SEARCHES FOR SUPERSYMMETRY AT HERA

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Supersymmetric signals were searched for in e^+p collisions collected by H1 and ZEUS in 1994 $\rightarrow$ 1997 corresponding to an integrated luminosity of about $40\,\mathrm{pb}^{-1}$ per experiment at a center-of-mass energy of 300 GeV. Within the framework of minimal supersymmetric extensions to the Standard Model which conserve R-parity, ZEUS found no evidence for the production of selectron and squark decaying directly into the lightest neutralino. H1 performed a search for direct single production of squarks of R-parity violating supersymmetry. The sensitivity to the corresponding Yukawa couplings was shown to be only weakly dependent on the free parameters of the minimal supersymmetric Standard Model and the reach in the mass-coupling plane extended to domains unexplored in other direct or indirect searches.

1 Introduction

Supersymmetry (SUSY) is one of the most likely ingredients for a theory beyond the Standard Model (SM). In particular the Minimal Supersymmetric extension of the Standard Model (MSSM) describes as well as the SM all experimental data, and in addition it offers among its appealing consequences solutions for the cancellation of quadratic divergences occurring in the scalar Higgs sector of the SM and models beyond the SM.

SUSY relates fermions to bosons and predicts for each SM particle a partner with spin differing by half a unit. For example selectrons $\tilde{e}_L, \tilde{e}_R$ are scalar partners of electrons e_L, e_R, and similarly squarks $(\tilde{u}_L, \tilde{d}_L)$, $\tilde{u}_R$, $\tilde{d}_R$ are the partners of up and down quarks. Two Higgs doublets with vacuum expectation values v_2, v_1 are necessary to generate masses for up-type quarks (v_2) and for down-type quarks and charged leptons (v_1). The partners of the gauge bosons $W^\pm, Z^0, \gamma$ and the two Higgs doublets are called gauginos and higgsinos. They can mix and form two charged mass eigenstates $\chi^\pm_{1,2}$ (charginos) and four neutral mass eigenstates $\chi^0_{1,2,3,4}$ (neutralinos).

Since supersymmetric particles are not observed at the masses of their SM partners, SUSY must be broken. In the MSSM, this breaking is achieved by adding extra mass parameters M_2 and M_1 for the $SU(2)$ and $U(1)$ gauginos. Thus the masses of charginos and neutralinos depend on $M_1, M_2, \tan\beta \equiv v_2/v_1$ and the higgsino mass parameter μ.

The MSSM is constructed to conserve R-parity (R_p): for a particle of spin S, the multiplicative quantum number $R_p \equiv (-1)^{3B+L+2S}$ distinguishes particles ($R_p = +1$) from SUSY particles ($R_p = -1$). Here B and L are baryon and lepton number, respectively. This implies that supersymmetric particles can only be produced in pairs and that the lightest supersymmetric particle (LSP), which is generally assumed to be χ^0_1, is stable. At HERA the dominant MSSM process is the production of a selectron and a squark via a t-channel exchange of a neutralino $ep \rightarrow \tilde{e}\tilde{q}X$. The $\tilde{e}$ and $\tilde{q}$ can then decay into any lighter gaugino and their SM partners. The decay involving χ^0_1 gives an experimentally clean signature of missing transverse energy plus an electron[a] and a hadronic system. Based on the e^+p collisions taken in 1994 $\rightarrow$ 1997 corresponding to an integrated luminosity of $46.6\,\mathrm{pb}^{-1}$, ZEUS has performed such a search[1] (Sec. 2).

