Study of Direct CP Violation in $B^{\pm} \to J/\psi K^{\pm}(\pi^{\pm})$ Decays

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

M. S. Rangel,[2] K. Ranjan,[28] P. N. Ratoff,[42] P. Renkel,[79] S. Reucroft,[63] P. Rich,[44] J. Rieger,[54] M. Rijssenbeek,[72] I. Ripp-Baudot,[19] F. Rizatdinova,[76] S. Robinson,[43] R. F. Rodrigues,[3] M. Rominsky,[75] C. Royon,[18] P. Rubinov,[50] R. Ruchti,[55] G. Safronov,[37] G. Sajot,[14] A. Sánchez-Hernández,[33] M. P. Sanders,[17] A. Santoro,[3] G. Savage,[50] L. Sawyer,[60] T. Scanlon,[43] D. Schaile,[25] R. D. Schamberger,[72] Y. Scheglov,[40] H. Schellman,[53] T. Schliephake,[26] C. Schwanenberger,[44] A. Schwartzman,[68] R. Schwienhorst,[65] J. Sekaric,[49] H. Severini,[75] E. Shabalina,[51] M. Shamim,[59] V. Shary,[18] A. A. Shchukin,[39] R. K. Shivpuri,[28] V. Siccardi,[19] V. Simak,[10] V. Sirotenko,[50] P. Skubic,[75] P. Slattery,[71] D. Smirnov,[55] G. R. Snow,[67] J. Snow,[74] S. Snyder,[73] S. Söldner-Rembold,[44] L. Sonnenschein,[17] A. Sopczak,[42] M. Sosebee,[78] K. Soustruznik,[9] B. Spurlock,[78] J. Stark,[14] J. Steele,[60] V. Stolin,[37] D. A. Stoyanova,[39] J. Strandberg,[64] S. Strandberg,[41] M. A. Strang,[69] E. Strauss,[72] M. Strauss,[75] R. Ströhmer,[25] D. Strom,[53] L. Stutte,[50] S. Sumowidagdo,[49] P. Svoisky,[55] A. Sznajder,[3] P. Tamburello,[45] A. Tanasijczuk,[1] W. Taylor,[6] J. Temple,[45] B. Tiller,[25] F. Tissandier,[13] M. Titov,[18] V. V. Tokmenin,[36] T. Toole,[61] I. Torchiani,[23] T. Trefzger,[24] D. Tsybychev,[72] B. Tuchming,[18] C. Tully,[68] P. M. Tuts,[70] R. Unalan,[65] L. Uvarov,[40] S. Uvarov,[40] S. Uzunyan,[52] B. Vachon,[6] P. J. van den Berg,[34] R. Van Kooten,[54] W. M. van Leeuwen,[34] N. Varelas,[51] E. W. Varnes,[45] I. A. Vasilyev,[39] M. Vaupel,[26] P. Verdier,[20] L. S. Vertogradov,[36] M. Verzocchi,[50] F. Villeneuve-Seguier,[43] P. Vint,[43] P. Vokac,[10] E. Von Toerne,[59] M. Voutilainen,[68,‖] R. Wagner,[68] H. D. Wahl,[49] L. Wang,[61] M. H. L. S. Wang,[50] J. Warchol,[55] G. Watts,[82] M. Wayne,[55] G. Weber,[24] M. Weber,[50] L. Welty-Rieger,[54] A. Wenger,[23,¶] N. Wermes,[22] M. Wetstein,[61] A. White,[78] D. Wicke,[26] M. Williams,[42] G. W. Wilson,[58] S. J. Wimpenny,[48] M. Wobisch,[60] D. R. Wood,[63] T. R. Wyatt,[44] Y. Xie,[77] S. Yacoob,[53] R. Yamada,[50] M. Yan,[61] T. Yasuda,[50] Y. A. Yatsunenko,[36] K. Yip,[73] H. D. Yoo,[77] S. W. Youn,[53] J. Yu,[78] A. Zatserklyaniy,[52] C. Zeitnitz,[26] T. Zhao,[82] B. Zhou,[64] J. Zhu,[72] M. Zielinski,[71] D. Zieminska,[54] A. Zieminski,[54,**] L. Zivkovic,[70] V. Zutshi,[52] and E. G. Zverev[38]

