

Physics

Physics Research Publications

Purdue University

Year 2008

Strong evidence for ZZ production in pp collisions at $\sqrt{s}=1.96$ TeV

T. Aaltonen, J. Adelman, T. Akimoto, M. G. Albrow, B. A. Gonzalez, S. Amerio, D. Amidei, A. Anastassov, A. Annovi, J. Antos, M. Aoki, G. Apollinari, A. Apresyan, T. Arisawa, A. Artikov, W. Ashmanskas, A. Attal, A. Aurisano, F. Azfar, P. Azzi-Bacchetta, P. Azzurri, N. Bacchetta, W. Badgett, A. Barbaro-Galtieri, V. E. Barnes, B. A. Barnett, S. Baroiant, V. Bartsch, G. Bauer, P. H. Beauchemin, F. Bedeschi, P. Bednar, S. Behari, G. Bellettini, J. Bellinger, A. Belloni, D. Benjamin, A. Beretvas, J. Beringer, T. Berry, A. Bhatti, M. Binkley, D. Bisello, I. Bizjak, R. E. Blair, C. Blocker, B. Blumenfeld, A. Bocci, A. Bodek, V. Boisvert, G. Bolla, A. Bolshov, D. Bortoletto, J. Boudreau, A. Boveia, B. Brau, A. Bridgeman, L. Brigliadori, C. Bromberg, E. Brubaker, J. Budagov, H. S. Budd, S. Budd, K. Burkett, G. Busetto, P. Bussey, A. Buzatu, K. L. Byrum, S. Cabrera, M. Campanelli, M. Campbell, F. Canelli, A. Canepa, D. Carlsmith, R. Carosi, S. Carrillo, S. Carron, B. Casal, M. Casarsa, A. Castro, P. Catastini, D. Cauz, M. Cavalli-Sforza, A. Cerri, L. Cerrito, S. H. Chang, Y. C. Chen, M. Chertok, G. Chiarelli, G. Chlachidze, F. Chlebana, K. Cho, D. Chokheli, J. P. Chou, G. Choudalakis, S. H. Chuang, K. Chung, W. H. Chung, Y. S. Chung, C. I. Ciobanu, M. A. Ciocci, A. Clark, D. Clark, G. Compostella, M. E. Convery, J. Conway, B. Cooper, K. Copic, M. Cordelli, G. Cortiana, F. Crescioli, C. C. Almenar, J. Cuevas, R. Culbertson, J. C. Cully, D. Dagenhart, M. Datta, T. Davies, P. de Barbaro, S. De Cecco, A. Deisher, G. De Lentdecker, G. De Lorenzo, M. Dell'Orso, L. Demortier, J. Deng, M. Deninno, D. De Pedis, P. F. Derwent, G. P. Di Giovanni, C. Dionisi, B. Di Ruzza, J. R. Dittmann, M. D'Onofrio, S. Donati, P. Dong, J. Donini, T. Dorigo, S. Dube, J. Efron, R. Erbacher, D. Errede, S. Errede, R. Eusebi, H. C. Fang, S. Farrington, W. T. Fedorko, R. G. Feild, M. Feindt, J. P. Fernandez, C. Ferrazza, R. Field, G. Flanagan, R. Forrest, S. Forrester, M. Franklin, J. C. Freeman, I. Furic, M. Gallinaro, J. Galyardt, F. Garbersen, J. E. Garcia, A. F. Garfinkel, K. Genser, H. Gerberich, D. Gerdes, S. Giagu, V. Giakoumopolou, P. Giannetti, K. Gibson, J. L. Gimmell, C. M. Ginsburg, N. Giokaris, M. Giordani, P. Giromini, M. Giunta, V. Glagolev, D. Glenzinski, M. Gold, N. Goldschmidt, A. Golossanov, G. Gomez, G. Gomez-Ceballos, M. Goncharov, O. Gonzalez, I. Gorelov, A. T. Goshaw, K. Goulios, A. Gresele, S. Grinstein, C. Grosso-Pilcher, R. C. Group,

U. Grundler, J. G. da Costa, Z. Gunay-Unalan, C. Haber, K. Hahn, S. R. Hahn, E. Halkiadakis, A. Hamilton, B. Y. Han, J. Y. Han, R. Handler, F. Happacher, K. Hara, D. Hare, M. Hare, S. Harper, R. F. Harr, R. M. Harris, M. Hartz, K. Hatakeyama, J. Hauser, C. Hays, M. Heck, A. Heijboer, B. Heinemann, J. Heinrich, C. Henderson, M. Herndon, J. Heuser, S. Hewamanage, D. Hidas, C. S. Hill, D. Hirschbuehl, A. Hocker, S. Hou, M. Houlden, S. C. Hsu, B. T. Huffman, R. E. Hughes, U. Husemann, J. Huston, J. Incandela, G. Introzzi, M. Iori, A. Ivanov, B. Iyutin, E. James, B. Jayatilaka, D. Jeans, E. J. Jeon, S. Jindariani, W. Johnson, M. Jones, K. K. Joo, S. Y. Jun, J. E. Jung, T. R. Junk, T. Kamon, D. Kar, P. E. Karchin, Y. Kato, R. Kephart, U. Kerzel, V. Khotilovich, B. Kilminster, D. H. Kim, H. S. Kim, J. E. Kim, M. J. Kim, S. B. Kim, S. H. Kim, Y. K. Kim, N. Kimura, L. Kirsch, S. Klimentenko, M. Klute, B. Knuteson, B. R. Ko, S. A. Koay, K. Kondo, D. J. Kong, J. Konigsberg, A. Korytov, A. V. Kotwal, J. Kraus, M. Kreps, J. Kroll, N. Krumnack, M. Kruse, V. Krutelyov, T. Kubo, S. E. Kuhlmann, T. Kuhr, N. P. Kulkarni, Y. Kusakabe, S. Kwang, A. T. Laasanen, S. Lai, S. Lami, S. Lammel, M. Lancaster, R. L. Lander, K. Lannon, A. Lath, G. Latino, I. Lazzizzera, T. LeCompte, J. Lee, J. Lee, Y. J. Lee, S. W. Lee, R. Lefevre, N. Leonardo, S. Leone, S. Levy, J. D. Lewis, C. Lin, C. S. Lin, J. Linacre, M. Lindgren, E. Lipeles, A. Lister, D. O. Litvintsev, T. Liu, N. S. Lockyer, A. Logunov, M. Loreti, L. Lovas, R. S. Lu, D. Lucchesi, J. Lueck, C. Luci, P. Lujan, P. Lukens, G. Lungu, L. Lyons, J. Lys, R. Lysak, E. Lytken, P. Mack, D. MacQueen, R. Madrak, K. Maeshima, K. Makhoul, T. Maki, P. Maksimovic, S. Malde, S. Malik, G. Manca, A. Manousakis, F. Margaroli, C. Marino, C. P. Marino, A. Martin, M. Martin, V. Martin, M. Martinez, R. Martinez-Ballarín, T. Maruyama, P. Mastrandrea, T. Masubuchi, M. E. Mattson, P. Mazzanti, K. S. McFarland, P. McIntyre, R. McNulty, A. Mehta, P. Mehtala, S. Menzemer, A. Menzione, P. Merkel, C. Mesropian, A. Messina, T. Miao, N. Miladinovic, J. Miles, R. Miller, C. Mills, M. Milnik, A. Mitra, G. Mitselmakher, H. Miyake, S. Moed, N. Moggi, C. S. Moon, R. Moore, M. Morello, P. M. Fernandez, J. Mulmenstadt, A. Mukherjee, T. Muller, R. Mumford, P. Murat, M. Mussini, J. Nachtman, Y. Nagai, A. Nagano, J. Naganoma, K. Nakamura, I. Nakano, A. Napier, V. Necula, C. Neu, M. S. Neubauer, J. Nielsen, L. Nodulman, M. Norman, O. Norriella, E. Nurse, S. H. Oh, Y. D. Oh, I. Oksuzian, T. Okusawa, R. Oldeman, R. Orava, K. Osterberg, S. P. Griso, C. Pagliarone, E. Palencia, V. Papadimitriou, A. Papaikonomou, A. A. Paramonov, B. Parks, S. Pashapour, J. Patrick, G. Pauletta, M. Paulini, C. Paus, D. E. Pellett, A. Penzo, T. J. Phillips, G. Piacentino, J. Piedra, L. Pinera, K. Pitts, C. Plager, L. Pondrom, X. Portell, O. Poukhov, N. Pounder, F. Prakoshyn, A. Pronko, J. Proudfoot, F. Ptohos, G. Punzi, J. Pursley, J. Rademacker, A. Rahaman, V. Ramakrishnan, N. Ranjan, I. Redondo, B. Reisert, V. Rekovic, P. Renton, M. Rescigno, S. Richter, F. Rimondi, L. Ristori, A. Robson, T. Rodrigo, E. Rogers, S. Rolli, R. Roser, M. Rossi, R. Rossin, P. Roy, A. Ruiz, J. Russ, V. Rusu, H. Saarikko, A. Safonov, W. K. Sakumoto, G. Salamanna, O. Salto, L. Santi, S. Sarkar, L. Sartori, K. Sato, A. Savoy-Navarro, T. Scheidle, P. Schlabach, E. E. Schmidt, M. A. Schmidt, M. P. Schmidt, M. Schmitt, T. Schwarz, L. Scodellaro, A. L. Scott, A. Scribano, F. Scuri, A. Sedov, S. Seidel, Y. Seiya, A. Semenov, L. Sexton-Kennedy, A. Sfyrla,

