Search for $R$-parity violating supersymmetry via the $LL\bar{E}$ couplings $\lambda_{121}$, $\lambda_{122}$ or $\lambda_{133}$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

DØ Collaboration

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Abstract

A search for gaugino pair production with a trilepton signature in the framework of $R$-parity violating supersymmetry via the couplings $\lambda_{121}$, $\lambda_{122}$, or $\lambda_{133}$ is presented. The data, corresponding to an integrated luminosity of $L \approx 360 \text{ pb}^{-1}$, were collected from April 2002 to August 2004 with the D0 detector at the Fermilab Tevatron Collider, at a center-of-mass energy of $\sqrt{s} = 1.96 \text{ TeV}$. This analysis considers final states with three charged leptons with the flavor combinations $ee\ell$, $\mu\mu\ell$, and $ee\tau$ ($\ell = e$ or $\mu$). No evidence for supersymmetry is found and limits at the 95% confidence level are set on the gaugino pair production cross section and lower bounds on the masses of the lightest neutralino and chargino are derived in two supersymmetric models.

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Supersymmetry (SUSY) [1] predicts the existence of a new particle for each standard model (SM) particle, differing by half a unit in spin but otherwise sharing the same quantum numbers.

The new scalar particles, known as squarks and sleptons, carry baryon ($B$) or lepton ($L$) quantum numbers, potentially leading to interactions violating $B$ or $L$ conservation. In the supersymmetric Lagrangian, there is a continuous $R$-invariance, which prevents lepton and baryon number violation, but also prevents gluinos and gravitinos from being massive.

In a supergravity scenario, the gravitino will acquire mass through the spontaneous breaking of local SUSY. The SUSY-
breaking is then communicated to the so-called observable sector so that, in particular, the gluino acquires its mass [2]. This breaks the continuous $R$-invariance, leaving only a discrete version, which is called $R$-parity [3]. Each particle is characterized by an $R$-parity quantum number defined as $R_p = (-1)^{3B+L+2S}$ ($S$ being the spin), such that SM particles have $R_p = 1$ and SUSY particles $R_p = -1$. The gauge symmetry allows $R$-parity violating ($R_p$) terms to be included in the superpotential [4]. These terms are:

$$W_{R_p} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \mu_i L_i H_u$$

where $L$ and $Q$ are the lepton and quark $SU(2)$ doublet superfields, while $\bar{E}$, $\bar{U}$, and $D$ denote the weak isospin singlet fields and the indices $i$, $j$, $k$ refer to the fermion families. The couplings strengths in the trilinear terms are given by the Yukawa gravity model (mSUGRA) [6], the universal soft breaking mass bilinear term $\mu$, the common gaugino mass, $m$ the common higgsino mixing mass parameter, $m_0$, and the indices $\lambda$, $\lambda'$, and $\lambda''$. Terms appearing in the first line of Eq. (1) violate lepton number by one unit, and the last term in the second line leads to baryon number violation. The bilinear term $\mu_i L_i H_u$ mixes lepton and Higgs ($H_u$) superfields.

This Letter reports on a search for chargino and neutralino pair production under the hypothesis that $R_p$ can only occur via a term of the type $\lambda_{ijk} L_i L_j \bar{E}_k$. A non-zero $R_p$-coupling $\lambda_{ijk}$ thus enables a slepton to decay into a lepton pair, as shown in Fig. 1 for the $R_p$-decay of the lightest neutralino. The so-called $LL\bar{E}$ couplings $\lambda_{ijk}$ specifically studied here, are $\lambda_{121}$, $\lambda_{122}$, and $\lambda_{133}$. One coupling is assumed to be dominant at a time, with any other $R_p$-coupling negligibly small.

The initial state at the Fermilab Tevatron Collider consists of hadrons, so the production of a single SUSY particle could only occur through a trilinear term including at least one baryon field, i.e. via $\lambda'$ or $\lambda''$ terms. Consequently, since only the $LL\bar{E}$ term ($\lambda$) is considered here, SUSY particles are produced pairwise in an $R$-parity conserving process [5], with $R_p$ manifesting itself in the decay only. Even though direct decays of heavy gauginos ($\chi'_{2,3,4,5}^0$) are possible, they predominantly cascade decay into the lightest supersymmetric particle (LSP), which in turn decays into SM particles via $R_p$. In all scenarios studied here, the lightest neutralino ($\chi_0^0$) is assumed to be the LSP.

