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Search for Squarks in ep-Collisions at HERA

H1 Collaboration

Abstract

A search for squarks in R-parity violating supersymmetry is performed in $e^{\pm}p$ collisions at HERA using the H1 detector. The full data sample available is used for the analysis. It corresponds to an integrated luminosity of 438 pb^{-1}. The resonant production of squarks via a Yukawa-type coupling λ' is considered, taking into account direct and indirect R-parity violating decay modes. No evidence for squark production is found in the (multi-)lepton and (multi-)jet final state topologies investigated. Mass dependent limits on λ'_{1j1} and λ'_{11k} $(j,k=1,2)$ are obtained in the framework of the Minimal Supersymmetric Standard Model. At the $95\,\%$ confidence level squarks of the first and second generation with masses up to 275 GeV are excluded in the considered part of the parameter space for Yukawa-type coupling of electromagnetic strength $\lambda' \gtrsim 0.3$.

1 Introduction

The ep collider HERA is ideally suited to search for new particles coupling to electron[1]–quark pairs. In supersymmetric models (SUSY) with R-parity violation ($\not{R}_p$), squarks can couple to electrons and quarks via Yukawa-type couplings λ'. At HERA, squarks could be produced resonantly via the fusion of the incoming $27.6\,\mathrm{GeV}$ electron and a quark from the incoming $920\,\mathrm{GeV}$ proton. Squark masses up to the electron-proton centre-of-mass energy, $\sqrt{s} = 319\,\mathrm{GeV}$, are kinematically accessible. The data used in this analysis were taken at a centre-of-mass energy of 319 GeV and correspond to an integrated luminosity of $255\,\mathrm{pb}^{-1}$ for e^+p collisions and $183\,\mathrm{pb}^{-1}$ for e^-p collisions. For the latter sample this is an increase by a factor of 13 compared to the analysis on HERA I data [2], while for the former an increase by a factor of 4 is reached.

In the most general supersymmetric theory that is renormalisable and gauge invariant with respect to the Standard Model (SM) gauge group, the R-parity $R_p = (-1)^{3B+L+2S}$, where B denotes the baryon number, L the lepton number and S the spin of a particle, is not conserved. Couplings between two ordinary fermions and a squark ($\tilde{q}$) or a slepton ($\tilde{l}$) are then allowed.

The $\not{R}_p$ Yukawa couplings responsible for squark production at HERA are described in the superpotential by the terms $\lambda'_{ijk}L_iQ_j\overline{D}_k$, where i, j and k are family indices. L_i, Q_j and D_k are superfields, which contain the left-handed leptons, the left-handed quarks and the right-handed down quark, respectively, together with their SUSY partners $\tilde{l}^i_L$, $\tilde{q}^j_L$ and $\tilde{d}^k_R$. Non-vanishing couplings λ'_{1jk} allow the resonant production of squarks at HERA through eq fusion [1]. The values of the couplings are not fixed by the theory. For simplicity, it is assumed here that one of the λ'_{1jk} dominates over all other possible trilinear couplings.

In $\not{R}_p$ SUSY all supersymmetric particles are unstable. Squarks can decay via their Yukawa coupling λ' into SM fermions. The $\tilde{d}_R$-type squarks can decay either into $e^- + u^j$ or $\nu_e + d^j$, while the $\tilde{u}_L$-type squarks decay into $e^+ + d^k$ only. The $\not{R}_p$ squark decays proceed directly via the couplings λ'_{11k} and λ'_{1j1}.

Squarks can also decay via their usual R_p conserving gauge couplings. The $\tilde{u}_L$-type squarks can undergo a gauge decay into states involving a neutralino χ^0_i ($i = 1 \ldots 4$), a chargino χ^+_i ($i = 1, 2$) or a gluino $\tilde{g}$. In contrast, $\tilde{d}_R$-type squarks decay to χ^0_i or $\tilde{g}$ only and decays into charginos are suppressed.

