

D^0 – \bar{D}^0 MIXING

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The detailed formalism for $D^0 - \bar{D}^0$ mixing is presented in the note on “ CP Violation in Meson Decays” in this *Review*. For completeness, we present an overview here. The time evolution of the D^0 – \bar{D}^0 system is described by the Schrödinger equation

$$i \frac{\partial}{\partial t} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2} \mathbf{\Gamma} \right) \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}, \quad (1)$$

where the \mathbf{M} and $\mathbf{\Gamma}$ matrices are Hermitian, and CPT invariance requires that $M_{11} = M_{22} \equiv M$ and $\Gamma_{11} = \Gamma_{22} \equiv \Gamma$. The off-diagonal elements of these matrices describe the dispersive and absorptive parts of the mixing.

Because CP violation is expected to be quite small here, it is convenient to label the mass eigenstates by the CP quantum number in the limit of CP conservation. Thus, we write

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle, \quad (2)$$

where

$$\left(\frac{q}{p} \right)^2 = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}. \quad (3)$$

The normalization condition is $|p|^2 + |q|^2 = 1$. Our phase convention is $CP|D^0\rangle = +|\bar{D}^0\rangle$, and the sign is chosen so that D_1 has CP even, or nearly so.

The corresponding eigenvalues are

$$\omega_{1,2} \equiv m_{1,2} - \frac{i}{2}\Gamma_{1,2} = \left(M - \frac{i}{2}\Gamma \right) \pm \frac{q}{p} \left(M_{12} - \frac{i}{2}\Gamma_{12} \right), \quad (4)$$

where $m_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths of the $D_{1,2}$.

We define dimensionless mixing parameters x and y by

$$x \equiv (m_1 - m_2)/\Gamma = \Delta m/\Gamma \quad (5)$$

and

$$y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma = \Delta\Gamma/2\Gamma, \quad (6)$$

where $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$. If CP is conserved, then M_{12} and Γ_{12} are real, $\Delta m = 2M_{12}$, $\Delta\Gamma = 2\Gamma_{12}$, and $p = q = 1/\sqrt{2}$. The signs of Δm and $\Delta\Gamma$ are to be determined experimentally.

The parameters x and y are measured in several ways. The most precise values are obtained using the time dependence of D decays. Since $D^0\text{--}\bar{D}^0$ mixing is a small effect, the identifying tag of the initial particle as a D^0 or a \bar{D}^0 must be extremely accurate. The usual tag is the charge of the distinctive slow pion in the decay sequence $D^{*+} \rightarrow D^0\pi^+$ or $D^{*-} \rightarrow \bar{D}^0\pi^-$. In current experiments, the probability of mistagging is about 0.1%. The large data samples produced at the B -factories allow the production flavor to also be determined by fully reconstructing charm on the “other side” of the event—significantly reducing the mistag rate [1]. Another tag of comparable accuracy is identification of one of the D 's produced from $\psi(3770) \rightarrow D^0\bar{D}^0$ decays. Although time-dependent analyses are not possible at symmetric charm-threshold facilities (the D^0 and \bar{D}^0 do not travel far enough), the quantum-coherent $C = -1$ $\psi(3770) \rightarrow D^0\bar{D}^0$ state provides time-integrated sensitivity [2,3].

Time-Dependent Analyses: We extend the formalism of this *Review's* note on “ CP Violation in Meson Decays.” In addition to the “right-sign” instantaneous decay amplitudes $\bar{A}_f \equiv \langle f|H|\bar{D}^0\rangle$ and $A_{\bar{f}} \equiv \langle \bar{f}|H|D^0\rangle$ for CP conjugate final states $f = K^+\pi^-, \dots$ and $\bar{f} = K^-\pi^+, \dots$, we include “wrong-sign” amplitudes $\bar{A}_{\bar{f}} \equiv \langle \bar{f}|H|\bar{D}^0\rangle$ and $A_f \equiv \langle f|H|D^0\rangle$.

It is conventional to normalize the wrong-sign decay distributions to the integrated rate of right-sign decays and to express time in units of the precisely measured neutral D -meson mean lifetime, $\tau_{D^0} = 1/\Gamma = 2/(\Gamma_1 + \Gamma_2)$. Starting from a pure $|D^0\rangle$ or $|\bar{D}^0\rangle$ state at $t = 0$, the time-dependent rates of decay to wrong-sign final states relative to the integrated right-sign decay rates are, to leading order:

$$r(t) \equiv \frac{|\langle f|H|D^0(t)\rangle|^2}{|\bar{A}_f|^2} = \left|\frac{q}{p}\right|^2 \left|g_+(t)\lambda_f^{-1} + g_-(t)\right|^2, \quad (7)$$

and

$$\bar{r}(t) \equiv \frac{|\langle \bar{f}|H|\bar{D}^0(t)\rangle|^2}{|A_{\bar{f}}|^2} = \left|\frac{p}{q}\right|^2 \left|g_+(t)\lambda_{\bar{f}} + g_-(t)\right|^2. \quad (8)$$

where

$$\lambda_f \equiv q\bar{A}_f/pA_f, \quad \lambda_{\bar{f}} \equiv q\bar{A}_{\bar{f}}/pA_{\bar{f}}, \quad (9)$$

and

$$g_{\pm}(t) = \frac{1}{2} (e^{-iz_1 t} \pm e^{-iz_2 t}), \quad z_{1,2} = \frac{\omega_{1,2}}{\Gamma}. \quad (10)$$

Note that a change in the convention for the relative phase of D^0 and \bar{D}^0 would cancel between q/p and \bar{A}_f/A_f and leave λ_f unchanged. We expand $r(t)$ and $\bar{r}(t)$ to second order in x and y for modes in which the ratio of decay amplitudes, $R_D = |A_f/\bar{A}_f|^2$, is very small.

