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A Search for Leptoquarks in H1 at HERA

H1 Collaboration

Abstract

A search for leptoquarks at HERA was performed in H1 using 1994 e^+p data corresponding to an integrated luminosity of about 3.15 pb $^{-1}$. Single leptoquarks were searched in direct electron-quark fusion processes taking into account possible branching into lepton-quark pairs of either the first or the second generation. No significant deviation from the Standard Model predictions is found in the various final states studied and exclusion limits are derived. Compared to results from the H1 1993 e^- data, a considerable improvement of the exclusion limits is obtained for the leptoquarks which could be produced via e^+-*valence quark* fusion with the e^+ beam in 1994. Leptoquarks coupling to first or second generation lepton-quark pairs with masses up to 200 GeV (depending on the leptoquark flavour) are excluded for coupling strengths weaker than α_{em}.

1 Introduction

The ep collider HERA is particularly suited for the search of leptoquark colour triplet bosons. Such particles appear naturally in various unifying theories beyond the Standard Model (SM) such as Grand Unified Theories and Superstring inspired E_6 models, and in some Compositeness and Technicolour models. They could be singly produced as s-channel resonances at HERA by the fusion of the 27.6 GeV initial state lepton with a quark of the 820 GeV incoming proton.

In this paper we present a search for singly produced leptoquarks in the H1 experiment at HERA. The decays of the leptoquarks in both first or second generation lepton-quark pairs are analysed.

The analysis uses 1994 e^+p data which corresponds to an integrated luminosity of 3.15 pb $^{-1}$, a factor ~ 8 increase compared to the 1993 e^-p data used in our earlier search for leptoquark production [1].

2 Phenomenology

We consider all possible scalar (S_I) and vector (V_I) leptoquarks of weak isospin I with dimensionless couplings $\lambda_{ij}^{L,R}$ to lepton-quark pairs, where ij denotes generation indices and L or R is the chirality of the lepton. Following the phenomenological ansatz of ref. [2] which introduces a general effective Lagrangian obeying the symmetries of the SM, there are 10 different leptoquark isospin multiplets, with couplings to left or right handed fermions [1]. Given the existing stringent constraints from low energy experiments (for a review see [4]), we restrict our search by the following simplifying assumptions:

- Only couplings to lepton-quark pairs of the same generation are considered, i.e. the analysis is restricted to a diagonal coupling matrix where $\lambda_{i=j}$ are the only non-vanishing couplings.
- One of the leptoquark multiplets is produced dominantly.
- The states in the leptoquark isospin doublets and triplets are degenerate in mass.
- Non-vanishing couplings exist only to either left- (λ^L) or right-handed (λ^R) leptons (i.e. $\lambda^L \cdot \lambda^R \sim 0$).
- The only possible decay channels lead to lepton + quark final states.

In practice, the searches are carried out assuming that $\lambda_{11} \neq 0$, leading to a production cross-section scaling approximately in λ_{11}^2 for the electron-quark fusion sub-process. We then treat two cases: 1) $\lambda_{11} \neq 0$ and $\lambda_{22} = 0$ or 2) $\lambda_{11} \neq 0$ and $\lambda_{22} \neq 0$. The second case allows for the striking s-channel lepton flavour violating sub-process $e + q \rightarrow \mu + q'$. In the s-channel, a leptoquark is produced at fixed $\sqrt{sx}$ where $\sqrt{s} \sim 300$ GeV is the energy available in the ep centre-of-mass frame and x is the incoming quark momentum fraction.

[1] A more detailed discussion of the leptoquark classification scheme may be found in our previous publications [1] or in [2, 3].

Hence, besides λ, the production cross-section depends mostly on the quark momentum density in the proton.

