

University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

Kenneth Bloom Publications

Research Papers in Physics and Astronomy

October 2008

Observation of ZZ Production in pp Collisions at $\sqrt{s} = 1.96$ TeV

V. M. Abazov

Joint Institute for Nuclear Research, Dubna, Russia

Kenneth A. Bloom

University of Nebraska-Lincoln, kenbloom@unl.edu

D0 Collaboration

Follow this and additional works at: <https://digitalcommons.unl.edu/physicsbloom>



Part of the [Physics Commons](#)

Abazov, V. M.; Bloom, Kenneth A.; and Collaboration, D0, "Observation of ZZ Production in pp Collisions at $\sqrt{s} = 1.96$ TeV" (2008). *Kenneth Bloom Publications*. 260.
<https://digitalcommons.unl.edu/physicsbloom/260>

This Article is brought to you for free and open access by the Research Papers in Physics and Astronomy at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Kenneth Bloom Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

Observation of ZZ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

V. M. Abazov,³⁶ B. Abbott,⁷⁵ M. Abolins,⁶⁵ B. S. Acharya,²⁹ M. Adams,⁵¹ T. Adams,⁴⁹ E. Aguilo,⁶ M. Ahsan,⁵⁹ G. D. Alexeev,³⁶ G. Alkhazov,⁴⁰ A. Alton,^{64,*} G. Alverson,⁶³ G. A. Alves,² M. Anastasoia,³⁵ L. S. Ancu,³⁵ T. Andeen,⁵³ B. Andrieu,¹⁷ M. S. Anzels,⁵³ M. Aoki,⁵⁰ Y. Arnoud,¹⁴ M. Arov,⁶⁰ M. Arthaud,¹⁸ A. Askew,⁴⁹ B. Åsman,⁴¹ A. C. S. Assis Jesus,³ O. Atramentov,⁴⁹ C. Avila,⁸ F. Badaud,¹³ L. Bagby,⁵⁰ B. Baldin,⁵⁰ D. V. Bandurin,⁵⁹ P. Banerjee,²⁹ S. Banerjee,²⁹ E. Barberis,⁶³ A.-F. Barfuss,¹⁵ P. Bargassa,⁸⁰ P. Baringer,⁵⁸ J. Barreto,² J. F. Bartlett,⁵⁰ U. Bassler,¹⁸ D. Bauer,⁴³ S. Beale,⁶ A. Bean,⁵⁸ M. Begalli,³ M. Begel,⁷³ C. Belanger-Champagne,⁴¹ L. Bellantoni,⁵⁰ A. Bellavance,⁵⁰ J. A. Benitez,⁶⁵ S. B. Beri,²⁷ G. Bernardi,¹⁷ R. Bernhard,²³ I. Bertram,⁴² M. Besançon,¹⁸ R. Beuselinck,⁴³ V. A. Bezzubov,³⁹ P. C. Bhat,⁵⁰ V. Bhatnagar,²⁷ C. Biscarat,²⁰ G. Blazey,⁵² F. Blekman,⁴³ S. Blessing,⁴⁹ K. Bloom,⁶⁷ A. Boehnlein,⁵⁰ D. Boline,⁶² T. A. Bolton,⁵⁹ E. E. Boos,³⁸ G. Borissov,⁴² T. Bose,⁷⁷ A. Brandt,⁷⁸ R. Brock,⁶⁵ G. Brooijmans,⁷⁰ A. Bross,⁵⁰ D. Brown,⁸¹ X. B. Bu,⁷ N. J. Buchanan,⁴⁹ D. Buchholz,⁵³ M. Buehler,⁸¹ V. Buescher,²² V. Bunichev,³⁸ S. Burdin,^{42,+} T. H. Burnett,⁸² C. P. Buszello,⁴³ J. M. Butler,⁶² P. Calfayan,²⁵ S. Calvet,¹⁶ J. Cammin,⁷¹ E. Carrera,⁴⁹ W. Carvalho,³ B. C. K. Casey,⁵⁰ H. Castilla-Valdez,³³ G. Cerminara,^{63,‡} S. Chakrabarti,¹⁸ D. Chakraborty,⁵² K. M. Chan,⁵⁵ A. Chandra,⁴⁸ E. Cheu,⁴⁵ F. Chevallier,¹⁴ D. K. Cho,⁶² S. Choi,³² B. Choudhary,²⁸ L. Christofek,⁷⁷ T. Christoudias,⁴³ S. Cihangir,⁵⁰ D. Claes,⁶⁷ J. Clutter,⁵⁸ M. Cooke,⁵⁰ W. E. Cooper,⁵⁰ M. Corcoran,⁸⁰ F. Couderc,¹⁸ M.-C. Cousinou,¹⁵ S. Crépe-Renaudin,¹⁴ V. Cuplov,⁵⁹ D. Cutts,⁷⁷ M. Ćwiok,³⁰ H. da Motta,² A. Das,⁴⁵ G. Davies,⁴³ K. De,⁷⁸ S. J. de Jong,³⁵ E. De La Cruz-Burelo,³³ C. De Oliveira Martins,³ K. DeVaughan,⁶⁷ J. D. Degenhardt,⁶⁴ F. Déliot,¹⁸ M. Demarteau,⁵⁰ R. Demina,⁷¹ D. Denisov,⁵⁰ S. P. Denisov,³⁹ S. Desai,⁵⁰ H. T. Diehl,⁵⁰ M. Diesburg,⁵⁰ A. Dominguez,⁶⁷ H. Dong,⁷² T. Dorland,⁸² A. Dubey,²⁸ L. V. Dudko,³⁸ L. Duflot,¹⁶ S. R. Dugad,²⁹ D. Duggan,⁴⁹ A. Duperrin,¹⁵ J. Dyer,⁶⁵ A. Dyshkant,⁵² M. Eads,⁶⁷ D. Edmunds,⁶⁵ J. Ellison,⁴⁸ V. D. Elvira,⁵⁰ Y. Enari,⁷⁷ S. Eno,⁶¹ P. Ermolov,^{38,‡‡} H. Evans,⁵⁴ A. Evdokimov,⁷³ V. N. Evdokimov,³⁹ G. Facini,⁶³ A. V. Ferapontov,⁵⁹ T. Ferbel,⁷¹ F. Fiedler,²⁴ F. Filthaut,³⁵ W. Fisher,⁵⁰ H. E. Fisk,⁵⁰ M. Fortner,⁵² H. Fox,⁴² S. Fu,⁵⁰ S. Fuess,⁵⁰ T. Gadfort,⁷⁰ C. F. Galea,³⁵ C. Garcia,⁷¹ A. Garcia-Bellido,⁷¹ V. Gavrilov,³⁷ P. Gay,¹³ W. Geist,¹⁹ W. Geng,^{15,65} C. E. Gerber,⁵¹ Y. Gershtein,⁴⁹ D. Gillberg,⁶ G. Ginter,⁷¹ N. Gollub,⁴¹ B. Gómez,⁸ A. Goussiou,⁸² P. D. Grannis,⁷² H. Greenlee,⁵⁰ Z. D. Greenwood,⁶⁰ E. M. Gregores,⁴ G. Grenier,²⁰ Ph. Gris,¹³ J.-F. Grivaz,¹⁶ A. Grohsjean,²⁵ S. Grünendahl,⁵⁰ M. W. Grünewald,³⁰ F. Guo,⁷² J. Guo,⁷² G. Gutierrez,⁵⁰ P. Gutierrez,⁷⁵ A. Haas,⁷⁰ N. J. Hadley,⁶¹ P. Haefner,²⁵ S. Hagopian,⁴⁹ J. Haley,⁶⁸ I. Hall,⁶⁵ R. E. Hall,⁴⁷ L. Han,⁷ K. Harder,⁴⁴ A. Harel,⁷¹ J. M. Hauptman,⁵⁷ J. Hays,⁴³ T. Hebbeker,²¹ D. Hedin,⁵² J. G. Hegeman,³⁴ A. P. Heinson,⁴⁸ U. Heintz,⁶² C. Hensel,^{22,§} K. Herner,⁷² G. Hesketh,⁶³ M. D. Hildreth,⁵⁵ R. Hirosky,⁸¹ J. D. Hobbs,⁷² B. Hoeneisen,¹² H. Hoeth,²⁶ M. Hohlfield,²² S. Hossain,⁷⁵ P. Houben,³⁴ Y. Hu,⁷² Z. Hubacek,¹⁰ V. Hynek,⁹ I. Iashvili,⁶⁹ R. Illingworth,⁵⁰ A. S. Ito,⁵⁰ S. Jabeen,⁶² M. Jaffré,¹⁶ S. Jain,⁷⁵ K. Jakobs,²³ C. Jarvis,⁶¹ R. Jesik,⁴³ K. Johns,⁴⁵ C. Johnson,⁷⁰ M. Johnson,⁵⁰ D. Johnston,⁶⁷ A. Jonckheere,⁵⁰ P. Jonsson,⁴³ A. Juste,⁵⁰ E. Kajfasz,¹⁵ J. M. Kalk,⁶⁰ D. Karmanov,³⁸ P. A. Kasper,⁵⁰ I. Katsanos,⁷⁰ D. Kau,⁴⁹ V. Kaushik,⁷⁸ R. Kehoe,⁷⁹ S. Kermiche,¹⁵ N. Khalatyan,⁵⁰ A. Khanov,⁷⁶ A. Kharchilava,⁶⁹ Y. M. Kharzheev,³⁶ D. Khatidze,⁷⁰ T. J. Kim,³¹ M. H. Kirby,⁵³ M. Kirsch,²¹ B. Klima,⁵⁰ J. M. Kohli,²⁷ J.