S. Z. Shalhout, M. D. Shapiro, T. Shears, P. F. Shepard, D. Sherman, M. Shimojima, M. Shochet, Y. Shon, I. Shreyber, A. Sidoti, P. Sinervo, A. Sisakyan, A. J. Slaughter, J. Slaunwhite, K. Sliwa, J. R. Smith, F. D. Snider, R. Snihur, M. Soderberg, A. Soha, S. Somalwar, V. Sorin, J. Spalding, F. Spinella, T. Spreitzer, P. Squillacioti, M. Stanitzki, R. St Denis, B. Stelzer, O. Stelzer-Chilton, D. Stentz, J. Strologas, D. Stuart, J. S. Suh, A. Sukhanov, H. Sun, I. Suslov, T. Suzuki, A. Taffard, R. Takashima, Y. Takeuchi, R. Tanaka, M. Tecchio, P. K. Teng, K. Terashi, J. Thom, A. S. Thompson, G. A. Thompson, E. Thomson, P. Tipton, V. Tiwari, S. Tkaczyk, D. Toback, S. Tokar, K. Tollefson, T. Tomura, D. Tonelli, S. Torre, D. Torretta, S. Tournear, W. Trischuk, Y. Tu, N. Turini, F. Ukegawa, S. Uozumi, S. Vallecorsa, N. van Remortel, A. Varganov, E. Vataga, F. Vazquez, G. Velez, C. Vellidis, V. Veszpremi, M. Vidal, R. Vidal, I. Vila, R. Vilar, T. Vine, M. Vogel, I. Volobouev, G. Volpi, F. Wurthwein, P. Wagner, R. G. Wagner, R. L. Wagner, J. Wagner-Kuhr, W. Wagner, T. Wakisaka, R. Wallny, S. M. Wang, A. Warburton, D. Waters, M. Weinberger, W. C. Wester, B. Whitehouse, D. Whiteson, A. B. Wicklund, E. Wicklund, G. Williams, H. H. Williams, P. Wilson, B. L. Winer, P. Wittich, S. Wolbers, C. Wolfe, T. Wright, X. Wu, S. M. Wynne, A. Yagil, K. Yamamoto, J. Yamaoka, T. Yamashita, C. Yang, U. K. Yang, Y. C. Yang, W. M. Yao, G. P. Yeh, J. Yoh, K. Yorita, T. Yoshida, G. B. Yu, I. Yu, S. S. Yu, J. C. Yun, L. Zanello, A. Zanetti, I. Zaw, X. Zhang, Y. Zheng, and S. Zucchelli

This paper is posted at Purdue e-Pubs.