Semileptonic decays: Consider the final state $f = K^+\ell^-\bar{\nu}_\ell$, where $A_f = \bar{A}_{\bar{f}} = 0$ in the Standard Model. The final state f is only accessible through mixing and $r(t)$ is

$$r(t) = |g_-(t)|^2 \left| \frac{q}{p} \right|^2 \approx \frac{e^{-t}}{4} (x^2 + y^2) t^2 \left| \frac{q}{p} \right|^2. \quad (11)$$

For $\bar{r}(t)$ q/p is replaced by p/q . In the Standard Model, CP violation in charm mixing is small and $|q/p| \approx 1$. In the limit of CP conservation, $r(t) = \bar{r}(t)$, and the time-integrated mixing rate relative to the time-integrated right-sign decay rate for semileptonic decays is

$$R_M = \int_0^\infty r(t) dt = \left| \frac{q}{p} \right|^2 \frac{x^2 + y^2}{2 + x^2 - y^2} = \frac{1}{2} (x^2 + y^2). \quad (12)$$

Table 1 summarizes results for R_M from semileptonic decays; the world average from the Heavy Flavor Averaging Group (HFAG) [10] is $R_M = (1.30 \pm 2.69) \times 10^{-4}$.

Wrong-sign decays to hadronic non- CP eigenstates: Consider the final state $f = K^+\pi^-$, where A_f is doubly Cabibbo-suppressed. The ratio of decay amplitudes is

$$\frac{A_f}{\bar{A}_f} = -\sqrt{R_D} e^{-i\delta_f}, \quad \left| \frac{A_f}{\bar{A}_f} \right| \sim O(\tan^2 \theta_c), \quad (13)$$

where R_D is the doubly Cabibbo-suppressed (DCS) decay rate relative to the Cabibbo-favored (CF) rate, δ_f is the strong phase difference between DCS and CF processes, and θ_c is the Cabibbo angle. The minus sign originates from the sign of V_{us} relative to V_{cd} .

Table 1: Results for R_M in D^0 semileptonic decays.

Year	Exper.	Final state(s)	$R_M (\times 10^{-3})$	90% C.L.
2008	Belle [4]	$K^{(*)+}e^{-}\bar{\nu}_e$	$0.13 \pm 0.22 \pm 0.20$	$< 0.61 \times 10^{-3}$
2007	BABAR [1]	$K^{(*)+}e^{-}\bar{\nu}_e$	$0.04_{-0.60}^{+0.70}$	$(-1.3, 1.2) \times 10^{-3}$
2005*	Belle [5]	$K^{(*)+}e^{-}\bar{\nu}_e$	$0.02 \pm 0.47 \pm 0.14$	$< 1.0 \times 10^{-3}$
2005	CLEO [6]	$K^{(*)+}e^{-}\bar{\nu}_e$	$1.6 \pm 2.9 \pm 2.9$	$< 7.8 \times 10^{-3}$
2004*	BABAR [7]	$K^{(*)+}e^{-}\bar{\nu}_e$	$2.3 \pm 1.2 \pm 0.4$	$< 4.2 \times 10^{-3}$
2002*	FOCUS [8]	$K^+\mu^{-}\bar{\nu}_\mu$	$-0.76_{-0.93}^{+0.99}$	$< 1.01 \times 10^{-3}$
1996	E791 [9]	$K^+\ell^{-}\bar{\nu}_\ell$	$(1.1_{-2.7}^{+3.0}) \times 10^{-3}$	$< 5.0 \times 10^{-3}$
HFAG [10]			0.13 ± 0.27	

*These measurements are excluded from the HFAG average. The FOCUS result is unpublished, the BABAR result has been superseded by Ref. 1, and the Belle result has been superseded by Ref. 4.

We characterize the violation of CP with the real-valued parameters A_M , A_D , and ϕ . We adopt the parametrization (see Refs. 11 and 12)

$$\left| \frac{q}{p} \right|^2 = \sqrt{\frac{1 + A_M}{1 - A_M}}, \quad (14)$$

$$\lambda_f^{-1} \equiv \frac{pA_f}{q\bar{A}_f} = -\sqrt{R_D} \left(\frac{(1 + A_D)(1 - A_M)}{(1 - A_D)(1 + A_M)} \right)^{1/4} e^{-i(\delta_f + \phi)}, \quad (15)$$

$$\lambda_{\bar{f}} \equiv \frac{q\bar{A}_{\bar{f}}}{pA_{\bar{f}}} = -\sqrt{R_D} \left(\frac{(1 - A_D)(1 + A_M)}{(1 + A_D)(1 - A_M)} \right)^{1/4} e^{-i(\delta_f - \phi)}. \quad (16)$$

From these relations, we obtain

$$\sqrt{\frac{1 + A_D}{1 - A_D}} = \frac{|A_f/\bar{A}_f|}{|\bar{A}_{\bar{f}}/A_{\bar{f}}|}, \quad (17)$$

and A_D is a measure of direct CP violation, while A_M is a measure of CP violation in mixing. The angle ϕ measures CP violation in interference between mixing and decay. While A_M is independent of the decay process, A_D and ϕ , in general, depend on f .

