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Search for Superlight Gravitinos at HERA

H1 Collaboration

Abstract

A search for gravitinos produced in positron-proton scattering is presented using the H1 detector at HERA. In models where the gravitino is the lightest supersymmetric particle, an R-parity violating t-channel exchange of a scalar electron can produce a neutralino, which subsequently decays into a photon and a superlight gravitino. The resulting event signature involves an isolated photon and missing transverse energy. No deviation from the Standard Model has been found. Limits on R-parity violating Yukawa couplings have been derived — for the first time at HERA independently of squark masses — for different neutralino and selectron masses in the framework of a Gauge Mediated Supersymmetry Breaking scenario.

1 Introduction

At HERA, in previous analyses of R-parity (R_P) violating Supersymmetry (SUSY) resonant squark production has been investigated [1]. Limits on various R_P-violating Yukawa couplings have been derived dependent on the squark mass. In this analysis, neutralino (χ_1^0) production has been studied via R_P-violating t-channel selectron exchange in positron proton scattering. The masses of squarks are assumed to be beyond the reach of HERA.

In Gauge Mediated Supersymmetry Breaking (GMSB) scenarios the slepton masses are usually much lower than the squark masses [2]. Therefore, the above process is studied within the framework of GMSB. Here the prompt decay of the neutralino into a photon and a gravitino is studied, which leads to prominent event signatures with a photon and large missing transverse momentum. Thus, the theoretical model investigated in this analysis is a combination of R_P-violating SUSY with a GMSB scenario. The gravitino is the lightest supersymmetric particle (LSP), while the neutralino is assumed to be the next-to-lightest supersymmetric particle (NLSP).

The data were taken from 1999 to 2000, when HERA was operating with a positron beam and a center of mass energy of $\sqrt{s} = 319\ \mathrm{GeV}$. They correspond to an integrated luminosity of $65.4\ \mathrm{pb}^{-1}$.

2 Theoretical Framework

2.1 Neutralino Production

R-parity is a discrete multiplicative symmetry. It can be written as $R_P = (-1)^{3B+L+2S}$, where B denotes the baryon number, L the lepton number and S the spin of a particle. For all superfields of the supersymmetric Standard Model, each Standard Model (SM) field has the quantum number $R_P = +1$ and its superpartner $R_P = -1$.

Given the particle content of the SM, the most general gauge and supersymmetry invariant superpotential [3] contains an R_P-violating Yukawa coupling between a left-handed selectron $\tilde{e}_L$, a left-handed up-type quark u_L^i and a right-handed down type anti-quark $\bar{d}_R^j$, where i and j denote generation indices. The corresponding part of the Lagrangian reads as:

$$\mathcal{L}_{\mathrm{RPV}} = \lambda'_{1jk}(-\tilde{e}_L u_L^j \bar{d}_R^k) + h.c. \tag{1}$$

At HERA, the presence of interactions (1) lead to neutralino production via t-channel selectron exchange. The search presented here is performed under the simplifying assumption that one of the couplings λ'_{1j1} ($j = 1, 2$) dominates.

2.2 Neutralino Decay

In GMSB models the gravitino mass is given by

$$m_{\tilde{G}} = \frac{F}{\sqrt{3} M_P} \tag{2}$$

where $M_P = 2.4 \cdot 10^{18}$ GeV is the reduced Planck mass and F the fundamental squared scale of Supersymmetry breaking. This leads to typically light (< 1 GeV) gravitino masses. Therefore the gravitino is the lightest SUSY particle. The couplings of SUSY particles to the gravitino are small, so the gravitino only emerges in the decay of the NLSP (which is the neutralino in our scenario), provided that the R_P-violating decay of the NLSP is not largely dominant.

The relevant part of the supersymmetric Lagrangian containing gravitino interactions with gauginos is given by

$$\mathcal{L}_{\tilde{G}} = \frac{1}{8M_P} \bar{\lambda}^A \gamma^\rho \sigma^{\mu\nu} \tilde{G}_\rho F^A_{\mu\nu} + h.c. \;, \tag{3}$$

where $\tilde{G}$ is the gravitino field, $\bar{\lambda}^A$ the gaugino field and $F^A_{\mu\nu}$ the corresponding field strength. At the level of an effective interaction, the spin-3/2 gravitino field can be well described by its spin-1/2 goldstino component when it appears as an external state, i.e.

$$\tilde{G}_\mu = \sqrt{\frac{2}{3}} \frac{i}{m_{\tilde{G}}} \partial_\mu \tilde{G} \;. \tag{4}$$

Using this limit (4) in (3), one derives the decay width of the neutralino into a gravitino and a photon:

$$\Gamma({\chi_i}^0 \to \gamma \tilde{G}) = \frac{\kappa_i m^5_{\chi_i^0}}{16\pi\, F^2} \;. \tag{5}$$

Here, $\kappa_i = |N_{i1} \cos\Theta_W + N_{i2} \sin\Theta_W|^2$ is the mixing parameter with N_{ij} the χ_i^0 ($i = 1, 2, 3, 4$) components in the notation of [4].