Two SUSY models are investigated. In the minimal supergravity model (mSUGRA) [6], the universal soft breaking mass parameter for all scalars at the unification scale, $m_0$, is set to 100 GeV or 1 TeV. At low $m_0$, the stau can be lighter than the second lightest neutralino ($\chi_{20}^0$) and the lightest chargino ($\chi'^+_1$), leading to a larger number of final states with taus. By contrast, a high value of $m_0$ prevents complex cascade decays involving sleptons. The universal trilinear coupling, $A_0$, has only a small influence on the gaugino pair production cross section and is set to zero as in the previous Run I analysis [7]. Searches for supersymmetric Higgs bosons at LEP [8] imply that $\tan\beta \leq 2$ is excluded, where $\tan\beta$ is the ratio of the vacuum expectation values of the two neutral Higgs fields. Since the cross section for gaugino pair production increases with increasing $\tan\beta$ due to decreasing masses, a value of $\tan\beta = 5$ (close to the LEP limit) is chosen to ensure conservative results. A higher value of $\tan\beta = 20$ is studied exclusively in the $ee\tau$ analysis, because the stau mass decreases with increasing $\tan\beta$, leading to an enhanced signal efficiency for this particular analysis. Both signs of the higgsino mixing mass parameter, $\mu$, are considered and the common gaugino mass, $m_{1/2}$, is varied.

In the specific minimal supersymmetric standard model (MSSM) [9] considered here, heavy squarks and sleptons (1 TeV) are assumed, while the GUT relation between $M_1$ and $M_2$, the masses of the superpartners of the $U(1)_Y$ and $SU(2)_L$ gauge bosons, is relaxed. The value of $\tan\beta$ is set to 5, and $M_1$ and $M_2$ are varied independently. The higgsino mixing mass parameter $\mu$ is set to 1 TeV, so that $\chi'^+_1$, $\chi'^+_4$, and $\chi'^+_5$ are heavy.

Within the domain of the SUSY parameters explored in this analysis, pair production of $\chi_{2,3,4,5}^0$ and $\chi'_{2,3,4,5}^0$ are the dominant processes, leading to final states with at least four charged leptons and two neutrinos. They come from either the decay of the $\chi'^+_1$, with the lepton flavors depending on $\lambda_{ijk}$, or from cascade decays of $\chi'_2$ and $\chi'_5$. The strengths of the couplings are set to 0.01 ($\lambda_{121}$ and $\lambda_{122}$) and 0.003 ($\lambda_{133}$). These values are well below the current limits of $\lambda_{121} < 0.5$, $\lambda_{122} < 0.085$, and $\lambda_{133} < 0.005$ for a slepton mass of 1 TeV, which have been derived from the upper limits $\lambda_{121} < 0.05$, $\lambda_{122} < 0.027$, and $\lambda_{133} < 0.0016$ obtained for a slepton mass of 100 GeV in Refs. [4,10]. Additionally, only neutrinos with a decay length of less than 1 cm are considered, which results in a cut-off at low neutralino masses [11], i.e. 30 GeV for $\lambda_{121}$ and $\lambda_{122}$, and 50 GeV for $\lambda_{133}$, again for slepton masses of 1 TeV. As the $\chi'^+_1$ can be light, the leptons can have small transverse (w.r.t. the beam axis) momentum and thus be difficult to detect. For this reason, only three charged leptons with the flavor combinations $e\ell\ell$, $\mu\mu\ell$, or $e\ell\ell$ ($\ell = e$ or $\mu$) are required.

The analysis is based on a dataset recorded with the D0 detector between April 2002 and August 2004, corresponding to an integrated luminosity of $L = 360 \pm 23$ pb$^{-1}$. Previous searches with the hypothesis of a $LL\bar{E}$ coupling have been performed by the D0 Collaboration with Tevatron Run I data collected at a center-of-mass energy $\sqrt{s} = 1.8$ TeV [7].

