D^0 Mixing and CP Violation

- Charm Mixing and $\Delta\Gamma$ Search
- CP Violation
- Summary

Hwanbae Park
Korea University

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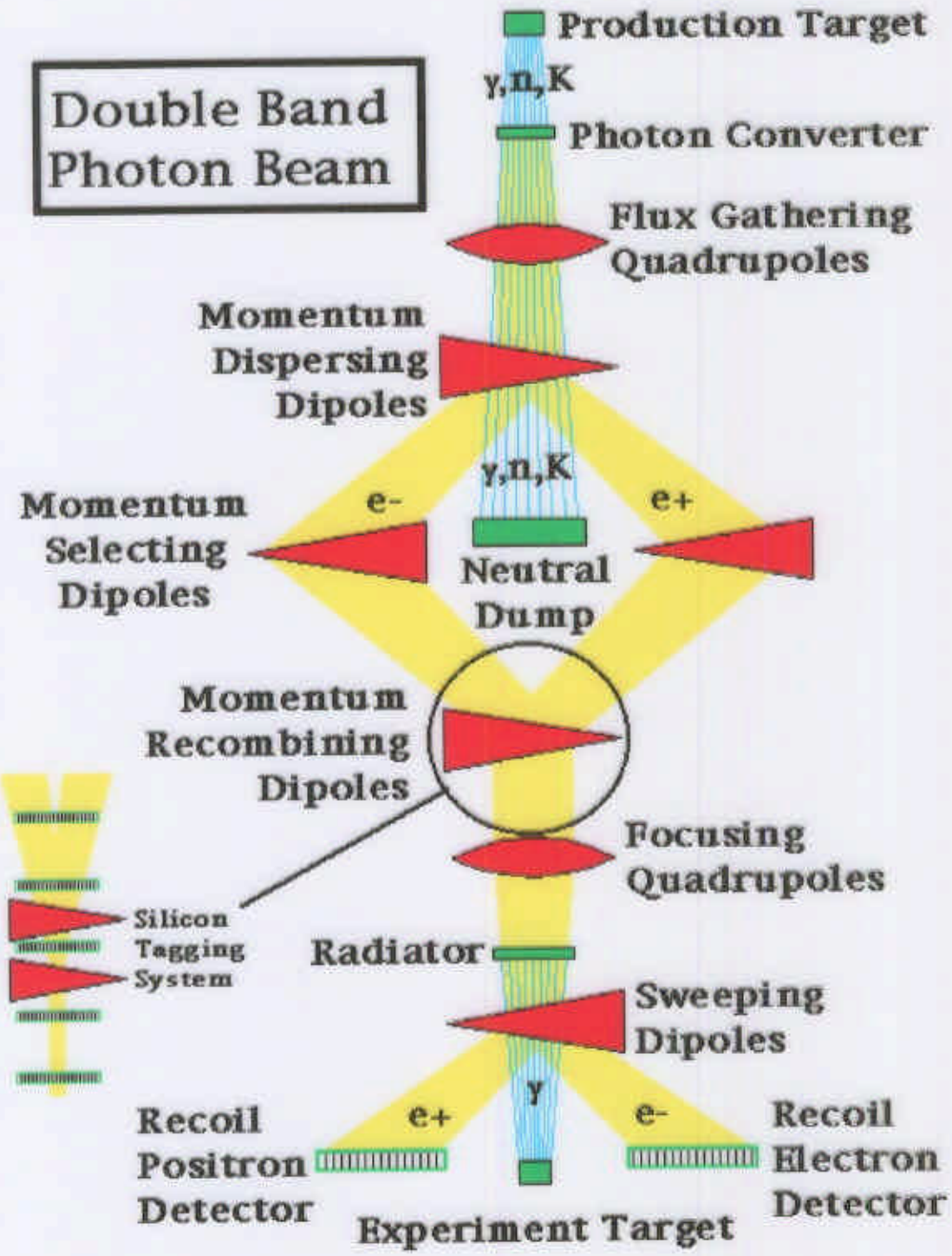
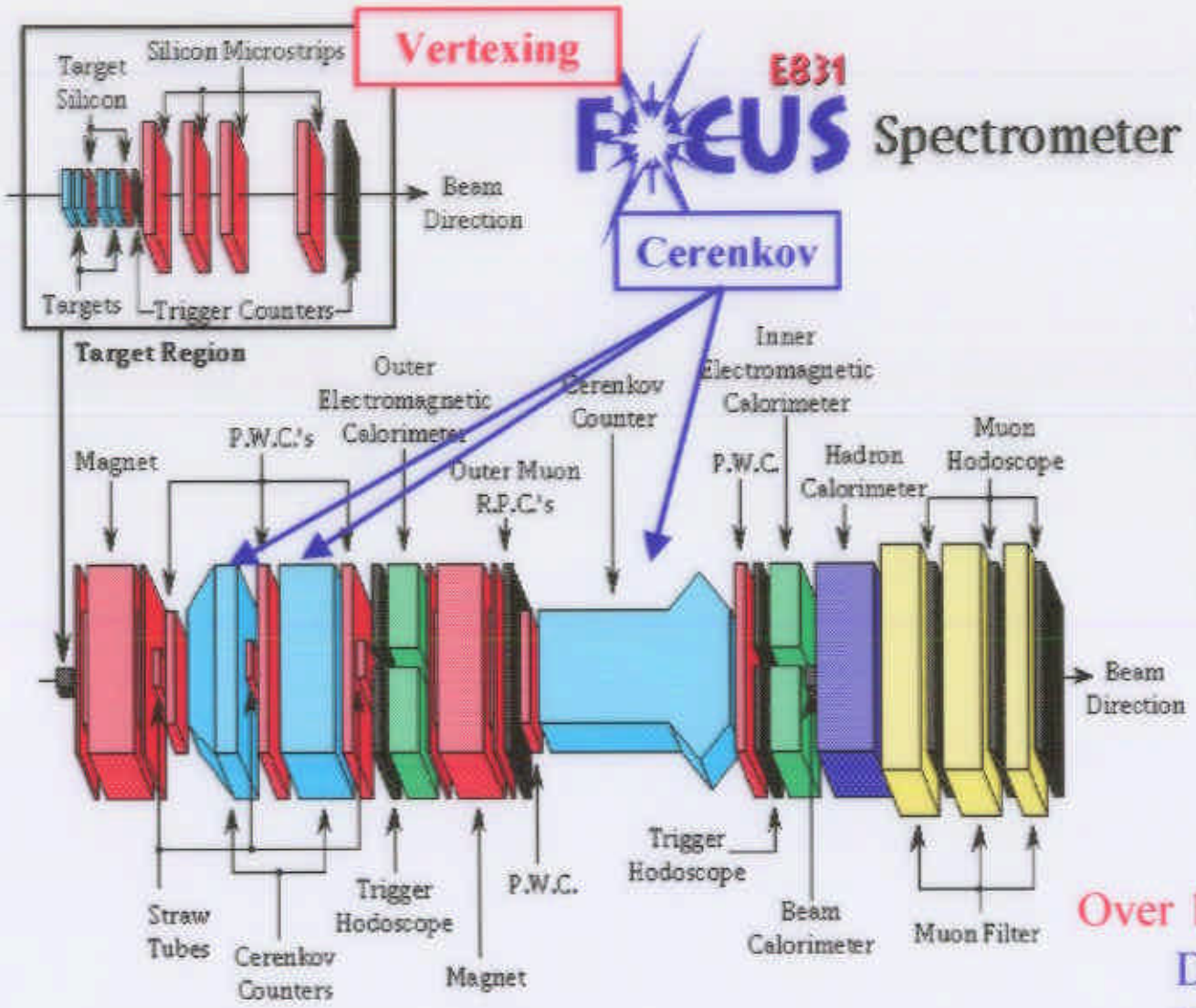
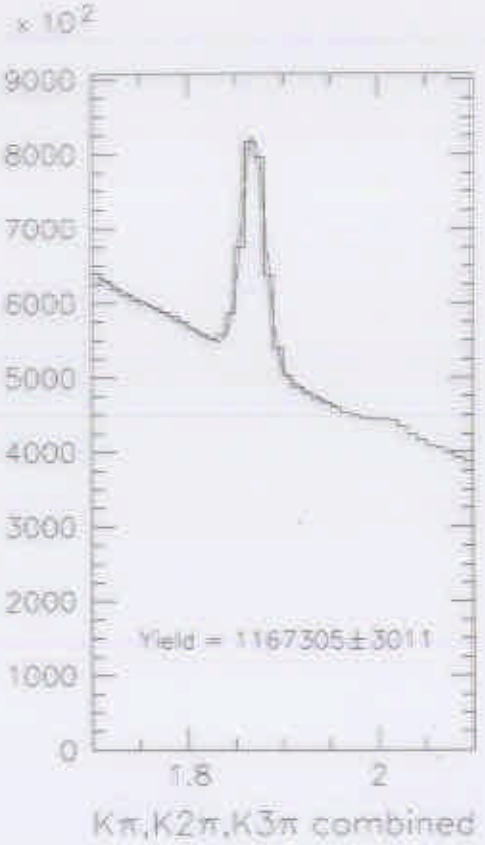
Schematic of Secondary Beam







