Search for lepton flavor violating decays of a heavy neutral particle in p(p)over-bar collisions at root s=1.8 TeV

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Search for Lepton Flavor Violating Decays of a Heavy Neutral Particle in $p\overline{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We report on a search for a high mass, narrow width particle that decays directly to $e\mu$, $e\tau$, or $\mu\tau$. We use approximately 110 pb^{-1} of data collected with the Collider Detector at Fermilab from 1992 to 1995. No evidence of lepton flavor violating decays is found. Limits are set on the production and decay of sneutrinos with R-parity violating interactions.

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Particles that decay to $e\mu$, $e\tau$, or $\mu\tau$ occur in a number of extensions to the standard model. Examples include Higgs bosons in models with multiple Higgs doublets [1–3], sneutrinos in supersymmetric models with R-parity violation (RPV) [4–6], horizontal gauge bosons [7], and Z' bosons [8]. In this Letter, we report results from a search based on final states containing $e\mu$. We are sensitive to $e\tau$ and $\mu\tau$ modes through $\tau \rightarrow \mu\nu\nu$ and $\tau \rightarrow e\nu\nu$, respectively. We analyze data from $p\overline{p}$ collisions at center of mass energy $\sqrt{s} = 1.8$ TeV recorded with the Collider Detector at Fermilab (CDF) during the 1992 to 1995 Tevatron run. The integrated luminosity is approximately 110 pb^{-1}.

The CDF detector has been described in detail elsewhere [9]. This analysis makes use of several detector subsystems. The position of $p\overline{p}$ collisions along the beam line is measured in the vertex time projection chambers (VTX). The central tracking chamber (CTC), located within the 1.4 T magnetic field of a superconducting solenoid, measures the momentum of charged particles. The transverse momentum resolution for muon and charged hadron tracks in the pseudorapidity interval $|\eta| < 1.1$ that are constrained to originate at the beam line is better than $0.1\% \times p_T$, where p_T is measured in GeV/c and is the momentum component transverse to the beam line. Sampling calorimeters surround the solenoid. The central electromagnetic calorimeter (CEM) covers $|\eta| < 1.1$ and measures the energy of electromagnetic showers with a resolution of about $(13.7/\sqrt{E_T} \oplus 2)\%$, where $\oplus$ means addition in quadrature and the transverse energy E_T is measured in GeV. The transverse energy is defined as $E\sin(\theta)$, with E being the shower energy measured in the calorimeter and θ the polar angle of the energy flow, from the $p\overline{p}$ interaction vertex to the calorimeter deposition. Within the CEM, proportional chambers (CES) measure the transverse shape of showers. Drift chambers located outside the calorimeters detect muons in the region $|\eta| < 1$. A measure of the energy carried by neutrinos escaping the detector is the missing transverse energy $\not{E}_T$, calculated from the vector sum of the energy depositions in the calorimeters and the momentum of muon tracks.

Events containing an electron and a muon are recorded by an assortment of single lepton, dilepton, and jet triggers [10]. We select events that have an electron with $E_T > 20$ GeV, a muon with $p_T > 20$ GeV/c, and a primary $p\overline{p}$ interaction vertex within 60 cm of the center of the detector. The electron and muon must have opposite charges. We identify electrons and muons using criteria that retain efficiency for very high momentum particles [11]. Electrons must have a shower contained within the sensitive region of the CEM and have a CTC track with $p_T > 13$ GeV/c that matches the position of the shower in the CES. The CEM determines the electron energy. Requirements on the p_T of the associated CTC track are kept loose because electrons can lose energy in the tracking volume due to bremsstrahlung. In cases in which an electron has $E_T < 100$ GeV or $p_T < 25$ GeV/c, there are additional requirements: The lateral distribution of energy must be consistent with an electromagnetic shower, and the ratio of energy measured in the calorimeter to the momentum measured in the CTC must be less than four. Electrons that appear to be one leg of a photon conversion—because the second leg is found or because the CTC track is not confirmed by hits in the VTX—are removed. Muons must have a track in the CTC that originates from the primary vertex and matches a track segment in the muon system. The energy along the muon path through the calorimeters must be consistent with a minimum ionizing particle. Electrons and muons are both required to be isolated from other energy deposition in the calorimeter. The combination of triggers is, within 1 standard deviation, fully efficient for events that satisfy the offline selection.

