

University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

Kenneth Bloom Publications

Research Papers in Physics and Astronomy

3-6-2009

Evidence for the Decay $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ and a Measurement of $\Delta\Gamma_s^{\text{CP}}/\Gamma_s$

V. M. Abazov

Joint Institute for Nuclear Research, Dubna, Russia

Kenneth A. Bloom

University of Nebraska-Lincoln, kenbloom@unl.edu

Gregory Snow

University of Nebraska-Lincoln, gsnow1@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.; Snow, Gregory; and Collaboration, D0, "Evidence for the Decay $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ and a Measurement of $\Delta\Gamma_s^{\text{CP}}/\Gamma_s$ " (2009). *Kenneth Bloom Publications*. 279.
<https://digitalcommons.unl.edu/physicsbloom/279>

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.

Evidence for the Decay $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ and a Measurement of $\Delta\Gamma_s^{CP}/\Gamma_s$

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. Anzelc,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 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 P. Calfayan,²⁵ S. Calvet,¹⁶ J. Cammin,⁷¹ M. A. Carrasco-Lizarraga,³³ E. Carrera,⁴⁹ W. Carvalho,³ B. C. K. Casey,⁵⁰ H. Castilla-Valdez,³³ S. Chakrabarti,⁷² D. Chakraborty,⁵² K. M. Chan,⁵⁵ A. Chandra,⁴⁸ E. Cheu,⁴⁵ 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 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 T. Dorland,⁸² A. Dubey,²⁸ L. V. Dudko,³⁸ L. Dufloc,¹⁶ S. R. Dugad,²⁹ D. Duggan,⁴⁹ A. Duperrin,¹⁵ S. Dutt,²⁷ 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 A. V. Ferapontov,⁵⁹ T. Ferbel,^{61,71} 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. Ginther,⁷¹ 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. Grünwald,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 T. Hoang,⁴⁹ J. D. Hobbs,⁷² B. Hoeneisen,¹² M. Hohlfeld,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 D. Karmanov,³⁸ P. A. Kasper,⁵⁰ I. Katsanos,⁷⁰ V. Kaushik,⁷⁸ R. Kehoe,⁷⁹ S. Kermiche,¹⁵ N. Khalatyan,⁵⁰ A. Khanov,⁷⁶ A. Kharchilava,⁶⁹ Y. N. 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-Garcia,^{33,||} A. L. Lyon,⁵⁰ A. K. A. Maciel,² D. Mackin,⁸⁰ R. J. Madaras,⁴⁶ P. Mättig,²⁶ 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 M. M. Meijer,³⁵ 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,¹⁵ M. Mulhearn,⁷⁰ O. Mundal,²² L. Mundim,³ E. Nagy,¹⁵ M. Naimuddin,⁵⁰ M. Narain,⁷⁷ H. A. Neal,⁶⁴ J. P. Negret,⁸ P. Neustroev,⁴⁰ H. Nilsen,²³ H. Nogima,³ S. F. Novaes,⁵ T. Nunnemann,²⁵ D. C. O'Neil,⁶ G. Obrant,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. Pétrouff,¹⁶ M. Petteni,⁴³ R. Piegai,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 P. Renkel,⁷⁹ P. Rich,⁴⁴ 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. Siccaldi,¹⁹ V. Simak,¹⁰ V. Sirotenko,⁵⁰ P. Skubic,⁷⁵ P. Slattery,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 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,³⁵ A. Sznajder,³ 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. R. J. Williams,⁴² G. W. Wilson,⁵⁸ S. J. Wimpenny,⁴⁸ M. Wobisch,⁶⁰ D. R. Wood,⁶³ T. R. Wyatt,⁴⁴ Y. Xie,⁷⁷ C. Xu,⁶⁴ S. Yacoub,⁵³ R. Yamada,⁵⁰ W.-C. Yang,⁴⁴ T. Yasuda,⁵⁰ Y. A. Yatsunenkov,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

(D0 Collaboration)

