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

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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 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 $\bar{D}^0$ decays. The measured CP violation parameter is $\mathcal{A}_T = (1.0 \pm 5.1_{\rm stat} \pm 4.4_{\rm syst}) \times 10^{-3}$.

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In the standard model (SM) of particle physics, CP violation arises from a complex phase in the Cabibbo-Kobayashi-Maskawa quark mixing matrix [1]. Physics beyond the SM, often referred to as new physics (NP), can manifest itself through the production of new particles, probably at high mass, or through rare processes not consistent with SM origins. SM predictions for CP asymmetries in charm meson decays are generally of $\mathcal{O}(10^{-3})$, at least 1 order of magnitude lower than current experimental limits [2]. Thus, the observation of CP violation with current sensitivities would be a NP signal. Among all hadronic D decays, singly Cabibbo suppressed decays are uniquely sensitive to CP violation in $c \to u\bar{q}q$ transitions, an effect not expected in Cabibbo favored or doubly Cabibbo suppressed decays [3].

In this paper we report a search for CP violation in the decay $D^0 \to K^+K^-\pi^+\pi^-$ using a kinematic triple product correlation of the form $C_T = \mathbf{p_1} \cdot (\mathbf{p_2} \times \mathbf{p_3})$, where each $\mathbf{p_i}$ is a momentum vector of one of the particles in the decay. The product is odd under time-reversal (T) and, assuming the CPT theorem, T violation is a signal for CP violation. Strong interaction dynamics can produce a nonzero value of the A_T asymmetry,

$$A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}, \quad (1)$$

where Γ is the decay rate for the process, even if the weak phases are zero. Defining as $\bar{A}_T$ the T-odd asymmetry measured in the CP-conjugate decay process,

$$\bar{A}_T \equiv \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}, \quad (2)$$

we can construct

$$\mathcal{A}_T = \frac{1}{2}(A_T - \bar{A}_T), \quad (3)$$

which is a true T-violating signal [4]. At least four particles are required in the final state so that the three used to define the triple product are independent [5] of each other. Singly Cabibbo suppressed decays having relatively high branching fractions and four different particles in the final state, therefore suitable for this type of analysis, are $D^0 \to K^+K^-\pi^+\pi^-$ (explored in this paper) and $D^+ \to K^+K^0_S\pi^+\pi^-$. A full angular analysis of these D decays is suggested as a method for searching for CP violation [6].

Following the suggestion by I. I. Bigi [7] to study CP violation using this technique, the FOCUS Collaboration made the first measurements using approximately 800 events and reported $\mathcal{A}_T(D^0 \to K^+K^-\pi^+\pi^-) = 0.010 \pm 0.057 \pm 0.037$ [8]. We perform a similar study using approximately 4.7×10^4 events.

This analysis is based on a 470 fb^{-1} data sample recorded at the $\Upsilon(4S)$ resonance and 40 MeV below the resonance by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage rings. The *BABAR* detector is described in detail elsewhere [9]. We mention here only the parts of the detector which are used in the present analysis. Charged particles are detected and their momenta measured with a combination of a cylindrical drift chamber (DCH) and a silicon vertex tracker (SVT), both operating within the 1.5 T magnetic field of a superconducting solenoid. The information from a ring-imaging Cherenkov detector combined with energy-loss measurements in the SVT and DCH provide identification of charged kaon and pion candidates.

The reaction [10]

$$e^+e^- \to XD^{*+}; \qquad D^{*+} \to \pi_s^+ D^0; \qquad D^0 \to K^+K^-\pi^+\pi^-, \quad (4)$$

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 requiring a χ^2 fit probability greater than 0.1%. 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 fit probability to be greater than 0.1%.

We require the D^0 to have a center-of-mass momentum greater than 2.5 GeV$/c$. This requirement removes any D^0 coming from B decays. We observe a contamination of the signal sample from $D^0 \to K^+K^-K^0_S$, where $K^0_S \to \pi^+\pi^-$. The $\pi^+\pi^-$ effective mass shows, in fact, a distinct K^0_S mass peak, which can be represented by a Gaussian distribution with $\sigma = 4.20 \pm 0.26$ MeV$/c^2$, and which accounts for 5.2% of the selected data sample. We veto K^0_S candidates within a window of 2.5σ. This cut, while reducing to negligible level the background from $D^0 \to K^+K^-K^0_S$, removes 5.8% of the signal events.

