Search for Physics Beyond Standard Model at HERA

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Abstract. The latest status of searches at HERA for physics beyond the Standard Model is summarized on behalf of the H1 and ZEUS collaborations. Emphasis is put on production of resonant particles accessible within the HERA center-of-mass energy, such as leptoquarks, squarks in R-parity-violating supersymmetry or excited fermions. Most of the results presented here are based on the full available statistics of positron-proton collisions, and also preliminary results from very recent electron-proton running are presented. Results which have been updated since this Ringberg '99 Workshop are also included.

1 Introduction

The HERA collider at DESY is a unique facility where electrons (or positrons) and protons interact at a high center-of-mass energy ($\sqrt{s}$), thus allowing to probe very short distances. An electron or positron beam of 27.5 GeV collides with a proton beam of 820 GeV (920 GeV since 1998), resulting in $\sqrt{s} = 300$ GeV (318 GeV). New phenomena in lepton-quark interactions due to physics at large energy scale could be observed at this unpreceded energy. Unlike e^+e^- or $\bar{p}p$ colliders, the initial state at HERA has both non-zero lepton and baryon numbers, which makes searches at HERA most powerful in discovering particles which carry both of these quantum numbers.

The H1 and ZEUS experiments have been taking data at HERA since 1992. Most of the results presented here are based on the large data sample of e^+p collisions taken between 1994–1997, corresponding to luminosities of 36.5 pb^{-1} and 47.7 pb^{-1} for H1 and ZEUS, respectively. From 1998 to spring 1999, HERA provided e^-p collisions with the increased proton beam energy. Preliminary results from 16 pb^{-1} of data taken in this period are also presented.

For most of the searches, major Standard Model (SM) background comes from neutral-current (NC) and charged-current (CC) deep inelastic scattering (DIS) processes, as illustrated in Fig. 1 (a). The NC process occurs via t-channel exchange of γ or Z boson, while the CC process turns the electron into a neutrino through W-boson exchange. The following kinematic variables are frequently used in DIS analyses:

$$Q^2 = -q^2 = -(k - k')^2 \ , \tag{1}$$

$$x = Q^2/(2q \cdot p) \ , \tag{2}$$

$$y = (q \cdot p)/(k \cdot p) \ , \tag{3}$$

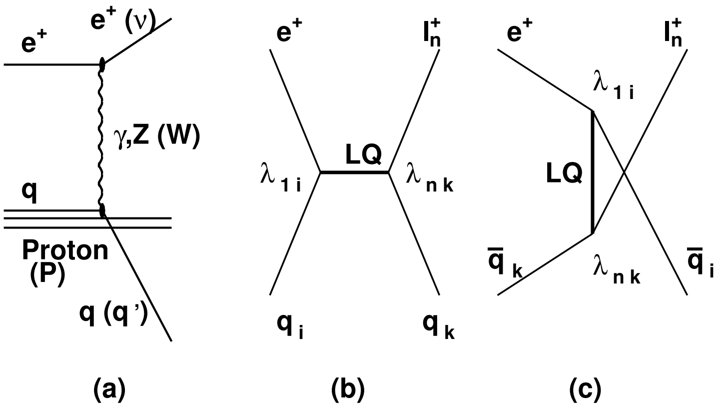

Fig. 1. Diagrams of (**a**) deep inelastic scattering of e^+p; (**b**) s-channel and (**c**)u-channel LQ processes involving $F = 0$ LQs

where k and k' are the four-momenta of the incoming and outgoing lepton, respectively, and p is the four-momentum of the incoming proton. Q^2 is the negative square of the momentum transfer (q), x is the Bjorken scaling variable and y is sometimes called the inelasticity parameter.

2 Leptoquarks and Related Searches

Leptoquarks (LQs) have both lepton (L) and baryon (B) numbers and couple directly to lepton-quark pairs. They appear in many models beyond SM, such as Grand Unified Theories, and naturally relate the two families of fermions: leptons and quarks. They carry color charges like quarks and have fractional electric charges. The set of LQs which preserves $SU(3) \times SU(2) \times U(1)$ symmetry has been specified by Buchmüller, Rückl and Wyler (BRW) [1]. They can be classified into scalar and vector LQs, and into $F = 0$ and $|F| = 2$ LQs, where $F = L + 3B$ denotes the fermion number.