Backgrounds with two isolated high p_T leptons arise from standard model production of Z/γ, WW, WZ, ZZ, and $t\bar{t}$. The cross sections for the first four of these processes are calculated at next-to-leading order using MCFM v1.0 [12] and MRST99 parton distribution functions [13]. The $t\bar{t}$ production cross section is taken from the parametrized formula of Ref. [14] evaluated at the Tevatron average top quark mass of 174.3 GeV$/c^2$ [15]. For each of the five processes, the fraction of events expected to pass the offline selection (the acceptance) is calculated by Monte Carlo using PYTHIA v5.7 [16], the CDF detector simulation, and the same analysis software used to select events in the data. The efficiency of the lepton identification requirements in the simulation is calibrated using electrons and muons from Z decays. For each background process, the expected number of events is estimated to be $\sigma_B A_B n_{ee}/(\sigma_{ee} A_{ee})$, where σ_B is the cross section for the background process, A_B is the acceptance for the background process, n_{ee} is the number of e^+e^- events observed in the data with a mass in the region of the Z peak, σ_{ee} is the Z/γ cross section times branching fraction to e^+e^-, and A_{ee} is the acceptance for e^+e^-. By normalizing to e^+e^- data, we eliminate uncertainties in the background level due to the integrated luminosity and the Z/γ cross section times branching fraction to leptons, and we reduce the uncertainty from lepton efficiencies. The $t\bar{t}$, WW, WZ, and ZZ cross sections are assigned uncertainties of 25%, 11%, 10%, and 10%, respectively. Other uncertainties are from the detector model (6%), Monte Carlo statistics (2%–4%), $Z \rightarrow ee$ statistics (2%), particle identification efficiencies (2%), and trigger efficiencies (1%). The remaining backgrounds arise from particles produced in jets. These include instrumental fakes and real leptons from b- and c-quark decays. All of them are denoted false leptons. The false lepton backgrounds are estimated using a method similar to that of Ref. [17], in which the probability for a false lepton to appear isolated is measured in a control sample of dijet data.

In a WW or $t\bar{t}$ event, the electron and the muon, originating from different W bosons, have largely independent directions, spin correlations not withstanding. To reduce these backgrounds, we require that the angle between the electron and muon in the plane transverse to the beam be at least 120°. This is almost fully efficient for two-body decays of a particle as heavy as the Z boson. For the $e\mu$ channel, there are no further requirements. An $e\mu$ event is additionally classified as an $e\tau$ event if the angle between the $\not\!\!E_T$ and the muon, $\Delta\phi(\mu, \not\!\!E_T)$, is less than 60°. This eliminates events that are not consistent with $\tau \rightarrow \mu\nu\nu$, since the tau is energetic enough that its decay products are nearly collinear. Likewise, an $e\mu$ event is additionally classified as a $\mu\tau$ event if $\Delta\phi(e, \not\!\!E_T) < 60°$. The distribution of $\Delta\phi(e, \not\!\!E_T)$ versus $\not\!\!E_T$ is shown in Fig. 1. Since the electrons and muons are nearly back-to-back in ϕ, $\Delta\phi(\mu, \not\!\!E_T)$ is approximately $\Delta\phi(e, \not\!\!E_T) + 180°$.

There are 19 $e\mu$ candidates in the data. Four of these are also $e\tau$ candidates, and 12 are also $\mu\tau$ candidates. The contributions of the various backgrounds to each channel are listed in Table I. The dominant source of background is $Z/\gamma \rightarrow \tau\tau$ where one tau decays to $e\nu\nu$ and the other to $\mu\nu\nu$. The small contribution from $Z/\gamma \rightarrow \mu\mu$ is from cases in which one muon is mistaken for an electron after radiating an energetic photon.