The D0 detector consists of a central tracking system surrounded by a uranium/liquid-argon sampling calorimeter and a system of muon detectors [12]. Charged particles are reconstructed using multiple layers of silicon detectors, as well as eight double layers of scintillating fibers in the 2 T axial magnetic field of a superconducting solenoid. The D0 calorime-

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**Fig. 1.** Two examples of $R_p$-decays of the lightest neutralino via $LL\bar{E}$ couplings $\lambda_{ijk}$. In each decay, two charged leptons and one neutrino are produced.
ter provides hermetic coverage up to pseudorapidities $|\eta| = |\ln(\tan(\theta/2))| \approx 4$ in a semi-projective tower geometry with longitudinal segmentation. The polar angle $\theta$ is measured from the geometric center of the detector with respect to the proton-beam direction. The muon system covers $|\eta| < 2$ and consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroidal magnets, followed by two more similar layers of detectors outside the toroids [13].

Events containing electrons or muons are selected for offline analysis by a real-time three-stage trigger system. A set of single and dilepton triggers is used to tag the presence of electrons or muons based on their characteristic energy deposits in the calorimeter, the presence of high-momentum tracks in the tracking system, and hits in the muon detectors.

$R$-parity violating supersymmetry events are modeled using SUSYGEN [14], with CTEQ5L [15] parton distribution functions (PDFs). The package SUSYGEN is interfaced with the program SUSPECT [16] for the evolution of masses and couplings from the renormalization group equations. Leading order (LO) cross sections of signal processes, obtained with SUSYGEN, are multiplied by a $K$ factor computed with GAUGINOS [17]. Standard model processes are generated using the Monte Carlo (MC) generator PYTHIA [18]. All MC events are processed through a detailed simulation of the detector geometry and response based on GEANT3 [19]. Multiple interactions per crossing as well as detector pile-up are included in the simulations. The SM background predictions are normalized using cross-section calculations at next-to-leading order (NLO) and next-to-NLO (for Drell–Yan production) with CTEQ6.1M PDFs [20]. Background from multijet production is estimated from data similar to the search samples, however, the lepton identification and isolation criteria are inverted ($ee\ell$ and $ee\tau$) or loosened ($\mu\mu\ell$). These samples are scaled at an early stage of the analysis where multijet production still dominates.

Electrons are identified based on their characteristic energy deposition in the calorimeter [21]. The fraction of energy deposited in the electromagnetic part of the calorimeter and the transverse shower profile inside a cone of radius $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.4$ around the cluster direction are considered (where $\phi$ is the azimuthal angle). In addition, a track must point to the energy deposition in the calorimeter and its momentum and the calorimeter energy must be consistent with each other. Remaining backgrounds from jets are suppressed based on the track multiplicity within $\Delta R = 0.4$ around the track direction.

Muons are reconstructed using track segments in the muon system, and each muon is required to have a matched central track measured with the tracking detectors [21]. Furthermore, muons are required to be isolated in both the tracking detectors and the calorimeter, which is essential for rejecting muons associated with heavy-flavor jets. The sum of the track transverse momenta ($p_T$) inside a cone of $\Delta R = 0.5$ around the muon direction should be less than 2.5 GeV and less than 6% of the muon $p_T$. For the calorimeter isolation, a transverse energy ($E_T$) of less than 2.5 GeV in a hollow cone of 0.1 $< \Delta R < 0.4$ around the muon direction is required and less than 8% of the muon’s transverse energy should be deposited in the calorimeter.

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be above 10 GeV and an NN output of more than NN > 0.9, corresponding to cut III in Table 1. To select events with real \( E_T \), which is expected due to neutrinos in the final state, a cut on \( E_T / \sqrt{S_T} \) is applied, where \( S_T \) is the total scalar transverse energy. It allows discrimination against events with fake \( E_T \), which may arise through statistical fluctuations in jet energy measurements.

