

*Physics**Physics Research Publications*

*Purdue University*Year 2008

Measurement of lifetime and decay-width difference in $B\text{-}S(0)\text{-}\rightarrow J/\psi\phi$ decays

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Measurement of Lifetime and Decay-Width Difference in $B_s^0 \rightarrow J/\psi\phi$ Decays

T. Aaltonen,²³ A. Abulencia,²⁴ J. Adelman,¹³ T. Akimoto,⁵⁴ M. G. Albrow,¹⁷ B. Álvarez González,¹¹ S. Amerio,⁴² D. Amidei,³⁴ A. Anastassov,⁵¹ A. Annovi,¹⁹ J. Antos,¹⁴ G. Apollinari,¹⁷ A. Apresyan,⁴⁷ T. Arisawa,⁵⁶ A. Artikov,¹⁵ W. Ashmanskas,¹⁷ A. Attal,³ A. Aurisano,⁵² F. Azfar,⁴¹ P. Azzi-Bacchetta,⁴² P. Azzurri,⁴⁵ N. Bacchetta,⁴² W. Badgett,¹⁷ A. Barbaro-Galtieri,²⁸ V. E. Barnes,⁴⁷ B. A. Barnett,²⁵ S. Baroiant,⁷ V. Bartsch,³⁰ G. Bauer,³² P.-H. Beauchemin,³³ F. Bedeschi,⁴⁵ P. Bednar,¹⁴ S. Behari,²⁵ G. Bellettini,⁴⁵ J. Bellinger,⁵⁸ A. Belloni,²² D. Benjamin,¹⁶ A. Beretvas,¹⁷ J. Beringer,²⁸ T. Berry,²⁹ A. Bhatti,⁴⁹ M. Binkley,¹⁷ D. Bisello,⁴² I. Bizjak,³⁰ R. E. Blair,² C. Blocker,⁶ B. Blumenfeld,²⁵ A. Bocci,¹⁶ A. Bodek,⁴⁸ V. Boisvert,⁴⁸ G. Bolla,⁴⁷ A. Bolshov,³² D. Bortoletto,⁴⁷ J. Boudreau,⁴⁶ A. Boveia,¹⁰ B. Brau,¹⁰ L. Brigliadori,⁵ C. Bromberg,³⁵ E. Brubaker,¹³ J. Budagov,¹⁵ H. S. Budd,⁴⁸ S. Budd,²⁴ K. Burkett,¹⁷ G. Busetto,⁴² P. Bussey,²¹ A. Buzatu,³³ K. L. Byrum,² S. 