SEARCHES FOR SUPERSYMMETRY AT HERA

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Searches for supersymmetry at HERA have been carried out by both experiments H1 and ZEUS. The increase of integrated luminosity ($\mathcal{L} \simeq 6\text{pb}^{-1}$) has allowed, for the first time, to search for new particles in the framework of the Minimal Supersymmetric Standard Model. Moreover, adding R-parity violating Yukawa couplings leads to a different phenomenology, and corresponding searches are also presented here.

1 Introduction and definitions

Supersymmetry (SUSY) is a very attractive ingredient of a theory beyond the Standard Model (SM). The SUSY extensions of the SM considered here, like the MSSM (Minimal Supersymmetric Standard Model) are minimal in fields. They contain in particular selectrons ($\tilde{e}_L, \tilde{e}_R$) and squarks ($\tilde{q}_L, \tilde{q}_R$), which are searched for in the presented analysis. Gauginos (i.e. the photino $\tilde{\gamma}$, the zino $\tilde{Z}$ and the winos $\tilde{W}^{\pm}$) and higgsinos mix to form four neutral mass eigenstates (called neutralinos) χ_i^0 ($i = 1..4$), and two charginos $\chi_j^{\pm}$ ($j = 1,2$). The masses and couplings of the χ^0 and $\chi^{\pm}$ can be expressed in terms of the basic MSSM parameters : the $U(1)$ and $SU(2)$ soft-breaking terms M_1 and M_2, the Higgs mixing parameter μ and the ratio $\tan\beta$ of the expectation values of the two neutral Higgses. For simplicity, it is assumed here that M_1 is related to M_2 as suggested by Grand Unification Theories (GUT), $M_1 = 5/3 M_2 \tan^2\theta_W$. No other GUT relation is used. Gluinos are assumed here to be very heavy.

In the strict MSSM frame, the conservation of R-parity (R_p) is imposed, where R_p is defined as $R_p \equiv (-1)^{3B+L+2S} = 1$ (for particles) = -1 (for sparticles), where B (L) and S denote the baryon (lepton) numbers and the spin. This ensures that SUSY particles are produced in pairs and that the Lightest Supersymmetric Particle (LSP) is stable. Searches for $\tilde{e}$ and $\tilde{q}$ in this frame will be presented in section 2.

However, gauge invariance and supersymmetry do not imply R_p conservation. R_p violating ($\not{R}_p$) terms, coupling one scalar fermion to two matter fermions, can be added to the MSSM superpotential. Such terms will induce LSP decay, leading to event topologies which differ strongly from the characteristic "missing energy" signal in the MSSM. The search for $\not{R}_p$ SUSY is thus complementary to that performed in the strict MSSM framework. We concentrate here on the $\not{R}_p$ terms $\lambda'_{ijk} L_i Q_j \bar{D}_k$, ijk being generation indices and the superfields L_i, Q_j, $\bar{D}_k$ containing respectively the left-handed lepton doublet, the quark doublet and the right-handed quark singlet. Such terms violate L and allow for a squark to couple to a lepton-quark pair. Thus, the ep collider HERA is ideally suited to search for squarks produced in resonance via a λ'_{1jk} coupling, via a fusion between the incident positron and a quark coming from the proton. Corresponding searches are presented in section 3.

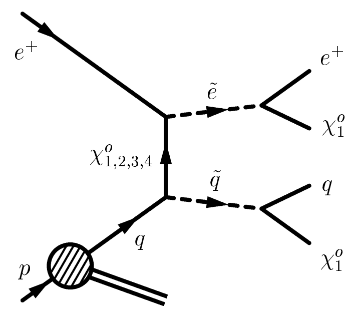

Figure 1: Lowest order Feynman diagram for $\tilde{e} + \tilde{q}$ production in ep collisions with subsequent decays of the sfermions.

2 MSSM Searches

Associated production of a selectron and a squark, via the exchange of a neutralino χ_i^0 has been studied by the H1 experiment [1]. The sensitivity is largest for $\tilde{\gamma}$-like χ_1^0 (χ_1^0 dominated by its photino component), and the selectron (squark) will dominantly decay into electron (quark) and χ_1^0. Decays

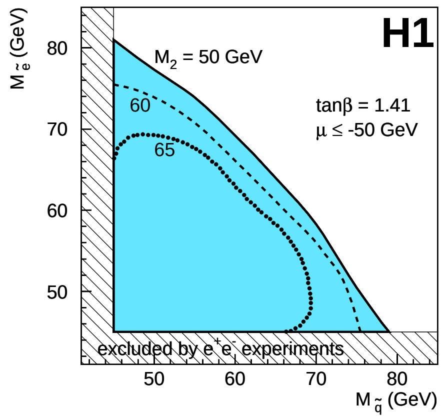

Figure 2: Exclusion limits on the selectron and squark masses at 95% confidence level. Grey domains are covered by H1 at HERA.

