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Search for leptoquarks in *ep* collisions at HERA

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Abstract

A search for leptoquarks in the $e^{\pm}(\nu, \bar{\nu})$-jets invariant-mass spectrum has been performed in the reaction $e^{\pm}p \rightarrow e^{\pm}(\nu, \bar{\nu})X$ with the ZEUS detector at HERA using an integrated luminosity of 130 pb^{-1}. The data were taken at center-of-mass energies of 300 and 318 GeV. No evidence for a leptoquark was found. Using a two-dimensional likelihood method, limits were set on the coupling strength in leptoquark models for leptoquark masses up to 400 GeV.

1 Introduction

HERA collides electrons (positrons) with protons at center-of-mass energies $\sqrt{s} \simeq 300{,}318$ GeV. At this high energy, interactions due to physics beyond the Standard Model (SM) may manifest themselves. Some of these models based on new physics predict the existence of resonant states carrying both baryon and lepton numbers, such as leptoquarks (LQ) [1] or squarks (in R-parity-violating supersymmetry) [2]. At HERA, these resonant states may be produced directly through $e^{\pm}$-quark fusion. They decay into $e^{\pm}$-quark, or $\nu(\bar{\nu})$-quark, yielding a peak in the lepton-jet invariant-mass spectrum for the $e^{\pm}p \rightarrow e^{\pm}(\nu)X$ reactions. Therefore, the search for these states was carried out by studying the final-state lepton-jet invariant mass in two channels: neutral current (NC) deep inelastic scattering (DIS), and charged current (CC) DIS.

The implications of this search are evaluated with the Buchmüller-Rückl-Wyler (BRW) LQ model. This model classifies 14 possible LQ species with $SU(3) \times SU(2) \times U(1)$ invariant couplings, seven of which have fermion number F=0 (F=3B+L, with B the baryon number and L the lepton number) and the remaining seven have F=2. For each LQ species, the branching ratios to NC-like decays and CC-like decays are fixed. Most LQs decay 100% into electron (positron) and quark, and were sought in the NC channel. Four kinds of LQs decay 50% into electron (positron) and quark, 50% into neutrino (antineutrino) and quark, and were searched for in both NC and CC channels.

This search extends previous ZEUS analyses [3, 4], and includes all data collected by the ZEUS experiment from 1994 to 2000. The $e^{+}p$ data collected during 1994-1997, with proton beam energy of 820 GeV and electron beam energy of 27.5 GeV, correspond to an integrated luminosity of 48.3 pb^{-1}. With the proton beam energy increased to 920 GeV, ZEUS collected 16.3 pb^{-1} of $e^{-}p$ data during 1998-1999 and 68 pb^{-1} of $e^{+}p$ data during 1999-2000.

2 Experimental Condition and MC Simulation

The ZEUS detector is described in detail elsewhere [5]. The main components used in the present analysis are the central tracking detector (CTD) [6] positioned in a 1.43 T solenoidal magnetic field and the uranium-scintillator sampling calorimeter (CAL) [7], composed of 3 parts: forward (FCAL)[1], barrel (BCAL) and rear (RCAL) ones. The CAL energy resolution, as measured under test beam conditions, are $\sigma(E)/E$=0.18/$\sqrt{E}$ for electrons [2] and $\sigma(E)/E$=0.35/$\sqrt{E}$ for hadrons (E in GeV). The CTD covers the polar angle $15° < \theta < 164°$. The transverse momentum resolution for the full-length tracks is $\sigma(p_T)/p_T$ =0.0058 $p_T\oplus$ 0.0065$\oplus$ 0.0014/p_T.

