

Search for sneutrino production in $e\mu$ final states in 5.3 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$

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We report the results of a search for R parity violating (RPV) interactions leading to the production of supersymmetric sneutrinos decaying into $e\mu$ final states using 5.3 fb^{-1} of integrated luminosity collected by the D0 experiment at the Fermilab Tevatron Collider. Having observed no evidence for production of $e\mu$ resonances, we set direct bounds on the RPV couplings λ'_{311} and λ_{312} as a function of sneutrino mass.

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In all standard model (SM) interactions, baryon number, B , and lepton number, L , are separately conserved. In the supersymmetric (SUSY) extension of the SM, B and L violating interactions are generally allowed. A new multiplicative quantum number is therefore introduced, $R = (-1)^{2S+3(B-L)}$, defined in terms of B , L and the spin quantum number S , which distinguishes SM particles ($R = +1$) from their SUSY partners ($R = -1$) [1]. If R parity is conserved in the minimal extension of the SM, no B and L violating interactions can occur.

All SUSY particles are pair-produced if R parity is conserved. RPV interactions allow single production of SUSY particles which significantly reduces the energy required to observe them at a collider.

The most general renormalizable gauge invariant R parity violating (RPV) supersymmetric potential can be found in [2]. The terms in the Lagrangian relevant to this analysis are

$$\begin{aligned} \mathcal{L}_{\text{RPV}} = & \\ & -\frac{1}{2}\lambda_{ijk}(\tilde{\nu}_{iL}\bar{l}_{kR}l_{jl} - \tilde{\nu}_{jL}\bar{l}_{kR}l_{il}) \\ & -\lambda'_{ijk}(\tilde{\nu}_{iL}\bar{d}_{kR}d_{jl}) + \text{h.c.}, \end{aligned} \quad (1)$$

where the indices $i, j, k = 1, 2, 3$ refer to fermion generation; l and d are the SM lepton and down quark fields; $\tilde{\nu}$ is the field of the SUSY partner of the neutrino, the sneutrino. These terms lead to the produc-

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tion of a single sneutrino in $d\bar{d}$ scattering. The search is performed under the hypothesis that only the third generation sneutrino ($\tilde{\nu}_\tau$) is produced and that it is the lightest SUSY particle. All couplings apart from λ'_{311} and $\lambda_{312} = \lambda_{321} = -\lambda_{231} = -\lambda_{132}$ are therefore assumed to be zero and the sneutrino decay is determined by the $e\mu$ and $d\bar{d}$ modes.

In this Letter, we report on a search for resonant production of a sneutrino decaying into an electron and a muon in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider in a data set with an integrated luminosity of 5.3 fb^{-1} , collected between April 2002 and June 2009. Observation of this process would provide direct evidence of physics beyond the SM [3]. Previous searches for high-mass $e\mu$ resonances by the CDF [4] and D0 [5] Collaborations were based on integrated luminosities of 1.0 fb^{-1} . In addition to using a significantly larger data sample, the signal sensitivity has been improved by increasing the lepton acceptance and by applying a neural network (NN) selection to distinguish jets from electrons.

Indirect two standard deviation bounds on the coupling constants, under the single coupling dominance assumption with a degenerate sparticle mass spectrum of $M \equiv M_{\tilde{\nu}_\tau} = 100 \text{ GeV}$, are given in Ref. [2] as

$$\lambda'_{311} \leq 0.12, \lambda_{312} \leq 0.07. \quad (2)$$

The sneutrino production cross section is determined by these two couplings and the sneutrino mass $M_{\tilde{\nu}_\tau}$. The final state is characterized by an electron and a muon, both of which are well-isolated and have high transverse momentum, p_T , of approximately $M_{\tilde{\nu}_\tau}/2$, and by a peak in the invariant $e\mu$ mass at $M_{\tilde{\nu}_\tau}$. The dominant SM background processes for this event topology are the production of $Z/\gamma^* \rightarrow \tau\tau$, dibosons ($WW/WZ/ZZ$), $t\bar{t}$ pairs, and W bosons in association with jets, where a jet is misidentified as a lepton.

