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Search for CP violation in D^0 and D^+ decays

The FOCUS Collaboration

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Abstract

A high statistics sample of photoproduced charm particles from the FOCUS (E831) experiment at Fermilab has been used to search for CP violation in the Cabibbo suppressed decay modes $D^+ \to K^-K^+\pi^+$, $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$. We have measured the following CP asymmetry parameters: $A_{CP}(K^-K^+\pi^+) = +0.006 \pm 0.011 \pm 0.005$, $A_{CP}(K^-K^+) = -0.001 \pm 0.022 \pm 0.015$ and $A_{CP}(\pi^-\pi^+) = +0.048 \pm 0.039 \pm 0.025$ where the first error is statistical and the second error is systematic. These asymmetries are consistent with zero with smaller errors than previous measurements.

1 Introduction

CP violation occurs if the decay rate for a particle differs from the decay rate of its CP-conjugate particle [1]. CP violation, which in the Standard Model (SM) is a consequence of a complex amplitude in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, has been observed to date only in the neutral-kaon system. In charm meson decays (as well as in K and B decays), two classes of CP violation exist: indirect and direct. In neutral-charm-meson decays, indirect CP violation may arise due to $D^0 - \overline{D}^0$ mixing. In the case of direct violation, CP violating effects occur in a decay process only if the decay amplitude is the sum of two different parts, whose phases are made of a weak (CKM) and a strong contribution due to final state interactions (FSI) [2]. The weak contributions to the phases change sign when going to the CP-conjugate process, while the strong ones do not. In singly Cabibbo-suppressed D decays, penguin terms in the effective Hamiltonian may provide the different phases of the two weak amplitudes.

Compared to the strange and bottom sectors, the SM predictions of CP violation for charm decays are much smaller [2–5], making the charm sector a good place to test the SM and to look for evidence of new physics. In the SM, direct CP violating asymmetries in D decays are predicted to be largest in singly Cabibbo-suppressed decays, at most 10^{-3}, and non-existent in Cabibbo-favored and doubly Cabibbo-suppressed decays [1]. However, a CP asymmetry could occur in the decay modes $D \to K_s \mathrm{n}\pi$ due to interference between Cabibbo-favored and doubly Cabibbo-suppressed decays.

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Experimentally, one looks at the Cabibbo-suppressed decay modes which have the largest combination of branching fraction and detection efficiency. For this reason we select the all-charged decay modes $D^+ \to K^-K^+\pi^+$, $D^0 \to K^-K^+$, and $D^0 \to \pi^-\pi^+$ (throughout this paper the charge conjugate state is implied, unless otherwise noted).

In D decays the charged D is self-tagging and the neutral D is tagged as either a D^0 or a $\overline{D}^0$ by using the sign of the bachelor pion in the $D^{*\pm}$ decay.

Before searching for a CP asymmetry we must account for differences, at the production level, between D and $\overline{D}$ in photoproduction (the hadronization process, in the presence of remnant quarks from the nucleon, gives rise to production asymmetries [6]). This is done by normalizing to the Cabibbo-favored modes $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$, with the additional benefit that most of the corrections due to inefficiencies cancel out, reducing systematic uncertainties. An implicit assumption is that there is no measurable CP violation in the Cabibbo-favored decays.

The CP asymmetry can be written as:

$$A_{CP} = \frac{\eta(D) - \eta(\overline{D})}{\eta(D) + \eta(\overline{D})} \qquad (1)$$

where η is (considering for example the decay mode $D^0 \to K^-K^+$):

$$\eta(D) = \frac{N(D^0 \to K^-K^+)}{N(D^0 \to K^-\pi^+)} \frac{\epsilon(D^0 \to K^-\pi^+)}{\epsilon(D^0 \to K^-K^+)}$$

where $N(D^0 \to K^-K^+)$ is the number of reconstructed candidate decays and $\epsilon(D^0 \to K^-K^+)$ is the efficiency obtained from Monte Carlo simulations.

The CP asymmetry parameter measures the direct CP asymmetry in the case of D^+ and the combined direct and indirect CP asymmetries for D^0 [7].

