Search for High-Mass Resonances Decaying to $e\mu$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We describe a general search for resonances decaying to a neutral $e\mu$ final state in $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV. Using a data sample representing 344 pb^{-1} of integrated luminosity recorded by the Collider Detector at Fermilab II experiment, we compare standard model predictions with the number of observed events for invariant masses between 50 and 800 GeV$/c^2$. Finding no significant excess (5 events observed vs 7.7 ± 0.8 expected for $M_{e\mu} > 100$ GeV$/c^2$), we set limits on sneutrino and Z' masses as functions of lepton family number violating couplings.

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An observed excess of high-mass opposite sign electron-muon pairs at the Tevatron would provide evidence of physics beyond the standard model (SM). Nearly every extension of the SM predicts flavor changing neutral current effects. General supersymmetric (SUSY) models, for instance, permit the violation of R-parity symmetry (RPV) and describe the lepton family number violating (LFV) production and decay of sneutrinos ($\tilde{\nu}$), the scalar superpartners of SM neutrinos [1]. Models with additional gauge symmetry can also accommodate an $e\mu$ signature through LFV decays of a new heavy neutral gauge boson, the Z' [2,3]. Signals from such processes may be easily detected at the Tevatron. SM backgrounds are small and characterized by invariant mass spectra that lie well below the range presumed for new physics.

We search for a general signature of high-mass opposite sign $e\mu$ pairs and are sensitive to both resonant and nonresonant production mechanisms. The CDF collaboration investigated the high-mass $e\mu$ channel in a Run I search for the direct RPV production and decay of the tau sneutrino ($\tilde{\nu}_\tau$) [4,5]. That analysis excluded sneutrino masses below $\sim$360 GeV$/c^2$ for a particular set of RPV coupling values. This Letter describes our continued investigation of this channel using data from Run II of the Tevatron taken with the upgraded Collider Detector at Fermilab (CDF II). The data sample we use represents an integrated luminosity of 344 ± 21 pb^{-1}, approximately 3 times that used in Run I. We search for an $e\mu$ resonance by examining invariant masses ($M_{e\mu}$) between 100 and 800 GeV$/c^2$ for an excess of events. We find event counts that are consistent with SM predictions and use our result to constrain models of LFV $\tilde{\nu}$ and Z' decay by excluding $e\mu$ coupling values as functions of the new particle masses. In contrast to searches that utilize low-energy data, where the effects of new heavy particles may be masked by cancellations of various contributions, the interpretation of our results is robust.

The CDF II detector is an azimuthally and forward-backward symmetric apparatus designed to study $p\bar{p}$ reactions at the Tevatron. The detector has a charged particle tracking system immersed in a 1.4 T magnetic field aligned coaxially with the $p\bar{p}$ beams. A 3.1 m long open-cell drift chamber, the Central Outer Tracker [6], covers the radial range from 40 to 137 cm and provides coverage for the pseudorapidity range $|\eta| \lesssim 1$ [7]. Segmented electromagnetic and hadronic sampling calorimeters surround the tracking system and measure the energies of interacting particles in the range $|\eta| < 3.6$ [8–10]. A set of drift chambers located outside the central hadron calorimeters and another set behind a 60 cm thick iron shield track muons with $|\eta| \leq 0.6$ [11]. Additional drift chambers and scintillation counters detect muons in the region $0.6 \leq |\eta| \leq 1.0$. Gas Čerenkov counters located in the $3.7 < |\eta| < 4.7$ region [12] measure the average number of inelastic $p\bar{p}$ collisions per bunch crossing and thereby determine the beam luminosity.

We use data collected with high-P_T triggers that require central ($|\eta| \lesssim 1.0$) lepton candidates. We select events that contain at least one reconstructed electron of $E_T > 20$ GeV and one reconstructed muon with $P_T > 20$ GeV$/c$. Energy deposited by the leptons in the central electromagnetic calorimeters must be of an isolated nature and should also satisfy the standard set of "tight" CDF lepton identification (ID) criteria [13].

We select oppositely charged $e\mu$ pairs and ensure that the lepton tracks come from a common $p\bar{p}$ interaction. We reject events containing cosmic-ray muons and photon-conversion electrons by imposing additional event topology requirements [13]. In order to maximize acceptance to a broad range of new physics signatures, we do not impose requirements on missing transverse energy or jets.

