PROCEEDINGS OF SCIENCE

SLAC-PUB-15523

Recent results on D^0-$\bar{D}^0$ mixing from BABAR and Belle

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We report on recent results from the B factories regarding $D^0-\bar{D}^0$ oscillation measurements. Time-dependent Dalitz plot analyses of the $D^0 \to K^0_S\pi^+\pi^-$ and $D^0 \to K^0_S K^+K^-$ decays have measured directly the mixing parameters x and y. The largest significance for charm mixing in a single measurement was obtained in the analysis of the ratio of the lifetime for $D^0 \to K^+K^-, \pi^+\pi^-$ to that for $D^0 \to K^-\pi^+$ with a significance of 4.1σ for BABAR and 3.2σ for Belle. Other time-dependent analyses based on $D^0 \to K^+\pi^-$ and $D^0 \to K^+\pi^-\pi^0$ decays reported similar or lower evidence for $D^0-\bar{D}^0$ oscillations. HFAG excludes the no-mixing hypothesis with a significance exceeding 10 σ when combining all the available measurements and no evidence for *CP* violation was found. The results reported here are based on 530 fb^{-1} and 1023 fb^{-1} of BABAR and Belle data respectively, accumulated at a center-of-mass energy near 10.6 GeV. 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.

Flavor Physics and CP Violation - FPCP 2010
May 25-29, 2010
Turin, Italy

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Work supported in part by US Department of Energy under contract DE-AC02-76SF00515.

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1. Introduction on $D^0 - \bar{D}^0$ mixing and notation

In the Standard Model (SM) $D^0 - \bar{D}^0$ oscillations are expected to proceed very slowly with respect to the D^0 lifetime. Calculations for the mixing parameters x and y, normalised mass and width differences of the mass eigenstates, allow for values as large as $\mathcal{O}(1\%)$, although these estimates are subject to large theoretical uncertainties [1, 2]. 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.* $D^0 = c\,\bar{u}$ and $\bar{D}^0 = \bar{c}\,u$. Hence, the study of charm mixing provides unique information for the understanding of the contribution of new particles in the mixing loop diagrams. In addition, *CP* violation (*CPV*) in charm mixing is expected to be much smaller than 10^{-2} [3]. Experimental evidence of *CPV* in D^0 mixing with the present statistics would represent a sign of new physics.

The two neutral D meson mass 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 $\bar{D}^0$,

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle, \tag{1.1}$$

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

$$x = \frac{m_1 - m_2}{\Gamma}, \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}, \tag{1.2}$$

where $\Gamma = (\Gamma_1 + \Gamma_2)/2$. The decay amplitudes for D^0 and $\bar{D}^0$ to decay into a final state f are defined as $A_f = \langle f|\mathscr{H}|D^0\rangle$ and $\bar{A}_f = \langle f|\mathscr{H}|\bar{D}^0\rangle$ 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 [3],

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = -R_m\left|\frac{\bar{A}_f}{A_f}\right| e^{i(\phi_f + \Delta_f)}, \qquad R_m = \left|\frac{q}{p}\right|, \tag{1.3}$$

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 $\left|A_f\right| \neq \left|\bar{A}_{\bar{f}}\right|$. Assuming *CP* conservation in the decay amplitude implies $\phi_f \equiv \phi$, independent of the specific final state f.

2. Event selection

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 between the reconstructed D^{*+} and D^0 masses (Δm), which has an experimental resolution of about 350 keV/c^2, is used to discriminate against background events by requiring typically that it be within 1 MeV/c^2 of the nominal value [4]. 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.

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

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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

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, 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 [4]. 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%.

3. Measurement of $D^0-\bar{D}^0$ mixing in $D^0 \to K^+\pi^-$ wrong-sign decays

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 $D^0 \to \bar{D}^0 \to K^+\pi^-$. 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

$$\frac{T_{\rm WS}(t)}{e^{-\Gamma t}} \propto R_{K\pi} + \sqrt{R_{K\pi}}y'\,\Gamma t + \frac{x'^2+y'^2}{4}(\Gamma t)^2\,, \tag{3.1}$$

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 [5] using a data sample corresponding to an integrated luminosity of $384\,{\rm fb}^{-1}$ 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 $1.5\,{\rm fb}^{-1}$ and a signal yield of $(12.7\pm0.3)\times10^3$ events [6]. The Belle experiment, using $400\,{\rm fb}^{-1}$ of data with a signal yield of 4024 ± 88 events, was able to exclude the no-mixing hypothesis at only the 2.1σ level [7]. 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.

