Search for Resonant Second Generation Slepton Production at the Fermilab Tevatron

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We present a search for supersymmetry in the R-parity violating resonant production and decay of smuons and muon sneutrinos in the channels $\tilde{\mu} \rightarrow \tilde{\chi}_1^0 \mu$, $\tilde{\mu} \rightarrow \tilde{\chi}_{2,3,4}^0 \mu$, and $\tilde{\nu}_\mu \rightarrow \tilde{\chi}_{1,2}^{\pm} \mu$. We analyzed 0.38 fb^{-1} of integrated luminosity collected between April 2002 and August 2004 with the D0 detector at the Fermilab Tevatron Collider. The observed number of events is in agreement with the standard model expectation, and we calculate 95% C.L. limits on the slepton production cross section times branching fraction to gaugino plus muon, as a function of slepton and gaugino masses. In the framework of minimal supergravity, we set limits on the coupling parameter λ'_{211}, extending significantly previous results obtained in Run I of the Tevatron and at the CERN LEP collider.

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Supersymmetry (SUSY) predicts the existence of a new particle for every standard model (SM) particle, differing by half a unit in spin. The quantum number R parity [1], defined as $R = (-1)^{3B+L+2S}$, where B, L, and S are the baryon, lepton, and spin quantum numbers, is $+1$ for SM and -1 for SUSY particles. Often R parity is assumed to be conserved, which leaves the lightest supersymmetric particle (LSP) stable. However, SUSY does not require R-parity conservation.

If R-parity violation ($\not{R}_p$) is allowed, the following trilinear and bilinear terms appear in the superpotential [2]:

$$W_{\not{R}_p} = \tfrac{1}{2}\lambda_{ijk}L_i^\alpha L_j^\beta \bar{E}_k + \lambda'_{ijk}L_i^\alpha Q_j^\beta \bar{D}_k + \tfrac{1}{2}\lambda''_{ijk}\bar{U}_i^\xi \bar{D}_j^\psi \bar{D}_k^\zeta + \mu_i L_i H_1, \quad (1)$$

where L and Q are the lepton and quark SU(2) doublet superfields and $\bar{E}$, $\bar{U}$, $\bar{D}$ denote the singlet fields. The indices have the following meaning: $i, j, k = 1, 2, 3 =$ family index; $\alpha, \beta = 1, 2 =$ weak isospin index; $\xi, \psi, \zeta = 1, 2, 3 =$ color index. The coupling strengths are given by the Yukawa coupling constants λ, λ', and λ''. The last term, $\mu_i L_i H_1$, mixes the lepton and the Higgs superfields. The λ and λ' couplings give rise to final states with multiple leptons, which provide excellent signatures at the Tevatron. A detailed review of $\not{R}_p$ SUSY is given in [3].

In the following, we assume that all $\not{R}_p$ couplings except λ'_{211} are zero. This implies (muon) lepton number violation. The $\not{R}_p$ coupling constants are already constrained by low-energy experiments, in particular $\lambda'_{211} < 0.059 m_{\tilde{q}}/100$ GeV [4]. For the squark masses $m_{\tilde{q}}$ kinematically accessible at the Tevatron, this limit on λ'_{211} is significantly improved by the present analysis.

The D0 Collaboration searched for resonant slepton production in Run I [5]. The H1 experiment at DESY searched for resonant squark production [6] in the framework of R-parity violating supersymmetry and published limits on the couplings λ'_{1jk}. The combined limits from the LEP collider at CERN are reviewed by [5]. Assuming R-parity violating decay via $LQ\bar{D}$ couplings, the limits are $m(\tilde{\chi}_1^0) \geq 39$ GeV, $m(\tilde{\chi}_1^\pm) \geq 103$ GeV, $m(\tilde{\nu}_\mu) \geq 78$ GeV, and $m(\tilde{\mu}) \geq 90$ GeV.

At $p\bar{p}$ colliders, an initial $q\bar{q}$ pair can produce a single slepton [7]. Assuming a nonzero λ'_{211} coupling, smuons or muon sneutrinos are produced. The s channel production is dominant and depends on the value of this coupling λ'_{211}. The contributions of the t and u channels are negligible compared to the resonant s channel [8]. The value of λ'_{211} influences the lifetime of the neutralino, but the signal cross sections corresponding to an observable $\tilde{\chi}_1^0$ decay length are not (yet) accessible.