The respective Feynman-Graph of the process analyzed in this paper is shown in Fig. 1.

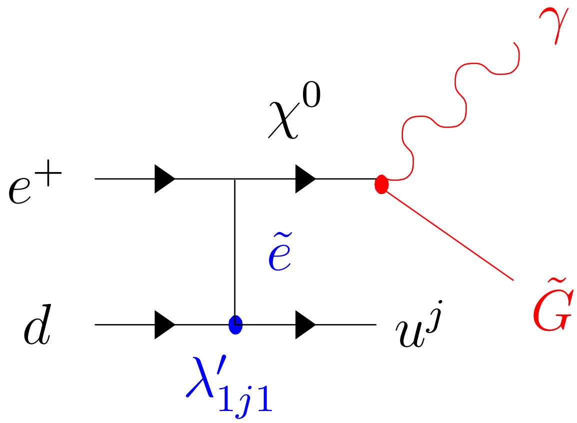

Figure 1: Neutralino production via selectron exchange, decaying into a gravitino and a photon.

3 The H1 Detector

The detector components of the H1 experiment [5] most relevant for this analysis are shortly described in the following. The interaction region is surrounded by a system of drift and multi-wire proportional chambers covering the polar angular range[1] $7^o < \theta < 176^o$. The tracking system is placed inside a finely segmented liquid argon (LAr) calorimeter covering the polar angular range $4^o < \theta < 154^o$ [6]. Energy resolutions of $\sigma_E/E \simeq 12\%/\sqrt{E(\mathrm{GeV})} \oplus 1\%$ for electrons and $\sigma_E/E \simeq 50\%/\sqrt{E(\mathrm{GeV})} \oplus 2\%$ for hadrons have been obtained in test beam measurements [7, 8]. The tracking system and calorimeters are surrounded by a superconducting solenoid and an iron yoke instrumented with streamer tubes. Leakage of hadronic showers outside the calorimeter is measured by analogue charge sampling of the streamer tubes with a resolution [9] of $\sigma_E/E \simeq 100\%/\sqrt{E(\mathrm{GeV})}$.

4 Monte Carlo Generation

For each possible SM background source, complete Monte Carlo simulations of the H1 detector response are performed. All of them correspond to a luminosity of more than 10 times that of the data.

For the simulation of the charged and neutral current (CC, NC) backgrounds, the DJANGO [10] event generator is used, which includes first order QED radiative corrections. QCD radiation is treated following the approach of the Colour Dipole Model [11] and is implemented

[1]The polar angle θ is measured with respect to the proton beam direction ($+z$).

using ARIADNE [12]. The hadronic final state is generated using the string fragmentation model [13]. The parton densities in the proton are taken from the CTEQ5L [14] parameterization. For direct and resolved photoproduction (γp) of light and heavy flavors, the PYTHIA event generator [15] is used, which relies on first order QCD matrix elements and uses leading-log parton showers and string fragmentation [13]. The GRV (GRV-G) parton densities [16] in the proton (photon) are used. The SM prediction for $ep \rightarrow eW^{\pm}X$ and $ep \rightarrow eZX$ is calculated with EPVEC [17].

For the simulation of the signal, we use the SUSYGEN [18] event generator. Initial and final state parton showers are simulated following the DGLAP [19] evolution equations, and string fragmentation [13, 15] is used for the non-perturbative part of the hadronization. The parton densities CTEQ5L [14] are evaluated at the scale of the Mandelstam variable $-t$. This scale is also chosen for the maximum virtuality of parton showers initiated by the final state quark. To allow a model independent interpretation of the results, the signal topology was simulated for a wide range of masses of the neutralino from $50~\mathrm{GeV}$ to $140~\mathrm{GeV}$ in steps of typically $10~\mathrm{GeV}$. The mass of the selectron was varied from $m_{\chi_1^0} + 1$ GeV to the theoretically allowed limit in the given GMSB scenario. The mass spectrum of supersymmetric particles has been calculated within GMSB using SUSPECT [20]. The events were passed through a complete simulation of the H1 detector. These simulations allowed the determination of signal selection efficiencies as a function of the masses of the neutralino and the selectron, since the step sizes for the simulation were small enough for a linear interpolation between them.

