D^0-$\overline{D}^0$ Mixing at CLEO-II.V

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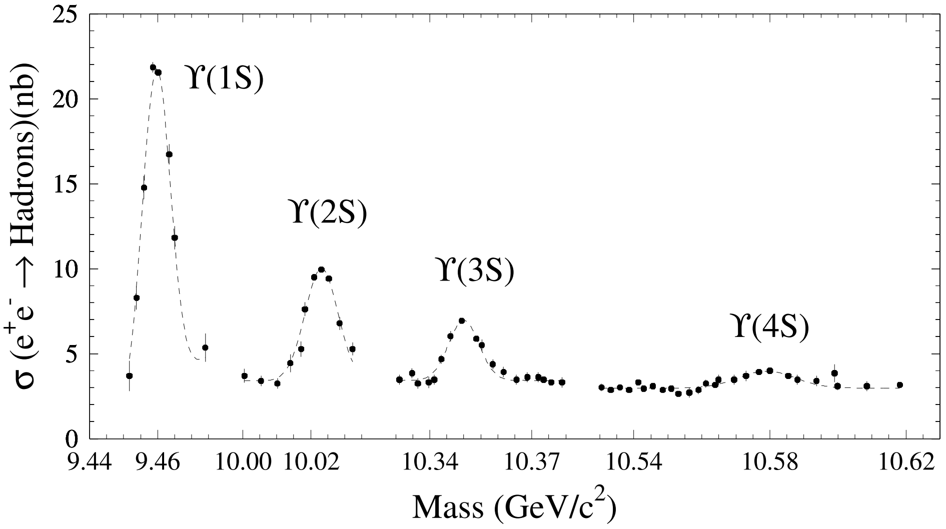
for the CLEO Collaboration

Outline:

- Detector Overview
- Brief Theoretical Overview
- CP Eigenstate Lifetime Analysis – $D^0 \rightarrow CP^+, CP^-, \overline{CP}$
  - Limit $\Delta\Gamma$ Mixing
- $D^0 \rightarrow K^+\pi^-$ "Wrong Sign"
  - Rate Analysis - $\frac{\mathcal{B}(D^0 \rightarrow K^+\pi^-)}{\mathcal{B}(D^0 \rightarrow K^-\pi^+)}$
  - Lifetime Analysis - $\langle\tau_{WS}\rangle$
  - Limit $\Delta\Gamma$ and ΔM Mixing

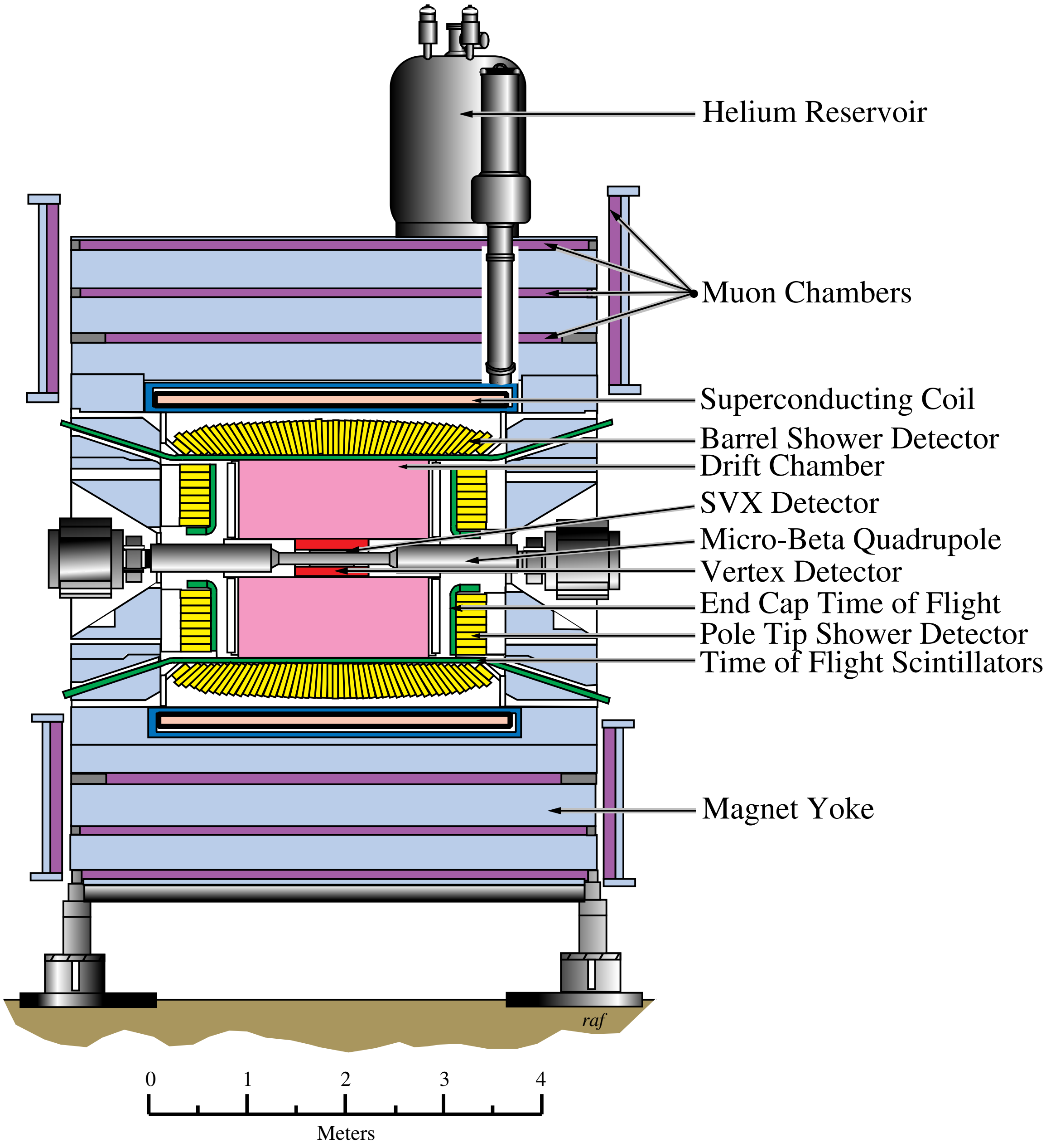
CESR - Cornell Electron Storage Ring

e^+e^- collider - $L_{\rm peak} \sim 8.0 \times 10^{32}{\rm cm}^{-2}{\rm s}^{-1}$ at the $\Upsilon(4S)$

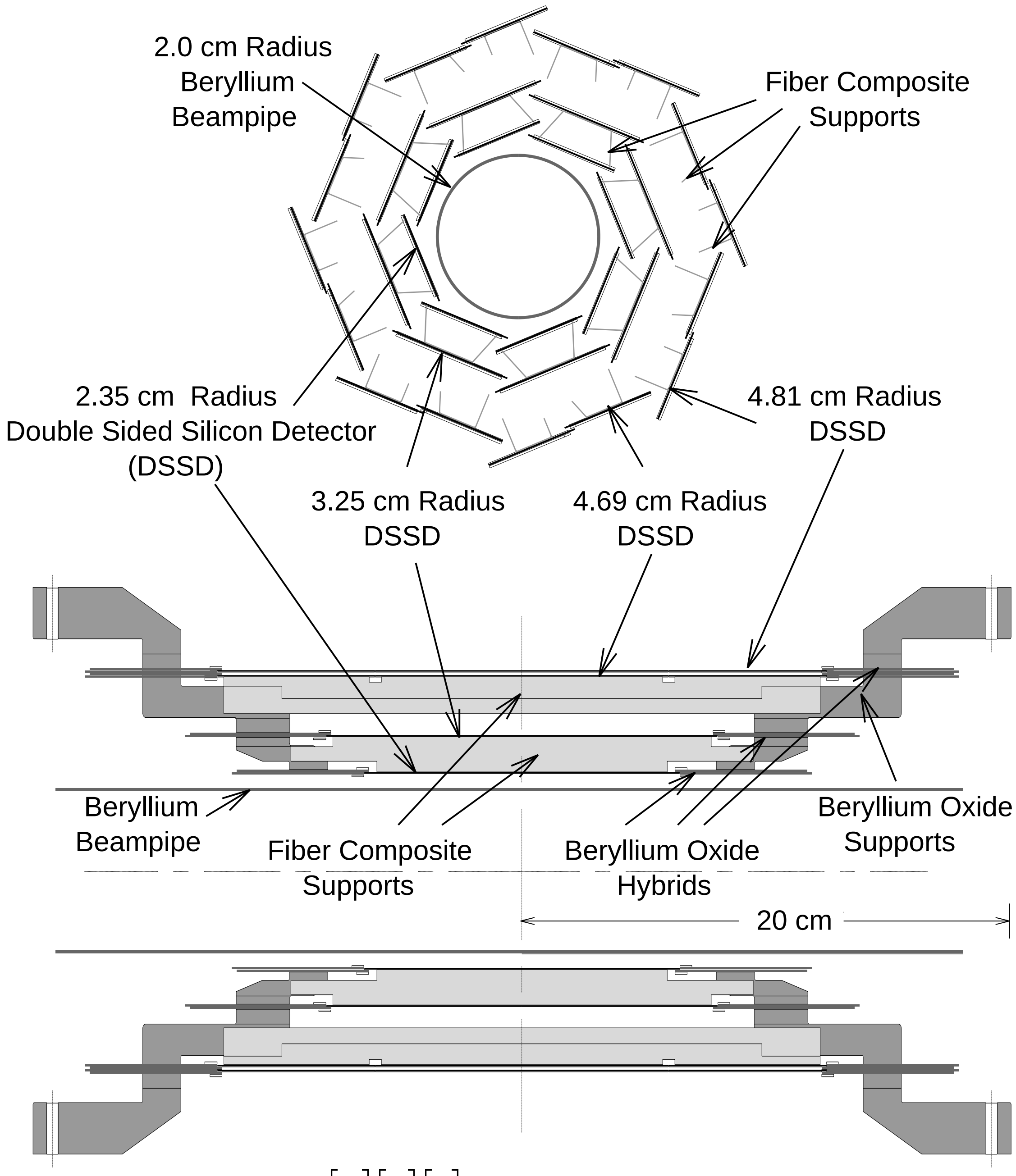


Operating point:	$\int L$ fb^{-1}	
	Presented at LLWI	CLEO II.V (Complete)
$\Upsilon(4S)$	3.6	6.3
Continuum	2.0	3.0
# charm mesons	21×10^6	35×10^6