A version of the Minimal Supersymmetric Standard Model (MSSM) is considered where the masses of the neutralinos, charginos and gluinos, as well as the couplings between and two SUSY particles and a SM fermion/boson, are determined by the following parameters: The "Higgs-mass" term μ, which mixes the Higgs superfields, M_1, M_2 and M_3 the SUSY soft-breaking mass parameters and $\tan\beta$, the ratio of the vacuum expectation values of the two neutral scalar Higgs fields. The parameters are defined at the electroweak scale. The sfermion masses are free parameters in this model.

[1] In the following the term *electron* refers to both electron and positron unless explicitly stated otherwise.

2 Data Analysis

To allow a model independent interpretation of the results, all possible final states at any given point in the parameter space have to be analysed, to ensure high sensitivity over the accessible parameter range. The following final states are considered:

- $\boldsymbol{eq}$ In this channel an isolated electron with a $P_T > 15$ GeV is required. The main background in this channel is due to neutral current processes, which has an identical topology. This background is further suppressed with a M_e dependent cut on the inelasitcity y.
- $\boldsymbol{\nu q}$ In this channel a missing energy of $P_T^{\text{miss}} > 30$ GeV is required. No high-P_T lepton candidates are allowed.
- $\boldsymbol{e^{\pm}MJ}$ These channels start from a comment multi-jet (MJ) preselection requiring two jets with $P_T > 15$ GeV. In addition an isolated electron $P_T > 6$ GeV is required. The channels are analysed separately for the charges of the electron of the same sign (RC, right sign) or opposite sign (WC, wrong sign) with respect to the incident lepton beam charge.
- $\boldsymbol{eeMJ}$, $\boldsymbol{e\mu MJ}$ In addition to the eMJ selection an additional isolated lepton (electron or muon) is required in these channels.
- $\boldsymbol{\nu\mu MJ}$ In addition to the MJ selection a missing energy of $P_T^{\text{miss}} > 26$ GeV and an isolated muon candidate $P_T > 5$ GeV is required in this channel.

In addtion to the outlined cuts, the particles in the selections are required to be emitted in the forward direction, mainly by requiring $Q^2 > 2500$ GeV, $Q^2 > 1000$ GeV or $\theta_e < 110°$. Here Q^2 is the negative four-momentum transfer at the electron vertex and the polar angle θ is measured with respect to the proton beam. The selections of the final states are exclusive with respect to each other. Also important is the $\boldsymbol{\nu MJ}$ final state, in particular for SUSY scenarios with a Zino-like neutralino, where weak decays are preferred. However, this channel is not included here due to large uncertainties connected with missing higher order QCD corrections.

The total yields of selected events in those channels in the e^+p and e^-p data samples are listed in table 1. No significant deviation from the SM is observed in any of the final state topologies resulting from direct or indirect R_p violating squark decays. Figures 1 and 2 show the invariant mass spectra for e^+p and e^-p data samples, respectively, for those channels where at least one data event was selected. Also shown is the (not normalised) signal shape for a squark with $M_{\tilde{q}} = 150$ GeV to demonstrate how SUSY would show up as a resonance peak.

3 Systematic Uncertainties

The following sources of systematic uncertainties are considered.

- The uncertainty on the electromagnetic energy scale varies depending on the polar angle from 0.7% in the central region to 2% in the forward region. The polar angle measurement uncertainty of electromagnetic clusters is 3mrad.
- The jet energy scale is known within 2%. The uncertainty on the jet polar angle determination is 10 mrad.
- The luminosity measurement has an uncertainty of 3%