The distributions of the lepton pair masses $m_{ll'}$ are shown in Fig. 2. For the $e\tau$ and $\mu\tau$ hypotheses, $m_{ll'}$ is calculated assuming that the tau momentum components are $p_x^\tau = p_x^l + \not\!\!E_x$, $p_y^\tau = p_y^l + \not\!\!E_y$, and $p_z^\tau = p_z^l \times (1 + \not\!\!E_T/p_T^l)$, where p^l is the momentum of the electron or muon to which the tau is assumed to have decayed [2,3]. The data show no indication of a signal peak. The distribution of observed events is compared to the expected

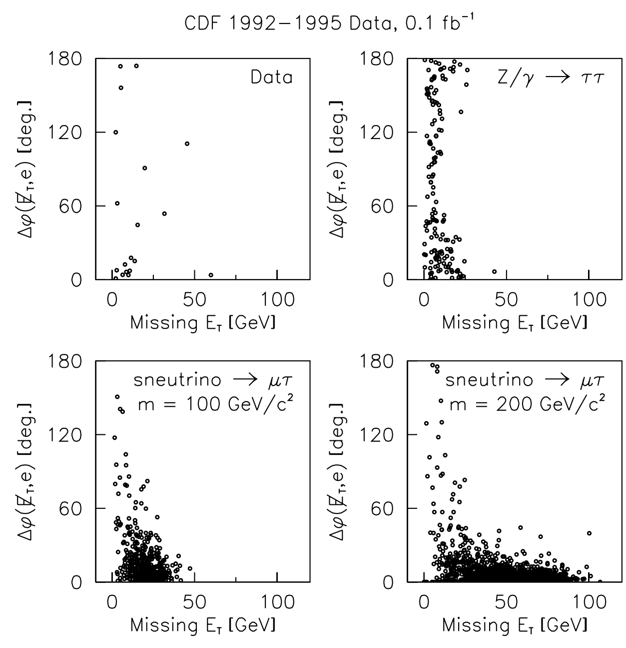

FIG. 1. The angle in the plane transverse to the beam line between the direction of the missing energy and the electron versus the missing transverse energy: data (upper left); simulated $Z/\gamma \rightarrow \tau\tau \rightarrow e\mu\nu\nu$, the dominant background (upper right); and a hypothetical signal $\tilde{\nu} \rightarrow \mu\tau \rightarrow \mu e\nu$ for a sneutrino mass of 100 GeV$/c^2$ (lower left) and 200 GeV$/c^2$ (lower right). The requirement $\Delta\phi(e, \mu) > 120°$ has already been imposed.

TABLE I. The expected number of background events and the observed number of candidates in each channel.

Source	$e\mu$	$e\tau$	$\mu\tau$
$Z/\gamma \to \tau\tau$	13.91 ± 0.99	5.20 ± 0.43	6.48 ± 0.59
$Z/\gamma \to \mu\mu$	0.27 ± 0.16	0	0.27 ± 0.16
WW	2.37 ± 0.32	0.42 ± 0.07	0.45 ± 0.08
WZ	0.13 ± 0.02	0.03 ± 0.01	0.04 ± 0.01
ZZ	0.024 ± 0.004	0.007 ± 0.001	0.007 ± 0.002
$t\bar{t}$	1.34 ± 0.36	0.40 ± 0.11	0.35 ± 0.10
False e	0.85 ± 0.44	-0.04 ± 0.23	0.96 ± 0.32
False μ	0.98 ± 0.27	-0.06 ± 0.11	1.07 ± 0.25
Total background	19.88 ± 1.42	5.95 ± 0.55	9.62 ± 0.81
Data	19	4	12

background shape using a Kolmogorov test. The test statistic probability is 19%, 65%, and 74% for $e\mu$, $e\tau$, and $\mu\tau$, respectively, consistent with the absence of a signal.

