Search for R-Parity Violating Decays of Sneutrinos to e⁺, τ⁻, and e⁻ Pairs in pp Collisions at \( s=1.96 \) TeV

Aaltonen, T.

2010-11-05

http://hdl.handle.net/10138/24098
https://doi.org/10.1103/PhysRevLett.105.191801

Downloaded from Helda, University of Helsinki institutional repository.

This is an electronic reprint of the original article.
This reprint may differ from the original in pagination and typographic detail.
Please cite the original version.
Search for R-parity Violating Decays of $\tau$ Sneutrinos to $\mu\mu$, $\mu\tau$, and $e\tau$ Pairs in pp Collisions at $\sqrt{s} = 1.96$ TeV

We present a search for $\tau$ sneutrino 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 $\tau$ sneutrinos decay to two charged leptons of different flavor. With the data consistent with the standard model expectations, we set the upper limits on $\sigma(p\bar{p} \to \tilde{\nu}_\tau) \times BR(\tilde{\nu}_\tau \to e\mu, \mu\tau, e\tau)$ and use these results to constrain the RPV couplings as a function of $\tau$ sneutrino mass.

PACS numbers: 14.60.St, 14.80.Ly, 12.60.Jv, 13.85.Qk
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 non-zero neutrino masses and angles [5] consistent with neutrino-oscillation data [6]. They can also explain the recently reported anomalous phase of the \(θ\) 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. Due to 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 \(τ\) sneu-

\[ W_{RPV} = \lambda^{ijk} L_i Q_j \bar{d}_k + \frac{1}{2} \lambda^{ijk} L_i L_j \bar{e}_k \]  

\(L\) and \(Q\) in Eq. (1) are the \(SU(2)\) doublet superfields of leptons and quarks; \(\bar{e}, \bar{u}, \bar{d}\) are the \(SU(2)\) singlet superfields of leptons, u-type and d-type quarks; \(\lambda'\) and \(\lambda\) are the Yukawa couplings at the production and decay vertex respectively; the indices \(i, j, k\) denote the fermion generations. We assume single-coupling dominance and the third super-generation to be the lightest. The couplings \(\lambda'_{311} = 0.10\) and \(\lambda_{33k} = 0.05\), 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 paper 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, described in detail elsewhere [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 CES, the central shower maximum detector which is embedded at a depth of six radiation lengths within the electromagnetic calorimeter [13]. 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 beamline and the pseudorapidity \(η = -\ln \tan \frac{θ}{2}\), where \(θ\) is the polar angle with respect to the beamline. The transverse energy and momentum of the reconstructed particles are defined as:

\(E_T = E \sin θ, p_T = p \sin θ\), 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 \(|η| \lesssim 1.0\). 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 sig-
significant energy due to the bremsstrahlung. The $\tau$ leptons are identified via their hadronic decays as narrow calorimeter clusters associated with one or three charged tracks [19]. As the neutrino from the $\tau$ decay escapes detection, the “visible” four-momentum of a $\tau$ candidate, $p_{\tau}^{\text{vis}}$, is reconstructed summing the four-momenta of charged particle tracks and neutral particle CES showers with a pion mass hypotheses. The resolution in $p_{\tau}^{\text{vis}}$ 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 $\tau$ candidate is required to have the visible transverse energy, $E_{T}^{\text{vis}}$, greater than 25 GeV and its most energetic track must have $p_T > 10$ 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 $\tau$ 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 $M_{\tau}^{\text{vis}}$ at high energy. Reconstructed $\tau$ candidates within $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.4$ of an identified electron or of a loosely-identified muon with large electromagnetic energy deposit in the calorimeter are excluded from the analysis.

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 $\Delta R = 0.4$ surrounding the leptons must be less than 10% of the lepton energy. Events with leptons consistent with a photon conversion or a cosmic ray hadron are excluded from the analysis.

Events with lepton candidates of a photon conversion or a cosmic ray hadron are excluded from the analysis.

