

# Experimental Prospects for $CP$ and $T$ Violation Studies in Charm\*

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We present the current status of experimental results and prospects for the determination of  $CP$  and  $T$  violation in the charm sector. Such measurements have acquired renewed interest in recent years in view of theoretical work, which has highlighted the possibility to probe experimental signatures from New Physics beyond the Standard Model, since the effect of  $CP$  violation due to Standard Model processes is expected to be highly suppressed in  $D$  decays. The current limits of experimental sensitivities for these studies are reaching the interesting theoretical regimes. We include new measurements from the Belle, BABAR, and CLEO-c collaborations.

## 1. Introduction

The amount of  $CP$  violation (CPV) currently discovered in nature is not sufficient to explain the universe as we see it. Looking in the charm sector is a natural extension of this task. Three are the kinds of CPV we deal with: CPV in the  $D^0 - \bar{D}^0$  mixing matrix, which is expected to be insignificant in the charm sector, CPV in the decay amplitudes, and CPV in the interference between mixing and decay, which should be very small as well. The second one is also known as direct CPV and will be covered in this paper.

The expression for the  $CP$  asymmetry resulting from a process  $f$  and its  $CP$  conjugate  $\bar{f}$  is given by:

$$A_{CP} = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})} = \frac{2\Im(A_1 A_2^*) \sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + \Re(A_1 A_2^*) \cos(\delta_1 - \delta_2)} \quad (1)$$

$A_1$  and  $A_2$  are two components of the decay amplitude and  $\delta_1 - \delta_2$  the corresponding strong phase difference. It follows that two amplitudes with different strong as well as weak phases are needed to have CPV. In the realm of the SM, usually this means a tree and a penguin amplitude. The kinds of processes described in the following are categorized as Cabibbo favored (CF,  $c \rightarrow s\bar{d}u$ ), suppressed (CS,  $c \rightarrow s\bar{s}u$ ,  $c \rightarrow d\bar{d}u$ ), and doubly suppressed (DCS,  $c \rightarrow d\bar{s}u$ ), according to the kind of vertices that intervene in the charm quark decay.

In contrast to the beauty sector, the Standard Model (SM) charm sector is largely  $CP$  conserving, as it involves 4 quarks and the  $2 \times 2$  Cabibbo mixing matrix is real. In singly Cabibbo suppressed decays diluted weak phases can produce asymmetries of the order  $10^{-3} - 10^{-4}$ , while no weak phases, hence no CPV, exist in CF and DCS decays, except for some minimal asymmetry in the  $D^+ \rightarrow K_S \pi^+$  mode. It is

interesting to notice that it is possible in principle to distinguish direct and indirect CPV, either combining direct  $CP$  asymmetries with time-dependent measurements both for CP eigenstates, or just using time integrated measurements for CF CP eigenstate modes (assuming negligible CPV in CF modes) as  $K_S \pi^0$  [1].

New Physics (NP) can contain  $CP$  violating couplings that could show up at the percent level [1] [2] [3] [4]. Several extensions of the SM predict such asymmetries, including models with lept-quarks, a fourth generation of fermions, right-handed weak currents, or extra Higgs doublets. Precision measurements and theory are required to detect NP. The charm sector is in a unique position to test physics beyond the SM. In particular it can test models where CPV is generated in the up-like quark sector. Flavor models where the CKM mixing is generated in the up sector generally predict large D-mixing and sizeable CPV in charm, but smaller effects in the beauty sector. Furthermore, SCS  $D$  decays are now more sensitive to gluonic penguin amplitudes than are charmless B decays [1]. In summary, finding CPV in CF and DCS decays or finding CPV above 0.1% in SCS decays would indicate NP.

