CP Violation Results in Charm

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ABSTRACT

Searches for CP violation in the charm sector from the E791, FOCUS, CLEO, BABAR and BELLE experiments are presented. Most analyses consider CP violation in two-body or quasi-two-body decays. Preliminary results from CLEO and FOCUS using Dalitz-plot analyses are also presented.

1 Introduction

The violation of charge-parity (CP) in charm decay requires two amplitudes with different strong and weak phases that interfere to produce CP violating effects. There are three distinct types of CP violation. (1) CP violation from a non-vanishing relative phase between the mass and width components of the mixing matrix usually called "indirect"; (2) Direct CP violation due to the two decay amplitudes having different weak phases; (3) Interference between decays

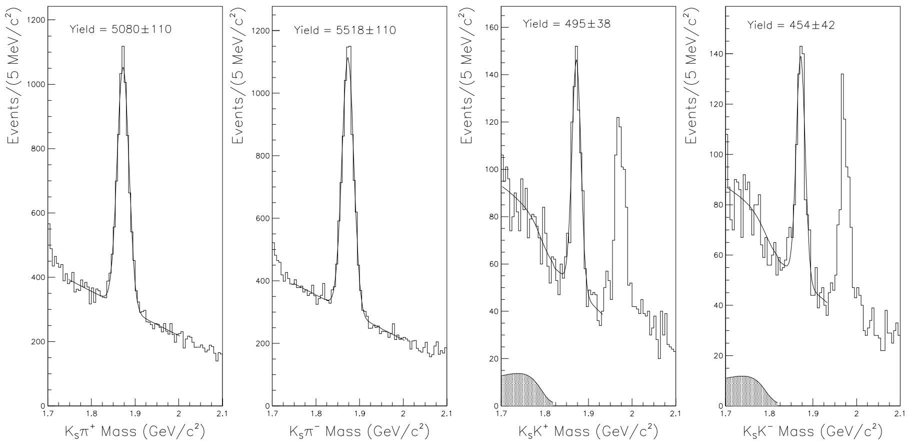

Figure 1: $D^+ \to K^0_S \pi^+, K^0_S K^+$ *Mass plots.*

with and without mixing. The CP conserving phase shift is usually generated by QCD final state interactions (FSI). In the Standard Model, the relative weak phase is typically between tree level and penguin amplitudes. Extensions to the Standard Model introduce additional amplitudes with weak phases that can contribute to CP violation. In the Standard Model, CP violation in the charm sector is small and $D^0 - \overline{D}^0$ mixing is highly suppressed, so at current experimental sensitivities searches for CP violation in charm is for physics beyond the Standard Model. Most CP violation results are from the FNAL fixed target experiments E791 [1)] and FOCUS [2)], and the CLEO [3)] experiment and search for direct CP violation. The CP violation asymmetry is defined as $A_{CP} \equiv \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})}$. A few results from CLEO, BABAR [4)] and BELLE [5)] experiments consider CP violation in mixing.

2 Direct CP Violation

2.1 Two-body decays

FOCUS has published results [6)] using the two-body decay modes $D^+ \to K^0_S \pi^+$, where Cabibbo favored and doubly-Cabibbo suppressed amplitudes can interfere, and $D^+ \to K^0_S K^+$ which is singly Cabibbo suppressed where interference

Table 1: *Branching Ratios (BR) and A_{CP} of $D^+ \to K^0_S\pi^+, K^0_S K^+$.*

	FOCUS BR [6]	PDG Average BR	A_{CP} [6]
$\frac{\Gamma(\overline{K^0}\pi^+)}{\Gamma(K^-\pi^+\pi^+)}$	(30.60±0.46±0.58)%	(32.0±4.0)%	(−1.6±1.5±0.9)%
$\frac{\Gamma(\overline{K^0}K^+)}{\Gamma(K^-\pi^+\pi^+)}$	(6.04±0.35±0.35)%	(7.7±2.2)%	(6.9±6.0±1.8)%
$\frac{\Gamma(\overline{K^0}K^+)}{\Gamma(\overline{K^0}\pi^+)}$	(19.96±1.20±1.06)%	(26.3±3.5)%	(7.1±6.1±1.4)%

