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

Darin Acosta

*University of Florida*, [acosta@phys.ufl.edu](mailto:acosta@phys.ufl.edu)

Kenneth A. Bloom

*University of Nebraska - Lincoln*, [kbloom2@unl.edu](mailto:kbloom2@unl.edu)

Collider Detector at Fermilab Collaboration

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

D. Acosta,<sup>14</sup> T. Affolder,<sup>7</sup> H. Akimoto,<sup>51</sup> M. G. Albrow,<sup>13</sup> D. Ambrose,<sup>37</sup> D. Amidei,<sup>28</sup> K. Anikeev,<sup>27</sup> J. Antos,<sup>1</sup> G. Apollinari,<sup>13</sup> T. Arisawa,<sup>51</sup> A. Artikov,<sup>11</sup> T. Asakawa,<sup>49</sup> W. Ashmanskas,<sup>2</sup> F. Azfar,<sup>35</sup> P. Azzi-Bacchetta,<sup>36</sup> N. Bacchetta,<sup>36</sup> H. Bachacou,<sup>25</sup> W. Badgett,<sup>13</sup> S. Bailey,<sup>18</sup> P. de Barbaro,<sup>41</sup> A. Barbaro-Galtieri,<sup>25</sup> V. E. Barnes,<sup>40</sup> B. A. Barnett,<sup>21</sup> S. Baroiant,<sup>5</sup> M. Barone,<sup>15</sup> G. Bauer,<sup>27</sup> F. Bedeschi,<sup>38</sup> S. Behari,<sup>21</sup> S. Belforte,<sup>48</sup> W. H. Bell,<sup>17</sup> G. Bellettini,<sup>38</sup> J. Bellinger,<sup>52</sup> D. Benjamin,<sup>12</sup> J. Bensinger,<sup>4</sup> A. Beretvas,<sup>13</sup> J. Berryhill,<sup>10</sup> A. Bhatti,<sup>42</sup> M. Binkley,<sup>13</sup> D. Bisello,<sup>36</sup> M. Bishai,<sup>13</sup> R. E. Blair,<sup>2</sup> C. Blocker,<sup>4</sup> K. Bloom,<sup>28</sup> B. Blumenfeld,<sup>21</sup> S. R. Blusk,<sup>41</sup> A. Bocci,<sup>42</sup> A. Bodek,<sup>41</sup> G. Bolla,<sup>40</sup> A. Bolshov,<sup>27</sup> Y. Bonushkin,<sup>6</sup> D. Bortoletto,<sup>40</sup> J. Boudreau,<sup>39</sup> A. Brandl,<sup>31</sup> C. Bromberg,<sup>29</sup> M. Brozovic,<sup>12</sup> E. Brubaker,<sup>25</sup> N. Bruner,<sup>31</sup> J. Budagov,<sup>11</sup> H. S. Budd,<sup>41</sup> K. Burkett,<sup>18</sup> G. Busetto,<sup>36</sup> K. L. Byrum,<sup>2</sup> S. Cabrera,<sup>12</sup> P. Calafiura,<sup>25</sup> M. Campbell,<sup>28</sup> W. Carithers,<sup>25</sup> J. Carlson,<sup>28</sup> D. Carlsmith,<sup>52</sup> W. Caskey,<sup>5</sup> A. Castro,<sup>3</sup> D. Cauz,<sup>48</sup> A. Cerri,<sup>25</sup> L. Cerrito,<sup>20</sup> A. W. Chan,<sup>1</sup> P. S. Chang,<sup>1</sup> P. T. Chang,<sup>1</sup> J. Chapman,<sup>28</sup> C. Chen,<sup>37</sup> Y. C. Chen,<sup>1</sup> M.-T. Cheng,<sup>1</sup> M. Chertok,<sup>5</sup> G. Chiarelli,<sup>38</sup> I. Chirikov-Zorin,<sup>11</sup> G. Chlachidze,<sup>11</sup> F. Chlebana,<sup>13</sup> L. Christofek,<sup>20</sup> M. L. Chu,<sup>1</sup> J. Y. Chung,<sup>33</sup> W.