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Review of Charm Sector Mixing and CP Violation

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The phenomenology of $D^0-\overline{D}^0$ mixing and CP violation is briefly described. Recent experimental results from BABAR, Belle, CDF, and CLEO-c are reviewed. No evidence for mixing or CP violation is found, and limits are set for the mixing parameters x, y, x', y', and several CP-violating parameters. Results are compared to theoretical predictions. Finally, future prospects at BESIII, LHC-b and a Super B-factory are discussed.

1 BRIEF HISTORY

The search for D^0–$\overline{D}^0$ mixing began following the discover of the D^0 meson at SPEAR [1]. The earliest searches for charm mixing were ‘indirect’, searching for like-sign muons rather than fully reconstructing D^0 mesons. The first direct searches recontructed the D^0, usually from a D^{*+} to tag the initial flavor, and searched for the wrong-sign final state $K^+\pi^-$. After experimental sensitivity to the expected doubly-Cabibbo suppressed (DCS) decay $D^0 \to K^+\pi^-$ was attained the search for charm mixing required a time-dependent analysis to disentangle the DCS decay ($D^0 \to K^+\pi^-$) and mixing followed by Cabibbo favored decay ($D^0 \to \overline{D}^0 \to K^+\pi^-$) amplitudes.

1.1 Indirect Searches for D^0–$\overline{D}^0$

Inclusive measurements of lepton pairs at muon or neutrino, or beam dump experiments can be used as a probe of charm mixing. Following the subtraction of the number of like-sign leptons from background sources and estimating the amount of charm produced these experiments constrain the amount of mixing. The results of indirect searches for D^0–$\overline{D}^0$ are summarized in Tab. 1. The best indirect limits were obtained by the experiment E615 where a 225 GeV pion beam was incident on a tungsten target. They searched for the reaction

$$\pi N \to D^0\overline{D}^0 \to (K^-\mu^+\nu)D^0 \to (K^-\mu^+\nu)^2 \tag{1}$$

Table 1: Indirect Searches for D^0–$\overline{D}^0$.

Experiment	Mixing Technique	90% C.L.
EMC (1981) [2]	$\mu^+ N \to \mu^+(\mu^+\mu^+)X$	20%
CCFRS (1982) [3]	$\pi^-\mathrm{Fe} \to \mu^+\mu^+$	4.4%
BDMS (1985) [4]	$\mu^+ N \to \mu^+\mu^-\mu^- X$	1.2%
CDHS (1985) [5]	$\nu N \to \mu^-\mu^-$	$5.1 \pm 2.3\%$
	$\overline{\nu} N \to \mu^+\mu^+$	$3.2 \pm 1.2\%$
E615 (1986) [6]	$\pi^- W \to \mu^-\mu^-$	0.56%
E744 (1988) [7]	$\nu N \to \mu^-\mu^-$, $\overline{\nu} N \to \mu^+\mu^+$	$< 9\%$

where only the final state muons were detected. The largest source of background was random μ pairs produced by other pion interactions in the same rf bucket. The angle between the π beam and one of the μ^+ distinguishes this background from D^0–$\overline{D}^0$ mixing. E615 observed 3973 like sign muon pairs with invariant mass greater than 2.0 GeV/c^2. Using their model of the angular dependence of charm hadroproduction, they set an upper limit on the contribution due to mixing of 63 events at the 90% confidence level. The estimate of $D\overline{D}$ production cross section is obtained by assuming that each $\overline{D}^0$ is accompanied by a D^0 or a D^+ with equal probability. Therefore $\sigma(D^0\overline{D}^0) = \frac{1}{2}\sigma(D^0) = 3.8 \pm 0.5\mu b$/nucleon where $\sigma(D^0)$ is an average of published cross sections from other hadroproduction experiments. The final limit obtained is $R_M < 0.56\%$ which corresponds to $x, y < 11\%$, all at the 90% confidence level.

1.2 Earlier Studies of $D^0 \to K^+\pi^-$

Experiments performed at e^+e^- storage rings or using photon or pion beams have used the decay chain $D^{*+} \to D^0\pi^+, D^0 \to K^\mp\pi^\pm$ where the charge of the pion from D^{*+} decay tags the production flavor of the D^0. Prior to the first reliable observation of $D^0 \to K^+\pi^-$ by CLEO II.V [8] many experiments searched for the ‘wrong sign’ decay. The limits from several experiments are given in Tab. 2.

