Change of Venue

In order to present a coherent overview of the $D^0 - \bar{D}^0$ Mixing program at CLEO,

the next 4 CLEO talks will be combined into a single presentation given by the 4 named speakers.

$D^0 - \bar{D}^0$ Mixing at CLEO

A search for physics beyond the Standard Model

Tony Hill
University of California, Santa Barbara
for the CLEO Collaboration

Outline

- Motivation and Overview — *Tony Hill*
- $D^0 \to Kl\nu$ (Semi-leptonic) — *Chris Sedlack*
- $D^0 \to P^+P^-$ (CP Eigenstates) — *Chris Sedlack*
- $D^0 \to K\pi, K\pi\pi^0, K\pi\pi\pi$ (Hadronic) — *Mike Marsh*
- Summary and Outlook — *David Asner*

Time evolution of the flavor eigenstates D^0 and $\overline{\mathrm{D}}^0$ are determined by Schrödinger's Equation

$$\frac{\partial}{\partial t}\left(\begin{array}{c} D^0 \\ \overline{D^0} \end{array}\right) = -i\mathbf{H}\left(\begin{array}{c} D^0 \\ \overline{D^0} \end{array}\right) = -i\left[\mathbf{M} - i\mathbf{\Gamma}/2\right]\left(\begin{array}{c} D^0 \\ \overline{D^0} \end{array}\right) \tag{1}$$

$\mathbf{M}$ and $\mathbf{\Gamma}$ are hermitian matrices $\Rightarrow$ observable masses and widths.

$$\frac{\partial}{\partial t}\left(\begin{array}{c} D^0 \\ \overline{D^0} \end{array}\right) = \left[\begin{array}{cc} -iM - \Gamma/2 & -iM_{12} - \Gamma_{12}/2 \\ -iM_{12}^* - \Gamma_{12}^*/2 & -iM - \Gamma/2 \end{array}\right]\left(\begin{array}{c} D^0 \\ \overline{D^0} \end{array}\right) \tag{2}$$

Off diagonal elements mix the flavor eigenstates.

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

$$\begin{aligned} m_{1,2} &= M \mp \mathrm{Re}[(M_{12} - i\Gamma_{12}/2)(M_{12}^* - i\Gamma_{12}^*/2)]^{\frac{1}{2}} \\ \gamma_{1,2} &= \Gamma \pm 2\mathrm{Im}[(M_{12} - i\Gamma_{12}/2)(M_{12}^* - i\Gamma_{12}^*/2)]^{\frac{1}{2}} \end{aligned} \tag{3}$$

and eigenstates

$$\begin{aligned} |D_2\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_1\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned} \tag{4}$$

$$\text{with} \qquad \frac{q}{p} = \frac{1+\epsilon}{1-\epsilon} = \left(\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}\right)^{\frac{1}{2}} = \exp 2i\phi_M \tag{5}$$

ϕ_M is a CP violating phase.

We define

$$\Delta M \equiv m_1 - m_2; \quad x \equiv \Delta M/\Gamma \tag{6}$$

$$\Delta\Gamma \equiv \gamma_1 - \gamma_2; \quad y \equiv \Delta\Gamma/2\Gamma \tag{7}$$

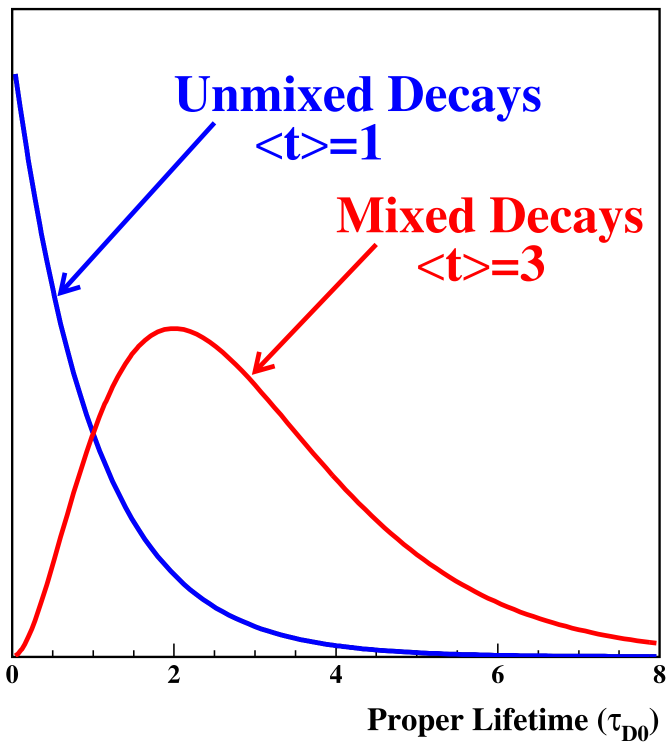
The $D^0 - \bar{D}^0$ mixing rate can be expressed as:

$$R_{mix} = \frac{1}{2}\left(x^2 + y^2\right) \tag{8}$$

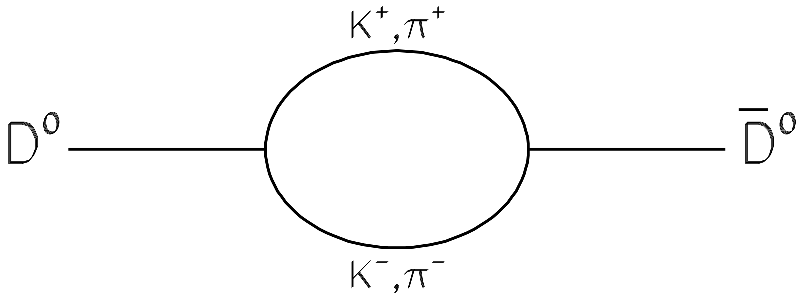
The propertime distribution for mixed decays gives us another independent piece of information about these decays -

$$|D^0_{mix}(t)\rangle = \frac{1}{2} R_{mix} t^2 \cdot e^{-t} \tag{9}$$

Proper Lifetime Distribution Comparison

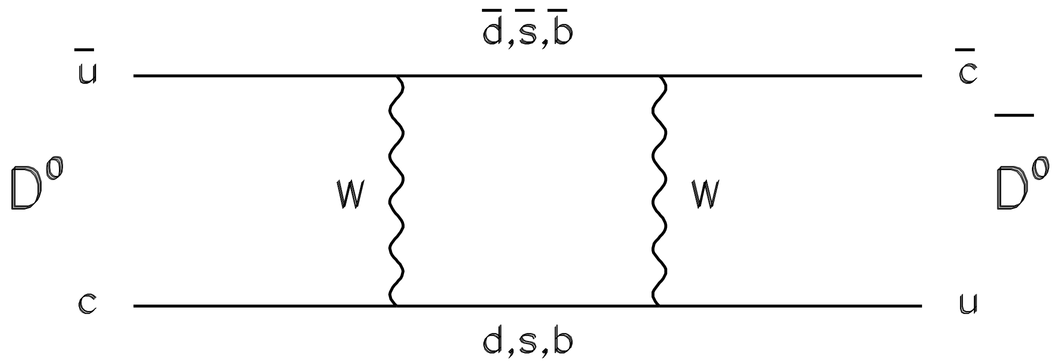


y mixing proceeds through real or on-shell intermediate states



- Standard Model can probably accommodate a measureable value for y

x mixing proceeds through virtual or off-shell intermediate states

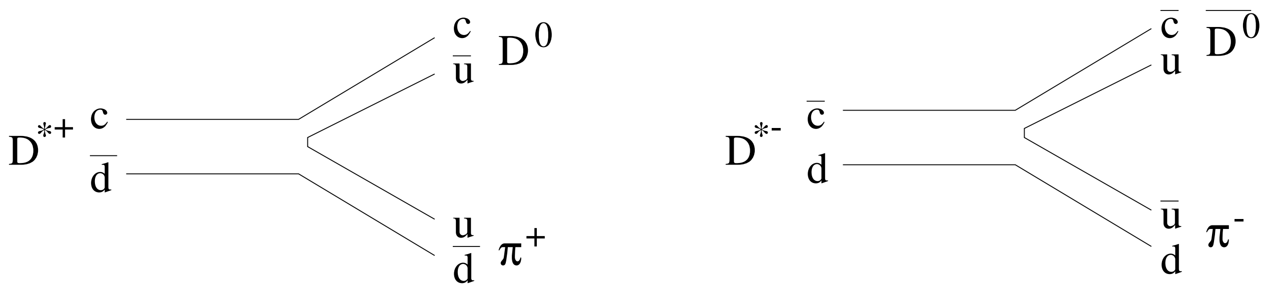


- Standard Model predicts $R_{mix} < O(10^{-8})$ if dominated by x.
- New Physics allows R_{mix} close to current experimental limits.
  - multiple scalar doublets ($M_H \sim 1\,TeV$)
  - fourth generation of quarks
  - supersymmetry with quark-squark alignment
  - light scalar leptoquarks ($M_{LQ} \leq 2\,TeV$)

Observing $D^0 - \bar{D}^0$ Mixing at CLEO

In order to observe mixing we must

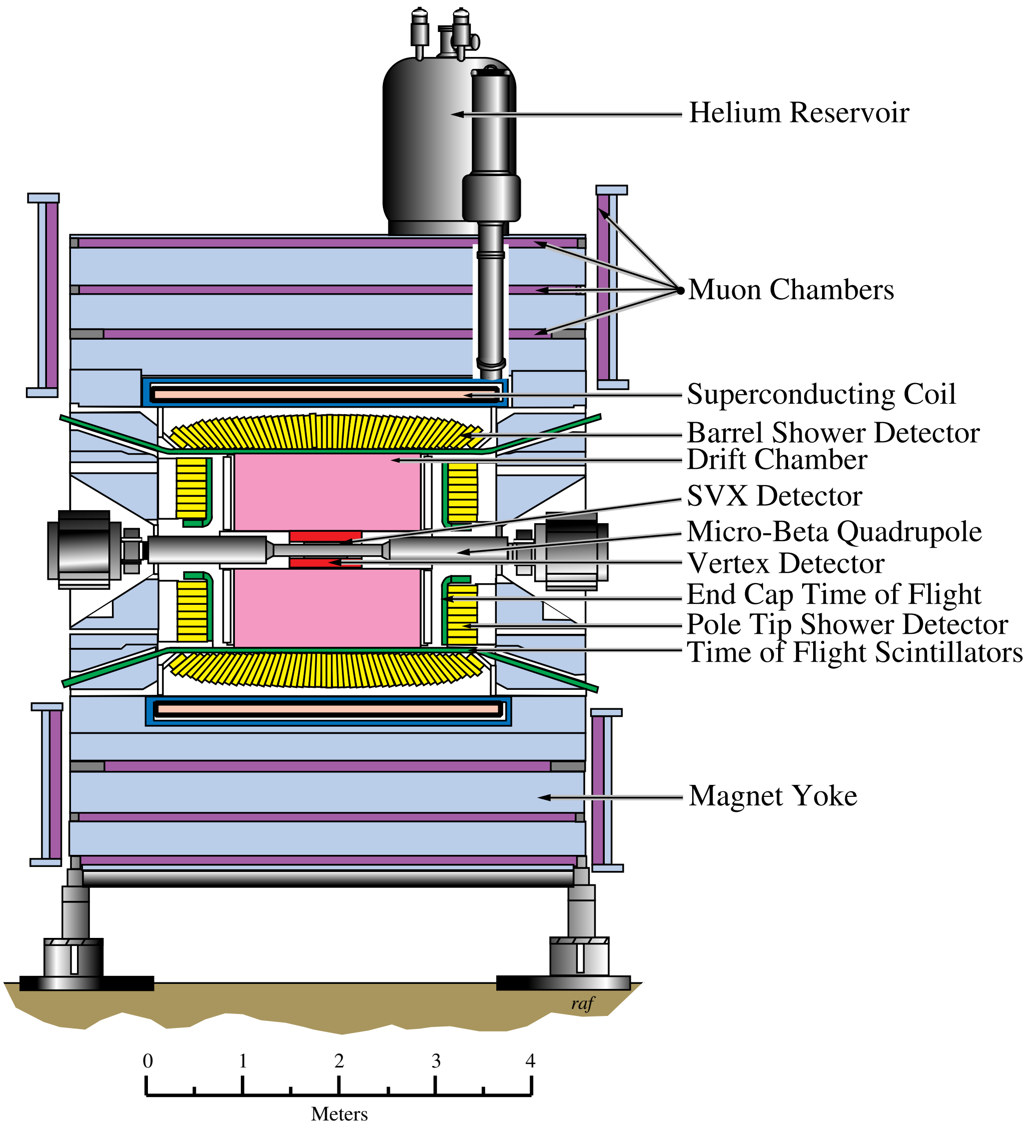
- know the flavor of the D^0 meson at birth
- know the flavor of the D^0 meson when it decays



We tag the flavor of the D^0 meson at birth by requiring the D^0 to have come from the decay $D^{*+} \to D^0 \pi^+_{soft}$.

