Measurement of the Direct *CP*-violating Charge Asymmetry in $D_s^{\pm} \to \phi\pi^{\pm}$ Decays

V. M. Abazov,[31] B. Abbott,[66] B. S. Acharya,[25] M. Adams,[45] T. Adams,[43] J. P. Agnew,[40] G. D. Alexeev,[31] G. Alkhazov,[35] A. Alton,[55,a] A. Askew,[43] S. Atkins,[53] K. Augsten,[7] C. Avila,[5] F. Badaud,[10] L. Bagby,[44] B. Baldin,[44] D. V. Bandurin,[43] S. Banerjee,[25] E. Barberis,[54] P. Baringer,[52] J. F. Bartlett,[44] U. Bassler,[15] V. Bazterra,[45] A. Bean,[52] M. Begalli,[2] L. Bellantoni,[44] S. B. Beri,[23] G. Bernardi,[14] R. Bernhard,[19] I. Bertram,[38] M. Besançon,[15] R. Beuselinck,[39] P. C. Bhat,[44] S. Bhatia,[57] V. Bhatnagar,[23] G. Blazey,[46] S. Blessing,[43] K. Bloom,[58] A. Boehnlein,[44] D. Boline,[63] E. E. Boos,[33] G. Borissov,[38] A. Brandt,[69] O. Brandt,[20] R. Brock,[56] A. Bross,[44] D. Brown,[14] X. B. Bu,[44] M. Buehler,[44] V. Buescher,[21] V. Bunichev,[33] S. Burdin,[38,b] C. P. Buszello,[37] E. Camacho-Pérez,[28] B. C. K. Casey,[44] H. Castilla-Valdez,[28] S. Caughron,[56] S. Chakrabarti,[63] K. M. Chan,[50] A. Chandra,[71] E. Chapon,[15] G. Chen,[52] S. W. Cho,[27] S. Choi,[27] B. Choudhary,[24] S. Cihangir,[44] D. Claes,[58] J. Clutter,[52] M. Cooke,[44] W. E. Cooper,[44] M. Corcoran,[71] F. Couderc,[15] M.-C. Cousinou,[12] D. Cutts,[68] A. Das,[41] G. Davies,[39] S. J. de Jong,[29,30] E. De La Cruz-Burelo,[28] F. Déliot,[15] R. Demina,[62] D. Denisov,[44] S. P. Denisov,[34] S. Desai,[44] C. Deterre,[20,c] K. DeVaughan,[58] H. T. Diehl,[44] M. Diesburg,[44] P. F. Ding,[40] A. Dominguez,[58] A. Dubey,[24] L. V. Dudko,[33] A. Duperrin,[12] S. Dutt,[23] M. Eads,[46] D. Edmunds,[56] J. Ellison,[42] V. D. Elvira,[44] Y. Enari,[14] H. Evans,[48] V. N. Evdokimov,[34] L. Feng,[46] T. Ferbel,[62] F. Fiedler,[21] F. Filthaut,[29,30] W. Fisher,[56] H. E. Fisk,[44] M. Fortner,[46] H. Fox,[38] S. Fuess,[44] P. H. Garbincius,[44] A. Garcia-Bellido,[62] J. A. García-González,[28] V. Gavrilov,[32] W. Geng,[12,56] C. E. Gerber,[45] Y. Gershtein,[59] G. Ginther,[44,62] G. Golovanov,[31] P. D. Grannis,[63] S. Greder,[16] H. Greenlee,[44] G. Grenier,[17] Ph. Gris,[10] J.-F. Grivaz,[13] A. Grohsjean,[15,c] S. Grünendahl,[44] M. W. Grünewald,[26] T. Guillemin,[13] G. Gutierrez,[44] P. Gutierrez,[66] J. Haley,[67] L. Han,[4] K. Harder,[40] A. Harel,[62] J. M. Hauptman,[51] J. Hays,[39] T. Head,[40] T. Hebbeker,[18] D. Hedin,[46] H. Hegab,[67] A. P. Heinson,[42] U. Heintz,[68] C. Hensel,[20] I. Heredia-De La Cruz,[28,d] K. Herner,[44] G. Hesketh,[40,f] M. D. Hildreth,[50] R. Hirosky,[72] T. Hoang,[43] J. D. Hobbs,[63] B. Hoeneisen,[9] J. Hogan,[71] M. Hohlfeld,[21] J. L. Holzbauer,[57] I. Howley,[69] Z. Hubacek,[7,15] V. Hynek,[7] I. Iashvili,[61] Y. Ilchenko,[70] R. Illingworth,[44] A. S. Ito,[44] S. Jabeen,[68] M. Jaffré,[13] A. Jayasinghe,[66] M. S. Jeong,[27] R. Jesik,[39] P. Jiang,[4] K. Johns,[41] E. Johnson,[56] M. Johnson,[44] A. Jonckheere,[44] P. Jonsson,[39] J. Joshi,[42] A. W. Jung,[44] A. Juste,[36] E. Kajfasz,[12] D. Karmanov,[