Combined D0 measurements constraining the *CP*-violating phase and width difference in the B_s^0 system

V. M. Abazov,[35] B. Abbott,[75] M. Abolins,[65] B. S. Acharya,[28] M. Adams,[51] T. Adams,[49] E. Aguilo,[5] S. H. Ahn,[30] M. Ahsan,[59] G. D. Alexeev,[35] G. Alkhazov,[39] A. Alton,[64,*] G. Alverson,[63] G. A. Alves,[2] M. Anastasoaie,[34] L. S. Ancu,[34] T. Andeen,[53] S. Anderson,[45] B. Andrieu,[16] M. S. Anzelc,[53] Y. Arnoud,[13] M. Arov,[52] A. Askew,[49] B. Åsman,[40] A. C. S. Assis Jesus,[3] O. Atramentov,[49] C. Autermann,[20] C. Avila,[7] C. Ay,[23] F. Badaud,[12] A. Baden,[61] L. Bagby,[52] B. Baldin,[50] D. V. Bandurin,[59] P. Banerjee,[28] S. Banerjee,[28] E. Barberis,[63] A.-F. Barfuss,[14] P. Bargassa,[80] P. Baringer,[58] C. Barnes,[43] J. Barreto,[2] J. F. Bartlett,[50] U. Bassler,[16] D. Bauer,[43] S. Beale,[5] A. Bean,[58] M. Begalli,[3] M. Begel,[71] C. Belanger-Champagne,[40] L. Bellantoni,[50] A. Bellavance,[67] J. A. Benitez,[65] S. B. Beri,[26] G. Bernardi,[16] R. Bernhard,[22] L. Berntzon,[14] I. Bertram,[42] M. Besançon,[17] R. Beuselinck,[43] V. A. Bezzubov,[38] P. C. Bhat,[50] V. Bhatnagar,[26] M. Binder,[24] C. Biscarat,[19] I. Blackler,[43] G. Blazey,[52] F. Blekman,[43] S. Blessing,[49] D. Bloch,[18] K. Bloom,[67] A. Boehnlein,[50] D. Boline,[62] T. A. Bolton,[59] G. Borissov,[42] K. Bos,[33] T. Bose,[77] A. Brandt,[78] R. Brock,[65] G. Brooijmans,[70] A. Bross,[50] D. Brown,[78] N. J. Buchanan,[49] D. Buchholz,[53] M. Buehler,[81] V. Buescher,[22] S. Burdin,[50] S. Burke,[45] T. H. Burnett,[82] E. Busato,[16] C. P. Buszello,[43] J. M. Butler,[62] P. Calfayan,[24] S. Calvet,[14] J. Cammin,[71] S. Caron,[33] W. Carvalho,[3] B. C. K. Casey,[77] N. M. Cason,[55] H. Castilla-Valdez,[32] S. Chakrabarti,[17] D. Chakraborty,[52] K. Chan,[5] K. M. Chan,[71] A. Chandra,[48] F. Charles,[18] E. Cheu,[45] F. Chevallier,[13] D. K. Cho,[62] S. Choi,[31] B. Choudhary,[27] L. Christofek,[77] T. Christoudias,[43] D. Claes,[67] B. Clément,[18] C. Clément,[40] Y. Coadou,[5] M. Cooke,[80] W. E. Cooper,[50] M. Corcoran,[80] F. Couderc,[17] M.-C. Cousinou,[14] B. Cox,[44] S. Crépé-Renaudin,[13] D. Cutts,[77] M. Ćwiok,[29] H. da Motta,[2] A. Das,[62] B. Davies,[42] G. Davies,[43] K. De,[78] P. de Jong,[33] S. J. de Jong,[34] E. De La Cruz-Burelo,[64] C. De Oliveira Martins,[3] J. D. Degenhardt,[64] F. Déliot,[17] M. Demarteau,[50] R. Demina,[71] D. Denisov,[50] S. P. Denisov,[38] S. Desai,[50] H. T. Diehl,[50] M. Diesburg,[50] M. Doidge,[42] A. Dominguez,[67] H. Dong,[72] L. V. Dudko,[37] L. Duflot,[15] S. R. Dugad,[28] D. Duggan,[49] A. Duperrin,[14] 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,[37] H. Evans,[54] A. Evdokimov,[36] V. N. Evdokimov,[38] A. V. Ferapontov,[59] T. Ferbel,[71] F. Fiedler,[24] F. Filthaut,[34] W. Fisher,[50] H. E. Fisk,[50] M. Ford,[44] M. Fortner,[52] H. Fox,[22] S. Fu,[50] S. Fuess,[50] T. Gadfort,[82] C. F. Galea,[34] E. Gallas,[50] E. Galyaev,[55] C. Garcia,[71] A. Garcia-Bellido,[82] V. Gavrilov,[36] P. Gay,[12] W. Geist,[18] D. Gelé,[18] C. E. Gerber,[51] Y. Gershtein,[49] D. Gillberg,[5] G. Ginther,[71] N. Gollub,[40] B. Gómez,[7] A. Goussiou,[55] P. D. Grannis,[72] H. Greenlee,[50] Z. D. Greenwood,[60] E. M. Gregores,[4] G. Grenier,[19] Ph. Gris,[12] J.