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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

4. Measurement of $D^0 - \bar{D}^0$ mixing in 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 be treated to a good approximation as a pure exponential [8], as follows,

$$T^+_{CP}(t) \propto e^{-\Gamma^+_{CP}t} \quad \text{for } D^0 \to f_{CP} \qquad\qquad T^-_{CP}(t) \propto e^{-\Gamma^-_{CP}t} \quad \text{for } \bar{D}^0 \to f_{CP} \tag{4.1}$$

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 $\eta^{CP}_f = \pm 1$ 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,

$$y_{CP} = \eta^{CP}_f \left[\frac{\tau_{K\pi}}{\langle\tau_{CP}\rangle} - 1\right], \qquad \Delta Y = \frac{\tau_{K\pi}}{\langle\tau_{CP}\rangle} A_\tau , \tag{4.2}$$

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* [9, 10]. The BABAR results are based on 384 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 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 [11], which is statistically independent of the flavor-tagged sample. The signal yields based on 384 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 [11]. No *CPV* results are provided for analyses using the untagged sample, where only *CP*-conserving fits are possible.

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

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

$$\frac{\tau_{OFF}-\tau_{ON}}{\tau_{OFF}+\tau_{ON}} = y_{CP}\frac{f_{ON}-f_{OFF}}{1+y_{CP}(1-f_{ON}-f_{OFF})}. \tag{4.3}$$

The value of y_{CP} is extracted by measuring the effective lifetime τ_{ON} in the ϕK^0_S 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 $y_{CP} = [0.11 \pm 0.61(\text{stat.}) \pm 0.52(\text{syst.})]\%$ [12].

5. Measurement of D^0-$\bar{D}^0$ mixing in the $D^0 \to K^+ \pi^- \pi^0$ decay

Similarly to the case of the WS $D^0 \to K^+\pi^-$ decays, the study of the time dependence of the WS $D^0 \to K^+\pi^-\pi^0$ decays is sensitive to $D^0 - \bar{D}^0$ oscillations. In this case, since we have a three-body decay, a time-dependent Dalitz plot analysis is required to distinguish the DCS contribution from the CF contribution originating from mixing. Assuming *CP* conservation and for small values of $|x|$ and $|y|$, the time-dependent WS decay rate as a function of the Dalitz variables $s_{12} = m^2_{K^+\pi^-}$ and $s_{13} = m^2_{K^+\pi^0}$ and decay time t is given by:

$$\begin{aligned}\Gamma_{\bar{f}}(s_{12},s_{13},t) \;=\; & e^{-\Gamma t}\{|A_{\bar{f}}(s_{12},s_{13})|^2 + |A_{\bar{f}}(s_{12},s_{13})||\bar{A}_{\bar{f}}(s_{12},s_{13})| \\ & \left[y''\cos\delta_{\bar{f}}(s_{12},s_{13}) - x''\sin\delta_{\bar{f}}(s_{12},s_{13})\right](\Gamma t) + \frac{x''^2+y''^2}{4}|\bar{A}_{\bar{f}}(s_{12},s_{13})|^2(\Gamma t)^2\}\end{aligned} \tag{5.1}$$

where $\bar{f} = K^+\pi^-\pi^0$, $A_{\bar{f}} = \langle \bar{f}|\mathscr{H}|D^0\rangle$ and $\bar{A}_{\bar{f}} = \langle \bar{f}|\mathscr{H}|\bar{D}^0\rangle$ are the decay amplitudes for the DCS and CF transitions, respectively, and $\delta_{\bar{f}}(s_{12},s_{13}) = arg[A^*_{\bar{f}}(s_{12},s_{13})\bar{A}_{\bar{f}}(s_{12},s_{13})]$. The first term in Eq. 5.1 represents the DCS contribution to the observed rate, the third term the CF contribution arising from mixing, while the second is generated by the interference between the two amplitudes. The decay distribution is sensitive to $y'' = y\cos\delta_{K\pi\pi^0} - x\sin\delta_{K\pi\pi^0}$ and $x'' = x\cos\delta_{K\pi\pi^0} + y\sin\delta_{K\pi\pi^0}$ where $\delta_{K\pi\pi^0}$ is the strong-phase difference between the CF and the DCS decay amplitudes and cannot be determined in the analysis of these decays alone. The CF amplitude $\bar{A}_{\bar{f}}$ is determined up to an overall phase and arbitrary amplitude in a time-independent Dalitz analysis of RS decays. The DCS amplitude $A_{\bar{f}}$ together with the parameters x'' and y'' are determined in a time-dependent Dalitz analysis of WS decays. In the Dalitz analysis, the CF and DCS amplitudes are parameterized using an isobar model [13].