Signal and background studies are performed using Monte Carlo (MC) samples generated by PYTHIA [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) $p\bar{p} \rightarrow \nu\tau$ production cross section [23]. The total $\nu_{\tau}$ width is defined by the $d\bar{d}$ and $l_{\ell_1}l_{\ell_2}$ decay modes as $\Gamma_{\nu_{\tau}} = (3 \lambda^2_{211} + 2 \lambda^2_{13k}) M_{\nu_{\tau}}/16 \pi$, where $M_{\nu_{\tau}}$ is the $\nu_{\tau}$ mass.

There are several sources of background events that pass our analysis selections. We classify these contributions based on whether the lepton candidates reconstructed in these events 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 mis-assignment 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) $Z/\gamma^* \rightarrow e\mu/\mu\mu$ 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, and their expected event yields are normalized to the NLO cross sections [24][26]. Events with two fake leptons (Type III) are dominated by multi-jet events with two jets misidentified as leptons and $\gamma$+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 $\mu$ or a $\tau$. The contribution of the processes in Type III is estimated using a data sample with two leptons of the 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 $\tau$’s, 1% for electrons, and 1% for muons [18]. The jet-to-$\tau$ misidentification probability is measured with an accuracy of 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 $\nu_{\tau}$ mass. Variations of the signal acceptance due to PDF uncertainties are less than 1%.

We search for a signal from $\nu_{\tau}$ decays into lepton pairs in the distributions for dilepton invariant mass, $M_{ll}$ (note that in the case of a hadronically decaying $\tau$, it is the $\tau$ visible energy that is used to calculate the mass). The low mass region, 50 GeV/$c^2 < M_{ll} < 110$ 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. With the normalization fixed, the backgrounds are extrapolated into the region $M_{ll} > 100$ GeV/$c^2$, where the search is performed as a “blind” counting experiment. Figure I compares data distributions in $M_{ll}$ 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 $\sigma(p\bar{p} \rightarrow \nu\tau) \times \text{BR}(\nu_{\tau} \rightarrow e\mu/\mu\tau/\tau\tau)$.  

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{Control Region} & \textbf{50 GeV}/c² < $M_{ll}$ < 110 GeV/c² \\
\hline
\textbf{Channel} & \textbf{e$\mu$} & \textbf{$\mu\tau$} & \textbf{e$\tau$} \\
\hline
\textbf{Physics Backgrounds} & 100.2\textpm2.6 & 252.4\textpm21.0 & 309.6\textpm24.7 \\
\hline
\textbf{Fake Backgrounds} & 9.4\textpm3.3 & 222.6\textpm31.7 & 577.8\textpm37.0 \\
\hline
\textbf{Total SM} & 109.6\textpm7.7 & 485.0\textpm40.9 & 887.4\textpm51.0 \\
\hline
\textbf{Observed} & 105 & 477 & 894 \\
\hline
\end{tabular}
\caption{The observed and predicted event yields in the control region. Uncertainties on the predicted yields include both statistical and systematic contributions.}
\end{table}
In each of the channels (eμ, μτ, and eτ), the expected and observed upper limits are calculated using a Bayesian technique at 95% credibility level (C.L.) as a function of $M_{\bar{\nu}_\tau}$. For a given $M_{\bar{\nu}_\tau}$, the limits are calculated by integrating the differential cross section $d\sigma/dM_{ll}$ over the region $M_{ll} > M_{ll}^{\text{min}}$, where $M_{ll}^{\text{min}}$ optimizes the search sensitivity for a selected $M_{\bar{\nu}_\tau}$. The search results for $M_{\bar{\nu}_\tau} = 500 \, \text{GeV}/c^2$ are summarized in Table II. Figure 2 shows the expected and observed 95% C.L. upper limits on $\sigma (p\bar{p} \to \bar{\nu}_\tau) \times \text{BR}(\bar{\nu}_\tau \to e\mu/\mu\tau/e\tau)$ as a function of $M_{\bar{\nu}_\tau}$. We also set 95% C.L. upper limits on $\lambda_{311}^2 \times \text{BR}(\bar{\nu}_\tau \to e\mu/\mu\tau/e\tau)$ as shown in Table III.

