

SEARCHES FOR LEPTOQUARKS, SQUARKS IN  $R_p$  SUSY  
 AND EXCITED FERMIONS AT HERA

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**Abstract**

Various searches for leptoquarks, scalar quarks in  $R_p$ -violating supersymmetric models, and excited fermions performed by the HERA experiments H1 and ZEUS are reviewed. No evidence for new particle production was observed from data collected by both experiments since 1994 in either electron-proton and positron-proton collisions. Stringent limits derived on the masses and couplings of these new particles are compared whenever appropriate with those from LEP, the Tevatron and low energy experiments.

**1 Introduction**

The  $ep$  collider HERA, which provides both baryonic ( $B$ ) and leptonic ( $L$ ) quantum numbers in the initial state, is ideally suited to search for new particles possessing couplings to a lepton-quark pair. Such particles could be leptoquarks (LQs) or scalar quarks (squarks,  $\tilde{q}$ ). LQs are color-triplet bosons which appear in many extensions of the Standard Model (SM). Squarks, the scalar supersymmetric (SUSY) partners of quarks, also couple to a lepton-quark pair in models which violate  $R$ -parity. The  $R$ -parity, defined as  $R_p = (-1)^{F+2S}$  with  $F(=3B+L)$  and  $S$  being respectively the fermion number and the spin, is a discrete symmetry. HERA also provides ideal conditions to look for excited fermions ( $e^*$ ,  $\nu^*$ , and  $q^*$ ) of the first generation. The existence of these excited states would provide clear evidence for fermion substructure.

This note briefly reviews all recent searches at HERA based on three independent data samples taken since 1994. The most recently published results were obtained using data collected from 1994 to 1997 at a center-of-mass energy  $\sqrt{s}(=\sqrt{4E_e E_p})$  of 300 GeV by colliding *positrons* of energy 27.5 GeV with protons of 820 GeV. The results from 1998-1999 *electron*-proton collisions at a slightly higher energy  $\sqrt{s} \simeq 320$  GeV (due to an increase of the proton beam energy to 920 GeV) are mostly still in their preliminary form. The new  $e^+p$  data taken in 1999-2000 at  $\sqrt{s} = 320$  GeV are being analyzed and first results are presented here. The searches for LQs and squarks in  $R_p$ -violating ( $R_p$ ) SUSY are presented, respectively, in Secs. 2 and 3. Sec. 4 describes the searches for excited fermions, followed by Sec. 5 with a summary and an outlook.

## 2 Searches for Leptoquarks

At HERA, LQs could be resonantly produced in the  $s$ -channel by the fusion of the initial state lepton with a quark from the proton or virtually exchanged in the  $u$ -channel. LQs can decay to  $e + q$  and  $\nu + q$  such that the amplitudes of the  $s$ - and  $u$ -channel diagrams interfere with those from deep inelastic scattering (DIS) processes of the neutral current (NC) and charged current (CC) interactions.

In general, the  $s$ -channel contribution dominates for LQ masses up to  $\sqrt{s}$ . The production cross-section can be written to, a good approximation, as  $\sigma_{\text{LQ}} = (J + 1) \frac{\pi\lambda^2}{4s} q\left(x = \frac{M_{\text{LQ}}^2}{s}\right)$  where  $J = 0$  and 1 respectively for scalar and vector LQs,  $\lambda$  is the Yukawa coupling at the LQ- $e$ - $q$  vertex, and  $q(x)$  is the parton density. The  $u$ -channel and interference contributions cannot produce a resonance peak and are only important for  $M_{\text{LQ}} \gtrsim \sqrt{s}$ .

The phenomenological model proposed by Buchmüller-Rückl-Wyler (BRW) [1] describes 14 LQs, of which 7 have  $F = 0$  and 7 have  $F = 2$ . The  $e^+p$  collisions provide the best sensitivity to the former since the fusion involves a quark instead of an antiquark. This is in contrast to the  $e^-p$  collisions where the  $F = 2$  states are best probed.