The CLEO collaboration reported first observation of $D^0 \to K^+\pi^-$ in 1993 [19], however the decay-time resolution was not sufficient to distinguish DCS decay from mixing. In 1997, the E791 collaboration reported the first study of the time evolution of $D^0 \to K^+\pi^-$ and $K^+\pi^-\pi^+\pi^-$ [20]. The sensitivity to the time-integrated rate is somewhat less than the CLEO result but precise decay time resolution allows constraints to be placed on D^0–$\overline{D}^0$ mixing. The constraints on mixing parameters

Table 2: Experimental Searches for $D^0 \to K^+\pi^-$. The number of Cabibbo-favored (CF) $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ is given in the second column. In the third column the limits on the mixing rate R_M before (after) 1990 are at 90% (95%) C.L.

Experiment	#CF	R_M
SPEAR (1977) [9]	~ 250	$< 16\%$
SPEAR (1977) [10]	~ 150	$< 18\%$
E87 (1980) [11]	~ 143	$< 11\%$
ACCMOR (1983) [12]	$\sim$ 10's	$< 7\%$
DELCO (1985) [13]	~ 100	$< 8.1\%$
HRS (1986) [14]	~ 70	$< 4\%$
ARGUS (1987) [15]	224	$< 1.4\%$
CLEO I.5 [16]	420	$R < 1.1\%$
E691 (1988) [17]	~ 1550	$< 0.65\%$
E687 (1994) [18]	~ 1000	-
CLEO II (1993) [19]	~ 6600	$R = 0.77 \pm 0.35\%$
E791 (1997) [20]	~ 5200	0.21 ± 0.09
Aleph (1998) [21]	~ 1000	$< 3.6\%$
CLEO II.V (2000) [8]	~ 13500	
FOCUS (2001) [22, 23]	$\sim$ 37k	$< 0.61\%$
BaBar (2003) [24]	$\sim$ 120k	$< 0.16\%$
Belle (2005) [26]	$\sim$ 227k	$< 0.046\%$
CDF (2006) [27]	$\sim$ 495k	-

obtained without the assumption of CP conservation were considerably weaker.

In 1999, E791 published [28] the first measurement of $y = (0.83 \pm 2.9 \pm 1.0)\%$ using the decays $D^0 \to K^+K^-$. Both CLEO II.V and the E831/FOCUS collaboration accumulated about 10 times the statistics of E791 in the singly-Cabibbo suppressed decay mode, $D^0 \to K^+K^-$. E831/FOCUS and CLEO II.V achieved a statistical precision of $\sim 1.4\%$ [29] and $\sim 2.5\%$ [30], respectively

2 CPV IN CHARM SECTOR

The violation of charge-parity (CP) in charm decay requires two amplitudes with different strong and weak phases that interfere to produce CP violating effects. There are three distinct types of CP violation: (1) CP violation from a non-vanishing relative phase between the mass and width components of the mixing matrix usually called "indirect"; (2) Direct CP violation due to the two decay amplitudes having different weak phases; (3) Interference between decays with and without mixing. The CP conserving phase shift is usually generated by QCD final state interactions (FSI) which

Table 3: CP Violation Results for D^0: All numbers are given in percent.

D^0 A_{CP}	E791	FOCUS	CLEO	BaBar	Belle	CDF
$K^+\pi^-$ [8, 23–25]		18±14±4	2^{+19}_{-20}	9.5±10.3	2.3±4.7	
$K^+\pi^-\pi^0$ [35, 36]			9^{+25}_{-22}		−0.6±5.3	
K^-K^+ [28, 30, 37, 38]	−1.0±4.9±1.2	−0.1±2.2±1.5	0.0±2.2±0.8		0.2±0.7	1.0±1.3±0.6
$\pi^-\pi^+$ [28, 30, 37, 38]	−4.9±7.8±3.0	4.8±3.9±2.5	1.9±3.2±0.8			2.0±1.2±0.6
$\pi^0\pi^0$ [39]			0.1±4.8			
$K^0_SK^0_S$ [39]			−23±19			
$K^0_S\pi^0$ [39]			0.1±1.3			
$K^0_S\pi^+\pi^-$ [40]			$-0.9 \pm 2.1^{+1.6}_{-5.7}$			
$K^0_S\phi$ [41]			2.8±9.4			
$K^-\pi^+\pi^0$ [42]			−3.1±8.6			
$\pi^+\pi^-\pi^0$ [43]			$-1^{+9}_{-7}\pm 5$			
$K^+\pi^-\pi^+\pi^-$ [36]					−1.8±4.4	
$K^+K^-\pi^+\pi^-$ [44]		−8.2±5.6±4.7				

are large in the charm sector. In the Standard Model (SM), the relative weak phase is typically between tree level and penguin amplitudes. Extensions to the Standard Model introduce additional amplitudes with weak phases that can contribute to CP violation.