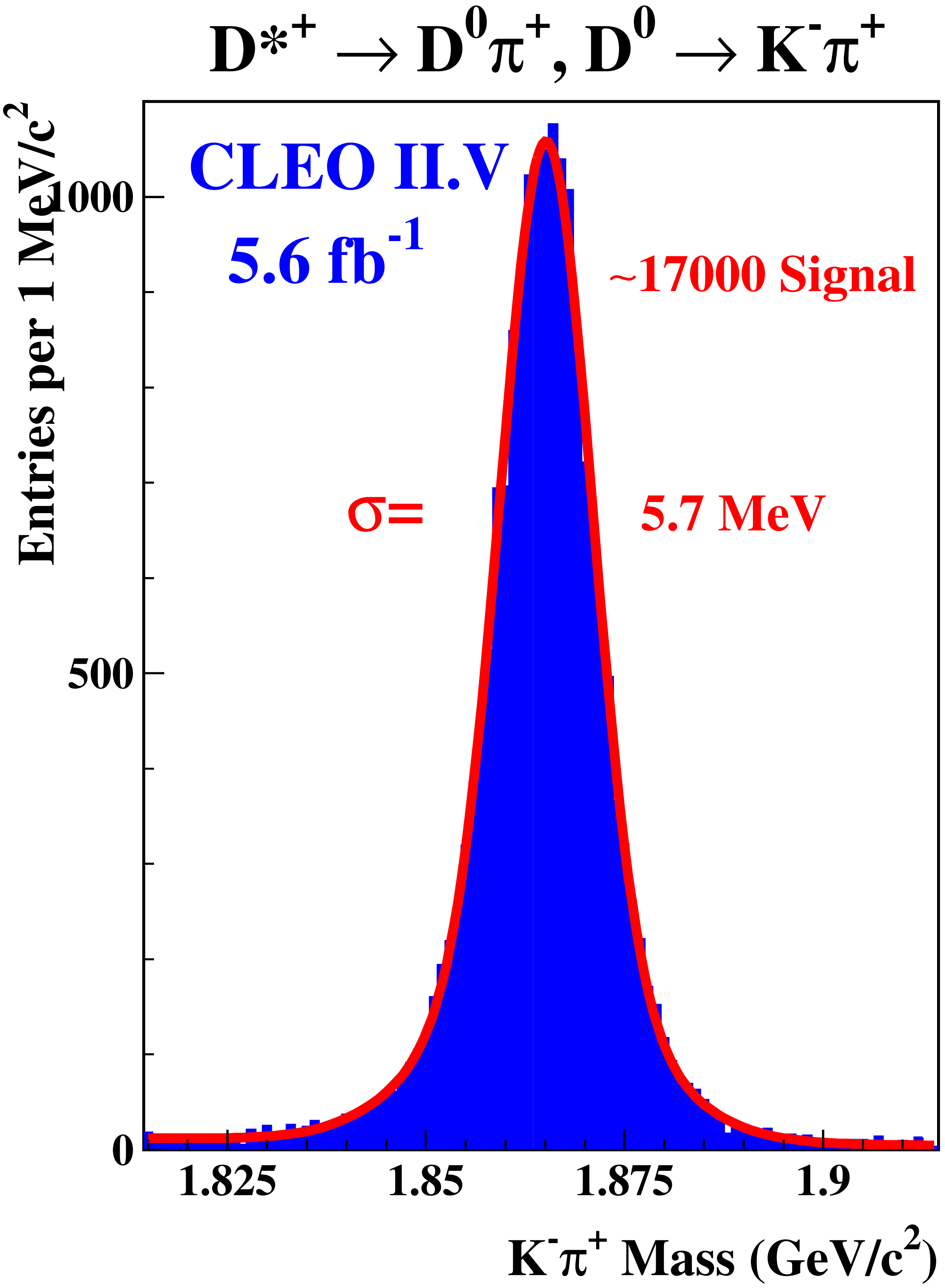
The D^0 flavor at the time of decay is determined from the final state products.

CLEO II.V

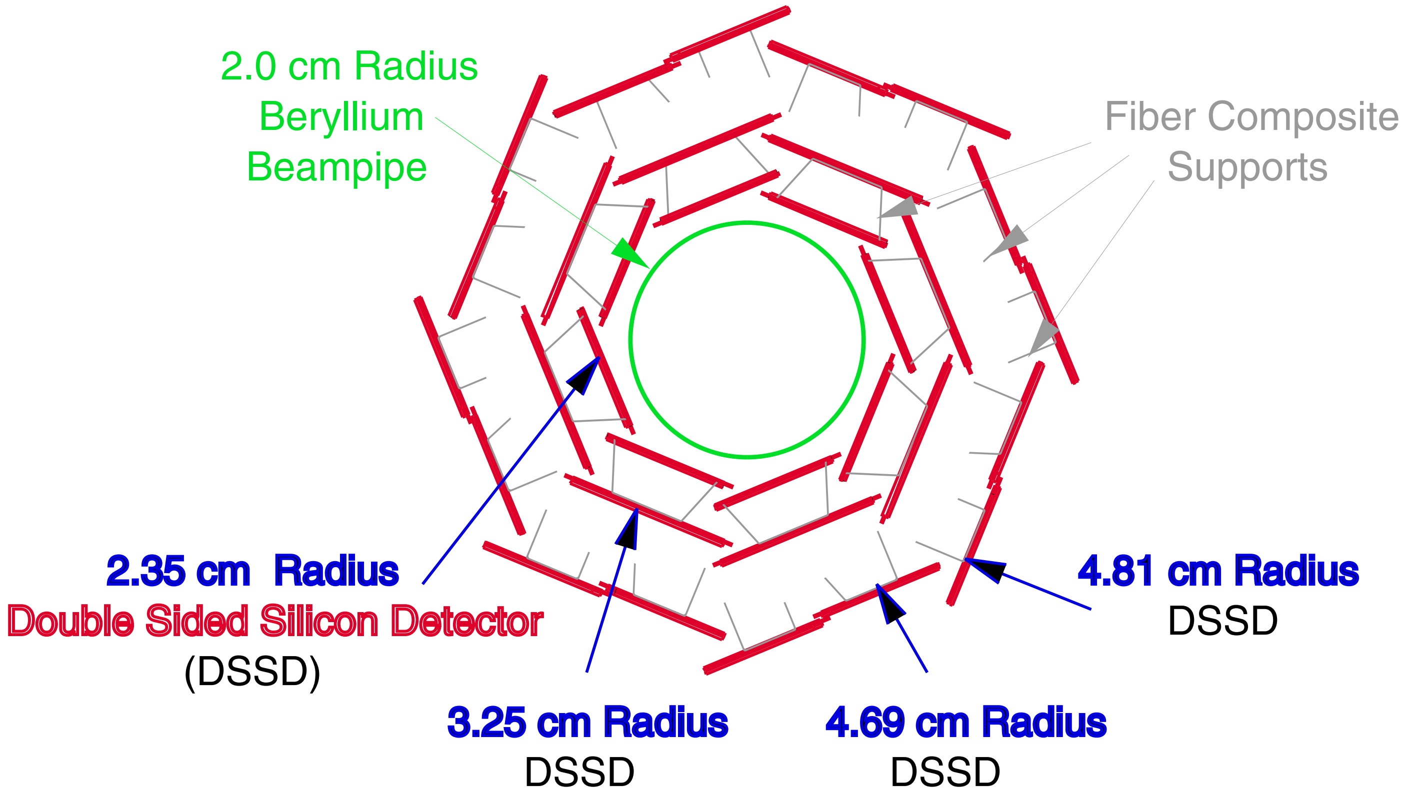


CLEO II.V mass resolution has been substantially improved by using helium/propane gas mixture in primary tracking volume and Kalman filtering techniques in track fitting.

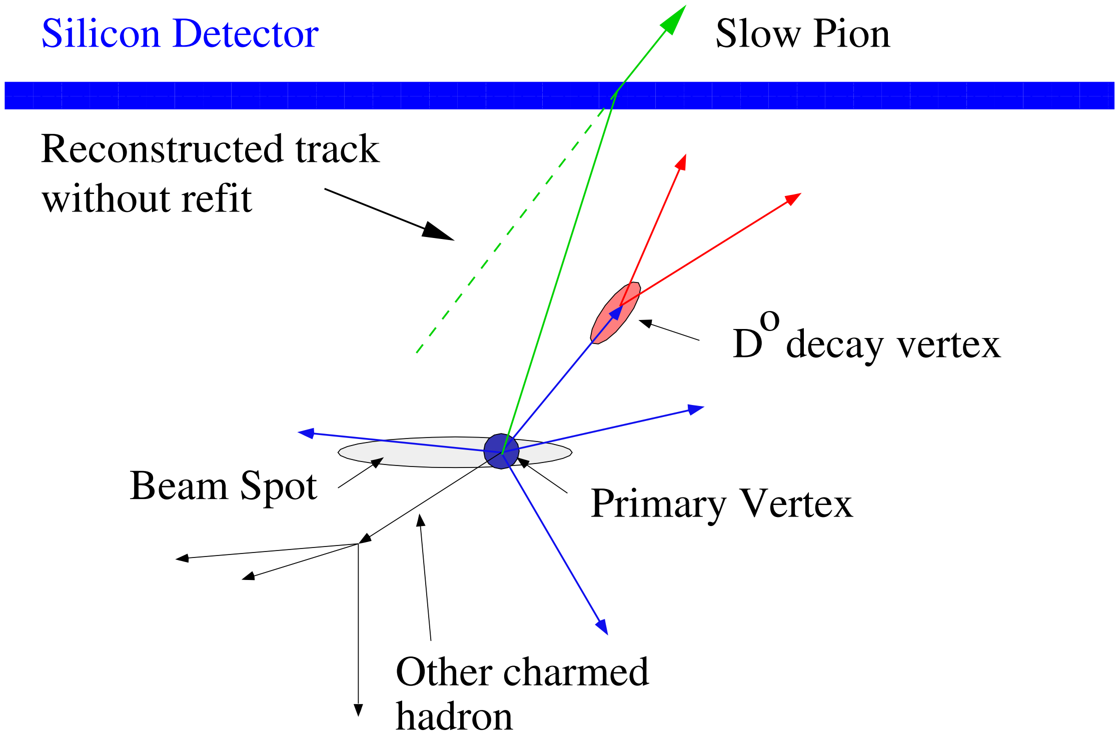
CLEO II.V Mass Resolution



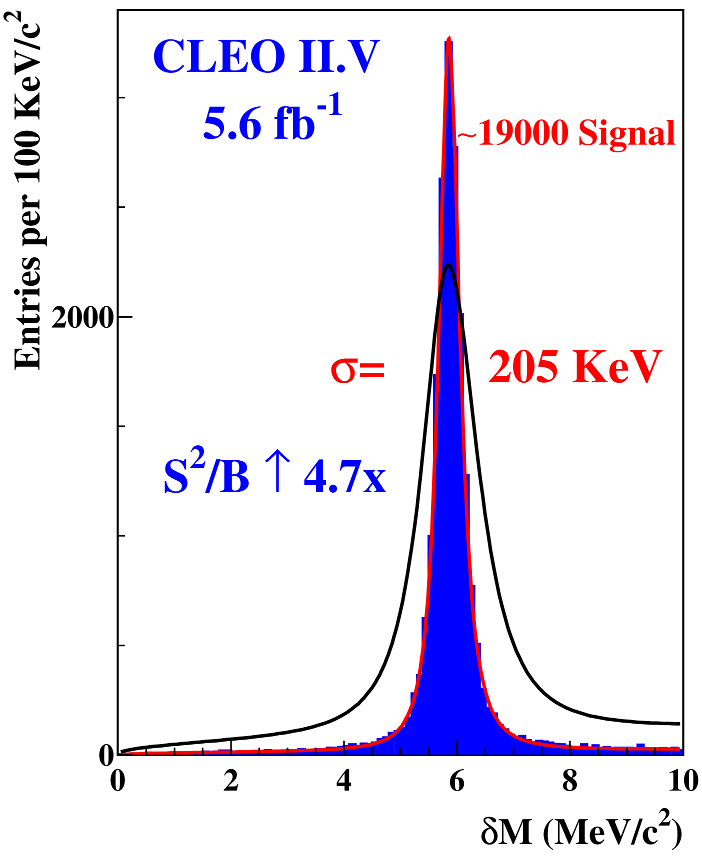
CLEO II.V Silicon Vertex Detector (SVX)