33] I. Katsanos,[58] R. Kehoe,[70] S. Kermiche,[12] N. Khalatyan,[44] A. Khanov,[67] A. Kharchilava,[61] Y. N. Kharzheev,[31] I. Kiselevich,[32] J. M. Kohli,[23] A. V. Kozelov,[34] J. Kraus,[57] A. Kumar,[61] A. Kupco,[8] T. Kurča,[17] V. A. Kuzmin,[33] S. Lammers,[48] P. Lebrun,[17] H. S. Lee,[27] S. W. Lee,[51] W. M. Lee,[44] X. Lei,[41] J. Lellouch,[14] D. Li,[14] H. Li,[72] L. Li,[42] Q. Z. Li,[44] J. K. Lim,[27] D. Lincoln,[44] J. Linnemann,[56] V. V. Lipaev,[34] R. Lipton,[44] H. Liu,[70] Y. Liu,[4] A. Lobodenko,[35] M. Lokajicek,[8] R. Lopes de Sa,[63] R. Luna-Garcia,[28,g] A. L. Lyon,[44] A. K. A. Maciel,[1] R. Madar,[19] R. Magaña-Villalba,[28] S. Malik,[58] V. L. Malyshev,[31] J. Mansour,[20] J. Martínez-Ortega,[28] R. McCarthy,[63] C. L. McGivern,[40] M. M. Meijer,[29,30] A. Melnitchouk,[44] D. Menezes,[46] P. G. Mercadante,[3] M. Merkin,[33] A. Meyer,[18] J. Meyer,[20,i] F. Miconi,[16] N. K. Mondal,[25] M. Mulhearn,[72] E. Nagy,[12] M. Narain,[68] R. Nayyar,[41] H. A. Neal,[55] J. P. Negret,[5] P. Neustroev,[35] H. T. Nguyen,[72] T. Nunnemann,[22] J. Orduna,[71] N. Osman,[12] J. Osta,[50] A. Pal,[69] N. Parashar,[49] V. Parihar,[68] S. K. Park,[27] R. Partridge,[68,e] N. Parua,[48] A. Patwa,[64,j] B. Penning,[44] M. Perfilov,[33] Y. Peters,[20] K. Petridis,[40] G. Petrillo,[62] P. Pétroff,[13] M.-A. Pleier,[64] V. M. Podstavkov,[44] A. V. Popov,[34] M. Prewitt,[71] D. Price,[40] N. Prokopenko,[34] J. Qian,[55] A. Quadt,[20] B. Quinn,[57] P. N. Ratoff,[38] I. Razumov,[34] I. Ripp-Baudot,[16] F. Rizatdinova,[67] M. Rominsky,[44] A. Ross,[38] C. Royon,[15] P. Rubinov,[44] R. Ruchti,[50] G. Sajot,[11] A. Sánchez-Hernández,[28] M. P. Sanders,[22] A. S. Santos,[1,h] G. Savage,[44] L. Sawyer,[53] T. Scanlon,[39] R. D. Schamberger,[63] Y. Scheglov,[35] H. Schellman,[47] C. Schwanenberger,[40] R. Schwienhorst,[56] J. Sekaric,[52] H. Severini,[66] E. Shabalina,[20] V. Shary,[15] S. Shaw,[56] A. A. Shchukin,[34] V. Simak,[7] P. Skubic,[66] P. Slattery,[62] D. Smirnov,[50] G. R. Snow,[58] J. Snow,[65] S. Snyder,[64] S. Söldner-Rembold,[40] L. Sonnenschein,[18] K. Soustruznik,[6] J. Stark,[11] D. A. Stoyanova,[34] M. Strauss,[66] L. Suter,[40] P. Svoisky,[66] M. Titov,[15] V. V. Tokmenin,[31] Y.-T. Tsai,[62] D. Tsybychev,[63] B. Tuchming,[15] C. Tully,[60] L. Uvarov,[35] S. Uvarov,[35] S. Uzunyan,[46] R. Van Kooten,[48] W. M. van Leeuwen,[29] N. Varelas,[45] E. W. Varnes,[41] I. A. Vasilyev,[34] A. Y. Verkheev,[31] L. S. Vertogradov,[31] M. Verzocchi,[44] M. Vesterinen,[40] D. Vilanova,[15] P. Vokac,[7] H. D. Wahl,[43] M. H. L. S. Wang,[44] J. Warchol,[50] G. Watts,[73] M. Wayne,[50] J. Weichert,[21] L. Welty-Rieger,[47] M. R. J. Williams,[48] G. W. Wilson,[52] M. Wobisch,[53] D. R. Wood,[54] T. R. Wyatt,[40] Y. Xie,[44] R. Yamada,[44] S. Yang,[4] T. Yasuda,[44] Y. A. Yatsunenko,[31] W. Ye,[63] Z. Ye,[44] H. Yin,[44] K. Yip,[64] S. W. Youn,[44] J. M. Yu,[55] J. Zennamo,[61] T. G. Zhao,[40] B. Zhou,[55] J. Zhu,[55] M. Zielinski,[62] D. Zieminska,[48] and L. Zivkovic[14]