When involving first generation fermions, the decay of the leptoquark into a lepton and a jet leads to signatures practically indistinguishable event-by-event from the SM neutral (NC) and charged current (CC) deep inelastic scattering (DIS). Statistically, the new signal may however be discriminated by the presence of a peak in the invariant mass distribution and by the specific angular distribution of the decay products which depends on the spin of the leptoquark. For vectors $d\sigma\,/\,dy \;\sim\; (1-y)^2$ where $y = \frac{1}{2}\,(1 + cos\theta^*)$ corresponds to the Bjorken scattering variable in DIS and θ^* is the decay polar angle in the leptoquark centre of mass (CM) frame. Scalars decay isotropically relative to the boost of their CM frame leading to a constant $d\sigma\,/\,dy$. This is markedly different from the $d\sigma\,/\,dy \;\sim\; y^{-2}$ distribution expected at fixed x for the dominant t-channel photon exchange in neutral current DIS events [2]. The strategy for the leptoquark search is thus to look for DIS–like events at high mass and high y, and to separate them statistically from the standard DIS background. In contrast, the $e + p \rightarrow \mu + X$ process is expected to be essentially background free at high Q^2 ($Q^2 = sxy$).

3 Analysis

For $e+X$ **final states** (where X stands here for any hadronic configuration) a pre-selection is carried which relies essentially on the electron finding and global energy conservation cuts. The event candidates must satisfy the following requirements (see [5] for a description of the relevant detector components):

1. A primary vertex in the range [3] $\mid z - \bar{z} \mid < 35$ cm with $\bar{z} = 3.4$ cm.

2. An electron with $E_{T,e} = E_e \sin\theta_e > 7$ GeV and $10^\circ \leq \theta_e \leq 145^\circ$ (a range covered by the H1 LAr calorimeter). There must be either only one electron candidate or the candidate with highest $E_{T,e}$ must be at largest polar angle.

3. A total missing transverse momentum $P_{T,miss} \approx \sqrt{(\sum E_x)^2 + (\sum E_y)^2} \leq 15$ GeV summed over all energy depositions in the calorimeters.

4. A minimal loss of longitudinal momentum in the direction of the incident electron; i.e. $43 \leq \sum (E - p_z) \leq 63$ GeV .

5. Less than 5 GeV in total in the backward calorimeters ($\theta \lesssim 152^\circ$).

6. The scaling variable y_e must satisfy $0.05 < y_e < 0.95$.

7. In case two electron candidates are found, these two candidates should not be balanced in $E_{T,e}$ and in azimuth, i.e. $E^1_{T,e}/E^2_{T,e} > 1.25$ and $\mid \Delta\phi_{1,2} - 180^\circ \mid > 2^\circ$.

[2] At high momentum transfer Z^0 and W exchanges become more important and contribute to less pronounced differences between signal and background.

[3] The incoming proton moves by definition in the forward (i.e. $z > 0$) direction with $\theta = 0^\circ$ polar angle.

8. Be accepted by LAr hardware triggers which use energy summed in coarsely segmented trigger readout towers [1] and be properly timed relative to interacting bunch crossings.

Cut (1) mainly suppresses beam–wall, beam–residual gas and background from cosmic rays. Cuts (2), (3) and (4) provide a powerful rejection of photoproduction contamination and eliminate DIS charged current events. Cut (4) also suppresses DIS NC-like events with a very hard γ emitted from the initial state electron. Cut (5) further suppresses DIS (or photoproduction) events at small momentum transfer with a misidentified electron in the LAr calorimeter. Cut (6) avoids the high y_e region where largest radiative corrections are expected and the low y_e region where the y_e and M_e resolutions severely degrade. Cut (7) removes QED Compton events. Finally, the requirement (8) ensures reliable control of event filtering efficiencies.

The electron identification which relies on electromagnetic shower estimators and an isolation criteria was described in [1]. For the isolation, we require that there be less than 10% additional energy in a cone centered on the electron pseudorapidity η_e and azimuth ϕ_e of opening $\sqrt{(\Delta\eta_e)^2 + (\Delta\phi_e)^2} < R$ where R=0.25. For the proper tagging of the final state electrons in DIS NC-like events at high Q^2, the identification criteria need not be too severe. Sufficiently loose criteria are moreover justified, in particular in the forward region, by the necessity to avoid efficiency losses for the leptoquark signal in $M_e - y_e$ regions where the DIS NC background becomes vanishingly small.