-F. Grivaz,[15] A. Grohsjean,[24] S. Grünendahl,[50] M. W. Grünewald,[29] F. Guo,[72] J. Guo,[72] G. Gutierrez,[50] P. Gutierrez,[75] A. Haas,[70] N. J. Hadley,[61] P. Haefner,[24] S. Hagopian,[49] J. Haley,[68] I. Hall,[75] R. E. Hall,[47] L. Han,[6] K. Hanagaki,[50] P. Hansson,[40] K. Harder,[44] A. Harel,[71] R. Harrington,[63] J. M. Hauptman,[57] R. Hauser,[65] J. Hays,[43] T. Hebbeker,[20] D. Hedin,[52] J. G. Hegeman,[33] J. M. Heinmiller,[51] A. P. Heinson,[48] U. Heintz,[62] C. Hensel,[58] K. Herner,[72] G. Hesketh,[63] M. D. Hildreth,[55] R. Hirosky,[81] J. D. Hobbs,[72] B. Hoeneisen,[11] H. Hoeth,[25] M. Hohlfeld,[15] S. J. Hong,[30] R. Hooper,[77] P. Houben,[33] Y. Hu,[72] Z. Hubacek,[9] V. Hynek,[8] I. Iashvili,[69] R. Illingworth,[50] A. S. Ito,[50] S. Jabeen,[62] M. Jaffré,[15] S. Jain,[75] K. Jakobs,[22] C. Jarvis,[61] A. Jenkins,[43] R. Jesik,[43] K. Johns,[45] C. Johnson,[70] M. Johnson,[50] A. Jonckheere,[50] P. Jonsson,[43] A. Juste,[50] D. Käfer,[20] S. Kahn,[73] E. Kajfasz,[14] A. M. Kalinin,[35] J. M. Kalk,[60] J. R. Kalk,[65] S. Kappler,[20] D. Karmanov,[37] J. Kasper,[62] P. Kasper,[50] I. Katsanos,[70] D. Kau,[49] R. Kaur,[26] R. Kehoe,[79] S. Kermiche,[14] N. Khalatyan,[62] A. Khanov,[76] A. Kharchilava,[69] Y. M. Kharzheev,[35] D. Khatidze,[70] H. Kim,[31] T. J. Kim,[30] M. H. Kirby,[34] B. Klima,[50] J. M. Kohli,[26] J.-P. Konrath,[22] M. Kopal,[75] V. M. Korablev,[38] J. Kotcher,[73] B. Kothari,[70] A. Koubarovsky,[37] A. V. Kozelov,[38] D. Krop,[54] A. Kryemadhi,[81] T. Kuhl,[23] A. Kumar,[69] S. Kunori,[61] A. Kupco,[10] T. Kurča,[19] J. Kvita,[8] D. Lam,[55] S. Lammers,[70] G. Landsberg,[77] J. Lazoflores,[49] P. Lebrun,[19] W. M. Lee,[50] A. Leflat,[37] F. Lehner,[41] V. Lesne,[12] J. Leveque,[45] P. Lewis,[43] J. Li,[78] L. Li,[48] Q. Z. Li,[50] S. M. Lietti,[4] J. G. R. Lima,[52] D. Lincoln,[50] J. Linnemann,[65] V. V. Lipaev,[38] R. Lipton,[50] Z. Liu,[5] L. Lobo,[43] A. Lobodenko,[39] M. Lokajicek,[10] A. Lounis,[18] P. Love,[42] H. J. Lubatti,[82] M. Lynker,[55] A. L. Lyon,[50] A. K. A. Maciel,[2] R. J. Madaras,[46] P. Mättig,[25] C. Magass,[20] A. Magerkurth,[64] N. Makovec,[15] P. K. Mal,[55] H. B. Malbouisson,[3] S. Malik,[67] V. L. Malyshev,[35] H. S. Mao,[50] Y. Maravin,[59] B. Martin,[13] R. McCarthy,[72] A. Melnitchouk,[66] A. Mendes,[14] L. Mendoza,[7] P. G. Mercadante,[4] M. Merkin,[37] K. W. Merritt,[50] A. Meyer,[20] J. Meyer,[21] M. Michaut,[17] H. Miettinen,[80] T. Millet,[19] J. Mitrevski,[70] J. Molina,[3] R. K. Mommsen,[44] N. K. Mondal,[28] J. Monk,[44] R. W. Moore,[5] T. Moulik,[58] G. S. Muanza,[19] M. Mulders,[50] M. Mulhearn,[70] O. Mundal,[22] L. Mundim,[3] E. Nagy,[14] M. Naimuddin,[50] M. Narain,[77] N. A. Naumann,[34] H. A. Neal,[64] J. P. Negret,[7] P. Neustroev,[39] H. Nilsen,[22] C. Noeding,[22] A. Nomerotski,[50] S. F. Novaes,[4] T. Nunnemann,[24] V. O'Dell,[50] D. C. O'Neil,[5] G. Obrant,[39] C. Ochando,[15] V. Oguri,[3] N. Oliveira,[3] D. Onoprienko,[59] N. Oshima,[50] J. Osta,[55] R. Otec,[9] G. J. Otero y Garzón,[51] M. Owen,[44] P. Padley,[80] M. Pangilinan,[62] N. Parashar,[56] S.-J. Park,[71] S. K. Park,[30] J. Parsons,[70] R. Partridge,[77] N. Parua,[72]