http://docs.lib.purdue.edu/physics_articles/829

Strong Evidence for ZZ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen,²³ J. Adelman,¹³ T. Akimoto,⁵⁴ M. G. Albrow,¹⁷ B. Álvarez González,¹¹ S. Amerio,⁴² D. Amidei,³⁴ A. Anastassov,⁵¹ A. Annovi,¹⁹ J. Antos,¹⁴ M. Aoki,²⁴ G. Apollinari,¹⁷ A. Apresyan,⁴⁷ T. Arisawa,⁵⁶ A. Artikov,¹⁵ W. Ashmanskas,¹⁷ A. Attal,³ A. Aurisano,⁵² F. Azfar,⁴¹ P. Azzi-Bacchetta,⁴² P. Azzurri,⁴⁵ N. Bacchetta,⁴² W. Badgett,¹⁷ A. Barbaro-Galtieri,²⁸ V. E. Barnes,⁴⁷ B. A. Barnett,²⁵ S. Baroiant,⁷ V. Bartsch,³⁰ G. Bauer,³² P.-H. Beauchemin,³³ F. Bedeschi,⁴⁵ P. Bednar,¹⁴ S. Behari,²⁵ G. Bellettini,⁴⁵ J. Bellinger,⁵⁸ A. Belloni,²² D. Benjamin,¹⁶ A. Beretvas,¹⁷ J. Beringer,²⁸ T. Berry,²⁹ A. Bhatti,⁴⁹ M. Binkley,¹⁷ D. Bisello,⁴² I. Bizjak,³⁰ R. E. Blair,² C. Blocker,⁶ B. Blumenfeld,²⁵ A. Bocci,¹⁶ A. Bodek,⁴⁸ V. Boisvert,⁴⁸ G. Bolla,⁴⁷ A. Bolshov,³² D. Bortoletto,⁴⁷ J. Boudreau,⁴⁶ A. Boveia,¹⁰ B. Brau,¹⁰ A. Bridgeman,²⁴ L. Brigliadori,⁵ C. Bromberg,³⁵ E. Brubaker,¹³ J. Budagov,¹⁵ H. S. Budd,⁴⁸ S. Budd,²⁴ K. Burkett,¹⁷ G. Busetto,⁴² P. Bussey,²¹ A. Buzatu,³³ K. L. Byrum,² S. Cabrera,^{16,r} M. Campanelli,³⁵ M. Campbell,³⁴ F. Canelli,¹⁷ A. Canepa,⁴⁴ D. Carlsmith,⁵⁸ R. Carosi,⁴⁵ S. Carrillo,^{18,l} S. Carron,³³ B. Casal,¹¹ M. Casarsa,¹⁷ A. Castro,⁵ P. Catastini,⁴⁵ D. Cauz,⁵³ M. Cavalli-Sforza,³ A. Cerri,²⁸ L. Cerrito,^{30,p} S. H. Chang,²⁷ Y. C. Chen,¹ M. Chertok,⁷ G. Chiarelli,⁴⁵ G. Chlachidze,¹⁷ F. Chlebana,¹⁷ K. Cho,²⁷ D. Chokheli,¹⁵ J. P. Chou,²² G. Choudalakis,³² S. H. Chuang,⁵¹ K. Chung,¹² W. H. Chung,⁵⁸ Y. S. Chung,⁴⁸ C. I. Ciobanu,²⁴ M. A. Ciocci,⁴⁵ A. Clark,²⁰ D. Clark,⁶ G. Compostella,⁴² M. E. Convery,¹⁷ J. Conway,⁷ B. Cooper,³⁰ K. Copic,³⁴ M. Cordelli,¹⁹ G. Cortiana,⁴² F. Crescioli,⁴⁵ C. Cuenca Almenar,^{7,r} J. Cuevas,^{11,o} R. Culbertson,¹⁷ J. C. Cully,³⁴ D. Dagenhart,¹⁷ M. Datta,¹⁷ T. Davies,²¹ P. de Barbaro,⁴⁸ S. De Cecco,⁵⁰ A. Deisher,²⁸ G. De Lentdecker,^{48,d} G. De Lorenzo,³ M. Dell'Orso,⁴⁵ L. Demortier,⁴⁹ J. Deng,¹⁶ M. Deninno,⁵ D. De Pedis,⁵⁰ P. F. Derwent,¹⁷ G. P. Di Giovanni,⁴³ C. Dionisi,⁵⁰ B. Di Ruzza,⁵³ J. R. Dittmann,⁴ M. D'Onofrio,³ S. Donati,⁴⁵ P. Dong,⁸ J. Donini,⁴² T. Dorigo,⁴² S. Dube,⁵¹ J. Efron,³⁸ R. Erbacher,⁷ D. Errede,²⁴ S. Errede,²⁴ R. Eusebi,¹⁷ H. C. Fang,²⁸ S. Farrington,²⁹ W. T. Fedorko,¹³ R. G. Feild,⁵⁹ M. Feindt,²⁶ J. P. Fernandez,³¹ C. Ferrazza,⁴⁵ R. Field,¹⁸ G. Flanagan,⁴⁷ R. Forrest,⁷ S. Forrester,⁷ M. Franklin,²² J. C. Freeman,²⁸ I. Furic,¹⁸ M. Gallinaro,⁴⁹ J. Galyardt,¹² F. Garbersson,¹⁰ J. E. Garcia,⁴⁵ A. F. Garfinkel,⁴⁷ K. Genser,¹⁷ H. Gerberich,²⁴ D. Gerdes,³⁴ S. Giagu,⁵⁰ V. Giakoumopolou,^{45,a} P. Giannetti,⁴⁵ K. Gibson,⁴⁶ J. L. Gimmell,⁴⁸ C. M. Ginsburg,¹⁷ N. Giokaris,^{15,a} M. Giordani,⁵³ P. Giromini,¹⁹ M. Giunta,⁴⁵ V. Glagolev,¹⁵ D. Glenzinski,¹⁷ M. Gold,³⁶ N. Goldschmidt,¹⁸ A. Golossanov,¹⁷ G. Gomez,¹¹ G. Gomez-Ceballos,³² M. Goncharov,⁵² O. González,³¹ I. Gorelov,³⁶ A. T. Goshaw,¹⁶ K. Goulianos,⁴⁹ A. Gresele,⁴² S. Grinstein,²² C. Grosso-Pilcher,¹³ R. C. Group,¹⁷ U. Grundler,²⁴ J. Guimaraes da Costa,²² Z. Gunay-Unalan,³⁵ C. Haber,²⁸ K. Hahn,³² S. R. Hahn,¹⁷ E. Halkiadakis,⁵¹ A. Hamilton,²⁰ B.-Y. Han,⁴⁸ J. Y. Han,⁴⁸ R. Handler,⁵⁸ F. Happacher,¹⁹ K. Hara,⁵⁴ D. Hare,⁵¹ M. Hare,⁵⁵ S. Harper,⁴¹ R. F. Harr,⁵⁷ R. M. Harris,¹⁷ M. Hartz,⁴⁶ K. Hatakeyama,⁴⁹ J. Hauser,⁸ C. Hays,⁴¹ M. Heck,²⁶ A. Heijboer,⁴⁴ B. Heinemann,²⁸ J. Heinrich,⁴⁴ C. Henderson,³² M. Herndon,⁵⁸ J. Heuser,²⁶ S. Hewamanage,⁴ D. Hidas,¹⁶ C. S. Hill,^{10,c} D. Hirschbuehl,²⁶ A. Hocker,¹⁷ S. Hou,¹ M. Houlden,²⁹ S.-C. Hsu,⁹ B. T. Huffman,⁴¹ R. E. Hughes,³⁸ U. Husemann,⁵⁹ J. Huston,³⁵ J. Incandela,¹⁰ G. Introzzi,⁴⁵ M. Iori,⁵⁰ A. Ivanov,⁷ B. Iyutin,³² E. James,¹⁷ B. Jayatilaka,¹⁶ D. Jeans,⁵⁰ E. J. Jeon,²⁷ S. Jindariani,¹⁸ W. Johnson,⁷ M. Jones,⁴⁷ K. K. Joo,²⁷ S. Y. Jun,¹² J. E. Jung,²⁷ T. R. Junk,²⁴ T. Kamon,⁵² D. Kar,¹⁸ P. E. Karchin,⁵⁷ Y. Kato,⁴⁰ R. Kephart,¹⁷ U. Kerzel,²⁶ V. Khotilovich,⁵² B. Kilminster,³⁸ D. H. Kim,²⁷ H. S. Kim,²⁷ J. E. Kim,²⁷ M. J. Kim,¹⁷ S. B. Kim,²⁷ S. H. Kim,⁵⁴ Y. K. Kim,¹³ N. Kimura,⁵⁴ L. Kirsch,⁶ S. Klimenko,¹⁸ M. Klute,³² B. Knuteson,³² B. R. Ko,¹⁶ S. A. Koay,¹⁰ K. Kondo,⁵⁶ D. J. Kong,²⁷ J. Konigsberg,¹⁸ A. Korytov,¹⁸ A. V. Kotwal,¹⁶ J. Kraus,²⁴ M. Kreps,²⁶ J. Kroll,⁴⁴ N. Krumnack,⁴ M. Kruse,¹⁶ V. Krutelyov,¹⁰ T. Kubo,⁵⁴ S. E. Kuhlmann,² T. Kuhr,²⁶ N. P. Kulkarni,⁵⁷ Y. Kusakabe,⁵⁶ S. Kwang,¹³ A. T. Laasanen,⁴⁷ S. Lai,³³ S. Lami,⁴⁵ S. Lammel,¹⁷ M. Lancaster,³⁰ R. L. Lander,⁷ K. Lannon,³⁸ A. Lath,⁵¹ G. Latino,⁴⁵ I. Lazzizzera,⁴² T. LeCompte,² J. Lee,⁴⁸ J. Lee,²⁷ Y. J. Lee,²⁷ S. W. Lee,^{52,q} R. Lefèvre,²⁰ N. Leonardo,³² S. Leone,⁴⁵ S. Levy,¹³ J. D. Lewis,¹⁷ C. Lin,⁵⁹ C. S. Lin,²⁸ J. Linacre,⁴¹ M. Lindgren,¹⁷ E. Lipeles,⁹ A. Lister,⁷ D. O. Litvintsev,¹⁷ T. Liu,¹⁷ N. S. Lockyer,⁴⁴ A. Loginov,⁵⁹ M. Loreti,⁴² L. Lovas,¹⁴ R.-S. Lu,¹ D. Lucchesi,⁴² J. Lueck,²⁶ C. Luci,⁵⁰ P. Lujan,²⁸ P. Lukens,¹⁷ G. Lungu,¹⁸ L. Lyons,⁴¹ J. Lys,²⁸ R. Lysak,¹⁴ E. Lytken,⁴⁷ P. Mack,²⁶ D. MacQueen,³³ R. Madrak,¹⁷ K. Maeshima,¹⁷ K. Makhoul,³² T. Maki,²³ P. Maksimovic,²⁵ S. Malde,⁴¹ S. Malik,³⁰ G. Manca,²⁹ A. Manousakis,^{15,a} F. Margaroli,⁴⁷ C. Marino,²⁶ C. P. Marino,²⁴ A. Martin,⁵⁹ M. Martin,²⁵ V. Martin,^{21,j} M. Martínez,³ R. Martínez-Ballarín,³¹ T. Maruyama,⁵⁴ P. Mastrandrea,⁵⁰ T. Masubuchi,⁵⁴ M. E. Mattson,⁵⁷ P. Mazzanti,⁵ K. S. McFarland,⁴⁸ P. McIntyre,⁵² R. McNulty,^{29,i} A. Mehta,²⁹ P. Mehtala,²³ S. Menzemer,^{11,k} A. Menzione,⁴⁵ P. Merkel,⁴⁷ C. Mesropian,⁴⁹ A. Messina,³⁵ T. Miao,¹⁷ N. Miladinovic,⁶ J. Miles,³² R. Miller,³⁵ C. Mills,²² M. Milnik,²⁶ A. Mitra,¹ G. Mitselmakher,¹⁸ H. Miyake,⁵⁴ S. Moed,²² N. Moggi,⁵ C. S. Moon,²⁷ R. Moore,¹⁷ M. Morello,⁴⁵ P. Movilla Fernandez,²⁸ J. Mülmenstädt,²⁸ A. Mukherjee,¹⁷ Th. Muller,²⁶ R. Mumford,²⁵ P. Murat,¹⁷ M. Mussini,⁵ J. Nachtman,¹⁷ Y. Nagai,⁵⁴ A. Nagano,⁵⁴ J. Naganoma,⁵⁶ K. Nakamura,⁵⁴

