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A Precise Measurement of the B_s^0 Lifetime

V.M. Abazov,[36] B. Abbott,[76] M. Abolins,[66] B.S. Acharya,[29] M. Adams,[52] T. Adams,[50] M. Agelou,[18] J.-L. Agram,[19] S.H. Ahn,[31] M. Ahsan,[60] G.D. Alexeev,[36] G. Alkhazov,[40] A. Alton,[65] G. Alverson,[64] G.A. Alves,[2] M. Anastasoaie,[35] T. Andeen,[54] S. Anderson,[46] B. Andrieu,[17] M.S. Anzelc,[54] Y. Arnoud,[14] M. Arov,[53] A. Askew,[50] B. Åsman,[41] A.C.S. Assis Jesus,[3] O. Atramentov,[58] C. Autermann,[21] C. Avila,[8] C. Ay,[24] F. Badaud,[13] A. Baden,[62] L. Bagby,[53] B. Baldin,[51] D.V. Bandurin,[36] P. Banerjee,[29] S. Banerjee,[29] E. Barberis,[64] P. Bargassa,[81] P. Baringer,[59] C. Barnes,[44] J. Barreto,[2] J.F. Bartlett,[51] U. Bassler,[17] D. Bauer,[44] A. Bean,[59] M. Begalli,[3] M. Begel,[72] C. Belanger-Champagne,[5] A. Bellavance,[68] J.A. Benitez,[66] S.B. Beri,[27] G. Bernardi,[17] R. Bernhard,[42] L. Berntzon,[15] I. Bertram,[43] M. Besançon,[18] R. Beuselinck,[44] V.A. Bezzubov,[39] P.C. Bhat,[51] V. Bhatnagar,[27] M. Binder,[25] C. Biscarat,[43] K.M. Black,[63] I. Blackler,[44] G. Blazey,[53] F. Blekman,[44] S. Blessing,[50] D. Bloch,[19] K. Bloom,[68] U. Blumenschein,[23] A. Boehnlein,[51] O. Boeriu,[56] T.A. Bolton,[60] F. Borcherding,[51] G. Borissov,[43] K. Bos,[34] T. Bose,[78] A. Brandt,[79] R. Brock,[66] G. Brooijmans,[71] A. Bross,[51] D. Brown,[79] N.J. Buchanan,[50] D. Buchholz,[54] M. Buehler,[82] V. Buescher,[23] S. Burdin,[51] S. Burke,[46] T.H. Burnett,[83] E. Busato,[17] C.P. Buszello,[44] J.M. Butler,[63] S. Calvet,[15] J. Cammin,[72] S. Caron,[34] W. Carvalho,[3] B.C.K. Casey,[78] N.M. Cason,[56] H. Castilla-Valdez,[33] S. Chakrabarti,[29] D. Chakraborty,[53] K.M. Chan,[72] A. Chandra,[49] D. Chapin,[78] F. Charles,[19] E. Cheu,[46] F. Chevallier,[14] D.K. Cho,[63] S. Choi,[32] B. Choudhary,[28] L. Christofek,[59] D. Claes,[68] B. Clément,[19] C. Clément,[41] Y. Coadou,[5] M. Cooke,[81] W.E. Cooper,[51] D. Coppage,[59] M. Corcoran,[81] M.-C. Cousinou,[15] B. Cox,[45] S. Crépé-Renaudin,[14] D. Cutts,[78] M. Ćwiok,[30] H. da Motta,[2] A. Das,[63] M. Das,[61] B. Davies,[43] G. Davies,[44] G.A. Davis,[54] K. De,[79] P. de Jong,[34] S.J. de Jong,[35] E. De La Cruz-Burelo,[65] C. De Oliveira Martins,[3] J.D. Degenhardt,[65] F. Déliot,[18] M. Demarteau,[51] R. Demina,[72] P. Demine,[18] D. Denisov,[51] S.P. Denisov,[39] S. Desai,[73] H.T. Diehl,[51] M. Diesburg,[51] M. Doidge,[43] A. Dominguez,[68] H. Dong,[73] L.V. Dudko,[38] L. Duflot,[16] S.R. Dugad,[29] A. Duperrin,[15] J. Dyer,[66] A. Dyshkant,[53] M. Eads,[68] D. Edmunds,[66] T. Edwards,[45] J. Ellison,[49] J. Elmsheuser,[25] V.D. Elvira,[51] S. Eno,[62] P. Ermolov,[38] J. Estrada,[51] H. Evans,[55] A. Evdokimov,[37] V.N. Evdokimov,[39] S.N. Fatakia,[63] L. Feligioni,[63] A.V. Ferapontov,[60] T. Ferbel,[72] F. Fiedler,[25] F. Filthaut,[35] W. Fisher,[51] H.E. Fisk,[51] I. Fleck,[23] M. Ford,[45] M. Fortner,[53] H. Fox,[23] S. Fu,[51] S. Fuess,[51] T. Gadfort,[83] C.F. Galea,[35] E. Gallas,[51] E. Galyaev,[56] C. Garcia,[72] A. Garcia-Bellido,[83] J. Gardner,[59] V. Gavrilov,[37] A. Gay,[19] P. Gay,[13] D. Gelé,[19] R. Gelhaus,[49] C.E. Gerber,[52] Y. Gershtein,[50] D. Gillberg,[5] G. Ginther,[72] N. Gollub,[41] B. Gómez,[8] K. Gounder,[51] A. Goussiou,[56] P.D. Grannis,[73] H. Greenlee,[51] Z.D. Greenwood,[61] E.M. Gregores,[4] G. Grenier,[20] Ph. Gris,[13] J.-F. Grivaz,[16] S. Grünendahl,[51] M.W. Grünewald,[30] F. Guo,[73] J. Guo,[73] G. Gutierrez,[51] P. Gutierrez,[76] A. Haas,[71] N.J. Hadley,[62] P. Haefner,[25] S. Hagopian,[50] J. Haley,[69] I. Hall,[76] R.E. Hall,[48] L. Han,[7] K. Hanagaki,[51] K. Harder,[60] A. Harel,[72] R. Harrington,[64] J.M. Hauptman,[58] R. Hauser,[66] J. Hays,[54] T. Hebbeker,[21] D. Hedin,[53] J.G. Hegeman,[34] J.M. Heinmiller,[52] A.P. Heinson,[49] U. Heintz,[63] C. Hensel,[59] G. Hesketh,[64] M.D. Hildreth,[56] R. Hirosky,[82] J.D. Hobbs,[73] B. Hoeneisen,[12] M. Hohlfeld,[16] S.J. Hong,[31] R. Hooper,[78] P. Houben,[34] Y. Hu,[73] V. Hynek,[9] I. Iashvili,[70] R. Illingworth,[51] A.S. Ito,[51] S. Jabeen,[63] M. Jaffré,[16] S. Jain,[76] K. Jakobs,[23] C. Jarvis,[62] A. Jenkins,[44] R. Jesik,[44] K. Johns,[46] C. Johnson,[71] M. Johnson,[51] A. Jonckheere,[51] P. Jonsson,[44] A. Juste,[51] D. Käfer,[21] S. Kahn,[74] E. Kajfasz,[15] A.M. Kalinin,[36] J.M. Kalk,[61] J.R. Kalk,[66] S. Kappler,[21] D. Karmanov,[38] J. Kasper,[63] I. Katsanos,[71] D. Kau,[50] R. Kaur,[27] R. Kehoe,[80] S. Kermiche,[15] S. Kesisoglou,[78] A. Khanov,[77] A. Kharchilava,[70] Y.M. Kharzheev,[36] D. Khatidze,[71] H. Kim,[79] T.J. Kim,[31] M.H. Kirby,[35] B. Klima,[51] J.M. Kohli,[27] J.-P. Konrath,[23] M. Kopal,[76] V.M. Korablev,[39] J. Kotcher,[74] B. Kothari,[71] A. Koubarovsky,[38] A.V. Kozelov,[39] J. Kozminski,[66] A. Kryemadhi,[82] S. Krzywdzinski,[51] T. Kuhl,[24] A. Kumar,[70] S. Kunori,[62] A. Kupco,[11] T. Kurča,[20,*] J. Kvita,[9] S. Lager,[41] S. Lammers,[71] G. Landsberg,[78] J. Lazoflores,[50] A.-C. Le Bihan,[19] P. Lebrun,[20] W.M. Lee,[53] A. Leflat,[38] F. Lehner,[42] C. Leonidopoulos,[71] V. Lesne,[13] J. Leveque,[46] P. Lewis,[44] J. Li,[79] Q.Z. Li,[51] J.G.R. Lima,[53] D. Lincoln,[51] J. Linnemann,[66] V.V. Lipaev,[39] R. Lipton,[51] Z. Liu,[5] L. Lobo,[44] A. Lobodenko,[40] M. Lokajicek,[11] A. Lounis,[19] P. Love,[43] H.J. Lubatti,[83] M. Lynker,[56] A.L. Lyon,[51] A.K.A. Maciel,[2] R.J. Madaras,[47] P. Mättig,[26] C. Magass,[21] A. Magerkurth,[65] A.-M. Magnan,[14] N. Makovec,[16] P.K. Mal,[56] H.B. Malbouisson,[3] S. Malik,[68] V.L. Malyshev,[36] H.S. Mao,[6] Y. Maravin,[60] M. Martens,[51] S.E.K. Mattingly,[78] R. McCarthy,[73] R. McCroskey,[46] D. Meder,[24] A. Melnitchouk,[67] A. Mendes,[15] L. Mendoza,[8] M. Merkin,[38] K.W. Merritt,[51] A. Meyer,[21] J. Meyer,[22] M. Michaut,[18] H. Miettinen,[81] T. Millet,[20] J. Mitrevski,[71] J. Molina,[3] N.K. Mondal,[29] J. Monk,[45] R.W. Moore,[5] T. Moulik,[59] G.S. Muanza,[16] M. Mulders,[51] M. Mulhearn,[71] L. Mundim,[3] Y.D. Mutaf,[73] E. Nagy,[15]

