# Time-Independent Measurements of $D^0$-$\overline{D}^0$ Mixing and Relative Strong Phases Using Quantum Correlations at CLEO-c

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**Abstract.** 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. We make use of fully and partially reconstructed $D^0\overline{D}^0$ pairs in both $C$ eigenstates. and we estimate experimental sensitivities based on a plausible CLEO-c dataset.

**Keywords:** charm, mixing, correlated production
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## INTRODUCTION

Neutral flavor oscillation in the $D$ meson system is highly suppressed within the Standard Model. 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, $\delta_{K\pi}$ the relative strong phase between Cabibbo favored (CF) and doubly-Cabibbo suppressed (DCS) amplitudes 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 $\frac{1}{2}(x^2+y^2)$ [1]. Standard Model based predictions for $x$ and $y$, as well as a variety of non-Standard Model expectations, span several orders of magnitude [2]. It is reasonable to expect that $x \approx y \approx 10^{-3}$ in the Standard Model.

The parameters $x$ and $y$ can be measured in a variety of ways. The most precise limits are obtained by exploiting the time-dependence of $D$ decays [1]. 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 $\mathscr{O}(1\%)$ level and $\cos\delta_{K\pi} \sim 0.1$ [3, 4] in 1 fb$^{-1}$ of $\psi(3770) \to D\overline{D}$. Although CLEO-c does not have sufficient sensitivity to observe Standard Model charm mixing the projected sensitivity in 1 fb$^{-1}$ at $\psi(3770)$ compares favorably with current experimental results; see Fig. 1.

Two classes of analyses are ongoing at CLEO-c - 1) "targeted" analyses of individual mixing and doubly-Cabibbo suppressed parameters typically based on one double tag rate; 2) a "comprehensive" analysis which simultaneously determines the same parameters by examining various single tag and double tag rates. Greater sensitivity to the mixing and doubly-Cabibbo suppressed parameters is anticipated in the comprehensive analysis as several single tag and double tag rates provide sensitivity to each parameter.

## Targeted Analyses

Measurements of each of the four parameters that describe $CP$ conserving mixing can in principle be determined individually by a series of "targeted" analyses. The techniques and projected sensitivities in 1 fb$^{-1}$ are described briefly in the subsections that follow. Greater detail can be found in Ref. [3].

**Mixing Rate $R_M$:** The measurement of $R_M$ can be determined unambiguously by considering the decays $\psi(3770) \to (K^-\pi^+)(K^-\pi^+)$ and $\psi(3770) \to (\ell^\pm(KX))(\ell^\pm(KX))$. The hadronic final state cannot be produced from DCS decay due to a quantum statistics argument - the C-odd initial state cannot produce the symmetric final state required by Bose statistics if both the $D^0$ and $\overline{D}^0$ decay into the same final state ($K\pi$). A fit utilizing six constraints make this channel effectively background free. The double semileptonic channel has fewer constraints due to the presence of two neutrinos. The number of "right-sign" $(K^-\pi^+)(K^+\pi^-)$ and $(\ell^\pm(KX))(\ell^\mp(KX))$ events in the two channels combined produced in 1 fb$^{-1}$ is expected to be $\sim 20,000$ corresponding to $\sqrt{2R_M} < 1.7\%$ @95% Confidence Level (C.L.).

**Relative Strong Phase $\cos\delta_{K\pi}$:** Final states where one $D$ decays to $K\pi$ and the other to a $CP$ eigenstate can be used to probe $\cos\delta_{K\pi}$. The $CP$-even eigenstates accessible to CLEO-c include $K^+K^-$, $\pi^+\pi^-$ and $K^0_S\pi^0\pi^0$ and the $CP$-odd eigenstates include $K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\omega$, $K^0_S\phi$, and $K^0_S\eta'$. The $CP$ content of the $K^0_S\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ Dalitz plots will also be utilized. Sensitivity to $\cos\delta_{K\pi}$ $\sim 1/(2\sqrt{R_D N})$ where $N$, the total number of $CP$ tagged $K\pi$, will be $\sim$9200 and $R_D$ is already well measured, thus leading to an expected precision of $\pm 0.09$ in $\cos\delta_{K\pi}$.

