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Search for $D^0-\overline{D}^0$ Mixing

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Abstract

We report on a search for $D^0-\overline{D}^0$ mixing made by a study of the 'wrong-sign' process $D^0 \to K^+\pi^-$. The data come from an integrated luminosity of e^+e^- collisions at $\sqrt{s} \approx 10\,\mathrm{GeV}$ consisting of 9.0 fb^{-1}, recorded with the CLEO-II.V detector. We measure the time-integrated rate of the 'wrong-sign' process $D^0 \to K^+\pi^-$, relative to that of the Cabibbo-favored process $\overline{D}^0 \to K^+\pi^-$, to be $R_{\mathrm{ws}} = (0.34 \pm 0.07 \pm 0.06)\%$. We study that rate as a function of the decay time of the D^0, to distinguish the rate of direct doubly-Cabibbo-suppressed decay from $D^0-\overline{D}^0$ mixing. The amplitudes that describe $D^0-\overline{D}^0$ mixing, x' and y', are consistent with zero. The one-dimensional limits, at the 95% C.L., that we determine are $(1/2)x'^2 < 0.05\%$, and $-5.9\% < y' < 0.3\%$. All results are preliminary.

Studies of the evolution of a K^0 or B_d^0 into the respective anti-particle, a $\overline{K}^0$ or $\overline{B}_d^0$, have guided the form and content of the Standard Model, and permitted useful estimates of the masses of the charm and top quark masses, prior to direct observation of those quarks. In this paper, we present the results of a search for the evolution of the D^0 into the $\overline{D}^0$, where the principal motivation is to glimpse new physics outside the Standard Model, prior to direct observation of that physics at the high energy frontier.

A D^0 can evolve into a $\overline{D}^0$ through on-shell intermediate states, such as K^+K^- with $m_{K^+K^-} = m_{D^0}$, or through off-shell intermediate states, such those that might be present due to 'new physics'. We denote the amplitude through the former (latter) states by $-iy$ (x), in units of $\Gamma_{D^0}/2$ [1], and we neglect all types of CP violation.

For comparison, in the $K^0-\overline{K}^0$ system the analogous y and $|x|$ are both near unity [2, 3]. The prediction that an initial K^0 will decay with two lifetimes, as described by the non-zero y, was famously made by Gell-Mann and Pais [4]. In the $B_d^0-\overline{B}_d^0$ system theory firmly predicts that y is negligible, and experiments have not yet sought y out. For the $D^0-\overline{D}^0$

system, y is likely to receive significant contributions from the Standard Model [5]. It may even be that y dominates the $D^0 \to \overline{D}^0$ amplitude.

It has been x, for both the $K^0 - \overline{K}^0$ and $B_d^0 - \overline{B}_d^0$ systems, that has provided information about the charm and top quark masses. A report of the first measurement in 1961 of $|x|$ for the K^0–$\overline{K}^0$ system noted 'We cannot compare our experimental value for $|x|$ with any theoretical calculation' [6]. By 1974, theory had caught up, and exploited $|x|$ for the $K^0 - \overline{K}^0$ system to predict the charm quark mass [7], just before that quark was discovered. The tiny, CP violating Im(x) for the K^0 is sensitive to the value of the top quark mass. The large value for the B_d^0 of $|x|$ (now 0.73 ± 0.03 [2]) indicated that the top quark is very massive [8], in distinction to contemporaneous data from the high energy frontier [9].

Many predictions for x in the $D^0 \to \overline{D}^0$ amplitude have been made [10]. The Standard Model contributions are suppressed down to at least $|x| \approx \tan^2 \theta_C \approx 0.05$ because D^0 decay is Cabibbo-favored; the GIM [11] cancellation could suppress $|x|$ down to $10^{-6} - 0.01$. Many non-Standard Models, particularly those that address patterns of quark flavor, predict $|x| \approx 0.01$ or greater. Contributions to x at this level can result from the presence of new particles with masses as high as 100 TeV [12]. Decisive signatures of such particles might include $|y| \ll |x|$, or CP-violating interference between a substantial imaginary component of x and either y, or a direct decay amplitude. In order to accurately assess the origin of a D^0–$\overline{D}^0$ mixing signal, the effects described by y must be distinguished from those that are described by x.

