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T. Aaltonen,[15,a] V. M. Abazov,[48,b] B. Abbott,[116,b] M. Abolins,[101,b] B. S. Acharya,[35,b] M. Adams,[79,b] T. Adams,[75,b] J. Adelman,[78,a] E. Aguilo,[7,b] G. D. Alexeev,[48,b] G. Alkhazov,[52,b] A. Alton,[99,ii] B. Álvarez González,[56,aa] G. Alverson,[94,b] G. A. Alves,[2,b] S. Amerio,[39a,a] D. Amidei,[99,a] A. Anastassov,[81,a] L. S. Ancu,[47,b] A. Annovi,[37,a] J. Antos,[53,a] M. Aoki,[77,b] G. Apollinari,[77,a] J. Appel,[77,a] A. Apresyan,[86,a] T. Arisawa,[41,a] Y. Arnoud,[17,b] M. Arov,[90,b] A. Artikov,[48,a] J. Asaadi,[123,a] W. Ashmanskas,[77,a] A. Askew,[75,b] B. Åsman,[57,b] O. Atramentov,[104,b] A. Attal,[54,a] A. Aurisano,[123,a] C. Avila,[10,b] F. Azfar,[65,a] J. BackusMayes,[128,b] F. Badaud,[16,b] W. Badgett,[77,a] L. Bagby,[77,b] B. Baldin,[77,b] D. V. Bandurin,[75,b] S. Banerjee,[35,b] A. Barbaro-Galtieri,[67,a] E. Barberis,[94,b] A.-F. Barfuss,[18,b] P. Baringer,[88,b] V. E. Barnes,[86,a] B. A. Barnett,[91,a] J. Barreto,[2,b] P. Barria,[40c,40a,a] J. F. 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Norniella,[82,a] S. F. Novaes,[5,b] T. Nunnemann,[30,b] E. Nurse,[63,a] L. Oakes,[65,a] G. Obrant,[52,b] S. H. Oh,[113,a] Y. D. Oh,[42,a] I. Oksuzian,[74,a] T. Okusawa,[39,a] D. Onoprienko,[89,b] R. Orava,[15,a] J. Orduna,[45,b] N. Osman,[62,b] J. Osta,[85,b] K. Osterberg,[15,a] G. J. Otero y Garzón,[1,b] M. Owen,[64,b] M. Padilla,[71,b] S. Pagan Griso,[39b,39a,a] C. Pagliarone,[42a,a] E. Palencia,[77,a] M. Pangilinan,[121,b] V. Papadimitriou,[77,a] A. Papaikonomou,[28,a] A. A. Paramanov,[76,a] N. Parashar,[84,b] V. Parihar,[121,b] S.-J. Park,[27,b] S. K. Park,[43,b] B. Parks,[114,a] J. Parsons,[108,b] R. Partridge,[121,b] N. Parua,[83,b] S. Pashapour,[6,a] J. Patrick,[77,a] A. Patwa,[112,b] G. Pauletta,[42b,42a,a] M. Paulini,[119,a] C. Paus,[96,a] T. Peiffer,[28,a] D. E. Pellett,[68,a] B. Penning,[77,b] A. Penzo,[42a,a] M. Perfilov,[50,b] K. Peters,[64,b] Y. Peters,[64,b] G. Petrillo,[110,b] P. Pétroff,[19,b] T. J. Phillips,[113,a] G. Piacentino,[40a,a]