For this analysis, the jet energy was measured in the CAL with a resolution of $\sigma(E_j) = 0.66\sqrt{E_j} \oplus 0.033E_j$, while the jet angle resolution is well parameterized as $0.016\theta_j \oplus 0.018\sqrt{\theta_j}$ rad. In the NC channel, the electron has an energy resolution of $\sigma(E_e) = 0.24\sqrt{E_e} \oplus 0.036E_e$ from the CAL and the angular resolution from the combined measurement of the CAL and CTD is 2.6 mrad. The luminosity was measured from the rate of the bremsstrahlung process $e^+p \rightarrow e^+p\gamma$ [8] and has an uncertainty of 1.6 %. A three-level trigger was used to select events online.

Background events from the Standard Model NC and CC DIS were simulated with DJANGOH 1.1 [9], which includes an interface to HERACLES 4.6.2 [10] for the simulation of electroweak radiative effects. The hadronic final state was simulated using the MEPS model of LEPTO 6.5 [11]. The CTEQ5D parton distribution set [12] was used to evaluate the nominal SM cross section. Simulated resonant-state events were generated using PYTHIA 6.1 [13]. Generated events were passed through a GEANT 3.13-based simulation [14] of the ZEUS detector. The same trigger and offline processing requirements as used for the data were applied to the simulated events.

3 Data Selection and Reconstruction

Since a leptoquark signal event has the same final state as an SM NC or CC DIS event, the selection is similar to that used in the SM NC and CC cross section measurement [15,16].

In the NC channel, where the LQ decays into $e^{\pm}q$, the events were required to have total transverse energy $E_T > 60$ GeV. An identified electron was required to have energy $E_e > 25$ GeV and to be well contained in FCAL or BCAL ($\theta_e < 126°$). At least one hadronic jet with transverse momentum $P_T^j > 15$ GeV, found using the longitudinally invariant k_T clustering algorithm [17] in inclusive mode [18], was required to be outside a box of 60×60 cm^2 centred around the proton beam in the FCAL, in order to ensure

[1] The ZEUS coordinate system is a right-handed Cartesian system, with the Z axis pointing in the proton beam direction, referred to as the "forward direction", and the X axis pointing left towards the center of HERA. The coordinate origin is at the nominal interaction point. The pseudorapidity is defined as $\eta = -\ln(\tan\frac{\theta}{2})$, where the polar angle, θ, is measured with respect to the proton beam direction.

[2] Unless otherwise specified, 'electron' refers to both positron and electron.

good energy containment. The quantity $\delta = \sum_i (E_i - E_i \cos\theta_i) = \sum_i (E_i - P_{Zi})$, where the sum runs over all CAL energy deposits, E_i, with polar angle θ_i, was required to be within 40 to 70 GeV, to avoid large QED initial-state radiation (ISR). Energy-momentum conservation implies that the invariant mass of the electron and the jets can be calculated as $M_{CJ} = \sqrt{2E_e(E + P_Z)}$, where $E + P_Z$ is calculated by summing over the scattered electron and all the jets with pseudorapidity $\eta < 3$ and $P_T^j > 15$ GeV. The resolution of the reconstructed mass changes from 4.5% to 4% when the LQ mass increases from 150 GeV to 290 GeV.

In the CC channel, where the LQ decays into ν $(\bar{\nu})$ q, the events were required to have missing transverse momentum $\not{P}_T > 20$ GeV and at least one jet with transverse momentum P_T^j >10 GeV and η_j <3. Assuming that all the missing momentum is carried away by one neutrino, the neutrino energy and angle can be calculated as:

$$\begin{aligned} E_\nu &= \frac{\not{P}_T{}^2 + (E - P_Z)_\nu^2}{2 \cdot (E - P_Z)_\nu} \\ \cos\theta_\nu &= \frac{\not{P}_T{}^2 - (E - P_Z)_\nu^2}{\not{P}_T{}^2 + (E - P_Z)_\nu^2} \end{aligned}$$

where $(E - P_Z)_\nu = 2E_e - (E - P_Z)$. The invariant mass of the ν-jet system, $M_{\nu js}$, was calculated using the sum of the 4-momenta of the neutrino and all the jets with $P_T^j > 10$ GeV and pseudorapidity $\eta_j < 3$. The resolution of the reconstructed mass varies from 7% to 4.5% as the LQ mass increases from 150 GeV to 290 GeV.

