D^o mixing at CLEO-II

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The CLEO collaboration reported the observation of the "wrong sign" decay $D^o \to K^+\pi^-$ in 1993 [1]. Recent upgrades to the CLEO detector [2], including the installation of a silicon vertex detector [3], have increased the sensitivity of the detector to $D^o \to K^+\pi^-$. Using 5.6 fb^{-1} of data we report a preliminary measurement of the rate of the wrong sign decay $D^o \to K^+\pi^-$, to be $\mathcal{B}(D^o \to K^+\pi^-)/\mathcal{B}(D^o \to K^-\pi^+) = (0.31 \pm 0.09 \pm 0.07)\%$. Additionally, combining this measurement with D^o proper lifetime information [4] we set a limit on $D^o - \overline{D}^o$ mixing of $\mathcal{B}(D^o \to \overline{D}^o \to K^+\pi^-)/\mathcal{B}(D^o \to K^-\pi^+) < 1.1 \times 10^{-2}$ @ 90% confidence limit.

I. INTRODUCTION

Ground state mesons such as the K^o, D^o, and B^o, which are electrically neutral and contain a quark and antiquark of different flavor, can evolve into their respective antiparticles, the $\overline{K}^o$, $\overline{D}^o$, and $\overline{B}^o$. Measurements of the rates of K^o–$\overline{K}^o$ mixing and B^o–$\overline{B}^o$ mixing have guided both the elucidation of the structure of the Standard Model, and the determination of the parameters that populate it. The mixing measurements permitted crude, but accurate, estimates of the masses of the then-hypothetical charm and top quark masses prior to direct observation of those quarks at the high energy frontier. Since $D^o - \overline{D}^o$ mixing is expected to be small in the Standard Model it provides sensitivity to new heavy non-Standard Model particles.

The mixing of $D^o \leftrightarrow \overline{D}^o$ can proceed either through real or virtual intermediate states. Real intermediate states ($K\pi$, $\pi\pi$, KK, ...) lead to lifetime differences between the D^o eigenstates ($\Delta\Gamma$ mixing), while virtual intermediate states lead to a mass difference (ΔM mixing). Both of these amplitudes are (at least) doubly Cabibbo suppressed compared to the total D^o decay amplitude. Additionally, the near degeneracy of the d and s quark masses compared to the W mass, causes the Glashow-Illiopolouos-Maini (GIM) cancellation to be particularly effective [5]. This introduces an additional suppression to the mixing amplitudes of from 10 to 10^3. The ratio of the mixing amplitudes to the total decay amplitude is given by x and y, for virtual and real amplitudes respectively.

The observation of a value of $|x|$ in the D^o–$\overline{D}^o$ system in excess of about 5×10^{-3} might be evidence of incomplete GIM-type cancellations among new families of particles, such as supersymmetric partners of quarks. [6] The evidence would be most compelling if either the mixing amplitude exhibited a large CP violation, or if the Standard Model contributions could be decisively determined. It is possible that in the Standard Model that $|y| > |x|$, [7] and a determination of y allows the estimation of at least some of the long-distance Standard Model contributions to x.

II. FORMALISM

In the two-body hadronic decay $D^o \to K\pi$, "Right sign" events are produced by the Cabibbo favored decay $D^o \to K^-\pi^+$. "Wrong sign" events, $D^o \to K^+\pi^-$, are produced either through the doubly Cabibbo suppressed tree diagram (DCSD) or through D^o mixing followed by the Cabibbo allowed decay, $D^o \to \overline{D}^o \to K^+\pi^-$. The decay time distribution of the D^o mesons allows us to separate the total wrong sign rate into its $\Delta\Gamma$, ΔM and DCSD components. In the limit of small mixing and no CP violation the decay time distribution is given by [8],

$$w(\tau) = (R_{\mathrm{DCSD}} + \sqrt{2R_{\mathrm{DCSD}}R_{\mathrm{Mix}}}\cos\phi\,\tau + \frac{1}{2}R_{\mathrm{Mix}}\tau^2)e^{-\tau} \tag{1}$$

where

$$R_{\mathrm{DCSD}} = \frac{\mathcal{B}(D^o \overset{\mathrm{DCSD}}{\to} K^+\pi^-)}{\mathcal{B}(D^o \to K^-\pi^+)} = \tan^4\theta_c, \quad R_{\mathrm{Mix}} = \frac{\mathcal{B}(D^o \to \overline{D}^o \to K^+\pi^-)}{\mathcal{B}(D^o \to K^-\pi^+)} = \frac{1}{2}(x^2+y^2), \tag{2}$$