The name FOCUS stands for **Pho**toproduction of **C**harm with an **U**pgraded **S**pectrometer with a lexical license. The word "upgrade" refers to the upgrade of the E687 (the predecessor experiment) spectrometer [8].

Charmed particles were produced by the interaction of high energy photons, obtained by means of bremsstrahlung of electron and positron beams (with typically 300 GeV endpoint energy), with a beryllium oxide target. The mean energy of the photon beam was approximately 180 GeV. The data were collected at Fermilab during the 1996–97 fixed-target run. More than 6.3×10^9 triggers were collected from which more than 1 million charmed particles have been reconstructed.

The particles from the interaction are detected in a large-aperture magnetic spectrometer with excellent vertex measurement, particle identification and calorimetric capabilities. The vertex detector consists of two systems of silicon microvertex detectors. The upstream system consists of 4 planes interleaved with the experimental target, while the downstream system consists of 12 planes of microstrips arranged in three views. These detectors provide high resolution separation of primary (production) and secondary (decay) vertices with an average proper time resolution of 30 fs for 2-track vertices. The momentum of the charged particles is determined by measuring their deflections in two analysis magnets of opposite polarity with five stations of multiwire proportional chambers. Kaons and pions in the D-meson final states are well separated up to 60 GeV/c of momentum using three multicell threshold Čerenkov counters.

2 Selection criteria

The final states are selected using a candidate driven vertex algorithm [8]. A secondary vertex is formed from the reconstructed tracks and the momentum vector of the D candidate is used as a *seed* to intersect the other tracks in the event to find the primary vertex. Once the production and decay vertices are determined, the distance ℓ between them and the relative error σ_ℓ are computed. Cuts on the ℓ/σ_ℓ ratio are applied to extract the D signals from the prompt background. The topological configuration of the event is evaluated with four tests: the primary and secondary vertex confidence levels (minimum values of 1% were required) and two measures of vertex isolation, a *no point-back isolation* and a *secondary vertex isolation*. The *no point-back isolation* cut requires that the maximum confidence level for a candidate-D daughter track to form a vertex with the tracks from the primary vertex be less than a certain threshold. The *secondary vertex isolation* cut requires that the maximum confidence level for another track to form a vertex with the D candidate be less than a certain threshold. The analyses differ mainly in the way the particle identification is handled and, less importantly, in the way the vertex cuts are applied. To minimize the systematic error we use identical vertex cuts on the signal and normalizing modes.

In the $D^+ \to K^-K^+\pi^+$ analysis, we require $\ell/\sigma_\ell > 10$, the *no point-back isolation* must be less than 20%, and the *secondary vertex isolation* less than 0.1%. The vertices (primary and secondary) have to lie inside a *fiducial volume*[16], the D momentum must be in the range $25 < P < 250$ GeV/c (a

[16] The reason for this cut lies in the presence of a trigger counter just upstream of the second microstrip device, therefore we defined the *fiducial volume* as the target region between the first slab of the experimental target and this trigger counter.