For charm decays, within the SM, the effective weak phase is highly diluted, $\sim \mathcal{O}(\lambda^4)$, and it can arise only in *singly-Cabibbo-suppressed* transitions, where one expects asymmetries to reach the $\mathcal{O}(0.1\%)$ level; significantly larger values would indicate new physics. *Any* asymmetry in *Cabibbo-allowed or doubly-suppressed* channels requires the intervention of new physics – except for $D^\pm \to K^0_S\pi^\pm$ [31], where the CP impurity in the K^0_S induces an asymmetry of 3.3×10^{-3}. Note that in going from Cabibbo-allowed to Cabibbo singly- and doubly- suppressed channels, the SM rate is *suppressed* by factors of about twenty and four hundred, respectively. This suppression enhances the visibility of new physics.

Decays to final states of *more than* two pseudoscalar or one pseudoscalar and one vector meson contain more dynamical information than given by their widths; their distributions as described by Dalitz plots [48] or T-odd moments can exhibit CP asymmetries that might be considerably larger than those for the width [49].

Most CP violation results are from the FNAL fixed target experiments E791 and FOCUS, and the CLEO experiment and search for direct CP violation. The CP

Table 4: CP Violation Results for D^+: All numbers are given in percent.

D^+ A_{CP}	E791	FOCUS	BaBar
$K^0_S\pi^+$ [34]		-1.6±1.5±0.9	
$K^0_S K^+$ [34]		6.9±6.0±1.8	
$K^+K^-\pi^+$ [37, 45–47]	-1.4±2.9	0.6±1.1±0.5	1.4±1.0±0.8
$\phi\pi^+$ [45]	-2.8±3.6		
K^*K^+ [45, 47]	-1.0±5.0		0.9±1.7±0.7
$\pi^-\pi^+\pi^+$ [45]	-1.7±4.2		
$K^0_S K^+\pi^+\pi^-$ [44]		-4.2±6.4±2.2	

violation asymmetry is defined as $A_{CP} \equiv \frac{\Gamma(D\to f)-\Gamma(\overline{D}\to\overline{f})}{\Gamma(D\to f)+\Gamma(\overline{D}\to\overline{f})}$. A few results from CLEO, BaBar and Belle experiments consider CP violation in mixing. The results tabulated in Tab. 3 and Tab. 4 show no evidence for CP violation. This is consistent with Standard Model expectations.

3 $D^0-\overline{D}^0$ MIXING

The formalism describing $D^0-\overline{D}^0$ mixing is given in several papers [31, 32]. The time evolution of a particle produced as a D^0 or $\overline{D}^0$, in the limit of CP conservation, is governed by four parameters: $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/2\Gamma$ which characterize the mixing matrix, δ the relative strong phase between Cabibbo favored (CF) and doubly-Cabibbo suppressed (DCS) amplitudes ($\delta_{K\pi}$ refers specifically to the $K\pi$ final state) and R_D the DCS decay rate relative to the CF decay rate. The mixing rate R_M is defined as $\frac{1}{2}(x^2+y^2)$. A D^0 can evolve into a $\overline{D}^0$ through on-shell intermediate states, such as K^+K^- with mass, $m_{K^+K^-} = m_{D^0}$, or through off-shell intermediate states, such as those that might be present due to new physics. This evolution through the former (latter) states is parametrized by the dimensionless variables $-iy$ (x).

Time-dependent analyses are not feasible at CLEO-c; however, the quantum-coherent $D^0\overline{D}^0$ state provides time-integrated sensitivity to x, y at $\mathcal{O}(1\%)$ level and $\cos\delta_{K\pi} \sim 0.1$ in 1 fb^{-1} of data at the $\psi(3770)$. Due to quantum correlations in the $C=-1$ and $C=+1$ $D^0\overline{D}^0$ pairs produced in the reactions $e^+e^- \to D^0\overline{D}^0(\pi^0)$ and $e^+e^- \to D^0\overline{D}^0\gamma(\pi^0)$, respectively [33], the time-integrated $D^0\overline{D}^0$ 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-$\overline{D}^0$ mixing.