(D0 Collaboration)

[1]LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
[2]Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
[3]Universidade Federal do ABC, Santo André, Brazil
[4]University of Science and Technology of China, Hefei, People's Republic of China
[5]Universidad de los Andes, Bogotá, Colombia
[6]Faculty of Mathematics and Physics, Center for Particle Physics, Charles University, Prague, Czech Republic
[7]Czech Technical University in Prague, Prague, Czech Republic
[8]Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
[9]Universidad San Francisco de Quito, Quito, Ecuador
[10]LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
[11]LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
[12]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
[13]LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
[14]LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France
[15]CEA, Irfu, SPP, Saclay, France
[16]IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
[17]IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
[18]III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
[19]Physikalisches Institut, Universität Freiburg, Freiburg, Germany
[20]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
[21]Institut für Physik, Universität Mainz, Mainz, Germany
[22]Ludwig-Maximilians-Universität München, München, Germany
[23]Panjab University, Chandigarh, India
[24]Delhi University, Delhi, India
[25]Tata Institute of Fundamental Research, Mumbai, India
[26]University College Dublin, Dublin, Ireland
[27]Korea Detector Laboratory, Korea University, Seoul, Korea
[28]CINVESTAV, Mexico City, Mexico
[29]Nikhef, Science Park, Amsterdam, The Netherlands
[30]Radboud University Nijmegen, Nijmegen, The Netherlands
[31]Joint Institute for Nuclear Research, Dubna, Russia
[32]Institute for Theoretical and Experimental Physics, Moscow, Russia
[33]Moscow State University, Moscow, Russia
[34]Institute for High Energy Physics, Protvino, Russia
[35]Petersburg Nuclear Physics Institute, Saint Petersburg, Russia
[36]Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d'Altes Energies (IFAE), Barcelona, Spain
[37]Uppsala University, Uppsala, Sweden
[38]Lancaster University, Lancaster LA1 4YB, United Kingdom
[39]Imperial College London, London SW7 2AZ, United Kingdom
[40]The University of Manchester, Manchester M13 9PL, United Kingdom
[41]University of Arizona, Tucson, Arizona 85721, USA
[42]University of California Riverside, Riverside, California 92521, USA
[43]Florida State University, Tallahassee, Florida 32306, USA
[44]Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
[45]University of Illinois at Chicago, Chicago, Illinois 60607, USA
[46]Northern Illinois University, DeKalb, Illinois 60115, USA
[47]Northwestern University, Evanston, Illinois 60208, USA
[48]Indiana University, Bloomington, Indiana 47405, USA
[49]Purdue University Calumet, Hammond, Indiana 46323, USA
[50]University of Notre Dame, Notre Dame, Indiana 46556, USA
[51]Iowa State University, Ames, Iowa 50011, USA
[52]University of Kansas, Lawrence, Kansas 66045, USA
[53]Louisiana Tech University, Ruston, Louisiana 71272, USA
[54]Northeastern University, Boston, Massachusetts 02115, USA
[55]University of Michigan, Ann Arbor, Michigan 48109, USA
[56]Michigan State University, East Lansing, Michigan 48824, USA
[57]University of Mississippi, University, Mississippi 38677, USA
[58]University of Nebraska, Lincoln, Nebraska 68588, USA

[59]*Rutgers University, Piscataway, New Jersey 08855, USA*
[60]*Princeton University, Princeton, New Jersey 08544, USA*
[61]*State University of New York, Buffalo, New York 14260, USA*
[62]*University of Rochester, Rochester, New York 14627, USA*
[63]*State University of New York, Stony Brook, New York 11794, USA*
[64]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[65]*Langston University, Langston, Oklahoma 73050, USA*
[66]*University of Oklahoma, Norman, Oklahoma 73019, USA*
[67]*Oklahoma State University, Stillwater, Oklahoma 74078, USA*
[68]*Brown University, Providence, Rhode Island 02912, USA*
[69]*University of Texas, Arlington, Texas 76019, USA*
[70]*Southern Methodist University, Dallas, Texas 75275, USA*
[71]*Rice University, Houston, Texas 77005, USA*
[72]*University of Virginia, Charlottesville, Virginia 22904, USA*
[73]*University of Washington, Seattle, Washington 98195, USA*

We present a measurement of the direct CP-violating charge asymmetry in $D_s^+ \to \phi\pi^\pm$ decays where the ϕ meson decays to K^+K^-, using the full Run II data set with an integrated luminosity of 10.4 fb^{-1} of proton-antiproton collisions collected using the D0 detector at the Fermilab Tevatron Collider. The normalized difference A_{CP} in the yield of D_s^+ and D_s^- mesons in these decays is measured by fitting the difference between their reconstructed invariant mass distributions. This results in an asymmetry of $A_{CP} = [-0.38 \pm 0.27]\%$, which is the most precise measurement of this quantity to date. The result is consistent with the standard model prediction of zero CP asymmetry in this decay.

Direct charge-parity (CP) symmetry violation (CPV) in the Cabbibo-preferred charm decay $D_s^+ \to \phi\pi^\pm$ should be nonexistent in the standard model (SM). In the SM, direct CPV will occur if there are tree and loop (penguin) processes that can interfere with different strong and weak phases. There will be no CPV in $D_s^\pm \to \phi\pi^\pm$ decays as all of the contributing processes have the same weak phase ($V_{cs}V_{ud}$) [1]. Any CPV in this channel would indicate the existence of physics beyond the SM (for examples, see Ref. [2]). The most recent investigation of this decay by the CLEO Collaboration yields a CP-violating charge asymmetry of $A_{CP}(D_s^\pm \to \phi\pi^\pm) = [-0.5 \pm 0.8(\text{stat}) \pm 0.4(\text{syst})]\%$ [3] where the direct CPV charge asymmetry in the decay $D_s^\pm \to \phi\pi^\pm$ is defined as

$$A_{CP} = \frac{\Gamma(D_s^+ \to \phi\pi^+) - \Gamma(D_s^- \to \phi\pi^-)}{\Gamma(D_s^+ \to \phi\pi^+) + \Gamma(D_s^- \to \phi\pi^-)}. \quad (1)$$

No CPV in this decay is assumed in measurements of the time-integrated flavor-specific semileptonic charge asymmetry in the decays of oscillating neutral B_s^0 mesons using the decay $(\bar{B}_s^0) \to B_s^0 \to D_s\mu X$ by the D0 [4] and LHCb [5] Collaborations, and in the search for direct CPV in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_S^0\pi^+$ decays by the LHCb Collaboration [6]. Assuming no CPV in $D_s^\pm \to \phi\pi^\pm$ decays, the LHCb Collaboration finds that the production asymmetry of $D_s^\pm \to \phi\pi^\pm$ decays in proton-proton interactions is $A_{\text{prod}} = [\sigma(D_s^+) - \sigma(D_s^-)]/[\sigma(D_s^+) + \sigma(D_s^-)] = [-0.33 \pm 0.22(\text{stat}) \pm 0.10(\text{syst})]\%$ [7] where $\sigma(D_s^\pm)$ is the inclusive prompt production cross section. D0 is the

only experiment which can test this assumption with sufficient sensitivity in the foreseeable future since the Tevatron collides protons on antiprotons which is a CP-invariant initial state, and that the systematic uncertainties for this process are small at D0 due to the specific features of the detector.