We report here on a study of the process $D^0 \to K^+\pi^-$. We use the charge of the 'slow' pion, π_s^+, from the decay $D^{*+} \to D^0\pi_s^+$ to deduce production of the D^0, and then we seek the rare 'wrong-sign' $K^+\pi^-$ final state (WS), in addition to the more frequent 'right-sign' final state, $K^-\pi^+$ (RS). The wrong-sign process, $D^0 \to K^+\pi^-$, can proceed either through direct doubly-Cabibbo-suppressed decay (DCSD), or through mixing followed by the Cabibbo-favored decay (CFD), $D^0 \to \overline{D}^0 \to K^+\pi^-$. Both processes contribute to the time integrated 'wrong-sign' rate, $R_{\rm ws}$:

$$R_{\rm ws} = \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(\overline{D}^0 \to K^+\pi^-)}.$$

To disentangle the two processes that could contribute to $D^0 \to K^+\pi^-$, we study the distribution of wrong-sign final states as a function of the proper decay time, t, of the D^0. The proper decay time is in units of the mean D^0 lifetime, $\tau_{D^0} = 415 \pm 4$ fs [2]. The differential 'wrong-sign' rate, relative to $\Gamma(\overline{D}^0 \to K^+\pi^-)$, is $r_{\rm ws}(t)$ [13, 14]:

$$r_{\rm ws}(t) \equiv [R_D + \sqrt{R_D}y't + \frac{1}{4}(x'^2 + y'^2)t^2]e^{-t}, \qquad (1)$$

where the modified mixing amplitudes x' and y' in Eqn. 1 are given by:

$$\begin{array}{rcl} y' & \equiv & y\cos\delta - x\sin\delta \\ x' & \equiv & x\cos\delta + y\sin\delta \end{array},$$

and δ is a possible strong phase between DCSD and CFD amplitudes:

$$-\sqrt{R_D}e^{-i\delta} \equiv \frac{\langle K^+\pi^-|T|D^0\rangle}{\langle K^+\pi^-|T|\overline{D}^0\rangle}.$$

The symbol R_D represents the DCSD rate, relative to the CFD rate. There are plausible theoretical arguments that δ is small [15, 16]. If both D^0 and $\overline{D}^0$ exclusively populate the $I = 1/2$ amplitude of $K^+\pi^-$, then δ would be zero. For the CFD, $\overline{D}^0 \to K^+\pi^-$, the $I = 3/2$ amplitude is indeed disfavored, with $|A_{3/2}/A_{1/2}| = 0.27 \pm 0.02$ [17]. A non-zero δ could develop if $D^0 \to K^+\pi^-$ populates the $I = 3/2$ amplitude differently than the CFD does. Crudely, one might guess $|\delta| < \sim |A_{3/2}/A_{1/2}| \sim 15^\circ$. The size of δ could be settled by measurements of the DCSD contributions to $D^+ \to K^+\pi^0$, $D^+ \to K_{\mathrm{L}}\pi^+$, and $D^0 \to K_{\mathrm{L}}\pi^0$, which are now feasible with our data set.

For decays to wrong-sign final states other than $K^+\pi^-$, such as $K^+\pi^-\pi^0$, or $K^+\pi^-\pi^+\pi^-$, there will be distinct strong phases. Moreover, the broad resonances that mediate those multibody hadronic decays, such as the K^*, ρ, etc., modulate those phases as a function of position on the Dalitz plot. Thus, multibody hadronic wrong-sign decays might afford an opportunity to distinguish x and y from x' and y'.