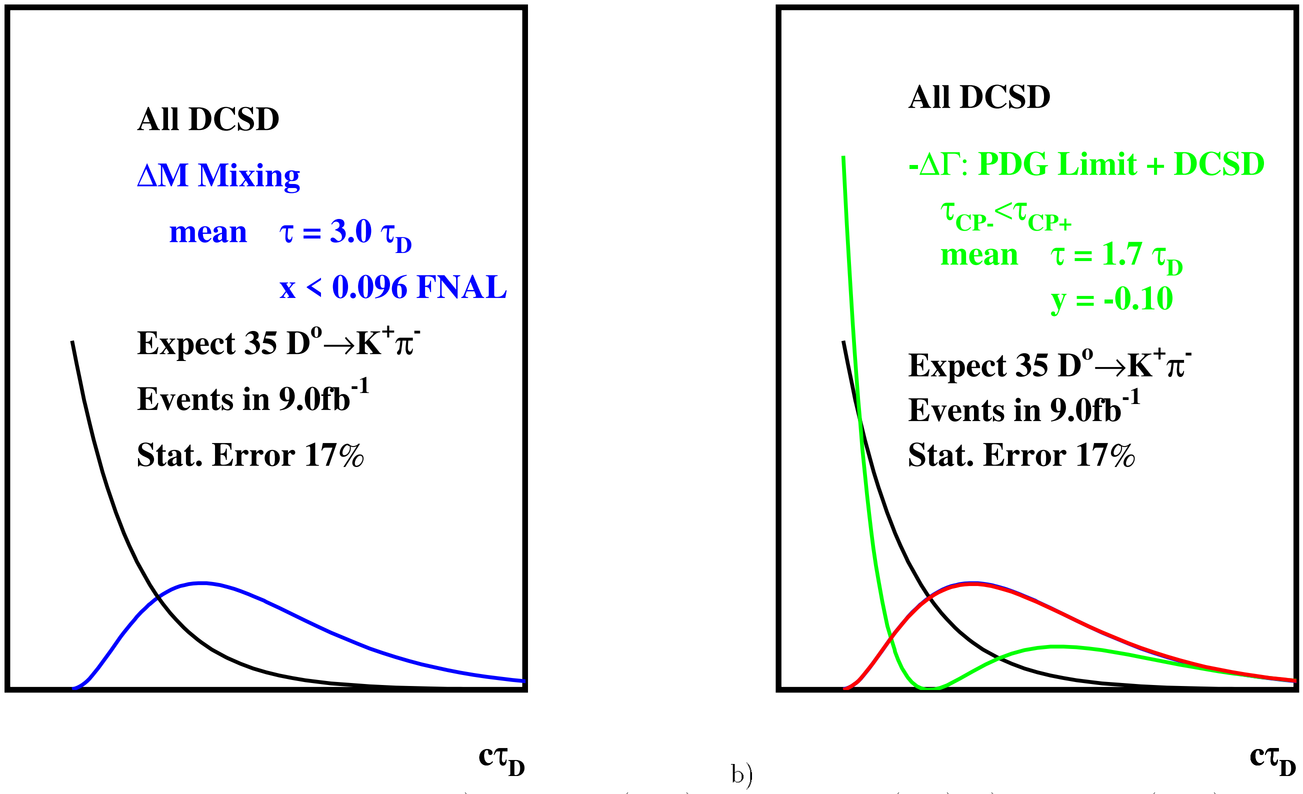
$$\text{and} \quad \phi = \arctan(-2\frac{\Delta M}{\Delta\Gamma}) + \delta_s = \arctan(-\frac{x}{y}) + \delta_s, \tag{3}$$

and δ_s is the strong phase between the $D^o \to K^+\pi^-$ and $\overline{D}^o \to K^+\pi^-$ amplitudes and is small by theoretical bias. Examples of the distribution for DCSD, ΔM mixing and $\Delta\Gamma$ mixing are plotted in Figure 1. The time-integrated wrong-sign rate is,

$$R_{\rm WS} = R_{\rm DCSD} + \sqrt{2R_{\rm DCSD}R_{\rm Mix}}\cos\phi + R_{\rm Mix}, \tag{4}$$

and the mean wrong-sign decay time is,

$$\langle\tau_{\rm WS}\rangle = \frac{R_{\rm DCSD} + 2\sqrt{2R_{\rm Mix}R_{\rm DCSD}}\cos\phi + 3R_{\rm Mix}}{R_{\rm DCSD} + \sqrt{2R_{\rm Mix}R_{\rm DCSD}}\cos\phi + R_{\rm Mix}} \tag{5}$$



a) b)

FIG. 1. Sample decay time distributions. a) Pure DCSD (black) and ΔM mixing (blue). b) Pure DCSD (black) and an interference between DCSD and $\Delta\Gamma$ mixing (red).