¹Universidad de Buenos Aires, Buenos Aires, Argentina²LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil³Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil⁴Universidade Federal do ABC, Santo André, Brazil⁵Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil⁶University 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 China⁸Universidad de los Andes, Bogotá, Colombia⁹Center for Particle Physics, Charles University, Prague, Czech Republic¹⁰Czech Technical University, Prague, Czech Republic¹¹Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic¹²Universidad San Francisco de Quito, Quito, Ecuador¹³LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France¹⁴LPSC, Université Joseph Fourier Grenoble I, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France¹⁵CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France¹⁶LAL, Université Paris-Sud, IN2P3/CNRS, Orsay, France¹⁷LPNHE, IN2P3/CNRS, Universités Paris VI and VII, Paris, France¹⁸CEA, Ifu, SPP, Saclay, France¹⁹IPHC, Université Louis Pasteur, CNRS/IN2P3, Strasbourg, France²⁰IPNL, Université Lyon I, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France²¹III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany²²Physikalisches Institut, Universität Bonn, Bonn, Germany²³Physikalisches Institut, Universität Freiburg, Freiburg, Germany²⁴Institut für Physik, Universität Mainz, Mainz, Germany²⁵Ludwig-Maximilians-Universität München, München, Germany²⁶Fachbereich Physik, University of Wuppertal, Wuppertal, Germany²⁷Panjab University, Chandigarh, India²⁸Delhi University, Delhi, India²⁹Tata Institute of Fundamental Research, Mumbai, India³⁰University College Dublin, Dublin, Ireland³¹Korea Detector Laboratory, Korea University, Seoul, Korea³²SungKyunKwan University, Suwon, Korea³³CINVESTAV, Mexico City, Mexico³⁴FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands³⁵Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands

- ³⁶*Joint Institute for Nuclear Research, Dubna, Russia*
³⁷*Institute for Theoretical and Experimental Physics, Moscow, Russia*
³⁸*Moscow State University, Moscow, Russia*
³⁹*Institute for High Energy Physics, Protvino, Russia*
⁴⁰*Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
⁴¹*Lund University, Lund, Sweden,*
Royal Institute of Technology and Stockholm University, Stockholm, Sweden,
and Uppsala University, Uppsala, Sweden
⁴²*Lancaster University, Lancaster, United Kingdom*
⁴³*Imperial College, London, United Kingdom*
⁴⁴*University of Manchester, Manchester, United Kingdom*
⁴⁵*University of Arizona, Tucson, Arizona 85721, USA*
⁴⁶*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
⁴⁷*California State University, Fresno, California 93740, USA*
⁴⁸*University of California, Riverside, California 92521, USA*
⁴⁹*Florida State University, Tallahassee, Florida 32306, USA*
⁵⁰*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
⁵¹*University of Illinois at Chicago, Chicago, Illinois 60607, USA*
⁵²*Northern Illinois University, DeKalb, Illinois 60115, USA*
⁵³*Northwestern University, Evanston, Illinois 60208, USA*
⁵⁴*Indiana University, Bloomington, Indiana 47405, USA*
⁵⁵*University of Notre Dame, Notre Dame, Indiana 46556, USA*
⁵⁶*Purdue University Calumet, Hammond, Indiana 46323, USA*
⁵⁷*Iowa State University, Ames, Iowa 50011, USA*
⁵⁸*University of Kansas, Lawrence, Kansas 66045, USA*
⁵⁹*Kansas State University, Manhattan, Kansas 66506, USA*
⁶⁰*Louisiana Tech University, Ruston, Louisiana 71272, USA*
⁶¹*University of Maryland, College Park, Maryland 20742, USA*
⁶²*Boston University, Boston, Massachusetts 02215, USA*
⁶³*Northeastern University, Boston, Massachusetts 02115, USA*
⁶⁴*University of Michigan, Ann Arbor, Michigan 48109, USA*
⁶⁵*Michigan State University, East Lansing, Michigan 48824, USA*
⁶⁶*University of Mississippi, University, Mississippi 38677, USA*
⁶⁷*University of Nebraska, Lincoln, Nebraska 68588, USA*
⁶⁸*Princeton University, Princeton, New Jersey 08544, USA*
⁶⁹*State University of New York, Buffalo, New York 14260, USA*
⁷⁰*Columbia University, New York, New York 10027, USA*
⁷¹*University of Rochester, Rochester, New York 14627, USA*
⁷²*State University of New York, Stony Brook, New York 11794, USA*
⁷³*Brookhaven National Laboratory, Upton, New York 11973, USA*
⁷⁴*Langston University, Langston, Oklahoma 73050, USA*
⁷⁵*University of Oklahoma, Norman, Oklahoma 73019, USA*
⁷⁶*Oklahoma State University, Stillwater, Oklahoma 74078, USA*
⁷⁷*Brown University, Providence, Rhode Island 02912, USA*
⁷⁸*University of Texas, Arlington, Texas 76019, USA*
⁷⁹*Southern Methodist University, Dallas, Texas 75275, USA*
⁸⁰*Rice University, Houston, Texas 77005, USA*
⁸¹*University of Virginia, Charlottesville, Virginia 22901, USA*
⁸²*University of Washington, Seattle, Washington 98195, USA*
(Received 13 November 2008; published 3 March 2009)

