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A Search for Leptoquark Bosons in ep Collisions at HERA

H1 Collaboration

Abstract

A search for scalar and vector leptoquarks coupling to first generation fermions is performed in the H1 experiment using data collected from 1994 to 2000. No significant 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 leptoquark couplings of electromagnetic strength, leptoquark masses up to 290 GeV are ruled out.

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 energy up to 920 GeV, with masses up to the centre-of-mass energy $\sqrt{s_{ep}}$.

This analysis presents a search for LQs coupling to first generation fermions using e^+p data collected at $\sqrt{s_{ep}} = 300$ GeV, e^-p data collected at $\sqrt{s_{ep}} = 320$ GeV, and e^+p data collected at $\sqrt{s_{ep}} = 320$ GeV. These data sets correspond to integrated luminosities of 37 pb^{-1}, 15 pb^{-1} and 65 pb^{-1}, respectively. They represent the full statistics accumulated by the H1 experiment between 1994 and 2000. The e^+p and e^-p data sets are largely complementary when searching for leptoquark resonances, since the e^+p (e^-p) data provide most sensitivity to leptoquarks with fermion number $F = 0$ ($F = 2$), i.e. LQs coupling to e^+ (e^-) and a *valence* quark. The search reported here considers the decays $\mathrm{LQ} \rightarrow eq$ and $\mathrm{LQ} \rightarrow \nu q$ 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 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 only [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[1] $4° < \theta < 154°$, 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 [2].

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 momentum 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 mass spectrum measured in the full e^+p data set is compared in Fig. 1a with the NC SM prediction, obtained using a Monte-Carlo calculation [3] and the MRST parametrization [4] for the parton densities. The distributions are shown before and after applying the mass dependent lower y cut designed

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

to maximize the significance of a scalar LQ in each e^+p data set. This y_{cut} decreases from ~ 0.5 at 100 GeV to ~ 0.45 at 200 GeV, reaching ~ 0.15 at 290 GeV. In the mass range $M_e > 62.5$ GeV and after applying this y cut, 880 events are observed in good agreement with the SM expectation of 869 ± 65 events. A good agreement is also observed when applying the y cut optimized for vector LQ searches (not shown). Fig. 1b shows the mass spectrum of the NC DIS-like events measured in the e^-p data set and the comparison with the SM prediction. The distributions are shown before and after applying the mass dependent lower y cut designed to maximize the significance of a vector LQ, which decreases from ~ 0.25 at 100 GeV to ~ 0.15 at 200 GeV, reaching 0.1 at 290 GeV. 514 events are observed after applying the mass dependent y cut, in good agreement with the SM expectation of 504 ± 38 events. A good agreement is also observed in the e^-p data set when applying the lower y cut optimized for scalar LQ searches (not shown).

