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

A. Abulencia,[23] D. Acosta,[17] J. Adelman,[13] T. Affolder,[10] T. Akimoto,[55] M.G. Albrow,[16] D. Ambrose,[16] S. Amerio,[43] D. Amidei,[34] A. Anastassov,[52] K. Anikeev,[16] A. Annovi,[18] J. Antos,[1] M. Aoki,[55] G. Apollinari,[16] J.-F. Arguin,[33] T. Arisawa,[57] A. Artikov,[14] W. Ashmanskas,[16] A. Attal,[8] F. Azfar,[42] P. Azzi-Bacchetta,[43] P. Azzurri,[46] N. Bacchetta,[43] H. Bachacou,[28] W. Badgett,[16] A. Barbaro-Galtieri,[28] V.E. Barnes,[48] B.A. Barnett,[24] S. Baroiant,[7] V. Bartsch,[30] G. Bauer,[32] F. Bedeschi,[46] S. Behari,[24] S. Belforte,[54] G. Bellettini,[46] J. Bellinger,[59] A. Belloni,[32] E. Ben Haim,[44] D. Benjamin,[15] A. Beretvas,[16] J. Beringer,[28] T. Berry,[29] A. Bhatti,[50] M. Binkley,[16] D. Bisello,[43] R. E. Blair,[2] C. Blocker,[6] B. Blumenfeld,[24] A. Bocci,[15] A. Bodek,[49] V. Boisvert,[49] G. Bolla,[48] A. Bolshov,[32] D. Bortoletto,[48] J. Boudreau,[47] A. Boveia,[10] B. Brau,[10] C. Bromberg,[35] E. Brubaker,[13] J. Budagov,[14] H.S. Budd,[49] S. Budd,[23] K. Burkett,[16] G. Busetto,[43] P. Bussey,[20] K. L. Byrum,[2] S. Cabrera,[15] M. Campanelli,[19] M. Campbell,[34] F. Canelli,[8] A. Canepa,[48] D. Carlsmith,[59] R. Carosi,[46] S. Carron,[15] M. Casarsa,[54] A. Castro,[5] P. Catastini,[46] D. Cauz,[54] M. Cavalli-Sforza,[3] A. Cerri,[28] L. Cerrito,[42] S.H. Chang,[27] J. Chapman,[34] Y.C. Chen,[1] M. Chertok,[7] G. Chiarelli,[46] G. Chlachidze,[14] F. Chlebana,[16] I. Cho,[27] K. Cho,[27] D. Chokheli,[14] J.P. Chou,[21] P.H. Chu,[23] S.H. Chuang,[59] K. Chung,[12] W.H. Chung,[59] Y.S. Chung,[49] M. Ciljak,[46] C.I. Ciobanu,[23] M.A. Ciocci,[46] A. Clark,[19] D. Clark,[6] M. Coca,[15] G. Compostella,[43] M.E. Convery,[50] J. Conway,[7] B. Cooper,[30] K. Copic,[34] M. Cordelli,[18] G. Cortiana,[43] F. Cresciolo,[46] A. Cruz,[17] C. Cuenca Almenar,[7] J. Cuevas,[11] R. Culbertson,[16] D. Cyr,[59] S. DaRonco,[43] S. D'Auria,[20] M. D'Onofrio,[3] D. Dagenhart,[6] P. de Barbaro,[49] S. De Cecco,[51] A. Deisher,[28] G. De Lentdecker,[49] M. Dell'Orso,[46] F. Delli Paoli,[43] S. Demers,[49] L. Demortier,[50] J. Deng,[15] M. Deninno,[5] D. De Pedis,[51] P.F. Derwent,[16] C. Dionisi,[51] J.R. Dittmann,[4] P. DiTuro,[52] C. Dörr,[25] S. Donati,[46] M. Donega,[19] P. Dong,[8] J. Donini,[43] T. Dorigo,[43] S. Dube,[52] K. Ebina,[57] J. Efron,[39] J. Ehlers,[19] R. Erbacher,[7] D. Errede,[23] S. Errede,[23] R. Eusebi,[16] H.C. Fang,[28] S. Farrington,[29] I. Fedorko,[46] W.T. Fedorko,[13] R.G. Feild,[60] M. Feindt,[25] J.P. Fernandez,[31] R. Field,[17] G. Flanagan,[48] L.R. Flores-Castillo,[47] A. Foland,[21] S. Forrester,[7] G.W. Foster,[16] M. Franklin,[21] J.C. Freeman,[28] I. Furic,[13] M. Gallinaro,[50] J. Galyardt,[12] J.E. Garcia,[46] M. Garcia