D^0–$\overline{D}^0$ MIXING

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Standard Model contributions to D^0–$\overline{D}^0$ mixing are strongly suppressed by CKM and GIM factors. Thus the observation of D^0–$\overline{D}^0$ mixing might be evidence for physics beyond the Standard Model. See Burdman and Shipsey [1] for a review of D^0–$\overline{D}^0$ mixing, Nelson [2] for a compilation of mixing predictions, and Ref. [3] for subsequent predictions.

Formalism: The time evolution of the D^0–$\overline{D}^0$ system is described by the Schrödinger equation

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

where the $\mathbf{M}$ and $\mathbf{\Gamma}$ matrices are Hermitian, and CPT invariance requires $M_{11} = M_{22} \equiv M$ and $\Gamma_{11} = \Gamma_{22} \equiv \Gamma$. The off-diagonal elements of these matrices describe the dispersive and absorptive parts of D^0–$\overline{D}^0$ mixing.

The two eigenstates D_1 and D_2 of the effective Hamiltonian matrix $(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma})$ are given by

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

The corresponding eigenvalues are

$$\lambda_{1,2} \equiv m_{1,2} - \tfrac{i}{2}\Gamma_{1,2} = \left(M - \tfrac{i}{2}\Gamma\right) \pm \frac{q}{p}\left(M_{12} - \tfrac{i}{2}\Gamma_{12}\right)\,, \tag{3}$$

where m_1 and Γ_1 are the mass and width of the D_1, etc., and

$$\left|\frac{q}{p}\right|^2 = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}\,. \tag{4}$$

We extend the formalism of this Review's note on "B^0–$\overline{B}^0$ Mixing" [4]. In addition to the "right-sign" instantaneous decay amplitudes $\overline{A}_f \equiv \langle f|H|\overline{D}^0\rangle$ and $A_{\overline{f}} \equiv \langle \overline{f}|H|D^0\rangle$ for CP conjugate final states f and $\overline{f}$, we include the "wrong-sign" amplitudes $\overline{A}_{\overline{f}} \equiv \langle \overline{f}|H|\overline{D}^0\rangle$ and $A_f \equiv \langle f|H|D^0\rangle$.

It is usual 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 D^0 mean lifetime, $\overline{\tau}_{D^0} = 1/\Gamma = 2/(\Gamma_1 + \Gamma_2)$. Starting from a pure $|D^0\rangle$ or $|\overline{D}^0\rangle$

state at $t = 0$, the time-dependent rates of production of the wrong-sign final states relative to the integrated right-sign states are then

$$r(t) = \frac{\left|\langle f|H|D^0(t)\rangle\right|^2}{\left|\overline{A}_f\right|^2} = \left|\frac{q}{p}\right|^2 \left|g_+(t)\,\chi_f^{-1} + g_-(t)\right|^2 \tag{5}$$

and

$$\overline{r}(t) = \frac{\left|\langle \overline{f}|H|\overline{D}^0(t)\rangle\right|^2}{\left|A_{\overline{f}}\right|^2} = \left|\frac{p}{q}\right|^2 \left|g_+(t)\,\chi_{\overline{f}} + g_-(t)\right|^2 , \tag{6}$$

where

$$\chi_f = \frac{q\overline{A}_f}{pA_f} \tag{7}$$

and

$$g_\pm(t) = \frac{1}{2}\left(e^{-iz_1t} \pm e^{-iz_2t}\right) , \quad z_{1,2} = \frac{\lambda_{1,2}}{\Gamma} . \tag{8}$$

Note that a change in the convention for the relative phase of D^0 and $\overline{D}^0$ would cancel between q/p and $\overline{A}_f/A_f$ and leave χ_f invariant.

Since D^0–$\overline{D}^0$ mixing is a small effect, the identification tag of the initial particle as a D^0 or a $\overline{D}^0$ 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 $D^{*-} \rightarrow \overline{D}^0\pi^-$. In current experiments, the mis-tag probability is about one per thousand. Another tag of comparable accuracy is identification of one of the D's from $\psi(3770) \rightarrow D^0\overline{D}^0$.