The effects of the above mentioned scale uncertainties on the SM expectation are determined by varying the corresponding experimental quantities by $\pm 1\sigma$ in the MC samples and propagating the variations through the whole analysis chain. The resulting experimental uncertainties have been determined for each analysis channel individually. In the eq channel the uncertainty was found to be 1%, while in the νq channel 6% have been determined. In the eMJ (RC and WC) channels the total systematic uncertainty anounts to 3%, in the $e\mu MJ$ and $e\nu MJ$ channels to 6%, in the $eeMJ$ channel to 10% and in the $\nu\mu MJ$ channel to 20%. Additional model uncertainties are attributed to the SM Monte Carlo event generators used in this analysis. An error of 10% is attributed to NC (RAPGAP) and CC (DJANGO) DIS processes with only one high P_T jet. To account for the uncertainty on higher order QCD corrections, an error of 15% is attributed to NC DIS and photoproduction processes (PYTHIA) with at least two high P_T jets. The uncertainty of CC DIS processes with at least two high P_T jets is estimated to be 20%. These errors include uncertainties from the proton parton distribution functions and from missing higher order QCD corrections.

The total error on the SM prediction is determined by adding the effects of all model and experimental systematic uncertainties in quadrature.

For the signal cross section further uncertainties arise from the determination of signal efficiencies (10%), the theoretical uncertainty on the production cross section (7% mainly from pdf uncertainty) and an uncertainty of the scale at which the pdf's are evaluated (7%).

4 Parameter Scan and Results

Due to the absence of any significant excess in data, mass dependent limits on the RPV couplings λ'_{1jk} are derived within a phenomenological version of the MSSM.

Given a particular point in the parameter space (μ, M_2 and $\tan\beta$), for every squark mass hypothesis $M_{\tilde{q}}$ a theoretical cross section σ_{th} is compared to an observed cross section σ_{obs} calculated for a given value of λ'. For every tested λ' the SUSY mass spectrum and branching ratios are recalculated until σ_{th} can be excluded at 95% CL. The resulting limit on the value of the coupling λ'_{11k} for $k = 1, 2$ is illustrated in figure 3 for the case of a $\tilde{\gamma}$-like neutralino χ_1^0 ($\mu = -200$ GeV, $M_2 = 80$ GeV, $\tan\beta = 2$) derived with the e^-p data sample. Slepton masses $M_{\tilde{l}}$ are fixed at 90 GeV, close to the lowest mass bound from $\not{R}_p$ sfermion searches at LEP [5]. The HERA sensitivity allows tests of λ' down to around 10^{-2} for squark masses of 100 GeV. For high squark masses the sensitivity degrades since the production cross section decreases strongly. In this scenario the production of squarks with masses up to $290\ \mathrm{GeV}$ at a coupling $\lambda'_{11k} = 0.2$ for $k = 1, 2$ can be ruled out at 95% CL.

Figure 3 (bottom) shows the branching ratios at the observed limit. The sum of analyzed branching ratios is about 80%, increasing with $M_{\tilde{q}}$. The difference to 100% is attributed to the νMJ channel, which is not included in the present analysis. The increase with $M_{\tilde{q}}$ is related to larger $\not R_p$ couplings and correspondingly large contributions from the eq and νq channels.

In order to investigate the dependence of the sensitivity on the MSSM parameters, a scan of M_2 and μ is performed for $\tan\beta = 2$. Parameter sets leading to a scalar LSP or LSP masses below $30\ \mathrm{GeV}$ are excluded from the scan. The resulting exclusion domains are compared to the HERA-I results in figures 4 and 5. Shown are the most and least sensitive exclusion limits in the scanned parameter range. For a Yukawa coupling of electromagnetic strength, *i.e.* $\lambda'_{1j1} = \sqrt{4\pi\alpha_{\mathrm{em}}} = 0.3$ ($\lambda'_{11k} = 0.3$), $\tilde{u}_L$, $\tilde{c}_L$ ($\tilde{d}_R$, $\tilde{s}_R$) squarks up to masses $\sim 275\ \mathrm{GeV}$ ($290\ \mathrm{GeV}$) are excluded at the 95% CL. For a coupling strength smaller by a factor of 100, masses up to $\sim 230\ \mathrm{GeV}$ ($270\ \mathrm{GeV}$) can be ruled out in part of the parameter range.

