

Search for  $CP$  violation with Kinematic Asymmetries in the  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  Decay

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We search for  $CP$  violation in the singly-Cabibbo-suppressed decay  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  using data corresponding to an integrated luminosity of  $988 \text{ fb}^{-1}$  collected by the Belle detector at the KEKB  $e^+e^-$  collider. We measure a set of five kinematically dependent  $CP$  asymmetries, of which four asymmetries are measured for the first time. The set of asymmetry measurements can be sensitive to  $CP$  violation via interference between the different partial-wave contributions to the decay and performed on other pseudoscalar decays. We find no evidence of  $CP$  violation.

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Charge-conjugation and parity ( $CP$ ) symmetry violation has been observed in various weak decays involving strange and beauty quarks [1] and is well described in the Standard Model (SM) by the Cabibbo-Kobayashi-Maskawa matrix [2]. But the magnitude of  $CP$  violation in the SM is too small to explain the baryon asymmetry in the visible universe [3]. Therefore, the search for additional processes that violate  $CP$  symmetry, which are not described by the SM, is of great interest to explain the matter-dominant universe.  $CP$  violation in the charm sector is expected to be small, less than  $\mathcal{O}(10^{-3})$  in the SM [4, 5], which makes it an excellent probe for  $CP$  violation beyond that of the SM [1].

$CP$  violation in the singly-Cabibbo-suppressed decay  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  was searched for using  $\hat{T}$ -odd correlations [6, 7], where  $\hat{T}$  reverses the direction of momenta and spin, which is different from the usual time reversal operator  $T$  [8]. No  $CP$  violation is observed up to now, but the  $\hat{T}$ -odd correlation measured may be weakly sensitive to  $CP$  violation in this decay [8]. In this Letter, we report the first measurement of a set of  $CP$ -violating kinematic asymmetries in  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  decays. The set of kinematic asymmetries probes the rich variety of interfering contributions in a decay, which can be sensitive to non-SM  $CP$ -violating phases.

Assuming  $CPT$  symmetry, we construct a  $CP$ -violating asymmetry by comparing amplitudes of the decay with their  $CP$ -conjugate amplitudes. Amplitudes of the decay can be extracted from  $\mathcal{A}_X$ , which we define as

$$\mathcal{A}_X \equiv \frac{\Gamma(X > 0) - \Gamma(X < 0)}{\Gamma(X > 0) + \Gamma(X < 0)}, \quad (1)$$

where  $X$  is a kinematic variable, such as the vector triple product of the final-state momenta used in Ref. [6, 7],  $\Gamma(X > 0)$  is the rate for  $D^0$  decays in which  $X > 0$ ; and  $\Gamma(X < 0)$ , for  $D^0$  decays in which  $X < 0$ . The  $CP$ -conjugated amplitudes can be extracted similarly for  $\bar{D}^0$  decays using  $\bar{X}$ . We can then define our  $CP$ -violating kinematic asymmetry as

$$a_X^{CP} \equiv \frac{1}{2} (\mathcal{A}_X - \eta_X^{CP} \bar{\mathcal{A}}_{\bar{X}}), \quad (2)$$

where  $\eta_X^{CP}$  is a  $CP$  eigenvalue specific to  $X$ .

We measure a set of kinematic asymmetries for five different  $X$ , where four asymmetries are measured for the first time and one asymmetry is proportional to the  $\hat{T}$ -odd correlation using the vector triple product of the

final-state momenta, which has been measured previously [6, 7]. The set can be sensitive to  $CP$  violation in the interference between the  $S$ -wave and  $P$ -wave production of the  $K^+ K^-$  and  $\pi^+ \pi^-$  pairs in the  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  decay. It covers the asymmetries that can be measured without considering the mass of the intermediate particles. The kinematic variables are constructed from the angles  $\theta_1$ ,  $\theta_2$ , and  $\Phi$ , where  $\theta_1$  is the angle between the  $K^+$  momentum and the direction opposite to that of the  $D^0$  momentum in the center-of-mass (CM) frame of the  $K^+ K^-$  system,  $\theta_2$  is defined in the same way as  $\theta_1$  substituting  $K^+$  with  $\pi^+$  and  $K^+ K^-$  with  $\pi^+ \pi^-$ , and  $\Phi$  is the angle between the decay planes of the  $K^+ K^-$  and  $\pi^+ \pi^-$  pairs in the CM frame of  $D^0$ . Three kinematic variables have  $\eta_X^{CP} = -1$ :  $\sin 2\Phi$ ,  $\cos \theta_1 \cos \theta_2 \sin \Phi$ , and  $\sin \Phi$ ; the last variable is proportional to the vector triple product of the final-state momenta. The remaining two kinematic variables have  $\eta_X^{CP} = +1$ :  $\cos \Phi$  and  $\cos \theta_1 \cos \theta_2 \cos \Phi$ . The kinematic asymmetries where  $\eta_X^{CP}$  is  $-1$ , commonly known as  $\hat{T}$ -odd correlations, are dependent on the imaginary part of the interference of amplitudes for production of the  $K^+ K^-$  and  $\pi^+ \pi^-$  states in different spin configurations [9–12]. The asymmetries where  $\eta_X^{CP}$  is  $+1$ , are dependent on the real part of the interference of amplitudes. Both types of asymmetries are non-zero in the case of  $CP$  violation. This set is measured for the first time for any four-body final state; these measurements can be performed for any other pseudoscalar meson that decays to four pseudoscalar mesons.