E. Pianori,[118,a] R. Piegaia,[1,b] L. Pinera,[74,a] J. Piper,[101,b] K. Pitts,[82,a] C. Plager,[70,a] M.-A. Pleier,[112,b] P. L. M. Podesta-Lerma,[45,nn] V. M. Podstavkov,[77,b] M.-E. Pol,[2,b] P. Polozov,[49,b] L. Pondrom,[129,a] A. V. Popov,[51,b] K. Potamianos,[86,a] O. Poukhov,[48,a,c] M. Prewitt,[125,b] D. Price,[83,b] F. Prokoshin,[48,dd] A. Pronko,[77,a] S. Protopopescu,[112,b] F. Ptohos,[77,l] E. Pueschel,[119,a] G. Punzi,[40b,40a,a] J. Pursley,[129,a] J. Qian,[99,b] A. Quadt,[27,b] B. Quinn,[102,b] J. Rademacker,[65,f] A. Rahaman,[120,a] V. Ramakrishnan,[129,a] M. S. Rangel,[19,b] K. Ranjan,[34,b] N. Ranjan,[86,a] P. N. Ratoff,[60,b] I. Razumov,[51,b] I. Redondo,[55,a] P. Renkel,[124,b] P. Renton,[65,a] M. Renz,[28,a] M. Rescigno,[41a,a] P. Rich,[64,b] S. Richter,[28,a] M. Rijssenbeek,[111,b] F. Rimondi,[37a,hh] I. Ripp-Baudot,[22,b] L. Ristori,[40a,a] F. Rizatdinova,[117,b] A. Robson,[59,a] T. Rodrigo,[56,a] T. Rodriguez,[118,a] E. Rogers,[82,a] S. Rolli,[97,a] M. Rominsky,[77,b] R. Roser,[77,a] M. Rossi,[42a,a] R. Rossin,[72,a] P. Roy,[6,a] C. Royon,[21,b] P. Rubinov,[77,b] R. Ruchti,[85,b] A. Ruiz,[56,a] J. Russ,[119,a] V. Rusu,[77,a] B. Rutherford,[77,a] H. Saarikko,[15,a] A. Safonov,[123,a] G. Safronov,[49,b] G. Sajot,[17,b] W. K. Sakumoto,[110,a] A. Sánchez-Hernández,[45,b] M. P. Sanders,[30,b] B. Sanghi,[77,b] L. Santi,[42b,42a,a] L. Sartori,[40a,a] K. Sato,[40,a] G. Savage,[77,b] V. Saveliev,[20,aa] A. Savoy-Navarro,[20,a] L. Sawyer,[90,b] T. Scanlon,[62,b] D. Schaile,[30,b] R. D. Schamberger,[111,b] Y. Scheglov,[52,b] H. Schellman,[81,b] P. Schlabach,[77,a] T. Schliephake,[31,b] S. Schlobohm,[128,b] A. Schmidt,[28,a] E. E. Schmidt,[77,a] M. A. Schmidt,[78,a] M. P. Schmidt,[73,a,c] M. Schmitt,[81,a] C. Schwanenberger,[64,b] T. Schwarz,[68,a] R. Schwienhorst,[101,b] L. Scodellaro,[56,a] A. Scribano,[40c,40a,a] F. Scuri,[40a,a] A. Sedov,[86,a] S. Seidel,[106,a] Y. Seiya,[39,a] J. Sekaric,[88,b] A. Semenov,[48,a] H. Severini,[116,b] L. Sexton-Kennedy,[77,a] F. Sforza,[40b,40a,a] A. Sfyrla,[82,a] E. Shabalina,[27,b] S. Z. Shalhout,[100,a] V. Shary,[21,b] A. A. Shchukin,[51,b] T. Shears,[61,a] P. F. Shepard,[120,a] M. Shimojima,[40,x] S. Shiraishi,[78,a] R. K. Shivpuri,[34,b] M. Shochet,[78,a] Y. Shon,[129,a] I. Shreyber,[49,a] V. Simak,[12,b] A. Simonenko,[48,a] P. Sinervo,[6,a] V. Sirotenko,[77,b] A. Sisakyan,[48,a] P. Skubic,[116,b] P. Slattery,[110,b] A. J. Slaughter,[77,a] J. Slaunwhite,[114,a] K. Sliwa,[97,a] D. Smirnov,[85,b] J. R. Smith,[68,a] F. D. Snider,[77,a] R. Snihur,[6,a] G. R. Snow,[103,b] J. Snow,[115,b] S. Snyder,[112,b] A. Soha,[77,a] S. Söldner-Rembold,[64,b] S. Somalwar,[104,a] L. Sonnenschein,[24,b] A. Sopczak,[60,b] V. Sorin,[54,a] M. Sosebee,[122,b] K. Soustruznik,[11,b] B. Spurlock,[122,b] P. Squillacioti,[40c,40a,a] M. Stanitzki,[73,a] J. Stark,[17,b] R. St. Denis,[59,a] B. Stelzer,[6,a] O. Stelzer-Chilton,[6,a] D. Stentz,[81,a] V. Stolin,[49,b] D. A. Stoyanova,[51,b] M. A. Strang,[107,b] E. Strauss,[111,b] M. Strauss,[116,b] R. Ströhmer,[30,b] J. Strologas,[106,a] D. Strom,[79,b] G. L. Strycker,[99,a] L. Stutte,[77,b] J. S. Suh,[42,a] A. Sukhanov,[74,a] I. Suslov,[48,a] P. Svoisky,[47,b] A. Taffard,[82,i] M. Takahashi,[64,b] R. Takashima,[38,a] Y. Takeuchi,[40,a] R. Tanaka,[38,a] A. Tanasijczuk,[1,b] J. Tang,[78,a] W. Taylor,[7,b] M. Tecchio,[99,a] P. K. Teng,[9,a] J. Thom,[77,a] J. Thome,[119,a] G. A. Thompson,[82,a] E. Thomson,[118,a] B. Tiller,[30,b] P. Tipton,[73,a] M. Titov,[21,b] S. Tkaczyk,[77,a] D. Toback,[123,a] S. Tokar,[53,a] V. V. Tokmenin,[48,b] K. Tollefson,[101,a] T. Tomura,[40,a] D. Tonelli,[77,a] S. Torre,[37,a] D. Torretta,[77,a] P. Totaro,[42b,42a,a] M. Trovato,[40d,40a,a] S.-Y. Tsai,[9,a] D. Tsybychev,[111,b] P. Ttito-Guzmán,[55,a] B. Tuchming,[21,b] Y. Tu,[118,a] C. Tully,[105,b] N. Turini,[40c,40a,a] P. M. Tuts,[108,b] F. Ukegawa,[40,a] R. Unalan,[101,b] S. Uozumi,[42,a] L. Uvarov,[52,b] S. Uvarov,[52,b] S. Uzunyan,[80,b] R. Van Kooten,[83,b] W. M. van Leeuwen,[46,e] N. van Remortel,[15,a] N. Varelas,[79,b] A. Varganov,[99,a] E. W. Varnes,[66,b] I. A. Vasilyev,[51,b] E. Vataga,[40d,40a,a] F. Vázquez,[74,q] G. Velev,[77,a] C. Vellidis,[32,a] P. Verdier,[23,b] L. S. Vertogradov,[48,b] M. Verzocchi,[77,b] M. Vesterinen,[64,b] M. Vidal,[55,a] I. Vila,[56,a] D. Vilanova,[21,b] R. Vilar,[56,a] P. Vint,[62,b] M. Vogel,[106,a] P. Vokac,[12,b] I. Volobouev,[67,bb] G. Volpi,[40b,40a,a] P. Wagner,[118,a] R. G. Wagner,[76,a] R. L. Wagner,[77,a] W. Wagner,[28,ff] J. Wagner-Kuhr,[28,a] H. D. Wahl,[75,b] T. Wakisaka,[39,a] R. Wallny,[70,a] M. H. L. S. Wang,[110,b] S. M. Wang,[9,a] A. Warburton,[6,a] J. Warchol,[85,b] D. Waters,[63,a] G. Watts,[128,b] M. Wayne,[85,b] G. Weber,[29,oo] M. Weber,[77,b] M. Weinberger,[123,a] J. Weinelt,[28,a] W. C. Wester III,[77,a] M. Wetstein,[92,b] A. White,[122,b] B. Whitehouse,[97,a] D. Whiteson,[118,i] D. Wicke,[29,b] A. B. Wicklund,[76,a] E. Wicklund,[77,a] S. Wilbur,[78,a] G. Williams,[6,a] H. H. Williams,[118,a] M. R. J. Williams,[60,b] G. W. Wilson,[88,b] P. Wilson,[77,a] S. J. Wimpenny,[71,b] B. L. Winer,[114,a] P. Wittich,[77,k] M. Wobisch,[90,b] S. Wolbers,[77,a] C. Wolfe,[78,a] H. Wolfe,[114,a] D. R. Wood,[94,b] T. Wright,[99,a] X. Wu,[58,a] F. Würthwein,[69,a] T. R. Wyatt,[64,b] Y. Xie,[77,b] C. Xu,[99,b] S. Yacoob,[81,b] A. Yagil,[69,a] R. Yamada,[77,b] K. Yamamoto,[39,a] J. Yamaoka,[113,a] U. K. Yang,[78,v] W.-C. Yang,[64,b] Y. C. Yang,[42,a] W. M. Yao,[67,a] T. Yasuda,[77,b] Y. A. Yatsunenko,[48,b] Z. Ye,[77,b] G. P. Yeh,[77,a] K. Yi,[77,r] H. Yin,[8,b] K. Yip,[112,b] J. Yoh,[77,a] H. D. Yoo,[121,b] K. Yorita,[41,a] T. Yoshida,[39,o] S. W. Youn,[77,b] G. B. Yu,[113,a] I. Yu,[42,a] J. Yu,[122,b] S. S. Yu,[77,a] J. C. Yun,[77,a] A. Zanetti,[42a,a] S. Zelitch,[127,b] Y. Zeng,[113,a] X. Zhang,[82,a] T. Zhao,[128,b] Y. Zheng,[70,g] B. Zhou,[99,b] J. Zhu,[111,b] M. Zielinski,[110,b] D. Zieminska,[83,b] L. Zivkovic,[108,b] and S. Zucchelli[37a,hh]