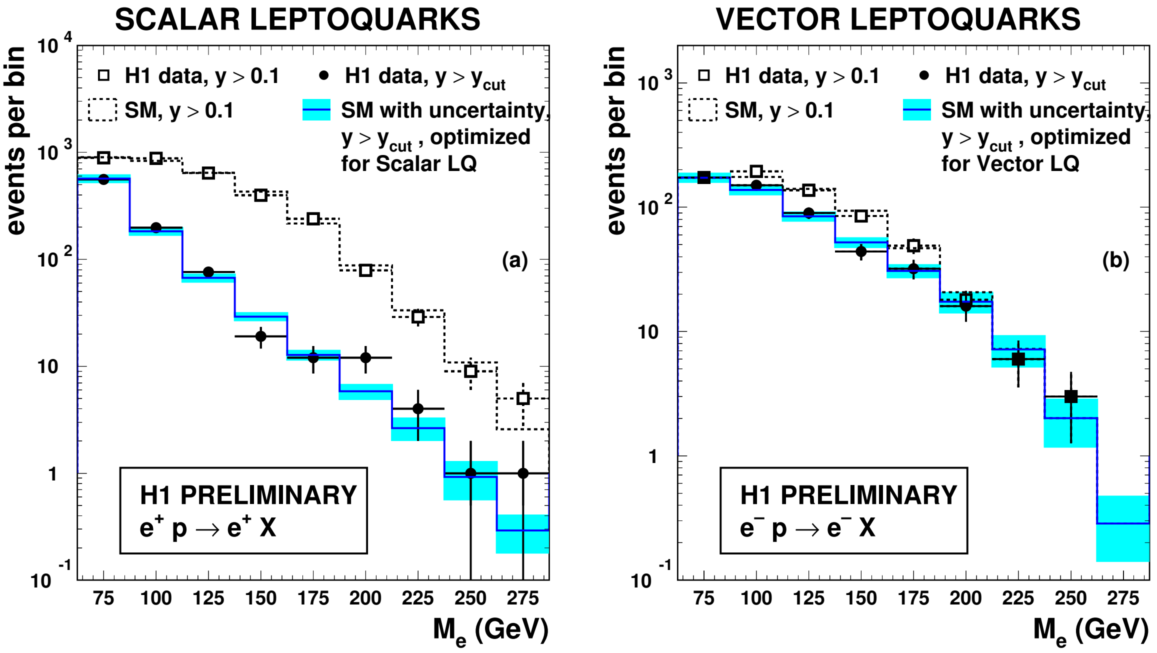

Figure 1: Mass spectra for the events from the NC DIS selection for (a) e^+p and (b) e^-p data (symbols), together with the corresponding DIS expectations (histograms). The data are shown before (open squares, dashed-line histogram) and after (filled dots, full-line histogram) a y cut designed to maximize 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.

The selection of CC-like events follows closely that presented in [1, 5]. 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, 692 (345) events are observed in the e^+p (e^-p) data set, in good agreement with the CC SM expectation of 673 ± 61 (350 ± 28) events. The observed and expected mass spectra are in good agreement as shown in Fig. 2a and Fig. 2b.

No evidence for LQ production is observed in the NC and CC data samples. Hence the data

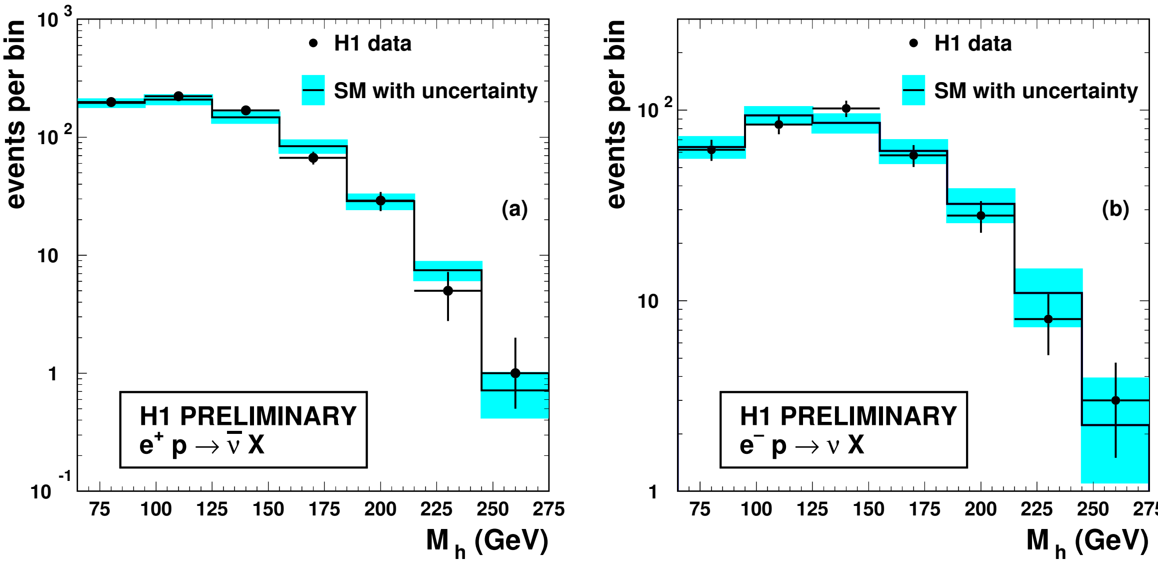

Figure 2: Mass spectra for the events from the CC DIS selection for (a) e^+p and (b) e^-p data (symbols), together with the corresponding DIS expectations (histograms). The grey boxes indicate the $\pm 1\sigma$ uncertainty due to the systematic errors on the CC DIS expectation.

are used to set constraints on LQs which couple to first generation fermions. The e^-p data are used to set constraints on $F = 2$ LQs, and the NC data from both e^+p data sets are used to constrain LQs with $F = 0$.