-H. Chung,<sup>52</sup> Y. S. Chung,<sup>41</sup> C. I. Ciobanu,<sup>33</sup> A. G. Clark,<sup>16</sup> M. Coca,<sup>41</sup> A. Connolly,<sup>25</sup> M. Convery,<sup>42</sup> J. Conway,<sup>44</sup> M. Cordelli,<sup>15</sup> J. Cranshaw,<sup>46</sup> R. Culbertson,<sup>13</sup> D. Dagenhart,<sup>4</sup> S. D'Auria,<sup>17</sup> S. De Cecco,<sup>43</sup> F. DeJongh,<sup>13</sup> S. Dell'Agnello,<sup>15</sup> M. Dell'Orso,<sup>38</sup> S. Demers,<sup>41</sup> L. Demortier,<sup>42</sup> M. Deninno,<sup>3</sup> D. De Pedis,<sup>43</sup> P. F. Derwent,<sup>13</sup> T. Devlin,<sup>44</sup> C. Dionisi,<sup>43</sup> J. R. Dittmann,<sup>13</sup> A. Dominguez,<sup>25</sup> S. Donati,<sup>38</sup> M. D'Onofrio,<sup>38</sup> T. Dorigo,<sup>36</sup> N. Eddy,<sup>20</sup> K. Einsweiler,<sup>25</sup> E. Engels, Jr.,<sup>39</sup> R. Erbacher,<sup>13</sup> D. Errede,<sup>20</sup> S. Errede,<sup>20</sup> R. Eusebi,<sup>41</sup> Q. Fan,<sup>41</sup> S. Farrington,<sup>17</sup> R. G. Feild,<sup>53</sup> J. P. Fernandez,<sup>40</sup> C. Ferretti,<sup>28</sup> R. D. Field,<sup>14</sup> I. Fiori,<sup>3</sup> B. Flaugher,<sup>13</sup> L. R. Flores-Castillo,<sup>39</sup> G. W. Foster,<sup>13</sup> M. Franklin,<sup>18</sup> J. Freeman,<sup>13</sup> J. Friedman,<sup>27</sup> Y. Fukui,<sup>23</sup> I. Furic,<sup>27</sup> S. Galeotti,<sup>38</sup> A. Gallas,<sup>32</sup> M. Gallinaro,<sup>42</sup> T. Gao,<sup>37</sup> M. Garcia-Sciveres,<sup>25</sup> A. F. Garfinkel,<sup>40</sup> P. Gatti,<sup>36</sup> C. Gay,<sup>53</sup> D. W. Gerdes,<sup>28</sup> E. Gerstein,<sup>9</sup> S. Giagu,<sup>43</sup> P. Giannetti,<sup>38</sup> K. Giolo,<sup>40</sup> M. Giordani,<sup>5</sup> P. Giromini,<sup>15</sup> V. Glagolev,<sup>11</sup> D. Glenzinski,<sup>13</sup> M. Gold,<sup>31</sup> N. Goldschmidt,<sup>28</sup> J. Goldstein,<sup>13</sup> G. Gomez,<sup>8</sup> M. Goncharov,<sup>45</sup> I. Gorelov,<sup>31</sup> A. T. Goshaw,<sup>12</sup> Y. Gotra,<sup>39</sup> K. Goulianos,<sup>42</sup> C. Green,<sup>40</sup> A. Gresele,<sup>3</sup> G. Grim,<sup>5</sup> C. Grosso-Pilcher,<sup>10</sup> M. Guenther,<sup>40</sup> G. Guillian,<sup>28</sup> J. Guimaraes da