([a]CDF Collaboration)
([b]D0 Collaboration)

[1]*Universidad de Buenos Aires, Buenos Aires, Argentina*
[2]*LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[3]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*

[4]Universidade Federal do ABC, Santo André, Brazil
[5]Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
[6]Institute of Particle Physics, McGill University, Montréal, Québec, Canada;
Simon Fraser University, Burnaby, British Columbia, Canada;
University of Toronto, Toronto, Ontario, Canada;
and TRIUMF, Vancouver, British Columbia, Canada
[7]Simon Fraser University, Burnaby, British Columbia, Canada;
and York University, Toronto, Ontario, Canada
[8]University of Science and Technology of China, Hefei, People's Republic of China
[9]Institute of Physics, Academia Sinica, Taipei, Taiwan, Republic of China
[10]Universidad de los Andes, Bogotá, Colombia
[11]Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic
[12]Czech Technical University in Prague, Prague, Czech Republic
[13]Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
[14]Universidad San Francisco de Quito, Quito, Ecuador
[15]Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland
[16]LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
[17]LPSC, Université Joseph Fourier Grenoble 1, France,
and CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
[18]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
[19]LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
[20]LPNHE, Université Paris VI and Université Paris VII, CNRS/IN2P3, Paris, France
[21]CEA, Irfu, SPP, Saclay, France
[22]IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
[23]IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France,
and Université de Lyon, Lyon, France
[24]III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
[25]Physikalisches Institut, Universität Bonn, Bonn, Germany
[26]Physikalisches Institut, Universität Freiburg, Freiburg, Germany
[27]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
[28]Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, Karlsruhe, Germany
[29]Institut für Physik, Universität Mainz, Mainz, Germany
[30]Ludwig-Maximilians-Universität München, München, Germany
[31]Fachbereich Physik, Bergische Univerität Wuppertal, Wuppertal, Germany
[32]University of Athens, 157 71 Athens, Greece
[33]Panjab University, Chandigarh, India
[34]Delhi University, Delhi, India
[35]Tata Institute of Fundamental Research, Mumbai, India
[36]University College Dublin, Dublin, Ireland
[37a]Istituto Nazionale di Fisica Nucleare Bologna, I-40127 Bologna, Italy
[37b]University of Bologna, I-40127 Bologna, Italy
[37]Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy
[39a]Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy
[39b]University of Padova, I-35131 Padova, Italy
[40a]Istituto Nazionale di Fisica Nucleare, Pisa, I-56127 Pisa, Italy
[40b]University of Pisa, I-56127 Pisa, Italy
[40c]University of Siena, I-56127 Pisa, Italy
[40d]Scuola Normale Superiore, I-56127 Pisa, Italy
[41a]Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, I-00185 Roma, Italy
[41b]Sapienza Università di Roma, I-00185 Roma, Italy
[42a]Istituto Nazionale di Fisica Nucleare Trieste/Udine, I-34100 Trieste, I-33100 Udine, Italy
[42b]University of Trieste/Udine, I-33100 Udine, Italy
[38]Okayama University, Okayama 700-8530, Japan
[39]Osaka City University, Osaka 588, Japan
[40]University of Tsukuba, Tsukuba, Ibaraki 305, Japan
[41]Waseda University, Tokyo 169, Japan
[42]Center for High Energy Physics: Kyungpook National University, Daegu, Korea;
Seoul National University, Seoul, Korea;
Sungkyunkwan University, Suwon, Korea;
Korea Institute of Science and Technology Information, Daejeon, Korea;

Chonnam National University, Gwangju, Korea;
Chonbuk National University, Jeonju, Korea
[43]*Korea Detector Laboratory, Korea University, Seoul, Korea*
[44]*SungKyunKwan University, Suwon, Korea*
[45]*CINVESTAV, Mexico City, Mexico*
[46]*FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands*
[47]*Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands*
[48]*Joint Institute for Nuclear Research, Dubna, Russia*
[49]*Institute for Theoretical and Experimental Physics, Moscow, Russia*
[50]*Moscow State University, Moscow, Russia*
[51]*Institute for High Energy Physics, Protvino, Russia*
[52]*Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
[53]*Comenius University, 842 48 Bratislava, Slovakia;*
Institute of Experimental Physics, 040 01 Kosice, Slovakia
[54]*Institut de Fisica d'Altes Energies, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*
[55]*Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain*
[56]*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[57]*Stockholm University, Stockholm, Sweden, and Uppsala University, Uppsala, Sweden*
[58]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[59]*Glasgow University, Glasgow G12 8QQ, United Kingdom*
[60]*Lancaster University, Lancaster LA1 4YB, United Kingdom*
[61]*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[62]*Imperial College London, London SW7 2AZ, United Kingdom*
[63]*University College London, London WC1E 6BT, United Kingdom*
[64]*The University of Manchester, Manchester M13 9PL, United Kingdom*
[65]*University of Oxford, Oxford OX1 3RH, United Kingdom*
[66]*University of Arizona, Tucson, Arizona 85721, USA*
[67]*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[68]*University of California Davis, Davis, California 95616, USA*
[69]*University of California San Diego, La Jolla, California 92093, USA*
[70]*University of California Los Angeles, Los Angeles, California 90024, USA*
[71]*University of California Riverside, Riverside, California 92521, USA*
[72]*University of California Santa Barbara, Santa Barbara, California 93106, USA*
[73]*Yale University, New Haven, Connecticut 06520, USA*
[74]*University of Florida, Gainesville, Florida 32611, USA*
[75]*Florida State University, Tallahassee, Florida 32306, USA*
[76]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
[77]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[78]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*
[79]*University of Illinois at Chicago, Chicago, Illinois 60607, USA*
[80]*Northern Illinois University, DeKalb, Illinois 60115, USA*
[81]*Northwestern University, Evanston, Illinois 60208, USA*
[82]*University of Illinois, Urbana, Illinois 61801, USA*
[83]*Indiana University, Bloomington, Indiana 47405, USA*
[84]*Purdue University Calumet, Hammond, Indiana 46323, USA*
[85]*University of Notre Dame, Notre Dame, Indiana 46556, USA*
[86]*Purdue University, West Lafayette, Indiana 47907, USA*
[87]*Iowa State University, Ames, Iowa 50011, USA*
[88]*University of Kansas, Lawrence, Kansas 66045, USA*
[89]*Kansas State University, Manhattan, Kansas 66506, USA*
[90]*Louisiana Tech University, Ruston, Louisiana 71272, USA*
[91]*The Johns Hopkins University, Baltimore, Maryland 21218, USA*
[92]*University of Maryland, College Park, Maryland 20742, USA*
[93]*Boston University, Boston, Massachusetts 02215, USA*
[94]*Northeastern University, Boston, Massachusetts 02115, USA*
[95]*Harvard University, Cambridge, Massachusetts 02138, USA*
[96]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[97]*Tufts University, Medford, Massachusetts 02155, USA*
[98]*Brandeis University, Waltham, Massachusetts 02254, USA*
[99]*University of Michigan, Ann Arbor, Michigan 48109, USA*
[100]*Wayne State University, Detroit, Michigan 48201, USA*