We look for backgrounds from charm decay modes with misidentified pions by assigning alternatively the pion mass to both kaons. Then we study the two-body, three-body, four-body, and five-body mass distributions (including the π_s^+). We observe a signal of $D_s^+ \to K^+K^-\pi^+\pi^-\pi_s^+$ in the five-particle mass distribution, which is taken into account in the following fit. No other signal is observed in the resulting mass spectra.

We define the mass difference Δm as

$$\Delta m \equiv m(K^+K^-\pi^+\pi^-\pi_s^+) - m(K^+K^-\pi^+\pi^-). \quad (5)$$

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.

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 $\sigma_{D^0} = 3.94 \pm 0.05$ MeV$/c^2$ for the D^0 mass and $\sigma_{D^{*+}} = 244 \pm 20$ keV$/c^2$ for the Δm. We define the signal region within $\pm 2\sigma_{D^0}$ and $\pm 3.5\sigma_{D^{*+}}$. 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 two-dimensional $[m(K^+K^-\pi^+\pi^-), \Delta m]$ 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 two-dimensional distribution contains approximately 1.5×10^5 events and is divided into a 100×100 grid.

The two-dimensional $[m(K^+K^-\pi^+\pi^-), \Delta m]$ distribution is described by five components:

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

(2) 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.

(3) 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 $m(K^+K^-\pi^+\pi^-)$.

(4) 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.

(5) $D_s^+ \to K^+K^-\pi^+\pi^-\pi^+$ contamination, called D_s^+. This background has been studied on Monte Carlo (MC) simulations and shows a characteristic linear narrow shape in the two-dimensional $[m(K^+K^-\pi^+\pi^-), \Delta m]$ 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. These events are generated using the GEANT4 program [11] and are processed through the same reconstruction and analysis chain as the real events. 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 [12] line shapes for peaking distributions, and we use polynomials and threshold functions for the nonpeaking backgrounds.

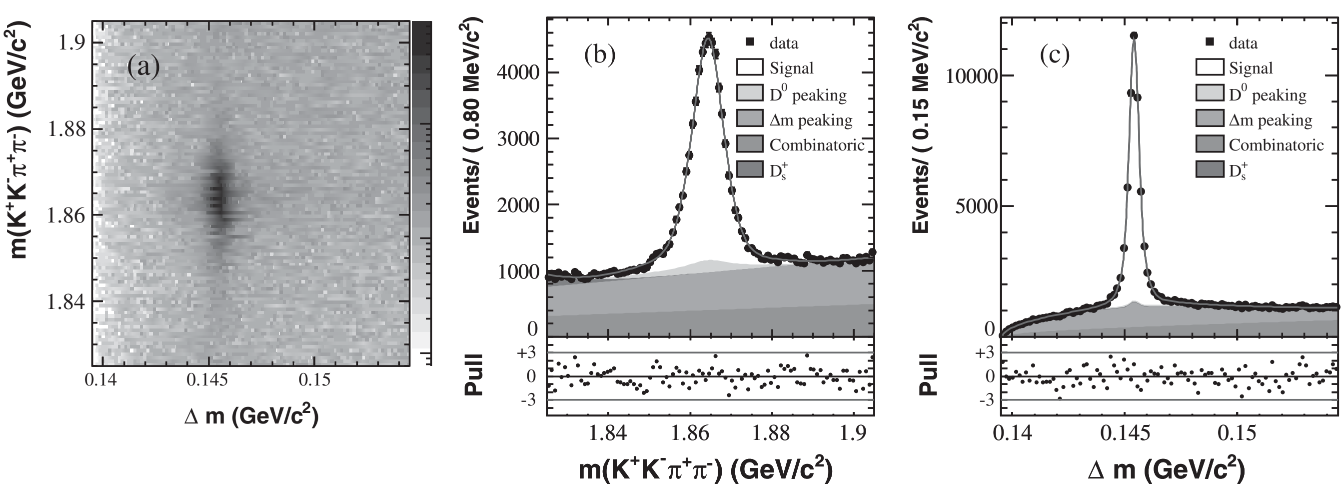

FIG. 1. (a) $m(K^+K^-\pi^+\pi^-)$ vs Δm for the total data sample. (b) $m(K^+K^-\pi^+\pi^-)$ and (c) Δm projections with curves from the fit results. Shaded areas indicate the different contributions. The fit residuals, represented by the pulls, are also shown under each distribution.