SM $e\mu$ backgrounds include $q\bar{q} \to Z/\gamma^* \to \tau\tau$ (Drell-Yan), top ($t\bar{t}$) and diboson (WW, WZ, and ZZ) production. We determine geometric and kinematic acceptances for these processes using the PYTHIA Monte Carlo generator [14] and a GEANT3 [15] based simulation of the CDF II detector. These simulations employ the CTEQ5L [16] parton distribution functions (PDF's) to model the momentum distribution of the initial-state partons. We define the acceptance for each background process, α_i, as the fraction of generated events that satisfy the lepton ID and event topology requirements. We correct the α_i by multiplying with trigger efficiencies ($\epsilon_{\rm trg}$) measured from $W \to e\nu$ and $Z \to \mu\mu$ data and factors ($f_{\rm reco}$, $f_{\rm ID}$) that account for differences in lepton reconstruction and ID efficiency between simulation and data [13]. We refer to the combined correction factor, $\epsilon_{\rm trg} \times f_{\rm reco} \times f_{\rm ID}$, as ϵ.

The expected contribution of each SM background is given by the product of $\alpha_i \times \epsilon$ with the corresponding cross section and the integrated luminosity of our data sample. We estimate top and diboson background contributions using next-to-leading order (NLO) cross sections: 6.1 pb for $t\bar{t}$ [17], 12.1 pb for WW, 3.7 pb for WZ, and 1.4 pb for ZZ [18]. We use a next-to-next-to-leading order continuum ($M_{ll} > 30$ GeV$/c^2$) cross section for the Drell-Yan process, 337.7 pb, which we calculate by scaling the PYTHIA leading order cross section by the ratio of NNLO to LO predictions obtained from PHOZPR calculations [19].

Jets that are misidentified as leptons account for approximately 5% of the total background. We determine the misidentification probability ("fake rate") [13] by examining separate data samples collected with various jet E_T triggers for the occurrence of leptons. The real leptonic content of these samples is assumed to be negligible. We obtain fake rates from the ratios of misidentified leptons and the number of jets in these samples. We then estimate the background from this source by applying the measured fake rates, parametrized as functions of E_T, to the jets in events in the high-P_T sample that contain a single lepton candidate.

We present the number of observed and predicted background events for two $M_{e\mu}$ regions in Table I. The dominant uncertainty on the background predictions arises from a 6% uncertainty in the luminosity measurement [20]. Additional uncertainty contributions include those associated with the SM cross sections, fake rate measurements, lepton ID and reconstruction scale factors, and PDF model.

TABLE I. Expected and observed event totals for low- and high-mass $M_{e\mu}$ regions. The uncertainties shown are the combination of statistical and systematic errors.

Channel	$50 < M_{e\mu} < 100$ GeV$/c^2$	$M_{e\mu} > 100$ GeV$/c^2$
$Z/\gamma^\star \to \tau\tau$	38.8 ± 2.9	0.6 ± 0.0
WW, WZ, ZZ	6.6 ± 0.5	3.5 ± 0.2
$t\bar{t}$	3.6 ± 0.5	3.2 ± 0.5
Fake Lepton	2.9 ± 1.7	$0.4^{+0.6}_{-0.4}$
Prediction	51.9 ± 3.4	7.7 ± 0.8
Observation	56	5

Overall, we find that uncertainties on our signal acceptance and background expectations have little impact on the limits we set.

The $50 \leq M_{e\mu} \leq 100\ \text{GeV}/c^2$ region listed in Table I represents an invariant mass range that is rich in background. Finding good agreement between our observation and predicted background in this region, we next consider the $M_{e\mu}$ range above $100\ \text{GeV}/c^2$. Here, too, we find good agreement. Figure 1 shows the observed and predicted background $M_{e\mu}$ distributions over a portion of the full 50–800 GeV/c^2 invariant mass range.