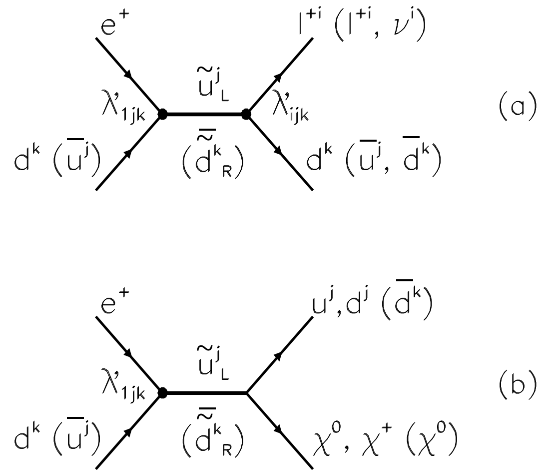

Figure 3: Production of squark via $\not{R}_p$ followed by $\not{R}_p$ decay (a) or gauge decay (b).

into heavier χ^0 or $\chi^\pm$ are taken into account in the derivation of exclusion limits. As the LSP is stable, such final states consist of one electron, one jet, and missing transverse momentum $\not{P}_\perp$. Requiring high enough $\not{P}_\perp$, no event candidate is observed combining 1994 and 1995 H1 data ($\mathcal{L} \simeq 6.4$ pb^{-1}), and less than one event is expected from Standard Model processes.

Exclusion limits have been derived and results are shown in Fig. 2, in the plane $(M_{\tilde{e}}, M_{\tilde{q}})$ for several values of M_2. Masses up to $(M_{\tilde{e}} + M_{\tilde{q}})/2 \leq$ 63 GeV can be excluded at 95% confidence level (CL), for $M_{\chi_1^0} \leq 35$ GeV . This limit applies as long as $M_{\tilde{e},\tilde{q}} - M_{\chi_1^0} \geq 20$ GeV , and decreases slightly when this difference becomes smaller. As can be seen on the figure, the domain covered by H1 (in grey) extends considerably the one excluded by LEP100, for small values of M_2 and negative μ.

3 R-Parity violating SUSY Searches

Squarks can be singly produced in resonance via an eq fusion, through one of the nine possible couplings λ'_{1jk}, as illustrated in Fig. 3. The production cross-section scales as λ'^2_{1jk} and with the probability $d^k(x)$ $(\bar{u}^j(x))$ to find a quark d^k $(\bar{u}^j)$ in the proton with a momentum fraction $x = M_{\tilde{q}}^2/S$. With an e^+ incident beam, HERA is best sensitive to couplings λ'_{1j1}, where mainly $\tilde{u}_L^j$ squarks (SUSY partners of left-handed u^j squarks) are produced via processes involving a valence d quark.

Squarks can then undergo either $\not{R}_p$ decays (Fig. 3a) into a lepton and a quark, either "gauge", i.e. R_p conserving, decays (Fig. 3b) involving a χ^0 or a χ^+. These are generally unstable. By gauge invariance, $\tilde{\bar{d}}_R^k$ squarks are not allowed to decay into a chargino.

We first assume that one coupling λ'_{1jk} is non vanishing and dominates other $\not{R}_p$ couplings. Gauge decays of $\tilde{q}$ will be followed by the decays of the χ. The lightest neutralino χ_1^0, assumed here to be the LSP, can undergo $\chi_1^0 \rightarrow e^\pm($ or $\nu) + 2$ jets. There is an equal probability for the χ^0 to decay into "right sign" (compared to incident beam) or "wrong sign" (i.e. e^-) lepton, which could lead to a striking signature with explicit lepton number violation. Note that a χ_1^0 dominated by its higgsino component generally has a very small decay width and decays outside detector, leading to large $\not{P}_\perp$. Decays of the χ_1^+ can involve a W boson $(\chi_1^+ \rightarrow W\chi_1^0 \rightarrow \chi_1^0 + 2$ fermions), or proceed via $\not{R}_p$ $(\chi_1^+ \rightarrow e^+ qq'$ or $\nu qq')$.

