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SUPERSYMMETRY AT HERA, RESULTS AND PROSPECTS*

Johannes Haller

Physikalisches Institut, Philosophenweg 16, 6900 Heidelberg, Germany
email: haller@mail.desy.de

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The existing results from HERA on searches for supersymmetry are reviewed in this article. Within the framework of the Minimal Supersymmetric Standard Model with R_p conservation, no evidence for the production of supersymmetric particles was found by H1 and ZEUS. HERA is particularly sensitive to the resonant production of squarks in SUSY models with R_p-violation ($\not{R}_p$). Searching for the process $eq \to \tilde{q} \to eq$ (or $e\chi$), in a large number of possible decay modes of the χ no evidence for $\tilde{q}$ production was found. The limit on the corresponding Yukawa coupling λ' was found to be weakly dependent of the free MSSM parameters and extends to domains not excluded by other direct or indirect searches. Squark masses up to 260 GeV can be ruled out for couplings of electro-magnetic strength. The interpretation of the HERA results in the framework of various constrained supersymmetric models are compared to the results from other experiments. The perspectives of SUSY searches at HERA are reviewed.

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1. Introduction

Supersymmetry (SUSY) is likely to be an essential property of a theory beyond the Standard Model (SM). Among the most compelling arguments for supersymmetry are the stability of a softly broken supersymmetry, which naturally avoids arbitrary fine tuning of parameters, and the 'explanation' of the hierarchy between the Grand Unification scale (or the Planck scale) and the electroweak mass scale.

The minimal supersymmetric extension of the Standard Model (MSSM) predicts for each SM particle a partner with spin differing by half a unit: squarks ($\tilde{u}_{\rm L}$, $\tilde{d}_{\rm L}$), $\tilde{u}_{\rm R}$, $\tilde{d}_{\rm R}$ are the partners of the up and down quarks, while

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selectrons $\tilde{e}_{\rm L}$, $\tilde{e}_{\rm R}$ are the partners of the electrons. Two scalar Higgs doublets with non zero vacuum expectation values (v_1 and v_2) are needed to generate masses for up-type quarks (v_2), down type quarks and charged leptons (v_1). The supersymmetric partners of the SU(2)×U(1) gauge bosons $\gamma, Z^0, W^\pm$ (Higgs doublets) are called gauginos (higgsinos). These states mix to form mass eigenstates called charginos ($\chi^\pm_{1,2}$) and neutralinos ($\chi^0_{1,2,3,4}$).

SUSY must be broken, as particles and their superpartners are not degenerate in mass. In the MSSM this is achieved by the introduction of extra mass parameters M_2 and M_1 for the SU(2) and U(1) gauginos. As a result the masses of charginos and neutralinos depend on M_1, M_2, $\tan\beta \equiv v_2/v_1$ and the higgsino mass term μ. For details on SUSY models see [1].

2. The MSSM at HERA

To conserve lepton and baryon number, the MSSM is constructed to conserve R-parity, $R_p = (-1)^{3B+L+2S}$, which is even (odd) for ordinary SM (SUSY) particles. This implies, that the Lightest SUSY Particle (LSP) is stable and that SUSY particles can only be produced in pairs.

At HERA the dominant MSSM process is the production of a selectron and a squark via a t-channel exchange of a neutralino $eq \to \tilde{e}\tilde{q}$ and the subsequent decays: $\tilde{e} \to e\chi, \tilde{q} \to q\chi$. Thus the signature is an electron with hight $p_{\rm t}$, a jet and missing energy. The HERA collaborations [2,3] set a limit to the sum of selectron and squark mass $(m_{\tilde{e}} + m_{\tilde{q}})/2 > 77\,{\rm GeV}$, which is no more competitive to new results from LEP and Tevatron in R_p-conserving models.

3. $\not{R}_p$ supersymmetry at HERA

The most general theory that is supersymmetric, gauge-invariant and renormalizable allows for additional terms in the superpotential that are excluded in the MSSM as they violate R_p:

$$W_{\not{R}_p} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \,,$$

where i, j, k are family indices and $\bar{E}$, $\bar{D}$ and $\bar{U}$ (L, Q) are right-handed singlet (left-handed doublet) superfields for charged leptons, down and up-type quarks respectively.

As HERA provides leptonic and baryonic quantum numbers in the initial state, the second $\not{R}_p$-term is of special interest at HERA; it allows for the resonant production of squarks in the s-channel. With an initial e^+-beam HERA is mainly probing the production of $\tilde{u}^j_{\rm L}$ squarks via Yukawa couplings λ'_{1j1}, as the production cross section is proportional to the quark densities $d_k(x = m^2_{\tilde{q}}/s)$.

