STATUS OF $D^0 - \overline{D}^0$ MIXING AND DOUBLY CABIBBO-SUPPRESSED D^0 DECAY RATE MEASUREMENTS

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$D^0 - \overline{D}^0$ mixing occurs when the weak eigenstates of the $D^0 - \overline{D}^0$ system have either masses or widths which differ. Such mixing is predicted to occur at very low levels in the Standard Model, but may occur at rates approaching the current experimental limits in models of physics beyond the Standard Model. The ALEPH experiment has results of a new search for mixing and doubly Cabibbo-suppressed decays using the experimental signature $D^{*+} \to \pi^+ D^0$; $D^0 \to K^+\pi^-$. Their results are compared to earlier results from the E791 and CLEO experiments. E791 has measured the decay rates for $D^0 \to^- K\pi^+$ and for $D^0 \to K^-K^+$ and directly derived a limit on the weak eigenstate width difference. Finally, CLEO 2.5 has acquired new data which promises to produce more sensitive measurements of mixing physics.

1 Introduction

$D^0 - \overline{D}^0$ mixing occurs when the weak eigenstates of the $D^0 - \overline{D}^0$ system have either masses or widths which differ. Such mixing is predicted to occur at very low levels in the Standard Model, but may occur at rates approaching the current experimental limits in models of physics beyond the Standard Model. The ALEPH experiment has results of a new search for mixing and doubly Cabibbo-suppressed decays using the experimental signature $D^{*+} \to \pi^+ D^0$; $D^0 \to K^+\pi^-$. Their results are compared to earlier results from the E791 and CLEO experiments. E791 has measured the decay rates for $D^0 \to K\pi$ and for $D^0 \to KK$ and directly derived a limit on the weak eigenstate width difference. Finally, CLEO 2.5 has acquired new data which promises to produce more sensitive measurements of mixing physics.

1.1 Some Formalism

The time evolution of a D^0 or $\overline{D}^0$ is determined by Schrodinger's Equation:

$$i\frac{\partial}{\partial t}\begin{pmatrix}|D^0\rangle \\ |\overline{D}^0\rangle\end{pmatrix} = \begin{bmatrix} M - i\Gamma/2 & M_{12} - i\Gamma_{12}/2 \\ M_{12}^* - i\Gamma_{12}^*/2 & M - i\Gamma/2 \end{bmatrix}\begin{pmatrix}|D^0\rangle \\ |\overline{D}^0\rangle\end{pmatrix} .$$

With the Hamiltonian written as

$$\mathbf{H} = a\,\mathbf{I} + b_x\,\sigma_\mathbf{x} + b_y\,\sigma_\mathbf{y} + b_z\,\sigma_\mathbf{z},$$
$$CP \Longleftrightarrow \sigma_\mathbf{x} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} .$$

Diagonalizing $\mathbf{H}$, Schrodinger's Equation has solutions of the form $e^{-i\omega t} = e^{-i(m-i\gamma/2)t}$ with eigenvalues

$$m_{H,L} = M \pm Re\left[(M_{12} - i\Gamma_{12})(M_{12}^* - i\Gamma_{12}^*)\right]$$
$$\gamma_{H,L} = \Gamma \mp Im\left[(M_{12} - i\Gamma_{12})(M_{12}^* - i\Gamma_{12}^*)\right]$$

for the "light" and "heavy" eigenstates

$$|D_L\rangle = p\,|D^0\rangle + q\,|\overline{D}^0\rangle$$
$$|D_H\rangle = p\,|D^0\rangle - q\,|\overline{D}^0\rangle$$

with

$$\frac{q}{p} = \frac{1+\epsilon_B}{1-\epsilon_B} = \left(\frac{M_{12}^* - i\Gamma_{12}^*}{M_{12} - i\Gamma_{12}}\right)^{\frac{1}{2}} = e^{2i\phi_M} .$$

We define the following variables which relate to experimental measurements.

$$\Delta m = m_H - m_L\ ; \qquad x = \Delta m/\Gamma$$
$$\Delta\Gamma = \gamma_h - \gamma_L\ ; \qquad y = \Delta\Gamma/2\Gamma$$

1.2 $D^0 - \overline{D}^0$ Mixing and DCSD Rates

Searching for $D^0 - \overline{D}^0$ mixing and/or D^0 doubly Cabibbo-suppressed decays requires knowing the strong eigenstate at birth (production) and again at death (decay). Two approaches have been used experimentally.