Over 1 million reconstructed in
$D^0 \to K^-\pi^+, K^-\pi^+\pi^-\pi^+$ and
$D^+ \to K^-\pi^+\pi^+$

Upgraded version of E687
Photoproduction experiment during '96–'97 fixed target run
Excellent vertexing and Particle identification

Methods to see x,y

• In hadronic D^0 decays, wrong sign final: mixing, double Cabbibo suppressed or interference (strong phase δ). → D^0 charge tagged by D^{*+} Time evolution study finds x´, y´.

$$K^-\pi^+ \xleftarrow{CF} D^0 \xrightarrow[DCS]{\bar{D}^0\ mixing} K^+\pi^-$$

$$\frac{dN_{ws}}{dt} \approx e^{-\Gamma t}\left\{\left(\frac{x^2+y^2}{2}\right)\frac{\Gamma^2 t^2}{2} + D_{DCS}^{\ 2} + D_{DCS}(-x\sin\delta + y\cos\delta)\Gamma t\right\}$$

$$\equiv \text{CLEO } y'(\sigma \approx 1.7\%)$$

• $D_{DCS} = 0$ in semileptonic decays. → Cleaner analysis but less sensitivity.

• Direct comparison of CP final state lifetime finds y_{CP}.

$$D^0 \to K^+K^- (CP+) \to \Gamma_2$$

$$D^0 \to K^-\pi^+ (CP+ : CP- = 1:1)$$

$$\to \Gamma(K^-\pi^+) \approx (\Gamma_1 + \Gamma_2)/2$$

$$y_{CP} = \frac{\tau(D \to K\pi)}{\tau(D \to KK)} - 1$$

• If we select 16532 $D^0 \to K^+K^-$ FOCUS events (S/N=2.3).

$$\sigma_y \approx \frac{\sigma(\tau(KK))}{\tau(KK)} \approx \frac{1}{\sqrt{N^*}} \approx 1.2\%$$

Event Selection

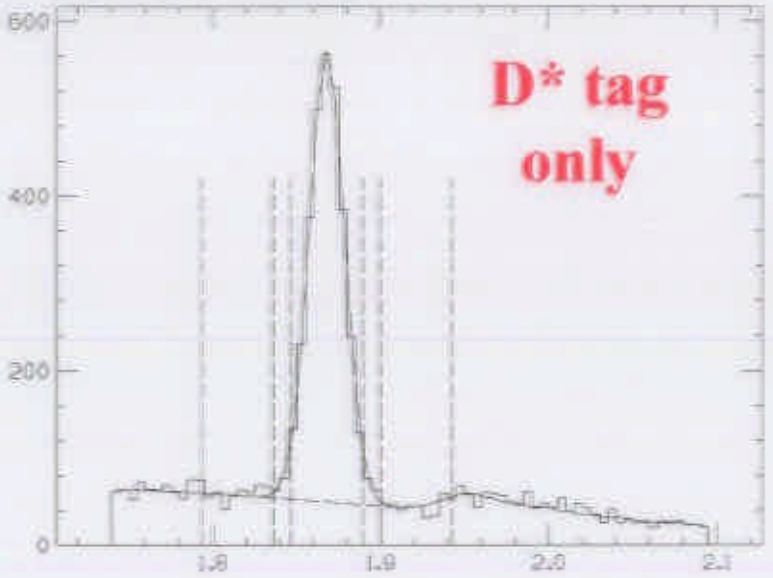
•Common base cuts:
detachment ($L/\sigma > 5$),
kaonicity ($W\pi - W_K > 4$)