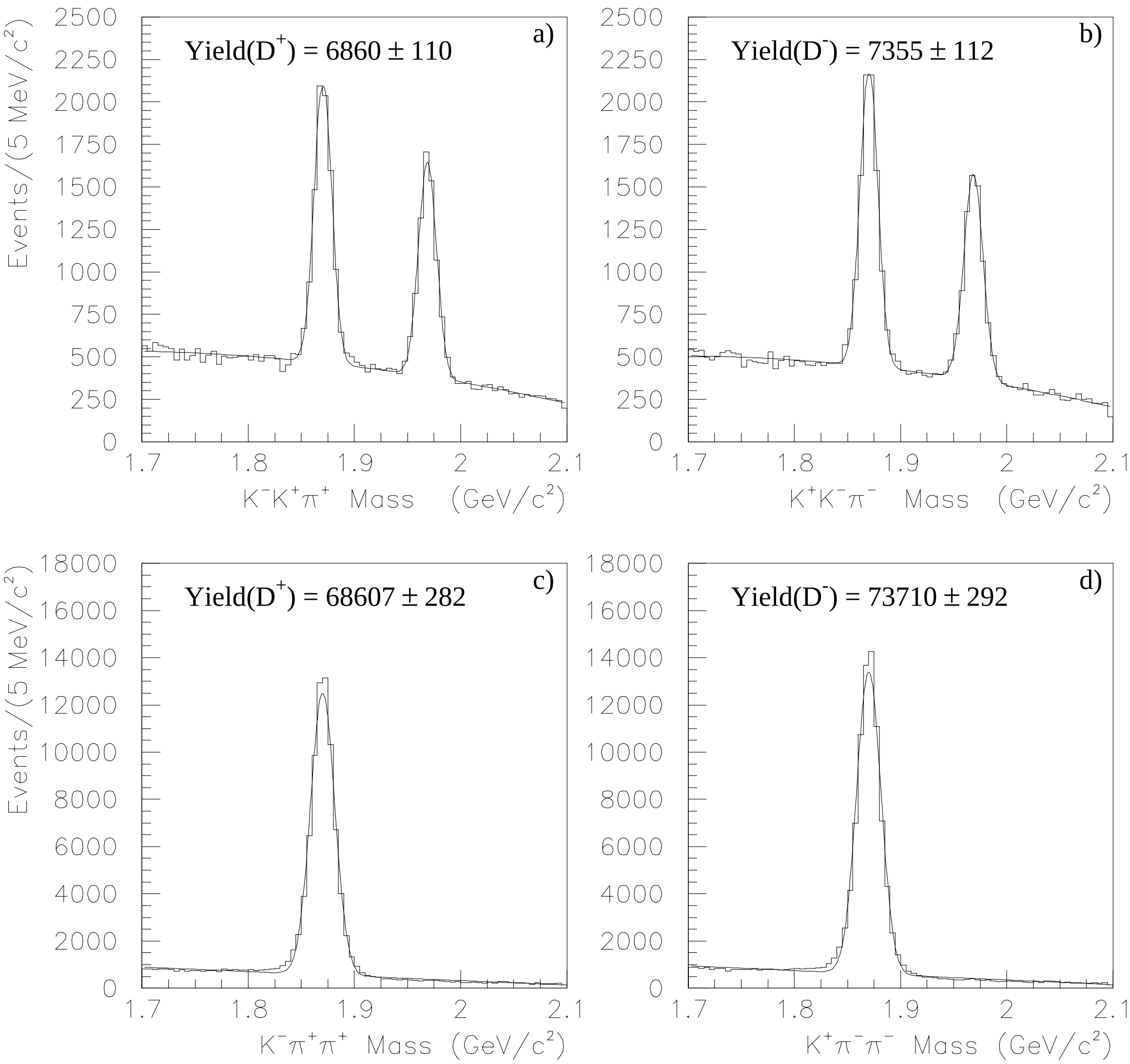

Fig. 1. (a) $K^-K^+\pi^+$ invariant mass distribution, (b) $K^+K^-\pi^-$ invariant mass distribution, (c) $K^-\pi^+\pi^+$ invariant mass distribution, (d) $K^+\pi^-\pi^-$ invariant mass distribution. The fits (solid curves) are described in the text and the numbers quoted are the yields.

very loose cut) and the primary vertex must be formed with at least two reconstructed tracks, in addition to the *seed* track. The Čerenkov particle identification cuts used in FOCUS are based on likelihood ratios between the various stable particle identification hypotheses. These likelihoods are computed for a given track from the observed firing response (on or off) of all cells within the track's ($\beta = 1$) Čerenkov cone for each of our three Čerenkov counters. The product of all firing probabilities for all cells within the three Čerenkov cones produces a χ^2-like variable $W_i = -2\ln(\text{Likelihood})$ where i ranges over the electron, pion, kaon and proton hypotheses (see reference [9] for more details). We require $W_\pi - W_K > 1$ for the tracks reconstructed as a kaon, and a pion consistency cut for the pion tracks. The pion consistency cut requires that no particle hypothesis is favored over the pion hypothesis with a $\Delta W = W_\pi - W_{min}$ exceeding 2. To remove contamination from the $D_s^+ \to K^-K^+\pi^+$ signal due to Čerenkov misidentified background from the decay mode $D^+ \to K^-\pi^+\pi^+$, we employ an *anti-reflection* cut which rejects candidates which, when reconstructed as $K^-\pi^+\pi^+$, are consistent with the D^+ hypothesis (we also reject events whose K^-K^+ mass exceeds 1.84 GeV/c^2 in order to exclude background due to $D^{*+} \to D^0\pi^+ \to (K^-K^+)\pi^+$). This cut has no effect in the vicinity of the $D^+ \to K^-K^+\pi^+$ signal peak.

