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Searches for stop production in e^+p collisions at HERA

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Abstract

A search for stop production in R-parity-violating supersymmetry has been performed with the ZEUS detector at HERA, using e^+p collisions at a center-of-mass energy of 318 GeV. The data were collected during 1999-2000 and correspond to an integrated luminosity of 65.5 pb^{-1}. The resonant production of stop via an R-parity-violating Yukawa coupling, λ'_{131}, was considered, focusing on the decay channel $\tilde{t} \to b\chi^+$ which has a sizeable branching ratio in a large part of the SUSY parameter space. The χ^+ subsequently decays via R-parity-violating or gauge couplings, leading to a final state with multiple jets and a lepton. The analysis concentrated on the study of the e^+ plus multi-jets final states. No evidence for stop production was found and limits were set on the coupling λ'_{131} as a function of the stop mass in the framework of the Minimal Supersymmetric Standard Model.

1 Introduction

The electron-proton collider HERA is an ideal place to search for possible exotic states originating from electron-quark fusion. Such new states naturally arise in grand unification theories that arrange quark and lepton in common multiplets (as leptoquarks) or in SUSY models that violate R-parity (as squarks). Scalar or vector leptoquark states have been previously searched for by the ZEUS Collaboration [1]; this paper presents a search in e^+p collisions for the stop-squark, the scalar partner of the top quark, which is expected to be the lightest squark.
The stop production proceeds, via an R-parity-violating Yukawa coupling λ'_{131} (where the subscripts are generation indices), as $e^+d \to \tilde{t}$. The decay leads to a rich topology since, beside the leptoquark-like $\tilde{t} \to e^+d$ channel, there are a number of possible gauge decays leading to final states with multi-jets and one or more leptons.
This paper focuses on the neutral-current (NC) channel induced by the gauge decay $\tilde{t} \to b\chi^+$ (where χ^+ denotes the chargino), followed by the R-parity-violating decay $\chi^+ \to e^+$ and two jets. This channel is dominant for χ^+ masses (M_{χ^+}) lower than stop mass ($M_{\tilde{t}}$) and not too much heavier than neutralino. Indeed, when M_{χ^+} is comparable to the sum of the neutralino (χ°) and W masses, the channel $\chi^+ \to \chi^\circ W$ becomes relevant leading to final states with missing P_t due to neutrinos coming from the leptonic W decay and R-parity-violating χ° decay.

The analysis presented in this paper uses e^+p data collected by the ZEUS detector in 1999-2000, corresponding to an integrated luminosity of 65.5 pb^{-1}. Similar searches for squark production at HERA have been performed by the H1 Collaboration [2, 3].

2 SUSY phenomenological backgrounds

The results were interpreted in the framework of the R-parity-violating Minimal Supersymmetric Standard Model (MSSM) where the masses of the neutralinos, charginos and gluinos are determined by the following MSSM parameters: the mass term μ which mixes the Higgs superfields, the soft SUSY-breaking parameters M_1, M_2 and M_3 for the $U(1)$, $SU(2)$ and $SU(3)$ gauginos, respectively, and $\tan\beta$, the ratio of the vacuum expectation value of the two neutral scalar Higgs fields. The masses of the first- and second-generation squarks and all the sleptons have been set at the TeV scale. The mass of the lighter stop[1]

[1] The partners of the left- and right-handed top, $\tilde{t}_L$ and $\tilde{t}_R$, mix togheter in two mass eigenstates, $\tilde{t}_1$ and $\tilde{t}_2$, which are strongly non-degenerate due to the large top mass. Throughout the paper, we refer to the lighter stop using the symbol $\tilde{t}$.

was varied in the range $110 - 250$ GeV, assuming $Mu_3 = Mq_3$[2].