2.1 LQ Production and Decay at HERA

Figures 1 (b) and (c) show LQ processes at HERA with s- and u-channel exchange of a LQ, with possible lepton- and/or quark-generation-changing interactions. Lepton-flavor-violating (LFV) LQs will be discussed in Sect. 2.4, and only first-generation LQs ($n = 1$ and $i = k = 1$ for the Yukawa couplings λ in the diagrams) are discussed here. According to the BRW model, the decay branching ratio of LQ to eq is either 100% or 50%, depending on the LQ quantum numbers. In the latter case, the remaining decay is to a νq final state. At HERA, highest sensitivity to first-generation LQs can be achieved by producing the LQs via a fusion between the lepton and the valence quarks (u, d), i.e. for $F = 0$ ($|F| = 2$) LQs in e^+p (e^-p) collisions.

An individual LQ event has exactly the same topology as a NC or CC DIS event. If the LQ mass, m_{LQ}, is smaller than $\sqrt{s}$ and the coupling λ is not too large (order of unity or less), the s-channel resonant production dominates. In this case there appears a sharp peak at $m_{\rm LQ}$ in the eq or νq invariant mass distributions, or at $x_0 = m^2_{\rm LQ}/s$ in the DIS variable x. The production cross section for this case can be simply approximated with the narrow-width approximation (NWA):

$$\sigma(ep \to LQ\ X) = (J+1)\frac{\pi}{4s}\lambda^2 q(x_0, m^2_{\rm LQ}) \ , \tag{4}$$

where λ is the Yukawa coupling, J is the spin of the LQ and q is the quark distribution function evaluated at the resonance x=x_0 with the scale $Q^2 = m^2_{\rm LQ}$. Another characteristic of LQ process is the different y distribution as compared to DIS. The s-channel production of a scalar LQ has a flat y distribution, while it is $(1-y)^2$ for the vector case. They are contrasted to the $1/y^2$ dependence of DIS processes at fixed x. Therefore, the search strategy is to start from a selection of NC or CC DIS events and then to look for a resonance peak in the large-y region.

The signal of a LQ with mass close to or above $\sqrt{s}$ looks different from what has been discussed above, but the sensitivity on such LQs does not vanish [2]. This will be discussed in Sect. 2.3.

2.2 Mass Distribution and Limits

Figure 2 shows the mass distribution from the H1 analysis [3] of 1994–1997 e^+p data. For the NC DIS selection, the mass is calculated using the energy and angle of the scattered positron, and for the CC DIS selection using the hadronic variables with the Jacquet-Blondel method [4]. Slight excess of events is observed in the NC channel at large y around 200 GeV, which comes mainly from the data taken during 1994–1996 and was particularly noteworthy before the 1997 data were added [5]. No significant excess was seen in the 1997 data alone, and overall significance has decreased in the whole data sample. The mass distribution in the CC channel is in good agreement with DIS expectation within the uncertainty.

From the observed and expected mass spectrum, the limits at 95% confidence level (CL) on the Yukawa coupling λ can be obtained for each LQ type, as shown in Fig. 3. At an electromagnetic strength $\lambda \sim 0.3$, the limits on scalar (vector) LQs extend up to 275 GeV (284 GeV). Here only limits on $F = 0$ LQs are shown, but also results on $|F| = 2$ LQs are obtained, with weaker limits than $F = 0$.

Also ZEUS has analysed e^+p data in NC [6] and CC [7] channels and obtained preliminary limits on LQs. In the NC channel, ZEUS observes a few outstanding events at large mass and large y, coming mainly from 1994–96 data [8], but the significance has decreased after adding the 1997 data which more than doubled the total integrated luminosity. More e^+p data will be needed to clarify the origin of these high-mass, high-y events events observed by H1 and ZEUS.

