Status of $D^0 - \overline{D}^0$ mixing and doubly Cabibbo-suppressed D^0 decay rate measurements

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special thanks to : Arun Tripathi (E791)
Guy Blaylock (E791)
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Michael Hosack (E831/FOCUS)

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From flavor eigenstates to weak eigenstates

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

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

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 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

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

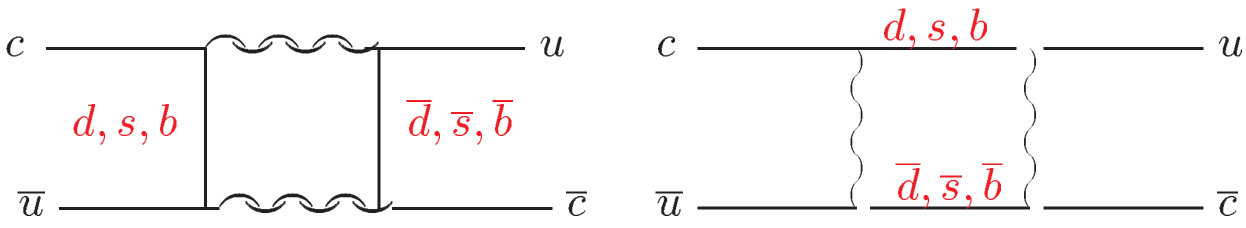
with which we define the mixing rate:

$$r_{\text{mix}} = \frac{1}{2}(x^2 + y^2)$$

From flavor eigenstates to weak eigenstates

From second order perturbation theory:

$$\Delta M \propto \sum_I \frac{\langle \overline{D^0} | H_W | I \rangle \langle I | H_W | D^0 \rangle}{|m_D^2 - m_I^2 + i\epsilon|}$$



These are the Standard Model box diagrams for short distance amplitudes which contribute to $D^0 - \overline{D}^0$ mixing

- In the Standard Model, $r_{\rm mix} < \mathcal{O}(10^{-8})$.
- New physics allows $r_{\rm mix}$ close to the current experimental limits. Possibilities include
  – multiple scalar doublets ($M_H \sim$ 1 TeV)
  – fourth generation of quarks
  – supersymmetry with quark-squark alignment
  – light scalar leptoquarks ($M_{\rm LQ} \leq 2$ TeV)

$D^0 - \overline{D^0}$ mixing and DCSD rates

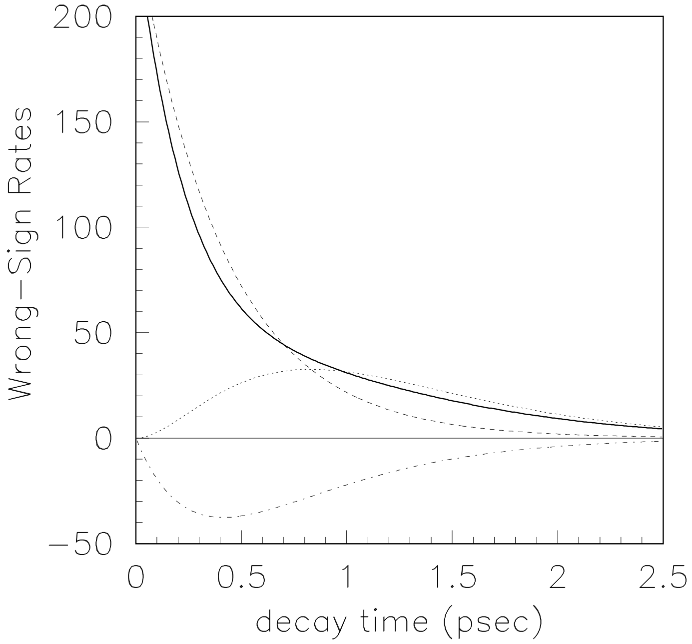
Searching for $D^0 - \overline{D^0}$ mixing and/or D^0 doubly Cabibbo-suppressed decays requires knowing the strong eigenstate at birth (production) and again at death (decay). Two approaches have been used experimentally.

- The MARK III experiment 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, CLEO, and E831) have used the slow pion from 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 $\overline{D^0} \to K^+ \ell^- \nu$, or
- ambiguously – using a hadronic decay such as $\overline{D^0} \to K^+ \pi^-$. These Cabibbo-favored decays can be confused with the doubly Cabibbo-suppressed decays $D^0 \to K^+ \pi^-$, which complicates the search for mixing when using hadronic final states.

DCSD-Mixing Interference



from Blaylock, Seiden, and Nir, Phys. Lett. **B355** (1995) 555-560: A hypothetical plot of the time dependence of wrong-sign decays. The dashed line represents the DCS contribution. The dotted line shows the contribution due to mixing. The dash-dot line shows the contribution from DCS-mixing interference when the interference is 30% of its maximum possible amplitude and destructive. The solid line is the sum of all three contributions. The vertical scale is arbitrary.

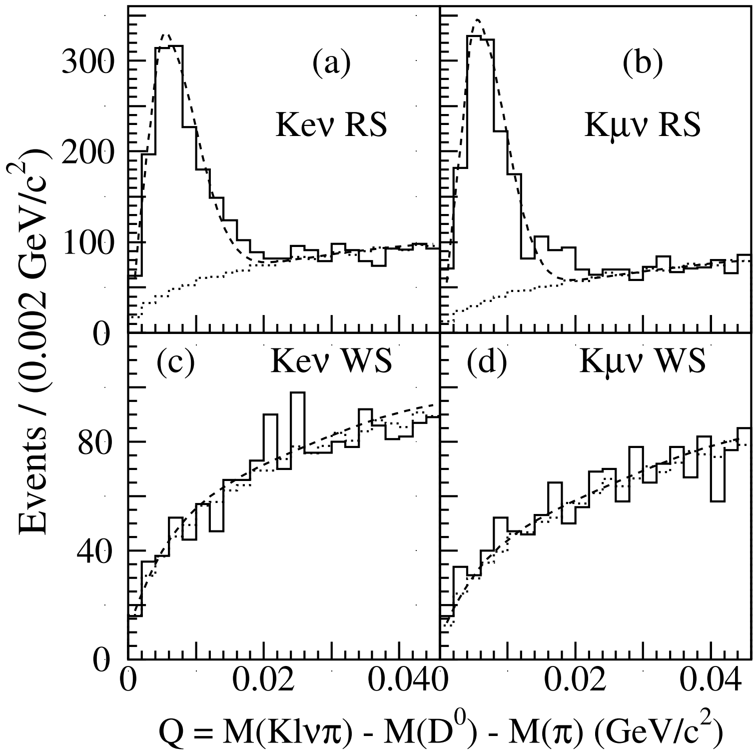
$$\Gamma[D^0(t) \to f] = e^{-\Gamma t} |\langle f|H|\overline{D^0}\rangle_{\mathrm{CF}}|^2 \left|\frac{q}{p}\right|^2$$
$$\times \left[|\lambda|^2 \;+\; \tfrac{1}{4}(x^2+y^2)(t/\tau)^2 \;+\; \left(y\Re(\lambda) \;+\; x\Im(\lambda)\right)(t/\tau)\right]$$