M. Naimuddin,[28] M. Narain,[63] N.A. Naumann,[35] H.A. Neal,[65] J.P. Negret,[8] S. Nelson,[50] P. Neustroev,[40] C. Noeding,[23] A. Nomerotski,[51] S.F. Novaes,[4] T. Nunnemann,[25] V. O'Dell,[51] D.C. O'Neil,[5] G. Obrant,[40] V. Oguri,[3] N. Oliveira,[3] N. Oshima,[51] R. Otec,[10] G.J. Otero y Garzón,[52] M. Owen,[45] P. Padley,[81] N. Parashar,[57] S.-J. Park,[72] S.K. Park,[31] J. Parsons,[71] R. Partridge,[78] N. Parua,[73] A. Patwa,[74] G. Pawloski,[81] P.M. Perea,[49] E. Perez,[18] K. Peters,[45] P. Pétroff,[16] M. Petteni,[44] R. Piegaia,[1] M.-A. Pleier,[22] P.L.M. Podesta-Lerma,[33] V.M. Podstavkov,[51] Y. Pogorelov,[56] M.-E. Pol,[2] A. Pompoš,[76] B.G. Pope,[66] A.V. Popov,[39] W.L. Prado da Silva,[3] H.B. Prosper,[50] S. Protopopescu,[74] J. Qian,[65] A. Quadt,[22] B. Quinn,[67] K.J. Rani,[29] K. Ranjan,[28] P.A. Rapidis,[51] P.N. Ratoff,[43] P. Renkel,[80] S. Reucroft,[64] M. Rijssenbeek,[73] I. Ripp-Baudot,[19] F. Rizatdinova,[77] S. Robinson,[44] R.F. Rodrigues,[3] C. Royon,[18] P. Rubinov,[51] R. Ruchti,[56] V.I. Rud,[38] G. Sajot,[14] A. Sánchez-Hernández,[33] M.P. Sanders,[62] A. Santoro,[3] G. Savage,[51] L. Sawyer,[61] T. Scanlon,[44] D. Schaile,[25] R.D. Schamberger,[73] Y. Scheglov,[40] H. Schellman,[54] P. Schieferdecker,[25] C. Schmitt,[26] C. Schwanenberger,[45] A. Schwartzman,[69] R. Schwienhorst,[66] S. Sengupta,[50] H. Severini,[76] E. Shabalina,[52] M. Shamim,[60] V. Shary,[18] A.A. Shchukin,[39] W.D. Shephard,[56] R.K. Shivpuri,[28] D. Shpakov,[64] V. Siccardi,[19] R.A. Sidwell,[60] V. Simak,[10] V. Sirotenko,[51] P. Skubic,[76] P. Slattery,[72] R.P. Smith,[51] G.R. Snow,[68] J. Snow,[75] S. Snyder,[74] S. Söldner-Rembold,[45] X. Song,[53] L. Sonnenschein,[17] A. Sopczak,[43] M. Sosebee,[79] K. Soustruznik,[9] M. Souza,[2] B. Spurlock,[79] J. Stark,[14] J. Steele,[61] K. Stevenson,[55] V. Stolin,[37] A. Stone,[52] D.A. Stoyanova,[39] J. Strandberg,[41] M.A. Strang,[70] M. Strauss,[76] R. Ströhmer,[25] D. Strom,[54] M. Strovink,[47] L. Stutte,[51] S. Sumowidagdo,[50] A. Sznajder,[3] M. Talby,[15] P. Tamburello,[46] W. Taylor,[5] P. Telford,[45] J. Temple,[46] B. Tiller,[25] M. Titov,[23] V.V. Tokmenin,[36] M. Tomoto,[51] T. Toole,[62] I. Torchiani,[23] S. Towers,[43] T. Trefzger,[24] S. Trincaz-Duvoid,[17] D. Tsybychev,[73] B. Tuchming,[18] C. Tully,[69] A.S. Turcot,[45] P.M. Tuts,[71] R. Unalan,[66] L. Uvarov,[40] S. Uvarov,[40] S. Uzunyan,[53] B. Vachon,[5] P.J. van den Berg,[34] R. Van Kooten,[55] W.M. van Leeuwen,[34] N. Varelas,[52] E.W. Varnes,[46] A. Vartapetian,[79] I.A. Vasilyev,[39] M. Vaupel,[26] P. Verdier,[20] L.S. Vertogradov,[36] M. Verzocchi,[51] F. Villeneuve-Seguier,[44] P. Vint,[44] J.-R. Vlimant,[17] E. Von Toerne,[60] M. Voutilainen,[68,†] M. Vreeswijk,[34] H.D. Wahl,[50] L. Wang,[62] J. Warchol,[56] G. Watts,[83] M. Wayne,[56] M. Weber,[51] H. Weerts,[66] N. Wermes,[22] M. Wetstein,[62] A. White,[79] D. Wicke,[26] G.W. Wilson,[59] S.J. Wimpenny,[49] M. Wobisch,[51] J. Womersley,[51] D.R. Wood,[64] T.R. Wyatt,[45] Y. Xie,[78] N. Xuan,[56] S. Yacoob,[54] R. Yamada,[51] M. Yan,[62] T. Yasuda,[51] Y.A. Yatsunenko,[36] K. Yip,[74] H.D. Yoo,[78] S.W. Youn,[54] C. Yu,[14] J. Yu,[79] A. Yurkewicz,[73] A. Zatserklyaniy,[53] C. Zeitnitz,[26] D. Zhang,[51] T. Zhao,[83] Z. Zhao,[65] B. Zhou,[65] J. Zhu,[73] M. Zielinski,[72] D. Zieminska,[55] A. Zieminski,[55] V. Zutshi,[53] and E.G. Zverev[38]