The final states of LQ decay are identical to NC and CC DIS processes. On the other hand, since the angular distributions of the decay products of a scalar or vector resonance are different from those of DIS (in particular for NC), a mass dependent angular cut, or equivalently a cut in  $y$ , is applied to maximize the signal significance. An excess of events was originally observed in the mass and  $Q^2$  distributions of the NC channel in the 1994-1996  $e^+p$  data corresponding to an integrated luminosity of about  $15 \text{ pb}^{-1}$  per experiment. However such an excess was not confirmed by later higher statistics samples of  $e^+p$  data ( $\sim 20 \text{ pb}^{-1}$  in 1997 and  $\sim 70 \text{ pb}^{-1}$  in 1999-2000) and by the  $e^-p$  data ( $\sim 15 \text{ pb}^{-1}$ ).

Since no evidence for LQ production was observed, upper limits were derived on the LQ cross-section and coupling  $\lambda$ . As an example, upper limits at 95% confidence level (CL) obtained for a LQ state  $\tilde{S}_{1/2,L}$  are shown in Fig. 1.

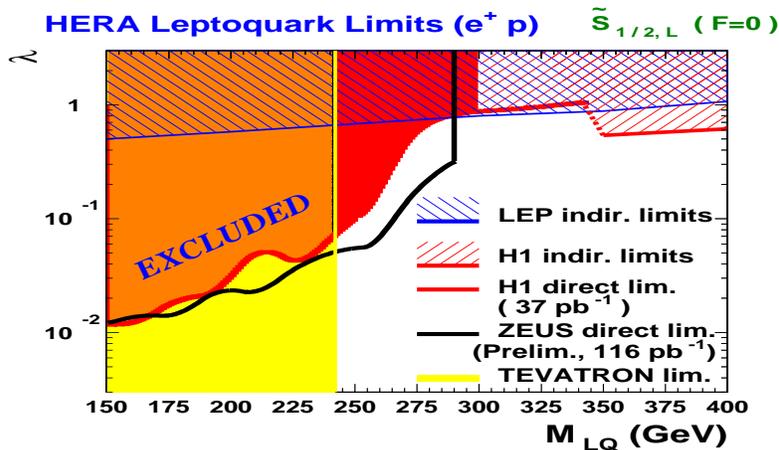


Figure 1: Upper exclusion limits at 95% CL on the Yukawa coupling  $\lambda$  as a function of the LQ mass for a left-handed scalar  $\tilde{S}_{1/2,L}$  with isospin 1/2 and fermion number  $F = 0$ .

The H1 direct limit [2] for masses below 300 GeV was derived from the 1994-1997  $e^+p$  data. By taking properly into account the  $u$ -channel and interference contributions, a sensitivity to coupling values  $\lesssim 1$  was established for masses up to 400 GeV. The better sensitivity at higher masses was achieved by a contact interaction analysis [3] where part of the 1999-2000  $e^+p$  data was combined with those of 1994-1997. The preliminary ZEUS limit, presented for the first time

in this workshop, was obtained using the full  $e^+p$  data. The higher sensitivity at  $M_{LQ} \gtrsim 250$  GeV is largely due to the increased  $\sqrt{s}$ . In comparison with limits from LEP [4] and the Tevatron [5], HERA thus provides the best sensitivity at the intermediate and high mass range.

In generic LQ models, the branching ratios of LQ decays in the NC and CC DIS -like modes are free parameters in contrast to the BRW model where they are fixed to 1, 1/2, or 0. If the LQ decays into  $e + q$  and  $\nu + q$  only, the combined preliminary H1 results obtained from the 1998-1999  $e^-p$  data are shown in Fig. 2. A similar analysis has been performed by ZEUS using the 1994-1997  $e^+p$  data [6]. The combined bounds are largely independent of the individual branching ratios. As soon as  $\lambda$  exceeds  $\sim 0.03$ , these limits extend considerably beyond the region excluded by D0, as represented by the shaded domain.

