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Search for gravitino production in R-parity violating supersymmetry at HERA

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Abstract

A search for light gravitino production in e^+p collisions has been performed with the ZEUS detector at HERA using an integrated luminosity of 65.1 pb^{-1}. In R-parity violating supersymmetric models a neutralino can be produced by the t-channel exchange of a selectron between the beam electron and an initial quark. In models where the gravitino is the lightest supersymmetric particle, the neutralino decays to a gravitino and a photon leading to a final state with an isolated high energy photon and large missing transverse momentum. Since no deviation from the Standard Model expectation was observed, lower limits for the neutralino and selectron masses have been derived in the framework of Gauge Mediated Supersymmetry Breaking.

1 Introduction

Despite its extraordinary success in describing particle interactions at low energies the Standard Model (SM) of elementary particle physics cannot satisfactorily explain the stability of the Higgs mass which radiatively acquires divergent contributions. One of the most promising candidates for solving this problem is Supersymmetry (SUSY) [1]. This fermion-boson symmetry predicts a supersymmetric partner (sparticle) for each SM particle differing by one half in its spin. As none of these particles have yet been detected, SUSY has to be a broken symmetry. In contrast to the Minimal Supersymmetric Standard Model (MSSM) newer supersymmetric models provide a more detailed description of the symmetry-breaking mechanism which turns out to be essential for the determination of the sparticle mass spectrum. In Gauge Mediated Supersymmetry Breaking models (GMSB) the information of supersymmetry breaking is communicated by extra messenger fields which couple to the SM particles and their superpartners via ordinary gauge interactions [2].

In the not yet excluded region of GMSB parameter space, the gravitino ($\tilde{G}$) is the lightest sparticle (LSP) [3]. When the neutralino, $\tilde{\chi}^0$, is the next-to-lightest sparticle (NLSP) it decays predominantly via $\tilde{\chi}^0_1 \rightarrow \gamma\tilde{G}$.

The scenario studied here is placed in the framework of R-parity (R_P) violating SUSY. While R_P-violating terms are often excluded from the Lagrangian, there is no theoretical prerequisite to require R_P conservation. Because of its unique initial state HERA is an ideal place to search for R_P-violating SUSY.

The signal process is shown in Fig. 1. It has a distinctive event topology, containing an isolated photon, missing transverse energy and one jet. As there is no contribution from squarks, the process provides a handle on Yukawa couplings independent of squark masses, for which strong bounds from Tevatron exist. The main background from SM processes comes from charged current (CC) deep inelastic scattering (DIS) with a radiated photon.

The analysis presented in this paper uses events from e^+p collisions with a centre-of-mass energy of $\sqrt{s} = 318\,\mathrm{GeV}$ taken by the ZEUS detector in the years 1999 and 2000, corresponding to an integrated luminosity of 65.5 pb^{-1}. A detailed description of the experimental setup can be found elsewhere [4].

In the investigated region of GMSB parameter space the branching ratio $\Gamma(\tilde{\chi}^0_1 \rightarrow \gamma\tilde{G})$ exceeds 98%. In deviation from the minimal GMSB model, slepton masses were treated as independent parameters. In particluar, the left-handed selectron is supposed to be lighter than the right-handed one. Therefore, a scan in the slepton-neutralino mass plane, $m_{\tilde{e}_L} - m_{\tilde{\chi}^0_1}$, was possible.

A search for events with gravitinos has been performed by the H1 Collaboration [5] in the same channel. Similar topologies have also been studied at LEP [6] and Tevatron [7] in the framework of R_P-conserving GMSB.

2 Event simulation

Complete Monte Carlo (MC) simulations of the ZEUS detector response were performed in order to estimate the expected SM contributions to the signature under study and determine the efficiencies for the potential SUSY signal. The number of used SM events represent at least twice the luminosity of the analysed data. SM background events from neutral current (NC) and CC DIS processes were simulated with the Djangoh [8] event generator which uses Heracles [9] to model first order QED radiation and is interfaced to the hadronisation program Ariadne [10]. Direct and resolved photoproduction events were simulated with Pythia [11]. The CTEQ5D [12] parametrisation of the parton densities in the proton was used.