Two squark decay modes can be distinguished: Firstly the squark may decay R_p-violating directly into a quark and a positron (neutrino). These decay modes are also relevant for leptoquark searches at HERA and contribute mostly at high couplings (*i.e.* high masses). In Fig. 1 examples for the second type of decay mode called gauge decays are shown. The squark first decays into a quark and a gaugino. Then the gaugino decays either R_p-violating into two quarks and a first family lepton or into two fermions and a lighter gaugino, which subsequently decays via the first mechanism into two quarks and a lepton. Both decays involve the $\not{R}_p$ coupling λ'.

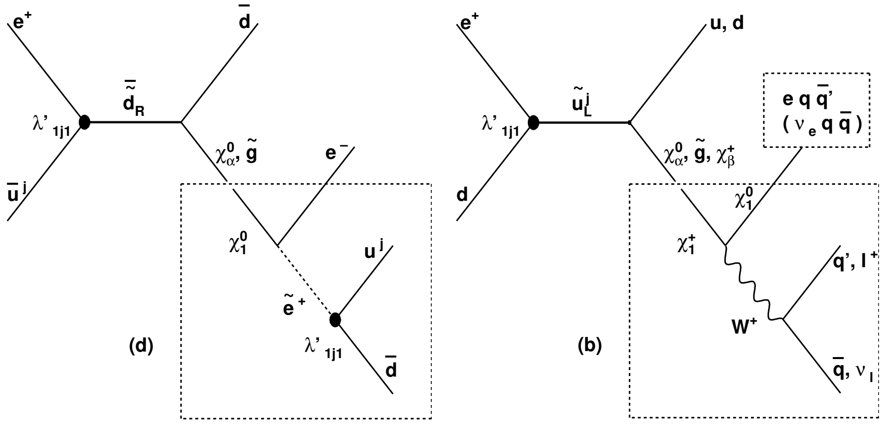

Fig. 1. Examples for production and gauge decays of squarks in $\not{R}_p$ SUSY at HERA.

These decay modes result in a large variety of decay topologies with leptons, jets and missing p_t. Among them are very striking signatures, like a 'wrong charge' (compared to the initial positron beam) electron. These decay channels have been investigated in great detail by the HERA collaborations [4, 5] for the data period 1994–1997 corresponding to $40\,\mathrm{pb}^{-1}$ with an initial e^+-beam. H1 sees no deviation in all decay channels, while ZEUS sees a small excess for the e + jets channel, which is still under investigation.

4. Limits in various $\not{R}_p$ supersymmetric models

Both collaborations set limits in the Unconstrained (phenomenological) MSSM, where the gaugino masses depend on the MSSM soft terms while the sfermion masses are free. The resulting limits on the coupling λ'_{1j1} are shown in Fig. 2(left). A scan has been performed in the SUSY parameter space by varying μ and M_2 for a fixed value of $\tan\beta$. The comparison of the weakest (all space points excluded) and the strongest (just parts of the parameter space excluded) limit shows that the results are widely model independent. For couplings of electro-magnetic strength ($\lambda'_{1j1} = 0.3$) squark masses up to 260 GeV are ruled out. The HERA sensitivity extends beyond indirect bounds [6] from low energy experiment for $\tilde{c}$ and $\tilde{t}$-production.

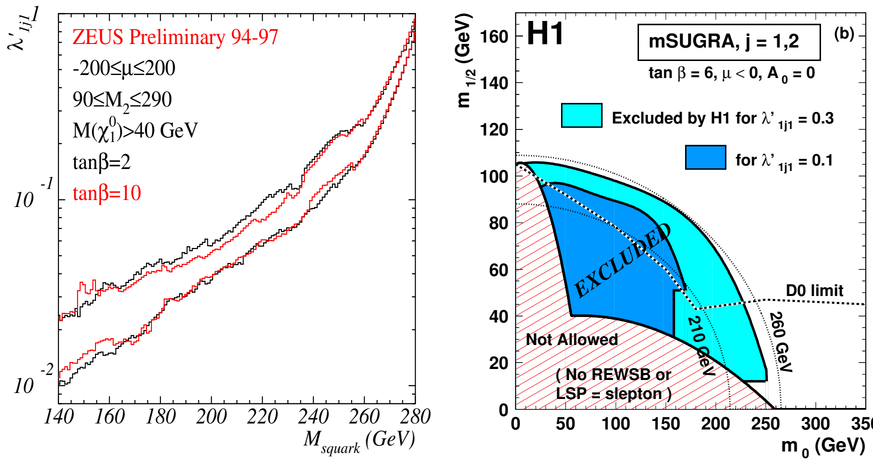

Fig. 2. Limits on λ' as a function of $m_{\tilde{q}}$ in the phenomenological MSSM (left) and limits in the mSUGRA model for $j = 1, 2$ (right).

