

Measurement of the wrong-sign decay $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$

E. White,⁵ A. J. Schwartz,⁵ I. Adachi,¹¹ H. Aihara,⁵⁶ D. M. Asner,⁴³ V. Aulchenko,³ T. Aushev,¹⁹ A. M. Bakich,⁵⁰ A. Bala,⁴⁴ V. Bhardwaj,³⁴ B. Bhuyan,¹³ G. Bonvicini,⁶² A. Bozek,³⁸ M. Bračko,^{28,20} J. Brodzicka,³⁸ T. E. Browder,¹⁰ V. Chekelian,²⁹ A. Chen,³⁵ P. Chen,³⁷ B. G. Cheon,⁹ K. Chilikin,¹⁹ R. Chistov,¹⁹ I.-S. Cho,⁶⁴ K. Cho,²³ V. Chobanova,²⁹ Y. Choi,⁴⁹ D. Cinabro,⁶² J. Dingfelder,² Z. Doležal,⁴ Z. Drásal,⁴ D. Dutta,¹³ S. Eidelman,³ D. Epifanov,⁵⁶ S. Esen,⁵ H. Farhat,⁶² J. E. Fast,⁴³ M. Feindt,²² T. Ferber,⁶ A. Frey,⁸ V. Gaur,⁵¹ N. Gabyshev,³ S. Ganguly,⁶² R. Gillard,⁶² Y. M. Goh,⁹ B. Golob,^{27,20} T. Hara,¹¹ K. Hayasaka,³³ H. Hayashii,³⁴ Y. Hoshi,⁵⁴ W.-S. Hou,³⁷ Y. B. Hsiung,³⁷ H. J. Hyun,²⁵ T. Iijima,^{33,32} A. Ishikawa,⁵⁵ R. Itoh,¹¹ Y. Iwasaki,¹¹ T. Iwashita,³⁴ I. Jaegle,¹⁰ T. Julius,³⁰ D. H. Kah,²⁵ J. H. Kang,⁶⁴ E. Kato,⁵⁵ C. Kiesling,²⁹ D. Y. Kim,⁴⁸ H. O. Kim,²⁵ J. B. Kim,²⁴ J. H. Kim,²³ M. J. Kim,²⁵ Y. J. Kim,²³ K. Kinoshita,⁵ J. Klucar,²⁰ B. R. Ko,²⁴ P. Kodyš,⁴ S. Korpar,^{28,20} P. Križan,^{27,20} P. Krokovny,³ B. Kronenbitter,²² T. Kuhr,²² T. Kumita,⁵⁸ A. Kuzmin,³ Y.-J. Kwon,⁶⁴ J. S. Lange,⁷ S.-H. Lee,²⁴ J. Li,⁴⁷ Y. Li,⁶¹ L. Li Gioi,²⁹ J. Libby,¹⁴ C. Liu,⁴⁶ Y. Liu,⁵ D. Liventsev,¹¹ P. Lukin,³ D. Matvienko,³ H. Miyata,⁴⁰ R. Mizuk,^{19,31} G. B. Mohanty,⁵¹ A. Moll,^{29,52} R. Mussa,¹⁸ E. Nakano,⁴² M. Nakao,¹¹ Z. Natkaniec,³⁸ M. Nayak,¹⁴ E. Nedelkowska,²⁹ C. Ng,⁵⁶ N. K. Nisar,⁵¹ S. Nishida,¹¹ O. Nitoh,⁵⁹ S. Ogawa,⁵³ S. Okuno,²¹ C. Oswald,² P. Pakhlov,^{19,31} G. Pakhlova,¹⁹ H. Park,²⁵ H. K. Park,²⁵ T. K. Pedlar,⁶⁵ R. Pestotnik,²⁰ M. Petrič,²⁰ L. E. Piilonen,⁶¹ M. Ritter,²⁹ M. Röhrken,²² A. Rostomyan,⁶ S. Ryu,⁴⁷ H. Sahoo,¹⁰ T. Saito,⁵⁵ Y. Sakai,¹¹ S. Sandilya,⁵¹ L. Santelj,²⁰ T. Sanuki,⁵⁵ Y. Sato,⁵⁵ V. Savinov,⁴⁵ O. Schneider,²⁶ G. Schnell,^{1,12} C. Schwanda,¹⁶ D. Semmler,⁷ K. Senyo,⁶³ O. Seon,³² M. E. Sevier,³⁰ M. Shapkin,¹⁷ T.-A. Shibata,⁵⁷ J.-G. Shiu,³⁷ B. Shwartz,³ A. Sibidanov,⁵⁰ Y.-S. Sohn,⁶⁴ A. Sokolov,¹⁷ E. Solovieva,¹⁹ S. Stanič,⁴¹ M. Starič,²⁰ M. Steder,⁶ T. Sumiyoshi,⁵⁸ U. Tamponi,^{18,60} G. Tatishvili,⁴³ Y. Teramoto,⁴² M. Uchida,⁵⁷ S. Uehara,¹¹ Y. Unno,⁹ S. Uno,¹¹ S. E. Vahsen,¹⁰ C. Van Hulse,¹ G. Varner,¹⁰ V. Vorobyev,³ M. N. Wagner,⁷ C. H. Wang,³⁶ M.-Z. Wang,³⁷ P. Wang,¹⁵ Y. Watanabe,²¹ K. M. Williams,⁶¹ E. Won,²⁴ Y. Yamashita,³⁹ S. Yashchenko,⁶ Y. Yusa,⁴⁰ Z. P. Zhang,⁴⁶ V. Zhilich,³ V. Zhulanov,³ and A. Zupanc²²