The D0 detector [6] comprises a central tracking system in a 2 T superconducting solenoidal magnet, surrounded by a central preshower detector (CPS), a calorimeter, and a muon system. The tracking system, a silicon microstrip tracker (SMT) and a scintillating fiber tracker (CFT), provides coverage for charged particles in the pseudorapidity range $|\eta| < 3$ [7]. The CPS is located immediately before the inner layer of the calorimeter and is formed of approximately one radiation length of lead absorber followed by three layers of scintillating strips. The calorimeter consists of a central calorimeter (CC) covering up to $|\eta| \approx 1.1$, and two end caps (EC) extending coverage to $|\eta| \approx 4.2$. Each consists of an inner electromagnetic (EM) section, followed by a hadronic section. The EM calorimeter has four longitudinal layers and transverse segmentation of 0.1×0.1 in $\eta-\phi$ space, 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. The coverage of the muon system is $|\eta| < 2$. The data acquisition system consists of

a three-level trigger, designed to accommodate the high instantaneous luminosity. For final states containing an electron with $p_T > 30 \text{ GeV}$, the trigger efficiency is close to 100%.

To simulate signal kinematics in the D0 detector, parton level signal events are generated using the COMPHEP [8] leading order Monte Carlo generator and then processed through PYTHIA [9] to include parton showering, hadronization, and particle decays. SM background processes are generated with PYTHIA, except for the W +jets inclusive samples, which are generated with ALPGEN [10] and PYTHIA for parton showering. All signal and background simulations use the CTEQ6L1 [11] parametrization of the parton distribution functions.

We use next-to-next-to-leading order (NNLO) cross sections for Drell-Yan $Z/\gamma^* \rightarrow \ell\ell$ ($\ell = e, \tau, \mu$) processes [12] and NLO cross sections for diboson [13], $t\bar{t}$ [14], and W +jets production [15]. All signal and background events are processed with a detailed GEANT-based D0 detector simulation [16] and are corrected for trigger effects and for the differences in the reconstruction efficiencies in the simulation compared to those in data.

Electrons are selected by requiring an EM cluster in the CC or in either EC with transverse energy $E_T > 30 \text{ GeV}$ within a cone of radius $\mathcal{R} = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.2$. The EM cluster in the CC must be in the range $|\eta| < 1.1$ and in the EC in the range $1.5 < |\eta| < 3.2$. At least 97% of the cluster energy must be deposited in the EM section of the calorimeter and the energy must be isolated in the calorimeter, $[E_{\text{tot}}(0.4) - E_{\text{EM}}(0.2)]/E_{\text{EM}}(0.2) < 0.07$, where $E_{\text{tot}}(\mathcal{R})$ and $E_{\text{EM}}(\mathcal{R})$ are the total energy and the energy in the EM section, respectively, within a cone of radius $\mathcal{R}$ around the electron direction. A track must point to the EM cluster for all electron candidates. A multi-variable likelihood discriminant, which includes information from the spatial track match, must be consistent with that for an electron in the CC. An NN is trained using information from the tracker, the calorimeter, and the CPS to further reject background from jets misidentified as electrons. The electron must also be spatially separated from reconstructed muons.

For the muon candidate, we require that the associated central track p_T exceeds 25 GeV and that the time measured for hits in the muon scintillation counters is consistent with an interaction originating from a $p\bar{p}$ collision. The central track fit must have $\chi^2/\text{ndf} < 4$ and the distance of closest approach (dca) of the track to the beam spot in the plane transverse to the beam direction should be less than 0.02 cm if the track has SMT hits and less than 0.2 cm otherwise. The sum of the transverse energy of calorimeter cells in the annulus $0.1 < \mathcal{R} < 0.4$ around the muon direction must be less than 2.5 GeV, and the sum of the transverse momentum of all tracks besides the muon track within $\mathcal{R} = 0.5$ must be less than 2.5 GeV.