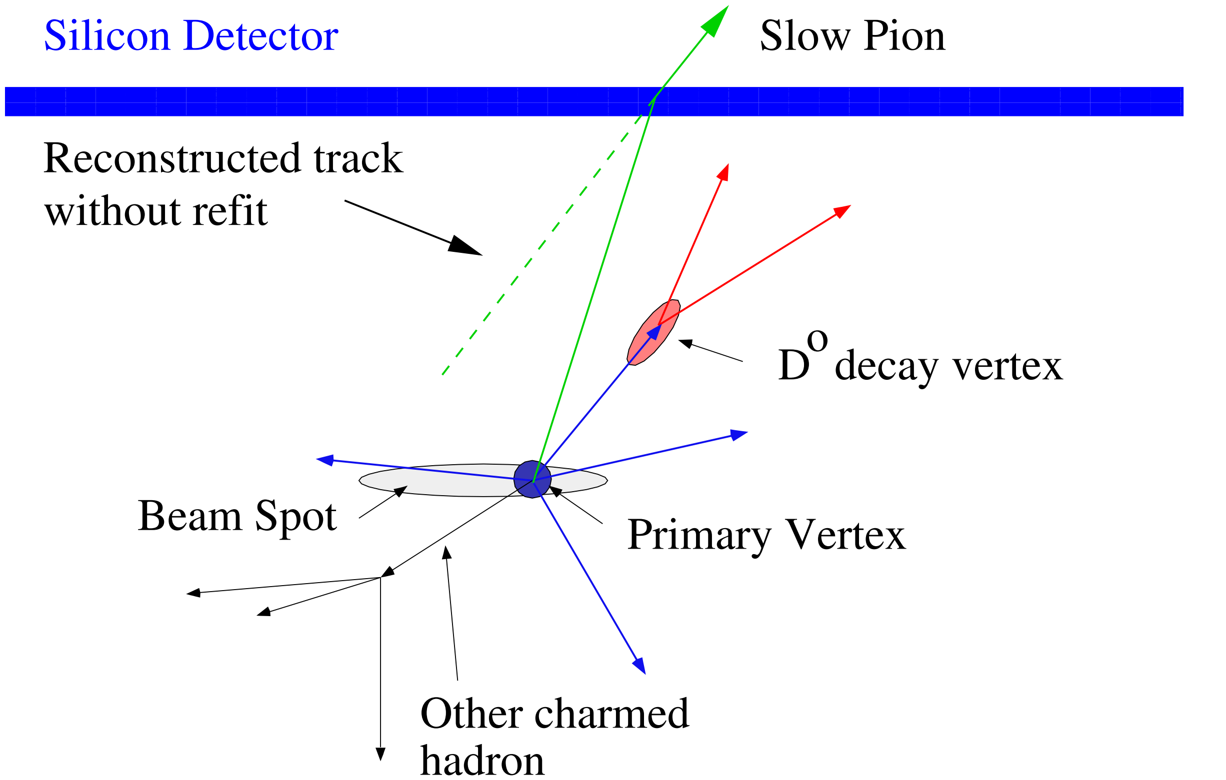
CLEO-II Detector

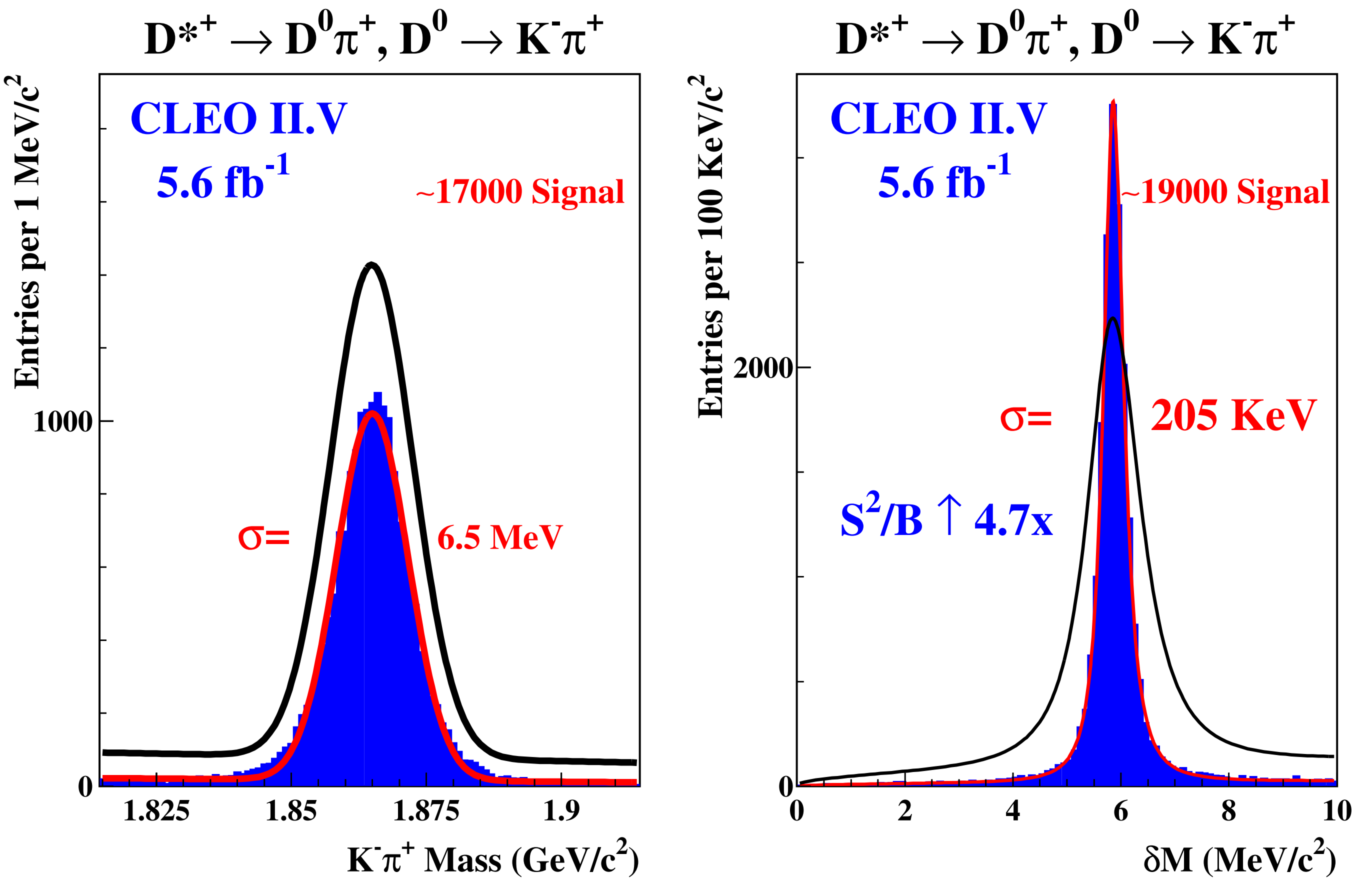


CLEO-II Silicon Vertex Detector



$\begin{bmatrix} u \\ \ \end{bmatrix}\begin{bmatrix} c \\ s \end{bmatrix}\begin{bmatrix} \ \\ b \end{bmatrix}$ *High Energy Physics*


Silicon Detector
Slow Pion
Reconstructed track
without refit
D^O decay vertex
Beam Spot
Primary Vertex
Other charmed
hadron


D*+ → D0π+, D0 → K-π+
CLEO II.V
5.6 fb-1
~17000 Signal
σ= 6.5 MeV
Entries per 1 MeV/c2
1000
0
1.825
1.85
1.875
1.9
K-π+ Mass (GeV/c2)
D*+ → D0π+, D0 → K-π+
CLEO II.V
5.6 fb-1
~19000 Signal
σ= 205 KeV
S2/B ↑ 4.7x
Entries per 100 KeV/c2
2000
0
0
2
4
6
8
10
δM (MeV/c2)