Sciveres,[28] A.F. Garfinkel,[48] C. Gay,[60] H. Gerberich,[23] D. Gerdes,[34] S. Giagu,[51] P. Giannetti,[46] A. Gibson,[28] K. Gibson,[12] C. Ginsburg,[16] N. Giokaris,[14] K. Giolo,[48] M. Giordani,[54] P. Giromini,[18] M. Giunta,[46] G. Giurgiu,[12] V. Glagolev,[14] D. Glenzinski,[16] M. Gold,[37] N. Goldschmidt,[34] J. Goldstein,[42] G. Gomez,[11] G. Gomez-Ceballos,[11] M. Goncharov,[53] O. González,[31] I. Gorelov,[37] A.T. Goshaw,[15] Y. Gotra,[47] K. Goulianos,[50] A. Gresele,[43] M. Griffiths,[29] S. Grinstein,[21] C. Grosso-Pilcher,[13] R.C. Group,[17] U. Grundler,[23] J. Guimaraes da Costa,[21] Z. Gunay-Unalan,[35] C. Haber,[28] S.R. Hahn,[16] K. Hahn,[45] E. Halkiadakis,[52] A. Hamilton,[33] B.-Y. Han,[49] J.Y. Han,[49] R. Handler,[59] F. Happacher,[18] K. Hara,[55] M. Hare,[56] S. Harper,[42] R.F. Harr,[58] R.M. Harris,[16] K. Hatakeyama,[50] J. Hauser,[8] C. Hays,[15] A. Heijboer,[45] B. Heinemann,[29] J. Heinrich,[45] M. Herndon,[59] D. Hidas,[15] C.S. Hill,[10] D. Hirschbuehl,[25] A. Hocker,[16] A. Holloway,[21] S. Hou,[1] M. Houlden,[29] S.-C. Hsu,[9] B.T. Huffman,[42] R.E. Hughes,[39] J. Huston,[35] J. Incandela,[10] G. Introzzi,[46] M. Iori,[51] Y. Ishizawa,[55] A. Ivanov,[7] B. Iyutin,[32] E. James,[16] D. Jang,[52] B. Jayatilaka,[34] D. Jeans,[51] H. Jensen,[16] E.J. Jeon,[27] S. Jindariani,[17] M. Jones,[48] K.K. Joo,[27] S.Y. Jun,[12] T.R. Junk,[23] T. Kamon,[53] J. Kang,[34] P.E. Karchin,[58] Y. Kato,[41] Y. Kemp,[25] R. Kephart,[16] U. Kerzel,[25] V. Khotilovich,[53] B. Kilminster,[39] D.H. Kim,[27] H.S. Kim,[27] J.E. Kim,[27] M.J. Kim,[12] S.B. Kim,[27] S.H. Kim,[55] Y.K. Kim,[13] L. Kirsch,[6] S. Klimenko,[17] M. Klute,[32] B. Knuteson,[32] B.R. Ko,[15] H. Kobayashi,[55] K. Kondo,[57] D.J. Kong,[27] J. Konigsberg,[17] A. Korytov,[17] A.V. Kotwal,[15] A. Kovalev,[45] A. Kraan,[45] J. Kraus,[23] I. Kravchenko,[32] M. Kreps,[25] J. Kroll,[45] N. Krumnack,[4] M. Kruse,[15] V. Krutelyov,[53] S. E. Kuhlmann,[2] Y. Kusakabe,[57] S. Kwang,[13] A.T. Laasanen,[48] S. Lai,[33] S. Lami,[46] S. Lammel,[16] M. Lancaster,[30] R.L. Lander,[7] K. Lannon,[39] A. Lath,[52] G. Latino,[46] I. Lazzizzera,[43] T. LeCompte,[2] J. Lee,[49] J. Lee,[27] Y.J. Lee,[27] S.W. Lee,[53] R. Lefèvre,[3] N. Leonardo,[32] S. Leone,[46] S. Levy,[13] J.D. Lewis,[16] C. Lin,[60] C.S. Lin,[16] M. Lindgren,[16] E. Lipeles,[9] A. Lister,[19] D.O. Litvintsev,[16] T. Liu,[16] N.S. Lockyer,[45] A. Loginov,[36] M. Loreti,[43] P. Loverre,[51] R.