In Fig.1, the invariant mass plots obtained with this set of cuts for the decay modes $D^+ \to K^-K^+\pi^+$, $D^- \to K^+K^-\pi^-$, and the normalizing decays $D^+ \to K^-\pi^+\pi^+$ and $D^- \to K^+\pi^-\pi^-$ are shown. In the $D^+ \to K^-\pi^+\pi^+$ analysis there is an additional cut on the D^0 mass formed by a kaon and a pion to remove the $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$ decay chain. The $KK\pi$ invariant mass distributions are fit with a Gaussian for the D^+ signal, a second Gaussian for the D_s^+ signal, and a quadratic polynomial for the background. A binned maximum likelihood fit finds 6860$\pm$110 $D^+ \to K^-K^+\pi^+$ and 7355$\pm$112 $D^- \to K^+K^-\pi^-$ events. The fit for the normalizing modes (fit with a Gaussian plus a linear polynomial) gives 68607$\pm$282 $D^+ \to K^-\pi^+\pi^+$ and 73710$\pm$292 $D^- \to K^+\pi^-\pi^-$ events.

In the $D^0 \to K^-K^+$ analysis, the sign of the bachelor pion in the $D^{*\pm}$ decay chain $D^{*+(-)} \to D^0(\overline{D}^0)\pi^{+(-)}$ is used to identify the neutral D as either a D^0 or a $\overline{D}^0$. We require that the mass difference between the D^0 and the D^* mass be within 4 MeV/c^2 with respect to the nominal mass difference [10]. We use $\ell/\sigma_\ell > 8$, while the *no point-back isolation* and the *secondary vertex isolation* cuts are unnecessary because the D^* tag sufficiently reduces the background. All the other cuts, except the *anti-reflection* cuts, are the same as those used in the $D^+ \to K^-K^+\pi^+$ analysis.

In Fig.2, we show the invariant mass plots, obtained with this set of cuts, for the decay modes $D^0 \to K^-K^+$, $\overline{D}^0 \to K^+K^-$, and the normalizing decays $D^0 \to K^-\pi^+$ and $\overline{D}^0 \to K^+\pi^-$. The peak in the KK invariant mass plots at $\approx$ 1.95 GeV/c^2 is due to the reflection of the $D^0 \to K^-\pi^+$ mode when the pion is misidentified as a kaon. A Monte Carlo simulation of this reflection reproduces the shape observed in the data. Consequently, the K^-K^+ invariant mass distributions are fit with a Gaussian for the D^0 signal, a function obtained by smoothing the reflection peak (only the shape of this reflection peak is modeled by our Monte Carlo simulation, the amplitude of this peak is given by a free parameter of the fit) and a quadratic polynomial for the background. From a binned maximum likelihood fit we find 1623 ± 47 $D^0 \to K^-K^+$ and 1707 ± 53 $\overline{D}^0 \to K^+K^-$ events. The fit for the normalizing modes (fit with a Gaussian plus a linear polynomial and excluding the low mass region to avoid possible contamination due to other charm hadronic decays involving an additional π^0) gives 18501$\pm$144 $D^0 \to K^-\pi^+$ and 19633$\pm$149 $\overline{D}^0 \to K^+\pi^-$

