# Search for $R$-Parity violating Supersymmetry with the DØ Detector

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**Abstract.** Searches for R-parity violating supersymmetry with the DØ detector at the Fermilab Tevatron $p\bar{p}$-collider are presented. In the case of non-zero $LL\bar{E}$ couplings $\lambda_{ijk} \gtrsim 0.01$, multi-lepton final states, and for a small coupling $\lambda_{122} \ll 0.01$ di-muon final states are studied. The case of non-zero $LQ\bar{D}$ coupling $\lambda'_{211}$ leads to final states with two muons and jets.

A total integrated luminosity of 0.38 fb$^{-1}$ collected between April 2002 and August 2004 is utilized. The observed numbers of events are in agreement with the Standard Model expectation, and limits on $\not{R}_p$ supersymmetry are derived, extending significantly previous bounds.

**Keywords:** R-Parity, violating, supersymmetry, mSUGRA, D0
**PACS:** 11.30.Pb, 04.65.+e, 12.60.Jv

## INTRODUCTION

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]:

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

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 $\lambda, \lambda'$ and $\lambda''$. The last term, $\mu_i L_i H_1$, mixes the lepton and the Higgs superfields. The $\lambda$ and $\lambda'$ couplings give rise to final states with multiple leptons, which provide excellent signatures at the Tevatron. All analyses presented here require that only one $\not{R}_p$ coupling is of significant size, since strict limits exist on the product of two couplings, i.e. from the proton lifetime [3]. A detailed review of $\not{R}_p$ SUSY is given in [4].

The data for this analysis were recorded by the DØ detector between April 2002 and August 2004 at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. The integrated luminosity corresponds to $380 \pm 25$ pb$^{-1}$. A detailed description of the DØ detector can be found in [5].

## Gaugino pair and associated production

The charginos and neutralinos are produced in pairs or associated. The produced sparticles (cascade) decay to the lightest neutralino $\tilde{\chi}_1^0$. When assuming a non-zero $LL\bar{E}$ coupling, then this neutralino decays into two charged leptons and one neutrino by violating R-parity. The final state therefore contains at least four charged leptons and two neutrinos which lead to missing transverse energy ($\not{E}_T$) in the detector.

This analysis requires the prompt decay of the lightest neutralino $\tilde{\chi}_1^0$, so that all particles originate from the same vertex, leading to the constraint that the corresponding $LL\bar{E}$-coupling ($\lambda_{121}$, $\lambda_{122}$, or $\lambda_{133}$) is larger than $\gtrsim 0.01$. For best acceptance, only three charged leptons are required to be identified. Three different analyses are performed depending on the flavors of the leptons in the final state $eel$, $\mu\mu l$, $ee\tau$, with $l = e, \mu$. All three analyses are optimized separately using SM and signal MC simulations. Details of the selection and the analyses can be found in [6].

Since no evidence for $\not{R}_p$-SUSY is observed in tri-lepton events, the analyses are combined. Upper limits on the chargino and neutralino pair production cross section are set. Lower bounds on the masses of the lightest neutralino and the lightest chargino are derived in mSUGRA and in an MSSM scenario with heavy sfermions, but assuming no GUT relation between the gaugino masses $M_1$ and $M_2$. All limits as shown in Fig. 1 are the most restrictive to date.