The most general SUSY theory which preserves gauge invariance of the SM allows, however, for R_p violating ($\not{R}_p$) Yukawa couplings $\lambda, \lambda', \lambda''$ between one scalar squark or slepton and two SM fermions:

$$W_{\not{R}_p} = \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k. \quad (1)$$

where $i, j, k = 1, 2, 3$ are generation indices, $L_i(Q_i)$ are the lepton (quark) $SU(2)_L$ doublet superfields and $\overline{E}_i(\overline{D}_j, \overline{U}_j)$ are the electron (down and up quark) $SU(2)_L$ singlet superfields. Of particular interest for HERA are the $\not{R}_p$ terms $\lambda' L_i Q_j \overline{D}_k$ as HERA provides both leptonic and baryonic quantum numbers in the initial state. The resonant squarks at HERA are thus singly produced (in contrast to the MSSM) in the s-channel with masses up to the kinematic limit of $\sqrt{s} \simeq 300\,\mathrm{GeV}$. From the theoretical understanding of unification, there is no clear preference between R_p-conservation and $\not{R}_p$, it is thus mandatory to experimentally search for both possibilities. Based on an integrated luminosity of $37\,\mathrm{pb}^{-1}$, H1 has searched for direct production of squarks via $\not{R}_p$ Yukawa coupling λ' by taking into account various possible $\not{R}_p$ decays and gauge decays of the squarks [2]. Such couplings could lead to leptoquark-like final states (Sec. 3) or to explicit manifestation of lepton flavour violation (Sec. 4).

The SM deep inelastic scattering (DIS) processes, neutral current (NC) and charged current (CC) interactions, become backgrounds for the searches considered

[a]Unless specified, an electron in the following can be either an electron or a positron.

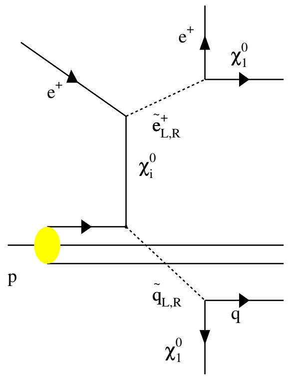

Figure 1: Selectron-squark production via neutralino exchange and the subsequent decays into the lightest supersymmetric particle χ_1^0.

here. The most commonly used DIS kinematic variables are Q^2, x and y, with $Q^2 = -q^2$, q being the four-momentum of the exchanged gauge bosons (γ, Z, W), x is the momentum fraction of the proton carried by the struck quark in the quark parton model, and y is related to Q^2 and x by $y = Q^2/(xs)$ with $0 < x, y < 1$. Experimentally, the kinematics for a NC DIS event is over-constrained as both H1 and ZEUS detectors measure not only the scattered electron but also the hadronic final state, while the kinematics for a CC DIS event can only be reconstructed from the hadronic information alone.

2 Search for $\tilde{e}$ and $\tilde{q}$ within MSSM

Within the MSSM, the production of a $\tilde{e}$ and a $\tilde{q}$ is the lowest order process in which supersymmetric particles could be produced at HERA (Fig. 1). The cross section depends on the MSSM parameters $M_1, M_2, \tan\beta, \mu$, and on the masses of the produced particles. The branching ratios for the decays $\tilde{e} \to e\chi_1^0$ and $\tilde{q} \to q\chi_1^0$ depend on the same MSSM parameters. To reduce the number of free parameters, the following assumptions are made: (i) $m_{\tilde{e}_L} = m_{\tilde{e}_R}, m_{\tilde{q}_L} = m_{\tilde{q}_R} = m_{\tilde{q}} (\tilde{q} \neq \tilde{t})$[b] (ii) $M_1 = 5/3 \tan^2\theta_W M_2$, and (iii) $m_{\tilde{q}} < m_{\tilde{g}}$ such that the decay $\tilde{q} \to q\tilde{g}$ is kinematically forbidden.

The main selection cuts are defined according to the event signature mentioned in Sec.1: (1) an isolated e with $p_t^e > 4\,\mathrm{GeV}$ ($> 10\,\mathrm{GeV}$ if $\theta_e < 0.35$), (2) a hadronic system with $p_t^{\mathrm{h}} > 4\,\mathrm{GeV}$, (3) a missing transverse momentum with $\not{P}_t > 10\,\mathrm{GeV}$, and (4) a set of final cuts $E - p_z < 50\,\mathrm{GeV}$, $\not{P}_t > 14\,\mathrm{GeV}$, $(E - p_z)/\not{P}_t < 1$ determined from an optimization procedure. The acceptance is close to zero for small mass differences $\Delta m = \min(m_{\tilde{e}} - m_{\chi_1^0}, m_{\tilde{q}} - m_{\chi_1^0})$ and reaches a plateau for $\Delta m > 10\,\mathrm{GeV}$. The level of the plateau increases from 25% at $m_{\tilde{e}} = m_{\tilde{q}} = 40\,\mathrm{GeV}$ to about 50% at $m_{\tilde{e}}$ or $m_{\tilde{q}} = 120\,\mathrm{GeV}$.