An important aspect of the expression Eqn. 1 for the two-body decay $D^0 \to K^+\pi^-$ is that the dependence on y' and x' is distinguishable due to the interference with the direct decay amplitude, which induces the term linear in t. Such behavior is complementary to the differential decay rate to CP eigenstates such as $D^0 \to K^+K^-$, which is sensitive to y alone, or that of $D^0 \to K^+\ell^-\overline{\nu}_\ell$, which is sensitive to $r_{\mathrm{mix}} \equiv (x^2+y^2)/2 = (x'^2+y'^2)/2$ alone.

Our data was accumulated between Jan. 1996 and Feb. 1999 from an integrated luminosity of e^+e^- collisions at $\sqrt{s} \approx 10\,\mathrm{GeV}$ consisting of $9.0\,\mathrm{fb}^{-1}$, provided by the Cornell Electron Storage Rings (CESR). The data were taken with CLEO-II multipurpose detector [18], upgraded in 1995 when a silicon vertex detector (SVX) was installed [19] and the drift chamber gas was changed from argon-ethane to helium-propane. The upgraded configuration is named CLEO-II.V, where the 'V' is short for Vertex.

We reconstruct candidates for the decay sequences $D^{*+} \to \pi_s^+ D^0$, followed by either $D^0 \to K^+\pi^-$ (wrong-sign) or $D^0 \to K^-\pi^+$ (right-sign). The sign of the slow charged pion tags the charm state at $t = 0$ as either D^0 or $\overline{D}^0$. The broad features of the reconstruction are similar to those employed in the recent CLEO-II.V measurement of the D meson lifetimes [20]. The following points are important in understanding how we have improved our sensitivity to $D^0 \to K^+\pi^-$, relative to earlier CLEO work [21, 22]:

1. The SVX allows substantially more precise measurement of charged particle trajectories in the dimension parallel to the colliding beam axis. When combined with improvements in track-fitting, the CLEO-II.V resolution for $Q = M_{\pi_s K\pi} - M$, where M is the mass of the $K^+\pi^-$ system, is $\sigma_Q = 190 \pm 6\,\mathrm{KeV}$, compared with the earlier value of $\sigma_Q = 750\,\mathrm{KeV}$ [21].

2. The use of helium-propane, in addition to improvements in track-fitting, have reduced the CLEO-II.V resolution for M to $\sigma_M = 6.4 \pm 0.1\,\mathrm{MeV}$, compared with the earlier value of $\sigma_M = 11\,\mathrm{MeV}$ [21].

3. Improved mass resolution, as well as rejections based on the momentum asymmetry of the two charged tracks, allow clean separation of the signal $D^0 \to K^+\pi^-$ from $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, and $D^0 \to K^-\pi^+$, and from multibody decays of the D^0, at a cost of about 35% of the signal acceptance. We use the modest π^+/K^+ separation provided by measurement of dE/dx in the CLEO-II.V drift chamber primarily for systematic studies. Addition of a new device with perfect π^+/K^+ identification and acceptance might enable the recovery of the 35% acceptance loss.

Multiple scattering on the field wires, which constitute 70% of the material, as measured in radiation lengths, in the CLEO-II.V drift chamber, appears to dominate the current σ_Q and σ_M. Should the track-fitting be altered to treat scattering on the field wires as discrete and localized, both σ_Q and σ_M might improve by as much as a factor of 2.

Our signal for the wrong-sign process $D^0 \to K^+\pi^-$ is shown in Fig. 1. We determine the background levels by performing a fit to the plane of $0 < Q < 20\,\mathrm{MeV}$ versus $1.76 < M < 1.97\,\mathrm{GeV}$, which has an area about 150 times larger than our signal region. Event samples generated by the Monte-Carlo method and fully simulated in our detector, corresponding to $90\,\mathrm{fb}^{-1}$ of integrated luminosity, are used to estimate the background shapes in the Q–M plane. The shapes are allowed to float in a fit to the data; the results of the fit are displayed in Fig 1. The excess of events in the signal region is prominent.

We describe the signal shape with the right-sign data that is within $7\,\sigma$ of the nominal CFD value in the Q–M plane. The results of the fit to the wrong-sign data are summarized in Table I.

