PROCEEDINGS OF SCIENCE

Results on Charm mixing and CP violation from the B Factories

Nicola Neri[*†]
Università di Pisa and INFN Sezione di Pisa
E-mail: nicola.neri@pi.infn.it

We report on recent results from B factories regarding charm mixing measurements and searches for CP violation in D^0 meson decays. Charm mixing is established with a significance exceeding 10 standard deviations when combining all the available measurements, while CP violation in D^0 decays is constrained below the percent level in decay modes such as $D^0 \to K^+K^-(\pi^0)$ and $D^0 \to \pi^+\pi^-(\pi^0)$. The results are based on 530 fb^{-1} and 950 fb^{-1} of BABAR and Belle data respectively, accumulated at a center-of-mass energy near 10.6 GeV, overall containing about 1.9×10^9 $e^+e^- \to c\bar{c}$ events. Data have been collected with the BABAR detector at the PEP-II asymmetric-energy B Factory at SLAC, and with the Belle detector at the KEKB asymmetric-energy B Factory at KEK.

12th International Conference on B-Physics at Hadron Machines - BEAUTY 2009
September 07 - 11 2009
Heidelberg, Germany

*Speaker.
†on behalf of the BABAR collaboration

PoS(BEAUTY 2009)025

1. Introduction

The neutral D meson system differs from the other neutral meson systems (K, B_d, B_s) since it is the only one made of up-type quarks, *i.e.* $D^0 = c\,\overline{u}$ and $\overline{D}^0 = \overline{c}\,u$. Charm mixing is expected to occur at the percent level or less, although this estimate is subject to large theoretical uncertainties [1, 2]. In the Standard Model (SM) the short-distance transition $\Delta C = 2$ occurs via a box diagram with down-type quarks in the loops: the d and s components are GIM-suppressed, and the b component is suppressed by the small CKM mixing factors. The SM long range contributions to charm mixing are expected to be orders of magnitude above the SM short range ones. The former can be represented as a coherent sum over on-shell intermediate states accessible to both D^0 and $\overline{D}^0$, and thus are inherently non-perturbative and cannot be calculated from first principles. In addition, *CP* violation (*CPV*) in charm mixing or in D^0 decay is expected to be below the per mil level [3]. Experimental evidence of *CPV* in D^0 mixing or in D^0 decays with the present statistics would represent a sign of new physics.

Relevant measurements of mixing parameters and searches for *CPV* will be presented in the following along with a statistical combination of the results.

2. Charm mixing and *CP* violation notation

The two neutral D meson mass (*i.e.* propagation) eigenstates D_1 and D_2, of masses m_1 and m_2 and widths Γ_1 and Γ_2, are linear combinations of production eigenstates with defined flavor content D^0 and $\overline{D}^0$,

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle, \tag{2.1}$$

with $|p|^2 + |q|^2 = 1$. If *CP* is conserved, then $q = p = 1/\sqrt{2}$ and the physical states are *CP* eigenstates. The mixing parameters x and y are defined as

$$x = \frac{m_1 - m_2}{\Gamma}, \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}, \tag{2.2}$$

where $\Gamma = (\Gamma_1 + \Gamma_2)/2$. The decay amplitudes for D^0 and $\overline{D}^0$ to decay into a final state f are defined as $A_f = \langle f|\mathscr{H}|D^0\rangle$ and $\overline{A}_f = \langle f|\mathscr{H}|\overline{D}^0\rangle$ respectively, where $\mathscr{H}$ is the Hamiltonian of the decay. In order to parameterize the effects of *CPV* we introduce the following quantities, adopting the same notation as in [4],

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = -R_m\left|\frac{\overline{A}_f}{A_f}\right| e^{i(\phi_f+\Delta_f)}, \qquad R_m = \left|\frac{q}{p}\right|, \tag{2.3}$$

where ϕ_f is the *CP* violating weak phase and Δ_f is the *CP* conserving strong phase. A value of $R_m \neq 1$ would indicate *CPV* in mixing. A non-zero value of ϕ_f would indicate *CPV* in the interference between mixing and decay. Direct *CPV* would be indicated by $|A_f| \neq |\overline{A}_{\bar{f}}|$. By assuming *CP* conservation in the decay then $\phi_f \equiv \phi$, and is independent of the specific final state f.