A measure of the CPV in mixing is obtained from the average of the direct measurements of the semileptonic charge asymmetry in decays of neutral B_s^0 mesons using the decay $(\bar{B}_s^0) \to B_s^0 \to D_s\mu X$ [4,5] yielding $a_{\text{sl}}^s = [-0.50 \pm 0.52]\%$. This asymmetry can also be extracted indirectly from measurements of charge asymmetries of single muons and like-sign dimuons [8], the semileptonic charge asymmetry of neutral B_d^0 mesons [using the average at the $\Upsilon(4S)$ [9] and the D0 result [10]], and the ratio of the decay width difference and the average decay width of B_d^0, $\Delta\Gamma_d/\Gamma_d$ [9] resulting in $a_{\text{sl}}^s(\text{indirect}) = [-1.46 \pm 0.78]\%$. While the difference between these two asymmetries is not significant, CPV in $D_s^\pm \to \phi\pi^\pm$ decays could potentially explain the 3.6 standard deviation discrepancy between the SM prediction and the measured charge asymmetries of like-sign dimuons [8] given that no such discrepancy has been observed in direct measurements of semileptonic charge asymmetries.

In this Letter, the D0 Collaboration presents a measurement of A_{CP} using the full Tevatron Run II data sample with an integrated luminosity of 10.4 fb^{-1}. We assume there is negligible net production asymmetry between D_s^+ and D_s^- mesons in proton-antiproton collisions. We also assume

that any integrated production asymmetry of b hadrons that decay to $D_s^\pm$ is negligible.

This measurement of A_{CP} makes use of the methods for extracting asymmetries used in the D0 analyses of the time-integrated flavor-specific semileptonic charge asymmetry in the decays of neutral B mesons [4,10]. We measure the raw asymmetry

$$A_{D_s} = \frac{N_{D_s^+} - N_{D_s^-}}{N_{D_s^+} + N_{D_s^-}},\qquad(2)$$

where $N_{D_s^+}$ ($N_{D_s^-}$) is the number of reconstructed $D_s^+ \rightarrow \phi\pi^+$ ($D_s^- \rightarrow \phi\pi^-$) decays. The charge asymmetry in $D_s^\pm$ decays is then given by (neglecting any terms second- or higher-order in the asymmetry)

$$A_{CP} = A_{D_s} - A_{\mathrm{det}} - A_{\mathrm{phys}},\qquad(3)$$

where A_{det} is due to residual reconstruction asymmetries in the detector, and A_{phys} is the charge asymmetry resulting from the decay of b hadrons to $D_s^\pm$ mesons.

The D0 detector has a central tracking system consisting of a silicon microstrip tracker and the central fiber tracker, both located within a 2 T superconducting solenoidal magnet [11,12]. A muon system, covering $|\eta| < 2$ [13], consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T toroidal magnets, followed by two similar layers after the toroids [14].

The polarities of the toroidal and solenoidal magnetic fields are reversed on average every two weeks so that the four solenoid-toroid polarity combinations are exposed to approximately the same integrated luminosity. This allows for a cancellation of first-order effects related to instrumental charge and momentum reconstruction asymmetries. To ensure a more complete cancellation of the uncertainties, the events are weighted according to the number of $\phi\pi^\pm$ decays collected in each configuration of the magnets' polarities (polarity weighting). The weighting is based on the number of events containing $D_s^\pm$ decay products that pass the selection criteria and the likelihood selection (described below), and that are in the $\phi\pi^\pm$ invariant mass range used for the fit.

As there was no dedicated trigger for hadronic decays of heavy flavor mesons, the data were collected with a suite of single and dimuon triggers. The trigger and off-line streaming requirements bias the composition of the data. The muon requirement will preferentially select events with semileptonic decays and may enhance the contribution of events produced by the decay of b hadrons. The effect of this bias is corrected using a Monte Carlo (MC) simulation (described below).

The $D_s^\pm \rightarrow \phi\pi^\pm$; $\phi \rightarrow K^+K^-$ decay is reconstructed as follows. Since the D0 detector is unable to distinguish between charged K and π mesons, the two particles from the ϕ decay are assumed to be kaons and are required to

have $p_T > 0.7$ GeV/c, opposite charge, and a reconstructed invariant mass of $M(K^+K^-) < 1.07$ GeV/c^2. The third particle, assumed to be the charged pion, is required to have $p_T > 0.5$ GeV/c. The three particles are combined to create a common $D_s^\pm$ decay vertex using the algorithm described in Ref. [15]. The cosine of the angle between the $D_s^\pm$ momentum and the vector from the $p\bar{p}$ collisions vertex to the $D_s^\pm$ decay vertex in the transverse plane is required to be greater than 0.95. The trajectories of the $D_s^\pm$ candidate tracks are required to be consistent with originating from a common vertex and to have an invariant mass of $1.7 < M(K^+K^-\pi^\pm) < 2.3$ GeV/c^2. To reduce combinatorial background, the $D_s^\pm$ vertex is required to have a displacement from the $p\bar{p}$ collision vertex in the transverse plane with a significance of at least four standard deviations.