We expand $r(t)$ and $\overline{r}(t)$ to second order in time for modes where the ratio of decay amplitudes $R_D = |A_f/\overline{A}_f|^2$ is very small. We define reduced mixing amplitudes x and y by

$$x \equiv \frac{2M_{12}}{\Gamma} = \frac{m_1 - m_2}{\Gamma} = \frac{\Delta m}{\Gamma} \tag{9}$$

and

$$y \equiv \frac{\Gamma_{12}}{\Gamma} = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma} . \tag{10}$$

In these equations, the middle relation holds in the limit of CP conservation, in which case the subscripts 1 and 2 indicate the CP-even and CP-odd eigenstates, respectively.

Semileptonic decays: In semileptonic decays, $A_f = \overline{A}_{\overline{f}} = 0$ in the Standard Model. Then in the limit of weak mixing, where $|ix + y| \ll 1$, $r(t)$ is given by

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

For $\overline{r}(t)$ one replaces q/p here by p/q; and in the limit of CP conservation, $r(t) = \overline{r}(t)$, and the time-integrated mixing rate relative to the time-integrated right-sign decay rate is

$$R_M = \int_0^\infty r(t)dt \approx \frac{1}{2}(x^2 + y^2) . \qquad (12)$$

The results from semileptonic decays are summarized in Table 1. The most sensitive mixing limit is from the FOCUS experiment [5]. Searching for the decay $D^0 \to K^+\mu^-\overline{\nu}_\mu$, it found $R_M < 1.31 \times 10^{-3}$ at the 95% C.L., assuming CP conservation. Semileptonic decays are less sensitive to mixing than are hadronic decays and thus have received less attention recently.

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

Year	Exper.	Final State(s)	R_M
2002	FOCUS [5]	$K^+\mu^-\overline{\nu}_\mu$	$< 1.31 \times 10^{-3}$ (95% C.L.)
2002	CLEO [6]	$K^{*+}e^-\overline{\nu}_e$	$< 8.6 \times 10^{-3}$ (95% C.L.)
1996	E791 [7]	$K^+\ell^-\overline{\nu}_\ell$	$< 5.0 \times 10^{-3}$ (90% C.L.)

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

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

where R_D is the doubly Cabibbo-suppressed decay rate relative to the Cabibbo-favored rate, and δ is a strong phase difference between doubly Cabibbo-suppressed and Cabibbo-favored processes. The minus sign originates from the sign of V_{us} relative to V_{cd}.

We characterize the violation of CP in the mixing amplitude, the decay amplitude, and the interference between mixing and decay, by real-valued parameters A_M, A_D, and ϕ. We adopt a parameterization similar to that of Nir [8] and CLEO [9] and express these quantities in a way that is convenient to describe the three types of CP violation:

$$\left|\frac{q}{p}\right| = 1 + A_M\,, \tag{14}$$

$$\chi_f^{-1} \equiv \frac{pA_f}{q\overline{A}_f} = \frac{-\sqrt{R_D}(1+A_D)}{(1+A_M)}\; e^{-i(\delta+\phi)}\,, \tag{15}$$

$$\chi_{\overline{f}} \equiv \frac{q\overline{A}_{\overline{f}}}{pA_{\overline{f}}} = -\frac{-\sqrt{R_D}(1+A_M)}{(1+A_D)}\; e^{-i(\delta-\phi)}\,. \tag{16}$$

In general, $\chi_{\overline{f}}$ and χ_f^{-1} are independent complex numbers. To leading order,

$$r(t) = e^{-t} \times \Bigg[R_D(1+A_D)^2 + \sqrt{R_D}(1+A_M)(1+A_D)y'_{-}t + \frac{(1+A_M)^2 R_M}{2}\,t^2\Bigg] \tag{17}$$

and

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

where

$$y'_{\pm} \equiv\; y'\cos\phi \pm x'\sin\phi = y\cos(\delta\mp\phi) - x\sin(\delta\mp\phi) \tag{19}$$

$$y' \equiv\; y\cos\delta - x\sin\delta,\quad x' \equiv x\cos\delta + y\sin\delta\,, \tag{20}$$

and R_M is the mixing rate relative to the time-integrated right-sign rate.