TABLE I. Fitted number of events for each category.

Category	Events	Fraction (%)
1. Signal	46 691 ± 241	30.8 ± 0.3
2. D^0 peaking	5178 ± 331	3.4 ± 0.2
3. Δm peaking	57 099 ± 797	37.7 ± 0.6
4. Combinatoric	40 512 ± 818	26.7 ± 0.6
5. D_s^+	2023 ± 156	1.3 ± 0.1
Total	151 503 ± 1223	

The event yields and fractions of the different components arising from the fit are given in Table I and shown in Fig. 1. The fit residuals shown under each distribution are represented by Pull $= (N_{\rm data} - N_{\rm fit})/\sqrt{N_{\rm data}}$.

Using momenta of the decay particles calculated in the D^0 rest frame, we define the triple product correlations C_T and $\bar{C}_T$ as

$$C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}), \qquad \bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}). \quad (6)$$

According to the D^{*+} tag and the C_T variable, we divide the total data sample into four subsamples, defined in Table II. These four data samples are fit with fixed PDFs from the total sample. The signal event yields are given in Table II. Figure 2 shows the $K^+K^-\pi^+\pi^-$ mass distributions for the four different C_T subsamples with fit projections in the Δm signal region previously defined.

We validate the method using $e^+e^- \to c\bar{c}$ MC simulations, where D^0 decays through the intermediate resonances with the branching fractions reported by the Particle Data Group [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. These reconstructed events give an asymmetry $\mathcal{A}_T = (1.1 \pm 1.1) \times 10^{-3}$, again consistent with zero.

To avoid potential bias, all event selection criteria are determined before separating the data into the four subsamples of Table II. Systematic uncertainties are obtained directly from the data. In these studies the true A_T and $\bar{A}_T$ central values are masked by adding unknown random offsets.

TABLE II. Definition of the four subsamples and the event yields from the fit.

Subsample	Events
(a) D^0, $C_T > 0$	10 974 ± 117
(b) D^0, $C_T < 0$	12 587 ± 125
(c) $\bar{D}^0$, $\bar{C}_T > 0$	10 749 ± 116
(d) $\bar{D}^0$, $\bar{C}_T < 0$	12 380 ± 124

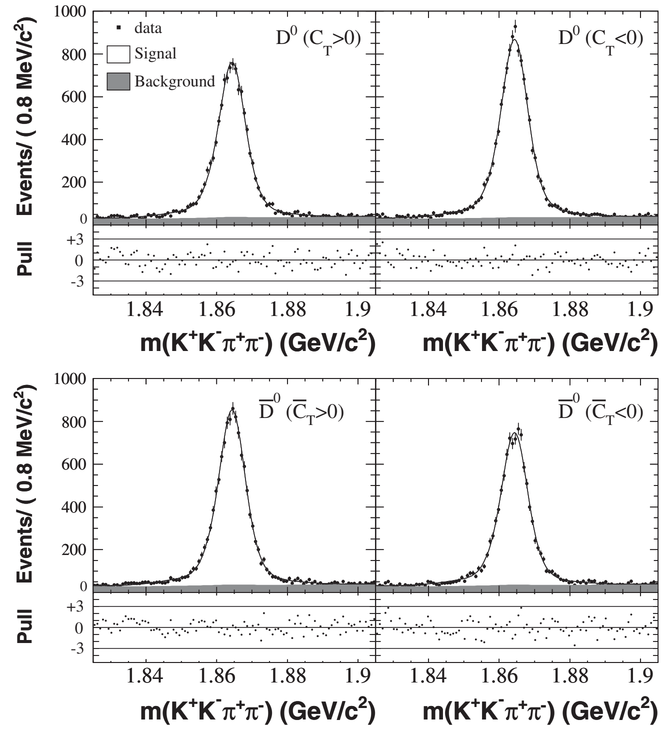

FIG. 2. Fit projections onto the $m(K^+K^-\pi^+\pi^-)$ for the four different C_T subsamples with cut on Δm. The shaded areas indicate the total backgrounds. The fit residuals, represented by the pulls are also shown under each distribution.

