Search for Scalar Neutrino Superpartners in $e + \mu$ Final States in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report a search for R-parity-violating production and decay of sneutrino particles in the $e\mu$ final state with $1.04 \pm 0.06\ \text{fb}^{-1}$ of data collected with the D_0 detector at the Fermilab Tevatron Collider in 2002–2006. Good agreement between the data and the standard model prediction is observed. With no evidence for new physics, we set limits on the R-parity-violating couplings λ'_{311} and λ_{312} as a function of the sneutrino mass.

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Supersymmetry (SUSY) postulates a symmetry between bosonic and fermionic degrees of freedom and predicts the existence of a supersymmetric partner for each standard model (SM) particle. Supersymmetric extensions of the SM provide mechanisms for solving the hierarchy problem and offer the possibility of unification of interactions. An R-parity quantum number is defined as $R = (-1)^{2S+L+3B}$ [1], where B, L, and S are, respectively, the baryon and lepton quantum numbers and the spin of the particle, such that SM particles have $R = +1$ and their SUSY partners have $R = -1$. R parity is often assumed to be conserved, which preserves L and B quantum number invariance and leaves the lightest supersymmetric particle (LSP) stable. However, there is no fully compelling reason for the assumption of R-parity conservation. In general, representations of a gauge-invariant and renormalizable superpotential, terms of R-parity violation (RPV), can be included as

$$W_{\rm RPV} = \tfrac{1}{2}\epsilon_{ab}\lambda_{ijk}L_i^a L_j^b E_k + \epsilon_{ab}\lambda'_{ijk}L_i^a Q_j^b D_k + \tfrac{1}{2}\epsilon_{\alpha\beta\gamma}\lambda''_{ijk}U_i^\alpha D_j^\beta D_k^\gamma + \epsilon_{ab}\mu_i L_i^a H_u^b, \quad (1)$$

where L and Q are the lepton and quark $SU(2)$ doublet superfields, respectively, and E, U, and D denote the singlet fields. The indices $i, j, k = 1, 2, 3$ refer to fermion generation; $a, b = 1, 2$ are $SU(2)$ isospin indices; and $\alpha, \beta, \gamma = 1, 2, 3$ are $SU(3)$ color indices. The bilinear terms μLH mix the lepton and the Higgs superfields, which could yield neutrino masses and introduce a natural description of neutrino oscillation [2]. The trilinear terms LLE and LQD represent lepton flavor-violating interactions, and the UDD terms lead to baryon number violation, where interaction strengths are given, respectively, by the dimensionless Yukawa coupling constants λ, λ', and λ''.

A single slepton could be produced in hadron collisions by LQD interactions and then decay into SM dilepton final states via LLE interactions. The observation of a high-mass dilepton resonance would be evidence of new physics beyond the SM [3]. In this Letter, we report a direct search for resonant production of sneutrinos decaying into an electron and a muon in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Tevatron. The search is performed under the hypothesis that the third-generation sneutrino ($\tilde{\nu}_\tau$) is the LSP and dominant, namely, by assuming that all couplings but λ'_{311} and $\lambda_{312} = \lambda_{321}$ are zero. The final state is characterized by an electron and a muon, both of which are well isolated and have high transverse momentum (p_T) which is approximately half of the sneutrino mass. The main background contributions are from $Z/\gamma^* \to \tau\tau$, WW, $t\bar{t}$, WZ, and ZZ processes that sequentially decay to $e\mu$ final states. High p_T leptons in the signal process allow us to employ high p_T thresholds to suppress the background.

The indirect 2σ upper limit on the product of $\lambda'_{311} \times \lambda_{312}$ from the Sindrum II experiment, reviewed by Ref. [4], is 2.1×10^{-8} for a degenerated sparticle mass spectrum of $M = 100$ GeV. Under the single coupling dominance assumption, where each coupling at a time is assumed to be nonzero, the indirect 2σ bounds are

$$\lambda'_{311} \le 0.12, \qquad \lambda_{312} \le 0.07, \qquad M \equiv M_{\tilde{\nu}_\tau} = 100 \text{ GeV}. \quad (2)$$

A direct search for this process has been performed by the CDF Collaboration with Tevatron run II data [5].