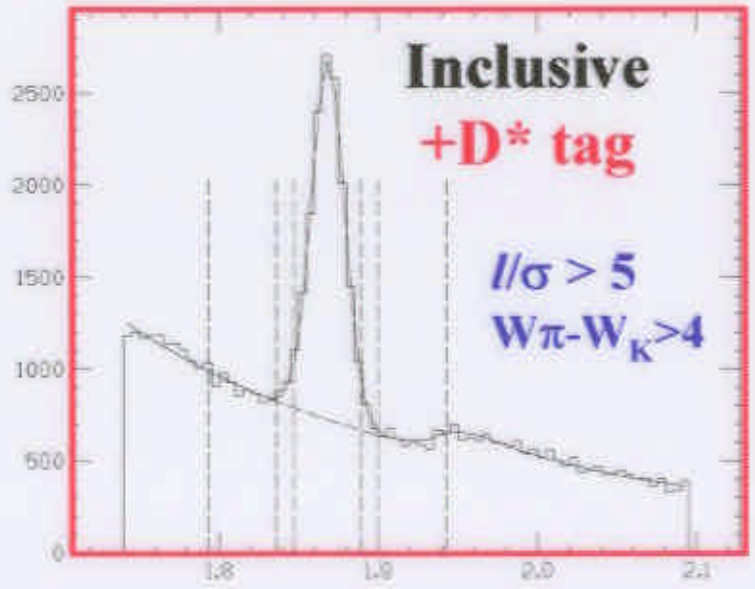
• Tagged sample:

$$|M(D^*) - M(D) - 145.4| < 3 \text{ MeV}$$

•Or inclusive sample:

More Cerenkov cuts :
pionicity ($W^* - W\pi > -2$),
Kaon ID ($W_P - W_K > -2$)
Primary vertex in target
Momentum sym: $|\alpha| < 0.7$
Resolution: $\sigma < 60$ fs





Direct comparison of CP final state

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

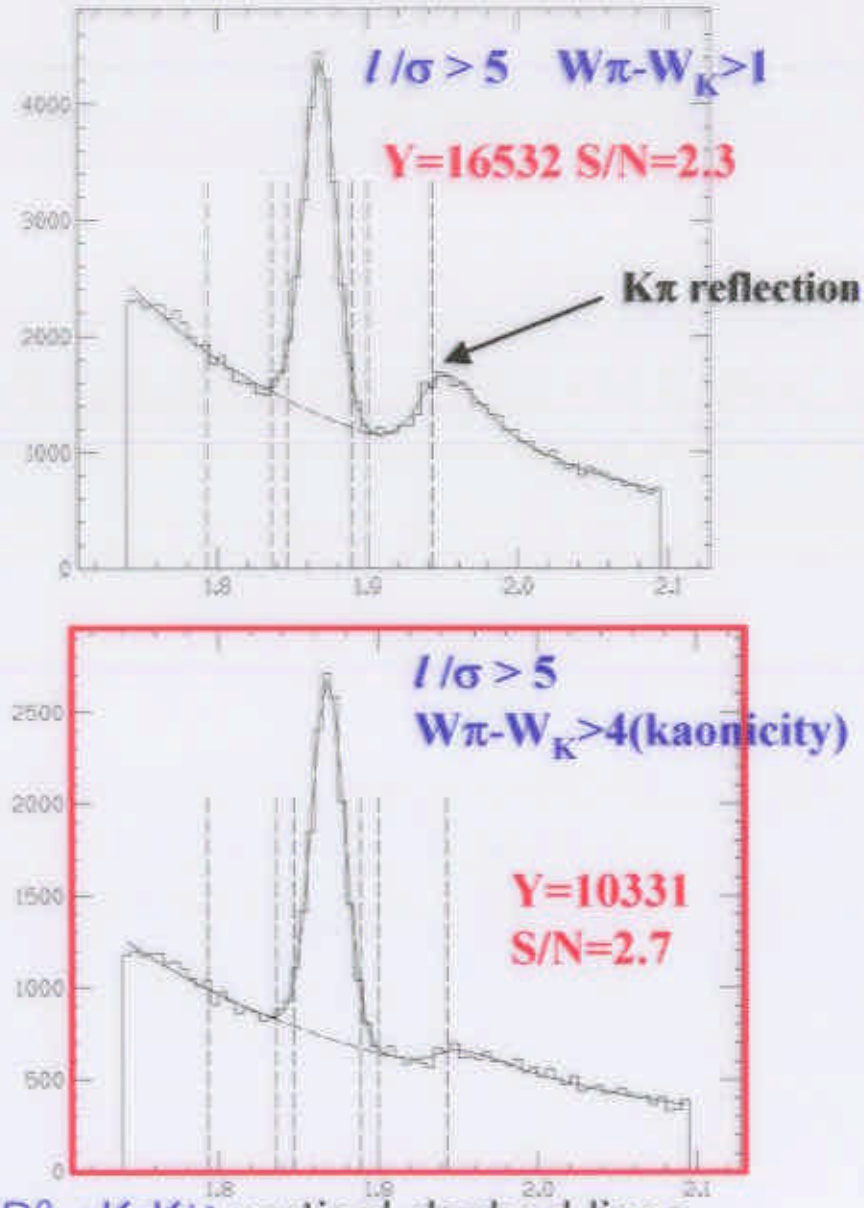
$D^0 \to K^-\pi^+$ (CP even: CP odd =1:1)