Costa,<sup>18</sup> R. M. Haas,<sup>14</sup> C. Haber,<sup>25</sup> S. R. Hahn,<sup>13</sup> E. Halkiadakis,<sup>41</sup> C. Hall,<sup>18</sup> T. Handa,<sup>19</sup> R. Handler,<sup>52</sup> F. Happacher,<sup>15</sup> K. Hara,<sup>49</sup> A. D. Hardman,<sup>40</sup> R. M. Harris,<sup>13</sup> F. Hartmann,<sup>22</sup> K. Hatakeyama,<sup>42</sup> J. Hauser,<sup>6</sup> J. Heinrich,<sup>37</sup> A. Heiss,<sup>22</sup> M. Hennecke,<sup>22</sup> M. Herndon,<sup>21</sup> C. Hill,<sup>7</sup> A. Hocker,<sup>41</sup> K. D. Hoffman,<sup>10</sup> R. Hollebeck,<sup>37</sup> L. Holloway,<sup>20</sup> S. Hou,<sup>1</sup> B. T. Huffman,<sup>35</sup> R. Hughes,<sup>33</sup> J. Huston,<sup>29</sup> J. Huth,<sup>18</sup> H. Ikeda,<sup>49</sup> C. Issever,<sup>7</sup> J. Incandela,<sup>7</sup> G. Introzzi,<sup>38</sup> M. Iori,<sup>43</sup> A. Ivanov,<sup>41</sup> J. Iwai,<sup>51</sup> Y. Iwata,<sup>19</sup> B. Iyutin,<sup>27</sup> E. James,<sup>28</sup> M. Jones,<sup>37</sup> U. Joshi,<sup>13</sup> H. Kambara,<sup>16</sup> T. Kamon,<sup>45</sup> T. Kaneko,<sup>49</sup> J. Kang,<sup>28</sup> M. Karagoz Unel,<sup>32</sup> K. Karr,<sup>50</sup> S. Kartal,<sup>13</sup> H. Kasha,<sup>53</sup> Y. Kato,<sup>34</sup> T. A. Keaffaber,<sup>40</sup> K. Kelley,<sup>27</sup> M. Kelly,<sup>28</sup> R. D. Kennedy,<sup>13</sup> R. Kephart,<sup>13</sup> D. Khazins,<sup>12</sup> T. Kikuchi,<sup>49</sup> B. Kilminster,<sup>41</sup> B. J. Kim,<sup>24</sup> D. H. Kim,<sup>24</sup> H. S. Kim,<sup>20</sup> M. J. Kim,<sup>9</sup> S. B. Kim,<sup>24</sup> S. H. Kim,<sup>49</sup> T. H. Kim,<sup>27</sup> Y. K. Kim,<sup>25</sup> M. Kirby,<sup>12</sup> M. Kirk,<sup>4</sup> L. Kirsch,<sup>4</sup> S. Klimenko,<sup>14</sup> P. Koehn,<sup>33</sup> K. Kondo,<sup>51</sup> J. Konigsberg,<sup>14</sup> A. Korn,<sup>27</sup> A. Korytov,<sup>14</sup> K. Kotelnikov,<sup>30</sup> E. Kovacs,<sup>2</sup> J. Kroll,<sup>37</sup> M. Kruse,<sup>12</sup> V. Krutelyov,<sup>45</sup> S. E. Kuhlmann,<sup>2</sup> K. Kurino,<sup>19</sup> T. Kuwabara,<sup>49</sup> N. Kuznetsova,<sup>13</sup> A. T. Laasanen,<sup>40</sup> N. Lai,<sup>10</sup> S. Lami,<sup>42</sup> S. Lammel,<sup>13</sup> J. Lancaster,<sup>12</sup> K. Lannon,<sup>20</sup> M. Lancaster,<sup>26</sup> R. Lander,<sup>5</sup> A. Lath,<sup>44</sup> G. Latino,<sup>31</sup> T. LeCompte,<sup>2</sup> Y. Le,<sup>21</sup> J. Lee,<sup>41</sup> S. W. Lee,<sup>45</sup> N. Leonardo,<sup>27</sup> S. Leone,<sup>38</sup> J. D. Lewis,<sup>13</sup> K. Li,<sup>53</sup> C. S. Lin,<sup>13</sup> M. Lindgren,<sup>6</sup> T. M. Liss,<sup>20</sup> J. B. Liu,<sup>41</sup> T. Liu,<sup>13</sup> Y. C. Liu,<sup>1</sup> D. O. Litvintsev,<sup>13</sup> O. Lobban,<sup>46</sup> N. S. Lockyer,<sup>37</sup> A. Loginov,<sup>30</sup> J. Loken,<sup>35</sup> M. Loreti,<sup>36</sup> D. Lucchesi,<sup>36</sup> P. Lukens,<sup>13</sup> S. Lusin,<sup>52</sup> L. Lyons,<sup>35</sup> J. Lys,<sup>25</sup> R. Madrak,<sup>18</sup> K. Maeshima,<sup>13</sup> P. Maksimovic,<sup>21</sup> L. Malferrari,<sup>3</sup> M. Mangano,<sup>38</sup> G. Manca,<sup>35</sup> M. Mariotti,<sup>36</sup> G. Martignon,<sup>36</sup> M. Martin,<sup>21</sup> A. Martin,<sup>53</sup> V. Martin,<sup>32</sup> M. Martínez,<sup>13</sup> J. A. J. Matthews,<sup>31</sup> P. Mazzanti,<sup>3</sup> K. S. McFarland,<sup>41</sup> P. McIntyre,<sup>45</sup> M. Menguzzato,<sup>36</sup> A. Menzione,<sup>38</sup> P. Merkel,<sup>13</sup> C. Mesropian,<sup>42</sup> A. Meyer,<sup>13</sup> T. Miao,<sup>13</sup> R. Miller,<sup>29</sup> J. S. Miller,<sup>28</sup> H. Minato,<sup>49</sup> S. Miscetti,<sup>15</sup> M. Mishina,<sup>23</sup> G. Mitselmakher,<sup>14</sup> Y. Miyazaki,<sup>34</sup> N. Moggi,<sup>3</sup> E. Moore,<sup>31</sup> R. Moore,<sup>28</sup> Y. Morita,<sup>23</sup> T. Moulik,<sup>40</sup> M. Mulhearn,<sup>27</sup> A. Mukherjee,<sup>13</sup> T. Muller,<sup>22</sup> A. Munar,<sup>38</sup> P. Murat,<sup>13</sup> S. Murgia,<sup>29</sup> J. Nachtman,<sup>6</sup> V. Nagaslaev,<sup>46</sup> S. Nahn,<sup>53</sup> H. Nakada,<sup>49</sup> I. Nakano,<sup>19</sup> R. Napora,<sup>21</sup> F. Niell,<sup>28</sup> C. Nelson,<sup>13</sup> T. Nelson,<sup>13</sup> C. Neu,<sup>33</sup> M. S. Neubauer,<sup>27</sup> D. Neuberger,<sup>22</sup> C. Newman-Holmes,<sup>13</sup> C.-Y. P. Ngan,<sup>27</sup> T. Nigmanov,<sup>39</sup> H. Niu,<sup>4</sup> L. Nodulman,<sup>2</sup> A. Nomerotski,<sup>14</sup> S. H. Oh,<sup>12</sup> Y. D. Oh,<sup>24</sup> T. Ohmoto,<sup>19</sup> T. Ohsugi,<sup>19</sup> R. Oishi,<sup>49</sup> T. Okusawa,<sup>34</sup> J. Olsen,<sup>52</sup> W. Orejudos,<sup>25</sup> C. Pagliarone,<sup>38</sup> F. Palmonari,<sup>38</sup> R. Paoletti,<sup>38</sup> V. Papadimitriou,<sup>46</sup> D. Partos,<sup>4</sup> J. Patrick,<sup>13</sup> G. Pauletta,<sup>48</sup> M. Paulini,<sup>9</sup> T. Pauly,<sup>35</sup> C. Paus,<sup>27</sup> D. Pellett,<sup>5</sup> A. Penzo,<sup>48</sup> L. Pescara,<sup>36</sup> T. J. Phillips,<sup>12</sup> G. Piacentino,<sup>38</sup> J. Piedra,<sup>8</sup> K. T. Pitts,<sup>20</sup> A. Pompoš,<sup>40</sup> L. Pondrom,<sup>52</sup> G. Pope,<sup>39</sup> T. Pratt,<sup>35</sup> F. Prokoshin,<sup>11</sup> J. Proudfoot,<sup>2</sup> F. Ptohos,<sup>15</sup> O. Pukhov,<sup>11</sup> G. Punzi,<sup>38</sup> J. Rademacker,<sup>35</sup> A. Rakitine,<sup>27</sup>