I. Nakano,³⁹ A. Napier,⁵⁵ V. Necula,¹⁶ C. Neu,⁴⁴ M. S. Neubauer,²⁴ J. Nielsen,^{28,f} L. Nodulman,² M. Norman,⁹ O. Norniella,²⁴ E. Nurse,³⁰ S. H. Oh,¹⁶ Y. D. Oh,²⁷ I. Oksuzian,¹⁸ T. Okusawa,⁴⁰ R. Oldeman,²⁹ R. Orava,²³ K. Osterberg,³³ S. Pagan Griso,⁴² C. Pagliarone,⁴⁵ E. Palencia,¹⁷ V. Papadimitriou,¹⁷ A. Papaikonomou,²⁶ A. A. Paramonov,¹³ B. Parks,³⁸ S. Pashapour,³³ J. Patrick,¹⁷ G. Pauletta,⁵³ M. Paulini,¹² C. Paus,³² D. E. Pellett,⁷ A. Penzo,⁵³ T. J. Phillips,¹⁶ G. Piacentino,⁴⁵ J. Piedra,⁴³ L. Pinera,¹⁸ K. Pitts,²⁴ C. Plager,⁸ L. Pondrom,⁵⁸ X. Portell,³ O. Poukhov,¹⁵ N. Pounder,⁴¹ F. Prakoshyn,¹⁵ A. Pronko,¹⁷ J. Proudfoot,² F. Ptohos,^{17,h} G. Punzi,⁴⁵ J. Pursley,⁵⁸ J. Rademacker,^{41,c} A. Rahaman,⁴⁶ V. Ramakrishnan,⁵⁸ N. Ranjan,⁴⁷ I. Redondo,³¹ B. Reisert,¹⁷ V. Rekovic,³⁶ P. Renton,⁴¹ M. Rescigno,⁵⁰ S. Richter,²⁶ F. Rimondi,⁵ L. Ristori,⁴⁵ A. Robson,²¹ T. Rodrigo,¹¹ E. Rogers,²⁴ S. Rolli,⁵⁵ R. Roser,¹⁷ M. Rossi,⁵³ R. Rossin,¹⁰ P. Roy,³³ A. Ruiz,¹¹ J. Russ,¹² V. Rusu,¹⁷ H. Saarikko,²³ A. Safonov,⁵² W. K. Sakumoto,⁴⁸ G. Salamanna,⁵⁰ O. Saltó,³ L. Santi,⁵³ S. Sarkar,⁵⁰ L. Sartori,⁴⁵ K. Sato,¹⁷ A. Savoy-Navarro,⁴³ T. Scheidle,²⁶ P. Schlabach,¹⁷ E. E. Schmidt,¹⁷ M. A. Schmidt,¹³ M. P. Schmidt,⁵⁹ M. Schmitt,³⁷ T. Schwarz,⁷ L. Scodellaro,¹¹ A. L. Scott,¹⁰ A. Scribano,⁴⁵ F. Scuri,⁴⁵ A. Sedov,⁴⁷ S. Seidel,³⁶ Y. Seiya,⁴⁰ A. Semenov,¹⁵ L. Sexton-Kennedy,¹⁷ A. Sfyrla,²⁰ S. Z. Shalhout,⁵⁷ M. D. Shapiro,²⁸ T. Shears,²⁹ P. F. Shepard,⁴⁶ D. Sherman,²² M. Shimojima,^{54,n} M. Shochet,¹³ Y. Shon,⁵⁸ I. Shreyber,²⁰ A. Sidoti,⁴⁵ P. Sinervo,³³ A. Sisakyan,¹⁵ A. J. Slaughter,¹⁷ J. Slaunwhite,³⁸ K. Sliwa,⁵⁵ J. R. Smith,⁷ F. D. Snider,¹⁷ R. Snihur,³³ M. Soderberg,³⁴ A. Soha,⁷ S. Somalwar,⁵¹ V. Sorin,³⁵ J. Spalding,¹⁷ F. Spinella,⁴⁵ T. Spreitzer,³³ P. Squillacioti,⁴⁵ M. Stanitzki,⁵⁹ R. St. Denis,²¹ B. Stelzer,⁸ O. Stelzer-Chilton,⁴¹ D. Stentz,³⁷ J. Strologas,³⁶ D. Stuart,¹⁰ J. S. Suh,²⁷ A. Sukhanov,¹⁸ H. Sun,⁵⁵ I. Suslov,¹⁵ T. Suzuki,⁵⁴ A. Taffard,^{24,e} R. Takashima,³⁹ Y. Takeuchi,⁵⁴ R. Tanaka,³⁹ M. Tecchio,³⁴ P. K. Teng,¹ K. Terashi,⁴⁹ J. Thom,^{17,g} A. S. Thompson,²¹ G. A. Thompson,²⁴ E. Thomson,⁴⁴ P. Tipton,⁵⁹ V. Tiwari,¹² S. Tkaczyk,¹⁷ D. Toback,⁵² S. Tokar,¹⁴ K. Tollefson,³⁵ T. Tomura,⁵⁴ D. Tonelli,¹⁷ S. Torre,¹⁹ D. Torretta,¹⁷ S. Tourneur,⁴³ W. Trischuk,³³ Y. Tu,⁴⁴ N. Turini,⁴⁵ F. Ukegawa,⁵⁴ S. Uozumi,⁵⁴ S. Vallecorsa,²⁰ N. van Remortel,²³ A. Varganov,³⁴ E. Vataga,³⁶ F. Vázquez,^{18,l} G. Velev,¹⁷ C. Vellidis,^{45,a} V. Veszpremi,⁴⁷ M. Vidal,³¹ R. Vidal,¹⁷ I. Vila,¹¹ R. Vilar,¹¹ T. Vine,³⁰ M. Vogel,³⁶ I. Volobouev,^{28,q} G. Volpi,⁴⁵ F. Würthwein,⁹ P. Wagner,⁴⁴ R. G. Wagner,² R. L. Wagner,¹⁷ J. Wagner-Kuhr,²⁶ W. Wagner,²⁶ T. Wakisaka,⁴⁰ R. Wallny,⁸ S. M. Wang,¹ A. Warburton,³³ D. Waters,³⁰ M. Weinberger,⁵² W. C. Wester III,¹⁷ B. Whitehouse,⁵⁵ D. Whiteson,^{44,e} A. B. Wicklund,² E. Wicklund,¹⁷ G. Williams,³³ H. H. Williams,⁴⁴ P. Wilson,¹⁷ B. L. Winer,³⁸ P. Wittich,^{17,g} S. Wolbers,¹⁷ C. Wolfe,¹³ T. Wright,³⁴ X. Wu,²⁰ S. M. Wynne,²⁹ A. Yagil,⁹ K. Yamamoto,⁴⁰ J. Yamaoka,⁵¹ T. Yamashita,³⁹ C. Yang,⁵⁹ U. K. Yang,^{13,m} Y. C. Yang,²⁷ W. M. Yao,²⁸ G. P. Yeh,¹⁷ J. Yoh,¹⁷ K. Yorita,¹³ T. Yoshida,⁴⁰ G. B. Yu,⁴⁸ I. Yu,²⁷ S. S. Yu,¹⁷ J. C. Yun,¹⁷ L. Zanello,⁵⁰ A. Zanetti,⁵³ I. Zaw,²² X. Zhang,²⁴ Y. Zheng,^{8,b} and S. Zucchelli⁵