Events are required to have exactly one high p_T isolated electron candidate and one high p_T isolated muon candidate. There is no requirement on the charge of the

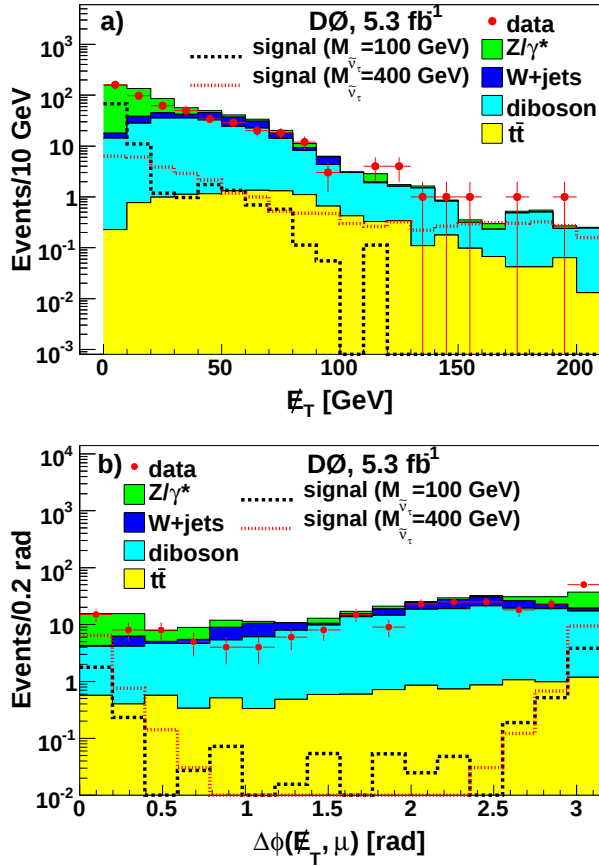


FIG. 1: (color online). Distributions of (a) $\cancel{E}_T$ and (b) $\Delta\phi(\cancel{E}_T, \mu)$ between the direction of the $\cancel{E}_T$ and the muon for $\cancel{E}_T > 20 \text{ GeV}$. The signal simulation is shown for $M_{\tilde{\nu}_\tau} = 100 \text{ GeV}$ (400 GeV) and $\sigma \times \text{BR} = 40 \text{ fb}$ (12.5 fb).

two leptons. Furthermore, events are only considered if the primary vertex is reconstructed within 60 cm of the center of the D0 detector in the z coordinate along the beam axis and if the difference between the z coordinates of the muon and the electron at the dca is less than 2 cm. Background from $Z/\gamma^* \rightarrow \tau\tau$ decays is heavily suppressed by the high p_T requirement for the two leptons. To reduce the background from $t\bar{t}$ production, events are rejected if they have at least one jet with $p_T > 25 \text{ GeV}$ in the range $|\eta| < 2.5$, where jets are reconstructed using an iterative seed-based cone algorithm [17]. Figure 1(a) shows the missing transverse energy ($\cancel{E}_T$) distribution and Fig. 1(b) the distribution of azimuthal angles between the $\cancel{E}_T$ and the muon direction, $\Delta\phi(\cancel{E}_T, \mu)$, for events with $\cancel{E}_T > 20 \text{ GeV}$. Good agreement between data and the total SM predictions is observed. Signal events have low $\cancel{E}_T$, but due to the limited muon momentum resolution, some $\cancel{E}_T$ is expected in $e\mu$ signal events that is either pointing in the muon direction or opposite to it. This is observed in Fig. 1(b) for signal events and for the topologically similar Drell-Yan process. Events with $\cancel{E}_T > 20 \text{ GeV}$ are therefore rejected only if $0.7 < \Delta\phi(\cancel{E}_T, \mu) < 2.3$.