We search for the semi-inclusive process $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ using 2.8 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ recorded by the D0 detector operating at the Fermilab Tevatron Collider. We observe 26.6 ± 8.4 signal events with a significance above background of 3.2 standard deviations yielding a branching ratio of $\mathcal{B}(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}) = 0.035 \pm 0.010(\text{stat.}) \pm 0.011(\text{syst.})$. Under certain theoretical assumptions, these double-charm final states saturate CP -even eigenstates in the B_s^0 decays resulting in a width difference of $\Delta\Gamma_s^{CP}/\Gamma_s = 0.072 \pm 0.021(\text{stat.}) \pm 0.022(\text{syst.})$.

The phenomenon of CP violation is believed to be intimately tied to explaining the matter dominance in the present-day Universe [1]. CP violation is expected to occur in the evolution of neutral particles that can mix between different eigenbases. For the B_s^0 system, the flavor eigenstates can be decomposed into heavy (H) and light (L) states based on mass or into even and odd states based on CP . The width differences between these eigenstates are defined by $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ and $\Delta\Gamma_s^{CP} = \Gamma_s^{\text{even}} - \Gamma_s^{\text{odd}}$, respectively. These two quantities are connected with the possible presence of new physics (NP) by $\Delta\Gamma_s = \Delta\Gamma_s^{CP} \cos\phi_s$, where ϕ_s is the CP violating mixing phase which constrains models of NP.

In the standard model (SM) a mixing parameter Γ_{12} , determining the size of the width difference between CP eigenstates, stems from the decays into final states common to both B and \bar{B} . Since this quantity is dominated by Cabibbo-Kobayashi-Maskawa (CKM)-favored tree-level decays, it is practically insensitive to NP. Because of the hierarchy of the quark mixing matrix [2], the width difference is governed by the partial widths of B_s^0 decays into final CP eigenstates through the $b \rightarrow c\bar{c}s$ quark-level transition, such as $B_s^0 \rightarrow D_s^+ D_s^-$ or $B_s^0 \rightarrow J/\psi\phi$. Topologically, the former type of decay mode is a color-allowed spectator, while the latter type is suppressed by the effective color factor. Thus, the semi-inclusive decay modes $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$, where $D_s^{(*)}$ denotes either D_s^\pm or $D_s^{\pm*}$, are interesting because they give the largest contribution to the difference between the widths of the heavy and light states. The other decay modes are estimated to contribute less than 0.01 to the projected ~ 0.15 value of $\Delta\Gamma_s/\Gamma_s$ [3], where $\Gamma_s (= 1/\tau_s) \equiv (\Gamma_L + \Gamma_H)/2$.