Time evolution of D^0 or $\overline{\mathrm{D}}^0$ is determined by Schrödinger's Equation

$$\frac{\partial}{\partial t}\begin{pmatrix} D^0 \\ \overline{D^0} \end{pmatrix} = \begin{bmatrix} -iM - \Gamma/2 & -iM_{12} - \Gamma_{12}/2 \\ -iM_{12}^* - \Gamma_{12}^*/2 & -iM - \Gamma/2 \end{bmatrix}\begin{pmatrix} D^0 \\ \overline{D^0} \end{pmatrix} \quad (1)$$

Diagonalizing, Schrödinger's Equation has solutions with eigenvalues

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

for the "light" and "heavy" eigenstates

$$\begin{aligned} |D_L\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \quad (3) \\ |D_H\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

with $$\frac{q}{p} = \frac{1+\epsilon}{1-\epsilon} = \left(\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}\right)^{\frac{1}{2}} = \exp 2i\phi_M \quad (4)$$

Define the variables which relate to experimental quantities.

$$\Delta M = m_H - m_L; \qquad x = \Delta M/\Gamma \quad (5)$$

Mixing via Virtual or off – shell intermediate states

$$\Delta\Gamma = \gamma_H - \gamma_L; \qquad y = \Delta\Gamma/2\Gamma$$

Mixing via Real or on – shell intermediate states

Standard Model Prediction:

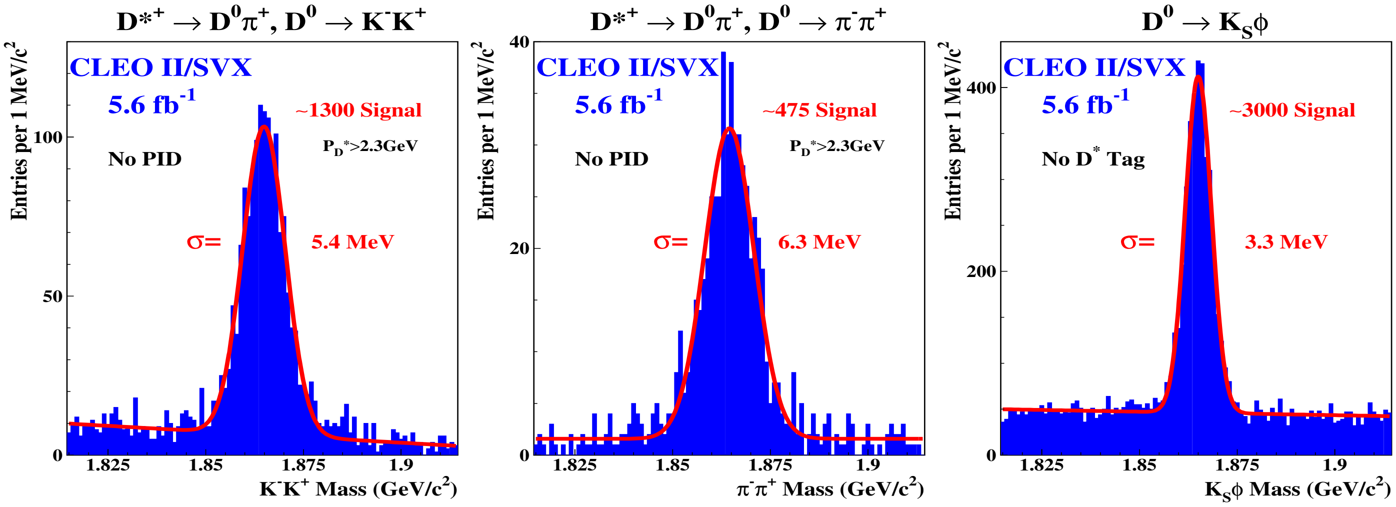
$x, |y| \sim (\tan^2\theta_c = 0.051)\times$(mass suppression factor $[\frac{1}{100} \to \frac{1}{20{,}000}]$)

GIM cancellation depends on SU(3) symmetry $\frac{\mathcal{B}(\mathrm{D}^0 \to K^+K^-)}{\mathcal{B}(\mathrm{D}^0 \to \pi^+\pi^-)} \sim 3$

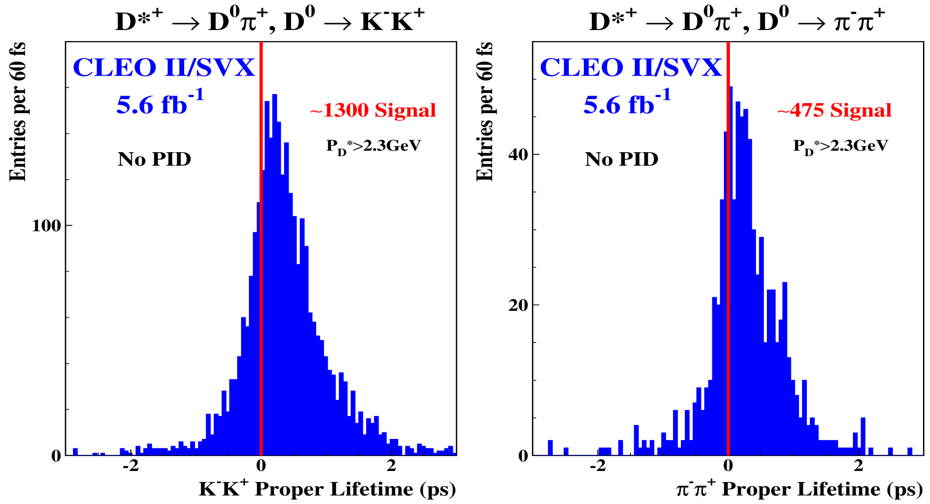
Lifetime Analysis $\mathrm{CP}^+, \mathrm{CP}^-, \overline{\mathrm{CP}}$ $\Rightarrow y = \frac{\Delta\Gamma}{2\Gamma}$

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

$\mathrm{D}^0 \rightarrow K^+K^-$ $\mathrm{D}^0 \rightarrow \pi^+\pi^-$ $\mathrm{D}^0 \rightarrow K^0_s\phi$



Mass (GeV/c^2)



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

Proper Decay Time (ps)

E791 has performed this analysis

- $\mathrm{CP}^+ = K^+K^-$
- $\overline{\mathrm{CP}} = K^-\pi^+$

E791 Reported at DPF'99

$$\Delta\Gamma = 0.04 \pm 0.14 \pm 0.05 \text{ ps}^{-1}$$
$$\Rightarrow -0.042 < y < 0.058 \text{ @ } 90\% \text{ C.L.}$$

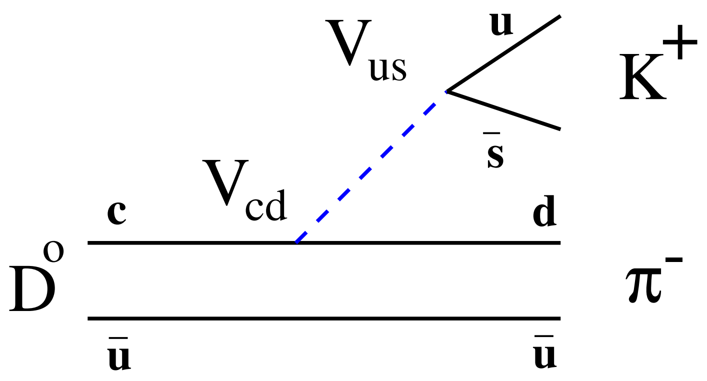
$$\Delta\Gamma < 0 \Rightarrow \mathrm{CP}^+ \text{ longer lifetime}$$
$$\Delta\Gamma > 0 \Rightarrow \mathrm{CP}^- \text{ longer lifetime}$$

CLEO II.V Sensitivity

- Only K^+K^- $|y| < 0.03$
- Including CP^- modes $|y| < 0.01$

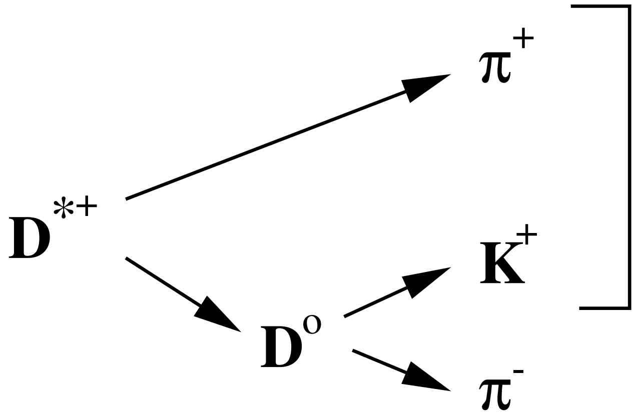
$\Rightarrow$ Remainder of Talk $\mathrm{D}^0 \rightarrow K^+\pi^-$

Doubly Cabibbo Suppressed Decays (DCSD)