The differences between the three terms in Eq. (17) and Eq. (18) probe the three fundamental types of CP violation. In the limit of CP conservation, A_M, A_D, and ϕ are all zero, and then $r(t) = \overline{r}(t)$:

$$r(t) = \overline{r}(t) = e^{-t}\left(R_D + \sqrt{R_D}\,y't + \frac{1}{2}R_M\,t^2\right)\,, \tag{21}$$

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

$$R = \int_0^\infty r(t)\,dt = R_D + \sqrt{R_D}\,y' + R_M\,. \qquad (22)$$

The ratio R of time-integrated wrong- and right-sign rates is the most readily accessible experimental quantity. The observations of non-zero R in $D^0 \to K^+\pi^-$ decay are summarized in Table 2. There has been improvement in precision since 1999, and the average, $R = (0.365 \pm 0.021)\,\%$, from recent experiments is about two standard deviations from the average of $R = (0.81 \pm 0.23)\,\%$ of the pre-1999 results. We restrict the subsequent discussion to the post-1999 experiments.

Table 2: Results for R in $D^0 \to K^+\pi^-$.

Year	Exper.	Technique	$R_D(\times 10^{-3})$	$A_D(\%)$
2003	BABAR [10]	$e^+e^-\to\Upsilon(4S)$	$3.57 \pm 0.22 \pm 0.27$	$9.5 \pm 6.1 \pm 8.3$
2002	Belle [11]	$e^+e^-\to\Upsilon(4S)$	$3.72 \pm 0.25^{+0.09}_{-0.14}$	-
2001	FOCUS [12]	γ BeO	$4.04 \pm 0.85 \pm 0.25$	-
2000	CLEO [9]	$e^+e^-\to\Upsilon(4S)$	$3.32^{+0.63}_{-0.65} \pm 0.40$	$2^{+19}_{-20} \pm 1$
1998	E791 [13]	π^-Pt	$6.8^{+3.4}_{-3.3} \pm 0.7$	-
1998	Aleph [14]	$e^+e^- \to Z^0$	$18.4 \pm 5.9 \pm 3.4$	-
1994	CLEO [15]	$e^+e^-\to\Upsilon(4S)$	$7.7 \pm 2.5 \pm 2.5$	-

The contributions to R can be extracted by fitting the $D^0 \to K^+\pi^-$ decay rates. Comparison of results is complicated because some experiments include CP violating terms, some do not. CLEO [9] and BABAR [10] allowed for CP violation in all three terms (i.e. measure $r(t)$ and $\overline{r}(t)$), and then quote limits on the mixing amplitudes after averaging D^0 and $\overline{D}^0$. A preliminary FOCUS result [12] assumes CP conservation. The results for y' and $x'^2/2$ are summarized in Table 3. Figure 1 shows the two-dimensional allowed regions.

Extraction of the amplitudes x and y from the results in Table 3 requires knowledge of the relative strong phase δ, a subject of theoretical discussion [16, 17]. In most cases, it appears difficult for theory to accommodate $\delta > 25°$, although

Table 3: Results from studies of the time dependence $r(t)$.

Year	Exper.	y' (95% C.L.)	$x'^2/2$ (95% C.L.)
2003	BABAR [10]	$-5.6 < y' < 3.9$ %	< 0.11 %
2001	FOCUS [12]	$-12.4 < y' < -0.5$ %	< 0.076 %
2000	CLEO [9]	$-5.8 < y' < 1.0$ %	< 0.041 %

the judicious placement of a $K\pi$ resonance could allow δ to be as large as $50°$.