In general, $\lambda_{\bar{f}}$ and λ_f^{-1} are independent complex numbers. More detail on CP violation in meson decays can be found in Ref. 13. To leading order, for A_D and $A_M \ll 1$,

$$r(t) = e^{-t} \left[R_D(1 + A_D) + \sqrt{R_D(1 + A_M)(1 + A_D)} y'_- t + \frac{1}{2}(1 + A_M)R_M t^2 \right] \quad (18)$$

and

$$\bar{r}(t) = e^{-t} \left[R_D(1 - A_D) + \sqrt{R_D(1 - A_M)(1 - A_D)} y'_+ t + \frac{1}{2}(1 - A_M)R_M t^2 \right] \quad (19)$$

Here

$$\begin{aligned} y'_{\pm} &\equiv y' \cos \phi \pm x' \sin \phi \\ &= y \cos(\delta_{K\pi} \mp \phi) - x \sin(\delta_{K\pi} \mp \phi) , \end{aligned} \quad (20)$$

where

$$\begin{aligned} x' &\equiv x \cos \delta_{K\pi} + y \sin \delta_{K\pi} , \\ y' &\equiv y \cos \delta_{K\pi} - x \sin \delta_{K\pi} , \end{aligned} \quad (21)$$

and $R_M = (x^2 + y^2)/2 = (x'^2 + y'^2)/2$ is the mixing rate relative to the time-integrated Cabibbo-favored rate.

The three terms in Eq. (18) and Eq. (19) probe the three fundamental types of CP violation. In the limit of CP conservation, A_M , A_D , and ϕ are all zero. Then

$$r(t) = \bar{r}(t) = e^{-t} \left(R_D + \sqrt{R_D} y' t + \frac{1}{2} R_M t^2 \right) , \quad (22)$$

and the time-integrated wrong-sign rate relative to the integrated right-sign rate is

$$R = \int_0^{\infty} r(t) dt = R_D + \sqrt{R_D} y' + R_M . \quad (23)$$

The ratio R is the most readily accessible experimental quantity. In Table 2 are also reported the measurements of R_D and A_D , and their HFAG average [10] from a general fit; all allow for both mixing and CP violation. Typically, the fit parameters are R_D , x'^2 , and y' . Table 3 summarizes the results for y' and x'^2 . Allowing for CP violation, the separate contributions to R can be extracted by fitting the $D^0 \rightarrow K^+ \pi^-$ and $\bar{D}^0 \rightarrow K^- \pi^+$ decay rates.

Table 3: Results on the time-dependence of $r(t)$ in $D^0 \rightarrow K^+\pi^-$ and $\overline{D}^0 \rightarrow K^-\pi^+$ decays. The CDF result assumes no CP violation. The FOCUS, CLEO, and Belle results restrict x'^2 to the physical region. The confidence intervals from FOCUS, CLEO, and BABAR are obtained from the fit, whereas Belle uses a Feldman-Cousins method, and CDF uses a Bayesian method.

Year	Exper.	y' (%)	x'^2 ($\times 10^{-3}$)
2007	CDF [14]	0.85 ± 0.76	-0.12 ± 0.35
2007	BABAR [15]	$0.97 \pm 0.44 \pm 0.31$	$-0.22 \pm 0.30 \pm 0.21$
2006	Belle [16]	$-2.8 < y' < 2.1$	< 0.72 (95% C.L.)
2005	FOCUS [17]	$-11.2 < y' < 6.7$	< 8.0 (95% C.L.)
2000	CLEO [18]	$-5.8 < y' < 1.0$	< 0.81 (95% C.L.)

Table 4 summarizes results for R measured in multibody final states with nonzero strangeness. Here R , defined in Eq. (23), becomes an average over the Dalitz plot.

Table 4: Results for R in $D^0 \rightarrow K^{(*)+}\pi^-(n\pi)$. The values of R need not be the same for different decay channels.

Year	Exper.	D^0 final state	R (%)
2006	BABAR [24]	$K^+\pi^-\pi^0$	$0.214 \pm 0.008 \pm 0.008$
2005	Belle [25]	$K^+\pi^-\pi^+\pi^-$	$0.320 \pm 0.018^{+0.018}_{-0.013}$
2005	Belle [25]	$K^+\pi^-\pi^0$	$0.229 \pm 0.015^{+0.013}_{-0.009}$
2002	CLEO [20]	$K^{*+}\pi^-$	$0.5 \pm 0.2^{+0.6}_{-0.1}$
2001	CLEO [26]	$K^+\pi^-\pi^+\pi^-$	$0.44^{+0.13}_{-0.12} \pm 0.06$
2001	CLEO [27]	$K^+\pi^-\pi^0$	$0.43^{+0.11}_{-0.10} \pm 0.07$
1998	E791 [19]	$K^+\pi^-\pi^+\pi^-$	$0.25^{+0.36}_{-0.34} \pm 0.03$