(Belle Collaboration)

¹University of the Basque Country UPV/EHU, 48080 Bilbao²University of Bonn, 53115 Bonn³Budker Institute of Nuclear Physics SB RAS and Novosibirsk State University, Novosibirsk 630090⁴Faculty of Mathematics and Physics, Charles University, 121 16 Prague⁵University of Cincinnati, Cincinnati, Ohio 45221⁶Deutsches Elektronen-Synchrotron, 22607 Hamburg⁷Justus-Liebig-Universität Gießen, 35392 Gießen⁸II. Physikalisches Institut, Georg-August-Universität Göttingen, 37073 Göttingen⁹Hanyang University, Seoul 133-791¹⁰University of Hawaii, Honolulu, Hawaii 96822¹¹High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801¹²Ikerbasque, 48011 Bilbao¹³Indian Institute of Technology Guwahati, Assam 781039¹⁴Indian Institute of Technology Madras, Chennai 600036¹⁵Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049¹⁶Institute of High Energy Physics, Vienna 1050¹⁷Institute for High Energy Physics, Protvino 142281¹⁸INFN-Sezione di Torino, 10125 Torino¹⁹Institute for Theoretical and Experimental Physics, Moscow 117218²⁰J. Stefan Institute, 1000 Ljubljana²¹Kanagawa University, Yokohama 221-8686²²Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie, 76131 Karlsruhe²³Korea Institute of Science and Technology Information, Daejeon 305-806²⁴Korea University, Seoul 136-713²⁵Kyungpook National University, Daegu 702-701²⁶École Polytechnique Fédérale de Lausanne (EPFL), Lausanne 1015²⁷Faculty of Mathematics and Physics, University of Ljubljana, 1000 Ljubljana²⁸University of Maribor, 2000 Maribor²⁹Max-Planck-Institut für Physik, 80805 München³⁰School of Physics, University of Melbourne, Victoria 3010

- ³¹Moscow Physical Engineering Institute, Moscow 115409
³²Graduate School of Science, Nagoya University, Nagoya 464-8602
³³Kobayashi-Maskawa Institute, Nagoya University, Nagoya 464-8602
³⁴Nara Women's University, Nara 630-8506
³⁵National Central University, Chung-li 32054
³⁶National United University, Miao Li 36003
³⁷Department of Physics, National Taiwan University, Taipei 10617
³⁸H. Niewodniczanski Institute of Nuclear Physics, Krakow 31-342
³⁹Nippon Dental University, Niigata 951-8580
⁴⁰Niigata University, Niigata 950-2181
⁴¹University of Nova Gorica, 5000 Nova Gorica
⁴²Osaka City University, Osaka 558-8585
⁴³Pacific Northwest National Laboratory, Richland, Washington 99352
⁴⁴Panjab University, Chandigarh 160014
⁴⁵University of Pittsburgh, Pittsburgh, Pennsylvania 15260
⁴⁶University of Science and Technology of China, Hefei 230026
⁴⁷Seoul National University, Seoul 151-742
⁴⁸Soongsil University, Seoul 156-743
⁴⁹Sungkyunkwan University, Suwon 440-746
⁵⁰School of Physics, University of Sydney, New South Wales 2006
⁵¹Tata Institute of Fundamental Research, Mumbai 400005
⁵²Excellence Cluster Universe, Technische Universität München, 85748 Garching
⁵³Toho University, Funabashi 274-8510
⁵⁴Tohoku Gakuin University, Tagajo 985-8537
⁵⁵Tohoku University, Sendai 980-8578
⁵⁶Department of Physics, University of Tokyo, Tokyo 113-0033
⁵⁷Tokyo Institute of Technology, Tokyo 152-8550
⁵⁸Tokyo Metropolitan University, Tokyo 192-0397
⁵⁹Tokyo University of Agriculture and Technology, Tokyo 184-8588
⁶⁰University of Torino, 10124 Torino
⁶¹CNP, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
⁶²Wayne State University, Detroit, Michigan 48202
⁶³Yamagata University, Yamagata 990-8560
⁶⁴Yonsei University, Seoul 120-749
⁶⁵Luther College, Decorah, Iowa 52101