where

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

E791 Semileptonic Mixing Data Samples

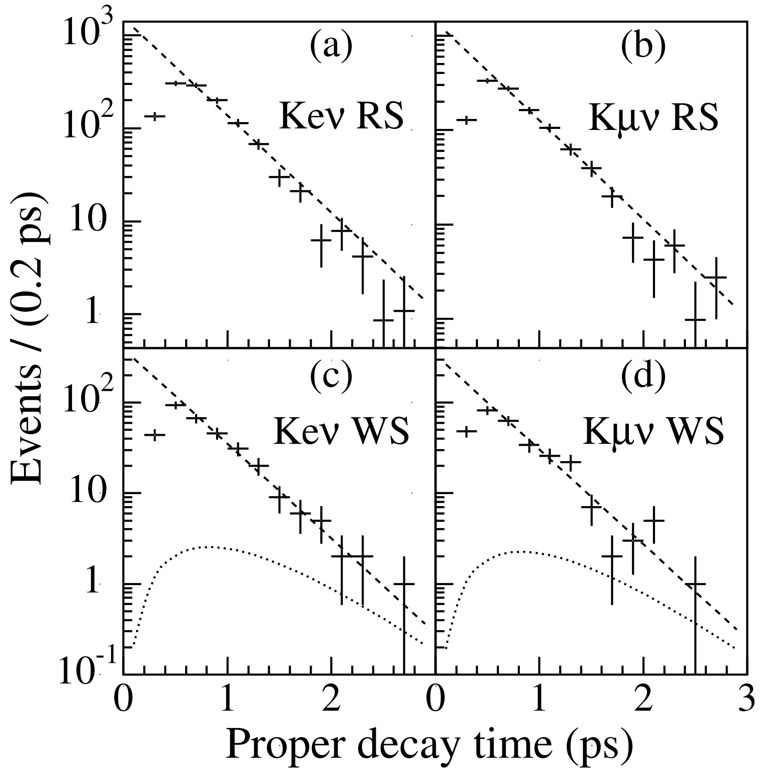
E.M. Aitala *et al.*, Phys. Rev. Lett. **77**, 2384 (1996)



- 2×10^{10} events, 500 GeV/c $\pi^- N$ interactions
- 5 foil targets, 1.5 mm gaps
- require
  - decay vertices in gaps
  - 8σ vertex separation
  - $1.15 \text{ GeV}/c^2 < M(K\ell) < 1.80 \text{ GeV}/c^2$
  - $1.6 \text{ GeV}/c^2 < M_{\min}(K\ell\nu) < 2.1 \text{ GeV}/c^2$
- use "event-mixing" to model background shape in Q

E791 Semileptonic Mixing Fit Results

E.M. Aitala *et al.*, Phys. Rev. Lett. **77**, 2384 (1996)



- Unbinned maximum likelihood fits for the $Ke\nu$ and $K\mu\nu$ samples, using the Q-value and proper decay time values, give

  $Ke\nu$ $N_{\rm RS} = 1237 \pm 45$; $N_{\rm mix} = 4.4^{+11.8}_{-10.5}$

  $K\mu\nu$ $N_{\rm RS} = 1267 \pm 44$; $N_{\rm mix} = 1.8^{+12.1}_{-11.0}$

- accounting for detector acceptance as a function of proper decay time and for different mixed and unmixed decay distributions

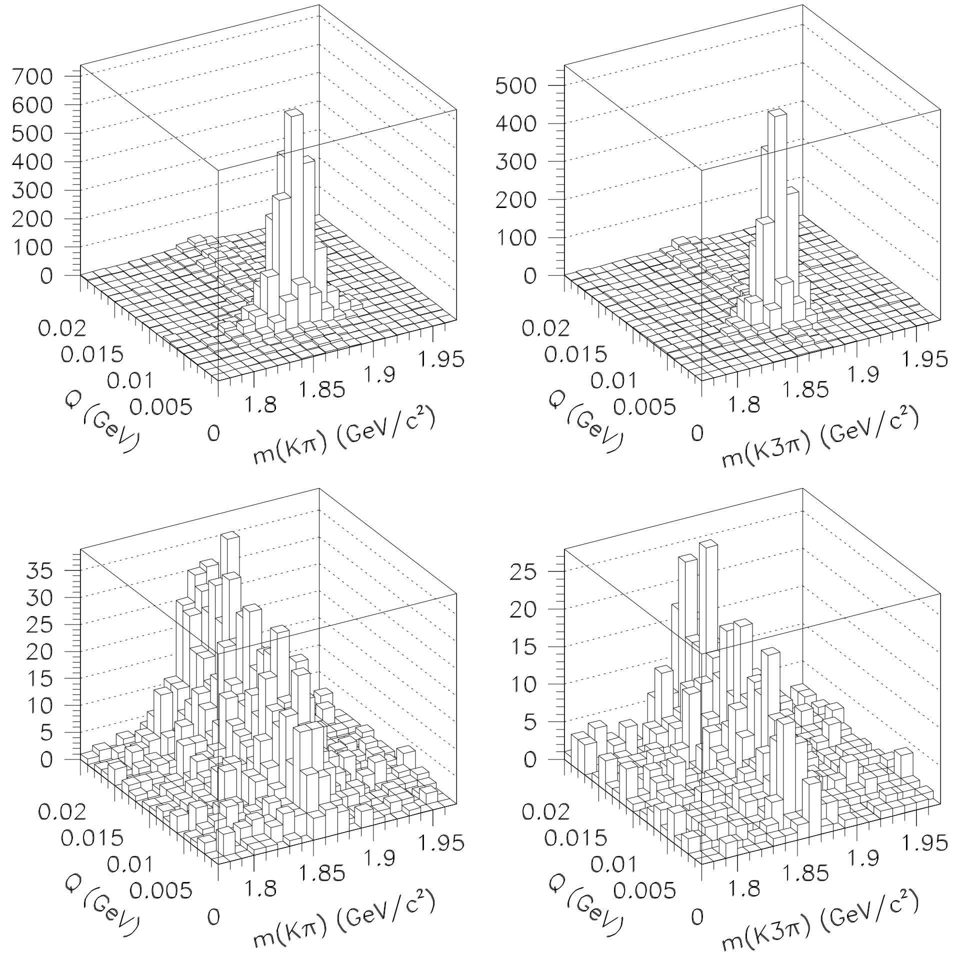
  $Ke\nu$ $r_{\rm mix} = (0.16^{+0.42}_{-0.37})\ \%$

  $K\mu\nu$ $r_{\rm mix} = (0.06^{+0.44}_{-0.40})\ \%$

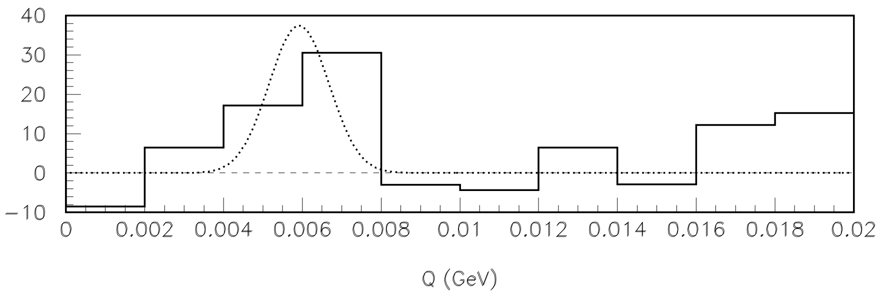
- combining these gives
  - $r_{\rm mix} = (0.11^{+0.30}_{-0.27})\ \%$
  - $r_{\rm mix} < 0.50\%$ at the 90% CL

E791 Hadronic Mixing Data Samples

E.M. Aitala *et al.*, Phys. Rev. **D 57**, 13 (1998)



The lego plots above show the right-sign (top) and wrong-sign (bottom) data samples used in E791's hadronic mixing analysis. The plot below shows the Q-value distribution for wrong-sign $D \rightarrow K\pi$ candidates in the $K\pi$ mass range 1.845 - 1.885 GeV$/c^2$. The plot has been background-subtracted using the fit with no mixing. The Gaussian overlay shows the size of the signal attributed to DCS decays by the fit.