A. Patwa,[73] G. Pawloski,[80] P. M. Perea,[48] K. Peters,[44] Y. Peters,[25] P. Pétroff,[15] M. Petteni,[43] R. Piegaia,[1] J. Piper,[65] M.-A. Pleier,[21] P. L. M. Podesta-Lerma,[32,†] V. M. Podstavkov,[50] Y. Pogorelov,[55] M.-E. Pol,[2] A. Pompoš,[75] B. G. Pope,[65] A. V. Popov,[38] C. Potter,[5] W. L. Prado da Silva,[3] H. B. Prosper,[49] S. Protopopescu,[73] J. Qian,[64] A. Quadt,[21] B. Quinn,[66] M. S. Rangel,[2] K. J. Rani,[28] K. Ranjan,[27] P. N. Ratoff,[42] P. Renkel,[79] S. Reucroft,[63] M. Rijssenbeek,[72] I. Ripp-Baudot,[18] F. Rizatdinova,[76] S. Robinson,[43] R. F. Rodrigues,[3] C. Royon,[17] P. Rubinov,[50] R. Ruchti,[55] G. Sajot,[13] A. Sánchez-Hernández,[32] M. P. Sanders,[16] A. Santoro,[3] G. Savage,[50] L. Sawyer,[60] T. Scanlon,[43] D. Schaile,[24] R. D. Schamberger,[72] Y. Scheglov,[39] H. Schellman,[53] P. Schieferdecker,[24] C. Schmitt,[25] C. Schwanenberger,[44] A. Schwartzman,[68] R. Schwienhorst,[65] J. Sekaric,[49] S. Sengupta,[49] H. Severini,[75] E. Shabalina,[51] M. Shamim,[59] V. Shary,[17] A. A. Shchukin,[38] R. K. Shivpuri,[27] D. Shpakov,[50] V. Siccardi,[18] R. A. Sidwell,[59] V. Simak,[9] V. Sirotenko,[50] P. Skubic,[75] P. Slattery,[71] D. Smirnov,[55] R. P. Smith,[50] G. R. Snow,[67] J. Snow,[74] S. Snyder,[73] S. Söldner-Rembold,[44] L. Sonnenschein,[16] A. Sopczak,[42] M. Sosebee,[78] K. Soustruznik,[8] M. Souza,[2] B. Spurlock,[78] J. Stark,[13] J. Steele,[60] V. Stolin,[36] A. Stone,[51] D. A. Stoyanova,[38] J. Strandberg,[64] S. Strandberg,[40] M. A. Strang,[69] M. Strauss,[75] R. Ströhmer,[24] D. Strom,[53] M. Strovink,[46] L. Stutte,[50] S. Sumowidagdo,[49] P. Svoisky,[55] A. Sznajder,[3] M. Talby,[14] P. Tamburello,[45] W. Taylor,[5] P. Telford,[44] J. Temple,[45] B. Tiller,[24] F. Tissandier,[12] M. Titov,[22] V. V. Tokmenin,[35] M. Tomoto,[50] T. Toole,[61] I. Torchiani,[22] T. Trefzger,[23] S. Trincaz-Duvoid,[16] D. Tsybychev,[72] B. Tuchming,[17] C. Tully,[68] P. M. Tuts,[70] R. Unalan,[65] L. Uvarov,[39] S. Uvarov,[39] S. Uzunyan,[52] B. Vachon,[5] P. J. van den Berg,[33] B. van Eijk,[35] R. Van Kooten,[54] W. M. van Leeuwen,[33] N. Varelas,[51] E. W. Varnes,[45] A. Vartapetian,[78] I. A. Vasilyev,[38] M. Vaupel,[25] P. Verdier,[19] L. S. Vertogradov,[35] M. Verzocchi,[50] F. Villeneuve-Seguier,[43] P. Vint,[43] J.-R. Vlimant,[16] E. Von Toerne,[59] M. Voutilainen,[67,‡] M. Vreeswijk,[33] H. D. Wahl,[49] L. Wang,[61] M. H. L. S. Wang,[50] J. Warchol,[55] G. Watts,[82] M. Wayne,[55] G. Weber,[23] M. Weber,[50] H. Weerts,[65] A. Wenger,[22,§] N. Wermes,[21] M. Wetstein,[61] A. White,[78] D. Wicke,[25] G. W. Wilson,[58] S. J. Wimpenny,[48] M. Wobisch,[50] D. R. Wood,[63] T. R. Wyatt,[44] Y. Xie,[77] S. Yacoob,[53] R. Yamada,[50] M. Yan,[61] T. Yasuda,[50] Y. A. Yatsunenko,[35] K. Yip,[73] H. D. Yoo,[77] S. W. Youn,[53] C. Yu,[13] J. Yu,[78] A. Yurkewicz,[72] A. Zatserklyaniy,[52] C. Zeitnitz,[25] D. Zhang,[50] T. Zhao,[82] B. Zhou,[64] J. Zhu,[72] M. Zielinski,[71] D. Zieminska,[54] A. Zieminski,[54] V. Zutshi,[52] and E. G. Zverev[37]