For both the NC-like and CC-like channels, 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. The signal efficiencies, including the mass bin requirement, vary with the LQ mass between 30% (20%) and 55% (45%) for scalar (vector) LQs decaying into eq, and between 20% and 50% 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 [6], corrected by multiplicative K-factors [7] 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 [8]. 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 $\pm 7\%$ 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 $F = 2$ $(F = 0)$ LQs coupling to e^-u (e^+u), and varies between 7% at low LQ masses up to 50% around 290 GeV for $F = 2$ $(F = 0)$

LQs coupling to e^-d (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 $\pm 7\%$ on the signal cross-section.

The phenomenological model proposed by Buchmüller, Rückl and Wyler (BRW) [6] describes 7 LQs with $F=0$ and 7 LQs with $F=2$. We use here the nomenclature of [9] 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. 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. Table 1 lists the 14 LQ types described by the BRW model.

$F=2$	Prod./Decay	β_e	$F=0$	Prod./Decay	β_e
		Scalar Leptoquarks			
${}^{1/3}S_0$	$e^-_L u_L \to e^- u$	$1/2$	${}^{5/3}S_{1/2}$	$e^+_R u_R \to e^+ u$	1
	$e^-_R u_R \to e^- u$	1		$e^+_L u_L \to e^+ u$	1
${}^{4/3}\tilde{S}_0$	$e^-_R d_R \to e^- d$	1	${}^{2/3}S_{1/2}$	$e^+_L d_L \to e^+ d$	1
${}^{4/3}S_1$	$e^-_L d_L \to e^- d$	1	${}^{2/3}\tilde{S}_{1/2}$	$e^+_R d_R \to e^+ d$	1
${}^{1/3}S_1$	$e^-_L u_L \to e^- u$	$1/2$			
		Vector Leptoquarks			
${}^{4/3}V_{1/2}$	$e^-_R d_L \to e^- d$	1	${}^{2/3}V_0$	$e^+_L d_R \to e^+ d$	1
	$e^-_L d_R \to e^- d$	1		$e^+_R d_L \to e^+ d$	$1/2$
${}^{1/3}V_{1/2}$	$e^-_R u_L \to e^- u$	1	${}^{5/3}\tilde{V}_0$	$e^+_L u_R \to e^+ u$	1
${}^{1/3}\tilde{V}_{1/2}$	$e^-_L u_R \to e^- u$	1	${}^{5/3}V_1$	$e^+_R u_L \to e^+ u$	1
			${}^{2/3}V_1$	$e^+_R d_L \to e^+ d$	$1/2$

Table 1: Leptoquark isospin families in the Buchmüller-Rückl-Wyler model. For each leptoquark, the superscript corresponds to its electric charge, while the subscript denotes its weak isospin. The leptoquarks are conventionally indexed with the chirality of the incoming *electron* which could mediate their production in e^-p collisions.

For LQs with $F=0$, the upper limits on the Yukawa coupling λ at the $e\,q\,\rm LQ$ vertex obtained at 95% confidence level (CL) are shown as a function of the LQ mass in Fig. 3a and Fig. 3b, for scalar and vector LQs respectively. For masses above ~ 270 GeV, these bounds improve by a factor of about 5 the limits obtained in [1] from the analysis of e^+p data at $\sqrt{s_{ep}}=300$ GeV. Constraints corresponding to $F=2$ LQs are shown in Fig. 3c and Fig. 3d. Constraints on LQs with masses above the HERA centre-of-mass energy were set in [1], where the interference between the LQ production and DIS processes was taken into account. These are shown for completeness in Fig. 3 in the rightmost part of each plot. For a Yukawa coupling of electromagnetic strength $\alpha_{\rm em}$ ($\lambda=\sqrt{4\pi\alpha_{\rm em}}=0.3$) this analysis rules out LQ masses below 275 to 290 GeV, depending on the LQ type.

Fig. 4 summarizes the constraints on the $\tilde{S}_{1/2,L}$ and on the $S_{0,L}$ obtained by H1, by the OPAL experiment at LEP [11], and by the Tevatron experiments [12]. For LQ masses above the HERA