As a specific signal model, we consider the process $d\bar{d} \to \tilde{\nu} \to ll'$ mediated by RPV interactions [4–6]. The RPV sneutrino couplings allowed in the supersymmetric Lagrangian are $[\lambda_{ijk}(\tilde{\nu}_L^j \bar{e}_R^k e_L^i - \tilde{\nu}_L^i \bar{e}_R^j e_L^k) + \lambda'_{ijk} \tilde{\nu}_L^i \bar{d}_R^k d_L^j] + \text{H.c.}$, where the indices i, j, and k label generations; λ_{ijk} is nonzero only for $i < j$; and mixing is ignored [4,18]. Constraints on the coupling strengths have been derived from measurements of low

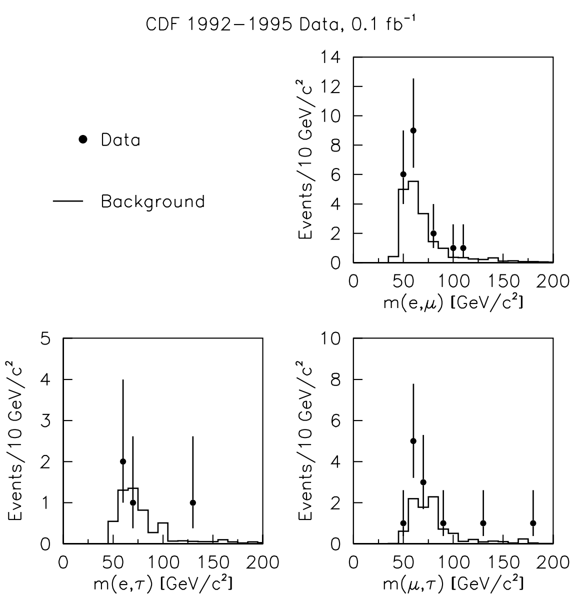

FIG. 2. The reconstructed mass of the lepton pairs. The points show the nineteen $e\mu$ candidates (upper), the four $e\tau$ candidates (lower left), and the twelve $\mu\tau$ candidates (lower right). The histograms show the total background in each sample. The $e\tau$ and $\mu\tau$ samples have no events in common; both are subsets of the $e\mu$ sample. $\not{E}_T$ is used in computing τ momentum, as explained in the text.

energy processes [18,19]. The upper bound on the coupling that mediates $d\bar{d} \to \tilde{\nu}_\tau$ is $\lambda'_{311} < 0.11 \times (m_{\tilde{d}_R}/100~\text{GeV})$. The limit is slightly stronger for λ'_{211} and much stronger for λ'_{111}. Of the couplings that contribute to $\tilde{\nu}_{\mu,\tau} \to ll'$, those with the loosest bounds are $\lambda_{132} < 0.062 \times (m_{\tilde{\mu}_R}/100~\text{GeV})$, $\lambda_{231} < 0.070 \times (m_{\tilde{e}_R}/100~\text{GeV})$, $\lambda_{233} < 0.070 \times (m_{\tilde{\tau}_R}/100~\text{GeV})$, and $\lambda_{122} < 0.049 \times (m_{\tilde{\mu}_R}/100~\text{GeV})$. Limits on μ–e conversion in nuclei severely restrict the $\lambda\lambda'$ products that contribute to the $e\mu$ channel, for example, $|\lambda_{231}\lambda'_{311}| < 4.1 \times 10^{-9}$ assuming sparticle masses of $100~\text{GeV}/c^2$ [20]. Searches at CERN e^+e^- collider rule out sneutrino masses $m_{\tilde{\nu}} < 86~\text{GeV}/c^2$ if any one (but only one) of the λ constants is nonzero [21]. Previous CDF searches have examined scenarios with λ'_{121} [22] and λ'_{333} [23] nonzero.