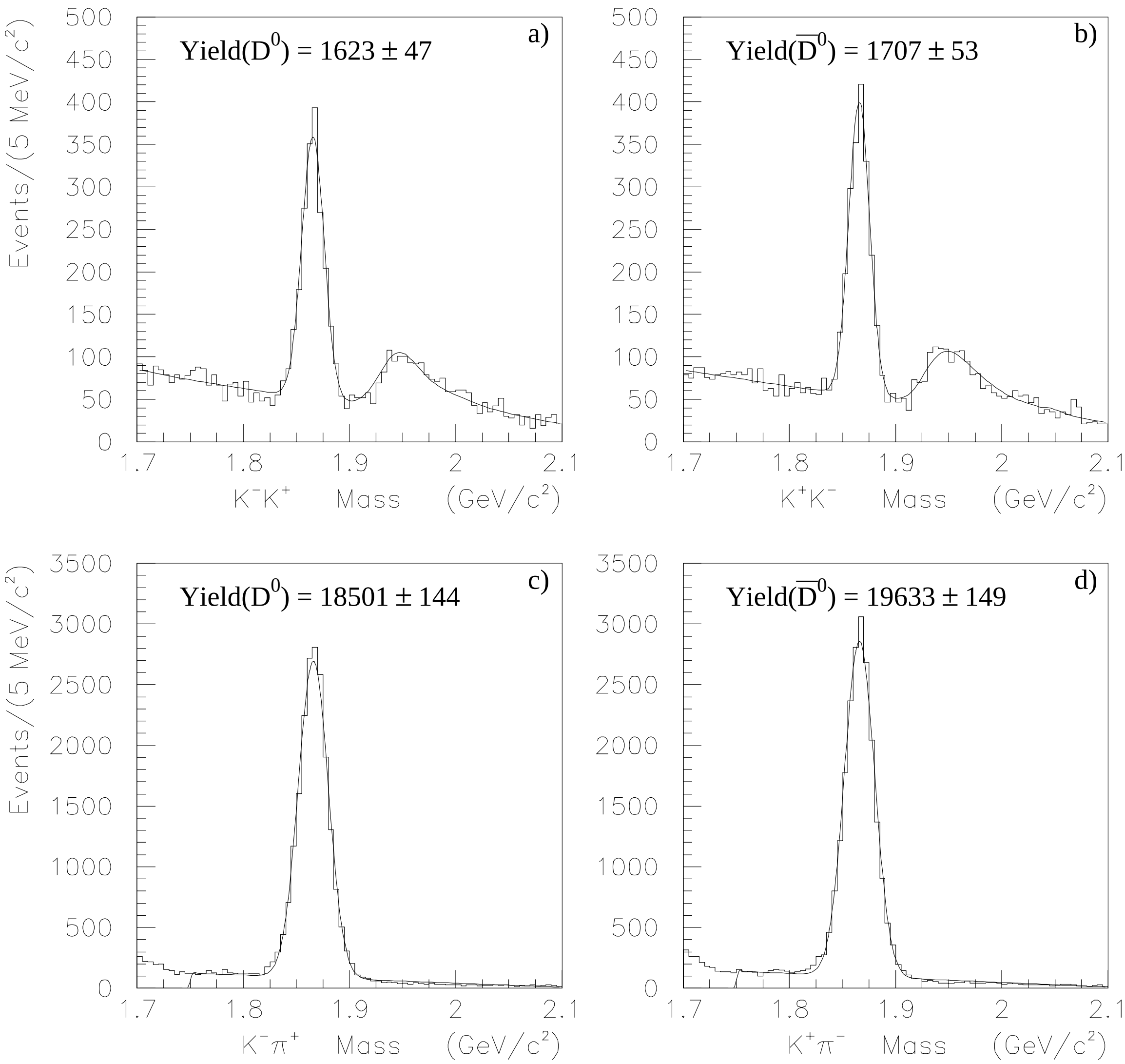

Fig. 2. (a) K^-K^+ invariant mass distribution, (b) K^+K^- invariant mass distribution, (c) $K^-\pi^+$ invariant mass distribution, (d) $K^+\pi^-$ invariant mass distribution. The fits (solid curves) are described in the text and the numbers quoted are the yields.

events.

The $D^0 \to \pi^-\pi^+$ analysis is identical to the $D^0 \to K^-K^+$ analysis with the exception of the Čerenkov identification. In order to reduce the large reflection peak from the $D^0 \to K^-\pi^+$ mode, a tight Čerenkov identification requirement ($W_K - W_\pi > 1$) for the pion tracks is implemented.