F. Ratnikov,<sup>44</sup> H. Ray,<sup>28</sup> D. Reher,<sup>25</sup> A. Reichold,<sup>35</sup> P. Renton,<sup>35</sup> M. Rescigno,<sup>43</sup> A. Ribon,<sup>36</sup> W. Riegler,<sup>18</sup> F. Rimondi,<sup>3</sup> L. Ristori,<sup>38</sup> M. Riveline,<sup>47</sup> W. J. Robertson,<sup>12</sup> T. Rodrigo,<sup>8</sup> S. Rolli,<sup>50</sup> L. Rosenson,<sup>27</sup> R. Roser,<sup>13</sup> R. Rossin,<sup>36</sup> C. Rott,<sup>40</sup> A. Roy,<sup>40</sup> A. Ruiz,<sup>8</sup> D. Ryan,<sup>50</sup> A. Safonov,<sup>5</sup> R. St. Denis,<sup>17</sup> W. K. Sakumoto,<sup>41</sup> D. Saltzberg,<sup>6</sup> C. Sanchez,<sup>33</sup> A. Sansoni,<sup>15</sup> L. Santi,<sup>48</sup> S. Sarkar,<sup>43</sup> H. Sato,<sup>49</sup> P. Savard,<sup>47</sup> A. Savoy-Navarro,<sup>13</sup> P. Schlabach,<sup>13</sup> E. E. Schmidt,<sup>13</sup> M. P. Schmidt,<sup>53</sup> M. Schmitt,<sup>32</sup> L. Scodellaro,<sup>36</sup> A. Scott,<sup>6</sup> A. Scribano,<sup>38</sup> A. Sedov,<sup>40</sup> S. Seidel,<sup>31</sup> Y. Seiya,<sup>49</sup> A. Semenov,<sup>11</sup> F. Semeria,<sup>3</sup> T. Shah,<sup>27</sup> M. D. Shapiro,<sup>25</sup> P. F. Shepard,<sup>39</sup> T. Shibayama,<sup>49</sup> M. Shimojima,<sup>49</sup> M. Shochet,<sup>10</sup> A. Sidoti,<sup>36</sup> J. Siegrist,<sup>25</sup> A. Sill,<sup>46</sup> P. Sinervo,<sup>47</sup> P. Singh,<sup>20</sup> A. J. Slaughter,<sup>53</sup> K. Sliwa,<sup>50</sup> F. D. Snider,<sup>13</sup> R. Snihur,<sup>26</sup> A. Solodsky,<sup>42</sup> T. Speer,<sup>16</sup> M. Spezziga,<sup>46</sup> P. Sphicas,<sup>27</sup> F. Spinella,<sup>38</sup> M. Spiropulu,<sup>10</sup> L. Spiegel,<sup>13</sup> J. Steele,<sup>52</sup> A. Stefanini,<sup>38</sup> J. Strologas,<sup>20</sup> F. Strumia,<sup>16</sup> D. Stuart,<sup>7</sup> A. Sukhanov,<sup>14</sup> K. Sumorok,<sup>27</sup> T. Suzuki,<sup>49</sup> T. Takano,<sup>34</sup> R. Takashima,<sup>19</sup> K. Takikawa,<sup>49</sup> P. Tamburello,<sup>12</sup> M. Tanaka,<sup>49</sup> B. Tannenbaum,<sup>6</sup> M. Tecchio,<sup>28</sup> R. J. Tesarek,<sup>13</sup> P. K. Teng,<sup>1</sup> K. Terashi,<sup>42</sup> S. Tether,<sup>27</sup> J. Thom,<sup>13</sup> A. S. Thompson,<sup>17</sup> E. Thomson,<sup>33</sup> R. Thurman-Keup,<sup>2</sup> P. Tipton,<sup>41</sup> S. Tkaczyk,<sup>13</sup> D. Toback,<sup>45</sup> K. Tollefson,<sup>29</sup> D. Tonelli,<sup>38</sup> M. Tonnesmann,<sup>29</sup> H. Toyoda,<sup>34</sup> W. Trischuk,<sup>47</sup> J. F. de Troconiz,<sup>18</sup> J. Tseng,<sup>27</sup> D. Tsybychev,<sup>14</sup> N. Turini,<sup>38</sup> F. Ukegawa,<sup>49</sup> T. Unverhau,<sup>17</sup> T. Vaiciulis,<sup>41</sup> J. Valls,<sup>44</sup> A. Varganov,<sup>28</sup> E. Vataga,<sup>38</sup> S. Vejckik III,<sup>13</sup> G. Velev,<sup>13</sup> G. Veramendi,<sup>25</sup> R. Vidal,<sup>13</sup> I. Vila,<sup>8</sup> R. Vilar,<sup>8</sup> I. Volobouev,<sup>25</sup> M. von der Mey,<sup>6</sup> D. Vucinic,<sup>27</sup> R. G. Wagner,<sup>2</sup> R. L. Wagner,<sup>13</sup> W. Wagner,<sup>22</sup> N. B. Wallace,<sup>44</sup> Z. Wan,<sup>44</sup> C. Wang,<sup>12</sup> M. J. Wang,<sup>1</sup> S. M. Wang,<sup>14</sup> B. Ward,<sup>17</sup> S. Waschke,<sup>17</sup> T. Watanabe,<sup>49</sup> D. Waters,<sup>26</sup> T. Watts,<sup>44</sup> M. Weber,<sup>25</sup> H. Wenzel,<sup>22</sup> W. C. Wester III,<sup>13</sup> B. Whitehouse,<sup>50</sup> A. B. Wicklund,<sup>2</sup> E. Wicklund,<sup>13</sup> T. Wilkes,<sup>5</sup> H. H. Williams,<sup>37</sup> P. Wilson,<sup>13</sup> B. L. Winer,<sup>33</sup> D. Winn,<sup>28</sup> S. Wolbers,<sup>13</sup> D. Wolinski,<sup>28</sup> J. Wolinski,<sup>29</sup> S. Wolinski,<sup>28</sup> M. Wolter,<sup>50</sup> S. Worm,<sup>44</sup> X. Wu,<sup>16</sup> F. Würthwein,<sup>27</sup> J. Wyss,<sup>38</sup> U. K. Yang,<sup>10</sup> W. Yao,<sup>25</sup> G. P. Yeh,<sup>13</sup> P. Yeh,<sup>1</sup> K. Yi,<sup>21</sup> J. Yoh,<sup>13</sup> C. Yosef,<sup>29</sup> T. Yoshida,<sup>34</sup> I. Yu,<sup>24</sup> S. Yu,<sup>37</sup> Z. Yu,<sup>53</sup> J. C. Yun,<sup>13</sup> L. Zanello,<sup>43</sup> A. Zanetti,<sup>48</sup> F. Zetti,<sup>25</sup> and S. Zucchelli<sup>31</sup>