In total, 1822 NC-like events satisfy all above requirements in the relevant mass range at $M_e > 45$ GeV where M_e is reconstructed from the final state electron energy E_e and angle θ_e as

$$M_e = \sqrt{s x_e} = \sqrt{\frac{Q_e^2}{y_e}}, \quad Q_e^2 = \frac{E_{T,e}^2}{1 - y_e}, \quad y_e = 1 - \frac{E_e - E_{z,e}}{2E_e^0},$$

where E_e^0 is the incident electron beam energy.

In order to compare with SM expectations for DIS NC, we make use of a Monte Carlo event generator [6], which includes the lowest order electroweak scattering process with QCD corrections to first order in α_s, complemented by leading-log parton showers and fragmentation [7]. The parton densities in the proton used throughout are taken from the MRS H parametrization which is close to recent F_2 structure function measurements at HERA (see [8]). All simulated events were passed through a detailed Monte Carlo program of the H1 detector including all acceptance, resolutions and efficiencies and the same reconstruction and analysis programs were used as for data. We estimate a mean expected background of 1867.5 ± 28.3 events. This is compatible within 1σ with the 1822 events observed in our single measurement. At largest masses, $M_e > 150$ GeV , 43 events are observed in excellent agreement with the SM mean of 41.3 ± 4.3 expected.

We further investigated possible contamination from direct and resolved photoproduction events of light and heavy quarks. This was studied on the one hand by looking for events with an electron tagged in the H1 luminosity detector when removing cut (5). This detector has an acceptance of $\sim 15\%$ for photoproduction events with comparable total transverse energy. No such events are found in the data. On the other hand, an upper limit on the contamination was also derived from Monte Carlo studies based on

the generator [7]. The parton densities in the photon are taken from the GRV-G LO parametrization [9]. We estimate the contamination to be $< 0.7\%$ for $\gamma + p \rightarrow jet + jet$ (direct and resolved photon processes) and $< 0.6\%$ from heavy flavour pair production by boson–gluon fusion processes.

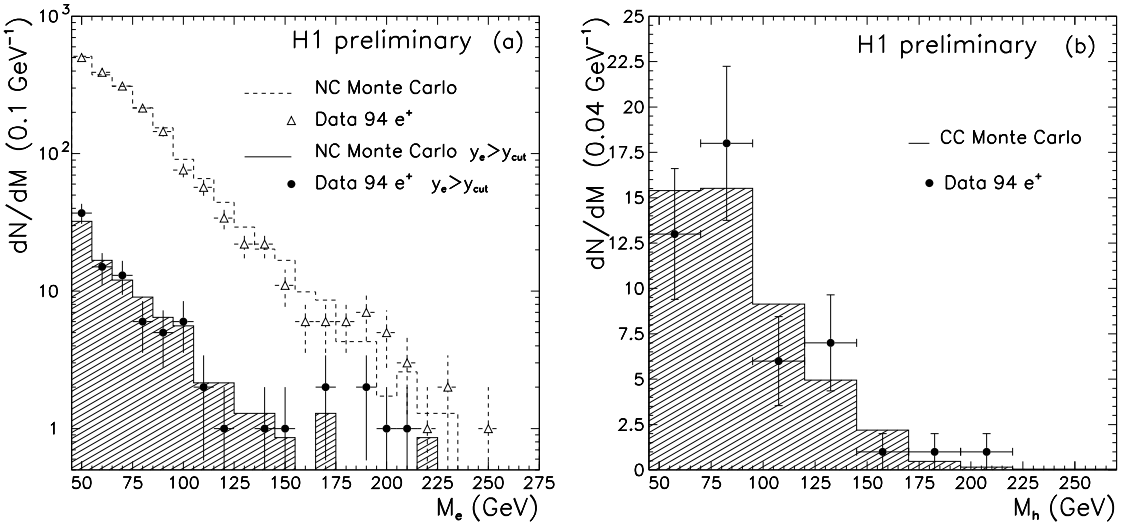

Figure 1: Mass spectra for $e + X$ (a) and $\nu + X$ (b) final states for data (closed points) and DIS Monte Carlo (shaded histograms). Also shown is the data (open triangles) and DIS NC Monte Carlo (dashed histogram) compared before the final y_e cut (see text).

