

## MIT Open Access Articles

*Observation of Exclusive Charmonium Production and gamma gamma -->mu+mu- in pp-bar Collisions at sqrt[s]=1.96 TeV*

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

**Citation:** CDF Collaboration et al. "Observation of Exclusive Charmonium Production and gamma gamma -->mu+mu- in pp-bar Collisions at s=1.96 TeV." Physical Review Letters 102.24 (2009): 242001. © 2009 The American Physical Society

**As Published:** <http://dx.doi.org/10.1103/PhysRevLett.102.242001>

**Publisher:** American Physical Society

**Persistent URL:** <http://hdl.handle.net/1721.1/51997>

**Version:** Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

**Terms of Use:** Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.



## Observation of Exclusive Charmonium Production and $\gamma\gamma \rightarrow \mu^+ \mu^-$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen,<sup>24</sup> J. Adelman,<sup>14</sup> T. Akimoto,<sup>56</sup> M. G. Albrow,<sup>18</sup> B. Álvarez González,<sup>12</sup> S. Amerio,<sup>44a,44b</sup> D. Amidei,<sup>35</sup> A. Anastassov,<sup>39</sup> A. Annovi,<sup>20</sup> J. Antos,<sup>15</sup> G. Apollinari,<sup>18</sup> A. Apresyan,<sup>49</sup> T. Arisawa,<sup>58</sup> A. Artikov,<sup>16</sup> W. Ashmanskas,<sup>18</sup> A. Attal,<sup>4</sup> A. Aurisano,<sup>54</sup> F. Azfar,<sup>43</sup> P. Azzurri,<sup>47d,47a</sup> W. Badgett,<sup>18</sup> A. Barbaro-Galtieri,<sup>29</sup> V. E. Barnes,<sup>49</sup> B. A. Barnett,<sup>26</sup> V. Bartsch,<sup>31</sup> G. Bauer,<sup>33</sup> P.-H. Beauchemin,<sup>62</sup> F. Bedeschi,<sup>47a</sup> D. Beecher,<sup>31</sup> S. Behari,<sup>26</sup> G. Bellettini,<sup>47b,47a</sup> J. Bellinger,<sup>60</sup> D. Benjamin,<sup>17</sup> A. Beretvas,<sup>18</sup> J. Beringer,<sup>29</sup> A. Bhatti,<sup>51</sup> M. Binkley,<sup>18</sup> D. Bisello,<sup>44b,44a</sup> I. Bizjak,<sup>31</sup> R. E. Blair,<sup>2</sup> C. Blocker,<sup>7</sup> B. Blumenfeld,<sup>26</sup> A. Bocci,<sup>17</sup> A. Bodek,<sup>50</sup> V. Boisvert,<sup>50</sup> G. Bolla,<sup>49</sup> D. Bortoletto,<sup>49</sup> J. Boudreau,<sup>48</sup> A. Boveia,<sup>11</sup> B. Brau,<sup>11</sup> A. Bridgeman,<sup>25</sup> L. Brigliadori,<sup>44a</sup> C. Bromberg,<sup>36</sup> E. Brubaker,<sup>14</sup> J. Budagov,<sup>16</sup> H. S. Budd,<sup>50</sup> S. Budd,<sup>25</sup> S. Burke,<sup>18</sup> K. Burkett,<sup>18</sup> G. Busetto,<sup>44b,44a</sup> P. Bussey,<sup>22</sup> A. Buzatu,<sup>62</sup> K. L. Byrum,<sup>2</sup> S. Cabrera,<sup>17</sup> C. Calancha,<sup>32</sup> M. Campanelli,<sup>36</sup> M. Campbell,<sup>35</sup> F. Canelli,<sup>14,18</sup> A. Canepa,<sup>46</sup> B. Carls,<sup>25</sup> D. Carlsmith,<sup>60</sup> R. Carosi,<sup>47a</sup> S. Carrillo,<sup>19</sup> S. Carron,<sup>62</sup> B. Casal,<sup>12</sup> M. Casarsa,<sup>18</sup> A. Castro,<sup>6b,6a</sup> P. Catastini,<sup>47c,47a</sup> D. Cauz,<sup>55b,55a</sup> V. Cavaliere,<sup>47c,47a</sup> M. Cavalli-Sforza,<sup>4</sup> A. Cerri,<sup>29</sup> L. Cerrito,<sup>31</sup> S. H. Chang,<sup>28</sup> Y. C. Chen,<sup>1</sup> M. Chertok,<sup>8</sup> G. Chiarelli,<sup>47a</sup> G. Chlachidze,<sup>18</sup> F. Chlebana,<sup>18</sup> K. Cho,<sup>28</sup> D. Chokheli,<sup>16</sup> J. P. Chou,<sup>23</sup> G. Choudalakis,<sup>33</sup> S. H. Chuang,<sup>53</sup> K. Chung,<sup>13</sup> W. H. Chung,<sup>60</sup> Y. S. Chung,<sup>50</sup> T. Chwalek,<sup>27</sup> C. I. Ciobanu,<sup>45</sup> M. A. Ciocci,<sup>47c,47a</sup> A. Clark,<sup>21</sup> D. Clark,<sup>7</sup> G. Compostella,<sup>44a</sup> M. E. Convery,<sup>18</sup> J. Conway,<sup>8</sup> M. Cordelli,<sup>20</sup> G. Cortiana,<sup>44b,44a</sup> C. A. Cox,<sup>8</sup> D. J. Cox,<sup>8</sup> F. Crescioli,<sup>47b,47a</sup> C. Cuenca Almenar,<sup>8</sup> J. Cuevas,<sup>12</sup> R. Culbertson,<sup>18</sup> J. C. Cully,<sup>35</sup> D. Dagenhart,<sup>18</sup> M. Datta,<sup>18</sup> T. Davies,<sup>22</sup> P. de Barbaro,<sup>50</sup> S. De Cecco,<sup>52a</sup> A. Deisher,<sup>29</sup> G. De Lorenzo,<sup>4</sup> M. Dell'Orso,<sup>47b,47a</sup> C. Deluca,<sup>4</sup> L. Demortier,<sup>51</sup> J. Deng,<sup>17</sup> M. Deninno,<sup>6a</sup> P. F. Derwent,<sup>18</sup> G. P. di Giovanni,<sup>45</sup> C. Dionisi,<sup>52b,52a</sup> B. Di Ruzza,<sup>55b,55a</sup> J. R. Dittmann,<sup>5</sup> M. D'Onofrio,<sup>4</sup> S. Donati,<sup>47b,47a</sup> P. Dong,<sup>9</sup> J. Donini,<sup>44a</sup> T. Dorigo,<sup>44a</sup> S. Dube,<sup>53</sup> J. Efron,<sup>40</sup> A. Elagin,<sup>54</sup> R. Erbacher,<sup>8</sup> D. Errede,<sup>25</sup> S. Errede,<sup>25</sup> R. Eusebi,<sup>18</sup> H. C. Fang,<sup>29</sup> S. Farrington,<sup>43</sup> W. T. Fedorko,<sup>14</sup> R. G. Feild,<sup>61</sup> M. Feindt,<sup>27</sup> J. P. Fernandez,<sup>32</sup> C. Ferrazza,<sup>47d,47a</sup> R. Field,<sup>19</sup> G. Flanagan,<sup>49</sup> R. Forrest,<sup>8</sup> M. J. Frank,<sup>5</sup> M. Franklin,<sup>23</sup> J. C. Freeman,<sup>18</sup> I. Furic,<sup>19</sup> M. Gallinaro,<sup>52a</sup> J. Galyardt,<sup>13</sup> F. Garberon,<sup>11</sup> J. E. Garcia,<sup>21</sup> A. F. Garfinkel,<sup>49</sup> K. Genser,<sup>18</sup> H. Gerberich,<sup>25</sup> D. Gerdes,<sup>35</sup> A. Gessler,<sup>27</sup> S. Giagu,<sup>55b,55a</sup> V. Giakoumopoulou,<sup>3</sup> P. Giannetti,<sup>47a</sup> K. Gibson,<sup>48</sup> J. L. Gimmell,<sup>50</sup> C. M. Ginsburg,<sup>18</sup> N. Giokaris,<sup>3</sup> M. Giordani,<sup>55b,55a</sup> P. Giromini,<sup>20</sup> M. Giunta,<sup>47b,47a</sup> G. Giurgiu,<sup>26</sup> V. Glagolev,<sup>16</sup> D. Glenzinski,<sup>18</sup> M. Gold,<sup>38</sup> N. Goldschmidt,<sup>19</sup> A. Golossanov,<sup>18</sup> G. Gomez,<sup>12</sup> G. Gomez-Ceballos,<sup>33</sup> M. Goncharov,<sup>33</sup> O. González,<sup>32</sup> I. Gorelov,<sup>38</sup> A. T. Goshaw,<sup>17</sup> K. Goulianos,<sup>51</sup> A. Gresele,<sup>44b,44a</sup> S. Grinstein,<sup>23</sup> C. Grosso-Pilcher,<sup>14</sup> R. C. Group,<sup>18</sup> U. Grundler,<sup>25</sup> J. Guimaraes