In figures 4 and 5 the results for the direct production of squarks are compared with indirect limits from virtual squark exchange in low energy experiments [8].

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H1 (Preliminary) — Search for Squarks in RPV SUSY					
	e^+p (255 pb^{-1})		e^-p (183 pb^{-1})		
Channel	Data	**SM Expectation**	Data	SM Expectation	Efficiency
eq	2116	2120 ± 260	2127	2190 ± 270	$25 - 40\%$
νq	–	–	3191	3320 ± 400	$45 - 65\%$
eMJ (RC)	225	219 ± 33	197	210 ± 32	$10 - 50\%$
eMJ (WC)	1	0.6 ± 0.4	0	1.3 ± 0.3	$10 - 20\%$
$eeMJ$	2	1.7 ± 0.5	0	1.5 ± 0.5	$10 - 40\%$
$e\mu MJ$	0	0.03 ± 0.02	0	0.03 ± 0.02	$10 - 20\%$
νeMJ	5	8.2 ± 2.0	3	5.6 ± 1.2	$10 - 40\%$
$\nu\mu MJ$	0	0.06 ± 0.03	0	0.05 ± 0.03	$10 - 20\%$

Table 1: Observed and predicted event yields for all $\tilde{q}$ decay channels considered in this analysis for the e^+p and e^-p data samples. The errors on the predictions include experimental and model uncertainties added in quadrature. $\tilde{u}_L$-type squarks (generated in e^+p collisions) cannot decay to νq. Also shown is the range of selection efficiencies for the given channel in the allowed range of $m_{\tilde{q}}$.