We simulate the signal process by generating events using the heavy Higgs (H') process in PYTHIA. The H' decay table is modified to include each of the $e\mu$, $e\tau$, and $\mu\tau$ modes in turn while all other decay channels are switched off. All initial states except for $d\bar{d}$ are inhibited. Events are generated for nine particle masses $m_{\tilde{\nu}}$ between 50 and 800 GeV/c^2. The events are passed through the CDF detector simulation and the analysis software used for the data. For each $m_{\tilde{\nu}}$ and each decay mode, the mean and rms $m_{ll'}$ is computed. The rms widths of the $e\mu$, $e\tau$, and $\mu\tau$ mass distributions are 3, 6, and 7 GeV/c^2, respectively, for $m_{\tilde{\nu}} = 100~\text{GeV}/c^2$. For $m_{\tilde{\nu}} = 400~\text{GeV}/c^2$ they are 30, 14, and 60 GeV/c^2. The broadening with $m_{\tilde{\nu}}$ is due to the muon p_T resolution and, to a lesser degree, the electron energy resolution. At low $m_{\tilde{\nu}}$, the resolution for the $e\tau$ and $\mu\tau$ modes is poorer than for $e\mu$ due to the inclusion of $\not{E}_T$. The $e\tau$ resolution degrades more slowly than the others because the muons from tau decays have lower momenta.

To study the full range of $m_{\tilde{\nu}}$ without gaps in which a signal might hide, we count events within 3 standard deviations of the mean $m_{ll'}$ for a sequence of $m_{\tilde{\nu}}$ values starting at 50 GeV/c^2 with step size from the ith to the $(i+1)$th value equal to one-tenth of the rms of the $m_{ll'}$ distribution at the ith point. The mean and rms of the $m_{ll'}$

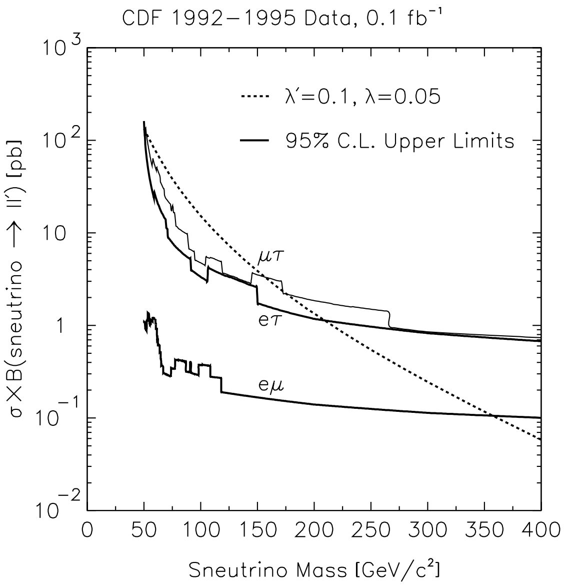

FIG. 3. 95% C.L. upper limits on $\sigma \times B(\tilde{\nu} \to e\mu)$, $\sigma \times B(\tilde{\nu} \to e\tau)$, and $\sigma \times B(\tilde{\nu} \to \mu\tau)$ as a function of sneutrino mass, together with the next-to-leading order cross section for the reference parameters.

distribution for each $m_{\tilde{\nu}}$ is linearly interpolated between values at the generated $m_{\tilde{\nu}}$ points. A 3 standard deviation window provides good statistical sensitivity while incurring little dependence on any possible systematic errors in the width or mean.

For each decay mode, we derive a 95% C.L. upper limit [24] on $\sigma \times B$ using the number of events, expected background, and acceptance in the mass window corresponding to each $m_{\tilde{\nu}}$ point. Figure 3 shows the limits as a function of $m_{\tilde{\nu}}$. The limits on $\sigma \times B(\tilde{\nu} \to e\tau)$ and $\sigma \times B(\tilde{\nu} \to \mu\tau)$ are higher than the limit on $\sigma \times B(\tilde{\nu} \to e\mu)$ because of the tau branching ratio to leptons and, particularly at low $m_{\tilde{\nu}}$, because the leptons from tau decays tend to fall below the 20 GeV/c p_T threshold.