4 Results

After the selection, 21509 events remained while 21445 events were expected in the NC channel from the SM MC simulation; in the CC channel, 2536 events were observed while 2586 events were expected. Figure 1 shows the invariant-mass spectra in the NC channel from e^+p and e^-p samples, respectively. Also shown are the ratio of the data to the SM MC expectations and the uncertainties on the MC expectations. The uncertainty is dominated by the uncertainties on the calorimeter energy scale and the parton density inside the proton and changes from $\sim$ 10% to $\sim$ 25% as the invariant mass increases from 200 GeV to 280 GeV. The uncertainty on the parton density was calculated using Botje's PDF fit [19]. Figure 2 shows the results from the CC channel. The uncertainty on the expectations is similar to that in the NC channel. In all the samples, the SM MC simulation describes the observed mass spectra very well.

Since there is no evidence for a narrow resonance in the lepton-jet mass spectra, limits were set on leptoquark production. A new method, based on a two-dimensional likelihood in the mass-$\cos\theta^*$ plane, was developed to obtain limits on the Yukawa coupling strength, λ, as a function of the LQ mass (θ^* is the angle between the incoming and outgoing leptons in the lepton-jet center-of-mass frame.). The limit on λ was obtained using a Bayesean integration over the likelihood with a prior assumption of flat λ^2 distribution. Taking into account the full SM+LQ cross section, including interference, it was possible to extend the limits on the LQ masses up to and beyond the HERA center-of-mass energy.

By using both the NC and CC channels, stringent limits could be set on those leptoquark types decaying both to eq and to $\nu q'$. This is shown in Figure 3 for the leptoquark S_0^L, which decays 50% to e^-u and 50% to νd. The limits from the NC channel only, from the CC channel only and from the combined channels are compared and shown in the plot. The limits from OPAL [20] and D0 [21] are also shown in the plot. For this leptoquark type, ZEUS sets stronger limits than OPAL. The limits for the Tevatron are independent of λ, and are 213 GeV for CDF and 225 GeV for D0 under the assumption that the leptoquark decays 100% through the NC channel. However, these limits depend on the decaying branching ratio. For the leptoquark decaying 50% through the NC channel, the D0 limit decreases to 203 GeV.

The limits for the 14 LQs are shown in Figure 4. At leptoquark masses of 400 GeV, where the interference term between the LQ and SM becomes important, most LQs are excluded with coupling strength $\lambda \geq 0.5$. The LQ mass limits for λ=0.1 are shown in Table 1. The leptoquark-exclusion region extends up to 283 GeV.

5 Conclusion

A search for a resonance decaying into a lepton and jets has been carried out. The invariant mass of the final-state lepton plus jets was directly calculated from the measured energies and angles of the lepton and the jets. No evidence was found for resonance production, either in the NC channel or in the CC channel. Therefore, limits were set on the coupling strength λ of the BRW LQs as a function of the LQ mass for leptoquarks coupling to $e^{\pm}$ and valence quarks. A new two-dimensional likelihood method was developed that allows the LQ-coupling limit to be extended beyond the HERA kinematic limit. At $\lambda = 0.1$, some LQs with mass up to 283 GeV were excluded.

References

[1] W. Buchmüller, R. Rückl and D. Wyler, Phys. Lett. B191 (1987) 442.

[2] J. Butterworth and H. Dreiner, Nucl. Phys. B397 (1993) 3, and references therein.

[3] ZEUS Collaboration, J. Breitweg et al., Eur. Phys. J. C16 (2000) 253.

[4] ZEUS Collaboration, J. Breitweg et al., Phys. Rev. D63 (2001) 052002.