da Costa,<sup>23</sup> Z. Gunay-Unalan,<sup>36</sup> C. Haber,<sup>29</sup> K. Hahn,<sup>33</sup> S. R. Hahn,<sup>18</sup> E. Halkiadakis,<sup>53</sup> A. Hamilton,<sup>21</sup> B.-Y. Han,<sup>50</sup> J. Y. Han,<sup>50</sup> F. Happacher,<sup>20</sup> K. Hara,<sup>56</sup> D. Hare,<sup>53</sup> M. Hare,<sup>57</sup> S. Harper,<sup>43</sup> R. F. Harr,<sup>59</sup> R. M. Harris,<sup>18</sup> M. Hartz,<sup>48</sup> K. Hatakeyama,<sup>51</sup> C. Hays,<sup>43</sup> M. Heck,<sup>27</sup> A. Heijboer,<sup>46</sup> J. Heinrich,<sup>46</sup> C. Henderson,<sup>33</sup> M. Herndon,<sup>60</sup> J. Heuser,<sup>27</sup> S. Hewamanage,<sup>5</sup> D. Hidas,<sup>17</sup> C. S. Hill,<sup>11</sup> D. Hirschbuehl,<sup>27</sup> A. Hocker,<sup>18</sup> S. Hou,<sup>1</sup> M. Houlden,<sup>30</sup> S.-C. Hsu,<sup>29</sup> B. T. Huffman,<sup>43</sup> R. E. Hughes,<sup>40</sup> U. Husemann,<sup>61</sup> M. Hussein,<sup>36</sup> J. Huston,<sup>36</sup> J. Incandela,<sup>11</sup> G. Introzzi,<sup>47a</sup> M. Iori,<sup>52b,52a</sup> A. Ivanov,<sup>8</sup> E. James,<sup>18</sup> D. Jang,<sup>13</sup> B. Jayatilaka,<sup>17</sup> E. J. Jeon,<sup>28</sup> M. K. Jha,<sup>6a</sup> S. Jindariani,<sup>18</sup> W. Johnson,<sup>8</sup> M. Jones,<sup>49</sup> K. K. Joo,<sup>28</sup> S. Y. Jun,<sup>13</sup> J. E. Jung,<sup>28</sup> T. R. Junk,<sup>18</sup> T. Kamon,<sup>54</sup> D. Kar,<sup>19</sup> P. E. Karchin,<sup>59</sup> Y. Kato,<sup>42</sup> R. Kephart,<sup>18</sup> J. Keung,<sup>46</sup> V. Khotilovich,<sup>54</sup> B. Kilminster,<sup>18</sup> D. H. Kim,<sup>28</sup> H. S. Kim,<sup>28</sup> H. W. Kim,<sup>28</sup> J. E. Kim,<sup>28</sup> M. J. Kim,<sup>20</sup> S. B. Kim,<sup>28</sup> S. H. Kim,<sup>56</sup> Y. K. Kim,<sup>14</sup> N. Kimura,<sup>56</sup> L. Kirsch,<sup>7</sup> S. Klimentenko,<sup>19</sup> B. Knuteson,<sup>33</sup> B. R. Ko,<sup>17</sup> K. Kondo,<sup>58</sup> D. J. Kong,<sup>28</sup> J. Konigsberg,<sup>19</sup> A. Korytov,<sup>19</sup> A. V. Kotwal,<sup>17</sup> M. Kreps,<sup>27</sup> J. Kroll,<sup>46</sup> D. Krop,<sup>14</sup> N. Krumnack,<sup>5</sup> M. Kruse,<sup>17</sup> V. Krutelyov,<sup>11</sup> T. Kubo,<sup>56</sup> T. Kuhr,<sup>27</sup> N. P. Kulkarni,<sup>59</sup> M. Kurata,<sup>56</sup> S. Kwang,<sup>14</sup> A. T. Laasanen,<sup>49</sup> S. Lami,<sup>47a</sup> S. Lammel,<sup>18</sup> M. Lancaster,<sup>31</sup> R. L. Lander,<sup>8</sup> K. Lannon,<sup>40</sup> A. Lath,<sup>53</sup> G. Latino,<sup>47c,47a</sup> I. Lazzizzera,<sup>44b,44a</sup> T. LeCompte,<sup>2</sup> E. Lee,<sup>54</sup> H. S. Lee,<sup>14</sup> S. W. Lee,<sup>54</sup> S. Leone,<sup>47a</sup> J. D. Lewis,<sup>18</sup> C.-S. Lin,<sup>29</sup> J. Linacre,<sup>43</sup> M. Lindgren,<sup>18</sup> E. Lipeles,<sup>46</sup> A. Lister,<sup>8</sup> D. O. Litvintsev,<sup>18</sup> C. Liu,<sup>48</sup> T. Liu,<sup>18</sup> N. S. Lockyer,<sup>46</sup> A. Loginov,<sup>61</sup> M. Loreti,<sup>44b,44a</sup> L. Lovas,<sup>15</sup> D. Lucchesi,<sup>44b,44a</sup> C. Luci,<sup>52b,52a</sup> J. Lueck,<sup>27</sup> P. Lujan,<sup>29</sup> P. Lukens,<sup>18</sup> G. Lungu,<sup>51</sup> L. Lyons,<sup>43</sup> J. Lys,<sup>29</sup> R. Lysak,<sup>15</sup> D. MacQueen,<sup>62</sup> R. Madrak,<sup>18</sup> K. Maeshima,<sup>18</sup> K. Makhoul,<sup>33</sup> T. Maki,<sup>24</sup> P. Maksimovic,<sup>26</sup> S. Malde,<sup>43</sup> S. Malik,<sup>31</sup> G. Manca,<sup>30</sup> A. Manousakis-Katsikakis,<sup>3</sup> F. Margaroli,<sup>49</sup> C. Marino,<sup>27</sup> C. P. Marino,<sup>25</sup> A. Martin,<sup>61</sup> V. Martin,<sup>22</sup> M. Martínez,<sup>4</sup> R. Martínez-Ballarín,<sup>32</sup> T. Maruyama,<sup>56</sup> P. Mastrandrea,<sup>52a</sup> T. Masubuchi,<sup>56</sup> M. Mathis,<sup>26</sup> M. E. Mattson,<sup>59</sup> P. Mazzanti,<sup>6a</sup> K. S. McFarland,<sup>50</sup> P. McIntyre,<sup>54</sup> R. McNulty,<sup>30</sup> A. Mehta,<sup>30</sup> P. Mehtala,<sup>24</sup> A. Menzione,<sup>47a</sup> P. Merkel,<sup>49</sup> C. Mesropian,<sup>51</sup> T. Miao,<sup>18</sup> N. Miladinovic,<sup>7</sup> R. Miller,<sup>36</sup> C. Mills,<sup>23</sup> M. Milnik,<sup>27</sup> A. Mitra,<sup>1</sup> G. Mitselmakher,<sup>19</sup> H. Miyake,<sup>56</sup> N. Moggi,<sup>6a</sup> C. S. Moon,<sup>28</sup> R. Moore,<sup>18</sup> M. J. Morello,<sup>47b,47a</sup> J. Morlock,<sup>27</sup> P. Movilla Fernandez,<sup>18</sup> J. Mülmenstädt,<sup>29</sup> A. Mukherjee,<sup>18</sup> Th. Muller,<sup>27</sup> R. Mumford,<sup>26</sup> P. Murat,<sup>18</sup> M. Mussini,<sup>6b,6a</sup> J. Nachtman,<sup>18</sup> Y. Nagai,<sup>56</sup>