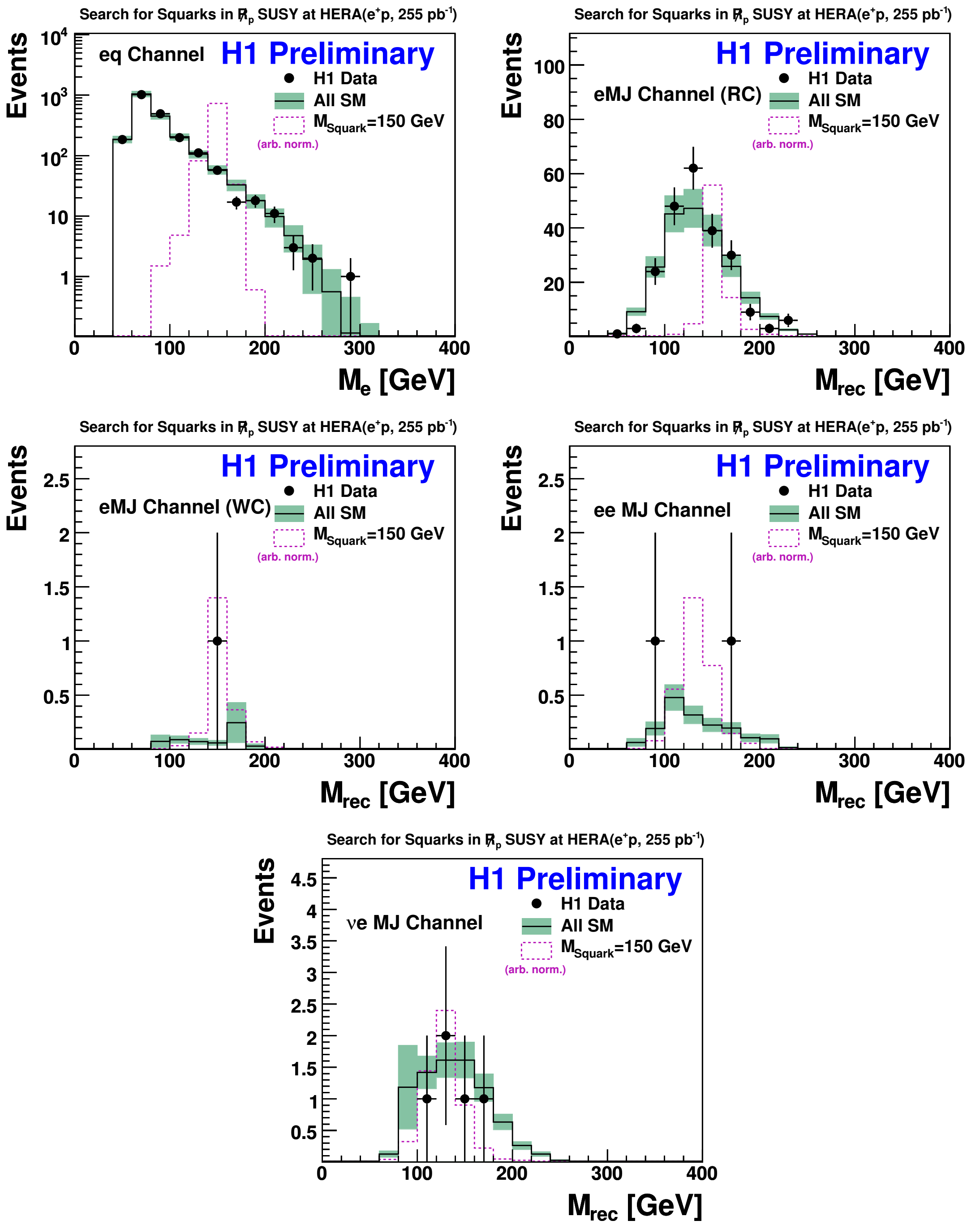

Figure 1: Invariant mass distributions in all selection channels in e^+p data. The dashed histogram indicates the signal from a quark with $m_{\tilde{q}} = 150$ GeV in arbitrary normalisation.