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Korytov,¹⁸ A. V. Kotwal,¹⁶ J. Kraus,²⁴ M. Kreps,²⁶ J. Kroll,⁴⁴ N. Krumnack,⁴ M. Kruse,¹⁶ V. Krutelyov,¹⁰ T. Kubo,⁵⁴ S. E. Kuhlmann,² T. Kuhr,²⁶ N. P. Kulkarni,⁵⁷ Y. Kusakabe,⁵⁶ S. Kwang,¹³ A. T. Laasanen,⁴⁷ S. Lai,³³ S. Lami,⁴⁵ S. Lammel,¹⁷ M. Lancaster,³⁰ R. L. Lander,⁷ K. Lannon,³⁸ A. Lath,⁵¹ G. Latino,⁴⁵ I. Lazzizzera,⁴² T. LeCompte,² J. Lee,⁴⁸ J. Lee,²⁷ Y. J. Lee,²⁷ S. W. Lee,^{52,r} R. Lefèvre,²⁰ N. Leonardo,³² S. Leone,⁴⁵ S. Levy,¹³ J. D. Lewis,¹⁷ C. Lin,⁵⁹ C. S. Lin,²⁸ M. Lindgren,¹⁷ E. Lipeles,⁹ A. Lister,⁷ D. O. Litvintsev,¹⁷ T. Liu,¹⁷ N. S. Lockyer,⁴⁴ A. Loginov,⁵⁹ M. Loreti,⁴² L. Lovas,¹⁴ R.-S. Lu,¹ D. Lucchesi,⁴² J. Lueck,²⁶ C. Luci,⁵⁰ P. Lujan,²⁸ P. Lukens,¹⁷ G. Lungu,¹⁸ L. Lyons,⁴¹ J. Lys,²⁸ R. Lysak,¹⁴ E. Lytken,⁴⁷ P. Mack,²⁶ D. MacQueen,³³ R. Madrak,¹⁷ K. Maeshima,¹⁷ K. Makhoul,³² T. Maki,²³ P. Maksimovic,²⁵ S. Malde,⁴¹ S. Malik,³⁰ G. Manca,²⁹ A. Manousakis,^{15,b} F. Margaroli,⁴⁷ C. Marino,²⁶ C. P. Marino,²⁴ A. Martin,⁵⁹ M. Martin,²⁵ V. Martin,^{21,k} M. Martínez,³ R. Martínez-Ballarín,³¹ T. Maruyama,⁵⁴ P. Mastrandrea,⁵⁰ T. Masubuchi,⁵⁴ M. E. Mattson,⁵⁷ P. Mazzanti,⁵ K. S. McFarland,⁴⁸ P. McIntyre,⁵² R. McNulty,^{29,j} A. Mehta,²⁹ P. Mehtala,²³ S. Menzemer,^{11,l} A. Menzione,⁴⁵ P. Merkel,⁴⁷ C. Mesropian,⁴⁹ A. Messina,³⁵ T. Miao,¹⁷ N. Miladinovic,⁶ J. Miles,³² R. Miller,³⁵ C. Mills,²² M. Milnik,²⁶ A. Mitra,¹ G. Mitselmakher,¹⁸ H. Miyake,⁵⁴ S. Moed,²² N. Moggi,⁵ C. S. Moon,²⁷ R. Moore,¹⁷ M. Morello,⁴⁵ P. Movilla Fernandez,²⁸ J. Mülmenstädt,²⁸ A. Mukherjee,¹⁷ Th. Müller,²⁶ R. Mumford,²⁵ P. Murat,¹⁷ M. Mussini,⁵ J. Nachtman,¹⁷ Y. Nagai,⁵⁴ A. Nagano,⁵⁴ J. Naganoma,⁵⁶ K. Nakamura,⁵⁴ I. Nakano,³⁹ A. Napier,⁵⁵ V. Necula,¹⁶ C. Neu,⁴⁴ M. S. Neubauer,²⁴