## 2. Current Experimental Results

There are several ways direct  $CP$  and  $T$  violation can be looked for: by measuring asymmetries in time integrated partial widths or in final state distributions of Dalitz plots or by measuring  $T$  violation via  $T$ -odd correlations with 4-body  $D$  decays. As an example of charged  $D$  decays, Fig. 1 shows the reconstructed mass distributions in  $D^+ \rightarrow K^- K^+ \pi^+$  and  $D^+ \rightarrow \pi^+ \pi^+ \pi^-$  candidates in the BABAR detector, with fairly large datasets ( $80 fb^{-1}$ ) [5]. The  $CP$  asymmetry results of these and many other analyses are listed in Table I.

As mentioned earlier, in the SM we can expect direct CPV at the  $10^{-3}$  level in SCS decays, but no CPV in CF modes. In the  $K^+ K^-$  and  $\pi^+ \pi^-$  modes it is puzzling that the ratio of their branching ratios is so different from 1 ( $\sim 2.8$ ). This entails the presence of

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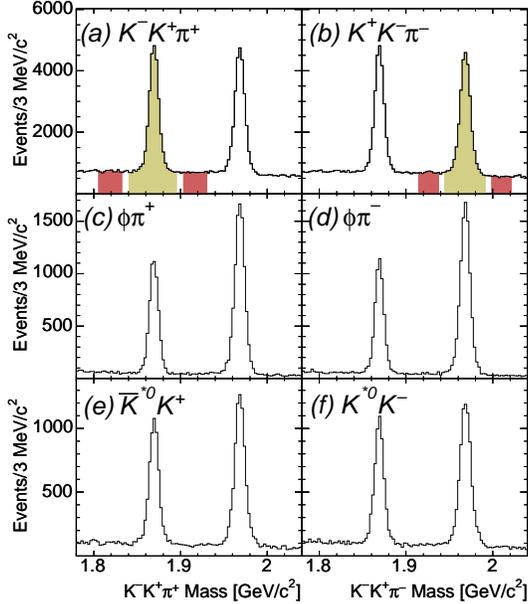


Figure 1: *BABAR*'s sample of  $D^+ \rightarrow K^- K^+ \pi^+$  and  $D^+ \rightarrow \pi^+ \pi^+ \pi^-$  candidates (mass distributions) used for CPV measurements.

large final state interactions (FSI) and/or large penguin contributions, which could be fertile ground for NP to manifest itself. Phenomenological calculations set SM limits at or well below the  $10^{-3}$  level [6]. The CDF collaboration has to date the best  $CP$  measurements for these modes. The asymmetries are normalized to the CF  $K\pi$  mode. Difficulties for this analysis are due to the track charge asymmetry which is calibrated with  $K_S$  control samples and to the partially reconstructed  $D$  background for the  $K^+ K^-$  mode. Total systematics are slightly above 0.5% [7].

A high precision analysis at *BABAR* reports  $A_{CP} = 0.00 \pm 0.34 \pm 0.13$  for the  $K^+ K^-$  mode and  $A_{CP} = -0.24 \pm 0.52 \pm 0.22$  for the  $\pi^+ \pi^-$  mode [8]. To keep the systematics so low, the keys are to calibrate charge and tagging asymmetries using data, namely the CF  $K\pi$  mode, and to account for forward-backward asymmetries due to QED effects, which can produce detection asymmetries in a detector as *BABAR*, due to the boost of the center of mass system with respect to the laboratory.

Charm factories benefit with respect to the beauty ones from a pure  $D\bar{D}$  final state with low multiplicity, hence high tagging efficiency. This makes them competitive with the high statistics at *BABAR* and *Belle*. Single tag efficiencies range from 25 to 65%, values unimaginable at the B-factories. Most of the new CP violation results from CLEO-c, with 281  $pb^{-1}$  of data, are for CF modes, with the exception of  $D^+ \rightarrow K^+ K^- \pi^+$  (see Tables I and II). The un-

certainties are of the order of 1% in most cases, For modes with charged kaons, the kaon systematics are the largest ones.