(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]*Universidade Federal do ABC, Santo André, Brazil*
[5]*Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil*
[6]*University of Alberta, Edmonton, Alberta, Canada, Simon Fraser University, Burnaby, British Columbia, Canada, York University, Toronto, Ontario, Canada, and McGill University, Montreal, Quebec, Canada*
[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]*LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France*
[14]*LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, France*
[15]*CPPM, IN2P3/CNRS, Université de la Méditerranée, Marseille, France*
[16]*LAL, Université Paris-Sud, IN2P3/CNRS, Orsay, France*
[17]*LPNHE, IN2P3/CNRS, Universités Paris VI and VII, Paris, France*
[18]*DAPNIA/Service de Physique des Particules, CEA, Saclay, France*
[19]*IPHC, Université Louis Pasteur et Université de Haute Alsace, CNRS/IN2P3, Strasbourg, France*
[20]*IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, 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]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
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We present a search for direct CP violation in $B^{\pm} \to J/\psi K^{\pm}(\pi^{\pm})$ decays. The event sample is selected from 2.8 fb^{-1} of $p\bar{p}$ collisions recorded by D0 experiment in run II of the Fermilab Tevatron Collider. The charge asymmetry $A_{CP}(B^+ \to J/\psi K^+) = +0.0075 \pm 0.0061(\mathrm{stat}) \pm 0.0030(\mathrm{syst})$ is obtained using a sample of approximately 40 000 $B^{\pm} \to J/\psi K^{\pm}$ decays. The achieved precision is of the same level as the expected deviation predicted by some extensions of the standard model. We also measured the charge asymmetry $A_{CP}(B^+ \to J/\psi \pi^+) = -0.09 \pm 0.08(\mathrm{stat}) \pm 0.03(\mathrm{syst})$.

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This Letter presents a study of the charge asymmetry in the decay $B^{\pm} \rightarrow J/\psi K^{\pm}(\pi^{\pm})$, which is defined as

$$A_{CP}(B^{+} \rightarrow J/\psi K^{+}(\pi^{+})) = \frac{N(B^{-} \rightarrow J/\psi K^{-}(\pi^{-})) - N(B^{+} \rightarrow J/\psi K^{+}(\pi^{+}))}{N(B^{-} \rightarrow J/\psi K^{-}(\pi^{-})) + N(B^{+} \rightarrow J/\psi K^{+}(\pi^{+}))}.$$

A nonzero value of $A_{CP}(B^{+} \rightarrow J/\psi K^{+}(\pi^{+}))$ corresponds to direct CP violation in this decay. In the $b \rightarrow sc\bar{c}$ transition (charge conjugate states are assumed throughout), the tree-level and $b \rightarrow s$ penguin amplitudes have a small relative weak phase, $\arg[-V_{cs}V_{cb}^{*}/V_{ts}V_{tb}^{*}]$. Therefore, the standard model predicts a small $A_{CP}(B^{+} \rightarrow J/\psi K^{+}) \sim 0.003$ [1]. Thus, the measurement of $A_{CP}(B^{+} \rightarrow J/\psi K^{+})$ is an important way of constraining those new physics models which predict an enhanced value of this asymmetry [1–3].

In $b \rightarrow dc\bar{c}$ transitions, on the contrary, the relative phase between the tree-level and $b \rightarrow d$ penguin amplitudes, $\arg[-V_{cd}V_{cb}^{*}/V_{td}V_{tb}^{*}]$, is expected to be significant so that direct CP violation may be of the order of 1% [4,5]. Decays governed by the $b \rightarrow dc\bar{c}$ transition have already been explored by the Belle Collaboration [6] and the *BABAR* Collaboration [7]. Here, we report a complementary measurement of the direct CP-violation asymmetry in the $b \rightarrow dc\bar{c}$ transition using the decay $B^{+} \rightarrow J/\psi \pi^{+}$.

The D0 detector is described in detail elsewhere [8]. The polarities of its solenoidal [8] and toroidal [9] magnets are reversed regularly during data taking, so that the four solenoid-toroid polarity combinations are exposed to approximately the same integrated luminosity. The reversal of magnet polarities helps to reduce the detector-related systematic effects in asymmetry measurements and is fully exploited in this study.