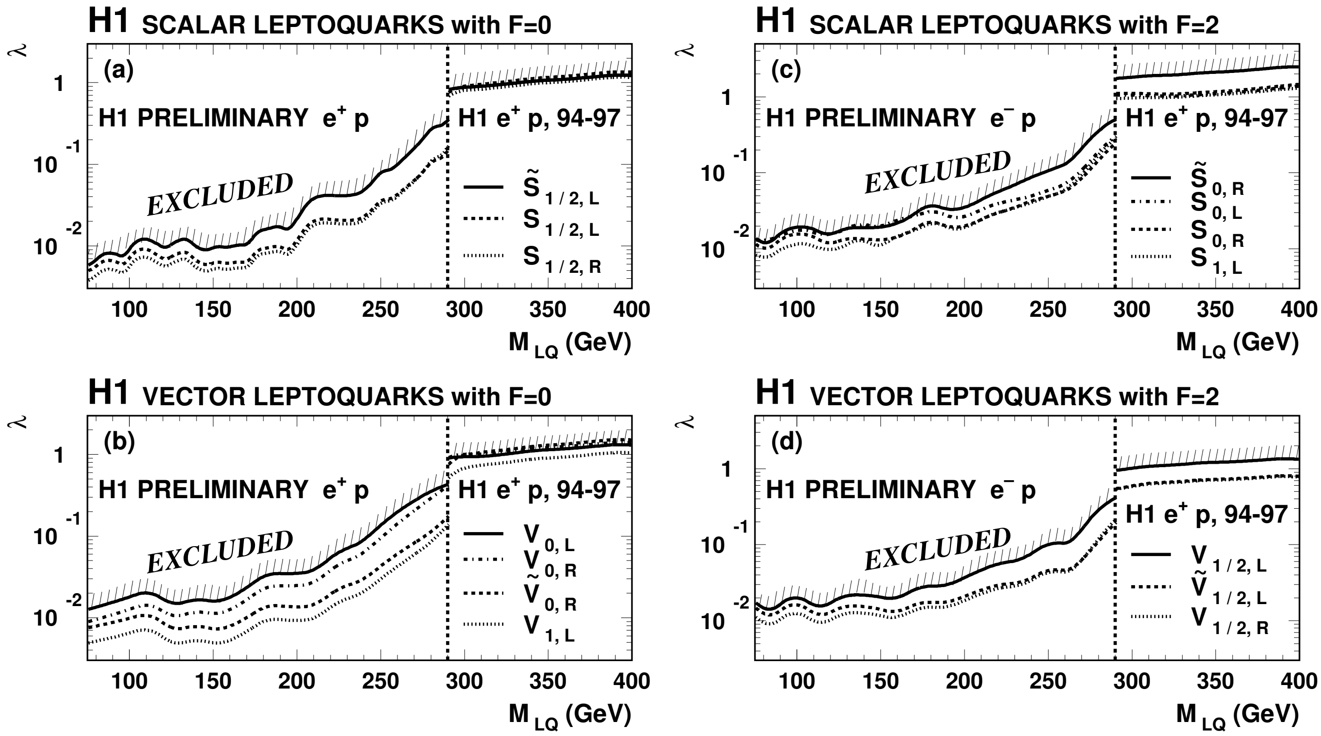

Figure 3: Exclusion limits for the 14 leptoquarks (LQs) described by the BRW model. The limits are expressed at 95% CL on the Yukawa coupling λ as a function of the leptoquark mass for the (a) scalar LQs with $F = 0$, (b) vector LQs with $F = 0$, (c) scalar LQs with $F = 2$ and (d) vector LQs with $F = 2$. Domains above the curves are excluded. Constraints on LQs with masses above the HERA centre-of-mass energy, obtained in [1] using the partial e^+p data sample at $\sqrt{s_{ep}} = 300$ GeV, are shown in the rightmost part of each plot.

centre-of-mass energy, the H1 constraints obtained from a contact interaction approach [10] are also shown.

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. Mass dependent constraints on the LQ branching ratios can then be set for a given value of λ. For a scalar LQ possessing the quantum numbers of the $\tilde{S}_{1/2,L}$ ($S_{1/2,L}$), which couples to e^+d (e^+u), Fig. 5a (Fig. 5b) shows the part of the β_e-$M_{\rm LQ}$ plane which is ruled out, for three values of the Yukawa coupling. The domain excluded by the D0 experiment at the Tevatron [12] is also shown. Fig. 6a shows exclusion areas in the same plane, for a scalar LQ possessing the quantum numbers of the $\tilde{S}_{0,R}$ (which couples to e^-d). 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. 6b. If the LQ decays into eq or νq only[2], the combination of both channels rules out the part of the plane on the left of the middle full curve, for $\lambda = 0.05$.

[2] 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.