A quantum interference effect that provides useful sensitivity to δ arises in the decay chain $\psi(3770) \to D^0\overline{D}^0 \to (f_{cp})(K^+\pi^-)$, where f_{cp} denotes a CP eigenstate from D^0 decay, such as K^+K^-[1, 18]. Here, the amplitude triangle relation

$$\sqrt{2}\, A(D_\pm \to K^-\pi^+) = A(D^0 \to K^-\pi^+) \pm A(\overline{D}^0 \to K^-\pi^+), \tag{23}$$

where $D_\pm$ denotes a CP eigenstate, implies that

$$1 \pm 2\sqrt{R_D}\, \cos\delta = 2\, \frac{B(D_\pm \to K^-\pi^+)}{B(D^0 \to K^-\pi^+)}\,, \tag{24}$$

or

$$\cos\delta = \frac{B(D_+ \to K^-\pi^+) - B(D_- \to K^-\pi^+)}{2\sqrt{R_D}\, B(D^0 \to K^-\pi^+)}\,, \tag{25}$$

neglecting CP violation and exploiting $R_D \ll \sqrt{R_D}$. Projections for 3 fb^{-1} of data at the $\psi(3770)$ indicate that δ could be measured to $20°$ if $|\cos\delta| \sim 1$, and to a few degrees if $\cos\delta \sim 0$ [19].

The strong phase δ might also be determined by constructing amplitude quadrangles from a complete set of branching fraction measurements of the other doubly Cabibbo-suppressed D decays to two pseudoscalars [20]. This analysis would have to assume that the amplitudes from both $\Delta I = 1$ and $\Delta I = 0$ that populate the total $I = 1/2$ $K\pi$ state have the same strong phase relative to the amplitude that populates the total $I = 3/2$ $K\pi$ state.

The Dalitz-plot analyses of doubly Cabibbo-suppressed D decays to a pseudoscalar and a vector allow the measurement of the relative strong phase between some amplitudes, providing additional contraints to the amplitude quadrangle [21] and thus the determination of the strong phase difference between the relevant doubly Cabibbo-suppressed and Cabibbo-favored amplitudes. In $D^0 \to K_S\pi\pi$, the doubly Cabibbo-suppressed and Cabibbo-favored decay amplitudes occupy the same Dalitz plot, which allows direct measurement of the relative strong phase. CLEO has measured the relative phase between $D^0 \to K^*(892)^+\pi^-$ and $D^0 \to K^*(892)^-\pi^+$ to be $(189 \pm 10 \pm 3^{+15}_{-5})^\circ$ [22], consistent with the 180° expected from Cabibbo factors and a small strong phase.

There are several results for R measured in multibody final states with nonzero strangeness. Here R, defined in Eq. (22), becomes an average over the Dalitz space, weighted by experimental efficiencies and acceptance. The results are summarized in Table 4.

Table 4: Results for R in $D^0 \to K^{(*)+}\pi^-(n\pi)$.

Year	Exper.	D^0 Final State	$R(\%)$
2002	CLEO [22]	$K^*(892)^+\pi^-$	$0.5 \pm 0.2^{+0.6}_{-0.1}$
2001	CLEO [23]	$K^+\pi^-\pi^+\pi^-$	$0.41^{+0.12}_{-0.11} \pm 0.04$
2001	CLEO [24]	$K^+\pi^-\pi^0$	$0.43^{+0.11}_{-0.10} \pm 0.07$
1998	E791 [13]	$K^+\pi^-\pi^+\pi^-$	$0.68^{+0.34}_{-0.33} \pm 0.07$

For multibody final states, Eqs. (13)–(22) apply to one point in the Dalitz space. Although x and y do not vary across the Dalitz space, knowledge of the resonant substructure is needed to extrapolate the strong phase difference δ from point to point. Both the sign and magnitude of x and y are experimentally accessible by studying the time-dependent resonant substructure in decay modes such as $D^0 \to K_S\pi^+\pi^-$ [25].

Decays to CP Eigenstates: When the final state f is a CP eigenstate, there is no distinction between f and $\overline{f}$, and then $A_f = A_{\overline{f}}$ and $\overline{A}_{\overline{f}} = \overline{A}_f$. We denote final states with CP

eigenvalues ± 1 by $f_\pm$. In analogy with Eqs. (5)–(6), the decay rates to CP eigenstates are then

$$
\begin{aligned}
r_\pm(t) &= \frac{\left|\langle f_\pm|H|D^0(t)\rangle\right|^2}{\left|\overline{A}_\pm\right|^2} \\
&= \frac{1}{4}\left| h_\pm(t)\left(\frac{A_\pm}{\overline{A}_\pm} \pm \frac{q}{p}\right) + h_\mp(t)\left(\frac{A_\pm}{\overline{A}_\pm} \mp \frac{q}{p}\right)\right|^2, \\
&\propto \frac{1}{|p|^2}\left| h_\pm(t) + \eta_\pm h_\mp(t)\right|^2, \qquad (26)
\end{aligned}
$$