[5] ZEUS Collaboration, "The ZEUS Detector", Status Report 1993, DESY 1993

[6] N. Harnew et al., Nucl. Inst. Methods A279 290 (1989);
B. Foster et al., Nucl. Phys. B (Proc. Suppl.) 32 181 (1993);
B. Foster et al., Nucl. Inst. Methods A 338 254 (1994).

[7] M. Derrick et al., Nucl. Inst. Methods A309 77 (1991);
A. Andresen et al., Nucl. Inst. Methods A309 101 (1991);
A. Caldwell et al., Nucl. Inst. Methods A321 356 (1992);
A. Bernstein et al., Nucl. Inst. Methods A336 23 (1993).

[8] J. Andruszków et al., DESY 92-066 (1992); ZEUS Collab., M. Derrick et al., Z. Phys. C63 391 (1994)

[9] A. Kwiatkowski, H. Spiesberger and H.-J. Möring, Comp. Phys. Commun. 69 155 (1992).

[10] G. A. Schuler and H. Spiesberger, in *Proc. Workshop on Physics at HERA*, ed. W. Buchmüller and G. Ingelman, DESY, 1991, p. 23; K.C. Hoeger, in *Proc. Workshop on Physics at HERA*, ed. W. Buchmüller and G. Ingelman, DESY, 1991, p. 43.

[11] G. Ingelman, A. Edin and J. Rathsman, Comp. Phys. Comm. 101 (1997) 108.

[12] H. L. Lai et al., Eur. Phys. J. C 12 (2000) 375.

[13] C. Friberg, E. Norrbin and T. Sjöstrand, Phys. Lett. B403 329 (1997).

[14] R. Brun et al., CERN-DD/EE/84-1 (1987).

[15] ZEUS Collaboration, J. Breitweg et al., Eur. Phys. J. C 11 (1999) 427.

[16] ZEUS Collaboration, J. Breitweg et al., Eur. Phys. J. C 12 (2000) 411.

[17] S. Catani et al., Nucl. Phys. B406 187 (1993).

[18] S.D. Ellis and D.E. Soper, Phys. Rev. D48 3160 (1993).

[19] M. Botje, Eur. Phys. J. C 21, 33 (2001).

[20] OPAL Collaboration, G. Abbiendi et al., Eur. Phys. J. C6 1 (1999).

[21] D0 Collaboration, B. Abbott et al., Phys. Rev. Lett. 80 2051 (1998).

LQ Type (F=0)	V_0^L	V_0^R	$\tilde{V}_0^R$	V_1^L	$S_{1/2}^L$	$S_{1/2}^R$	$\tilde{S}_{1/2}^L$
M(GeV)(λ=0.1)	268	271	279	283	281	281	270
LQ Type (F=2)	S_0^L	S_0^R	$\tilde{S}_0^R$	S_1^L	$V_{1/2}^L$	$V_{1/2}^R$	$\tilde{V}_{1/2}^L$
M(GeV)(λ=0.1)	274	272	249	274	248	273	272