ZEUS has also looked at the most recent e^-p data taken during 1998–99 [9]. These data enhance very much the sensitivity to $|F| = 2$ LQs, and the increased center-of-mass energy in addition extends the sensitivity at the highest mass

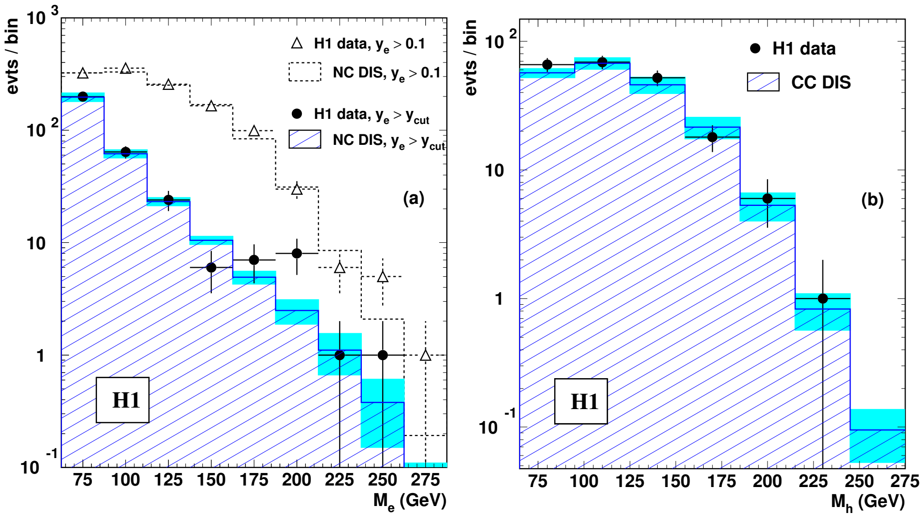

Fig. 2. Mass spectum for (**a**) NC-like and (**b**) CC-like event selection from H1 e^+p data (*points*) compared with DIS expectations (*histograms*). In (**a**), the distribution is shown before and after the mass-dependent lower cut in y designed to enhance the signal significance. The shaded boxes on the histograms indicate the uncertainties on the expectations

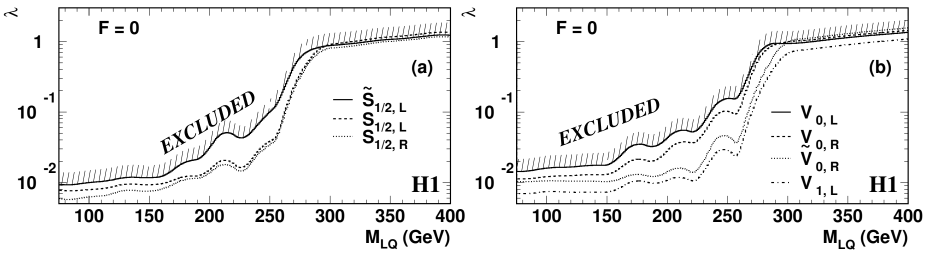

Fig. 3. Upper limits at 95% CL on Yukawa couplings λ as a function of the LQ masses for (**a**) scalar and (**b**) vector $F = 0$ leptoquarks. In the plots shown here, only NC data have been used

region ($\sim 300\,\mathrm{GeV}$) close to the kinematical limit. Figure 4 shows the mass distribution of events from NC DIS selection. Here the mass (M_{ej}) is the invariant mass between the electron and jet, calculated directly using their energies and angles. The agreement with SM DIS expectation is very good, and the limits on Yukawa coupling for $|F| = 2$ LQs are plotted in Fig. 5. At $\lambda \sim 0.3$, the exclusion limits extend up to about 290 GeV at 95% CL.

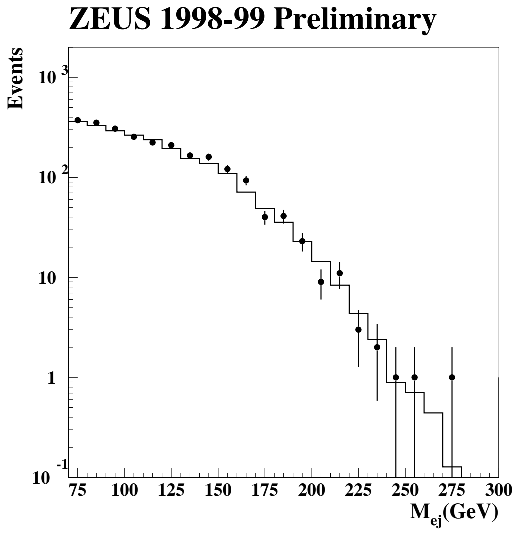

Fig. 4. Electron-jet invariant mass distribution from ZEUS e^-p data (*points*) compared to NC DIS expectation (*histogram*)