In case of indirect CPV and final  $CP$  eigenstates, the time integrated and time dependent  $CP$  asymmetries are universal and equal to each other. In contrast, for direct CPV, the time-integrated asymmetries in principle are not expected to be universal. Hence parts of phase-space in a multi-body decay might have different asymmetries (which may even cancel each other out when integrated over the whole phase-space). In addition, NP might not show up in the decay rates asymmetries but instead in the phase difference between amplitudes. 3-body decays permit the measurement of such phase differences. The Dalitz plot technique allows increased sensitivity to  $CP$  asymmetry by probing the decay amplitude rather than the decay rate and access to both CP eigenstates and non  $CP$  eigenstates with relatively high statistics. The CLEO-c collaboration has measured the  $CP$  asymmetry in the  $\pi^+ \pi^- \pi^0$  mode (integrated over the sum of all amplitudes in the Dalitz plot) and has also performed a full fledged Dalitz plot analysis of the  $D^0 \rightarrow K_S \pi^+ \pi^-$  decay [9]. The *BABAR* and *Belle* collaborations can exploit their larger datasets for similar measurements.

T violation measurements can be performed exploiting T-odd correlations between the momenta of the decay products of 4-body  $D$  decays as  $KK\pi\pi$ , while assuming  $CPT$  conservation:

$$C_T = p_{K^+} \cdot (p_{\pi^+} \times p_{\pi^-}). \quad (2)$$

Under time reversal  $C_T$  changes sign, but its being different from 0 is not sufficient to establish T-violation as final state interactions can fake this asymmetry [10]. To overcome this problem the analogous quantity from the  $CP$  conjugate decay can be defined as:

$$\overline{C_T} = p_{K^-} \cdot (p_{\pi^-} \times p_{\pi^+}). \quad (3)$$

Finding  $\overline{C_T} \neq -C_T$  establishes T violation. T-odd asymmetries can be built as:

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)} \quad (4)$$

$$\overline{A_T} = \frac{\Gamma(\overline{C_T} > 0) - \Gamma(\overline{C_T} < 0)}{\Gamma(\overline{C_T} > 0) + \Gamma(\overline{C_T} < 0)} \quad (5)$$

and the T violation asymmetry as:

$$A_{T-viol} = \frac{1}{2}(A_T - \overline{A_T}) \quad (6)$$

and if this is different from 0, T violation is established, even in the presence of strong phases [11].

As for the available measurements the only ones to date are from the FOCUS collaboration (see Tables I and II). The CLEO, BABAR, and Belle experiments should better this analysis with their larger and cleaner data samples.

Most of the measurements of  $CP$  and  $T$  violation in neutral  $D$  decays to date are shown in Table I. No evidence of direct CPV has been found. The best limits are of the order of one to few percent statistical errors with systematics of similar magnitude; few measurements have errors below the 1% level. Most of these are old measurements, except for the new ones from the CLEO-c collaboration and the ones “byproducts” of the mixing analyses of the BABAR and Belle collaborations.

Table I  $A_{CP}$  measurements to date using neutral  $D$  decays. The last row reports a measurement of  $A_T$  by the FOCUS collaboration.

