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Search for *CP* Violation in the Decays $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$

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We measure CP-violating asymmetries of neutral charmed mesons in the modes $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ with the highest precision to date by using $D^0 \to K^-\pi^+$ decays to correct detector asymmetries. An analysis of $385.8\,\mathrm{fb}^{-1}$ of data collected with the BaBar detector yields values of $a_{CP}^{KK} = (0.00 \pm 0.34\,(\mathrm{stat.}) \pm 0.13\,(\mathrm{syst.}))\%$ and $a_{CP}^{\pi\pi} = (-0.24 \pm 0.52\,(\mathrm{stat.}) \pm 0.22\,(\mathrm{syst.}))\%$, which agree with Standard Model predictions.

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Charge-parity (CP) violation in decays of charmed mesons at levels as large as 1% has not yet been experimentally ruled out [1], and at this level would be evidence of unknown physical phenomena [2, 3]. The *CP*-even decays $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ [4] are Cabibbo suppressed, with the two neutral charmed mesons, D^0 and $\overline{D}^0$, sharing the final states. *CP*-violating asymmetries in these modes are predicted to be $\mathcal{O}(0.001\%–0.01\%)$ in the Standard Model of particle physics [5], yet have not been measured precisely due to limited sample sizes and relatively large systematic effects [6].

We search for *CP* violation in decays of charmed mesons produced from charm-quark pairs in the reaction $e^+e^- \to c\bar{c}$ by measuring the asymmetries in the partial decay widths, Γ,

$$a_{CP}^{KK} = \frac{\Gamma(D^0 \to K^-K^+) - \Gamma(\overline{D}^0 \to K^+K^-)}{\Gamma(D^0 \to K^-K^+) + \Gamma(\overline{D}^0 \to K^+K^-)} \quad (1)$$

$$a_{CP}^{\pi\pi} = \frac{\Gamma(D^0 \to \pi^-\pi^+) - \Gamma(\overline{D}^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^-\pi^+) + \Gamma(\overline{D}^0 \to \pi^+\pi^-)}. \quad (2)$$

In this construction, a_{CP}^{hh}, $h = K, \pi$, includes all *CP* violating contributions, direct and indirect [2]. The presence of direct *CP* violation in one or both modes would be signaled by a non-vanishing difference between the modes, $a_{CP}^{KK} - a_{CP}^{\pi\pi} \neq 0$.

Precise quantification of asymmetry in D^0-flavor assignment, called tagging, has long been considered the primary experimental challenge in these measurements. We develop a new technique for measuring and correcting this asymmetry using only the recorded data. However, forward-backward (FB) asymmetry in $c\bar{c}$ production may be more significant at the center-of-mass energy of e^+e^- collisions in *BABAR*, $\sqrt{s} \approx 10.6\,\text{GeV}$. This production asymmetry will create a difference in the numbers of reconstructed D^0 and $\overline{D}^0$ events due to the FB detection asymmetries coming from the boost of the center-of-mass system (CMS) relative to the laboratory.

The production asymmetry has two physical components. Interference in $e^+e^- \to c\bar{c}$ as mediated by either a virtual γ or a virtual Z^0 contributes at the percent level at this energy, and is well understood. In addition, asymmetries induced by higher-order QED effects are expected to have polar angle dependence and to peak sharply in the forward and backward directions [7]. Although well-considered for μ-pair production [8], the precise shape of this contribution for D production is not known.

We use a data sample corresponding to an integrated luminosity of $385.8\,\text{fb}^{-1}$ collected with the *BABAR* detector [9] at the PEP-II e^+e^- collider at SLAC. The production vertices of charged particles are measured with a silicon-strip detector (SVT), and their momenta are measured by the SVT and a drift chamber (DCH) in a $1.5\,\text{T}$ magnetic field. Information from a Cherenkov-radiation detector, along with energy-deposition measurements from the SVT and DCH, provide K-π discrimination.