Fig. 2 shows (a) the dielectron invariant mass in the \( \text{ee} \ell \) analysis after cut I of Table 1, (b) the missing transverse energy distribution in the \( \mu \mu \ell \) analysis after cut III of Table 1, and (c) the neural network output for a loose \( Z \rightarrow \tau \tau \rightarrow \tau_{\text{had}} \mu \) selection, which is used as an identification criterion for taus in the \( ee \tau \) analysis. The \( \mu + \text{jet} \) opposite-sign data sample (OS) represents the control sample, while the \( \mu + \text{jet} \) like-sign data sample (LS) is used to model the multijet background. The different contributions are scaled to the control sample by fitting the \( E_T \) spectrum of the tau candidate. While in (a), (b) the signal is scaled by a factor of 50, an arbitrary scale is used in (c), since the search and control samples are completely independent of each other and no meaningful scale can be defined for the signal contribution w.r.t. \( Z \rightarrow \tau \tau \) or \( \mu + \text{jet} \) data.

The number of observed events in data and the expected background from SM processes with its respective statistical and systematic uncertainties are given in Table 1. The background composition at the final stage of the \( \text{ee} \ell \) and \( \mu \mu \ell \) analyses is similar. Diboson production constitutes the largest background fraction (\( \text{ee} \ell: 86\%, \mu \mu \ell: 61\% \)), followed by multijet (\( \text{ee} \ell: 11\%), or \( t\bar{t} \) production (\( \mu \mu \ell: 36\% \)). In case of the \( \text{ee} \tau \) analysis, the main background is \( Z/\gamma^* \rightarrow \text{ee} \) (44%). Events from diboson, multijet and \( Z/\gamma^* \rightarrow \tau \tau \) contribute 20%, 16%, and 1% respectively.

| Cut | Data | Background |
|-----|------|------------|
| I \( p_T^{\ell} > 12 \text{ GeV}, p_T^{\ell} > 8 \text{ GeV} \) | 19283 | 19588 ± 81 ± 3332 |
| II \( \Delta \Phi(\mu, E_T) > 0.1 \) | 14918 | 15275 ± 72 ± 2598 |
| III \( \gamma \) and Z veto (\( E_T, M_{\mu\mu} \)) plane | 564 | 506 ± 13 ± 86 |
| IV \( p_T^{\ell} > 4 \text{ GeV or } p_T^{\ell} > 5 \text{ GeV} \) | 0 | 0.4 ± 0.1 ± 0.1 |

| Cut | Data | Background |
|-----|------|------------|
| I \( p_T^{\ell} > 10 \text{ GeV}, p_T^{\ell} > 10 \text{ GeV} \) | 20437 | 20905 ± 70 ± 1555 |
| II \( M_{\text{ee}} < 80 \text{ GeV} \) | 2831 | 2531 ± 32 ± 329 |
| III \( \tau: E_T > 10 \text{ GeV}, \text{NN} > 0.9 \) | 16 | 11.0 ± 2.8 ± 2.0 |
| IV \( \Delta \Phi(\mu, E_T) > 0.1 \) | 0 | 1.3 ± 1.7 ± 0.5 |

Fig. 2. (a) The dielectron invariant mass distribution of the \( \text{ee} \ell \) analysis after cut I, Table 1; (b) the \( E_T \) distribution of the \( \mu \mu \ell \) analysis after cut III, Table 1; and (c) the combination of the \( \pi \) and \( p \)-like NN outputs of a loose \( Z \rightarrow \tau \tau \rightarrow \tau_{\text{had}} \mu \) selection used as the \( \tau \) identification criterion in the \( \text{ee} \tau \) analysis. In (c) like-sign (opposite-sign) \( \mu + \text{jet} \) data is abbreviated LS (OS) and signal refers to the mSUGRA point \( m_0 = 1 \text{ TeV}, \tan \beta = 5, \mu > 0, A_0 = 0, \) and \( m_{1/2} = 280 \text{ GeV}, \) scaled by a factor of 50 in (a), (b) and arbitrarily in (c), details in the text.
and 14%, respectively. The number of events observed in data is in good agreement with the expectation from SM processes at all stages of the three analyses.

The numbers of events expected from SM background and from signal depend on several quantities, each one introducing a systematic uncertainty. The relative uncertainty due to the luminosity measurement is 6.5%. The relative uncertainty on trigger efficiencies ranges from about 11% for Drell–Yan (DY) background with low dilepton invariant masses (15 GeV < M_{ll} < 60 GeV) to about 1% for the signal. Lepton identification and reconstruction efficiencies give 3% (e), 4% (μ), and 12% (τ) per lepton candidate, and the photon conversion veto adds another 0.4%. The relative systematic uncertainties due to the resolution of the electron or muon energies and E_T are estimated by varying the resolutions in the MC simulation and are found to be less than 1% (e), 1.5% (μ), and 2% (E_T).