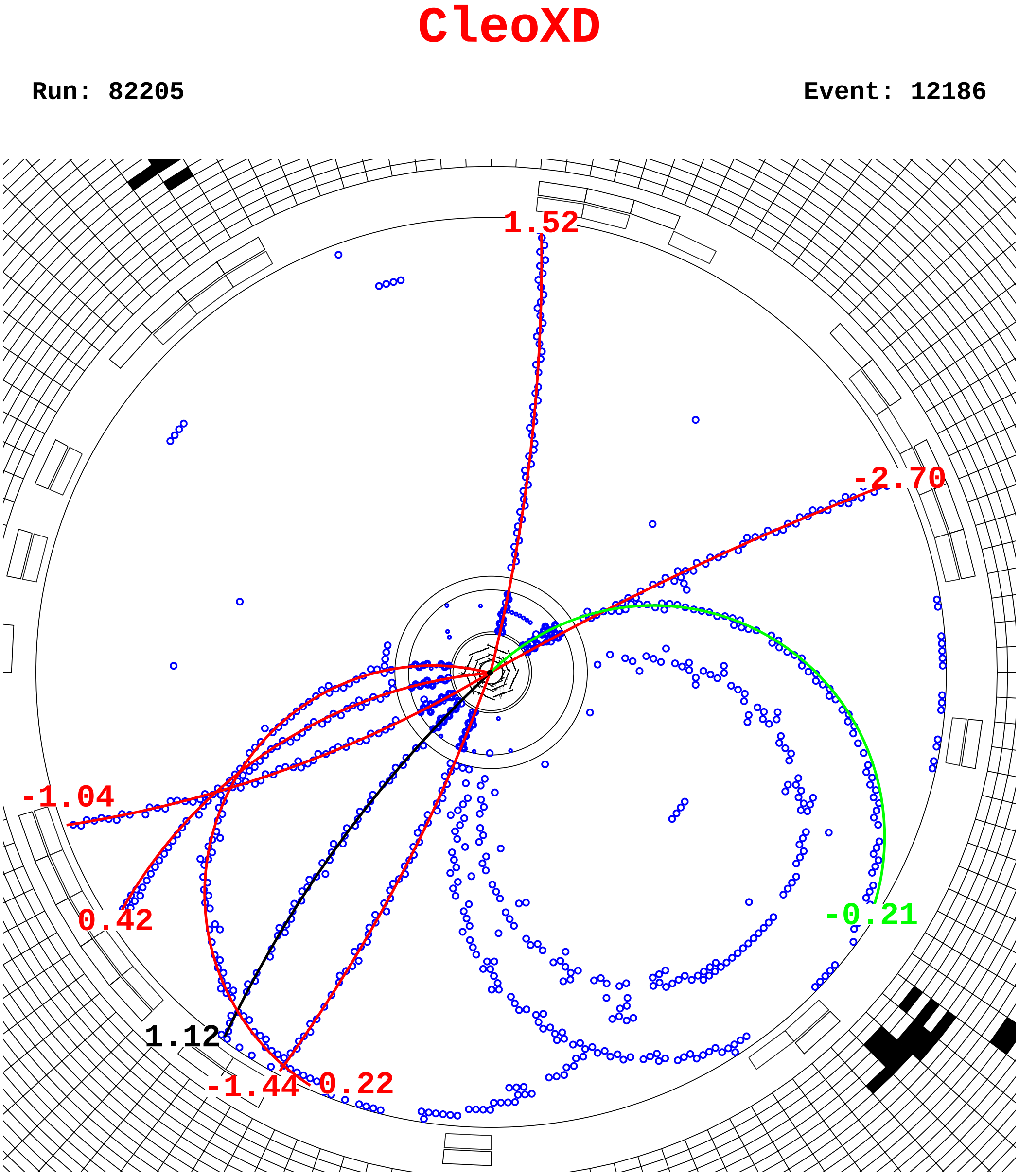
The CLEO II.V SVX detector is a 3 layer, double-sided device that delivers precision tracking information in 3 dimensions very close to a high current beam and is the prototype for detectors to be used in CLEO III, BaBar and BELLE.



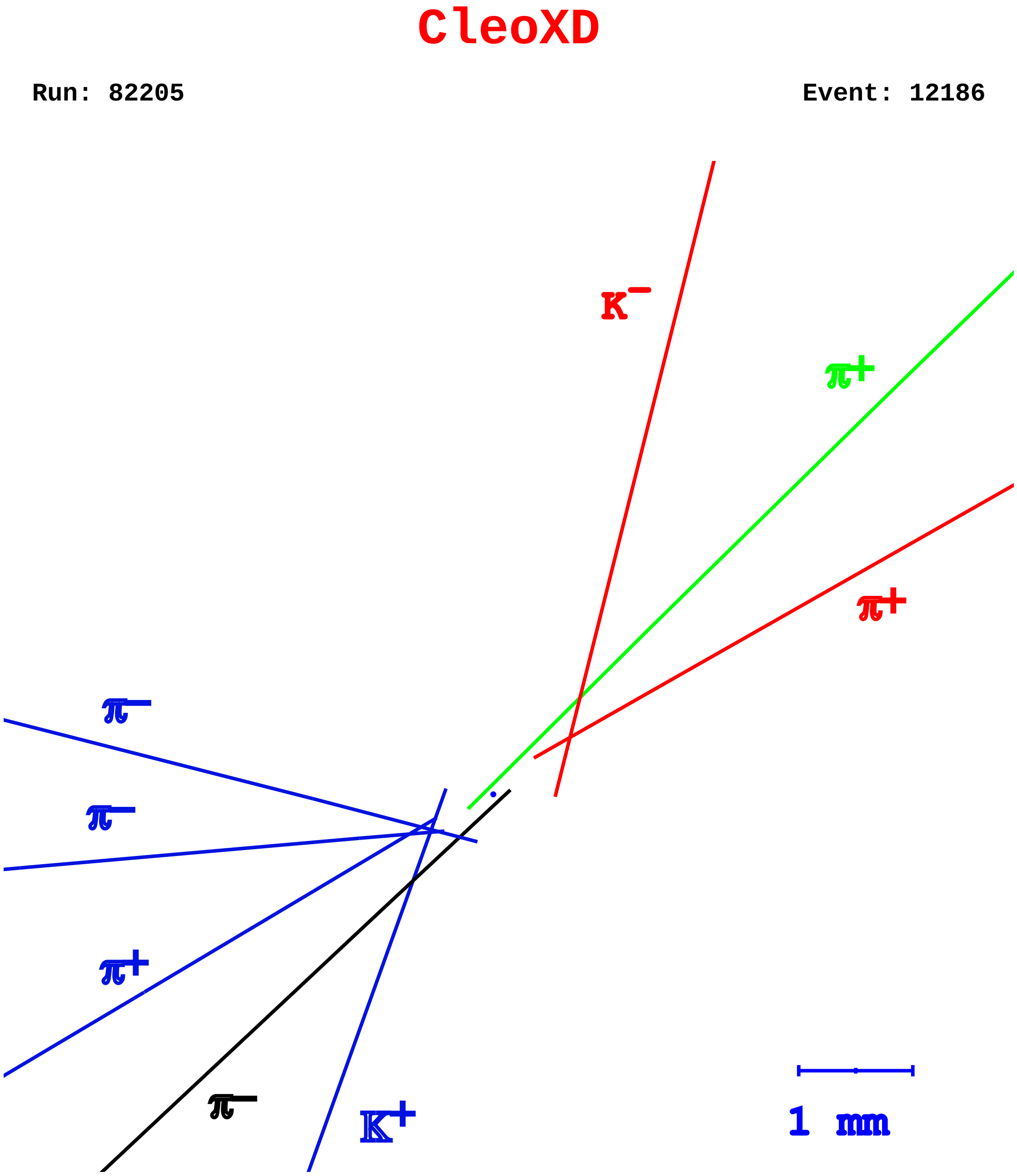
$D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+$



A Charm Event in CLEO II.V



Charm Vertexing in CLEO II.V



This event shows a $D^{+*} \rightarrow D^0\pi^+_{soft} \rightarrow K^-\pi^+\pi^+_{soft}$ in the upper right with a $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$ and a fragmentation π^- in the lower left.

Summary

The level of mixing predicted by the standard model is small enough that effects from physics beyond the standard model may be seen.

The effect of mixing is most visible in the proper lifetime distribution.

CLEO is in a unique position to make these measurements:

- $9\, fb^{-1}$ of data (35 million charm hadrons)
- e^+e^- environment (low backgrounds)
- best spectrometer in the business (charged AND neutral)
- precision lifetime information (new SVX detector)
- many D^0 decay modes can be reconstructed at CLEO

We are pursuing $D^0 - \bar{D}^0$ mixing on several fronts:

- Semi-leptonic decays
- CP eigenstate decays
- Hadronic decays

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

Part II: Semileptonic D decays and D decays to CP Eigenstates

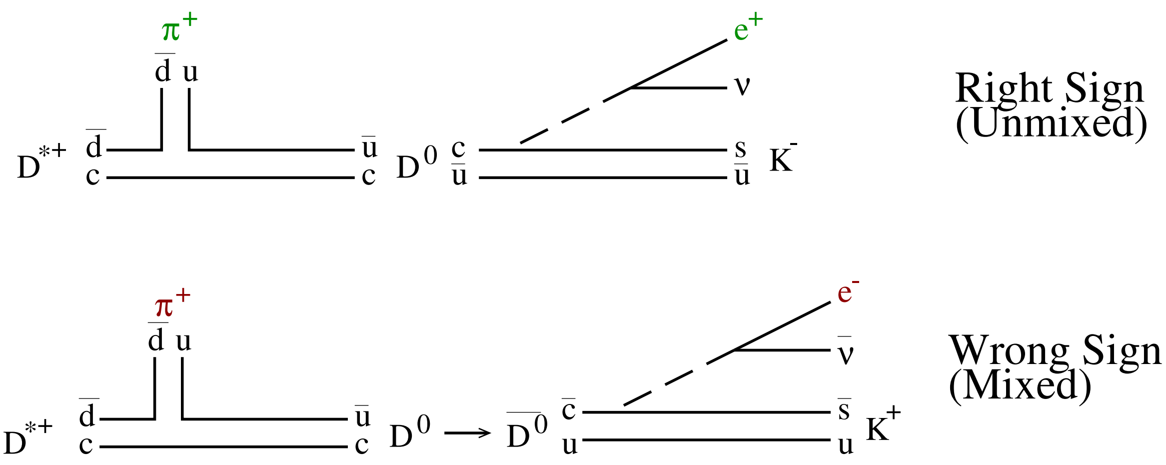
Chris Sedlack
U. of Illinois, Urbana-Champaign

Outline

- Semileptonic Method
  - Semileptonic D Decays
  - Lifetime Considerations
- CP Eigenstates
  - CP Eigenstates and Mixing
  - Measurement of CP^+ Lifetime
  - Outlook for CP^- Analysis

Semileptonic D Mixing

The main power of the semileptonic D mixing analysis lies in its unambiguous flavor tagging:



By observing the number of "right sign" and "wrong sign" decays, we may extract a mixing rate, R_{mix}:

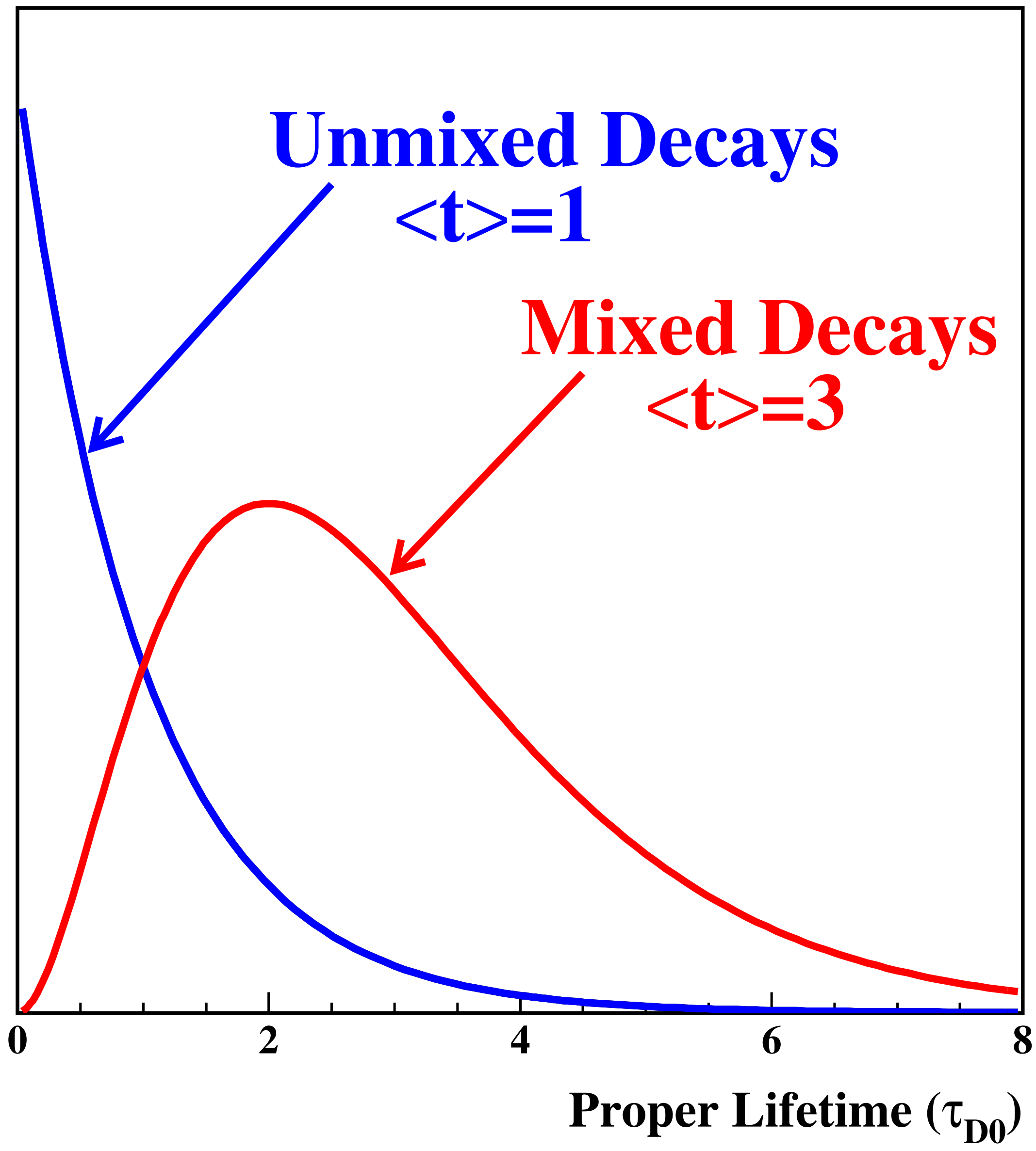
$$R_{mix} = \frac{N(D^0 \to \overline{D^0} \to K^+ e^- \overline{\nu})}{N(D^0 \to K^- e^+ \nu)}$$

Recall that the time-dependent rate for mixing is proportional to $t^2 e^{-t}$.