(The CDF Collaboration)

<sup>1</sup>*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*

<sup>2</sup>*Argonne National Laboratory, Argonne, Illinois 60439, USA*

<sup>3</sup>*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*

<sup>4</sup>*Brandeis University, Waltham, Massachusetts 02254, USA*

<sup>5</sup>*University of California at Davis, Davis, California 95616, USA*

<sup>6</sup>*University of California at Los Angeles, Los Angeles, California 90024, USA*

<sup>7</sup>*University of California at Santa Barbara, Santa Barbara, California 93106, USA*

<sup>8</sup>*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*

<sup>9</sup>*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*

<sup>10</sup>*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*

<sup>11</sup>*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*

<sup>12</sup>*Duke University, Durham, North Carolina 27708, USA*

<sup>13</sup>*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

<sup>14</sup>*University of Florida, Gainesville, Florida 32611, USA*

<sup>15</sup>*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*

<sup>16</sup>*University of Geneva, CH-1211 Geneva 4, Switzerland*

<sup>17</sup>*Glasgow University, Glasgow G12 8QQ, United Kingdom*

<sup>18</sup>*Harvard University, Cambridge, Massachusetts 02138, USA*

<sup>19</sup>*Hiroshima University, Higashi-Hiroshima 724, Japan*

<sup>20</sup>*University of Illinois, Urbana, Illinois 61801, USA*

<sup>21</sup>*The Johns Hopkins University, Baltimore, Maryland 21218, USA*

<sup>22</sup>*Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*

<sup>23</sup>*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305, Japan*

<sup>24</sup>*Center for High Energy Physics: Kyungpook National University, Taegu 702-701, Korea; Seoul National University, Seoul 151-742, Korea; and SungKyunKwan University, Suwon 440-746, Korea*

<sup>25</sup>*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

<sup>26</sup>*University College London, London WC1E 6BT, United Kingdom*

<sup>27</sup>*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

<sup>28</sup>*University of Michigan, Ann Arbor, Michigan 48109, USA*

<sup>29</sup>*Michigan State University, East Lansing, Michigan 48824, USA*

<sup>30</sup>*Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*

<sup>31</sup>*University of New Mexico, Albuquerque, New Mexico 87131, USA*

<sup>32</sup>*Northwestern University, Evanston, Illinois 60208, USA*

<sup>33</sup>*The Ohio State University, Columbus, Ohio 43210, USA*

- <sup>34</sup>*Osaka City University, Osaka 588, Japan*  
<sup>35</sup>*University of Oxford, Oxford OX1 3RH, United Kingdom*  
<sup>36</sup>*Universita di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*  
<sup>37</sup>*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*  
<sup>38</sup>*Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*  
<sup>39</sup>*University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*  
<sup>40</sup>*Purdue University, West Lafayette, Indiana 47907, USA*  
<sup>41</sup>*University of Rochester, Rochester, New York 14627, USA*  
<sup>42</sup>*Rockefeller University, New York, New York 10021, USA*  
<sup>43</sup>*Istituto Nazionale de Fisica Nucleare, Sezione di Roma, University di Roma I, "La Sapienza," I-00185 Roma, Italy*  
<sup>44</sup>*Rutgers University, Piscataway, New Jersey 08855, USA*  
<sup>45</sup>*Texas A&M University, College Station, Texas 77843, USA*  
<sup>46</sup>*Texas Tech University, Lubbock, Texas 79409, USA*  
<sup>47</sup>*Institute of Particle Physics, University of Toronto, Toronto M5S 1A7, Canada*  
<sup>48</sup>*Istituto Nazionale di Fisica Nucleare, University of Trieste/ Udine, Italy*  
<sup>49</sup>*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*  
<sup>50</sup>*Tufts University, Medford, Massachusetts 02155, USA*  
<sup>51</sup>*Waseda University, Tokyo 169, Japan*  
<sup>52</sup>*University of Wisconsin, Madison, Wisconsin 53706, USA*  
<sup>53</sup>*Yale University, New Haven, Connecticut 06520, USA*  
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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  $110 \text{ pb}^{-1}$  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  $p\bar{p}$  collisions at center of mass energy  $\sqrt{s} = 1.8 \text{ TeV}$  recorded with the Collider Detector at Fermilab (CDF) during the 1992 to 1995 Tevatron run. The integrated luminosity is approximately  $110 \text{ pb}^{-1}$ .

The CDF detector has been described in detail elsewhere [9]. This analysis makes use of several detector subsystems. The position of  $p\bar{p}$  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  $\text{GeV}/c$  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  $\text{GeV}$ . The transverse energy is

defined as  $E \sin(\theta)$ , with  $E$  being the shower energy measured in the calorimeter and  $\theta$  the polar angle of the energy flow, from the  $p\bar{p}$  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  $\cancel{E}_T$ , 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  $E_T > 20 \text{ GeV}$ , a muon with  $p_T > 20 \text{ GeV}/c$ , and a primary  $p\bar{p}$  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  $p_T > 13 \text{ GeV}/c$  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  $E_T < 100 \text{ GeV}$  or  $p_T < 25 \text{ GeV}/c$ , 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  $Z/\gamma$ ,  $WW$ ,  $WZ$ ,  $ZZ$ , 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  $174.3 \text{ GeV}/c^2$  [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  $\sigma_B$  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,  $\sigma_{ee}$  is the  $Z/\gamma$  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  $Z/\gamma$  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 notwithstanding. To reduce these backgrounds, we require that the angle between the electron and muon in the plane transverse to the beam be at least  $120^\circ$ . 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  $\cancel{E}_T$  and the muon,  $\Delta\phi(\mu, \cancel{E}_T)$ , is less than  $60^\circ$ . 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  $\Delta\phi(e, \cancel{E}_T) < 60^\circ$ . The distribution of  $\Delta\phi(e, \cancel{E}_T)$  versus  $\cancel{E}_T$  is shown in Fig. 1. Since the electrons and muons are nearly back-to-back in  $\phi$ ,  $\Delta\phi(\mu, \cancel{E}_T)$  is approximately  $\Delta\phi(e, \cancel{E}_T) + 180^\circ$ .