3. Selection of the events

Flavor tagged signal events are selected via the cascade decay $D^{*+} \to D^0\pi_s^+$ [1], and the flavor of the D meson is identified at production by the charge of the soft pion (π_s). The difference

[1] Consideration of charge conjugation is implied throughout this paper, unless otherwise stated.

between the reconstructed D^{*+} and D^0 masses (Δm), which has an experimental resolution of about 350 keV$/c^2$, is used to remove background events by requiring typically that it be within 1 MeV$/c^2$ of the nominal value [5]. In addition, flavor untagged signal events can be used in *CP*-conserving mixing analyses, thus exploiting about four times larger signal yield/ fb^{-1} despite a worse purity.

In order to reject background events with correctly reconstructed D^0 candidates from B meson decays, the D^0 momentum, evaluated in the e^+e^- center-of-mass (CM) frame, is required to be greater than $2.4-2.5$ GeV$/c$ for most of the analyses. The D^0 proper time-of-flight, t, is determined from a combined fit to the D^0 production and decay vertices. In this vertex-constrained fit the D^0 candidate and the π_s track, when available, are constrained to originate from the e^+e^- luminous region. The average error on the proper time, σ_t, is about 0.2 ps, *i.e.* approximately half of the D^0 lifetime [5]. Particle identification algorithms are used to identify charged tracks from D^0 decay with typical efficiency of about 85% for kaons, with a corresponding pion misidentification rate as kaon of about 2%.

4. Charm mixing results

Here we briefly describe the most relevant and recent analyses used by the *BABAR* and Belle experiments for the measurement of the mixing parameters.

4.1 Wrong-sign decays $D^0 \to K^+\pi^-$

The final wrong-sign (WS) state can be produced either via the doubly Cabibbo-suppressed (DCS) decay $D^0 \to K^+\pi^-$ or via mixing followed by the Cabibbo-favored (CF) decay $D^0 \to \overline{D}^0 \to K^+\pi^-$. The time dependence of the WS decay of a meson produced as a D^0 at time $t = 0$, in the limit of small mixing ($|x|$, $|y| \ll 1$) and *CP* conservation, can be approximated as

$$\frac{T_{\rm WS}(t)}{e^{-\Gamma t}} \propto R_{K\pi} + \sqrt{R_{K\pi}}y'\,\Gamma t + \frac{x'^2+y'^2}{4}(\Gamma t)^2\,, \tag{4.1}$$

where $R_{K\pi}$ is the ratio of DCS to CF decay rates, $x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$, $y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$, and $\delta_{K\pi} = -\Delta_f$ is the strong phase between the DCS and CF amplitudes.

The *BABAR* experiment found evidence of mixing at the 3.9σ level [6] using a data sample corresponding to an integrated luminosity of 384 fb^{-1} and a signal yield of 4030 ± 88 events. Almost identical results were obtained by the CDF experiment, with a mixing significance of 3.8σ, from an integrated luminosity of about 1.5 fb^{-1} and a signal yield of $(12.7 \pm 0.3) \times 10^3$ events [7]. The Belle experiment, using 400 fb^{-1} of data with a signal yield of 4024 ± 88 events, was able to exclude the no-mixing hypothesis at only the 2.1σ level [8]. The results from the different experiments for the *CP*-conserving mixing analyses are reported in Table 1. For measurements at B factories the statistical error dominates the overall uncertainty. No evidence for *CP* violation was found.