- The MARK III experiment[1] searched for mixing using coherent $D^0 - \overline{D}^0$ production at the $\Psi(3770)$. If one D decays as a particle, then the other D can decay to the same final state *only* if it mixes into the particle state.
- Most experiments (including ALEPH, E791, and CLEO) have used the strong decay $D^{*+} \to \pi^+ D^0$ to identify the strong eigenstate at birth.

The strong eigenstate at death can be identified either

- unambiguously – using a semileptonic decay such as $D^0 \to \overline{D}^0 \to K^+\ell^-\nu$, or

- ambiguously – using a hadronic decay such as $D^0 \rightarrow \overline{D}^0 \rightarrow K^+\pi^-$. These Cabibbo-favored decays can be confused with the unmixed doubly Cabibbo-suppressed decays $D^0 \rightarrow K^+\pi^-$, which complicates the search for mixing when using hadronic final states.

The decay to "wrong-sign" final states takes the form[2]

$$\Gamma[D^0(t) \rightarrow f] = e^{-\Gamma t}|\langle f|H|\overline{D}^0\rangle_{\rm CF}|^2 \left|\frac{q}{p}\right|^2$$

$$\times \left[|\lambda|^2 + \tfrac{1}{4}(x^2+y^2)(t/\tau)^2 + (y\Re(\lambda) + x\Im(\lambda))(t/\tau)\right]$$

where
$$\lambda \equiv \frac{p}{q}\frac{\langle f|H|D^0\rangle_{\rm DCS}}{\langle f|H|\overline{D}^0\rangle_{\rm CF}}$$

and we define the following shorthand for use later:

$$r_{\rm dcsd} = |\lambda|^2$$
$$r_{\rm mix} = \tfrac{1}{2}(x^2+y^2)$$
$$r_{\rm int} = (y\Re(\lambda) + x\Im(\lambda))$$

2 Results from the ALEPH Collaboration

The ALEPH Collaboration submitted new results to this conference[3]. The data were extracted from four million Z decays collected in their detector from 1991 - 1995. They used the decay chain $D^{*+} \rightarrow \pi^+ D^0$ to identify the strong eigenstate at birth. They used the decays $D^0 \rightarrow K^-\pi^+$ as normalization, and searched for the decay chains $D^0 \rightarrow \overline{D}^0 \rightarrow K^+\pi^-$ and $D^0 \rightarrow K^+\pi^-$. They identified their signal by selecting D-meson candidates with $|M(K\pi) - M(D^0)| < 30$ MeV/c^2 and looking at the $D^{*+} - D^0$ mass difference distribution $\Delta M = M(K\pi\pi^+) - M(K\pi)$ which has very good resolution. In selecting $K\pi$ candidates, ALEPH required first that only one of the mass hypothesis assignments produced a candidate within the D^0 window considered. Subsequently, they required the dE/dx measured in at least 50 of the 338 layers of the TPC to be consistent with the assigned particle hypotheses. A more complete description of the data selection (and analysis) is available in their publication, from which this discussion has been extracted.

The right- and wrong-sign data from ALEPH are shown in Figs. (1a) and (1b). Within a ΔM window from 143.5 MeV/c^2 to 147.5 MeV/c^2 they find the numbers of right-sign and wrong-sign events to be $N_{\rm RS} = 1038.8 \pm 32.5 \pm 4.4$ and $N_{\rm WS} = 21.3 \pm 6.1 \pm 3.5$ after the combinatorial background is subtracted. Of the 21.3 wrong-sign events, 2.2 ± 1.0 are real physics background events whose proper time distribution is assumed to be exponential with the D^0 lifetime. This leaves a signal of $19.1 \pm 6.1 \pm 3.5$ $K^+\pi^-$ events which result from a combination of $D^0 - \overline{D}^0$ mixing and doubly Cabibbo-suppressed D^0 decays.