A. Nagano,<sup>56</sup> J. Naganoma,<sup>56</sup> K. Nakamura,<sup>56</sup> I. Nakano,<sup>41</sup> A. Napier,<sup>57</sup> V. Necula,<sup>17</sup> J. Nett,<sup>60</sup> C. Neu,<sup>46</sup> M. S. Neubauer,<sup>25</sup> S. Neubauer,<sup>27</sup> J. Nielsen,<sup>29</sup> L. Nodulman,<sup>2</sup> M. Norman,<sup>10</sup> O. Normiella,<sup>25</sup> E. Nurse,<sup>31</sup> L. Oakes,<sup>43</sup> S. H. Oh,<sup>17</sup> Y. D. Oh,<sup>28</sup> I. Oksuzian,<sup>19</sup> T. Okusawa,<sup>42</sup> R. Orava,<sup>24</sup> K. Osterberg,<sup>24</sup> S. Pagan Griso,<sup>44b,44a</sup> E. Palencia,<sup>18</sup> V. Papadimitriou,<sup>18</sup> A. Papaikononou,<sup>27</sup> A. A. Paramonov,<sup>14</sup> B. Parks,<sup>40</sup> S. Pashapour,<sup>62</sup> J. Patrick,<sup>18</sup> G. Pauletta,<sup>55b,55a</sup> M. Paulini,<sup>13</sup> C. Paus,<sup>33</sup> T. Peiffer,<sup>27</sup> D. E. Pellett,<sup>8</sup> A. Penzo,<sup>55a</sup> T. J. Phillips,<sup>17</sup> G. Piacentino,<sup>47a</sup> E. Pianori,<sup>46</sup> L. Pinera,<sup>19</sup> J. Pinfold,<sup>62</sup> K. Pitts,<sup>25</sup> C. Plager,<sup>9</sup> L. Pondrom,<sup>60</sup> O. Poukhov,<sup>16,\*</sup> N. Pounder,<sup>43</sup> F. Prakoshyn,<sup>16</sup> A. Pronko,<sup>18</sup> J. Proudfoot,<sup>2</sup> F. Ptohos,<sup>18</sup> E. Pueschel,<sup>13</sup> G. Punzi,<sup>47b,47a</sup> J. Pursley,<sup>60</sup> J. Rademacker,<sup>43</sup> A. Rahaman,<sup>48</sup> V. Ramakrishnan,<sup>60</sup> N. Ranjan,<sup>49</sup> I. Redondo,<sup>32</sup> P. Renton,<sup>43</sup> M. Renz,<sup>27</sup> M. Rescigno,<sup>52a</sup> S. Richter,<sup>27</sup> F. Rimondi,<sup>6b,6a</sup> L. Ristori,<sup>47a</sup> A. Robson,<sup>22</sup> T. Rodrigo,<sup>12</sup> T. Rodriguez,<sup>46</sup> E. Rogers,<sup>25</sup> S. Rolli,<sup>57</sup> R. Roser,<sup>18</sup> M. Rossi,<sup>55a</sup> R. Rossin,<sup>11</sup> P. Roy,<sup>62</sup> A. Ruiz,<sup>12</sup> J. Russ,<sup>13</sup> V. Rusu,<sup>18</sup> H. Saarikko,<sup>24</sup> A. Safonov,<sup>54</sup> W. K. Sakumoto,<sup>50</sup> O. Saltó,<sup>4</sup> L. Santi,<sup>55b,55a</sup> S. Sarkar,<sup>52b,52a</sup> L. Sartori,<sup>47a</sup> K. Sato,<sup>18</sup> A. Savoy-Navarro,<sup>45</sup> P. Schlabach,<sup>18</sup> A. Schmidt,<sup>27</sup> E. E. Schmidt,<sup>18</sup> M. A. Schmidt,<sup>14</sup> M. P. Schmidt,<sup>61,\*</sup> M. Schmitt,<sup>39</sup> T. Schwarz,<sup>8</sup> L. Scodellaro,<sup>12</sup> A. Scribano,<sup>47c,47a</sup> F. Scuri,<sup>47a</sup> A. Sedov,<sup>49</sup> S. Seidel,<sup>38</sup> Y. Seiya,<sup>42</sup> A. Semenov,<sup>16</sup> L. Sexton-Kennedy,<sup>18</sup> F. Sforza,<sup>47a</sup> A. Sfyrta,<sup>25</sup> S. Z. Shalhout,<sup>59</sup> T. Shears,<sup>30</sup> P. F. Shepard,<sup>48</sup> M. Shimojima,<sup>56</sup> S. Shiraishi,<sup>14</sup> M. Shochet,<sup>14</sup> Y. Shon,<sup>60</sup> I. Shreyber,<sup>37</sup> A. Sidoti,<sup>47a</sup> P. Sinervo,<sup>62</sup> A. Sisakyan,<sup>16</sup> A. J. Slaughter,<sup>18</sup> J. Slaunwhite,<sup>40</sup> K. Sliwa,<sup>57</sup> J. R. Smith,<sup>8</sup> F. D. Snider,<sup>18</sup> R. Snihur,<sup>62</sup> A. Soha,<sup>8</sup> S. Somalwar,<sup>53</sup> V. Sorin,<sup>36</sup> J. Spalding,<sup>18</sup> T. Spreitzer,<sup>62</sup> P. Squillacioti,<sup>47c,47a</sup> M. Stanitzki,<sup>61</sup> R. St. Denis,<sup>22</sup> B. Stelzer,<sup>62</sup> O. Stelzer-Chilton,<sup>62</sup> D. Stentz,<sup>39</sup> J. Strogas,<sup>38</sup> G. L. Strycker,<sup>35</sup> D. Stuart,<sup>11</sup> J. S. Suh,<sup>28</sup> A. Sukhanov,<sup>19</sup> I. Suslov,<sup>16</sup> T. Suzuki,<sup>56</sup> A. Taffard,<sup>25</sup> R. Takashima,<sup>41</sup> Y. Takeuchi,<sup>56</sup> R. Tanaka,<sup>41</sup> M. Tecchio,<sup>35</sup> P. K. Teng,<sup>1</sup> K. Terashi,<sup>51</sup> J. Thom,<sup>18</sup> A. S. Thompson,<sup>22</sup> G. A. Thompson,<sup>25</sup> E. Thomson,<sup>46</sup> P. Tipton,<sup>61</sup> P. Ttito-Guzmán,<sup>32</sup> S. Tkaczyk,<sup>18</sup> D. Toback,<sup>54</sup> S. Tokar,<sup>15</sup> K. Tollefson,<sup>36</sup> T. Tomura,<sup>56</sup> D. Tonelli,<sup>18</sup> S. Torre,<sup>20</sup> D. Torretta,<sup>18</sup> P. Totaro,<sup>55b,55a</sup> S. Tourneur,<sup>45</sup> M. Trovato,<sup>47a</sup> S.-Y. Tsai,<sup>1</sup> Y. Tu,<sup>46</sup> N. Turini,<sup>47c,47a</sup> F. Ukegawa,<sup>56</sup> S. Vallecorsa,<sup>21</sup> N. van Remortel,<sup>24</sup> A. Varganov,<sup>35</sup> E. Vataga,<sup>47c,47a</sup> F. Vázquez,<sup>19</sup> G. Velev,<sup>18</sup> C. Vellidis,<sup>3</sup> M. Vidal,<sup>32</sup> R. Vidal,<sup>18</sup> I. Vila,<sup>12</sup> R. Vilar,<sup>12</sup> T. Vine,<sup>31</sup> M. Vogel,<sup>38</sup> I. Volobouev,<sup>29</sup> G. Volpi,<sup>47b,47a</sup> P. Wagner,<sup>46</sup> R. G. Wagner,<sup>2</sup> R. L. Wagner,<sup>18</sup> W. Wagner,<sup>27</sup> J. Wagner-Kuhr,<sup>27</sup> T. Wakisaka,<sup>42</sup> R. Wallny,<sup>9</sup> S. M. Wang,<sup>1</sup> A. Warburton,<sup>62</sup> D. Waters,<sup>31</sup> M. Weinberger,<sup>54</sup> J. Weinelt,<sup>27</sup> W. C. Wester III,<sup>18</sup> B. Whitehouse,<sup>57</sup> D. Whiteson,<sup>46</sup> A. B. Wicklund,<sup>2</sup> E. Wicklund,<sup>18</sup> S. Wilbur,<sup>14</sup> G. Williams,<sup>62</sup> H. H. Williams,<sup>46</sup> P. Wilson,<sup>18</sup> B. L. Winer,<sup>40</sup> P. Wittich,<sup>18</sup> S. Wolbers,<sup>18</sup> C. Wolfe,<sup>14</sup> T. Wright,<sup>35</sup> X. Wu,<sup>21</sup> F. Würthwein,<sup>10</sup> S. Xie,<sup>33</sup> A. Yagil,<sup>10</sup> K. Yamamoto,<sup>42</sup> J. Yamaoka,<sup>17</sup> U. K. Yang,<sup>14</sup> Y. C. Yang,<sup>29</sup> W. M. Yao,<sup>29</sup> G. P. Yeh,<sup>18</sup> J. Yoh,<sup>18</sup> K. Yorita,<sup>58</sup> T. Yoshida,<sup>42</sup> G. B. Yu,<sup>50</sup> I. Yu,<sup>28</sup> S. S. Yu,<sup>18</sup> J. C. Yun,<sup>18</sup> L. Zanello,<sup>52b,52a</sup> A. Zanetti,<sup>55a</sup> L. Zhang,<sup>62</sup> X. Zhang,<sup>25</sup> Y. Zheng,<sup>9</sup> and S. Zucchelli<sup>6b,6a</sup>