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

(CDF Collaboration)

¹*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*²*Argonne National Laboratory, Argonne, Illinois 60439, USA*³*Institut de Física d'Altes Energies, Universitat Autònoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*⁴*Baylor University, Waco, Texas 76798, USA*⁵*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*⁶*Brandeis University, Waltham, Massachusetts 02254, USA*⁷*University of California, Davis, Davis, California 95616, USA*⁸*University of California, Los Angeles, Los Angeles, California 90024, USA*⁹*University of California, San Diego, La Jolla, California 92093, USA*¹⁰*University of California, Santa Barbara, Santa Barbara, California 93106, USA*¹¹*Instituto de Física de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*¹²*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*¹³*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*¹⁴*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*¹⁵*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*¹⁶*Duke University, Durham, North Carolina 27708, USA*¹⁷*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*¹⁸*University of Florida, Gainesville, Florida 32611, USA*¹⁹*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*²⁰*University of Geneva, CH-1211 Geneva 4, Switzerland*²¹*Glasgow University, Glasgow G12 8QQ, United Kingdom*²²*Harvard University, Cambridge, Massachusetts 02138, USA*²³*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*²⁴*University of Illinois, Urbana, Illinois 61801, USA*

- ²⁵The Johns Hopkins University, Baltimore, Maryland 21218, USA
²⁶Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany
²⁷Center for High Energy Physics: Kyungpook National University, Daegu 702-701, Korea;
 Seoul National University, Seoul 151-742, Korea;
 SungKyunKwan University, Suwon 440-746, Korea;
 Korea Institute of Science and Technology Information, Daejeon, 305-806, Korea;
 Chonnam National University, Gwangju, 500-757, Korea
²⁸Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
²⁹University of Liverpool, Liverpool L69 7ZE, United Kingdom
³⁰University College London, London WC1E 6BT, United Kingdom
³¹Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain
³²Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
³³Institute of Particle Physics: McGill University, Montréal, Canada H3A 2T8;
 and University of Toronto, Toronto, Canada M5S 1A7
³⁴University of Michigan, Ann Arbor, Michigan 48109, USA
³⁵Michigan State University, East Lansing, Michigan 48824, USA
³⁶University of New Mexico, Albuquerque, New Mexico 87131, USA
³⁷Northwestern University, Evanston, Illinois 60208, USA
³⁸The Ohio State University, Columbus, Ohio 43210, USA
³⁹Okayama University, Okayama 700-8530, Japan
⁴⁰Osaka City University, Osaka 588, Japan
⁴¹University of Oxford, Oxford OX1 3RH, United Kingdom
⁴²University of Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy
⁴³LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France
⁴⁴University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
⁴⁵Istituto Nazionale di Fisica Nucleare Pisa, Universities of Pisa, Siena, Siena and Scuola Normale Superiore, I-56127 Pisa, Italy
⁴⁶University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
⁴⁷Purdue University, West Lafayette, Indiana 47907, USA
⁴⁸University of Rochester, Rochester, New York 14627, USA
⁴⁹The Rockefeller University, New York, New York 10021, USA
⁵⁰Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, University of Rome “La Sapienza,” I-00185 Roma, Italy
⁵¹Rutgers University, Piscataway, New Jersey 08855, USA
⁵²Texas A&M University, College Station, Texas 77843, USA
⁵³Istituto Nazionale di Fisica Nucleare, University of Trieste/Udine, 34127 Trieste, Italy
⁵⁴University of Tsukuba, Tsukuba, Ibaraki 305, Japan
⁵⁵Tufts University, Medford, Massachusetts 02155, USA
⁵⁶Waseda University, Tokyo 169, Japan
⁵⁷Wayne State University, Detroit, Michigan 48201, USA
⁵⁸University of Wisconsin, Madison, Wisconsin 53706, USA
⁵⁹Yale University, New Haven, Connecticut 06520, USA
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We measure the mean lifetime $\tau = 2/(\Gamma_L + \Gamma_H)$ and the decay-width difference $\Delta\Gamma = \Gamma_L - \Gamma_H$ of the light and heavy mass eigenstates of the B_s^0 meson, B_{sL}^0 and B_{sH}^0 , in $B_s^0 \rightarrow J/\psi\phi$ decays using 1.7 fb^{-1} of data collected with the CDF II detector at the Fermilab Tevatron $p\bar{p}$ collider. Assuming CP conservation, a good approximation for the B_s^0 system in the standard model, we obtain $\Delta\Gamma = 0.076_{-0.063}^{+0.059}(\text{stat}) \pm 0.006(\text{syst}) \text{ ps}^{-1}$ and $\tau = 1.52 \pm 0.04(\text{stat}) \pm 0.02(\text{syst}) \text{ ps}$, the most precise measurements to date. Our constraints on the weak phase and $\Delta\Gamma$ are consistent with CP conservation.

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In the standard model (SM), the mass and flavor eigenstates of the B_s^0 meson differ. This gives rise to particle-antiparticle oscillations [1], which proceed in the SM through weak interaction processes, and whose phenomenology depends on the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. The time (t) evolution of B_s^0 mesons is governed by the Schrödinger equation

$$i \frac{d}{dt} \begin{pmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2} \mathbf{\Gamma} \right) \begin{pmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{pmatrix},$$

