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in pp Collisions at $\sqrt{s}=1.96$ TeV

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Search for R -Parity Violating Decays of Sneutrinos to $e\mu$, $\mu\tau$, and $e\tau$ Pairs in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present a search for supersymmetric neutrino $\tilde{\nu}$ production using the Tevatron $p\bar{p}$ collision data collected with the CDF II detector and corresponding to an integrated luminosity of 1 fb^{-1} . We focus on the scenarios predicted by the R -parity violating (RPV) supersymmetric models in which sneutrinos decay to two charged leptons of different flavor. With the data consistent with the standard model expectations,

we set upper limits on $\sigma(p\bar{p} \rightarrow \tilde{\nu}) \times BR(\tilde{\nu} \rightarrow e\mu, \mu\tau, e\tau)$ and use these results to constrain the RPV couplings as a function of the sneutrino mass.

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Supersymmetric (SUSY) extensions of the standard model (SM) are among the leading candidates for a theory which can solve the hierarchy problem and provide a framework for unifying particle interactions [1]. Gauge-invariant and renormalizable interactions introduced in the SUSY models can violate the conservation of baryon (B) and lepton (L) number and lead to a proton lifetime shorter than the current experimental limits [2]. This problem is usually solved by postulating conservation of an additional quantum number, R -parity $R_p = (-1)^{3(B-L)+2s}$, where s is the particle spin [3]. However, models with R -parity-violating (RPV) interactions conserving spin and either B or L can also avoid direct contradiction with the proton lifetime upper limits [4]. Such models have the advantage that they naturally introduce lepton-flavor violation and can generate nonzero neutrino masses and angles [5] consistent with neutrino-oscillation data [6]. They can also explain the recently reported anomalous phase of the b to s transition [7]. From an experimental standpoint, RPV interactions allow for single production of supersymmetric particles (sparticles) in high-energy particle collisions and for sparticles to decay directly into SM particles only; this makes the lightest sparticle unstable and critically affects the experimental strategy of the SUSY searches. Because of their clean final-state signatures, processes of single slepton production followed by decay to a pair of SM charged leptons become promising search channels for R -parity violating SUSY particles [8].

In this Letter we report a search for a heavy sneutrino, produced in quark-antiquark $d\bar{d}$ annihilation and decaying via lepton-flavor-violating interactions into $e\mu/\mu\tau/e\tau$ final states. The search is performed using data corresponding to an integrated luminosity of 1 fb^{-1} collected in $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ by the CDF II detector at the Tevatron. The results are analyzed in the framework of the minimal supersymmetric extensions of the SM [1], where the RPV part of the superpotential relevant to the sneutrino production and decay can be written as

$$W_{\text{RPV}} = \lambda'^{ijk} \mathbf{L}_i \mathbf{Q}_j \bar{\mathbf{d}}_k + \frac{1}{2} \lambda^{ijk} \mathbf{L}_i \mathbf{L}_j \bar{\mathbf{e}}_k. \quad (1)$$

$\mathbf{L}$ and $\mathbf{Q}$ in Eq. (1) are the $SU(2)$ doublet superfields of leptons and quarks; $\mathbf{e}$ and $\mathbf{d}$ are the $SU(2)$ singlet superfields of leptons and quarks; λ' and λ are the Yukawa couplings at the production and decay vertex respectively; the indices i, j , and k denote the fermion generations. We assume single-coupling dominance [9], heavy squarks, and the tau sneutrino $\tilde{\nu}_\tau$ to be the lightest supersymmetric particle. The couplings $\lambda'_{311} = 0.10$ and $\lambda_{i3k} = 0.05$, compatible with the current indirect limits [9], are chosen as a benchmark point. Heavy sneutrinos have been extensively

searched for at LEP [9]. Recently, searches for heavy sneutrinos decaying into the $e\mu$ final state have been performed by the CDF [10] and D0 collaborations [11]. The results in this Letter supersede [10]. This analysis also represents the first search for lepton-flavor-violating decays of heavy sneutrinos into final states involving a third generation lepton, the τ , at the Tevatron.