No acceptance corrections are needed to compute $R_{\mathrm{ws}} = (0.34 \pm 0.07)\%$ from Table I. The dominant systematic errors all stem from the potentially inaccurate modeling of the initial and acceptance-corrected shapes of the

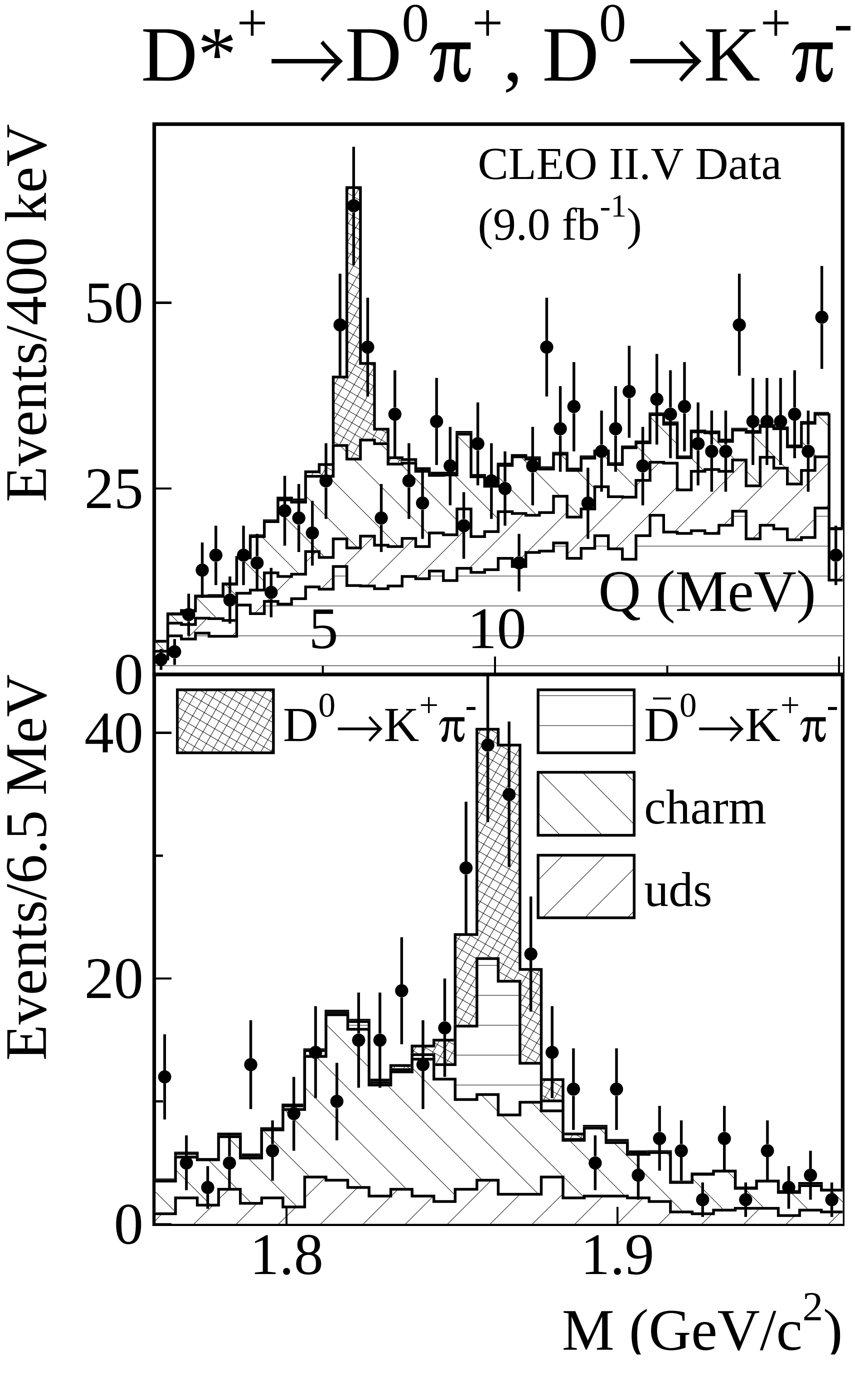

Figure 1: Signal for the wrong-sign process $D^0 \to K^+\pi^-$. For the top plot, M is within 14 MeV of the nominal CFD value, and for the bottom plot, Q is within 500 KeV of the nominal CFD value. The data are the full circles with error bars, the fit to the signal is cross-hatched, and the fits to the backgrounds are singly hatched. The results of the fit are summarized in Table I.