In the Shifman-Voloshin (SV) limit [4], given by $m_b \rightarrow 2m_c \rightarrow 0$ with $N_c \rightarrow \infty$ (where N_c is the number of colors), $\Delta\Gamma_s^{CP}$ is saturated by $\Gamma(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)})$. Then the width difference can be related to the branching ratio of B_s^0 mesons to this inclusive double-charm final state by [5,6]

$$2\mathcal{B}(B_s \rightarrow D_s^{(*)} D_s^{(*)}) \simeq \Delta\Gamma_s^{CP} \left[\frac{\frac{1}{1-2x_f} + \cos\phi_s}{2\Gamma_L} + \frac{\frac{1}{1-2x_f} - \cos\phi_s}{2\Gamma_H} \right], \quad (1)$$

where x_f is the fraction of the CP -odd component of the decay $\Gamma_s^{\text{odd}}/\Gamma_s^{\text{even}} = x_f/(1-x_f)$. Therefore, given the CP structure of the final state, $\Delta\Gamma_s^{CP}$ can be measured using the information from branching ratios without lifetime fits. The irreducible theoretical uncertainty of this approach stems from the omission of CKM-suppressed decays through the $b \rightarrow u\bar{u}s$ transition which is of order $2|V_{ub}V_{us}/V_{cb}V_{cs}| \sim 3\%-5\%$.

In this Letter, we report the first evidence for the decay $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$. The study uses a data sample of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV corresponding to an integrated luminosity of 2.8 fb^{-1} recorded by the D0 detector oper-

ating at the Fermilab Tevatron Collider during 2002–2007. This supersedes our previous study of the same final state based on 1.3 fb^{-1} [7]. A similar study based on events containing two ϕ mesons has been reported by the ALEPH Collaboration at the CERN LEP Collider [8].

This analysis considers the B_s^0 decay into two $D_s^{(*)}$ mesons. No attempt is made to identify the photon or π^0 emanating from the D_s^* decay. We search for one hadronic D_s decay to $\phi\pi$ and one semileptonic D_s decay to $\phi\mu\nu$, where both ϕ mesons decay to K^+K^- . The branching fraction is extracted by normalizing the $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ decay to the $B_s^0 \rightarrow D_s^{(*)} \mu\nu$ decay.

D0 is a general purpose detector [9] consisting of a central tracking system, uranium/liquid-argon calorimeters, and an iron toroid muon spectrometer. The central tracking system allows charged particles to be reconstructed. This system is composed of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT) embedded in a 2 T solenoidal magnetic field. Muons are identified and reconstructed with a magnetic spectrometer located outside of the calorimeter. The spectrometer contains magnetized iron toroids and three superlayers of proportional drift tubes along with scintillation trigger counters. Information from the muon and tracking systems is used to form muon triggers. For the events used by this analysis, the muon from the semileptonic D_s decay satisfies the inclusive single-muon triggers.

Muons are identified by requiring segments reconstructed in at least two out of the three superlayers in the muon system and associated with a trajectory reconstructed with hits in both the SMT and the CFT. We select muon candidates with transverse momentum $p_T > 2.0 \text{ GeV}/c$ and total momentum $p > 3.0 \text{ GeV}/c$.

ϕ mesons are formed from two opposite sign charged particles with $p_T > 0.7 \text{ GeV}/c$ in the event assuming a kaon mass hypothesis. We require at least one kaon to have an impact parameter clearly separated from the $p\bar{p}$ interaction point (primary vertex) with at a minimum 4 standard deviations significance. The two-kaon systems

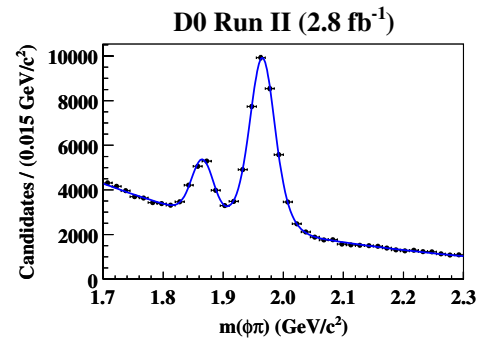


FIG. 1 (color online). Invariant mass distribution of the $\phi\pi$ system for the $B_s^0 \rightarrow D_s^{(*)} \mu\nu$ sample. The two peaks correspond to the D_s^\pm candidates (lower masses) and D_s^* candidates (higher masses).

satisfying $p_T(KK) > 2.0 \text{ GeV}/c$ and $1.010 < m(KK) < 1.030 \text{ GeV}/c^2$ are selected as ϕ candidates.