The event generator Susygen [13], interfaced to Pythia, was used for the simulation of the signal topology. It uses internally the Suspect program [14] for the calculation of the sparticle mass spectrum. Events were generated for 8 different neutralino masses between 59 GeV and 114 GeV and 3 different selectron masses for each neutralino mass. In addition, a scan over the effective cross section ($\sigma_{\text{eff}} = \sigma \times \text{BR}$) was performed in steps of 2 GeV in $m_{\tilde{e}_L}$ and the results were interpolated along $m_{\tilde{\chi}_1^0}$.

It was found that the signal selection efficiency depends mainly on the neutralino mass; its dependence on the selectron mass is small and was neglected.

3 Event selection

The events resulting from the process $e^+q \rightarrow \tilde{\chi}_1^0 q' \rightarrow \gamma\tilde{G}q'$ are characterised by missing transverse momentum, due to the undetected gravitino, an isolated, high energy photon, and one or more jets. Due to the similar event topology the preselected sample consists mainly of CC DIS events. Additionally, in the final selection a photon was required. The cuts for preselection and final selection were made as loose as possible in order to keep the signal efficiency high. Cuts were made by a multidimensional cut method aiming for a good separation of signal and background (see Section 3.2).

3.1 Preselection

Data events were triggered using standard ZEUS triggers for CC DIS events. For the selection of signal like CC DIS events the following conditions were required. Some of them were also used at trigger level with a lower threshold.

- Z-coordinate of the event vertex compatible with an ep interaction, $|Z_{\rm vtx}| < 40\,{\rm cm}$;
- missing transverse momentum, $P_T^{\rm miss} > 20\,{\rm GeV}$;
- the difference in azimuthal angle of the jet of highest transverse energy and the photon $\Delta\phi({\rm jet1}, \gamma) < 3.0$ rad. This cut rejects mainly NC DIS events, it was only applied when an electron candidate with $E^e > 4\,{\rm GeV}$ and $-2.8 < \eta^e < 2.8$ was found;
- $Q^2_{\rm JB} > 700\,{\rm GeV}^2$;
- $y_{\rm JB} > 0.1$, here $Q^2_{\rm JB}$ and $y_{\rm JB}$ are the usual DIS kinematic variables reconstructed using the Jacquet-Blondel method (see *e.g.* [15]);
- $E - P_Z < 65\,{\rm GeV}$; where E is the total energy measured in the calorimeter (CAL), $E = \sum_i E_i$, and P_Z is the Z component of the vector $\vec{P} = \sum_i E_i \vec{r}_i$; in both cases the sum runs over all CAL cells, E_i is the energy of the CAL cell i, and $\vec{r}_i$ is a unit vector along the line joining the reconstructed vertex to the center of the cell i;
- at least one jet with $E_T^{\rm jet} > 6\,{\rm GeV}$ and $-1.5 < \eta^{\rm jet} < 2.5$.

Additionally, cleaning cuts were applied against non-ep events coming from cosmic and proton-beam related background, and the event time was required to be consistent with the bunch crossing time.

After the preselection cuts, 959 events survived in good agreement with the prediction from SM MC of 960.1 ± 4.8 events. Figure 2 shows the distributions for $Q^2_{\rm JB}$, E_T and P_T/E_T of the entire visible event, number of jets, $E_T^{\rm jet}$ and $\eta^{\rm jet}$ of the jet with the highest E_T. The MC prediction gives a good description of the data for all distributions. Signal efficiencies after the preselection vary between 66% and 79% depending on the GMSB parameters.

3.2 Final selection

For photon identification an electron finder based on the pattern of energy deposits in the calorimeter was used with the additional requirement that no track is associated to the electron candidate. For this analysis the photon candidate was required to fulfill the conditions of $E^\gamma > 4\,{\rm GeV}$ and $-2.8 < \eta^\gamma < 2.8$. Additionally, it was required that the distance between the calorimetric cluster of the photon candidate and the nearest track should be at least 30 cm. Signal efficiencies after the final selection varied between 59%

and 71%. After applying these additional cuts, 177 data events remained compared to an expectation of 170.1 ± 1.7 from SM MC. Fig. 3 shows the distributions of the photon variables E^γ, E_T^γ and η^γ. The data distributions are well described by the MC.