between tree and penguin may occur. The production mechanism in fixed target experiments yields different number of D and $\overline{D}$ and so must normalize relative to another copious decay mode which is unlikely to exhibit CP violation, in this case $D^+ \to K^-\pi^+\pi^+$. The $D^\pm \to K^0_S\pi^\pm, K^0_S\pi^\pm$ mass plots are shown in Fig. 1. These decay modes will also manifest CP violation in K^0–$\overline{K}^0$ mixing. The results tabulated in Table 1 show no evidence for CP violation. This is consistent with Standard Model expectations $O(\sim 10^{-3})$.

2.2 Three-body decays

Direct CP violation searches in analyses of charm decays to three-body final states are more complicated than two-body decays. Three methods have been used to search for CP asymmetries. (1) Integrate over phase space and construct A_{CP} as in two-body decays; (2) Examine CP asymmetry in the quasi-two-body resonances; (3) Perform a full Dalitz-plot analysis for D and $\overline{D}$ separately. The Dalitz-plot analysis procedure [7, 8] allows increased sensitivity to CP violation by probing decay amplitudes rather than the decay rate. Both E791 [9] and FOCUS have analyzed $D^+ \to K^+K^-\pi^+$ using method (1). E791 has also analyzed $D^+ \to K^-K^+\pi^+$ using method (2). These results are

Table 2: *CP Asymmetry in Three-body Decays.*

	E791 [9]	FOCUS [10]
$A_{CP}(K^-K^+\pi^+)$	$(-1.4 \pm 2.9)\%$	$(0.6 \pm 1.1 \pm 0.5)\%$
$A_{CP}(\phi\pi^+)$	$(-2.8 \pm 3.6)\%$	Dalitz-plot analyses
$A_{CP}(K^*K^+)$	$(-1.0 \pm 5.0)\%$	in
$A_{CP}(\pi^+\pi^-\pi^+)$	$(-1.7 \pm 4.2)\%$	progress

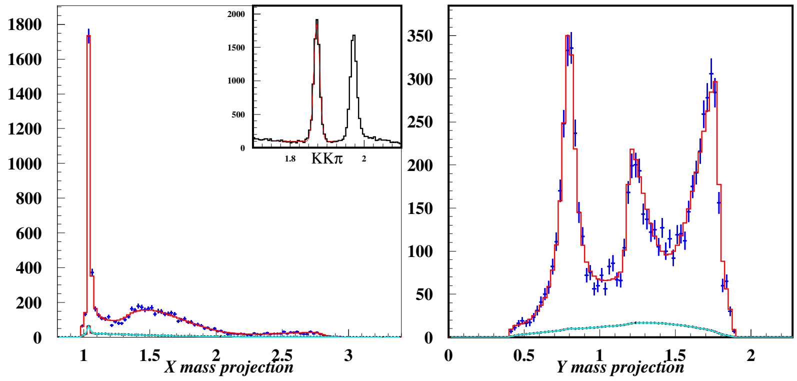

Figure 2: *FOCUS Dalitz-plot Analysis of $D^+ \to K^+K^-\pi^+$ [10]: Projection of data (points) and fit (contour) for Left: m^2_{KK} and Right: $m^2_{K\pi}$.*

shown in Table 2. FOCUS has a Dalitz-plot analysis in progress [10]. The $D^+ \to K^+K^-\pi^+$ Dalitz plot is well described by eight quasi-two-body decay channels. The projections of the data and fit are shown in Fig. 2. A signature of CP violation in charm Dalitz-plot analyses is different amplitudes and phases for D and $\overline{D}$ samples. The amplitudes and phases for $D^+ \to K^+K^-\pi^+$, $D^- \to K^-K^+\pi^-$ and the combined sample are shown graphically in Fig. 3. No evidence for CP violation is observed.