(Received 21 July 2013; published 30 September 2013)

A measurement of the rate for the “wrong-sign” decay $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$ relative to that for the “right-sign” decay $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ is presented. Using 791 fb^{-1} of data collected with the Belle detector, we obtain a branching fraction ratio of $R_{\text{ws}} = [0.324 \pm 0.008(\text{stat}) \pm 0.007(\text{sys})]\%$. Multiplying this ratio by the world average value for the branching fraction $\mathcal{B}(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-)$ gives a branching fraction $\mathcal{B}(D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-) = (2.61 \pm 0.06_{-0.08}^{+0.09}) \times 10^{-4}$.

DOI: [10.1103/PhysRevD.88.051101](https://doi.org/10.1103/PhysRevD.88.051101)

PACS numbers: 13.25.Ft, 12.15.Ff, 14.40.Lb

Studies of mixing in neutral meson systems have had an important impact on the development of the standard model. Historically, mixing was first observed in the $K^0 - \bar{K}^0$ system [1], then later in the $B^0 - \bar{B}^0$ system [2], and most recently in the $B_s^0 - \bar{B}_s^0$ [3] and $D^0 - \bar{D}^0$ [4–6] systems. Mixing in the $D^0 - \bar{D}^0$ system is strongly suppressed due to Cabibbo-Kobayashi-Maskawa [7] matrix elements and the GIM mechanism [8]. It has been measured using several methods [9], one of which compares the time dependence of “wrong-sign” $D^0 \rightarrow K^+ \pi^- (X)$ decays to that of “right-sign” $D^0 \rightarrow K^- \pi^+ (X)$ decays [5,6,10–12]. Wrong-sign decays can occur either via a doubly Cabibbo-suppressed (DCS) amplitude such as $D^0 \rightarrow K^+ \pi^- (X)$ or

via D^0 mixing to \bar{D}^0 , followed by a Cabibbo-favored (CF) decay such as $\bar{D}^0 \rightarrow K^+ \pi^- (X)$.

In this article we present a measurement for the rate of the wrong-sign (WS) decay $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$ relative to that of the right-sign (RS) decay $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ using a data sample of 791 fb^{-1} [13]. Assuming negligible CP violation, the ratio of decay rates can be expressed as [14]

$$\begin{aligned}
 R_{\text{ws}} &\equiv \frac{\Gamma(D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-)}{\Gamma(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-)} \\
 &= R_D + \alpha y' \sqrt{R_D} + \frac{1}{2}(x'^2 + y'^2), \quad (1)
 \end{aligned}$$

where R_D is the squared magnitude of the ratio of the DCS to CF amplitudes, α is a suppression factor that accounts for strong-phase variation over the phase space ($0 \leq \alpha \leq 1$) [11], and x' and y' are the mixing parameters $x \equiv \Delta m/\bar{\Gamma}$ and $y \equiv \Delta\Gamma/2\bar{\Gamma}$ rotated by the effective strong-phase difference δ between DCS and CF amplitudes: $x' = x \cos \delta + y \sin \delta$ and $y' = y \cos \delta - x \sin \delta$. The parameters x and y depend only on the mass difference (ΔM) and decay width difference ($\Delta\Gamma$) between the $D^0 - \bar{D}^0$ mass eigenstates, and the mean decay width ($\bar{\Gamma}$). The Belle Collaboration has previously measured $R_{ws} = [0.320 \pm 0.018(\text{stat})_{-0.013}^{+0.018}(\text{sys})]\%$ [15]. The measurement presented here supersedes this previous result. We use an improved reconstruction code that has a higher reconstruction efficiency for low momentum tracks. The data used in this analysis corresponds to an integrated luminosity of 791 fb^{-1} collected at or near the $\Upsilon(4S)$ resonance.