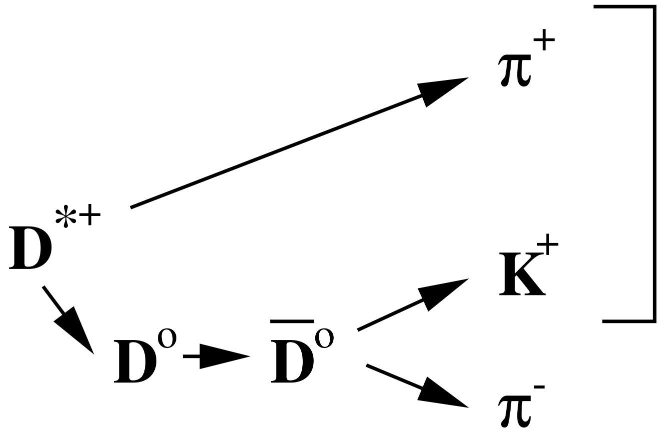


$$\frac{\mathcal{B}\left(D^0\to\overline{f}\right)}{\mathcal{B}\left(D^0\to f\right)} \sim \tan^4\theta_c$$

$$\mathcal{B}\left(D^0\to\overline{f}\right) > \mathcal{B}\left(D^0\to\overline{D}^0\to\overline{f}\right)$$



Wrong Sign
DCSD Decay



Wrong Sign
Mixing

Distinguish Mixing and DCSD with Decay Time Distribution

Time Dependent Wrong-Sign Rate

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

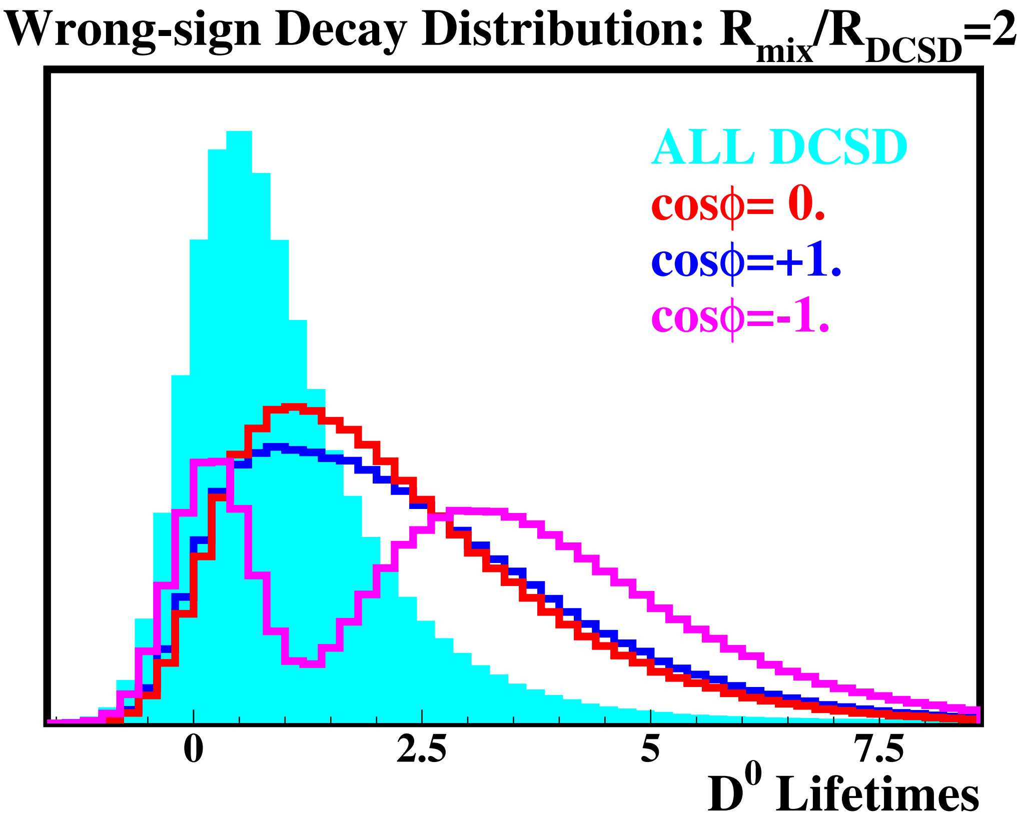
$$\begin{aligned}
\mathrm{R_{Mix}} &= \frac{1}{2}\left(x^2 + y^2\right) \\
\phi &= \tan^{-1}\left(\frac{x}{y}\right) + \delta_s \\
x &= \frac{\Delta M}{\Gamma} \\
y &= \frac{\Delta\Gamma}{2\Gamma}
\end{aligned}$$

(Very) Brief Analysis Outline

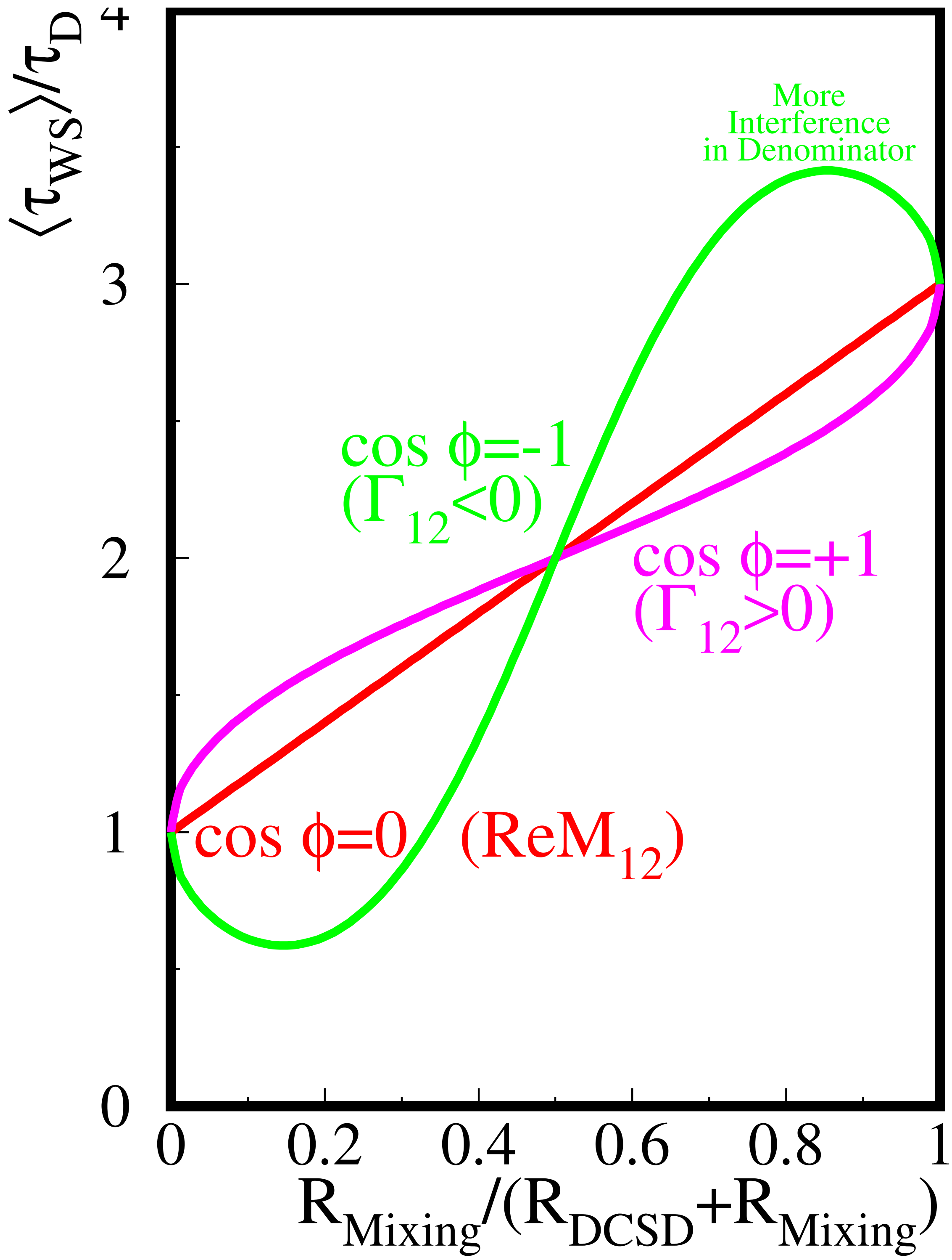
- Measure Time Integrated wrong-sign rate (R_{ws}).
- Measure (Upper Limit) for wrong-sign decay time (τ_{ws})
- Determine mixing limits

1. 2D mixing limit in $\mathrm{R_{DCSD}}$ vs $\mathrm{R_{Mix}}$ with $\cos\phi = 0$
2. 3D mixing limit in $\mathrm{R_{DCSD}}$ vs $\mathrm{R_{Mix}}$ vs $\cos\phi$
   $\Rightarrow \mathrm{R_{Mix}}$ vs $\cos\phi$
3. 2D mixings limit in x vs y