The decay $B^{+} \rightarrow J/\psi K^{+}(\pi^{+})$ with $J/\psi \rightarrow \mu^{+}\mu^{-}$ is selected from 2.8 fb^{-1} recorded by D0. Each muon is required to be identified by the muon system, to have an associated track in the central tracking system with at least two measurements in the silicon microstrip tracker, and a transverse momentum $p_T^{\mu} > 1.5$ GeV$/c$ with respect to the beam axis. At least one of the two muons is required to have matching track segments both inside and outside the toroidal magnet. The dimuon system must have a reconstructed invariant mass between 2.80 and 3.35 GeV$/c^2$. An additional charged particle with $p_T > 0.5$ GeV$/c$, total momentum above 0.7 GeV$/c$, and at least two measurements in the silicon microstrip tracker, is selected. This particle is assigned the kaon mass and is required to have a common vertex with the two muons, with the χ^2 of the vertex fit being less than 16 for 3 degrees of freedom. The displacement of this vertex from the primary interaction point is required to exceed 3 standard deviations in the plane perpendicular to the beam direction. The primary vertex of the $p\bar{p}$ interaction is determined for each event using the method described in [10]. The average position of the beam-collision point is included as a constraint.

From each set of three particles fulfilling these requirements, a B^{+} candidate is constructed. The momenta of the muons are corrected using the J/ψ mass constraint. To further improve the B^{+} selection, a likelihood ratio method [11] is applied. The details of the B^{+} selection can be found in [12]. All B^{+} candidates satisfying the selection criteria are used for this analysis.

The resulting invariant mass distribution of the $J/\psi K$ system is shown in Fig. 1 with the result of an unbinned likelihood fit to the sum of contributions from $B \rightarrow J/\psi K$, $B \rightarrow J/\psi \pi$, and $B \rightarrow J/\psi K^{*}$ decays, as well as combinatorial background (BKG). The mass distribution of the $J/\psi K$ system from the $B \rightarrow J/\psi K$ hypothesis is parametrized by a Gaussian function with the width depending on the momentum of the K candidate. The parameters of this dependence are determined directly in the fit. The mass distribution of the $J/\psi \pi$ system from the $B \rightarrow J/\psi \pi$ hypothesis is parametrized by a Gaussian function with the same width. It is then transformed into the distribution of the $J/\psi K$ system by assigning the kaon mass to the pion. The decay $B \rightarrow J/\psi K^{*}$ with $K^{*} \rightarrow K\pi$, where the pion is not reconstructed, produces a broad $J/\psi K$ mass distribution with the threshold near $m(B) - m(\pi)$. It is parametrized using the Monte Carlo simulation. The combinatorial background is described by an exponential function. The fractions of the $J/\psi K$, $J/\psi \pi$, and $J/\psi K^{*}$ signal depend on the kaon momentum. The Monte Carlo simulation shows that this dependence can be modeled by the same polynomial function with different scaling factors for $J/\psi K$, $J/\psi \pi$, and $J/\psi K^{*}$ fractions. The coefficients of the polynomial and the scaling factors are determined from the fit. The $B \rightarrow J/\psi K$ signal contains $40\,222 \pm 242(\text{stat})$ events, while the $B \rightarrow J/\psi \pi$ signal contains $1578 \pm 119(\text{stat})$ events.

To measure the charge asymmetry A between the $J/\psi K^{-}(\pi^{-})$ and $J/\psi K^{+}(\pi^{+})$ final states, both physics

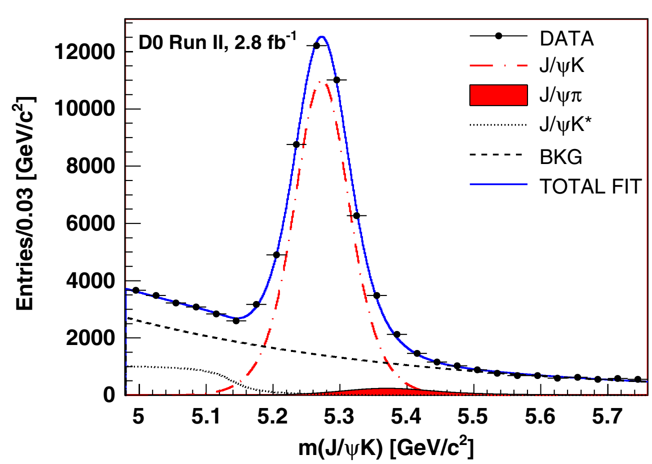

FIG. 1 (color online). The $J/\psi K$ invariant mass distribution together with the result from the unbinned likelihood fit (the undivided sample).

and detector effects contributing to the possible imbalance of events with positive and negative kaons must be taken into account. One physics source of asymmetry is direct CP violation in the $B^+ \to J/\psi K^+(\pi^+)$ decay. In addition, forward-backward charge asymmetry of events produced in the proton-antiproton collisions can also be present. Detector effects can give rise to an artificial asymmetry if, for example, the reconstruction efficiencies of positive and negative particles are different. However, a positive particle produces the same track as a negative particle in the detector with reversed magnet polarity. Therefore, essentially all detector effects can be canceled by regularly reversing the magnet polarity.