This analysis uses the data sample recorded by the Belle detector [13] at the  $e^+e^-$  asymmetric-energy collider KEKB [14], where the CM energy of the collisions was varied from the mass of the  $\Upsilon(1S)$  resonance up to that of the  $\Upsilon(6S)$  resonance. The total data sample corresponds to an integrated luminosity of  $988 \text{ fb}^{-1}$  [15].

Monte Carlo (MC) samples are used to devise the selection criteria, identify the different sources of background, model the data, validate the fit procedure, and determine systematic uncertainties. Inclusive MC samples were generated with **EvtGen** [16], where the number of generated events corresponds to six times the integrated luminosity of the data sample. The detector response was simulated with **GEANT3** [17]. To simulate the effect of beam-induced background, the generated events have data solely due to the beam backgrounds overlaid.

Since the final state is self-conjugate, the flavor of the  $D^0$  mesons is identified by reconstructing the de-

cay chains  $D^{*+} \rightarrow D^0 \pi_s^+$ , with  $D^0$  decaying into  $K^+ K^- \pi^+ \pi^-$ , where  $\pi_s^+$  is referred to as the slow pion. Here, and elsewhere in this Letter, charge-conjugate states are implied unless stated explicitly otherwise.

We select charged tracks that originate from close to the  $e^+e^-$  interaction point (IP) by requiring the impact parameters to be less than 4 cm in the beam direction and 2 cm in the plane transverse to the beam direction. To ensure the tracks are well reconstructed, we require they each have a transverse momentum greater than 0.1 GeV/c and at least two associated hits in the silicon vertex detector in both the beam direction and azimuthal direction. Charged tracks are identified as pions or kaons depending on the ratio of particle identification likelihoods  $\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$ , which are constructed from information recorded by the central drift chamber, time-of-flight scintillation counters, and aerogel threshold Cherenkov counter. We identify a charged track as a kaon when this ratio is above 0.6; otherwise it is assumed to be a pion. The kaon and pion identification efficiencies are typically over 80%, and the misidentification probabilities are below 10% [18].

We form a  $D^0$  candidate from each combination of two oppositely charged kaon tracks and two oppositely charged pion tracks. We require each  $D^0$  candidate have an invariant mass within 0.1 GeV/ $c^2$  of the nominal  $D^0$  mass [1, 19], where the range is larger than 10 times the mass resolution of the reconstructed  $D^0$  candidate, and a momentum in the CM frame greater than 1.8 GeV/c. For each surviving candidate, we perform a vertex- and mass-constrained fit to the kaons and pions; we require the vertex fit to have a probability greater than 0.1%. We also perform a fit where each candidate is fit under the hypothesis that the trajectory of the candidate originates from the IP and require the fit to have a probability greater than 0.005%.

To veto the Cabibbo-favored  $D^0 \rightarrow K^+ K^- K_s^0$  decays, we veto  $D^0$  candidates whose daughter pion pairs have invariant masses within 12.05 MeV/ $c^2$  of the nominal  $K_s^0$  mass [1], which is five times the mass resolution of the reconstructed  $K_s^0$  candidate.

We form each combination of a positively charged pion track and  $D^0$  candidate into a  $D^{*+}$  candidate and perform a vertex fit on the pion, where the fit is constrained to the intersection of the  $D^0$  candidate trajectory with the IP region. We require each  $D^{*+}$  candidate have a momentum in the CM frame greater than 2.5 GeV/c. We also require the  $D^{*+}$  candidate have a mass difference ( $\Delta m$ ) with respect to its daughter  $D^0$  less than 0.16 GeV/ $c^2$ .