The slepton can then decay into a lepton and a gaugino without violating R parity. The λ'_{211} coupling allows neutralino decays in the detector via virtual sparticles (such as muon sneutrinos, smuons, and squarks) into two 1st generation quarks and one 2nd generation lepton [9]. The $\tilde{\chi}_1^0$ decay branching fractions as predicted by mSUGRA, with the ratio of the Higgs expectation values $\tan\beta = 5$, the sign of the Higgsino mass parameter $\mu < 0$, and the common trilinear scalar coupling $A_0 = 0$, are assumed, leading to $\mathrm{BR}(\tilde{\chi}_1^0 \to \mu q_1 \bar{q}'_1) \approx \mathrm{BR}(\tilde{\chi}_1^0 \to \nu_\mu q_1 \bar{q}_1)$. The dominant slepton intermediate decays as well as the corresponding final states are indicated in Table I.

Because of the challenging multijet QCD environment and the advantage of the ability to reconstruct the neutralino and smuon masses, at least two muons were required in the final state. This leaves the three channels (i) $\tilde{\mu} \to \tilde{\chi}_1^0 \mu$, (ii) $\tilde{\mu} \to \tilde{\chi}_{2,3,4}^0 \mu$, and (iii) $\tilde{\nu}_\mu \to \tilde{\chi}_{1,2}^\pm \mu$ which are analyzed independently. The analyses are insensitive to events where the $\tilde{\chi}_1^0$ decays into $\nu_\mu \bar{q} q'$ and where no second muon is created in the cascade.

The data for this analysis were recorded by the D0 detector between April 2002 and August 2004 at a center-of-mass energy of 1.96 TeV. The integrated luminosity corresponds to 380 ± 25 pb^{-1}.

The D0 detector [10] has a central tracking system consisting of a silicon microstrip tracker and a central fiber tracker, both located within a 2 T superconducting solenoidal magnet, with designs optimized for tracking and vertexing at pseudorapidities $|\eta| < 3$ and $|\eta| < 2.5$, respectively. A liquid-argon and uranium calorimeter has a central section covering pseudorapidities $|\eta| \lesssim 1.1$, and two end calorimeters that extend coverage to $|\eta| \approx 4.2$. The muon system covering $|\eta| < 2.0$ consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T iron toroids, followed by two similar layers behind the toroids. The first level of the trigger (level 1) is based on fast information from the tracking, calorimetry, and muon

TABLE I. Smuon and muon-sneutrino decay channels: the final states correspond to $\tilde{\chi}_1^0 \to \mu q_1 \bar{q}'_1$ and $\tilde{\chi}_1^\pm \to q q' \tilde{\chi}_1^0$.

$\tilde{l}$ decay channel	Dominant final states
$\tilde{\mu} \to \tilde{\chi}^0 \mu$	2μ, 2 jets
$\tilde{\mu} \to \tilde{\chi}^\pm \nu_\mu$	1μ, $\not{E}_T$, 4 jets
$\tilde{\nu}_\mu \to \tilde{\chi}^0 \nu_\mu$	1μ, $\not{E}_T$, 2 jets
$\tilde{\nu}_\mu \to \tilde{\chi}^\pm \mu$	2μ, 4 jets