with mass matrix \mathbf{M} and decay matrix $\mathbf{\Gamma}$. The mass difference, $\Delta m = m_H - m_L \approx 2|M_{12}|$, between the heavy and light mass eigenstates, B_{sH}^0 and B_{sL}^0 , determines the frequency of B_s^0 oscillations, a quantity precisely measured in Ref. [2]. The mean lifetime, $\tau = 2/(\Gamma_L + \Gamma_H)$, is expected to be equal to the mean B^0 lifetime within 1% [3]. The decay-width difference, $\Delta\Gamma = \Gamma_L - \Gamma_H$, is predicted in the SM to be $0.096 \pm 0.039 \text{ ps}^{-1}$ [4] and was first measured by the CDF Collaboration [5] and, recently, by the D0 Collaboration with higher precision [6]. It depends on

the CP -violating weak phase difference between the B_s^0 - \bar{B}_s^0 mixing amplitude and the amplitudes of the subsequent B_s^0 and \bar{B}_s^0 decays to common final states, $\phi_s = \arg(-M_{12}/\Gamma_{12})$, via the relation $\Delta\Gamma = 2|\Gamma_{12}|\cos(\phi_s)$. While the SM expectation, $\phi_s^{\text{SM}} = 4 \times 10^{-3}$ [4], is small, contributions from new physics processes to B_s^0 mixing can lead to a significantly different value of the phase, $\phi_s = \phi_s^{\text{SM}} + \phi_s^{\text{NP}}$. The same new physics contribution ϕ_s^{NP} would be present in the relative phase between mixing and $b \rightarrow c\bar{c}s$ quark transitions, $2\beta_s = 2\beta_s^{\text{SM}} - \phi_s^{\text{NP}}$, in which the SM contribution is defined in terms of CKM matrix elements by $\beta_s^{\text{SM}} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$ [4]. Since both ϕ_s^{SM} and β_s^{SM} are significantly smaller than the current experimental resolution, we can approximate $2\beta_s = -\phi_s^{\text{NP}} = -\phi_s$. Thus the measurement of a sizable value of $2\beta_s$ inconsistent with zero would indicate new physics. In the case of a nonzero $|\Gamma_{12}|$, an analysis of time-dependent decay rates of B_s^0 mesons to two vector mesons becomes sensitive to the weak phase $2\beta_s$, even without information on the B_s^0 flavor at production, because of the interference between CP eigenstates.

In this Letter, we present the measurement of the B_s^0 meson mean lifetime τ and decay-width difference $\Delta\Gamma$ using $B_s^0 \rightarrow J/\psi\phi$ decays followed by $J/\psi \rightarrow \mu^+\mu^-$ and $\phi \rightarrow K^+K^-$ decays. Charge-conjugate modes are implied throughout this Letter. We also extract information about the weak phase $2\beta_s$. The final state is a mixture of CP -even and CP -odd states that are distinguished using the angular distributions of the decay products. Since the B_s^0 is a pseudoscalar and the J/ψ and ϕ are vector mesons, the orbital angular momentum between the two decay products can have the magnitudes $\ell = 0, 1$, or 2 . The final state is CP -even in S - and D -wave decays and CP -odd in P -wave decays. The angular distributions are expressed in terms of three angles, θ_T , ϕ_T , and ψ_T , defined in the transversity basis [7]. The angles θ_T and ϕ_T are the polar and azimuthal angles of the μ^+ in the rest frame of the J/ψ , where the x axis is defined by the momentum direction of the B_s^0 and the xy plane by the $\phi \rightarrow K^+K^-$ decay plane with a positive y component of the K^+ momentum. The angle ψ_T is the polar angle of the K^+ with respect to the opposite of the B_s^0 flight direction in the ϕ rest frame.