lifetime finds y_{CP}:

$$y_{CP} = \frac{\tau(D \to K\pi)}{\tau(D \to KK)} - 1$$

D → Kπ: 119738 selected

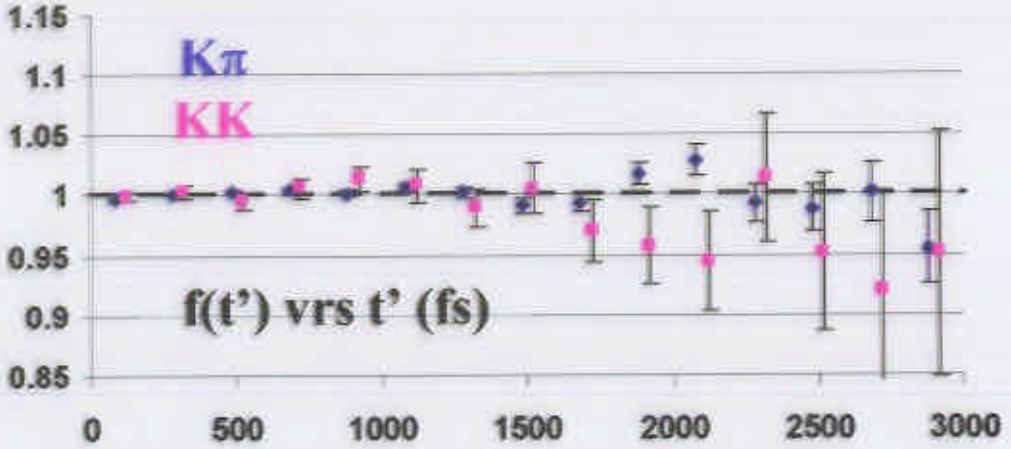
D → KK: 10331 selected



$D^0 \to K^-K^+$: vertical dashed lines Indicate signal and sideband regions used for lifetime and Ycp fits

Background Lifetime

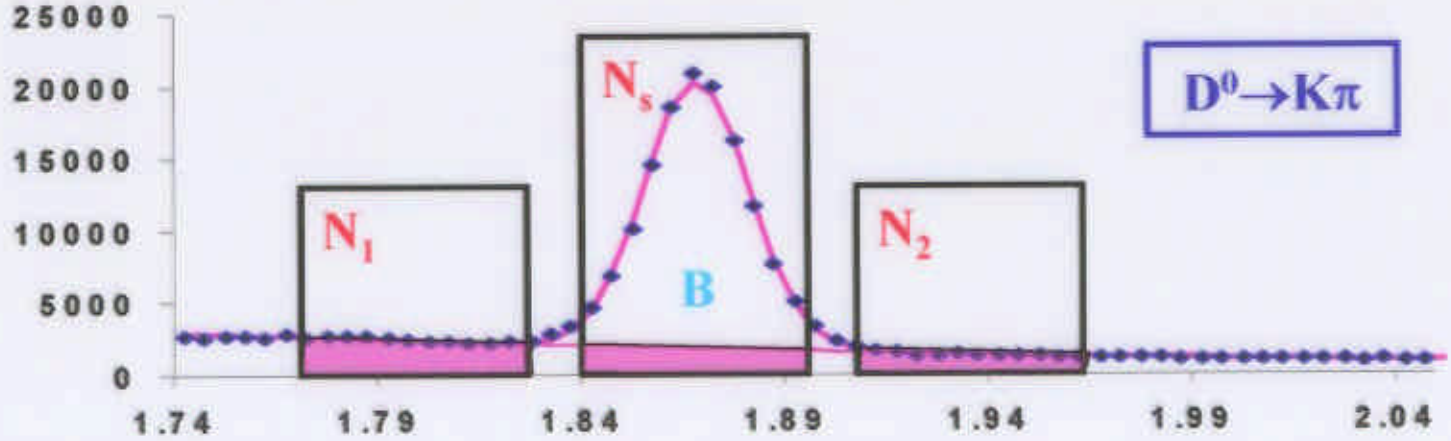
- Binned maximum likelihood fit
- f(t') : Acceptance correction
- b_i: background time dist. from sidebands
- μ_i:time dist. of signal region



- Fit for τ and B : w or w/o B-tie term.