(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>*University of Athens, 157 71 Athens, Greece*<sup>4</sup>*Institut de Fisica d'Altes Energies, Universitat Autònoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*<sup>5</sup>*Baylor University, Waco, Texas 76798, USA*<sup>6a</sup>*Istituto Nazionale di Fisica Nucleare Bologna, I-40127 Bologna, Italy*<sup>6b</sup>*University of Bologna, I-40127 Bologna, Italy*<sup>7</sup>*Brandeis University, Waltham, Massachusetts 02254, USA*<sup>8</sup>*University of California, Davis, Davis, California 95616, USA*<sup>9</sup>*University of California, Los Angeles, Los Angeles, California 90024, USA*<sup>10</sup>*University of California, San Diego, La Jolla, California 92093, USA*<sup>11</sup>*University of California, Santa Barbara, Santa Barbara, California 93106, USA*<sup>12</sup>*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*<sup>13</sup>*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*<sup>14</sup>*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*<sup>15</sup>*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*<sup>16</sup>*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*<sup>17</sup>*Duke University, Durham, North Carolina 27708, USA*<sup>18</sup>*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*<sup>19</sup>*University of Florida, Gainesville, Florida 32611, USA*<sup>20</sup>*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*<sup>21</sup>*University of Geneva, CH-1211 Geneva 4, Switzerland*<sup>22</sup>*Glasgow University, Glasgow G12 8QQ, United Kingdom*<sup>23</sup>*Harvard University, Cambridge, Massachusetts 02138, USA*

- <sup>24</sup>*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*
- <sup>25</sup>*University of Illinois, Urbana, Illinois 61801, USA*
- <sup>26</sup>*The Johns Hopkins University, Baltimore, Maryland 21218, USA*
- <sup>27</sup>*Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
- <sup>28</sup>*Center for High Energy Physics: Kyungpook National University, Daegu 702-701, Korea; Seoul National University, Seoul 151-742, Korea; Sungkyunkwan University, Suwon 440-746, Korea; Korea Institute of Science and Technology Information, Daejeon, 305-806, Korea; Chonnam National University, Gwangju, 500-757, Korea*
- <sup>29</sup>*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
- <sup>30</sup>*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
- <sup>31</sup>*University College London, London WC1E 6BT, United Kingdom*
- <sup>32</sup>*Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain*
- <sup>33</sup>*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
- <sup>34</sup>*Institute of Particle Physics: University of Alberta, Edmonton, Canada, T6G 2G7; McGill University, Montréal, Québec, Canada H3A 2T8; Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6; University of Toronto, Toronto, Ontario, Canada M5S 1A7; and TRIUMF, Vancouver, British Columbia, Canada V6T 2A3*
- <sup>35</sup>*University of Michigan, Ann Arbor, Michigan 48109, USA*
- <sup>36</sup>*Michigan State University, East Lansing, Michigan 48824, USA*
- <sup>37</sup>*Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*
- <sup>38</sup>*University of New Mexico, Albuquerque, New Mexico 87131, USA*
- <sup>39</sup>*Northwestern University, Evanston, Illinois 60208, USA*
- <sup>40</sup>*The Ohio State University, Columbus, Ohio 43210, USA*
- <sup>41</sup>*Okayama University, Okayama 700-8530, Japan*
- <sup>42</sup>*Osaka City University, Osaka 588, Japan*
- <sup>43</sup>*University of Oxford, Oxford OX1 3RH, United Kingdom*
- <sup>44a</sup>*Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy*
- <sup>44b</sup>*University of Padova, I-35131 Padova, Italy*
- <sup>45</sup>*LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France*
- <sup>46</sup>*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
- <sup>47a</sup>*Istituto Nazionale di Fisica Nucleare Pisa, I-56127 Pisa, Italy*
- <sup>47b</sup>*University of Pisa, I-56127 Pisa, Italy*
- <sup>47c</sup>*University of Siena, I-56127 Pisa, Italy*
- <sup>47d</sup>*Scuola Normale Superiore, I-56127 Pisa, Italy*
- <sup>48</sup>*University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*
- <sup>49</sup>*Purdue University, West Lafayette, Indiana 47907, USA*
- <sup>50</sup>*University of Rochester, Rochester, New York 14627, USA*
- <sup>51</sup>*The Rockefeller University, New York, New York 10021, USA*
- <sup>52a</sup>*Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, I-00185 Roma, Italy*
- <sup>52b</sup>*Sapienza Università di Roma, I-00185 Roma, Italy*
- <sup>53</sup>*Rutgers University, Piscataway, New Jersey 08855, USA*
- <sup>54</sup>*Texas A&M University, College Station, Texas 77843, USA*
- <sup>55a</sup>*Istituto Nazionale di Fisica Nucleare Trieste/Udine, I-34100 Trieste, Italy*
- <sup>55b</sup>*University of Trieste/Udine, I-33100 Udine, Italy*
- <sup>56</sup>*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
- <sup>57</sup>*Tufts University, Medford, Massachusetts 02155, USA*
- <sup>58</sup>*Waseda University, Tokyo 169, Japan*
- <sup>59</sup>*Wayne State University, Detroit, Michigan 48201, USA*
- <sup>60</sup>*University of Wisconsin, Madison, Wisconsin 53706, USA*
- <sup>61</sup>*Yale University, New Haven, Connecticut 06520, USA*
- <sup>62</sup>*Institute of Particle Physics: University of Alberta, Edmonton, Canada T6G 2G7; McGill University, Montréal, Québec, Canada H3A 2T8; Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6; University of Toronto, Toronto, Ontario, Canada M5S 1A7; and TRIUMF, Vancouver, British Columbia, Canada V6T 2A3*