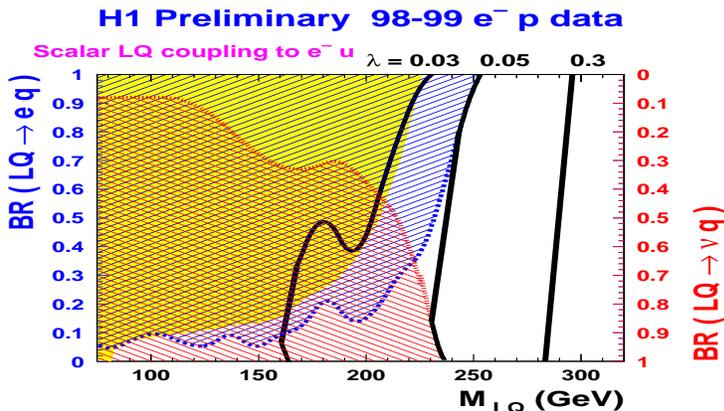


Figure 2: Mass dependent exclusion limits at 95% CL in generic LQ models for a scalar LQ which couples to  $e^-u$  shown as the dashed (dotted) curve as a function of the branching ratio  $BR(LQ \rightarrow eq)$  ( $BR(LQ \rightarrow \nu q)$ ) for an example coupling  $\lambda = 0.05$ . The combined limits are represented with solid curves for three coupling values. The region excluded by D0 is indicated with the shaded area.

### 3 Searches for Squarks in $\mathcal{R}_p$ SUSY

SUSY is one of the most likely ingredients for a theory beyond the SM. In particular, the Minimal Supersymmetric extension of the SM (MSSM) describes all experimental data just as well as the SM. The most general SUSY theory which preserves gauge invariance of the SM allows for  $\mathcal{R}_p$  Yukawa couplings  $\lambda, \lambda', \lambda''$  between one squark or slepton and two SM fermions:  $W_{\mathcal{R}_p} = \lambda L_i L_j \bar{E}_k + \lambda' L_i Q_j \bar{D}_k + \lambda'' \bar{U}_i \bar{D}_j \bar{D}_k$ , where  $i, j, k = 1, 2, 3$  are generation indices,  $L_i(Q_i)$  are the left-handed lepton (quark) doublet superfields and  $\bar{E}_i(\bar{D}_i, \bar{U}_i)$  are the right-handed electron (down and up quark) singlet superfields. Of particular interest for HERA are the  $\mathcal{R}_p$  terms  $\lambda' L_i Q_j \bar{D}_k$ . The squarks at HERA are thus singly produced in the  $s$ -channel with masses up to the kinematic limit.

In the case where both production and decay occur through the same  $\lambda'_{1jk}$ , the squarks in  $\mathcal{R}_p$ -SUSY behave as scalar LQs and the constraints obtained on LQs are also applicable for squarks. There are however other decay modes in which a squark decays to a quark and a gaugino (chargino or neutralino) with  $\mathcal{R}_p$ -conserving gauge couplings. Because of the gauge decay modes, the resulting constraints on the mass and coupling of squarks depend on the various parameters in the SUSY phase space. The search sensitivity is improved considerably when the gauge decay modes are combined with those of  $\mathcal{R}_p$  decays.

With  $e^+p$  collisions, HERA is most sensitive to the couplings  $\lambda'_{1j1}$  amongst the nine possible couplings  $\lambda'_{1jk}$ , where mainly  $\tilde{u}_L^j$  squarks are produced via processes involving a valence  $d$  quark<sup>1</sup>. Mass dependent limits [7] on  $\lambda'$  were derived by both H1 and ZEUS within the MSSM model and by H1 within the minimal supergravity model, a more constrained SUSY model. The model dependence of the results was studied in detail by performing a scan of the MSSM parameters and was found to be small. The HERA direct searches improve the best indirect limits on  $\lambda_{1j1}, j = 2, 3$  from atomic parity violation measurements by a factor of up to 3. In a large part of the MSSM parameter space covered by the scan, the existence of squarks coupling to a  $e^+d$  pair with masses up to 260 GeV is excluded at 95% CL for a coupling of electromagnetic strength.