-P. Konrath,²³ A. V. Kozelov,³⁹ J. Kraus,⁶⁵ T. Kuhl,²⁴ A. Kumar,⁶⁹ A. Kupco,¹¹ T. Kurča,²⁰ V. A. Kuzmin,³⁸ J. Kvita,⁹ F. Lacroix,¹³ D. Lam,⁵⁵ S. Lammers,⁷⁰ G. Landsberg,⁷⁷ P. Lebrun,²⁰ W. M. Lee,⁵⁰ A. Leflat,³⁸ J. Lellouch,¹⁷ J. Li,^{78,‡‡} L. Li,⁴⁸ Q. Z. Li,⁵⁰ S. M. Lietti,⁵ J. K. Lim,³¹ J. G. R. Lima,⁵² D. Lincoln,⁵⁰ J. Linnemann,⁶⁵ V. V. Lipaev,³⁹ R. Lipton,⁵⁰ Y. Liu,⁷ Z. Liu,⁶ A. Lobodenko,⁴⁰ M. Lokajicek,¹¹ P. Love,⁴² H. J. Lubatti,⁸² R. Luna,³ A. L. Lyon,⁵⁰ A. K. A. Maciel,² D. Mackin,⁸⁰ R. J. Madaras,⁴⁶ P. Mättig,²⁶ C. Magass,²¹ A. Magerkurth,⁶⁴ P. K. Mal,⁸² H. B. Malbouisson,³ S. Malik,⁶⁷ V. L. Malyshev,³⁶ Y. Maravin,⁵⁹ B. Martin,¹⁴ R. McCarthy,⁷² A. Melnitchouk,⁶⁶ L. Mendoza,⁸ P. G. Mercadante,⁵ M. Merkin,³⁸ K. W. Merritt,⁵⁰ A. Meyer,²¹ J. Meyer,^{22,§} J. Mitrevski,⁷⁰ R. K. Mommsen,⁴⁴ N. K. Mondal,²⁹ R. W. Moore,⁶ T. Moulik,⁵⁸ G. S. Muanza,²⁰ M. Mulhearn,⁷⁰ O. Mundal,²² L. Mundim,³ E. Nagy,¹⁵ M. Naimuddin,⁵⁰ M. Narain,⁷⁷ N. A. Naumann,³⁵ H. A. Neal,⁶⁴ J. P. Negret,⁸ P. Neustroev,⁴⁰ H. Nilsen,²³ H. Nogima,³ S. F. Novaes,⁵ T. Nunnemann,²⁵ V. O'Dell,⁵⁰ D. C. O'Neil,⁶ G. Odrant,⁴⁰ C. Ochando,¹⁶ D. Onoprienko,⁵⁹ N. Oshima,⁵⁰ N. Osman,⁴³ J. Osta,⁵⁵ R. Otec,¹⁰ G. J. Otero y Garzón,⁵⁰ M. Owen,⁴⁴ P. Padley,⁸⁰ M. Pangilinan,⁷⁷ N. Parashar,⁵⁶ S.-J. Park,^{22,§} S. K. Park,³¹ J. Parsons,⁷⁰ R. Partridge,⁷⁷ N. Parua,⁵⁴ A. Patwa,⁷³ G. Pawloski,⁸⁰ B. Penning,²³ M. Perfilov,³⁸ K. Peters,⁴⁴ Y. Peters,²⁶ P. Pétroff,¹⁶ M. Petteni,⁴³ R. Piegaia,¹ J. Piper,⁶⁵ M.-A. Pleier,²² P. L. M. Podesta-Lerma,^{33,§} V. M. Podstavkov,⁵⁰ Y. Pogorelov,⁵⁵ M.-E. Pol,² P. Polozov,³⁷ B. G. Pope,⁶⁵ A. V. Popov,³⁹ C. Potter,⁶ W. L. Prado da Silva,³ H. B. Prosper,⁴⁹ S. Protopopescu,⁷³ J. Qian,⁶⁴ A. Quadt,^{22,||} B. Quinn,⁶⁶ A. Rakitine,⁴² M. S. Rangel,² K. Ranjan,²⁸ P. N. Ratoff,⁴² I. Razumov,³⁹ P. Renkel,⁷⁹ P. Rich,⁴⁴ J. Rieger,⁵⁴ M. Rijssenbeek,⁷² I. Ripp-Baudot,¹⁹ F. Rizatdinova,⁷⁶ S. Robinson,⁴³ R. F. Rodrigues,³