Peak lifetime (mixing signal): $2\tau_{D^0}$

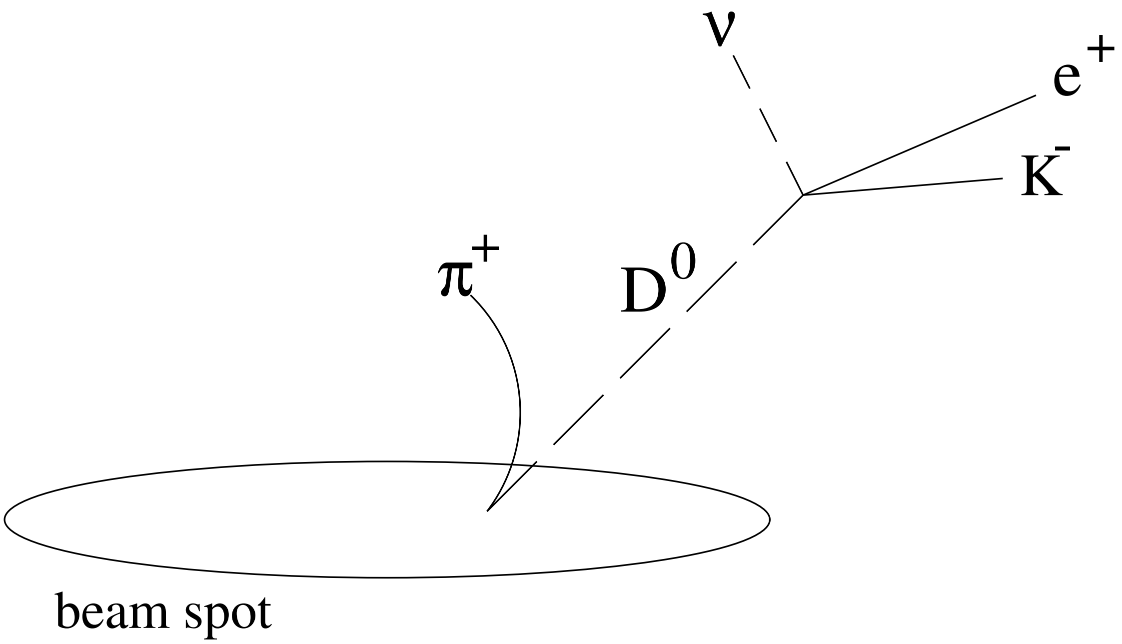
Average lifetime (mixing signal): $3\tau_{D^0}$

Proper Lifetime Distribution Comparison



This lifetime distribution will provide significant wrong sign background rejection.

Measuring the Lifetime



Since we calculate the D^0 decay time as:

$$t_{D^0} = \frac{y_{vtx} - y_{beam}}{c} \frac{m_{D^0}}{p_y}$$

We need to get a handle on four pieces of information:

- $|p_{D^0}|$ - obtained $\pm 20\%$ from π momentum
- The direction of the D^0 momentum - obtained $\pm 9^\circ$ from π direction
- y_{vtx} - obtained from vertexing of K, e
- y_{beam} - known to $\pm 2 - 3\mu m$

Semileptonic Summary

- Semileptonic decay modes offer excellent handle on R_{mix}
- CLEO II.V detector allows good resolution of decay lifetime, despite the presence of the neutrino
- Feasibility studies suggest a sensitivity to R_{mix} at the level of about 0.2% using the 9 fb^{-1} CLEO II.V data set for the semielectronic decay mode. We expect significant gains from the addition of more modes and the use of lifetime information

CP Eigenstate Analysis

In general, the CP^+ and CP^- eigenstates can have different decay widths (Γ^+ and Γ^-) and lifetimes.

$$y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Delta\tau}{\tau_+ + \tau_-}$$

If we can measure the difference in lifetime between CP^+ and CP^- decays, we have a measurement of y and therefore, $\Delta\Gamma$.

CP^+ Modes

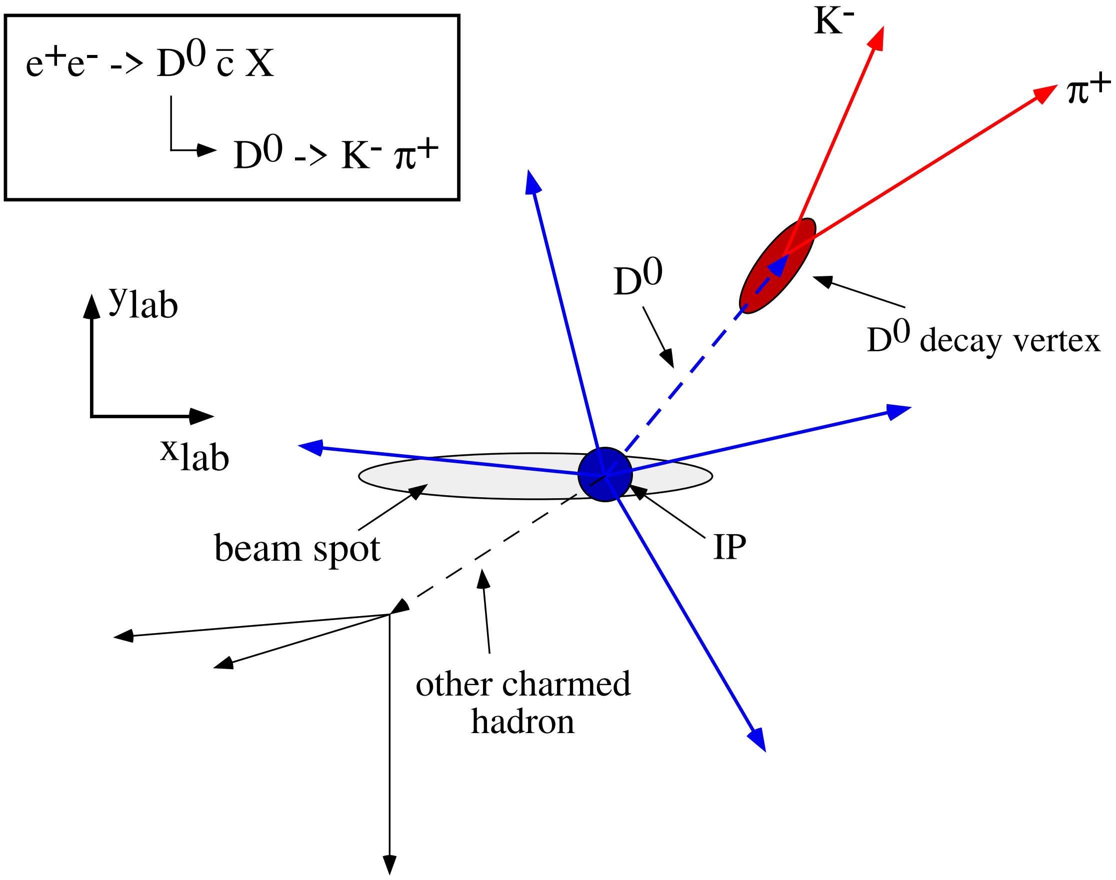
- K^+K^-
- $\pi^+\pi^-$

CP^- Modes

- $K_s\phi$
- $K_s\omega$

Lifetime Measurement Technique

Form 3D vertex with the D^0 daughters.

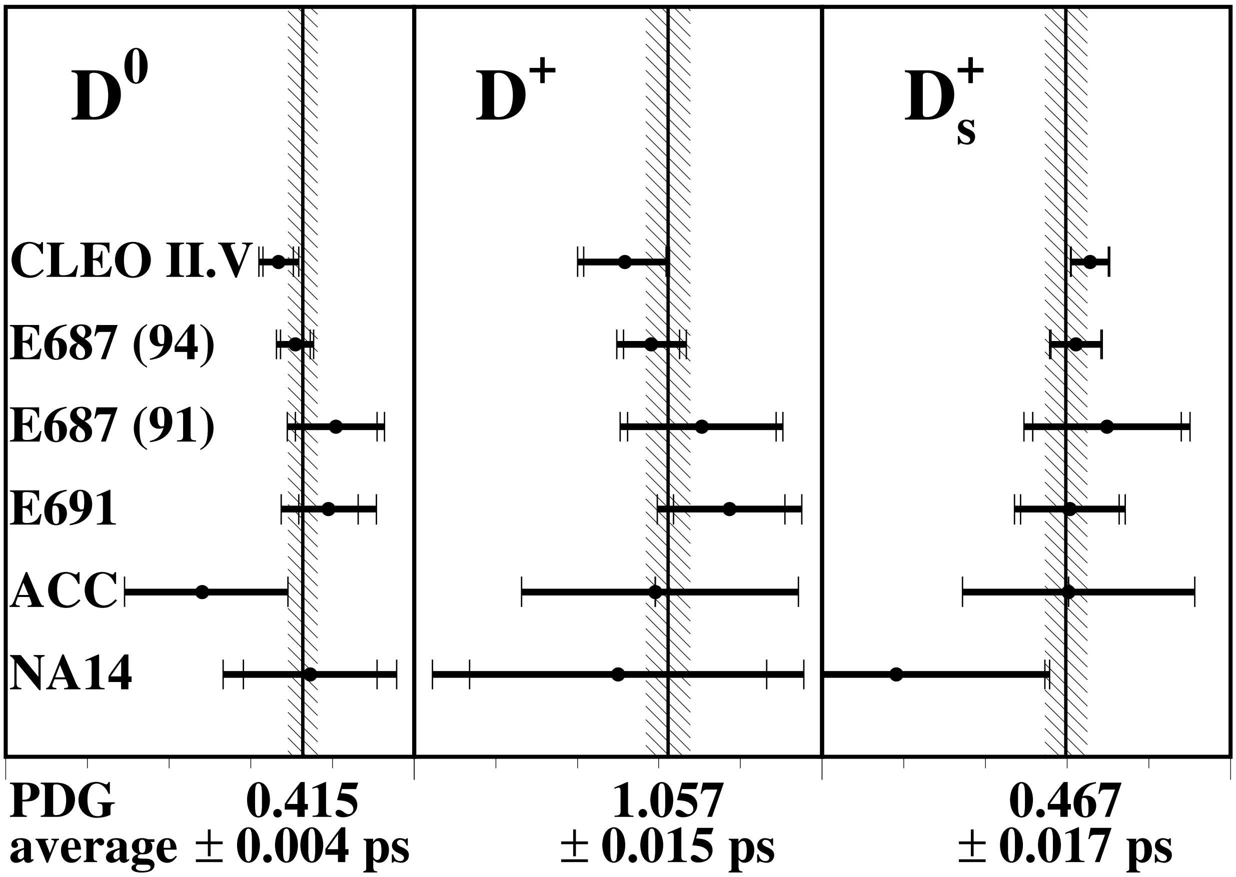


Use only the y flight information and beam spot to calculate a proper-time.

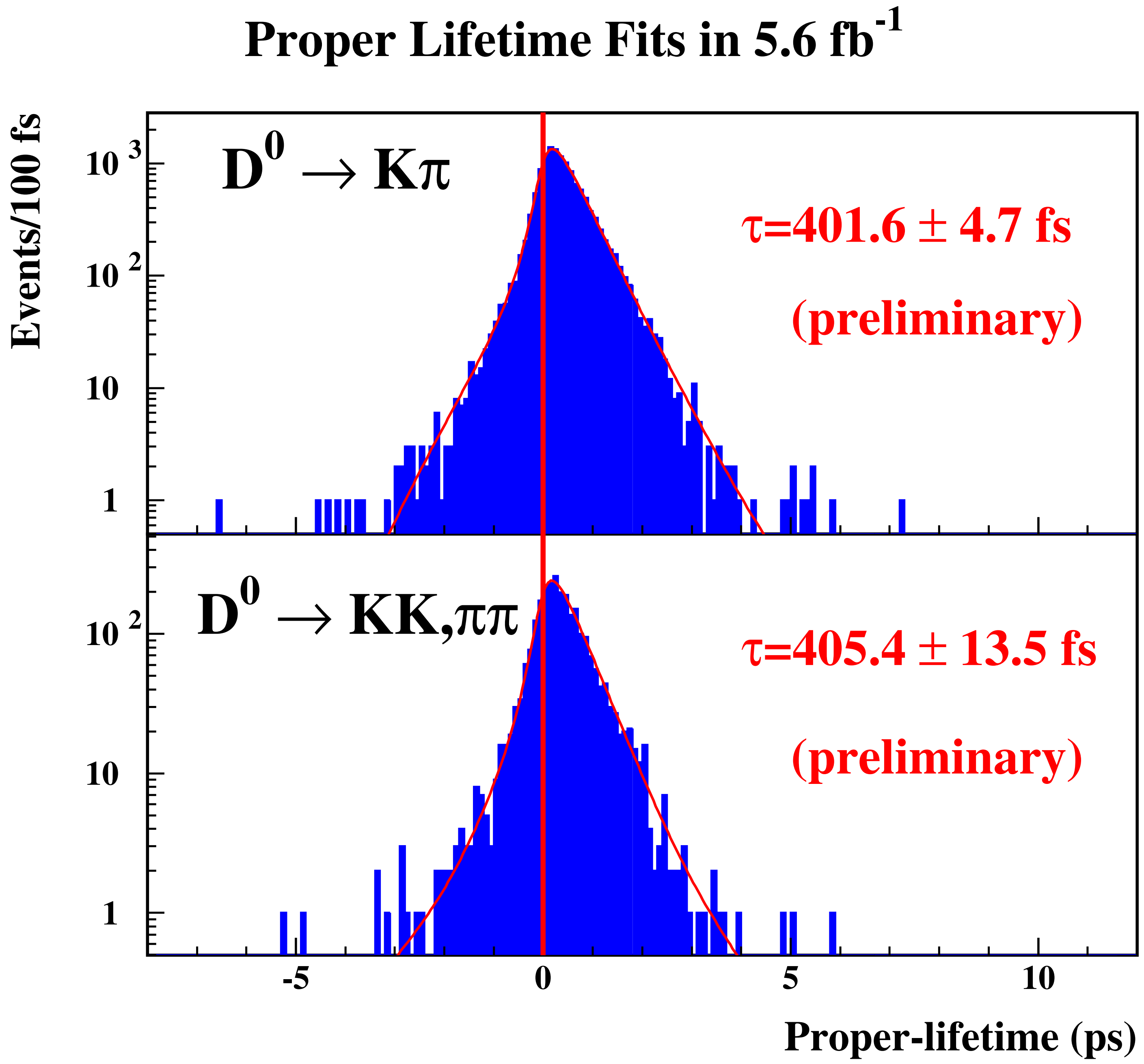
$$t_{D^0} = \frac{y_{vtx} - y_{beamspot}}{c} \cdot \frac{m_{D^0}}{p_y}$$

We then fit the proper time distribution using a 7 parameter unbinned maximum likelihood fit to obtain the signal lifetime.