The hadronic D_s meson is reconstructed by combining the ϕ candidate with a third track with $p_T > 0.5 \text{ GeV}/c$ which is assigned the pion mass. The pion is required to have charge opposite to that of the muon. The three particles must form a well reconstructed vertex displaced from the primary vertex [10]. We require the cosine of the angle between the D_s momentum and the direction from the primary vertex to the D_s vertex to be greater than 0.9. For the signal decay chain of a pseudoscalar to a vector plus pseudoscalar, followed by the decay of the vector to two pseudoscalars, $\cos\theta_\phi$ is distributed quadratically, where θ_ϕ is the decay angle of a kaon in the ϕ rest frame with respect to the direction of the D_s meson, and hence a constraint $|\cos\theta_\phi| > 0.3$ is imposed.

The $B_s^0 \rightarrow D_s^{(*)} \mu \nu$ decay vertex is reconstructed based on the momentum and direction of the reconstructed hadronic D_s candidate and its intersection with the track of an oppositely charged muon. This vertex is required to be located between the primary vertex and the D_s vertex, whereby the individual B_s and D_s vertex displacements are consistent with a $p\bar{p} \rightarrow B_s \rightarrow D_s$ decay chain. The invariant mass of the B_s^0 candidate is required to be less than $5.2 \text{ GeV}/c^2$. We require the daughter particles of the B_s^0 meson to be well isolated from other tracks. Background is further suppressed using a likelihood ratio technique [11] that combines information from the invariant masses and momenta of the reconstructed particles, vertex quality, and the ϕ helicity angle.

The $\phi\pi$ invariant mass distribution for $B_s^0 \rightarrow D_s^{(*)} \mu \nu$ candidates is shown in Fig. 1. Maxima corresponding to the $D_s \rightarrow \phi\pi$ decay and the $D^\pm \rightarrow \phi\pi$ decay are clearly observed. The D_s signal originates from $\sim 90\%$ semileptonic B_s^0 decays and $\sim 10\%$ decays of the type $B \rightarrow D_s D$ followed by semileptonic D decay. These fractions are determined from Monte Carlo (MC) simulation using the known or estimated branching fractions from the Particle Data Group (PDG) [12] or EVTGEN [13]. Approximately

2% of the events are due to direct charm production $p\bar{p} \rightarrow DD$, determined by using full simulation and reconstruction of DD^* candidates. The overall sample composition is verified using studies of the B lifetime and mixing parameters [14,15].

For the second ϕ candidate, we search for an additional pair of oppositely charged particles in the event imposing the same criteria as for the first ϕ meson. The two kaon tracks are combined with the muon track to produce a common vertex for the semileptonic D_s candidate. We require the D_s candidate to originate from a common vertex to the hadronic D_s candidate to complete the $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ decay. This approach is justified since the average transverse decay length of the D_s meson relative to the B_s^0 meson decay vertex is $\sim 1.0 \text{ mm}$ with an uncertainty of $\sim 0.6 \text{ mm}$. By applying the same selection criteria as in the normalization $B_s^0 \rightarrow D_s^{(*)} \mu \nu$ decay sample, many detector related systematic effects cancel. The total invariant mass is required to lie between 4.30 and $5.20 \text{ GeV}/c^2$.