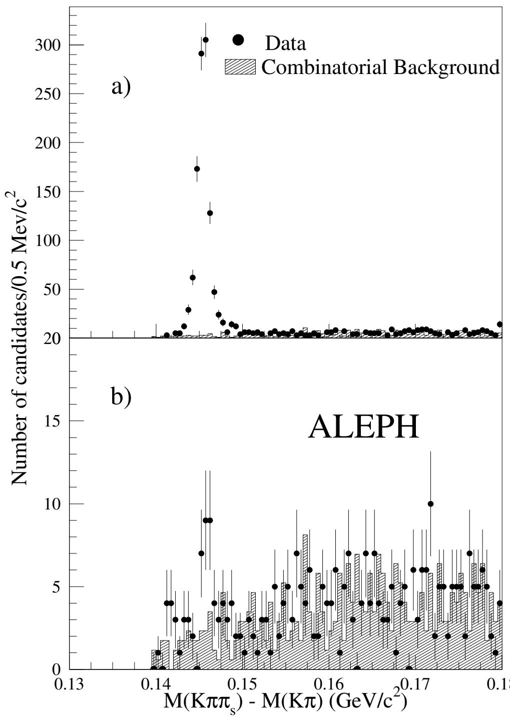

Figure 1: Mass-difference distribution (a) for candidates of the decay channel $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$ and (b) candidates of the decay channel $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^+\pi^-$. The dots with error bars are data while the hatched histogram represents the distribution of the combinatorial background.

The proper time distributions of the mixing and DCSD signals differ, which allows the separation of the two. Assuming small mixing and neglecting CP-violating terms, the time evolution detailed for D^0 decay above becomes

$$N(D^0 \rightarrow K^+\pi^-)(t) \propto$$
$$\left[r_{\rm dcsd} + \sqrt{2 r_{\rm mix} r_{\rm dcsd}}\cos\phi(t/\tau) + \tfrac{1}{2}r_{\rm mix}(t/\tau)^2\right] e^{-t/\tau}$$

The second term describes the interference between the mixing and DCSD amplitudes, and $\cos\phi$ is the phase angle parameterizing this interference.

The proper decay time of a D^0 candidate is calculated from the distance between the primary vertex and the D^0 decay vertex projected along the direction of the flight of the D^0, using the reconstructed momentum and mass of the candidate. The average resolution of the proper decay time is ≈ 0.1 ps and is dominated by the uncertainty of the D^0 vertex ($\approx 40\mu$m). The distribution of proper time in the signal region for the wrong-sign sample is shown in Fig. 2a and for the right-sign sample