[b]The mass eigenstates $\tilde{e}_{1,2}(\tilde{q}_{1,2})$ are generally different from the interaction eigenstates $\tilde{e}_{L,R}(\tilde{q}_{L,R})$. The degree of mixing being proportional to the lepton (quark) masses is however small and is neglected here, since the contribution from the top quark is negligible.

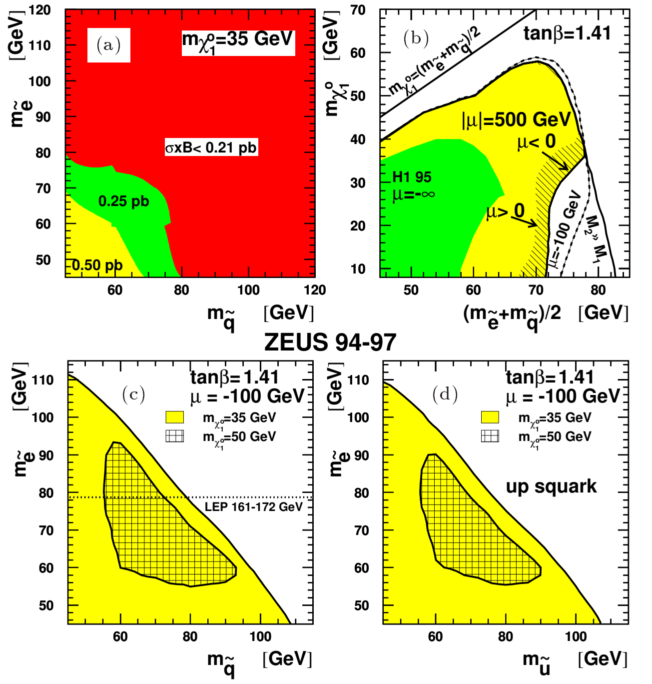

Figure 2: Upper limits at 95% CL on $\sigma \times B$ (a) and excluded regions at 95% CL for degenerate $\tilde{e}$ and $\tilde{q}$ (b,c) and for the up squark alone (d).

One event survived the selection criteria and was identified as containing a high-Q^2 positron with associated $\not{P}_t$ in the calorimeter due to two muons in the final state. The expected SM background is $1.99^{+0.57}_{-0.84}$ events from five considered SM reactions: W production processes (dominant contribution), NC DIS events (second dominant contribution), CC DIS events, lepton pair production (l^+l^-) and photoproduction (negligible).

The resulting upper limits on the $\tilde{e}, \tilde{q}$ production cross section times the branching ratios $(\sigma \times B)$ for the decay to the lightest neutralino χ_1^0 at 95% CL are shown in Fig. 2(a). When compared with the theoretical value from model calculations, exclusion areas in the parameter space of the MSSM are derived (Fig. 2(b)). For large $|\mu|$ the excluded region reaches $(m_{\tilde{e}} + m_{\tilde{q}})/2 = 77\,\mathrm{GeV}$ for a 40 GeV neutralino. This limit worsens at lower neutralino masses, because new decay channels to charginos and next to the lightest neutralino open and compete with the direct decay to χ_1^0. In the limit $M_2 \gg M_1$, the charginos and the next to lightest neutralino masses increase leaving only the direct decay channel to χ_1^0 open. The excluded region is limited by the small cross section of the process at large $(m_{\tilde{e}} + m_{\tilde{q}})/2$, while for large neutralino masses it is limited by the efficiency that falls to