E791 Hadronic Mixing Fit Results

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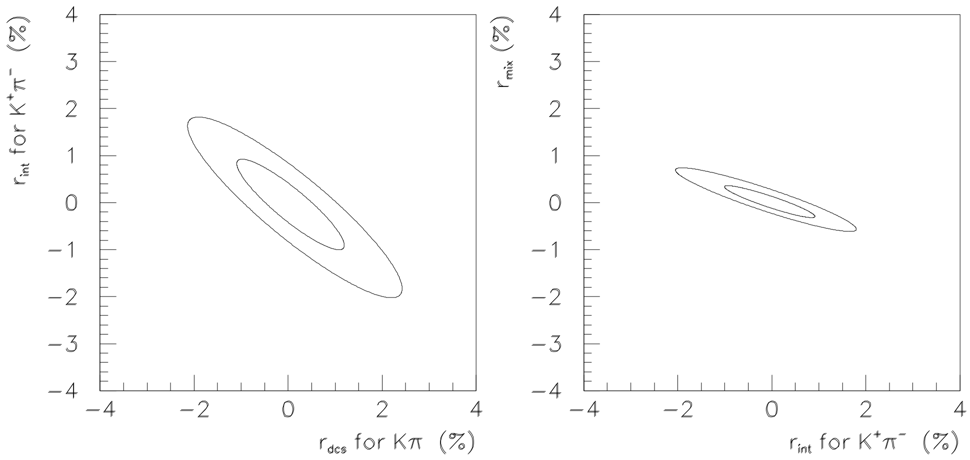
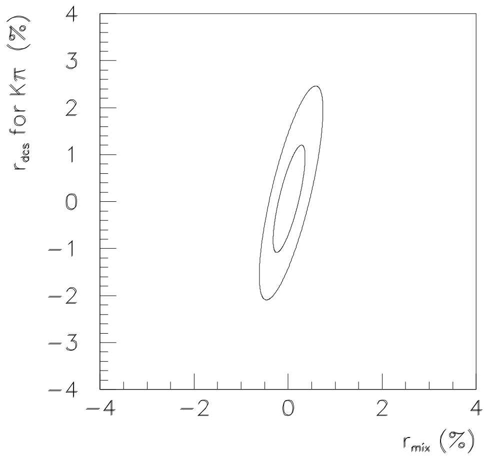




These likelihood contours correspond to $\Delta\ln\mathcal{L} = 0.5$ and 2.0 for the fit with CP violation in the interference term only. They illustrate the correlations among the three parameters $r_{\rm DCS}(K\pi)$, $r_{\rm mix}$, and $r_{\rm int}(K\pi)$.

- Standard Model $\Rightarrow R_{\rm mix} < 10^{-7}$
- $R_{\rm mix} \gg 10^{-7} \Rightarrow$ new physics with CP violation
- new physics probably produces CP violation via the interference term only, in which case
  - $r_{\rm DCS}(D^0 \rightarrow K^+\pi^-) = r_{\rm DCS}(\overline{D^0} \rightarrow K^-\pi^+)$
  - $r_{\rm DCS}(D^0 \rightarrow K^+\pi^+\pi^-\pi^-) = r_{\rm DCS}(\overline{D^0} \rightarrow K^-\pi^-\pi^+\pi^+)$
  - $r_{\rm mix}(D^0 \rightarrow \overline{D^0}) = r_{\rm mix}(\overline{D^0} \rightarrow D^0)$

E791 $D^0 - \overline{D}^0$ mixing and DCSD results

from semileptonic D^0 decays

E.M. Aitala *et al.*, Phys. Rev. Lett. **77**, 2384 (1996)

$$\begin{aligned} Ke\nu:&\quad N_{\rm RS} = 1237 \pm 45, \quad N_{\rm mix} = 4.4^{+11.8}_{-10.5} \\ K\mu\nu:&\quad N_{\rm RS} = 1267 \pm 44, \quad N_{\rm mix} = 1.8^{+12.1}_{-11.0} \end{aligned}$$

$$\Rightarrow r_{\rm mix} = (0.11^{+0.30}_{-0.27})\%$$

$$\Rightarrow r_{\rm mix} < 0.50\% \text{ at the } 90\% \text{ CL}$$

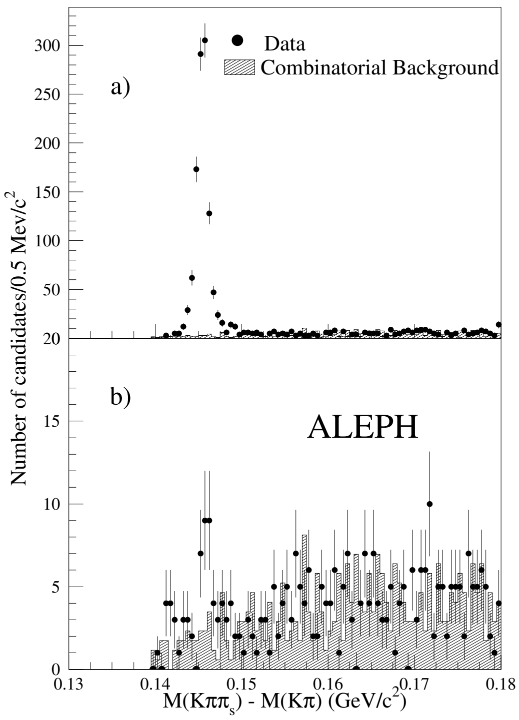
from hadronic D^0 decays

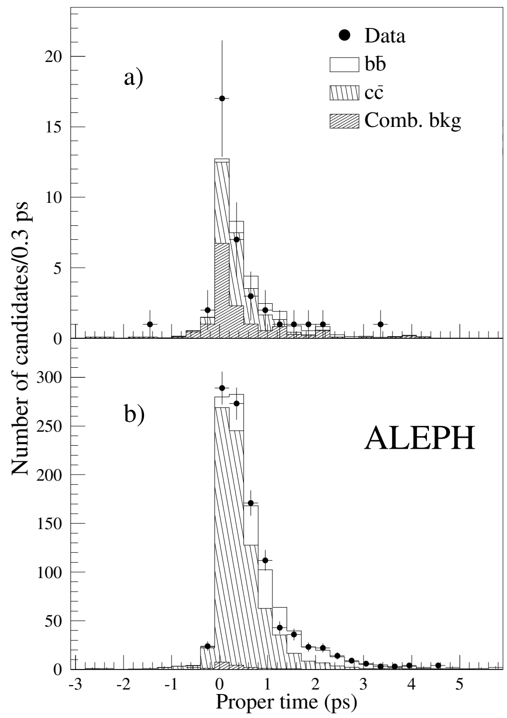
E.M. Aitala *et al.*, Phys. Rev. **D57**, 13 (1998)

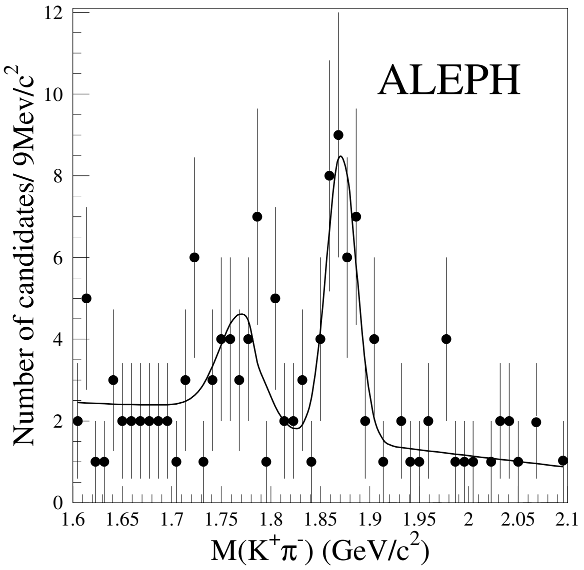
$$\begin{aligned} D^0 \to K^-\pi^+ &: \quad 2269 \pm 49 \\ \overline{D}^0 \to K^+\pi^- &: \quad 2966 \pm 56 \\ D^0 \to K^-\pi^-\pi^+\pi^+ &: \quad 1314 \pm 42 \\ \overline{D}^0 \to K^+\pi^+\pi^-\pi^- &: \quad 1677 \pm 42 \end{aligned}$$