$$\mu_i = (N_s - B)\frac{f(t'_i)\exp(-t'_i/\tau)}{\Sigma_i f(t'_i)e^{-t'_i/\tau}} + B\frac{b_i}{\Sigma_i b_i}$$

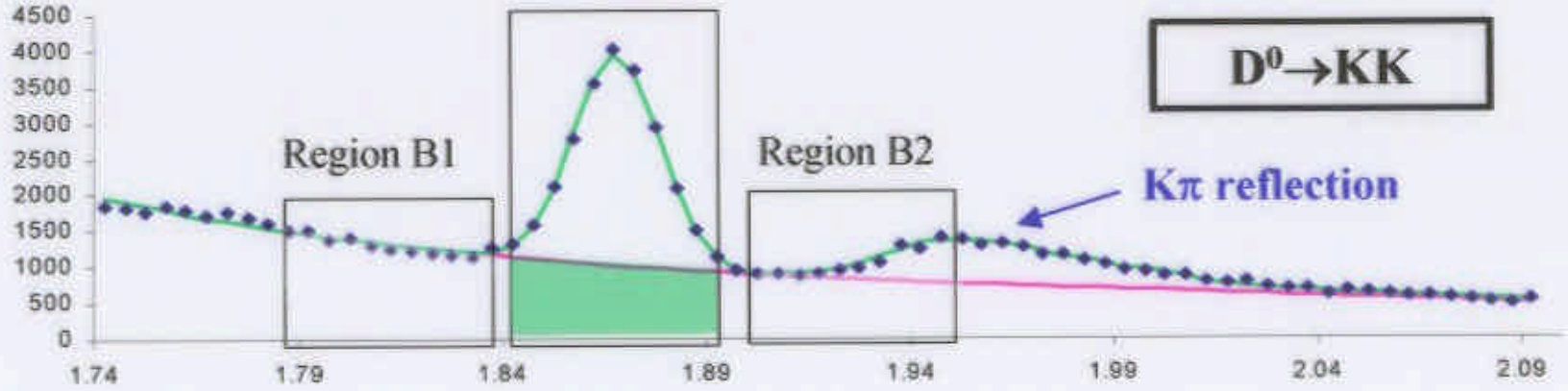
$$w = -2\left(\sum_i \ln\left\{\frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}\right\}\right) - 2\ln\left\{\frac{(2B)^{(N_1+N_2)} e^{-(2B)}}{(N_1+N_2)!}\right\}$$