[101]*Michigan State University, East Lansing, Michigan 48824, USA*
[102]*University of Mississippi, University, Mississippi 38677, USA*
[103]*University of Nebraska, Lincoln, Nebraska 68588, USA*
[104]*Rutgers University, Piscataway, New Jersey 08855, USA*
[105]*Princeton University, Princeton, New Jersey 08544, USA*
[106]*University of New Mexico, Albuquerque, New Mexico 87131, USA*
[107]*State University of New York, Buffalo, New York 14260, USA*
[108]*Columbia University, New York, New York 10027, USA*
[109]*The Rockefeller University, New York, New York 10021, USA*
[110]*University of Rochester, Rochester, New York 14627, USA*
[111]*State University of New York, Stony Brook, New York 11794, USA*
[112]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[113]*Duke University, Durham, North Carolina 27708, USA*
[114]*The Ohio State University, Columbus, Ohio 43210, USA*
[115]*Langston University, Langston, Oklahoma 73050, USA*
[116]*University of Oklahoma, Norman, Oklahoma 73019, USA*
[117]*Oklahoma State University, Stillwater, Oklahoma 74078, USA*
[118]*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
[119]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[120]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*
[121]*Brown University, Providence, Rhode Island 02912, USA*
[122]*University of Texas, Arlington, Texas 76019, USA*

[a]Deceased.

[b]Now at Temple University, Philadelphia, PA 19122, USA.

[c]Deceased.

[d]Visitor to CDF from University of Massachusetts Amherst, Amherst, MA 01003, USA.

[e]Visitor to CDF from Universiteit Antwerpen, B-2610 Antwerp, Belgium.

[f]Visitor to CDF from University of Bristol, Bristol BS8 1TL, United Kingdom.

[g]Visitor to CDF from Chinese Academy of Sciences, Beijing 100864, China.

[h]Visitor to CDF from Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy.

[i]Visitor to CDF from University of California Irvine, Irvine, CA 92697, USA.

[j]Visitor to CDF from University of California Santa Cruz, Santa Cruz, CA 95064, USA.

[k]Visitor to CDF from Cornell University, Ithaca, NY 14853, USA.

[l]Visitor to CDF from University of Cyprus, Nicosia CY-1678, Cyprus.

[m]Visitor to CDF from University College Dublin, Dublin 4, Ireland.

[n]Visitor to CDF from University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom.

[o]Visitor to CDF from University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017.

[p]Visitor to CDF from Kinki University, Higashi-Osaka City, Japan 577-8502.

[q]Visitor to CDF from Universidad Iberoamericana, Mexico D.F., Mexico.

[r]Visitor to CDF from University of Iowa, Iowa City, IA 52242, USA.

[s]Visitor to CDF from Iowa State University, Ames, IA 50011, USA.

[t]Visitor to CDF from Kansas State University, Manhattan, KS 66506, USA.

[u]Visitor to CDF from Queen Mary, University of London, London, E1 4NS, United Kingdom.

[v]Visitor to CDF from University of Manchester, Manchester M13 9PL, United Kingdom.

[w]Visitor to CDF from Muons, Inc., Batavia, IL 60510, USA.

[x]Visitor to CDF from Nagasaki Institute of Applied Science, Nagasaki, Japan.

[y]Visitor to CDF from University of Notre Dame, Notre Dame, IN 46556, USA.

[z]Visitor to CDF from Obninsk State University, Obninsk, Russia.

[aa]Visitor to CDF from University de Oviedo, E-33007 Oviedo, Spain.

[bb]Visitor to CDF from Texas Tech University, Lubbock, TX 79609, USA.

[cc]Visitor to CDF from IFIC (CSIC-Universitat de Valencia), 56071 Valencia, Spain.

[dd]Visitor to CDF from Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile.

[ee]Visitor to CDF from University of Virginia, Charlottesville, VA 22906, USA.

[ff]Visitor to CDF from Bergische Universität Wuppertal, 42097 Wuppertal, Germany.

[gg]Visitor to CDF from Yarmouk University, Irbid 211-63, Jordan.

[hh]On leave from J. Stefan Institute, Ljubljana, Slovenia.

[ii]Visitor to D0 from Augustana College, Sioux Falls, SD, 61201, USA.

[jj]Visitor to D0 from The University of Liverpool, Liverpool, United Kingdom.

[kk]Visitor to D0 from SLAC, Menlo Park, CA, 94025, USA.

[ll]Visitor to D0 from ICREA/IFAE, Barcelona, Spain.

[mm]Visitor to D0 from Centro de Investigacion en Computacion—IPN, Mexico City, Mexico.

[123]*Texas A&M University, College Station, Texas 77843, USA*
[124]*Southern Methodist University, Dallas, Texas 75275, USA*
[125]*Rice University, Houston, Texas 77005, USA*
[126]*Baylor University, Waco, Texas 76798, USA*
[127]*University of Virginia, Charlottesville, Virginia 22901, USA*
[128]*University of Washington, Seattle, Washington 98195, USA*
[129]*University of Wisconsin, Madison, Wisconsin 53706, USA*
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We combine results from searches by the CDF and D0 collaborations for a standard model Higgs boson (H) in the process $gg \to H \to W^+W^-$ in $p\bar{p}$ collisions at the Fermilab Tevatron Collider at $\sqrt{s} = 1.96$ TeV. With 4.8 fb^{-1} of integrated luminosity analyzed at CDF and 5.4 fb^{-1} at D0, the 95% confidence level upper limit on $\sigma(gg \to H) \times \mathcal{B}(H \to W^+W^-)$ is 1.75 pb at $m_H = 120$ GeV, 0.38 pb at $m_H = 165$ GeV, and 0.83 pb at $m_H = 200$ GeV. Assuming the presence of a fourth sequential generation of fermions with large masses, we exclude at the 95% confidence level a standard-model-like Higgs boson with a mass between 131 and 204 GeV.

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Exploring the mechanism for breaking the $SU(2) \times U(1)$ electroweak gauge symmetry is a priority in high energy physics. Not only are this symmetry and its breaking [1] necessary components for the consistency of the successful standard model (SM) [2], but measurable properties of the breaking mechanism are also very sensitive to possible phenomena that have not yet been observed at collider experiments. Measuring these properties, or setting limits on them, can constrain broad classes of extensions to the SM.