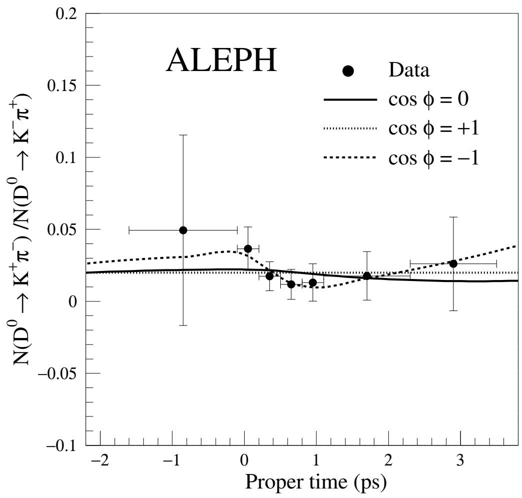
Fit type	fit result	90% CL upper limit
CP violation only in interference term	$r_{\rm mix} = (0.39^{+0.36}_{-0.32} \pm 0.16)\%$	$r_{\rm mix} < 0.85\%$
Most general, no CP assumptions	$r_{\rm mix}(\overline{D}^0 \to D^0) = (0.18^{+0.43}_{-0.39} \pm 0.17)\%$ $r_{\rm mix}(D^0 \to \overline{D}^0) = (0.70^{+0.58}_{-0.53} \pm 0.18)\%$	
No CP violation, no interference	$r_{\rm mix} = (0.21^{+0.09}_{-0.09} \pm 0.02)\%$	
No mixing	$r_{\rm dcsd}(K\pi) = (0.68^{+0.34}_{-0.33} \pm 0.07)\%$ $r_{\rm dcsd}(K\pi\pi\pi) = (0.25^{+0.36}_{-0.34} \pm 0.03)\%$	

Aleph Data from 1991 - 1995









Mixing and DCSD results from Aleph – 1

from 4×10^6 hadronic Z decays,

require $|M(K\pi) - M(D^0)| < 30$ MeV$/c^2$, no ambiguity without particle id, and TPC dE/dx from at least 50 / 338 layers consistent with particle hypotheses.

count the number of events with 143.5 MeV$/c^2 < \Delta M <$ 147.5 MeV$/c^2$.

subtract the ***combinatorial background*** estimated from the D^0 sideband with $M(K\pi) > 2.1$ GeV$/c^2$.

$$\Rightarrow N_{\mathrm{RS}} = 1038.8 \pm 32.5 \pm 4.3$$

$$\Rightarrow N_{\mathrm{WS}} = 21.3 \pm 6.1 \pm 3.4$$

estimate 2.2 ± 1.0 ***physical background*** wrong-sign events.

$$\Rightarrow N_{K^+\pi^-} = 19.1 \pm 6.1 \pm 3.5$$

If no mixing, then

$$\Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+) = (1.84 \pm 0.59 \pm 0.34)\%$$

If the wrong-sign decay time distribution is fit assuming DCSD and mixing amplitudes, ***but no interference*** (including 0.1 ps resolution),

$$\Rightarrow N_{\mathrm{DCSD}} = 20.8^{+8.4}_{-7.4} \pm 4.0$$

$$\Rightarrow N_{\mathrm{mix}} = -2.0 \pm 4.4 \pm 1.1$$

Mixing and DCSD results from Aleph – 2

constrain $N_{\rm mix}$ to be postive,

$$\Rightarrow N_{\rm DCSD} = 18.4^{+6.2}_{-5.8} \pm 3.2$$

$$\Rightarrow N_{\rm mix} = 0^{+3.0\ +1.4}$$

which translates to

$$r_{\rm dcsd} = (1.77^{+0.60}_{-0.56} \pm 0.31)\%$$

$$r_{\rm mix} < 0.92\% \text{ at } 95\% \text{ CL}$$

Assuming ***fully destructive interference*** between the mixing and DCSD amplitudes,

$$r_{\rm mix} < 3.6\% \text{ at } 95\% \text{ CL}$$

Nota Bene: even this last fit assumes CP invariance.

Measuring $\Delta\Gamma$ directly

- $D^0 \to K^- K^+$ is a CP eigenstate
- $D^0 \to K^- \pi^+$ is a CP mixture

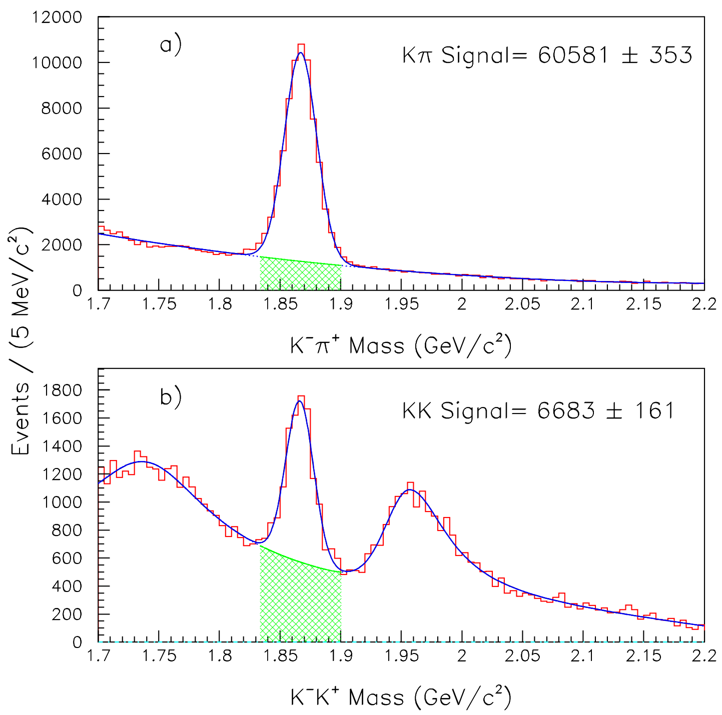
Assuming that the weak eigenstates are CP even and odd, and that the $D^0 \to K\pi$ decay is an even mixture:

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

To determine $\Delta\Gamma$ experimentally, E791 measures $\Gamma(D^0 \to K^+ K^+)$ and $\Gamma(D^0 \to K^- \pi^+)$ separately and then takes the difference. The signals are measured in bins of reduced proper lifetime and corrected for detection efficiency. The value of (limit on) $|y|$ determined from this measurement can be compared to that extracted from the limit on $r_{\rm mix}$:

$$\frac{1}{2}(x^2 + y^2) < 0.50\%$$

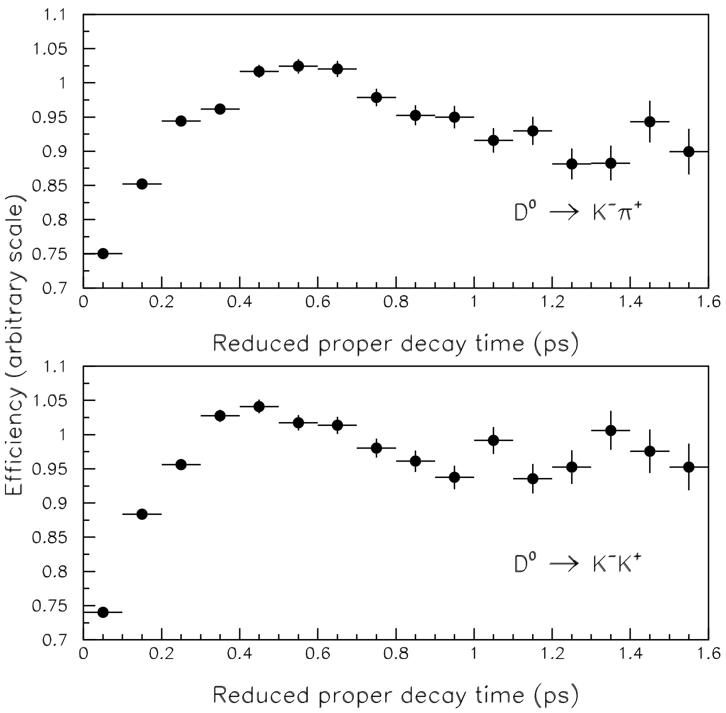
$$\Rightarrow |y| < 0.1$$



$D^0 \to K\pi$
$\approx 35,400$ events
60581 ± 353 weighted
172σ

$D^0 \to KK$
≈ 3200 events
6683 ± 161 weighted
42σ

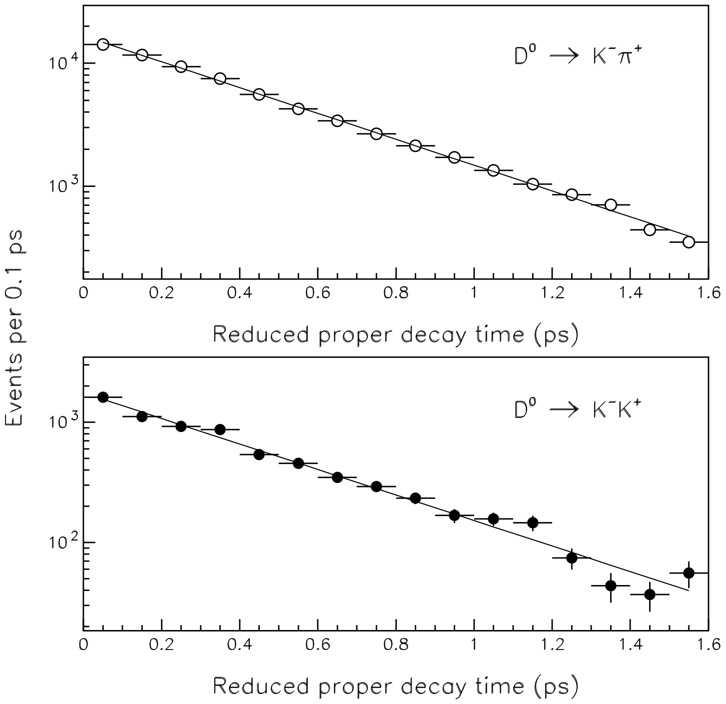
E791 D^0 Lifetime Measurements



$D^0 \to K^-\pi^+$ (CP mix)
relative efficiencies

from Monte Carlo

$D^0 \to K^-K^+$ (CP even)
relative efficiencies



$D^0 \to K^-\pi^+$ (CP mix)
$\Gamma = (2.420 \pm 0.019)$ ps^{-1}
$\tau = (0.413 \pm 0.003)$ ps

statistical errors only

$D^0 \to K^-K^+$ (CP even)
$\Gamma = (2.441 \pm 0.068)$ ps^{-1}
$\tau = (0.410 \pm 0.011)$ ps

PDG98: $\tau(D^0) = (0.415 \pm 0.004)$ ps

E791 D^0 Lifetime Measurements

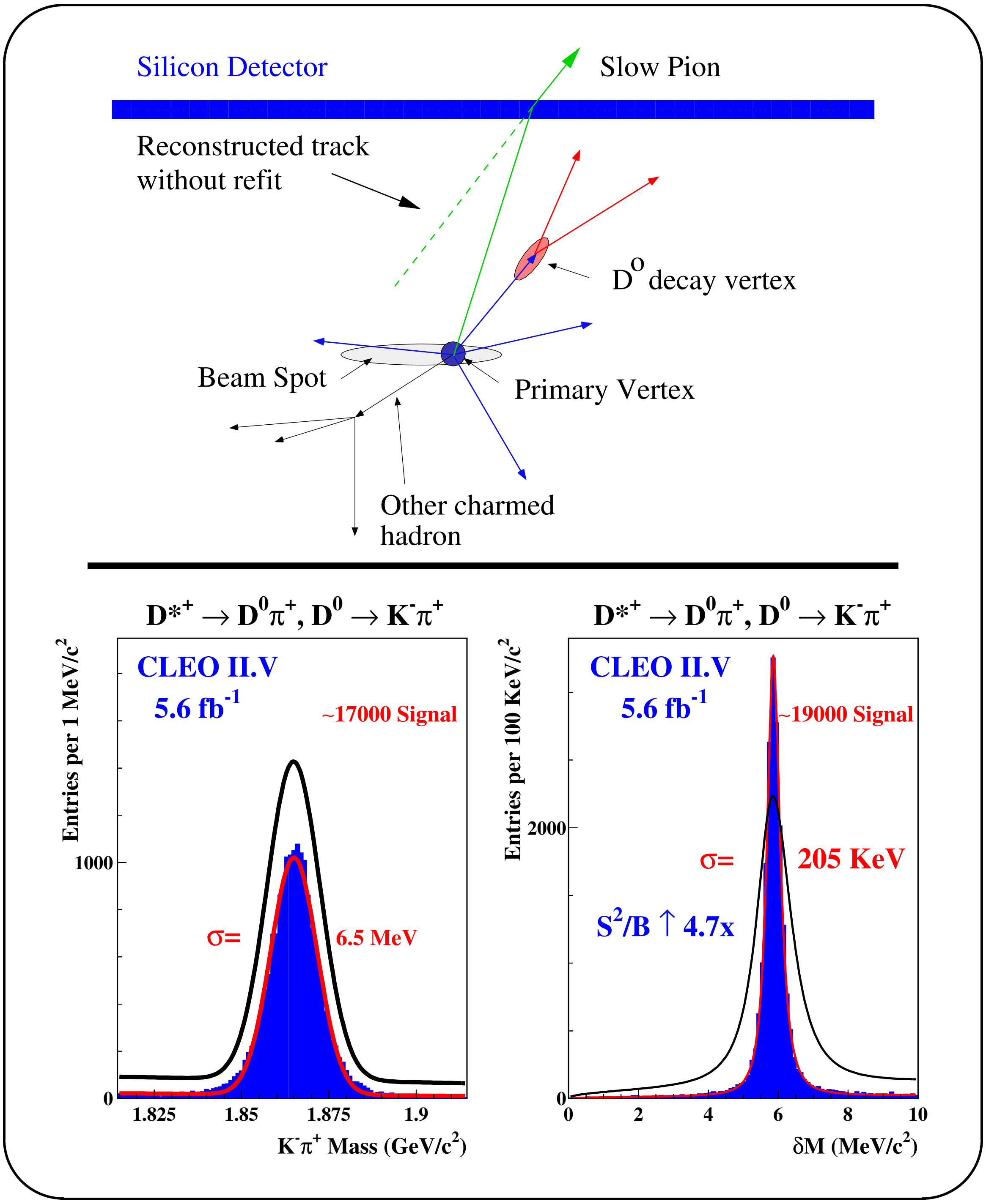
Systematic error in	$\tau_{K\pi}$ (ps)	τ_{KK} (ps)	$\Delta\Gamma$ (ps^{-1})
Fit Range	0.002	0.003	0.024
Selection Criteria	0.001	0.002	0.020
Particle ID Weighting	0.001	0.003	0.024
MC Production Model	0.003	0.003	0.000
Fixed Width	0.001	0.002	0.030
Total	0.004	0.006	0.050

- $\Delta\Gamma = 2\left[\Gamma(D^0 \to KK) - \Gamma(D^0 \to K\pi)\right]$
  $= (0.04 \pm 0.14 \pm 0.05)\ \text{ps}^{-1}$
  $\Rightarrow -0.20\ \text{ps}^{-1} < \Delta\Gamma < 0.28\ \text{ps}^{-1}$ at the 90% CL
- or, equivalently,
  $y = 0.008 \pm 0.029 \pm 0.010$
  $\Rightarrow -0.04 < y < 0.06$ at the 90% CL
- which can be compared to $|y| < 0.1$ derived from $r_{\text{mix}} < 0.50\%$

	$\tau_{K\pi}$ (ps)	τ_{KK} (ps)
E791	$0.413 \pm 0.003 \pm 0.004$	$0.410 \pm 0.011 \pm 0.006$
E687	$0.413 \pm 0.004 \pm 0.003$	—
E691	$0.422 \pm 0.008 \pm 0.010$	—
PDG	0.415 ± 0.004	—