(DØ 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] *Institute of High Energy Physics, Beijing, People's Republic of China*
[7] *University of Science and Technology of China, Hefei, People's Republic of China*
[8] *Universidad de los Andes, Bogotá, Colombia*
[9] *Center for Particle Physics, Charles University, Prague, Czech Republic*
[10] *Czech Technical University, Prague, Czech Republic*
[11] *Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
[12] *Universidad San Francisco de Quito, Quito, Ecuador*
[13] *Laboratoire de Physique Corpusculaire, IN2P3-CNRS, Université Blaise Pascal, Clermont-Ferrand, France*
[14] *Laboratoire de Physique Subatomique et de Cosmologie, IN2P3-CNRS, Universite de Grenoble 1, Grenoble, France*
[15] *CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France*
[16] *IN2P3-CNRS, Laboratoire de l'Accélérateur Linéaire, Orsay, France*
[17] *LPNHE, IN2P3-CNRS, Universités Paris VI and VII, Paris, France*
[18] *DAPNIA/Service de Physique des Particules, CEA, Saclay, France*
[19] *IReS, IN2P3-CNRS, Université Louis Pasteur, Strasbourg, France, and Université de Haute Alsace, Mulhouse, France*
[20] *Institut de Physique Nucléaire de Lyon, IN2P3-CNRS, Université Claude Bernard, Villeurbanne, France*
[21] *III. Physikalisches Institut A, RWTH Aachen, Aachen, Germany*
[22] *Physikalisches Institut, Universität Bonn, Bonn, Germany*
[23] *Physikalisches Institut, Universität Freiburg, Freiburg, Germany*
[24] *Institut für Physik, Universität Mainz, Mainz, Germany*
[25] *Ludwig-Maximilians-Universität München, München, Germany*
[26] *Fachbereich Physik, University of Wuppertal, Wuppertal, Germany*
[27] *Panjab University, Chandigarh, India*