Following the method applied in [13,14], the event sample of Fig. 1 is divided into eight subsamples corresponding to all possible combinations of the solenoid polarity $\beta = \pm 1$, the sign of the pseudorapidity of the $J/\psi K$ system $\gamma = \pm 1$, and the sign of the kaon candidate charge $q = \pm 1$. In each subsample, the number $n_q^{\beta\gamma}$ of the events in the contributing channels, $J/\psi K$, $J/\psi \pi$, and $J/\psi K^*$, is obtained from the unbinned likelihood fit to the mass distribution $m(J/\psi K)$ using the same likelihood function as for the whole sample. All parameters of the fits apart from the fractions of the $J/\psi K$ signal, the $J/\psi \pi$ signal, and the $J/\psi K^*$ signal are fixed to the values determined from the fit to the whole sample.

The number of events in the $J/\psi K$ and $J/\psi \pi$ channels for each $\beta\gamma q$ subsample are used to disentangle the physics asymmetries and the detector effects. The $n_q^{\beta\gamma}$ can be expressed through the physics and the detector asymmetries as follows [13]:

$$n_q^{\beta\gamma} = \tfrac{1}{4} N \epsilon^\beta (1 + qA)(1 + q\gamma A_{\rm fb})(1 + \gamma A_{\rm det})(1 + q\beta\gamma A_{q\beta\gamma})(1 + q\beta A_{q\beta})(1 + \beta\gamma A_{\beta\gamma}). \quad (1)$$

Here N is the total number of signal events, ϵ^β is the fraction of integrated luminosity with solenoid polarity β ($\epsilon^+ + \epsilon^- = 1$), A is the charge asymmetry to be measured, $A_{\rm fb}$ accounts for possible forward-backward asymmetric B meson production, $A_{\rm det}$ is the detector asymmetry for kaons emitted in the forward and backward direction, $A_{q\beta\gamma}$ accounts for the change in acceptance of kaons of different sign bent by the solenoid in different directions, $A_{q\beta}$ is the detector asymmetry, which accounts for the change in the kaon reconstruction efficiency when the solenoid polarity is reversed, and $A_{\beta\gamma}$ accounts for any detector-related forward-backward asymmetries that remain after the solenoid polarity flip. We apply a χ^2 fit of Eq. (1) to the number of events in all subsamples and extract all asymmetries and the total number of events in the $J/\psi K$ and $J/\psi \pi$ channels together with the fraction of events with positive solenoid polarity ϵ^+, which is constrained to be the same for both channels. Results are presented in Table I. The charge asymmetry between $B^- \to J/\psi K^-$ and $B^+ \to J/\psi K^+$ is measured to be $A(J/\psi K) = -0.0070 \pm 0.0060$, and the charge asymmetry between $B^- \to J/\psi \pi^-$ and $B^+ \to J/\psi \pi^+$ is found to be $A(J/\psi \pi) = -0.09 \pm 0.08$. The detector asymmetries are all consistent with zero, since the acceptance of the charged particles of different sign inside the solenoid is the same. However, we measure these asymmetries directly and do not rely on assumptions. The forward-backward asymmetry is also consistent with zero, as expected in the standard model. As a result of the fit, the measured asymmetries show different degree of correlation, with the largest correlation, 0.83, being obtained between A and $A_{q\beta}$. The presence of correlations between the asymmetries is directly reflected in the statistical uncertainties of the measurement.

TABLE I. Physics and detector asymmetries for $J/\psi K$ and $J/\psi \pi$ channels. ϵ^+ is constrained to be the same for both channels.