III. EXPERIMENTAL TECHNIQUE

We reconstruct the decay chain $D^{*+} \to D^o\pi^+$; $D^o \to K^+\pi^-$. The charge of the soft pion from the D^{*+} decay allows us to tag the flavor of the D^o at the moment of production. Combining that with the charge of the kaon determines whether the event is right or wrong sign.

For right sign events, as shown in Figure 3-a, we observe the mass distribution of the $K\pi$ combinations ($M_{K\pi}$) to peak at the D^o mass. Additionally, when we construct the quantity δm, which is $M_{K\pi\pi} - M_{K\pi} - M_\pi$, we see a peak at the D^* - D^o - π mass difference. These events allow us to model the wrong sign signal shape since the right sign and wrong sign events have identical kinematics.

The signal shape is Gaussian in each of the two dimensions. The resolution on $M_{K\pi}$ is 6.5 MeV and is dominated by momentum mismeasurements. It is shown for right sign events in Figure 2-a. The resolution on δm is dominated by multiple scattering of the slow pion from the D^*. Using information from the silicon vertex detector we determine the decay point of the D^* by extrapolating from the reconstructed D^o spatial vertex back to the beam spot along the D^o momentum vector. We can then refit the soft pion momentum vector through this additional point which improves the measured δm mass resolution from about 700 to 205 KeV. The soft pion refit also reduces backgrounds since background soft pions are often inconsistent with production at the primary vertex. The combination of these two effects leads to an increase in signal squared over background of 4.7, as shown in Figure 2-b.

The main backgrounds to the analysis all have shapes that are distinct from signal in the $M_{K\pi}$ vs. δm plane. Figure 3b shows right sign events where the pion from the D^o decay is misidentified as a kaon and vice versa. This double misidentification leaves the δm peak intact but smeares out the D^o peak. Figure 3c shows background events composed of a properly reconstructed $D^o \to K^-\pi^+$ decay plus a random slow track. They are indistinguishable from signal in $M_{K\pi}$, since they are real D^o decays. However, the events distribute themselves in δm according to phase space and produce equal numbers of right and wrong sign events. Lastly, there are $D^{*+} \to D^o\pi^+; D^o \to X$ decays. For instance, if a $D^o \to \pi^+\pi^-\pi^0$ decay is misreconstructed it can peak broadly around the D^o mass if the π^0 mass is neglected and one of the other pions is misidentified as a kaon. Since the momentum vector of the actual and the misreconstructed D^o are close, the δm distribution is broadly peaked about the D^* - D^o - π mass difference.

IV. WRONG-SIGN RATE R_{WS} AND MEAN DECAY TIME $\langle \tau_{\mathrm{WS}} \rangle$

We have performed a binned maximum likelihood fit of the MC-generated background components to the two dimensional data on the $M_{K\pi}$ vs. δm plane, to obtain R_{WS}.

$$R_{\mathrm{WS}} = \frac{\Gamma(D^o \to K^+\pi^-)}{\Gamma(D^o \to K^-\pi^+)} = 0.0031 \pm .0009(stat) \pm .0007(syst) \tag{6}$$

The fit also yields a breakdown of the background event content in Fig. 4a and 4b.

The proper time distribution of events within the signal region is shown in Figure 5 for both right sign and wrong sign events. Events with poorly measured proper times are excluded. The mean proper time of the right sign decays is $(0.97 \pm 0.02) \times c\tau_{D^o}$ which is consitent with a pure exponential decay with the D^o lifetime. The wrong sign events have a mean proper time of $(0.6 \pm 0.2) \times c\tau_{D^o}$. According to the fit, the wrong sign events are composed of signal (17.3 ± 5.4), real D^o decays (8.9 ± 0.8) and other backgrounds (5.8 ± 0.1). If we assume that D^o decays have a lifetime of one $c\tau_{D^o}$and the other backgrounds have a lifetime of zero, which is a conservative assumption, then we determine the signal lifetime to be $(0.65 \pm 0.40) \times c\tau_{D^o}$. Care must be taken when using this measurement to determine a 90% confidence level upper limit since the physically allowed region of $\langle \tau_{\mathrm{WS}} \rangle$ ranges between one and three for all DCSD or all $D^o - \overline{D}^o$ mixing when $\cos\phi = 0$.