Using the above technique, CLEO II.V has been able to make a measurement (submitted to PRL) of D meson lifetimes competitive with the world's previous best measurements.



Measuring the Lifetimes



Extracting y

If CP invariance holds, $K^-\pi^+$ is an equal admixture of CP^+ and CP^-, with lifetime given by:

$$\tau_{K\pi} = \frac{1}{2}(\tau_+ + \tau_-)$$

Which allows us to rewrite our expression for y as:

$$y = \frac{\tau_+ - \tau_-}{\tau_+ + \tau_-} = \frac{\tau_+}{\tau_{K\pi}} - 1$$

Based on our present measurements of the $K\pi$ and CP^+ lifetimes, we can set a limit on y of:

$$y = -0.032 \pm 0.034 \text{ (stat) } \pm 0.008 \text{ (syst)}$$

OR

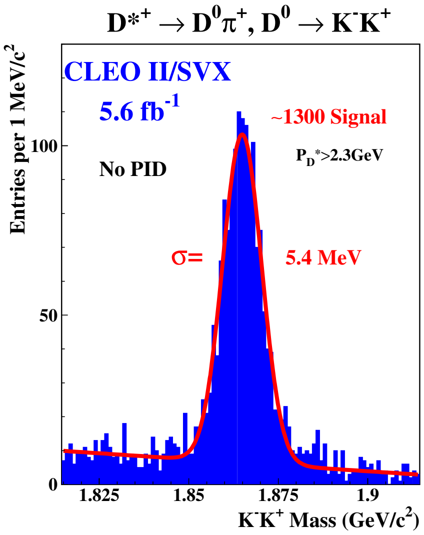
$$-0.076 \leq y \leq 0.012 \text{ (90\% confidence)}$$

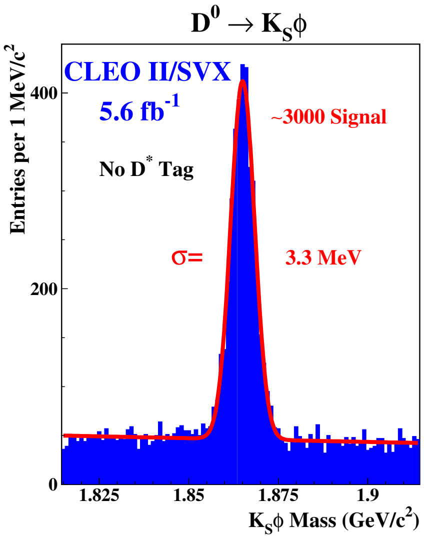
(Preliminary)

CP^- Eigenstate Prospects

Better statistics than CP^+

- D^* tag not needed
- Larger branching fraction





We estimate that these modes have the potential to constrain y to ± 0.01 if $y = 0$.

CP Eigenstates Summary

- CP eigenstates allow us to measure y in a straightforward manner
- CLEO II.V detector provides excellent resolution of decay lifetime
- (Preliminary) measurements of the lifetime of CP^+ eigenstates set limit of $-0.076 \leq y \leq 0.012$.
- Measurements of the lifetime of CP^- eigenstates likely to be even more powerful, setting limits on the order of $|y| \leq 0.01$.

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

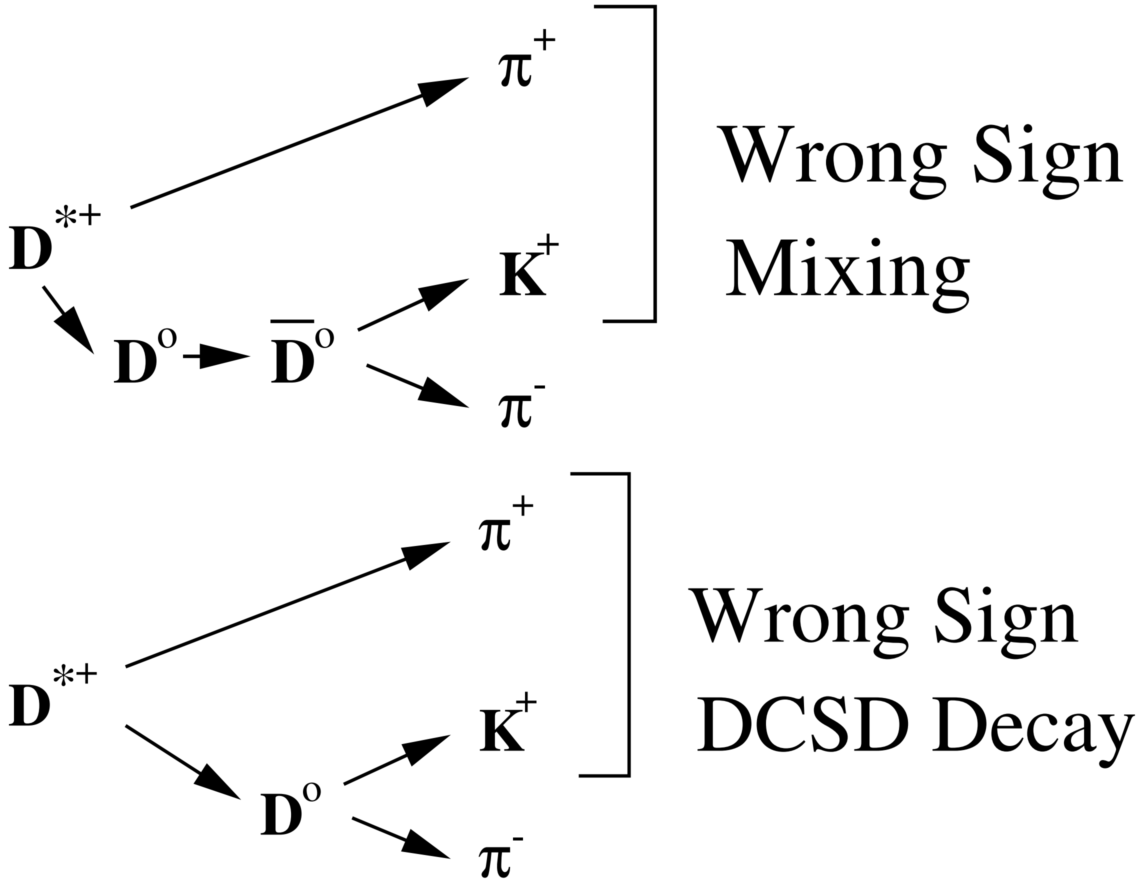
Part III: Wrong-Sign Hadronic Modes

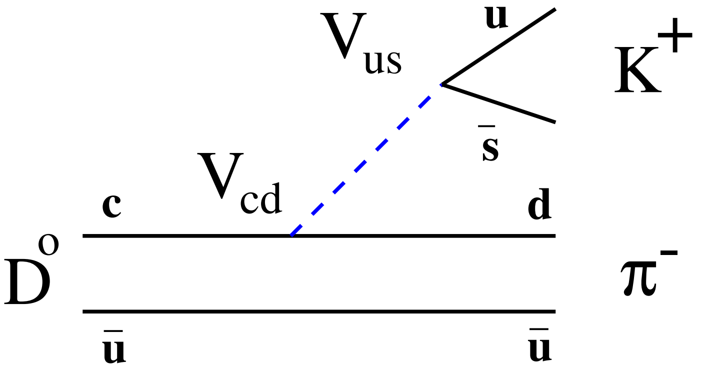
Mike Marsh – University of Illinois, Urbana-Champaign
for the CLEO Collaboration

Outline:

- Brief Theoretical Overview
- Discuss Analysis Technique for $\mathrm{D}^0 \to K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-$
  - Wrong-sign Rate Analysis - $\frac{\mathcal{B}(\mathrm{D}^0 \to K^+\pi^-)}{\mathcal{B}(\mathrm{D}^0 \to K^-\pi^+)}$
  - Wrong-sign Lifetime Analysis
- Present Result for $\mathrm{D}^0 \to K^+\pi^-$

Mixing in Hadronic Modes





$$\frac{\mathcal{B}\left(D^0 \to \overline{f}\right)}{\mathcal{B}\left(D^0 \to f\right)} \sim \tan^4 \theta_c$$

Distinguish Mixing and DCSD with Decay Time Distribution

Time Dependent Wrong-Sign Rate

$$(\mathrm{R}_{\mathrm{DCSD}} + [\sqrt{2\mathrm{R}_{\mathrm{DCSD}}\mathrm{R}_{\mathrm{Mix}}}\cos\phi]t + \tfrac{1}{2}\mathrm{R}_{\mathrm{Mix}}t^2) \times \exp(-t)$$

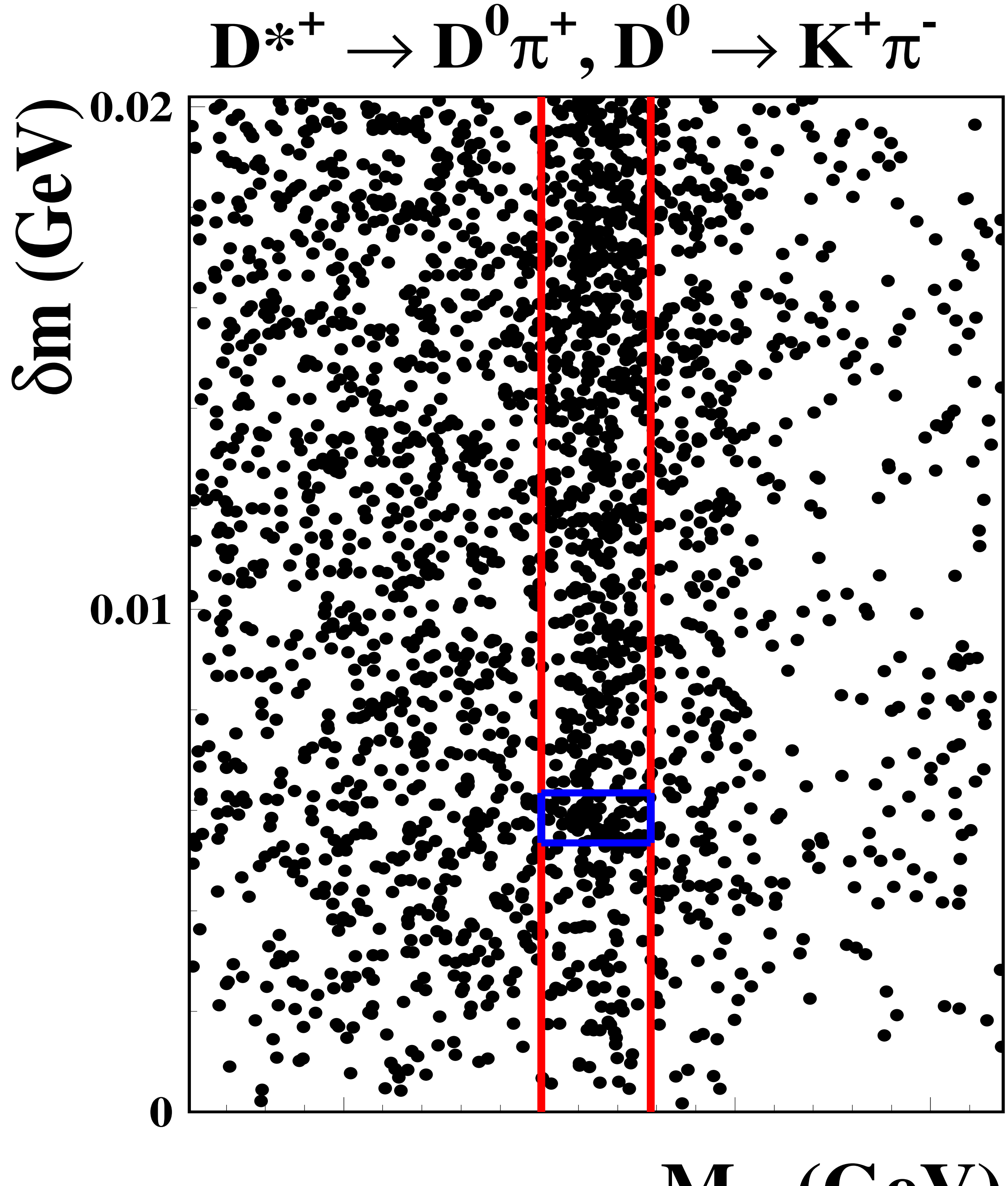
$$\begin{aligned}
\mathrm{R}_{\mathrm{Mix}} &= \frac{1}{2}\left(x^2 + y^2\right) \\
\phi &= \tan^{-1}\left(\frac{x}{y}\right) + \delta_s \\
x &= \frac{\Delta M}{\Gamma} \\
y &= \frac{\Delta\Gamma}{2\Gamma}
\end{aligned}$$