Extraction of the mixing parameters x and y from the results in Table 3 requires knowledge of the relative strong phase $\delta_{K\pi}$. An interference effect that provides useful sensitivity to $\delta_{K\pi}$ arises in the decay chain $\psi(3770) \rightarrow D^0\overline{D}^0 \rightarrow (f_{CP})(K^+\pi^-)$, where f_{CP} denotes a CP -even or -odd eigenstate from D^0

decay, such as K^+K^- or $K_S^0\pi^0$, respectively [28]. Here, the amplitude relation

$$\sqrt{2} A(D_{\pm} \rightarrow K^- \pi^+) = A(D^0 \rightarrow K^- \pi^+) \pm A(\overline{D}^0 \rightarrow K^- \pi^+). \quad (24)$$

where D_{\pm} denotes a CP -even or -odd eigenstate, implies that

$$\cos \delta_{K\pi} = \frac{|A(D_+ \rightarrow K^- \pi^+)|^2 - |A(D_- \rightarrow K^- \pi^+)|^2}{2\sqrt{R_D} |A(D^0 \rightarrow K^- \pi^+)|^2}. \quad (25)$$

This neglects CP violation and uses $\sqrt{R_D} \ll 1$.

For multibody final states, Eqs. (13)–(23) apply separately to each point in phase-space. Although x and y do not vary across the space, knowledge of the resonant substructure is needed to extrapolate the strong phase difference δ from point to point to determine x and y .

A time-dependent analysis of $D^0 \rightarrow K^+\pi^-\pi^0$ from BABAR [24,29] determines the *relative* strong phase variation across the Dalitz plot and reports $x'' = (2.61_{-0.68}^{+0.57} \pm 0.39)\%$, and $y'' = (-0.06_{-0.64}^{+0.55} \pm 0.34)\%$, where x'' and y'' are defined as

$$\begin{aligned} x'' &\equiv x \cos \delta_{K\pi\pi^0} + y \sin \delta_{K\pi\pi^0}, \\ y'' &\equiv y \cos \delta_{K\pi\pi^0} - x \sin \delta_{K\pi\pi^0}, \end{aligned} \quad (26)$$

in parallel to x' , y' , and $\delta_{K\pi}$ of Eq. (21). Here $\delta_{K\pi\pi^0}$ is the remaining strong phase difference between the DCS $D^0 \rightarrow K^+\rho^-$ and the CF $\overline{D}^0 \rightarrow K^+\rho^-$ amplitudes and does not vary across the Dalitz plot. Both strong phases, $\delta_{K\pi}$ and $\delta_{K\pi\pi^0}$, can be determined from time-integrated CP asymmetries in correlated $D^0\overline{D}^0$ produced at the $\psi(3770)$ [28,30].

Both the sign and magnitude of x and y without phase or sign ambiguity may be measured using the time-dependent resonant substructure of multibody D^0 decays [31,21]. In $D^0 \rightarrow K_S^0\pi^+\pi^-$, the DCS and CF decay amplitudes populate the same Dalitz plot, which allows direct measurement of the relative strong phases. CLEO [20] and Belle [21] have measured the relative phase between $D^0 \rightarrow K^*(892)^+\pi^-$ and $D^0 \rightarrow K^*(892)^-\pi^+$ to be $(189 \pm 10 \pm 3_{-5}^{+15})^\circ$ and $(171.9 \pm 1.3 \text{ (stat. only)})^\circ$, respectively. These results are close to the 180° expected from Cabibbo factors and a small strong phase. Table 5 summarizes the results from Belle [21] of a time-dependent Dalitz-plot analysis of $D^0 \rightarrow K_S^0\pi^+\pi^-$.

Table 5: Results from Belle time-dependent Dalitz-plot analysis of $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ [21]. The errors are statistical, experimental systematic, and decay-model systematic, respectively.

Result	95% C.L. interval
No CP Violation	
$x = (0.80 \pm 0.29_{-0.07-0.14}^{+0.09+0.10})\%$	$(0.0, 1.6)\%$
$y = (0.33 \pm 0.24_{-0.12-0.08}^{+0.08+0.06})\%$	$(-0.34, 0.96)\%$
With CP Violation	
$x = (0.81 \pm 0.30_{-0.07-0.16}^{+0.10+0.09})\%$	$ x < 1.6\%$
$y = (0.37 \pm 0.25_{-0.13-0.08}^{+0.07+0.07})\%$	$ y < 1.04\%$
$ q/p = 0.86_{-0.29-0.03}^{+0.30+0.06} \pm 0.08$	
$\phi = (-14_{-18-3-4}^{+16+5+2})^\circ$	

In addition, Belle [21] has results for both the relative phase (statistical errors only) and ratio R (central values only) of the DCS fit fraction relative to the CF fit fractions for $K^*(892)^+ \pi^-$, $K_0^*(1430)^+ \pi^-$, $K_2^*(1430)^+ \pi^-$, $K^*(1410)^+ \pi^-$, and $K^*(1680)^+ \pi^-$. The systematic uncertainties on R must be evaluated. The values for R in units of $\tan^4 \theta_c$ are 2.94 ± 0.12 , 22.0 ± 1.6 , 34 ± 4 , 87 ± 13 , and 500 ± 500 . For $K^+ \pi^-$, the corresponding value for R_D is $(1.28 \pm 0.02) \times \tan^4 \theta_c$. Similarly, BABAR [22] has reported central values for R for $K^*(892)^+ \pi^-$, $K_0^*(1430)^+ \pi^-$, and $K_2^*(1430)^+ \pi^-$. The values for R in units of $\tan^4 \theta_c$ are 3.45 ± 0.31 , 7.7 ± 3.0 , and 1.7 ± 1.7 , respectively. Recently, BABAR [23] has used a K-matrix formalism to describe the $\pi\pi$ S-wave in $K_S^0 \pi^+ \pi^-$. The reported values for R in units of $\tan^4 \theta_c$ are 2.78 ± 0.11 , 0.5 ± 0.2 , and 1.4 ± 0.5 , respectively. The large differences in R among these final states could point to an interesting role for hadronic effects.