Combining the different $\tilde{q}$ decays with all possible decays for the χ, the expected final states can be classified in three families : A) $\not{R}_p$ decays of $\tilde{q}$ into $e^+ + q$ or $\nu + q$; B) Gauge decays of $\tilde{q}$ leading to $e^\pm$ + 3 jets signatures (e.g. $\tilde{q} \rightarrow q\chi_1^0$ followed by $\chi_1^0 \rightarrow e^\pm qq$); C) Gauge decays of $\tilde{q}$ with missing

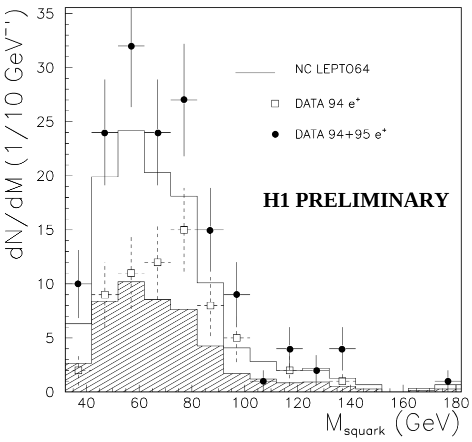

Figure 4: Invariant mass spectrum for class B) candidates in 1994 and 1994+1995 data, compared to Monte-Carlo expectations from DIS Neutral Current background.

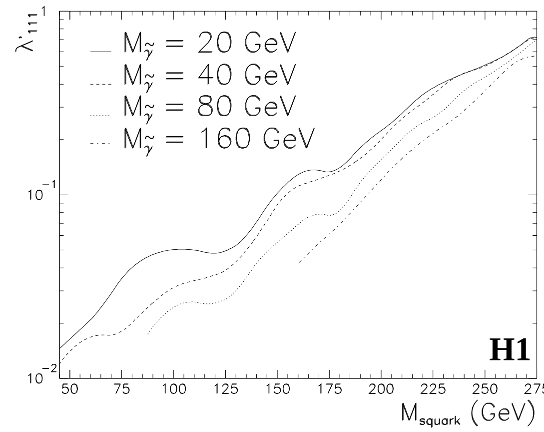

Figure 5: Exclusion upper limits at 95% confidence level. The regions above the curves are excluded. The limits also apply to λ'_{121} and λ'_{131} within $\simeq 10\%$.

transverse momentum, jet(s) and/or charged lepton(s).

Events of class A) are individually indistinguishable from Deep Inelastic Scattering (DIS) processes. Looking for the signal in these channels is similar to the search for leptoquarks [2]. The characteristic angular distribution for the decay products of a scalar particle is used to reduce DIS background, and after selection cuts no significant deviation from the SM predictions is observed in this channel, combining 1994 and 1995 e^+ H1 data [2]. No class B) candidate in the "wrong sign" channel (i.e. $e^+p \to e^- + 3$ jets $+ X$) has been observed combining 1994 and 1995 H1 data. In the "right sign" channel, the recently published analysis of 1994 H1 data [3] ($\mathcal{L} \simeq 2.6\text{pb}^{-1}$) showed a slight excess (2.9σ) in the invariant mass spectrum for masses around $70-80$ GeV . This analysis has been improved in two ways. The peak resolution on the invariant mass (i.e. the reconstructed "squark" mass) has been improved by a factor $\simeq 2$ by imposing overall kinematical constraints. Moreover, exploiting spin dependence allows a better reduction of DIS background. The usual Bjorken variable $y_e = 1 - E_e/E_e^0 \sin^2\theta_e$ is computed from the scattered positron kinematics. A similar variable y_{jet} is then defined for the highest P_T jet found in the azimuthal hemisphere opposite to the positron, $y_{jet} = 1/2(1 + \cos\theta^*_{jet})$, θ^*_{jet} being the polar angle of this jet in the $e-q$ CM frame. For DIS events, y_e is also equal to $1/2(1+\cos\theta^*_e)$, so that $\sum y = y_e + y_{jet} \simeq 1$. For signal events, a flat distribution in y_{jet} is expected since the jet emerges from the scalar quark decay. The y_e distribution appears strongly shifted towards high values, since the final state e only carries a fraction of the χ momentum. Hence, cutting on $\sum y$ allows to distinguish the signal from DIS background. With this new analysis, as can be seen in Fig. 4, the excess for invariant masses around 80 GeV is still present on 1994 H1 data, but is not very significant when combining with 1995 data.

For family C), the observation is compatible with SM expectations. An interesting event [3,4] $e^+p \to \mu^+ + X$ has however been observed in 1994 H1 data and belongs to this family.