Experiment(year)	Decay mode	$A_{CP}\%$
CDF(2005)	$D^0 \rightarrow K^+K^-$	$2.0 \pm 1.2 \pm 0.6$
CLEO(2002)	$D^0 \rightarrow K^+K^-$	$0.0 \pm 2.2 \pm 0.8$
FOCUS(2000)	$D^0 \rightarrow K^+K^-$	$-0.1 \pm 2.2 \pm 1.5$
CDF(2005)	$D^0 \rightarrow \pi^+\pi^-$	$1.0 \pm 1.3 \pm 0.6$
CLEO(2002)	$D^0 \rightarrow \pi^+\pi^-$	$1.9 \pm 3.2 \pm 0.8$
FOCUS(2000)	$D^0 \rightarrow \pi^+\pi^-$	$4.8 \pm 3.9 \pm 2.5$
CLEO(2001)	$D^0 \rightarrow K_S^0 K_S^0$	$-23 \pm 19$
CLEO(2001)	$D^0 \rightarrow \pi^0 \pi^0$	$0.1 \pm 4.8$
CLEO(2001)	$D^0 \rightarrow K_S^0 \pi^0$	$0.1 \pm 1.3$
CLEO(1995)	$D^0 \rightarrow K_S^0 \phi$	$2.8 \pm 9.4$
CLEO(2005)	$D^0 \rightarrow \pi^+\pi^-\pi^0$	$1_{-7}^{+9} \pm 5$
CLEO(2004)	$D^0 \rightarrow K_S^0 \pi^+\pi^-$	$-0.9 \pm 2.1_{-5.7}^{+1.6}$
Belle(2005)	$D^0 \rightarrow K^+\pi^+\pi^-\pi^-$	$-1.8 \pm 4.4$
FOCUS(2005)	$D^0 \rightarrow K^+K^-\pi^+\pi^-$	$-8.2 \pm 5.6 \pm 4.7$
CLEO(2007)	$D^0 \rightarrow K_S^-\pi^+$	$-0.4 \pm 0.5 \pm 0.9$
CLEO(2007)	$D^0 \rightarrow K_S^-\pi^+\pi^0$	$0.2 \pm 0.4 \pm 0.8$
CLEO(2007)	$D^0 \rightarrow K^-\pi^+\pi^+\pi^-$	$0.7 \pm 0.5 \pm 0.9$
Belle(2005)	$D^0 \rightarrow K^+\pi^-\pi^0$	$-0.6 \pm 5.3$
BABAR(2007)	$D^0 \rightarrow K^+\pi^-$	$-2.1 \pm 5.2 \pm 1.5$
Belle(2007)	$D^0 \rightarrow K^+\pi^-$	$2.3 \pm 4.7$
FOCUS(2005) $A_T$	$D^0 \rightarrow K^+K^-\pi^-\pi^+$	$1.0 \pm 5.7 \pm 3.7$

Table II reports the results for charged  $D$  decays, where many new results from CLEO-c in SCS  $D_s$  decays and in several CF decays are listed. With the CLEO-c result, together with the ones from BABAR and FOCUS, the  $KK\pi$  mode is becoming one of the most interesting precision-wise. Table III lists the average  $CP$  asymmetry measurements by mode. Some of the averages are from HFAG group [12], some are my own, hence probably not as correct, as not all correlations are taken into account. Clearly there is still work to do.

Table II  $A_{CP}$  measurements to date using charged  $D$  decays. The last two rows report measurements of  $A_T$  by the FOCUS collaboration.