The decay $D^{*+} \to D^0\pi^+$ enables the discrimination between D^0 and $\overline{D}^0$. The CLEO collaboration has searched for CP violation integrated across the Dalitz plot in $D^0 \to K^\mp\pi^\pm\pi^0$, $K^0_S\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ decays. The integrated CP violation across the Dalitz plot is determined by

$$\mathcal{A}_{CP} = \int \frac{|\mathcal{M}_{D^0}|^2 - |\mathcal{M}_{\overline{D}^0}|^2}{|\mathcal{M}_{D^0}|^2 + |\mathcal{M}_{\overline{D}^0}|^2} dm^2_{ab}dm^2_{bc} / \int dm^2_{ab}dm^2_{bc}. \tag{1}$$

The CLEO results for integrated CP asymmetry in D^0 decays are reported in Table 3. No evidence of CP violation has been observed.

CLEO has considered CP violation more generally in a simultaneous fit to the $D^0 \to K^0_S\pi^+\pi^-$ and $\overline{D}^0 \to K^0_S\pi^+\pi^-$ Dalitz plots, shown in Fig. 4. In the isobar model [7], each resonance, j, has its own amplitude, a_j, and phase, δ_j. A second process, not necessarily of Standard Model origin, is allowed

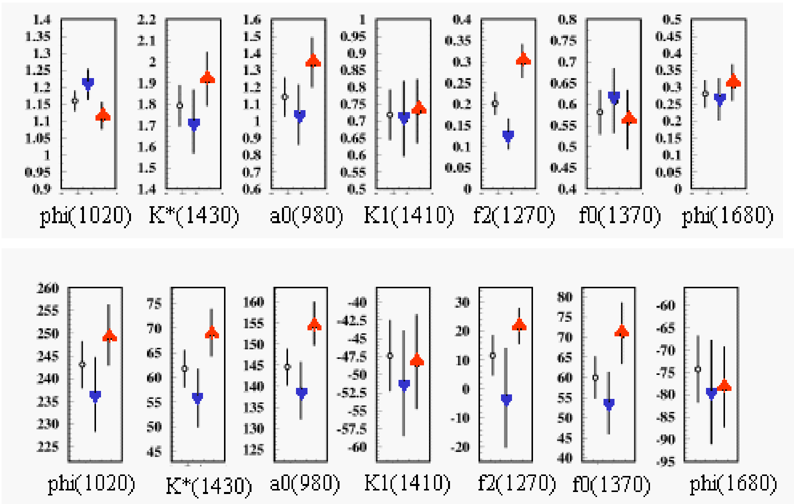

Figure 3: *FOCUS results for $D^+ \to K^+K^-\pi^+$ [10]. Amplitudes(top) and phases(bottom) of resonant substructure for $D^\pm$ (left), D^+ (center), D^- (right).*

to contribute to each j-th resonance. In general, the amplitudes to the j-th quasi-two-body state can be expressed as

$$(a_j e^{i(\delta_j \pm \phi_j)} \pm b_j e^{i(\delta_j \pm \phi_j)})\mathcal{A}_j = a_j e^{i(\delta_j \pm \phi_j)}(1 \pm \frac{b_j}{a_j})\mathcal{A}_j, \qquad (2)$$

with '+' for D^0 and '−' for $\overline{D}^0$ and $\mathcal{A}_j = \mathcal{A}_j(m^2_{K^0_S\pi}, m^2_{\pi\pi})$ is the spin-dependent Breit-Wigner amplitude for resonance j as described in Ref. [7]. Thus a_j and δ_j are explicitly CP conserving amplitude and phase, b_j is an explicity CP violating amplitude normalized by the CP conserving amplitude a_j, and ϕ_j