M. Rominsky,⁷⁵ C. Royon,¹⁸ P. Rubinov,⁵⁰ R. Ruchti,⁵⁵ G. Safronov,³⁷ G. Sajot,¹⁴ A. Sánchez-Hernández,³³
M. P. Sanders,¹⁷ B. Sanghi,⁵⁰ G. Savage,⁵⁰ L. Sawyer,⁶⁰ T. Scanlon,⁴³ D. Schaile,²⁵ R. D. Schamberger,⁷² Y. Scheglov,⁴⁰
H. Schellman,⁵³ T. Schliephake,²⁶ S. Schlobohm,⁸² C. Schwanenberger,⁴⁴ A. Schwartzman,⁶⁸ R. Schwienhorst,⁶⁵
J. Sekaric,⁴⁹ H. Severini,⁷⁵ E. Shabalina,⁵¹ M. Shamim,⁵⁹ V. Shary,¹⁸ A. A. Shchukin,³⁹ R. K. Shivpuri,²⁸ V. Siccadi,¹⁹
V. Simak,¹⁰ V. Sirotenko,⁵⁰ P. Skubic,⁷⁵ P. Slattey,⁷¹ D. Smirnov,⁵⁵ G. R. Snow,⁶⁷ J. Snow,⁷⁴ S. Snyder,⁷³
S. Söldner-Rembold,⁴⁴ L. Sonnenschein,¹⁷ A. Sopczak,⁴² M. Sosebee,⁷⁸ K. Soustruznik,⁹ B. Spurlock,⁷⁸ J. Stark,¹⁴
J. Steele,⁶⁰ V. Stolin,³⁷ D. A. Stoyanova,³⁹ J. Strandberg,⁶⁴ S. Strandberg,⁴¹ M. A. Strang,⁶⁹ E. Strauss,⁷² M. Strauss,⁷⁵
R. Ströhmer,²⁵ D. Strom,⁵³ L. Stutte,⁵⁰ S. Sumowidagdo,⁴⁹ P. Svoisky,⁵⁵ A. Sznajder,³ P. Tamburello,⁴⁵ A. Tanasijczuk,¹
W. Taylor,⁶ B. Tiller,²⁵ F. Tissandier,¹³ M. Titov,¹⁸ V. V. Tokmenin,³⁶ I. Torchiani,²³ D. Tsybychev,⁷² B. Tuchming,¹⁸
C. Tully,⁶⁸ P. M. Tuts,⁷⁰ R. Unalan,⁶⁵ L. Uvarov,⁴⁰ S. Uvarov,⁴⁰ S. Uzunyan,⁵² B. Vachon,⁶ P. J. van den Berg,³⁴
R. Van Kooten,⁵⁴ W. M. van Leeuwen,³⁴ N. Varelas,⁵¹ E. W. Varnes,⁴⁵ I. A. Vasilyev,³⁹ P. Verdier,²⁰ L. S. Vertogradov,³⁶
M. Verzocchi,⁵⁰ D. Vilanova,¹⁸ F. Villeneuve-Seguié,⁴³ P. Vint,⁴³ P. Vokac,¹⁰ M. Voutilainen,^{67,†} R. Wagner,⁶⁸
H. D. Wahl,⁴⁹ M. H. L. S. Wang,⁵⁰ J. Warchol,⁵⁵ G. Watts,⁸² M. Wayne,⁵⁵ G. Weber,²⁴ M. Weber,^{50,**} L. Welty-Rieger,⁵⁴
A. Wenger,^{23,++} N. Wermes,²² M. Wetstein,⁶¹ A. White,⁷⁸ D. Wicke,²⁶ M. Williams,⁴² G. W. Wilson,⁵⁸ S. J. Wimpenny,⁴⁸
M. Wobisch,⁶⁰ D. R. Wood,⁶³ T. R. Wyatt,⁴⁴ Y. Xie,⁷⁷ S. Yacoub,⁵³ R. Yamada,⁵⁰ W.-C. Yang,⁴⁴ T. Yasuda,⁵⁰
Y. A. Yatsunenko,³⁶ H. Yin,⁷ K. Yip,⁷³ H. D. Yoo,⁷⁷ S. W. Youn,⁵³ J. Yu,⁷⁸ C. Zeitnitz,²⁶ S. Zelitch,⁸¹ T. Zhao,⁸² B. Zhou,⁶⁴
J. Zhu,⁷² M. Zielinski,⁷¹ D. Zieminska,⁵⁴ A. Zieminski,^{54,‡‡} L. Zivkovic,⁷⁰ V. Zutshi,⁵² and E. G. Zverev³⁸