-S. Lu,[1] D. Lucchesi,[43] P. Lujan,[28] P. Lukens,[16] G. Lungu,[17] L. Lyons,[42] J. Lys,[28] R. Lysak,[1] E. Lytken,[48] P. Mack,[25] D. MacQueen,[33] R. Madrak,[16] K. Maeshima,[16] T. Maki,[22] P. Maksimovic,[24] S. Malde,[42] G. Manca,[29] F. Margaroli,[5] R. Marginean,[16] C. Marino,[23] A. Martin,[60] V. Martin,[38] M. Martínez,[3] T. Maruyama,[55] H. Matsunaga,[55] M.E. Mattson,[58] R. Mazini,[33] P. Mazzanti,[5] K.S. McFarland,[49] P. McIntyre,[53] R. McNulty,[29] A. Mehta,[29] S. Menzemer,[11] A. Menzione,[46] P. Merkel,[48] C. Mesropian,[50] A. Messina,[51] M. von der Mey,[8] T. Miao,[16] N. Miladinovic,[6] J. Miles,[32] R. Miller,[35] J.S. Miller,[34] C. Mills,[10] M. Milnik,[25] R. Miquel,[28] A. Mitra,[1] G. Mitselmakher,[17] A. Miyamoto,[26] N. Moggi,[5] B. Mohr,[8] R. Moore,[16] M. Morello,[46] P. Movilla Fernandez,[28] J. Mülmenstädt,[28] A. Mukherjee,[16] Th. Muller,[25] R. Mumford,[24] P. Murat,[16] J. Nachtman,[16] J. Naganoma,[57] S. Nahn,[32] I. Nakano,[40] A. Napier,[56] D. Naumov,[37] V. Necula,[17] C. Neu,[45] M.S. Neubauer,[9] J. Nielsen,[28] T. Nigmanov,[47] L. Nodulman,[2] O. Norniella,[3] E. Nurse,[30] T. Ogawa,[57] S.H. Oh,[15] Y.D. Oh,[27] T. Okusawa,[41] R. Oldeman,[29] R. Orava,[22] K. Osterberg,[22] C. Pagliarone,[46] E. Palencia,[11] R. Paoletti,[46] V. Papadimitriou,[16] A.A. Paramonov,[13] B. Parks,[39] S. Pashapour,[33] J. Patrick,[16] G. Pauletta,[54] M. Paulini,[12] C. Paus,[32] D.E. Pellett,[7] A. Penzo,[54] T.J. Phillips,[15] G. Piacentino,[46] J. Piedra,[44] L. Pinera,[17] K. Pitts,[23] C. Plager,[8] L. Pondrom,[59] X. Portell,[3] O. Poukhov,[14] N. Pounder,[42] F. Prakoshyn,[14] A. Pronko,[16] J. Proudfoot,[2] F. Ptohos,[18] G. Punzi,[46] J. Pursley,[24] J. Rademacker,[42] A. Rahaman,[47] A. Rakitin,[32] S. Rappoccio,[21] F. Ratnikov,[52] B. Reisert,[16] V. Rekovic,[37] N. van Remortel,[22] P. Renton,[42] M. Rescigno,[51] S. Richter,[25] F. Rimondi,[5] L. Ristori,[46] W.J. Robertson,[15] A. Robson,[20] T. Rodrigo,[11] E. Rogers,[23] S. Rolli,[56] R. Roser,[16] M. Rossi,[54] R. Rossin,[17] C. Rott,[48] A. Ruiz,[11] J. Russ,[12] V. Rusu,[13] H. Saarikko,[22] S. Sabik,[33] A. Safonov,[53] W.K. Sakumoto,[49] G. Salamanna,[51] O. Saltó,[3] D. Saltzberg,[8] C. Sanchez,[3] L. Santi,[54] S. Sarkar,[51] L. Sartori