A natural extension to the SM that can be tested with Higgs boson search results at the Fermilab Tevatron Collider is the presence of a fourth generation of fermions with masses much larger than those of the three known generations [3]. While fits to precision electroweak data favor a low-mass Higgs boson in the SM, the addition of a fourth generation of fermions to the SM modifies the fit parameters such that a heavy Higgs boson is consistent for up to $m_H \approx 300$ GeV at the 68% confidence level (CL) [4]. Measurements of the Z boson decay width [5] exclude models in which the fourth neutrino mass eigenstate has a mass less than 45 GeV. If the neutrino masses are very large, however, a fourth generation of fermions is not yet excluded.

One consequence of the extra fermions is that the ggH coupling is enhanced by a factor of roughly three relative to the SM coupling [4,6,7]. Since the lowest-order ggH coupling arises from a quark loop. The top quark contribution is the largest due to its large coupling with the Higgs boson. In the limit $m_{q4} \gg m_H$, where m_{q4} is the fourth-generation quark mass, the Higgs boson coupling cancels the mass dependence for each of the three propagators in the loop, and the contribution to the ggH coupling becomes asymptotically independent of the masses of the two fourth-generation quarks. Each additional fourth-generation quark then contributes as much as the top quark, and the ggH coupling is thus enhanced by a factor K_e of approximately three.

The production cross section will be enhanced by a factor of K_e^2. For m_H near the low end of our search range, $m_H \approx 110$ GeV, the $gg \to H$ production cross section is enhanced by roughly a factor of 9 relative to the SM prediction. This factor drops to approximately 7.5 near the upper end of the search range, $m_H \approx 300$ GeV, assuming asymptotically large masses for the fourth-generation quarks. The reason for this drop is that the denominator of the enhancement factor, the SM cross section, has a larger contribution from the SM top quark as m_H nears $2m_t$. The partial decay width for $H \to gg$ is enhanced by the same factor as the production cross section. However, because the decay $H \to gg$ is loop mediated, the $H \to W^+W^-$ decay continues to dominate for Higgs boson masses $m_H > 135$ GeV.

We consider two scenarios for the masses of the fourth-generation fermions. In the first scenario, the "low-mass" scenario, we set the mass of the fourth-generation neutrino to $m_{\nu 4} = 80$ GeV, and the mass of the fourth-generation charged lepton to $m_{\ell 4} = 100$ GeV in order to evade experimental constraints [8] and to have the maximum impact on the Higgs boson decay branching ratios. In the second scenario, the "high-mass" scenario, we set $m_{\nu 4} = m_{\ell 4} = 1$ TeV, so that the fourth-generation leptons do not affect the decay branching ratios of the Higgs boson. In both scenarios, we choose the masses of the quarks to be those of the second scenario in Ref. [7], that is, we set the mass of the fourth-generation down-type quark to be $m_{d4} = 400$ GeV and the mass of the fourth-generation up-type quark to be $m_{u4} = m_{d4} + 50 \text{ GeV} + 10\log(m_H/115 \text{ GeV})$ GeV. The other mass spectrum of Ref. [7] chooses $m_{d4} = 300$ GeV, resulting in slightly larger predictions for $\sigma(gg \to H)$. We use the next-to-next-to-leading order (NNLO) production cross section calculation of Ref. [7], which builds on the NNLO SM calculations of Refs. [9–16], the results of which are also listed in Ref. [17].

The CDF and D0 Collaborations have searched for the SM Higgs boson in the decay $H \to W^+W^-$ using all SM production processes: $gg \to H$, $qq \to WH$, $qq \to ZH$, and vector-boson fusion (VBF) [18–20]. The results of these searches for the SM Higgs boson cannot be used directly to constrain fourth-generation models, as the ggH coupling is enhanced but the WWH and ZZH couplings are not, and the signal acceptances and the backgrounds in the multiple analysis channels differ for the various production modes. Therefore, these searches rely on the SM to predict the ratios of the production rates of the $gg \to H$, WH, ZH, and VBF signals. Previous external analyses have used the Tevatron's SM Higgs boson search results to constrain fourth-generation models, incorrectly arguing that the WH, ZH, and VBF production rates are not significant, thus obtaining only approximate results. Furthermore, the SM results [18–20] extend only up to m_H of 200 GeV. This paper addresses both of these issues by placing limits on $\sigma(gg \to H) \times \mathcal{B}(H \to W^+W^-)$ up to $m_H = 300$ GeV.

Previously, the CDF and D0 collaborations have published searches for the process $gg \to H \to W^+W^-$, also neglecting the WH, ZH, and VBF signal contributions [21,22]. The D0 search includes a fourth-generation interpretation. Here we update these searches with those using 4.8 fb^{-1} from CDF [18] and 5.4 fb^{-1} from D0 [19]. We present new limits on $\sigma(gg \to H) \times \mathcal{B}(H \to W^+W^-)$ in which the $gg \to H$ production mechanism is considered as the unique signal source. These limits are compared to models for Higgs boson production in which the ggH coupling is enhanced by the presence of a single additional generation of fermions. In this comparison, the decay branching ratios of the Higgs boson are also modified to reflect changes due to the fourth generation relative to the SM prediction. While the decays of the heavy quarks and leptons may include W bosons in the final state, we do not include these as additional sources of signal. The branching ratios for $H \to W^+W^-$ are calculated using HDECAY [23] modified to include fourth-generation fermions [4]. The modified Higgs branching ratio to W^+W^- is multiplied by the cross section [7] to predict the fourth-generation enhanced $gg \to H \to W^+W^-$ production rate.

The event selections are similar for the corresponding CDF and D0 analyses. Both collaborations select events with large $\not\!\!E_T$ and two oppositely charged, isolated leptons, targeting the $H \to W^+W^-$ signal in which both W bosons decay leptonically. The D0 analysis classifies events in three channels defined by the number of charged leptons (e or μ), e^+e^-, $e^\pm\mu^\mp$, and $\mu^+\mu^-$ and no classification based upon jet multiplicity. The CDF analysis separates opposite-sign candidate events into five nonoverlapping channels. Events are classified by their jet multiplicity (0, 1, or ≥ 2), and the 0 and 1 jet channels are further divided according to whether both leptons are in the central part of the detector or if either lepton is in the forward part of the detector. Two changes have been made in the D0 event selection from the analysis presented in Ref. [19]. For higher Higgs boson masses ($m_H > 200$ GeV), the dilepton azimuthal-opening angle distribution is no longer peaked at low values ($\Delta\phi(\ell, \ell) < 1$). Therefore, to enhance the signal acceptance for large m_H, the requirement on the dilepton azimuthal-opening angle [$\Delta\phi(\ell, \ell)$] has been removed for $e^\pm\mu^\mp$ candidate events and relaxed to $\Delta\phi(\ell, \ell) < 2.5$ in the e^+e^- and $\mu^+\mu^-$ candidate events. In addition, a requirement on the ϕ-opening angle between the leading muon and the missing transverse energy, $\Delta\phi(\mu, \not\!\!E_T) > 0.5$, has been included to remove additional background in a signal-free region. The predicted contributions from the different background processes are compared with the numbers of events observed in data for the CDF and D0 analyses in Tables I and II, respectively.