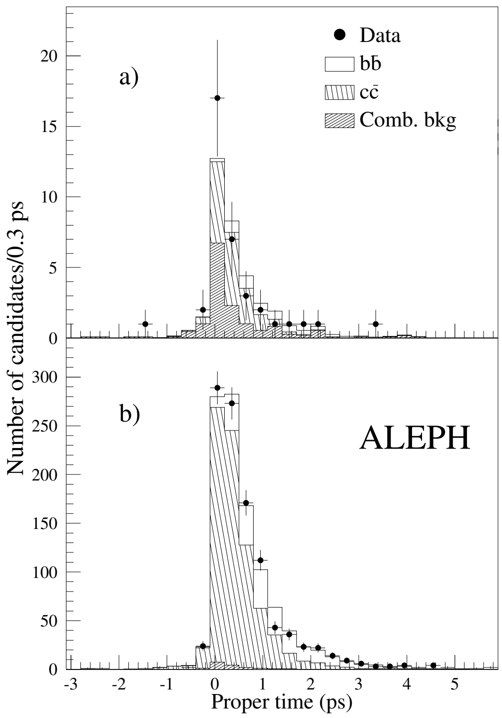

Figure 2: Proper time distribution for (a) the $D^0 \to K^+\pi^-$ candidates, and (b) for the $D^0 \to K^-\pi^+$ candidates. The dots with error bars are the data. The histograms are the contributions of $c\bar{c}$, $b\bar{b}$, and background events resulting from the unconstrained fit when no interference between the mixing and DCSD amplitudes is assumed.

is shown in Fig. 2b. The data are indicated as dots with error bars. The histograms indicate the contributions from $c\bar{c}$ events, $b\bar{b}$ events, and background events, determined using a binned maximum likelihood fit. The direct $c\bar{c} \to D^0X$ fraction (rather than the $b\bar{b} \to c\bar{c} \to D^0X$) is found to be $(77.0 \pm 2.7 \pm 0.5)\%$ in fitting the right-sign sample. The background in the wrong-sign sample is a sum of combinatorial background, whose proper time dependence is measured in the data from the side band regions in the ΔM plot, and a physics background contribution whose proper time distribution is assumed to be exponential with a decay constant given by the D^0 lifetime.

Fitting the proper time distribution of the wrong-sign sample with the interference term set to zero ($\cos\phi = 0$), gives $N_{\rm dcsd} = 20.8^{+8.4}_{-7.4} \pm 4.0$ and $N_{\rm mix} = -2.0 \pm 4.4 \pm 1.1$. The fitted value of $N_{\rm mix}$ is outside the physical region, implying that no mixing is observed. The 95% CL upper limit on the number of mixed events is found to be $N_{\rm mix} < 9.6$, from which the mixing limit is found to be $r_{\rm mix} < 0.92\%$ at the 95% CL. Setting $N_{\rm mix} = 0$, the doubly Cabibbo-supressed decay rate for $D^0 \to K^+\pi^-$ is found to be $r_{\rm dcsd} = (1.77^{+0.60}_{-0.56} \pm 0.31)\%$.

The effect of interference was studied by fitting the data with fully constructive ($\cos\phi = +1$) and fully destructive ($\cos\phi = -1$) interference. The respective upper limits were found to be $r_{\rm mix} < 0.96\%$ at the 95% CL and $r_{\rm mix} < 3.6\%$ at the 95% CL.

These results can be compared with previously published results from other experiments. CLEO measured the rate of right-sign and wrong-sign $D^0 \to K\pi$ events with no decay-time information. Assuming no mixing, they reported[4] $r_{\rm dcsd} = (0.77 \pm 0.25 \pm 0.25)\%$. E791 searched for right- and wrong-sign D^0 decays to $K\pi$ and $K\pi\pi\pi$[5]. Assuming no mixing, they reported $r_{\rm dcsd} = (0.68^{+0.34}_{-0.33} \pm 0.07)\%$ for the $K\pi$ final state. Allowing full interference between mixing and DCSD amplitudes, and allowing CP violation in the interference term but not allowing CP violation in the mixing or DCSD terms themselves, they reported $r_{\rm mix} < 0.85\%$ at the 90% CL. From a mixing analysis using semileptonic D^0 decays[6] rather than hadronic D^0 decays (which eliminates the DCSD amplitudes and the possibility of their interfering with mixing amplitudes), E791 reported $r_{\rm mix} < 0.50\%$ at the 90% CL.