V. PREVIOUS D^o-$\overline{D}^o$ MIXING LIMITS

Three groups have reported non-zero measurements of R_{WS} evaluated for the case $\cos\phi = 0$ and assuming no CP violation.

- CLEO-II [1], equivalent to $R_{\mathrm{WS}} = R_{\mathrm{DCSD}} + R_{\mathrm{Mix}} = (0.77 \pm 0.35)\%$
- E791 [9], where $R_{\mathrm{DCSD}} = (0.68 \pm 0.35)\%$, and $R_{\mathrm{Mix}} = (0.21 \pm 0.09)\%$, where, for R_{Mix}, $D^o \to K^+\pi^-\pi^+\pi^-$ contribute in addition to $D^o \to K^+\pi^-$; no report of a non-zero R_{Mix} was made.
- Aleph [10], where $R_{\mathrm{DCSD}} = (1.84 \pm 0.68)\%$, and an upper limit of $R_{\mathrm{Mix}} < 0.92\%$ is obtained, at 95% C.L.

Additionally, the E691 collaboration [11] limited $R_{\mathrm{Mix}} < 0.37\%$, at 90% C.L., where again $D^o \to K^+\pi^-\pi^+\pi^-$ contribute in addition to $D^o \to K^+\pi^-$, and $R_{\mathrm{DCSD}} < 1.5\%$ at 90% C.L. The E791 [12] collaboration sought $D^o \to K^+\ell^-\overline{\nu}_\ell$, and set the limit that $R_{\mathrm{Mix}} < 0.5\%$. The regions allowed by the above work, in the R_{Mix} vs. R_{DSCD} plane, for $\cos\phi = 0$, are shown in Fig. 6.

VI. CLEO-II.V CHARM MIXING LIMITS

The mixing limits determined from $D^o \to K^+\pi^-$with $5.6fb^{-1}$ of CLEO-II.V data in column 1 of table I are combined with $D^o\to CP^+$ analysis from E791 [13] (table I,column 2). The CLEO-II.V sensitivity ($9.1fb^{-1}$) combining $D^o \to K^+\pi^-$,$K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$ and $D^o\to CP$ analyses is listed in column 3. A factor of 2-5 (3-10) improvement in precision is obtained over the PDG [14] with $5.6fb^{-1}$ ($9.1fb^{-1}$). The CLEO II.V limit for $x \sim \tan^2\theta_{\rm Cabibbo}$, is more or less the largest level that D^o-$\overline{D}^o$ mixing can be in the Standard Model.

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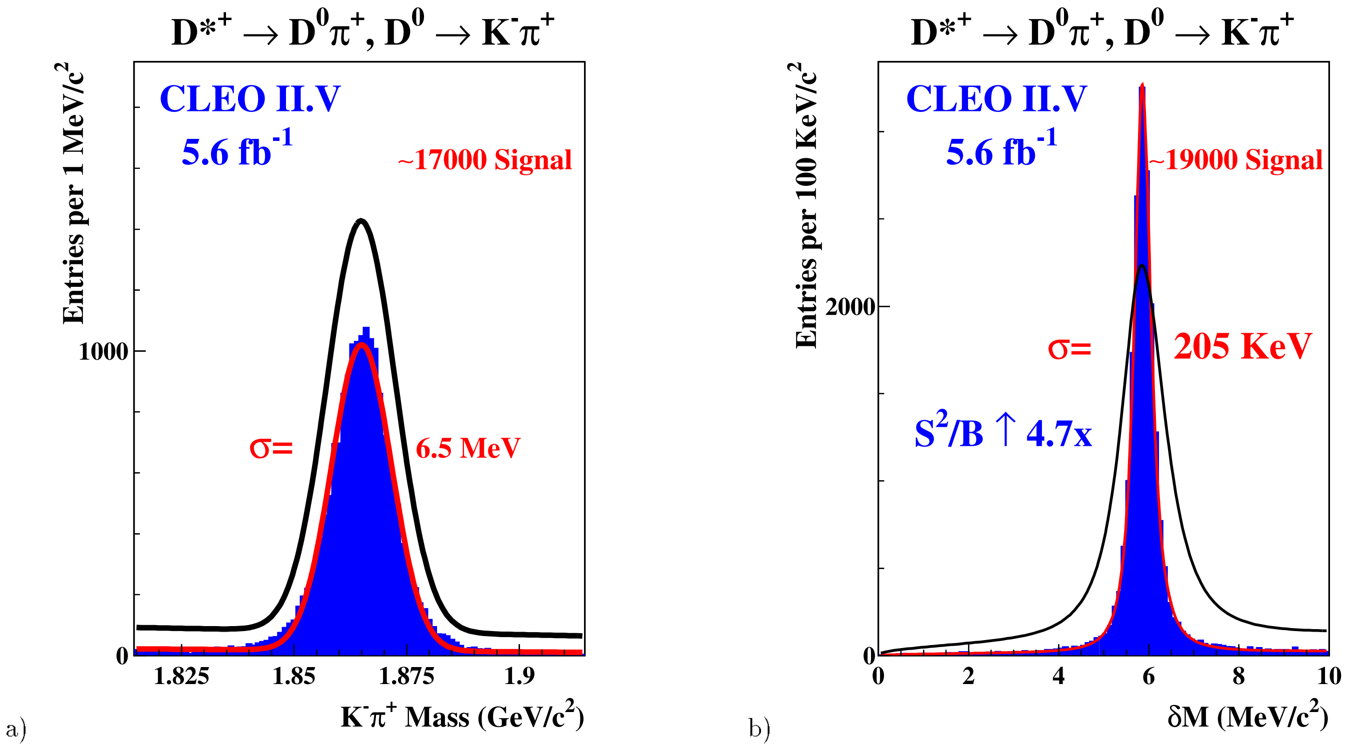