To improve the significance of the $D_s^\pm$ selection, we use a likelihood ratio [16] to combine several variables that discriminate between signal and the combinatoric background: the helicity angle between the $D_s^\pm$ and $K^\mp$ momenta in the center-of-mass frame of the ϕ meson; the isolation of the $D_s^\pm$ system, defined as $I = |\vec{p}(D_s^\pm)|/[|\vec{p}(D_s^\pm)| + \Sigma|\vec{p}_i|]$, where $\vec{p}(D_s^\pm)$ is the vector sum of the momenta of the three tracks that make up the $D_s^\pm$ meson and $\Sigma|\vec{p}_i|$ is the sum of momenta of all charged particles not associated with the $D_s^\pm$ meson in a cone of $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.5$ around the $D_s^\pm$ direction [13]; the χ^2 of the $D_s^\pm$ vertex fit; the invariant mass $M(K^+K^-)$; $p_T(K^+K^-)$; the cosine of the angle between the $D_s^\pm$ momentum and the vector from the $p\bar{p}$ collision vertex to the $D_s^\pm$ decay vertex, and the separation between the $K^\pm$ and $\pi^\pm$ mesons with the same charge, defined as $\sqrt{(\phi_K - \phi_\pi)^2 + (\eta_K - \eta_\pi)^2}$. The signal is modeled using a MC simulation of $D_s^\pm \rightarrow \phi\pi^\pm$ decays and the background is modeled using the data (which is dominated by background events) before applying the likelihood selection. The requirement on the likelihood ratio variable is chosen to minimize the statistical uncertainty on A_{CP} obtained using the signal extraction procedure described below.

The $M(K^+K^-\pi^\pm)$ distribution is displayed in bins of 6 MeV/c^2 over a range of $1.7 < M(K^+K^-\pi^\pm) < 2.3$ GeV/c^2, and the number of signal and background events is extracted by a χ^2 fit of an empirical model to the data (Fig. 1). The $D_s^\pm$ meson mass distribution is well modeled by two Gaussian functions constrained to have the same mean, but with different widths and normalizations. There is negligible peaking background under the $D_s^\pm$ peak. A second peak in the $M(K^+K^-\pi^\pm)$ distribution corresponding to the Cabibbo-suppressed $D^\pm \rightarrow \phi\pi^\pm$ decay is also modeled by two Gaussian functions with widths set to those of the $D_s^\pm$ meson model scaled by the ratio of the fitted $D^\pm$ and $D_s^\pm$ masses. The combinatoric background is modeled by a fifth-order polynomial function. Partially reconstructed decays such as $D_s^\pm \rightarrow \phi\pi^\pm\pi^0$ where the π^0 is not reconstructed are modeled with a threshold function
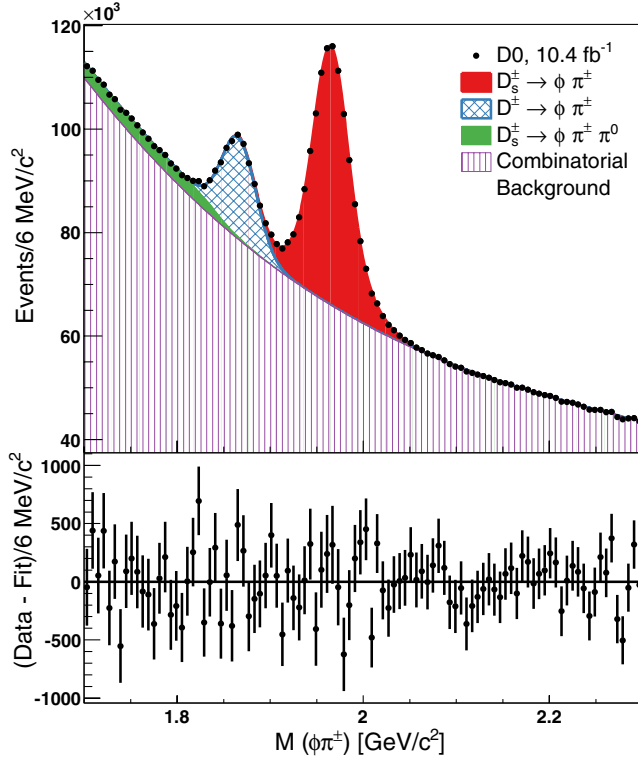
FIG. 1 (color online). The polarity-weighted $\phi\pi^{\pm}$ invariant mass distribution. The lower mass peak is due to the decay $D^{\pm} \to \phi\pi^{\pm}$ while the second peak is due to the $D_s^{\pm}$ meson decay. Note the zero suppression on the vertical axis. The bottom panel shows the fit residuals. The error bars represent the statistical uncertainties.

that extends to the $D_s^{\pm}$ mass after the π^0 mass has been subtracted, given by $T(m) = \arctan[p_1(mc^2 - p_2)] + p_3$, where p_i are fit parameters. In the fit, p_1 is fixed to the value obtained from simulation while the other parameters are allowed to vary.