We quantify the consistency between the $M_{e\mu}$ distributions presented in Fig. 1 by performing a χ^2 test, using variable-width $M_{e\mu}$ bins to achieve sufficient predicted background occupancies for the Gaussian approximation of Poisson statistics. The test results in a total reduced χ^2 statistic (χ^2/N_{dof}) of $14.0/11 = 1.27$, under the assumption that systematic uncertainties in each bin are completely correlated. The statistic implies a p value, the probability of finding a larger χ^2, of $\sim$23%. This value provides a statistical basis for accepting our results as consistent with SM expectations.

Finding no evidence of new physics in the $M_{e\mu}$ spectrum, we turn from the model-independent search to constraints on specific models; RPV sneutrino and LFV Z' decay. In RPV SUSY models, the s-channel $d\bar{d} \rightarrow \tilde{\nu}_i(\bar{\tilde{\nu}}_i) \rightarrow e\mu$ process is governed by two LFV couplings. λ'_{i11} determines the sneutrino production cross section from d and $\bar{d}$ while λ_{1i2} gives the sneutrino branching ratio to $e\mu$ [21]. The index i refers to the lepton generation of the sneutrino. We do not consider initial states that include up-type quarks since RPV sneutrino hadro-production occurs only through a $L_iQ_j\bar{D}_k$ term in the superpotential [21]. The final state for this process consists of $e\mu$ only, i.e., it does not contain additional neutrinos or a SUSY lightest supersymmetric particle.

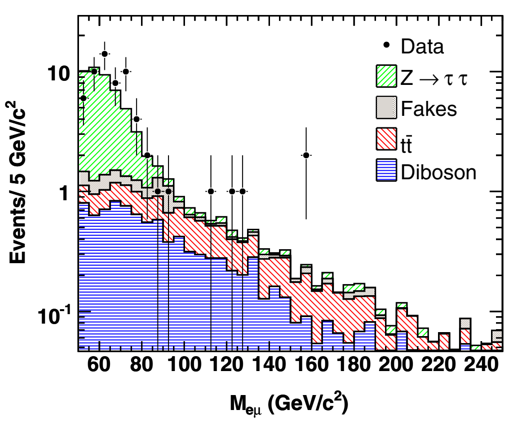

FIG. 1 (color online). Observed and predicted $M_{e\mu}$ Distributions. The observed $e\mu$ invariant mass spectrum agrees well with that of the combined SM and fake lepton backgrounds. No events are observed in data beyond $159\ \text{GeV}/c^2$.

Since strong limits exist for $\tilde{\nu}_e$ and $\tilde{\nu}_\mu$ couplings [22], we focus instead on the third generation sneutrino, $\tilde{\nu}_\tau$. We assume the "single coupling dominance" hypothesis [22] and set all λ and λ' couplings but λ'_{311} and λ_{132} to zero so that contributions to the $e\mu$ channel originate from the $\tilde{\nu}_\tau$ only. Previous limits on λ'_{311} and λ_{132} from low-energy experiments are 0.10 and 0.05 [23], assuming squark and slepton masses of $100\ \text{GeV}/c^2$.

We show an example NLO $\sigma \times \text{BR}$ [24] that corresponds to $\lambda'_{311} = 0.10$ and $\lambda_{132} = 0.05$ in Fig. 2. We use such curves for different λ_{132} and λ'_{311} values and a mass-dependent $\alpha \times \epsilon$ calculated from PYTHIA Monte Carlo simulations of the $d\bar{d} \rightarrow \tilde{\nu}_\tau(\bar{\tilde{\nu}}_\tau) \rightarrow e\mu$ process to obtain signal expectations over the 100 to 800 GeV/c^2 range. Assuming coupling values of $\lambda_{132} = 0.05$ and $\lambda'_{311} = 0.1$, for example, we find that a hypothetical 300 GeV/c^2 $\tilde{\nu}_\tau$ signal consists of 16.2 ± 1.3 events.