5 Event Selection

To reject non-ep background, it is required that the events are not rejected by a set of beam halo and cosmic muon filters [21], that they satisfy constraints on their timing relative to the nominal time of the beam bunch crossings, and that a primary interaction vertex is reconstructed within ± 35 cm around the nominal vertex value.

The decay $\chi^0 \rightarrow \gamma\tilde{G}$ is characterized by missing transverse energy and by an electromagnetic cluster in the calorimeter. The main SM background is expected from CC DIS. Events are selected with a total vector sum of the transverse momentum in all calorimeters p_t^{calo} greater than 25 GeV and an identified photon of transverse momentum $P_{t,\gamma}$ greater than 15 GeV.

The photon is identified by a shower shape analysis of energy deposits in the LAr calorimeter, selecting isolated and compact electromagnetic clusters. To reject NC DIS background in which the scattered electron (sometimes misinterpreted as a photon) is dominantly scattered through small angles, photon candidates are accepted in the forward region of the detector only ($\theta_\gamma < 80^o$). The minimal polar angle of the photon is 10^o. For $\theta_\gamma > 20^o$ an electromagnetic cluster is only accepted if it is *not* associated with a charged track in the central tracking system fulfilling matching criteria of cluster energy and track momentum. To reduce the influence of photons from collinear QED radiation from the quark line, the photon must be isolated so that no other calorimeter cluster with an energy larger than 500 MeV lies within a pseudorapidity-azimuthal cone centered around the photon direction and of opening $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.5$, where $\eta = -\ln \tan \frac{\theta}{2}$. Furthermore, $\sum(E - p_z) > 15$ GeV is required[2] to reduce CC-DIS background.

Having applied all selection cuts, 1 event is found for an expected background of 2.55 ± 1.30 events. The background is composed of 2.0 events from CC DIS, 0.35 events from NC DIS and 0.20 events from W/Z production with negligible contributions from γp. The selection efficiency for the signal ranges between 10% and 30%.

6 Systematic Uncertainties

The error on the expectation from Standard Model processes has been calculated by taking into account the systematic errors described below. The experimental error sources considered are:

- an uncertainty of 1.5% on the integrated luminosity;
- an uncertainty of 2% on the track reconstruction efficiency;
- an uncertainty on the absolute calibration of the calorimeters for electromagnetic energies, ranging between 0.7% in the central part to 3% in the forward region of the LAr calorimeter;
- an uncertainty of 2% on the absolute hadronic energy scale.

The following theoretical uncertainties on the SM cross-sections are considered:

- The lack of QED radiation from the quark line in the DJANGO generator leads to an uncertainty of the CC DIS background expectation which was conservatively estimated to be 40% following [22]. For NC DIS an uncertainty of 7% is attributed to the proton structure. For W/Z production an uncertainty of 30% is estimated because only LO contributions are included. However, NLO contributions to W production are small [23].

As theoretical uncertainties on the signal cross-section, the following is considered:

- an uncertainty of 10% from the parton densities;
- an uncertainty of 20% from the variation of the factorization scale;
- an uncertainty of 10% from the interpolation procedure used for the determination of signal detection efficiencies and signal cross sections, dependent on the neutralino and selectron masses;
- an uncertainty of 3% due to limited statistics in the signal simulation.

[2]The summation runs over all energy deposits in the calorimeters.

7 GMSB Model Dependent Interpretations

No significant deviation from the SM has been observed (see Section 5), so limits in a GMSB model are derived, using the search results including the effects of systematic errors on the signal detection efficiencies and background expectation [24].