Further systematic uncertainties on the experimental cross-section limits concern the theoretical uncertainties on SM background MC cross sections, ranging from 3% to 17%, depending on the process, and including PDF uncertainties. Since PYTHIA does not model the Z boson p_T accurately, a relative uncertainty of 3% to 15%, depending on the dilepton mass, is added for MC Drell–Yan events. The influence of PDF uncertainties on the signal acceptance is estimated to be 4%.

Theoretical uncertainties on the signal cross sections are due to variations of the renormalization and factorization scales (5%), the LO cross section (2%), the K factor (3%), and the choice of PDF (9%). As gaugino pair production mostly proceeds via s-channel exchange of virtual γ, W, or Z bosons, the latter uncertainty is deduced from studies of the DY cross section at similar masses. The uncertainty on the DY cross section due to the choice of PDF is estimated to be 6%, using the CTEQ6.1M uncertainty function set [20]. An additional 3% is added linearly to account for the lower DY cross section if calculated with CTEQ6 PDFs, compared to its estimation with CTEQ5 PDFs, which are used for the signal MC generation. An additional, conservative, systematic uncertainty of +10% to −15% is added to account for the lower LO cross section from SUSYGEN compared to the one obtained with PYTHIA. All of these uncertainties are assumed to be independent, and are added in quadrature. The total systematic uncertainty of −11% and +15% is represented by the grey-shaded bands of the signal cross-section curve in Fig. 3.

When setting limits, the eee, μμτ, and eee analyses are combined for each coupling (λ_{121}, λ_{122}, λ_{133}) in order to enhance the signal sensitivity. All signal and background samples, as well as the data are processed by all analyses according to the three channels. Events selected in multiple channels are assigned only to the analysis with the largest signal-to-background ratio, and are removed from all other analyses. The percentage of common signal events for any two analyses is less than 13%, while no common data or SM background events are found. Table 2 shows the efficiencies of the analyses for a typical mSUGRA point (m_0 = 1 TeV, tan β = 5, μ > 0, A_0 = 0, and m_{1/2} = 280 GeV). Correlations between the signal efficiencies in the three channels are taken into account in the calculation of the systematic uncertainties.

Since no evidence for gaugino pair production is observed, upper limits on the cross sections are extracted in two models: in mSUGRA (with m_0 = 100 GeV or 1 TeV, tan β = 5 or 20, μ > 0, and A_0 = 0) and in an MSSM model assuming no GUT relation between M_1 and M_2 and assuming heavy squarks and sleptons, i.e. the higgsino mixing mass parameter, μ, and all sfermion masses are set to 1 TeV. Limits are calculated at the 95% C.L. using the LEP CL_S method [24] taking into account correlated uncertainties between SM and signal processes.

For mSUGRA (m_0 = 1 TeV and tan β = 5), the expected and observed cross-section limits (95% C.L.) are shown in Fig. 3 as functions of the \tilde{χ}_1^0 and \tilde{χ}_1^± masses.

Studies for m_0 = 100 GeV and tan β = 5 and 20 are done for λ_{133}. Particularly interesting is the region of high tan β values, where the stau is the next-to-lightest supersymmetric particle. In such a case, decays of SUSY particles into final states with stau leptons can be dominant and consequently increase the efficiency of the eee channel. Lower bounds on the masses of the \tilde{χ}_1^0 and the \tilde{χ}_1^± are given in Table 3.

In the MSSM, the exclusion domain is presented in the (\tilde{χ}_1^0, \tilde{χ}_1^±) mass plane in Fig. 4. The cut-off of the exclusion domain towards low neutralino masses, i.e. at m_{\tilde{χ}_1^0} = 30 GeV for λ_{121} and λ_{122}, and at m_{\tilde{χ}_1^0} = 50 GeV for λ_{133}, is due to the combined effect of the mean decay length of the lightest neutralino (cho-
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