Toy MC: Interference Impacts Decay Distribution

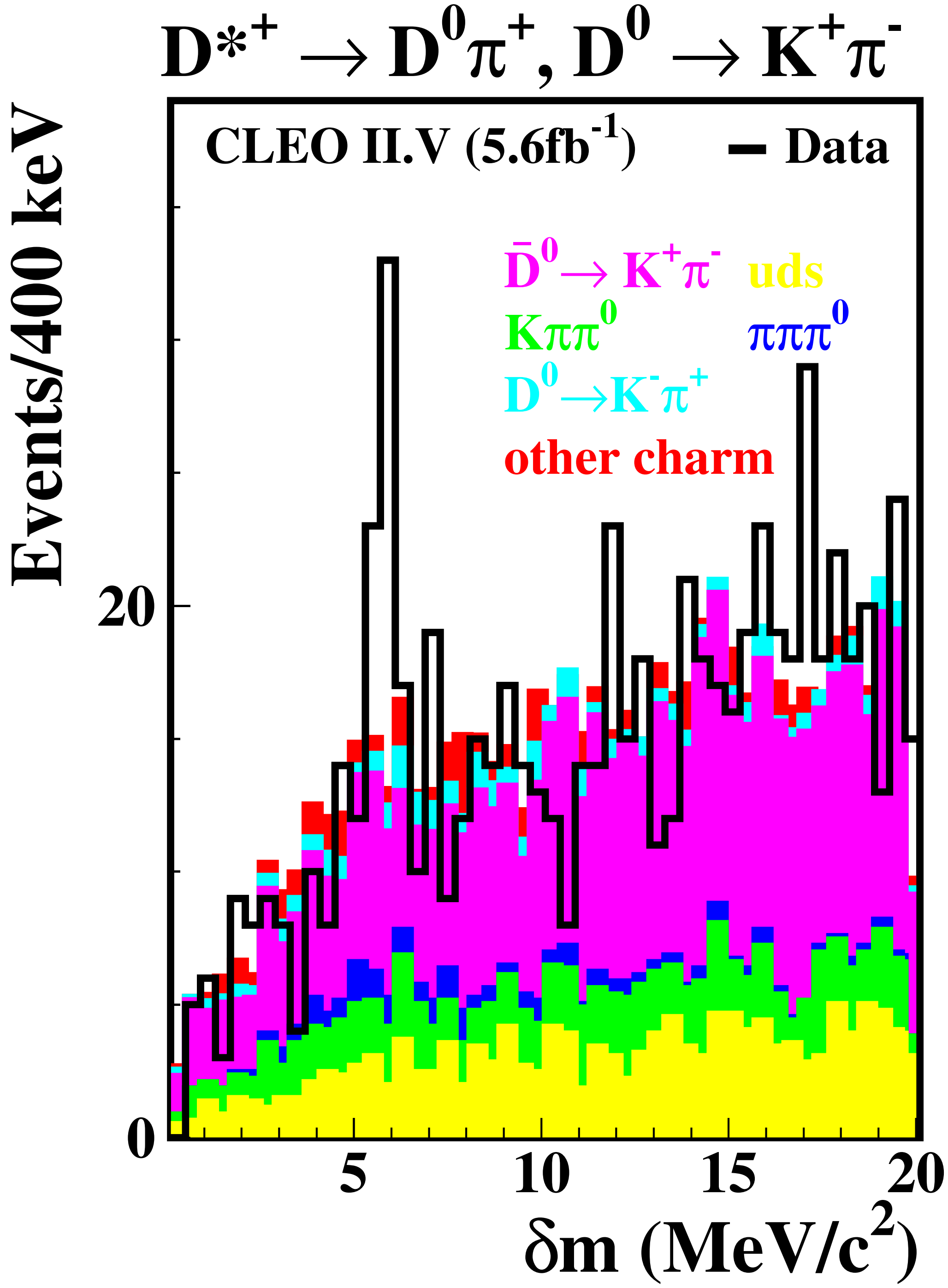


- Pure DCSD ($\langle \mathrm{t} \rangle = \tau_{D^0}$) Pure Mixing ($\langle \mathrm{t} \rangle = 3\tau_{D^0}$)
- Presence of Mixing changes the MEAN of wrong-sign decay distribution
- Determining an Upper Limit on the mean wrong-sign decay time is straight-forward.
- Presence of Interference SIGNIFICANTLY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



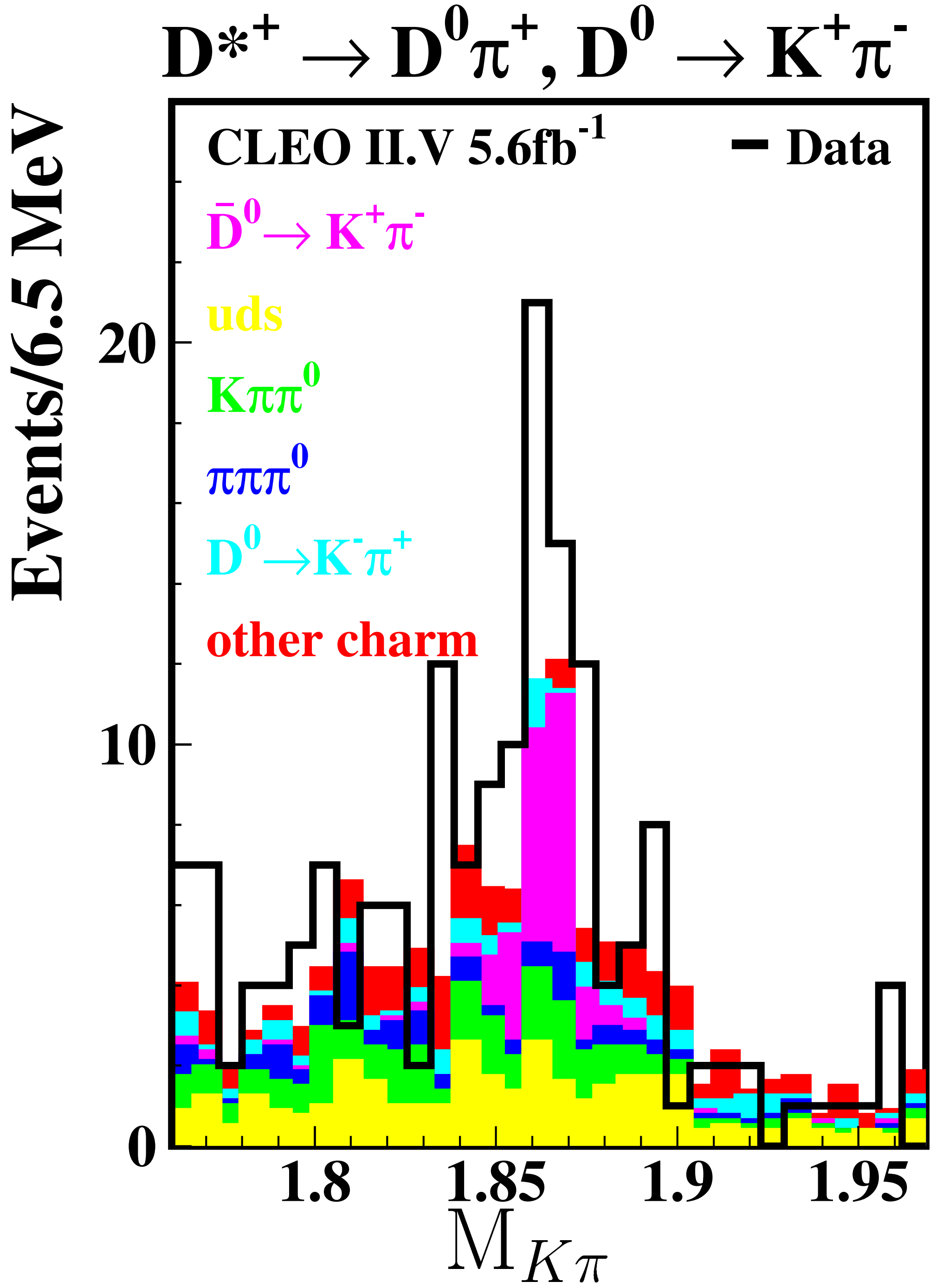
$\langle\tau_{WS}\rangle/\tau_D$
0
1
2
3
4
More
Interference
in Denominator
cos φ=-1
(Γ12<0)
cos φ=+1
(Γ12>0)
cos φ=0 (ReM12)
0
0.2
0.4
0.6
0.8
1
$R_{Mixing}/(R_{DCSD}+R_{Mixing})$