The data sample was collected by the Belle detector [16] located at the KEKB asymmetric-energy e^+e^- collider [17]. The Belle detector is a large-solid-angle magnetic spectrometer consisting of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) based on CsI (TI) crystals. These detector elements are located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. Muon identification is provided by an array of resistive plate chambers (KLM) interspersed with iron shielding that is used as the magnetic flux return. For charged hadron identification, a likelihood ratio $\mathcal{L}_K \equiv \mathcal{L}(K)/(\mathcal{L}(K) + \mathcal{L}(\pi))$ is formed based on dE/dx measured in the CDC and the response of the ACC and TOF. Charged kaons are identified using a likelihood requirement that is about 86% efficient for K^\pm and has a π^\pm misidentification rate of about 8%.

We reconstruct the decay $D^{*\pm} \rightarrow D^0 \pi_s^\pm$, $D^0 \rightarrow K^\pm \pi^\mp \pi^+ \pi^-$, in which the charge of the low-momentum (or ‘‘slow’’) pion π_s^\pm identifies the flavor of the neutral D candidate. For each event, the $D^0 \rightarrow K^\pm \pi^\mp \pi^+ \pi^-$ candidate is formed from combinations of four charged tracks. We require that the likelihood ratio \mathcal{L}_K be greater than 0.7 for kaons and less than 0.4 for pions. For each track candidate, the distance of closest approach to the interaction point (IP) along the beam line is required to be less than 5.0 cm. In the plane transverse to the beam line, the distance of closest approach is required to be less than 2.0 cm for pion candidates and less than 1.0 cm for kaon candidates. To suppress backgrounds from semileptonic decays, we reject tracks satisfying electron or muon identification criteria based on information from the ECL and KLM detectors. This veto has an efficiency of 95% for signal events and reduces the number of electron (muon) background events by 93% (95%). We require that each track used to reconstruct the D^0 have at least two SVD hits

in both the $r - \phi$ and z coordinates. We retain events having a $K\pi\pi\pi$ invariant mass ($M_{K3\pi}$) satisfying $1.81 \text{ GeV}/c^2 < M_{K3\pi} < 1.92 \text{ GeV}/c^2$.

For $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$, when the momenta of a daughter kaon and pion are similar, their masses can be exchanged without a significant effect upon $M_{K3\pi}$. This misidentification leads to ‘‘feed-through’’ background from RS $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ decays in the WS sample. To suppress this background, we recalculate $M_{K3\pi}$ of WS candidates after swapping the kaon and pion mass assignments and reject events in which $|M_{K3\pi}(\text{swapped}) - m_{D^0}| < 20 \text{ GeV}/c^2$. From Monte Carlo (MC) simulation, we find that this veto has a signal efficiency of 92% while rejecting 94% of this background.

To suppress backgrounds from the singly Cabibbo-suppressed decay $D^0 \rightarrow K_S^0 K^+ \pi^-$ followed by $K_S^0 \rightarrow \pi^+ \pi^-$, we veto events in which either of the $\pi^+ \pi^-$ daughter combinations has an invariant mass within $20 \text{ MeV}/c^2$ (3.3σ in resolution) of the K_S^0 mass. This veto has an efficiency of 97% for signal events and reduces the number of K_S^0 background events in Monte Carlo by 90%.

To suppress background from random combinations of tracks, the daughter tracks from the D^0 candidate are required to originate from a common vertex. To reconstruct the D^* candidate, we perform a vertex fit that constrains the D^0 and the π_s candidate to the IP of the beams. The resolution on the mass difference $Q \equiv M_{\pi_s K3\pi} - M_{K3\pi} - m_\pi$ is significantly improved by this requirement. We require that the χ^2 probability for each vertex fit be greater than 0.1% and that $Q < 10 \text{ MeV}/c^2$. To eliminate D mesons produced in $B\bar{B}$ events, we require that the momentum of the D^* candidate be greater than $2.5 \text{ GeV}/c$ in the center-of-mass frame. After all selection requirements, the fraction of events containing multiple candidates is 8.6%. For these events, we select the candidate that minimizes the sum of χ^2 values divided by the sum of degrees of freedom (d.o.f.), where each sum extends over both vertex fits.