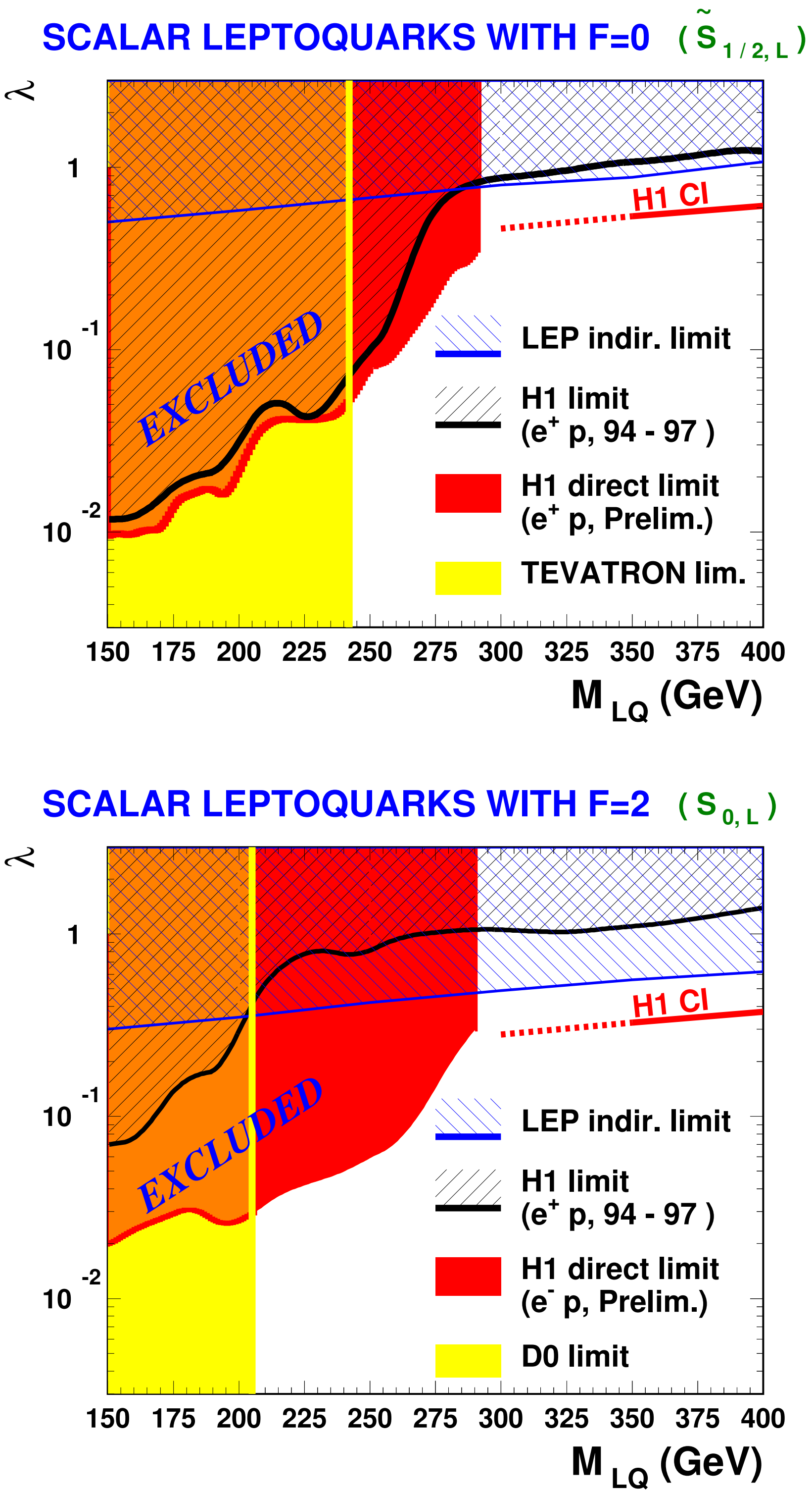

Figure 4: Exclusion limits at 95% CL on the Yukawa coupling λ as a function of the leptoquark (LQ) mass for (top) a scalar LQ with $F = 0$ and (bottom) a scalar LQ with $F = 2$ described by the BRW model. Shaded and hatched domains are excluded.