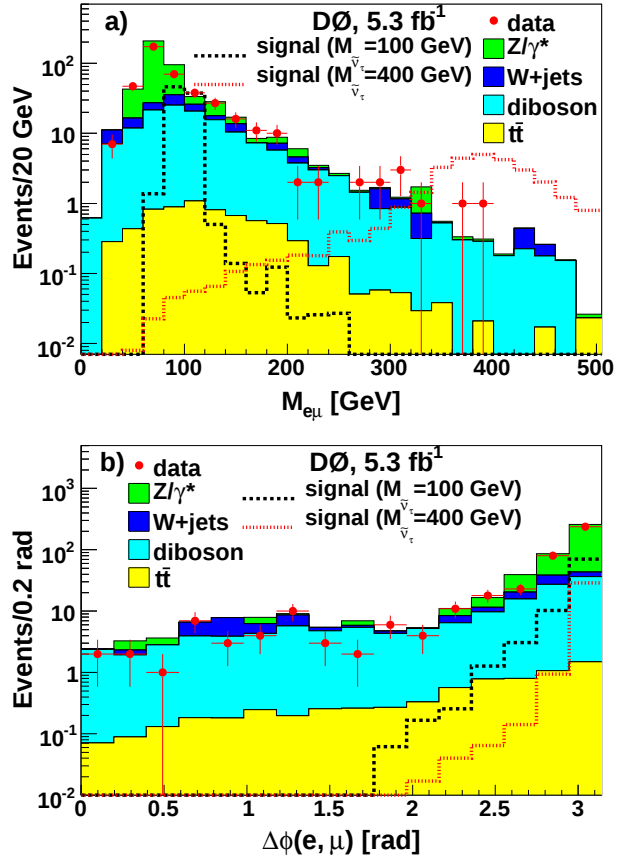


FIG. 2: (color online). Distributions of (a) $M_{e\mu}$ and (b) $\Delta\phi(e, \mu)$ for data compared to the sum of all background processes after the final event selection, rejecting, in addition, events with $\cancel{E}_T > 20 \text{ GeV}$ and $0.7 < \Delta\phi(\cancel{E}_T, \mu) < 2.3$. The signal simulation is shown for $M_{\tilde{\nu}_\tau} = 100 \text{ GeV}$ (400 GeV) and $\sigma \times \text{BR} = 40 \text{ fb}$ (12.5 fb).

TABLE I: The numbers of selected events in data and estimated background contributions for an integrated luminosity of 5.3 fb^{-1} with their total uncertainties.

Process	Number of events
Drell-Yan (Z/γ^*)	254 ± 26
Diboson (WW, WZ, ZZ)	116 ± 12
$t\bar{t}$	5.8 ± 1.0
W +jets	34.1 ± 5.9
Total background	410 ± 38
Data	414

The resulting distribution of the electron and muon invariant mass $M_{e\mu}$ and the azimuthal angle $\Delta\phi(e, \mu)$ between the electron and muon direction are shown in Fig. 2. The kinematic variables of the $e\mu$ final state are well described by the sum of the SM background contributions. The background contributions and the number of selected candidates are summarized in Table I. About 80% of the Drell-Yan background is due to $Z/\gamma^* \rightarrow \tau\tau$ events.

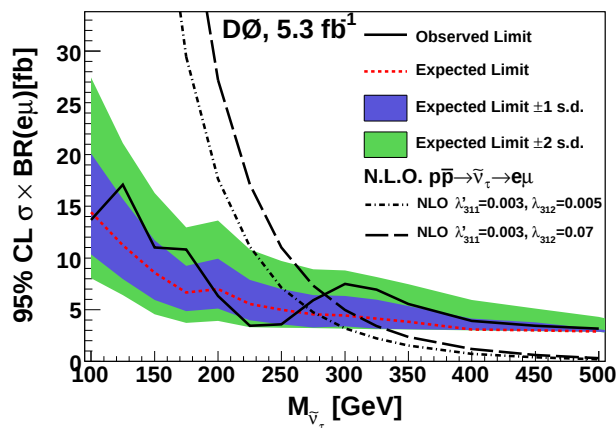


FIG. 3: (color online). The observed and median expected upper limits on $\sigma \times \text{BR}$ for the process $p\bar{p} \rightarrow \tilde{\nu}_\tau + X \rightarrow e\mu + X$ as function of $M_{\tilde{\nu}_\tau}$. The median expected limits are shown together with the ± 1 and ± 2 standard deviation bands. The theoretical cross sections for $\lambda'_{311} = 0.003$ and $\lambda_{312} = 0.005$ and 0.07 are also shown.