Correlated production of this double-charm decay, where both D_s mesons originate from the same parent B_s^0 meson, is then determined by examining the two-dimensional distribution of $m(\phi\pi)$ from hadronic D_s candidates versus $m(KK)$ from semileptonic candidates. We perform a maximum likelihood fit to this distribution with four components: The correlated $D_s D_s$ component is modeled as the product of signal terms in both dimensions, the uncorrelated components are modeled as the product of the signal term in one dimension and the background term in the other dimension, and the background correlation is modeled as the combination of the background terms in both dimensions. Signal and background models are expected to be identical with those for the $B_s^0 \rightarrow D_s^{(*)} \mu \nu$ sample, from which the parameters of the signal models are determined. Projections of the two-dimensional likelihood fit onto both axes are displayed in Fig. 2. The fit returns a yield of 31.0 ± 9.4 correlated events.

Three possible sources of background are considered in the correlated sample. Direct charm production from $p\bar{p}$ is

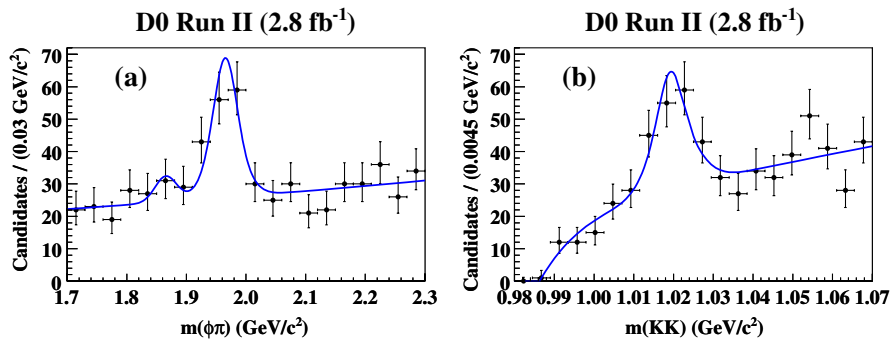


FIG. 2 (color online). Projections of the two-dimensional maximum likelihood fit onto invariant mass spectra of the (a) $\phi\pi$ system from hadronic D_s decays and (b) KK system from semileptonic D_s decays. The peaks in both distributions are explored to search for the correlation between the two systems.

estimated based on the fraction of prompt charm measured directly in the inclusive $D_s^{(*)}\mu\nu$ sample $[(10.3 \pm 2.5)\%]$ along with the decay fraction of the second charm quark to a D_s meson and the reconstruction efficiency for this decay. Because of a shorter decay length of the charm decay, the lifetime requirement reduces its contribution significantly leading to an estimate of $(1.9 \pm 0.5)\%$.

The second background source arises from the semi-leptonic $B_s^0 \rightarrow D_s^{(*)}\phi\mu\nu$ decay. This can be extracted by studying the $m(\phi\mu)$ spectrum. In this variable, $B_s^0 \rightarrow D_s^{(*)}D_s^{(*)}$ events tend towards lower values, while $B_s^0 \rightarrow D_s^{(*)}\phi\mu\nu$ events tend towards higher values.

The third source consists of $B^{\pm,0} \rightarrow D_s^{(*)}D_s^{(*)}KX$ events. This background can be extracted by studying the visible mass of all reconstructed daughter particles $m(D_s\phi\mu)$. The mass tends to have higher values for $B_s^0 \rightarrow D_s^{(*)}D_s^{(*)}$ than for $B^{\pm,0} \rightarrow D_s^{(*)}D_s^{(*)}KX$.

These backgrounds are estimated with MC samples by repeating the fit in three separate regions chosen so that mainly one source contributes to each region in the $m(\phi\mu) - m(D_s\phi\mu)$ plane. The separate components, the signal and the two latter backgrounds, are then extracted based on the expected distribution over the three regions of the three components. We find a signal yield of 26.6 ± 8.4 events originating from the $B_s^0 \rightarrow D_s^{(*)}D_s^{(*)}$ process after subtracting the correlated background events.