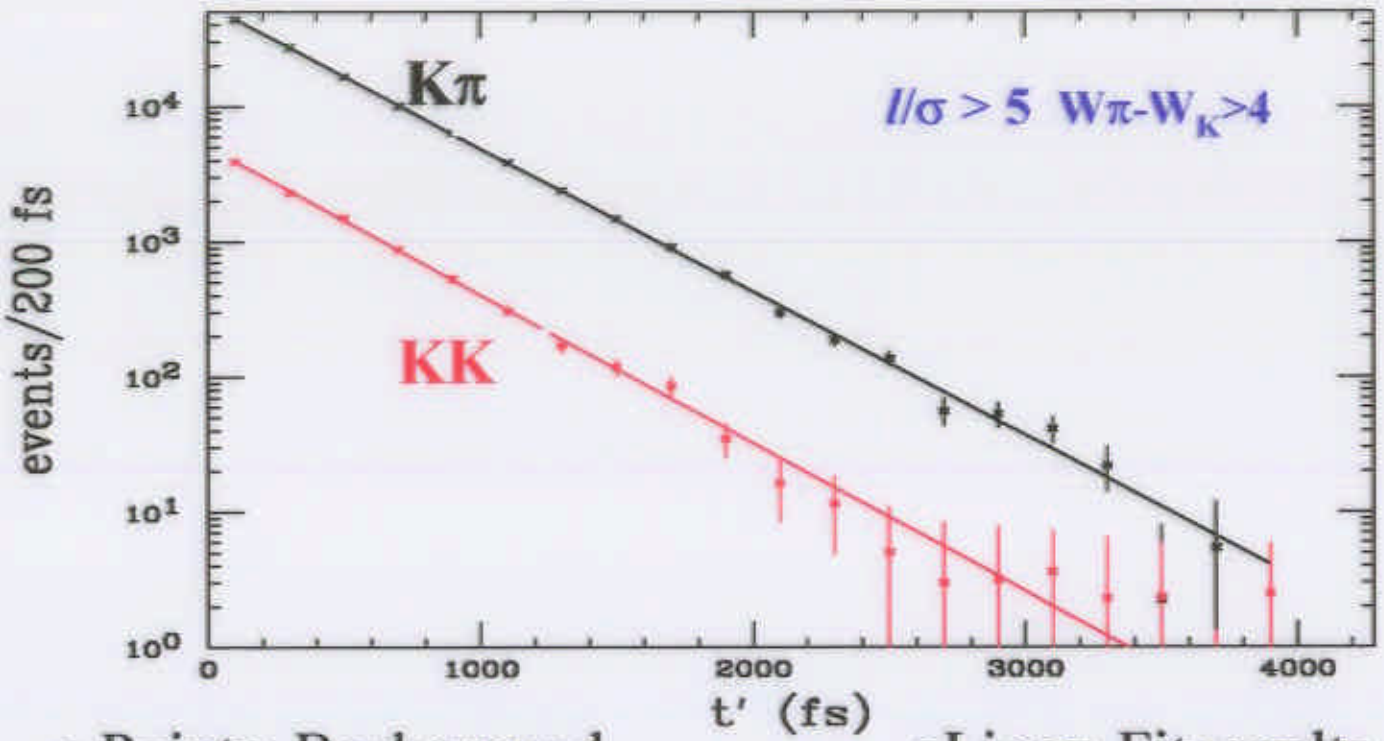
Fitting Technique

- The KK sample has some Kπ reflection at upper side; B2 = Kπ + nominal → one more player in fitting.
- Subtract Kπ reflection by a mass fit.
  - The reflection mass shape from MC.
  - The subtraction level by the mass fit.
  - Time evolution of the reflection from τ (Kπ)

- Background under KK signal ≅ B1 + (B2 - Kπ reflection)
- Simultaneous time evolution fit of both Kπ and KK histos.
- Fit parameters in final fit are: τ (Kπ), y_{CP}, B(Kπ), B(KK)

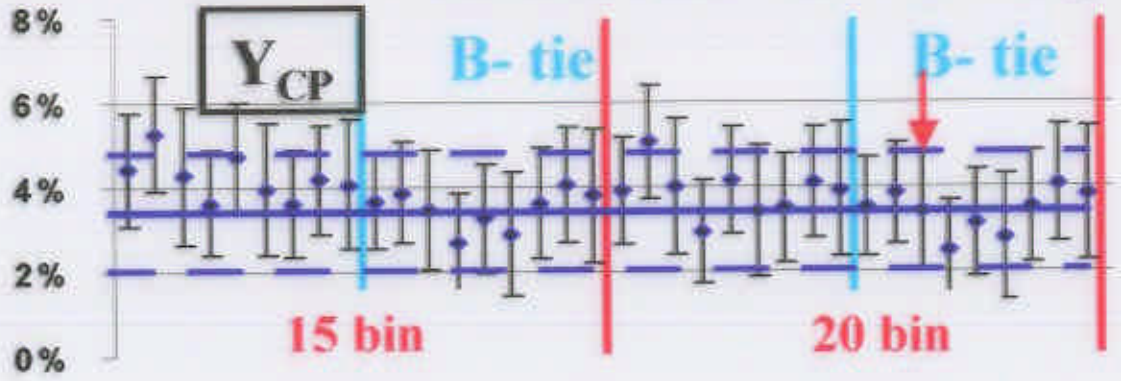


Subtracted Time Evolution

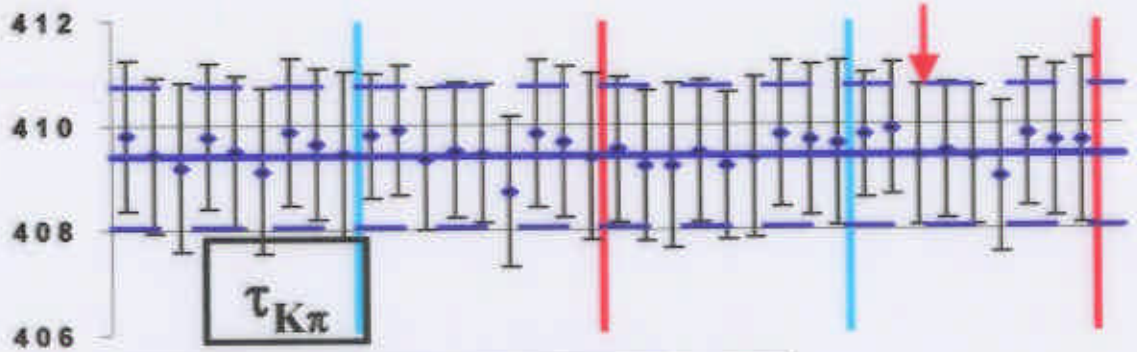


- Points: Background subtracted and f(t') corrected time evolution of **Kπ** and **KK** events in the final fit.
- Lines: Fit results

