

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

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(Received 31 August 2007; published 15 February 2008)

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

Evidence for quantum-mechanical oscillations in neutral charmed mesons has recently been reported [1,2], increasing the importance of understanding the relative behaviors in this particle-antiparticle system. Unknown processes could contribute significantly to these oscillations, and there are many theoretical scenarios in which particle-antiparticle asymmetries are also expected. Charge-parity ( $CP$ ) violation in time-integrated decay rates of charmed mesons at levels as large as 1% has not yet been experimentally ruled out [3], and at this level would be evidence of unknown physical phenomena [4,5]. The  $CP$ -even decays  $D^0 \rightarrow K^- K^+$  and  $D^0 \rightarrow \pi^- \pi^+$  [6] are Cabibbo suppressed, with the two neutral charmed mesons,  $D^0$  and  $\bar{D}^0$ , 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 [7], yet have not been measured precisely due to limited sample sizes and relatively large systematic effects [8].

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

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

$$a^{\pi\pi} = \frac{\Gamma(D^0 \rightarrow \pi^- \pi^+) - \Gamma(\bar{D}^0 \rightarrow \pi^+ \pi^-)}{\Gamma(D^0 \rightarrow \pi^- \pi^+) + \Gamma(\bar{D}^0 \rightarrow \pi^+ \pi^-)}. \quad (2)$$

In this construction,  $a_{CP}^{hh}$ ,  $h = K, \pi$ , includes all  $CP$  violating contributions, direct and indirect [4]. The presence of direct  $CP$  violation in one or both modes would be signaled by a nonvanishing difference between the modes,  $a_{CP}^{KK} - a_{CP}^{\pi\pi} \neq 0$ . Indirect  $CP$ -violating asymmetries in these modes arising from  $D^0$ - $\bar{D}^0$  oscillations have been measured in analyses of decay-time distributions [9], most recently with a precision of 0.30% [2].

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*,  $\sqrt{s} \approx 10.6$  GeV. This production asymmetry will create a difference in the numbers of reconstructed  $D^0$  and  $\bar{D}^0$  events due to the FB detection asymmetries coming from the boost of the center-of-mass system (c.m.s.) relative to the laboratory.

The production asymmetry has two physical components. Interference in  $e^+ e^- \rightarrow c\bar{c}$  as mediated by either a virtual  $\gamma$  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 [10]. Although well considered for  $\mu$ -pair production [11], 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 [12] 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 T magnetic field. Information from a Cherenkov-radiation detector, along with energy-deposition measurements from the SVT and DCH, provide  $K$ - $\pi$  discrimination.

We analyze neutral  $D$  mesons produced from  $D^{*+} \rightarrow D^0 \pi_s^+$ ; the charge of the  $\pi_s$ , 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  $D^0 \rightarrow K^- \pi^+$  with (tagged) and without (nontagged) soft-pion flavor tagging. The only detector asymmetry present in reconstruction of the signal modes is due to the tagging  $\pi_s$ , since the  $CP$  final states are reconstructed identically for  $D^0$  and  $\bar{D}^0$ .

We reconstruct the four decay chains  $D^0 \rightarrow K^- \pi^+$ ;  $D^{*+} \rightarrow D^0 \pi_s^+$ ,  $D^0 \rightarrow K^- \pi^+$ ;  $D^{*+} \rightarrow D^0 \pi_s^+$ ,  $D^0 \rightarrow K^- K^+$ ; and  $D^{*+} \rightarrow D^0 \pi_s^+$ ,  $D^0 \rightarrow \pi^- \pi^+$ . We require  $D^0$  candidates to have center-of-mass momenta greater than 2.4 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  $\phi$  coordinates of the SVT. We require  $\pi_s^\pm$  candidates to have a lab momentum greater than 100 MeV/ $c$  and at least six position measurements in the SVT.

For  $h = K, \pi$ , we accept candidates with an invariant mass  $1.79 < m_{hh} < 1.93$  GeV/ $c^2$  and, for final states with a  $\pi_s$ , an invariant mass difference  $0.140 < \Delta m < 0.152$  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  $\pi_s$  to originate from a common vertex within the  $e^+ e^-$  interaction region. We select candidates for which the  $\chi^2$  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 c.m.s. with respect to the beam axis satisfies  $|\cos\theta_{D^0}^{c.m.s.}| < 0.8$ .

We statistically separate signal from background in the selected events by calculating signal weights based on an optimized likelihood function [13]. The likelihood function is composed of probability density functions (PDFs) that are fitted to the mass distributions using the maximum likelihood technique. For the nontagged 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  $\Delta m$  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  $\pi_s$  candidate; this background category peaks in  $m_{hh}$  but does not peak in  $\Delta m$ . The PDFs in this analysis are nearly identical to those used in an analysis of the decay  $D^0 \rightarrow K^+ \pi^-$  [1], 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  $\bar{D}^0$  distributions, we use the same signal PDF 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  $\bar{D}^0$ , with fitted PDFs overlaid, are shown in Fig. 1. This analysis is sensitive only to ratios of  $D^0$ -signal yields to  $\bar{D}^0$ -signal yields, and not to absolute yields, so the final results are relatively insensitive to the exact forms of the PDFs.