δ_s expected to be small $(0^\circ \; . \; \delta_s \; . \; 14^\circ)$

(Very) Brief Analysis Outline

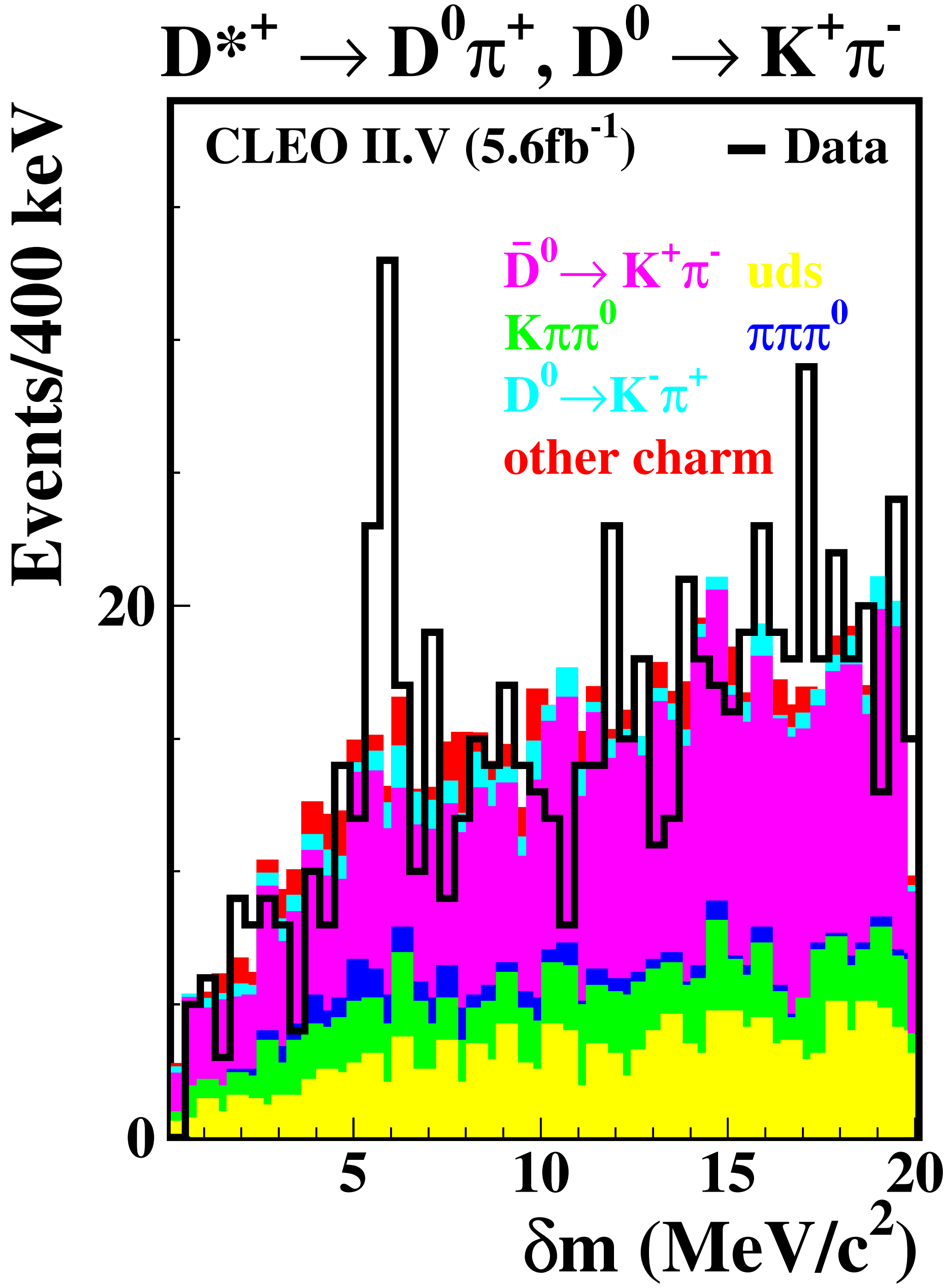
- Measure time-integrated wrong-sign rate (R_{ws})
- Measure proper lifetime distribution for wrong-sign decays (t_{ws})
- Determine mixing limits
  $\Rightarrow$ Next Talk by David Asner

Wrong-Sign Data



Significant background from
real D^0s *not* from D^{*+}s

Fit Components, δm Projection

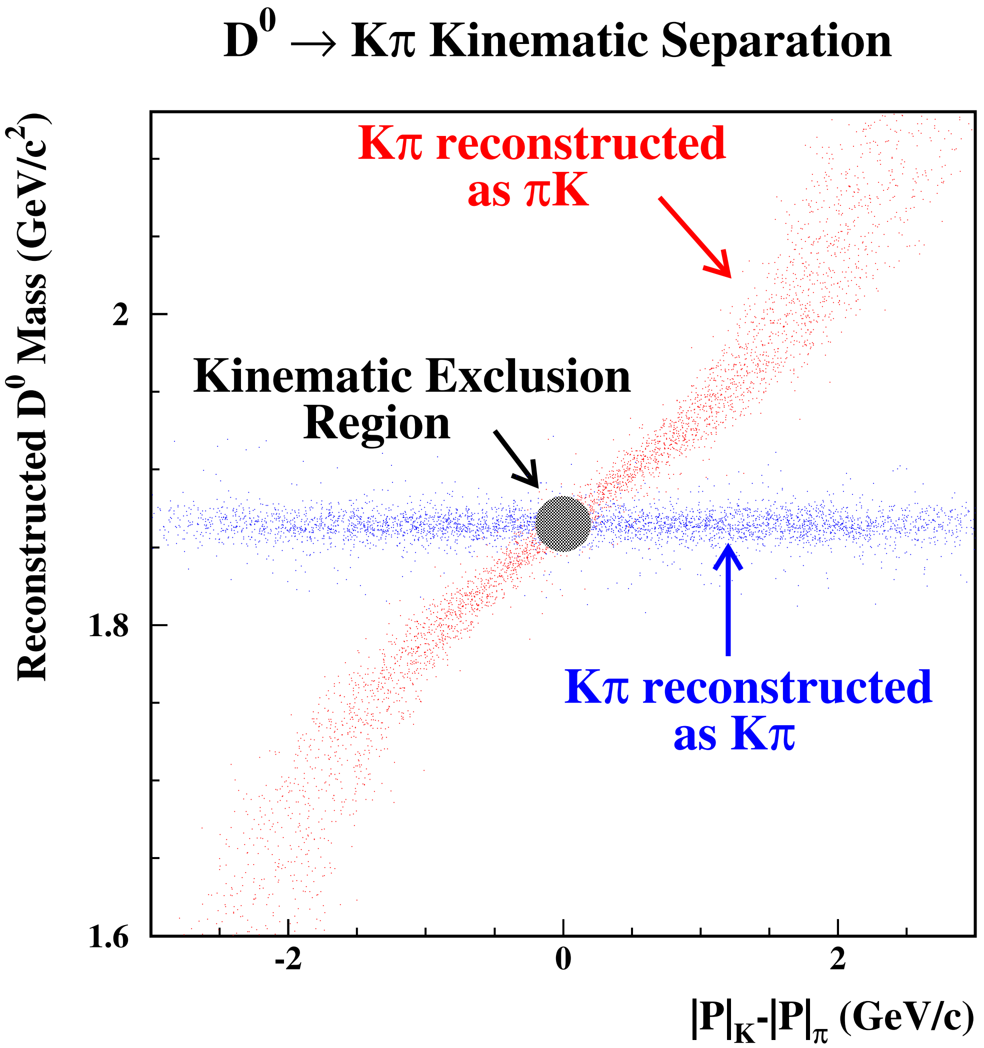


$$R_{\mathrm{ws}} = (0.31 \pm 0.09 \pm 0.07)\%$$

(Preliminary)

Background Rejection

Right-Sign Feedthrough

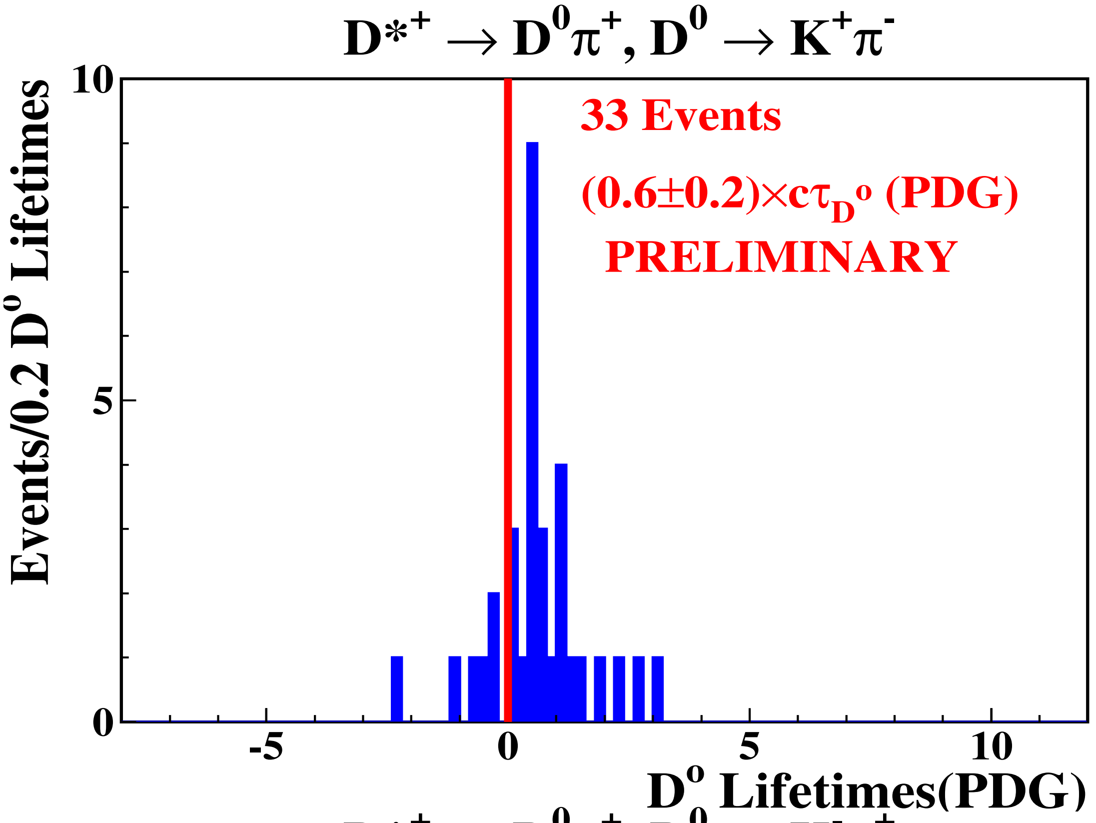


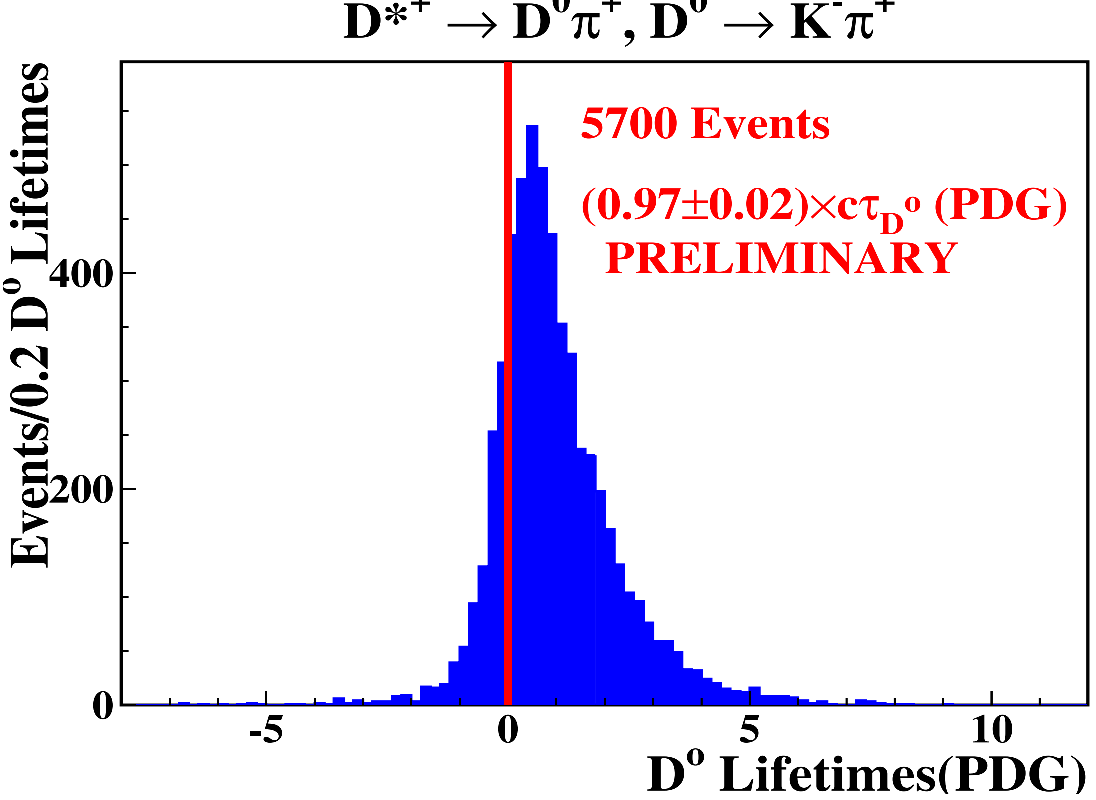
Requiring decay asymmetry suppresses misidentified right-sign background.