The raw asymmetry [Eq. (2)] is extracted by fitting the $M(K^+K^-\pi^{\pm})$ distribution of the $D_s^{\pm}$ candidates using a χ^2 minimization. The fit is performed simultaneously, using the same models, on the sum (Fig. 1) and the difference (Fig. 2) of the $M(K^+K^-\pi^+)$ distribution for the D_s^+ candidates and the $M(K^+K^-\pi^-)$ distribution for the D_s^- candidates. The functions used to model the two distributions are

$$W_{\text{sum}} = W_{D_s} + W_D + W_{\text{comb}} + W_{\text{part}}, \quad (4)$$

$$W_{\text{diff}} = A_{D_s}W_{D_s} + A_D W_D + A_{\text{comb}}W_{\text{comb}} + A_{\text{part}}W_{\text{part}}, \quad (5)$$

where W_{D_s}, W_D, W_{comb}, and W_{part} describe the $D_s^{\pm}$ and $D^{\pm}$ mass peaks, the combinatorial background, and the partially reconstructed events, respectively. The asymmetry of the $D^{\pm}$ mass peak is A_D, A_{comb} is the asymmetry of the combinatorial background, and A_{part} is the asymmetry of the partially reconstructed events.
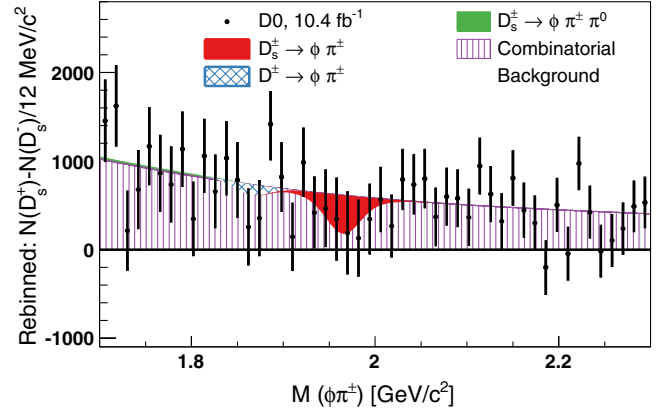

FIG. 2 (color online). The fit to the differences between the numbers of D_s^+ and D_s^- mesons as a function of the $\phi\pi^{\pm}$ mass (for clarity the data has been rebinned).

The result of the fit is shown in Figs. 1 and 2 with a total $\chi^2 = 171$ for 179 degrees of freedom corresponding to a p value of 0.65. The number of signal events in the sample is $N(D_s^{\pm}) = 452013 \pm 1866$ and the fitted asymmetry parameters are $A_{D_s} = (-0.43 \pm 0.26)\%$, $A_D = (-0.31 \pm 0.67)\%$, $A_{\text{comb}} = (0.46 \pm 0.04)\%$, and $A_{\text{part}} = (0.4 \pm 2.1)\%$. The value of the background asymmetry, A_{comb}, is consistent with approximately half the combinatoric background being $K^+K^-K^{\pm}$ or $K^{\pm}\pi^+\pi^-$ events with an average kaon reconstruction asymmetry of 1%.

To test the sensitivity and accuracy of the fitting procedure, the sign of the charge of the pion is randomized in the data set used in the analysis to introduce an asymmetry signal. We simulate a range of raw signals with asymmetries from $A_{D_s} = -2.0\%$ to $+2.0\%$ in steps of 0.2%, and A_D from -2.0% to $+2.0\%$ in steps of 0.5% with 1000 pseudoexperiments performed for each step. Each pseudoexperiment is performed with the same statistics as the measurement. No significant systematic biases are found, and the uncertainties are consistent with the expectation due to the sample size.

Systematic uncertainties of the fitting method are evaluated by varying the fitting procedure. The mass range of the fit is shifted from $1.700 < M(K^+K^-\pi^{\pm}) < 2.300$ GeV/c^2 to $1.724 < M(K^+K^-\pi^{\pm}) < 2.270$ GeV/c^2 in steps of 6 MeV/c^2 resulting in an uncertainty on the asymmetry of 0.044%. The functions modeling the signal are modified to fit the $D^{\pm}$ and $D_s^{\pm}$ mass peaks by single Gaussian functions, the background is fitted by varying between a fourth and seventh order polynomial function, and the parameter p_1 in the threshold function is allowed to vary. This yields an uncertainty on the asymmetry of 0.008%. The width of the mass bins is changed between 1 and 12 MeV/c^2 resulting in an uncertainty of 0.033%. The systematic uncertainty is assigned to be half of the maximal variation in the asymmetry for each of these sources added in quadrature. The total effect of these systematic sources of

uncertainty is a systematic uncertainty of 0.056% on the raw asymmetry A_{D_s}.

As a cross-check, variations of the various asymmetry models are also examined. The asymmetries introduced by the functions used to model the threshold behavior and the combinatoric background are set to the same value, $A_{\text{comb}} = A_{\text{part}}$. In a separate check the asymmetry of the threshold function is set to zero. Given the statistical and systematic uncertainties, the observed variations of 0.009% can be neglected.

The residual detector tracking charge asymmetry has been studied in Refs. [4,10,17] using $K_S^0 \to \pi^+\pi^-$ and $K^{*\pm} \to K_S^0\pi^\pm$ decays. After polarity weighting, no significant residual track reconstruction asymmetries have been found, and no correction for tracking asymmetries needs to be applied. The tracking asymmetry of charged pions has been found to be less than 0.05%, using MC simulations, which is assigned as a systematic uncertainty.

Any asymmetry between the reconstruction of K^+ and K^- mesons cancels as we require that the two kaons form a ϕ meson. However, there is a small residual asymmetry in the momentum of the kaons produced by the decay of the ϕ meson due to ϕ-$f_0(980)$ interference [18]. The kaon asymmetry is measured using the decay $K^{*0} \to K^+\pi^-$ [10] and is used to determine the residual asymmetry due to this interference, $A_{KK} = [-0.042 \pm 0.023(\text{syst})]\%$.