The decay  $D^0 \rightarrow K^- \pi^+$  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 Figs. 2(a) and 2(b)]. These must be corrected to isolate the soft-pion asymmetry.

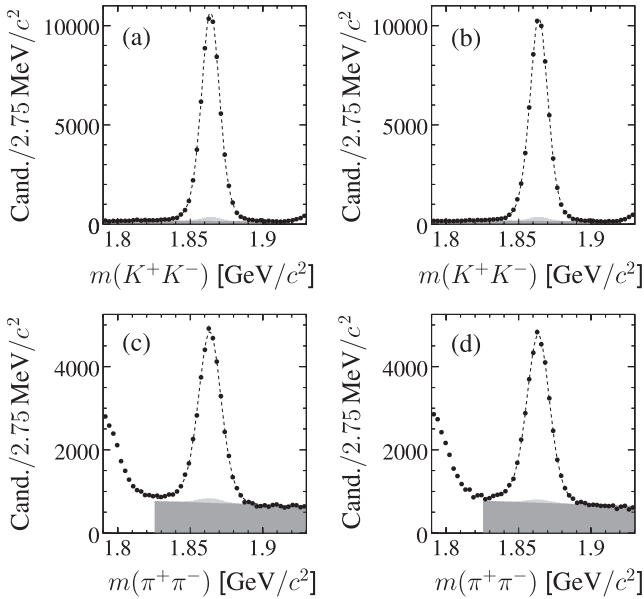


FIG. 1. Invariant mass distributions of the  $KK$  final state tagged as (a)  $D^0$  and (b)  $\bar{D}^0$ , and the  $\pi\pi$  final state tagged as (c)  $D^0$  and (d)  $\bar{D}^0$ . Distributions of data (points with error bars) in the signal region  $0.1434 < \Delta m < 0.1474$   $\text{GeV}/c^2$  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.

Using the nontagged  $K\pi$  sample, we produce a map of the relative reconstruction efficiency between  $D^0$  and  $\bar{D}^0$  in this final state in terms of the momenta of both  $D^0$  daughters, shown by components in Figs. 2(a) and 2(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  $\pi$  efficiency-map components, we obtain a four-dimensional relative-efficiency map for correcting  $D^0 \rightarrow K^- \pi^+$  relative to  $\bar{D}^0 \rightarrow K^+ \pi^-$ . The presence of prompt  $D^0$  decays not originating from a  $D^{*+}$  in the nontagged sample extends 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  $D^0/\bar{D}^0$  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  $\phi$  is found to be uncorrelated with other momentum variables. Therefore, the  $\phi$  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  $\pi_s$  map to correct for the soft-pion tagging

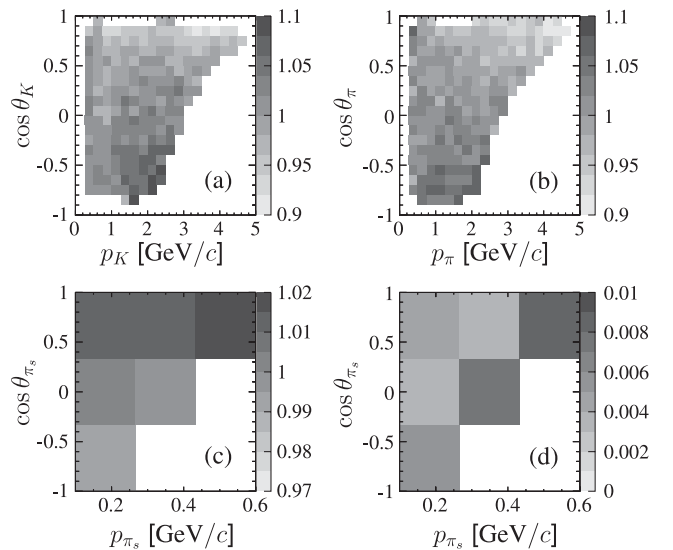


FIG. 2.  $K\pi$  efficiency-map components obtained from the nontagged  $D^0$  daughters (a)  $K$  and (b)  $\pi$ , and (c)  $\pi_s$  efficiency map with (d) statistical errors from the tagged  $K\pi$  sample. Maps are produced from the ratios of candidate numbers of  $D^0$  to  $\bar{D}^0$ .