Experiment(year)	Decay mode	$A_{CP}\%$
BABAR(2005)	$D^+ \rightarrow K^+K^-\pi^+$	$1.4 \pm 1.0 \pm 0.8$
BABAR(2005)	$D^+ \rightarrow \phi\pi^+$	$0.2 \pm 1.5 \pm 0.6$
BABAR(2005)	$D^+ \rightarrow K_S^0 K^+$	$0.9 \pm 1.7 \pm 0.7$
CLEO(2007)	$D^+ \rightarrow K^+K^-\pi^+$	$-0.1 \pm 1.5 \pm 0.8$
FOCUS(2000)	$D^+ \rightarrow K^+K^-\pi^+$	$0.6 \pm 1.1 \pm 0.5$
E791(1997)	$D^+ \rightarrow K^+K^-\pi^+$	$-1.4 \pm 2.9$
E791(1997)	$D^+ \rightarrow \phi\pi^+$	$-2.8 \pm 3.6$
E791(1997)	$D^+ \rightarrow K_S^0 K^+$	$-1.0 \pm 5.0$
FOCUS(2002)	$D^+ \rightarrow K_S^0 \pi^+$	$-1.6 \pm 1.5 \pm 0.9$
CLEO(2007)	$D^+ \rightarrow K_S^0 \pi^+$	$-0.6 \pm 1.0 \pm 0.3$
CLEO(2007)	$D^+ \rightarrow K_S^0 \pi^+ \pi^0$	$0.3 \pm 0.9 \pm 0.3$
CLEO(2007)	$D^+ \rightarrow K_S^0 \pi^+ \pi^+ \pi^-$	$0.1 \pm 1.1 \pm 0.6$
CLEO(2007)	$D^+ \rightarrow K^-\pi^+\pi^+$	$-0.5 \pm 0.4 \pm 0.9$
CLEO(2007)	$D^+ \rightarrow K^-\pi^+\pi^+\pi^0$	$1.0 \pm 0.9 \pm 0.9$
CLEO(2007)	$D_S^+ \rightarrow K^+\eta$	$-20 \pm 18$
CLEO(2007)	$D_S^+ \rightarrow K^+\eta'$	$-17 \pm 37$
CLEO(2007)	$D_S^+ \rightarrow K_S^0 \pi^+$	$27 \pm 11$
CLEO(2007)	$D_S^+ \rightarrow K^+\pi^0$	$2 \pm 29$
E791(1997)	$D^+ \rightarrow \pi^+\pi^+\pi^-$	$-1.7 \pm 4.2$
FOCUS(2005) $A_T$	$D^+ \rightarrow K_S^0 K^+ \pi^+ \pi^-$	$2.3 \pm 6, 2 \pm 2.2$
FOCUS(2005) $A_T$	$D_S^+ \rightarrow K_S^+ K^+ \pi^+ \pi^-$	$-3.6 \pm 6.7 \pm 2.3$

### 3. Future Prospects

The future prospects for these measurements are very promising. For the  $KK$  and  $\pi\pi$  modes both B-factories and CDF are expected to reach very interesting sensitivities of the order of few per thousand. The issue at the Tevatron will be whether the trigger can cope with the increase of luminosity. The  $D^+ \rightarrow KK\pi$  mode should hit interesting limits as well, if systematics can be hold under control. Very promising are also measurements from Dalitz plot analyses using SCS modes, where we have the added puzzle that it is not known where (if anywhere) CPV can show up in the Dalitz plane. Furthermore, the asymmetry could be large, but confined to only a part of the phase-space.

For the T-correlation analyses, as aforementioned there are large datasets of 4-body  $D$  decays available. The BABAR and Belle collaborations could achieve statistical uncertainties at or below 0.5% if systematics can be kept as low.

If the present machines cannot fully probe the extent of the CP asymmetries allowed by NP or given to us by nature, new experiments at BESIII and at the super B-factories at KEK and/or Frascati, or LHC-b

Table III Average  $CP$  asymmetry measurements by mode.

Decay mode	$A_{CP}\%$
$D^0 \rightarrow K^+ K^-$	$+1.4 \pm 1.2$
$D^0 \rightarrow K_S^0 K_S^0$	$-2.3 \pm 1.9$
$D^0 \rightarrow \pi^+ \pi^-$	$+1.3 \pm 1.3$
$D^0 \rightarrow \pi^0 \pi^0$	$+0.1 \pm 4.8$
$D^0 \rightarrow \pi^+ \pi^- \pi^0$	$+1 \pm 9$
$D^0 \rightarrow K_S^0 \pi^0$	$+0.1 \pm 1.3$
$D^0 \rightarrow K^- \pi^+$	$-0.4 \pm 1.0$
$D^0 \rightarrow K^- \pi^+ \pi^0$	$+0.2 \pm 0.9$
$D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$	$+0.7 \pm 1.0$
$D^0 \rightarrow K^+ \pi^-$	$-0.8 \pm 3.1$
$D^0 \rightarrow K^+ \pi^- \pi^0$	$-0.1 \pm 5.2$
$D^0 \rightarrow K^+ S^0 \pi^+ \pi^0$	$-0.9 \pm 4.2$
$D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$	$-1.8 \pm 4.4$
$D^0 \rightarrow K^+ K^- \pi^- \pi^+$	$-8.2 \pm 7.3$
$D^+ \rightarrow K_S^0 \pi^+$	$-0.9 \pm 0.9$
$D^+ \rightarrow K_S^0 \pi^+ \pi^0$	$+0.3 \pm 0.9$
$D^+ \rightarrow K_S^0 \pi^+ \pi^+ \pi^-$	$+0.1 \pm 1.3$
$D^+ \rightarrow K^- \pi^+ \pi^+$	$-0.5 \pm 1.0$
$D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0$	$+1.0 \pm 1.3$
$D^+ \rightarrow K_S^0 K^+$	$+7.1 \pm 6.2$
$D^+ \rightarrow K^+ K^- \pi^+$	$+0.6 \pm 0.8$
$D^+ \rightarrow \pi^+ \pi^- \pi^+$	$-1.7 \pm 4.2$
$D^+ \rightarrow K_S^0 K^+ \pi^+ \pi^-$	$-4.2 \pm 6.8$