4.2 Decays to *CP* eigenstates

Mixing parameters can also be measured by studying the proper decay time distribution for D^0 decays to *CP* eigenstates. Due to the small values of x and y, each decay time distribution can

PoS(BEAUTY 2009)025

Table 1: Wrong-sign $D^0 \to K^+\pi^-$ mixing results for the *CP*-conserving hypothesis. The uncertainties include statistical and systematic components. The mixing significance is given in terms of the equivalent number of Gaussian standard deviations.

Experiment	$R_D(10^{-3})$	$y'\,(10^{-3})$	$x'^2\,(10^{-3})$	Mix. Significance
BABAR	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9
CDF	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35	3.8
Belle	3.64 ± 0.17	$0.6\,^{+4.0}_{-3.9}$	$0.18\,^{+0.21}_{-0.23}$	2.1

be treated to a good approximation as a pure exponential [9], as follows,

$$T^+_{CP}(t) \propto e^{-\Gamma^+_{CP}t} \qquad \text{for } D^0 \to f_{CP} \qquad\qquad T^-_{CP}(t) \propto e^{-\Gamma^-_{CP}t} \qquad \text{for } \bar{D}^0 \to f_{CP} \tag{4.2}$$

with effective lifetimes $\tau^\pm \equiv 1/\Gamma^\pm_{CP}$, where $\Gamma^+_{CP} = \Gamma\left[1+\eta^{CP}_f|q/p|(y\cos\phi - x\sin\phi)\right]$ and $\Gamma^-_{CP} = \Gamma\left[1+\eta^{CP}_f|p/q|(y\cos\phi + x\sin\phi)\right]$ are the decay constants, and $\eta^{CP}_f = \pm1$ is the *CP* eigenvalue for the final state f_{CP}. By measuring the ratio of the effective lifetimes τ^+ (τ^-) in D^0 ($\bar{D}^0$) $\to f_{CP}$ to the D^0 lifetime, $\tau_{K\pi}$, in $D^0 \to K^-\pi^+$ decay, we extract the mixing and *CPV* parameters y_{CP} and ΔY,

$$y_{CP} = \eta^{CP}_f\left[\frac{\tau_{K\pi}}{\langle\tau_{CP}\rangle} - 1\right], \qquad \Delta Y = \frac{\tau_{K\pi}}{\langle\tau_{CP}\rangle}A_\tau\,, \tag{4.3}$$

where $\langle\tau_{CP}\rangle = (\tau^+ + \tau^-)/2$ and $A_\tau = (\tau^+ - \tau^-)/(\tau^+ + \tau^-)$. Both y_{CP} and ΔY are zero if there is no mixing, while $y_{CP} \equiv y$ and ΔY is zero if *CP* is conserved[2].

Both BABAR and Belle collaborations found evidence for mixing in the analysis of the ratio of the lifetime for $D^0 \to K^+K^-, \pi^+\pi^-$ to that for $D^0 \to K^-\pi^+$ flavor-tagged decays; neither found evidence for *CPV* [10, 11]. The BABAR results are based on $384\,\text{fb}^{-1}$ of data with signal yields of about 70×10^3, 30×10^3, 730×10^3 events, and signal purities of 99.6%, 98.0%, 99.9%, for K^+K^-, $\pi^+\pi^-$, $K^-\pi^+$ respectively. The Belle results are based on $540\,\text{fb}^{-1}$ of data with signal yields of about 110×10^3, 50×10^3, 1.2×10^6 events, and signal purities of 98%, 92%, 99%, for K^+K^-, $\pi^+\pi^-$, $K^-\pi^+$ respectively. Mixing and *CPV* results are reported in Table 2. The BABAR collaboration, performed a similar analysis using K^+K^- and $K^-\pi^+$ flavor-untagged events [12], which is statistically independent of the flavor-tagged sample. The signal yields based on $384\,\text{fb}^{-1}$ of data are about 260×10^3, 2.7×10^6 events with signal purities of 80.9% and 90.4% for K^+K^-, $K^-\pi^+$ respectively. The mixing results are shown in Table 2 along with the combined tagged plus untagged results [12]. No *CPV* results are provided for analyses using the untagged sample, where only *CP*-conserving fits are possible.