(Received 16 February 2009; published 15 June 2009)



In CDF we have observed the reactions  $p + \bar{p} \rightarrow p + X + \bar{p}$ , with  $X$  being a centrally produced  $J/\psi$ ,  $\psi(2S)$ , or  $\chi_{c0}$ , and  $\gamma\gamma \rightarrow \mu^+\mu^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV. The event signature requires two oppositely charged central muons, and either no other particles or one additional photon detected. Exclusive vector meson production is as expected for elastic photoproduction,  $\gamma + p \rightarrow J/\psi(\psi(2S)) + p$ , observed here for the first time in hadron-hadron collisions. We also observe exclusive  $\chi_{c0} \rightarrow J/\psi + \gamma$ . The cross sections  $\frac{d\sigma}{dy}|_{y=0}$  for  $J/\psi$ ,  $\psi(2S)$ , and  $\chi_{c0}$  are  $3.92 \pm 0.25(\text{stat}) \pm 0.52(\text{syst})$  nb,  $0.53 \pm 0.09(\text{stat}) \pm 0.10(\text{syst})$  nb, and  $76 \pm 10(\text{stat}) \pm 10(\text{syst})$  nb, respectively, and the continuum is consistent with QED. We put an upper limit on the cross section for Odderon exchange in exclusive  $J/\psi$  production.

DOI: 10.1103/PhysRevLett.102.242001

PACS numbers: 13.85.Fb, 12.38.Qk, 12.40.Vv, 13.60.-r

In central exclusive production processes,  $p + \bar{p} \rightarrow p + X + \bar{p}$ , the colliding hadrons emerge intact with small transverse momenta,  $p_T$  [1], and the produced state  $X$  is in the central region, with small rapidity  $|y|$ , and is fully measured. If regions of rapidity exceeding about 5 units are devoid of particles, only photon and Pomeron [2],  $\mathbb{P}$ , exchanges are significant, where  $\mathbb{P}$  consists mostly of two gluons in a color singlet state with charge parity  $C = +1$ . Odderon,  $O$ , exchange, with 3 gluons in a  $C = -1$  state [3–5], is allowed in  $p\bar{p}$ , but not  $ep$ , collisions, and would appear as an enhancement in exclusive  $J/\psi$  and  $\psi(2S)$  production in  $p\bar{p}$  compared to the expectation from pure photoproduction in  $ep$ . Using the CDF II detector at the Fermilab Tevatron, we previously observed [6]  $p + \bar{p} \rightarrow p + e^+e^- + \bar{p}$  in agreement with QED, and found candidates [7] for  $p + \bar{p} \rightarrow p + \gamma\gamma + \bar{p}$  consistent with QCD expectations [8]. In this Letter we report measurements of exclusive dimuon production,  $X = \mu^+\mu^-$ , with  $M_{\mu\mu} \in [3.0, 4.0]$  GeV/ $c^2$ , directly [QED, Fig. 1(a)], or from photoproduced  $J/\psi(3097)$  or  $\psi(2S)(3686)$  [Fig. 1(b)] decay, and  $\chi_{c0}(3415) \rightarrow J/\psi + \gamma \rightarrow \mu^+\mu^-\gamma$  [Fig. 1(c)]. Lower masses were excluded by muon range, and higher masses by trigger rate limitations. Exclusive photoproduction of vector mesons has been measured in  $ep$  collisions at HERA [9], but not previously observed in hadron-hadron collisions. The theoretical uncertainty on the QED cross section is  $<0.3\%$ ; this process is distinct from Drell-Yan production ( $q\bar{q} \rightarrow \mu^+\mu^-$ ), which is negligible in this regime.

At the LHC, in  $pp$  collisions with  $\sqrt{s} = 10\text{--}14$  TeV, central exclusive production of states such as  $X = H$  and  $W^+W^-$ , where  $H$  is a Higgs boson, are allowed [10]. Apart from their intrinsic interest, our measurements confirm the viability of the proposed LHC studies. The  $p + \chi_{c0} + \bar{p}$  [Fig. 1(c)] and  $p + H + p$  [as in Fig. 1(c) but with a top quark loop] cross sections are related [11], and  $p + \mu^+\mu^- + p$  can be used to calibrate forward proton spectrometers.

We used  $p\bar{p}$  collision data at  $\sqrt{s} = 1.96$  TeV with an integrated luminosity  $L = 1.48 \text{ fb}^{-1}$  delivered to the CDF II detector. This is a general purpose detector described elsewhere [12]. Surrounding the collision region is a tracking system consisting of silicon microstrip detectors and a cylindrical drift chamber in a 1.4 Tesla solenoidal field.

The tracking system has  $\approx 100\%$  efficiency for reconstructing isolated tracks with  $p_T \geq 1$  GeV/ $c$  and  $|\eta| < 0.6$  [1]. A barrel of 216 time-of-flight counters outside the cylindrical drift chamber is surrounded by calorimeters with separate electromagnetic (EM) and hadronic sections covering the range  $|\eta| < 3.6$ . Drift chambers outside the calorimeters were used to measure muons with  $|\eta| < 0.6$  [13]. The regions  $3.6 < |\eta| < 5.2$  are covered by lead-liquid scintillator calorimeters [14]. Gas Cherenkov counters covering  $3.7 < |\eta| < 4.7$  determined the luminosity with a 6% uncertainty [15]. We did not have detectors able to measure the forward  $p$  and  $\bar{p}$ , but beam shower scintillation counters (BSC1–BSC3), located along the beam pipe, detected products of  $p(\bar{p})$  fragmentation, such as  $p \rightarrow p\pi\pi$ , with  $|\eta| < 7.4$ .