In Fig.3 the invariant mass plots for the decay modes $D^0 \to \pi^-\pi^+$ and $\overline{D}^0 \to \pi^+\pi^-$ are shown. As in the $D^0 \to K^-K^+$ case, the peak at $\approx 1.75\,\mathrm{GeV}/c^2$ is due to the reflection of the $D^0 \to K^-\pi^+$ mode. Again our Monte Carlo simulation reproduces the shape observed in the data. The $\pi^-\pi^+$ invariant

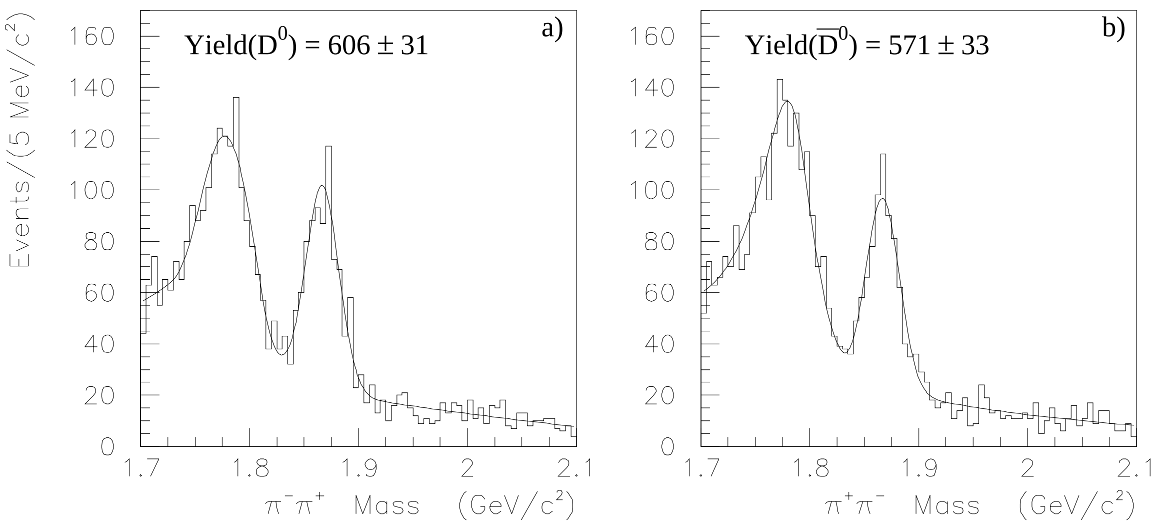

Fig. 3. (a) $\pi^-\pi^+$ invariant mass distribution, (b) $\pi^+\pi^-$ invariant mass distribution. The fits (solid curves) are described in the text and the numbers quoted are the yields.

mass distributions are fit with a Gaussian for the D^0 signal, a function obtained by smoothing the reflection peak, and a quadratic polynomial for the background. A binned maximum likelihood fit gives 606 ± 31 $D^0 \to \pi^-\pi^+$ and 571 ± 33 $\overline{D}^0 \to \pi^+\pi^-$ events.

3 *CP* asymmetry measurements

Because the efficiency is strongly dependent on the D momentum, it is necessary to verify that the observed momentum spectrum is reproduced by the Monte Carlo simulation. A mismatch could generate a false asymmetry. Fig.4 shows the D^0 momentum for the decay mode $D^0 \to K^-\pi^+$ for real data (points with errors) and Monte Carlo data (histogram). The D^0 momentum spectrum is obtained (both in real data and Monte Carlo data) by subtracting the events contained in the sideband regions from the events in the signal region. The two histograms are normalized by area. The agreement is good.

The measured asymmetries are reported in table 1 along with a comparison to previous measurements. The analysis of the decay mode $D^+ \to K^-K^+\pi^+$ is complicated by the possibility of intermediate resonant states, such as $K^{*0}K^+$ and $\phi\pi^+$. We think that in this case a Dalitz plot analysis is the appropriate tool to investigate CP asymmmetry effects. This topic will be the subject of a future paper.