background contributions in the Q-M plane. We assess these systematic errors by substantial variation of the fit regions, dE/dx criteria, and kinematic criteria; the total systematic error we assess is 0.06%.

Our complete result for $R_{\rm ws}$ is summarized in Table II. As we describe later, our data are consistent with an absence of $D^0-\overline{D}^0$ mixing, so our best estimate for the relative DCSD rate, R_D, is that it equals $R_{\rm ws}$.

There are two directly comparable measurements of $R_{\rm ws}$: one is from CLEO-II [21], $R_{\rm ws} = (0.77 \pm 0.25 \pm 0.25)\%$ which used a data set independent of that used here; the second is from Aleph [23], $R_{\rm ws} = (1.84 \pm 0.59 \pm 0.34)\%$; comparison of our result and these are marginally consistent with $\chi^2 = 6.0$ for 2 DoF, for a C.L. of 5.0%.

We have split our sample into candidates for $D^0 \to K^+\pi^-$ and $\overline{D}^0 \to K^-\pi^+$. There is no evidence for a CP-violating time-integrated asymmetry. From Table I, it is straightforward to estimate the 1σ statistical error on the CP violating time-integrated asymmetry as $\sqrt{107}/54.8 \approx 20\%$.

TABLE I. Event yields in a signal region of $2.4\,\sigma$ centered on the nominal Q and M values. The total number of candidates is 107. The bottom row describes the normalization sample.

Component	**# Events**
$D^0 \to K^+\pi^-$ (WS Signal)	54.8 ± 10.8
random $\pi^\pm + D^0/\overline{D}^0$	24.3 ± 1.8
$c\overline{c}$	12.3 ± 0.8
uds	8.6 ± 0.4
$D^0 \to$ Pseudoscalar-Vector	7.0 ± 0.4
$\overline{D}^0 \to K^+\pi^-$ (RS Normalization)	16126 ± 126

TABLE II. Result for $R_{\rm ws}$. For the branching ratio $\mathcal{B}(D^0 \to K^+\pi^-)$ we take the absolute branching ratio $\mathcal{B}(\overline{D}^0 \to K^+\pi^-) = (3.85 \pm 0.09)\%$. The third error results from the uncertainty in this absolute branching ratio. As discussed in the text, our best estimate is that $R_D = R_{\rm ws}$.

Quantity	**Result**
$R_{\rm ws}$	$(0.34 \pm 0.07 \pm 0.06)\%$
$R_{\rm ws}/\tan^4\theta_C$	$(1.28 \pm 0.25 \pm 0.21)$
$\mathcal{B}(D^0 \to K^+\pi^-)$	$(1.31 \pm 0.26 \pm 0.22 \pm 0.03) \times 10^{-4}$

Given the absence of a significant time-integrated CP asymmetry, we undertake a study of the decay time dependence wrong-sign rate based upon Eqn. 1. We reconstruct the proper D^0 decay time primarily from the vertical displacement of the $K^+\pi^-$ vertex from the e^+e^- collision 'ribbon,' which is infinitesimal in its vertical extent. We require a well-reconstructed vertex in 3-dimensions, which causes a loss of about 12% of the candidates described in Table I. Our resolution, in units of the mean D^0 life, is about 1/2. Study of the plentiful right-sign sample allows us to fix our detailed resolution function, and shows that biases in the reconstruction of the proper decay time contribute negligibly to the wrong-sign results.