We measure RS and WS signal yields by performing a two-dimensional binned maximum likelihood fit to the $M_{K3\pi}$ and Q distributions. The signal and background probability density functions (PDFs) are determined from MC samples having sizes four times that of the data set. Background PDF shapes are determined separately for RS and WS distributions and fixed in the fit. The backgrounds are divided into four categories: (1) ‘‘random π_s ,’’ in which a CF $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ decay is correctly reconstructed but is subsequently combined with a random slow pion having the WS charge; (2) ‘‘broken charm,’’ in which a true $D^{*+} \rightarrow D^0 \pi_s^+$ decay is combined with a misreconstructed D^0 ; (3) ‘‘combinatoric,’’ consisting of remaining backgrounds from $e^+e^- \rightarrow c\bar{c}$ production; and (4) ‘‘uds,’’ consisting of combinatorial backgrounds from continuum $e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$ production. As no significant correlations are found between $M_{K3\pi}$ and Q for the signal or

E. WHITE *et al.*

backgrounds, we model each PDF as the product of one-dimensional functions. Background PDF shapes are parametrized in Q using a threshold function of the form $Q^{1/2} + aQ^{3/2}$ for the random π_s , combinatoric, and uds components, while a broad Gaussian is used for the broken charm component. For $M_{K3\pi}$, a second-order Chebyshev polynomial is used for the combinatoric and uds components, and an ARGUS function [18] is used for the broken charm component. The random π_s background is parametrized in $M_{K3\pi}$ using the same shape as used for the signal (see below). We compare data and MC events in the sideband regions $|Q - 5.865 \text{ MeV}/c^2| > 2.0 \text{ MeV}/c^2$ for numerous kinematic distributions and find good agreement. These distributions include the D^* momentum, the χ^2 value of the vertex fits, particle identification likelihoods, the cosine of the angle between the D^0 and each of its daughter particles, and the momentum of each final state particle. The background normalizations are floated in the fit.

The RS signal PDF is parametrized in $M_{K3\pi}$ as the sum of one Gaussian and two bifurcated Gaussians:

$$\begin{aligned} \mathcal{L}(M_{K3\pi}) = & f_1 G(\mu, \sigma_1) + (1 - f_1) f_2 G(\mu, \sigma_2^L, \sigma_2^R) \\ & + (1 - f_1)(1 - f_2) G(\mu, \sigma_3^L, \sigma_3^R), \end{aligned} \quad (2)$$

where μ is the common mean, σ^L (σ^R) is the left (right) width of the bifurcated Gaussians, and f_i is the relative fraction of each component. In Q , the signal PDF is parametrized as the sum of a bifurcated Student's t distribution and a bifurcated Gaussian:

$$\begin{aligned} \mathcal{L}(Q) = & f_4 S(\bar{\mu}, \sigma_4^L, \sigma_4^R, \alpha_1, \alpha_2) \\ & + (1 - f_4) G(\bar{\mu}, \sigma_5^L, \sigma_5^R), \end{aligned} \quad (3)$$

where $\bar{\mu}$ is the common mean; σ_5 is the width of the bifurcated Gaussian; and f_4 , σ_4 , and α are the relative fraction, variance, and skewness, respectively, of the Student's t distribution. For the fit to data, the fractions f_2 and f_4 are fixed to values obtained from MC simulation while all other parameters are floated.

The RS signal PDF is also used for the WS signal PDF. Since the WS and RS samples are fitted simultaneously, the ratio of WS to RS signal yields is extracted directly from the fit. We obtain a RS yield of 990594 ± 1901 events and a ‘‘raw’’ ratio of WS to RS yields of $R'_{\text{ws}} = (0.339 \pm 0.008)\%$. This value must be corrected for the ratio of overall efficiencies of RS and WS decays. Projections of the fit are shown in Fig. 1. The fitted RS yield and R'_{ws} value correspond to a WS yield of 3358 ± 79 events. The goodness of fit is satisfactory: for WS (RS) decays, $\chi^2/\text{d.o.f.} = 1.17$ (1.89) for $M_{K3\pi}$ and 0.90 (1.43) for Q .

As $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$ and $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ decays proceed largely through intermediate resonances, RS and WS events are expected to have different distributions across the phase space. If the detector acceptance and reconstruction efficiencies vary over phase space, the

PHYSICAL REVIEW D **88**, 051101(R) (2013)