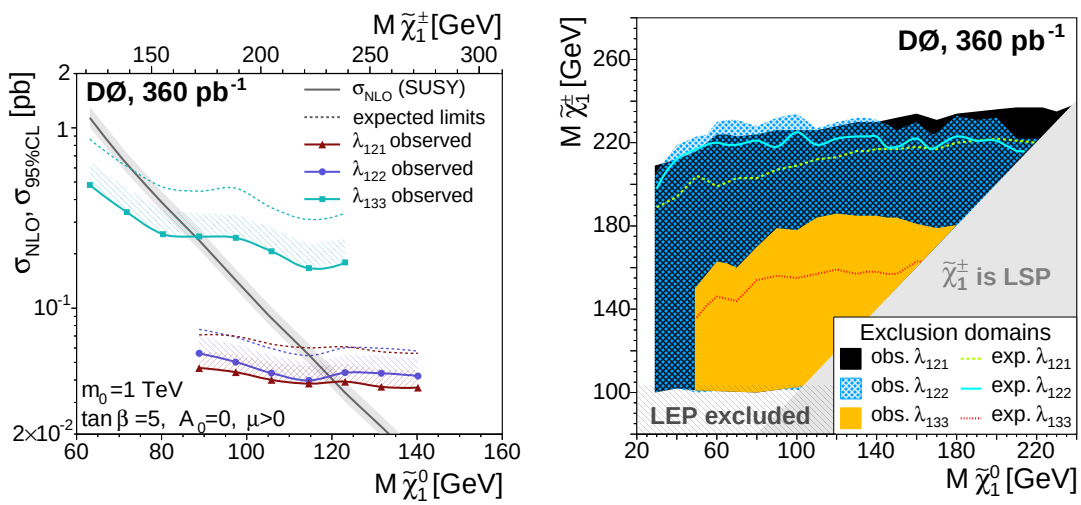


**FIGURE 1.** Cross section limit for three different $LL\bar{E}$ couplings compared to the mSUGRA cross section prediction (left). Within mSUGRA with relaxed gaugino GUT relation exclusion contours for each coupling $\lambda_{121}$, $\lambda_{122}$, $\lambda_{133}$ in the m($\tilde{\chi}_1^0$)–m($\tilde{\chi}_1^\pm$) plane are derived (right). [6]

## Neutral long lived particles (NLLP)

Here, a *small* $LL\bar{E}$ coupling $\lambda_{122}$ is assumed leading to long neutralino $\tilde{\chi}_1^0$ lifetimes and a displaced di-muon vertex. The primary vertex was reconstructed using all tracks, except those associated with muons. The primary vertex is required to be within 0.3 cm of the beamline in *x* and *y* and within 60 cm of the detector center in *z*. Two muons must originate from the same secondary vertex, that is displaced $5-20$ cm with respect to the primary vertex. Details can be found in [7].

This analysis is sensitive to neutral, long-lived particles decaying to $\mu\mu$+X. The background is estimated to be $0.75 \pm 1.1$ (stat) $\pm 1.1$ (syst) events. No events were selected and a limit on the product of NLLP pair production cross section times decay branching fraction into $\mu\mu + X$ is set as a function of the lifetime. The 95% CL cross section limit for a mass of 10 GeV and a lifetime of $4 \times 10^{-11}$ s is 0.14 pb. The result as shown in Fig. 2 excludes an interpretation of the NuTeV excess [8] of di-muon events in a large class of models.

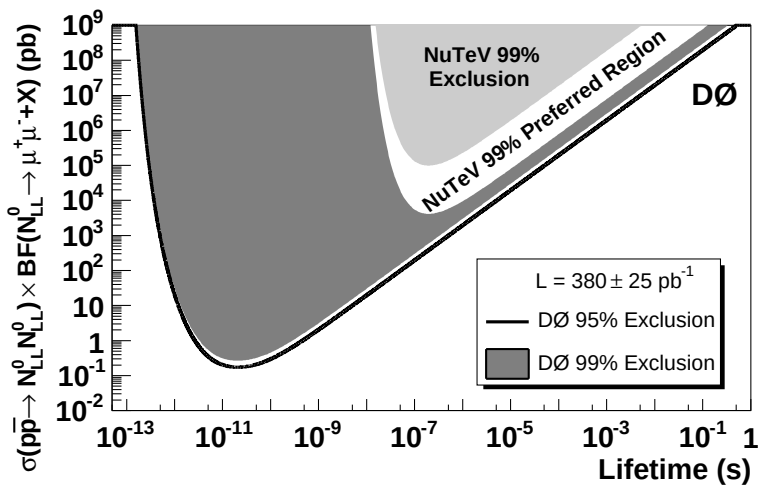


**FIGURE 2.** Cross section limit with 95% CL. The interpretation of the NuTeV excess in the di-muon channel arising from the decay of neutral long lived particles is shown as well and can be excluded. [7]

## Resonant Second Generation Slepton Production

The $LQ\bar{D}$ coupling offers the opportunity to produce sleptons in $p\bar{p}$-collisions as resonances. For a non-zero coupling $\lambda'_{211}$ this is either a smuon or a muon sneutrino. The slepton cascade decays into the lightest neutralino $\tilde{\chi}_1^0$ and associated leptons. The neutralino decays via the same *R*-parity violating coupling $\lambda'_{211}$ into a $2^{nd}$ generation lepton and two jets. The cross section is proportional to $(\lambda'_{211})^2$, so that limits on this coupling can be derived.