,[46] K. Sato,[55] P. Savard,[33] A. Savoy-Navarro,[44] T. Scheidle,[25] P. Schlabach,[16] E.E. Schmidt,[16] M.P. Schmidt,[60] M. Schmitt,[38] T. Schwarz,[34] L. Scodellaro,[11] A.L. Scott,[10] A. Scribano,[46] F. Scuri,[46] A. Sedov,[48] S. Seidel,[37] Y. Seiya,[41] A. Semenov,[14] L. Sexton-Kennedy,[16] I. Sfiligoi,[18] M.D. Shapiro,[28] T. Shears,[29] P.F. Shepard,[47] D. Sherman,[21] M. Shimojima,[55] M. Shochet,[13] Y. Shon,[59] I. Shreyber,[36] A. Sidoti,[44] P. Sinervo,[33] A. Sisakyan,[14] J. Sjolin,[42] A. Skiba,[25] A.J. Slaughter,[16] K. Sliwa,[56] J.R. Smith,[7] F.D. Snider,[16] R. Snihur,[33] M. Soderberg,[34] A. Soha,[7] S. Somalwar,[52] V. Sorin,[35] J. Spalding,[16] M. Spezziga,[16] F. Spinella,[46] T. Spreitzer,[33] P. Squillacioti,[46] M. Stanitzki,[60] A. Staveris-Polykalas,[46] R. St. Denis,[20] B. Stelzer,[8] O. Stelzer-Chilton,[42] D. Stentz,[38] J. Strologas,[37] D. Stuart,[10] J.S. Suh,[27] A. Sukhanov,[17] K. Sumorok,[32] H. Sun,[56] T. Suzuki,[55] A. Taffard,[23] R. Takashima,[40] Y. Takeuchi,[55] K. Takikawa,[55] M. Tanaka,[2] R. Tanaka,[40] N. Tanimoto,[40] M. Tecchio,[34] P.K. Teng,[1] K. Terashi,[50] S. Tether,[32] J. Thom,[16] A.S. Thompson,[20] E. Thomson,[45] P. Tipton,[49] V. Tiwari,[12] S. Tkaczyk,[16] D. Toback,[53] S. Tokar,[14] K. Tollefson,[35] T. Tomura,[55] D. Tonelli,[46] M. Tönnesmann,[35] S. Torre,[18] D. Torretta,[16] S. Tourneur,[44] W. Trischuk,[33] R. Tsuchiya,[57] S. Tsuno,[40] N. Turini,[46] F. Ukegawa,[55] T. Unverhau,[20] S. Uozumi,[55] D. Usynin,[45] A. Vaiciulis,[49] S. Vallecorsa,[19] A. Varganov,[34] E. Vataga,[37] G. Velev,[16] G. Veramendi,[23] V. Veszpremi,[48] R. Vidal,[16] I. Vila,[11] R. Vilar,[11] T. Vine,[30] I. Vollrath,[33] I. Volobouev,[28] G. Volpi,[46] F. Würthwein,[9] P. Wagner,[53] R. G. Wagner,[2] R.L. Wagner,[16] W. Wagner,[25] R. Wallny,[8] T. Walter,[25] Z. Wan,[52] S.M. Wang,[1] A. Warburton,[33] S. Waschke,[20] D. Waters,[30] W.C. Wester III,[16] B. Whitehouse,[56] D. Whiteson,[45] A.B. Wicklund,[2] E. Wicklund,[16] G. Williams,[33] H.H. Williams,[45] P. Wilson,[16] B.L. Winer,[39] P. Wittich,[16] S. Wolbers,[16] C. Wolfe,[13] T. Wright,[34] X. Wu,[19] S.M. Wynne,[29] A. Yagil,[16] K. Yamamoto,[41] J. Yamaoka,[52] T. Yamashita,[40] C. Yang,[60] U.K. Yang,[13] Y.C. Yang,[27] W.M. Yao,[28] G.P. Yeh,[16] J. Yoh,[16] K. Yorita,[13] T. Yoshida,[41] G.B. Yu,[49] I. Yu,[27] S.S. Yu,[16] J.C. Yun,[16] L. Zanello,[51] A. Zanetti,[54] I. Zaw,[21] F. Zetti,[46] X. Zhang,[23] J. Zhou,[52] and S. Zucchelli[5]