Our asymmetry measurements have been tested by modifying each of the

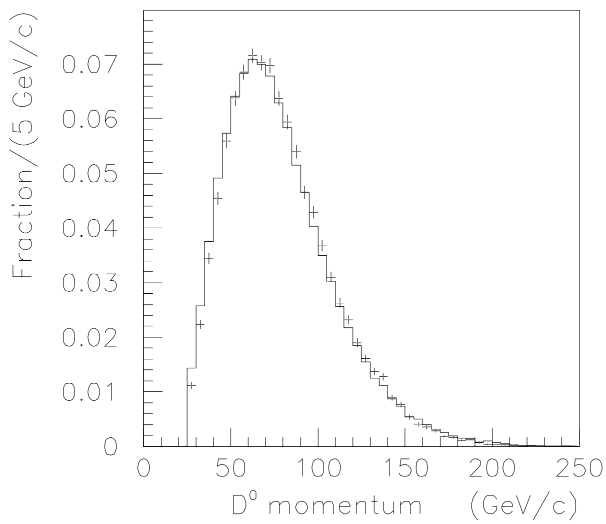

Fig. 4. D^0 momentum for the decay mode $D^0 \to K^-\pi^+$. The points with errors correspond to the real data, the histogram to the Monte Carlo data.

vertex cuts individually; the results are always consistent.

Table 1
Measured CP asymmetries ($\times 10^{-2}$).

Experiment	$D^+ \to K^-K^+\pi^+$	$D^0 \to K^-K^+$	$D^0 \to \pi^-\pi^+$
E687 [11]	-3.1 ± 6.8	$+2.4 \pm 8.4$	
CLEO II [12]		$+8.0 \pm 6.1$	
E791 [13,14]	-1.4 ± 2.9	$-1.0 \pm 4.9 \pm 1.2$	$-4.9 \pm 7.8 \pm 3.0$
This measurement	$+0.6 \pm 1.1 \pm 0.5$	$-0.1 \pm 2.2 \pm 1.5$	$+4.8 \pm 3.9 \pm 2.5$

The systematic errors on these measurements reflect uncertainties in reconstruction efficiency, Čerenkov particle identification, and hadronic absorption of secondaries in the target and spectrometer materials. The estimates were obtained by splitting our data into independent samples depending on D momentum and the different periods in which the data were collected. The main reason for this time depedence is the insertion of the upstream silicon system (in the target region) during the 1997 fixed-target run period. A technique modeled after the *S-factor method* from the Particle Data Group [10] was used to separate true systematic variations from statistical fluctuations. The asymmetry is evaluated for each of the statistically independent subsamples and a *scaled variance* is calculated; the *split sample* variance is defined as the difference between the reported statistical variance and the scaled variance if the scaled variance exceeds the statistical variance. For all decays studied, the scaled variance is less than the statistical variance, so it does not contribute to the systematic uncertainty. The evaluation of systematic effects related to different fit procedures is performed on the whole sample. The asymmetry is

Table 2
Contributions to the systematic uncertainty for the measured asymmetries.

Source	$A_{CP}(K^-K^+\pi^+)$	$A_{CP}(K^-K^+)$	$A_{CP}(\pi^-\pi^+)$
Split sample	no contribution	no contribution	no contribution
Fit variant	0.0016	0.0144	0.0243
Monte Carlo statistics	0.0050	0.0054	0.0055
Total systematic error	0.0053	0.0154	0.0249

calculated using various fit conditions (these include the choice of the estimator, the background shape and, in the case of the D^0 analysis, the shape of the reflection peak) and the sample variance is used because the fit variants are all *a priori* likely. To obtain the final systematic error, the variance from the different fitting procedures and a further contribution, due to the uncertainties in the efficiency calculation and finite statistics of the Monte Carlo events, are then added in quadrature. Table 2 shows the contribution of each of these sources to the total systematic uncertainty for the CP asymmetry measurements.

The measured asymmetries are consistent with zero within the errors.

4 Summary and Conclusions

We have searched for CP violation in the Cabibbo-suppressed decay modes $D^+ \to K^-K^+\pi^+$, $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ using a high statistics sample of photoproduced charm particles from the FOCUS (E831) experiment at Fermilab. We have measured the following CP asymmetry parameters: $A_{CP}(K^-K^+\pi^+) = +0.006 \pm 0.011 \pm 0.005$, $A_{CP}(K^-K^+) = -0.001 \pm 0.022 \pm 0.015$ and $A_{CP}(\pi^-\pi^+) = +0.048 \pm 0.039 \pm 0.025$ where the first error is statistical and the second error is systematic.

These asymmetries are consistent with zero and represent a substantial improvement over previous measurements.

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