BABAR performed this analysis using 658,986 RS and 3,009 WS signal events with a purity of about 99% and 50%, respectively [14]. The mixing parameters determined from the WS fit are reported in Table 3. The no-mixing hypothesis is excluded with a significance of 3.2 σ. No evidence of *CPV* was found when fitting separately for D^0 and $\bar{D}^0$ events. The time-integrated mixing rate was determined to be: $R_{\text{mix}} = (x''^2 + y''^2)/2 = (x^2+y^2)/2 = (2.9 \pm 1.6) \times 10^{-4}$, where the error includes both statistical and systematic uncertainties. The major sources of systematic error on the mixing parameters include uncertainties in modeling the background decay time distribution in the signal region, uncertainties in the mass and width of each resonance in the Dalitz model, the values chosen for the decay time and decay time error selection criteria, uncertainties in modeling the decay time signal resolution function.

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Table 3: Mixing parameters from time-dependent WS $D^0 \to K^+\pi^-\pi^0$ Dalitz plot analysis. The first error is statistical, the second systematic. The mixing significance is given in terms of the equivalent number of Gaussian standard deviations.

Quantity	Value (%)	Significance
x''	$2.39 \pm 0.61 \pm 0.32$	$3.2\ \sigma$
y''	$-0.14 \pm 0.60 \pm 0.40$	

6. Measurement of D^0-$\bar{D}^0$ mixing in $D^0 \to K_S^0\ \pi^+\ \pi^-$ and $D^0 \to K_S^0\ K^+\ K^-$ decays

In three-body decays where the final states f and $\overline{f}$ belong to the same D^0 Dalitz plot (e.g. $D^0 \to K_S^0\pi^+\pi^-$, $D^0 \to K_S^0K^+K^-$), the event distribution as a function of the Dalitz plot position and proper time is sensitive to $D^0 - \bar{D}^0$ oscillations in a unique way. In fact, by assuming *CP* conservation in the decay and a phenomenological parameterization for the D^0 decay amplitude (Dalitz model), we can extract the mixing parameters x and y directly, without strong phase uncertainties. The sensitivity to x and y arises mostly from regions in the Dalitz plot where CF and DCS amplitudes interfere and from regions populated by *CP* eigenstates.

This method was pioneered by CLEO collaboration [15] using a data sample of 9 fb^{-1} and later extended to a significantly larger data sample by Belle [16], using 540 fb^{-1} of data. BABAR has recently presented a combined result for the $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to K_S^0K^+K^-$ decay modes [17], using 468.5 fb^{-1} of data.

The D^0 decay amplitudes are described by a coherent sum of quasi-two-body amplitudes [18]. The dynamical properties of the P- and D-wave amplitudes are parameterized through intermediate resonances with mass dependent relativistic Breit-Wigner (BW) or Gounaris- Sakurai (GS) propagators, Blatt-Weisskopf centrifugal barrier factors, and Zemach tensors for the angular distribution [18]. The main differences between the BaBar and Belle Dalitz model for the $K_S^0\pi^+\pi^-$ decay mode are in the paramaterization of the $\pi^+\pi^-$ and $K\pi$ S-wave dynamics. The Belle analysis uses a similar parameterization as for as the P- and D-waves amplitudes, based on BW functions. In the BaBar analysis the $\pi^+\pi^-$ S-wave dynamics is described through a K-matrix formalism with the P-vector approximation [19] and the $K\pi$ S-wave is described with a BW for the $K_0^*(1430)^{\pm}$ with a coherent non-resonant contribution parametrized by a scattering length and effective range [20]. BABAR has selected about 540,800 (79,900) $K_S^0\pi^+\pi^-$ ($K_S^0K^+K^-$) signal events with a purity of about 98.5% (99.2%), while Belle has selected about 534,410 $K_S^0\pi^+\pi^-$ signal events with a purity of about 95%. The results for the *CP*-conserving fits are reported in Table 4. The Belle analysis also performed a fit allowing for *CP* violation that has measured $|q/p| = 0.86 \pm^{+0.30}_{-0.29}\ ^{+0.06}_{-0.03} \pm 0.08$ and $\phi = (-14^{+16}_{-18}\ ^{+5}_{-3}\ ^{+2}_{-4})^{\circ}$. The reported errors are statistical, experimental systematic, and decay-model systematic, respectively.