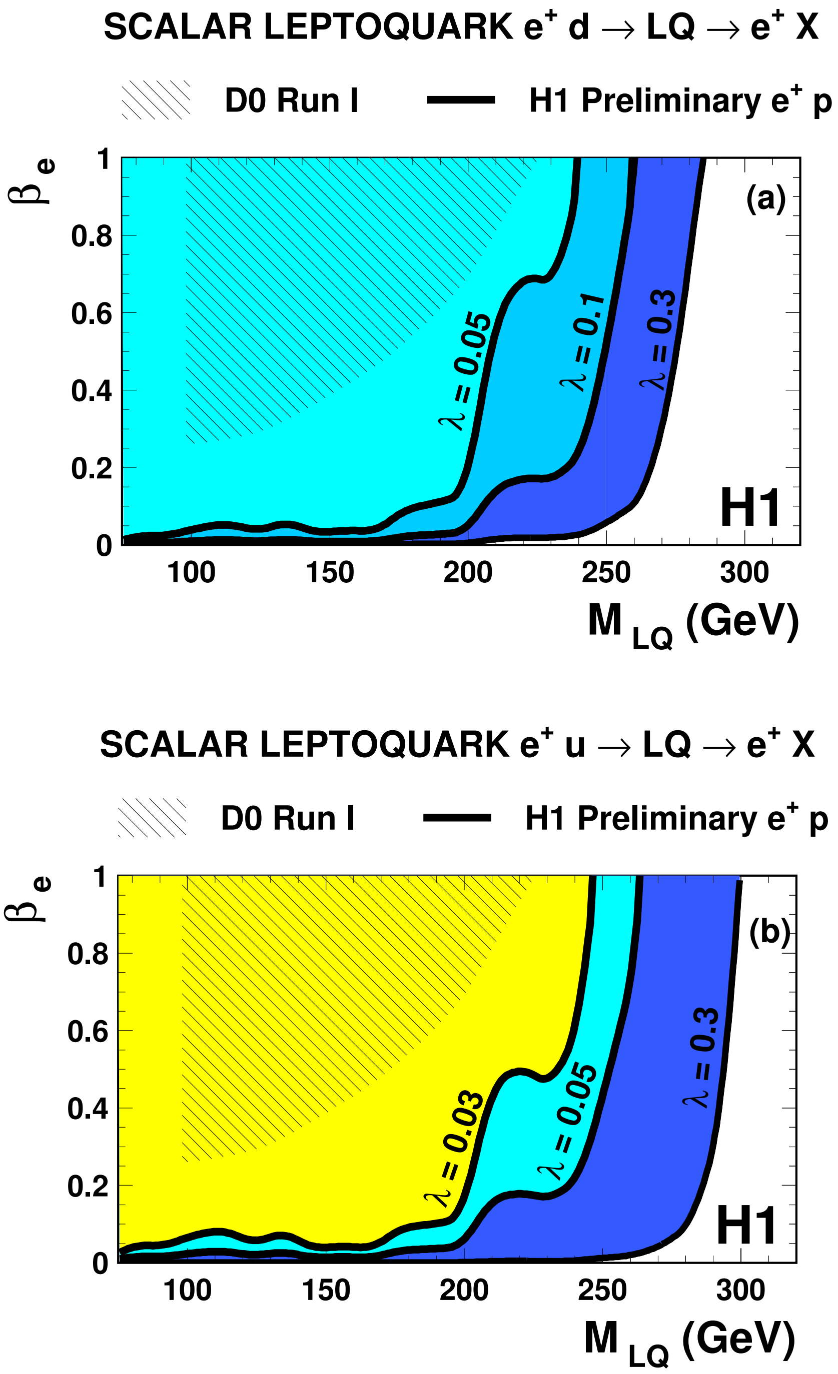

Figure 5: Mass dependent exclusion limits at 95% CL on the branching ratio β_e of a scalar leptoquark (LQ) which couples (a) to e^+d (with the quantum numbers of the $\tilde{S}_{1/2,L}$) and (b) to e^+u (with the quantum numbers of the $S_{1/2,L}$). In (a) and (b), the hatched region represents the domain excluded by the D0 experiment [12].

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 λ greater than ~ 0.03, these extend considerably beyond the region excluded by the D0 experiment [12].

To summarize, a search for resonantly produced leptoquarks has been performed using all e^+p and e^-p data collected by H1 between 1994 and 2000. No signal has been observed and constraints on leptoquarks have been set, which extend beyond the domains excluded by other experiments. For a Yukawa coupling of electromagnetic strength, leptoquark masses up to 290 GeV can be ruled out.