(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]*Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil*
[5]*University of Alberta, Edmonton, Alberta, Canada, Simon Fraser University, Burnaby, British Columbia, Canada, York University, Toronto, Ontario, Canada, and McGill University, Montreal, Quebec, Canada*
[6]*University of Science and Technology of China, Hefei, People's Republic of China*
[7]*Universidad de los Andes, Bogotá, Colombia*
[8]*Center for Particle Physics, Charles University, Prague, Czech Republic*
[9]*Czech Technical University, Prague, Czech Republic*
[10]*Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
[11]*Universidad San Francisco de Quito, Quito, Ecuador*
[12]*Laboratoire de Physique Corpusculaire, IN2P3-CNRS, Université Blaise Pascal, Clermont-Ferrand, France*
[13]*Laboratoire de Physique Subatomique et de Cosmologie, IN2P3-CNRS, Universite de Grenoble 1, Grenoble, France*
[14]*CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France*
[15]*Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS et Université Paris-Sud, Orsay, France*
[16]*LPNHE, IN2P3-CNRS, Universités Paris VI and VII, Paris, France*
[17]*DAPNIA/Service de Physique des Particules, CEA, Saclay, France*
[18]*IPHC, IN2P3-CNRS, Université Louis Pasteur, Strasbourg, France, and Université de Haute Alsace, Mulhouse, France*
[19]*IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France*
[20]*III. Physikalisches Institut A, RWTH Aachen, Aachen, Germany*
[21]*Physikalisches Institut, Universität Bonn, Bonn, Germany*
[22]*Physikalisches Institut, Universität Freiburg, Freiburg, Germany*
[23]*Institut für Physik, Universität Mainz, Mainz, Germany*
[24]*Ludwig-Maximilians-Universität München, München, Germany*
[25]*Fachbereich Physik, University of Wuppertal, Wuppertal, Germany*
[26]*Panjab University, Chandigarh, India*
[27]*Delhi University, Delhi, India*
[28]*Tata Institute of Fundamental Research, Mumbai, India*

[29]*University College Dublin, Dublin, Ireland*
[30]*Korea Detector Laboratory, Korea University, Seoul, Korea*
[31]*SungKyunKwan University, Suwon, Korea*
[32]*CINVESTAV, Mexico City, Mexico*
[33]*FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands*
[34]*Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands*
[35]*Joint Institute for Nuclear Research, Dubna, Russia*
[36]*Institute for Theoretical and Experimental Physics, Moscow, Russia*
[37]*Moscow State University, Moscow, Russia*
[38]*Institute for High Energy Physics, Protvino, Russia*
[39]*Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
[40]*Lund University, Lund, Sweden, Royal Institute of Technology and Stockholm University, Stockholm, Sweden, and Uppsala University, Uppsala, Sweden*
[41]*Physik Institut der Universität Zürich, Zürich, Switzerland*
[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*

[*]Visitor from Augustana College, Sioux Falls, SD, USA
[†]Visitor from ICN-UNAM, Mexico City, Mexico.
[‡]Visitor from Helsinki Institute of Physics, Helsinki, Finland.
[§]Visitor from Universität Zürich, Zürich, Switzerland.