The D0 detector comprises a central tracking system in a 2 T superconducting solenoidal magnet, a liquid-argon/uranium calorimeter, and a muon spectrometer [6]. The tracking system consists of a silicon microstrip tracker and a scintillating fiber tracker (CFT) with eight layers mounted on thin coaxial barrels; it provides coverage for charged particles in the pseudorapidity range $|\eta| < 3$, which is defined as $\eta \equiv -\ln[\tan(\frac{\theta}{2})]$, where θ is the polar angle with respect to the proton beam direction. The calorimeter consists of a central section (CC) covering up to $|\eta| \approx 1.1$ and two end caps (ECs) extending coverage to $|\eta| \approx 4.2$, each housed in a separate cryostat. Each section consists of an inner electromagnetic (EM) compartment, followed by a hadronic compartment. The EM calorimeter has four longitudinal layers and transverse segmentation of 0.1×0.1 in η-ϕ space (where ϕ is the azimuthal angle), except in the third layer, where it is 0.05×0.05. The muon system resides beyond the calorimeter and consists of a layer of tracking detectors and scintillation trigger counters before 1.8 T iron toroidal magnets, followed by two similar layers after the toroids. Luminosity is measured by using plastic scintillator arrays located in front of the EC cryostats, covering $2.7 < |\eta| < 4.4$. The data acquisition system consists of a three-level trigger, designed to accommodate the high instantaneous luminosity. For final states containing an electron with p_T above 30 GeV, the trigger efficiency is close to 100%. The data sample used in this analysis was collected between April 2002 and February 2006 and corresponds to an integrated luminosity of 1.04 ± 0.06 fb^{-1}.

Only electrons in the CC region are considered in this analysis. The electron selection requires (i) an EM cluster with a cone of radius $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.2$ in the central calorimeter, with transverse energy $E_T > 30$ GeV, where E_T is defined as the cluster energy times $\sin\theta$; (ii) at least 90% of the cluster energy be deposited in the EM section of the calorimeter; (iii) the calorimeter isolation variable (I) should be less than 0.15, where $I \equiv \frac{E_{\rm tot}(0.4) - E_{\rm EM}(0.2)}{E_{\rm EM}(0.2)}$, $E_{\rm tot}(0.4)$ is the total energy in a cone of radius 0.4, and $E_{\rm EM}(0.2)$ the EM energy in a cone of radius 0.2 around the electron candidate direction; (iv) the transverse and longitudinal shower profiles be consistent with those of electrons; and (v) a track pointing to the EM cluster. To suppress the misidentification of jets as electrons, an electron likelihood discriminant based on the calorimeter variables and additional tracking information is defined. To ensure a high efficiency for signal events, we impose the likelihood requirement on electron candidates in the 30 GeV $< E_T <$ 100 GeV region and not the $E_T \geq$ 100 GeV region, where the jet contamination is substantially reduced. The reconstruction efficiencies of electrons are determined from a $Z \rightarrow e^+e^-$ data sample to be $(80 \pm 2)\%$ for $E_T <$ 100 GeV and $(86 \pm 2)\%$ for $E_T \geq$ 100 GeV.

The muon candidate is required to be separated from the electron candidate by $\Delta R > 0.2$ and from any jets by $\Delta R > 0.5$, where jets are reconstructed by using an iterative seed-based cone algorithm [7]. In addition, we require (i) that the track p_T be above 25 GeV; (ii) hits in the muon scintillation counters with a time consistent with originating from the proton-antiproton collision; (iii) at least 8 CFT hits along the track; (iv) the E_T sum of the calorimeter cells in the annulus cone of $0.1 < \Delta R < 0.4$ be less than 2.5 GeV; and (v) the transverse momentum sum of all tracks besides the muon track within a cone of radius $\Delta R = 0.5$ be less than 2.5 GeV. The reconstruction efficiency of muons determined from a $Z \rightarrow \mu^+\mu^-$ data sample is $(81 \pm 2)\%$.