The data were collected by the CDF II detector at the Fermilab Tevatron $p\bar{p}$ collider between February 2002 and January 2007, and correspond to an integrated luminosity of 1.7 fb^{-1} . The CDF II detector [8] consists of a magnetic spectrometer surrounded by electromagnetic and hadronic calorimeters and muon detectors. The tracking system is composed of a silicon microstrip detector [9] surrounded by an open-cell drift chamber (COT) [10]. We detect muons in planes of multiwire drift chambers and scintillators [11] in the pseudorapidity range $|\eta| \leq 1.0$. Charged particle identification is provided by the time-of-flight system [12], complemented by the ionization-energy-loss measurement in the COT (dE/dx). Events with $J/\psi \rightarrow$

$\mu^+\mu^-$ decays used in this analysis were recorded using a dimuon trigger, which required two oppositely charged COT tracks matched to muon chamber track segments with a dimuon mass between 2.7 and 4.0 GeV/c^2 .

In the offline analysis, $B_s^0 \rightarrow J/\psi\phi$ decays are reconstructed following the procedure described in Ref. [5]. We train an artificial neural network (ANN) to separate B_s^0 decays from the combinatorial background, which is the dominant one. We model the signal with simulated events and use data from B_s^0 mass sidebands (see Fig. 1) to model the combinatorial background. The input variables to the ANN are kinematic quantities, vertex fit quality parameters, and particle-identification information obtained from the muon system, the time-of-flight detector, and the dE/dx measurements. The requirement on the ANN output is selected by maximizing the significance $S/\sqrt{S+B}$ on data where S (B) is the number of signal (background) events in a $\pm 20 \text{ MeV}/c^2$ window around the B_s^0 mass peak position. The selected sample contains about 2500 $B_s^0 \rightarrow J/\psi\phi$ decays. The resulting mass distribution is shown in Fig. 1.

To extract τ and $\Delta\Gamma$, we perform an unbinned maximum likelihood fit with probability density functions (PDFs) depending on mass, lifetime, and transversity angles.

For the PDFs of the background, we use empirical models with floating fit parameters determined from the data. The background has a prompt component and a non-prompt component. The mass PDF is parametrized by a straight-line function for each component. The lifetime distribution is described by a δ function at $t = 0$ for the prompt component, a positive exponential for the long-lived nonprompt component, and a negative and positive exponential for mismeasured candidates. All lifetime components are convolved with a Gaussian to account for the lifetime resolution estimated on a candidate-by-candidate basis. Because correlations among the three angles are negligible, we factorize the angular PDF as a product of polynomials in $\cos^2(\theta_T)$, $\cos(2\phi_T)$, and $\cos(\psi_T)$. The an-

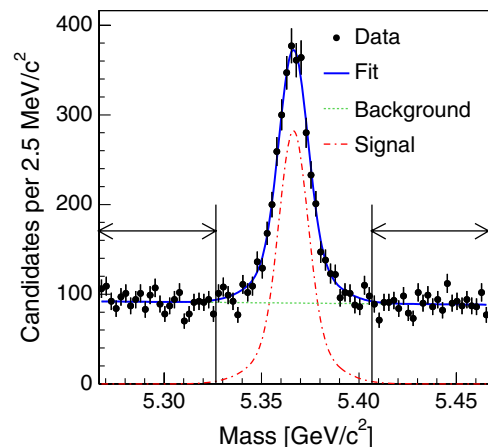


FIG. 1 (color online). Invariant $J/\psi\phi$ mass distribution with fit projection overlaid. The arrows indicate the sideband regions.

gular distributions of prompt and nonprompt background events agree within uncertainties, and are chosen to be identical in the likelihood function.

For the signal, the mass distribution is described by the sum of two Gaussians. The lifetime and the angles $\vec{\rho} = (\cos(\theta_T), \phi_T, \cos(\psi_T))$ are correlated for B_s^0 signal events. The lifetime-angular distribution without acceptance effects is given by