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We combine the D0 measurement of the width difference between the light and heavy B_s^0 mass eigenstates and of the CP-violating mixing phase determined from the time-dependent angular distributions in the $B_s^0 \to J/\psi\phi$ decays along with the charge asymmetry in semileptonic decays also measured with the D0 detector. With the additional constraint from the world average of the flavor-specific B_s^0 lifetime, we obtain $\Delta\Gamma_s \equiv (\Gamma_L - \Gamma_H) = 0.13 \pm 0.09\ \text{ps}^{-1}$ and $|\phi_s| = 0.70^{+0.39}_{-0.47}$ or $\Delta\Gamma_s = -0.13 \pm 0.09\ \text{ps}^{-1}$ and $|\phi_s| = 2.44^{+0.47}_{-0.39}$. The data sample corresponds to an integrated luminosity of 1.1 fb^{-1} accumulated with the D0 detector at the Fermilab Tevatron Collider.

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One of the great challenges for elementary particle physics is to trace all possible sources of the violation of CP symmetry. In the standard model (SM) of particle physics, CP symmetry is violated through the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [1]. Although the SM picture of CP violation has so far been confirmed by all laboratory measurements, it has an unsolved problem: the level of CP violation in the SM is too small to produce the observed baryon number density in the universe [2]. Sources of CP violation beyond the CKM mechanism must, therefore, exist to account for the deficit. One signal of CP violation arises in the mixing of doublets of neutral mesons.

In the SM, the light (L) and heavy (H) mass eigenstates of the mixed B_s^0 system are expected to have sizeable mass and decay width differences: $\Delta M_s \equiv M_H - M_L$ and $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$. The two mass eigenstates are expected to be almost pure CP eigenstates. The CP-violating mixing phase is predicted [3] to be $\phi_s = (4.2 \pm 1.4) \times 10^{-3}$. New phenomena may alter ϕ_s leading to a reduction of the observed $\Delta\Gamma_s$ compared to the SM prediction [3] $\Delta\Gamma_s^{SM}$: $\Delta\Gamma_s = \Delta\Gamma_s^{\text{SM}} \times |\cos\phi_s|$. While B_s^0-$\bar{B}_s^0$ oscillations have been detected [4] and the mass difference has recently been measured to high precision [5], the CP-violating phase remains unknown. The D0 experiment [6] at the Fermilab Tevatron Collider has conducted a series of studies [7–10] of B_s^0 mesons produced in proton-antiproton ($p\bar{p}$) interactions. This report utilizes these results to obtain the best estimate of the CP-violating phase in the B_s^0 system.

In Ref. [7], we studied the decay sequence $B_s^0 \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$. From a fit to the time-dependent angular distribution of the decay products, we obtained the mean lifetime, $\bar{\tau}_s = 1/\bar{\Gamma}_s$ (where $\bar{\Gamma}_s \equiv (\Gamma_H + \Gamma_L)/2$), $\Delta\Gamma_s$, and the first direct constraint on ϕ_s. As discussed in Ref. [7], there is a 4-fold ambiguity in the result for ϕ_s: $\pm\phi_s$ and $\pm(\pi - \phi_s)$. The sign of $\sin\phi_s$ is reversed with the simultaneous reversal of the signs of the cosines of the CP-conserving strong phases δ_1 and δ_2. (We adopted the amplitude definition and sign convention of Ref. [11]). The possible solutions are

$$\begin{aligned}
|\phi_s| &= 0.79 \pm 0.56(\text{stat})^{+0.01}_{-0.14}(\text{syst}),\\
\Delta\Gamma_s &= 0.17 \pm 0.08(\text{stat}) \pm 0.02(\text{syst})\text{ps}^{-1};\\
|\phi_s| &= 2.35 \pm 0.56(\text{stat})^{+0.14}_{-0.01}(\text{syst}),\\
\Delta\Gamma_s &= -0.17 \pm 0.08(\text{stat}) \pm 0.02(\text{syst})\text{ps}^{-1}.
\end{aligned} \tag{1}$$

The solutions with positive $\Delta\Gamma_s$ are consistent with the SM prediction [7].