**Mixing Parameter $y$:** Tagging one of the $D$ mesons as a $CP$ eigenstate, $y$ can be determined by measuring the flavor specific branching ratios of the other meson. The flavor tag width is independent of the $CP$ quantum number however the branching ratio is inversely proportional to the total width. Consequently, charm threshold experiments have time-integrated sensitivity to $y$. Neglecting factors related to DCS decays which are described in detail in Ref. [19], we can construct the ratio $\frac{2\Gamma[\psi\to(D\to CP)(D\to \text{flavor})]}{\Gamma[\psi\to(D\to CP)(D\to X)Br(D\to \text{flavor})]} \sim (1\pm y)$ where $X$ represents an inclusive set of all states. A positive $y$ would make the above ratio $> 1$ for $CP+$ tags.

The decay $D^0 \to K^0_S\pi^+\pi^-$ is measured with a Dalitz plot analysis to proceed through intermediate states that are $CP+$ eigenstates, such as $K^0_S f_0$, $CP-$ such as $K^0_S\rho$ and flavor eigenstates such as $K^{*-}\pi^+$ [20]. The presence of mixing through $y$ would introduce an intensity modulation across the Dalitz plot as a function of the $CP$ of the contributing amplitudes. The sensitivity at CLEO-c to $y$ with Dalitz plot analyses has not yet been fully evaluated. Preliminary estimates suggests a limit of $y \sim$ few% @95% C.L. is attainable with the CLEO-c data.

**Mixing Parameter $x$:** Measurement of $y$ and $R_M$ as outlined above allow the value $x$ to be determined. The upper limit on $R_M$ corresponds to a limit of $|x| < 1.7\%$ @95% C.L..

**Doubly Cabibbo Suppressed Rate $R_D$:** Although $R_D$ is determined by the ratio of $(K^-\pi^+)(K^-\ell^+\nu)$ to $(K^-\pi^+)(K^+\ell^-\overline{\nu})$ up to corrections that are second order in $x$ and $y$, a more precise measurement is attainable using a $D^{*+}$ tag to measure $D^0 \to K^+\pi^-$ relative to $D^0 \to K^-\pi^+$ [1].

## Comprehensive Analysis

The comprehensive analysis simultaneously determines mixing and doubly-Cabibbo suppressed parameters by examining various single tag and double tag rates explicitly accounting for QC. Due to quantum correlations (QC) 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 $e^+e^- \to D^0\overline{D}^0\gamma$, 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.

We consider in the comprehensive analysis the following categories of final states:

- $f$ or $\bar{f}$: hadronic states that can be reached 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 doubly Cabibbo-suppressed $\overline{D}^0$ transitions. We include in this category Cabibbo-suppressed transitions as well as self-conjugate final states of mixed $CP$, such as non-resonant $K^0_S\pi^+\pi^-$.
- $\ell^+$ or $\ell^-$: 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.

We calculate decay rates for $D^0\overline{D}^0$ pairs to all possible combinations of the above categories of final states in Ref. [19], for both $C = -1$ and $C = +1$, reproducing the work of Refs. [21, 22]. Such $D^0\overline{D}^0$ combinations, where both $D$ final states are specified, are referred to as double tags (or DT). In addition, we calculate rates for single tags (or ST), where either the $D^0$ or $\overline{D}^0$ is identified and the other neutral $D$ decays generically. Any DT event also contains two ST decays, and ST rates are obtained by summing the corresponding DT rates.

Using a double tag technique pioneered by MARK III [23, 24], CLEO-c has recently measured $\mathscr{B}(D^0 \to K^-\pi^+)$, $\mathscr{B}(D^0 \to K^-\pi^+\pi^0)$, and $\mathscr{B}(D^0 \to K^-\pi^+\pi^+\pi^-)$ in a self-normalizing way (*i.e.*, without knowledge of the luminosity or $D^0\overline{D}^0$ production cross section) [25]. Measured ST and DT yields and efficiencies are combined in a least-squares fit [26] to extract the branching fractions and the number of $D^0\overline{D}^0$ pairs produced. Quantum correlations were not accounted for in this analysis, and only flavored final states were considered.