The presence of neutrinos in the final state prevents event-by-event reconstruction of the Higgs boson mass

TABLE I. Expected and observed event yields in the 0-jet exclusive, 1-jet exclusive, and 2-jet inclusive samples at final selection for the CDF analysis summed across all lepton categories. The systematic uncertainty is shown for all samples. The signal expectation is given for the low-mass fourth-generation scenario with an SM Higgs mass of 200 GeV with a predicted $\sigma(gg \to H) \times \text{BR}(H \to W^+W^-)$ of 1.02 pb.

CDF Run II $\int \mathcal{L} = 4.8$ fb^{-1}	0-jet	1-jet	$\geq$ 2-jets
$Z/\gamma^* \to \ell^+\ell^-$	128 ± 30	133 ± 42	51 ± 17
$t\bar{t}$	1.99 ± 0.31	48.4 ± 7.6	145 ± 24
WW	447 ± 48	121 ± 13	25.6 ± 5.8
WZ	19.7 ± 2.7	20.0 ± 2.7	5.30 ± 0.73
ZZ	29.9 ± 4.1	8.0 ± 1.1	2.36 ± 0.32
W + jets	154 ± 37	59 ± 15	21.9 ± 5.9
$W\gamma$	112 ± 19	16.2 ± 3.6	2.72 ± 0.67
Total Background	893 ± 79	406 ± 52	254 ± 33
$gg \to H$ ($M_H = 200$ GeV)	35.2 ± 5.0	20.2 ± 5.1	8.5 ± 5.1
Data	950	393	224

TABLE II. Expected and observed event yields in each channel at the final selection for the D0 analysis summed across all jet multiplicities. The systematic uncertainty after fitting is shown for all samples at final selection. The signal expectation is given for the low-mass fourth-generation scenario with an SM Higgs mass of 200 GeV with a predicted $\sigma(gg \to H) \times \mathrm{BR}(H \to W^+W^-)$ of 1.02 pb.

D0 Run II $\int \mathcal{L} = 5.4$ fb^{-1}	$e^\pm\mu^\mp$	e^+e^-	$\mu^+\mu^-$
$Z/\gamma^* \to e^+e^-$	<0.1	370 ± 24	···
$Z/\gamma^* \to \mu^+\mu^-$	7.0 ± 0.1	···	2056 ± 58
$Z/\gamma^* \to \tau^+\tau^-$	28.0 ± 0.2	0.8 ± 0.1	6.9 ± 0.6
$t\bar{t}$	176 ± 15	58.9 ± 5.5	74.9 ± 6.8
WW	304 ± 18	102 ± 7.3	145 ± 11
WZ	13.4 ± 0.2	18.1 ± 1.0	31.4 ± 2.0
ZZ	1.1 ± 0.1	15.2 ± 0.9	26.9 ± 1.7
W + jets/γ	156 ± 12	154 ± 14	118 ± 13.7
Multijet	10.4 ± 2.5	1.4 ± 0.1	72.7 ± 13.7
Total Background	696 ± 26	720 ± 32	2532 ± 58
$gg \to H$ (M_H = 200 GeV)	36.5 ± 5.4	15.8 ± 2.2	19.0 ± 2.9
Data	684	719	2516

and thus other variables are used for separating the signal from the background. For example, the angle $\Delta\phi(\ell, \ell)$ in signal events is smaller on average than that in background events, the missing transverse momentum is larger, and the total transverse energy of the jets is lower. In these analyses, the final discriminants are neural-network (NN) [24,25] outputs based on several kinematic variables. For CDF, the list of network inputs includes likelihood ratio discriminant variables constructed from matrix-element probabilities [18].

Both CDF and D0 have extended their searches to the range $110 < m_H < 300$ GeV. Separate neural networks are trained to distinguish the $gg \to H$ signal from the backgrounds for each of the test masses, which are separated by increments of 5 or 10 GeV. Distributions of the network outputs for CDF and D0 are shown in Figs. 1 and 2, comparing the data with predictions for a Higgs boson of mass $m_H = 200$ GeV. Because the background composition and the signal kinematics are functions of the number of jets in the event, the CDF NN output distributions are shown separately for 0, 1, and 2 or more jets, summed over lepton categories. For D0, as the detector response is different for electrons and muons, the NN distributions are shown separately for e^+e^-, $e^\pm\mu^\mp$, and $\mu^+\mu^-$ selections.

The details of the signal and background estimations and the systematic uncertainties are provided in Refs. [18–20]. We set limits on $\sigma(gg \to H) \times \mathcal{B}(H \to W^+W^-)$ as a function of m_H. We use the same two statistical methods employed in Ref. [20], namely, the modified frequentist

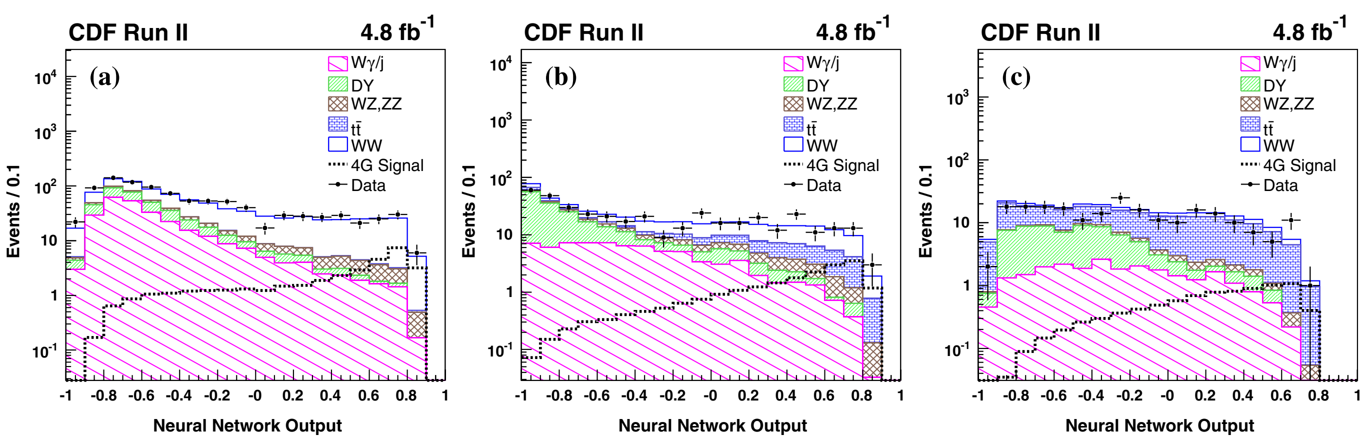

FIG. 1 (color online). Distributions of the neural-network outputs for the search for a Higgs boson of mass $m_H = 200$ GeV, from CDF. The data are shown as points with uncertainty bars, and the background predictions are shown stacked. The figures show the distributions for events with (a) zero, (b) one, and (c) two or more identified jets, respectively. The distributions are summed over lepton categories. The fourth-generation signal, normalized to the prediction of the low-mass scenario, is shown not stacked.