(CDF Collaboration)^a¹*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*²*Argonne National Laboratory, Argonne, Illinois 60439, USA*³*Institut de Física d'Altes Energies, Universitat Autònoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*⁴*Baylor University, Waco, Texas 76798, USA*⁵*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*⁶*Brandeis University, Waltham, Massachusetts 02254, USA*⁷*University of California, Davis, Davis, California 95616, USA*⁸*University of California, Los Angeles, Los Angeles, California 90024, USA*⁹*University of California, San Diego, La Jolla, California 92093, USA*¹⁰*University of California, Santa Barbara, Santa Barbara, California 93106, USA*¹¹*Instituto de Física de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*¹²*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*¹³*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*¹⁴*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*¹⁵*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*¹⁶*Duke University, Durham, North Carolina 27708*¹⁷*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*¹⁸*University of Florida, Gainesville, Florida 32611, USA*¹⁹*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*²⁰*University of Geneva, CH-1211 Geneva 4, Switzerland*²¹*Glasgow University, Glasgow G12 8QQ, United Kingdom*²²*Harvard University, Cambridge, Massachusetts 02138, USA*²³*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*

- ²⁴University of Illinois, Urbana, Illinois 61801, USA
²⁵The Johns Hopkins University, Baltimore, Maryland 21218, USA
²⁶Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany
²⁷Center 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
²⁸Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
²⁹University of Liverpool, Liverpool L69 7ZE, United Kingdom
³⁰University College London, London WC1E 6BT, United Kingdom
³¹Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain
³²Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
³³Institute of Particle Physics: McGill University, Montréal, Canada H3A 2T8;
 and University of Toronto, Toronto, Canada M5S 1A7
³⁴University of Michigan, Ann Arbor, Michigan 48109, USA
³⁵Michigan State University, East Lansing, Michigan 48824, USA
³⁶University of New Mexico, Albuquerque, New Mexico 87131, USA
³⁷Northwestern University, Evanston, Illinois 60208, USA
³⁸The Ohio State University, Columbus, Ohio 43210, USA
³⁹Okayama University, Okayama 700-8530, Japan
⁴⁰Osaka City University, Osaka 588, Japan
⁴¹University of Oxford, Oxford OX1 3RH, United Kingdom
⁴²University of Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy
⁴³LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France
⁴⁴University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
⁴⁵Istituto Nazionale di Fisica Nucleare Pisa, Universities of Pisa, Siena
 and Scuola Normale Superiore, I-56127 Pisa, Italy
⁴⁶University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
⁴⁷Purdue University, West Lafayette, Indiana 47907, USA
⁴⁸University of Rochester, Rochester, New York 14627, USA
⁴⁹The Rockefeller University, New York, New York 10021, USA
⁵⁰Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, University of Rome "La Sapienza," I-00185 Roma, Italy
⁵¹Rutgers University, Piscataway, New Jersey 08855, USA
⁵²Texas A&M University, College Station, Texas 77843, USA
⁵³Istituto Nazionale di Fisica Nucleare, University of Trieste/Udine, Italy
⁵⁴University of Tsukuba, Tsukuba, Ibaraki 305, Japan
⁵⁵Tufts University, Medford, Massachusetts 02155, USA
⁵⁶Waseda University, Tokyo 169, Japan
⁵⁷Wayne State University, Detroit, Michigan 48201, USA
⁵⁸University of Wisconsin, Madison, Wisconsin 53706, USA
⁵⁹Yale University, New Haven, Connecticut 06520, USA
 (Received 1 February 2008; published 22 May 2008)

We report the first evidence of Z boson pair production at a hadron collider with a significance exceeding 4 standard deviations. This result is based on a data sample corresponding to 1.9 fb^{-1} of integrated luminosity from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ collected with the Collider Detector at Fermilab II detector. In the $\ell\ell'\ell'\ell'$ channel, we observe three ZZ candidates with an expected background of $0.096_{-0.063}^{+0.092}$ events. In the $\ell\ell\nu\nu$ channel, we use a leading-order calculation of the relative ZZ and WW event probabilities to discriminate between signal and background. In the combination of $\ell\ell'\ell'\ell'$ and $\ell\ell\nu\nu$ channels, we observe an excess of events with a probability of 5.1×10^{-6} to be due to the expected background. This corresponds to a significance of 4.4 standard deviations. The measured cross section is $\sigma(p\bar{p} \rightarrow ZZ) = 1.4_{-0.6}^{+0.7}(\text{stat} + \text{syst}) \text{ pb}$, consistent with the standard model expectation.

DOI: [10.1103/PhysRevLett.100.201801](https://doi.org/10.1103/PhysRevLett.100.201801)

PACS numbers: 12.15.Ji, 13.40.Em, 13.85.Qk, 14.70.Hp

Measurements of heavy vector boson pair production (WW , WZ , ZZ) are of great importance because they test the electroweak sector of the standard model (SM). Diboson production provides a sensitive probe of new

physics, including anomalous trilinear gauge couplings [1], new particles such as the Higgs boson [2], and large extra dimensions [3]. Important tests of electroweak physics have been made recently at the Fermilab Tevatron with

the first observation of WW production in hadron collisions [4,5] and the first observation of WZ production [6]. The production of Z pairs has been observed in e^+e^- collisions at LEP [7], but not in hadron collisions. As a window to new physics, ZZ production is particularly interesting because of the absence of $ZZ\gamma$ and ZZZ couplings in the SM, and because of the very low backgrounds in the four charged-lepton channel.