Table 3: *Integrated CP Asymmetry in Dalitz-plot Analysis.*

	Decay Mode	$\mathcal{A}_{CP}(\%)$
CLEO [7]	$D^0 \to K^-\pi^+\pi^0$	-3.1 ± 8.6
CLEO [11]	$D^0 \to K^+\pi^-\pi^0$	9^{+22}_{-25}
CLEO [8]	$D^0 \to K^0_S\pi^+\pi^-$	$-0.9 \pm 2.1^{+1.0+1.3}_{-4.3-3.7}$
CLEO [12]	$D^0 \to \pi^+\pi^-\pi^0$	$1^{+9}_{-7} \pm 9$

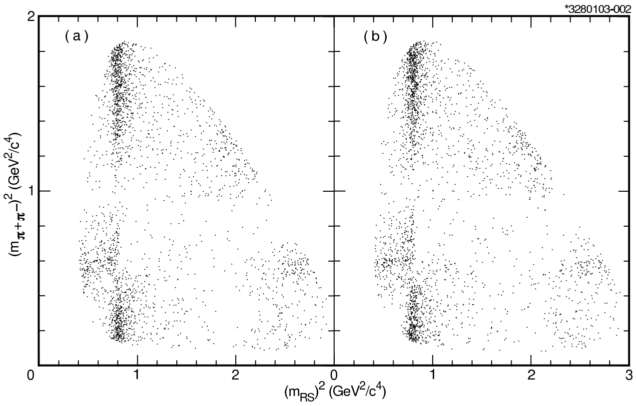

Figure 4: *CLEO II.V:* $D^0 \to K^0_S \pi^+\pi^-$ *and* $\overline{D}^0 \to K^0_S \pi^+\pi^-$ *Dalitz plots* [8].

Table 4: *CLEO II.V: CP Asymmetry in* $D^0 \to K^0_s \pi^+\pi^-$ [8].

Component	Amplitude Ratio (b_j/a_j)	Phase (ϕ_j)
$K^*(892)^+\pi^-, K^*(892)^+ \to K^0\pi^+$	$-0.12^{+0.21+0.09+0.11}_{-0.22-0.15-0.03}$	$6^{+21+13+18}_{-22-35-4}$
$\overline{K}^0\rho^0$	$0.001\pm0.022^{+0.011+0.002}_{-0.009-0.011}$	$-1^{+16+9+21}_{-18-31-3}$
$\overline{K}^0\omega, \omega \to \pi^+\pi^-$	$-0.14^{+0.10+0.11+0.01}_{-0.11-0.01-0.02}$	$-8^{+17+8+20}_{-19-30-3}$
$K^*(892)^-\pi^+, K^*(892)^- \to \overline{K}^0\pi^-$	$-0.002\pm0.012^{+0.008+0.002}_{-0.003-0.002}$	$-3^{+16+9+21}_{-18-30-3}$
$\overline{K}^0 f_0(980), f_0(980) \to \pi^+\pi^-$	$-0.04\pm0.06^{+0.13+0.00}_{-0.04-0.04}$	$9^{+16+10+20}_{-17-29-3}$
$\overline{K}^0 f_2(1270), f_2(1270) \to \pi^+\pi^-$	$0.16^{+0.28+0.15+0.11}_{-0.27-0.37-0.18}$	$22^{+19+12+20}_{-20-32-2}$
$\overline{K}^0 f_0(1370), f_0(1370) \to \pi^+\pi^-$	$0.08^{+0.06+0.01+0.06}_{-0.05-0.11-0.03}$	$8^{+15+10+20}_{-17-28-4}$
$K^*_0(1430)^-\pi^+, K^*_0(1430)^- \to \overline{K}^0\pi^-$	$-0.02\pm0.06^{+0.04+0.00}_{-0.02-0.01}$	$-3^{+17+13+23}_{-19-36-2}$
$K^*_2(1430)^-\pi^+, K^*_2(1430)^- \to \overline{K}^0\pi^-$	$-0.05\pm0.12^{+0.04+0.04}_{-0.14-0.00}$	$3^{+17+10+21}_{-18-31-2}$
$K^*(1680)^-\pi^+, K^*(1680)^- \to \overline{K}^0\pi^-$	$-0.20^{+0.28+0.05+0.02}_{-0.27-0.22-0.01}$	$-3^{+19+20+27}_{-20-25-2}$

is an explicitly CP violating phase. In the absence of CP violation b_j and ϕ_j would be zero. The results of the fit to the D^0 and $\overline{D}^0 \to K^0_S\pi^+\pi^-$ Dalitz plots are consistent with each other and with no CP violation. The fractional CP violating amplitude and CP violating phase, b_j/a_j and ϕ_j are given in Table 4.