Decays to CP Eigenstates: When the final state f is a CP eigenstate, there is no distinction between f and \bar{f} , and $A_f = A_{\bar{f}}$ and $\bar{A}_{\bar{f}} = \bar{A}_f$. We denote final states with CP eigenvalues ± 1 by f_\pm and write λ_\pm for λ_{f_\pm} .

The quantity y may be measured by comparing the rate for D^0 decays to non- CP eigenstates such as $K^-\pi^+$ with decays to CP eigenstates such as K^+K^- [12]. If decays to K^+K^- have a shorter effective lifetime than those to $K^-\pi^+$, y is positive.

In the limit of slow mixing ($x, y \ll 1$) and the absence of direct CP violation ($A_D = 0$), but allowing for small indirect CP violation ($|A_M|, |\phi| \ll 1$), we can write

$$\lambda_{\pm} = \left| \frac{q}{p} \right| e^{i\phi} . \quad (27)$$

In this scenario, to a good approximation, the decay rates for states that are initially D^0 and \bar{D}^0 to a CP eigenstate have exponential time dependence:

$$r_{\pm}(t) \propto \exp(-t/\tau_{\pm}) , \quad (28)$$

$$\bar{r}_{\pm}(t) \propto \exp(-t/\bar{\tau}_{\pm}) , \quad (29)$$

where τ is measured in units of $1/\Gamma$.

The effective lifetimes are given by

$$1/\tau_{\pm} = 1 \pm \left| \frac{q}{p} \right| (y \cos \phi - x \sin \phi) , \quad (30)$$

$$1/\bar{\tau}_{\pm} = 1 \pm \left| \frac{p}{q} \right| (y \cos \phi + x \sin \phi) . \quad (31)$$

The effective decay rate to a CP eigenstate combining both D^0 and \bar{D}^0 decays is

$$r_{\pm}(t) + \bar{r}_{\pm}(t) \propto e^{-(1 \pm y_{CP})t} . \quad (32)$$

Here

$$y_{CP} = \frac{1}{2} \left(\left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) y \cos \phi - \frac{1}{2} \left(\left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) x \sin \phi \quad (33)$$

$$\approx y \cos \phi - A_M x \sin \phi . \quad (34)$$

If CP is conserved, $y_{CP} = y$.

All measurements of y_{CP} and A_{Γ} are relative to the $D^0 \rightarrow K^-\pi^+$ decay rate. Table 6 summarizes the current status of

Table 6: Results for y_{CP} from $D^0 \rightarrow K^+K^-$ and $\pi^+\pi^-$.

Year	Exper.	final state(s)	$y_{CP}(\%)$	$A_\Gamma(\times 10^{-3})$
2009	BABAR [32]	K^+K^-	$1.16 \pm 0.22 \pm 0.18$	-
2009	Belle [33]	$K_S^0 K^+ K^-$	$0.11 \pm 0.61 \pm 0.52$	-
2008	BABAR* [34]	$K^+K^-, \pi^+\pi^-$	$1.03 \pm 0.33 \pm 0.19$	$2.6 \pm 3.6 \pm 0.8$
2007	Belle [35]	$K^+K^-, \pi^+\pi^-$	$1.31 \pm 0.32 \pm 0.25$	$0.1 \pm 3.0 \pm 1.5$
2001	CLEO [36]	$K^+K^-, \pi^+\pi^-$	$-1.2 \pm 2.5 \pm 1.4$	—
2001	Belle [37]	K^+K^-	$-0.5 \pm 1.0^{+0.7}_{-0.8}$	—
2000	FOCUS [38]	K^+K^-	$3.42 \pm 1.39 \pm 0.74$	—
1999	E791 [39]	K^+K^-	$0.8 \pm 2.9 \pm 1.0$	—
HFAG Avg. [10]			1.11 ± 0.22	0.12 ± 0.25

*This measurement is included in the result reported by Ref. 32.

measurements. Belle [35] and BaBar [32,34] have reported y_{CP} and the decay-rate asymmetry for CP even final states

$$A_\Gamma = \frac{\bar{\tau}_+ - \tau_+}{\bar{\tau}_+ + \tau_+} = \frac{(1/\tau_+) - (1/\bar{\tau}_+)}{(1/\tau_+) + (1/\bar{\tau}_+)} \quad (35)$$

$$= \frac{1}{2} \left(\left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) y \cos \phi - \frac{1}{2} \left(\left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) x \sin \phi \quad (36)$$

$$\approx A_M y \cos \phi - x \sin \phi . \quad (37)$$

If CP is conserved, $A_\Gamma = 0$. Recently, Belle [33] has reported y_{CP} for the final state $K_S^0 K^+ K^-$ which is dominated by the CP odd final state $K_S^0 \phi$.

Substantial work on the time-integrated CP asymmetries in decays to CP eigenstates are consistent with no CP -violation at the few-percent level [40].

Coherent $D^0\bar{D}^0$ Analyses: Measurements of R_D , $\cos \delta_{K\pi}$, x , and y can be made simultaneously in a combined fit to the single-tag (ST) and double-tag (DT) yields, or individually by a series of “targeted” analyses [28,30].