In order to minimise the number of free paramaters and to enhance the contribution of the NC channel $\tilde{t}$ decay, the following additional assumptions were made:

- only the Yukawa coupling λ'_{131} was assumed to be non-zero;
- a large μ scenario, $|\mu| > 600$ GeV was assumed;
- the χ° was required to be the lightest supersymmetric particle (LSP) and $M_1 =$ 110 GeV in order to get $M_{\chi^\circ} \sim 40 - 100$ GeV, above the LEP limit [4];
- $M_3 = 1$ TeV in order to suppress the decay channel $\tilde{t} \to t\tilde{g}$;
- the mass difference $M_{\tilde{t}} - M_{\tilde{\chi}^+}$ was required to be larger than 10 GeV so that the decay to $\tilde{t} \to b\tilde{\chi}^+$ was dominant. The above assumptions lead to M_2 values always close (within a few GeV) to M_{χ^+}.

Figure 1 shows for one particular scenario ($\mu = 800$ GeV, $\tan\beta = 5$, $\lambda'_{131} = 0.1$, $M_{\tilde{t}} - M_{\tilde{\chi}^+} = 20$ GeV) how the different final states compete.

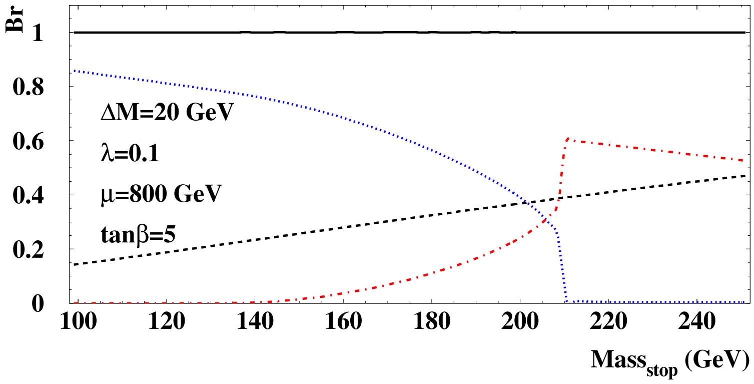

Figure 1: *Branching ratios for the different decay channels: e^+ +multi-jets (dotted), ν +multi-jets (dashed-dotted), e^+ +jet (dashed).*

The signal cross section was evaluated by means of the program COMPHEP [5]. The same program, interfaced to the Monte Carlo (MC) PYTHIA [6], was also used to simulate the full signal process.

[2] Mu_3 and Mq_3 are the soft SUSY breaking masses for the doublet left-handed and singlet right-handed third-family squarks.

3 Event selection

Since the events we searched for are characterized by a high-energy positron in the final state, the trigger selection was based on a standard NC trigger used in the ZEUS searches for resonance states decaying in eq [1] and in the NC DIS studies [7].

The pre-selection was designed to select a sample of high-Q^2 NC events. The following conditions were required, while some of them were also used at the trigger level with a lower threshold.

- Z-coodinate of the event vertex compatible with an ep interaction, $|Z_{vtx}| < 50$ cm.
- A high-energy positron reconstructed combining both calorimeter and tracking information [8]. A positron energy, $E_e > 8$ GeV, was required, while this cut was increased to $E_e > 20$ GeV for very forward positrons ($\theta_e < 0.3$, where θ_e is the positron polar angle) that are outside the acceptance of the central tracking detector.
- $40 < \sum_i (E - P_z)_i < 70$ GeV, where the sum runs over the final-state positron and all the other calorimeter energy deposits. For events like NC DIS, where only particles in the very forward direction escape detection, this quantity approximately equals to $2E_e^{beam} = 55$ GeV, where E_e^{beam} is the positron beam energy.
- $Q^2_{DA} > 1000$ GeV^2 and $0.2 < y_{DA} < 0.98$, where Q^2_{DA} and y_{DA} are the DIS kinematic variables reconstructed using the polar angles of the positron and of the hadronic system [9]. The above conditions were imposed in order to restrict the search to a region where the signal is enhanced with respect to NC DIS and the reconstruction of the kinematic variables is reliable.
- $M_{eX} > 100$ GeV, where M_{eX} is the invariant mass of the positron and the hadronic system evaluated using the following relation that exploits longitudinal and transverse momentum conservation:

  $$M^2_{eX} = 2E_e^{beam} \sum_i (E + P_z)_i \tag{1}$$

  where E and P_z are the energy of the calorimeter deposits and its z-projection. The sum runs over the final-state positron and all the other energy deposits having a polar angle $\theta_i > 0.1$, to exclude the proton remnant.