Table 1: *Mass limit of the 14 BRW LQs at λ=0.1.*

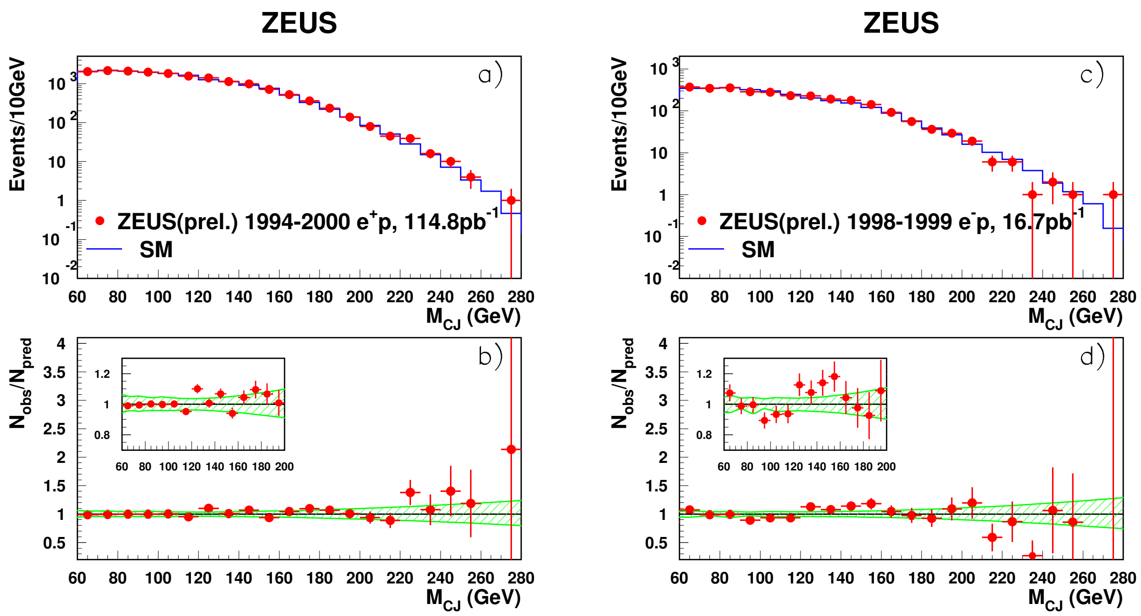

Figure 1: *The electron-jets invariant-mass spectra from the ZEUS data (points) and from the SM MC (histogram) are shown in a) - b) for the e^+p data and in c) - d) for the e^-p data. The ratio of the data to the SM MC expectations are given in the lower plots. The shaded area shows the systematic uncertainty on the ratio. The inset shows the region $60 < M_{CJ} < 200$ GeV in more detail.*

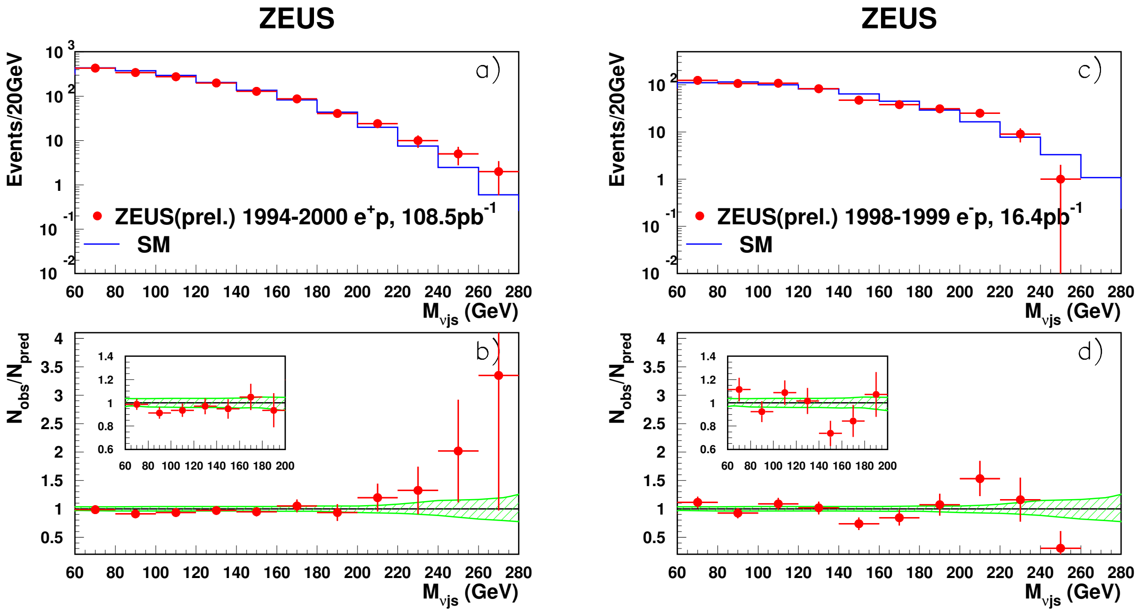

Figure 2: *The neutrino-jets invariant-mass spectra from the ZEUS data (points) and from the SM MC (histogram) are shown in a) - b) for the e^+p data and in c) - d) for the e^-p data. The ratio of the data to the SM MC expectations are given in the lower plots. The shaded area in the lower plots shows the systematic uncertainty on the ratio. The inset shows the region $60 < M_{\nu js} < 200$ GeV in more detail.*

