NC and CC analyses, for a scalar LQ which couples to e^-u (with the quantum numbers of the $S_{0,L}$) and decaying only into eq and νq for three example values of the Yukawa coupling λ. The regions on the left of the full curves are excluded at 95% CL. For $\lambda = 0.05$, the part of the β_e-M_{LQ} (β_ν-M_{LQ}) plane on the left of the dashed (dotted) curve is excluded by the NC (CC) analysis. The branching ratios β_e and β_ν are shown on the left and right axes respectively. In (a) and (b), the hatched region represents the domain excluded by the D0 experiment [12].