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

| Final state   | Raw yields             |                        | Corr. used  | Postcorrection yields |             |
|---------------|------------------------|------------------------|-------------|-----------------------|-------------|
|               | $D^0$                  | $\bar{D}^0$            |             | $D^0$                 | $\bar{D}^0$ |
| $K\pi$        | $3\,363\,000 \pm 6000$ | $3\,368\,000 \pm 6000$ | None        | ...                   | ...         |
| $K\pi\pi_s$   | $705\,100 \pm 1000$    | $703\,500 \pm 1000$    | $K\pi$ Map  | 633 300               | 630 100     |
| $KK\pi_s$     | $65\,730 \pm 340$      | $63\,740 \pm 330$      | $\pi_s$ Map | 65 210                | 63 490      |
| $\pi\pi\pi_s$ | $32\,210 \pm 310$      | $31\,930 \pm 310$      | $\pi_s$ Map | 31 900                | 31 760      |

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 postcorrection yields for the calibration and signal samples in this analysis. In calculating these corrections, histogram bins near kinematic boundaries with fewer than 5000 events are removed.

$CP$  violation would appear as an asymmetry in  $D^0/\bar{D}^0$  yields, independent of any kinematic variables. Because of the FB asymmetry in production, we calculate yield asymmetries as a function of  $\cos\theta = \cos\theta_{D^0}^{\text{c.m.s.}}$  and decompose these into even and odd parts. We define

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

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

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

where  $n_{D^0}$  and  $n_{\bar{D}^0}$  are the numbers of signal events for  $D^0$  and  $\bar{D}^0$  after applying the weights discussed above,  $a_{CP}$  is the even component, and  $a_{FB}(\cos\theta)$  the odd component. Equations (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  $\chi^2$  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  $\Delta m$  and an alternative two-dimensional signal shape in the fits to the tagged samples.

TABLE II. Summary of systematic uncertainties.

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

Another source is the binning choices made and dependences in the  $\pi_s$ -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  $\phi$  dependence to the efficiency correction. We find the largest uncertainty here arises from the particular choice of binning in the  $\pi_s$ -efficiency map. Because the systematic uncertainty in applying the  $\pi_s$ -efficiency correction is the same for both modes, we evaluate its size using 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  $\bar{D}^0$ . 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.

For  $KK$ , we measure  $a_{CP}^{KK} = (0.00 \pm 0.34(\text{stat}) \pm 0.13(\text{syst}))\%$ . For  $\pi\pi$ , we measure  $a^{\pi\pi} = (-0.24 \pm 0.52(\text{stat}) \pm 0.22(\text{syst}))\%$ . Statistical uncertainties of

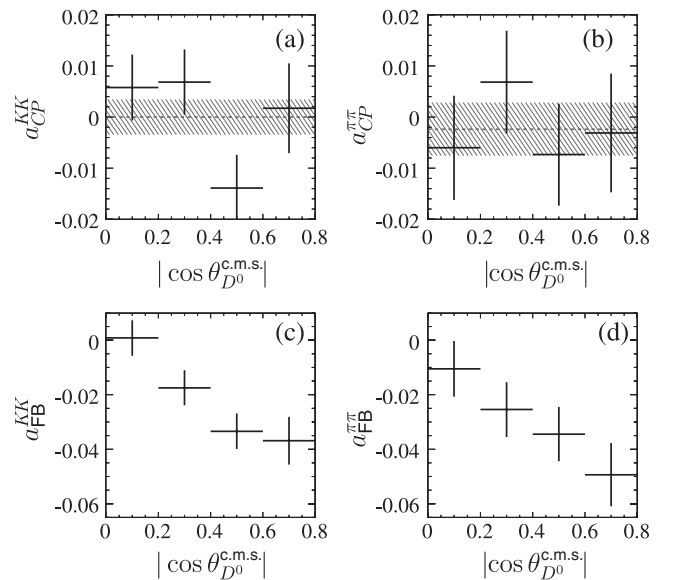


FIG. 3.  $CP$ -violating asymmetries in (a)  $KK$  and (b)  $\pi\pi$ , and forward-backward asymmetries in (c)  $KK$  and (d)  $\pi\pi$ . In (a) and (b), the dashed lines represent the central values and the hatched regions the  $1\sigma$  intervals, obtained from  $\chi^2$  minimizations.

0.1% in the  $\pi_s$  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  $\chi^2$  minimizations in Figs. 3(a) and 3(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 [5], some of which predict significant levels of  $CP$  violation in these modes. The asymmetries observed in Figs. 3(c) and 3(d) represent the two standard model asymmetries discussed. Although an exact prediction of these forward-backward asymmetries does not exist, the observed values do not contradict expectations. Thus, although we report both the most precise measurements of time-integrated  $CP$  asymmetries in charm decays and the first measurements of the FB asymmetry in charm-pair production at  $\sqrt{s} \approx 10.6$  GeV, we do not report evidence of unknown phenomena at work in the neutral charmed meson system.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (U.S.), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MES (Russia), MEC (Spain), and STFC (U.K.). Individuals have received support from the Marie Curie EIF (European Union) and the A.P. Sloan Foundation.

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