We analyze neutral D mesons produced from $D^{*+} \to D^0\pi_s^+$; the charge of the π_s, a low momentum (soft) pion, indicates the flavor of the D^0 at production. To correct for asymmetry in this flavor tag, we measure the relative detection efficiency for soft pions in recorded data using the decay $D^0 \to K^-\pi^+$ with (tagged) and without (non-tagged) soft-pion flavor tagging. The only detector asymmetry present in reconstruction of the signal modes is due to the tagging π_s, since the *CP* final states are reconstructed identically for D^0 and $\overline{D}^0$.

We reconstruct the four decay chains $D^0 \to K^-\pi^+$; $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+$; $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-K^+$; and $D^{*+} \to D^0\pi_s^+$, $D^0 \to \pi^-\pi^+$. We require D^0 candidates to have center-of-mass momenta greater than $2.4\,\text{GeV}/c$, which removes almost all B decays. Each D^0 daughter must satisfy a likelihood-based particle-identification selection and must have at least two position measurements in each of the z and ϕ coordinates of the SVT. We require $\pi_s^\pm$ candidates to have a lab momentum greater than $100\,\text{MeV}/c$ and at least six position measurements in the SVT.

For $h = K, \pi$, we accept candidates with an invariant mass $1.79 < m_{hh} < 1.93\,\text{GeV}/c^2$ and, for final states with a π_s, an invariant mass difference $0.140 < \Delta m < 0.152\,\text{GeV}/c^2$, where $\Delta m \equiv m_{hh\pi_s} - m_{hh}$. For each D^0 candidate, we constrain the h^+h^- tracks to originate from a common vertex; for applicable final states, we also require the D^0 and π_s to originate from a common vertex within the e^+e^- interaction region. We select candidates for which the χ^2 probability of the vertex fit of the two D^0 daughters is greater than 0.005. For the KK and $\pi\pi$ modes, final asymmetries are calculated using events for which the polar angle of the D^0 momentum in the CMS with respect to the beam axis satisfies $|\cos\theta_{D^0}^{\text{CMS}}| < 0.8$.

We statistically separate signal from background in the selected events by calculating signal weights based on an optimized likelihood function [10]. The likelihood function is composed of probability density functions (PDFs) that are fitted to the mass distributions using the maximum likelihood technique. For the non-tagged sample, a one-dimensional PDF is fitted to the $m_{K\pi}$ distribution; for the tagged samples, two-dimensional PDFs are fitted to the m_{hh} and Δm distributions. Two-dimensional PDFs are used for the tagged samples to account for possible asymmetries in the background from correctly reconstructed D^0 decays with a misassociated π_s candidate; this background category peaks in m_{hh} but does not peak in Δm. The PDFs in this analysis are nearly identical to those used in an analysis of the decay $D^0 \to K^+\pi^-$ [11], since the signal shapes and background sources are very similar. Although the PDFs are motivated by studies of simulated events, all of the shape parameters are varied in the fits to recorded data. Our selection of PDFs is treated as a source of systematic uncertainty. Because the signal shape is indistinguishable for D^0 and $\overline{D}^0$ distributions, we use the same signal PDF