While there is no unique GMSB model, there are typically [25–27] six new parameters in addition to those of the SM:

$$F,\ \Lambda,\ M,\ N,\ \tan\beta \text{ and } \mathrm{sign}(\mu)\,. \tag{6}$$

The intrinsic SUSY breaking scale is $\sqrt{F}$, which also determines the $\tilde{G}$ mass according to $m_{\tilde{G}} \simeq 2.5 \cdot F/(100\ \mathrm{TeV})^2\,\mathrm{eV}$ corresponding to (2). Since $\sqrt{F}$ affects primarily the lifetime of the NLSP, we do not vary it for this paper, but simply assume that this lifetime is short enough to have no effect on our detection efficiencies. Furthermore, it is assumed that $\sqrt{F}$ is low enough so that the R_P-violating decays of the neutralino are suppressed compared to the decays $\chi_1^0 \to \gamma\tilde{G}$ (cf. Eq. (5)). Thus, the branching ratio $\mathrm{BR}(\chi_1^0 \to \gamma\tilde{G})$ is set to 100%, which is fulfilled within an uncertainty of 3% for all values of λ'_{1j1} presented in this paper, taking $\sqrt{F}$ above the present limits [28]. The contributions due to χ_i^0 production ($i = 2, 3, 4$) can be neglected.

The parameter Λ sets the overall mass scale for SUSY particles, M is the mass of the messenger particles, N is the number of sets[3] of messenger particles, and $\tan\beta$ is the usual ratio of the Higgs vacuum expectation values. The final parameter sign(μ) is the sign of the Higgs sector mixing parameter, μ (the magnitude of μ is calculable from the other parameters in the minimal model by imposing radiative electroweak symmetry breaking).

We work in a theoretical framework based on [25], but assuming that the left-handed selectron mass is equal to the right-handed one. The theoretical calculations are embedded in the SUSYGEN [18] generator. For the limits presented below, $\tan\beta = 1.5$, $N = 2$ and a negative μ is chosen. The remaining free GMSB parameters Λ and M have been transformed into the parameters $m_{\tilde{e},R}$ ($= m_{\tilde{e},L} = m_{\tilde{e}}$) and $m_{\chi_1^0}$. So, in the following, the limits are presented as a function of $m_{\tilde{e}}$ and $m_{\chi_1^0}$. The parameter range considered in this analysis corresponds then to a scan of $17.3 \leq \Lambda \leq 51.5$ TeV and $450 \leq M \leq 5.3 \cdot 10^7$ TeV. To determine whether a set of masses ($m_{\chi_1^0}$, $m_{\tilde{e}}$) is excluded by this analysis, we use the numbers of observed and expected events for which the invariant mass from the photon and the missing particle lies within a mass interval of ± 15 GeV centered on $m_{\chi_1^0}$.

In Figure 2, excluded regions at the 95% confidence level are presented in the plane spanned by $m_{\tilde{e}}$ and $m_{\chi_1^0}$ for different values of of the R_P-violating coupling.[4] For selectron masses very

[3] N is technically the Dynkin index of the gauge representation of the messenger fields. To preserve gauge coupling unification, the messengers are assumed to form a GUT representation. In the simplest form, each of the N messenger particle sets has the quantum numbers of a $\mathbf{5} + \bar{\mathbf{5}}$ of $\mathbf{SU(5)}$. The maximum number of messengers can be restricted by requiring the gauge interactions remain perturbative up the GUT scale, although this bound depends on M. For $M = 100$ TeV, $N \leq 5$, while for $M = 10^{10}$ TeV, $N \leq 10$.

[4] The step from $m_{\chi_1^0} = 98$ GeV to $m_{\chi_1^0} = 99$ GeV in the excluded region for $\lambda'_{1j1} = 1.0$ comes from the fact that the observed event has a reconstructed invariant mass from the photon and the missing particle (which corresponds to the neutralino mass) of 83.3 GeV. Due to the neutralino mass interval of ± 15 GeV, for $m_{\chi_1^0} = 98$ GeV this event is considered in the limit calculation, but for $m_{\chi_1^0} = 99$ GeV it is not, which leads to an improved limit and thus to a larger excluded region at $m_{\chi_1^0} = 99$ GeV.

close to the neutralino mass and for $\lambda'_{1j1} = 1.0$, neutralino masses up to 108 GeV can be excluded.

The excluded regions in Figure 2 can be compared to the region excluded by OPAL [29] analyzing $e^+e^- \rightarrow \chi_1^0\chi_1^0 \rightarrow \gamma\tilde{G}\gamma\tilde{G}$ in an R-parity-conserving SUSY scenario. OPAL are mostly sensitive to right-handed selectrons (exchanged in the t-channel) and perform a scan over the GMSB parameter space. Their result for $\tan\beta = 2$ excludes the region $m_{\chi_1^0} \lesssim 91$ GeV (almost independently of the selectron mass) at the 95% confidence level. Thus, for not too low values of λ'_{1j1}, H1 can extend the region excluded by OPAL.[5]

In Figure 3, lower limits at 95% confidence level on λ'_{1j1} ($j = 1, 2$) are given as a function of $m_{\chi_1^0}$ for various assumptions for the difference between selectron and neutralino mass.[6] While λ'_{111} is already tightly constrained by neutrinoless double beta decay searches [30], these are the first limits derived on λ'_{121} which are independent of squark masses.