For a clear identification of possible signal events, the neutralino mass and the square of the four-momentum transfered by the selectron, $Q^2_{\tilde{e}_L}$, have been reconstructed applying longitudinal and transverse momentum conservation and assuming a massless gravitino. Figure 4 shows the distributions for $E-P_z$, $E_T^\gamma + E_T^{\rm jet}$, $\Delta\phi(\tilde{G}, {\rm jet})$, $\eta^{\chi_1^0}$, $Q^2_{\tilde{e}_L}$ and $m_{\tilde{\chi}_1^0}$. These variables were selected from a set of about 50 event variables as they show the best signal to background separation and include the six degrees of freedom of the signal event topology. Good agreement is also seen here between data and MC.

To optimize the signal to background ratio a multivariate discriminant method as described elsewhere [16] was used. The discriminant value is calculated for each event by considering the probability density distributions of the signal and the background obtained from MC simulations. The discriminant distributions are shown in Fig. 5. For the SUSY signal, separate discriminant distributions were calculated for all generated GMSB points. Figure 6 shows how signal efficiency and signal to background ratio depend on a cut on the discriminant.

3.3 Systematic uncertainties

The systematic uncertainties on the SUSY signal and SM background expectations were evaluated by considering the following sources.

- the uncertainty of the absolute energy scale of the calorimeter leads to an uncertainty of the background cross section of 2.5% and of the signal cross section of 0.6%;
- the measurement of the integrated luminosity has an uncertainty of 2.25%;
- using Meps [17] instead of Ariadne results in an uncertainty of 1.7% for the background MC;
- the theoretical uncertainty for the d quark parton density in the proton in the relevant x-range is 7% for signal and CC background;
- the scale uncertainty due to the leading-order nature of the signal MC gives an additional theoretical uncertainty of 10% for the signal;
- the uncertainty on the signal efficiency due to the interpolation between different parameter points was 2.5%.

Additionally, cut variations of the thresholds for $Z_{\rm vtx}$, $Q^2_{\rm JB}$, P_T^{miss}, $y_{\rm JB}$ and $\Delta\phi({\rm jet1}, \gamma)$ were performed to check the stability of the selection. All systematic errors were added in quadrature separately for signal and background. The total systematic uncertainties are 10.4% for the signal and 13.2% for the background. These uncertainties were included in the numerical calculation of the limits as uncorrelated Gaussian fluctuations of the expected number of signal and background events.

4 Results

No deviation from SM expectations was observed in the signal region. Therefore a scan over the GMSB parameter space was performed as described in Section 2. Limits were calculated at 95% confidence level (CL) by using a modified frequentist approach based on likelihood ratios [18] which takes statistical and systematical uncertainties into account. An interpolation of the CL values is performed to obtain the limit plot in the selectron-neutralino mass plane as shown in Fig. 7.

5 Conclusions

A search for neutralino production in e^+p collisions was performed assuming its decay into a light gravitino and a photon. The analysed data was taken by the ZEUS detector at HERA in the year 1999 and 2000 corresponding to an integrated luminosity of 65.5 pb^{-1}. No deviation from the SM was observed for the investigated event topology of a photon, a jet and missing transverse energy. As such events are expected in gauge mediated SUSY breaking models with R_P-violation the results have been used to derive constraints in the selectron-neutralino mass plane. Selectron masses up to $m_{\tilde{e}_L} = 180\,\mathrm{GeV}$ and neutralino masses up to $m_{\tilde{\chi}_1^0} = 118\,\mathrm{GeV}$ can be ruled out at 95% CL for Yukawa couplings $\lambda'_{1j1} = 1$ $(j = 1, 2)$.