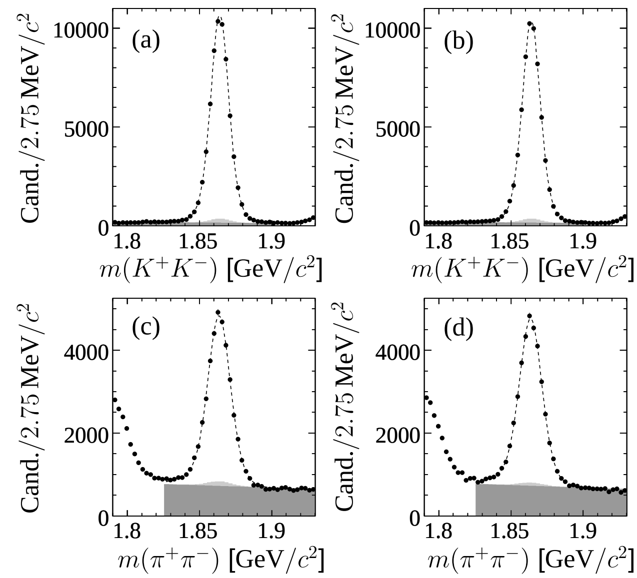

FIG. 1: Invariant mass distributions of the KK final state tagged as (a) D^0 and (b) $\overline{D}^0$, and the $\pi\pi$ final state tagged as (c) D^0 and (d) $\overline{D}^0$. Distributions of data (points with error bars) in the signal region $0.1434 < \Delta m < 0.1474\,\mathrm{GeV}/c^2$ are overlaid with fitted PDFs (dashed line, shaded areas). The white regions under the central peaks represent signal events, the light gray misassociated $\pi_s^\pm$ events, and the dark gray remaining nonpeaking background. The data are shown over ranges extended beyond the fitted regions to illustrate the physical background shapes.

to describe both flavors of a mode and fit it to them simultaneously to reduce statistical uncertainties. The KK and $\pi\pi$ invariant mass distributions for D^0 and $\overline{D}^0$, with fitted PDFs overlaid, are shown in Fig. 1. This analysis is sensitive only to ratios of D^0-signal yields to $\overline{D}^0$-signal yields, and not to absolute yields, so the final results are relatively insensitive to the exact forms of the PDFs.

The decay $D^0 \to K^-\pi^+$ is chosen as a calibration mode because it provides an easily reconstructed independent sample with high statistics. However, detector asymmetries in reconstruction of the D^0 final state cannot be ignored (see Fig. 2(a,b)). These must be corrected to isolate the soft-pion asymmetry.

Using the non-tagged $K\pi$ sample, we produce a map of the relative reconstruction efficiency between D^0 and $\overline{D}^0$ in this final state in terms of the momenta of both D^0 daughters, shown by components in Fig. 2(a,b). For each D^0 daughter, we consider the momentum magnitude and polar angle in the lab with respect to the beam axis; these components are correlated. The daughters are, however, factorizable from one another. By considering the normalized product of the K and π efficiency-map components, we obtain a four-dimensional relative-efficiency map for correcting $D^0 \to K^-\pi^+$ relative to $\overline{D}^0 \to K^+\pi^-$. The presence of prompt D^0 decays not originating from a D^{*+} in the non-tagged sample extends

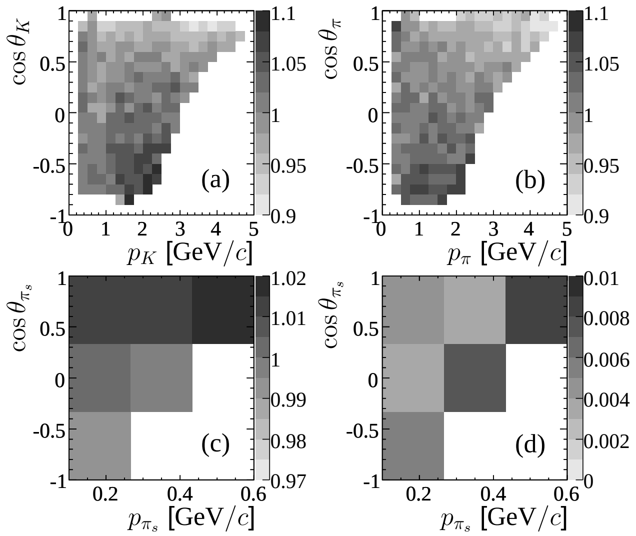

FIG. 2: $K\pi$ efficiency-map components obtained from the non-tagged D^0 daughters (a) K and (b) π, and (c) π_s efficiency map with (d) statistical errors from the tagged $K\pi$ sample. Maps are produced from the ratios of candidate numbers of D^0 to $\overline{D}^0$.

the kinematic boundaries of the map but does not otherwise affect it.