The “comprehensive” analysis simultaneously measures mixing and DCS parameters by examining various ST and DT rates. Due to quantum correlations in the $C = -1$ and $C = +1$ $D^0\bar{D}^0$ pairs produced in the reactions $e^+e^- \rightarrow D^0\bar{D}^0(\pi^0)$ and $e^+e^- \rightarrow D^0\bar{D}^0\gamma(\pi^0)$, respectively, the time-integrated $D^0\bar{D}^0$

decay rates are sensitive to interference between amplitudes for indistinguishable final states. The size of this interference is governed by the relevant amplitude ratios and can include contributions from $D^0\text{--}\bar{D}^0$ mixing.

The following categories of final states are considered:

f or \bar{f} : Hadronic states accessed from either D^0 or \bar{D}^0 decay but that are not CP eigenstates. An example is $K^-\pi^+$, which results from Cabibbo-favored D^0 transitions or DCS \bar{D}^0 transitions.

ℓ^+ or ℓ^- : Semileptonic or purely leptonic final states, which, in the absence of mixing, tag unambiguously the flavor of the parent D^0 .

f_+ or f_- : CP -even and CP -odd eigenstates, respectively.

The decay rates for $D^0\bar{D}^0$ pairs to all possible combinations of the above categories of final states are calculated in Ref. 2, for both $C = -1$ and $C = +1$, reproducing the work of Ref. 3. Such $D^0\bar{D}^0$ combinations, where both D final states are specified, are double tags. In addition, the rates for single tags, where either the D^0 or \bar{D}^0 is identified and the other neutral D decays generically are given in Ref. 2.

CLEO-c has reported results using 281 pb⁻¹ of $e^+e^- \rightarrow \psi(3770)$ data [41,42], where the quantum-coherent $D^0\bar{D}^0$ pairs are in the $C = -1$ state. The values of y , R_M , and $\cos\delta_{K\pi}$ are determined from a combined fit to the ST (hadronic only) and DT yields. The hadronic final states included are $K^-\pi^+$ (f), $K^+\pi^-$ (\bar{f}), K^-K^+ (f_+), $\pi^+\pi^-$ (f_+), $K_S^0\pi^0\pi^0$ (f_+), $K_L^0\pi^0$ (f_+), $K_S^0\pi^0$ (f_-), $K_S^0\eta$ (f_-), and $K_S^0\omega$ (f_-). The two flavored final states, $K^-\pi^+$ and $K^+\pi^-$, can be reached via CF or DCS transitions.

Semileptonic DT yields are also included, where one D is fully reconstructed in one of the hadronic modes listed above, and the other D is partially reconstructed, requiring that only an electron be found. When the electron is accompanied by a flavor tag ($D \rightarrow K^-\pi^+$ or $K^+\pi^-$), only the “right-sign” DT sample, where the electron and kaon charges are the same, is used.

The main results of the CLEO-c analysis are the determination of $\cos\delta_{K\pi} = 1.10 \pm 0.35 \pm 0.07$, and World Averages for the

mixing parameters from an “extended” fit that combines the CLEO-c data with previous mixing and branching-ratio measurements [41,42]. In these fits, which allow $\cos \delta_{K\pi}$ and x^2 to be unphysical, the no-mixing result ($x = y = 0$) is excluded at 5.0σ . Constraining $\cos \delta_{K\pi}$ and $\sin \delta_{K\pi}$ to $[-1, +1]$ —that is interpreting $\delta_{K\pi}$ as an angle—yields $\delta_{K\pi} = (22_{-12-11}^{+11+9})^\circ$. Note that measurements of y (Table 5 and Table 6) and y' (Table 3) contribute to the determination of $\delta_{K\pi}$.

Coherent $D^0\bar{D}^0$ production can also be used to determine the average strong phase difference, $\bar{\delta}_f$, and coherence factor, R_f , for a flavor-specific multibody final state, f , such as $K^-\pi^+\pi^0$ [43]. Determining the mixing parameters using multibody decays, without using knowledge of resonant substructure, requires both R_f and $\bar{\delta}_f$. Furthermore, the measurement of R_f improves the determination of the Unitarity Triangle angle γ [44,45]. The parameters $\bar{\delta}_f$ and R_f are defined by

$$R_f e^{-i\bar{\delta}_f} = \frac{\int \mathcal{A}_f(\mathbf{x})\mathcal{A}_{\bar{f}}(\mathbf{x})d\mathbf{x}}{A_f A_{\bar{f}}}. \quad (38)$$

Here $\mathcal{A}_f(\mathbf{x})$ ($\mathcal{A}_{\bar{f}}(\mathbf{x})$) is the amplitude for $D^0 \rightarrow f$ ($D^0 \rightarrow \bar{f}$) at a point in multibody phase space described by parameters \mathbf{x} , and $A_f^2 = \int |\mathcal{A}_f(\mathbf{x})|^2 d\mathbf{x}$. A value of R_f close to unity indicates that only a few intermediate states, with limited overlap in phase space, dominate the decay. Note that while $\bar{\delta}_{K\pi} = \delta_{K\pi}$ (defined in Eq. (13)), knowledge of the resonant substructure is required to relate $\bar{\delta}_{K\pi\pi^0}$ and $\bar{\delta}_{K3\pi}$ to $\delta_{K\pi\pi^0}$ (defined below Eq. (26)) and $\delta_{K3\pi}$, respectively.