Flavor-specific decays are those particular decay channels where the flavor of the B_s^0 (i.e., whether B_s^0 or $\bar{B}_s^0$) can be determined from the decay products, e.g., from the charge of the lepton in B_s^0 semileptonic decay. These decays are 50% CP even and 50% CP odd at $t = 0$ and provide independent constraints on the parameters of the system. An effective mean lifetime, resulting from a single-exponential fit to the decay time distribution, $\tau_{\text{fs}} = 1/\Gamma_{\text{fs}}$, is related to the physics parameters $\bar{\Gamma}_s$ and $\Delta\Gamma_s$ through the equation $\Gamma_{\text{fs}} = \bar{\Gamma}_s - (\Delta\Gamma_s)^2/2\bar{\Gamma}_s + \mathcal{O}(\Delta\Gamma_s)^3/\bar{\Gamma}_s^2$ [12] (see Fig. 1). We use the world-average value, $\tau_{\text{fs}} = 1/\Gamma_{\text{fs}} = 1.440 \pm 0.036$ ps [13], from a fit including the recent D0 measurement, $\tau_{\text{fs}} = 1/\Gamma_{\text{fs}} = 1.398 \pm 0.044(\text{stat})^{+0.028}_{-0.025}(\text{syst})$ ps [8].

Independently, we obtained another constraint on the parameters of the B_s^0 system from the measurements of the semileptonic charge asymmetry induced by B_s^0 mixing. In general, the semileptonic charge asymmetry for a $\bar{b}q$ meson state B_q^0 is defined as [14]

$$A_{SL}^q = \frac{N(\bar{B}_q^0 \to \ell^+ X) - N(B_q^0 \to \ell^- X)}{N(\bar{B}_q^0 \to \ell^+ X) + N(B_q^0 \to \ell^- X)}. \tag{2}$$

It is related to the CP phase ϕ_q by [15]

$$A_{SL}^q = \frac{\Delta\Gamma_q}{\Delta M_q}\tan\phi_q. \tag{3}$$

In Ref. [9], we measured the same-sign dimuon charge asymmetry defined as

$$A_{SL}^{\mu\mu} = \frac{N(b\bar{b} \to \mu^+\mu^+ X) - N(b\bar{b} \to \mu^-\mu^- X)}{N(b\bar{b} \to \mu^+\mu^+ X) + N(b\bar{b} \to \mu^-\mu^- X)}. \tag{4}$$

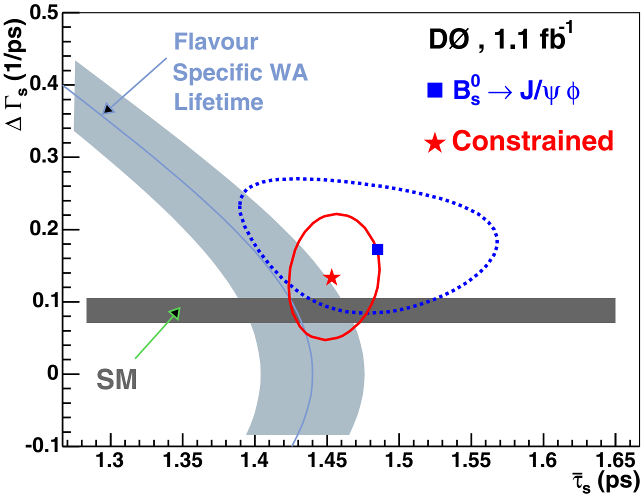

FIG. 1 (color online). The error ellipse ($\Delta \ln(\mathcal{L}) = 0.5$) in the plane $\Delta\Gamma_s$ versus $\bar{\tau}_s$ for the fit to the $B_s^0 \to J/\psi\phi$ data (dashed blue line) and for the fit with the constraint from the two D0 measurements of the charge asymmetry in semileptonic B_s^0 decay, and from the world-average flavor-specific lifetime (solid red line). Also shown is a one-σ band representing the world-average result [13] for $\tau_{\rm fs}$ (see text) and a one-σ band representing the theoretical prediction based on a QCD calculation assuming only standard model inputs $\Delta\Gamma_s^{SM} = 0.088 \pm 0.017\ {\rm ps}^{-1}$ [3].

Both B_d^0 and B_s^0 contribute to this quantity [16], and the result of Ref. [9] is given as

$$A_{SL}^d + \frac{f_s Z_s}{f_d Z_d} A_{SL}^s = -0.0092 \pm 0.0044({\rm stat}) \pm 0.0032({\rm syst});$$
$$Z_q = \frac{1}{1-y_q^2} - \frac{1}{1+x_q^2}; \qquad x_q = \Delta M_q/\Gamma_q;$$
$$y_q = \Delta\Gamma_q/(2\Gamma_q); \tag{5}$$

where A_{SL}^d and A_{SL}^s are the charge asymmetries of the B_d^0 and B_s^0 semileptonic decays, and f_d and f_s are the production rates of B_d^0 and B_s^0 mesons in the hadronization of the b quark, respectively. In deriving relation (5), it is assumed that there is no direct CP violation in semileptonic B decays and that the semileptonic width of all B mesons is the same. Using the world-average values [14] $f_d = 0.398 \pm 0.012$, $f_s = 0.103 \pm 0.014$, $x_d = 0.776 \pm 0.008$, and $Z_d = 0.376 \pm 0.006$, we obtain

$$\frac{f_s Z_s}{f_d Z_d} = 0.70 \pm 0.07({\rm syst}) \pm 0.10({\rm PDG}). \tag{6}$$