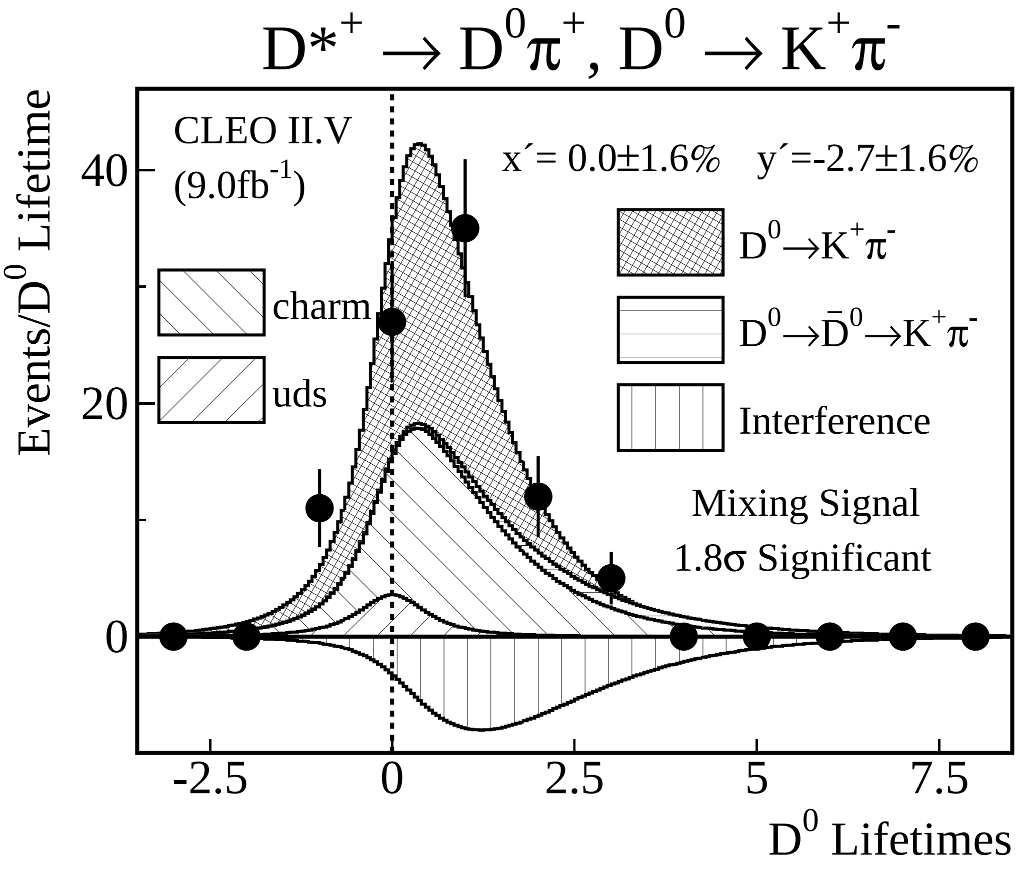

Figure 2: Distribution in t for the $D^0 \to K^+\pi^-$ candidates. The data are shown as the full circles with error bars. All other information comes from the fit to the data, The smooth curves show the various specific contributions as labeled. The cross hatched region is the net contribution from $D^0 \to K^+\pi^-$, after incorporation of the (destructive) interference and mixing.

The distribution of proper decay times, t, for wrong-sign candidates that are within $2.4\,\sigma$ of the nominal CFD value in the $Q-M$ plane is shown in Fig. 2. Maximum-likelihood fits are made to those data. The backgrounds are described by levels and shapes deduced from the fit to the $Q-M$ plane, and from study of the simulated data sample. The wrong-sign signal is described by Eqn. 1, folded with our resolution function.

For the benchmark fit to the wrong-sign data, x' and y' are constrained to be zero. This fit has a confidence level of 84%, indicating a good fit.

The mixing amplitudes x' and y' are then allowed to freely vary, and the best fit values are shown in Fig. 2 and in Table III. The fit improves slightly when x' and y' are allowed to float to the values that maximize the likelihood. However, the small value of the likelihood change $\sqrt{-2\Delta \ln \mathcal{L}} = 1.8\,\sigma$ (including systematic errors) does not permit us to eliminate the possibility that the improvement is due to a statistical fluctuation.