3 E791's Direct Measurement of $\Delta\Gamma$

Fermilab experiment E791 has studied the reduced proper lifetime distributions of a $D^0 \to K^-K^+$ sample and of a $D^0 \to K^-\pi^+$ sample selected from the same data set using very similar criteria. Assuming that the weak eigenstates are CP even and odd, and that the $D^0 \to K^-\pi^+$ decay is an equal CP admixture, the width difference can be extracted directly:

$$\begin{aligned}\Gamma(D^0 \to K^-K^+) - \Gamma(D^0 \to K^-\pi^+)& \\ \approx \Gamma_1 - \tfrac{1}{2}(\Gamma_1 + \Gamma_2)& \\ = \tfrac{1}{2}(\Gamma_1 - \Gamma_2)& \\ = \tfrac{1}{2}\Delta\Gamma&\end{aligned}$$

To determine $\Delta\Gamma$ experimentally, one may either measure $\Gamma(D^0 \to K^-K^+)$ and $\Gamma(D^0 \to K^-\pi^+)$ separately and then take the difference, or one may directly compare the number of decays observed at any decay time. This latter procedure tends to reduce the effect of common systematic uncertainties in reconstruction acceptance $\times$ efficiency. In any bin of reduced proper lifetime,

$$n(D^0 \to K^-K^+) = A_{KK}\, e^{-\Gamma_1 t}$$

$$n(D^0 \to K^-\pi^+) = A_{K\pi}\, e^{-\frac{1}{2}(\Gamma_1+\Gamma_2)t}$$

$$\Rightarrow \ln\left[\frac{n(D^0 \to K^-K^+)}{n(D^0 \to K^-\pi^+)}\right] = \ln\left(\frac{A_{KK}}{A_{K\pi}}\right) - \frac{\Delta\Gamma}{2}t$$

Thus, the slope of the logarithm of the ratio of the number of $D^0 \to K^-K^+$ events compared to the number of $D^0 \to K^-\pi^+$ events as a function of reduced proper lifetime is directly proportional to $\Delta\Gamma$.

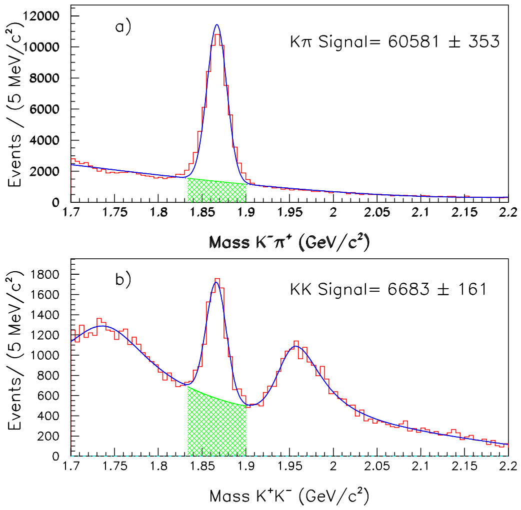

Figure 3: (a) The $D^0 \to K^-\pi^+$ sample used in E791's $\Delta\Gamma$ measurement; (b) $D^0 \to K^-K^+$ sample used in E791's $\Delta\Gamma$ measurement;

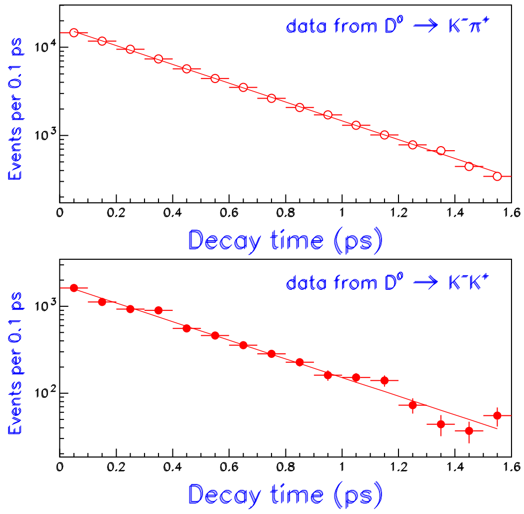

Figure 4: (a) The reduced proper decay time distribution for E791's $D^0 \to K^-\pi^+$ data, weighted for acceptance. (b) The reduced proper decay time distribution for E791's $D^0 to K^-K^+$ data, corrected for Čerenkov efficiency and weighted for acceptance.