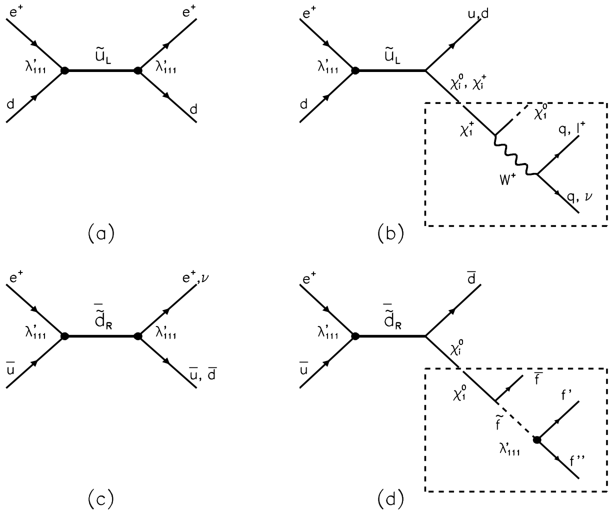

Figure 3: Lowest order s-channel diagrams for first generation squark production at HERA followed by (a), (c) $\not{R}_p$ decays and (b), (d) gauge decays. In (b) and (d), the emerging neutralino or chargino might subsequently undergo $\not{R}_p$ decays of which examples are shown in the dashed boxes for (b) the χ_1^+ and (d) the χ_1^0.

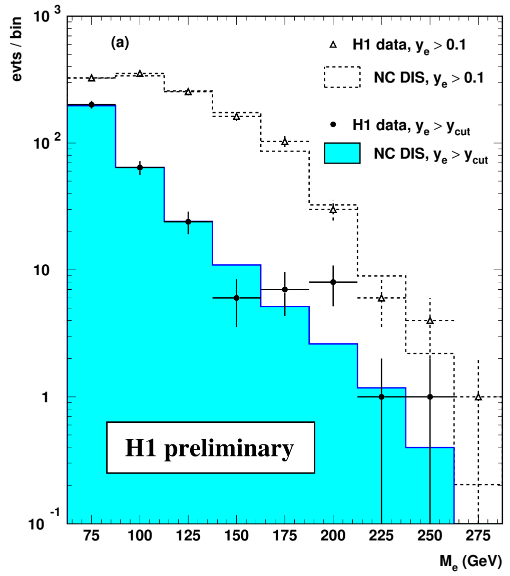

Figure 4: Mass spetra for eq topology. The subscript e in y_e and $M_e(=\sqrt{sx})$ indicates that the event kinematics is reconstructed with the measured energy and angle of the scattered electron.

zero as $\Delta m \to 0$. A large variation in $\tan\beta$ results only in slight changes. In the range $45 < (m_{\tilde{e}} + m_{\tilde{q}})/2 < 85$ GeV the up quark contribution to the cross section ranges between 70% to 90% because it dominates the parton densities at high x. The limits on the $\tilde{u}$ mass alone (Fig. 2(d)), assuming all other squarks to be much heavier, are only ~ 2 GeV below the limit obtained for degenerate squark masses (Fig. 2(c)). The mass limits substantially improve those limits previously published by H1[3] due to the seven-fold increase in the integrated luminosity. These limits are at the same level as those obtained from LEP[4c] and are complementary to those obtained from Tevatron[6] as they investigate different regions of the MSSM parameter space[d].

3 Search for $\tilde{q}$ within $\not{R}_p$-SUSY

In contrast to the MSSM, in $\not{R}_p$-SUSY, the squarks can be singly produced and they can decay not only via their gauge couplings to a quark/antiquark and a neutralino/chargino (Fig. 3(b,d)) but also via their Yukawa coupling into SM fermions (leptoquark-like, Fig. 3(a,c)). Moreover, the LSP (again assumed to be χ_1^0), which is no longer stable, decays via λ'_{1jk} into a quark, an antiquark and a lepton.