CLEO-c has reported results for R_f and $\bar{\delta}_f$ ($f = K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$) using 818 pb⁻¹ of $e^+e^- \rightarrow \psi(3770)$ data [46]. The DT rates of f tagged by f_\pm , f , or another flavor-specific final state with a kaon of the same sign, *e.g.* $K^-\pi^+\pi^0$ *vs.* $K^-\pi^+$, provide the sensitivity to the parameters [43]. A similar analysis strategy is adopted to that reported in Refs [41,42]. Two fits to the DT rates are performed with and without external constraints on the mixing parameters x , y , and $\delta_{K\pi}$. The results of these fits are shown in Table 7. The results of Ref. 46 are not yet included in the HFAG average [10].

Table 7: Results from CLEO-c for mixing parameters from coherent $D^0\bar{D}^0$ decays.

Parameter	Mixing constrained	Mixing unconstrained
$\delta_{K\pi}(\circ)$ [41,42]	22^{+14}_{-16}	< 75 @95% C.L.
$\delta_{K\pi}(\circ)$ [46]	$28.5^{+9.6}_{-9.5}$	50^{+38}_{-28}
x (%) [46]	0.96 ± 0.25	$-0.8^{+2.9}_{-2.5}$
y (%) [46]	0.81 ± 0.16	$0.7^{+2.4}_{-2.7}$
$R_{K\pi\pi^0}$ [46]	0.84 ± 0.07	$0.78^{+0.11}_{-0.25}$
$\bar{\delta}_{K\pi\pi^0}(\circ)$ [46]	47^{+14}_{-17}	59^{+32}_{-28}
$R_{K3\pi}$ [46]	$0.33^{+0.26}_{-0.23}$	$0.36^{+0.24}_{-0.30}$
$\bar{\delta}_{K3\pi}(\circ)$ [46]	-66^{+26}_{-23}	-62^{+62}_{-53}

Summary of Experimental Results: Several recent results indicate that charm mixing is at the upper end of the range of Standard Model estimates.

For $D^0 \rightarrow K^+\pi^-$, BABAR [15] and CDF [14] find evidence for oscillations with 3.9σ ($\Delta\text{Log}\mathcal{L}$) and 3.8σ (Bayesian), respectively. The most precise measurement for mixing parameters is from Belle [16], which excludes $x'^2 = y' = 0$ at 2.1σ .

For y_{CP} in $D^0 \rightarrow K^+K^-$ and $\pi^+\pi^-$, Belle [35] and BABAR [32] find 3.2σ and 4.1σ effects. The most sensitive measurement of y is in $D^0 \rightarrow K_S^0\pi^+\pi^-$ from Belle [21] and is only 1.2σ significant. In the same analysis, Belle also finds a 2.4σ result for x . The current situation would benefit from better knowledge of the strong phase difference $\delta_{K\pi}$ than provided by the current CLEO-c result [41,42]. This would allow one to unfold x and y from the $D^0 \rightarrow K^+\pi^-$ measurements of x'^2 and y' , and directly compare them to the $D^0 \rightarrow K_S^0\pi^+\pi^-$ results.

The experimental data consistently indicate that the D^0 and \bar{D}^0 do mix. The mixing is presumably dominated by long-range processes. Under the assumption that the observed mixing is due entirely to short-range processes, significant constraints on a variety of new physics models are obtained [47]. A serious limitation to the interpretation of charm oscillations in terms of New Physics is the theoretical uncertainty of the Standard Model prediction. However, recent evidence opens the window

to searches for CP violation, which would provide unequivocal evidence of New Physics.

HFAG Averaging of Charm Mixing Results:

The Heavy Flavor Averaging Group (HFAG) has made a global fit to all mixing measurements to obtain values of x , y , $\delta_{K\pi}$, $\delta_{K\pi\pi^0}$, R_D , $A_D \equiv (R_D^+ - R_D^-)/(R_D^+ + R_D^-)$, $|q/p|$, and $\text{Arg}(q/p) \equiv \phi$. Correlations among observables are taken into account by using the error matrices from the experiments. The measurements of $D^0 \rightarrow K^{(*)+}\ell^-\bar{\nu}$, K^+K^- , $\pi^+\pi^-$, $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $K_S^0\pi^+\pi^-$, and $K_S^0K^+K^-$ decays, as well as CLEO-c results for double-tagged branching fractions measured at the $\psi(3770)$.