Combinatorics

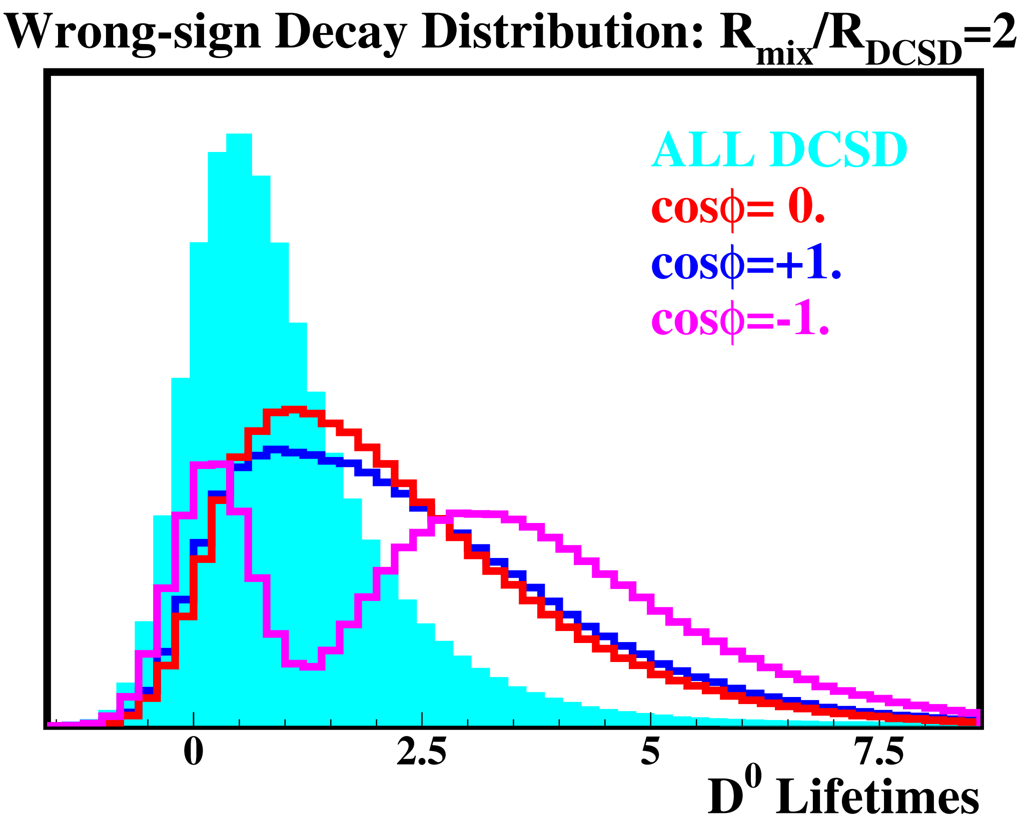
Combinatoric backgrounds suppressed by $\frac{dE}{dx}$ particle ID.

Proper Decay Time





Toy MC: Interference Impacts Decay Distribution



- Pure DCSD ($\langle t \rangle = \tau_{D^0}$) Pure Mixing ($\langle t \rangle = 3\tau_{D^0}$)
- Presence of Mixing changes the MEAN of wrong-sign decay distribution
- Measuring the mean wrong-sign decay time is straight-forward.
- Presence of Interference SIGNIFICANTLY alters shape of decay distribution.

Wrong-Sign Decay Time

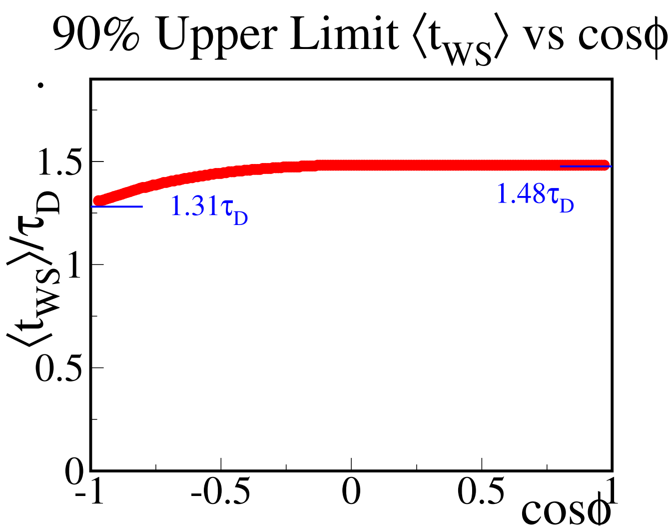
Wrong-sign Lifetimes - A Statistical Approach

Mode	$N_{\rm fit}$	$\langle t \rangle$ (τ_{D^0})
Signal	17.3 ± 5.4	?
Real D^0	8.9 ± 0.8	1.0
Other	5.8 ± 0.1	0.0

Mode	$\langle t \rangle$ (τ_{D^0})
DCSD	1.0
Mixing	3.0

$$\langle t_{\rm wrong\ sign} \rangle = (0.65 \pm 0.40({\rm stat{+}syst})) \times \tau_{D^0}$$

(Preliminary)



$t_{\rm wrong\ sign}$ UL @ 90% CL

(Preliminary)

$< 1.48\tau_{\rm D^0}$	$\cos\phi = 0$
$< 1.48\tau_{\rm D^0}$	$\cos\phi = 1$
$< 1.31\tau_{\rm D^0}$	$\cos\phi =$-1

Summary

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

(Preliminary)

- first measurement at 3σ, using 60% of the dataset

$$\langle t_{\rm wrong\ sign}\rangle = (0.65 \pm 0.40(\rm stat{+}syst)) \times \tau_{D^0}$$

(Preliminary)

Still to come...

- Lifetime fit to $(\mathrm{R}_{\mathrm{DCSD}} + [\sqrt{2\mathrm{R}_{\mathrm{DCSD}}\mathrm{R}_{\mathrm{Mix}}}\cos\phi]t + \frac{1}{2}\mathrm{R}_{\mathrm{Mix}}t^2) \times \exp(-t)$
- Full $9fb^{-1}$ CLEO II.V dataset
- $\mathrm{D}^0 \rightarrow K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-$

$D^0 - \bar{D}^0$ Mixing

Part IV: Mixing Limits

David Asner – UC Santa Barbara
for the CLEO Collaboration

Outline:

- Review Results from Previous CLEO talks
- Present Technique to Limit Mixing
  - $\Delta\Gamma$ from CP Eigenstate Lifetime Analysis
  - ΔM and $\Delta\Gamma$ from R_{ws} and $\langle t_{WS} \rangle$
- Review World Average mixing limits in PDG98
- Preliminary Results and Projected Sensitivity

Highlights From Previous Talks

- CLEO is in a unique position to make these measurements:
  - best spectrometer in the business (charged AND neutral)
  - $9\,fb^{-1}$ of data (35 million charm hadrons)
  - e^+e^- environment (low backgrounds)
  - precision lifetime information (new SVX detector)
  - many D^0 decay modes can be reconstructed
- CP Eigenstate Lifetime Analysis
  - CLEO II.V CP Eigenstate $(5.6 fb^{-1})$ $-0.076 < \frac{\Delta\Gamma}{2\Gamma} < 0.012$
  - E791 CP Eigenstate $-0.042 < \frac{\Delta\Gamma}{2\Gamma} < 0.058$
- CLEO II.V Hadronic Analyses $(5.6 fb^{-1})$
  - Most precise wrong-sign rate measurement
    $R_{\mathrm{ws}} = (0.31 \pm 0.09 \pm 0.07)\%$ PRELIMINARY
  - Reasonable flight-distance resolution
    $t_{\mathrm{ws}} = (0.65 \pm 0.40(\mathrm{stat} + \mathrm{sys})) \times \tau_{D^0}$ PRELIMINARY
- DCSD and Mixing amplitudes can interfere:
  - $(\mathrm{R_{DCSD}} + [\sqrt{2\mathrm{R_{DCSD}}\mathrm{R_{Mix}}}\cos\phi]t + \frac{1}{2}\mathrm{R_{Mix}}t^2) \times \exp(-t)$
  - where $\mathrm{R_{Mix}} = \frac{1}{2}(x^2 + y^2)$ and ϕ function of Dalitz location
  - $K\pi$ only $\phi = \tan^{-1}\left(-2\frac{\Delta M}{\Delta\Gamma}\right) + \delta_s = \tan^{-1}\left(-\frac{x}{y}\right) + \delta_s$

– δ_s expected to be small (Phys.Lett.B383:475-481,1996)

$\Rightarrow$ convert $\mathrm{R_{mix}}, \cos\phi$ limits to $x = \dfrac{\Delta M}{\overline{\Gamma}}$ and $y = \dfrac{\Delta\Gamma}{2\overline{\Gamma}}$

Time-integrate wrong-sign rate

$$R_{\mathrm{WS}} = R_{\mathrm{DCSD}} + \sqrt{2R_{\mathrm{DCSD}}R_{\mathrm{Mix}}}\cos\phi + R_{\mathrm{Mix}},$$

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

Mean wrong-sign decay time

$$\langle t_{\mathrm{WS}}\rangle = \frac{R_{\mathrm{DCSD}} + 2\sqrt{2R_{\mathrm{Mix}}R_{\mathrm{DCSD}}}\cos\phi + 3R_{\mathrm{Mix}}}{R_{\mathrm{DCSD}} + \sqrt{2R_{\mathrm{Mix}}R_{\mathrm{DCSD}}}\cos\phi + R_{\mathrm{Mix}}}$$

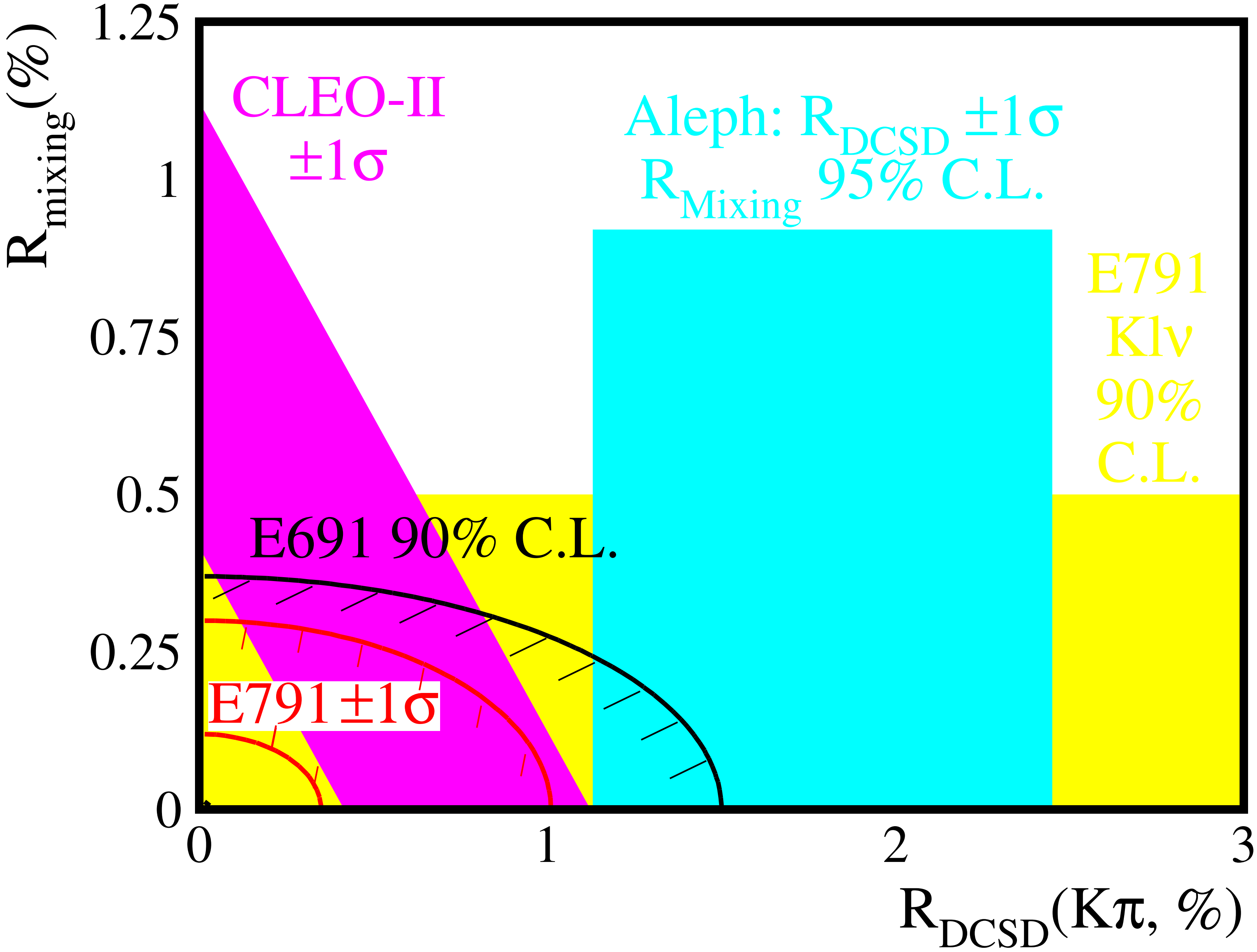
$t_{\mathrm{ws}} = (0.65 \pm 0.40(\mathrm{stat} + \mathrm{sys})) \times \tau_{D^0}$ PRELIMINARY