Using $673\,\text{fb}^{-1}$ of data, the Belle collaboration performed a lifetime-difference analysis using the $K^0_SK^+K^-$ final state, by measuring the effective lifetime of the *CP*-even and *CP*-odd components of the $K^0_SK^+K^-$ Dalitz plot. The lifetime asymmetry in these regions is related to y_{CP} as follows

$$\frac{\tau_{OFF} - \tau_{ON}}{\tau_{OFF} + \tau_{ON}} = y_{CP}\frac{f_{ON} - f_{OFF}}{1 + y_{CP}(1 - f_{ON} - f_{OFF})}. \tag{4.4}$$

[2] Belle collaboration quotes *CPV* results in terms of $A_\Gamma \equiv -A_\tau$.

Table 2: Fit results for y_{CP} and for the *CPV* observable used (ΔY for BABAR and $A_\Gamma \equiv -A_\tau$ for Belle). The first error is statistical, the second systematic. The mixing significance is given in terms of the equivalent number of Gaussian standard deviations.

Sample	y_{CP} (%)	*CPV* (%)	Mix. Significance
Belle tagged	$1.31 \pm 0.32 \pm 0.25$	$+0.01 \pm 0.30 \pm 0.15$	3.2
BABAR tagged	$1.24 \pm 0.39 \pm 0.13$	$-0.26 \pm 0.36 \pm 0.08$	3.0
BABAR untagged	$1.12 \pm 0.26 \pm 0.22$	-	3.3
BABAR tag.+untag.	$1.16 \pm 0.22 \pm 0.18$	-	4.1

The value of y_{CP} is extracted by measuring the effective lifetime τ_{ON} in the ϕK_S^0 region (mainly *CP*-odd) and the mean lifetime τ_{OFF} in the sidebands (mainly *CP*-even), along with the corresponding fractions f_{ON} and f_{OFF} of *CP*-even events in these regions. With this technique, Belle has measured $y_{CP} = [0.11 \pm 0.61(\text{stat.}) \pm 0.52(\text{syst.})]\%$ [13].

5. Search for *CP* violation in D^0 decays

The search for *CPV* in neutral *D* meson decays provides a unique probe for new physics. The SM predicts very small effects, smaller than $\mathcal{O}(10^{-3})$ [1, 3]. In addition, Cabibbo-suppressed decays such as $D^0 \to K^+K^-(\pi^0), \pi^+\pi^-(\pi^0)$ are sensitive to new physics contributions from penguin and dipole operators [4]. The observation of *CP* asymmetries at the level of the current experimental sensitivity, $\mathcal{O}(10^{-2})$, would be a clear sign of physics beyond the SM [1, 4].

5.1 The two-body decays $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$

The BABAR and Belle collaborations performed a search for *CPV* in neutral *D* mesons [14, 15] produced from the reaction $e^+e^- \to c\bar{c}$, by measuring the time-integrated asymmetries

$$a_{CP}^{hh} = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\bar{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\bar{D}^0 \to h^+h^-)}, \qquad a_{CP}^{hh} = a_d^{hh} + a_m^{hh} + a_i^{hh} \tag{5.1}$$

where $h = K$ or π. In this construction a_{CP}^{hh} includes the three *CP* violating contributions: direct (a_d^{hh}), indirect in mixing (a_m^{hh}), and indirect in the interference between decays with and without mixing (a_i^{hh}) [4]. The precise measurement of the time-integrated asymmetry is experimentally challenging: the forward-backward (FB) asymmetry in $e^+e^- \to c\bar{c}$ production coupled with the asymmetric detector efficiency as a function of polar angle results in different yields for D^0 and $\bar{D}^0$. The only detector asymmetry present in reconstruction of the signal modes is due to the tagging π_s, since the *CP* final states are reconstructed identically for D^0 and $\bar{D}^0$. The BABAR collaboration proposed a novel technique to experimentally determine the time-integrated asymmetry [14], later followed by Belle [15]. The technique is based on the usage of both tagged and untagged high-statistics $D^0 \to K^-\pi^+$ control samples for measuring the relative tagging efficiency for D^0 and $\bar{D}^0$ directly on data, and on the measurement of the event yields as a function of the cosine of the polar angle of the D^0 in the CM frame, to deal with FB production asymmetries. The BABAR results