and

$$
\overline{r}_\pm(t) = \frac{\left|\langle f_\pm|H|\overline{D}^0(t)\rangle\right|^2}{\left|A_\pm\right|^2} \propto \frac{1}{|q|^2}\left| h_\pm(t) - \eta_\pm h_\mp(t)\right|^2, \qquad (27)
$$

where

$$
h_\pm(t) = g_+(t) \pm g_-(t) = e^{-iz_\pm t}\,, \qquad (28)
$$

and

$$
\eta_\pm \equiv \frac{pA_\pm \mp q\overline{A}_\pm}{pA_\pm \pm q\overline{A}_\pm} = \frac{1 \mp \chi_\pm}{1 \pm \chi_\pm}\,, \qquad (29)
$$

and the variable $\eta_\pm$ describes CP violation; $\eta_\pm$ can receive contributions from each of the three fundamental types of CP violation.

The quantity y may be measured by comparing the rate for decays to non-CP eigenstates such as $D^0 \to K^-\pi^+$ with decays to CP eigenstates such as $D^0 \to K^+K^-$ [17]. A positive y would make K^+K^- decays appear to have a higher decay rate than $K^-\pi^+$ decays. The decay rate for a D^0 into a CP eigenstate is not described by a single exponential in the presence of CP violation.

In the limit of weak mixing, where $|ix + y| \ll 1$, and small CP violation, where $|A_M|$, $|A_D|$, and $|\sin\phi| \ll 1$, the time dependence of decays to CP eigenstates is proportional to a single exponential:

$$
r_\pm(t) \propto e^{-[1 \pm \left|\frac{p}{q}\right|(y\cos\phi - x\sin\phi)]t}, \qquad (30)
$$

$$
\overline{r}_\pm(t) \propto e^{-[1 \pm \left|\frac{q}{p}\right|(y\cos\phi + x\sin\phi)]t}, \qquad (31)
$$

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

Here

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

and

$$A_{\rm prod} \equiv \frac{N(D^0) - N(\overline{D}^0)}{N(D^0) + N(\overline{D}^0)} \quad (34)$$

is defined as the production asymmetry of the D^0 and $\overline{D}^0$. Note that deviations from the decay rate measured in non-CP eigenstates does not require $y \neq 0$ but can be due to $x\sin\phi \neq 0$. This possibility is distinguished by a relative sign difference in the exponents of Eqs. (30) and (31) describing the D^0 and $\overline{D}^0$ samples, respectively.

In the limit of CP conservation, $A_\pm = \pm\overline{A}_\pm$, $\eta_\pm = 0$, $y = y_{CP}$, and

$$r_\pm(t)\left|\overline{A}_\pm\right|^2 = \overline{r}_\pm(t)\left|A_\pm\right|^2 = e^{-(1\pm y_{CP})t} . \quad (35)$$

The possibility of CP violation has not been considered in general in any of the analyses of y, although specific cases have been considered. Belle [26] and BABAR [27] have allowed CP violation in interference and mixing. Neither result considered CP violation in direct decay. All measurements are relative to the $D^0 \to K^-\pi^+$ decay rate. The current status of measurements of y is summarized in Table 5 and in Fig. 1.

Table 5: Results for y from $D^0 \to K^+K^-$ and $\pi^+\pi^-$.