FIG. 2. The experimental resolutions in; a) $M_{K\pi}$, b) δm. The black line is the distribution before the soft pion refit.

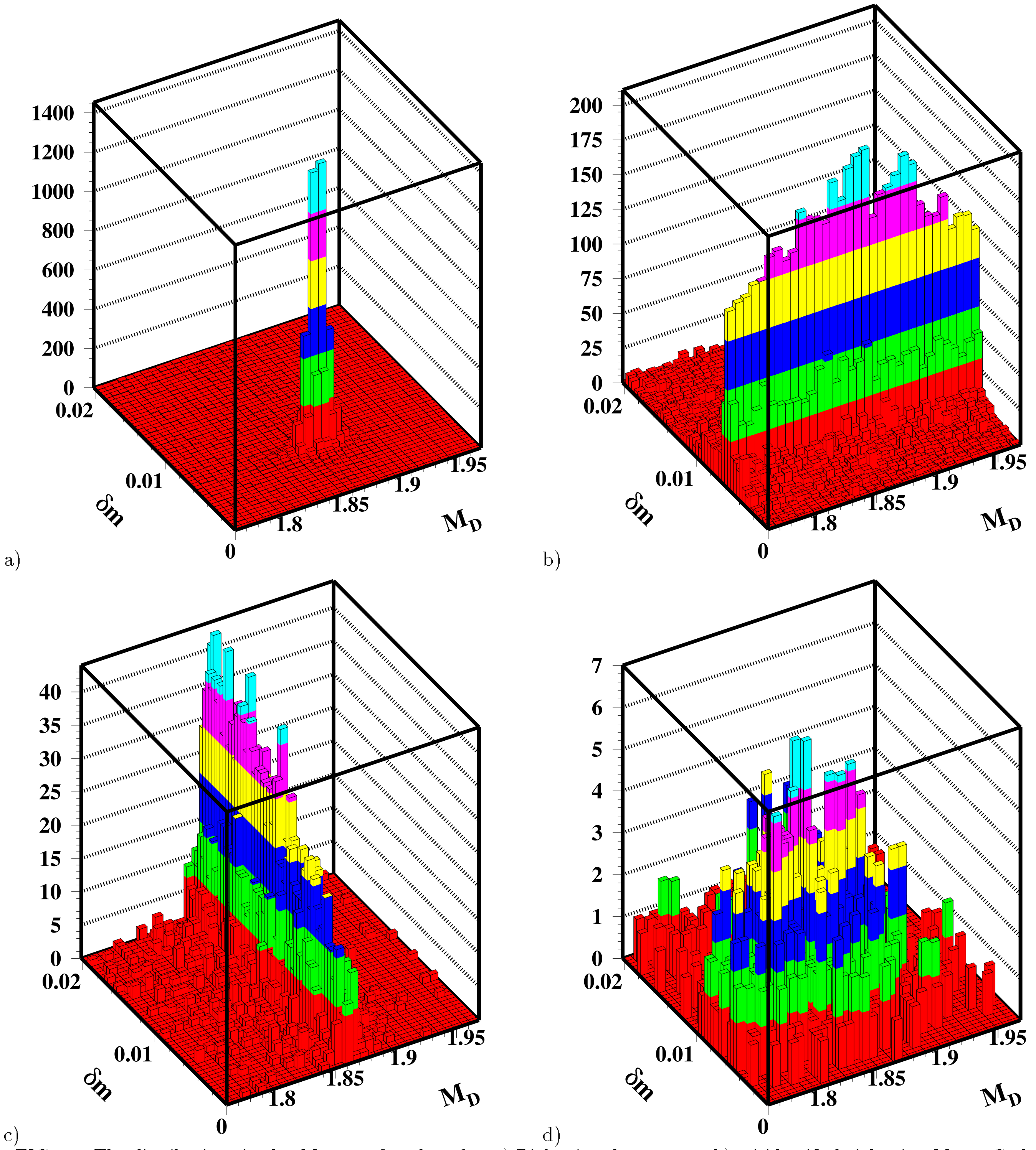
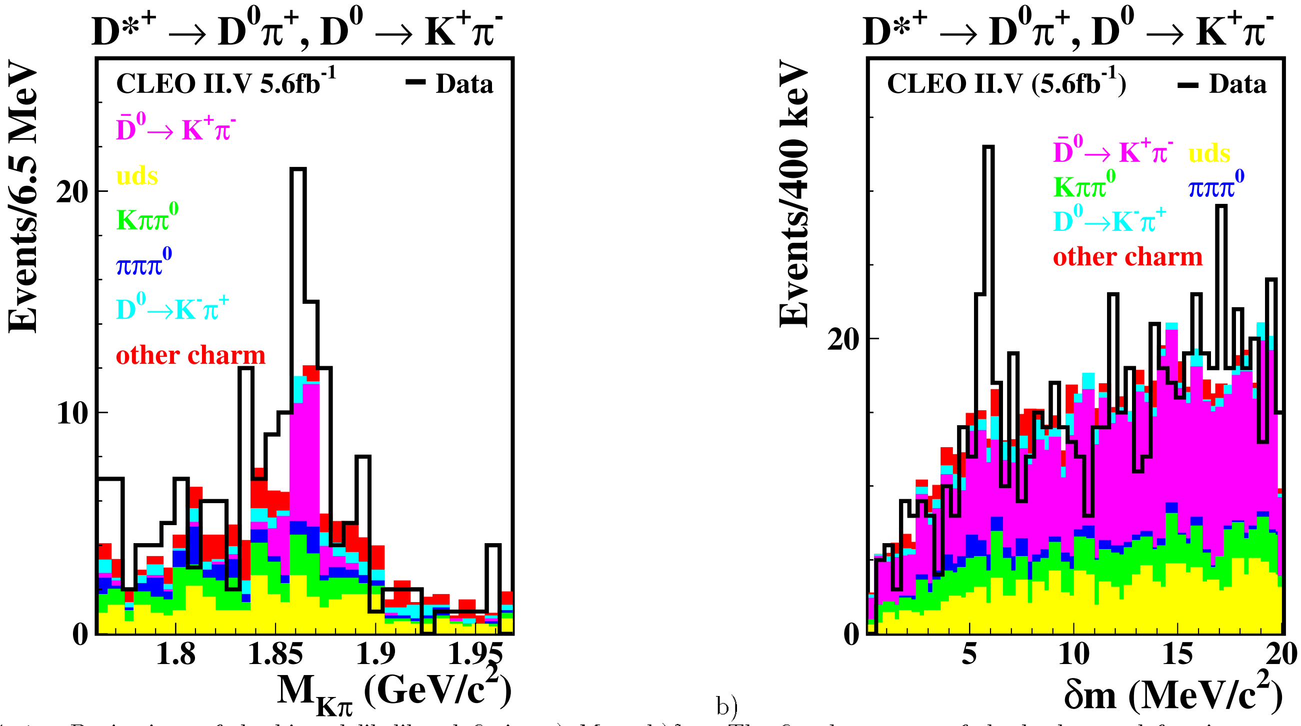


FIG. 3. The distributions in the $M_{K\pi}$ vs. δm plane for; a) Right sign data events, b) misidentified right sign Monte Carlo events, c) $D^{o} \to K^{-}\pi^{+}$ decays with a random soft track Monte Carlo events, d) $D^{*+} \to D^{o}\pi^{+}$ decays with a misreconstructed $D^{o} \to \pi^{+}\pi^{-}\pi^{0}$decay Monte Carlo events.



a) b)

FIG. 4. Projections of the binned likelihood fit in; a) $M_{K\pi}$, b) δm. The fitted amounts of the background fractions are plotted.