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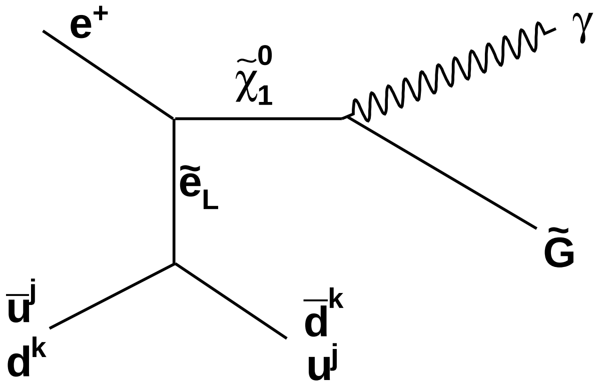

Figure 1: *Feynman diagram of the signal process:* R_P*-violating t-channel exchange of a left-handed selectron between a positron and a quark leads to the production of a neutralino which decays into a gravitino and a photon.*

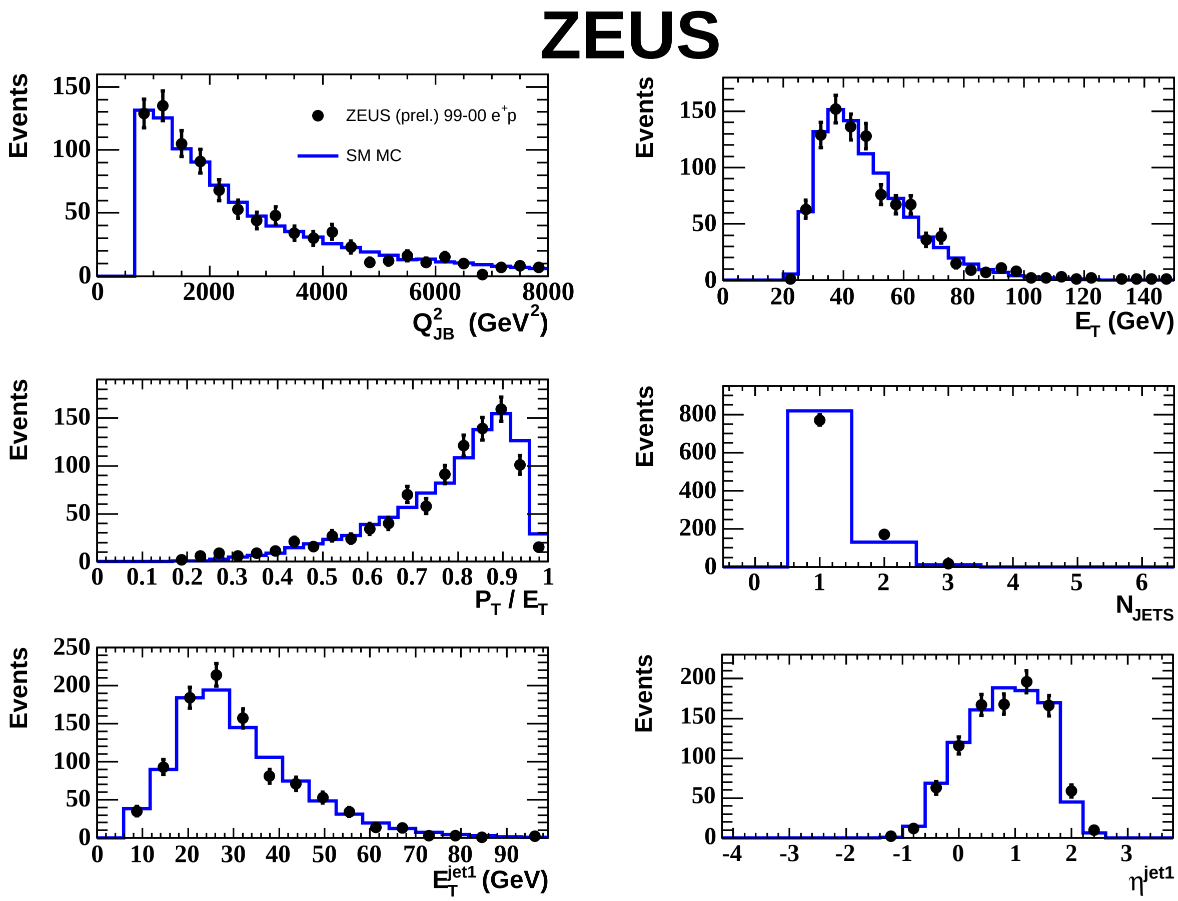

Figure 2: *Distributions of kinematic variables after preselection. Shown are the distributions for data events (dots), and SM background MC (solid line) of* $Q^2_{\rm JB}$*,* E_T*,* P_T/E_T*, number of jets,* $E_T^{\rm jet}$ *of the highest* E_T *jet and* $\eta^{\rm jet}$ *of the highest* E_T *jet.*