3.1 $D^0-\overline{D}^0$ Mixing Formalism and Results

Standard Model based predictions for x and y, as well as a variety of non-Standard Model expectations, span several orders of magnitude [31, 50]. Several non-Standard Models predict $|x| > 0.01$. Contributions to x at this level could result from the presence of new particles with masses as high as 100-1000 TeV [51, 52]. The Standard Model short-distance contribution to x is determined by the box diagram in which two virtual quarks and two virtual W bosons are exchanged. Short distance contributions to y are expected to be less than x. Both x and y are beyond current experimental sensitivity. Long distance effects are expected to be larger but are difficult to estimate due to the large number of resonances near the D^0 pole. It is likely that x and y contribute similarly to mixing in the Standard Model.

The parameters x and y can be measured in a variety of ways. The most precise constraints are obtained by exploiting the time-dependence of D decays. Previous attempts to measure x and y include: the measurement of the wrong sign semileptonic branching ratio $D^0 \to K\ell\nu$ [53–57] which is sensitive to the mixing rate $R_M = \frac{x^2+y^2}{2}$; decay rates to CP eigenstates $D^0 \to K^+K^-, \pi^+\pi^-$ [29, 30, 58–61] which are sensitive to y; and the wrong sign $D^0 \to K^+\pi^-$ [8, 23, 24, 26] hadronic branching ratio which measures $x'^2 = (y \sin\delta_{K\pi} + x\cos\delta_{K\pi})^2$ and $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$.

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

$$r(t) \quad = \quad \left|\frac{q}{p}\right|^2 \left|g_+(t)\,\chi_f^{-1} + \, g_-(t)\,\right|^2 \tag{2}$$

and

$$\overline{r}(t) \quad = \quad \left|\frac{p}{q}\right|^2 \left|g_+(t)\,\chi_{\overline{f}} + \, g_-(t)\,\right|^2 , \tag{3}$$

where

$$\chi_f \equiv q\overline{A}_f/pA_f\,, \quad \chi_{\overline{f}} \equiv q\overline{A}_{\overline{f}}/pA_{\overline{f}}\,, \tag{4}$$

q and p are complex coefficients relating flavor eigenstates to mass eigenstates, $\mathcal{A}_f$ ($\overline{\mathcal{A}}_f$) and $\mathcal{A}_{\overline{f}}$ ($\overline{\mathcal{A}}_{\overline{f}}$) are amplitudes for a pure D^0 ($\overline{D}^0$) state to decay to f and $\overline{f}$, respectively, and

$$g_\pm(t) = \frac{1}{2}\left(e^{-iz_1t} \pm e^{-iz_2t}\right) \ , \quad z_{1,2} = \frac{\lambda_{1,2}}{\Gamma}\,. \tag{5}$$

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.

Table 5: Results for R_M in D^0 semileptonic decays.

Exper.	Final state(s)	R_M (90 (95)% C.L.)
Belle [57]	$K^{(*)+}e^-\overline{\nu}_e$	$<1.0 \times 10^{-3}$
CLEO [56]	$K^{(*)+}e^-\overline{\nu}_e$	$<7.8 \times 10^{-3}$
BaBar [55]	$K^{(*)+}e^-\overline{\nu}_e$	$<4.2(4.6) \times 10^{-3}$
FOCUS [54]	$K^+\mu^-\overline{\nu}_\mu$	$<1.01(1.31) \times 10^{-3}$
E791 [53]	$K^+\ell^-\overline{\nu}_\ell$	$<5.0 \times 10^{-3}$

Semileptonic

In semileptonic D 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

$$r(t) = |g_-(t)|^2 \left|\frac{q}{p}\right|^2 \approx \frac{e^{-t}}{4}(x^2+y^2)\, t^2 \left|\frac{q}{p}\right|^2 . \tag{6}$$

For $\overline{r}(t)$ one replaces q/p here with p/q. 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

$$R_M = \int_0^\infty r(t)dt = \left|\frac{q}{p}\right|^2 \frac{x^2+y^2}{2+x^2-y^2} \approx \frac{1}{2}(x^2+y^2) . \tag{7}$$

Table 5 summarizes results from semileptonic decays.