There are 414 candidate events found in the data. The expectation from SM processes is 410 ± 38 events, where the uncertainty includes the statistical uncertainty of the MC, the systematic uncertainties from the integrated luminosity (6.1%), reconstruction and trigger efficiencies (0.5%), which are all taken to be fully correlated between the background sources, and the uncertainties on the cross sections ($Z/\gamma^* \rightarrow \ell\ell$ 3.5%, $t\bar{t}$ 14.8%, diboson production 2.7% – 6.6%, and W +jets 8.5%). Additional PDF uncertainties on the signal acceptance are estimated from the CTEQ6.1M eigenvector PDF sets and lie in the range 0.4% – 0.6%, depending on $M_{\tilde{\nu}_\tau}$.

The $M_{e\mu}$ distribution is used to calculate an upper limit on the production cross section multiplied by the branching ratio, $\sigma \times \text{BR}$, for the process $p\bar{p} \rightarrow \tilde{\nu}_\tau + X \rightarrow e\mu + X$ with a modified frequentist (CL_s) method [18], under the assumption that the total width of the produced resonance is much narrower than the detector resolution. The observed cross section upper limits as a function of the $M_{\tilde{\nu}_\tau}$ hypothesis are shown in Fig. 3, together with the median expected limits.

These limits are translated into upper limits on couplings as a function of $M_{\tilde{\nu}_\tau}$ using the theoretical signal cross section [3]. A mass dependent K -factor, ranging from 1.64 at $M_{\tilde{\nu}_\tau} = 100$ GeV to 1.29 at $M_{\tilde{\nu}_\tau} = 500$ GeV, is applied to the cross section to include next-to-leading order (NLO) QCD corrections [19]. The limits are obtained by fixing one of the coupling constants and then

setting the upper limit on the other for different $M_{\tilde{\nu}_\tau}$. In Fig. 4, the observed upper limits on λ'_{311} for four assumed values of λ_{312} are shown. For $M_{\tilde{\nu}_\tau} = 100$ GeV and $\lambda_{312} \leq 0.07$, couplings $\lambda'_{311} > 6.2 \times 10^{-4}$ are excluded at the 95% C.L.

In summary, we have searched for a high mass, narrow $e\mu$ resonance in D0 data corresponding to an integrated luminosity of 5.3 fb^{-1} . A total of 414 $e\mu$ events is selected in data, in agreement with the predicted number of SM events, 410 ± 38 . The kinematic distributions are well described by the SM predictions. The upper limits on the production cross section for such a resonance are about a factor of 5 lower than for our previous result [5] and about a factor 6 lower for $M_{\tilde{\nu}_\tau} = 500$ GeV compared to a search performed in the $e\mu$ channel by the CDF Collaboration with 1 fb^{-1} of integrated luminosity [4]. We have also derived limits on the parameters of a SUSY model that predicts a sneutrino resonance decaying into $e\mu$ via R parity violating production and decay of sneutrinos.

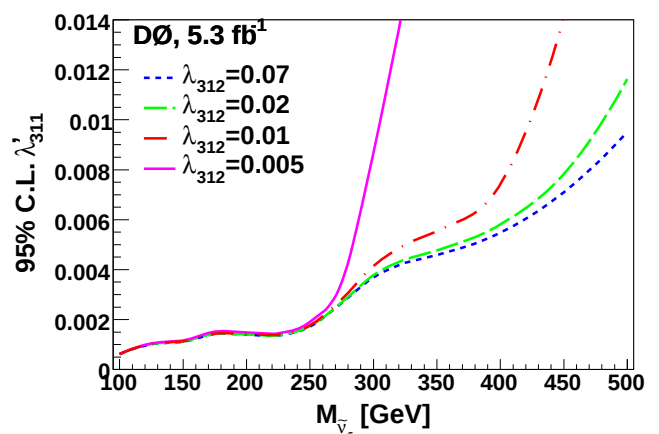


FIG. 4: (color online). The 95% C.L. observed upper limits on λ'_{311} for four values of λ_{312} as a function of $M_{\tilde{\nu}_\tau}$.

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