The full process that we consider in this search is $p\bar{p} \rightarrow Z/\gamma^*Z/\gamma^*$. For brevity, we denote $Z/\gamma^*Z/\gamma^*$ as ZZ throughout this Letter. The most sensitive previous search for ZZ production in hadron collisions was reported by the D0 Collaboration using data corresponding to 1 fb^{-1} of integrated luminosity. That search used only the four charged-lepton channel and set a limit on the cross section of $\sigma(ZZ) < 4.4 \text{ pb}$ at 95% C.L. [8]. The next-to-leading-order (NLO) ZZ cross section for $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ is $1.4 \pm 0.1 \text{ pb}$ in the zero-width Z boson approximation [9].

In this Letter, we report a signal for ZZ production in hadron collisions which has a probability of 5.1×10^{-6} to be due to the expected background. The production is observed in $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ using a data sample corresponding to 1.9 fb^{-1} of integrated luminosity collected by the CDF II detector. We consider both $ZZ \rightarrow \ell\ell\ell'\ell'$ and $ZZ \rightarrow \ell\ell\nu\nu$ decays, where ℓ and ℓ' are electrons or muons directly from Z decay or from the leptonic decay of τ 's when one or both Z bosons decay to τ leptons. In the $ZZ \rightarrow \ell\ell\ell'\ell'$ channel, we have a small sensitivity to the γ^* contribution and its interference with the Z boson, while this sensitivity is negligible for the $ZZ \rightarrow \ell\ell\nu\nu$ channel.

The CDF II detector is described elsewhere [10]. We specify the geometry using the azimuthal angle ϕ and the pseudorapidity $\eta \equiv -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the proton beam axis. The pseudorapidity of a particle assumed to originate from the center of the detector is referred to as η_d . The branching fraction of the ZZ state to four e or μ leptons, including those from leptonic τ decays, is only 0.51%. When coupled with the small SM cross section, only a small number (~ 14) of $ZZ \rightarrow \ell\ell\ell'\ell'$ are expected to be produced in 1.9 fb^{-1} at the Tevatron. The finite CDF II acceptance further reduces the expected number of observed $ZZ \rightarrow \ell\ell\ell'\ell'$ events.

We use the lepton identification strategy developed for the WZ observation analysis [6], which was designed to have high acceptance for multilepton final states. The lepton candidates are divided into seven exclusive categories: three for muons, three for electrons, and one for tracks that project to detector regions with insufficient calorimeter coverage for energy measurement. One of the muon categories uses the muon chambers and the other two consist of minimum ionizing tracks that use either the central ($|\eta_d| < 1.1$) or forward ($1.2 < |\eta_d| < 2.0$) calorimeters. The three electron categories are central ($|\eta_d| <$

1.1), forward ($1.2 < |\eta_d| < 2.0$) with a matched silicon-based track, and forward ($1.2 < |\eta_d| < 2.8$) without a matched silicon-based track.

To suppress jets being misidentified as leptons, all lepton candidates are required to pass a calorimeter-based isolation requirement such that the sum of the E_T for the calorimeter towers not associated with the lepton in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ around the lepton direction is less than 10% of the E_T for electrons or p_T for muons and track lepton candidates. The transverse energy E_T of an EM cluster or calorimeter tower is $E \sin\theta$, where E is the associated energy. Similarly, p_T is the track momentum transverse to the beam line.

To infer the presence of neutrinos in $ZZ \rightarrow \ell\ell\nu\nu$ decay, we use missing transverse energy $\vec{\cancel{E}}_T = -\sum_i E_i \hat{n}_{T,i}$, where $\hat{n}_{T,i}$ is the transverse component of the unit vector pointing from the interaction point to calorimeter tower i . The $\vec{\cancel{E}}_T$ calculation is corrected for muons and track leptons, which do not deposit all of their energy in the calorimeter. We analogously define the scalar sum $\sum E_T = \sum_i E_{T,i}$ applying the same corrections.

We require events to pass at least one of four trigger selection criteria. The central electron trigger requires an EM energy cluster with $E_T > 18 \text{ GeV}$ matched to a track with $p_T > 8 \text{ GeV}/c$. For the $ZZ \rightarrow ee\nu\nu$ channel only, a trigger for forward electrons requires an EM energy cluster with $E_T > 20 \text{ GeV}$ and an uncorrected, calorimeter-based measurement of $\cancel{E}_T > 15 \text{ GeV}$. Two muon triggers are based on stubs from the corresponding muon detectors matched to a track with $p_T > 18 \text{ GeV}/c$. Trigger efficiencies are measured in leptonic W and Z boson data samples [11].

The $ZZ \rightarrow \ell\ell\ell'\ell'$ candidates are selected from events with exactly four charged-lepton candidates using requirements that were optimized with Monte Carlo simulation without reference to the data. At least one lepton is required to satisfy the trigger criteria and have $E_T > 20 \text{ GeV}$ ($p_T > 20 \text{ GeV}/c$) for electrons (muons). We loosen this requirement to 10 GeV (GeV/c) for the other leptons to increase the ZZ kinematic acceptance. We require at least two same-flavor, opposite-sign lepton pairs in the event. Trackless electrons are considered to have either charge, and track-only leptons either flavor. One pair must have invariant mass $M_{\ell^+\ell^-}$ in the range $[76, 106] \text{ GeV}/c^2$, while the requirement for the other pair is extended to $[40, 140] \text{ GeV}/c^2$ to increase the acceptance for off-shell Z decays.

The acceptance for the ZZ process is determined using PYTHIA [12] followed by a GEANT-based simulation [13] of the CDF II detector. An efficiency correction, of up to 10% per lepton, is applied to the simulation based on measurements of the lepton reconstruction and identification efficiencies using observed $Z \rightarrow \ell^+\ell^-$ events.

The dominant backgrounds to the $ZZ \rightarrow \ell\ell\ell'\ell'$ selection are the Drell-Yan Z/γ^* process (DY) with two jets

misidentified as leptons ($Z + \text{jets}$) and DY with an additional photon and a jet, both misidentified as leptons ($Z\gamma + \text{jets}$). The $Z + \text{jets}$ and $Z\gamma + \text{jets}$ background contributions are estimated from data by extrapolating from a sample of events that contain three identified leptons and a jet j_l containing a track or EM energy cluster similar to those required in the lepton identification. The contribution of each event to the total yield is scaled by the probability that the j_l is identified as a lepton. This probability $p(j_l)$ is determined from multijet events collected with jet-based triggers and is a function of the $j_l p_T$ and type of lepton. A correction to $p(j_l)$ is applied for the small real lepton contribution using Monte Carlo simulation of single W and Z boson processes. In this background sample, one of the three identified leptons is likely to be either a jet or a photon misidentified as a lepton. An event with two leptons and two j_l jets enters the three lepton plus j_l sample if either of the j_l jets is misidentified as a lepton, but will enter the four identified lepton sample only if both j_l jets are misidentified as leptons. Therefore, the contribution from this category of events is double counted. A correction for this is made by subtracting the yield of two leptons plus two j_l jets scaled by $p(j_{l,1}) \times p(j_{l,2})$. As the three lepton plus j_l sample has significant contributions from the $ZZ \rightarrow \ell\ell\ell'\ell'$ signal itself when one of the leptons is not fully identified but is counted as a j_l , an anti-isolation requirement of $>20\%$ (see previous definition of calorimeter-based isolation) is applied to the j_l selection.

As a cross-check, we estimate the $Z\gamma + \text{jet}$ background contribution in an alternative way using the yield of three lepton plus j_l events in simulated $Z\gamma + \text{jet}$ data scaled by $p(j_l)$. We correct this with the ratio of data to simulation for an analogous calculation of two identified leptons and one j_l scaled by $p(j_l)$ in $Z + \text{jets}$ events. This estimate of the $Z\gamma + \text{jet}$ background is in good agreement with the nominal estimate based solely on the data.