(CDF Collaboration)

[1]*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2]*Argonne National Laboratory, Argonne, Illinois 60439*
[3]*Institut de Fisica d'Altes Energies, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*
[4]*Baylor University, Waco, Texas 76798*
[5]*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*
[6]*Brandeis University, Waltham, Massachusetts 02254*
[7]*University of California, Davis, Davis, California 95616*
[8]*University of California, Los Angeles, Los Angeles, California 90024*
[9]*University of California, San Diego, La Jolla, California 92093*
[10]*University of California, Santa Barbara, Santa Barbara, California 93106*
[11]*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[12]*Carnegie Mellon University, Pittsburgh, PA 15213*
[13]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[14]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[15]*Duke University, Durham, North Carolina 27708*
[16]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[17]*University of Florida, Gainesville, Florida 32611*
[18]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[19]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[20]*Glasgow University, Glasgow G12 8QQ, United Kingdom*
[21]*Harvard University, Cambridge, Massachusetts 02138*
[22]*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*
[23]*University of Illinois, Urbana, Illinois 61801*
[24]*The Johns Hopkins University, Baltimore, Maryland 21218*

[25] Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany
[26] High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305, Japan
[27] Center for High Energy Physics: Kyungpook National University, Taegu 702-701; Seoul National University, Seoul 151-742; and SungKyunKwan University, Suwon 440-746; Korea
[28] Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720
[29] University of Liverpool, Liverpool L69 7ZE, United Kingdom
[30] University College London, London WC1E 6BT, United Kingdom
[31] Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain
[32] Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
[33] Institute of Particle Physics: McGill University, Montréal, Canada H3A 2T8; and University of Toronto, Toronto, Canada M5S 1A7
[34] University of Michigan, Ann Arbor, Michigan 48109
[35] Michigan State University, East Lansing, Michigan 48824
[36] Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia
[37] University of New Mexico, Albuquerque, New Mexico 87131
[38] Northwestern University, Evanston, Illinois 60208
[39] The Ohio State University, Columbus, Ohio 43210
[40] Okayama University, Okayama 700-8530, Japan
[41] Osaka City University, Osaka 588, Japan
[42] University of Oxford, Oxford OX1 3RH, United Kingdom
[43] University of Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy
[44] LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France
[45] University of Pennsylvania, Philadelphia, Pennsylvania 19104
[46] Istituto Nazionale di Fisica Nucleare Pisa, Universities of Pisa, Siena and Scuola Normale Superiore, I-56127 Pisa, Italy
[47] University of Pittsburgh, Pittsburgh, Pennsylvania 15260
[48] Purdue University, West Lafayette, Indiana 47907
[49] University of Rochester, Rochester, New York 14627
[50] The Rockefeller University, New York, New York 10021
[51] Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, University of Rome "La Sapienza," I-00185 Roma, Italy
[52] Rutgers University, Piscataway, New Jersey 08855
[53] Texas A&M University, College Station, Texas 77843
[54] Istituto Nazionale di Fisica Nucleare, University of Trieste/ Udine, Italy
[55] University of Tsukuba, Tsukuba, Ibaraki 305, Japan
[56] Tufts University, Medford, Massachusetts 02155
[57] Waseda University, Tokyo 169, Japan
[58] Wayne State University, Detroit, Michigan 48201
[59] University of Wisconsin, Madison, Wisconsin 53706
[60] Yale University, New Haven, Connecticut 06520

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We describe a general search for resonances decaying to a neutral $e\mu$ final state in $p\overline{p}$ 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 CDF 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 electron-muon pairs at the Tevatron would provide evidence of physics beyond the Standard Model (SM). This signature arises in many new physics models through the lepton family number violating (LFV) decays of predicted heavy particles. General supersymmetric models permit the violation of R-parity symmetry (RPV), for instance, and describe the 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]. Signals from such processes may be easily detected at the Tevatron. Backgrounds from lepton number conserving processes of the SM are small and characterized by invariant mass spectra that lie well below the range presumed for new physics.

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 ($\tilde{\nu}_\tau$) [3]. That analysis excluded sneutrino masses below ~ 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 three 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.

The CDF II detector [4] is an azimuthally and forward-backward symmetric apparatus designed to study $p\overline{p}$ reactions at the Tevatron. We briefly describe the detector components used in this analysis below. The detector has a charged particle tracking system immersed in a 1.4 T magnetic field aligned coaxially with the $p\overline{p}$ beams. A 3.1 m long open-cell drift chamber, the Central Outer Tracker (COT) [5], covers the radial range from 40 to 137 cm and provides coverage for the pseudo-rapidity range $|\eta| \lesssim 1$ [6]. Segmented electromagnetic and hadronic sampling calorimeters surround the tracking system and measure the energy of interacting particles in the range $|\eta| < 3.6$ [7–9]. A set of drift chambers located outside the central hadron calorimeters and another set behind a 60 cm thick iron shield track muons with $|\eta| \leq 0.6$. [10]. Additional drift chambers and scintillation counters detect muons in the region $0.6 \leq |\eta| \leq 1.0$. Gas Cerenkov counters located in the $3.7 < |\eta| < 4.7$ region [11] measure the average number of inelastic $p\overline{p}$ 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 [12].