This $K\pi$ map is used to weight the D^0 candidates in the slow-pion tagged $K\pi$ sample, eliminating asymmetries due to the $D^0/\overline{D}^0$ daughters. Because all charm production is subject to the same production asymmetries, these are simultaneously removed from the tagged $K\pi$ sample by this correction. After the weights have been applied, the remaining asymmetry in the sample is due to the relative soft-pion efficiency.

We produce a map of the relative soft-pion efficiency in terms of the pion-momentum magnitude and polar angle in the lab (Fig. 2(c)). Charm production is azimuthally uniform, and ϕ is found to be uncorrelated with other momentum variables. Therefore, the ϕ dependence is accounted for by an integrated scale factor. The uncertainties shown (Fig. 2(d)) are due to the statistical uncertainties in the sample yields. Signal-mode D^0 yields are weighted with this π_s map to correct for the soft-pion tagging asymmetry. The signal modes (with remaining production asymmetries) can thus be analyzed for evidence of CP violation. In Table I, we list the raw and post-correction yields for the calibration and signal samples in this analysis. In calculating these corrections, histogram bins near kinematic boundaries with fewer than 5,000 events are removed.

CP violation would appear as an asymmetry in $D^0/\overline{D}^0$ yields, independent of any kinematic variables. Because of the FB asymmetry in production, we calculate yield asymmetries as a function of $\cos\theta = \cos\theta^{\rm CMS}_{D^0}$ and de-

TABLE I: Signal yields in reconstructed modes. Listed uncertainties are statistical only. Corrections are applied only to D^0 samples, but all post-correction samples are restricted to the phase space of the correction map.

Final state	Raw yields D^0	Raw yields $\overline{D}^0$	Post-correction yields Corr. used	Post-correction yields D^0	Post-correction yields $\overline{D}^0$
$K\pi$	3,363,000 ± 6,000	3,368,000 ± 6,000	none	—	—
$K\pi\pi_s$	705,100 ± 1,000	703,500 ± 1,000	$K\pi$ map	633,300	630,100
$KK\pi_s$	65,730 ± 340	63,740 ± 330	π_s map	65,210	63,490
$\pi\pi\pi_s$	32,210 ± 310	31,930 ± 310	π_s map	31,900	31,760

compose these into even and odd parts. We define

$$a^{\pm}(\cos\theta) = \frac{n_{D^0}(\pm|\cos\theta|) - n_{\overline{D}^0}(\pm|\cos\theta|)}{n_{D^0}(\pm|\cos\theta|) + n_{\overline{D}^0}(\pm|\cos\theta|)} \quad (3)$$

$$a_{CP} = a_{CP}(\cos\theta) \approx \left(a^{+}(\cos\theta) + a^{-}(\cos\theta)\right)/2 \quad (4)$$

$$a_{\rm FB}(\cos\theta) \approx \left(a^{+}(\cos\theta) - a^{-}(\cos\theta)\right)/2, \quad (5)$$

where n_{D^0} and $n_{\overline{D}^0}$ are the numbers of signal events for D^0 and $\overline{D}^0$ after applying the weights discussed above, a_{CP} is the even component and $a_{\rm FB}(\cos\theta)$ the odd component. Eqs. 4 and 5 are approximate as second-order terms in $a^{\pm}$ have been omitted. The even part, representing CP-violating effects, would provide evidence of a uniform yield asymmetry. The odd part represents the production asymmetry, including higher-order QED contributions. From the several values of a_{CP} obtained as a function of $|\cos\theta|$, we obtain a central value from a χ^2 minimization.