In correlated $D^0\overline{D}^0$ decay, the ST and DT rates no longer depend solely on the branching fractions of interest; the rates are modified by $x$, $y$, and the magnitudes and phases of various amplitude ratios. Therefore, one must correct the measured ST and DT yields in order to extract the branching fractions. Conversely, as shown in Ref. [19], using these yields, it is possible to determine simultaneously the mixing and amplitude ratio parameters as well as the relevant branching fractions. The least-squares fit described in Ref. [26] can be extended to extract the parameters $\{\mathscr{A} - y,\ R_M,\ r_f,\ z_f\}$ for $C = -1$ or $\{\mathscr{A},\ y,\ r_f,\ z_f,\ w_f x\}$ for $C = +1$, where $\mathscr{A} \equiv \sum_f A_f^2 r_f z_f$, $z_f \equiv 2\cos\delta_f$ and $w_f \equiv 2\sin\delta_f$. For simplicity, we include only one such mode in the analysis: $D \to K^\pm\pi^\mp$, so $f = K^-\pi^+$, and $A_{K\pi}$ ($r_{K\pi} = \sqrt{R_D}$) is the magnitude of the CF (DCS) amplitude to final state $K\pi$. When fitting $C = -1$ and $C = +1$ simultaneously one can also determine $x^2$, so the free parameters are $\{\mathscr{A},\ y,\ x^2,\ r_f,\ z_f,\ w_f x\}$.

**TABLE 1.** Estimated uncertainties (statistical and systematic, respectively) for $\Gamma_{D^0\overline{D}^0} = 3.5 \times 10^6$. For the last two columns, $\Gamma^{C=-1}_{D^0\overline{D}^0} = \alpha\Gamma^{C=+1}_{D^0\overline{D}^0} = 3.5 \times 10^6$, where $\alpha$ is 1 or 4. The uncertainties on $\cos\delta_{K\pi}$ and $x\sin\delta_{K\pi}$ are half of those on $z_{K\pi}$ and $w_{K\pi}x$, respectively.

| Parameter | Value | $C=-1$ | $C=+1$ | $C=-1$ and $+1$ | |
|---|---|---|---|---|---|
| | | | | $\alpha=1$ | $\alpha=4$ |
| $\mathscr{A}-y(\%)$ | 0 | $\pm1.3\pm0.9$ | | | |
| $R_M(\%)$ | 0 | $\pm0.03\pm0.03$ | | | |
| $r_{K\pi}(\%)$ | 0.06 | $\pm0.57\pm0.03$ | $\pm0.95\pm0.07$ | $\pm0.49\pm0.03$ | $\pm0.55\pm0.03$ |
| $z_{K\pi}$ | $-2$ | $\pm0.42\pm0.12$ | $\pm0.49\pm0.12$ | $\pm0.31\pm0.09$ | $\pm0.38\pm0.10$ |
| $y(\%)$ | 0 | | $\pm1.7\pm0.6$ | $\pm1.0\pm0.4$ | $\pm1.2\pm0.5$ |
| $\mathscr{A}(\%)$ | 0 | | $\pm0.010\pm0.008$ | $\pm0.002\pm0.005$ | $\pm0.003\pm0.005$ |
| $w_{K\pi}x$ | 0 | | $\pm0.043\pm0.012$ | $\pm0.025\pm0.007$ | $\pm0.033\pm0.010$ |
| $x^2(\%)$ | 0 | | | $\pm0.06\pm0.06$ | $\pm0.06\pm0.06$ |

The estimated uncertainties on the fit parameters based on $3.5\times10^6$ $D^0\overline{D}^0$ pairs, in either the $C=-1$ or $C=+1$ configuration are presented in Table 1 using reconstruction efficiencies similar to those found at CLEO-c and assuming no background ($\sigma_N = \sqrt{N}$).

In Figure 1, we plot the projected 95% confidence level (C.L.) contour for $\Gamma^{C=-1}_{D^0\overline{D}^0} = 4\Gamma^{C=+1}_{D^0\overline{D}^0} = 3.5\times10^6$ and $\cos\delta_{K\pi} = -1$. We note that our sensitivity to $x$ depends strongly on the value of $\delta_{K\pi}$, while our sensitivity to $y$ does not, and lowering the value of $|\cos\delta_{K\pi}|$ would reduce the area of the contour. In general, our expected upper limits compare favorably with the current best limits on charm mixing.