[28] Delhi University, Delhi, India
[29] Tata Institute of Fundamental Research, Mumbai, India
[30] University College Dublin, Dublin, Ireland
[31] Korea Detector Laboratory, Korea University, Seoul, Korea
[32] SungKyunKwan University, Suwon, Korea
[33] CINVESTAV, Mexico City, Mexico
[34] FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands
[35] Radboud 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] Physik Institut der Universität Zürich, Zürich, Switzerland
[43] Lancaster University, Lancaster, United Kingdom
[44] Imperial College, London, United Kingdom
[45] University of Manchester, Manchester, United Kingdom
[46] University of Arizona, Tucson, Arizona 85721, USA
[47] Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
[48] California State University, Fresno, California 93740, USA
[49] University of California, Riverside, California 92521, USA
[50] Florida State University, Tallahassee, Florida 32306, USA
[51] Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
[52] University of Illinois at Chicago, Chicago, Illinois 60607, USA
[53] Northern Illinois University, DeKalb, Illinois 60115, USA
[54] Northwestern University, Evanston, Illinois 60208, USA
[55] Indiana University, Bloomington, Indiana 47405, USA
[56] University of Notre Dame, Notre Dame, Indiana 46556, USA
[57] Purdue University Calumet, Hammond, Indiana 46323, USA
[58] Iowa State University, Ames, Iowa 50011, USA
[59] University of Kansas, Lawrence, Kansas 66045, USA
[60] Kansas State University, Manhattan, Kansas 66506, USA
[61] Louisiana Tech University, Ruston, Louisiana 71272, USA
[62] University of Maryland, College Park, Maryland 20742, USA
[63] Boston University, Boston, Massachusetts 02215, USA
[64] Northeastern University, Boston, Massachusetts 02115, USA
[65] University of Michigan, Ann Arbor, Michigan 48109, USA
[66] Michigan State University, East Lansing, Michigan 48824, USA
[67] University of Mississippi, University, Mississippi 38677, USA
[68] University of Nebraska, Lincoln, Nebraska 68588, USA
[69] Princeton University, Princeton, New Jersey 08544, USA
[70] State University of New York, Buffalo, New York 14260, USA
[71] Columbia University, New York, New York 10027, USA
[72] University of Rochester, Rochester, New York 14627, USA
[73] State University of New York, Stony Brook, New York 11794, USA
[74] Brookhaven National Laboratory, Upton, New York 11973, USA
[75] Langston University, Langston, Oklahoma 73050, USA
[76] University of Oklahoma, Norman, Oklahoma 73019, USA
[77] Oklahoma State University, Stillwater, Oklahoma 74078, USA
[78] Brown University, Providence, Rhode Island 02912, USA
[79] University of Texas, Arlington, Texas 76019, USA
[80] Southern Methodist University, Dallas, Texas 75275, USA
[81] Rice University, Houston, Texas 77005, USA
[82] University of Virginia, Charlottesville, Virginia 22901, USA
[83] University of Washington, Seattle, Washington 98195, USA