	$J/\psi K$	$J/\psi \pi$
N	40 217 + 243	1577 + 118
ϵ^+	0.5060 ± 0.0030	
A	−0.0070 + 0.0060	−0.09 + 0.08
$A_{\rm fb}$	0.0013 + 0.0060	0.04 + 0.09
$A_{\rm det}$	−0.0033 + 0.0060	0.21 + 0.08
$A_{q\beta\gamma}$	−0.0050 + 0.0060	−0.02 + 0.09
$A_{q\beta}$	0.0001 + 0.0060	−0.19 + 0.08
$A_{\beta\gamma}$	−0.0030 + 0.0060	0.05 + 0.08

In addition to the detector effects, the charge asymmetry $A(B \to J/\psi K)$ is affected by the difference in the interaction cross section of K^+ and K^- with the detector material [15], which is due to the fact that the reaction $K^- N \to Y\pi$ (where Y are hyperons Λ, Σ, etc.) has no $K^+ N$ analog. The difference in the interaction cross section results in a lower reconstruction efficiency of K^- and a negative kaon charge asymmetry $A_K = [N(K^-) - N(K^+)]/[N(K^-) + N(K^+)]$, which shifts the $A(J/\psi K)$ asymmetry. The kaon asymmetry is measured directly in data by comparing the exclusive decay $c \to D^{*+} \to D^0 \pi^+$, $D^0 \to \mu^+ \nu_\mu K^-$ and its charge conjugate. It is expected from theory that there is no CP violation in the semileptonic D^0 decays [16]. The possible CP-violating effects in $B \to D^{*\pm} X$ decays are estimated to give a negligible contribution. Therefore, the observed asymmetry is only due to kaon reconstruction. The decay of D^* produces a clear peak in the mass difference, $\Delta m = m(\mu K \pi) - m(\mu K)$. Its width depends on the mass $m(\mu K)$. An example of the Δm distribution for $1.6 < m(\mu K) < 1.7$ GeV$/c^2$ is shown in Fig. 2. The combinatorial background under the peak is determined using events where all three particles (muon, kaon, and pion) have the same charge. It is rescaled to match the number of signal events in the Δm region outside the D^* peak and subtracted from the total number of events in the mass band under the D^* peak. The width of this band is varied depending on the mass of the μK system to ensure maximal signal significance.

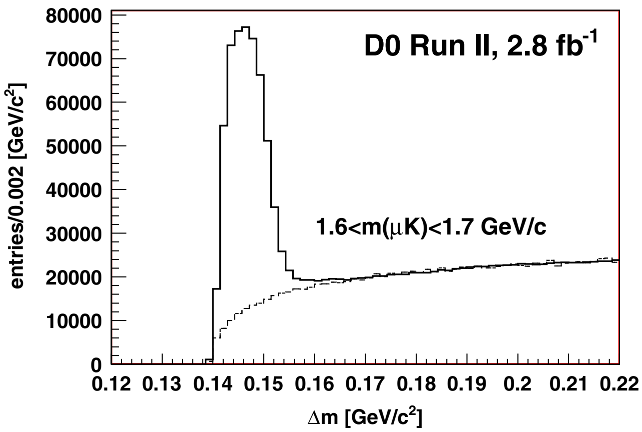

FIG. 2 (color online). The Δm distribution (solid line) for $1.6 < m(\mu K) < 1.7\ \text{GeV}/c^2$. The background distribution of events with wrong charge correlation of a muon and a kaon (dashed line) is also shown. It is rescaled to match the number of signal events for $0.19 < \Delta m < 0.22\ \text{GeV}/c^2$.

The detector charge asymmetries are disentangled from the kaon asymmetry using the same detector model of Eq. (1). To account for the momentum dependence of the kaon cross section [15], the kaon asymmetry is measured in different bins of kaon momentum p_K, as shown in Fig. 3. The obtained asymmetry is convoluted with the kaon momentum distribution in the $B \to J/\psi K$ decay giving the kaon asymmetry in the $B \to J/\psi K$ decay $A_K = -0.0145 \pm 0.0010$. Finally, we obtain $A_{CP}(B^+ \to J/\psi K^+) = A(J/\psi K) - A_K = +0.0075 \pm 0.0061(\text{stat})$.

The systematic uncertainty of $A_{CP}(B^+ \to J/\psi K^+)$ is estimated as follows. The systematic uncertainty from the unbinned fit of the $J/\psi K$ invariant mass distribution is estimated by varying the parameters fixed during the fit in the $\beta\gamma q$ subsamples by $\pm 1\sigma$, and is found to be 0.0002. The systematic uncertainty from the choice of the fitting range is found to be 0.0004. The shape of the $J/\psi K^*$ contribution to the likelihood function is parametrized using the Monte Carlo simulation, and therefore produces an uncertainty in the number of signal events. We repeat the fit with different models of $J/\psi K^*$ contribution, including a model without any such contribution. The maximal deviation in the resulting asymmetry is found to be 0.0025, which is taken as the systematic uncertainty from this source.