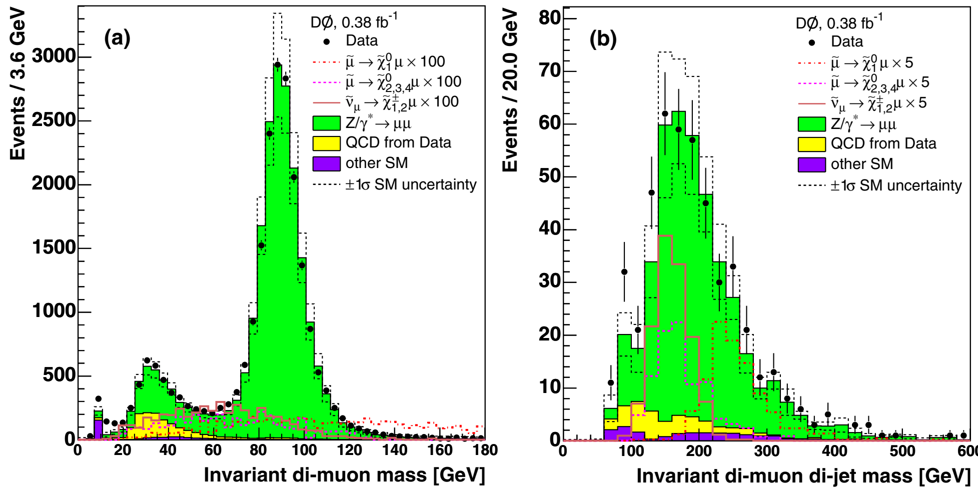

FIG. 1 (color online). Invariant di-muon mass in the two-muon sample (a) and reconstructed 4-body mass of two muons and two jets (b). The cascade decays in channels (ii) and (iii) lead to less energy per particle, thus lower invariant masses. The signal expectation for the point with $m_{\tilde{l}} = 260$ GeV and $m_{\tilde{\chi}_1^0} = 100$ GeV is scaled in plot (a) by a factor of 100 and in plot (b) by a factor of 5. The dominant SM background is $Z/\gamma^* \to \mu\mu$; other SM backgrounds are $Z/\gamma^* \to \tau\tau$; WW, WZ, ZZ, $t\bar{t}$, and Υ production. The total SM $\pm 1\sigma$ uncertainty is shown as dashed black lines. The data are in good agreement with the SM expectation.

systems. At the next trigger stage (level 2), the rate is reduced further. These first two levels of triggering rely mainly on hardware and firmware. The final level of the trigger, level 3, with access to the full event information, uses software algorithms to reduce the rate to tape to 50 Hz.

The signal was simulated with SUSYGEN [11]. The leading-order SUSYGEN signal cross sections have been multiplied by higher order, slepton-mass dependent QCD-correction factors [12] of size 1.4–1.5 calculated with the CTEQ6M [13] parton distribution functions (PDFs). The influence of the PDF uncertainty on the cross section is 3%–6%, estimated from the CTEQ6M error functions. The influence of the renormalization scale and the factorization scale μ_F is less than 5% for all slepton masses below 500 GeV, if $m(\tilde{l})/2 \leq \mu_F \leq 2m(\tilde{l})$ [14].

The dominant background is inclusive production of $Z/\gamma^* \to \mu\mu$. It was simulated with the PYTHIA [15] Monte Carlo (MC) generator and normalized using the predicted next-to-next-to-leading-order cross section [16], calculated with the CTEQ6 PDFs. All other SM processes contribute only slightly to the total background as seen in Fig. 1. These contributions were simulated using the PYTHIA generator and normalized using next-to-leading-order cross section predictions calculated using CTEQ6M PDFs. All MC events were passed through a detailed detector simulation based on GEANT [17], followed by the reconstruction program used for data.

Events were collected with di-muon triggers requiring at least two muons at level 1. At level 3 at least one track or one muon with a varying transverse momentum p_T threshold of typically 5–15 GeV was required. To account for the trigger effects, simulated events were weighted using efficiencies determined from the data.

All events were required to contain two muons. One of the muons was required to have $p_T > 15$ GeV, and the second muon was required to have $p_T > 8$ GeV. A central track match was required for both muons. The muons in the signal are expected to be isolated. We define muons as "loose" ("tight") isolated, if the sum of the p_T of the tracks in a cone with radius $R_{\rm cone} = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.5$, where $\eta = -\ln\tan\frac{\theta}{2}$ is the pseudorapidity and θ is the azimuthal angle, around the muon direction is less than 10 GeV (2.5 GeV), and the sum of the transverse energies of the calorimeter cells in a hollow cone ($0.1 \leq R_{\rm cone} \leq 0.4$) is less than 10 GeV (2.5 GeV). Both selected muons were required to pass the tight isolation requirement. The invariant di-muon mass distribution of this di-muon sample

TABLE II. Expected and observed events at different stages of the event selection. The signal efficiency is given for the point with $m_{\tilde{l}} = 260$ GeV and $m_{\tilde{\chi}_1^0} = 100$ GeV with respect to the total slepton production. The first uncertainty on the SM expectation is statistical; the second is due to systematics.

Cut	Data	SM expectation			Signal efficiency
2μ selection	23 206	22 700±	70±	2900	5.5% ± 0.7%
p_T jet$_1$ > 15 GeV	3852	3760±	40±	560	4.8% ± 0.6%
p_T jet$_2$ > 15 GeV	475	430±	10±	80	2.4% ± 0.3%

TABLE III. Effect of the systematic uncertainties in the two-muon and two-jet sample on background and signal cross sections. The muon ID contribution comprises the uncertainties due to muon reconstruction, isolation, track finding and matching, and resolution for the two muons. The systematic uncertainties on the signal strongly depend on the neutralino mass, so a typical range is given.