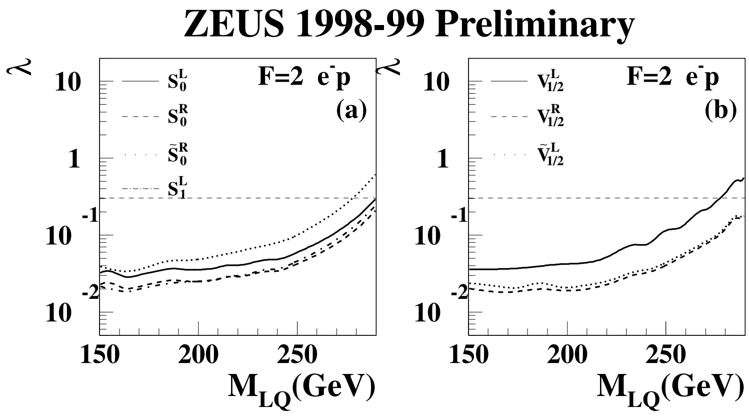

Fig. 5. Coupling limits at 95% CL as a function of the LQ masses for (**a**) scalar and (**b**) vector $|F| = 2$ leptoquarks. The horizontal lines indicate the coupling strength for an electroweak scale, $\lambda \sim 0.3$

2.3 High-Mass Leptoquark and Contact Interactions

The LQ mass range in Fig. 3 extends beyond the center-of-mass energy 300 GeV up to 400 GeV. The H1 analysis takes into account not only the s-channel contribution but also u-channel and interference terms between the LQ and SM DIS diagrams. When the LQ mass is high, these terms become important and actually the LQ is not resonantly produced but gives virtual effects on DIS-like final states [2]. In this case, the mass spectrum would not have a narrow peak but a broad mass range would be affected, and also at smaller y values. The range in mass and cut in y are thus changed accordingly. On the other hand, the ZEUS analysis uses NWA and the quoted limits stop before the coupling becomes too large.

When the mass is even higher, the effect of LQ can be described as an effective four-fermion interaction known as $eeqq$ contact interaction (CI). CI is an effective theory for physics at high mass scales in their approximation at the low-energy limit, and can represent not only heavy LQs but also a variety of models beyond SM such as new heavy vector bosons or composite models of fermions. The effect is parameterized by the ratio of the coupling and the mass scale, g/Λ, and usually the convention $g^2{=}4\pi$ is adopted. Depending on the chiral structure of the interaction, many CI models can be constructed and modify the $eq \to eq$ cross section differently. The common effect is the increase of cross section at high Q^2, with the interference effect at intermediate Q^2 which can be constructive or destructive depending on the model.

ZEUS has analysed 1994–97 e^+p data in terms of 30 scenarios of CI and derived lower limits on Λ. For details of the analysis, refer to [10]. The limits at 95% CL range between 1.7 TeV to 5 TeV for the scenarios considered. It is worth to note that $eeqq$ CI can be tested also at LEP2 ($e^+e^- \to q\bar{q}$) and at Tevatron ($q\bar{q} \to e^+e^-$). Generally the limits from competing colliders are comparable, and in some cases ZEUS limits are most stringent or the only existing limits.

H1 has released preliminary results on CI from e^+p data [11] and interprets the limits also in terms of LQ mass and coupling ratio, m_{LQ}/λ. The limits, valid for $m_{\mathrm{LQ}} \gg \sqrt{s}$, range between 202 GeV and 952 GeV for various type of LQs.

2.4 Lepton-Flavor Violation

The processes in Figs. 1 (b) and (c) can allow for the case $n > 1$, where the outgoing lepton is a muon or tau lepton, leading to an explicit lepton-flavor violation forbidden in the SM. The event signature is striking and can be searched for with little background from SM processes.