We separate the $ZZ \rightarrow \ell\ell\ell'\ell'$ candidates into two exclusive categories based on whether or not they contain at least one forward electron without a track because the background from $Z\gamma + \text{jets}$ is much larger in candidates with a forward trackless electron. The expected signal and background yields, assuming $\sigma(ZZ) = 1.4 \pm 0.1$ pb, and the observed yields are shown in Table I.

The statistical significance of the $ZZ \rightarrow \ell\ell\ell'\ell'$ yield is determined using a maximum likelihood fit with two bins,

one for each of the $ZZ \rightarrow \ell\ell\ell'\ell'$ categories. We define $\Delta \ln \mathcal{L}$ as the logarithm of the likelihood ratio between this fit and the no signal hypothesis. In 10^7 background-only Monte Carlo experiments, only 109 have larger $\Delta \ln \mathcal{L}$ than that observed in data. This corresponds to a background-only probability (p value) of 1.1×10^{-5} and a signal significance equivalent to 4.2 standard deviations.

The $ZZ \rightarrow \ell\ell\nu\nu$ candidates are selected from events with exactly two lepton candidates excluding events with forward electrons without a track which are contaminated by large $W\gamma$ backgrounds. At least one lepton is required to satisfy the trigger and have $E_T > 20$ GeV ($p_T > 20$ GeV/ c) for electrons (muons). This requirement is loosened to 10 GeV (GeV/ c) for the other lepton. We apply a track-based isolation selection in which the sum of the p_T of the tracks not associated with the lepton within a cone of $\Delta R < 0.4$ around the lepton is required to be less than 10% of the momentum of the track associated with the lepton.

Aside from ZZ production, other SM processes that can lead to two high- p_T leptons include events from DY , a W decay with photon ($W\gamma$) or jet ($W + \text{jets}$) misidentified as a lepton, and $t\bar{t}$, WW , and WZ production. The DY background is suppressed by requiring sufficiently large \cancel{E}_T in the event to remove contributions from mismeasured leptons and/or jets. This is achieved by requiring $\cancel{E}_{T,\text{rel}} > 25$ GeV, where

$$\cancel{E}_{T,\text{rel}} \equiv \begin{cases} \cancel{E}_T & \text{if } \Delta\phi_{\cancel{E}_T,(\ell,\text{jet})} > \frac{\pi}{2} \\ \cancel{E}_T \sin\Delta\phi_{\cancel{E}_T,(\ell,\text{jet})} & \text{if } \Delta\phi_{\cancel{E}_T,(\ell,\text{jet})} < \frac{\pi}{2} \end{cases} \quad (1)$$

and $\Delta\phi_{\cancel{E}_T,(\ell,\text{jet})}$ is the angle between $\vec{\cancel{E}}_T$ and the nearest lepton or jet. To suppress events with \cancel{E}_T from mismeasured unclustered energy, we require $\cancel{E}_T/\sqrt{(\sum E_T)} > 2.5$ GeV $^{1/2}$. We suppress $t\bar{t}$ background by requiring fewer than two reconstructed jets with $E_T > 15$ GeV and $|\eta_d| < 2.5$ in the event. We require the lepton pair to be consistent with the same-flavor, opposite-sign property of Z decay and have dilepton invariant mass $M_{\ell\ell} > 16$ GeV/ c^2 to suppress QCD backgrounds.

The acceptances for the WW , WZ , ZZ , $W\gamma$, and $t\bar{t}$ processes are determined using the same detector simulation as described for the $ZZ \rightarrow \ell\ell\ell'\ell'$ channel. Events are simulated with the MC@NLO program for WW [14], PYTHIA for WZ , ZZ , and $t\bar{t}$ [12], and the generator described in [15]

TABLE I. Expected and observed number of $ZZ \rightarrow \ell\ell\ell'\ell'$ candidate events. The first uncertainty is statistical and the second one is systematic.

Category	Candidates without a trackless electron	Candidates with a trackless electron
ZZ	$1.990 \pm 0.013 \pm 0.210$	$0.278 \pm 0.005 \pm 0.029$
$Z + \text{jets}$	$0.014^{+0.010}_{-0.007} \pm 0.003$	$0.082^{+0.089}_{-0.060} \pm 0.016$
Total	$2.004^{+0.016}_{-0.015} \pm 0.210$	$0.360^{+0.089}_{-0.060} \pm 0.033$
Observed	2	1

for $W\gamma$. An additional correction is applied to the $W\gamma$ background estimate based on a measurement of the photon conversion veto efficiency in data. The background from $W + \text{jets}$ is estimated from the yield of one identified lepton plus one j_l scaled by $p(j_l)$. As the sample size is sufficiently large, a loose calorimeter-based isolation cut ($< 30\%$) is applied to the j_l samples to reduce the magnitude of the extrapolation from the j_l to the fully identified lepton.

We observe 276 events in the selected region which is expected to contain 256 ± 21 events of which only 14 ± 2 are from the $ZZ \rightarrow \ell\ell\nu\nu$ process in the SM. Approximately half of the yield is due to the WW process. However, $ZZ \rightarrow \ell\ell\nu\nu$ and WW have different kinematic properties which are exploited to statistically separate the contribution of these two processes to the dataset. We calculate an event-by-event probability density for the observed lepton momenta and \cancel{E}_T using leading-order calculations of the differential decay rate for the processes [9]. The event probability density is

$$P(x_{\text{obs}}) = \frac{1}{\langle\sigma\rangle} \int \frac{d\sigma_{LO}(y)}{dy} \epsilon(y) G(x_{\text{obs}}, y) dy, \quad (2)$$

where the elements of y (x_{obs}) are the true (observed) values of the lepton momenta and \cancel{E}_T , $\frac{d\sigma_{LO}}{dy}$ is the parton level cross section differential in those observables, $\epsilon(y)$ is the detector acceptance and efficiency function, and $G(x_{\text{obs}}, y)$ is the transfer function representing the detector resolution. The constant $\langle\sigma\rangle$ normalizes the total event probability to unity. The missing information due to the fact that we have two neutrinos in the final state is integrated over in this calculation. We then form a likelihood ratio discriminant LR which is the signal probability divided by the sum of signal and background probabilities $LR = P_{ZZ}/(P_{ZZ} + P_{WW})$. The distribution of $\log_{10}(1 - LR)$ for the data compared to the summed signal and background expectation is shown in Fig. 1.

For both $\ell\ell\ell\ell'$ and $\ell\ell\nu\nu$ channels, the systematic uncertainties associated with the Monte Carlo simulation affect the WW , WZ , ZZ , $W\gamma$, and $t\bar{t}$ expectations similarly. The uncertainties from the lepton selection and trigger efficiency measurements are propagated through the analysis, giving uncertainties from 1.0% to 1.4% and 2.1% to 6.1% for the respective efficiencies of the different signal and background processes. The detector acceptance variation due to PDF uncertainties is assessed to be in the range 1.9%–4.1% using the 20 pairs of PDF sets described in [16]. We assign a 6% luminosity uncertainty to signal and background estimates obtained from simulation [17]. The cross section uncertainties are 10% for WW [9], WZ [9], and $W\gamma$ [18], and 15% for $t\bar{t}$ [19,20].