We consider three sources of systematic error to be significant. One source is the choice of PDFs used to describe the signal and background distributions, which affects the statistical background subtraction. We estimate this systematic uncertainty by substituting different background shapes in m and Δm and an alternative two-dimensional signal shape in the fits to the tagged samples. Another source is the binning choices made and dependences in the π_s-efficiency correction. We estimate the size of this uncertainty by varying the number of bins and the required number of events per bin in histograms used to calculate efficiencies, and by adding a ϕ dependence to the efficiency correction. We find the largest uncertainty here arises from the particular choice of binning in the π_s-efficiency map. Because the systematic uncertainty in applying the π_s-efficiency correction is the same for both modes, we evaluate its size using

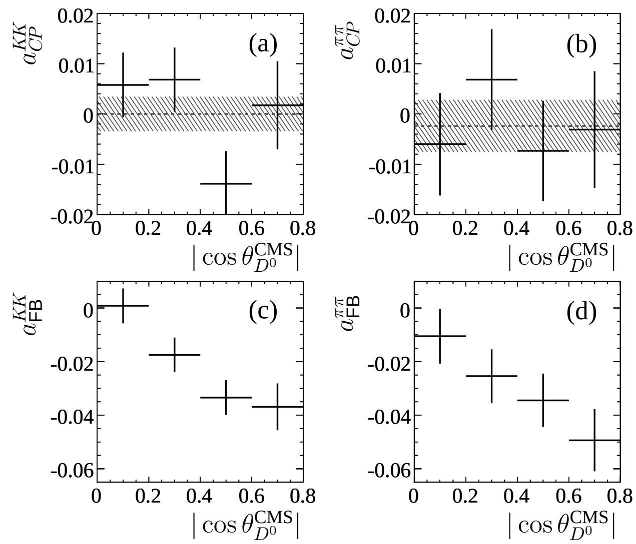

FIG. 3: CP-violating asymmetries in (a) KK and (b) $\pi\pi$, and forward-backward asymmetries in (c) KK and (d) $\pi\pi$. In (a) and (b), the dashed lines represent the central values and the hatched regions the 1σ intervals, obtained from χ^2 minimizations.

the larger signal sample. Finally, we consider the procedure for extracting a_{CP}. We vary the binning and the accepted range of $|\cos\theta|$; the largest uncertainty comes from the latter. All other sources of systematic uncertainty are highly suppressed because the final states are reconstructed identically for D^0 and $\overline{D}^0$. We summarize the contributions to the total systematic uncertainty in Table II. The smaller $\pi\pi$ sample size influences the calculation of its systematic uncertainty.

TABLE II: Summary of systematic uncertainties.

Category	Δa_{CP}^{KK}	$\Delta a_{CP}^{\pi\pi}$
2-Dim. PDF shapes	±0.04%	±0.05%
π_s correction	±0.08%	±0.08%
a_{CP} extraction	±0.09%	±0.20%
Quadrature sum	±0.13%	±0.22%

For KK, we measure $a_{CP}^{KK} = (0.00 \pm 0.34\,(\text{stat.}) \pm 0.13\,(\text{syst.}))\%$. For $\pi\pi$, we measure $a_{CP}^{\pi\pi} = (-0.24 \pm 0.52\,(\text{stat.}) \pm 0.22\,(\text{syst.}))\%$. Statistical uncertainties of 0.1% in the π_s correction have been included in the final statistical uncertainty values. The even and odd asymmetries for each mode as a function of $|\cos\theta|$ are shown in Fig. 3. We conclude from the χ^2 minimizations in Fig. 3(a,b) that there is no evidence of CP violation in either of the Cabibbo-suppressed two-body modes of D^0 decay. This result is in agreement with Standard Model predictions. It also provides a new constraint on theories beyond the Standard Model [3], some of which predict significant levels of CP violation in these modes. The asymmetries observed in Fig. 3(c,d) represent the two Standard Model asymmetries discussed. Although an exact prediction of these forward-backward asymmetries does not exist, the observed values are consistent with expectations.

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