We calculate an upper limit $\sigma \times \text{BR}$ for $d\bar{d} \rightarrow \tilde{\nu}_\tau(\bar{\tilde{\nu}}_\tau) \rightarrow e\mu$ using the numbers of observed and predicted background events in bins of $M_{e\mu}$. We scan the $M_{e\mu}$ range in steps of $10\ \text{GeV}/c^2$ and use the simulated mass resolution at each step to weight all data and background events between 100 and 800 GeV/c^2. A Bayesian algorithm [25] is used with a uniform prior to translate the weighted event totals to a 95% confidence level (C.L.) upper limit on the number of signal events in data. We divide this limit by the integrated luminosity and signal $\alpha \times \epsilon$ to obtain a 95% C.L. upper limit on the $\sigma \times \text{BR}$ for the process. The $\alpha \times \epsilon$ for a generic spin-0 particle decaying to $e\mu$ is mass dependent, increasing slowly from $\sim$10% at

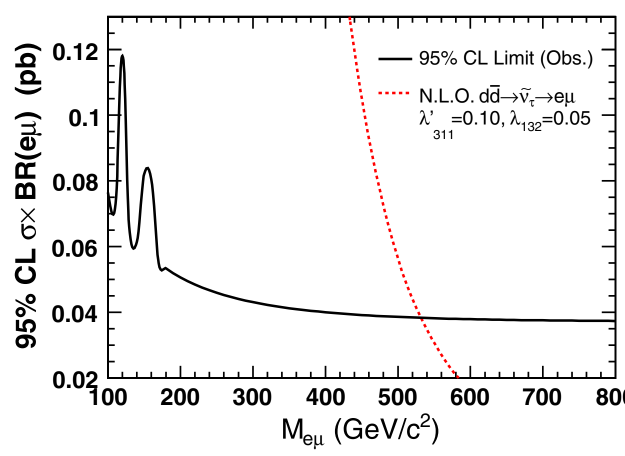

FIG. 2 (color online). Observed 95% C.L. upper limit on $\sigma \times \text{BR}$ for $d\bar{d} \rightarrow \tilde{\nu}_\tau(\bar{\tilde{\nu}}_\tau) \rightarrow e\mu$ (solid line) and the NLO prediction (dashed line) as a function of $e\mu$ invariant mass. Their intersection gives a 530 GeV/c^2 $\tilde{\nu}_\tau$ mass limit for the values of λ'_{311} and λ_{132} indicated. Because of small differences in the signal acceptances, the 95% C.L. upper limit on the Z' $\sigma \times \text{BR}$ (not shown) is larger than that of the sneutrino, $\sim$0.02 pb greater at 200 GeV/c^2 and $\sim$0.003 pb greater at 600 GeV/c^2, for example.

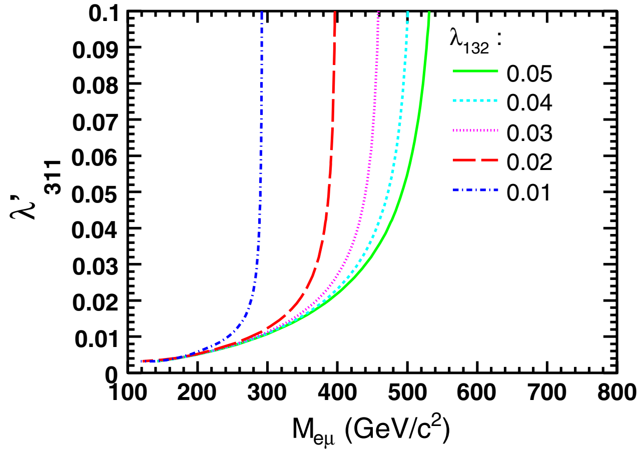

FIG. 3 (color online). $\lambda'_{311} - M_{e\mu}$ exclusion regions. Regions to the left of the five curves shown represent ranges of λ'_{311} values that we exclude at 95% C.L. as a function of $\tilde{\nu}_\tau$ mass. Each region corresponds to a fixed value of λ_{132}.

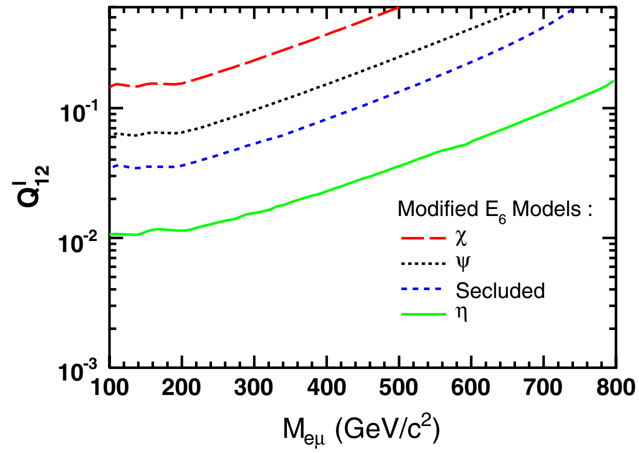

FIG. 4 (color online). $Q^l_{12} - M_{e\mu}$ exclusion regions depicting 95% C.L. upper limits on the LFV Q^l_{12} coupling in extended ψ, χ, η, and secluded E_6 models.