The signal is normalized to the total $B_s^0 \rightarrow D_s^{(*)}\mu\nu$ yield taking into account the composition of the sample as discussed earlier. The reconstruction efficiency ratio between the two samples is estimated from MC calculations to be 0.082 ± 0.015 . This small value results from the softer muon momentum spectrum in charm decays as compared to bottom decays. The systematic uncertainty in the ratio contains uncertainties from the modeling of the B_s^0 momentum spectrum, the decay form factors and sample composition, and the trigger and reconstruction efficiencies. Our efficiency model is verified by comparing the expected and measured D_s yield and the relative $B_s^0 \rightarrow D_s^{(*)}D_s^{(*)}$ to $B_s^0 \rightarrow D_s^{(*)}\mu\nu$ yields as a function of muon p_T .

Using all of the above inputs, the branching ratio is measured as

$$\mathcal{B}(B_s^0 \rightarrow D_s^{(*)}D_s^{(*)}) = 0.035 \pm 0.010(\text{stat.}) \\ \pm 0.008(\text{exp.syst.}) \pm 0.007(\text{ext.}),$$

where the ‘‘ext.’’ uncertainty arises from the external input branching ratios taken from the PDG [12]. This uncertainty contributes $\sim 45\%$ to the total systematic uncertainty (exp.syst. \oplus ext.), which leaves room for further improvements in the result. The experimental systematic uncertainty accounts for the rest of the total systematic uncertainty, containing a 37% component from the reconstruction efficiency ratio, 11% from the background esti-

mation, and 4% from the fitting procedure. All other uncertainties are $\leq 1\%$.

The probability that the total background would fluctuate to the measured event yield or higher is evaluated to be 1.2×10^{-3} through pseudoexperiments including systematic uncertainties. This corresponds to a significance of 3.2 standard deviations.

Information on the mixing-induced CP asymmetry in the B_s^0 system can be extracted from the branching fraction measurement through Eq. (1). Since the CP structure of the decay is presently not accessible in either theory or experiment, several scenarios for different x_f values can be considered. In the heavy quark hypothesis [3] along with the SV limit, the CP -odd component of the decay vanishes, leaving the inclusive final state to be CP -even, i.e., $x_f = 0$, with a theoretical uncertainty of $\sim 5\%$ [16]. This scenario is illustrated in Fig. 3, presenting the constraint in the $\Delta\Gamma_s - \phi_s$ plane from this measurement assuming the relation $\Delta\Gamma_s = \Delta\Gamma_s^{CP} \cos\phi_s$. Confidence-level (C.L.) contours from the flavor-tagged decay $B_s^0 \rightarrow J/\psi\phi$ at D0 [17] are superimposed. We take the mean lifetime of B_s^0 meson from Ref. [12].

Furthermore, within the SM framework, the mass eigenstates coincide with the CP eigenstates, and the expression used in the previous studies [7,8] is recovered. Our measurement gives

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} \simeq \frac{2\mathcal{B}(B_s^0 \rightarrow D_s^{(*)}D_s^{(*)})}{1 - \mathcal{B}(B_s^0 \rightarrow D_s^{(*)}D_s^{(*)})} \\ = 0.072 \pm 0.021(\text{stat.}) \pm 0.022(\text{syst.}).$$

This result is consistent with the SM prediction [18] as well

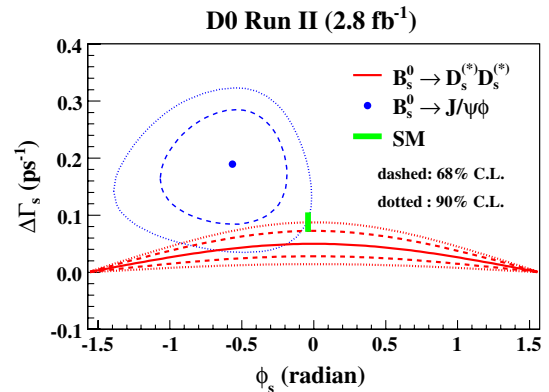


FIG. 3 (color online). Constraints in the $\Delta\Gamma_s - \phi_s$ plane. The solid line represents our measurement under the theoretical assumptions stated in the text and with $x_f = 0$. Two pairs of lines are 68% (dashed) and 90% (dotted) C.L. intervals of $\Delta\Gamma_s$ for a given assumed value of ϕ_s . Contours from the $B_s^0 \rightarrow J/\psi\phi$ decay are the equivalent C.L. regions of $(\Delta\Gamma_s, \phi_s)$ when measuring simultaneously both parameters. No theoretical uncertainties are reflected in the plot. The SM prediction is represented by the thick vertical line.