CDF II is a general-purpose particle detector [12]. This measurement uses information from the central tracker [13], calorimeters [14,15], and muon detectors [16] for charged lepton reconstruction and identification. Reconstruction of photons and π^0 mesons makes extensive use of the central shower maximum detector (CES) [14]. The luminosity is measured by a hodoscopic system of Cherenkov counters [17]. The event geometry and kinematics are described using the azimuthal angle ϕ around the beam line and the pseudorapidity $\eta = -\ln \tan \frac{\theta}{2}$, where θ is the polar angle with respect to the beam line. The transverse energy and momentum of the reconstructed particles are defined as: $E_T = E \sin \theta$, $p_T = p \sin \theta$, where E is the energy and p is the momentum.

The data used in this measurement are collected using inclusive high- p_T electron and muon triggers which select high- p_T electron and muon candidates with $|\eta| \lesssim 1.0$. After event reconstruction, electron and muon candidates with $p_T \geq 20 \text{ GeV}/c$ are identified using the procedures described in [18]. In addition we use independent measurements of the electron energy in the CES to improve the overall electron selection efficiency and identification of electron candidates radiating significant energy due to the bremsstrahlung. The τ leptons are identified via their hadronic decays as narrow calorimeter clusters associated with one or three charged tracks [19]. As the neutrino from the τ decay escapes detection, the “visible” four-momentum of a τ candidate, p_τ^{vis} , is reconstructed summing the four-momenta of charged particle tracks and neutral particle CES showers with a pion mass hypotheses. The resolution in p_τ^{vis} is further improved by combining measurements of the track momenta and energies of the CES showers with the energy measurements in the calorimeter. A reconstructed τ candidate is required to have the visible transverse energy, E_T^{vis} , greater than 25 GeV and its most energetic track must have $p_T > 10 \text{ GeV}/c$. The invariant mass of its decay products, $M_\tau^{\text{vis}} = \sqrt{p_\tau^{\text{vis}2}}$, is required to be consistent with the τ lepton decay: $M_\tau^{\text{vis}} < (1.8 + 0.0455 \times (E_T^{\text{vis}}/\text{GeV} - 20)) \text{ GeV}/c^2$, where the second term in the formula accounts for a degradation of the resolution in M_τ^{vis} at high energy.

Events selected for the analysis are required to have two identified central ($|\eta| < 1$) lepton candidates of different

flavor and opposite electric charge. The leptons have to be isolated: the extra energy measured within a cone of radius $\Delta R \leq 0.4$ surrounding the leptons must be less than 10% of the lepton energy. Events with leptons consistent with a photon conversion or a cosmic ray hypothesis are removed from the analysis sample [18].

Signal and background studies are performed using Monte Carlo (MC) samples generated by PYTHIA 6.2 [20] with the Tune A of CTEQ5L parton distribution functions [21]. The detector response is simulated with a GEANT3-based package [22]. The trigger, reconstruction, and identification efficiencies are measured using Z events as calibration samples [18].

The predicted yield of signal events is calculated using the next-to-leading order (NLO) $p\bar{p} \rightarrow \tilde{\nu}_\tau$ production cross section [23]. The total $\tilde{\nu}_\tau$ width is defined by the $d\bar{d}$ and $l_i l_k$ decay modes as $\Gamma_{\tilde{\nu}_\tau} = (3\lambda_{311}^2 + 2\lambda_{i3k}^2)M_{\tilde{\nu}_\tau}/16\pi$, where $M_{\tilde{\nu}_\tau}$ is the $\tilde{\nu}_\tau$ mass.