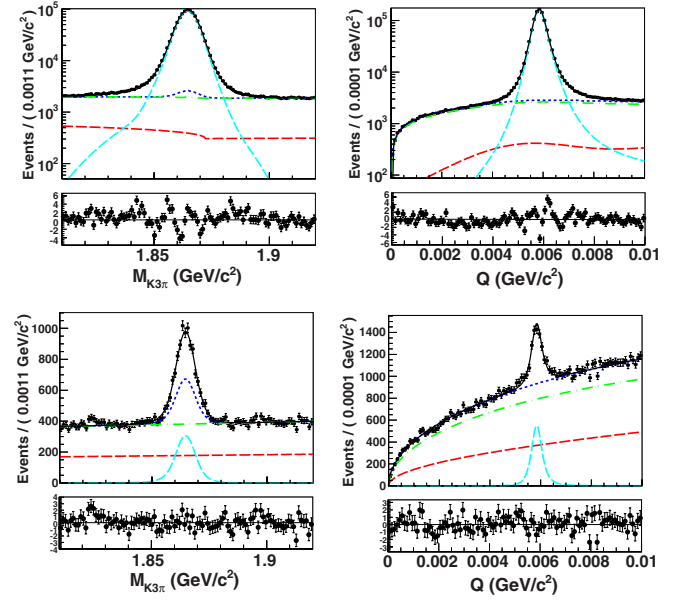


FIG. 1 (color online). Fit projections for $M_{K3\pi}$ (left) and Q (right). The top (bottom) row shows $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ ($D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$) candidates. Events plotted for $M_{K3\pi}$ are required to lie in the signal region for Q , and vice versa. The peaking dashed curves show the signal PDF (cyan); the nonpeaking dashed curves show broken charm and uds backgrounds (red); the dash-dotted curves include combinatoric backgrounds (green); and the dotted curves include random π_s backgrounds (blue). The fit residuals $(N_o - N_p)/\sqrt{N_o}$ are plotted below each fit projection, where N_o (N_p) is the observed (predicted) event yield.

overall efficiencies for RS and WS decays will differ from each other. The ratio of these efficiencies is needed to correct R'_{ws} .

To obtain the ratio of efficiencies, we divide RS and WS events into 576 bins in a five-dimensional phase space. These dimensions consist of the invariant mass combinations for $K^\pm \pi^\pm$, $K^\pm \pi_1^\mp$, $K^\pm \pi_2^\mp$, $\pi^\pm \pi_1^\mp$, and $\pi^\pm \pi_2^\mp$, where π_1 and π_2 label the pions with same sign charge, and $|p_{\pi_1}| > |p_{\pi_2}|$. The binning is chosen to correspond to the structure present in these variables. The efficiency for each bin (ϵ_i) is obtained using MC. We estimate background in the data for bin i by multiplying the total background yield (N_{bkg}) by the fraction of background events in that bin (f_i) as obtained from MC simulation. The total background yield is determined from the two-dimensional fit to the $M_{K3\pi}$ - Q distribution of data. The total signal yield is calculated as

$$N'(K\pi\pi\pi) = \sum_{i=1}^{576} \frac{N_i - N_{\text{bkg}} \cdot f_i}{\epsilon_i}, \quad (4)$$

where N_i is the number of candidate events in bin i . The reconstruction efficiency for either $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$ or $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ decays is calculated as

$$\epsilon(K\pi\pi\pi) = \frac{1}{N'} \sum_{i=1}^{576} (N_i - N_{\text{bkg}} \cdot f_i), \quad (5)$$

and thus

$$R_{\text{ws}} = R'_{\text{ws}} \cdot \frac{\epsilon(K^-\pi^+\pi^+\pi^-)}{\epsilon(K^+\pi^-\pi^+\pi^-)} = \frac{N'(K^+\pi^-\pi^+\pi^-)}{N'(K^-\pi^+\pi^+\pi^-)}. \quad (6)$$

Only events located within a signal region $|m_{K^3\pi} - m_{D^0}| < 0.01$ GeV and $|Q - Q_0| < 0.002$ GeV/ c^2 are used to determine the efficiency correction. The efficiency-corrected yields are $N'(K^+\pi^-\pi^+\pi^-) = 37297 \pm 881$ and $N'(K^-\pi^+\pi^+\pi^-) = (1.151 \pm 0.002) \times 10^7$; thus $R_{\text{ws}} = (0.324 \pm 0.008)\%$.

We consider various sources of systematic uncertainty as listed in Table I. Since we measure the ratio of topologically similar RS and WS decays, many systematic uncertainties cancel.

To determine the systematic uncertainty associated with the ratio of efficiencies, we propagate the statistical errors for ϵ_i and f_i via a Monte Carlo method as follows. We generate values for ϵ_i and f_i in all 576 bins. These values are sampled from Gaussian distributions having mean values equal to the nominal parameter values and standard deviations equal to their uncertainties. We then recalculate R_{ws} using these sampled values. We repeat this procedure 10^5 times and plot the resulting distribution of R_{ws} . The rms of this distribution (± 0.0041) is taken as the systematic error associated with the efficiency correction.

