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Search for CP violation using T-odd correlations in $D^0 \to K^+ K^- \pi^+ \pi^-$ decays at *BABAR*.

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Abstract. We search for CP violation in a sample of 4.7×10^4 Cabibbo suppressed $D^0 \to K^+ K^- \pi^+ \pi^-$ decays. We use $470\,\mathrm{fb}^{-1}$ of data recorded by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage rings running at center-of-mass energies near 10.6 GeV. CP violation is searched for in the difference between the T-odd asymmetries, obtained using triple product correlations, measured for D^0 and $\overline{D}^0$ decays. The measured $\mathcal{A}_T$ violation parameter is $\mathcal{A}_T = (1.0 \pm 5.1_{\mathrm{stat}} \pm 4.4_{\mathrm{syst}}) \times 10^{-3}$.

In Standard Model, CP violation arises from Kobayashi-Maskawa phase in Cabibbo-Kobayashi-Maskawa quark mixing matrix[1, 2]. Theoretical attempts to predict the effect of CP violation in Cabibbo suppressed charmed decays have been made in the past[3], obtaining a limit of 0.1% not excluding even 1% effects. The same paper suggests that this limit can be lowered by at least one order of magnitude by oscillations, which have been recently observed[4, 5].

CP violation in charm decays can be exploited by many New Physics models[6] both at tree and one-loop level; among these the latter expect a CP violation asymmetry at the order $\mathcal{O}(10^{-2})$, which is now the level of experimental sensitivity[7].

We make use of T-odd correlations[8] to build a T odd observable: assuming CPT theorem, CP violation is straightforward once T violation is found. One way to build a T odd observable rely on the mixed product $\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$, where each $\vec{v}_i$ is a momentum or a spin. A non-zero triple product correlation is then evidenced by the asymmetry

$$A_T = \frac{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) - \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)}{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) + \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)},$$

where Γ is the decay rate of the process. There is however a technical complication due to strong phases, which can fake this signal. The true T violation observable is then

$$\mathcal{A}_T = \frac{1}{2}(A_T - \bar{A}_T),$$

where $\bar{A}_T$ is the charge conjugate of A_T, in which by definition the weak phase changes its sign, while the strong does not. This observable can be built in the $D^0 \to K^+ K^- \pi^+ \pi^-$ decays defining $C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$, using the momenta $\vec{p}_i$ of the final state particles in the D^0 rest frame, and taking ($\bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$)

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)} \qquad \bar{A}_T = \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}.$$

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The reaction [9]

$$e^+e^- \to X\ D^{*+};\ D^{*+} \to \pi_s^+ D^0;\ D^0 \to K^+K^-\pi^+\pi^-,$$

where X indicates any system composed by charged and neutral particles, has been reconstructed from the sample of events having at least five charged tracks. We first reconstruct the D^0 candidate: all $K^+K^-\pi^+\pi^-$ combinations assembled from well-measured and positively identified kaons and pions are constrained to a common vertex. To reconstruct the D^{*+} candidate, we perform a vertex fit of the D^0 candidates with all combinations of charged tracks having a laboratory momentum below 0.65 GeV/c (π_s^+) with the constraint that the new vertex is located in the interaction region. We require the D^0 to have a center-of-mass momentum greater than 2.5 GeV/c: this requirement removes D^0 coming from B decays. We observe a contamination of the signal sample from $D^0 \to K^+K^-K_S^0$, where $K_S^0 \to \pi^+\pi^-$. The $\pi^+\pi^-$ effective mass shows, in fact, a distinct K_S^0 mass peak, which can be represented by a Gaussian distribution with $\sigma = 4.20 \pm 0.26$ MeV/c^2, which accounts for 5.2% of the selected data sample. We veto K_S^0 candidates within a window of 2.5 σ. This cut, while reducing to negligible level the background from $D^0 \to K^+\ K^-\ K_S^0$, removes 5.8% of the signal events.

Defining the mass difference $\Delta m \equiv m(K^+K^-\pi^+\pi^-\pi_s^+) - m(K^+K^-\pi^+\pi^-)$, Figure 1(a) shows the scatter plot $m(K^+K^-\pi^+\pi^-)$ vs. Δm for all the events. Figure 1(b) shows the $m(K^+K^-\pi^+\pi^-)$ projection, Fig. 1(c) shows the Δm projection.