After these selection criteria, 24% of events have multiple  $D^{*+}$  and/or  $D^{*-}$  candidates. We select either a  $D^{*+}$  or  $D^{*-}$  candidate for each event, based on the smallest  $\chi^2$  for the  $D^0$  mass fit. If there are multiple  $D^{*+}$  and/or  $D^{*-}$  candidates formed with this  $D^0$ , we select the one whose  $\pi_s^+$  or  $\pi_s^-$  has the smallest impact parameter in the

transverse plane. Studies with the MC sample indicate that 93% of the multiple-candidate events are correctly selected. The efficiency for the  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  decay with the stated selections is 11%. A total of 474,971 events are reconstructed from the data sample.

After all selection criteria, our data sample contains events that fall into four different categories: correctly reconstructed  $D^0$  mesons coming from correctly reconstructed  $D^{*+}$  mesons, which we call signal events; events with correctly reconstructed  $D^0$  mesons coming from misreconstructed  $D^{*+}$  candidates, which we call random- $\pi_s$  events; events with a partially reconstructed  $D^0$  candidate and the  $\pi_s^+$  from a  $D^{*+}$ , which we call partial- $D^*$  events; and events with both  $D^0$  and  $D^{*+}$  candidates misreconstructed, which we call combinatorial events.

We calculate the  $CP$ -violating kinematic asymmetry with the yield of the signal events for each flavor of  $D^0$  and each sign of the relevant kinematic variable. To do this, we perform four separate fits to the data for each kinematic variable. Each fit is a binned two-dimensional extended maximum-likelihood fit to the reconstructed  $D^0$  mass and  $\Delta m$ . The data used in the fit are limited to those within 30 MeV/ $c^2$  of the nominal  $D^0$  mass [1, 19] for  $m(K^+ K^- \pi^+ \pi^-)$  and within  ${}^{+7.6}_{-5.9}$  MeV/ $c^2$  of the nominal  $\Delta m$  [1], where the lower limit corresponds to the nominal  $\pi^\pm$  mass. The data are binned into 200 equal-width bins in each dimension. These additional requirements on  $m(K^+ K^- \pi^+ \pi^-)$  and  $\Delta m$  have a negligible effect on the selection efficiency.

One model is used for all fits. It contains components describing signal, random  $\pi_s$ , partial- $D^*$ , and combinatorial events. The yield of each component is free in each fit, but parameters governing the shapes of the components are fixed from a single fit to all the data regardless of  $D^0$  flavor and  $X$ .

The signal component is the product of a sum of bifurcated Gaussian and Gaussian probability density functions (PDFs) for  $m(K^+ K^- \pi^+ \pi^-)$  and a sum of Gaussian and JohnsonSU [20] PDFs for  $\Delta m$ . The combinatorial component is the product of a Chebyshev function for  $m(K^+ K^- \pi^+ \pi^-)$  and a threshold function for  $\Delta m$ . The random- $\pi_s$  component is the product of the signal shape for  $m(K^+ K^- \pi^+ \pi^-)$  and the combinatorial shape for  $\Delta m$ . And the partial- $D^*$  component is the product of a Chebyshev function for  $m(K^+ K^- \pi^+ \pi^-)$  and a Bifurcated Gaussian PDF for  $\Delta m$ , where the shape parameters for the partial- $D^*$  component are fixed to those obtained from a fit to an inclusive MC sample.

Figure 1 shows the results of the fit to all the data, from which the shapes of all components are fixed for all remaining fits; the model agrees well with the data, as can be seen from the pulls, which are defined as the difference between the data points and the model expectation divided by the expectation uncertainty. As an example of a set of fits used to determine the  $CP$ -violating kinematic asymmetry, we show separate fit results for positive

TABLE I. Fit results for the yield of signal in the subsamples of each kinematic variable  $X$ . The uncertainties are statistical only.