(The D0 Collaboration)

¹Universidad de Buenos Aires, Buenos Aires, Argentina

²LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

³Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

⁴Universidade Federal do ABC, Santo André, Brazil

⁵Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil

⁶University of Alberta, Edmonton, Alberta, Canada,

Simon Fraser University, Burnaby, British Columbia, Canada,

York University, Toronto, Ontario, Canada,

and McGill University, Montreal, Quebec, Canada

⁷University of Science and Technology of China, Hefei, People's Republic of China

⁸Universidad de los Andes, Bogotá, Colombia

⁹Center for Particle Physics, Charles University, Prague, Czech Republic

¹⁰Czech Technical University, Prague, Czech Republic

¹¹Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

¹²Universidad San Francisco de Quito, Quito, Ecuador

¹³LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France

¹⁴LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France

¹⁵CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

¹⁶LAL, Université Paris-Sud, IN2P3/CNRS, Orsay, France

¹⁷LPNHE, IN2P3/CNRS, Universités Paris VI and VII, Paris, France

¹⁸CEA, Ifu, SPP, Saclay, France

¹⁹IPHC, Université Louis Pasteur, CNRS/IN2P3, Strasbourg, France

²⁰IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France

²¹III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany

²²Physikalisches Institut, Universität Bonn, Bonn, Germany

²³Physikalisches Institut, Universität Freiburg, Freiburg, Germany

²⁴Institut für Physik, Universität Mainz, Mainz, Germany

²⁵Ludwig-Maximilians-Universität München, München, Germany

²⁶Fachbereich Physik, University of Wuppertal, Wuppertal, Germany

²⁷Panjab University, Chandigarh, India

²⁸Delhi University, Delhi, India

²⁹Tata Institute of Fundamental Research, Mumbai, India

³⁰University College Dublin, Dublin, Ireland

³¹Korea Detector Laboratory, Korea University, Seoul, Korea

³²SungKyunKwan University, Suwon, Korea

³³CINVESTAV, Mexico City, Mexico

³⁴FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands

- ³⁵Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands
³⁶Joint Institute for Nuclear Research, Dubna, Russia
³⁷Institute for Theoretical and Experimental Physics, Moscow, Russia
³⁸Moscow State University, Moscow, Russia
³⁹Institute for High Energy Physics, Protvino, Russia
⁴⁰Petersburg Nuclear Physics Institute, St. Petersburg, Russia
⁴¹Lund University, Lund, Sweden, Royal Institute of Technology and Stockholm University, Stockholm, Sweden, and Uppsala University, Uppsala, Sweden
⁴²Lancaster University, Lancaster, United Kingdom
⁴³Imperial College, London, United Kingdom
⁴⁴University of Manchester, Manchester, United Kingdom
⁴⁵University of Arizona, Tucson, Arizona 85721, USA
⁴⁶Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
⁴⁷California State University, Fresno, California 93740, USA
⁴⁸University of California, Riverside, California 92521, USA
⁴⁹Florida State University, Tallahassee, Florida 32306, USA
⁵⁰Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
⁵¹University of Illinois at Chicago, Chicago, Illinois 60607, USA
⁵²Northern Illinois University, DeKalb, Illinois 60115, USA
⁵³Northwestern University, Evanston, Illinois 60208, USA
⁵⁴Indiana University, Bloomington, Indiana 47405, USA
⁵⁵University of Notre Dame, Notre Dame, Indiana 46556, USA
⁵⁶Purdue University Calumet, Hammond, Indiana 46323, USA
⁵⁷Iowa State University, Ames, Iowa 50011, USA
⁵⁸University of Kansas, Lawrence, Kansas 66045, USA
⁵⁹Kansas State University, Manhattan, Kansas 66506, USA
⁶⁰Louisiana Tech University, Ruston, Louisiana 71272, USA
⁶¹University of Maryland, College Park, Maryland 20742, USA
⁶²Boston University, Boston, Massachusetts 02215, USA
⁶³Northeastern University, Boston, Massachusetts 02115, USA
⁶⁴University of Michigan, Ann Arbor, Michigan 48109, USA
⁶⁵Michigan State University, East Lansing, Michigan 48824, USA
⁶⁶University of Mississippi, University, Mississippi 38677, USA
⁶⁷University of Nebraska, Lincoln, Nebraska 68588, USA
⁶⁸Princeton University, Princeton, New Jersey 08544, USA
⁶⁹State University of New York, Buffalo, New York 14260, USA
⁷⁰Columbia University, New York, New York 10027, USA
⁷¹University of Rochester, Rochester, New York 14627, USA
⁷²State University of New York, Stony Brook, New York 11794, USA
⁷³Brookhaven National Laboratory, Upton, New York 11973, USA
⁷⁴Langston University, Langston, Oklahoma 73050, USA
⁷⁵University of Oklahoma, Norman, Oklahoma 73019, USA
⁷⁶Oklahoma State University, Stillwater, Oklahoma 74078, USA
⁷⁷Brown University, Providence, Rhode Island 02912, USA
⁷⁸University of Texas, Arlington, Texas 76019, USA
⁷⁹Southern Methodist University, Dallas, Texas 75275, USA
⁸⁰Rice University, Houston, Texas 77005, USA
⁸¹University of Virginia, Charlottesville, Virginia 22901, USA
⁸²University of Washington, Seattle, Washington 98195, USA
(Received 6 August 2008; published 23 October 2008)

We present an observation for $ZZ \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ ($\ell, \ell' = e$ or μ) production in $p\bar{p}$ collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV. Using 1.7 fb^{-1} of data collected by the D0 experiment at the Fermilab Tevatron Collider, we observe three candidate events with an expected background of $0.14^{+0.03}_{-0.02}$ events. The significance of this observation is 5.3 standard deviations. The combination of D0 results in this channel, as well as in $ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$, yields a significance of 5.7 standard deviations and a combined cross section of $\sigma(ZZ) = 1.60 \pm 0.63(\text{stat})^{+0.16}_{-0.17}(\text{syst}) \text{ pb}$.

Studies of the pair production of electroweak gauge bosons provide an interesting test of the electroweak theory predictions [1]. In contrast with other diboson processes, Z boson pair production (ZZ) does not involve trilinear gauge boson interactions within the standard model (SM). The observation of an unexpectedly high cross section could indicate the presence of anomalous ZZZ or $ZZ\gamma$ couplings [2]. The SM prediction for the total ZZ production cross section in $p\bar{p}$ collisions at the Fermilab Tevatron Collider at $\sqrt{s} = 1.96$ TeV is $\sigma(ZZ) = 1.4 \pm 0.1$ pb [3]. The requirement of leptonic Z boson decays reduces the observable cross section, making its measurement rather challenging. The accumulation of integrated luminosities in excess of 3 fb^{-1} at the Fermilab Tevatron Collider and the development of highly optimized event selection criteria has now made possible the direct observation of ZZ production.

Previous investigations of ZZ production have been performed both at the Fermilab Tevatron $p\bar{p}$ and the CERN e^+e^- (LEP) [4] Colliders. The D0 collaboration reported a search for $ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ ($\ell, \ell' = e$ or μ) with 1 fb^{-1} of data that provided a 95% C.L. limit of $\sigma(ZZ) < 4.4$ pb [5]. The CDF collaboration reported a signal for ZZ production with a significance of 4.4 standard deviations from combined $ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ and $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ searches, and measured a production cross section of $\sigma(ZZ) = 1.4_{-0.6}^{+0.7}$ pb [6].

In this Letter, we present a search for Z boson pairs where the Z bosons have decayed to either electron or muon pairs, resulting in final states consisting of four electrons ($4e$), four muons (4μ), or two muons and two electrons ($2\mu 2e$). Data used in this analysis were collected with the D0 detector at the Fermilab Tevatron $p\bar{p}$ Collider at $\sqrt{s} = 1.96$ TeV between June 2006 and May 2008. The integrated luminosities [7] for the three analyzed channels are about 1.7 fb^{-1} . This result is later combined with that from an earlier similar analysis [5] using data collected from October 2002 to February 2006 and corresponding to an integrated luminosity of 1 fb^{-1} .