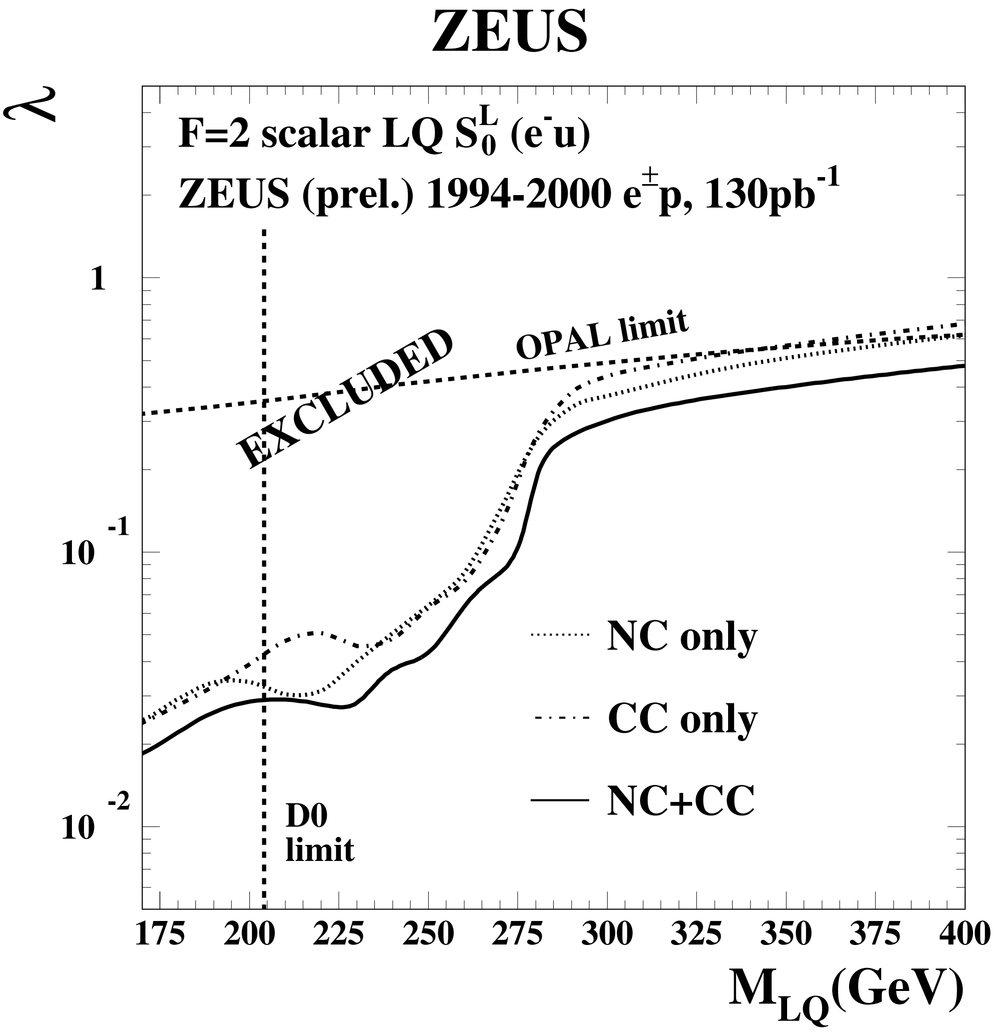

Figure 3: *The limit on the Yukawa coupling strength, λ, as a function of the leptoquark mass for the S_0^L leptoquark. Also shown are the limits using the NC sample only, the CC sample only and the limits from OPAL and D0. The region above the curves (and on the left of the D0 line) is excluded.*