With e^+p collisions, HERA is best sensitive to couplings λ'_{1j1} among the nine possible couplings λ'_{1jk}, where mainly $\tilde{u}_L^j$ squarks are produced via processes involving a valence d quark. On the contrary, future HERA e^-p data will allow to better probe couplings λ'_{11k} and $\tilde{d}_R^k$ squarks.

Depending on whether the produced squarks undergo a $\not{R}_p$ decay or a gauge decay, there are many different final state event topologies, e.g. (a) a lepton plus a jet, (b) a neutrino plus a jet, (c) a right sign lepton plus multijets, and (d) a wrong sign lepton plus multijets.

Topology (a) is indistinguishable from a NC DIS event on an event-by-event basis. Statistically, however, one expects for the signal a resonant peak in the mass distribution and a flat distribution in y ($1/y^2$ distribution for NC DIS events). For this reason, a mass dependent y cut is chosen and it allows to reduce significantly the NC DIS background (Fig. 4). The other selection cuts are basically the same as in the high Q^2 paper[7]. The total efficiency varies between 35% at 75 GeV, 50% at 200 GeV and 70% at 250 GeV. In total 312 events are observed, which is in good agreement with the SM expectation of 306 ± 23 events. Data are found to be well described by MC, although an excess of events still remains in the mass range 200 ± 12.5 GeV where 8 events are observed while 3.01 ± 0.54 are expected. This clustering is however less significant than that observed with 1994 $\to$ 1996 data alone[7].

Topology (b) has only a low sensitivity with the e^+ beam since the produced squarks $\tilde{d}_R^{k*}$ couples to a sea quark $\overline{u}$ from the proton (Fig. 3(c)), the density of which is small at high x. Thus it will not be considered in the following.

The main SM background for topology (c) is also

[c]The Limits from LEP have been improved recently[5].

[d]For example, in contrast to Tevatron, the gluinos are assumed here to be heavy.

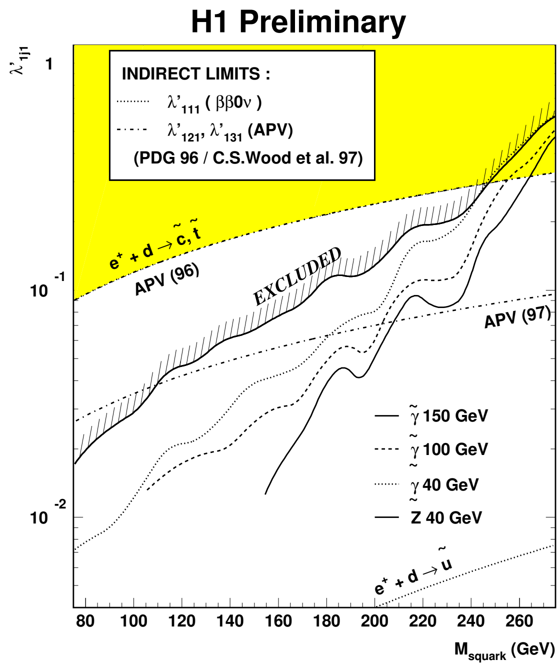

Figure 5: Exclusion upper limits at 95% CL for the couplings λ'_{1j1} as a function of squark mass, for various masses and mixtures of the χ_1^0; also represented are the most stringent indirect limits on λ'_{1j1}.

from NC DIS where QCD radiation leads to multijets. Two main cuts are $y > 0.4$ and $\theta_e < 110°$. The latter cut exploits the fact that for high y NC DIS events, one hard jet is usually scattered in the backward region of the calorimeter (the proton beam direction is defined as the forward direction), on the contrary jets coming from a squark will be boosted in the forward direction independent of y. The efficiency varies from about 30% for a 100 GeV squark decaying into a 40 GeV χ_1^0 to about 50% when these masses are set respectively at 200 GeV and 80 GeV. In total 289 candidates are observed, which is in good agreement with the mean SM background of 285.7 ± 28.0 expected from NC DIS and photoproduction (the latter has a contribution of less than 3%).

Topology (d) has such a striking final state that it is essentially background free. Indeed, when the negative charge of the lepton track with good quality is required in addition to the cuts applied for topology (c), only one event survives, which is compatible with 0.49 ± 0.2 events coming from NC DIS.