The level 1 trigger required at least one muon track with  $p_T > 1.4$  GeV/ $c$  and no signal in BSC1 ( $5.4 \lesssim |\eta| \lesssim 5.9$ ), and a higher level trigger required a second track with opposite charge. The offline event selection closely followed that described in Ref. [6], where we observed exclusive  $e^+e^-$  production. We required two oppositely charged muon tracks, each with  $p_T > 1.4$  GeV/ $c$  and  $|\eta| < 0.6$ , accompanied by either (a) no other particles in the event or (b) only one additional EM shower with  $E_T^{\text{EM}} > 80$  MeV and  $|\eta| < 2.1$ . Condition (a) defines an exclusive dimuon event. The exclusivity efficiency  $\varepsilon_{\text{exc}}$  is the probability that the exclusive requirement is not spoiled by another inelastic interaction in the same bunch crossing, or by noise in a detector element. This efficiency was measured [6] as the fraction of bunch crossing triggers that pass the exclusivity requirement (a). We found  $\varepsilon_{\text{exc}} = 0.093$  with negligible uncertainty. The product  $\varepsilon_{\text{exc}}L = L_{\text{eff}} = 139 \pm 8 \text{ pb}^{-1}$  was the effective luminosity for single interactions.

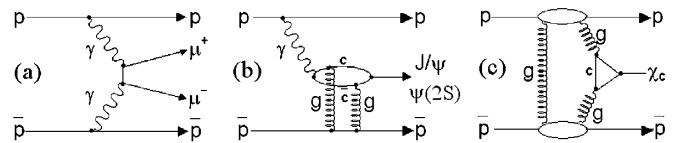


FIG. 1. Feynman diagrams for (a)  $\gamma\gamma \rightarrow \mu^+\mu^-$ , (b)  $\gamma\mathbb{P} \rightarrow J/\psi(\psi(2S))$ , and (c)  $\mathbb{P}\mathbb{P} \rightarrow \chi_c$ , with the 2-gluon exchange forming a Pomeron.

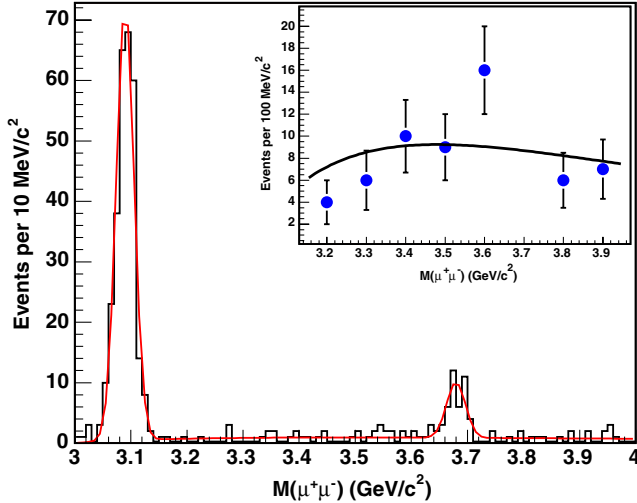


FIG. 2 (color online). Mass  $M_{\mu\mu}$  distribution of 402 exclusive events, with no EM shower (histogram), together with a fit to two Gaussians for the  $J/\psi$  and  $\psi(2S)$ , and a QED continuum. All three shapes are predetermined, with only the normalizations floating. Inset: Data above the  $J/\psi$  and excluding  $3.65 < M_{\mu\mu} < 3.75$   $\text{GeV}/c^2$  [ $\psi(2S)$ ] with the fit to the QED spectrum times acceptance (statistical uncertainties only).

After these selections, cosmic rays were the main background. They were all rejected, with no significant loss of real events, by timing requirements in the time-of-flight counters and by requiring the three-dimensional opening angle between the muon tracks to be  $\Delta\theta_{3D}(\mu\mu) < 3.0$  rad. Within a fiducial kinematic region (FKR) [ $|\eta(\mu)| < 0.6$ , and  $M_{\mu\mu} \in [3.0, 4.0]$   $\text{GeV}/c^2$ ], there are 402 events with no EM shower. The  $M_{\mu\mu}$  spectrum is shown in Fig. 2. The  $J/\psi$  and  $\psi(2S)$  are prominent, together with a continuum. The spectrum is well fitted by two Gaussians with expected

masses and widths (dominated by the resolution) and a continuum whose shape is given by the product of the QED spectrum ( $\gamma\gamma \rightarrow \mu^+\mu^-$ ), acceptance, and efficiency, as shown in Fig. 2 (inset). The numbers of events from the fit are given in Table I, with statistical uncertainties. The numbers given in Table I for backgrounds, acceptances, and efficiencies show systematic uncertainties estimated by varying parameters within acceptable bounds.

Backgrounds to exclusive  $\mu^+\mu^-$  events are (see Table I) (a) proton fragmentation, if the products are not detected in the forward detectors, (b) for the  $J/\psi$ ,  $\chi_{c0}$  events with a photon that did not give an EM shower above 80 MeV, and (c) events with some other particle not detected. The probability of a  $p$  or  $\bar{p}$  fragmenting at the  $p\gamma p(p^*)$  vertex was calculated with the LPAIR Monte Carlo (MC) simulation [17] to be  $0.17 \pm 0.02(\text{syst})$ , and the probability that all the fragmentation products have  $|\eta| > 7.4$  to be  $0.14 \pm 0.02(\text{syst})$ . If a proton fragments, the decay products may not be detected through BSC inefficiency, estimated from data to be  $0.08 \pm 0.01$ . The fragmentation probability at the  $p\mathbb{P}p(p^*)$  vertex was taken from the ratio of single diffractive fragmentation to elastic scattering at the Tevatron [18] to be  $0.24 \pm 0.05$ .

We compared the kinematics of the muons, e.g.  $p_T(\mu^+\mu^-)$  and  $\Delta\phi_{\mu\mu}$ , with simulations for the three classes:  $J/\psi$ ,  $\psi(2S)$  [19], and QED [17] with  $M_{\mu\mu} \in [3.2, 3.6]$  and  $[3.8, 4.0]$   $\text{GeV}/c^2$  to exclude the  $J/\psi$  and  $\psi(2S)$ . The distributions agree well with the simulations; the few events that are outside expectations are taken to be nonexclusive background. Figure 3 shows the distributions of  $p_T(\mu^+\mu^-)$ . As expected,  $\langle p_T \rangle$  is smaller for the QED process, and the data agree well with STARLIGHT [19], apart from two events with  $p_T > 0.8$   $\text{GeV}/c$  where no events are expected. Comparing data with LPAIR we estimate that the nonexclusive background is  $(9 \pm 5)\%$  of the observed

TABLE I. Numbers of events fitted to classes  $J/\psi$ ,  $\psi(2S)$ ,  $\chi_{c0}$ , and QED. Backgrounds are given as percentages of the fit events, and efficiencies are to be applied to the events without background. The stated branching fraction  $\mathcal{B}$  for the  $\chi_{c0}$  is the product of the  $\chi_{c0} \rightarrow J/\psi + \gamma$  and  $J/\psi \rightarrow \mu^+\mu^-$  branching fractions [16]. For events (fit) the uncertainty is only statistical; all other uncertainties are purely systematic except when both are given. The cross sections include a 6% luminosity uncertainty.