The comparison of the measured data and DIS NC predictions is shown in the mass spectra of Fig. 1a. The measured mass spectrum is seen before and after having applied a mass dependant y_e cut which ranges from 0.5 around $M_e = 45$ GeV to 0.10 around $M_e = 250$ GeV , and which is designed to optimize the signal significance for scalar leptoquark searches. In both cases the SM model expectations are in excellent agreement with the data. After the y_e cut, we observe 94 events while 93.3 ± 6.3 events are expected for $e + X$ data at $M_e > 45$ GeV . At large masses, $M_e > 100$ GeV , 13 events are observed in good agreement with the mean SM expectation of 13.8 ± 2.4. At largest masses, $M_e > 150$ GeV , 7 events are observed in agreement with the mean expectation of 3.9 ± 1.3.

For $\nu + X$ **final states** the pre-selection mainly relies on the absence of an electron candidate and large missing momenta. Here also, we essentially follow the prescription of our previous paper [1]. The event candidates must satisfy the following requirements:

1. A primary vertex in the range $\mid z - \bar{z} \mid < 27$ cm with $\bar{z} = 3.4$ cm.
2. No electron satisfying the above requirements.
3. $P_{T,miss} > 15$ GeV .

4. The total transverse energy $E_T \approx \sum \mid \vec{P}_T \mid$ should match the total missing transverse momentum $P_{T,miss}$ such that $(E_T - P_{T,miss})/E_T < 0.5$.

5. The event must survive a set of halo and cosmic muon filters.

6. At least one charged track linked to the primary vertex over the angular range $7^\circ \leq \theta \leq 155^\circ$ covered by the central and forward tracking in H1 [1] (at least three when $\theta \geq 35^\circ$).

7. Be accepted by LAr hardware triggers which use energy summed in coarsely segmented trigger readout towers [1] and be properly timed relative to interacting bunch crossings.

Cut (1) is made slightly more severe than for $e + X$ final states given the absence of kinematical constraint that was provided by the electron versus hadronic measurements. Cuts (2), (3) and (4) provide a powerful rejection of photoproduction contamination and eliminate DIS NC events. Cuts (5) and (6) reject halo and cosmic muons. Here also the requirement (7) ensures reliable control of event filtering efficiencies. Finally, the events are visually scanned to remove obvious remaining cosmic events.

In total, 47 CC-liked events satisfy all above requirements in the relevant mass range at $M_h > 45$ GeV where M_h is reconstructed by summing over all visible final state "hadrons":

$$M_h = \sqrt{\frac{Q_h^2}{y_h}}, \quad Q_h^2 = \frac{P_{T,miss}^2}{1 - y_h}, \quad y_h = \frac{\sum (E - p_z)}{2E_e^0}.$$

This is in excellent agreement with SM expectation of 47.9 ± 1.4 events obtained using the Monte Carlo event generator [10] which includes all radiative channels and QCD dipole parton showers. The mass spectra for the measured data and DIS CC Monte Carlo predictions shown in Fig. 1b are in excellent agreement over the full mass range.

For $\mu + X$ **final states** we can make use of the CC-liked event sample since such events are characterized by a large $P_{T,miss}$ when calculated from calorimetry. Such $P_{T,miss}$ is only slightly affected by the minimal energy deposition of the muon. In addition, we require :

1. A charged track of more than 100 MeV linked to the primary vertex must be found in a $\theta - \phi$ cone of 15° centered on the muon angles deduced from the kinematical constraints using the hadronic flow.

The efficiency to find the charged track in cut (1) was derived from the $e + X$ event sample searching for the electron track candidate when applying the same criteria as above. This efficiency is found to be $\sim 70\%$ for masses in the range $45 \leq M_h \leq 225$ GeV . Higher masses lead to a charged lepton falling out of the range where such an empirical determination of the efficiency could be made.

We observe no candidate satisfying the $\mu + X$ selection [4].

[4]It should be noted that the $e^+p \to \mu^+X$ event observed by H1 and discussed in [11] does not (by far) satisfy the kinematical constraints of a $eq \to LQ \to \mu q'$ event.