Under the assumption that only one of the Yukawa couplings λ'_{1j1} dominates[e], mass dependent upper limits on these couplings are derived by combining these three topologies (Fig. 5). The sensitivity on λ'_{1j1} for squark masses below about 200 GeV is better by roughly a factor 2 for a $\tilde{\gamma}$-like χ_1^0 than for a χ_1^0 dominated by its zino component due to the higher part of the total branching actually being analyzed in the three considered topologies. The sensitivity achieved increases with the $\tilde{\gamma}$ mass due to the higher efficiency in topology (c). For electromagnetic coupling strengths $\lambda'_{1j1} = \sqrt{4\pi\alpha_{em}} \simeq 0.3$, squark masses up to 262 GeV are excluded at 95% CL. This reach in the mass-coupling plane extends beyond that covered by other collider experiements, [2] e.g. (i) in their leptoquark-like searches, D0 and CDF rule out $\tilde{u}_L^j$ squark masses below 200 GeV for a branching ratio $B(\tilde{u}_L^j \to e^+ q) \geq 50\%$ (the excluded mass domain is lowered to about 110 GeV when $B(\tilde{u}_L^j \to e^+ q) \leq 10\%$, which can be natually small in $\not{R}_p$-SUSY), (ii) the light stop mass limit is estimated to be $130 - 150$ GeV in models in which R_p is violated by a λ'_{13k} coupling from the specific SUSY searches performed by D0 and CDF. The results are also compared to the best indirect limits. The most stringent constraint comes from the non-observation of neutrinoless double beta decay but only concerns coupling λ'_{111}. For couplings λ'_{121} and λ'_{131}, the limits derived by H1 are comparable or more stringent than the best indirect limits coming from Atomic Parity Violation.

4 Search for lepton flavor violation within $\not{R}_p$-SUSY

Under the assumption that one product of couplings $\lambda'_{1j1} \times \lambda'_{ljk} (l = 2, 3)$ is non-vanishing and donimates over all remaining couplings, namely squarks $\tilde{u}_L^j$ are produced via coupling λ'_{1j1} and decay via λ'_{ljk}, striking explicit lepton flavour violation processes $e^+ d \to \tilde{u}_L^j \to \mu^+ (\tau^+) d^k$ may occur.

H1 has observed 5 events of the type $e^+ p \to \mu^\pm X$. [8] None of these events survive as soon as the kinematic constraints of a $2 \to 2$ body process is imposed.[f]

H1 has also searched for squarks coupling to a third generation lepton leading to τq final states. No candidate is observed while 0.8 ± 0.3 events are expected from SM processes. The efficiency ranges from $\sim 10\%$ for a 100 GeV squark to $\sim 25\%$ for squark masses above 200 GeV. Under a further assumption that the gauge decays of squarks are forbidden (so that the only squark decay modes are $\tilde{u}_L^j \to e^+ d$ and $\tilde{u}_L^j \to \tau^+ d^k$), exclusion limits at 95% CL on λ'_{3jk} as a function of squark masses have been derived by fixing the production coupling λ'_{1j1} to a given value (Fig. 6). A similar analysis to that presented here has been published by the ZEUS Collaboration with an integrated luminosity of about 3 pb^{-1} using

[e] This is not unreasonable as in the SM the top quark Yukawa coupling is almost a factor 40 larger than the bottom Yukawa coupling.

[f] On the other hand, part of the observed muon events are kinematically compatible [9] as proceeding through the process $e^+ d \to \tilde{t}_1 \to \tilde{b}_1 W^+$ with subsequent decays $\tilde{b}_1 \to d\overline{\nu}_e, W^+ \to \mu^+ \nu_\mu$ as suggested by T. Kon *et al.* [10].