The average and resolution of the reconstructed mass have been evaluated using the signal MC. The average is slightly overestimated at low masses (3% at 100 GeV), while the agreement improves towards high masses (< 1% above 150 GeV). The resolution is between 5 and 1.5% in the mass range $100 - 300$ GeV.
After the pre-selection cuts 2376 events survived, in good agreement with the expectation of the SM MC, 2301^{+94}_{-98}. The reported errors are dominated by systematic uncertainties

(see section 4). The SM prediction is dominated by the NC DIS. This process was simulated using the LEPTO 6.5 [10] program which uses the matrix element plus parton shower (MEPS) to model the QCD cascade.
Figure 2 shows the distributions of mass, y_{DA}, Q^2_{DA} and circularity (see next paragraph for the definition) for data (triangles) and MC (dashed histograms); reasonable agreement is achieved for all the variables.

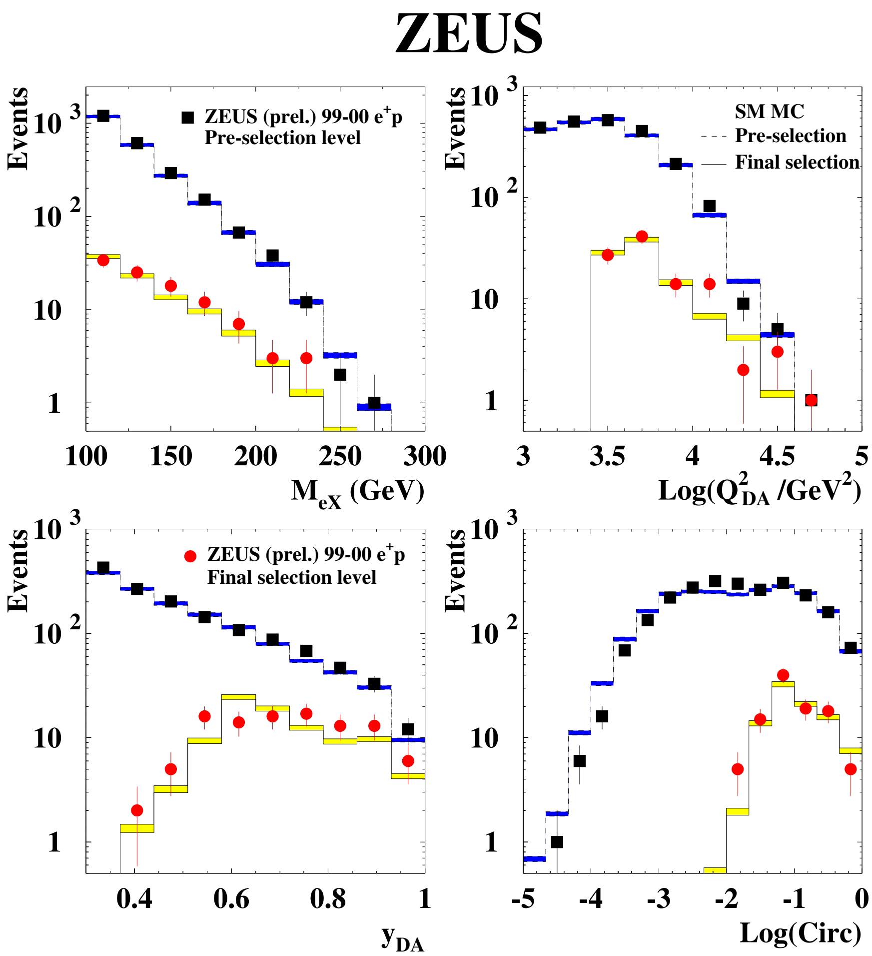

Figure 2: *Comparison between data (dots) and SM MC (histograms) for M_{eX}, Q^2_{DA}, y_{DA} and circularity, after the pre-selection and the final selection.*