The charge asymmetry introduced by requiring the data to satisfy muon triggers needs to be included in the overall detector asymmetry. The effect of the residual reconstruction asymmetry of the muon system has been measured using $J/\psi \to \mu^+\mu^-$ decays as described in Ref. [10]. This asymmetry is determined as a function of p_T^μ and $|\eta^\mu|$, and the final correction is obtained by a weighted average over the normalized $(p_T^\mu, |\eta^\mu|)$ yields, as determined from fits to the $M(K^+K^-\pi^\pm)$ distribution. The resulting correction is $A_\mu = [-0.036 \pm 0.010(\text{syst})]\%$.

The combined residual detector asymmetry correction is

$$A_{\text{det}} = A_\mu + A_{KK} = [-0.078 \pm 0.056(\text{syst})]\%, \quad (6)$$

which includes the 0.05% systematic uncertainty on the residual asymmetry in track reconstruction. The remaining corrections are the physics background asymmetries contributing to A_{phys}, which are the only corrections extracted from MC simulation. The $D_s^\pm$ signal decays can also be produced in the decay chain of b hadrons. We assume that the decays of excited $D_s^\pm$ states proceed via the strong and electromagnetic interactions and do not introduce any CPV.

Most decays of B_s^0 mesons result in the production of a $D_s^\pm$ meson. These can be grouped into three categories. Semileptonic decays, $B_s^0 \to \ell^+\nu D_s^- X$, have a nonzero time-integrated flavor-specific semileptonic charge asymmetry of $a_{\text{sl}}^s = [-0.79 \pm 0.43]\%$ obtained by taking the average of direct and indirect measurements [4,5,8–10]. The correction for this asymmetry is given by the product of the

fraction of $D_s^\pm$ events produced by semileptonic B_s^0 decays, $f_{B_s^0}$, and the fraction of B_s^0 events that have mixed, $F_{B_s^0}^{\text{osc}}$. Since a_{sl}^s is proportional to $N_{D_s^-} - N_{D_s^+}$, it has the opposite sign to A_{D_s}. The second category is made up of B_s^0 meson decays to a pair of $D_s^\pm$ mesons which have no effect on the measured value of A_{CP} since equal numbers of D_s^+ and D_s^- are produced. The remaining category contains hadronic decays producing one $D_s^\pm$ meson, $B_s^0 \to D_s^\pm X$. Since 93% [9] of B_s^0 decays produce a $D_s^\pm$ meson, any net asymmetry will be small. The contributions of this process to the charge asymmetries in the production of $D_s^\pm$ mesons are assumed to be small and are neglected.

The remaining b hadron decay processes that contribute to A_{CP} are $B_d^0 \to D_s^\pm X$, $B^\pm \to D_s^\pm X$, and the small number of b baryon and B_c meson decays. It is assumed that any CPV in these decays has a negligible effect on the measurement.

To determine A_{phys}, a MC sample is created using the PYTHIA event generator [19] modified to use EVTGEN [20] for the decay of hadrons containing b and c quarks. The PYTHIA inclusive jet production model is used. Events recorded in random beam crossings are overlaid on the simulated events to emulate the effect of additional collisions in the same bunch crossing. These events are processed by the full simulation chain, and by the same reconstruction and selection algorithms as used for data. Events are selected that contain at least one $D_s^\pm \to \phi\pi^\pm$; $\phi \to K^+K^-$ decay. Each event is classified based on the decay chain that is matched to the reconstructed particles.

The effects of trigger selection and track reconstruction are estimated by weighting by the p_T of the reconstructed $D_s^\pm$ to match the distribution of the data. The trigger and off-line streaming requirements are accounted for by requiring a reconstructed muon in each of the MC events and weighting the muons to match the p_T^μ-η^μ distributions of muons in the data. The weights are obtained by taking the ratio of the muon p_T^μ-η^μ distributions in the selected data sample and a sample obtained using the zero-bias trigger condition. These weights are then applied to the MC simulation.

A large fraction of the data was collected at high instantaneous luminosities, and there is some probability that the muon and the $D_s^\pm$ candidate originate from different proton-antiproton collisions. This probability is determined by measuring the separation along the z axis of the intersection of the $D_s^\pm$ trajectory and the track of the highest p_T muon in the event. The fraction of events that come from separate $p\bar{p}$ interactions is estimated to be 6.4%. This effect is accounted for in the simulation.

From these studies, the sample is predicted to be composed of 71% $D_s^\pm$ mesons produced directly, 10% from the hadronic decays of B_s^0 mesons (which includes $B_s^0 \to D_s^{\pm(*)}D_s^{\mp(*)}$), 6% each from the decay of $B^\pm$ and B_d^0 mesons, and 1% from the decay of b baryons. The fraction of events that originate from B_s^0 semileptonic decays is

found to be $f_{B_s^0} = 5.8\%$, and the fraction of events that have oscillated to be $F_{B_s^0}^{\text{osc}} = 50\%$. In addition to the MC statistical uncertainty, the systematic uncertainty on A_{phys} is determined by varying the following quantities by their uncertainties: the branching ratios and production fractions of B and D mesons, the D- and B-meson lifetimes, and $\Delta\Gamma_s$. The largest sources of uncertainty is the fraction of events in which a c quark forms a $D_s^\pm$ meson, $f(c \to D_s^\pm) = 0.080 \pm 0.017$ [21], and the semileptonic branching fraction of B_s^0 mesons, $\mathcal{B}(B_s^0 \to \ell^+ \nu D_s^- X) = (9.5 \pm 2.7)\%$. The uncertainty on the correction due to a_{sl}^s is 0.024%, yielding an asymmetry resulting from the decay of b hadrons into $D_s^\pm$ mesons of

$$A_{\text{phys}} = [0.023 \pm 0.024(\text{syst})]\%. \tag{7}$$

Several consistency checks are performed by dividing the data into smaller samples using additional selections based on data-taking periods, magnet polarities, $D_s^\pm$ transverse momentum, and $D_s^\pm$ pseudorapidity. The resulting variations of A_{CP} are statistically consistent with the results of Eq. (8) (see below).