CLEO II.5 Preliminary Data from 5.6 fb^{-1}

D. Asner CLEO 5



LLWI February 14-20, 1999

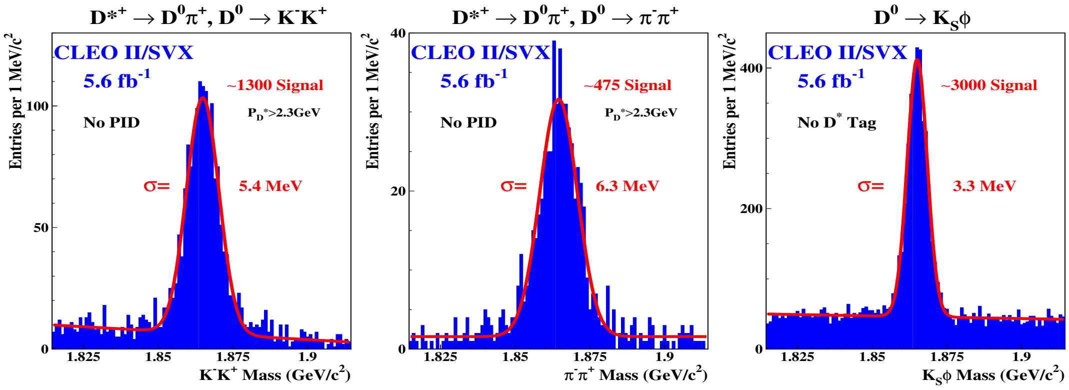
courtesy of David Asner

CLEO II.5 Preliminary Data from 5.6 fb^{-1}

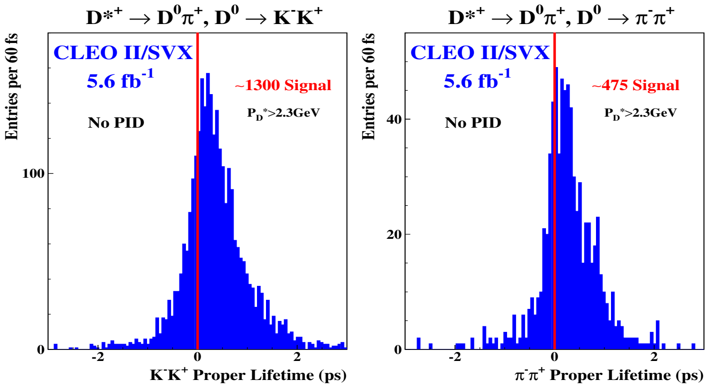
Lifetime Analysis $\mathrm{CP}^+, \mathrm{CP}^-, \overline{\mathrm{CP}}$ $\Rightarrow y = \frac{\Delta\Gamma}{2\Gamma}$

- $\mathrm{CP}^+ = K^+K^-, \pi^+\pi^-$
- $\mathrm{CP}^- = K_s^0\phi, K_s^0\omega, K_s^0\pi^0, K_s^0\rho^0, K_s^0\eta$
- $\overline{\mathrm{CP}} = K^-\pi^+$

$\mathrm{D}^0 \to K^+K^-$ $\mathrm{D}^0 \to \pi^+\pi^-$ $\mathrm{D}^0 \to K_s^0\phi$



Mass (GeV/c^2)



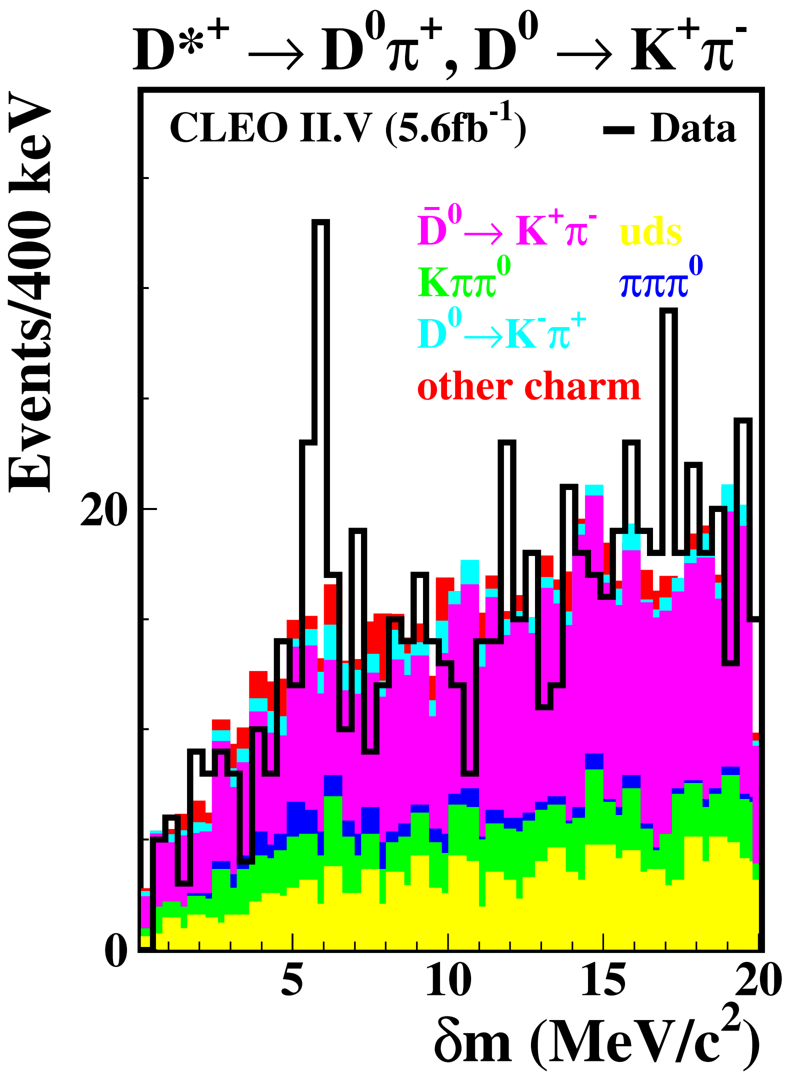
CP^- modes have $10\times$ the statistics of CP^+ modes

Proper Decay Time (ps)