The final selection was optimized to minimize the expected cross-section limit for stop production. The variables used in the optimization were Q^2_{DA}, y_{DA} and the circularity, defined as:

$$Circ = 2(1 - max(\lambda_1, \lambda_2)) \tag{2}$$

where λ_1, λ_2 are the eigenvalues of the matrix M :

$$M_{ij} = \frac{\sum_k P_{i,k} P_{j,k}}{\sum_k (P^2_{x,k} + P^2_{y,k})} \tag{3}$$

where $i, j = x, y$, $P_{i(j)}$ is the $x(y)$-projection of the calorimeter energy deposits and the sums run over the final-state positron and all other deposits with $\theta_i > 0.1$. The circularity is a measure of the event distributions in the transverse plane. NC DIS events with a back-to-back topology have lower values of circularity than multi-jet events, which exhibit more isotropic distribution. The NC DIS MC fails to reproduce the jet multiplicity of the data (MC undershoots the number of multi-jet events typically by 20%), and, as a consequence, also the circularity is not accurately reproduced. In order to improve the agreement between data and MC, the jet multiplicity in the MC was reweighted using the data outside the mass window used for the signal search (see Section 5). This procedure led to a quite good agreement between data and MC for the circularity distribution (see Fig. 2 lower right), especially for the high-circularity region where the signal is expected. The following final conditions resulted from the optimization procedure:

- $Q^2_{DA} > 3000$ GeV^2,
- $y_{DA} > 0.6 \div 0.2$,
- $\log_{10}(Circ) > -1.25 \div -3.0$,

where the ranges reported are for masses between 100 and 300 GeV: the cuts become looser with the increasing mass, due to the decreasing expected background from SM processes. After the final selection, 103 events were found in the data, to be compared with $94.1^{+5.3}_{-5.7}$ expected from SM processes dominated by NC DIS. Figure 2 shows the comparison between data (dots) and MC (solid histograms) for M_{eX}, Q^2_{DA}, y_{DA} and circularity; good agreement is observed.

4 Systematic checks

The following sources of systematic uncertainty in the SM predictions were taken into account:

- uncertainty on the NC DIS cross section evaluated using the program EPDFLIB [11];
- uncertainty related to the knowledge of the calorimeter energy scale, $\pm 1\%$ ($\pm 2\%$) for the electromagnetic (hadronic) section;
- uncertainty in the integrated-luminosity measurement, $\pm 2\%$.

5 Results

Since no evidence for e^+-jets resonances was found, 95% CL upper limits on λ'_{131} as a function of the stop mass were evaluated. A scan of the mass spectrum in 1 GeV steps was performed using a sliding window of width $\pm 2 \div 4\,\sigma_{M_{eX}}$ (the mass window width was also optimized to minimize the expected cross-section limit on stop production; it increases towards large masses). At each stop mass, the 95% CL cross-section limit was evaluated from the data events, the SM predictions and the signal efficiencies (varying in the range $20-50\%$ for masses between 110 and 250 GeV) in the considered mass window. A Bayesian approach assuming a flat prior on the signal cross section was used. The systematic uncertainties on the expected SM background have been taken into account in the limit setting. The limits on λ'_{131} were then obtained using the cross sections and branching ratios calculated by COMPHEP for each SUSY scenario considered: $|\mu| = 600\,, 800\,, 1000$ GeV, $\tan\beta = 2\,, 5\,, 10$ and $\Delta M_{\tilde{t}\chi^+} = 10\,, 20\,, 30$ GeV, the mass difference between the stop and the chargino. Figure 3 shows the 95% CL limit on λ'_{131} as a function of the stop mass for $\mu = 800$ GeV, $M_{\tilde{t}\chi^+} = 20$ GeV and for different values of $\tan\beta = 2\,, 5\,, 10$. For the other scenarios considered, the results are very similar for stop masses $\lesssim 200$ GeV. The limits for masses up to 200 GeV improve on the low-energy limits coming from atomic parity violation (APV) measurements (dashed line) [12] and depend weakly on the different SUSY parameters used. The H1 collaboration obtained similar constraints [2] using different SUSY scenarios.