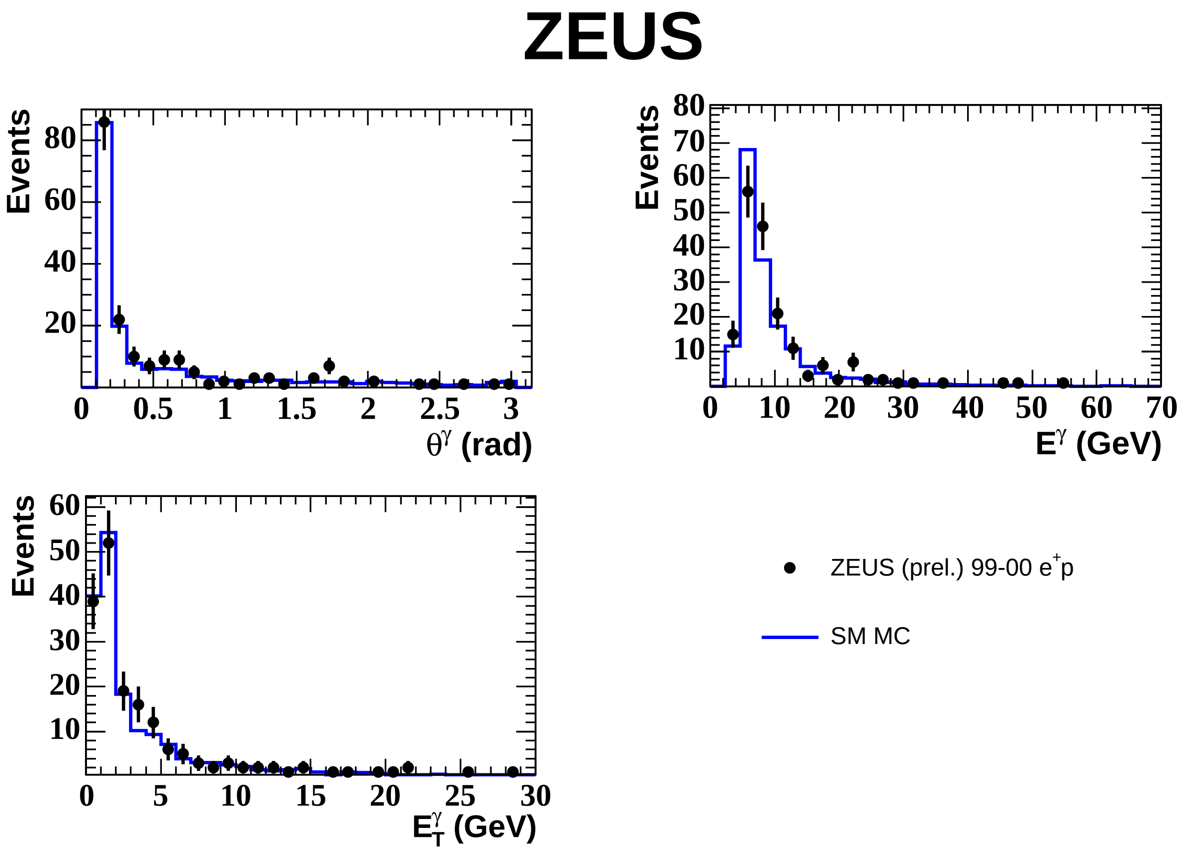

Figure 3: *Distributions of photon variables after final selection.*

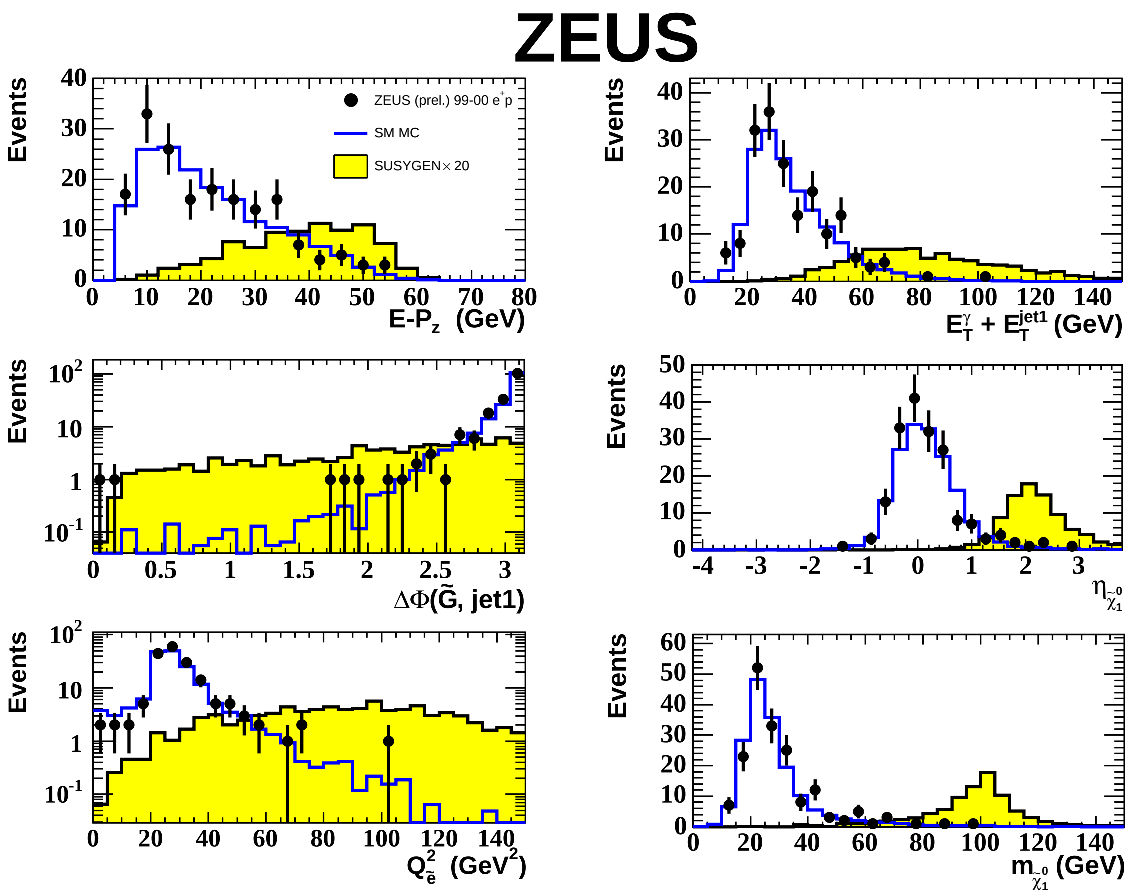

Figure 4: *Distributions of the six variables used in the discriminant method after the final selection. The SUSY signal is an example for $m_{\tilde{\chi}_1^0} = 100.4\,GeV$ and $m_{\tilde{e}_L} - m_{\tilde{\chi}_1^0} = 40\,GeV$. For better visibility the signal has been multiplied by 20 in these plots.*