courtesy of David Asner

CLEO II.5 Preliminary Data from 5.6 fb^{-1}

Fit Components, δm Projection



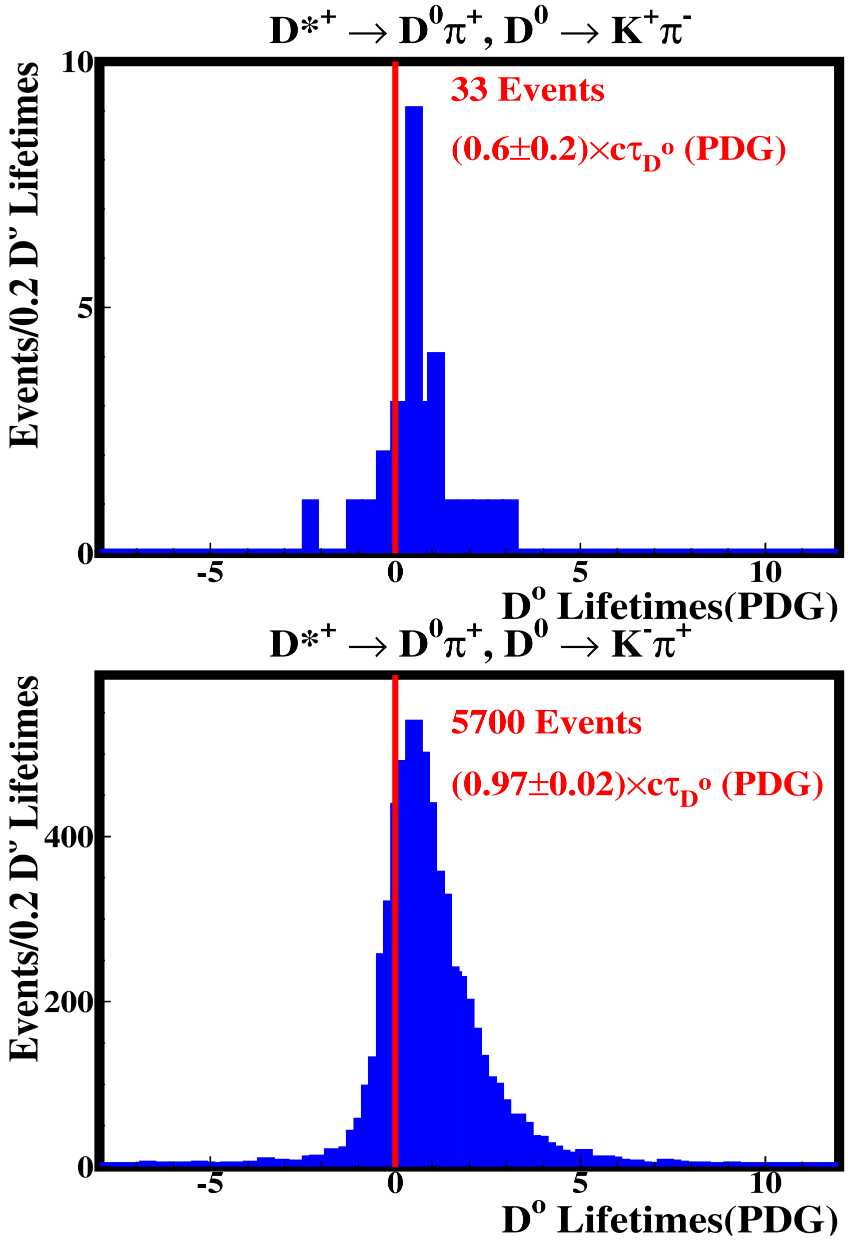
$$R_{\rm ws} = (0.31 \pm 0.09 \pm 0.07)\%$$

courtesy of David Asner

CLEO II.5 Preliminary Data from 5.6 fb^{-1}

D. Asner CLEO 15

Proper Decay Time



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courtesy of David Asner

CLEO 2.5 Preliminary Data

- first skims from 5.6 fb^{-1}
- have 9.1 fb^{-1} on tape

beam resolutions: $\sigma_y \approx 10\mu\mathrm{m}$; $\sigma_x \approx 250\mu\mathrm{m}$.
D^0 from $D^{*+} \to \pi^+$; D^0 for mixing/DCSD and $\Delta\Gamma$ studies.
intersect D^0 momentum vector with the beam "ribbon" to constrain primary vertex point (giving $\sigma_{\mathrm{separation}} \approx 40\mu\mathrm{m}$); refit slow pion track; improves ΔM resolution by a factor of 2 $\Rightarrow \sigma(\Delta M) \approx 205$ MeV/c^2.

$$\begin{aligned} D^0 \to K^-\pi^+ :\ & \text{required } p(D^*) > 1.5\,\mathrm{GeV}/c \\ & \Rightarrow \approx 19,000 \text{ signal events} \\ & \Rightarrow \approx 90\%\ c\bar{c};\ \approx 10\%\ b\bar{b} \end{aligned}$$

$$\begin{aligned} D^0 \to K^-K^+,\ \pi^-\pi^+ :\ & \text{required } p(D^*) > 2.3\,\mathrm{GeV}/c \\ & \Rightarrow \approx 1300\ KK,\ 475\ \pi\pi \\ & \Rightarrow \approx 100\%\ c\bar{c} \end{aligned}$$

Prognosis: significantly improved measurements of mixing and DCSD rates; better measurements of $\Delta\Gamma$.

E831/FOCUS

E831 (FOCUS) is a Fermilab photoproduction experiment.

- $\langle E(e^{\pm})\rangle \approx 300$ GeV
- $\langle E(\gamma)\rangle \approx 150-200$ GeV
- $\langle E(D)\rangle \approx 60$ GeV

The experiment has a "conventional" fixed-target detector.

- single-sided silicon strip detectors with 25 μm, 50 μm, and 100 μm pitch
- threshold Čerenkov detectors for kaon identification
- iron filters with scintillating paddle arrays (inner) and resistive plate chambers (outer) for muon identification

Mixing analysis to date uses $D^{*+} \rightarrow \pi^+ D^0$; $D^0 \rightarrow K\mu\nu$ sample. The sample with $D^0 \rightarrow Ke\nu$ is about the same size.

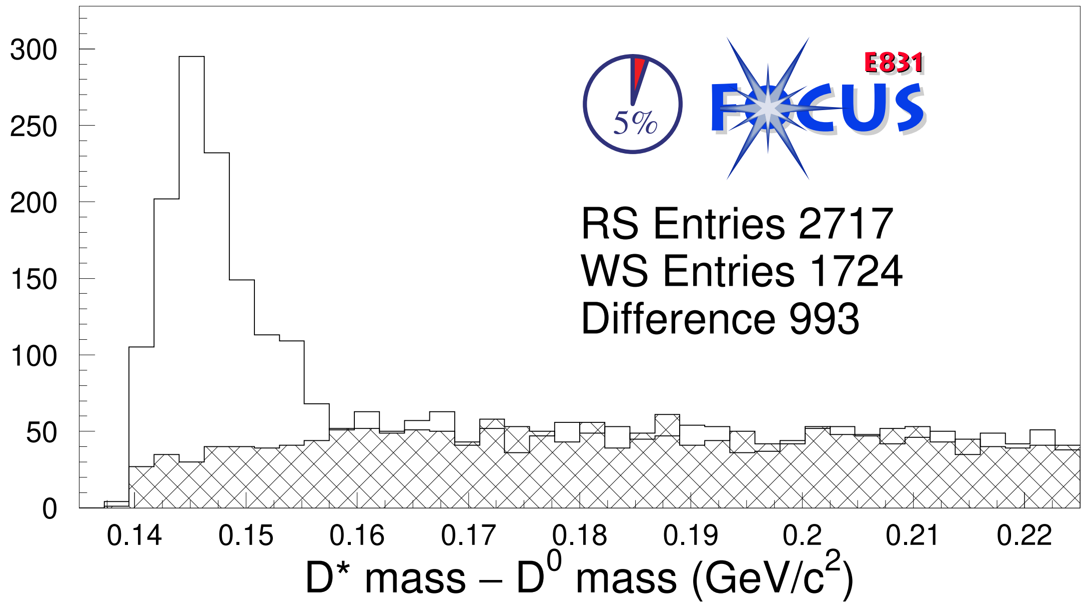
- $\langle \sigma_z \rangle \approx 400\mu$m
- require vertex separation $\ell/\sigma_z > 5$
- signal is background-subtracted in two dimensions using event mixing to determine background shape.