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We report a measurement of the B_s^0 lifetime in the semileptonic decay channel $B_s^0 \to D_s^- \mu^+ \nu X$ (and its charge conjugate), using approximately 0.4 fb^{-1} of data collected with the D0 detector during 2002–2004. We have reconstructed 5176 $D_s^- \mu^+$ signal events, where the D_s^- is identified via the decay $D_s^- \to \phi \pi^-$, followed by $\phi \to K^+ K^-$. Using these events, we have measured the B_s^0

lifetime to be $\tau(B_s^0) = 1.398 \pm 0.044$ (stat)$^{+0.028}_{-0.025}$ (syst) ps. This is the most precise measurement of the B_s^0 lifetime to date.

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Measuring the lifetimes of different b hadrons tests the mechanism of heavy hadron decay. The spectator model predicts that all hadrons with the same heavy flavor content have identical lifetimes. However, observed charmed hadron lifetimes suggest that non-spectator effects, such as interference between contributing amplitudes, are not negligible in heavy hadron decays. This suggest that a mechanism beyond the simple spectator model may be required. A theoretical model called the Heavy Quark Expansion (HQE) [1] includes such effects and predicts lifetime differences among the different bottom hadrons. The B-meson lifetimes are related to an element of the CKM matrix, V_{cb}, which is one of the fundamental parameters in the standard model.

In this Letter, we present a high-statistics measurement of the B_s^0 lifetime, using a large sample of semileptonic B_s^0 decays collected in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV with the D0 detector at the Fermilab Tevatron Collider in 2002 – 2004. The data correspond to approximately 0.4 fb^{-1} of integrated luminosity. B_s^0 mesons were identified through their semileptonic decay $B_s^0 \to D_s^- \mu^+ \nu X$ [12], where the D_s^- meson decays via $D_s^- \to \phi\pi^-$, followed by $\phi \to K^+K^-$.

The D0 detector is described in detail elsewhere [2]. The detector components most important to this analysis are the central tracking and muon systems. The D0 central-tracking system consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet, with designs optimized for tracking and vertexing at pseudorapidities $|\eta| < 3$ and $|\eta| < 2.5$, respectively (where $\eta = -\ln[\tan(\theta/2)]$). A liquid-argon and uranium calorimeter has a central section covering pseudorapidities up to ≈ 1.1, and two end calorimeters that extend the coverage to $|\eta| \approx 4.2$ all three are housed in separate cryostats [3]. The muon system is located outside the calorimeters and has pseudorapidity coverage $|\eta| < 2$. It consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroids, followed by two similar layers after the toroids [4].

Events with semileptonic B-meson decays were selected using a suite of inclusive single-muon triggers in a three-level trigger system. Off-line muons were identified by extrapolation of the muon track segments, formed by the hits in the muon system, to the tracks found in the central tracking system. Each muon was required to have a momentum greater than 3 GeV/c and a transverse momentum greater than 2 GeV/c.

The primary vertex of each $p\bar{p}$ interaction was reconstructed using selected tracks and the mean beam-spot position, which was updated every few hours. The initial primary vertex was defined by all available well-reconstructed tracks [5]. The precision of the primary vertex reconstruction was on average 20 μm in the plane perpendicular to the beam direction and about 40 μm in the beam direction.

To reconstruct $D_s^- \to \phi\pi^-$ decays, tracks with $p_T >$ 1.0 GeV/c were assigned the kaon mass and oppositely-charged pairs were combined to form a ϕ candidate. Each ϕ candidate was required to have a mass in the range 1.008 – 1.032 GeV/c^2, compatible with the reconstructed ϕ mass at D0. The ϕ candidate was then combined with another track of $p_T > 0.7$ GeV/c. For the "right-sign" combinations, we required the charge of the track to be opposite to that of the muon and assigned the pion mass to this track. The three tracks selected were combined to form a common vertex (the D_s^- vertex). To have a good vertex determination, all selected tracks were required to have at least one SMT hit and one CFT hit. The confidence level of the combined vertex fit was required to be greater that 0.1%, and the p_T of the D_s^- candidate was required to be larger than 3.5 GeV/c.

The secondary vertex, where the B_s^0 decays to a muon and a D_s^- meson, was obtained by finding the intersection of the trajectory of the muon track and the flight path of the D_s^- candidate. The confidence level of that vertex had to be greater that 0.01%. To further reduce combinatorial background, the reconstructed D_s^- decay vertex was required to be displaced from the primary vertex in the direction of the D_s^- momentum.