Uncertainty	Background	Signal
Jet energy scale	13.7%	2%–26%
Muon ID	7.8%	8%–14%
Luminosity (does not apply to QCD)	5.5%	6.5%
Trigger efficiency	5.2%	4%–9%
MC σ, K-factor, PDF	3.7%	5%
QCD background estimation	3.1%	—
MC statistics	2.2%	3%–24%

is shown in Fig. 1(a). At least two jets with transverse momentum $p_T \geq 15$ GeV and reconstructed with a cone algorithm ($R_{\text{cone}} = 0.5$) [18] were required. Only jets within $|\eta| < 2.0$ were used. The reconstructed slepton mass with two muons and two jets is shown in Fig. 1(b). The event selection is summarized in Table II.

Background from multijet QCD events was extracted from data using loose muon isolation requirements. This QCD enriched data sample was scaled to match the data in a signal free region. At least one isolation criterion with respect to other energy depositions in the calorimeter or to other tracks must not be tight for at least one muon to create an orthogonal sample utilized to model the QCD background.

Two-dimensional selection requirements in planes spanned by the reconstructed $\tilde{l}$ and $\tilde{\chi}$ candidate masses, the invariant di-muon and di-jet masses, and the sums of muon momenta and jet momenta were used to separate the signal s from SM backgrounds b. The selection requirements were chosen so that the signal efficiency $\times$ signal purity $\propto \frac{s}{\sqrt{s+b}}$ of a specific cut, applied on a training sample, was maximized. The selection requirements were optimized for each (slepton mass, gaugino mass) combination (117 in total).

In the $\tilde{\mu} \rightarrow \tilde{\chi}_1^0 \mu$ analysis (i), the slepton mass was reconstructed with the two leading muons and the two jets. In the signal MC calculation, the leading muon usually originates from the slepton decay vertex. The neutralino mass was therefore reconstructed with both jets and the next-to-leading muon.

Hadronic decays of vector bosons from the gaugino cascade to $\tilde{\chi}_1^0$ can lead to additional jets in channels (ii) and (iii). A simple likelihood was calculated for each combination to reconstruct a vector boson and the neutralino candidate mass. The slepton mass was reconstructed from all jets with $E_T > 15$ GeV and the two leading muons.

After the optimization, for the point with $m_{\tilde{l}} = 260$ GeV and $m_{\tilde{\chi}_1^0} = 100$ GeV, we find 14/28/8 events in the data while $11.9 \pm 2.1^{+1.5}_{-1.6}/25.4 \pm 3.2^{+6.7}_{-4.2}/6.5 \pm 1.6^{+2.0}_{-1.2}$ events are expected from SM backgrounds for the three channels, respectively, with a typical signal efficiency of up to 2%. For all 117 mass combinations, the data are in agreement with the SM expectation throughout the entire event selection range.

The systematic uncertainties from different sources were added in quadrature. For the limit calculation, the total systematic uncertainties of the background and signal samples were taken to be 100% correlated. A summary of the uncertainties is given in Table III with their contributions to the two-muon and two-jet sample.

In the absence of an excess in the data, we set cross section limits on resonant slepton production. To be as model independent as possible, we calculated 95% C.L. with respect to the slepton production cross section times branching fraction to gaugino plus muon using the C.L.$_s$ method [19]. The limit is then given in the slepton-mass and gaugino-mass plane, as shown in Fig. 2. In addition, our results are shown in Fig. 3 as λ'_{211} exclusion contours interpreted within the mSUGRA framework, with $\tan\beta = 5$, $\mu < 0$, and $A_0 = 0$. The slepton-mass and gaugino-mass pair define the universal scalar and fermion masses m_0 and