The value of (limit on) y determined from this measurement can be compared to the limit on y extracted from the most stringent limit on $r_{\rm mix}$, that reported by E791 from its search for mixing using semileptonic D^0 decays:

$$r_{\rm mix} = \frac{1}{2}(x^2 + y^2) < 0.50\%$$
$$\Rightarrow y < 0.1$$

The $D^0 \to K^-\pi^+$ and $D^0 \to K^-K^+$ samples used for this analysis are shown in Figs. 3a and 3b. Similar plots are created for each bin of reduced proper decay time (using the length beyond the minimum required to survive the analysis selection criteria). Because Čerenkov identification was used to improve the statistical significance of the $D^0 \to K^-K^+$ signal, each $D^0 \to K^-K^+$ event was weighted to correct for efficiency. In addition, the net signal in each bin of reduced proper decay time was corrected for acceptance. Assuming *CP* conservation, the K^-K^+ final state is an even eigenstate, and the decay $D^0 \to K^-K^+$ is exactly exponential. The decay $D^0 \to K^-\pi^+$ is a superposition of two exponentials with very similar decay constants. The difference between the components is small enough (based on previously measured limits on $r_{\rm mix}$) that fitting the $D^0 \to K^-\pi^+$ reduced proper decay time distribution as a single exponential will produce a very good estimate of the average of the two inverse lifetimes. Accordingly, the distributions of the net signals as functions of reduced proper decay time, shown in Figs. 4a and 4b, were fit as exponentials. The inverse lifetimes were found to be Γ [for $D^0 \to K\pi$] = (2.456 ± 0.018) ps^{-1} and Γ [for $D^0 \to KK$] = (2.472 ± 0.066) ps^{-1} where the errors are statistical only. The corresponding lifetimes are $\tau = (0.407 \pm 0.003)$ ps [for $D^0 \to K\pi$] and $\tau = (0.404 \pm 0.011)$ ps [for $D^0 \to KK$]. The final systematic errors are expected to be roughly equal to the statistical errors for the $D^0 \to K\pi$ measurement. For comparison, the Particle Data Group[7] reports $\tau(D^0) = 0.415 \pm 0.004$ ps.

The decay width difference was determined directly by comparing the numbers of $D^0 \to K^-K^+$ and $D^0 \to K^-\pi^+$ events, after the corrections described above, in bins of reduced proper decay time. Fitting the ratio, the error on the slope gives $\Delta\Gamma = (-0.022 \pm 0.073)$ ps^{-1} (statistical error only). From this, one finds, $y = \Delta\Gamma/(2\Gamma) = -0.005 \pm 0.015 \pm$ syst. The final systematic error is expected to be approximately the same size as the statistical error. It thus appears that the constraint on $\Delta\Gamma$ from this direct measurement will be significantly more stringent than those from mixing measurements to date.

4 First data from CLEO 2.5

CLEO 2.5 is currently (September, 1998) taking data. They had 6 fb^{-1} of data on tape at the time of the conference (late July, 1998), of which 4 fb^{-1} had been skimmed and examined. They expect $8-9$ fb^{-1} by the end of the run. Some charm data is shown in Figs. 6 and 7.

The horizontal and vertical beam resolutions are $\sigma_x \approx 350\mu$m and $\sigma_y \approx 10\mu$m. The plots show very good signals for D^0 from $D^{*+} \to \pi^+, D^0$ which can be used for mixing/DCSD and lifetime difference studies. To improve mass resolutions, the D^0 momentum vectors