Since the ϕ meson has spin 1 and the D_s^- and π^- mesons are spin 0 particles, the helicity angle, Φ, defined as the angle between the directions of the K^- and D_s^- in the ϕ rest frame, has a distribution proportional to $\cos^2\Phi$. A cut of $|\cos\Phi| > 0.4$ was applied to further reduce combinatorial background, which was found to have a flat distribution. In order to suppress the physics background originating from $D^{(*)}D^{(*)}$ processes, we required that the transverse momentum of the muon with respect to the D_s^- meson, p_{Trel}, exceed 2 GeV/c. The $D_s^-\mu^+$ invariant mass was also restricted to 3.4 – 5.0 GeV/c^2, to further reduce the physics background and to be consistent with a B-meson candidate. In order to increase the significance of the B_s^0 signal, we further required that the isolation of the B be greater than 0.65, since the number of tracks near the B_s^0 candidate tends to be small. Isolation was defined as $\mathcal{I} = p^{tot}(\mu^+D_s^-)/(p^{tot}(\mu^+D_s^-) + \sum p_i^{tot})$, where the sum $\sum p_i^{tot}$ was taken over all charged particles in the cone $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.5$, with $\Delta\phi$ and $\Delta\eta$ being the azimuthal angle and the pseudorapidity with respect to the $(\mu^+D_s^-)$ direction. The muon, kaon, and pion tracks were not included in the sum.

The lifetime of the B_s^0, τ, is related to the decay length in the transverse plane, L_{xy}, by $L_{xy} = c\tau p_T/m$, where p_T is the transverse momentum of the B_s^0 and m is its invariant mass. L_{xy} is defined as the displacement of the B_s^0 vertex from the primary vertex projected onto the transverse momentum of the $D_s^-\mu^+$ system. When the B_s^0 decays semileptonically, it cannot be fully reconstructed and thus $p_T(B_s^0)$ is not determined. The p_T of the $D_s^-\mu^+$ system was used instead, as the best approximation.

A correction factor distribution, $K = p_T(D_s^-\mu^+)/p_T(B_s^0)$, was introduced to estimate the $p_T(B_s^0)$. Therefore, the quantity used to extract the B_s^0 lifetime is called the pseudo-proper decay length (PPDL). The correction factor K was determined using Monte Carlo methods. This correction was applied statistically by smearing the exponential decay distribution when extracting $c\tau(B_s^0)$ from the PPDL in the lifetime fit.

In the cases with more than one B_s^0 candidate per event, we chose the one with the highest vertex confidence level. We also required the pseudo-proper decay length uncertainty to be less than 500 microns. The resulting invariant mass distribution of the D_s^- candidates is shown in Fig. 1. The D_s^- invariant mass distribution for "right-sign" $D_s^-\mu^+$ candidates was fitted using a Gaussian, to describe the signal, and a second-order polynomial, to describe the combinatorial background. A second Gaussian was included for the Cabibbo-suppressed $D^- \to \phi\pi^-$ decay. The best fit result is shown in the same figure. The fit yields a signal of 5176 ± 242 (stat) $\pm$ 314 (syst) D_s^- candidates and a mass of 1958.8 ± 0.9 MeV/c^2, slightly shifted from the PDG value of 1968.3 ± 0.5 MeV/c^2 [6]. The width of the D_s^- Gaussian is 22.6 ± 1.0 MeV/c^2. The systematic uncertainty comes from the fit. For the D^- meson, the fit yields 1551 events. Figure 1 also shows the invariant mass distribution of the "wrong-sign" candidates.

Monte Carlo (MC) samples were generated using PYTHIA [7] for the production and hadronization phase, and EvtGen [8] for decaying the b and c hadrons. Detector acceptance and smearing were taken into account using the full D0 detector simulation based on the GEANT package [9]. Generated Monte Carlo signal samples include contributions from $D_s^-\mu^+\nu$, $D_s^{*-}\mu^+\nu$, $D_{s0}^{*-}\mu^+\nu$, $D_{s1}^{'-}\mu^+\nu$, and $D_s^{(*)-}\tau^+\nu$.

Apart from the background due to combinatorial processes such as a prompt muon and an identified D_s^- meson, there could be real physics processes that produce a muon and a D_s^- meson, where neither comes from the semileptonic decay of the B_s^0 meson. These "right-sign" $D_s^-\mu^+$ combinations are included in the signal sample and are defined as "physics backgrounds." These events can come from several sources. Prompt D_s^- mesons from $c\bar{c}$ production at the interaction point can combine with high-p_T muons generated either via direct production or

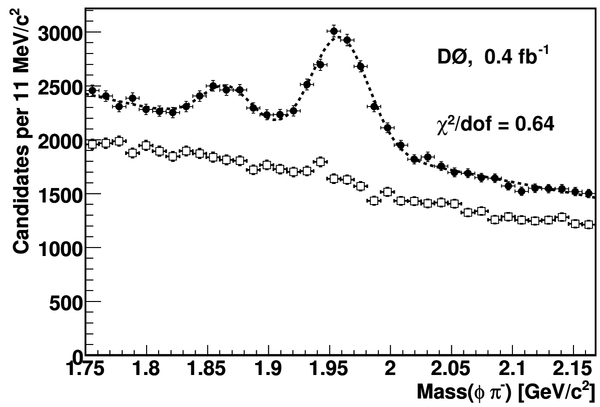

FIG. 1: The mass distribution of $\phi\pi^-$ candidates. Points with errors bars show the "right-sign" $D_s^-\mu^+$ combinations, and the open squares show the corresponding "wrong-sign" distribution. The dashed curve represents the result of the fit to the "right-sign" combinations. The two peaks are associated with the D^- and D_s^- mesons, respectively.