$$\begin{aligned} \frac{d^4 P(\vec{\rho}, t)}{d\vec{\rho} dt} \propto & |A_0|^2 f_1(\vec{\rho}) \mathcal{T}_+ + |A_{\parallel}|^2 f_2(\vec{\rho}) \mathcal{T}_+ + |A_{\perp}|^2 f_3(\vec{\rho}) \mathcal{T}_- + |A_0| |A_{\parallel}| f_5(\vec{\rho}) \cos(\delta_{\parallel}) \mathcal{T}_+ \\ & + |A_{\parallel}| |A_{\perp}| f_4(\vec{\rho}) \cos(\delta_{\perp} - \delta_{\parallel}) \sin(2\beta_s) (e^{-\Gamma_H t} - e^{-\Gamma_L t})/2 + |A_0| |A_{\perp}| f_6(\vec{\rho}) \cos(\delta_{\perp}) \sin(2\beta_s) (e^{-\Gamma_H t} - e^{-\Gamma_L t})/2, \end{aligned} \quad (1)$$

where

$$\begin{aligned} \mathcal{T}_{\pm} &= [(1 \pm \cos(2\beta_s))e^{-\Gamma_L t} + (1 \mp \cos(2\beta_s))e^{-\Gamma_H t}]/2, \\ f_1(\vec{\rho}) &= 2\cos^2(\psi_T)(1 - \sin^2(\theta_T)\cos^2(\phi_T)), \\ f_2(\vec{\rho}) &= \sin^2(\psi_T)(1 - \sin^2(\theta_T)\sin^2(\phi_T)), \\ f_3(\vec{\rho}) &= \sin^2(\psi_T)\sin^2(\theta_T), \\ f_4(\vec{\rho}) &= -\sin^2(\psi_T)\sin(2\theta_T)\sin(\phi_T), \\ f_5(\vec{\rho}) &= \sin(2\psi_T)\sin^2(\theta_T)\sin(2\phi_T)/\sqrt{2}, \\ f_6(\vec{\rho}) &= \sin(2\psi_T)\sin(2\theta_T)\cos(\phi_T)/\sqrt{2}. \end{aligned} \quad (2)$$

The quantities A_0 , A_{\perp} , and A_{\parallel} are the linear polarization amplitudes at $t = 0$, and δ_{\perp} and δ_{\parallel} are the strong phases of A_{\perp} and A_{\parallel} relative to A_0 , respectively.

The lifetime-angle distribution is invariant under each of the two transformations ($2\beta_s \rightarrow -2\beta_s$, $\delta_{\perp} \rightarrow \delta_{\perp} + \pi$) and ($\Delta\Gamma \rightarrow -\Delta\Gamma$, $2\beta_s \rightarrow 2\beta_s + \pi$). Because of this four-fold ambiguity, this measurement is insensitive to the sign of both $2\beta_s$ and $\Delta\Gamma$.

The signal lifetime terms are convolved with the same Gaussian resolution function used for the background, which employs the candidate-by-candidate lifetime uncertainty. To account for different distributions of the lifetime uncertainty between signal and background, their PDFs are included in the likelihood. These PDFs are derived from sideband-subtracted signal events and from sideband events, respectively.

The angular distribution of B_s^0 decays described in Eq. (1) is modified by detector acceptance as well as trigger and selection efficiencies. This effect is taken into account with an acceptance function $\epsilon(\vec{\rho})$ derived from simulated $B_s^0 \rightarrow J/\psi\phi$ decays. The factor $\epsilon(\vec{\rho})$ is described by a three-dimensional histogram with 20 bins in each of the angles.

We consider possible systematic uncertainties due to the signal mass model, the lifetime resolution model, the $\mathcal{O}(3\%)$ contamination by $B^0 \rightarrow J/\psi K^*$ decays misreconstructed and selected as B_s^0 candidates not included in the background model, the acceptance description, the silicon detector alignment, and the model for the angular distribution of the background. The largest systematic uncertainty for $\Delta\Gamma$ is caused by B^0 mesons reconstructed as B_s^0 me-

sons. The largest contributions to the systematic uncertainty on τ are the lifetime resolution model and the silicon detector alignment. The dominant source of systematic uncertainties on the amplitudes is the angular background model.