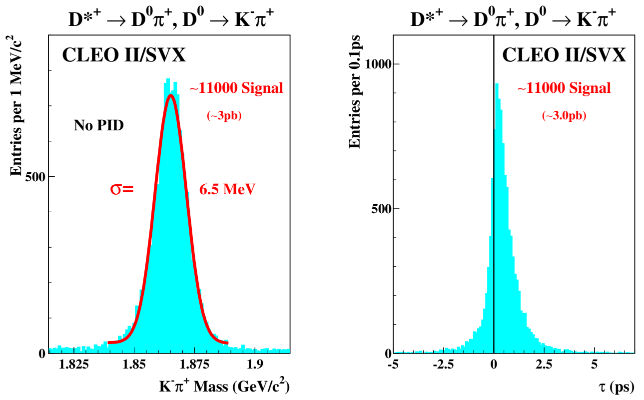

Figure 5: The $D^0 \to K^-\pi^+$ signal from 4 fb^{-1} of data, requiring ΔM consistent with $D^{*+} \to \pi^+ D^0$, on the left. The proper decay time distribution for these events, on the right.

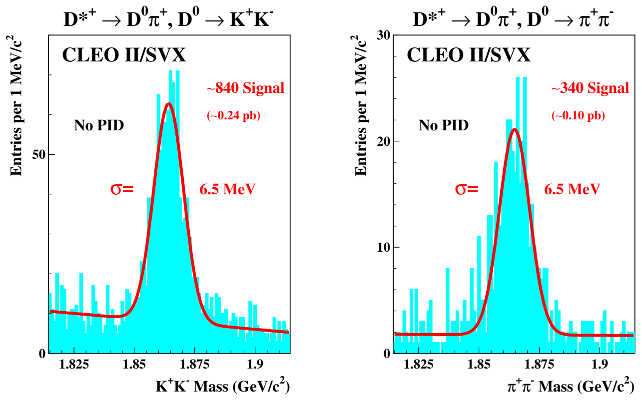

Figure 6: The $D^0 \to K^-K^+$ signal from 4 fb^{-1} of data, requiring ΔM consistent with $D^{*+} \to \pi^+ D^0$, on the left. The $D^0 \to \pi^-\pi^+$ signal from 4 fb^{-1} of data, requiring ΔM consistent with $D^{*+} \to \pi^+ D^0$, on the right.

were intersected with the beam "ribbon" to constrain the primary vertex point (giving σ(separation) $\approx 100\mu$m). The slow pion momenta were then refit, which improved the ΔM resolution by better than a factor of 2 giving $\sigma(\Delta M) \approx 250$ MeV$/c^2$.

In studying $D^0 \to K^-\pi^+$, the D^{*+} momentum was required to be greater than 1.5 GeV$/c$. The plot on the left-hand side of Fig. 5 shows a clean signal of approximately 11,000 events after requiring $|\Delta M| < 500$ keV$/c^2$. Approximately 90% of the signal comes from $c\bar{c}$ events and 10% from $b\bar{b}$ events. The decay time distribution of these D^0's is shown in the plot on the right-hand side of Fig. 6. This extrapolates to $\approx 25,000$ events for the full run which can be compared to ≈ 1000 from ALEPH and ≈ 5000 from E791.

Fig. 6 shows clean $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ signals, again originating from $D^{*+} \to \pi^+ D^0$. For these samples, the D^{*+} momentum was required to be greater than 1.5 GeV$/c$, and essentially 100% of the signal comes from $c\bar{c}$ events. The 840 event $D^0 \to K^-K^+$ signal extrapolates to ≈ 1800 clean events for the full run. This can be compared to $N_{\rm eff}$ $[\equiv (\mathcal{S}/\sigma)^2]$ ≈ 1700 from E791 (which does not require the D^0 to come from a D^{*+} for its lifetime difference analysis). If CLEO chooses to combine its $D^0 \to K^-K^+$ and its $D^0 \to \pi^-\pi^+$ data for a lifetime difference study (both are CP-even eigenstates), the sample will be 40% larger. And it should be possible to increase the sample again by using D^0's which are not D^{*+} decay products.

It is also worth noting that the CLEO 2.5 signals shown here used no particle identification. Altogether, CLEO 2.5 should have significantly improved measurements of $D^0 - \overline{D}^0$ mixing and DCSD rates and very competitive direct measurements of $\Delta\Gamma$.

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