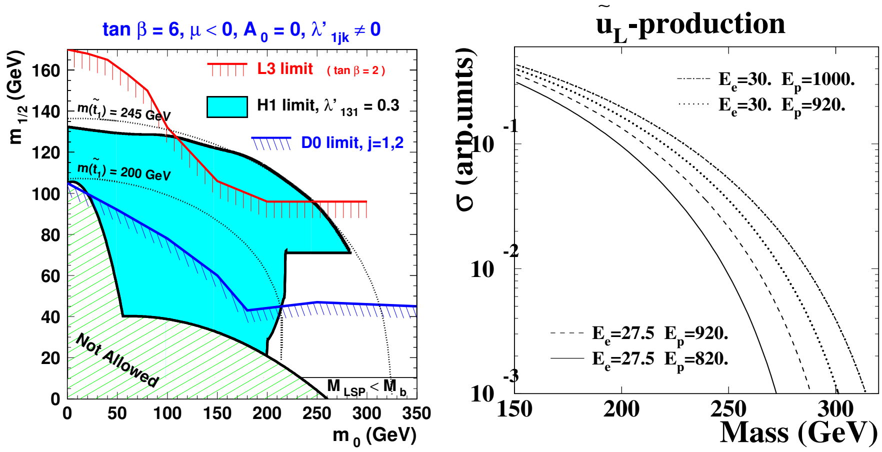

Fig. 3. mSUGRA limits for stop ($j = 3$) production (left) and production cross section of up-type squarks for various beam energies in arb. units (right).

H1 also gives limits in the mSUGRA model where a common sfermion (gaugino) mass m_0 ($m_{1/2}$) is assumed at the GUT scale and the electroweak symmetry breaking is driven by radiative corrections. This model is completely determined by four parameters: m_0, $m_{1/2}$, $\tan\beta$, A_0 and a sign of μ. The resulting limits in the $(m_{1/2}, m_0)$-plane is shown in Fig. 2(right) for negative μ and a fixed value of $\tan\beta$ ($A_0 = 0$). The HERA sensitivity follows the squark iso-mass line of 260 GeV shown for illustration. The comparison with other experiments shows that HERA and the Tevatron give complementary information for $j = 1, 2$. For $j = 3$ (Fig. 3(left)) HERA is able to cover a larger part of the $(m_{1/2}, m_0)$-plane, as the $\tilde{t}$ is the lightest squark in mSUGRA. For intermediate m_0 HERA reaches the sensitivity of LEP. Their limit is expected not to depend very much on $\tan\beta$ and it is shown for a different value of $\tan\beta$ for illustration.

5. Future prospects of SUSY searches st HERA

HERA was running with an e^--beam in 98/99. The 15 pb^{-1} taken in this period allow to probe the production of $\tilde{d}_{\rm R}$ squarks via $R\!\!\!/_p$ couplings λ'_{11k} complementing the $\tilde{u}$ squarks in the e^+-data discussed before.

In 99/00 the integrated luminosity of e^+ data has been tripled and the center of mass energy has been increased from 300 GeV to 320 GeV, resulting in a strongly increased production cross section at high squark masses due to the steeply falling quark densities in the proton. With these data the sensitivity on $\lambda'_{1j1}(m_{\tilde{q}})$ can be improved by a factor of two in the high mass region. This will result in an increase of 15 GeV for the $\tilde{q}$ masses probed at electro-magnetic coupling strength.

The effect of increasing the beam energies of HERA are shown in Fig. 3(right) where the production cross section of $\tilde{u}^j_{\rm L}$ squark is shown as a function of the squark mass for various beam energies. At high masses large factors can be gained for the production cross section with higher center of mass energies.

For the HERA II period five times higher luminosities are expected and the electron beam will be polarized ($P_e \approx 0.6 - 0.7$). The squark production processes in $R\!\!\!/_p$ SUSY with polarized beams are $e^+_{\rm R} + d_{\rm L} \to \tilde{u_{\rm L}}^j$ and $e^-_{\rm L} + u_{\rm L} \to \tilde{d_{\rm R}}^k$. So a $e^+_{\rm R}$-beam or a $e^-_{\rm L}$-beam are very useful for $R\!\!\!/_p$ SUSY search at HERA II; but the crucial point is $\sqrt{s}$.

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