We select oppositely charged $e\mu$ pairs and ensure that the lepton tracks share a common vertex, *i.e.,* they 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 [12].

SM $e\mu$ backgrounds include $q\bar{q} \to Z/\gamma^\star \to \tau\tau$ (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 [13] and a GEANT3 [14] based simulation of the CDF II detector. These simulations employ the CTEQ5L [15] 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 PYTHIA generated events that are reconstructed after simulation and satisfy the lepton ID and event topology requirements. We correct the α_i by multiplying with trigger efficiencies (ϵ_{trg}) measured from $W \to e\nu$ and $Z \to \mu\mu$ data and factors (f_{reco}, f_{ID}) that account for differences in lepton reconstruction and ID efficiency between simulation and data [12]. We refer to the combined correction factor, $\epsilon_{trg} \times f_{reco} \times f_{ID}$, 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 $t\bar{t}$ [16], 12.1 pb for WW, 3.7 pb for WZ and 1.4 pb for ZZ [17]. 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 [18].

Jets that are misidentified as leptons account for approximately 5% of the total background. We determine the misidentification probability ("fake rate") [12] 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, parameterized as functions of E_T, to the jets in events in the high-P_T sample that contain a single lepton candidate.

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
Diboson	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

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.

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 [19]. Additional uncertainty contributions include those associated with the SM cross sections, fake rate measurements, lepton ID and reconstruction scale factors, PDF model, and the statistical uncertainties associated with the Monte Carlo acceptance calculations.

The $50 \leq M_{e\mu} \leq 100$ 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 GeV/c^2. Here, too, we find good agreement. Figure 1 shows the observed and predicted background $M_{e\mu}$ distributions over the full $50-800$ GeV/c^2 invariant mass range.

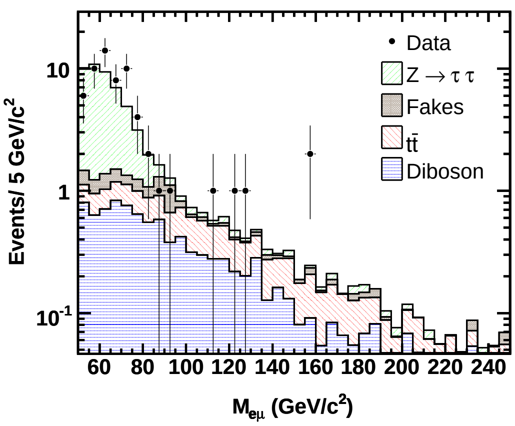

FIG. 1: Observed and predicted $M_{e\mu}$ Distributions. The observed $e\mu$ invariant mass spectrum agrees well with that of the combined SM and fake lepton backgrounds.

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 $17.2/14 = 1.23$, under the assumption that systematic uncertainties in each bin are completely correlated. The statistic implies a p-value, the probability that SM physics will lead to results that disagree more with our SM Monte Carlo predictions that the results we observe, of $\sim 25\%$. 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 supersymmetric models, the s-channel $d\bar{d} \to \tilde{\nu}_i(\bar{\tilde{\nu}}_i) \to e\mu$ 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 $e\mu$ [20]. 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, which stipulates a down-type super-multiplet $\bar{D}_k$ [20].

Since strong limits exist for $\tilde{\nu}_e$ and $\tilde{\nu}_\mu$ couplings [21], we focus instead on the third generation sneutrino, $\tilde{\nu}_\tau$. We assume the "single coupling dominance" hypothesis [21] 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} are 0.10 and 0.05 [22], assuming squark and slepton masses of 100 GeV/c^2. These indirect bounds are derived from measurements of low-energy processes [22, 23] and become weaker for larger squark and slepton masses.