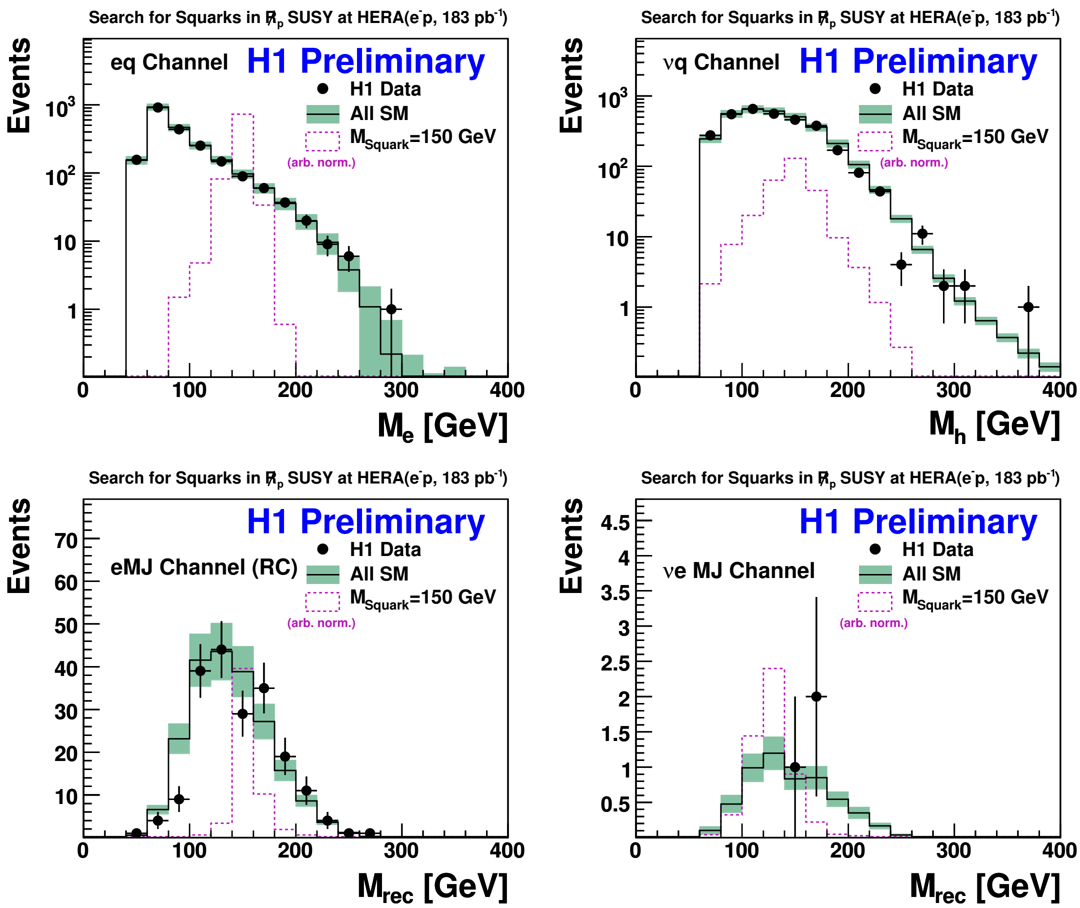

Figure 2: Invariant mass distributions in all selection channels in e^-p data. The dashed histogram indicates the signal from a quark with $m_{\tilde{q}} = 150\,\text{GeV}$ in arbitrary normalisation.