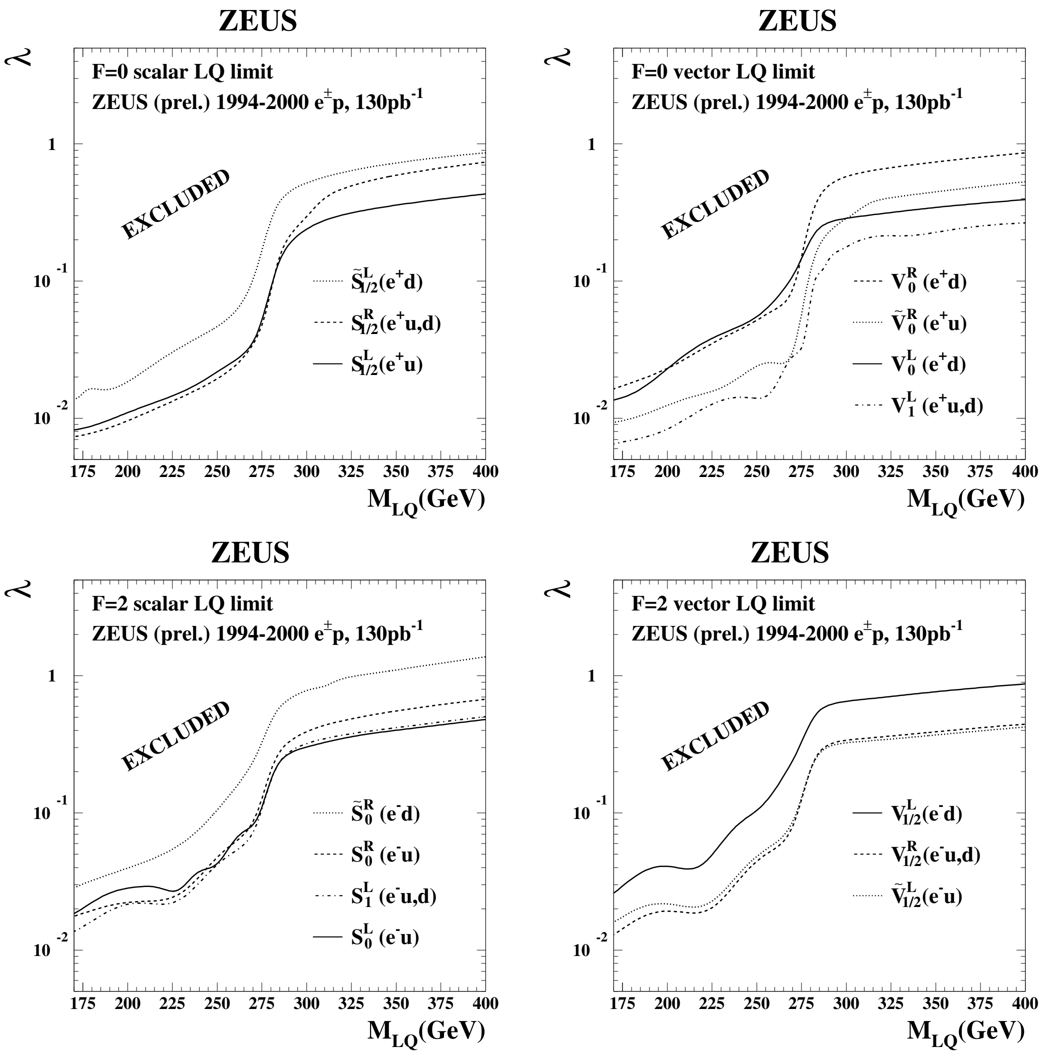

Figure 4: *Limits on the Yukawa coupling strength, λ, as a function of the leptoquark mass for the BRW model leptoquarks.*