The value of Z_s was computed using the measured values of $\Delta\Gamma_s$ [7], $\bar{\tau}_s$ [7], and ΔM_s [5]: $Z_s = 1.015^{+0.018}_{-0.010}$. We have tested that propagating the Z_s dependence on $\Delta\Gamma_s$ has a negligible effect on the final results. The systematic uncertainty arises mainly from a conservative estimate of a possible variation in the reconstruction efficiency of muons from semileptonic decays of different B mesons [17]. The Particle-Data-Group uncertainty is due to propagating the statistical and systematic errors of the world-average inputs [14] to the uncertainty of the ratio.

The asymmetry A_{SL}^d has been measured at B factories where only B_d^0 and $B^\pm$ mesons are produced. The average value of A_{SL}^d is [13]: $A_{SL}^d = -0.0047 \pm 0.0046$. Combining this value and (5) and (6), and adding statistical and systematic uncertainties in quadrature, we obtain

$$A_{SL}^s = -0.0064 \pm 0.0101. \tag{7}$$

In Ref. [10], we measured A_{SL}^s directly by using all events with at least one muon that were consistent with the sequential decay $B_s^0 \to \mu\nu D_s$ with $D_s \to \phi\pi$. The result of this measurement is

$$A_{SL}^s = +0.0245 \pm 0.0193({\rm stat}) \pm 0.0035({\rm syst}). \tag{8}$$

The measurements (7) and (8) are nearly independent since the fraction of dimuon final states in the sample of semileptonic B_s^0 decays used in Ref. [10] is only about 10% [18], and the fraction of semileptonic decays $B_s^0 \to \mu\nu D_s$ with $D_s \to \phi\pi$ in the dimuon sample used in Ref. [9] is less than 1%. Also, the systematic uncertainties of the two measurements are uncorrelated. The main source of systematic uncertainty in (7) is the correction due to $K^\pm$ decays, while in the case of the measurement (8) it is the fitting procedure.

Their combination gives the best estimate of the charge asymmetry in semileptonic B_s^0 decays:

$$A_{SL}^s = 0.0001 \pm 0.0090. \tag{9}$$

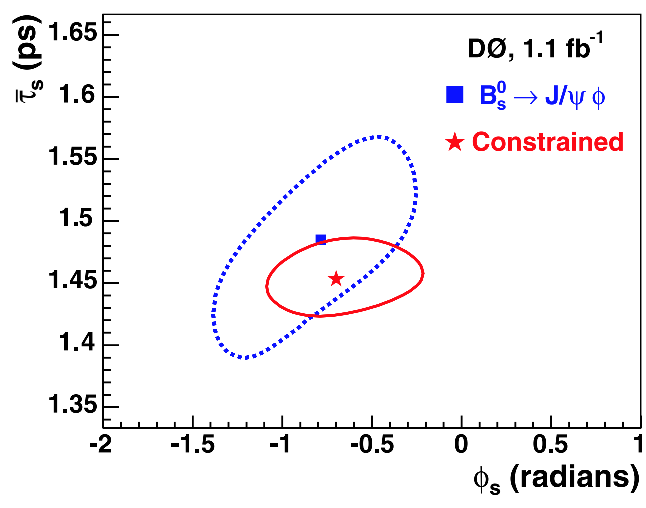

FIG. 2 (color online). The error ellipse ($\Delta \ln(\mathcal{L}) = 0.5$) in the plane ($\bar{\tau}_s$, ϕ_s) for the solution with $\phi_s < 0$, $\cos\delta_1 > 0$, and $\cos\delta_2 < 0$ of the fit to the $B_s^0 \to J/\psi\phi$ data (dashed blue line) and of the fit with both the constraint from the two D0 measurements of the charge asymmetry in semileptonic B_s^0 decay, and from the world-average flavor-specific lifetime (solid red line).