To estimate the contribution associated with event selection criteria, we vary each selection criterion over a suitable range and remeasure R_{ws} for each variation. The identification likelihood ratio \mathcal{L}_K is varied over the range 0.5–0.9 for kaon candidates and 0.1–0.5 for pion candidates. The momentum requirement for D^* candidates is varied over the range 2.3–2.7 GeV/ c . For each selection criterion, the largest positive and negative deviation of R_{ws} from the nominal value is taken as the systematic error.

TABLE I. Summary of systematic errors for R_{ws} . The total systematic error is obtained by summing all contributions in quadrature.

| Source | $+\Delta R$ (%) | $-\Delta R$ (%) |
|-------------------------|-----------------|-----------------|
| Kaon ID | 0.0008 | 0.0006 |
| Pion ID | 0.0003 | 0.0024 |
| D^* momentum | 0.0029 | 0.0037 |
| Multiple candidates | 0.0024 | 0.0024 |
| uds background | 0.0012 | 0.0002 |
| Combinatoric background | 0.0034 | 0.0025 |
| Slow π background | 0.0009 | 0.0003 |
| Broken charm | 0.0010 | 0.0008 |
| Efficiency correction | 0.0041 | 0.0041 |
| Efficiency binning | 0.0014 | 0.0 |
| Total | 0.0070 | 0.0070 |

The error due to multiple candidates is obtained by removing all events containing multiple candidates (8.6% of events) and refitting for R_{ws} ; the deviation observed is taken as the error. To determine the uncertainty associated with background PDF shapes (which are taken from MC and differ for RS and WS events), we vary the parameters of each background PDF by $\pm 1\sigma$, where σ corresponds to the statistical error from the fit to MC. For each variation, the data is refit and the deviation of R_{ws} from the nominal value is recorded. The uncertainty due to a given background PDF is taken as the sum in quadrature of all deviations observed when varying the individual parameters. The systematic error due to uncertainty in the signal PDF is negligibly small. To check for possible bias in our fit results, we repeat the fit for Monte Carlo samples (each corresponding to the size of the data set) having different values of R_{ws} . Comparing the fit results for R_{ws} with the true values shows no visible fit bias. The total systematic error is taken to be the sum in quadrature of all individual contributions. Our final result is

$$R_{\text{ws}} = (0.324 \pm 0.008 \pm 0.007)\%. \quad (7)$$

Multiplying this value by the well-measured RS branching fraction $\mathcal{B}(D^0 \rightarrow K^-\pi^+\pi^+\pi^-) = (8.07^{+0.21}_{-0.19})\%$ [19] gives a WS branching fraction

$$\mathcal{B}(D^0 \rightarrow K^+\pi^-\pi^+\pi^-) = (2.61 \pm 0.06^{+0.09}_{-0.08}) \times 10^{-4}. \quad (8)$$

By combining our measurement of R_{ws} with world average values [9] for x and y , and recent measurements [20] of α and δ , we extract R_D from Eq. (1). We use a MC method to propagate the errors for the parameters and obtain $R_D = (0.327^{+0.019}_{-0.016})\%$.

In summary, we have measured the wrong-sign ratio $R_{\text{ws}} = \Gamma(D^0 \rightarrow K^+\pi^-\pi^+\pi^-)/\Gamma(D^0 \rightarrow K^-\pi^+\pi^+\pi^-)$ using e^+e^- data collected at or near the $Y(4S)$ resonance. After correcting for differences in reconstruction efficiencies between RS and WS events, we obtain $R_{\text{ws}} = (0.324 \pm 0.008 \pm 0.007)\%$, where the first uncertainty is statistical and the second is systematic. This is the most precise measurement of R_{ws} to date. Using a MC method to extract R_D from Eq. (1), we obtain $R_D = (0.327^{+0.019}_{-0.016})\%$. Multiplying R_{ws} by the branching fraction for $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ gives $\mathcal{B}(D^0 \rightarrow K^+\pi^-\pi^+\pi^-) = (2.61 \pm 0.06^{+0.09}_{-0.08}) \times 10^{-4}$. This result is substantially more precise than the current Particle Data Group value of $(2.61^{+0.21}_{-0.19}) \times 10^{-4}$ [19].