Hadronic

Consider the final state $f = K^+\pi^-$, where A_f is doubly-Cabibbo suppressed. The ratio of decay amplitudes is

$$\frac{A_f}{\overline{A}_f} = -\sqrt{R_D}\, e^{-i\delta}, \qquad \left|\frac{A_f}{\overline{A}_f}\right| \sim O(\tan^2\theta_c) , \tag{8}$$

where R_D is the doubly Cabibbo suppressed decay rate relative to the Cabibbo-favored (CF) rate, the minus sign originates from the sign of V_{us} relative to V_{cd}, and δ is the phase difference between DCS and CF processes not attributed to the first-order electroweak spectator diagram.

The violation of CP in the mixing amplitude, the decay amplitude, and the interference between mixing and decay, is characterized by the real-valued parameters A_M, A_D, and ϕ.

Table 6: Results for R in $D^0 \to K^+\pi^-$.

Exper.	$R(\times 10^{-3})$	$A_D(\%)$
CDF [27]	$4.05 \pm 0.21 \pm 0.11$	—
Belle [26]	$3.77 \pm 0.08 \pm 0.05$	—
FOCUS [23]	$4.29 \pm 0.63 \pm 0.28$	$18.0 \pm 14.0 \pm 4.1$
BaBar [24]	$3.57 \pm 0.22 \pm 0.27$	$9.5 \pm 6.1 \pm 8.3$
CLEO [8]	$3.32^{+0.63}_{-0.65} \pm 0.40$	$2^{+19}_{-20} \pm 1$

Table 7: Results from studies of the time dependent $r(t)$.

Exper.	y' (95% C.L.)	$x'^2/2$ (95% C.L.)
Belle [26]	$-2.8 < y' < 2.1$ %	< 0.036 %
FOCUS [23]	$-11.2 < y' < 6.7$ %	< 0.40 %
BaBar [24]	$-5.6 < y' < 3.9$ %	< 0.11 %
CLEO [8]	$-5.8 < y' < 1.0$ %	< 0.041 %

In the limit of CP conservation, A_M, A_D, and ϕ are all zero, and then

$$r(t) = \overline{r}(t) = e^{-t}\left(R_D + \sqrt{R_D}\, y't + \frac{1}{2}R_M\, t^2\right) , \tag{9}$$

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

$$R = \int_0^\infty r(t)\, dt = R_D + \sqrt{R_D}\, y' + R_M\, . \tag{10}$$

Here

$$y' \equiv\ y\cos\delta - x\sin\delta,\ \ x' \equiv x\cos\delta + y\sin\delta\, , \tag{11}$$

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

The ratio R is the most readily accessible experimental quantity. Table 6 gives recent measurements of R in $D^0 \to K^+\pi^-$ decay. The average of these results, $R = (0.380 \pm 0.008)\,\%$, is about two standard deviations from the average of earlier, less precise results, $R = (0.81 \pm 0.23)\,\%$, which we have omitted.

The contributions to R—allowing for CP violation—can be extracted by fitting the $D^0 \to K^+\pi^-$ and $\overline{D}^0 \to K^-\pi^+$ decay rates. Table 6 gives the constraints on A_D