Therefore, our principal results concerning mixing are the one-dimensional intervals, which correspond to a 95% confidence level, that are given in the second column of Table III.

Additionally, we evaluate a contour in the two-dimensional plane of y' versus x' which, at 95% confidence level, contains the true value of x' and y'. To do so, we determine the contour around our best fit values where the $-\ln \mathcal{L}$ has increased by 3.0 units. All other fit variables, including the DCSD rate and background contributions, are allowed to float to distinct, best fit values at each point on the contour. The interior of the contour is shown, as the small, dark, cross-hatched region near the origin of Fig. 3. On the axes of x' and y', this contour falls slightly outside the one-dimensional intervals listed in Table III, as expected.

TABLE III. Results of the fit, where x' and y' are free to float, to the distribution of $D^0 \to K^+\pi^-$ candidates in t. The data and the fit components are shown in Fig. 2.

Parameter	**Best Fit**	**95% C.L.**
R_D	$(0.50^{+0.11}_{-0.12} \pm 0.08)\%$	$0.22\% < R_D < 0.77\%$
y'	$(-2.7^{+1.5}_{-1.6} \pm 0.2)\%$	$-5.9\% < y' < 0.3\%$
x'	$(0 \pm 1.6 \pm 0.2)\%$	$\lvert x' \rvert < 3.2\%$
$(1/2)x'^2$		$< 0.05\%$

We have evaluated the allowed regions of other experiments [24, 25, 26, 27] at 95% C.L., and shown those regions in Fig. 3.

All results described here are preliminary.

If we assume that δ is small, which is plausible [15, 16] then $x' \approx x$ and we can indicate the impact of our work in limiting predictions of $D^0-\overline{D}^0$ mixing from extensions to the Standard Model. Eighteen of the predictions recently tabulated [10] have some inconsistency with our limit. Among those predictions, some authors have made common assumptions, however.

Because our data is consistent with an absence of $D^0-\overline{D}^0$ mixing, our best information on the DCSD rate, R_D, is that it equals $R_{\rm ws}$, as summarized in Table II.

We will soon complete studies where we allow various types of CP violation to modify Eqn. 1. Also, the D^0 decay modes K^+K^-, $\pi^+\pi^-$,