Under the assumption of CP conservation ($2\beta_s = 0$), we obtain

$$\begin{aligned} \tau &= 1.52 \pm 0.04 \pm 0.02 \text{ ps}, \\ \Delta\Gamma &= 0.076_{-0.063}^{+0.059} \pm 0.006 \text{ ps}^{-1}, \\ |A_0|^2 &= 0.531 \pm 0.020 \pm 0.007, \\ |A_{\perp}|^2 &= 0.239 \pm 0.029 \pm 0.011, \\ |A_{\parallel}|^2 &= 0.230 \pm 0.026 \pm 0.009. \end{aligned}$$

The first uncertainties are statistical, the second ones systematic. We do not quote a point estimate of the strong phase δ_{\parallel} because its likelihood profile is nonparabolic due to a symmetry point at $\delta_{\parallel} = \pi$ which makes an uncertainty estimate unreliable. This analysis is insensitive to the second strong phase δ_{\perp} if $2\beta_s = 0$ [see Eq. (1)]. The invariant mass, proper decay time, and angular distributions with fit projections overlaid are shown in Figs. 1–3. The measured mean lifetime is compatible with the B^0 lifetime [13] as predicted by theory [3]. The measured

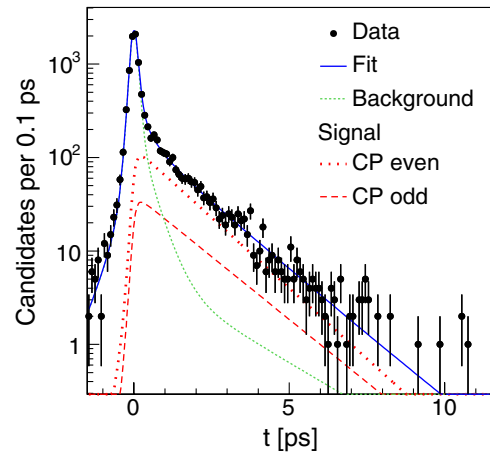


FIG. 2 (color online). Lifetime distribution with fit projection overlaid.

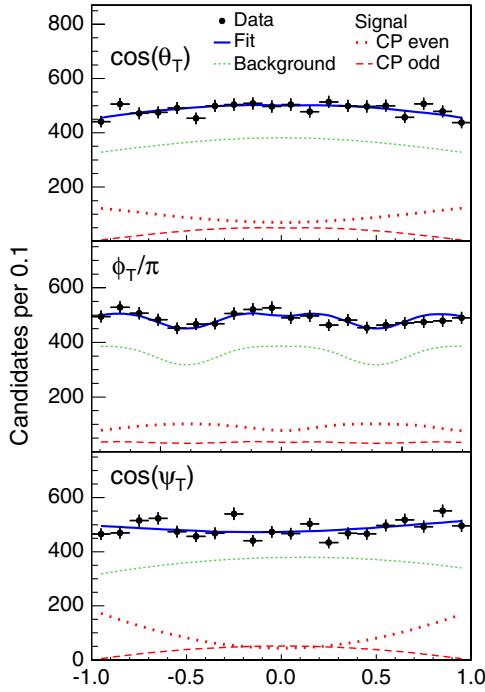


FIG. 3 (color online). Angular distributions with fit projection overlaid.

amplitudes are consistent with the ones observed in $B^0 \rightarrow J/\psi K^*$ decays [14] as expected under the assumption of SU(3) flavor symmetry.

For the constraints on the CP -violating phase, we construct a 90% (95%) confidence level region in the $2\beta_s$ - $\Delta\Gamma$ plane using the likelihood-ratio ordering of Feldman and Cousins [15]. We choose this method instead of a point estimate because it is not affected by the bias we observe in simulated experiments. The bias is of the order of the statistical uncertainty for input values of $\Delta\Gamma$ or $2\beta_s$ close to zero, which are near to the SM expectation. The bias can be understood from Eq. (1). If $2\beta_s$ approaches zero, the two terms proportional to $\sin(2\beta_s)$ vanish, and this analysis becomes insensitive to δ_\perp . The same effective loss of degrees of freedom in the fit occurs when $\Delta\Gamma$ approaches zero and multiple degenerate solutions for $2\beta_s$ and δ_\perp exist.