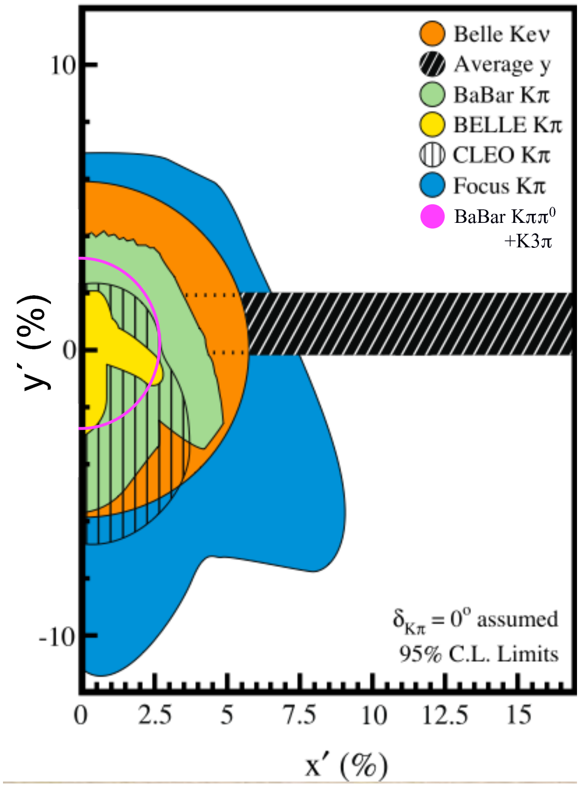

Figure 1: Allowed regions in the x',y' plane. The allowed region for y is the average of the results from E791 [58], FOCUS [29], CLEO [30], BaBar [61], and Belle [59,60]. Also shown is the limit from $D^0 \to K^{(*)}\ell\nu$ from Belle [57] and limits from $D \to K\pi$ from CLEO [8], BaBar [24], Belle [26] and FOCUS [23]. We assume $\delta = 0$ to place the y results.

with $x' = y' = 0$. Table 7 summarizes the results for y' and $x'^2/2$. Figure 1 shows the two-dimensional allowed regions. No meaningful constraints on A_M and ϕ have been reported.

Extraction of the amplitudes x and y from the results in Tab. 7 requires knowledge of the relative strong phase δ, a subject of theoretical discussion [62–65]. In most cases, it appears difficult for theory to accommodate $\delta > 25°$, although the judicious placement of a $K\pi$ resonance could allow δ to be as large as 40°.

In $D^0 \to K^0_S\pi^+\pi^-$, the DCS and CF decay amplitudes populate 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 $(189 \pm 10 \pm 3^{+15}_{-5})°$ [66], consistent with the 180° expected from Cabibbo factors and a small strong phase.

Table 8: Results for R in $D^0 \to K^{(*)+}\pi^-(n\pi)$.

Exper.	D^0 final state	$R(\%)$
BaBar [70]	$K^+\pi^-\pi^0$	$0.214 \pm 0.008 \pm 0.008$
Belle [36]	$K^+\pi^-\pi^+\pi^-$	$0.320 \pm 0.019^{+0.018}_{-0.013}$
Belle [36]	$K^+\pi^-\pi^0$	$0.229 \pm 0.017^{+0.013}_{-0.009}$
CLEO [66]	$K^{*+}\pi^-$	$0.5 \pm 0.2^{+0.6}_{-0.1}$
CLEO [67]	$K^+\pi^-\pi^+\pi^-$	$0.41^{+0.12}_{-0.11} \pm 0.04$
CLEO [35]	$K^+\pi^-\pi^0$	$0.43^{+0.11}_{-0.10} \pm 0.07$
E791 [20]	$K^+\pi^-\pi^+\pi^-$	$0.68^{+0.34}_{-0.33} \pm 0.07$

Multibody

There are several results for R measured in multibody final states with nonzero strangeness. Here R, defined in Eqn. 10, becomes an average over the Dalitz space, weighted by experimental efficiencies and acceptance. Table 8 summarizes the results.

For multibody final states, Eqn.8-10 apply to one point in the Dalitz 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. Both the sign and magnitude of x and y (rather than x'^2 and y') may be measured using the time-dependent resonant substructure of multibody D^0 decays. CLEO has performed a time-dependent Dalitz-plot analysis of $D^0 \to K^0_S\pi^+\pi^-$, and reports $(-4.5 < x < 9.3)\%$ and $(-6.4 < y < 3.6)\%$ at the 95% confidence level, without phase or sign ambiguity [68] . Recently, BaBar has searched for mixing in the multibody decays $D^0 \to K^+\pi^-\pi^0$ [70] and $D^0 \to K^+\pi^-\pi^+\pi^-$ [69]. The combined result is $R_M = (0.020^{+0.011}_{-0.010})\%$ or $R_M < 0.042\%$ at the 95% confidence level.

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 $\overline{A}_{\overline{f}} = \overline{A}_f$.

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 $D^0 \to K^+K^-$ [65]. A positive y would make K^+K^- decays appear to have a shorter lifetime than $K^-\pi^+$ decays. The decay rate for a D^0 into a CP eigenstate is not described by a just single exponential in the presence of CP violation. However, 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

Table 9: Results for y from $D^0 \to K^+K^-$ and $\pi^+\pi^-$. Belle [60] and BaBar [61] also measure A_Γ to be $(-2.0 \pm 6.3 \pm 3.0)$ and $(-8 \pm 6 \pm 2) \times 10^{-3}$.