Fit Components, δm Projection



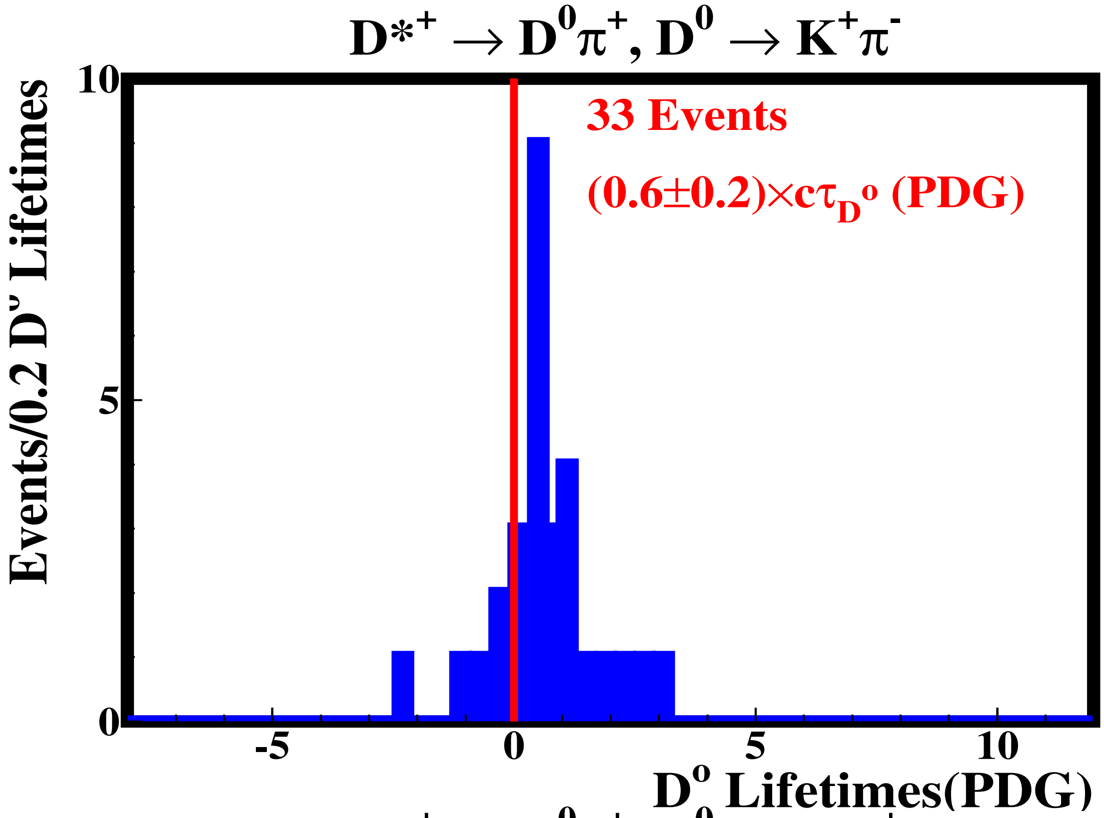
$$R_{\mathrm{ws}} = (0.31 \pm 0.09 \pm 0.07)\%$$

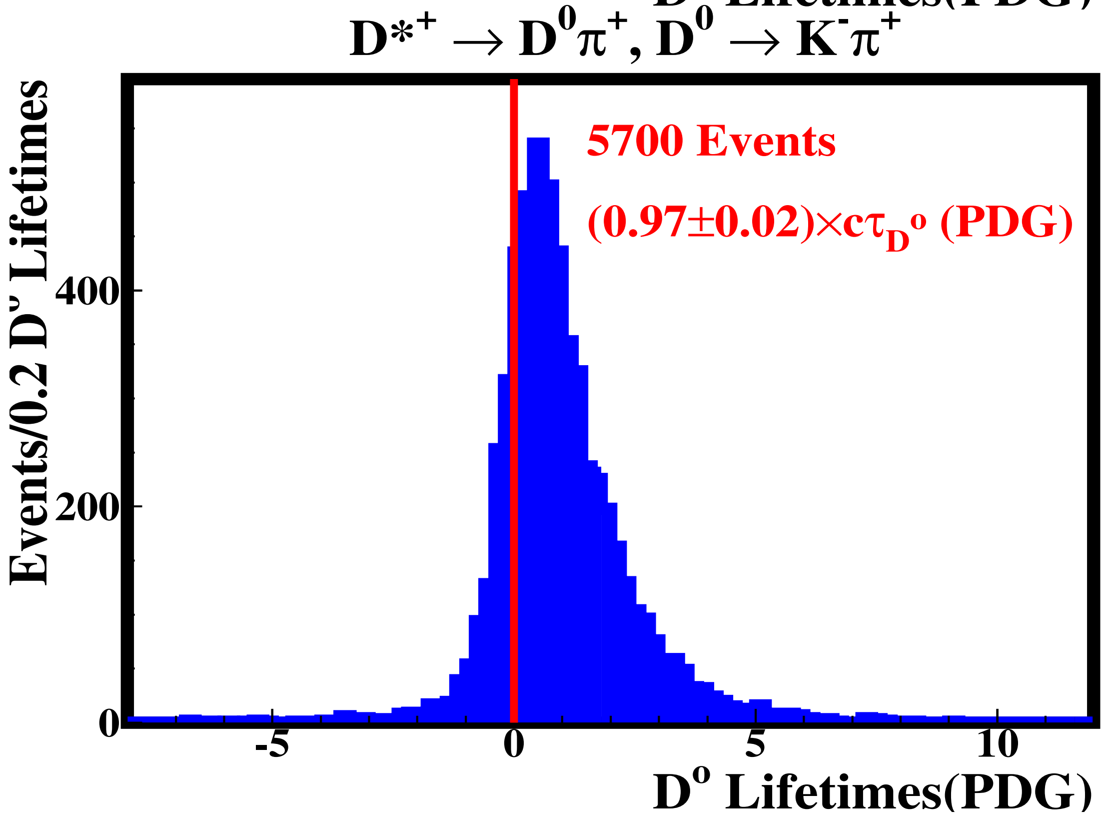
Fit Components, $M_{K\pi}$ Projection



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

Proper Decay Time





Wrong-Sign Summary

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

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

$$R_{ws} = 0.33 \pm 0.13(\mathrm{stat})\% \qquad D^{*+}\mathrm{tags}$$

$$R_{ws} = 0.30 \pm 0.13(\mathrm{stat})\% \qquad D^{*-}\mathrm{tags}$$

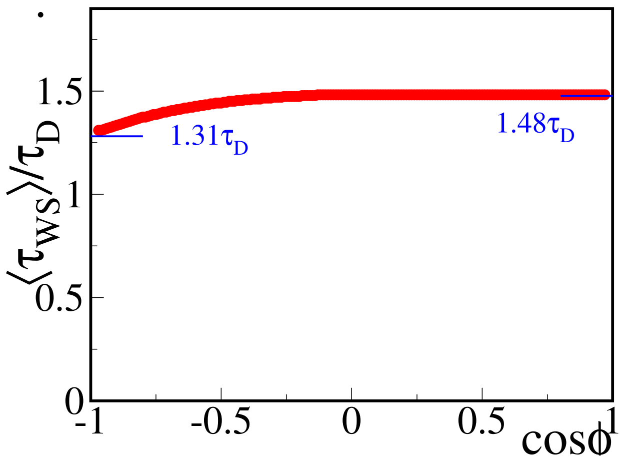
Wrong-sign Lifetimes - A Statistical Approach

Mode	N_{fit}	τ (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	τ (τ_{D^0})
DCSD	1.0
Mixing	3.0

$$\tau_{\mathrm{wrong\ sign}} = (0.65 \pm 0.40(\mathrm{stat})) \times \tau_{D^0}$$

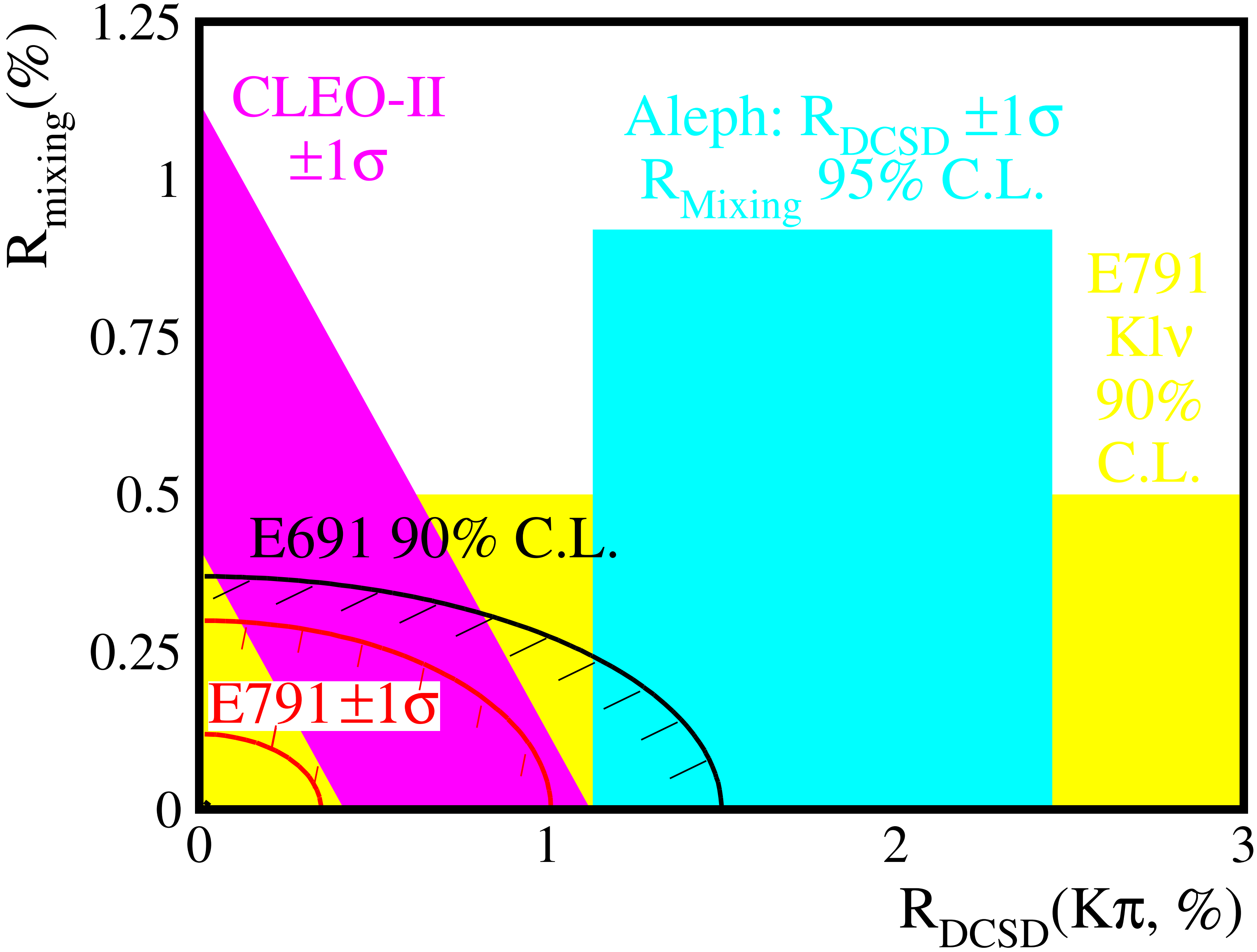
90% Upper Limit $\langle\tau_{WS}\rangle$ vs cosϕ