8 Conclusions

We have searched for events containing a photon and large missing transverse momentum, expected in R_P-violating models with gauge mediated SUSY breaking, at a center-of-mass energy of $\sqrt{s} = 319$ GeV with the H1 detector at HERA. No evidence for a deviation from the SM was found. Limits which constrain minimal models of gauge mediated supersymmetry breaking have been derived for different values of the R_P-violating coupling. For the first time, limits on the R_P-violating coupling λ'_{121} have been derived independently of squark masses.

[5]The differences between our signal cross sections for $\tan\beta = 1.5$ and $\tan\beta = 2.0$ are only a few per cent.

[6]The two steps from $m_{\chi_1^0} = 68$ GeV to $m_{\chi_1^0} = 69$ GeV and from $m_{\chi_1^0} = 98$ GeV to $m_{\chi_1^0} = 99$ GeV in the limit curve come —as discussed in the previous footnote —again from the fact that the observed event lies inside or outside the considered neutralino mass interval leading to a weaker or stronger limit, respectively.

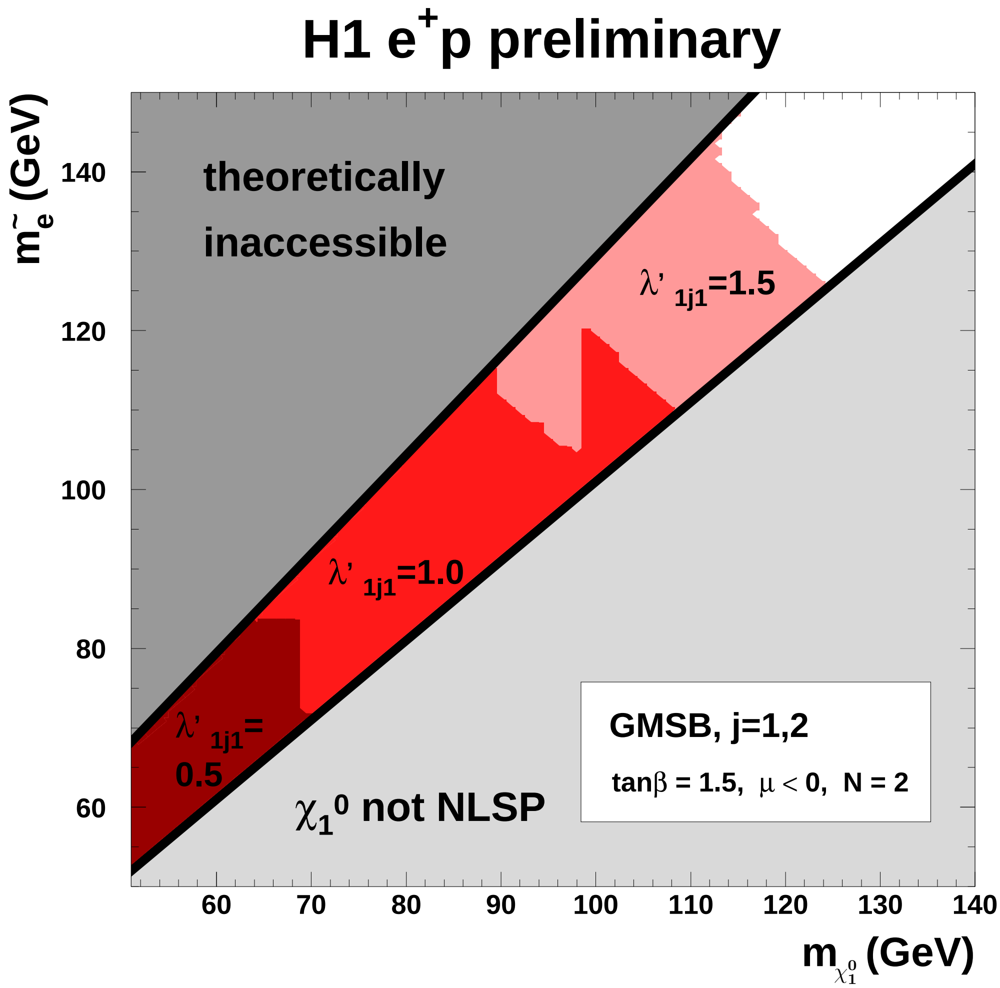

Figure 2: Excluded region at the 95% confidence level in the plane spanned by selectron and neutralino mass for different values of $\lambda'_{1j1} = 0.5$ (dark red), 1.0 (red), 1.5 (light red) ($j = 1, 2$). Within the considered GMSB scenario, the region in the upper left rectangle (dark grey) is theoretically not accessible. The region in the lower right rectangle (light grey) is not analyzed because the neutralino is required to be the next-to-lightest supersymmetric particle.

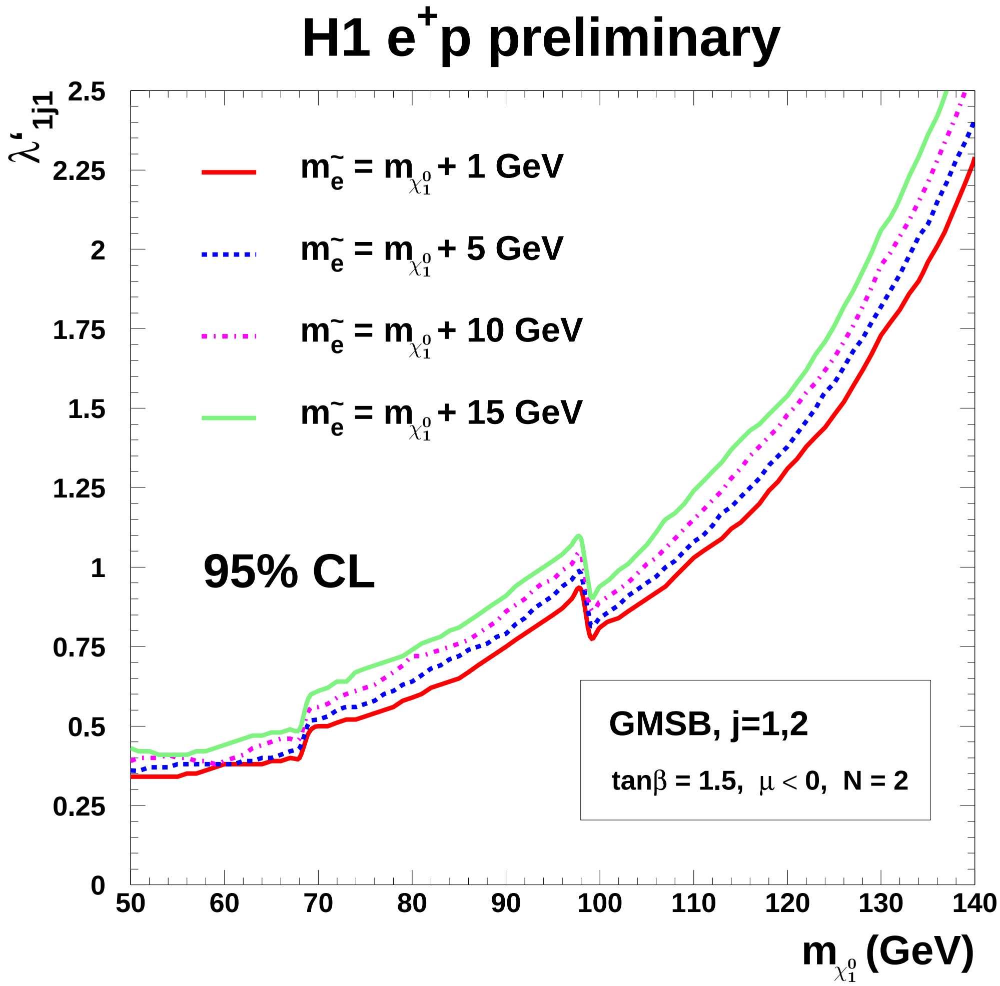

Figure 3: Upper limit at the 95% confidence level on R_P-violating couplings λ'_{1j1} ($j = 1, 2$) as a function of the neutralino mass for a difference between selectron and neutralino mass of 1 GeV (solid, dark), 5 GeV (dashed), 10 GeV (dashed-dotted) and 15 GeV (solid, light).

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