Exper.	D^0 final state(s)	$y_{CP}(\%)$
Belle [60]	K^+K^-	$1.15 \pm 0.69 \pm 0.38$
BaBar [61]	$K^+K^-, \pi^+\pi^-$	$0.8 \pm 0.4^{+0.5}_{-0.4}$
CLEO [30]	$K^+K^-, \pi^+\pi^-$	$-1.1 \pm 2.5 \pm 1.4$
Belle [59]	K^+K^-	$-0.5 \pm 1.0^{+0.7}_{-0.8}$
FOCUS [29]	K^+K^-	$3.4 \pm 1.4 \pm 0.7$
E791 [28]	K^+K^-	$0.8 \pm 2.9 \pm 1.0$
Average		0.90 ± 0.42

single exponential:

$$r_\pm(t) \propto \exp\left(-[1 \pm \left|\tfrac{p}{q}\right|(y\cos\phi - x\sin\phi)]t\right), \tag{12}$$

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

$$r_\pm(t) + \overline{r}_\pm(t) \propto e^{-(1\pm y_{CP})t}. \tag{13}$$

When equal numbers of D^0 and $\overline{D}^0$ are produced

$$y_{CP} = y\cos\phi\left[\tfrac{1}{2}\left(\left|\tfrac{p}{q}\right| + \left|\tfrac{q}{p}\right|\right)\right] \tag{14}$$

$$-x\sin\phi\left[\tfrac{1}{2}\left(\left|\tfrac{p}{q}\right| - \left|\tfrac{q}{p}\right|\right)\right] \tag{15}$$

The possibility of CP violation has been considered in the limit of weak mixing and small CP violation. In this limit there is no sensitivity to CP violation in direct decay. Allowing for CP violation in interference and mixing Belle [60] and BaBar [61] have measured A_Γ, where

$$A_\Gamma \equiv \frac{r_\pm(t) - \overline{r}_\pm(t)}{r_\pm(t) - \overline{r}_\pm(t)} \approx A_M\, y\cos\phi - x\sin\phi. \tag{16}$$

In the limit of CP conservation, $y = y_{CP}$.

All measurements of y and A_Γ are relative to the $D^0 \to K^-\pi^+$ decay rate. Table 9 summarizes the current status of measurements. The average of the six y_{CP} measurements is $0.90 \pm 0.42\,\%$.

Table 10: CLEO-c preliminary results from time-integrated yields at $\psi(3770) \to D\overline{D}$. Errors are statistical only. Systematic uncertainties are anticipated to be smaller.

Parameter	CLEO-c [75]	Other results (%)
y	-0.058 ± 0.066	0.90 ± 0.42
$\cos\delta_{K\pi}$	1.09 ± 0.66	—
R_M	$(1.7 \pm 1.5)\times10^{-3}$	<0.1 (95% C.L.)
$x^2/2$	$<0.44\%$ (95% C.L.)	<0.036 (95% C.L.)

Coherent $D^0-\overline{D}^0$ Analyses

Measurements of R_D, $\cos\delta$, 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 [71, 72].

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 $C = +1$ $D^0\overline{D}^0$ pairs produced in the reactions $e^+e^- \to D^0\overline{D}^0(\pi^0)$ and $e^+e^- \to D^0\overline{D}^0\gamma(\pi^0)$, respectively, the time-integrated $D^0\overline{D}^0$ 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-$\overline{D}^0$ mixing.

The following categories of final states are considered:

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

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

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

The decay rates for $D^0\overline{D}^0$ pairs to all possible combinations of the above categories of final states are calculated in Ref. [63], for both $C = -1$ and $C = +1$, reproducing the work of Refs. [62, 73, 74]. Such $D^0\overline{D}^0$ combinations, where both D final states are specified, are double tags. In addition, the rates for single tags, where either the D^0 or $\overline{D}^0$ is identified and the other neutral D decays generically are given in Ref. [63].