The D0 detector [8] consists of a central tracking system, comprised of a silicon microstrip tracker (SMT), and a central fiber tracker (CFT), providing coverage to pseudorapidity $|\eta| < 3$ [9], both located within a 2 T superconducting solenoidal magnet. Three liquid argon and uranium calorimeters provide coverage to $|\eta| < 4$. Electromagnetic objects are well reconstructed in the regions of the central calorimeter (CC) with coverage to $|\eta| < 1.1$ and the end calorimeters (EC) with coverage of $1.5 < |\eta| < 3.2$. A muon system surrounds the calorimetry, consisting of three layers of scintillators and drift tubes and 1.8 T iron toroids, with a coverage of $|\eta| < 2$.

This analysis employs a combination of single and dielectron triggers for the $4e$ channel. Similarly, single and dimuon triggers are used for the 4μ channel. The $2\mu 2e$ channel uses a combination of all these triggers,

and additional specific electron-muon triggers. The triggering efficiency for events with four leptons having high transverse momentum (p_T) that satisfy all offline selection requirements exceeds 99%.

For the $4e$ channel, we require four electrons with ordered transverse energies $E_T > 30, 25, 15$, and 15 GeV, respectively. Electrons must be reconstructed either in the CC region or in the EC region, and be isolated from other energy clusters in the calorimeter. Electrons in the CC region are required to satisfy identification criteria based on a multivariate discriminant derived from calorimeter shower shape and a matched track reconstructed in the SMT and CFT. Electrons in the EC are not required to have a matched track, but must satisfy more stringent shower shape requirements. At least two electrons must be in the CC region. With no requirement applied on the charge of the electrons at this stage to increase selection efficiency, three possible ZZ combinations can be formed for each $4e$ event. Events are required to have a solution for which one ee combination has an invariant mass > 70 GeV and the other > 50 GeV. Finally, events are split into three categories, depending on the number of electrons in the CC region. Subsamples with two electrons, with three electrons, and with four or more electrons in the CC region are denoted as $4e_{2C}$, $4e_{3C}$, and $4e_{4C}$, respectively. The three exclusive subsamples contain significantly different levels of background contamination and thus the separation of the subsamples provides more sensitivity to the search.

For the 4μ channel, each muon must satisfy quality criteria based on scintillator and wire chamber information from the muon system, and have a matched track in the central tracker. We require that the four most energetic muons have ordered transverse momenta $p_T > 30, 25, 15$, and 15 GeV, respectively. At least three muons in the event must be isolated, each passing a requirement of less than 2.5 GeV of transverse energy deposited in the calorimeter in the annulus $0.1 < \Delta R < 0.4$ centered around the muon track [10]. Finally, the muon is required to be well reconstructed and to originate from the primary event vertex. Of the three possible ZZ combinations per event that can be formed without considering muon charge at this stage, a solution is required where one $\mu\mu$ combination has an invariant mass > 70 GeV and the other > 50 GeV.

For the $2\mu 2e$ channel, the two most energetic electrons and muons in an event must have $E_T(p_T) > 25, 15$ GeV. All muons and electrons must satisfy the single lepton selection criteria defined for the $4e$ and 4μ final states. In addition, electrons and muons are required to be spatially separated by $\Delta R > 0.2$ to remove $Z \rightarrow \mu\mu$ background with muons radiating photons giving events with two muon and two trackless electron candidates. At least one muon must satisfy the same calorimeter isolation requirement imposed in the 4μ final state. A solution is required where one pair of same flavor leptons has an invariant mass > 70 GeV, and the other > 50 GeV.

Finally, events are split into three categories depending on the number of electrons in the CC region. Subsamples with no electron, with one electron, and with two or more electrons in the CC are denoted as $2\mu 2e_{0C}$, $2\mu 2e_{1C}$, and $2\mu 2e_{2C}$, respectively. As in the $4e$ channel, these subsamples have significantly different levels of background contamination.

A Monte Carlo (MC) simulation is used to determine the expected number of signal events in each subchannel. The small contribution from ZZ events with at least one Z boson decaying into tau pairs is also included in the signal. Simulated events are generated using PYTHIA [11] and passed through a detailed GEANT-based simulation [12] of the detector response. Differences between MC simulations and data in the reconstruction and identification efficiencies for electrons and muons are corrected using efficiencies derived from large data samples of inclusive $Z \rightarrow \ell\ell$ ($\ell = e$, or μ) events. The systematic uncertainty in the signal is dominated by the uncertainty in the theoretical cross section (6.25%), the uncertainty on the lepton identification and reconstruction efficiencies ($\approx 4\%$ for the $4e$ and 4μ subchannels and $\approx 2.5\%$ for the $2\mu 2e$ subchannels), and a 6.1% uncertainty on the luminosity measurement [7]. Additional smaller sources of systematic uncertainty arise from energy and momentum resolutions and MC modeling of the signal process.

Backgrounds to the ZZ signal originate from top quark pair ($t\bar{t}$) production and from events with W and/or Z bosons that decay to leptons and additional jets or photons. The jets can then be misidentified as leptons or contain true electrons or muons from in-flight decays of pions, kaons, or heavy-flavored hadrons.

The background from $t\bar{t}$ production is estimated from MC calculations, assuming the cross section of $\sigma(t\bar{t}) = 7.9$ pb [13] for a top quark mass of 170 GeV. The systematic uncertainty includes a 10% uncertainty on $\sigma(t\bar{t})$, as well as contributions from the variation in cross section and acceptance originating from uncertainties on the mass of the top quark.