Three resonant slepton channels (i) $\tilde{\mu} \to \tilde{\chi}_1^0 \mu$, (ii) $\tilde{\mu} \to \tilde{\chi}_{2,3,4}^0 \mu$, and (iii) $\tilde{\nu}_\mu \to \tilde{\chi}_{1,2}^{\pm} \mu$ resulting in di-muon and multi-jet final states for neutralino decays $\tilde{\chi}_1^0 \to \mu q \bar{q}$ are analyzed separately. For the further discrimination of the signal and the Standard

Model background, the analyses make use of the possibility to reconstruct the neutralino $m(\tilde{\chi}_1^0) = m(\mu,q,q)$ and the slepton $m(\tilde{l}) = m(\mu,\mu,q,q)$ masses. More details can be found in [9].

In the absence of an excess in the data, cross section limits on resonant slepton production were set. To be as model independent as possible, limits with respect to the slepton production cross section times branching fraction to gaugino plus muon are calculated. The results are interpreted within the mSUGRA framework with $\tan\beta = 5$, $\mu < 0$, and $A_0 = 0$ and an exclusion contour w.r.t. $\lambda'_{211}$ is derived. All three channels were combined to form one limit for $q\bar{q} \to \tilde{l}$. Lower limits for the slepton mass of 210, 340 and 363 GeV independent of other masses are obtained for $\lambda'_{211}$ values of 0.04, 0.06 and 0.10, respectively, a signifi cant improvement compared to previous results.

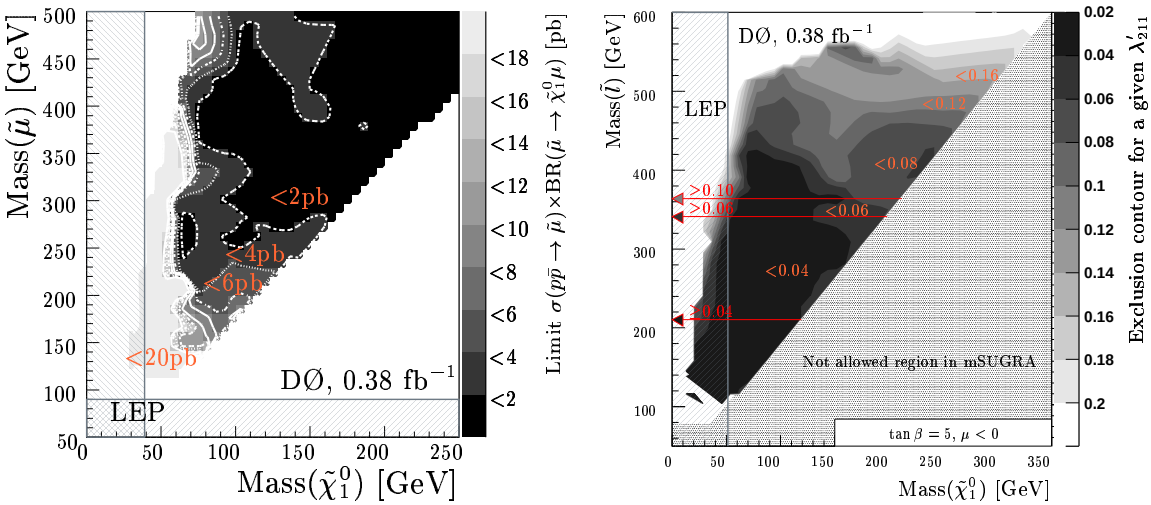


**FIGURE 3.** Cross section times branching fraction limit for the process $\tilde{\mu} \to \tilde{\chi}_1^0\mu$ (left). All three resonant slepton production channels can be combined within mSUGRA and are translated into an exclusion contour with respect to the $LQ\bar{D}$ coupling strength $\lambda'_{211}$ (right). [9]

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