The H1 analysis [3] observes no candidate event consistent with $eq \to \mu q'$ or $eq \to \tau q'$ process, with the expected background from SM being 0.12 ± 0.05 and 0.77 ± 0.30 events, respectively. The limits are interpreted in terms of a coupling for low-mass LFV LQs, and also in terms of indirect effects of high-mass LFV LQs like the CI analysis. In the latter case, the limits are given on the quantity $\lambda_{1i}\lambda_{nk}/m_{\mathrm{LQ}}^2$. In some cases where second- or third-generation quarks are involved, and especially for the e–τ LFV case, H1 gives more stringent limits than low-energy processes such as rare decays of τ or B.

ZEUS has recently given preliminary results from a LFV LQ search in the muon channel using 1994–97 data. No candidate is found where 0.3 events are expected from the SM background. Limits have been obtained for the low-mass LFV LQs. Under the assumption that the couplings to eq and $\mu q'$ have the same electroweak strength, 95% CL lower limit for the mass of LQs extends up to 285 GeV [12].

3 Supersymmetry with R-parity Violation

Supersymmetry (SUSY) is one of the most promising extension of the SM. Extensive searches are being performed at the high-energy colliders LEP2 and Tevatron, and HERA is not an exception. HERA's potential for SUSY discovery is maximal in the case of the R-parity-violating (RPV) extension of Minimal SUSY Standard Model (MSSM).

3.1 Phenomenology

R-parity is a multiplicative quantum number defined as $R=(-1)^{L+3B+2S}$, where S is the spin of the particle, and is assumed to be conserved in MSSM. R takes the value 1 for SM particles and -1 for their SUSY partners. The consequences of the R-parity conservation are that SUSY particles are always produced in pairs, and that the lightest SUSY particle (LSP) cannot decay.

However, the general supersymmetric and gauge-invariant superpotential contains additional terms which violate R-parity [13]

$$\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k . \quad (5)$$

Here L and Q denote the left-handed lepton and quark doublet superfields; $\overline{E}$, $\overline{D}$, and $\overline{U}$ are the right-handed singlet superfields for charged leptons, down-type quarks and up-type quarks, respectively. The indices i, j, k denote the generation. For each term and generation combination, a Yukawa coupling $\lambda(\lambda', \lambda'')$ is introduced in the model as an additional parameter.

Of particular interest for HERA is the second term with λ'_{1jk}, which makes single production of a squark ($\tilde{q}$) possible through the electron-quark fusion. This process is very much like the scalar leptoquark production discussed earlier. If the squark decays to eq with the same Yukawa coupling, the analysis is exactly the same as in the LQ search. However, there are also R-parity-conserving decays with gauge couplings $\tilde{q} \to q\chi^0$ and $\tilde{q} \to q'\chi^\pm$. These decays to neutralino/chargino compete with the LQ-like decay, and the branching ratio depends on the unknown Yukawa coupling and on the MSSM parameters.

The neutralino or chargino decays subsequently to a lighter gaugino (cascade decay), or directly through the RPV coupling. Even the LSP, usually taken to be χ_1^0, decays to SM particles via $\chi_1^0 \to e^\pm qq$ and $\chi_1^0 \to \nu(\bar{\nu})qq$. Therefore, there are variety of final states of squarks involved in the RPV SUSY phenomenology.

3.2 Experimental Results

The preliminary ZEUS analysis of 1994–97 e^+p data [14] makes a simplifying assumption that $\tilde{q} \to q\chi_1^0$ dominates the gauge decay and ignores cascade decays and charginos. The nature of χ_1^0 is assumed to be a pure photino, in which case the branching ratios to eq and $q\chi_1^0$ decays follow a simple formula [15].

The final states are classified to eq, e^+qqq and e^-qqq. The second topology looks like a NC event with multiple jets in the hadronic final state. The last

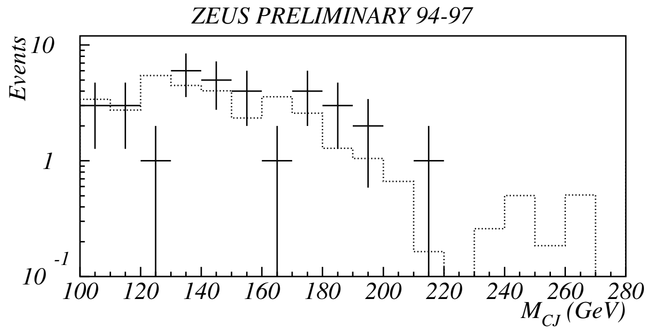

Fig. 6. Mass distribution of events selected in e^+qqq channel for data (*crosses*) and expectation (*dashed histogram*)