There are several sources of background events; they are classified based on whether the lepton candidates originated from a “real” lepton (produced from a W or Z decay) or were a result of a hadron being misidentified as a lepton, lepton-flavor misassignment, or a secondary lepton inside a jet. We collectively refer to the lepton candidates of the second category as “fakes” and classify each contributing background process into type I, II, and III according to the typical number of real and fake leptons reconstructed. Type I contains events with two real leptons and includes $Z/\gamma^* \rightarrow \tau\tau$, diboson (WW, WZ, ZZ) and $t\bar{t}$ events. Type I is therefore called physics background. Type II includes events with one reconstructed fake lepton. They come from either (i) the $W/Z/\gamma^* + \text{jet}(s)$ events where one of the reconstructed leptons is in fact a jet misidentified as a lepton or (ii) $Z/\gamma^* \rightarrow ee/\mu\mu$ events with one of the leptons misidentified as a lepton of a different flavor. The backgrounds in type I and II are estimated using MC simulations, and their expected event yields are normalized to the NLO cross sections [24–26]. Events with two fake leptons (type III) are dominated by multijet events with two jets misidentified as leptons and $\gamma + \text{jets}$ events; in the latter case, a converted photon is not identified as such and gets reconstructed as an electron and a jet is misidentified as a μ or a τ . The contribution of the processes in type III is estimated using a data sample with two leptons of the

TABLE I. The observed and predicted event yields in the control region. Uncertainties on the predicted yields include both statistical and systematic contributions.

Control region	$50 \text{ GeV}/c^2 < M_{ll} < 110 \text{ GeV}/c^2$		
Channel	$e\mu$	$\mu\tau$	$e\tau$
Physics backgrounds	100.2 ± 6.5	262.4 ± 21.0	309.6 ± 24.7
Fake backgrounds	9.4 ± 3.3	222.6 ± 31.7	577.8 ± 37.0
Total SM	109.6 ± 7.7	485.0 ± 40.9	887.4 ± 51.0
Observed	105	477	894

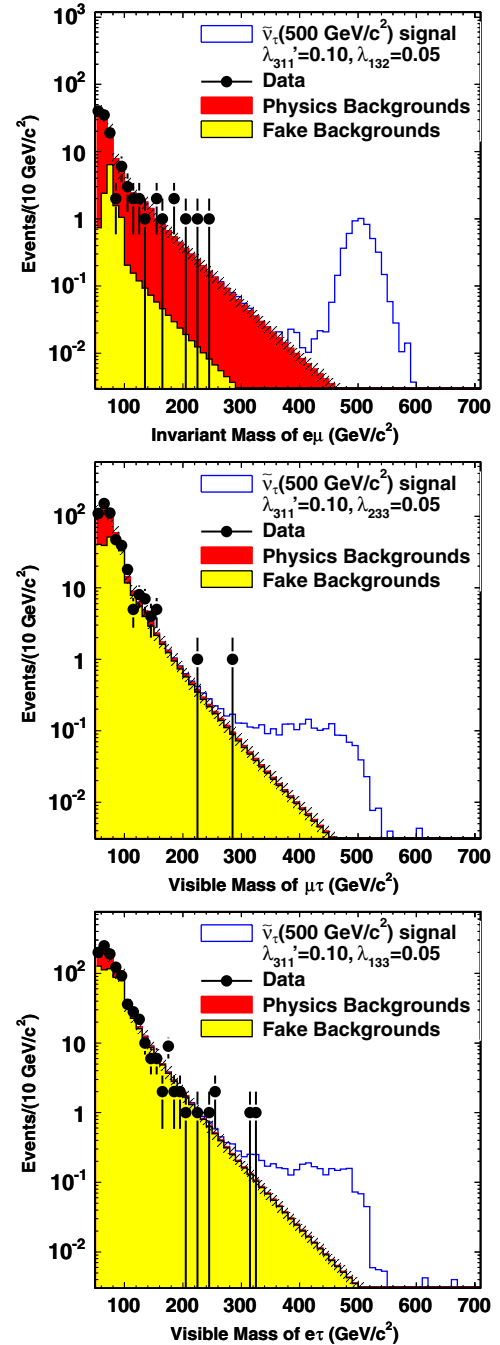


FIG. 1 (color online). Expected SM and observed distributions in M_{ll} for $e\mu$, $\mu\tau$ and $e\tau$ channels. Also shown is an expected $\tilde{\nu}_\tau$ signal for $M_{\tilde{\nu}_\tau} = 500 \text{ GeV}/c^2$ and RPV couplings $\lambda'_{311} = 0.10$ and $\lambda_{i3k} = 0.05$.

same-charge and assuming no charge correlation between the two misidentified leptons. Both type II and III are called fake background.