We thank the KEKB group for the excellent operation of the accelerator; the KEK cryogenics group for the efficient operation of the solenoid; and the KEK computer group, the National Institute of Informatics, and the PNNL/EMSL computing group for valuable computing and SINET4 network support. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology

(MEXT) of Japan, the Japan Society for the Promotion of Science (JSPS), and the Tau-Lepton Physics Research Center of Nagoya University; the Australian Research Council and the Australian Department of Industry, Innovation, Science and Research; Austrian Science Fund under Grant No. P 22742-N16; the National Natural Science Foundation of China under Contracts No. 10575109, No. 10775142, No. 10875115 and No. 10825524; the Ministry of Education, Youth and Sports of the Czech Republic under Contract No. MSM0021620859; the Carl Zeiss Foundation, the Deutsche Forschungsgemeinschaft and the Volkswagen-Stiftung; the Department of Science and Technology of India; the Istituto Nazionale di Fisica Nucleare of Italy; the BK21 and WCU program of the Ministry Education Science and Technology, National Research Foundation of Korea Grants No. 2010-0021174, No. 2011-0029457,

No. 2012-0008143 and No. 2012R1A1A2008330, BRL program under NRF Grant No. KRF-2011-0020333, and GSDC of the Korea Institute of Science and Technology Information; the Polish Ministry of Science and Higher Education and the National Science Center; the Ministry of Education and Science of the Russian Federation and the Russian Federal Agency for Atomic Energy; the Slovenian Research Agency; the Basque Foundation for Science (IKERBASQUE) and the UPV/EHU under program UFI 11/55; the Swiss National Science Foundation; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy and the National Science Foundation. This work is supported by a Grant-in-Aid from MEXT for Science Research in a Priority Area (“New Development of Flavor Physics”), and from JSPS for Creative Scientific Research (“Evolution of Tau-lepton Physics”).

-
- [1] R. Good, R. Matsen, F. Muller, O. Piccioni, W. Powell, H. White, W. Fowler, and R. Birge, *Phys. Rev.* **124**, 1223 (1961).
- [2] H. Albrecht *et al.* (ARGUS Collaboration), *Phys. Lett. B* **192**, 245 (1987); M. Artuso *et al.* (CLEO Collaboration), *Phys. Rev. Lett.* **62**, 2233 (1989).
- [3] A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **97**, 242003 (2006); **97**, 062003 (2006); V. M. Abazov *et al.* (DØ Collaboration), *Phys. Rev. Lett.* **97**, 021802 (2006).
- [4] M. Starič *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **98**, 211803 (2007).
- [5] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **98**, 211802 (2007).
- [6] R. Aaij *et al.* (LHCb Collaboration), *Phys. Rev. Lett.* **110**, 101802 (2013).
- [7] M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973); N. Cabibbo, *Phys. Rev. Lett.* **10**, 531 (1963).
- [8] S. L. Glashow, J. Iliopoulos, and L. Maiani, *Phys. Rev. D* **2**, 1285 (1970).
- [9] For a synopsis see Y. Amhis *et al.* (Heavy Flavor Averaging Group), [arXiv:1207.1158](https://arxiv.org/abs/1207.1158); and online update at www.slac.stanford.edu/xorg/hfag/charm/index.html.
- [10] L. M. Zhang *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **96**, 151801 (2006).
- [11] B. Aubert *et al.* (BABAR Collaboration), *Phys. Rev. Lett.* **97**, 221803 (2006).
- [12] T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **100**, 121802 (2008).
- [13] The inclusion of charge-conjugated modes is implied throughout this paper.
- [14] S. Bergmann, Y. Grossman, Z. Ligeti, Y. Nir, and A. A. Petrov, *Phys. Lett. B* **486**, 418 (2000).
- [15] X. C. Tian *et al.* (Belle Collaboration), *Phys. Rev. Lett.* **95**, 231801 (2005).
- [16] A. Abashian *et al.* (Belle Collaboration), *Nucl. Instrum. Methods Phys. Res. Sect. A* **479**, 117 (2002); also see detector section in J. Brodzicka *et al.*, *Prog. Theor. Exp. Phys.* **2012**, 04D001 (2012).
- [17] S. Kurokawa and E. Kikutani, *Nucl. Instrum. Methods Phys. Res. Sect., A* **499**, 1 (2003), and other papers included in this volume; T. Abe *et al.*, *Prog. Theor. Exp. Phys.* **2013**, 03A001 (2013) and following articles up to 03A011.
- [18] H. Albrecht *et al.* (ARGUS Collaboration), *Phys. Lett. B* **241**, 278 (1990).
- [19] J. Beringer *et al.* (Particle Data Group), *Phys. Rev. D* **86**, 010001 (2012).
- [20] N. Lowrey *et al.* (CLEO Collaboration), *Phys. Rev. D* **80**, 031105 (2009).