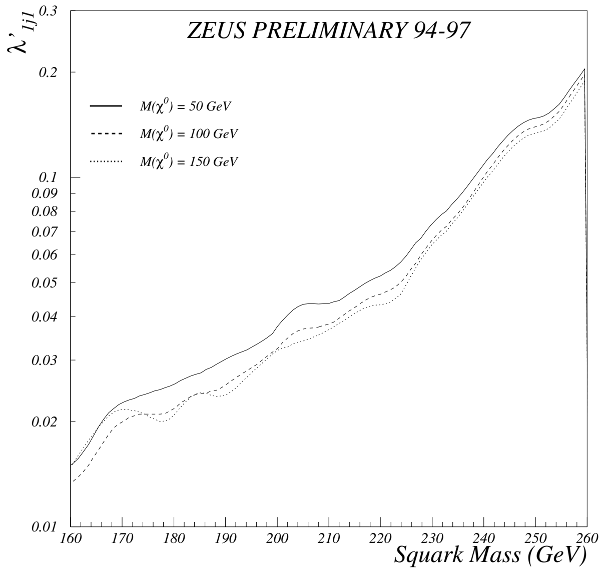

Fig. 7. The 95% CL upper limits on the RPV Yukawa couplings λ'_{1j1} as a function of the mass of the squark $\tilde{u}_j$ for different neutralino masses $M(\chi^0)$

topology has a "wrong sign" lepton for the e^+p collision and is a very clean channel with small background. The $\nu(\bar{\nu})qqq$ final states, contributing 12% of the χ_1^0 decay, is not investigated in this analysis.

Figure 6 shows the mass distribution of ZEUS events passing the cuts for e^+qqq channel. Here, 33 events are observed while 33.6 events are expected from SM, mainly from NC DIS and a small contribution from photoproduction processes. In the e^-qqq channel, no event is observed while 0.06 events is expected from the background. Since no signal for a resonance is found, limits are derived on the couplings (assuming only one λ'_{1j1} to be non-zero at a time) as a function

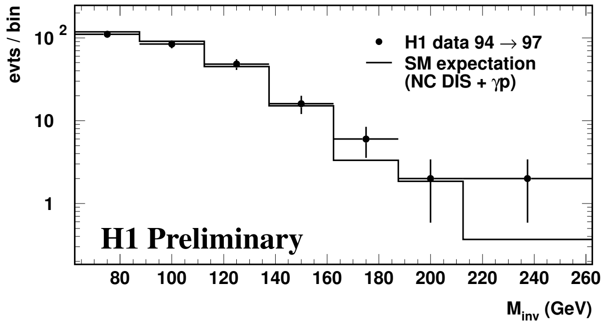

Fig. 8. Mass spectrum for e + *multijets* final states for data (*points*) and SM expectation (*histogram*)

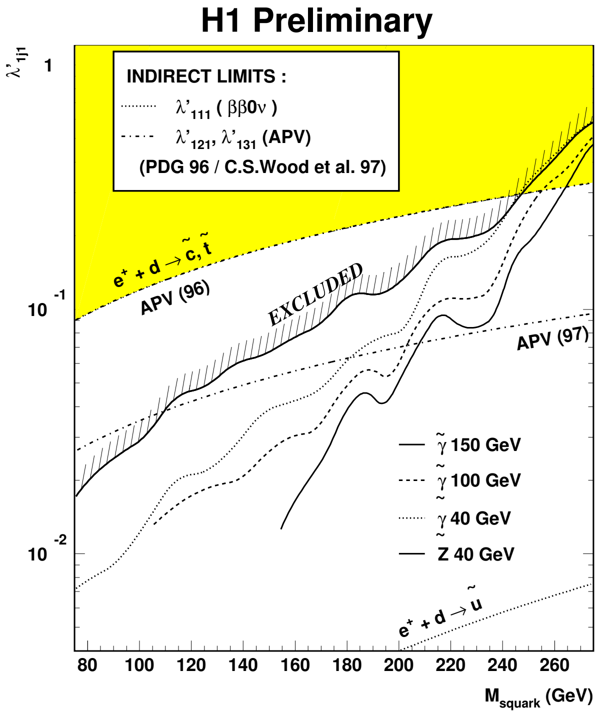

Fig. 9. Upper limits at 95% CL for the RPV couplings λ'_{1j1} as a function of the squark mass, compared with most stringent indirect limits