The dominant sources of experimental systematic uncertainty are due to the limited statistics of full detector simulations (used to study potential biases due to the event selection, invariant mass resolution, residual correlations between the fit variables, and fitting procedure), variation of the selection criteria and instrumental effects arising from the small misalignment of the detector. The systematic error due to Dalitz model is small compared with the statistical error and is dominated

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Table 4: Mixing results for the three-body $D^0 \to K^0_S h^+ h^-$ decays ($h = K, \pi$) for the *CP*-conserving hypothesis. The first error is statistical, the second is systematic and the third is due to the Dalitz model uncertainty. The mixing significance is given in terms of the equivalent number of Gaussian standard deviations.

Experiment	Decay	$x\,(\%)$	$y\,(\%)$	Significance
CLEO	$K^0_S\pi^+\pi^-$	$1.9^{+3.2}_{-3.3} \pm 0.4 \pm 0.4$	$-1.4 \pm 2.4 \pm 0.8 \pm 0.4$	-
Belle	$K^0_S\pi^+\pi^-$	$0.80 \pm 0.29^{+0.09}_{-0.07}{}^{+0.10}_{-0.14}$	$0.33 \pm 0.24^{+0.08}_{-0.12}{}^{+0.06}_{-0.08}$	$2.2\ \sigma$
BABAR	$K^0_S\pi^+\pi^-$ $K^0_S K^+K^-$	$0.16 \pm 0.23 \pm 0.12 \pm 0.08$	$0.57 \pm 0.20 \pm 0.13 \pm 0.07$	$1.9\ \sigma$

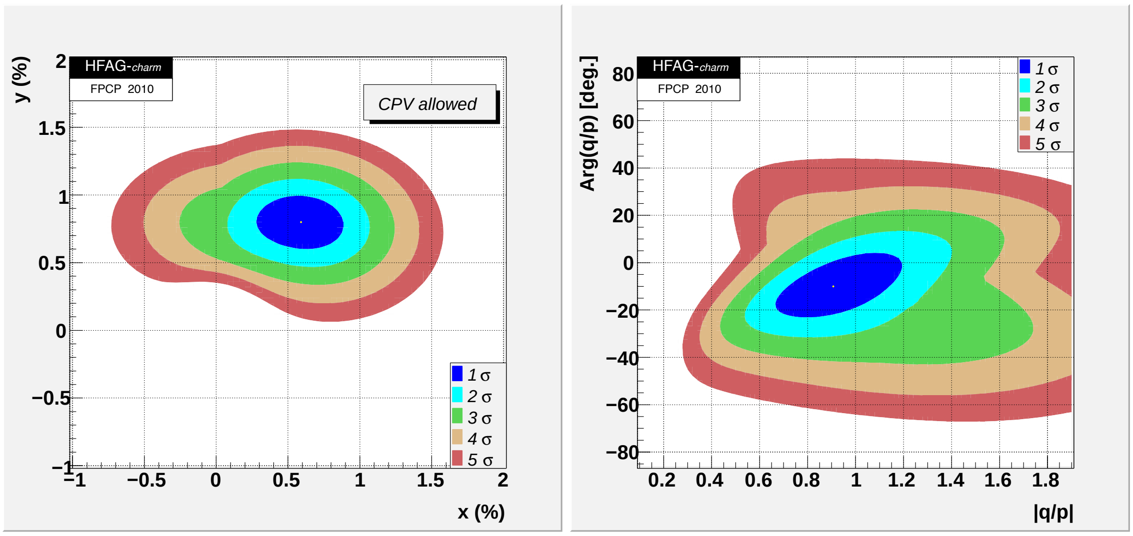

Figure 1: Contour plots for mixing parameters x and y (left) and for *CP* violation parameters $|q/p|$ and $\arg(q/p)$ (right). The plots represent the world-average results from the HFAG.

by the uncertainties on DCS and on the definite *CP* decay amplitudes.

7. Summary

We have reported recent results on $D^0 - \bar{D}^0$ mixing from the B factories. 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. By combining all the relevant measurements, the HFAG group has determined world-average values and confidence intervals for the mixing and *CPV* parameters [21]. 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.

Mixing and *CPV* violation results are in agreement with SM predictions, within the large theoretical uncertainties, providing useful constraints upon new physics models. In most of the mixing and *CPV* measurements the statistical error is dominant, and the systematic error can be kept under

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control using high-statistics control samples of data. Future high-statistics experiments, such as LHCb, BelleII and SuperB [22], should significantly improve the precision of these measurements, and hence provide stringent tests of the SM.

Acknowledgements

The author would like to thank BABAR and Belle colleagues for providing excellent results and the organizers of the conference for the invitation.

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