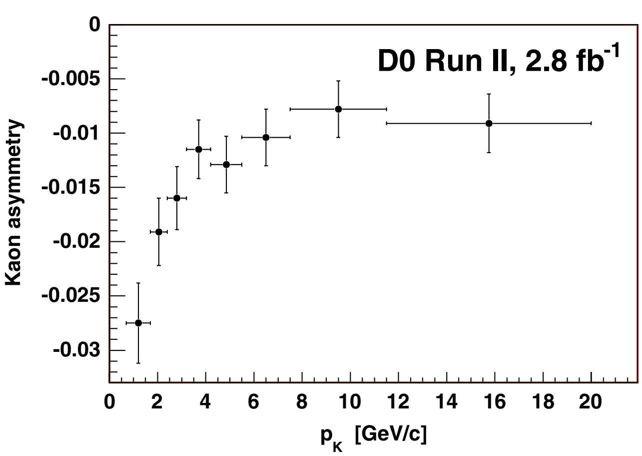

FIG. 3 (color online). Dependence of the kaon asymmetry, $A_K = [N(K^-) - N(K^+)]/[N(K^-) + N(K^+)]$, on the kaon momentum p_K in eight bins of approximately equal statistics. Errors are statistical.

To measure the kaon asymmetry in the detector, we subtract the combinatorial background under the D^* peak (see Fig. 2, dashed line). To estimate the uncertainty from the background definition, we select the background from the events with the pion charge opposite to that of the muon and the kaon, and recalculate the kaon asymmetry. The resulting deviation in $A_{CP}(B^+ \to J/\psi K^+)$ is 0.0008. Also, the sample used to measure the kaon asymmetry contains a contribution of D^0 semileptonic decays without a charged kaon in the final state. They are taken into account assuming the same selection efficiency as the dominant $D^0 \to \mu\nu K$ decay. To find the impact of this assumption on the result, we repeat the measurement of the kaon asymmetry assuming a zero reconstruction efficiency for additional D^0 decay modes. The resulting deviation in $A_{CP}(B^+ \to J/\psi K^+)$ is 0.0005. To estimate the systematic uncertainty from the choice of p_K bins (see Fig. 3), we repeat the convolution with coarser binning. The resulting deviation in $A_{CP}(B^+ \to J/\psi K^+)$ is 0.0014. After adding all contributions in quadrature, the total systematic uncertainty on $A_{CP}(B^+ \to J/\psi K^+)$ is 0.0030, which is dominated by the uncertainty from the $J/\psi K^*$ modeling.

The systematic uncertainty of $A_{CP}(B^+ \to J/\psi \pi^+)$ is estimated similarly to that of $A_{CP}(B^+ \to J/\psi K^+)$. The only sizable contributions are 0.01 from the variation of the fitting range and 0.02 from the $J/\psi K^*$ modeling. The total systematic uncertainty is 0.03.

In conclusion, the direct CP-violating asymmetry in the $B^+ \to J/\psi K^+$ decay is measured to be $A_{CP}(B^+ \to J/\psi K^+) = +0.0075 \pm 0.0061(\text{stat}) \pm 0.0030(\text{syst})$, which is consistent with other measurements [17–19], as well as with the world average, $A_{CP}(B^+ \to J/\psi K^+) = +0.015 \pm 0.017$ [15], but has a factor of 2 improvement in precision, thus providing the most stringent bounds for new models predicting large values of $A_{CP}(B^+ \to J/\psi K^+)$. The direct CP-violating asymmetry in the $B^+ \to J/\psi \pi^+$ decay is measured to be $A_{CP}(B^+ \to J/\psi \pi^+) = -0.09 \pm 0.08(\text{stat}) \pm 0.03(\text{syst})$. Our result agrees with the previous measurements of this asymmetry [18,20] and has a competitive precision.

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*Visitor from: Augustana College, Sioux Falls, SD, USA.
†Visitor from: The University of Liverpool, Liverpool, UK.
‡Visitor from: ICN-UNAM, Mexico City, Mexico.
§Visitor from: II. Physikalisches Institut, Georg-August-University, Göttingen, Germany.
‖Visitor from: Helsinki Institute of Physics, Helsinki, Finland.
¶Visitor from: Universität Zürich, Zürich, Switzerland.
**Deceased.

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