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  $p_x^\tau = p_x^l + \cancel{E}_x$ ,  $p_y^\tau = p_y^l + \cancel{E}_y$ , and  $p_z^\tau = p_z^l \times (1 + \cancel{E}_T/p_T^l)$ , 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

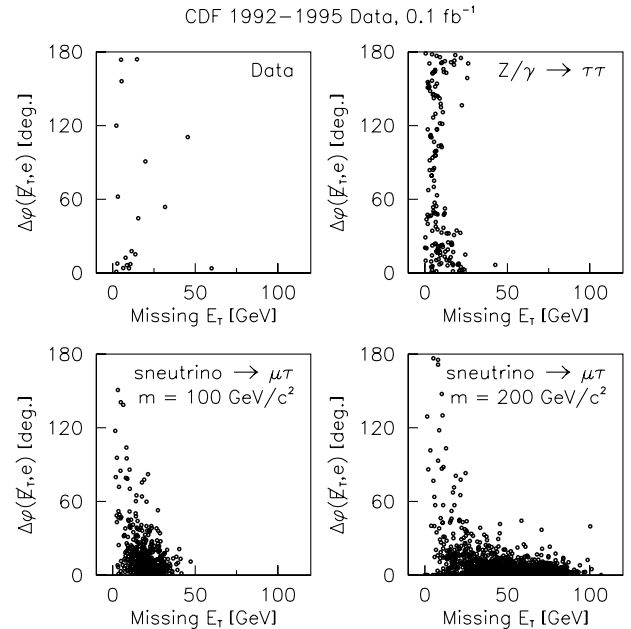


FIG. 1. The angle in the plane transverse to the beam line between the direction of the missing energy and the electron versus the missing transverse energy: data (upper left); simulated  $Z/\gamma \rightarrow \tau\tau \rightarrow e\mu\nu\nu$ , the dominant background (upper right); and a hypothetical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

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

Source	$e\mu$	$e\tau$	$\mu\tau$
$Z/\gamma \rightarrow \tau\tau$	$13.91 \pm 0.99$	$5.20 \pm 0.43$	$6.48 \pm 0.59$
$Z/\gamma \rightarrow \mu\mu$	$0.27 \pm 0.16$	0	$0.27 \pm 0.16$
$WW$	$2.37 \pm 0.32$	$0.42 \pm 0.07$	$0.45 \pm 0.08$
$WZ$	$0.13 \pm 0.02$	$0.03 \pm 0.01$	$0.04 \pm 0.01$
$ZZ$	$0.024 \pm 0.004$	$0.007 \pm 0.001$	$0.007 \pm 0.002$
$t\bar{t}$	$1.34 \pm 0.36$	$0.40 \pm 0.11$	$0.35 \pm 0.10$
False $e$	$0.85 \pm 0.44$	$-0.04 \pm 0.23$	$0.96 \pm 0.32$
False $\mu$	$0.98 \pm 0.27$	$-0.06 \pm 0.11$	$1.07 \pm 0.25$
Total background	$19.88 \pm 1.42$	$5.95 \pm 0.55$	$9.62 \pm 0.81$
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  $d\bar{d} \rightarrow \tilde{\nu} \rightarrow ll'$  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;  $\lambda_{ijk}$  is nonzero only for  $i < j$ ; and mixing is ignored [4,18]. Constraints on the coupling strengths have been derived from measurements of low

energy processes [18,19]. The upper bound on the coupling that mediates  $d\bar{d} \rightarrow \tilde{\nu}_\tau$  is  $\lambda'_{311} < 0.11 \times (m_{\tilde{d}_R}/100 \text{ GeV})$ . The limit is slightly stronger for  $\lambda'_{211}$  and much stronger for  $\lambda'_{111}$ . Of the couplings that contribute to  $\tilde{\nu}_{\mu,\tau} \rightarrow ll'$ , 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  $\mu$ - $e$  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  $\lambda$  constants is nonzero [21]. Previous CDF searches have examined scenarios with  $\lambda'_{121}$  [22] and  $\lambda'_{333}$  [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  $800 \text{ GeV}/c^2$ . 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  $\text{GeV}/c^2$ , 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  $\text{GeV}/c^2$ . 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  $\cancel{E}_T$ . 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  $50 \text{ GeV}/c^2$  with step size from the  $i$ th to the  $(i+1)$ th value equal to one-tenth of the rms of the  $m_{ll'}$  distribution at the  $i$ th point. The mean and rms of the  $m_{ll'}$