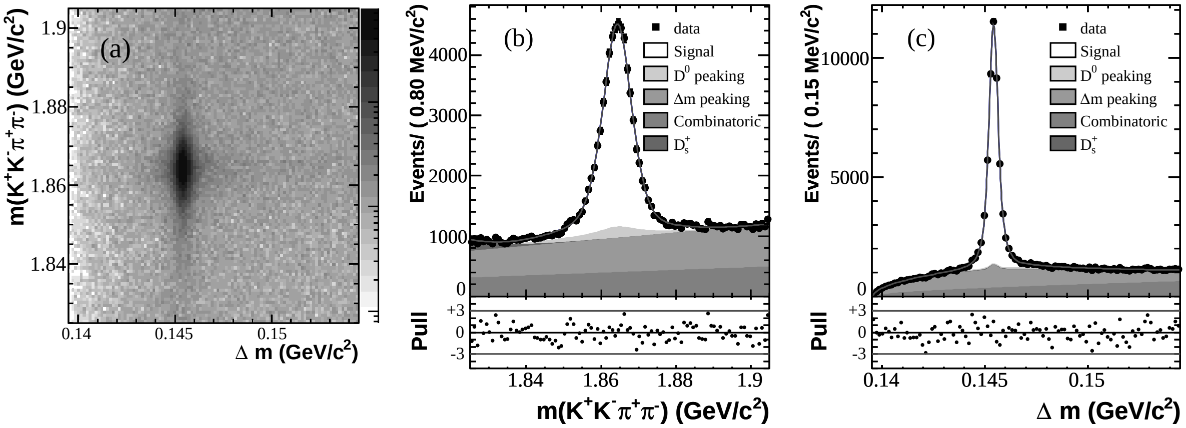

Figure 1. (a) $m(K^+K^-\pi^+\pi^-)$ vs. Δm for the total data sample. (b) $m(K^+K^-\pi^+\pi^-)$ and (c) Δm projections with curves from the fit results. Shaded areas indicate the different contributions. The fit residuals, represented by the pulls, are also shown under each distribution.

We perform a fit to the $m(K^+K^-\pi^+\pi^-)$ and Δm distributions, using a polynomial background and a single Gaussian. The fit gives $\sigma_{D^0} = 3.94 \pm 0.05\,\mathrm{MeV}/c^2$ for the D^0 and $\sigma_{\Delta m} = 244 \pm 20\,\mathrm{keV}/c^2$ for the Δm. We define the signal region within $\pm 2\sigma_{D^0}$ and $\pm 3.5\sigma_{\Delta m}$. The total yield of tagged D^0 mesons in the signal region is approximately 4.7×10^4 events.

The D^0 yields to be used in the calculation of the T asymmetry are determined using a binned, extended maximum-likelihood fit to the 2-D ($m(K^+K^-\pi^+\pi^-)$, Δm) distribution obtained with the two observables $m(K^+K^-\pi^+\pi^-)$ and Δm in the mass regions defined in the ranges $1.825 < m(K^+K^-\pi^+\pi^-) < 1.915$ GeV/c^2 and $0.1395 < \Delta m < 0.1545$ GeV/c^2 respectively. Events having more than one slow pion candidate in this mass region are removed (1.8 % of the final sample). The final 2-D distribution contains approximately 1.5×10^5 events and is divided into a 100×100 grid.

The 2-D ($m(K^+K^-\pi^+\pi^-)$, Δm) distribution is described by five components:

(i) True D^0 signal originating from a D^{*+} decay. This component has characteristic peaks in both observables $m(K^+K^-\pi^+\pi^-)$ and Δm.

(ii) Random π_s^+ events where a true D^0 is associated to an incorrect π_s^+, called D^0 peaking. This contribution has the same shape in $m(K^+K^-\pi^+\pi^-)$ as signal events, but does not peak in Δm.

(iii) Misreconstructed D^0 decays where one or more of the D^0 decay products are either not reconstructed or reconstructed with the wrong particle hypothesis, called Δm peaking. Some of these events show a peak in Δm, but not in $m(K^+K^-\pi^+\pi^-)$.

(iv) Combinatorial background where the K^+, K^-, π^+, π^- candidates are not fragments of the same D^0 decay, called combinatoric. This contribution does not exhibit any peaking structure in $m(K^+K^-\pi^+\pi^-)$ or Δm.

(v) $D_s^+ \to K^+ K^- \pi^+ \pi^- \pi^+$ contamination, called D_s^+. This background has been studied on Monte Carlo (MC) simulations and shows a characteristic linear narrow shape in the 2-D ($m(K^+K^-\pi^+\pi^-)$, Δm) distribution, too small to be directly visible in Fig. 1(a).

The functional forms of the probability density functions (PDFs) for the signal and background components are based on studies of MC samples. However, all parameters related to these functions are determined from two-dimensional likelihood fits to data over the full $m(K^+K^-\pi^+\pi^-)$ vs. Δm region. We make use of combinations of Gaussian and Johnson SU [11] lineshapes for peaking distributions, and we use polynomials and threshold functions for the non-peaking backgrounds. The results of the fit are shown in Fig. 1. The fit residuals shown under each distribution are represented by $Pull = (N_{data} - N_{fit})/\sqrt{N_{data}}$.

According to the D^{*+} tag and the C_T variable, we divide the total data sample into four subsamples, defined in Table 1. These four data samples are fit simultaneously to the same model. The signal event yields are given in Table 1.