of the squark mass, shown in Fig. 7. Here $j = 1, 2, 3$ corresponds to $e^+d \to \tilde{u}, \tilde{c}, \tilde{t}$ production, respectively. The analysis is repeated for three different χ_1^0 masses.

The preliminary H1 analysis of 1994–97 e^+p data [16] takes neutralino mixing into account and investigates SUSY parameter space of a photino-dominated neutralino and a zino-dominated neutralino. It also calculates the branching ratio of cascade decays with χ_2^0 and χ_1^+. Figure 8 shows the mass distribution in the e + *multijets* channel. With softer selection cuts than those used in the ZEUS analysis, 289 candidates are observed while the SM expectation is 285.7 ± 28.0 events. In the "wrong sign" channel, one candidate passes the selection while the background is expected to be 0.49 ± 0.2. No evidence for a squark is found, and the limit on the Yukawa coupling is shown in Fig. 9 for three different masses of photino-dominated neutralino and one case of zino-dominated neutralino. The coupling λ'_{111} is strongly constrained by the neutrino-less double-beta decay, but the results on λ'_{121} and λ'_{131} are competitive with atomic-parity-violation experiments.

4 Excited Fermions

The composite models of fermions regard them as being built from more fundamental particles. In such models, leptons and/or quarks can be excited to a higher-mass state and decay "radiatively" to the stable ground state (normal fermions), emitting gauge bosons such as photon, W or Z bosons. At HERA, excited states of electrons or quarks can be created through the t-channel photon or Z exchange in eq interaction, and excited neutrinos or quarks can be created through the W exchange. The excited electrons can also be produced in the elastic process $ep \to e^* p$. The search strategy is to reconstruct a photon, W or Z boson (V) in an event and look for a resonance peak in the $f - V$ invariant mass, where f is an electron, a quark or a neutrino (missing momentum).

The preliminary H1 analysis of 1994–97 e^+p data [17] searches for excited fermions in the decay channels $e^* \to e\gamma, eZ, \nu W; \nu^* \to \nu\gamma, \nu Z, eW; q^* \to q\gamma, q'W$.

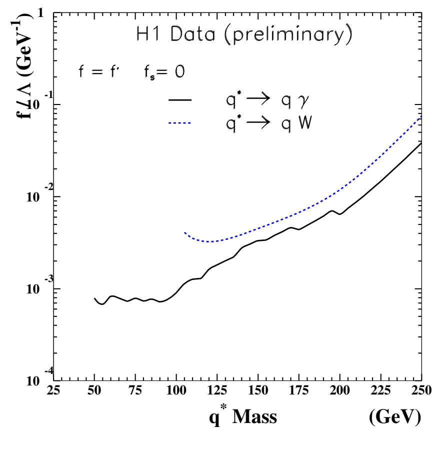

Fig. 10. Upper limit at 95% CL for the excited quark coupling divided by the compositeness scale, f/Λ, as a function of the q^* mass

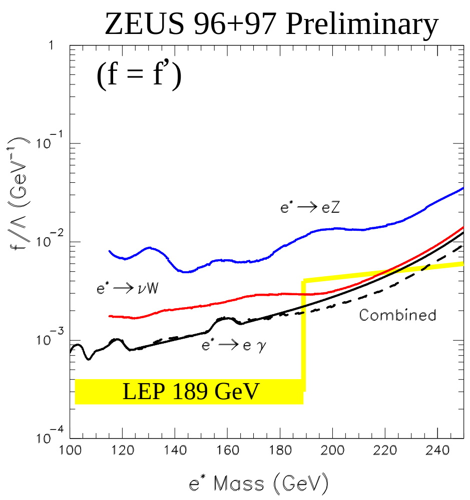

Fig. 11. Upper limits on f/Λ at 95% CL for e^* production, as a function of the e^* mass. The combined limit from the three decay channels (*dashed line*) is also shown

The hadronic decays of W, Z and leptonic decays $W \to e\nu$; $Z \to e\bar{e}, \nu\bar{\nu}$ have been exploited. In all cases, the numbers of observed events are in agreement with the SM expectations and no evidence for a resonance has been found.