## REFERENCES


1. D. Asner, $D^0$-$\overline{D}^0$ Mixing in Review of Particle Physics, *Phys. Lett.*, **B592**, 1 (2004).
2. H. N. Nelson, in *Proc. of the 19th Intl. Symp. on Photon and Lepton Interactions at High Energy LP99* ed. J.A. Jaros and M.E. Peskin, SLAC (1999); S. Bianco, F. L. Fabbri, D. Benson and I. Bigi, Riv. Nuovo Cim. **26N7**, 1 (2003); A. A. Petrov, eConf **C030603**, MEC05 (2003) [arXiv:hep-ph/0311371]; I. I. Y. Bigi and N. G. Uraltsev, Nucl. Phys. B **592**, 92 (2001); Z. Ligeti, AIP Conf. Proc. **618**, 298 (2002) [arXiv:hep-ph/0205316]; A. F. Falk, Y. Grossman, Z. Ligeti and A. A. Petrov, Phys. Rev. D **65**, 054034 (2002); C. K. Chua and W. S. Hou, arXiv:hep-ph/0110106.
3. R. A. Briere *et al.*, CLNS-01-1742 (2001).
4. Gronau, M., Grossman, Y., and Rosner, J. L., *Phys. Lett.*, **B508**, 37–43 (2001).
5. E. M. Aitala *et al.* [E791 Collaboration], Phys. Rev. Lett. **83**, 32 (1999).
6. J. M. Link *et al.* [FOCUS Collaboration], Phys. Lett. B **485**, 62 (2000).
7. S. E. Csorna *et al.* [CLEO Collaboration], Phys. Rev. D **65**, 092001 (2002).
8. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **91**, 121801 (2003).
9. K. Abe *et al.* [Belle Collaboration], arXiv:hep-ex/0308034.
10. E. M. Aitala *et al.* [E791 Collaboration], Phys. Rev. Lett. **77**, 2384 (1996).
11. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D **70**, 091102 (2004).
12. C. Cawlfield *et al.* [CLEO Collaboration], Phys. Rev. D **71**, 077101 (2005)
13. K. Abe *et al.* [Belle Collaboration], arXiv:hep-ex/0507020.
14. R. Godang *et al.* [CLEO Collaboration], Phys. Rev. Lett. **84**, 5038 (2000).
15. B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **91**, 171801 (2003).
16. K. Abe *et al.* [Belle Collaboration], Phys. Rev. Lett. **94**, 071801 (2005).
17. J. M. Link *et al.* [FOCUS Collaboration], Phys. Lett. B **618**, 23 (2005).
18. D. M. Asner *et al.* [CLEO Collaboration], Phys. Rev. D **72**, 012001 (2005).