After removing the offsets, we measure the following asymmetries:

$$A_T = (-68.5 \pm 7.3_{\rm stat} \pm 5.8_{\rm syst}) \times 10^{-3},$$
$$\bar{A}_T = (-70.5 \pm 7.3_{\rm stat} \pm 3.9_{\rm syst}) \times 10^{-3}. \quad (7)$$

We observe nonzero values of A_T and $\bar{A}_T$ 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. Final state interaction effects are common in hadronic D decays because of the complex interference patterns between intermediate resonances formed between hadrons in the final states [14].

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

$$\mathcal{A}_T = (1.0 \pm 5.1_{\rm stat} \pm 4.4_{\rm syst}) \times 10^{-3}. \quad (8)$$

The sources of systematic uncertainties considered in this analysis are listed in Table III. The estimates of their values are derived as follows:

(1) The PDFs used to describe the signal are modified, replacing the Johnson SU function by a crystal ball function [15], obtaining fits of similar quality.
(2) As in 1., for the peaking background.
(3) We increase the number of bins of the two-dimensional $[m(K^+K^-\pi^+\pi^-), \Delta m]$ distribution to a (120×120) grid and decrease to a grid of (80×80).

TABLE III. Systematic uncertainty evaluation on $\mathcal{A}_T$, A_T, and $\bar{A}_T$ in units of 10^{-3}.

Effect	$\mathcal{A}_T$	A_T	$\bar{A}_T$
1. Alternative signal PDF	0.2	0.3	0.2
2. Alternative misreconstructed D^0 PDF	0.5	0.1	0.9
3. Bin size	0.2	0.4	0.3
4. Particle identification	3.5	4.2	2.9
5. $p^*(D^0)$ cut	1.7	1.6	2.4
6. $\cos\theta^*$ dependence	0.9	0.0	0.2
7. Fit bias	1.4	3.0	0.3
8. Mistag	0.0	0.0	0.0
9. Detector asymmetry	1.1	2.1	0.0
Total	4.4	5.8	3.9

(4) The particle identification algorithms used to identify kaons and pions are modified to more stringent conditions in different combinations. We notice that the difference between different selection efficiencies is significantly larger than the uncertainties on efficiency of the default selection. On the other hand, the use of the discrepancy between data and MC obtained using high statistics control samples, gives a much lower contribution.

(5) The $p^*(D^0)$ cut is increased to 2.6 GeV/c and 2.7 GeV/c.

(6) 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 $D^0/\bar{D}^0$ production asymmetry that varies linearly with the quark production angle with respect to the e^- direction. Since *BABAR* is an asymmetric detector, the final yields of D^0 and $\bar{D}^0$ are not equal. 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 $[\cos(\theta^*)_{D^0} < -0.3]$. We observe that the $\mathcal{A}_T$ angular variation is, within the large statistical errors, consistent with zero as expected from the MC

(7) Fit bias: we use MC simulations to compute the difference between the generated and reconstructed $\mathcal{A}_T$.

(8) 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.

(9) Detector asymmetry: we use the value obtained from the MC simulation where D^0 decays uniformly over the phase space.

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 have a statistical component, 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 $\approx 0.5\%$.

The study of triple product correlations in *B* decays shows evidence for final state interaction but also gives asymmetries consistent with zero, in agreement with SM expectations [16]. These results constrain the possible effects of new physics in this observable [3]. The results from this analysis fix a reference point, since the study of *T*-odd correlations plays an important role in the physics program of present and future charm and *B* factories.

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