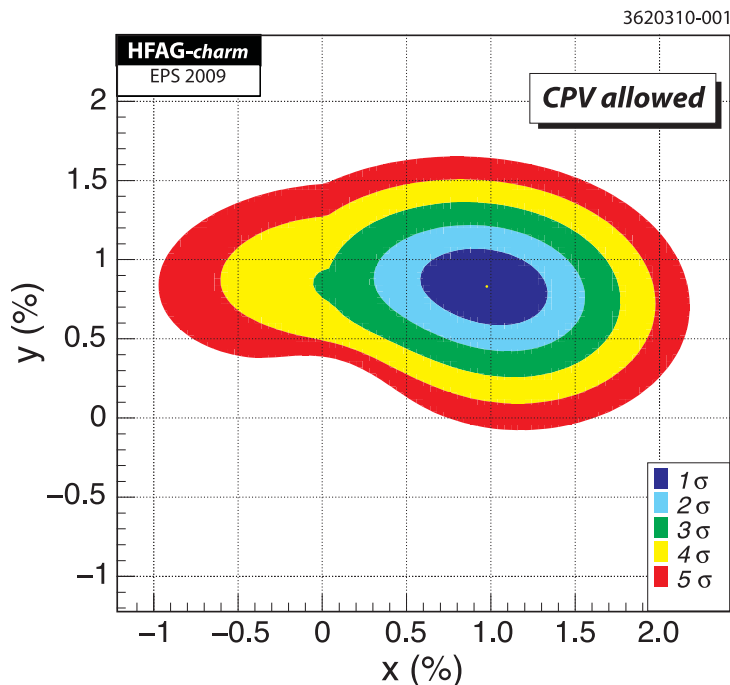


Figure 1: Two-dimensional 1σ - 5σ contours for (x, y) from measurements of $D^0 \rightarrow K^{(*)+}\ell\nu$, h^+h^- , $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $K_S^0\pi^+\pi^-$, and $K_S^0K^+K^-$ decays, and double-tagged branching fractions measured at the $\psi(3770)$ resonance (from HFAG [10]). Color version at end of book.

Table 8: HFAG Charm Mixing Average allowing for CP violation [10].

Parameter	HFAG average	95% C.L. interval
$x(\%)$	$0.98^{+0.24}_{-0.26}$	[0.46, 1.44]
$y(\%)$	0.83 ± 0.16	[0.51, 1.14]
$R_D(\%)$	0.337 ± 0.009	[0.320, 0.353]
$\delta_{K\pi}(\circ)$	$26.4^{+9.6}_{-9.9}$	[5.9, 45.8]
$\delta_{K\pi\pi^0}(\circ)$	$14.8^{+20.2}_{-22.1}$	[-30.3, 53.8]
$A_D(\%)$	-2.2 ± 2.4	[-6.9, 2.6]
$ q/p $	$0.86^{+0.18}_{-0.15}$	[0.60, 1.22]
$\phi(\circ)$	$-9.6^{+8.3}_{-9.5}$	[-22.1, 6.3]

For the global fit, confidence contours in the two dimensions (x, y) and $(|q/p|, \phi)$ are obtained by letting, for any point in the two-dimensional plane, all other fit parameters take their preferred values. Figures 1 and 2 show the resulting 1-to-5 σ contours. The fits exclude the no-mixing point $(x = y = 0)$ at 10.2σ , whether or not CP violation is allowed. The parameters x and y differ from zero by 3.2σ and 4.8σ , respectively. One-dimensional likelihood functions for parameters are obtained by allowing, for any value of the parameter, all other fit parameters to take their preferred values. The resulting likelihood functions give central values, 68.3% C.L. intervals, and 95% C.L. intervals as listed in Table 8.

From the results of the HFAG averaging, the following can be concluded: (1) Since CP violation is small and y_{CP} is positive, the CP -even state is shorter-lived, as in the $K^0\bar{K}^0$ system. (2) However, since x appears to be positive, the CP -even state is heavier, unlike in the $K^0\bar{K}^0$ system. (3) The strong phase difference $\delta_{K\pi}$ is unlikely to be small. (4) There is no evidence yet for CP -violation in the $D^0\bar{D}^0$ system. Observing CP -violation at the current level of sensitivity would indicate new physics.

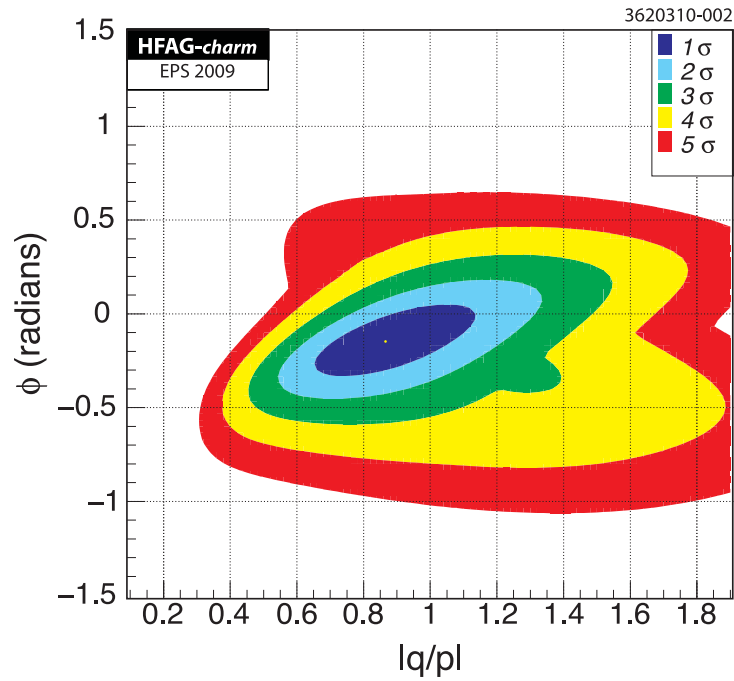


Figure 2: Two-dimensional 1σ - 5σ contours for $(|q/p|, \text{Arg}(q/p))$ from measurements of $D^0 \rightarrow K^{(*)+}\ell\nu$, h^+h^- , $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $K_S^0\pi^+\pi^-$, and $K_S^0K^+K^-$ decays, and double-tagged branching fractions measured at the $\psi(3770)$ resonance (from HFAG [10]). Color version at end of book.

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