4 Results

In absence of significant deviation from the SM expectations, we now derive rejection limits for the Yukawa couplings as a function of mass. For each contributing channel, we use the number of observed events, the signal detection efficiencies and the expected number of background events within a mass bin which slides over the accessible mass range. The statistical procedure which folds in channel per channel the statistical and systematic errors is described in detail in [1]. The signal detection efficiencies are typically determined over a coupling-mass grid with steps in mass of 25 GeV and for coupling values corresponding roughly to the expected ultimate sensitivity. Detailed Monte Carlo simulation of about 500 events per point on the grid is performed followed by the application of the full analysis chain.

For **Monte Carlo** simulation of the searched leptoquark signals, we make use of the event generator of ref. [12] which was described in more details in [1] and which takes into account initial state QED radiation and QCD corrections in the initial and final state and properly corrects the kinematics at the decay vertex for effects of the parton shower masses. The efficiencies for the detection of leptoquark decays in the $LQ \to eq$ channel only weakly depend on the leptoquark mass. For scalar leptoquarks, these range from 29% at 45 GeV to 56% at 150 GeV in the middle of the mass range considered here. These figures include the effect of the mass dependent y_e cut ($y_e > 0.5$ at 45 GeV and $y_e > 0.35$ at 150 GeV) and the finite width of the sliding mass bin which is chosen to contain about 68% of the signal at a given mass. For vector leptoquarks, the comparable efficiencies range from 29% at 45 GeV ($y_e > 0.25$) to 52% at 150 GeV ($y_e > 0.20$). For the leptoquark decays in the $LQ \to \nu q$ channel, the efficiencies range from 34% at 45 GeV to 61% at 150 GeV for scalar leptoquarks and from 33% at 45 GeV 52% at 150 GeV for vector leptoquarks. In the decay channel $LQ \to \mu + X$, these numbers are further multiplied by the factors of about 70% from the "muon track" identification efficiency.

Systematics errors come from the uncertainty on the luminosity measurement (2%), the absolute energy calibration (which gives an uncertainty on the background estimation of 10%), the choice of the scale entering the structure function calculation (leads to $\approx 7\%$ uncertainties in the cross-section) and the choice of the parton density parametrization.

The exclusion limits obtained on the coupling $\lambda = \lambda_{11}$ at 95% confidence level (CL) are shown in Fig. 2 as a function of the leptoquark mass. The derivation combines the two decay channels (when relevant) with branching ratios determined from the theory [2].

For leptoquarks which in the s-channel are produced by the fusion of the e^+ with a $\bar{q}$, the exclusion domain is only slightly improved compared to our previously published results based on 1993 e^- beam data [1]. On the contrary, considerable improvement is obtained for other leptoquarks which can be produced in a e^+-*valence quark* fusion. At $M = 150$ GeV , in the middle accessible mass range, the exclusion domain is extended by more than an order of magnitude. This is partly thanks to the increase of integrated luminosity and partly thanks to the valence versus sea quark momentum densities in the proton. For these most favorable cases (Fig. 2c and d), leptoquarks with masses up to about 250 GeV are excluded for coupling strengths $\lambda_{11}^2/4\pi$ weaker than α_{em}. Coupling strengths down to an order of magnitude weaker than α_{em} are excluded for leptoquarks of masses up to 200 GeV .

The excluded domain in the mass-coupling plane extends beyond the mass range covered by the published results from the D0 experiment at the TEVATRON [13] which excludes at 95% level scalar leptoquarks with masses below 116 (130) GeV and vector leptoquarks with masses below 180 (190) GeV with branching ratio 0.5 (1.0) into electron and quark. These limits are essentially independent of the Yukawa couplings probed at HERA. On the other hand the production of vector leptoquarks from virtual gluons there depends on assumptions of the size of their anomalous coupling to gluons.