CLEO-c has reported preliminary results using 281 pb^{-1} of $e^+e^- \to \psi(3770)$ data [75], where the quantum coherent $D^0\overline{D}^0$ pairs are in the $C = -1$ state. The values of y, R_M, and $\cos\delta$ are determined from a combined fit to the ST (hadronic only) and DT yields. The hadronic final states included in the analysis are $K^-\pi^+$ (f), $K^+\pi^-$ ($\overline{f}$), K^-K^+ ($S+$), $\pi^+\pi^-$ (S_+), $K^0_S\pi^0\pi^0$ (S_+), and $K^0_S\pi^0$ (S_-). Both of 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 the electron be found. When the electron is accompanied by a flavor tag ($D \to K^-\pi^+$ or $K^+\pi^-$), only the "right-sign" DT sample, where the electron and kaon charges are the same, is used. Extraction of the DCS "wrong-sign" semileptonic yield is not feasible with the current CLEO-c data sample, and the parameter R_D is constrained to the world average. Table 10 shows the results of the fit to the CLEO-c data.

4 SUMMARY OF CHARM MIXING

The 95% C.L. allowed region in x' versus y' are plotted in Fig. 1. The most stringent limits are from Belle constrain mixing in $D^0 \to K^+\pi^-$ to be $x'^2 < 2.7\%$ and $(-1.0\% < y' < 0.7\%$ [26] at 95% confidence level (C.L.). This result excludes $x'^2 = y' =$ at the 96.9% C.L. Other results are enticing too. The most recent limits from BaBar [69, 70] constrains D mixing in the multibody processes $D^0 \to K^+\pi^-\pi^0$ and $D^0 \to K^+\pi^-\pi^+\pi^-$ to be $R_M = (0.020^{+0.011}_{-0.010})\%$ or $R_M < 4.2 \times 10^{-4}$ at 95% C.L. Here the no mixing solution is excluded at the 97.9% C.L. Furthermore, the average of the six y_{CP} measurements from E791 [58], FOCUS [29], CLEO [30], BaBar [61], and Belle [59,60] is $0.90 \pm 0.42\,\%$. This could be an indication that the observation of $D^0 - \overline{D}^0$ mixing is just around the corner. Of course, it is noteworthy that earlier measurements also indicated hints of a mixing signal. In 1997, E791 reported $R_M = (0.21 \pm 0.09 \pm 0.02)\%$ [20], in 2000 CLEO II.V reported $y' = (-2.5 \pm 1.5 \pm 0.3)\%$ [8], and in 2002 FOCUS reported $y = (3.4 \pm 1.4 \pm 0.7)\%$ [29].

5 FUTURE PROSPECTS

To make significant improvement compared to the current experimental limits, an ideal charm experiment would provide a huge sample ($\sim$ 100 times the existing datasets), well understood backgrounds, efficient charged and neutral reconstruction, near 4π solid angle acceptance, particle ID for clean data samples, and precise lifetime measurements. Most of these attributes also characterise a good beauty experiment.

There are four experiments at various stages of development with significant potential for charm physics, two at e^+, e^- colliders (BESIII and Super-B), and two at hadron machines (LHCb and PANDA); two are beauty experiments, and only one a dedicated charm experiment.

BESIII [76, 77] will accumulate data at charm threshold and expects to integrate 20 times the data sample of CLEO-c.

A Super-B factory [78] would not only produce $\sim 1.5 \times 10^{10}$ $B\overline{B}$ meson pairs but also a similar number of τ pairs and about 7×10^{10} charm mesons per year. The possibility of running near charm threshold is being considered for the ILC inspired design. A month or two of operation in this mode would be sufficient to increase the world data sample of coherently produced $D^0 - \overline{D}^0$ (including BESIII) by an order of magnitude [79].

LHCb is the dedicated B physics experiment at the LHC, due to start its first physics run in 2008. It is expected to accumulate very high statistics in charged two and four body D^0 decays, for instance writing to tape 400,000 wrong-sign $K^\pm\pi^\mp$ decays per year [80]. An upgraded experiment is also being considered with the potential to increase these statistics by a further order of magnitude [81].

PANDA [82] is a fixed target experiment at the FAIR anti-proton storage ring. PANDA has a rich QCD and charm physics program including charmonium spectroscopy and an open charm studies. PANDA expects to produce about 100 charmed pairs per second around $\psi(4040)$. For a reconstruction efficiency of 30% ($S/B \sim 3$) [83] this corresponds to $\sim 20M$ reconstructed $D^0 \to K^-\pi^+$ in a year of $10^7 s$.

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