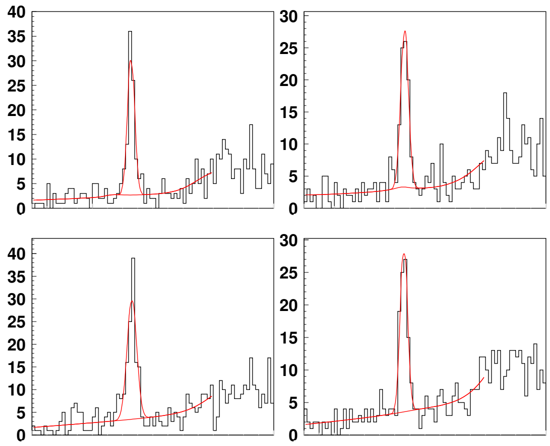

Figure 5: *Top (Bottom):* $D^0\,(\overline{D}^0)$ $m_{K^-K^+\pi^-\pi^+}$ *for Left (Right):* $C_T < 0(> 0)$.

2.3 Four-body decays

FOCUS has searched for T-violation using the four-body decay modes $D^0 \to K^+K^-\pi^+\pi^-$ [13]. A T-odd correlation can be formed wit the momenta, $C_T \equiv (\vec{p}_{K^+}.(\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}))$. Under time-reversal, $C_T \to -C_T$, however $C_T \neq 0$ does not establish T-violation. Since time reversal is implemented by an anti-unitary operator, $C_T \neq 0$, can be induced by FSI [14]. This ambiguity can be resolved by measuring $\overline{C}_T \equiv (\vec{p}_{K^+}.(\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}))$ in $\overline{D}^0 \to K^+K^-\pi^+\pi^-$; $C_T \neq \overline{C}_T$ establishes T violation. FOCUS reports a preliminary asymmetry $A_T = 0.075 \pm 0.064$ from a sample of ~ 400 decays. The mass distributions for D^0 and $\overline{D}^0$ for C_T and $\overline{C}_T$ greater than and less than zero are shown in Fig. 5.

3 CP Violation in $D^0 - \overline{D}^0$ Mixing

E791 [15], FOCUS [16] and CLEO [17] have all searched for CP violation in the Cabibbo suppressed decays to CP eigenstates, $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$. These measurements, tabulated in Table 5, are approaching the 1% level, where non-Standard Model physics may appear.

Time dependent A_{CP} measurements performed by BABAR [18] and BELLE [19] can distinguish direct and indirect CP violation. Since mixing is small the decay

Table 5: *CP Asymmetry in* $D^0 \to K^+K^-, \pi^+\pi^-$.

Expt	$A_{CP}(KK)$ (%)	$A_{CP}(\pi\pi)$ (%)
E791 [15]	$-1.0 \pm 4.9 \pm 1.2$	$-4.9 \pm 7.8 \pm 3.0$
FOCUS [16]	$-0.1 \pm 2.2 \pm 1.5$	$4.8 \pm 3.9 \pm 2.5$
CLEO [17]	$0.0 \pm 2.2 \pm 0.8$	$1.9 \pm 3.2 \pm 0.8$
Expt	Mode(s)	$\Im(x)$ (%)
BELLE [19]	K^+K^-	$-0.20 \pm 0.63 \pm 0.30$
BABAR [18]	$K^+K^-, \pi^+\pi^-$	$-0.8 \pm 0.6 \pm 0.2$

time to CP eigenstates can be fit with a single exponential $\exp\left[-\Gamma(1 + y \mp \Im(x))\right]$. The signature of CP violation is D^0 and $\overline{D}^0$ having different decay rates, $\Im(x) \neq 0$, to CP eigenstates. The results are tabulated in Table 5 and are consistent with the absence of CP violation.