The systematic uncertainties in this search arise from a number of sources. The uncertainty on the luminosity measurement is 6% [27]. Uncertainties on lepton identification efficiency are 3% for τ 's, 1% for electrons, and 1% for muons [18]. The jet-to- τ misidentification probability

TABLE II. Expected and observed number of events in $e\mu$, $\mu\tau$, and $e\tau$ channels. The expected yields of $\tilde{\nu}_\tau$ events are calculated for $M_{\tilde{\nu}_\tau} = 500 \text{ GeV}/c^2$ and RPV couplings $\lambda'_{311} = 0.10$ and $\lambda_{i3k} = 0.05$.

Channel	$e\mu$	$\mu\tau$	$e\tau$
$M_{\text{II}}^{\text{min}}(\text{GeV}/c^2)$	440	300	310
Physics backgrounds	0.03 ± 0.01	0.1 ± 0.02	0.2 ± 0.03
Fake backgrounds	0.01 ± 0.01	0.3 ± 0.1	0.6 ± 0.1
Total SM background	0.04 ± 0.01	0.4 ± 0.1	0.9 ± 0.1
Expected signal	5.9 ± 0.1	2.0 ± 0.1	2.7 ± 0.1
Observed	0	0	2

measured in jet triggered data is the same as the probability in MC simulations within 15%. Uncertainties in the parton distribution functions (PDF) result in the systematic error on the predicted signal cross section, which varies from 4% to 20% and increases with the $\tilde{\nu}_\tau$ mass. Variations of the signal acceptance due to PDF uncertainties are less than 1%.

We search for a signal from $\tilde{\nu}_\tau$ decays into lepton pairs in the distributions for dilepton invariant mass, M_{II} (the visible energy is used in case of the τ). The low mass region, $50 \text{ GeV}/c^2 < M_{\text{II}} < 110 \text{ GeV}/c^2$, is used to validate the event selection and the background normalization. The observed and expected event yields in this region are in good agreement, as summarized in Table I. The search is performed as a “blind” counting experiment in the region

TABLE III. 95% C.L. upper limits on $\lambda_{311}^2 \times BR(\tilde{\nu}_\tau \rightarrow e\mu/\mu\tau/e\tau)$.

$M_{\tilde{\nu}_\tau}(\text{GeV}/c^2)$	$e\mu$	$\mu\tau$	$e\tau$
300	6×10^{-5}	4×10^{-4}	5×10^{-4}
400	2×10^{-4}	1×10^{-3}	9×10^{-4}
500	7×10^{-4}	2×10^{-3}	3×10^{-3}
600	2×10^{-3}	7×10^{-3}	5×10^{-3}
700	8×10^{-3}	2×10^{-2}	2×10^{-2}

$M_{\text{II}} > 110 \text{ GeV}/c^2$. Figure 1 compares data distributions in M_{II} to the SM expectations for each of the three channels. With no statistically significant excesses observed, we use the data to set upper limits on $\sigma(p\bar{p} \rightarrow \tilde{\nu}_\tau) \times BR(\tilde{\nu}_\tau \rightarrow e\mu/\mu\tau/e\tau)$.

In each of the channels ($e\mu$, $\mu\tau$, $e\tau$), the expected and observed upper limits are calculated using a Bayesian technique [28] at 95% credibility level (C.L.) as a function of $M_{\tilde{\nu}_\tau}$. For a given $M_{\tilde{\nu}_\tau}$, the limits are calculated by integrating the differential cross section $d\sigma/dM_{\text{II}}$ over the region $M_{\text{II}} > M_{\text{II}}^{\text{min}}$, where $M_{\text{II}}^{\text{min}}$ optimizes the search sensitivity for a selected $M_{\tilde{\nu}_\tau}$. The search results for $M_{\tilde{\nu}_\tau} = 500 \text{ GeV}/c^2$ are summarized in Table II. Figure 2 shows the expected and observed 95% C.L. upper limits on $\sigma(p\bar{p} \rightarrow \tilde{\nu}_\tau) \times BR(\tilde{\nu}_\tau \rightarrow e\mu/\mu\tau/e\tau)$ as a function of $M_{\tilde{\nu}_\tau}$. We also set 95% C.L. upper limits on $\lambda_{311}^2 \times BR(\tilde{\nu}_\tau \rightarrow e\mu/\mu\tau/e\tau)$ as shown in Table III.