The systematic uncertainty on the $W + \text{jets}$ background to $ZZ \rightarrow \ell\ell\nu\nu$ candidates and the $Z + \text{jets}$ and $Z\gamma + \text{jets}$ background to the $ZZ \rightarrow \ell\ell\ell\ell'$ is estimated to be 20% from differences in the observed probability that a jet is

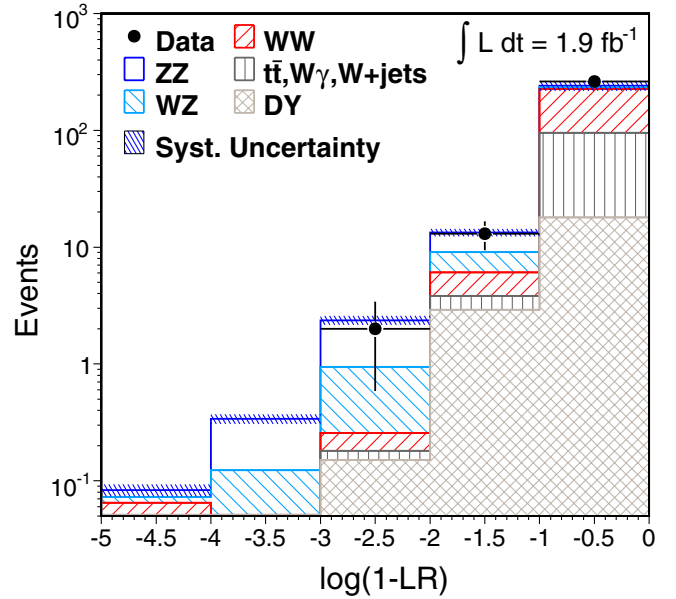


FIG. 1 (color online). Distribution of the discriminating variable $\log_{10}(1 - LR)$ for the $ZZ \rightarrow \ell\ell\nu\nu$ search.

identified as a lepton for jets collected using different jet E_T trigger thresholds. These variations correspond to changing the parton composition of the jets and the relative amount of contamination from real leptons.

For the $ZZ \rightarrow \ell\ell\nu\nu$, the systematic uncertainty on the DY background yield due to the \cancel{E}_T resolution modeling is estimated to be 20% from comparisons of the data and Monte Carlo simulation in a sample of dilepton events. For the $W\gamma$ background contribution, there is an additional uncertainty of 20% from the detector material description and conversion veto efficiency.

We define four independent control samples based on the $ZZ \rightarrow \ell\ell\nu\nu$ selection where one of the cuts is removed or inverted to test our modeling of background-dominated data. Removing the \cancel{E}_T requirement produces a DY -dominated sample which tests luminosity accounting, lepton reconstruction efficiency, and non- \cancel{E}_T related trigger efficiencies that apply to both the $\ell\ell\ell\ell'$ and $\ell\ell\nu\nu$ final states; we observe (expect) 160 980 ($160\,000 \pm 18\,000$) events, where the uncertainty combines statistical and systematic contributions. Inverting the charge sign requirement to select same-sign dilepton events tests our modeling of photons and jets misidentified as leptons; we observe (expect) 161 (138 ± 19) events. Inverting the $\cancel{E}_T/\sqrt{\sum E_T}$ requirement but selecting $\cancel{E}_{T,\text{rel}} > 25$ GeV events tests our modeling of the effect of unclustered energy on the \cancel{E}_T ; we observe (expect) 55 (59 ± 9) events. Finally, inverting the $\cancel{E}_{T,\text{rel}} > 25$ GeV requirement but selecting $\cancel{E}_T > 25$ GeV events tests our modeling of mismeasured leptons or jets at high \cancel{E}_T ; we observe (expect) 151 (178 ± 30) events. The observed yields are in good agreement with the expectations in each selection set.

We combine the $ZZ \rightarrow \ell\ell\nu\nu$ with the $ZZ \rightarrow \ell\ell\ell'\ell'$ results by extending the likelihood fit previously described to include the $\log_{10}(1 - LR)$ distribution. The p value for the $ZZ \rightarrow \ell\ell\nu\nu$ alone is 0.12 and the combined p value is 5.1×10^{-6} corresponding to a significance equivalent to 4.4 standard deviations. This is the first evidence of ZZ production at a hadron collider with a significance exceeding 4 standard deviations. We determine the ZZ cross section by fitting the data for the fraction of the expected SM yield in the full acceptance and scaling the zero-width Z boson approximation cross section by that fraction. The measured cross section is $\sigma(p\bar{p} \rightarrow ZZ) = 1.4^{+0.7}_{-0.6}$ pb, consistent with the SM expectation. This is the first measurement of the ZZ cross section in hadron collisions.

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 Comisión Interministerial de Ciencia y Tecnología, Spain; the European Community's Human Potential Programme; the Slovak R&D Agency; and the Academy of Finland.

^aVisitor from University of Athens, 15784 Athens, Greece.

^bVisitor from Chinese Academy of Sciences, Beijing 100864, China.

^cVisitor from University of Bristol, Bristol BS8 1TL, United Kingdom.

^dVisitor from University Libre de Bruxelles, B-1050 Brussels, Belgium.

^eVisitor from University of California Irvine, Irvine, CA 92697, USA.

^fVisitor from University of California Santa Cruz, Santa Cruz, CA 95064, USA.

^gVisitor from Cornell University, Ithaca, NY 14853, USA.

^hVisitor from University of Cyprus, Nicosia CY-1678, Cyprus.

ⁱVisitor from University College Dublin, Dublin 4, Ireland.

^jVisitor from University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom.

^kVisitor from University of Heidelberg, D-69120 Heidelberg, Germany.

^lVisitor from Universidad Iberoamericana, Mexico D.F., Mexico.

^mVisitor from University of Manchester, Manchester M13 9PL, United Kingdom.

ⁿVisitor from Nagasaki Institute of Applied Science, Nagasaki, Japan.

^oVisitor from University de Oviedo, E-33007 Oviedo, Spain.

^pVisitor from Queen Mary, University of London, London, E1 4NS, United Kingdom.

^qVisitor from Texas Tech University, Lubbock, TX 79409, USA.

^rVisitor from IFIC(CSIC-Universitat de Valencia), 46071 Valencia, Spain.

- [1] K. Hagiwara *et al.*, Nucl. Phys. **B282**, 253 (1987).
- [2] P. Higgs, Phys. Lett. **12**, 132 (1964).
- [3] M. Kober, B. Koch, and M. Bleicher, Phys. Rev. D **76**, 125001 (2007).
- [4] V.M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **94**, 151801 (2005).
- [5] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **94**, 211801 (2005).
- [6] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **98**, 161801 (2007).
- [7] J. Alcaraz *et al.* (The LEP Collaborations ALEPH, DELPHI, L3, OPAL, and the LEP Electroweak Working Group), arXiv:hep-ex/0612034.
- [8] V. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **100**, 131801 (2008).
- [9] J.M. Campbell and R.K. Ellis, Phys. Rev. D **60**, 113006 (1999), we use MCFM version 5.1 with CTEQ6m PDFs.
- [10] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).
- [11] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **94**, 091803 (2005).
- [12] T. Sjöstrand, S. Mrenna, and P. Skands, J. High Energy Phys. 05 (2006) 026.
- [13] R. Brun *et al.*, version 3.15, CERN-DD-78-2-REV.
- [14] S. Frixione and B.R. Webber, J. High Energy Phys. 06 (2002) 029.
- [15] U. Baur and E.L. Berger, Phys. Rev. D **47**, 4889 (1993).
- [16] S. Kretzer *et al.* (CTEQ Collaboration), Phys. Rev. D **69**, 114005 (2004).
- [17] D. Acosta *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **494**, 57 (2002).
- [18] U. Baur, T. Han, and J. Ohnemus, Phys. Rev. D **57**, 2823 (1998).
- [19] N. Kidonakis and R. Vogt, Phys. Rev. D **68**, 114014 (2003).
- [20] M. Cacciari *et al.*, J. High Energy Phys. 04 (2004) 068.