As a benchmark, Fig. 3 also shows the theoretical cross section times branching fraction for $d\bar{d} \to \tilde{\nu}_\tau \to e^+\mu^-$ plus $d\bar{d} \to \tilde{\nu}_\tau \to e^-\mu^+$ as a function of $m_{\tilde{\nu}}$ in the case $\lambda'_{311} = 0.1$ and $\lambda_{132} = 0.05$. The curve is obtained using next-to-leading order values of $\sigma(d\bar{d} \to \tilde{\nu})$ for $\lambda' = 0.01$ [25,26], which we scale by $(\lambda'/0.01)^2$. $B(\tilde{\nu} \to e\mu)$ is calculated assuming that weak decays of the sneutrino are kinematically forbidden and that the only nonzero RPV couplings are λ'_{311} and λ_{132}.

In conclusion, we find no evidence for new particles with lepton flavor violating decays. We set limits on the cross section for single sneutrino production times the branching fractions $B(\tilde{\nu} \to e\mu)$, $B(\tilde{\nu} \to e\tau)$, and $B(\tilde{\nu} \to \mu\tau)$ as a function of the sneutrino mass. For a sneutrino mass of 200 GeV/c^2, the 95% C.L. upper limits on $\sigma \times B$ are 0.14, 1.2, and 1.9 pb for the $e\mu$, $e\tau$, and $\mu\tau$ modes, respectively.

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[1] J. L. Diaz-Cruz and J. J. Toscano, Phys. Rev. D **62**, 116005 (2000).
[2] T. Han and D. Marfatia, Phys. Rev. Lett. **86**, 1442 (2001).
[3] K. A. Assamagan, A. Deandrea, and P.-A. Delsart, Phys. Rev. D **67**, 035001 (2003).
[4] J. Kalinowsky, R. Ruckl, H. Speisberger, and P. M. Zerwas, Phys. Lett. B **414**, 297 (1997).
[5] B. Allanach *et al.*, hep-ph/9906224.
[6] S. Dimopoulos, R. Esmailzadeh, L. J. Hall, J.-P. Merlo, and G. D. Starkman, Phys. Rev. D **41**, 2099 (1990).
[7] H.-U. Bengtsson, W.-S. Hou, A. Soni, and D. H. Stork, Phys. Rev. Lett. **55**, 2762 (1985).
[8] B. Murakami, Phys. Rev. D **65**, 055003 (2002).
[9] F. Abe *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **271**, 387 (1988).
[10] F. Abe *et al.*, Phys. Rev. D **50**, 2966 (1994).
[11] F. Abe *et al.*, Phys. Rev. Lett. **79**, 2192 (1997).
[12] J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999).
[13] A. D. Martin, R. G. Roberts, W. J. Stirling, and R. S. Thorne, Eur. Phys. J. C **14**, 133 (2000).
[14] S. Catani, M. L. Mangano, P. Nason, and L. Trentadue, Phys. Lett. B **378**, 329 (1996).
[15] D. E. Groom *et al.*, Eur. Phys. J. C **15**, 1 (2000).
[16] T. Sjostrand, Comput. Phys. Commun. **82**, 74 (1994).
[17] B. Abbott *et al.*, Phys. Rev. D **61**, 072001 (2000).
[18] V. Barger, G. F. Giudice, and T. Han, Phys. Rev. D **40**, 2987 (1989).
[19] B. C. Allanach, A. Dedes, and H. K. Dreiner, Phys. Rev. D **60**, 075014 (1999).
[20] A. Faessler, R. Kosmas, S. Kovalenko, and J. D. Vergados, Nucl. Phys. **B587**, 25 (2000).
[21] R. Barate *et al.*, Eur. Phys. J. C **19**, 415 (2001).
[22] F. Abe *et al.*, Phys. Rev. Lett. **83**, 2133 (1999).
[23] F. Abe *et al.*, Phys. Rev. Lett. (to be published).
[24] R. M. Barnett *et al.*, Phys. Rev. D **54**, 1 (1996).
[25] D. Choudhury and S. Majhi (private communication).
[26] D. Choudhury, S. Majhi, and V. Ravindran, hep-ph/0207247.