For leptoquarks possessing a coupling λ_{11} to first generation lepton-quark pairs as well as a coupling λ_{22} to second generation lepton-quark pairs, the exclusion limits at 95% CL are plotted in terms of the product $\lambda_{11} \times Br_{\mu}^{1/2}$ in Fig. 2; $Br_{\mu} = \lambda_{22}^2/\left(\lambda_{11}^2 + \lambda_{22}^2\right)$ is the branching fraction into $\mu + X$ final states. The limits are plotted for the four leptoquark types for which a non-vanishing coupling product $\lambda_{11} \times \lambda_{22}$ is not definitly excluded from the reach of HERA from indirect searches [4]. For $\lambda_{11}^2 \times Br_{\mu}/4\pi = \alpha_{em}$ in Fig. 2, masses up to 250 GeV (depending on the leptoquark flavour) are excluded.

In comparison, the published results from the CDF experiment at the TEVATRON [14] excludes at 95% level second generation leptoquarks with masses below 98 (133) GeV with branching ratio 0.5 (1.0) into $\mu + q$ pairs.

5 Conclusions

We have searched for leptoquarks coupling to either the first or to both first (λ_{11}) and second (λ_{22}) generation lepton-quark pairs. No evidence for the resonant production of such new particles was found and mass dependant exclusion limits at 95% confidence level were derived for the couplings.

Leptoquarks with masses up to about 250 GeV (depending on the leptoquark flavours) are excluded for coupling strengths weaker than α_{em}. For some of the leptoquark flavours, the exclusion domain extends down in coupling strength to more than an order of magnitude below our previously published results, and far beyond the mass reach of other existing colliders.

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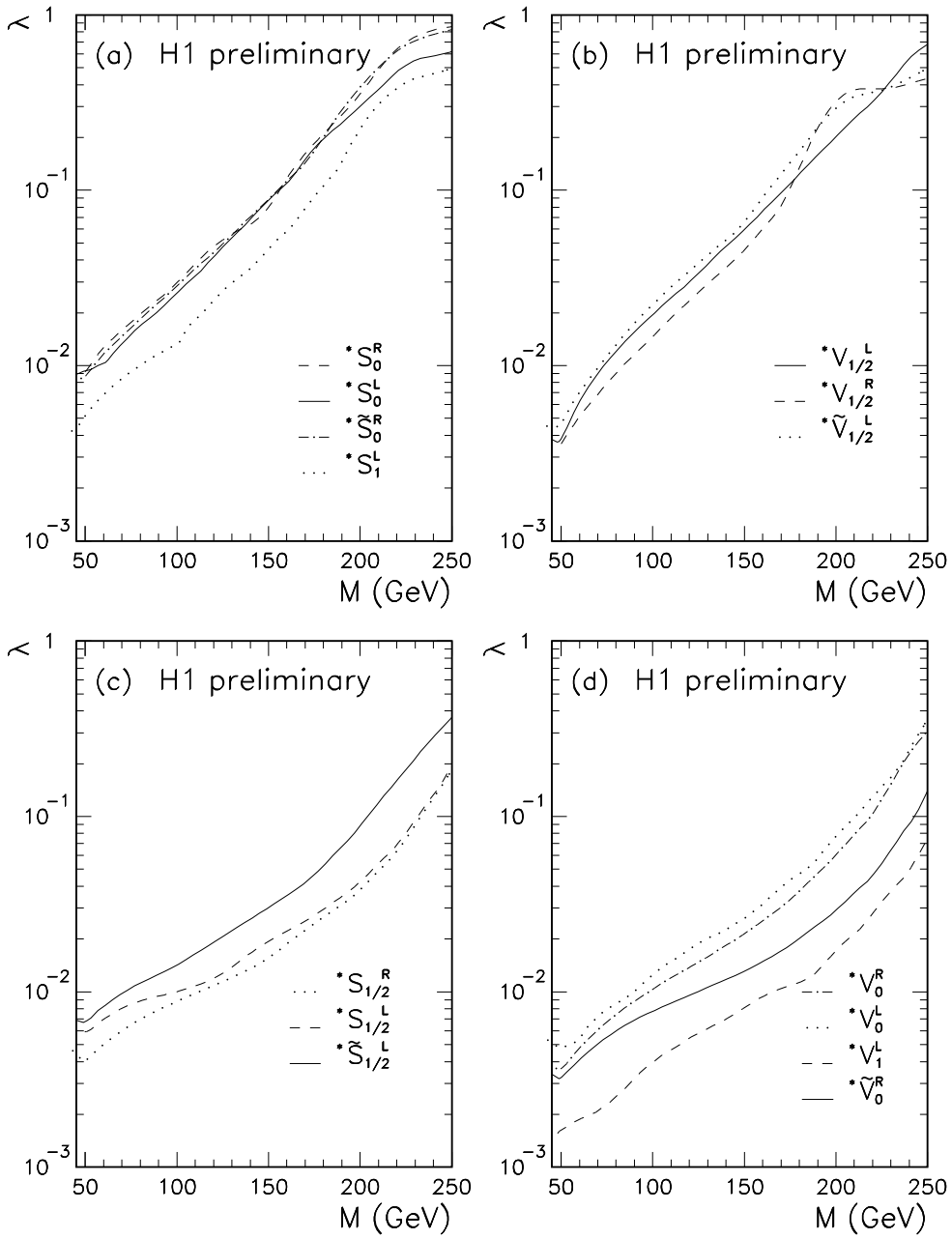