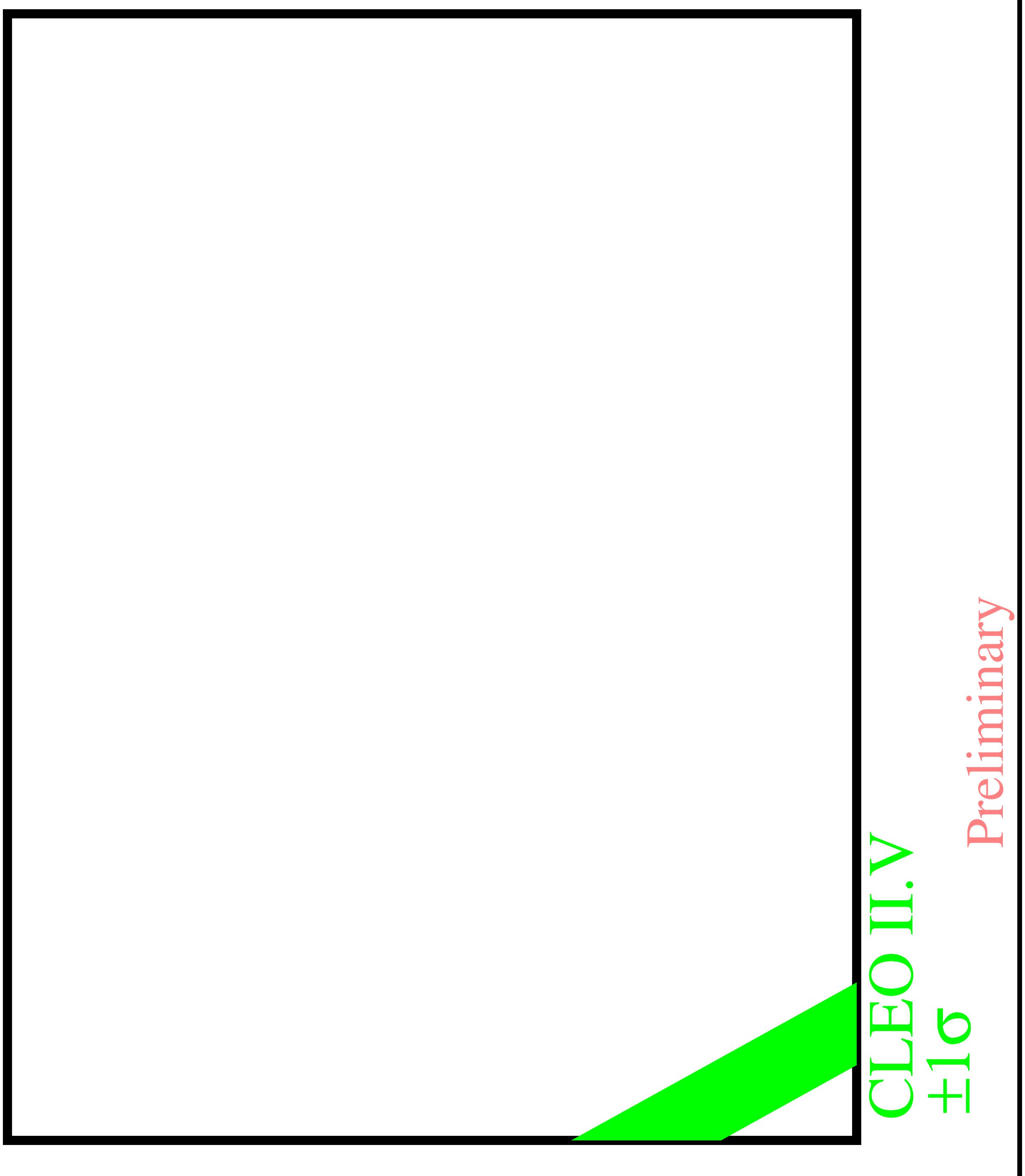


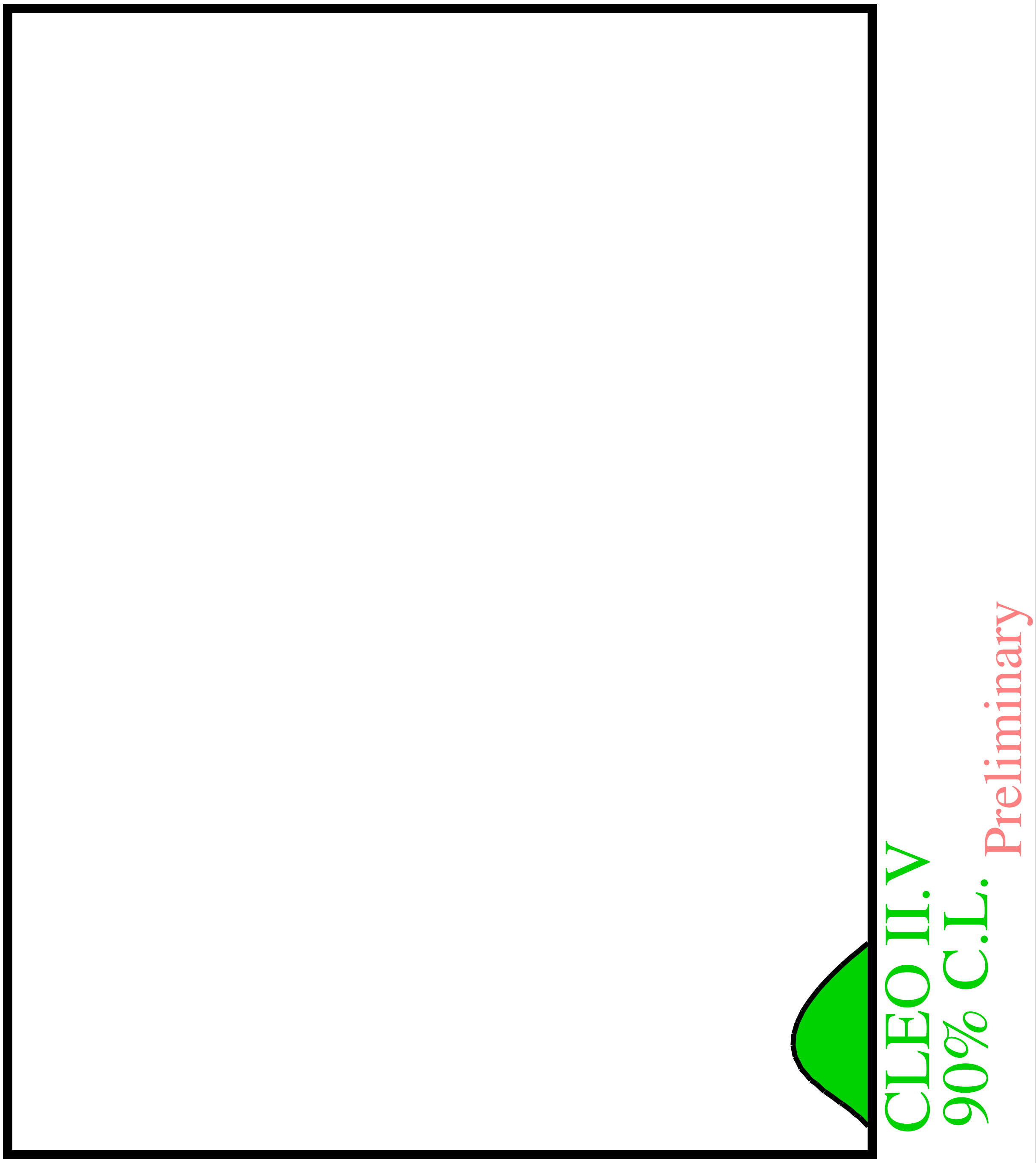
$\tau_{\mathrm{wrong\ sign}}$ UL @ 90% CL