| $X$                                     | $D^0 (X > 0)$    | $D^0 (X < 0)$    | $\bar{D}^0 (\bar{X} > 0)$ | $\bar{D}^0 (\bar{X} < 0)$ |
|-----------------------------------------|------------------|------------------|---------------------------|---------------------------|
| $\cos \Phi$                             | $21,913 \pm 181$ | $32,544 \pm 216$ | $21,657 \pm 180$          | $32,623 \pm 216$          |
| $\sin \Phi$                             | $29,177 \pm 205$ | $25,277 \pm 194$ | $25,474 \pm 194$          | $28,800 \pm 204$          |
| $\sin 2\Phi$                            | $23,096 \pm 187$ | $31,355 \pm 211$ | $31,455 \pm 211$          | $22,805 \pm 186$          |
| $\cos \theta_1 \cos \theta_2 \cos \Phi$ | $31,065 \pm 211$ | $23,398 \pm 188$ | $30,963 \pm 210$          | $23,304 \pm 187$          |
| $\cos \theta_1 \cos \theta_2 \cos \Phi$ | $26,016 \pm 196$ | $28,441 \pm 203$ | $28,353 \pm 203$          | $25,919 \pm 195$          |

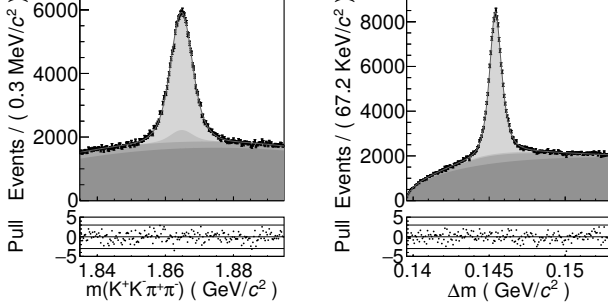


FIG. 1. Data (black points) and fit results (shaded regions) for the fit to all the data in projections of  $m(K^+K^-\pi^+\pi^-)$  (left) and  $\Delta m$  (right). The shaded regions are stacked upon each other and show, from lowest to highest, the combinatorial, partial- $D^*$ , random- $\pi_s$ , and signal components. The lower plots show the pulls for the fit; the unlabeled horizontal lines indicate  $\pm 3$ .

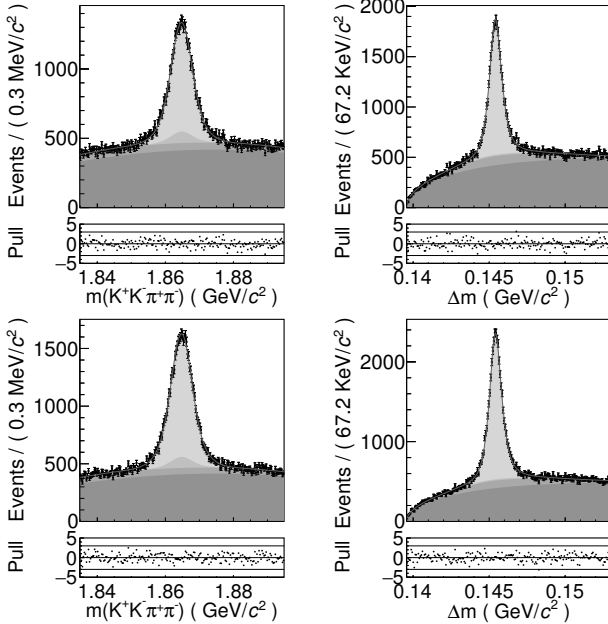


FIG. 2. Two-dimensional fit results, distributions and pull of the data subsamples projected on the observables  $m(K^+K^-\pi^+\pi^-)$  (left) and  $\Delta m$  (right). The distribution sequence follows Fig. 1. Top histograms show the  $D^0 (\sin 2\Phi > 0)$  subsample while the bottom histograms show the  $D^0 (\sin 2\Phi < 0)$  subsample.

and negative  $\sin 2\Phi$  for  $D^0$  samples in Fig. 2. The signal yields determined by the fits are given in Table I for each  $D^0$  flavor and kinematic variable sign.

Several sources of systematic uncertainty are considered. Individual uncertainties and the total systematic uncertainty are listed in Table II. The bias from the model PDF is estimated by changing the signal model, partial- $D^*$  model, and combinatorial model. We change the signal model and partial- $D^*$  model to products of one-dimensional Gaussian-kernel-estimated PDFs [21] and the combinatorial model to a product of one-dimensional PDFs obtained from an inclusive MC sample. The difference between the measured values is assigned as a systematic uncertainty.