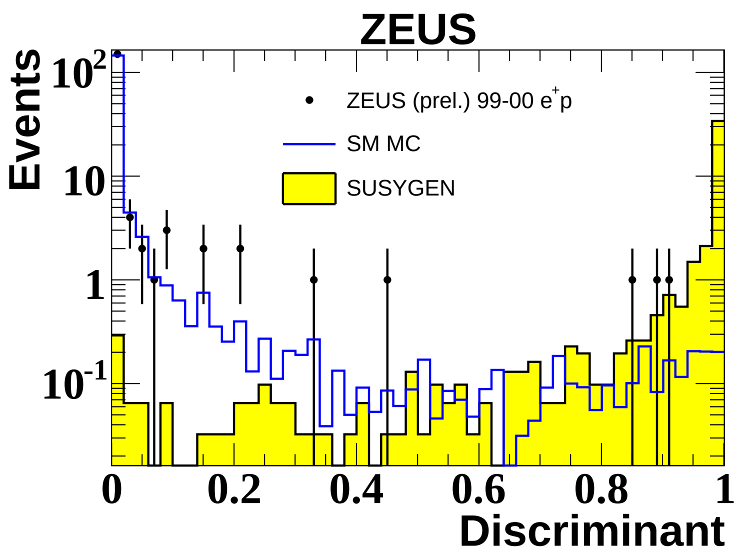

Figure 5: *Discriminant distributions for events after final selection: Data (dots), SM background (solid line) and SUSY signal (filled area). The SUSY signal is an example for* $m_{\tilde{\chi}_1^0} = 100.4\ GeV$ *and* $m_{\tilde{e}_L} - m_{\tilde{\chi}_1^0} = 40\ GeV$.

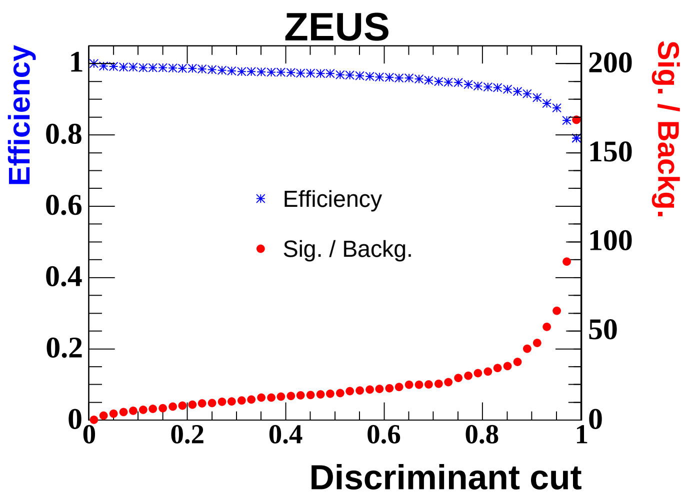

Figure 6: *Efficiency (crosses, left axis) and signal-to-background ratio (dots, right axis) as functions of a discriminant cut.*

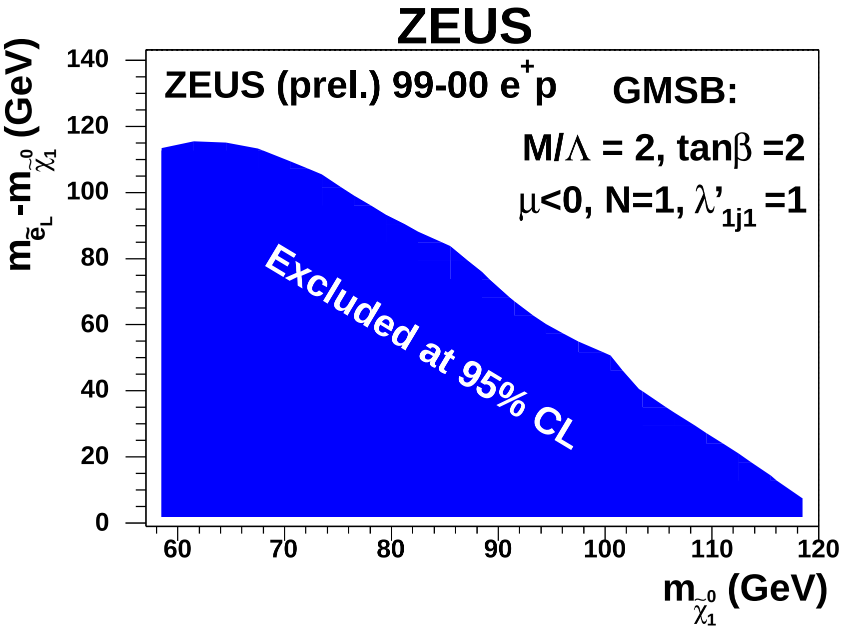

Figure 7: *Region excluded at 95% CL (filled area) in the selectron-neutralino mass plane for $M/\Lambda = 2$, $tan\beta = 2$, $\mu < 0$, N=1 and $\lambda'_{1j1} = 1$ $j = (1, 2)$.*