Limits on R_{WS} and t_{WS} define 3D allowed region in

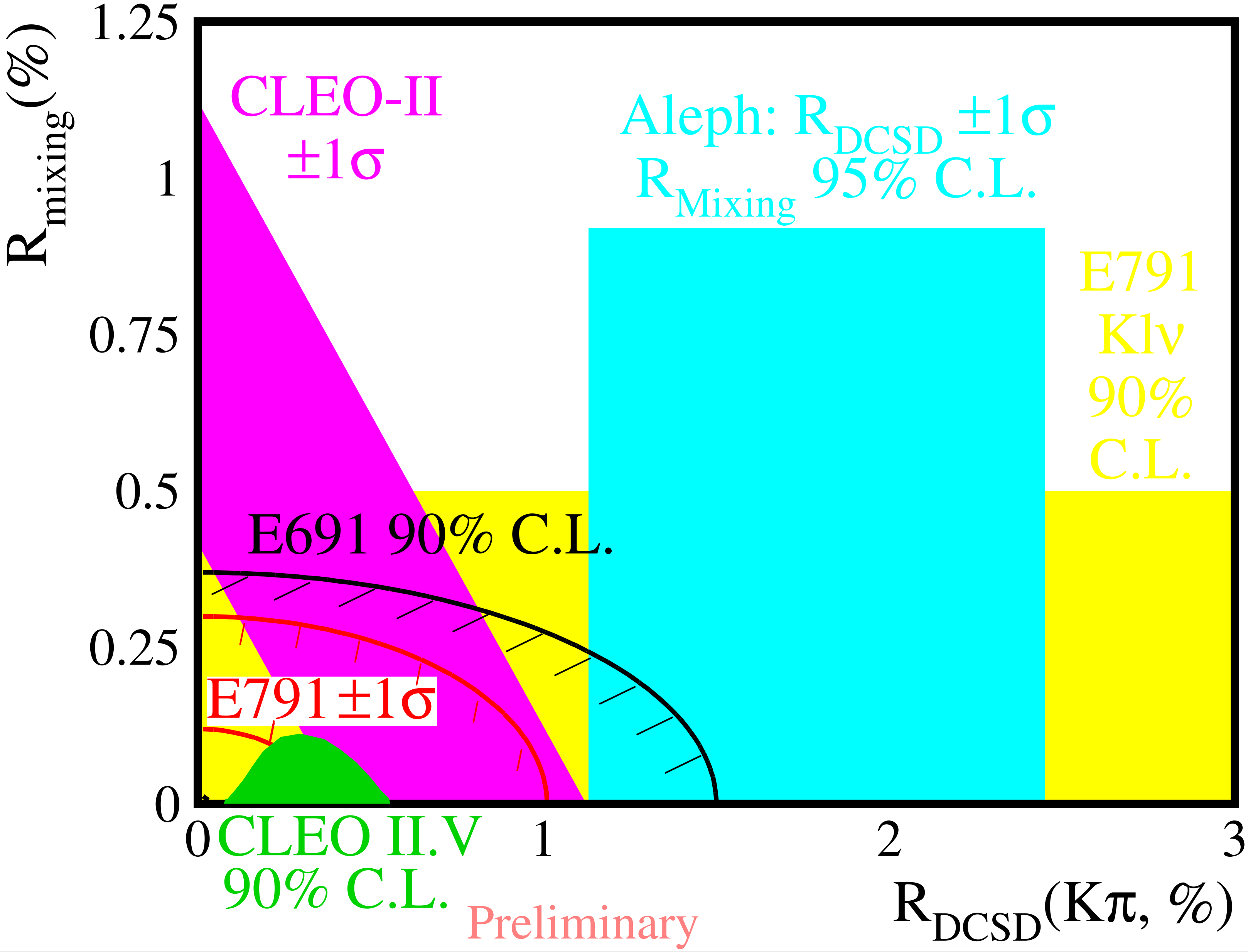
$$R_{\mathrm{DCSD}} \text{ vs } R_{\mathrm{mix}} \text{ vs } \cos\phi$$

- E691, E791, CLEO-II, Aleph have published results
  $\rightarrow$ Compare CLEO-II.V preliminary result at $\cos\phi$=0
- Maximally destructive interference ($\cos\phi$=-1) yields weakest limit on R_{Mix} $\rightarrow$ 2D projection of R_{mix} vs $\cos\phi$
- Convert R_{mix} vs $\cos\phi$ to x vs y
- Combine with CP eigenstate analysis

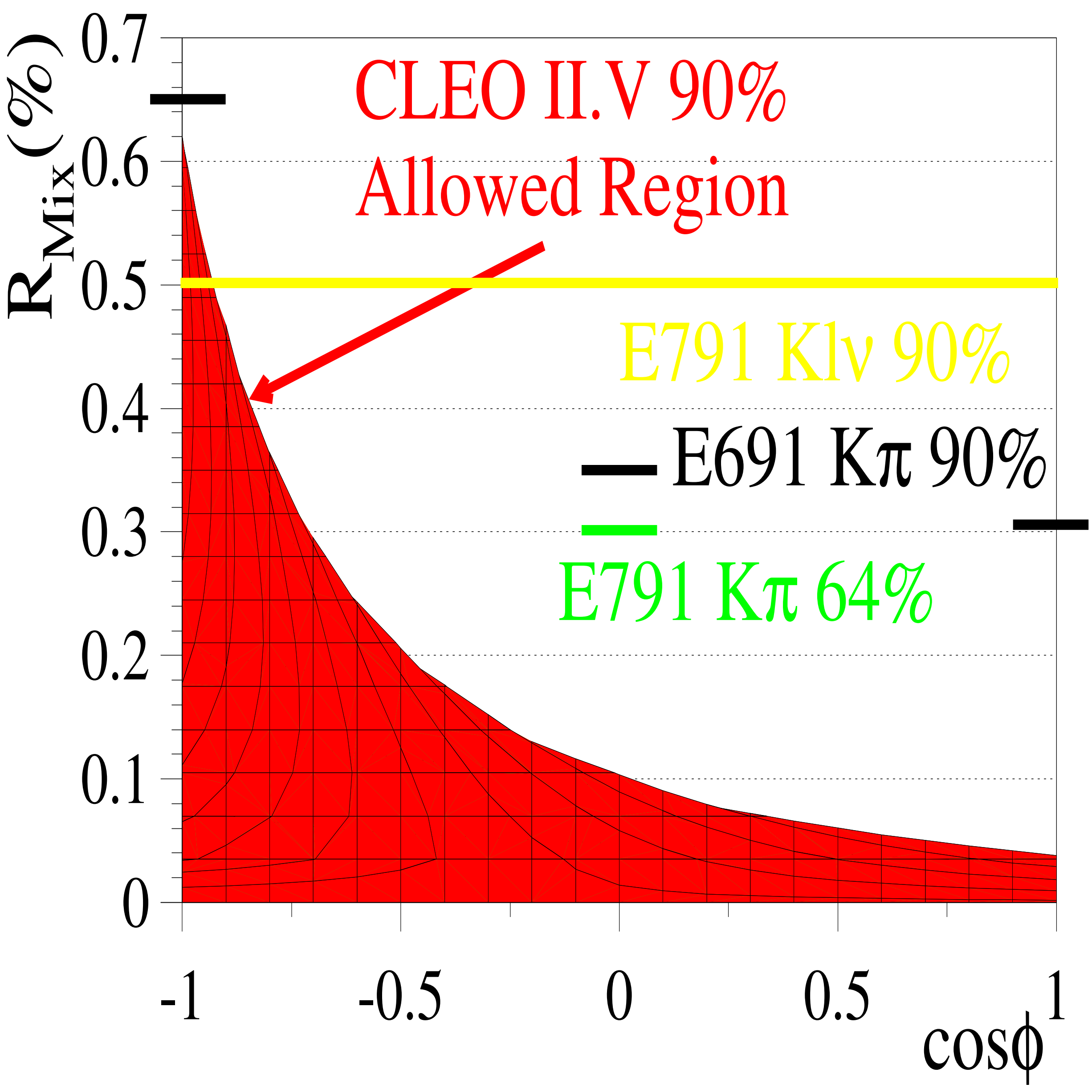
D^0 Mixing Allowed Regions ($\cos\phi=0$)



D^0 Mixing Allowed Regions ($\cos\phi=0$)



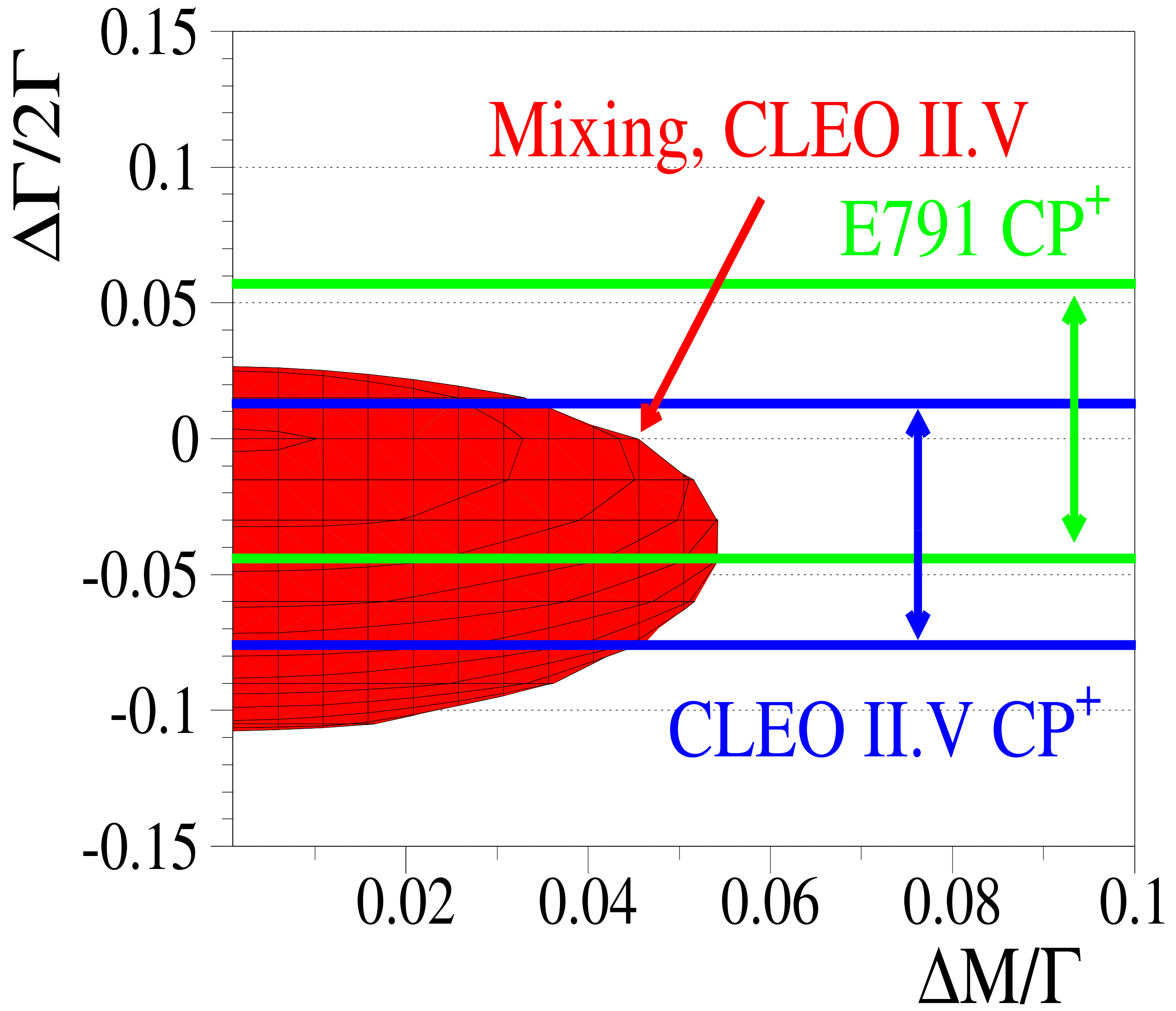
PRELIMINARY



- CLEO-II.V limits significantly tighter than other Hadronic analyses. Full Dataset will constrain $R_{mix} < 5 \times 10^{-4}$ (wrong-sign + CP eigenstate analyses)
- DCSD amplitude has a relative minus sign since $\sin\theta_c = V_{cd} = -V_{us}$ and $y > 0$ is expected (as in K^0) implies

$\cos\phi$ near 1 in the Standard Model.

90% Allowed Regions



- CLEO II.V Mixing Analysis $\frac{\Delta M}{\Gamma} < 0.054$

  Preliminary $-0.108 < \frac{\Delta\Gamma}{2\Gamma} < 0.027$

- CLEO II.V CP Eigenstate

  Preliminary $-0.076 < \frac{\Delta\Gamma}{2\Gamma} < 0.012$

- E791 CP Eigenstate $-0.042 < \frac{\Delta\Gamma}{2\Gamma} < 0.058$

Competitive Mixing Limits from CLEO II.V

	Preliminary	Projected	E791
$x = \frac{\Delta M}{\Gamma}$	< 0.054	< 0.03*	< 0.1
$y > 0, +\frac{\Delta\Gamma}{2\Gamma}$	< 0.012	< 0.01	< 0.058
$y < 0, -\frac{\Delta\Gamma}{2\Gamma}$	> -0.076	> -0.01	> -0.042
$\mathrm{R}_{\mathrm{Mix}}$	$< 0.25\%$	$< 0.05\%$	0.5%

* $D^0 \rightarrow$ Semileptonic analysis may have greater sensitivity

- CLEO-II.V has obtained the most restrictive $D^0 - \bar{D}^0$ mixing limits using $5.6 fb^{-1}$
- CLEO mixing program has many internal crosschecks from statistically independent analyses
- E831 (FOCUS) data sample $\sim 200\times$ E691. Statistics and previous fixed target results suggest sensitivity comparable to CLEO-II.V dataset ($9.1 fb^{-1}$).
- The level of mixing predicted by the standard model is small enough that effects from physics beyond the standard model may be seen.
- CLEO-III,BELLE,BaBar will have greater sensitivity