Table 3: *CPV* asymmetries in two- and three-body decays. The first error is statistical, the second systematic.

Exp.	a_{CP}^{KK} (%)	$a_{CP}^{\pi\pi}$ (%)	$a_{CP}^{KK\pi^0}$ (%)	$a_{CP}^{\pi\pi\pi^0}$ (%)
BABAR	$0.00 \pm 0.34 \pm 0.13$	$-0.24 \pm 0.52 \pm 0.22$	$0.00 \pm 0.34 \pm 0.13$	$-0.24 \pm 0.52 \pm 0.22$
Belle	$-0.43 \pm 0.30 \pm 0.11$	$0.43 \pm 0.52 \pm 0.12$	-	0.43 ± 1.30

are based on 386 fb^{-1} of data with signal yields of about 130×10^3, 60×10^3 events for K^+K^-, $\pi^+\pi^-$ respectively. The Belle results are based on 540 fb^{-1} of data with similar signal yields. The measured *CPV* asymmetries, which are consistent with zero, are listed in Table 3.

5.2 The three-body decays $D^0 \to \pi^-\pi^+\pi^0$ and $D^0 \to K^-K^+\pi^0$

The three-body decays $D^0 \to \pi^-\pi^+\pi^0$ and $D^0 \to K^-K^+\pi^0$ proceed via *CP* eigenstates (e.g. $\rho^0\pi^0$, $\phi\pi^0$) and also via flavor states (e.g. $\rho^{\pm}\pi^{\mp}$, $K^{*\pm}K^{\mp}$), thus making it possible to probe *CPV* in both types of amplitudes and in the interference between them. In addition, measuring interference effects in a Dalitz plot probes asymmetries in both magnitudes and phases of the amplitudes, not simply in the overall decay rates.

The *BABAR* experiment searched for *CPV* asymmetries in $\pi^-\pi^+\pi^0$ and $K^-K^+\pi^0$ decays using four different methods: difference between D^0 and $\bar{D}^0$ Dalitz plots, difference in the Legendre polynomial moments of the D^0 and $\bar{D}^0$ two-body mass distributions, phase-space-integrated asymmetries, and difference in Dalitz plot fit results for amplitudes and phases. Only the last is a model-dependent approach. Using 385 fb^{-1} of data signal yields of about 82×10^3 and 11×10^3 events and signal purities of 98% were obtained for the $\pi^+\pi^-\pi^0$ and $K^+K^-\pi^0$ modes respectively. No evidence was found for *CPV* at the percent level in both decay modes using any of the four methods [16]. The Belle experiment has measured the phase-space-integrated asymmetry in $\pi^-\pi^+\pi^0$ using 532 fb^{-1} of data, with a signal yield of about 120×10^3 events. No evidence for *CPV* was found [17]. The results for phase-space-integrated asymmetries for three-body decays, $a_{CP}^{hh\pi^0}$ ($h = K, \pi$), are reported in Table 3.

6. Summary

No single measurement exceeds 5σ significance for charm mixing. By combining the above results with other relevant measurements, the HFAG group has determined world-average values and confidence intervals for the mixing and *CPV* parameters [18]. The no-mixing hypothesis is excluded at the 10.2σ level, and there is no evidence for *CPV*. The results are summarized in the contour plots shown in Fig. 1. No evidence for *CPV* was found in $K^+K^-(\pi^0)$ and $\pi^+\pi^-(\pi^0)$ decays, for which a summary of the results is reported in Table 3.