The selection criteria applied in this analysis preferentially select the P-wave decay, $D_s^\pm \to \phi\pi^\pm$, over the continuum process $D_s^\pm \to K^+ K^- \pi^\pm$ and other processes that result in a $K^+ K^- \pi^\pm$ final state. In particular the helicity angle between the $D_s^\pm$ and $K^\mp$ momenta in the center-of-mass frame of the ϕ meson and the invariant mass $M(K^+ K^-)$ used in the likelihood ratio select $D_s^\pm \to \phi\pi^\pm$ decays. To study the possible effect of other non-P-wave contributions, these variables are removed from the likelihood ratio and replaced with the requirement $1.01 < M(K^+ K^-) < 1.03$ GeV/c^2. The analysis is reoptimized, and the asymmetry is found to be $[-0.63 \pm 0.35(\text{stat}) \pm 0.08(\text{syst})]\%$ which is consistent with the main analysis and with the SM expectation of zero CPV.

The systematic uncertainty due to the fitting procedure (0.056%) added in quadrature with the uncertainties on A_{det} (0.056%) and A_{phys} (0.024%) results in a total systematic uncertainty of 0.08%. The direct CP-violating charge asymmetry in $D_s^\pm$ mesons is found to be

$$A_{CP} = [-0.38 \pm 0.26(\text{stat}) \pm 0.08(\text{syst})]\%, \tag{8}$$

corresponding to a total absolute uncertainty of 0.27%. This is the most precise measurement of direct CPV in the decay $D_s^\pm \to \phi\pi^\pm$, and the result is in agreement with the SM expectation of zero CPV in this decay.

[a]Visitor from Augustana College, Sioux Falls, SD, USA.
[b]Visitor from The University of Liverpool, Liverpool, United Kingdom.
[c]Visitor from DESY, Hamburg, Germany.
[d]Visitor from Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico.
[e]Visitor from SLAC, Menlo Park, CA, USA.
[f]Visitor from University College London, London, United Kingdom.
[g]Visitor from Centro de Investigacion en Computacion - IPN, Mexico City, Mexico.
[h]Visitor from Universidade Estadual Paulista, São Paulo, Brazil.
[i]Visitor from Karlsruher Institut für Technologie (KIT) - Steinbuch Centre for Computing (SCC), Karlsruhe, Germany.
[j]Visitor from Office of Science, U.S. Department of Energy, Washington, D.C. 20585, USA.

[1] I. I. Bigi and A. I. Sanda, *Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology* (Cambridge University Press, Cambridge England, 2009), 2nd ed., Vol. 28.
[2] A. Bharucha *et al.* (LHCb Collaboration), Eur. Phys. J. C **73**, 2373 (2013).
[3] P. U. E. Onyisi *et al.* (CLEO Collaboration), Phys. Rev. D **88**, 032009 (2013).
[4] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **110**, 011801 (2013).
[5] R. Aaij *et al.* (LHCb Collaboration), Phys. Lett. B **728**, 607 (2014).
[6] R. Aaij *et al.* (LHCb Collaboration), J. High Energy Phys. 06 (**2013**) 112.
[7] R. Aaij *et al.* (LHCb Collaboration), Phys. Lett. B **713**, 186 (2012).
[8] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **89**, 012002 (2014).
[9] J. Beringer *et al.* (Particle Data Group), Phys. Rev. D **86**, 010001 (2012), and 2013 partial update for the 2014 edition.
[10] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **86**, 072009 (2012).
[11] V. M. Abazov *et al.* (D0 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **565**, 463 (2006).
[12] R. Angstadt *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **622**, 298 (2010).
[13] The pseudorapidity is given by $\eta = -\ln[\tan(\theta/2)]$, θ is the polar angle between the track momentum and the proton beam direction, and ϕ is the azimuthal angle of the track.
[14] V. M. Abazov *et al.* (D0 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **552**, 372 (2005).
[15] J. Abdallah *et al.* (DELPHI Collaboration), Eur. Phys. J. C **32**, 185 (2004).

[16] G. Borisov, Nucl. Instrum. Methods Phys. Res., Sect. A **417,** 384 (1998).

[17] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **82,** 032001 (2010); (D0 Collaboration) Phys. Rev. Lett. **105,** 081801 (2010).

[18] M. Starič *et al.* (Belle Collaboration), Phys. Rev. Lett. **108,** 071801 (2012).

[19] T. Sjöstrand, S. Mrenna, and P. Z. Skands, J. High Energy Phys. 05 (**2006**) 026.

[20] D. G. Lange, Nucl. Instrum. Methods Phys. Res., Sect. A **462,** 152 (2001); D. G. Lange for details see http://www.slac .stanford.edu/~lange/EvtGen.

[21] C. Amsler *et al.* (Particle Data Group), Phys. Lett. B **667,** 1 (2008).