To suppress the WZ and ZZ background, events having two muon candidates with $p_T > 5$ GeV or two electron candidates with $p_T > 8$ GeV are rejected. In order to suppress the $t\bar{t}$ background, events with missing transverse energy $\not{E}_T > 15$ GeV that is not aligned or antialigned in azimuth with the muon $[0.6 < \Delta\phi(\not{E}_T, \mu) < 2.5$ rad] as well as events with at least one jet with $p_T > 30$ GeV and $|\eta| < 2.5$ are rejected.

The partonic signal events are generated by using the COMPHEP program [8] and CTEQ6L [9] parton distribution functions (PDFs). The cross section of the process depends on sneutrino mass M and the LQD and LLE coupling constants as [3]

$$\hat{\sigma}_{e\mu} \propto (\lambda'_{311})^2(\lambda_{312})^2 \frac{1}{|\hat{s} - M^2 + i\Gamma M|^2}, \qquad (3)$$

where Γ, the total width of the LSP sneutrino, includes all decay modes ($d\bar{d}$ and $e\mu$) and also depends on the LQD and LLE couplings as

$$\Gamma = [3(\lambda'_{311})^2 + 2(\lambda_{312})^2]\frac{M}{16\pi}. \qquad (4)$$

A mass-dependent K factor is applied to include next-to-leading order (NLO) QCD corrections [10]. The partonic signal events are processed through PYTHIA [11] to include parton showering, hadronization, and particle decays. The influence of the PDF uncertainty on the cross section times acceptance is 6.2%–8.6% depending on the sneutrino mass, estimated from the CTEQ6M error functions. The cross section uncertainty from the choice of renormalization scale and factorization scale is about 4%. Standard model background processes are generated with PYTHIA and CTEQ6L1. The contribution of Drell-Yan Z/γ^* processes is normalized by using the next-to-next-to-leading-order cross section [12]. The contributions of WW, WZ, and $t\bar{t}$ processes are normalized with NLO cross sections [13,14]. All signal and background events are processed with a detailed GEANT-based D0 detector simulation [15] and are corrected for trigger effects and the differences in the reconstruction efficiencies compared to those in the data. The background from misidentification of photons or jets as leptons, such as $W\gamma$ and W + jet and QCD dijet events, is estimated from data and is found to be negligible given our stringent event selection criteria.

TABLE I. The numbers of selected events in the data and different estimated background contributions.

Process	Events
$Z/\gamma^* \rightarrow \tau\tau$	42.9 ± 4.2
WW	13.7 ± 1.5
$t\bar{t}$	1.4 ± 0.3
WZ	1.2 ± 0.2
Total background	59.2 ± 5.3
Data	68

The number of selected events in data and the estimated background contributions are summarized in Table I. The ZZ contribution is found to be negligible after the event selection and is not listed. There are 68 candidates found in the data. The expectation from the SM processes is 59.2 ± 5.3 events, where the uncertainty includes the statistical uncertainty and uncertainties from the integrated

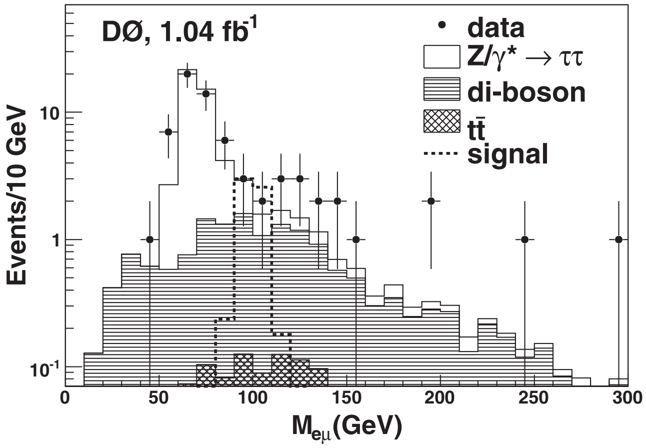

FIG. 1. Invariant mass of the electron-muon system. The di-boson contribution includes the WW and WZ processes. The dashed line indicates the signal Monte Carlo simulation of sneutrino with mass of 100 GeV and $\sigma \times$ BR of 0.057 pb.