in charm decays. These $c\bar{c}$ background events are expected to have very short lifetimes and thus could introduce a significant bias in the B_s^0 lifetime measurement. Backgrounds that originate from $\bar{B}$ mesons and provide the $D_s^-\mu^+$ final state, but not via the semileptonic decay $B_s^0 \to D_s^-\mu^+\nu X$, are called non-$B_s^0$ backgrounds. This kind of background is expected to have a relatively long lifetime, thus its effect on the B_s^0 lifetime fit is smaller than that of the charm background. There are three sources of such events: $\bar{B}^0 \to D_s^{(*)-}D^{(*)+}X$, $B^- \to D_s^{(*)-}\bar{D}^{(*)0}X$, and $\bar{B}_s^0 \to D_s^{(*)-}D^{(*)}X$. In the case of the first two processes, the $D^{(*)+}$ or the $\bar{D}^{(*)0}$ mesons decay semileptonically, while in the last process the two $D^{(*)}$ mesons, which can be a $D^{(*)+}$ or $\bar{D}^{(*)0}$ or even a $D_s^{(*)+}$, can decay semileptonically. However, the momentum of the muon coming from the decay of the $D^{(*)}$ is softer than that for the signal, since it comes from the decay of a secondary charm hadron. This implies that the contribution of these modes to the signal sample is reduced by the kinematic cuts. The contribution of each of these processes to the B_s^0 signal was evaluated using Monte Carlo methods.

The lifetime of the B_s^0 was found using a fit to the PPDL distribution. We defined a signal sample using the D_s^- mass distribution in the region from 1913.6 MeV/c^2 to 2004.0 MeV/c^2, corresponding to $\pm 2\sigma$ from the fitted mean mass, 1958.8 MeV/c^2. The PPDL distribution of the combinatorial background events contained in the signal sample was defined using "right-sign" events from the D_s^- sidebands (1755.3 – 1800.5 MeV/c^2 and 2117.1 – 2162.3 MeV/c^2) and "wrong-sign" events from the interval 1755.3 – 2162.3 MeV/c^2. The combinatorial background due to random track combinations was modeled by the sideband sample events. This assumption is supported by the mass distribution of the "wrong-sign" combinations where no enhancement is visible in the D_s^- mass region (see Fig. 1). By adding the "wrong-sign" combinations to the "right-sign" sideband events, we define the parameters of the combinatorial background events in the D_s^- signal sample more precisely.

The PPDL distribution obtained from the signal sample was fitted using an unbinned maximum log-likelihood method. Both the B_s^0 lifetime and the background shape were determined in a simultaneous fit to the signal and background samples. The likelihood function $\mathcal{L}$ is given by

$$\mathcal{L} = \mathcal{C}_{sig} \prod_i^{N_S} [f_{sig}\mathcal{F}^i_{sig} + (1 - f_{sig})\mathcal{F}^i_{bck}] \prod_j^{N_B} \mathcal{F}^j_{bck},$$

where N_S, N_B are the number of events in the signal and background samples and f_{sig} is the ratio of D_s^- signal events obtained from the D_s^- mass distribution fit to the total number of events in the signal sample. To constrain f_{sig}, we factored in an additional likelihood term using the number of D_s^- signal events observed from the invariant mass distribution, and its uncertainty, $\mathcal{C}_{sig}$.

The signal probability distribution function (PDF), $\mathcal{F}^i_{sig}$, comprises a normalized exponential decay function convoluted with a Gaussian resolution function. The K-factor correction was also convoluted with the exponential decay function. Since a priori, we do not know the decay length uncertainty, which we estimated on an event-by-event basis, an overall global scale factor, s, was introduced as a free parameter in the B_s^0 lifetime fit. The events from non-B_s^0 background were taken into account in the fit by including similar PDFs to those in the signal but using fixed parameters according to the world-average values [6]. The weight of each process was determined using MC methods. A different K-factor distribution was also used for each process. The $c\bar{c}$ background entered in the fit as a Gaussian with fixed parameters as determined by MC methods.

The combinatorial background sample, $\mathcal{F}^i_{bck}$, was parametrized using a Gaussian distribution function for the resolution plus several exponential decays, two for the negative values in the PPDL distribution (one short and one long component) and two for the positive values of the distribution. It was found that this model better describes such a PPDL distribution.

Figure 2 shows the PPDL distribution of the $D_s^-\mu^+$ signal sample with the fit result superimposed (dashed curve). The dotted curve represents the sum of the background probability function over the events in the signal sample. The B_s^0 signal is represented by the filled area.