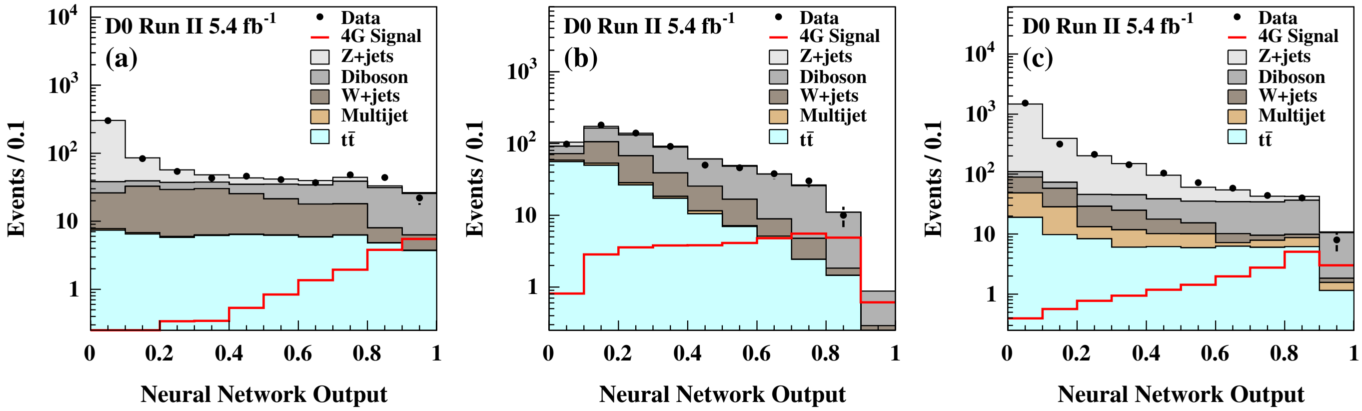

FIG. 2 (color online). Distributions of the neural-network outputs for the search for a Higgs boson of mass $m_H = 200$ GeV, from D0 summed over all jet multiplicities. (a) shows the distribution for the di-electron selection, (b) shows the distribution for the electron-muon selection, and (c) shows the distribution for the di-muon selection. The data are shown as points with uncertainty bars, and the background predictions are shown stacked. The background uncertainty is the post-fit systematic uncertainty. The fourth-generation signal, normalized to the prediction of the low-mass scenario, is shown not stacked.

($\mathrm{CL_s}$) and Bayesian techniques in order to study the consistency of the results. Each method is applied at each test mass to calculate an observed upper limit on $\sigma(gg \to H) \times \mathcal{B}(H \to W^+W^-)$. Pseudoexperiments drawn from systematically varied background-only predictions are used to compute the limits we expect to obtain in the absence of a signal. We present both the Bayesian and $\mathrm{CL_s}$ observed and expected limits in Ref. [17]. The limits calculated with the two methods agree within 6% for all Higgs boson mass hypotheses. Correlated systematic uncertainties are treated in the same way as they are in Ref. [20]. The sources of correlated uncertainty between CDF and D0 are the total inelastic $p\bar{p}$ cross section used in the luminosity measurement, the SM diboson background production cross sections (WW, WZ, and ZZ), and the $t\bar{t}$ and single top quark production cross sections. Instrumental effects such as trigger efficiencies, lepton identification efficiencies and misidentification rates, and the jet energy scales used by CDF and D0 remain uncorrelated. To minimize the degrading effects of systematics on the search sensitivity, the signal and background contributions are fit to the data observations by maximizing a likelihood function over the systematic uncertainties for both the background-only and signal-plus-background hypotheses [26]. When setting limits on $\sigma(gg \to H) \times \mathcal{B}(H \to W^+W^-)$, we do not include the theoretical uncertainty on the prediction of $\sigma(gg \to H) \times \mathcal{B}(H \to W^+W^-)$ in the fourth-generation models since these limits are independent of the predictions. When setting limits on m_H in the context of fourth-generation models, however, we include the uncertainties on the theoretical predictions as described below.

Before computing the cross section limits, we investigate the properties of the signal and background predictions in each bin of the analyses, as well as those of the observed data. Because there are many channels to combine, we represent the data in a compact form by sorting the bins of each analysis by their signal-to-background ratio s/b, where s and b are the number of signal and background events, repetitively. The predictions and observations in bins of similar s/b are then collected. For the $m_H = 200$ GeV search, the background-subtracted data distribution compared with the signal prediction can be seen in Fig. 3. The background used and its uncertainties are shown after fitting to the data. No significant excess is observed in the data, and the theory predicts a measurable excess over the background.

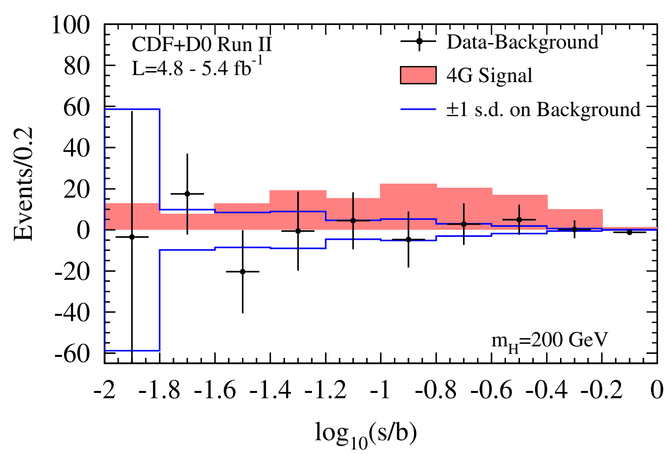

FIG. 3 (color online). Background-subtracted data distribution for the discriminant histograms, summed for bins of s/b, for the $m_H = 200$ GeV combined search. The background is fitted to the data under the background-only hypothesis, and the uncertainty on the background is the post-fit systematic uncertainty. The signal, which is normalized to the low-mass fourth-generation SM expectation, is shown with a filled histogram. The uncertainties shown on the background-subtracted data points are the square roots of the post-fit background predictions in each bin, representing the expected statistical uncertainty on the data.