Class	$J/\psi$	$\psi(2S)$	$\chi_{c0}(1P)$	$\gamma\gamma \rightarrow \mu^+\mu^-$
Acceptances:				
Detector (%)	$18.8 \pm 2.0$	$54 \pm 3$	$19 \pm 2$	$41.8 \pm 1.5$
Efficiencies:				
$\mu$ -quality (%)	$33.4 \pm 1.7$	$45 \pm 6$	$33 \pm 2$	$41.8 \pm 2.3$
Photon (%)	...	...	$83 \pm 4$	...
Events(fit)	$286 \pm 17$	$39 \pm 7$	$65 \pm 8$	$77 \pm 9$
Backgrounds:				
Fragmentation (%)	$9 \pm 2$	$9 \pm 2$	$11 \pm 2$	$8 \pm 2$
Nonexclusive (%)	$3 \pm 3$	$3 \pm 3$	$3 \pm 3$	$9 \pm 5$
$\chi_{c0}$ (%)	$4.0 \pm 1.6$	...	...	...
$\mathcal{B} \rightarrow \mu^+\mu^-$ (%)	$5.93 \pm 0.06$	$0.75 \pm 0.08$	$0.076 \pm 0.007$	...
$\mathcal{B}\sigma_{\text{FKR}}$ (pb)	$28.4 \pm 2.0(\text{stat}) \pm 6.0(\text{syst})$	$1.02 \pm 0.17(\text{stat}) \pm 0.19(\text{syst})$	$8.0 \pm 0.9(\text{stat}) \pm 0.9(\text{syst})$	$27 \pm 0.3(\text{stat}) \pm 0.4(\text{syst})$
$\frac{d\sigma}{dy} _{y=0}$ (nb)	$3.92 \pm 0.25(\text{stat}) \pm 0.52(\text{syst})$	$0.53 \pm 0.09(\text{stat}) \pm 0.10(\text{syst})$	$76 \pm 10(\text{stat}) \pm 10(\text{syst})$	...

(QED) events. The  $\psi(2S)$  data are well fitted by the STARLIGHT photoproduction simulation [19]. The distribution of  $p_T(J/\psi)$  is well fitted by STARLIGHT, apart from five events with  $p_T(J/\psi) > 1.4$  GeV/c [Fig. 3(b)]. These could be due to nonexclusive background, some  $\chi_{c0}$  radiative decays with an undetected photon, or an Odderon component.

To measure  $\chi_{c0}$  production we required one EM shower with  $E_T^{\text{EM}} > 80$  MeV in addition to the two muons; if two adjacent towers had enough energy, they were combined. There are 65 events in the  $J/\psi$  peak and eight continuum events; these are likely to be  $\gamma\gamma \rightarrow \mu^+\mu^-$  with a bremsstrahlung. We interpret the 65 events as  $\chi_{c0} \rightarrow J/\psi + \gamma$  production and decay. The distribution of the mass formed from the  $J/\psi$  and the EM shower energy, while broad, has a mean value equal to the  $\chi_{c0}$  mass. The  $E_T^{\text{EM}}$  spectrum is well fitted by an empirical function which extrapolates to only  $3.6 \pm 1.3(\text{syst})$   $\chi_{c0}$  candidates with showers below 80 MeV. The  $p_T(J/\psi)$  and  $\Delta\phi_{\mu\mu}$  distributions for the events with an  $E_T^{\text{EM}}$  signal are consistent with all these  $J/\psi$  being from  $\chi_{c0}$  decay, as simulated by CHICMC [20]. Additional photon inefficiency comes from conversion in material,  $7 \pm 2\%$ , and dead regions of the calorimeter,  $5.0 \pm 2.5\%$ , giving a total inefficiency  $17 \pm 4\%$ , which gives a background to exclusive  $J/\psi$  of  $4.0 \pm 1.6\%$  (all errors systematic).

We calculated acceptances and efficiencies using the LPAIR [17] and STARLIGHT [19] MC generators for QED,  $J/\psi$  and  $\psi(2S)$ , and CHICMC [20] for  $\chi_{c0}$  production. Generated events were passed through a GEANT-based [21] simulation of the CDF detector. The trigger efficiency for muons rose steeply between 1.4 GeV/c and 1.5 GeV/c, where it exceeded 90%. As we triggered on one muon, the trigger efficiency for events with two muons was  $>99\%$  for  $M_{\mu\mu} > 3$  GeV/ $c^2$ .

Figure 2 (inset) shows the subset of the Fig. 2 data above  $3.15$  GeV/ $c^2$  (to exclude the  $J/\psi$ ), excluding the bin  $3.65$ – $3.75$  GeV/ $c^2$  which contains the  $\psi(2S)$ . The curve shows the product of the QED spectrum and acceptance  $\times$  efficiency,  $A\epsilon$ , with only the normalization floating, from the 3-component fit to the full spectrum. The continuum data agrees with the QED expectation. The integral from

$3$  GeV/ $c^2$  to  $4$  GeV/ $c^2$  is  $77 \pm 9(\text{stat})$  events, and after correcting for backgrounds and efficiencies (Table I), the measured cross section for QED events with  $|\eta(\mu^\pm)| < 0.6$  and  $M_{\mu\mu} \in [3.0, 4.0]$  GeV/ $c^2$  is  $\sigma = 2.7 \pm 0.3(\text{stat}) \pm 0.4(\text{syst})$  pb, in agreement with the QED prediction  $2.18 \pm 0.01$  pb [17].

For the prompt  $J/\psi$  and  $\psi(2S)$  cross sections, we took the number of events from the Gaussian fits, subtracted backgrounds, and corrected for  $A\epsilon$  to obtain  $\mathcal{B}\sigma_{\text{FKR}}$  for both muons in the fiducial kinematic region (see Table I). To obtain  $\frac{d\sigma}{dy}|_{y=0}$  from  $\sigma_{\text{FKR}}$  we used the STARLIGHT MC program, which gives the ratio of these two cross sections for each resonance, and divided by the branching fractions  $\mathcal{B}$ . We found  $\frac{d\sigma}{dy}|_{y=0}(J/\psi) = 3.92 \pm 0.25(\text{stat}) \pm 0.52(\text{syst})$  nb. This agrees with the predictions  $2.7_{-0.2}^{+0.6}$  nb [19] and  $3.4 \pm 0.4$  nb [22] among others [23,24]. We found  $\frac{d\sigma}{dy}|_{y=0}(\psi(2S)) = 0.53 \pm 0.09(\text{stat}) \pm 0.10(\text{syst})$  nb compared with a prediction [19]  $0.46_{-0.04}^{+0.11}$  nb. The ratio  $R = \frac{\psi(2S)}{J/\psi} = 0.14 \pm 0.05$  is in agreement with the HERA value [9]  $R = 0.166 \pm 0.012$  at similar  $\sqrt{s(\gamma p)}$ .

After correcting the 65  $\chi_{c0}$  candidates for backgrounds and efficiencies, and applying the branching fraction  $\mathcal{B}(\chi_{c0} \rightarrow J/\psi + \gamma) = 0.0128 \pm 0.0011$  [16], we found  $\frac{d\sigma}{dy}|_{y=0}(\chi_{c0}) = 76 \pm 10(\text{stat}) \pm 10(\text{syst})$  nb. The  $\chi_{c2}(3556)$  may be present, although it is strongly suppressed by the  $J_z = 0$  rule [11] and is forbidden at  $0^\circ$  scattering angle. Exclusive  $gg \rightarrow \chi_{c1}(3511)$ ,  $J^{\text{PC}} = 1^{++}$  is forbidden by the Landau-Yang theorem, but may occur with off-shell gluons [25]. It is nevertheless forbidden by symmetry arguments [26] when both  $p$  and  $\bar{p}$  scatter at  $0^\circ$ . Because of the limited  $M(J/\psi + \gamma)$  resolution we cannot distinguish these states; we assume  $\chi_{c1}$  and  $\chi_{c2}$  to be negligible. If several states  $\chi_{ci}$  are present,  $\sum \mathcal{B}_i \sigma_{i,\text{FKR}} = 8.0 \pm 0.9(\text{stat}) \pm 0.9(\text{syst})$  pb. Theoretical predictions have large (often unstated) uncertainties, but are compatible with our measurement. Reference [11] predicted  $\frac{d\sigma}{dy}|_{y=0}(\chi_{c0}) = 130$  nb; however, the Particle Data Group (PDG) value [16] of the  $\chi_c$  width has since been reduced by a factor 1.45, correcting their prediction to 90 nb. Yuan [27] predicted 160 nb (again the factor  $\frac{1}{1.45}$  should be applied) and Bzdak [28] 45 nb.