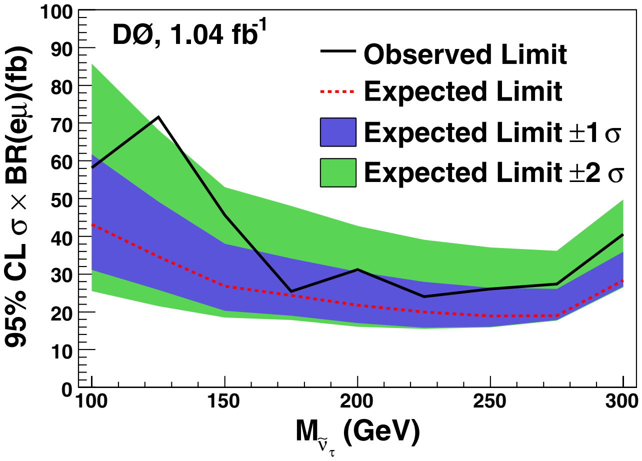

FIG. 2 (color online). The observed and expected upper limits on $\sigma \times$ BR at 95% C.L. for the process $p\bar{p} \rightarrow \tilde{\nu}_\tau + X \rightarrow e\mu + X$ as a function of the sneutrino mass, assuming that the sneutrino total width is much narrower than our detector resolution.

luminosity (6%), reconstruction and trigger efficiencies (3.1%), and background cross sections [Z/γ^* (3.5%), $t\bar{t}$ (14.7%), and diboson production (5.6%–6.6%)]. The kinematic variables of the final state are well described by the sum of the SM background contributions. The distribution of the electron and muon invariant mass ($M_{e\mu}$) is shown in Fig. 1.

By using the $M_{e\mu}$ distributions, we calculate an upper limit on $\sigma \times$ (branching ratio, BR) for the process $p\bar{p} \rightarrow \tilde{\nu}_\tau + X \rightarrow e\mu + X$ with a modified frequentist (CL$_s$) method [16], under the assumption that the total width is much narrower than the detector resolution. The upper limits as a function of the sneutrino mass are shown in Fig. 2. We fix one of the coupling constants and set the upper limit on the other for different sneutrino masses. Shown in Fig. 3 are the observed upper limits on λ'_{311} for four assumed values of λ_{312}. For a sneutrino with mass of 100 GeV, $\lambda'_{311} > 1.6 \times 10^{-3}$ is excluded at 95% C.L. when $\lambda_{312} = 0.01$.

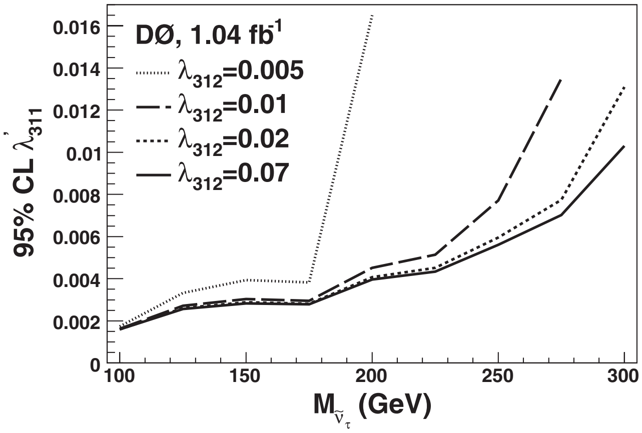

FIG. 3. The observed upper limits on λ'_{311} at 95% C.L. for four fixed values of λ_{312} as a function of the sneutrino mass.

In summary, we have studied the production of high p_T electron-muon pair final states with about 1 fb^{-1} of D0 data. We select 68 events, while the SM expectation is 59.2 ± 5.3 events. The distributions of kinematic variables are in good agreement with the SM predictions. We set limits on the parameters of a particular supersymmetric model which predicts an enhancement of the high p_T electron-muon final state via R-parity-violating production and decay of sneutrino particles. These are the most stringent direct limits to date.

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