at the LHC definitely will. Data taking at BESIII is expected to start in 2008. With 3 years of running it will get up to 20 times the CLEO-c dataset. The super B-factories should record  $\sim 10 ab^{-1}$  of data per year. At least the super B-factory at Frascati is designed to run at the psi(3770) as well with an estimated  $1 ab^{-1}$  of data per year. LHC-b will implement a dedicated  $D^*$  trigger as well, selecting huge and clean samples of hadronic  $D$  decays. This should assure a  $D^*$  dataset of the order of 100 times the one at CDF in the first year of nominal luminosity running. With all this data we will reach a phase of high precision CPV measurements, with uncertainties of the order of  $10^{-4}$  ( $6 \times 10^{-5}$ ) with one year of nominal running at LHC-b (super-B factories).

## 4. Conclusions

Charm physics provides unique opportunities for indirect searches for new physics. The theoretical calculations of the  $D^0$  mixing parameters have large uncertainties, hence physics beyond the standard model will be hard to rule out from  $D^0$  mixing measurements alone. The observation of large CPV would

instead be a clear and robust signal of new physics. There have been some exciting new results this year from the CLEO-c, Belle, and BABAR collaborations. The total uncertainties are at the 1% level in several modes, but still far from observation. Experiments are just now entering the interesting domain. The future ahead is very promising with good sensitivities achievable by current experiments and high precision measurements expected with future and planned efforts.

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## References

- [1] Y. Grossman, A.L. Kagan, Y. Nir, Phys. Rev. D **75**, 036008 (2007).
- [2] I.I. Bigi, Int. J. Mod. Phys. A21, 5404-5415 (2006).
- [3] A.A. Petrov, Nucl. Phys. Proc. Suppl. 142, 333-339 (2005).
- [4] S. Bianco, F.L. Fabbri, D. Benson, I. Bigi, Riv. Nuovo Cim. 26N7, 1 (2003).
- [5] The BABAR Collaboration, B. Aubert *et al.*, Phys. Rev. D **71**, 091101 (2005)
- [6] F. Buccella *et al.*, Phys. Rev. D **51**, 3478 - 3486 (1995).
- [7] The CDF Collaboration, D. Acosta *et al.*, Phys. Rev. Lett. 94, 122001 (2005).
- [8] The BABAR Collaboration, B. Aubert *et al.*, submitted to Phys. Rev. Lett. e-Print: arXiv:0709.2715.
- [9] The CLEO-c Collaboration, D. Asner *et al.*, Phys. Rev. D **70**, 091101 (2004).
- [10] I.I. Bigi, A.I. Sanda, "CP Violation", Cambridge University Press 2000.
- [11] E. Golowich and G. Valencia, Phys. Rev. D **40**, 112 (1989). I.I. Bigi, Proceedings of KAON2001, 417 (2001).
- [12] E. Barberio *et al.*, arXiv:0704.3575 [hep-ex] and online update at <http://www.slac.stanford.edu/xorg/hfag>.