Mixing and *CPV* violation results are in agreement with SM predictions, within the large theoretical uncertainties, providing useful constraints upon new physics models. The *B* factories have produced the most precise measurements so far, and should improve their precision by exploiting the entire data samples and performing additional analyses. In most of the mixing and *CPV* measurements the statistical error is dominant, and the systematic error can be kept under control using high-statistics control samples of data. Future high-statistics experiments, such as

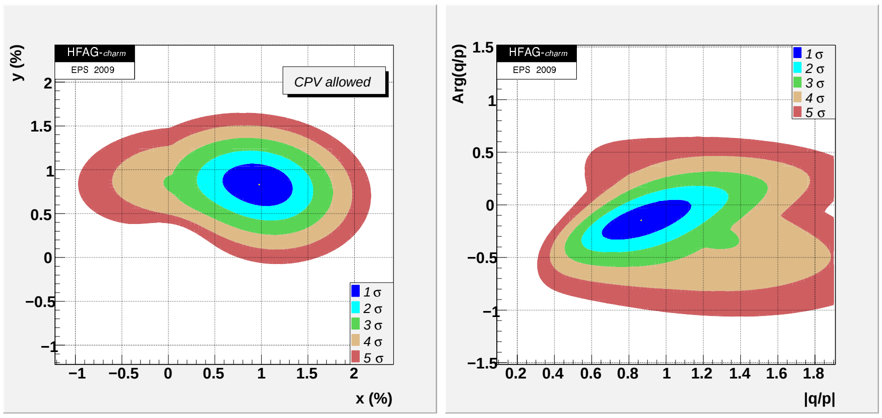

Figure 1: Contour plots for mixing parameters x and y (left) and for *CP* violation parameters $|q/p|$ and $\arg(q/p)$ (right). The plots represent the world-average results from the HFAG.

LHCb, BelleII and SuperB [19], should significantly improve the precision of these measurements, and hence provide stringent tests of the SM.

References

[1] S. Bianco, F. L. Fabbri, D. Benson and I. Bigi, Riv. Nuovo Cim. **26N7**, 1 (2003).

[2] G. Burdman and I. Shipsey, Ann. Rev. Nucl. Part. Sci. **53**, 431 (2003).

[3] F. Buccella, M. Lusignoli, G. Miele, A. Pugliese and P. Santorelli, Phys. Rev. D **51**, 3478 (1995).

[4] Y. Grossman, A. L. Kagan and Y. Nir, Phys. Rev. D **75**, 036008 (2007).

[5] C. Amsler *et al.* [Particle Data Group], Phys. Lett. B **667**, 1 (2008).

[6] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **98**, 211802 (2007).

[7] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **100**, 121802 (2008).

[8] L. M. Zhang *et al.* [Belle Collaboration], Phys. Rev. Lett. **96**, 151801 (2006).

[9] S. Bergmann, Y. Grossman, Z. Ligeti, Y. Nir and A. A. Petrov, Phys. Lett. B **486**, 418 (2000).

[10] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D **78**, 011105(R) (2008).

[11] M. Staric *et al.* [Belle Collaboration], Phys. Rev. Lett. **98**, 211803 (2007).

[12] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D **80**, 071103 (2009).

[13] A. Zupanc *et al.* [Belle Collaboration], Phys. Rev. D **80**, 052006 (2009).

[14] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **100**, 061803 (2008).

[15] M. Staric *et al.* [Belle Collaboration], Phys. Lett. B **670**, 190 (2008).

[16] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D **78**, 051102 (2008).

[17] K. Arinstein [Belle Collaboration], Phys. Lett. B **662**, 102 (2008).

[18] A. J. Schwartz, arXiv:0911.1464 [hep-ex].

[19] D. G. Hitlin *et al.*, arXiv:0810.1312 [hep-ph].