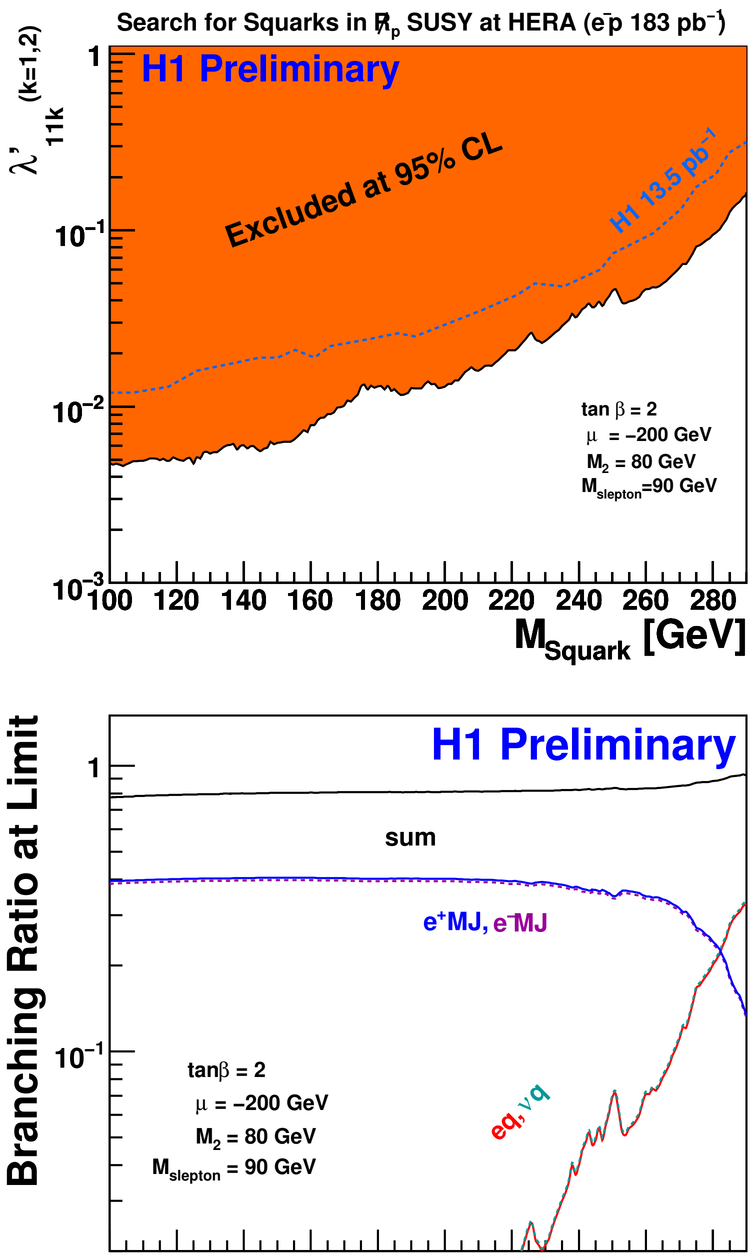

Figure 3: (a) Exclusion limits at 95% CL on λ'_{11k} $(k = 1, 2)$. A slepton mass of 90 GeV is assumed. For comparison, the corresponding limit from the HERA-I analysis is also indicated. (b) Branching ratios to the decay channels considered in this analysis for λ' values at the observed limit.

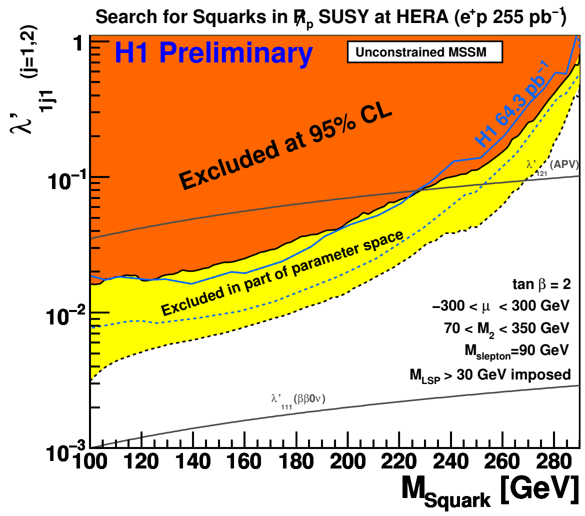

Figure 4: Exclusion limits ($95\,\%$ CL) on λ'_{1j1} for (a) $j = 1, 2$ as a function of the squark mass from a scan of the MSSM parameter space as indicated in the figures. The two full curves indicate the strongest and the weakest limits on λ' in the parameter space investigated. Indirect limits from neutrinoless double beta decay experiments ($\beta\beta 0\nu$) and atomic parity violation (APV) are also shown.

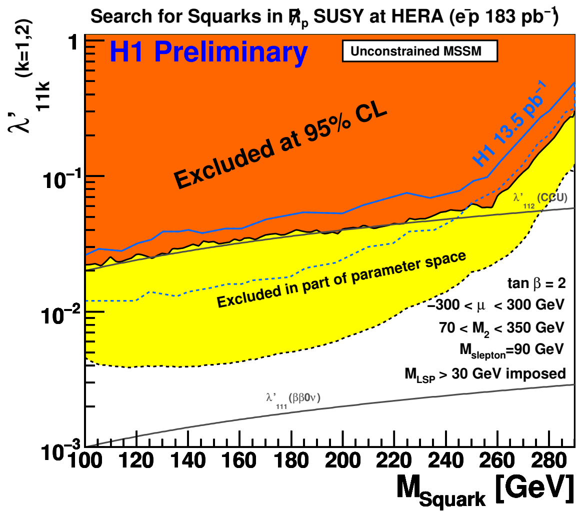

Figure 5: Exclusion limits ($95\ \%$ CL) on λ'_{11k} for (a) $k = 1, 2$ as a function of the squark mass from a scan of the MSSM parameter space. The two full curves indicate the strongest and the weakest limits on λ'. Indirect limits from neutrinoless double beta decay experiments ($\beta\beta0\nu$) and tests of charged current universality (CCU) are also shown.