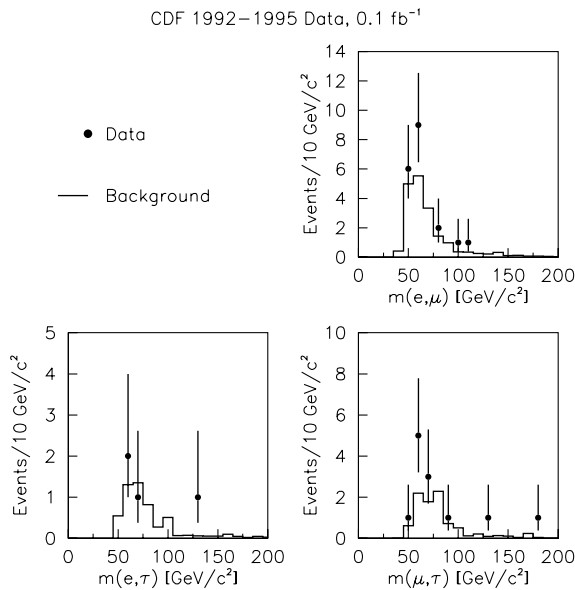


FIG. 2. The reconstructed mass of the lepton pairs. The points show the nineteen  $e\mu$  candidates (upper), the four  $e\tau$  candidates (lower left), and the twelve  $\mu\tau$  candidates (lower right). The histograms show the total background in each sample. The  $e\tau$  and  $\mu\tau$  samples have no events in common; both are subsets of the  $e\mu$  sample.  $\cancel{E}_T$  is used in computing  $\tau$  momentum, as explained in the text.

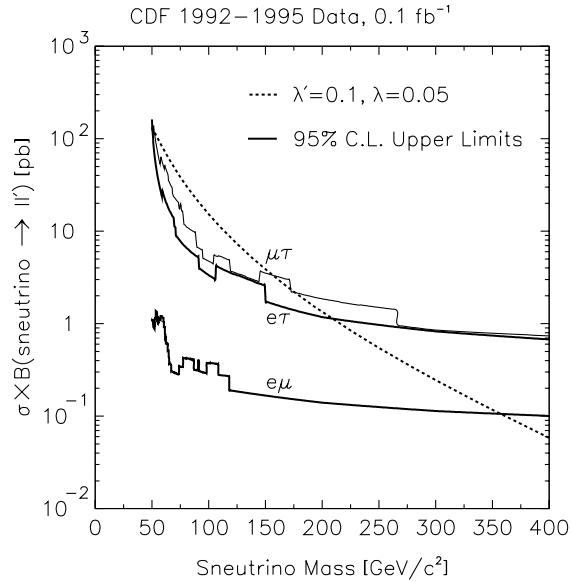


FIG. 3. 95% C.L. upper limits on  $\sigma \times B(\tilde{\nu} \rightarrow e\mu)$ ,  $\sigma \times B(\tilde{\nu} \rightarrow e\tau)$ , and  $\sigma \times B(\tilde{\nu} \rightarrow \mu\tau)$  as a function of sneutrino mass, together with the next-to-leading order cross section for the reference parameters.

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  $\sigma \times B(\tilde{\nu} \rightarrow e\tau)$  and  $\sigma \times B(\tilde{\nu} \rightarrow \mu\tau)$  are higher than the limit on  $\sigma \times B(\tilde{\nu} \rightarrow e\mu)$  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  $d\bar{d} \rightarrow \tilde{\nu}_\tau \rightarrow e^+\mu^-$  plus  $d\bar{d} \rightarrow \tilde{\nu}_\tau \rightarrow e^-\mu^+$  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  $\sigma(d\bar{d} \rightarrow \tilde{\nu})$  for  $\lambda' = 0.01$  [25,26], which we scale by  $(\lambda'/0.01)^2$ .  $B(\tilde{\nu} \rightarrow e\mu)$  is calculated assuming that weak decays of the sneutrino are kinematically forbidden and that the only nonzero RPV couplings are  $\lambda'_{311}$  and  $\lambda_{132}$ .

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  $B(\tilde{\nu} \rightarrow e\mu)$ ,  $B(\tilde{\nu} \rightarrow e\tau)$ , and  $B(\tilde{\nu} \rightarrow \mu\tau)$  as a function of the sneutrino mass. For a sneutrino mass of 200 GeV/c<sup>2</sup>, 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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