Acknowledgements

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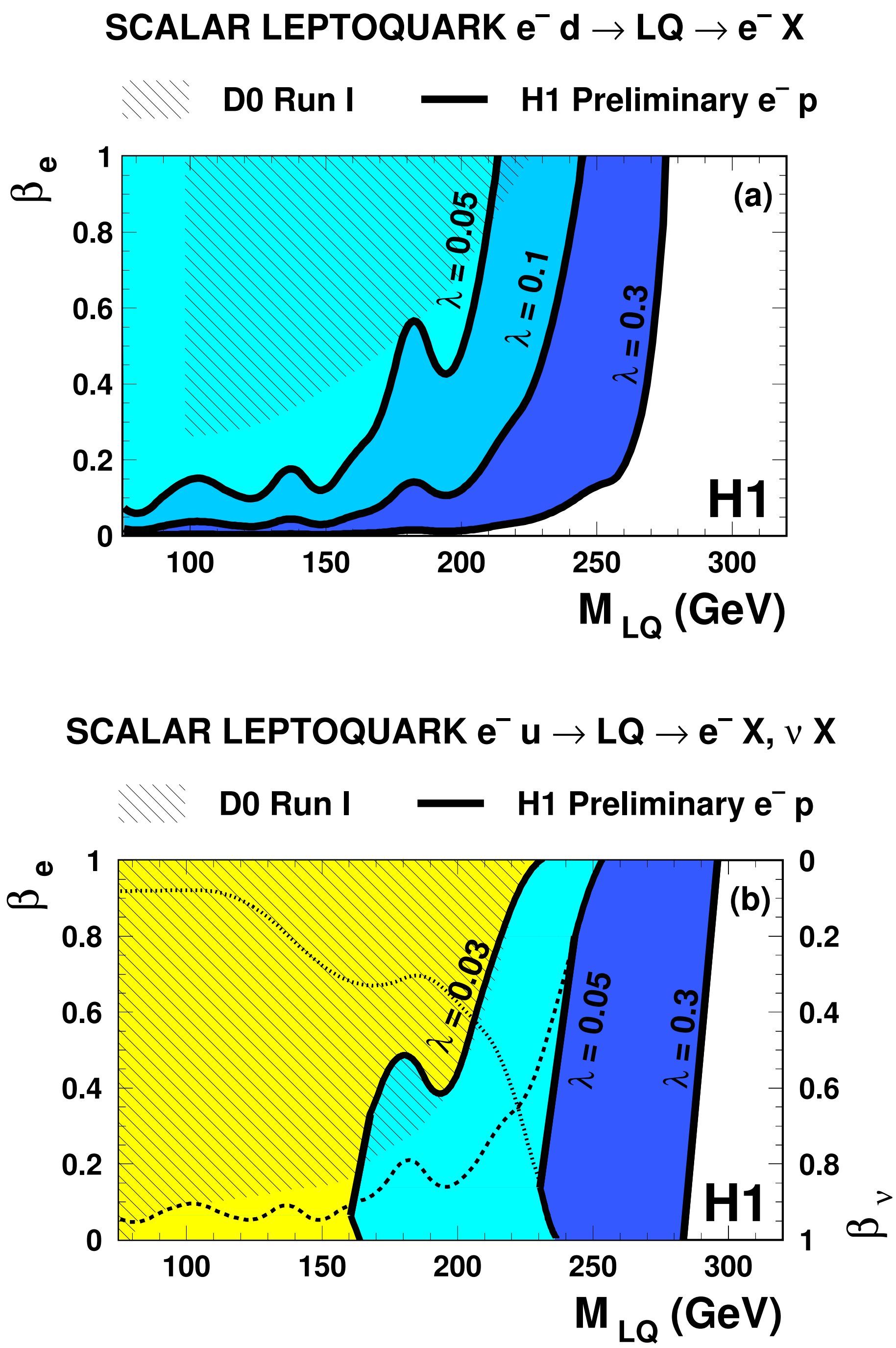

Figure 6: (a) Mass dependent exclusion limits at 95% CL on the branching ratio β_e of a scalar leptoquark (LQ) which couples to e^-d (with the quantum numbers of the $\tilde{S}_{0,R}$). The hatched region represents the domain excluded by the D0 experiment [12]. (b) Domains ruled out by the combination 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 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-$M_{\rm LQ}$ (β_ν-$M_{\rm LQ}$) 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. The hatched region represents the domain excluded by the D0 experiment [12], combining the eq and νq decay modes of the LQ..