Figure 2: Upper limits at 95% CL as a function of mass on the coupling $\lambda^{L,R}$ for scalar and vector leptoquarks decaying into lepton+$\bar{q}$ (a,b) and lepton+q (c,d).

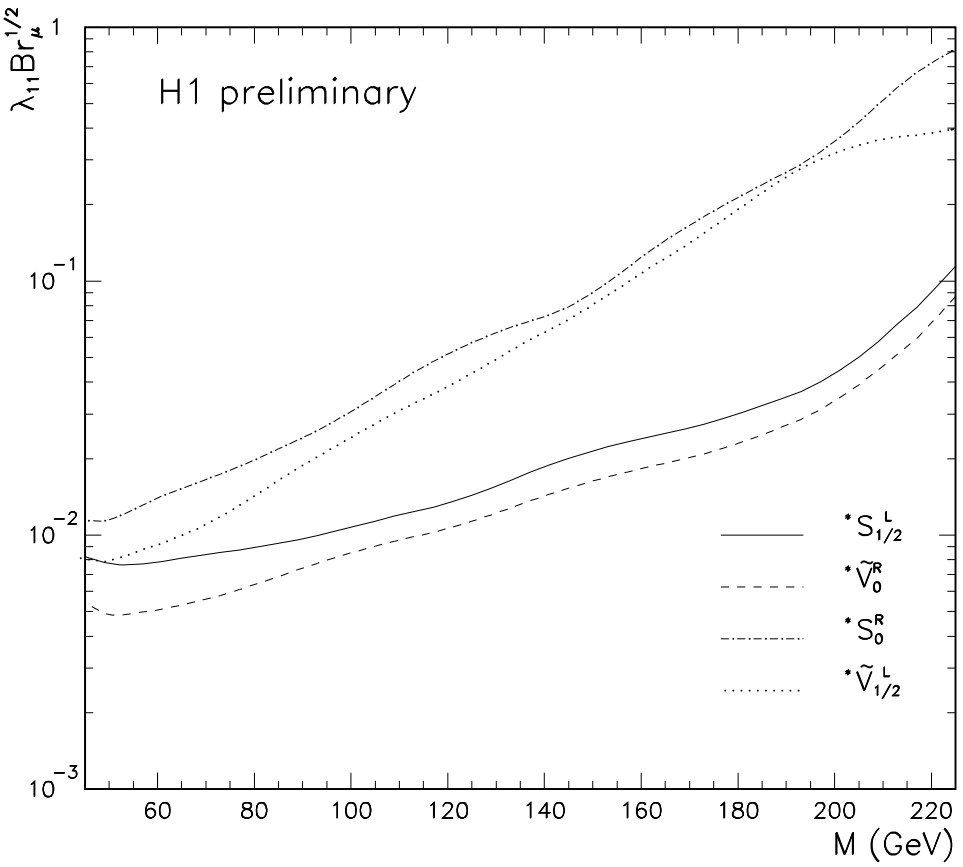

Figure 3: Upper limits at 95% CL on the product $\lambda_{11} \times Br_\mu^{1/2}$ as a function of mass for four scalar or vector leptoquarks decaying into $\mu + q$ or $\mu + \bar{q}$.