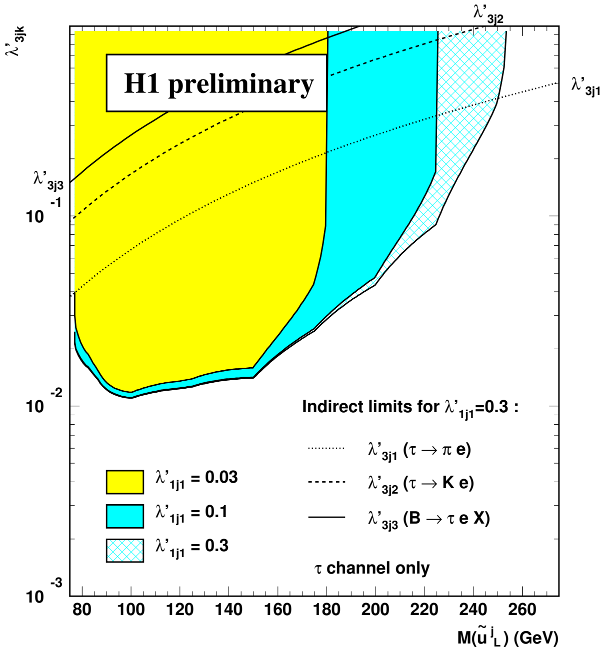

Figure 6: Exclusion upper limits at 95% CL for the coupling λ'_{3jk} as a function of squark mass, for several fixed values of λ'_{1j1} (greyed domains). The regions above the full, dashed and dash-dotted curves correspond to the best relevant indirect limits.

1994 e^+p data[11]. When the two couplings are both equal to 0.03, the analysis presented here extends the squark mass range by about 65 GeV. The only relevant indirect limits [12] come from the process $\tau \rightarrow \pi e, \tau \rightarrow Ke$ and $B \rightarrow \tau e X$.[g] H1 direct limits improve these constraints by typically one order of magnitude.

5 Summary and Outlook

SUSY processes have been searched for at HERA using full e^+p data taken in 1994 → 1997. Within the MSSM, ZEUS has found no evidence for the production of selectron and squarks decaying directly into the lightest neutralino. Excluded regions reach $(m_{\tilde{e}} + m_{\tilde{q}})/2 = 77$ GeV at 95% CL for $m_{\chi_1^0} = 40$ GeV and large values of the MSSM parameter $|\mu|$. The process is dominated by the $\tilde{u}$ contribution and the exclusion limit is 75 GeV when only the $\tilde{u}$ squark is considered. These mass values are still far away from the HERA kinematic limit and are currently limited by the available integrated luminosity.

H1 has searched for within R-parity violating SUSY direct production of single resonant squarks decaying via R-parity violating as well as gauge couplings. Notwithstanding an excess at masses around 200 GeV in channel with a positron and one jet as the final states, no significant evidence for the production of squarks was found and mass dependent limits on the R-parity violating couplings were derived. Squarks with masses up to 262 GeV are excluded at 95% CL for a strength of the Yukawa coupling of $\alpha_{\rm em}$. The limits extend beyond the domain covered by other collider experiments, and for some R-parity violating couplings, are better than the most stringent indirect constraints.

Lepton flavour violation processes have been sought. No candidates satisfying a $2 \rightarrow 2$ body process kinematics are found. The resulting H1 direct limits on λ'_{3jk} improve the only relevant indirect limits by typically one order of magnitude.

HERA will provide e^-p collisions in 1998 and probably also in 1999 with an expected integrated luminosity of 50 pb^{-1}. The proton beam energy will increase by more than 10% from 820 GeV to 920 GeV. In two years from now, there will be a major luminosity upgrade, which will result in a factor of more than 5 increase in the peak luminosity providing a total integrated luminosity of 1 fb^{-1} in the period 2000 → 2005 corresponding to a yearly luminosity of 150 pb^{-1} per experiment. Therefore new potential for SUSY searches or discovery is expected in the next years from HERA.

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[g] Note that better indirect limits on couplings λ'_{3jk} alone exist. However these only concern the $\tilde{d}_R$ and can thus be evaded assuming e.g. $\tilde{u}^j_L$ to be much lighter than other squarks, which could be achieved especially in the case of a light stop ($j = 3$).