FIG. 1: Expected SM and observed distributions in $M_{ll}$ for $e\mu$, $\mu\tau$, and $e\tau$ channels. Also shown is an expected $\bar{\nu}_\tau$ signal for $M_{\bar{\nu}_\tau} = 500 \, \text{GeV}/c^2$ and RPV couplings $\lambda_{311} = 0.10$ and $\lambda_{33k} = 0.05$.

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

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 $\sigma (p\bar{p} \to \bar{\nu}_\tau) \times \text{BR}(\bar{\nu}_\tau \to e\mu/\mu\tau/e\tau)$ in the mass range up to 800 GeV/c^2. Using

TABLE II: Expected and observed number of events in $e\mu$, $\mu\tau$, and $e\tau$ channels. The expected yields of $\bar{\nu}_\tau$ events are calculated for $M_{\bar{\nu}_\tau} = 500 \, \text{GeV}/c^2$ and RPV couplings $\lambda_{311} = 0.10$ and $\lambda_{33k} = 0.05$.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$e\mu$</th>
<th>$\mu\tau$</th>
<th>$e\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{ll}^{\text{min}}$ (GeV/c^2)</td>
<td>440</td>
<td>300</td>
<td>310</td>
</tr>
<tr>
<td>Physics Backgrounds</td>
<td>0.03±0.01</td>
<td>0.1±0.02</td>
<td>0.2±0.03</td>
</tr>
<tr>
<td>Fake Backgrounds</td>
<td>0.01±0.01</td>
<td>0.3±0.1</td>
<td>0.6±0.1</td>
</tr>
<tr>
<td>Total SM background</td>
<td>0.04±0.01</td>
<td>0.4±0.1</td>
<td>0.9±0.1</td>
</tr>
<tr>
<td>Expected signal</td>
<td>5.9±1</td>
<td>2.0±0.1</td>
<td>2.7±0.1</td>
</tr>
<tr>
<td>Observed</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>
these cross section limits, we constrain $\lambda'_{311}^2 \times \text{BR}(\tilde{\nu}_\tau \to e\mu/\mu\tau/e\tau)$ as a function of $M_{\tilde{\nu}_\tau}$. This analysis sets to the first Tevatron limits for lepton-flavor violating decays of heavy sneutrinos into final states involving a third generation lepton. For the RPV couplings $\lambda_{ijk} = 0.05$ the observed 95% C.L. lower limits on $M_{\tilde{\nu}_\tau}$ 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.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

<table>
<thead>
<tr>
<th>$M_{\tilde{\nu}_\tau}$ (GeV/$c^2$)</th>
<th>$e\mu$</th>
<th>$\mu\tau$</th>
<th>$e\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>$6 \times 10^{-4}$</td>
<td>$4 \times 10^{-4}$</td>
<td>$5 \times 10^{-4}$</td>
</tr>
<tr>
<td>400</td>
<td>$2 \times 10^{-3}$</td>
<td>$1 \times 10^{-3}$</td>
<td>$9 \times 10^{-4}$</td>
</tr>
<tr>
<td>500</td>
<td>$7 \times 10^{-4}$</td>
<td>$2 \times 10^{-3}$</td>
<td>$3 \times 10^{-3}$</td>
</tr>
<tr>
<td>600</td>
<td>$2 \times 10^{-3}$</td>
<td>$7 \times 10^{-3}$</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<tr>
<td>700</td>
<td>$8 \times 10^{-3}$</td>
<td>$2 \times 10^{-2}$</td>
<td>$2 \times 10^{-2}$</td>
</tr>
</tbody>
</table>