The detector bias is estimated from a control sample of  $D^0 \rightarrow K^-\pi_{\text{low}}^+\pi^-\pi_{\text{high}}^+$  events, where momentum is used to differentiate between the  $\pi_{\text{high}}^+$  and  $\pi_{\text{low}}^+$ . This decay is Cabibbo-favored in which all kinematic asymmetries are expected to be much smaller than the measurement precision [4]. The kinematic variables are calculated in the same way as for the  $K^+K^-\pi^+\pi^-$  final state, substituting  $K^+$  with  $\pi_{\text{low}}^+$ . The kinematic asymmetries are found to be consistent with zero, and we assign their statistical uncertainties as the systematic uncertainties related to any detector bias.

The detector resolution of the kinematic variables could affect the kinematic asymmetries. The kinematic asymmetries are measured with an inclusive MC sample where  $CP$  is conserved for the  $K^+K^-\pi^+\pi^-$  decay. They are consistent with zero, and we conservatively assign their statistical uncertainties as the systematic uncertainties related to the detector resolution.

We estimate the impact of incorrectly assigning the flavor of the  $D^0$  by using an MC sample and find that it does not affect the kinematic asymmetries.

To assess whether there is a bias introduced by the likelihood fit and to check the extraction of kinematic asymmetries from the two-dimensional binned fit, we generate MC samples with different asymmetries and compare the fit results with the generated values. The average difference between the measured and generated value is assigned as a systematic uncertainty.

The various sources of systematic uncertainty are independent of each other. Therefore we estimate the total

TABLE II. Contributions to the systematic uncertainty (in per mille) for each  $CP$ -violating kinematic asymmetry  $a_X^{CP}$ .

| Effect                      | $a_{\cos \Phi}^{CP}$ | $a_{\sin \Phi}^{CP}$ | $a_{\sin 2\Phi}^{CP}$ | $a_{\cos \theta_1 \cos \theta_2 \cos \Phi}^{CP}$ | $a_{\cos \theta_1 \cos \theta_2 \sin \Phi}^{CP}$ |
|-----------------------------|----------------------|----------------------|-----------------------|--------------------------------------------------|--------------------------------------------------|
| Signal model PDF            | 0.1                  | 0.3                  | 0.1                   | 0.2                                              | 0.0                                              |
| Partial- $D^*$ model PDF    | 0.1                  | 0.1                  | 0.2                   | 0.2                                              | 0.0                                              |
| Combinatorial model PDF     | 0.1                  | 0.1                  | 0.3                   | 0.0                                              | 0.3                                              |
| Detector bias               | 0.6                  | 0.6                  | 0.6                   | 0.6                                              | 0.6                                              |
| Detector resolution         | 1.6                  | 1.6                  | 1.6                   | 1.5                                              | 1.5                                              |
| Incorrect flavor assignment | 0.0                  | 0.0                  | 0.0                   | 0.0                                              | 0.0                                              |
| Likelihood fit bias         | 0.1                  | 0.1                  | 0.1                   | 0.1                                              | 0.1                                              |
| Total                       | 1.7                  | 1.7                  | 1.8                   | 1.6                                              | 1.6                                              |

systematic uncertainty by summing the uncertainties in quadrature. As a note, the kinematic asymmetries are constructed such that they are insensitive to the intrinsic production asymmetry [7].

We find the  $CP$ -violating kinematic asymmetries to be

$$a_{\cos \Phi}^{CP} = (3.4 \pm 3.6 \pm 1.7) \times 10^{-3}, \quad (3)$$

$$a_{\sin \Phi}^{CP} = (5.2 \pm 3.7 \pm 1.7) \times 10^{-3}, \quad (4)$$

$$a_{\sin 2\Phi}^{CP} = (3.9 \pm 3.6 \pm 1.8) \times 10^{-3}, \quad (5)$$

$$a_{\cos \theta_1 \cos \theta_2 \cos \Phi}^{CP} = (-0.2 \pm 3.6 \pm 1.6) \times 10^{-3}, \quad (6)$$

$$a_{\cos \theta_1 \cos \theta_2 \sin \Phi}^{CP} = (0.2 \pm 3.7 \pm 1.6) \times 10^{-3}, \quad (7)$$

where the first and second uncertainties are statistical and systematic, respectively.

In conclusion, we search for  $CP$  violation in  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  by measuring a set of five kinematic asymmetries. The set of measurements can be sensitive to  $CP$  violation via the rich variety of interference between the different partial-wave contributions to the decay. It can be performed on any other pseudoscalar meson that decays into four pseudoscalar mesons. Four asymmetries are measured for the first time. The set of  $CP$ -violating kinematic asymmetries is consistent with  $CP$  conservation and provide new constraints on new physics models [4, 8, 10].

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