We show an example NLO $\sigma \times BR$ [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 $d\bar{d} \to \tilde{\nu}_\tau(\bar{\tilde{\nu}}_\tau) \to e\mu$ 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 $\sigma \times BR$ for $d\bar{d} \to \tilde{\nu}_\tau(\bar{\tilde{\nu}}_\tau) \to e\mu$ 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 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 (CL) 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% CL upper limit on the $\sigma \times BR$ 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 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 $\sigma \times BR$ curves 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 λ'_{311}-$M_{e\mu}$ plane by plotting the mass limit as a function of both RPV couplings. Figure 3 shows the exclusion region parameterized by five assumed values of λ_{132}. The plot indicates, for example, that we exclude at 95% CL λ'_{311} values above ~ 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% CL 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] by extending these models to include the Q^l_{12}

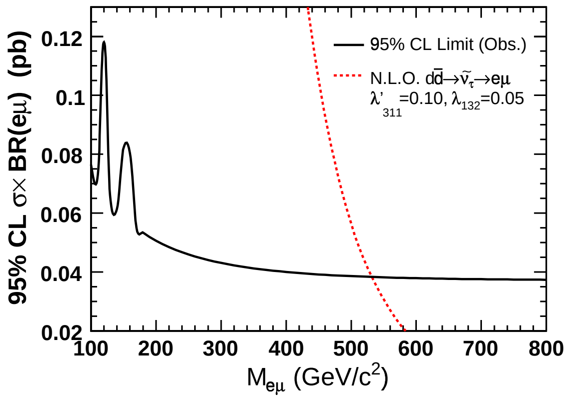

FIG. 2: Observed 95% CL upper limit on $\sigma \times BR$ for $d\bar{d} \rightarrow \tilde{\nu}_\tau(\bar{\tilde{\nu}}_\tau) \rightarrow e\mu$ (solid line) and the NLO prediction (dashed line) as a function of $e\mu$ invariant mass. Their intersection gives a 530 GeV/c^2 $\tilde{\nu}_\tau$ mass limit for the values of λ'_{311} and λ_{132} indicated. Peaks in the observed upper limit below $\sim$ 180 GeV/c^2 are consistent with 2σ fluctuations from SM expectations. Due to small differences in the signal acceptances, the 95% CL upper limit on the Z' $\sigma \times BR$ (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.

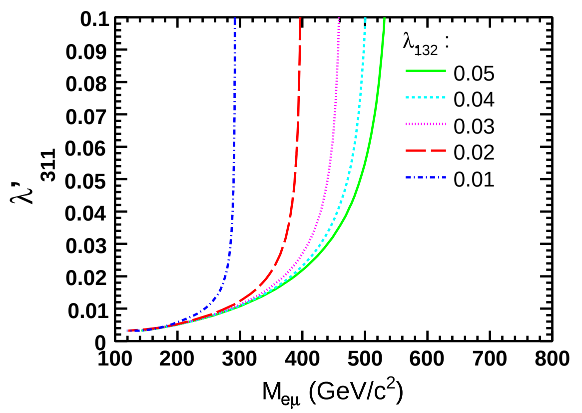

FIG. 3: $\lambda'_{311} - M_{e\mu}$ Exclusion Regions. Regions to the left of the five curves shown represent ranges of λ'_{311} values that we exclude at 95% CL as a function of $\tilde{\nu}_\tau$ mass. Each region corresponds to a fixed value of λ_{132}.

coupling [27]. This introduces $Z' \rightarrow e\mu$ decays with a BR that we calculate from Q^l_{12} in the same way that BR's to dileptons are determined from diagonal $U(1)'$ couplings in the original E_6 models.

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.

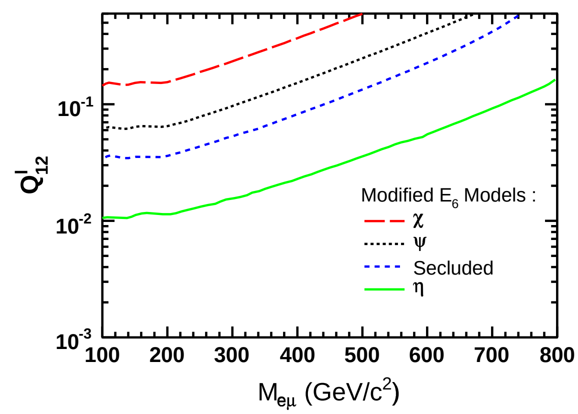

FIG. 4: $Q^l_{12} - M_{e\mu}$ Exclusion Regions depicting 95% CL upper limits on the LFV Q^l_{12} coupling in extended ψ, χ, η and Secluded E_6 models.

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% CL 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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