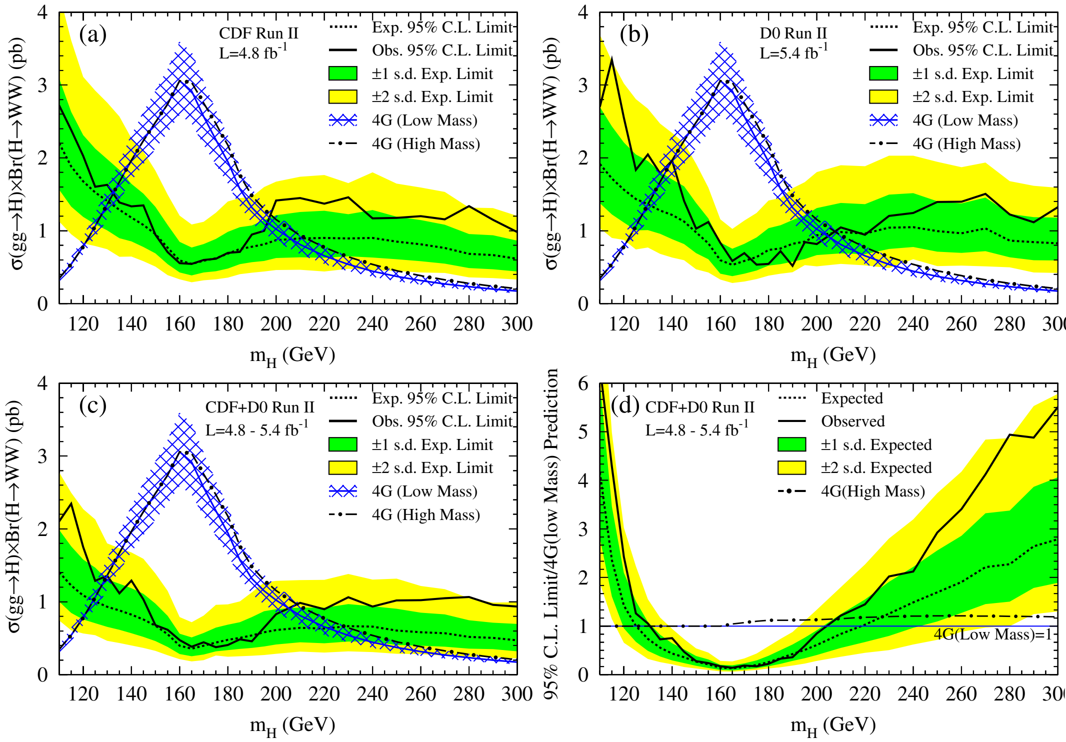

FIG. 4 (color online). The CDF, D0, and combined observed (solid black lines) and median expected (dashed black lines) 95% C.L. upper limits on $\sigma(gg \to H) \times \mathcal{B}(H \to W^+W^-)$ are shown in figures (a) through (c). The shaded bands indicate the ± 1 standard deviation (SD) and ± 2 SD intervals on the distribution of the limits that are expected if a Higgs boson signal is not present. Also shown on each graph, is the prediction for a fourth-generation model in the low-mass and high-mass scenarios, 4G (low mass) and 4G (high mass), respectively. The hatched areas indicate the theoretical uncertainty from PDF and scale uncertainties. The lighter curves show the high-mass theoretical prediction. Figure (d) shows the 95% CL combined limit relative to the low-mass theoretical prediction, where the uncertainties in the signal prediction are included in the limit. Also shown in figure (d) is the prediction of the signal rate in the high-mass scenario, divided by that of the low-mass scenario.

The separate limits on $\sigma(gg \to H) \times \mathcal{B}(H \to W^+W^-)$ from CDF and D0 are shown in Figs. 4(a) and 4(b), respectively. Since CDF separates the different jet categories into separate channels, theoretical uncertainties on the relative contributions of the $gg \to H$ signal in the separate jet channels [27] are included in the same way as signal acceptance uncertainties. The combined limits on $\sigma(gg \to H) \times \mathcal{B}(H \to W^+W^-)$ are shown in Fig. 4(c) along with the fourth-generation theory predictions for the high-mass and low-mass scenarios. The 95% CL upper limit on $\sigma(gg \to H) \times \mathcal{B}(H \to W^+W^-)$ is 1.75 pb at $m_H = 120$ GeV, 0.38 pb at $m_H = 165$ GeV, and 0.83 pb at $m_H = 200$ GeV. The uncertainty bands shown on the low-mass theoretical prediction are the sum in quadrature of the MSTW 2008 [28] 90% CL parton distribution function (PDF) uncertainties and the factorization and renormalization scale uncertainties from Table 1 of Ref. [7], which are also reported Ref. [17], giving a total uncertainty of 15% for $m_H = 160$ GeV. The scale uncertainties are determined by recalculating the cross sections with the scale multiplied by factors of 1/2 and 2. The scale uncertainties are independent of m_H and are similar to the uncertainties for SM $\sigma(gg \to H)$ predictions [12,29]. The PDF uncertainties, however, grow with increasing m_H, as higher-x gluons are required to produce more massive Higgs bosons.

In order to set limits on m_H in these two scenarios, we perform a second combination, including the uncertainties on the theoretical predictions of $\sigma(gg \to H) \times \mathcal{B}(H \to W^+W^-)$ due to scale and PDF uncertainties at each value of m_H tested. The resulting limits are computed relative to the model prediction, and are shown in Fig. 4(d) for the low-mass scenario, which gives the smaller excluded range of m_H. In this scenario, we exclude at the 95% CL an SM-like Higgs boson with a mass in the range 131–204 GeV. Using the median limits on $\sigma(gg \to H) \times \mathcal{B}(H \to W^+W^-)$, expected in the absence of a signal, to quantify the sensitivity, we expect to exclude the mass range 125–218 GeV. In the high-mass scenario, which predicts a larger $\mathcal{B}(H \to W^+W^-)$ at high m_H than that predicted in the low-mass scenario, we exclude at the 95% CL the mass range 131–208 GeV and expect to exclude the mass range 125–227 GeV.

In summary, we presented a combination of CDF and D0 searches for the $gg \to H \to W^+W^-$ process and set an upper limit on $\sigma(gg \to H) \times \mathcal{B}(H \to W^+W^-)$ as a function of m_H. We compared these limits with the prediction of the minimal SM with a sequential fourth generation of heavy fermions added on, and excluded at the 95% CL the Higgs boson mass range $131 < m_H < 204$ GeV, with an expected excluded range of 125–218 GeV.

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