4 Summary and Future Outlook

Searches for CP violation in charm decay at fixed target and e^+e^- facilities are summarized in Table 6 and 7, respectively, including additional results not discussed in the text. FOCUS and CLEO continue work on studying CP violation using Dalitz-plot analyses, $D^+ \to K^+K^-\pi^+, \pi^+\pi^-\pi^+$ and $D^0 \to K^0_S\pi^0\pi^0$, respectively. BABAR and BELLE have each accumulated twenty-five times the statistics of CLEO II.V, approaching sensitivity to CP violation in Kaon mixing, in modes like $D \to K^0_S\pi$. Presently CLEO-c [24] is taking data at the $\psi(3770)$ with the goal of accumulating 18 million $D\overline{D}$ events and attain sensitivity comparable to 1 ab^{-1} of B-factory data. In addition, CLEO-c will exploit the CP coherent $D\overline{D}$ system to probe CP violation. Beginning in 2009 the BTeV experiment [25] will start to accumulate $\sim 1000\times$ the charm statistics of FOCUS opening up a new regime in charm CP and T violation studies.

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Table 6: *Fixed Target Experiments: CP Violation Searches in Charm.*

A_{CP} mode	E791(%)	FOCUS(%)
$D^0 \to K^- K^+$	$-1.0 \pm 4.9 \pm 1.2$ [15]	$-0.1 \pm 2.2 \pm 1.5$ [16]
$D^0 \to \pi^- \pi^+$	$-4.9 \pm 7.8 \pm 3.0$ [15]	$4.8 \pm 3.9 \pm 2.5$ [16]
$D^+ \to K_S^0 \pi^+$		$-1.6 \pm 1.5 \pm 0.9$ [6]
$D^+ \to K_S^0 K^+$		$6.9 \pm 6.0 \pm 1.8$ [6]
$D^+ \to K^- K^+ \pi^+$	-1.4 ± 2.9 [9]	$0.6 \pm 1.1 \pm 0.5$ [10]
$D^+ \to \phi \pi^+$	-2.8 ± 3.6 [9]	
$D^+ \to K^* K^+$	-1.0 ± 5.0 [9]	
$D^+ \to \pi^- \pi^+ \pi^+$	-1.7 ± 4.2 [9]	

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Table 7: e^+e^- *Experiments: CP Violation Searches in Charm.*

A_{CP} mode	CLEO	BABAR(%)	BELLE(%)
$D^0 \to K^+\pi^-$	2^{+19}_{-20} [20]	9.5 ± 10.3 [21]	
$D^0 \to K^+\pi^-\pi^0$	9^{+25}_{-22} [11]		
$D^0 \to K^-K^+$	$0.0\pm2.2\pm0.8$ [17]	-0.8 ± 0.6 [18]	0.2 ± 0.7 [19]
$D^0 \to \pi^-\pi^+$	$1.9\pm3.2\pm0.8$ [17]	-0.8 ± 0.6 [18]	
$D^0 \to \pi^0\pi^0$	0.1 ± 4.8 [22]		
$D^0 \to K^0_S K^0_S$	-23 ± 19 [22]		
$D^0 \to K^0_S\pi^0$	0.1 ± 1.3 [22]		
$D^0 \to K^0_S\pi^+\pi^-$	$-3.9^{+4.6}_{-4.9}$ [8]		
$D^0 \to K^0_S\phi$	2.8 ± 9.4 [23]		
$D^0 \to K^-\pi^+\pi^0$	-3.1 ± 8.6 [7]		
$D^0 \to \pi^+\pi^-\pi^0$	-1^{+13}_{-11} [12]		

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