100% of the data has been reconstructed

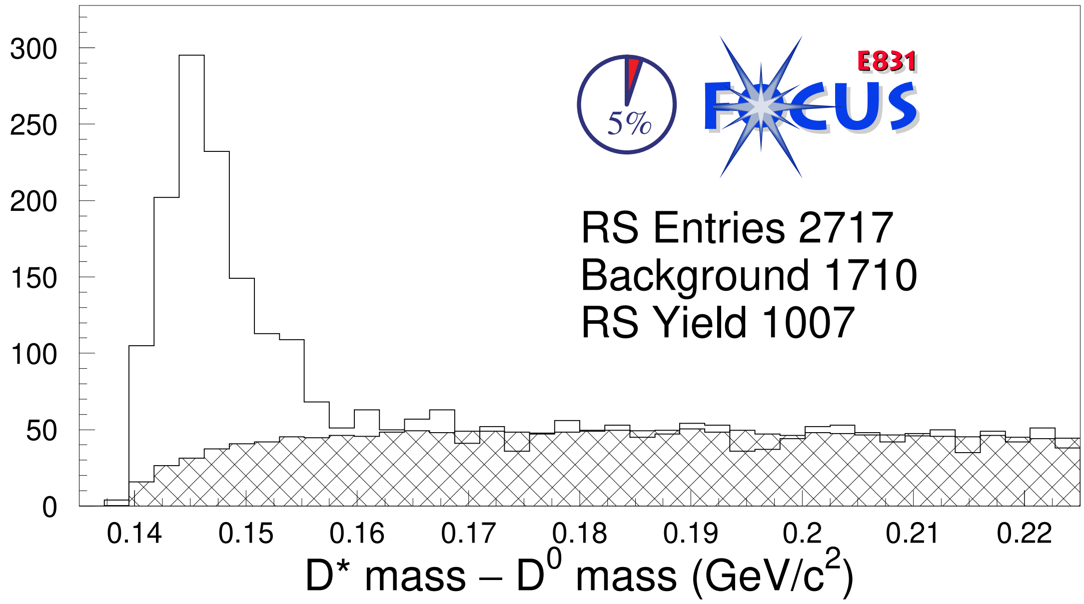
5% of the data has been analyzed

E831 Preliminary Data

Semimuonic Right Sign and Wrong Sign

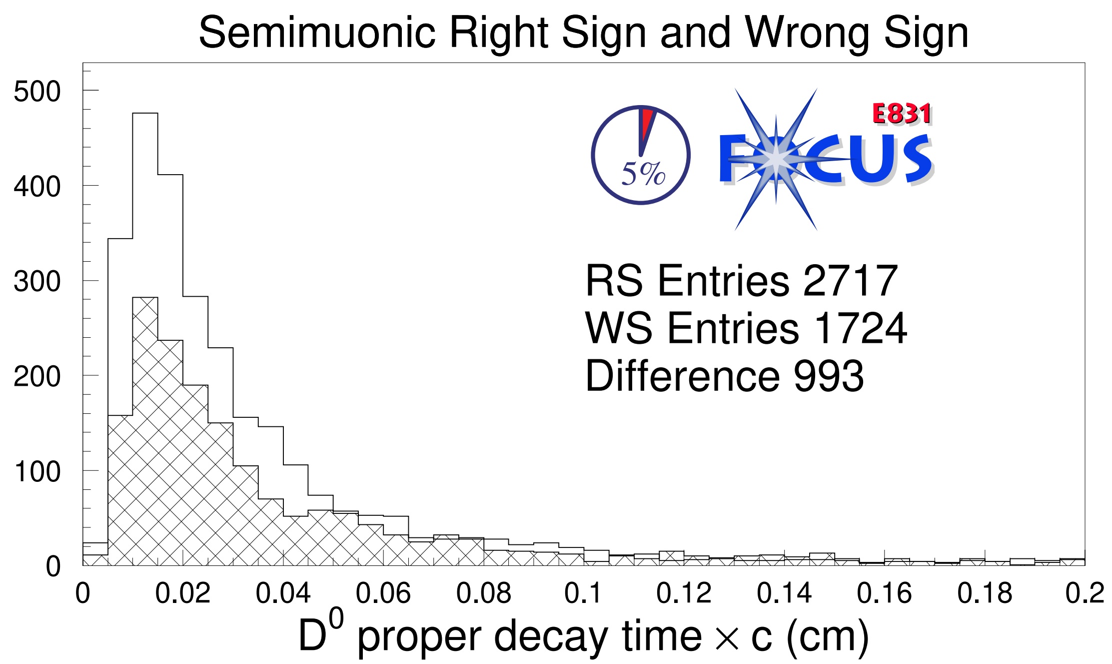


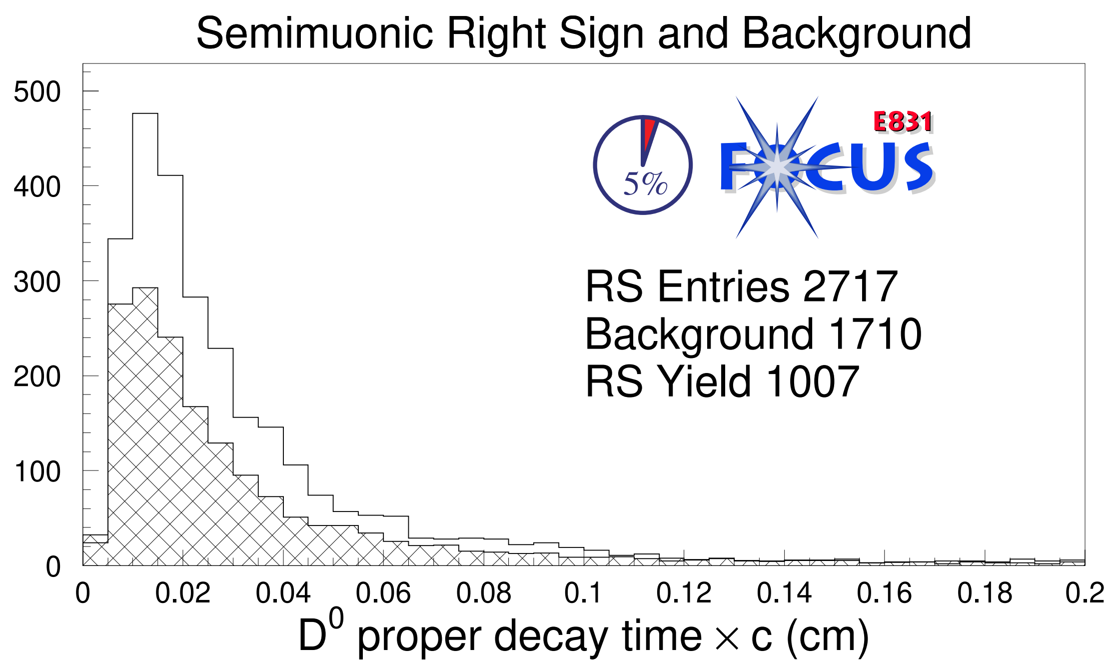
Semimuonic Right Sign and Background



courtesy Michael Hosack

E831 Preliminary Data





courtesy Michael Hosack

Summary

Aleph	$N_{\rm RS} = 1029 \pm 33 \pm 4$ $N_{\rm WS} = 19 \pm 6 \pm 4$ $r_{\rm dcsd} = (1.77^{+0.60}_{-0.56} \pm 0.31)\%$ $r_{\rm mix} < 0.92\%$ at the 95% CL $r_{\rm mix} < 3.6\%$ at the 95% CL	$D^0 \to K^-\pi^+$ from $D^{*+} \to \pi^+ D^0$ assuming no mixing assuming no interference assuming fully destructive interference
E791	$r_{\rm mix} < 0.50\%$ $r_{\rm mix} < 0.85\%$ $r_{\rm dcsd} = (0.68^{+0.34}_{-0.33} \pm 0.07)\%$	from semileptonic decays CP violation allowed only in the interference term assuming no mixing
CLEO	$r_{\rm dcsd} = (0.77 \pm 0.25 \pm 0.25)\%$	Phys. Rev. Lett. **72**, 1406 (1994)
E791	$y = 0.008 \pm 0.029 \pm 0.010$ $-0.04 < y < 0.06$, 90% CL	compare to $\lvert y \rvert < 0.10$ from $r_{\rm mix} < 0.50\%$
CLEO 2.5	$\approx 30,000$ clean $D^0 \to K\pi$ ≈ 2100 clean $D^0 \to K^-K^+$ ≈ 5000 clean $D^0 \to \phi K^0_S$	from $D^{*+} \to \pi^+ D^0$. Compare to $\approx$ 5000 $D^0 \to K\pi$ and $D^0 \to K\pi\pi\pi$ in E791. compare to $N_{\rm eff} \approx 1700$ in E791 (which did not require a D^*).
E831	$\approx 40,000$ clean $D^0 \to K\ell\nu$	from $D^{*+} \to \pi^+ D^0$. Compare to ≈ 2500 used in E791.