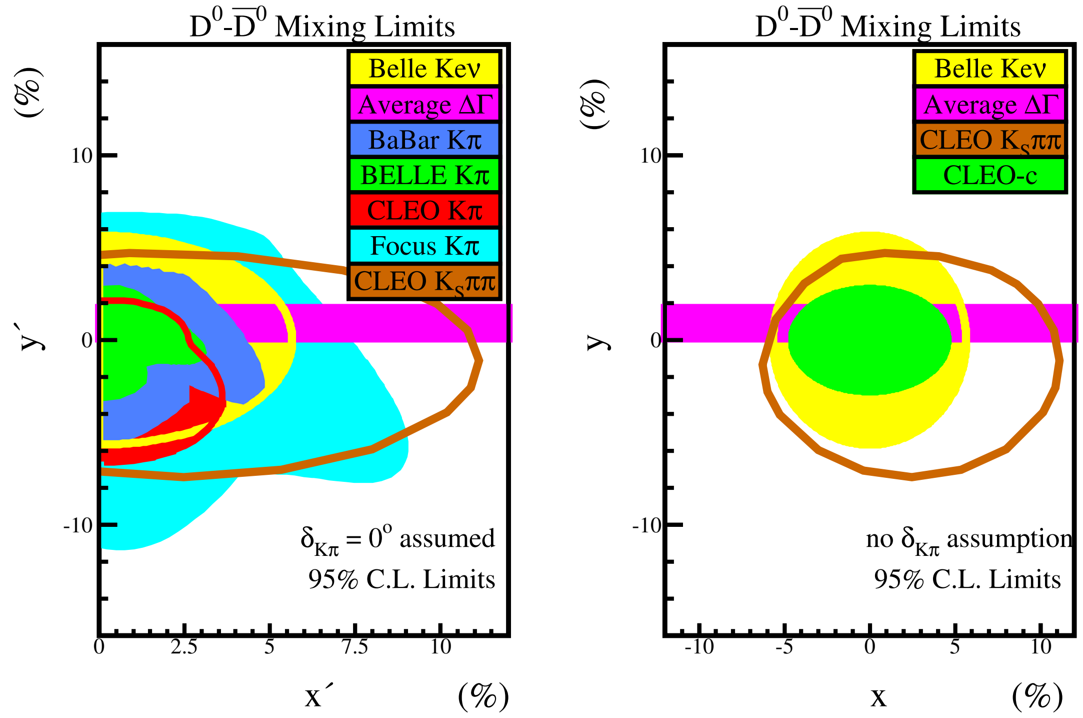


**FIGURE 1.** **Left**: Current allowed regions in the plane of $y'_{K\pi}$ versus $x'_{K\pi}$. The allowed region for $\Delta\Gamma$ is the average of the results from E791 [5], FOCUS [6], CLEO [7], BABAR [8], and Belle [9]. Also shown is the limit from $D^0 \to K^{(*)}\ell\nu$ from Belle [13]. Semileptonic results from E791 [10], BABAR [11], and CLEO [12] are not shown. The limits from $D \to K\pi$ from CLEO [14], BABAR [15], and Belle [16] allow for *CP* violation in the decay amplitude, in the mixing amplitude, and in the interference between these two processes, while the FOCUS [17] result does not. The CLEO experiment has constrained $x$ and $y$ with a time-dependent Dalitz-plot analysis of $D^0 \to K^0_S\pi^+\pi^-$ [18]. In depicting the $y$ and Dalitz-plot results, we assume $\delta_{K\pi} = 0$; a non-zero value for $\delta_{K\pi}$ would rotate the $\Delta\Gamma$ and $D^0 \to K^0_S\pi^+\pi^-$ confidence regions clockwise about the origin by an angle $\delta_{K\pi}$. All results are consistent with the absence of mixing. **Right:** Current and projected allowed regions in the plane of $y$ versus $x$. The allowed region for $\Delta\Gamma$ is the average of the results from from E791 [5], FOCUS [6], CLEO [7], BABAR [8] and Belle [9]. Also shown is the limit from $D^0 \to K^{(*)}\ell\nu$ from Belle [13]. Semileptonic results from E791 [10], BABAR [11], and CLEO [12] are not shown. The CLEO experiment has constrained $x$ and $y$ with a time-dependent Dalitz-plot analysis of $D^0 \to K^0_S\pi^+\pi^-$ [18]. All results are consistent with the absence of mixing. We superimpose our projected 95% C.L. contour for $\Gamma^{C=-1}_{D^0\overline{D}^0} = 4\Gamma^{C=+1}_{D^0\overline{D}^0} = 3.5\times10^6$ and $\cos\delta_{K\pi} = -1$. Lowering the value of $|\cos\delta_{K\pi}|$ would reduce the area of the contour.


19. D. M. Asner and W. M. Sun, arXiv:hep-ph/0507238, submitted to Phys. Rev. D.
20. Muramatsu, H., *et al.*, [CLEO Collaboration], *Phys. Rev. Lett.*, **89**, 251802 (2002).
21. M. Gronau, Y. Grossman and J. L. Rosner, Phys. Lett. B **508**, 37 (2001).
22. D. Atwood and A. A. Petrov, Phys. Rev. D **71**, 054032 (2005).
23. R. M. Baltrusaitis *et al.* [MARK III Collaboration], Phys. Rev. Lett. **56**, 2140 (1986).
24. J. Adler *et al.* [MARK III Collaboration], Phys. Rev. Lett. **60**, 89 (1988).
25. Q. He *et al.* [CLEO Collaboration], Phys. Rev. Lett. **95**, 121801 (2005).
26. W. M. Sun, arXiv:physics/0503050, submitted to Nucl. Instrum. Methods Phys. Res., Sec. A.