In conclusion, we have searched for production of a massive sneutrino decaying to $e\mu$, $\mu\tau$, or $e\tau$ final states via R -parity violating interactions. We find the data consistent with the SM predictions and calculate the 95% C.L. upper limits on the $\sigma(p\bar{p} \rightarrow \tilde{\nu}_\tau) \times BR(\tilde{\nu}_\tau \rightarrow e\mu/\mu\tau/e\tau)$ in the mass range up to $800 \text{ GeV}/c^2$. Using these cross section limits, we constrain $\lambda_{311}^2 \times BR(\tilde{\nu}_\tau \rightarrow e\mu/\mu\tau/e\tau)$ as a function of $M_{\tilde{\nu}_\tau}$. This analysis sets the first Tevatron limits for lepton-flavor violating decays of heavy sneutrinos into final states involving a third generation lepton. For the RPV couplings $\lambda'_{311} = 0.10$ and $\lambda_{i3k} = 0.05$ the observed 95% C.L. lower limits on $\tilde{\nu}_\tau$ mass are $558 \text{ GeV}/c^2$ in the $e\mu$ channel, $441 \text{ GeV}/c^2$ in the $\mu\tau$ channel, and $442 \text{ GeV}/c^2$ in the $e\tau$ channel. In the paper we explicitly refer to $\tilde{\nu}_\tau$. We note that the analysis is flavour-independent and limits on the $\sigma(p\bar{p} \rightarrow \tilde{\nu}_{e,\mu}) \times BR(\tilde{\nu}_{e,\mu} \rightarrow e\mu/\mu\tau/e\tau)$ are the same as presented in Table III and Fig. 2.

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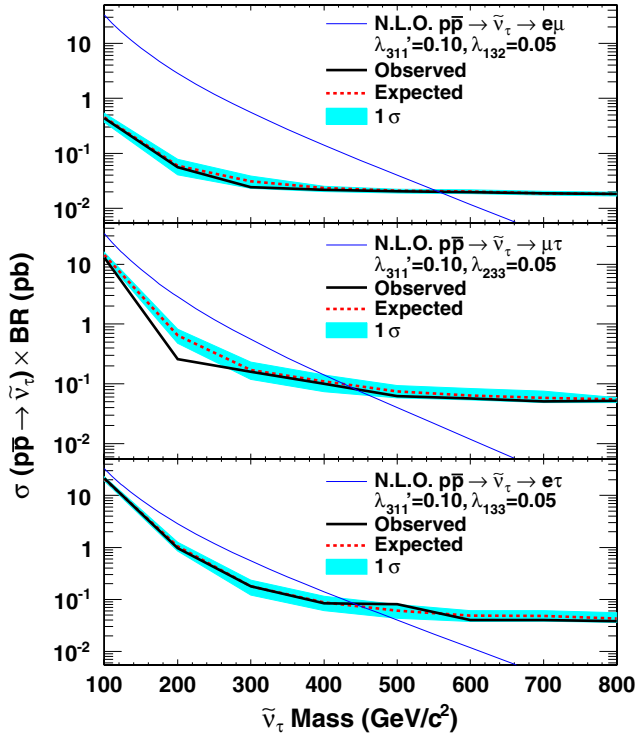


FIG. 2 (color online). The expected and observed 95% C.L. upper limits on $\sigma(p\bar{p} \rightarrow \tilde{\nu}_\tau) \times BR(\tilde{\nu}_\tau \rightarrow e\mu/\mu\tau/e\tau)$ as a function of $M_{\tilde{\nu}_\tau}$.

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