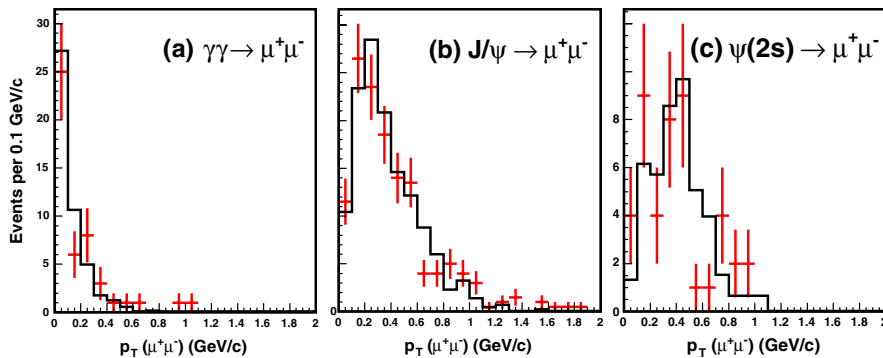


FIG. 3 (color online).  $p_T$  distribution of  $\mu^+\mu^-$  (points with statistical error bars) for (a) QED,  $M_{\mu\mu} \in [3.2, 3.6] + [3.8, 4.0]$  GeV/ $c^2$ , (b)  $J/\psi$ , and (c)  $\psi(2S)$ . The MC predictions (with no background) are shown by the histograms, normalized to the data.

If the  $J/\psi$  and  $\psi(2S)$  cross sections were larger than expected for photoproduction, it would be evidence for Odderon exchange. Taking a theoretical value of  $\frac{d\sigma}{dy}|_{y=0}(J/\psi) = 3.0 \pm 0.3$  nb for photoproduction, compatible with the predictions, we give a 95% C.L. upper limit  $\frac{d\sigma}{dy}|_{y=0}(J/\psi) < 2.3$  nb for Odderon exchange ( $O^{\mathbb{P}} \rightarrow J/\psi$ ). Bzdak *et al.* [29] predicted the ratio of Odderon: photon exchange in  $J/\psi$  production to be 0.3–0.6, consistent with our limit.

In conclusion we have observed, for the first time in hadron-hadron collisions, exclusive photoproduction of  $J/\psi$  and  $\psi(2S)$ , exclusive double Pomeron production of  $\chi_{c0}$ , and the QED process  $\gamma\gamma \rightarrow \mu^+\mu^-$ . The photoproduction process has previously been studied in  $ep$  collisions at HERA, with similar kinematics ( $\sqrt{s(\gamma p)} \approx 100$  GeV), and the cross sections are in agreement. We put an upper limit on an Odderon contribution to exclusive  $J/\psi$  production. Our observation of exclusive  $\chi_{c0}$  production implies that exclusive Higgs boson production should occur at the LHC [10] and imposes constraints on the  $p + p \rightarrow p + H + p$  cross section.

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

\*Deceased.

- [1] A cylindrical coordinate system is used with the  $z$  axis along the proton beam direction;  $\theta$  is the polar angle and  $\phi$  is the azimuthal angle. Transverse momentum is  $p_T = |p| \sin\theta$ , and transverse energy is  $E_T = E \sin\theta$  where  $E$  is the energy. Pseudorapidity is  $\eta = -\ln(\tan\frac{\theta}{2})$ , and for the charmonium states we use longitudinal rapidity  $y = -\ln\frac{E+p_z}{E-p_z}$ .
- [2] See, e.g., J. R. Forshaw and D. A. Ross, *Quantum Chromodynamics and the Pomeron* (Cambridge University Press,

Cambridge, England, 1997); S. Donnachie *et al.*, *Pomeron Physics and QCD* (Cambridge University Press, Cambridge, England, 2002).

- [3] A. Schäfer, L. Mankiewicz, and O. Nachtmann, *Phys. Lett. B* **272**, 419 (1991).
- [4] V. A. Khoze, A. D. Martin, and M. G. Ryskin, *Eur. Phys. J. C* **24**, 459 (2002).
- [5] C. Ewerz, arXiv:hep-ph/0306137.
- [6] A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **98**, 112001 (2007).
- [7] T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **99**, 242002 (2007).
- [8] V. A. Khoze, A. D. Martin, M. G. Ryskin, and W. J. Stirling, *Eur. Phys. J. C* **38**, 475 (2005).
- [9] See, e.g., H. Jung, *Acta Phys. Pol. Supp.* **1**, 531 (2008), and references therein.
- [10] M. G. Albrow *et al.*, arXiv:0806.0302 [J. Inst. (to be published)].
- [11] V. A. Khoze, A. D. Martin, M. G. Ryskin, and W. J. Stirling, *Eur. Phys. J. C* **35**, 211 (2004); V. A. Khoze, A. D. Martin, and M. G. Ryskin, *Eur. Phys. J. C* **19**, 477 (2001); **20**, 599(E) (2001); (private communication).
- [12] D. Acosta *et al.* (CDF Collaboration), *Phys. Rev. D* **71**, 032001 (2005) and references therein.
- [13] G. Ascoli *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **268**, 33 (1988).
- [14] M. Gallinaro *et al.*, *IEEE Trans. Nucl. Sci.* **52**, 879 (2005).
- [15] D. Acosta *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **494**, 57 (2002).
- [16] C. Amsler *et al.*, *Phys. Lett. B* **667**, 1 (2008).
- [17] J. A. M. Vermaseren, *Nucl. Phys. B* **229**, 347 (1983); S. P. Baranov *et al.*, in *Proc. Physics at HERA* (DESY, Hamburg, 1991), p. 1478.
- [18] F. Abe *et al.* (CDF Collaboration), *Phys. Rev. D* **50**, 5518 (1994); **50**, 5535 (1994).
- [19] S. Klein and J. Nystrand, *Phys. Rev. Lett.* **92**, 142003 (2004); (private communication).
- [20] W. J. Stirling (private communication).
- [21] S. Agostinelli *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [22] L. Motyka and G. Watt, *Phys. Rev. D* **78**, 014023 (2008).
- [23] W. Schäfer and A. Szczurek, *Phys. Rev. D* **76**, 094014 (2007).
- [24] V. P. Goncalves and M. V. T. Machado, *Eur. Phys. J. C* **40**, 519 (2005).
- [25] R. S. Pasechnik, A. Szczurek, and O. V. Teryaev, arXiv:0901.4187.
- [26] A. D. Kaidalov, V. A. Khoze, A. D. Martin, and M. G. Ryskin, *Eur. Phys. J. C* **31**, 387 (2003).
- [27] F. Yuan, *Phys. Lett. B* **510**, 155 (2001).
- [28] A. Bzdak, *Phys. Lett. B* **619**, 288 (2005).
- [29] A. Bzdak, L. Motyka, L. Szymanowski, and J.-R. Cudell, *Phys. Rev. D* **75**, 094023 (2007).