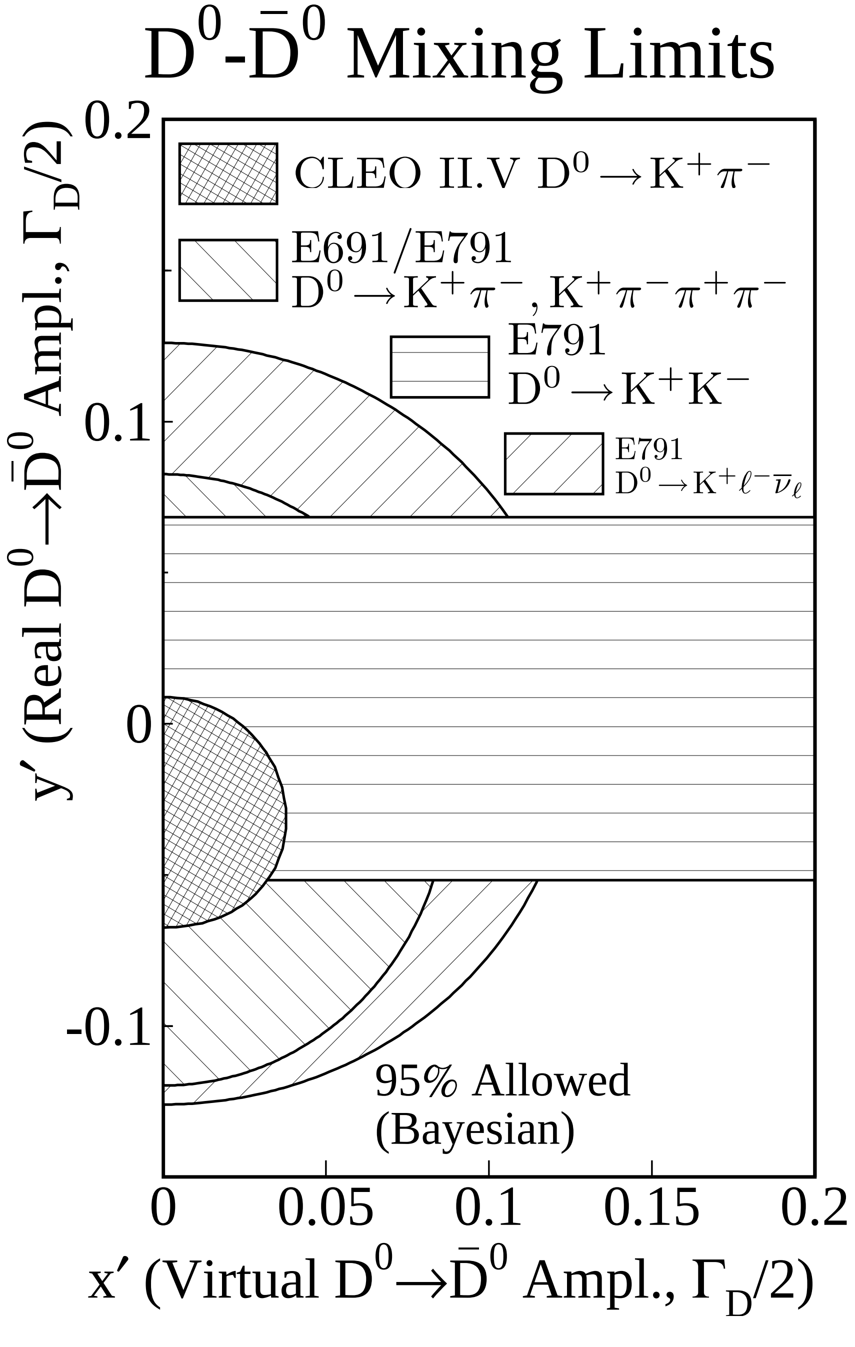

Figure 3: Limits in the y' vs. x' plane. Our experiment limits, at 95% C.L., the true values of x' and y' to occupy the cross-hatched region near the origin. Also shown are the similar zones from other recent experiments. We assume $\delta = 0$ to place the recent work of E791 that utilized $D^0 \to K^+K^-$; a non-zero δ would rotate the E791 confidence region clockwise about the origin by an angle of δ.

$K_S\phi$, $K_S\pi^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, and $K^+\ell^-\overline{\nu}_l$ are under active investigation, using the CLEO-II.V data. The $(K_S\pi^+)$ resonance bands in $D^0 \to K_S\pi^+\pi^-$ permit investigation of $D^0 \to \overline{D}^0$, with sensitivity heightened by coherent interference that is modulated by resonant phases.

The entire CLEO-II.V data set, suitably exploited, could be used to observe $D^0 - \overline{D}^0$ mixing if either $|x|$ or $|y|$ exceed approximately 1 %.

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[3] Specifically, from the previous reference, for the K^0 system $x = -0.947 \pm 0.003$, and $y = 0.99655 \pm 0.00003$. In our convention $|y|$ is bounded by 1, and signed by the CP eigenvalue of the dominant real intermediate state(s), which is 2π (to which we assign CP=+1) for $K^0 \to \overline{K}^0$. For $D^0 \to \overline{D}^0$ there are real intermediate states that are not CP eigenstates, such as $K\pi$, but the convention is straightforward to generalize. Then, we define x as proportional to the mass difference between the eigenstate that decays preferentially to CP=+1 final states and the other eigenstate, that decays preferentially to CP=−1 states. The study reported here is sensitive (when $\delta = 0$) to the magnitude $|x|$ for the $D^0 \to \overline{D}^0$ amplitude and to the magnitude, and sign, of y for the $D^0 \to \overline{D}^0$ amplitude.

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