To estimate the misidentified lepton background, we first measure the probability for a jet to produce an electron or muon that satisfy the identification criteria from data using a “tag and probe” method [5]. The probability for a jet to

mimic an electron, parametrized in terms of jet E_T and η , is equal to 4×10^{-4} for the case of CC electrons with a matched track and 5×10^{-3} in the case of EC electrons for which no track matching is applied. The probability for a 15 GeV (100 GeV) jet to produce a muon of $p_T > 15$ GeV is $10^{-4}(10^{-2})$ without requiring muon isolation, and it is $10^{-5}(10^{-4})$ when the muon is required to be isolated. A systematic uncertainty of 30% on the jet-to-lepton misidentification probabilities is estimated by varying the selection criteria of the control samples used.

The probabilities for jets to be misidentified as electrons are then applied to jets in $eee + \text{jets}$ and $\mu\mu e + \text{jets}$ data to determine the background to the $4e$ and $2\mu 2e$ channels, respectively. This method takes into account contributions from $Z + \text{jets}$, $Z + \gamma + \text{jets}$, $WZ + \text{jets}$, $WW + \text{jets}$, $W + \text{jets}$, and events with ≥ 4 jets. However, this method double counts the contribution from $Z + \text{jets}$. A correction is measured, amounting to $\approx 20\%$, to correct for the double counting. The probabilities for jets to contain a muon are applied to jets in $\mu\mu + \text{jets}$ data to determine a background estimate for the 4μ channel. Systematic uncertainties on this background arise from the 30% uncertainty in measured misidentification rates, and from the limited statistics of the data remaining in the samples after selection.

Table I summarizes the expected signal and background contributions to each subchannel, as well as the number of candidate events in data. The total signal and background expectations are 1.89 ± 0.08 events and $0.14^{+0.03}_{-0.02}$ events, respectively. We observe a total of three candidate events in the data, two in the $4e_{4C}$ subchannel and one in the 4μ subchannel. Table II summarizes some of their kinematic characteristics. The quoted dilepton masses in the table correspond to one out of the three possible combinations having opposite charge within the pairs and having a dilepton mass closest to that of the Z boson. Figure 1 shows the distribution of the four lepton invariant mass for data and for the expected signal and background.

We extract the significance of the observed event distributions using a negative log-likelihood ratio (LLR) test statistic [14]. As input, we use the expected yields (number of events) from signal and background, separated into the seven subchannels compared to the observed yields. The

TABLE I. The integrated luminosity, expected number of signal ($Z/\gamma^* Z/\gamma^*$) and background events [$t\bar{t}$ and $Z(\gamma) + \text{jets}$ which includes all $W/Z/\gamma + \text{jets}$ contributions], and the number of observed candidates in the seven $ZZ \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ subchannels. Uncertainties reflect statistical and systematic contributions added in quadrature.

Subchannel	$4e_{2C}$	$4e_{3C}$	$4e_{4C}$	4μ	$2\mu 2e_{0C}$	$2\mu 2e_{1C}$	$2\mu 2e_{2C}$
Luminosity (fb^{-1})	1.75 ± 0.11	1.75 ± 0.11	1.75 ± 0.11	1.68 ± 0.10	1.68 ± 0.10	1.68 ± 0.10	1.68 ± 0.10
Signal	0.084 ± 0.008	0.173 ± 0.015	0.140 ± 0.012	0.534 ± 0.043	$0.058^{+0.007}_{-0.006}$	0.352 ± 0.040	$0.553^{+0.045}_{-0.044}$
$Z(\gamma) + \text{jets}$	$0.030^{+0.009}_{-0.008}$	$0.018^{+0.008}_{-0.007}$	$0.002^{+0.002}_{-0.001}$	0.0003 ± 0.0001	$0.03^{+0.02}_{-0.01}$	0.05 ± 0.01	$0.008^{+0.004}_{-0.003}$
$t\bar{t}$	$0.0012^{+0.0016}_{-0.0009}$	0.005 ± 0.002	$0.0007^{+0.0009}_{-0.0005}$
Observed events	0	0	2	1	0	0	0

TABLE II. Characteristics of the observed candidate events. η and ϕ values are measured relative to the location of the $p\bar{p}$ collision. $M_{\ell\ell}$ is the mass of the lepton pair.

		e_1^+	e_2^+	e_3^-	e_4^-
4e candidate 1	p_T (GeV)	107	59	52	16
	η	0.66	0.25	-0.64	-0.85
	ϕ	4.10	1.08	0.46	2.62
	$M_{\ell\ell}$ (GeV)	$e_1^+ e_4^-$ 89 ± 3		$e_2^+ e_3^-$ 61 ± 2	
		e_1^+	e_2^+	e_3^-	e_4^-
4e candidate 2	p_T (GeV)	83	75	35	26
	η	0.64	0.40	0.85	1.17
	ϕ	6.16	3.80	3.83	1.40
	$M_{\ell\ell}$ (GeV)	$e_1^+ e_3^-$ 99 ± 3		$e_2^+ e_4^-$ 90 ± 4	
		μ_1^+	μ_2^-	μ_3^-	μ_4^+
4 μ candidate	p_T (GeV)	115	77	42	24
	η	0.04	-1.01	0.77	-1.93
	ϕ	1.69	4.26	5.29	0.36
	$M_{\ell\ell}$ (GeV)	$\mu_1^+ \mu_3^-$ 148^{+32}_{-18}		$\mu_2^- \mu_4^+$ 90^{+12}_{-8}	

modified frequentist method returns the probability (p -value) of the background-only fluctuating to give the observed yields or higher. In 5×10^9 background pseudoexperiments, we find 213 trials with an LLR value smaller or equal to that observed in data. This gives a p -value of 4.3×10^{-8} which corresponds to a 5.3 standard deviation (σ) observed significance (3.7σ expected). The probability for the signal plus background hypothesis to

give less signal-like observations than the observed one is 0.87. A correction factor of 0.93, derived using PYTHIA, is used to convert the measured cross section for $(Z/\gamma^*) \times (Z/\gamma^*)$ into that for ZZ production. Minimizing the LLR function we obtain a cross section of $\sigma(ZZ) = 1.75^{+1.27}_{-0.86}(\text{stat}) \pm 0.13(\text{syst})$ pb for this analysis.