6 Conclusions

A search for stop production in e^+p collisions at HERA was performed, using an integrated luminosity of 65.5 pb^{-1} collected by the ZEUS detector during the 1999-2000 data taking. No evidence for resonances in the decay channel e^+-jets was found. The results have been interpreted in the framework of the R-parity-violating MSSM, setting constraints on the Yukawa coupling λ'_{131}. The ZEUS result, for $M_{\tilde{t}} < 200$ GeV, improves on low-energy limits from APV measurements.

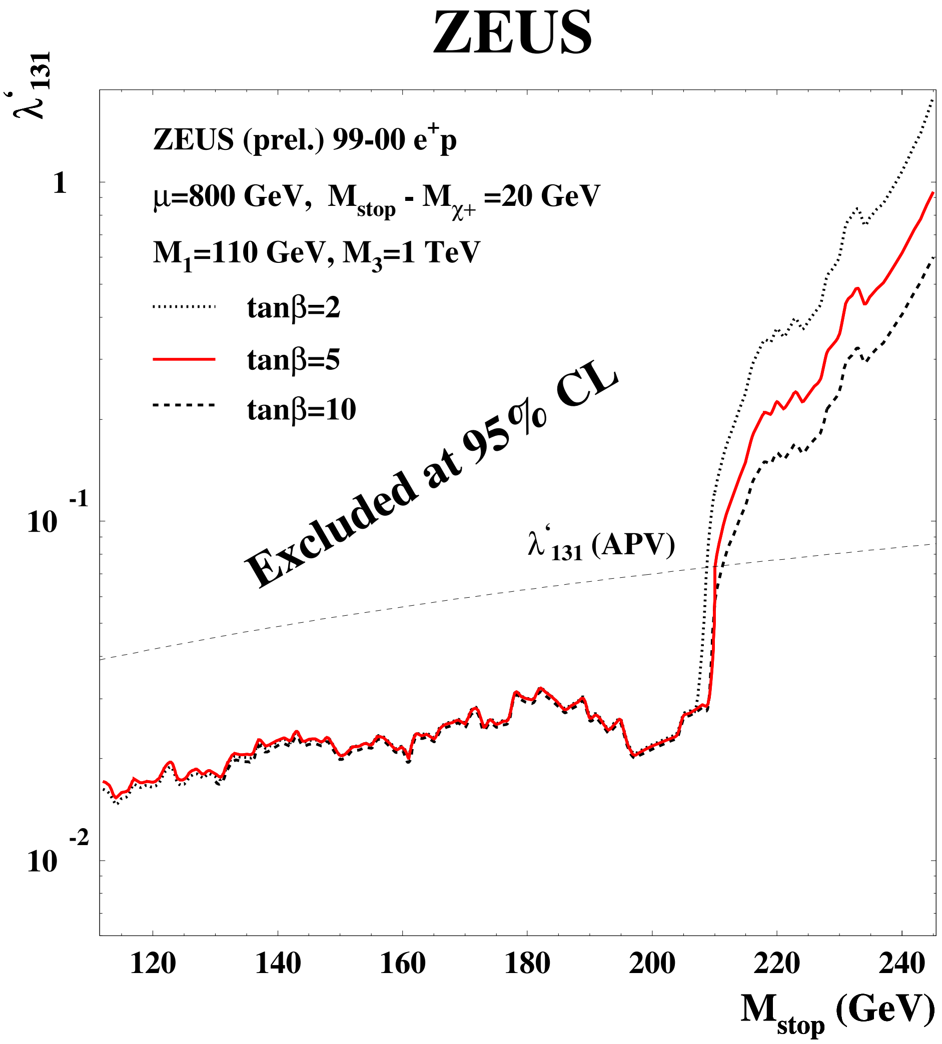

Figure 3: *Limits on λ'_{131} as a function of the stop mass for different values of the SUSY parameter space. Low-energy limit from APV measurements is also reported.*

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