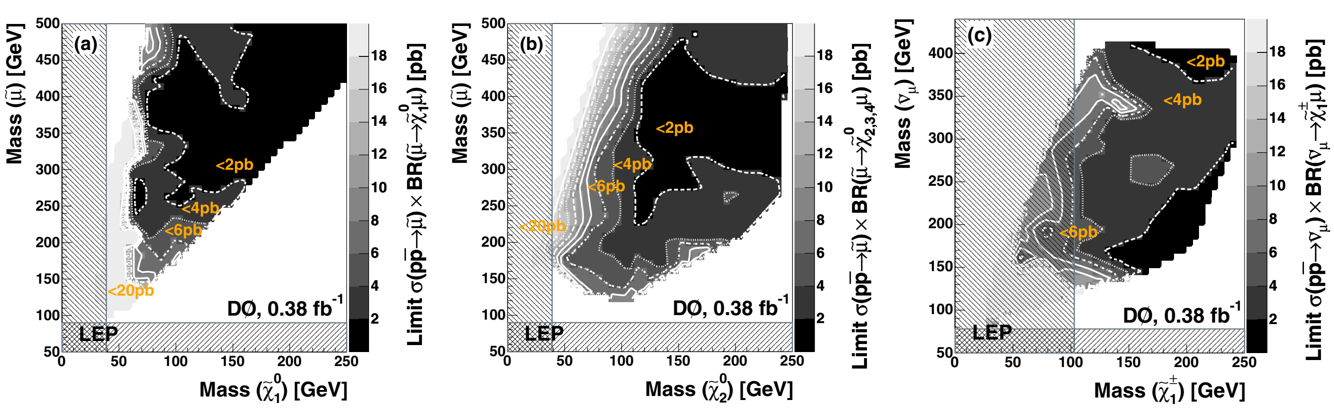

FIG. 2 (color online). 95% C.L. on slepton production cross section times branching fraction to gaugino plus muon for the channels (i) $\tilde{\mu} \rightarrow \tilde{\chi}_1^0 \mu$ (a), (ii) $\tilde{\mu} \rightarrow \tilde{\chi}_{2,3,4}^0 \mu$ (b), and (iii) $\tilde{\nu}_\mu \rightarrow \tilde{\chi}_{1,2}^\pm \mu$ (c) as a function of slepton and gaugino masses. The darkest region corresponds to a cross section of less that 2 pb. Successively lighter regions have successively higher limits.

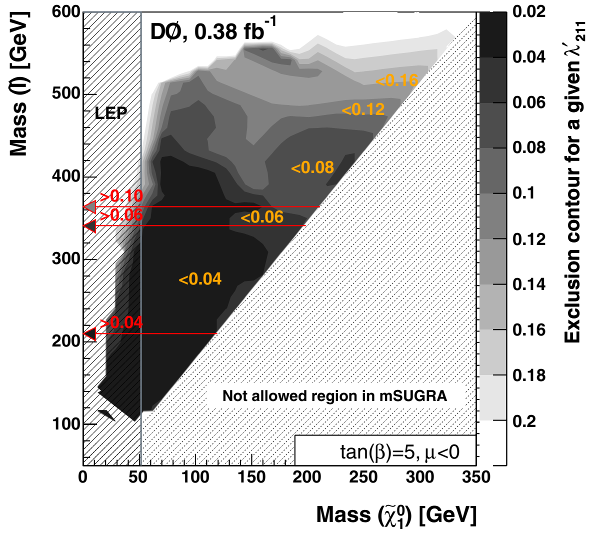

FIG. 3 (color online). 95% C.L. exclusion contour on λ'_{211} couplings within the mSUGRA framework for $\tan\beta = 5$ and $\mu < 0$. The arrows indicate limits on the slepton mass $\tilde{l}$, for a given coupling λ'_{211}.

$m_{1/2}$. All three channels were combined to form one limit for $q\bar{q} \to \tilde{l}$, with $\tilde{l} = \tilde{\mu}, \tilde{\nu}_\mu$.

A lower limit on the slepton mass for a given $LQ\bar{D}$ coupling λ'_{211} can be extracted from Fig. 3. These limits do not depend on other masses. They are indicated by arrows and summarized in Table IV. Similarly, the exclusion contour can be translated within mSUGRA into constraints on other masses and parameters.

In summary, we have searched for R-parity violating supersymmetry via a nonzero $LQ\bar{D}$ coupling λ'_{211} in final states with at least two muons and two jets. No excess in comparison with SM expectation was found and we set model independent cross section limits, improved compared to D0 Run I by 1 order of magnitude. The limits are interpreted within the mSUGRA framework and translated into the best constraints to date on the coupling strength λ'_{211}. D0 Run I excluded slepton masses up to 280 GeV for $\lambda'_{211} = 0.09$ and $m(\tilde{\chi}_1^0) = 200$ GeV. Now, slepton masses up to 358 GeV can be excluded, for $\lambda'_{211} = 0.09$ independent of other masses.

TABLE IV. Limits on the slepton mass $\tilde{l}$ for a given $LQ\bar{D}$ coupling λ'_{211} and $\tan\beta = 5$, $\mu < 0$ from Fig. 3.

Excluded slepton-mass range	Coupling strength
$m(\tilde{l}) \leq 210$ GeV	for $\lambda'_{211} \geq 0.04$
$m(\tilde{l}) \leq 340$ GeV	for $\lambda'_{211} \geq 0.06$
$m(\tilde{l}) \leq 363$ GeV	for $\lambda'_{211} \geq 0.10$

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