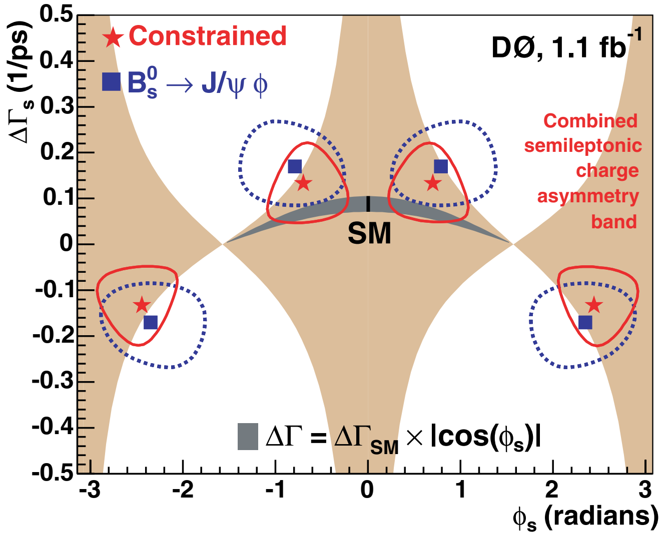

FIG. 3 (color online). The error ellipses ($\Delta \ln(\mathcal{L}) = 0.5$) in the plane ($\Delta\Gamma_s$, ϕ_s) for the four solutions of fit to the $B_s^0 \to J/\psi\phi$ data (dashed blue lines) and of the fit with the constraint from the two D0 measurements of the charge asymmetry in semileptonic B_s^0 decay, and from the world-average flavor-specific lifetime (solid red lines). The central values for all four solutions of the unconstrained and constrained fits are indicated by blue squares and red stars, respectively. Also shown are the SM prediction (vertical black bar at $\phi_s = 0$), the band representing the relation $\Delta\Gamma_s = \Delta\Gamma_s^{SM} \times |\cos\phi_s|$, with $\Delta\Gamma_s^{SM} = 0.088 \pm 0.017$ ps^{-1} [3] (dark shade), and the area corresponding to Eq. (10) (light shade).

Using relation (3) and the result $\Delta M_s = 17.8 \pm 0.1$ ps^{-1} from the CDF experiment [5], we obtain:

$$\Delta\Gamma_s \cdot \tan\phi_s = A_{SL}^s \cdot \Delta M_s = 0.00 \pm 0.16 \text{ ps}^{-1}. \quad (10)$$

We have repeated the fit to the $B_s^0 \to J/\psi\phi$ data, including the constraints from Eq. (10), and from the world-average measurement of τ_{fs} discussed earlier. To illustrate the fit results and the impact of the constraints, in Figs. 1–3 we present likelihood contours in three planes, $\Delta\Gamma_s$ versus $\bar{\tau}_s$, $\bar{\tau}_s$ versus ϕ_s, and $\Delta\Gamma_s$ versus ϕ_s, respectively. The contours indicate error ellipses, $\Delta \ln(\mathcal{L}) = 0.5$, corresponding to the confidence level of 39%. The 4-fold ambiguity remains unresolved. The likelihood profile as a function of ϕ_s for the first solution listed in Eq. (1) is shown in Fig. 4. The extracted value of ϕ_s deviates from zero by 1.2 standard deviations.

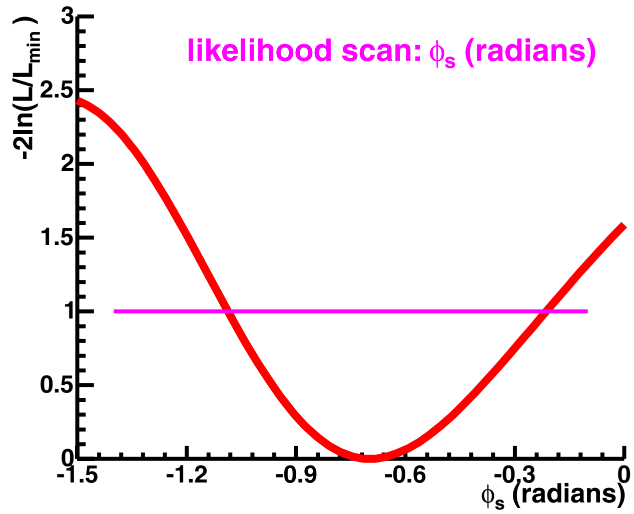

FIG. 4 (color online). The likelihood scan versus ϕ_s for the constrained fit (see text).

In summary, for the solution with $\phi_s < 0$, $\cos\delta_1 > 0$, and $\cos\delta_2 < 0$, we find the decay width difference and the CP-violating phase in the B_s^0 system to be

$$\Delta\Gamma_s = 0.13 \pm 0.09 \text{ ps}^{-1}, \qquad \phi_s = -0.70^{+0.47}_{-0.39}. \quad (11)$$

The measurement uncertainty is dominated by the limited statistics. The systematic uncertainties include a variation of the background model in the analysis of the decay $B_s^0 \to J/\psi\phi$, detector acceptance, and sensitivity to the details of the track and vertex reconstruction. The results are consistent with the SM predictions [3].

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