Table 1. Definition of the four subsamples and the event yields from the fit.

Subsample	Events
(a) D^0, $C_T > 0$	10974 ± 117
(b) D^0, $C_T < 0$	12587 ± 125
(c) $\overline{D}^0$, $\overline{C}_T > 0$	10749 ± 116
(d) $\overline{D}^0$, $\overline{C}_T < 0$	12380 ± 124

We validate the method using $e^+e^- \to c\overline{c}$ MC simulations, where D^0 decays through the intermediate resonances with the branching fractions reported in the PDG [13]. We obtain a T asymmetry $\mathcal{A}_T = (2.3 \pm 3.3) \times 10^{-3}$, consistent with the generated value of 1.0×10^{-3}.

To test the effect of possible asymmetries generated by the detector, we use signal MC in which the D^0 decays uniformly over phase space. In this case possible asymmetries are generated only by the detector efficiency: $\mathcal{A}_T = -(1.1 \pm 1.1) \times 10^{-3}$, again consistent with zero.

To avoid potential bias, all event selection criteria are determined before evaluating $\mathcal{A}_T$. Systematic uncertainties are obtained directly from the data. In these studies the true A_T and $\overline{A}_T$ central values are masked by adding unknown random offsets. Removing the offsets:

$$A_T = (-68.5 \pm 7.3_{\text{stat}} \pm 5.8_{\text{syst}}) \times 10^{-3} \qquad \overline{A}_T = (-70.5 \pm 7.3_{\text{stat}} \pm 3.9_{\text{syst}}) \times 10^{-3}. \quad (1)$$

We observe non-zero values of A_T and $\overline{A}_T$ indicating that final state interaction effects are significant in this D^0 decay. No effect is found, on the other hand, in the analysis of MC samples.

The result for the *CP* violation parameter, $\mathcal{A}_T$, is

$$\mathcal{A}_T = (1.0 \pm 5.1_{\text{stat}} \pm 4.4_{\text{syst}}) \times 10^{-3}. \tag{2}$$

The sources of systematic uncertainties considered in this analysis and the estimates of their values are derived as follows:

(i) The PDFs used to describe the signal are modified, replacing the Johnson SU function by a Crystal Ball function [12], obtaining fits of similar quality ($\sigma_{sys} = 0.2 \times 10^{-3}$).

(ii) As the same as (i), for the peaking background ($\sigma_{sys} = 0.5 \times 10^{-3}$).

(iii) We increase the number of bins of the 2-D ($m(K^+K^-\pi^+\pi^-)$, Δm) distribution to a (120×120) grid and decrease to a grid of (80×80) ($\sigma_{sys} = 0.2 \times 10^{-3}$).

(iv) The particle identification algorithms used to identify kaons and pions are modified to more stringent conditions in different combinations ($\sigma_{sys} = 3.5 \times 10^{-3}$).

(v) The $p^*(D^0)$ cut is increased to 2.6 GeV/c and 2.7 GeV/c ($\sigma_{sys} = 1.7 \times 10^{-3}$).

(vi) We study possible intrinsic asymmetries due to the interference between the electromagnetic $e^+e^- \to \gamma^* \to c\bar{c}$ and weak neutral current $e^+e^- \to Z^0 \to c\bar{c}$ amplitudes. This interference produces a $D^0/\overline{D}^0$ production asymmetry that varies linearly with the quark production angle with respect to the e^- direction. We constrain the possible systematics by measuring $\mathcal{A}_T$ in three regions of the center-of-mass D^0 production angle θ^*: forward ($0.3 < \cos(\theta^*)_{D^0}$), central ($-0.3 < \cos(\theta^*)_{D^0} \leq 0.3$), and backward ($\cos(\theta^*)_{D^0} < -0.3$) ($\sigma_{sys} = 0.9 \times 10^{-3}$).

(vii) Fit bias: we use MC simulations to compute the difference between the generated and reconstructed $\mathcal{A}_T$ ($\sigma_{sys} = 1.4 \times 10^{-3}$).

(viii) Mistag: there are a few ambiguous cases with more than one D^* in the event. We use MC simulations where these events are included or excluded from the analysis. This effect has a negligible contribution to the systematic uncertainty.

(ix) Detector asymmetry: we use the value obtained from the MC simulation where D^0 decays unifromly over the phase space ($\sigma_{sys} = 1.1 \times 10^{-3}$).

In the evaluation of the systematic uncertainties, we keep, for a given category, the largest deviation from the reference value and assume symmetric uncertainties. Thus, most systematic uncertainties are statistical in nature, and are conservatively estimated.

In conclusion, we search for *CP* violation using T-odd correlations in a high statistics sample of Cabibbo suppressed $D^0 \to K^+K^-\pi^+\pi^-$ decays. We obtain a T-violating asymmetry consistent with zero with a sensitivity of ≈ 0.5 %. These results constrain the possible effects of New Physics in this observable.

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