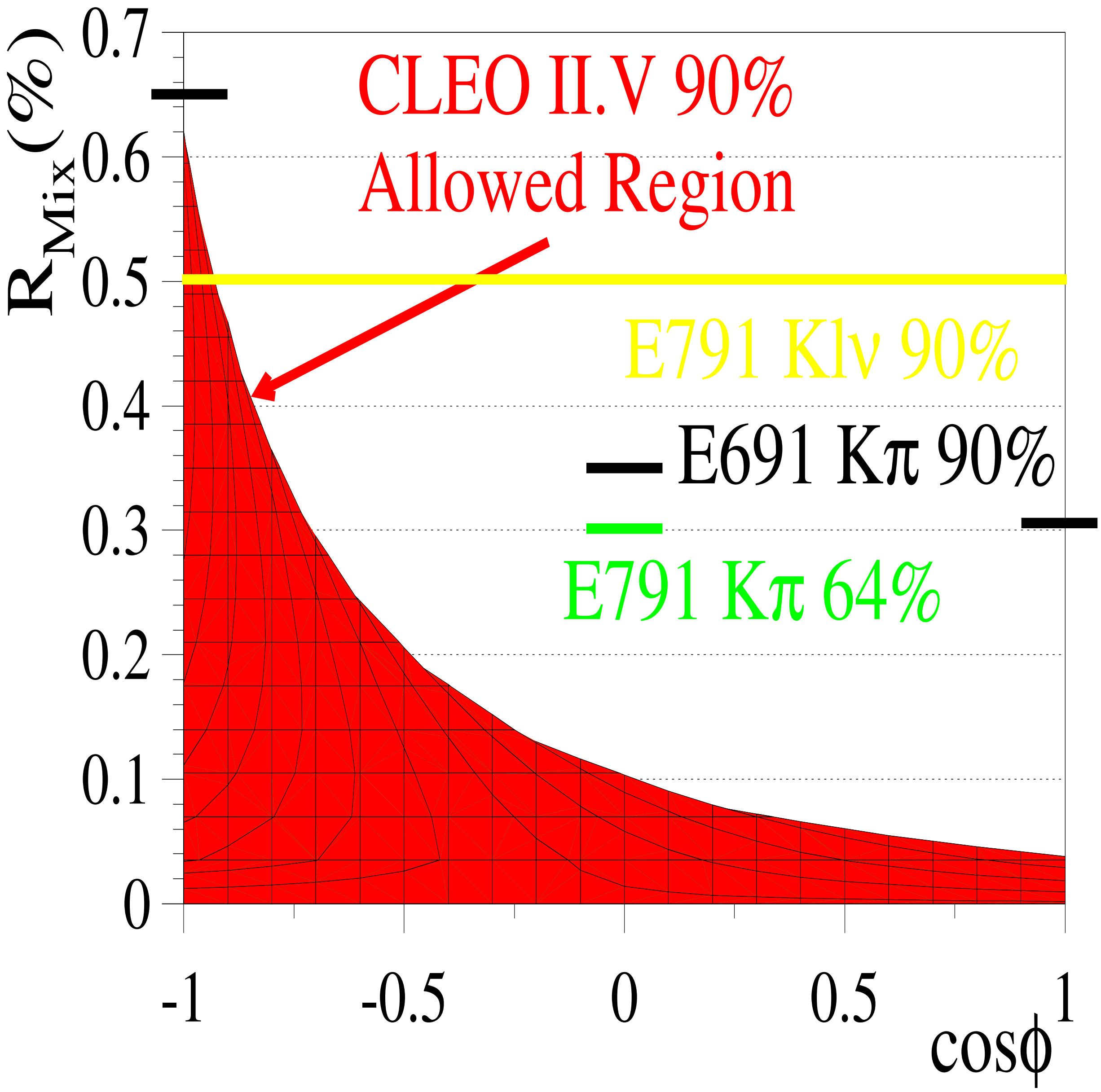
$< 1.48\tau_{D^0}$	$\cos\phi = 0$
$< 1.48\tau_{D^0}$	$\cos\phi = 1$
$< 1.31\tau_{D^0}$	$\cos\phi = -1$

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



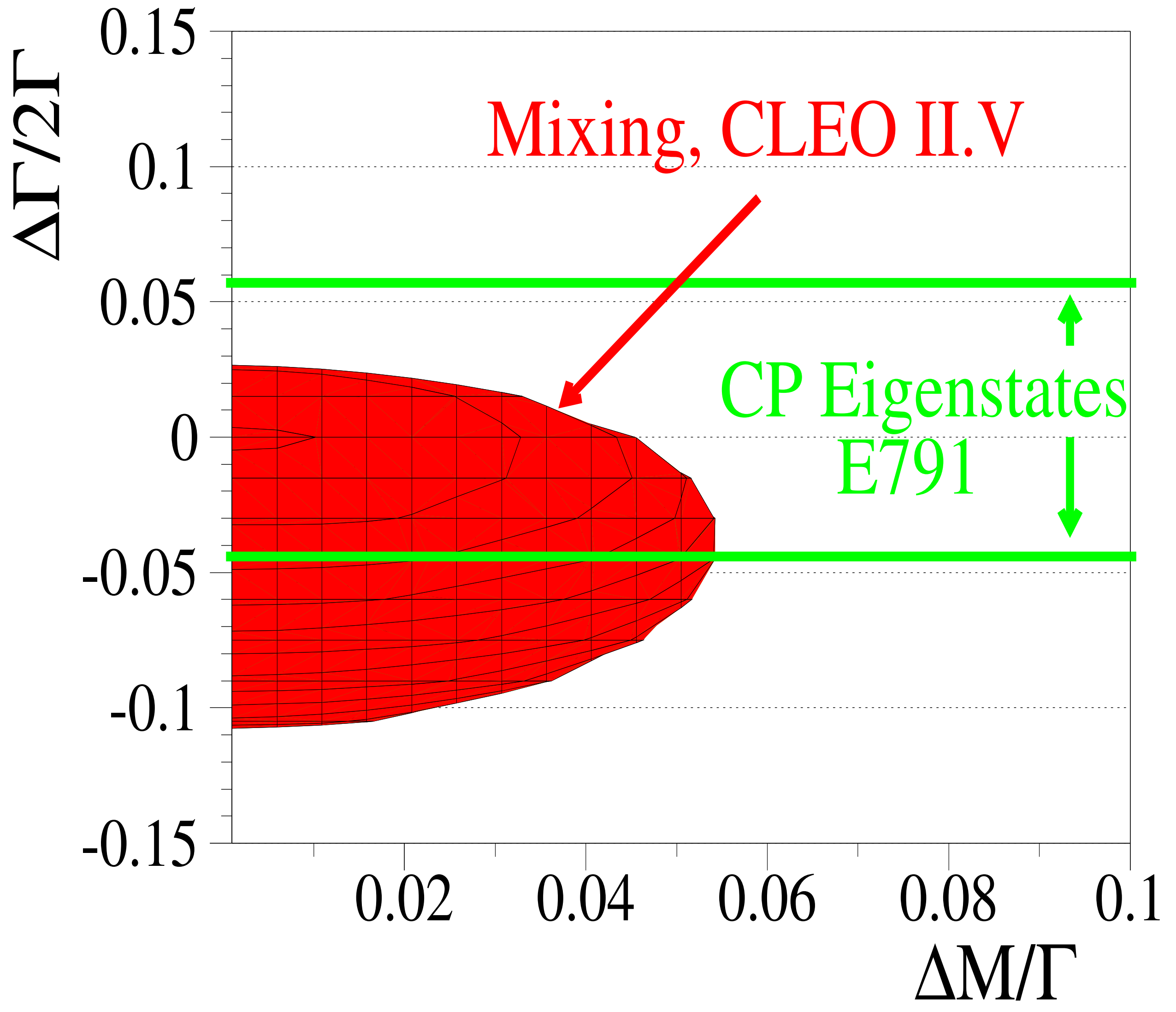

CLEO II.V
$\pm 1\sigma$
Preliminary


CLEO II.V
90% C.L.
Preliminary



- $R_{\rm Mix} < 1.1 \times 10^{-3}$ @ 90% C.L. $\cos\phi = 0$
- $R_{\rm Mix} < 0.4 \times 10^{-3}$ @ 90% C.L. $\cos\phi = +1$
- $R_{\rm Mix} < 6.2 \times 10^{-3}$ @ 90% C.L. $\cos\phi = -1$

90% Allowed Region



- CLEO II.V Mixing Analysis

$$\frac{\Delta M}{\Gamma} < 0.054$$

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

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

Most Precise Relative Branching Fraction Measurement

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

$$R_{\rm ws} = 0.33 \pm 0.13(\text{stat})\% \qquad \text{D}^{*+}\text{tags}$$

$$R_{\rm ws} = 0.30 \pm 0.13(\text{stat})\% \qquad \text{D}^{*-}\text{tags}$$

Competitive Mixing Limits from CLEO II.V

	LLWI	Projected	E791
$x = \frac{\Delta M}{\Gamma}$	< 0.054	< 0.04*	< 0.1
$+y = +\frac{\Delta\Gamma}{2\Gamma}$	< 0.027	< 0.01	< 0.058
$-y = -\frac{\Delta\Gamma}{2\Gamma}$	> -0.108	> -0.01	> -0.042
R_{Mix} with $\cos\phi = 0$	$< 0.11\%$	$< 0.03\%$	0.3%
R_{DCSD}	$< 1.1\%$	$< 0.8\%$	-

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

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Future analysis plans include

- Fit of the wrong-sign decay time distribution
- Determine CP violation limits