Combining all channels, exclusion limits on the mass of the squarks have been derived, using 1994 H1 data. These are shown on Fig. 5 depending on the $R\!\!\!/_p$ coupling. For coupling strength $\lambda'^2/4\pi = \alpha_{em}$, masses of $\tilde{q}$ up to 240 GeV are excluded at 95% CL by this analysis. This extends far beyond the $\simeq 100$ GeV limit which could be inferred from dilepton Tevatron data. How these exclusion limits depend on the MSSM parameters has also been studied [5]. By folding in the right parton densities, limits on the other λ'_{1jk} couplings can be inferred from the derived limits on λ'_{111}. Table 1 shows how H1 direct limits compare to

Table 1: H1 and indirect upper limits at 95% CL on λ'_{1jk} for $M_{\tilde{q}} = 150$ GeV and $M_{\tilde{\gamma}} = 40$ GeV .

	H1 limits	Indirect limits	
λ'_{111}	0.056	0.003	$\beta\beta 0\nu$ decay
λ'_{112}	0.14	0.05	CC-univ.
λ'_{113}	0.18	0.05	CC-univ.
λ'_{121}	0.058	0.6	D^+ decays
λ'_{122}	0.19	0.04	ν_e-mass
λ'_{123}	0.30	0.6	D^+ decays
λ'_{131}	0.06	0.7	$\Gamma_h/\Gamma_e \mid^Z$
λ'_{132}	0.22	0.7	$\Gamma_h/\Gamma_e \mid^Z$
λ'_{133}	0.55	0.002	ν_e-mass

most stringent indirect limits.

Assuming now that two $R\!\!\!/_p$ couplings λ'_{1jk} and λ'_{2jk} or λ'_{3jk} are non vanishing (and assumed equal for simplification), spectacular Lepton Flavor Violation processes would be expected, with μ or τ in final state (Fig. 3a, with $l = \mu, \tau$). Such an analysis has been performed by the ZEUS collaboration [6], assuming the χ^0_1 to be a pure photino, and neglecting decays of $\tilde{q}$ other than $R\!\!\!/_p$ or $\tilde{q} \to q + \tilde{\gamma}$. Final states are classified into two families : both with large $P\!\!\!/_\perp$ but with or without an identified electron. In each class, after final selection, no event candidate is observed combining 93 and 94 ZEUS data, while less than 1 is expected from SM predictions.
Results are shown in Fig. 6, where the upper solid lines correspond to a vanishingly small photino mass, and the lower ones to cases where $M_{\tilde{\gamma}} \geq M_{\tilde{q}}$. For $R\!\!\!/_p$ couplings of the electromagnetic strength, masses of $\tilde{q}$ up to $\simeq 240$ GeV are excluded at 95% CL. A sensitivity better than existing indirect LFV limits is obtained at $M_{\tilde{q}} = 150$ GeV for some coupling combinations.

4 Conclusions

The search for supersymmetric particles at HERA has not yet lead to a discovery, but a new domain has been covered. In the MSSM frame, selectrons and squarks up to $\simeq 65$ GeV have been excluded at 95% confidence level. In models where R-parity is violated via Yukawa couplings λ'_{1jk}, squarks up to 240 GeV are excluded if the strength of the λ'_{1jk} coupling is comparable to α_{em}. Considering a combination of couplings $\lambda'_{1jk} \times \lambda'_{2(3)jk}$, a similar mass range has been probed.

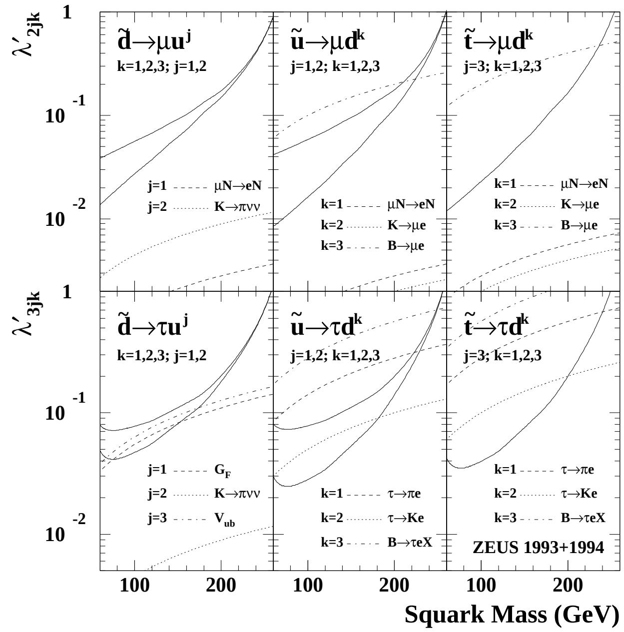

Figure 6: Exclusion upper limits at 95% CL (solid lines) on the coupling λ'_{2jk} (λ'_{3jk}) depending on the squark mass. Indirect limits are also represented.

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