The derived limits are based on a specific phenomenological model of excited fermions [18] in which the cross sections depend on coupling constants f, f' and f_s for the gauge groups $SU(2), U(1)$ and $SU(3)$, respectively, and the compositeness scale Λ. The decay branching ratio of excited fermions are determined once relationships between the couplings are fixed. Figure 10 shows, as an example, the limit on f/Λ for the excited quark production under the assumption $f = f'$ and $f_s = 0$. The latter condition makes the results complementary to the searches at Tevatron, where the production of q^* is assumed to occur through the quark-gluon fusion ($f_s \neq 0$) [19].

ZEUS has made a preliminary search for e^* using the data taken during 1996–97 (37 pb^{-1}) [20]. The decays $e^* \to e\gamma, eZ, \nu W$ are exploited with the hadronic decay of W and Z. No evidence for a resonance has been found, and the limits on f/Λ using the same model [18] have been derived under the assumption $f = f'$. The limits are shown in Fig. 11. A combined limit from the three decay channels is also derived. It can be seen that limits from LEP2 are more stringent below its center-of-mass energy, and HERA limits are competitive above it, where the on-shell production of e^* is not possible at LEP2 and limits come from searching for the signs of virtual e^* exchanges in the process $e^+e^- \to \gamma\gamma$ [21].

ZEUS has also performed a preliminary search for ν^* using the recent e^-p data taken in 1998–99 [20]. Using this smaller integrated luminosity (16 pb^{-1})

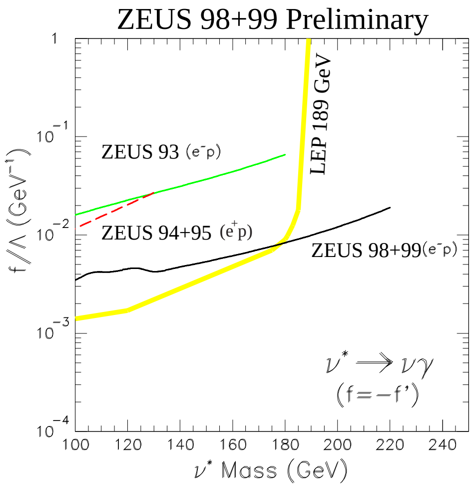

Fig. 12. Upper limits on f/Λ at 95% CL for ν^* production, as a function of the ν^* mass

than e^+p data is far more beneficial in ν^* search, since the production cross section in e^+p at high ν^* mass is strongly suppressed compared to e^-p. It is due to the smaller d-quark density compared to u quark at high x and the $(1-y)^2$ suppression factor coming from the chiral nature of W exchange. The search has been done in $\nu^* \to \nu\gamma$ channel only, and two observed events are in agreement with the SM expectation of 1.8 ± 0.2. The obtained limit on f/Λ for the case $f = -f'$ (the $\nu^* \to \nu\gamma$ decay vanishes for the case $f = f'$) is shown in Fig. 12.

5 Conclusion and Outlook

Extensive searches for physics beyond the Standard Model are being performed by the two collaborations H1 and ZEUS at HERA. No convincing signal of new particles has been established so far, giving limits on their production which are competitive with the searches at other colliders.

HERA is planning to continue running until May 2000 with the current design and then undergoes major upgrade plans in order to increase the luminosity. There will be new final-focusing magnets close to the interaction point, which means that also the detectors will be modified during the upgrade shutdown.

The new running from 2001, with five times more luminosity than the current design value, will bring an order of $1\,\mathrm{fb}^{-1}$ of integrated luminosity. This large amount of data allows the experiments to make high-statistics analyses at large-Q^2 and high-mass regions, which will eventually unreveal the breakdown of Standard Model if the new physics is existing within the reach of HERA.

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