To obtain the likelihood-ratio distribution for given values of $\Delta\Gamma$ and $2\beta_s$, we use experiments simulated with values for all other parameters determined by a fit to data [16]. We checked that alternate choices of these values do not affect the coverage properties of our algorithm. Systematic uncertainties are not included in the algorithm, since they are all negligible.

The resulting confidence region is shown in Fig. 4. Since both B_s^0 mass eigenstates have the same angular distribution at $2\beta_s = \pm\pi/2$, the sensitivity on $\Delta\Gamma$ decreases towards this value. For the SM expectation ($\Delta\Gamma \approx 0.1 \text{ ps}^{-1}$ and $2\beta_s \approx 0$), we find the probability to get an equal or greater likelihood ratio than the one observed in

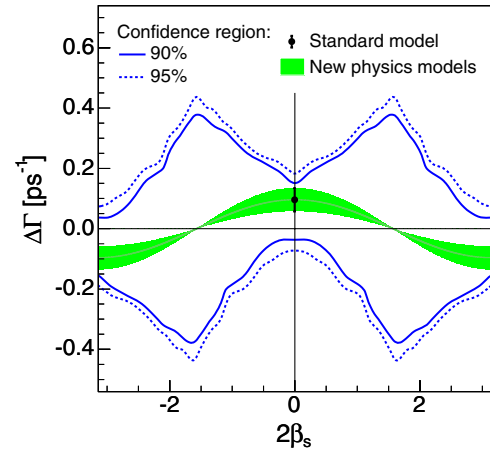


FIG. 4 (color online). Regions at the 90% and 95% confidence level in the $2\beta_s$ - $\Delta\Gamma$ plane compared with the SM prediction and the region allowed in new physics models given by $\Delta\Gamma = 2|\Gamma_{12}|\cos(\phi_s)$ [4].

data to be $p = 22\%$, corresponding to an agreement at 1.2 Gaussian standard deviations.

In summary, we report the measurement of the mean lifetime, the width difference, and the amplitudes in $B_s^0 \rightarrow J/\psi\phi$ decays assuming CP conservation. This measurement improves the precision of the current best measurement [6] by 30%–50%. It is in good agreement with previous results and the SM expectation. In addition we derive constraints on $\Delta\Gamma$ and the CP -violating phase $2\beta_s$. Our data are consistent with the SM expectation of $2\beta_s \approx 0$, but sizable values allowed within new physics models cannot be ruled out.

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^aDeceased.

- ^bVisitor from University of Athens, 15784 Athens, Greece.
- ^cVisitor from Chinese Academy of Sciences, Beijing 100864, China.
- ^dVisitor from University of Bristol, Bristol BS8 1TL, United Kingdom.
- ^eVisitor from University Libre de Bruxelles, B-1050 Brussels, Belgium.
- ^fVisitor from University of California Irvine, Irvine, CA 92697, USA.
- ^gVisitor from University of California Santa Cruz, Santa Cruz, CA 95064, USA.
- ^hVisitor from Cornell University, Ithaca, NY 14853, USA.
- ⁱVisitor from University of Cyprus, Nicosia CY-1678, Cyprus.
- ^jVisitor from University College Dublin, Dublin 4, Ireland.
- ^kVisitor from University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom.
- ^lVisitor from University of Heidelberg, D-69120 Heidelberg, Germany.
- ^mVisitor from Universidad Iberoamericana, Mexico D.F., Mexico.
- ⁿVisitor from University of Manchester, Manchester M13 9PL, England.
- ^oVisitor from Nagasaki Institute of Applied Science, Nagasaki, Japan.
- ^pVisitor from University de Oviedo, E-33007 Oviedo, Spain.
- ^qVisitor from Queen Mary, University of London, London, E1 4NS, England.
- ^rVisitor from Texas Tech University, Lubbock, TX 79409, USA.
- ^sVisitor from IFIC (CSIC-Universitat de Valencia), 46071 Valencia, Spain.
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