This result is combined with the results from an independent $ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ search [15], and the previous $(Z/\gamma^*)(Z/\gamma^*) \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$ analysis [5] which used a separate data sample with a looser mass requirement $M(\ell\ell) > 30$ GeV. The earlier search contributes no signal events, and we have scaled its background estimate to the tighter kinematic range used in the recent analysis. The combination of the three analyses is performed taking into account the correlations of systematic uncertainties between subchannels and among analyses. The resulting p -value is 6.2×10^{-9} , and the significance for observation of ZZ production increases to 5.7σ (4.8σ expected). The probability for the signal plus background hypothesis to give less signal-like observations than the observed one is 0.71. We therefore report the observation of a ZZ signal at a hadron collider with a combined cross section of $\sigma(ZZ) = 1.60 \pm 0.63(\text{stat})^{+0.16}_{-0.17}(\text{syst})$ pb, consistent with the standard model expectation.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom, and RFBR (Russia); CNPq, FAPERJ, FAPESP, and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC (United Kingdom); MSM and GACR (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); CAS and CNSF (China); Alexander von Humboldt Foundation (Germany); and the Istituto Nazionale di Fisica Nucleare (Italy).

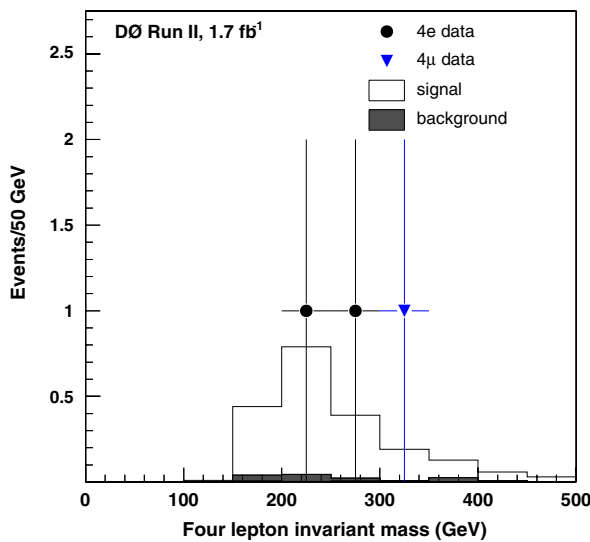


FIG. 1 (color online). Distribution of four lepton invariant mass in data, expected signal, and expected background.

- *Visitor from Augustana College, Sioux Falls, SD, USA.
- +Visitor from The University of Liverpool, Liverpool, UK.
- ‡Visitor from INFN Torino, Torino, Italy.
- §Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacán, Mexico.
- ||Visitor from II. Physikalisches Institut, Georg-August-University, Göttingen, Germany.
- ¶Visitor from Helsinki Institute of Physics, Helsinki, Finland.
- **Visitor from Universität Bern, Bern, Switzerland.
- ++Visitor from Universität Zürich, Zürich, Switzerland.
- ‡‡Deceased.

- [1] R. W. Brown and K. O. Mikaelian, Phys. Rev. D **19**, 922 (1979).

- [2] U. Baur and D. Rainwater, Phys. Rev. D **62**, 113011 (2000).
- [3] J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999).
- [4] R. Barate *et al.* (ALEPH Collaboration), Phys. Lett. B **469**, 287 (1999); J. Abdallah *et al.* (DELPHI Collaboration), Eur. Phys. J. C **30**, 447 (2003); M. Acciarri *et al.* (L3 Collaboration), Phys. Lett. B **465**, 363 (1999); G. Abbiendi *et al.* (OPAL Collaboration), Eur. Phys. J. C **32**, 303 (2003).
- [5] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **100**, 131801 (2008).
- [6] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **100**, 201801 (2008).
- [7] T. Andeen *et al.*, Fermilab Report No. FERMILAB-TM-2365, 2007.
- [8] V. M. Abazov *et al.* (D0 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **565**, 463 (2006).
- [9] The D0 coordinate system is cylindrical with the z axis along the proton beamline and the polar and azimuthal angles denoted as θ and ϕ , respectively. The pseudo-rapidity is defined as $\eta = -\ln[\tan(\theta/2)]$.
- [10] The variable ΔR between two objects i and j is defined as $\Delta R = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$.
- [11] T. Sjöstrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).
- [12] R. Brun and F. Carminati, CERN Program Library Long Writeup No. W5013, 1993 (unpublished).
- [13] N. Kidonakis and R. Vogt, Phys. Rev. D **68**, 114014 (2003).
- [14] W. Fisher, Fermilab Report No. FERMILAB-TM-2386-E, 2007.
- [15] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **78**, 072002 (2008).