100 GeV$/c^2$ to $\sim$27% at 800 GeV$/c^2$. We account for uncertainties on the signal and background expectations in limit calculation although the final results are largely insensitive to these numbers.

The intersection of the observed upper limit and a NLO $\sigma \times$ BR curve defines a $\tilde{\nu}_\tau$ mass limit for specific values of the λ'_{311} and λ_{132} couplings, as shown in Fig. 2. We construct exclusion regions in the $\lambda'_{311} - M_{e\mu}$ plane by plotting the mass limit as a function of both RPV couplings. Figure 3 shows the exclusion region parametrized by five assumed values of λ_{132}. The plot indicates, for example, that we exclude at 95% C.L. λ'_{311} values above $\sim$0.01 for a sample $\tilde{\nu}_\tau$ mass of 300 GeV$/c^2$ and $\lambda_{132} \gtrsim 0.02$.

Our search is also sensitive to LFV Z' decay. The $p\bar{p} \to Z' \to e\mu$ process proceeds through diagonal $U(1)'$ couplings at the initial-state vertex and an off-diagonal LFV $U(1)'$ coupling, Q^l_{12}, that determines the Z' branching ratio (BR) to $e\mu$ [2]. We set 95% C.L. limits on Q^l_{12} as a function of the Z' mass using NLO $\sigma \times$ BR's from a group of E_6-inspired models. Although E_6 models do not incorporate the LFV Q^l_{12} coupling by construction, we use these models because they provide a theoretical reference by specifying initial-state Z'-quark coupling and a NLO Z' production cross section. We utilize NLO cross sections provided by the χ, ψ, secluded, and η E_6 models [26] and extend these models to include the Q^l_{12} coupling [27], which introduces $Z' \to e\mu$ decays.

We set limits on Q^l_{12} as a function of the Z' mass following the procedure previously described for RPV $\tilde{\nu}_\tau$ decay. The $\alpha \times \epsilon$ we use in calculating the upper limit on $\sigma \times$ BR is obtained from PYTHIA Monte Carlo simulations in which the Z' is required to couple to a left-handed leptonic LFV current, as may be favored in E_6-motivated $U(1)'$ models that incorporate LFV [27]. Z' acceptance ($\sim$8% at 100 GeV$/c^2$, and increasing to $\sim$20% at 800 GeV$/c^2$) is smaller than that for the scalar sneutrino due to the spin-1 nature of the particle.

The $Q^l_{12} - M_{e\mu}$ regions that we exclude for the modified χ, ψ, secluded, and η models are shown in Fig. 4. Assuming initial-state Z' couplings specified by the η model, for example, we exclude Q^l_{12} values above $\sim$0.01–0.1 for Z' masses between 200 and 700 GeV$/c^2$. Because the LFV Q^l_{12} coupling is not intrinsic to E_6 models, our limits should not be interpreted as constraints on the models themselves.

In summary, we searched in 344 pb^{-1} of CDF II data for high-mass $e\mu$ events and found an $M_{e\mu}$ distribution consistent with SM predictions. With no evidence for new physics, we set correlated 95% C.L. limits on the mass and λ'_{311} and λ_{132} RPV couplings of the $\tilde{\nu}_\tau$. We achieve a $\sim$170 GeV$/c^2$ improvement in the $\tilde{\nu}_\tau$ mass limit for specific RPV coupling values of $\lambda'_{311} = 0.1$ and $\lambda_{132} = 0.05$ [28] and, more generally, exclude $\tilde{\nu}_\tau$ masses over a range of λ'_{311} and λ_{132} values. We also place limits on potential LFV Q^l_{12} couplings of the Z' boson as a function of its mass using E_6-like models of $U(1)'$ symmetry.

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