as with the current world average value [16]. Therefore, if the CP structure of the final state can be disentangled and the theoretical errors can be controlled, this approach can provide a powerful constraint on mixing and CP violation in the B_s^0 system.

In summary, we performed a study of B_s^0 decays into the semi-inclusive double-charm final state using an integrated luminosity of 2.8 fb^{-1} at the D0 experiment. We see evidence of this process and measure the branching ratio as $\mathcal{B}(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}) = 0.035 \pm 0.010(\text{stat.}) \pm 0.011(\text{syst.})$. Based on this measurement and under certain theoretical assumptions, mixing and CP violation information in the B_s^0 meson system are extracted. This is the first single measurement that demonstrates a nonzero width difference in the B_s^0 system at greater than 3σ significance. In particular, in the absence of NP, the fractional width difference is derived as $\Delta\Gamma_s^{CP}/\Gamma_s = 0.072 \pm 0.021(\text{stat.}) \pm 0.022(\text{syst.})$.

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); MSMT 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); and the Alexander von Humboldt Foundation (Germany).

*Visitor from Augustana College, Sioux Falls, SD, USA.

†Visitor from Rutgers University, Piscataway, NJ, USA.

‡Visitor from The University of Liverpool, Liverpool, United Kingdom.

§Visitor from II. Physikalisches Institut, Georg-August-University, Göttingen, Germany.

||Visitor from Centro de Investigacion en Computacion - IPN, Mexico City, Mexico.

¶Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacán, Mexico.

**Visitor from Helsinki Institute of Physics, Helsinki, Finland.

††Visitor from Universität Bern, Bern, Switzerland.

‡‡Visitor from Universität Zürich, Zürich, Switzerland.

§§Deceased.

- [1] A. D. Sakharov, JETP Lett. **5**, 24 (1967).
- [2] G. C. Branco and L. Lavoura, Phys. Rev. D **38**, 2295 (1988).
- [3] R. Aleksan *et al.*, Phys. Lett. B **316**, 567 (1993).
- [4] M. A. Shifman and M. B. Voloshin, Yad. Fiz. **47**, 801 (1988) [Sov. J. Nucl. Phys. **47**, 511 (1988)].
- [5] K. Anikeev *et al.*, arXiv:hep-ph/0201071.
- [6] I. Dunietz, R. Fleischer, and U. Nierste, Phys. Rev. D **63**, 114015 (2001).
- [7] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **99**, 241801 (2007).
- [8] R. Barate *et al.* (ALEPH Collaboration), Phys. Lett. B **486**, 286 (2000).
- [9] V. M. Abazov *et al.* (D0 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **565**, 463 (2006).
- [10] J. Abdallah *et al.* (DELPHI Collaboration), Eur. Phys. J. C **32**, 185 (2004).
- [11] G. Borisov, Nucl. Instrum. Methods Phys. Res., Sect. A **417**, 384 (1998).
- [12] C. AMSLER *et al.*, Phys. Lett. B **667**, 1 (2008).
- [13] D. J. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001).
- [14] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **97**, 241801 (2006).
- [15] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **97**, 021802 (2006).
- [16] E. Barberio *et al.* (Heavy Flavor Averaging Group), arXiv:0808.1297.
- [17] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **101**, 241801 (2008). This measurement establishes $\Delta\Gamma_s > 0$ with a significance of 2.4 standard deviations.
- [18] A. Lenz and U. Nierste, J. High Energy Phys. **06** (2007) 072.