To test the resolutions, pulls, fitting, and selection criteria, we performed detailed studies using MC ensembles of events similar to those in data and found no significant biases in our analysis procedure. In order to study the

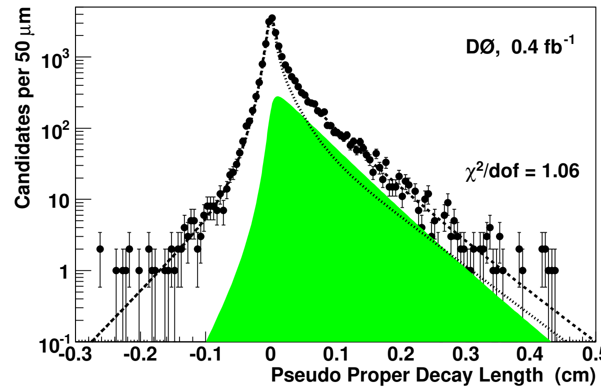

FIG. 2: Pseudo-proper decay length distribution for $D_s^-\mu^+$ candidates with the result of the fit superimposed as the dashed curve. The dotted curve represents the combinatorial background and the filled area represents the B_s^0 signal.

stability of the B_s^0 lifetime measurement, we split the data sample into two parts according to different kinematic and geometric parameters, compared the fitted results, and found the lifetimes consistent within their uncertainties. We also varied the selection criteria and mass fit ranges, and did not observe any significant shifts. We performed an extensive study of our fitting procedure, looking for any possible bias using MC ensembles with statistics of the size of our dataset and distributions as those in data. These samples were fitted, and the mean and width of the distributions of extracted parameters were found to be consistent with the fits to data. One final check of the procedure involved performing a similar lifetime fit to a control sample defined by the Cabibbo-suppressed decay $D^- \to \phi\pi^-$, which can be observed in the invariant mass distribution of Fig. 1. We found that 89.1% of the sample comes from $B^0 \to D^-\mu^+X$, and the B^0 lifetime to be 1.541 ± 0.093 ps, where the uncertainty is statistical only. This result is in good agreement with the world average B^0 lifetime [6, 10].

We considered and evaluated various sources of systematic uncertainties. The major contributions come from the determination of the combinatorial background, the model for the resolution, and the physics background. To determine the systematics due to the uncertainty on the combinatorial background, we tested other assumptions on the background samples: we used just the events in the sidebands, just the events in the wrong-sign combinations, and removed either the right sideband or the left sideband samples. We also modified the definitions of those samples, changing the mass window sizes and positions. The largest difference in $c\tau$ observed in these variations of background modeling is 4.3 μm, which was taken to be the systematic uncertainty due to this source. The effect of uncertainty in the resolution of the decay length was studied using an alternative global scale factor, s. We repeated the lifetime fit with fixed values of s obtained from MC samples and from a different lifetime analysis [11]. Using a variation of the resolution scale by a factor of two beyond these bounds, we found a 3.7 μm variation in $c\tau$. The uncertainty from the physics background was evaluated by varying the branching fractions of the different processes as well as the shapes of the lifetime templates, as given by their known lifetime values [6]. The variations were within one standard deviation. Assuming no correlation between them, we added the effects of all the variations in quadrature and found a total contribution of $^{+2.9}_{-4.2}$ μm. Using a similar procedure, we evaluated the uncertainty coming from the determination of the $c\bar{c}$ background and found a difference of $^{+2.3}_{-0.8}$ μm.

To evaluate the uncertainty associated with the K factor determination, we modified the kinematics of the event using a different decay model, a different p_T spectrum for the b quark, and a different p_T spectrum for the muon. We also varied the amount of each component of the $B_s^0 \to D_s^- \mu^+ X$ signal. In each case, the K factor was re-evaluated and the fit repeated. We added all K factor variation effects in quadrature and found a total uncertainty of $^{+3.6}_{-2.1}$ μm.

There are two requirements in our selection method that could potentially change the final result by altering the shape of the PPDL distribution: $p_{Trel} > 2$ GeV/c and the positive displacement from the primary vertex of the reconstructed D_s^- decay vertex. Using MC methods, we evaluated their effects by removing them one at a time. The largest variation observed was $^{+3.0}_{-0.3}$ μm, and the selection efficiency is flat as a function of proper decay time. The effect of a possible misalignment of the SMT system was tested in Ref. [11]. We repeated the study using Monte Carlo signal samples and observed the same shift of $c\tau = 2$ μm, which was taken as a systematic uncertainty due to possible misalignment. The total systematic uncertainty from all of these sources added in quadrature is $^{+8.4}_{-7.6}$ μm.

In summary, using an integrated luminosity of approximately 0.4 fb^{-1}, we have measured the B_s^0 lifetime in the decay channel $D_s^- \mu^+ \nu X$ under the assumption of a single-exponential decay and found it to be $\tau(B_s^0) = 1.398 \pm 0.044$ (stat) $^{+0.028}_{-0.025}$ (syst) ps. The result is in good agreement with previous experiments as well as the current world average value for all flavor-specific decays, $\tau(B_s^0) = 1.442 \pm 0.066$ ps [10]. Our B_s^0 lifetime measurement is the most precise to date and exceeds the precision of the current world average measurement $\tau(B_s^0)_{PDG} = 1.461 \pm 0.057$ ps [6], where semileptonic and hadronic decays were combined. This measurement suggest that the B_s^0 lifetime is different from the B^0 lifetime by more than 1%, as suggested by HQE.

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[*] On leave from IEP SAS Kosice, Slovakia.
[†] Visitor from Helsinki Institute of Physics, Helsinki, Finland.

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