Year	Exper.	D^0 Final State(s)	$y(\%)$
2003	Belle [26]	K^+K^-	$y_{CP} = 1.15 \pm 0.69 \pm 0.38$
2003	BABAR [27]	$K^+K^-, \pi^+\pi^-$	$y\cos\phi = 0.8 \pm 0.4^{+0.5}_{-0.4}$
2001	CLEO [28]	$K^+K^-, \pi^+\pi^-$	$y_{CP} = -1.1 \pm 2.5 \pm 1.4$
2001	Belle [29]	K^+K^-	$y_{CP} = -0.5 \pm 1.0^{+0.7}_{-0.8}$
2000	FOCUS [30]	K^+K^-	$y_{CP} = 3.4 \pm 1.4 \pm 0.7$
1999	E791 [31]	K^+K^-	$y_{CP} = 0.8 \pm 2.9 \pm 1.0$

Substantial work on the integrated CP asymmetries in decays to CP eigenstates indicates that A_{CP} is consistent with zero at the few percent level [32]. The expression for the integrated CP asymmetry that includes the possibility of CP violation in mixing is

$$A_{CP} = \frac{\Gamma(D^0 \to f_\pm) - \Gamma(\overline{D}^0 \to f_\pm)}{\Gamma(D^0 \to f_\pm) + \Gamma(\overline{D}^0 \to f_\pm)} \tag{36}$$

$$= \frac{|q|^2 - |p|^2}{|q|^2 + |p|^2} + 2\mathrm{Re}(\eta_\pm)\,. \tag{37}$$

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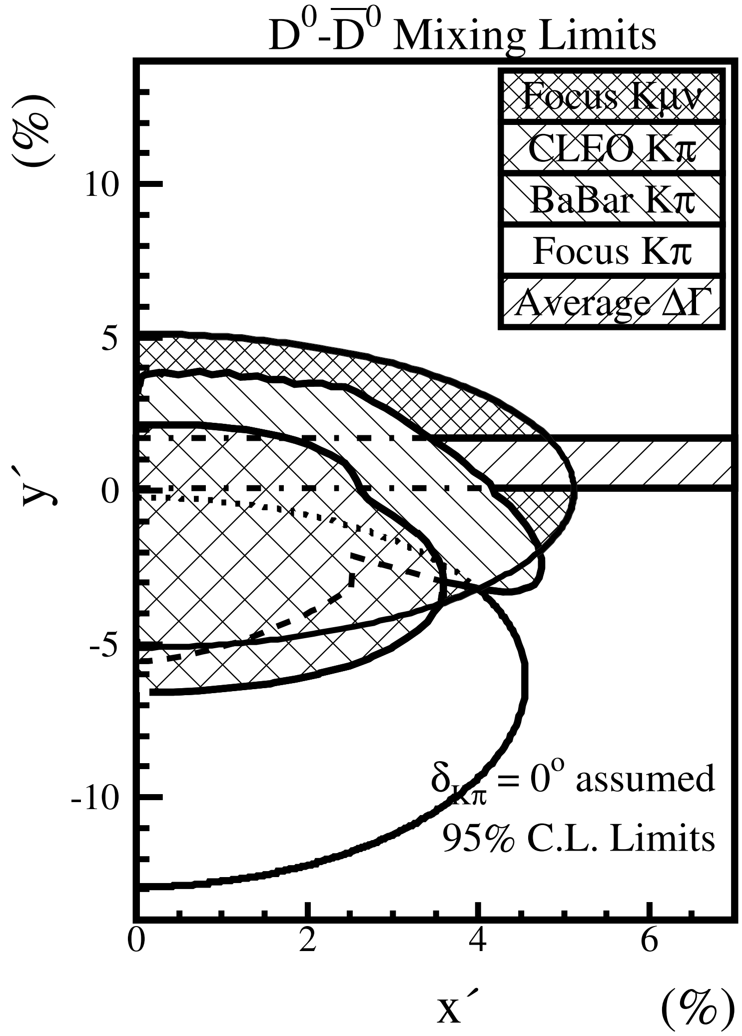

Figure 1: Current allowed regions in the plane of y' versus x'. The regions for CLEO and BaBar allow CP violation in the decay amplitude, in the mixing amplitude, and in the interference between these two processes. The FOCUS result does not allow CP violation. The allowed region for $\Delta\Gamma$ is the average of the y_{CP} [26, 28–31] results and the BABAR measurement of $y \cos\phi$ [27] and does not include $y = 0$. We assume $\delta = 0$ to place the $\Delta\Gamma$ results. A non-zero value for δ would rotate this confidence region clockwise about the origin by an angle δ. See full-color version on color pages at end of book.

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