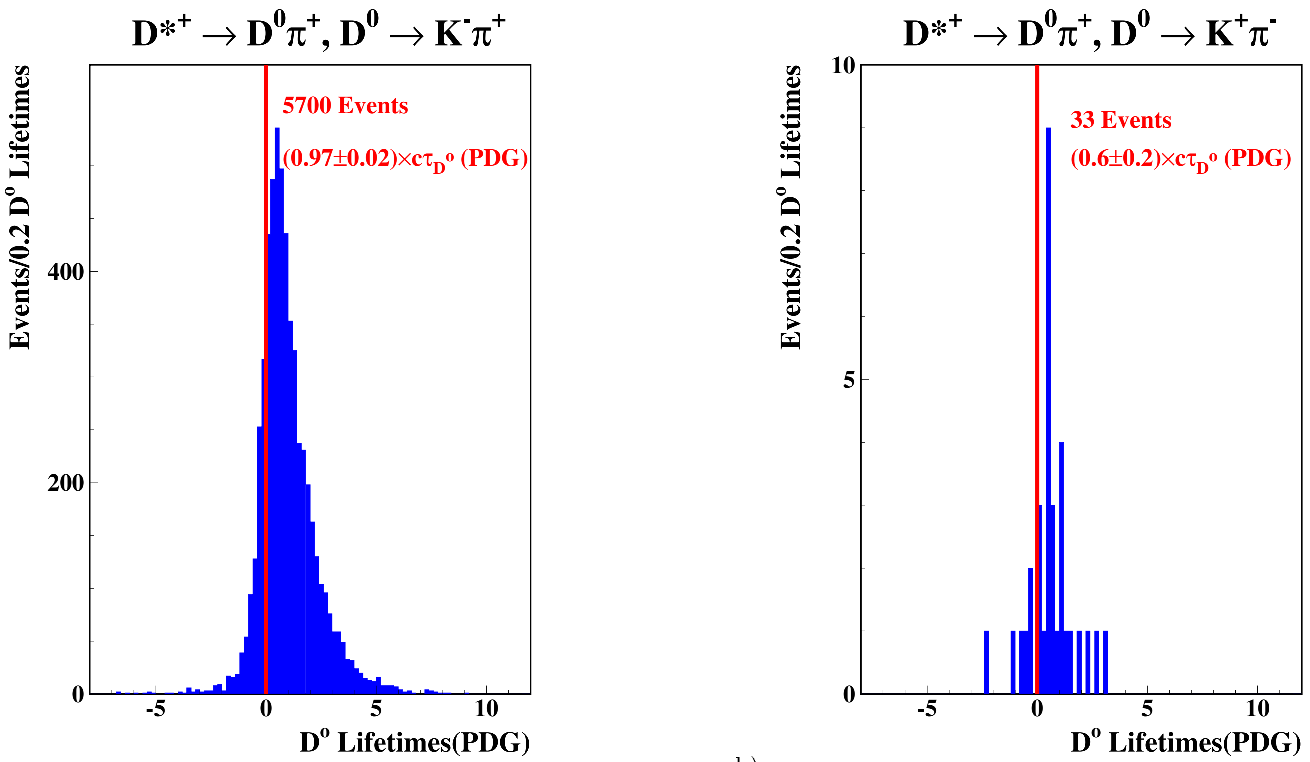


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FIG. 5. The decay time distributions for events in the signal region for; a) Right sign events, b) Wrong sign events.