## 4 Searches for Excited Fermions

At HERA, excited fermions ( $f^*$ ) could be singly produced via the  $t$ -channel exchange of a gauge boson, and would subsequently decay into a SM fermion and a boson. Collider searches are generally interpreted in the framework of the phenomenological model [8], where the interactions of  $f^*$  with a SM fermion and an electroweak boson (a gluon),  $L_{\text{eff}} = \frac{1}{2\Lambda} F_R^* \sigma^{\mu\nu} [gf \frac{\tau^a}{2} W_{\mu\nu}^a + g' f' \frac{Y}{2} B_{\mu\nu} + g_s f_s \frac{\lambda^a}{2} G_{\mu\nu}^a] F_L + h.c.$ , are parameterized via the compositeness scale  $\Lambda$  and relative couplings  $f$  and  $f'$  ( $f_s$ ).

The search has investigated the decays of  $f^*$  into  $\gamma$ ,  $Z$ , and  $W$ , followed by the subsequent decay of the boson into  $e$ ,  $\mu$ ,  $\nu$ , or hadrons. No deviation from the SM predictions has been observed, which leads to constraints on the considered model. Based on the 1994-1997  $e^+p$  data at  $\sqrt{s} = 300$  GeV, upper limits<sup>2</sup> for  $f/\Lambda$  (with  $f = f'$ )<sup>3</sup> ranging from  $7 \times 10^{-4}$  to  $10^{-2}$  GeV<sup>-1</sup> were obtained for an  $e^*$  mass ranging from 50 GeV to 250 GeV. For an  $\nu^*$  mass ranging from 50 to 200 GeV, the values of the limits for  $f/\Lambda$  (with  $f = -f'$ ) vary between  $3 \times 10^{-3}$  and  $10^{-1}$  GeV<sup>-1</sup>. The limits when  $f = f'$  were less stringent due to the absence of the dominant decay  $\nu^* \rightarrow \nu\gamma$ . Assuming  $f/\Lambda = 1/M_{l^*}$ , masses below 223 and 114 GeV are excluded at 95% CL, respectively, for the  $e^*(f = f')$  and  $\nu^*(f = -f')$  production. These limits extend beyond those obtained at LEP where the constraints are limited either to beam energies for  $l^*$  produced in pairs or to the center-of-mass energies for  $l^*$  produced singly. Limits for the  $q^*$  on  $f/\Lambda$  assuming  $f = f'$  and  $f_s = 0$  (i.e. only electroweak couplings) vary between  $9 \times 10^{-4}$  and  $2 \times 10^{-2}$  GeV<sup>-1</sup> for  $q^*$  masses ranging from 50 to 250 GeV. The HERA limits are complementary to those from the Tevatron where stringent bounds were set on  $q^*$  produced in  $qg$  fusion via the coupling  $f_s$ .

Using the 1998-1999  $e^-p$  data, preliminary limits [9, 10] on  $f/\Lambda$  for  $\nu^*$  have been obtained by both HERA experiments, which improve significantly the limit based on the  $e^+p$  data, e.g. by H1 from 114 GeV to 150 GeV for  $f = -f'$ , due to the much higher production cross-section.

## 5 Summary and Outlook

New particle production of leptoquarks, scalar quarks, and excited fermions has been extensively searched for at HERA. Many final results based on the 1994-1997  $e^+p$  data were published. Some preliminary results using the 1998-1999  $e^-p$  are available, which either complement the searches for new particle types (e.g.  $F = 2$  versus  $F = 0$  LQs probed respectively with  $e^-p$  and  $e^+p$  data) or extend substantially the limits (e.g. for  $\nu^*$ ).

<sup>1</sup>On the contrary, the  $e^-p$  data are well suited to probe couplings  $\lambda'_{11k}$  and  $\tilde{d}_R^k$  squarks.

<sup>2</sup>The values given here are from H1 [9], similar limits have also been obtained by ZEUS [10].

<sup>3</sup>The case  $f = -f'$  was not considered since the production cross-section of the  $e^*$  would be very small due to the vanishing coupling constant.

Higher sensitivity has been obtained using the 1999-2000  $e^+p$  data on the Yukawa coupling of the LQ and such an improvement is also expected for searches for squarks and excited fermions. HERA limits were found to be competitive and complementary in comparison with those from other high energy machines and low energy experiments.

The HERA machine and both the H1 and ZEUS detectors are being upgraded. A factor of about 5 increase in the luminosity and the improved detectors after the upgrade will provide new particle hunters with new and exciting opportunities in the next years before the era of the LHC.

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