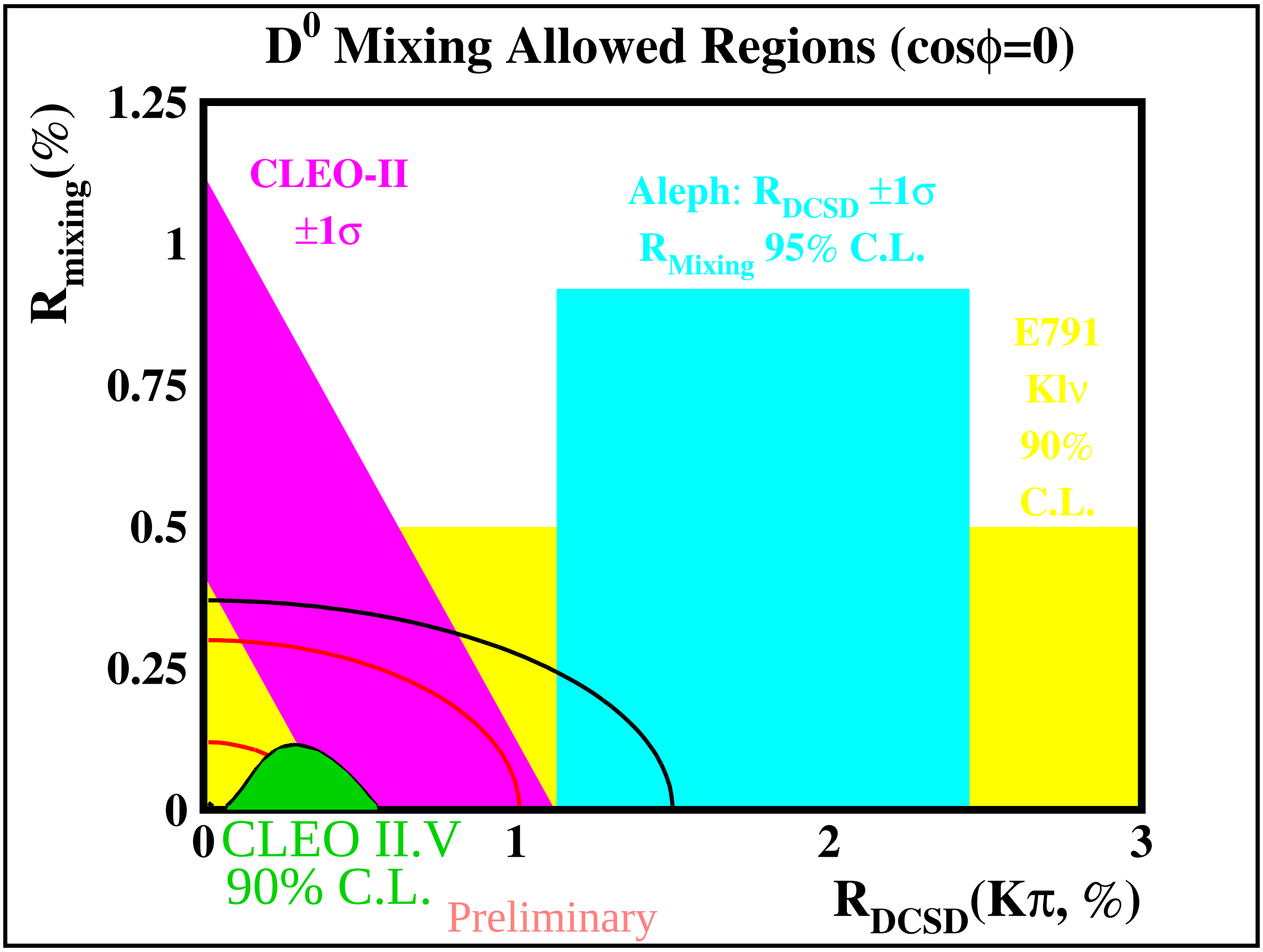

FIG. 6. The world mixing and DCSD limits assuming $\cos\phi = 0$.

TABLE I. Comparison of Mixing Limits. column 1:current mixing limits determined from $D^o \to K^+\pi^-$with $5.6 fb^{-1}$ of CLEO-II.V data, column 2: E791 $D^o \to CP^+$ analysis combined with column 1, column 3: Projected sensitivity of Full CLEO-II.V dataset

	CLEO-II.V ($5.6 fb^{-1}$)	CLEO-II.V +E791	CLEO-II.V (Projected) (Final)	RPP98
x	$\lvert x\rvert < .054$	$\lvert x\rvert < .054$	$\lvert x\rvert < .03$	$\lvert x\rvert < .096$
y	$-.108 < y < .027$	$-.042 < y < .027$	$\lvert y\rvert < .01$	$\lvert y\rvert < .10$
R_{ws}	$.31 \pm .09\%$	$.31 \pm .09\%$	$\pm .05\%$	$.72 \pm .25\%$
R_{Mix}	$< 1.1\%$	$< 0.25\%$	$< 0.05\%$	$< 0.5\%$
R_{DCSD}	$0.1 < R_{DCSD} < 1.1\%$	$0.1 < R_{DCSD} < 1.1\%$	-	$< 4.9\%$