Results and Systematics



RMS spread is 0.63%



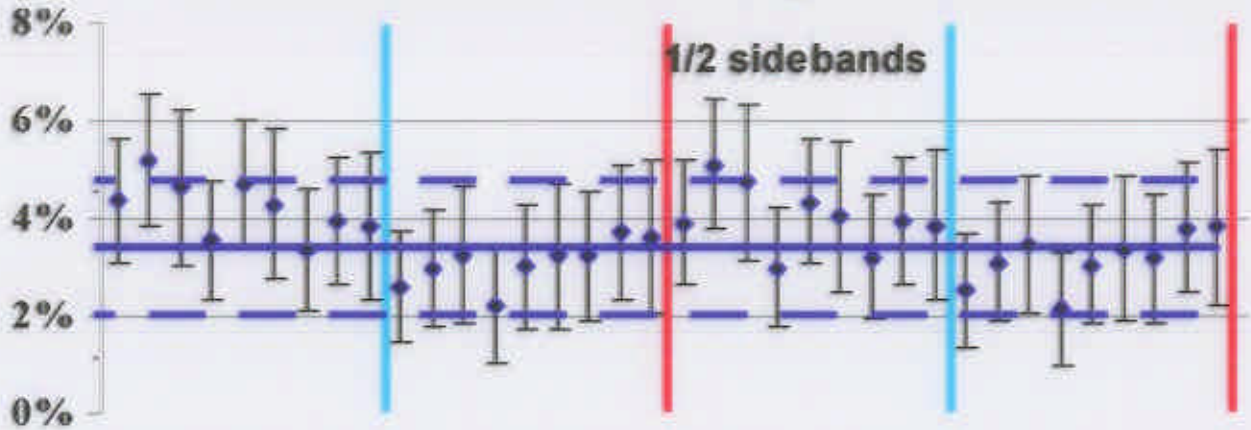
RMS spread is 0.28 fs

9 sets of clean-up and 4 different fit options:3 K ID × 3 L/σ × B-tie or not × 15/20 bin = 36 fit variants shown.

Systematic error is considerably smaller than statistical error:

$$y_{CP} = 3.42 \pm 1.39 \pm 0.74\ \%$$

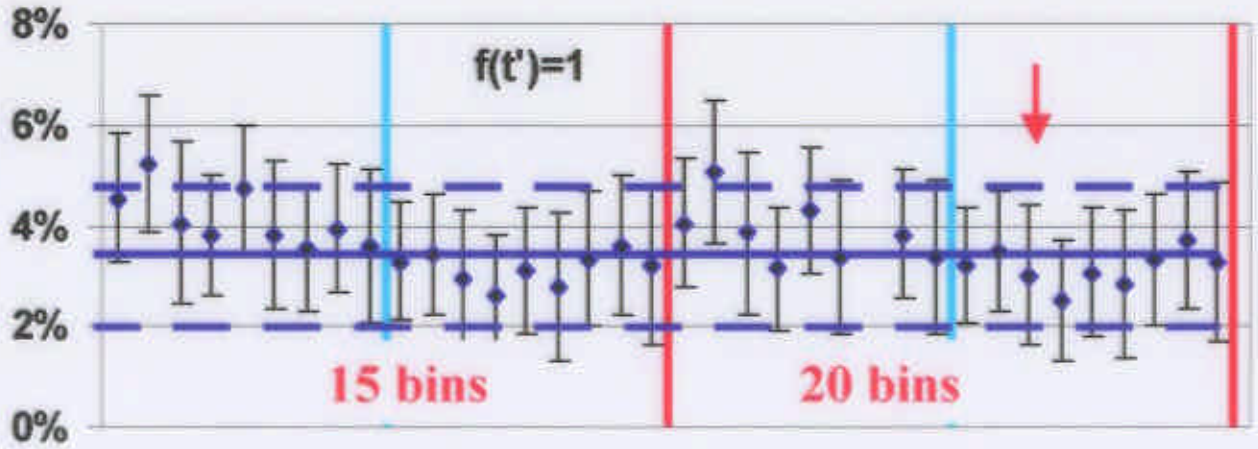
Additional systematic checks



Half Sideband Tests

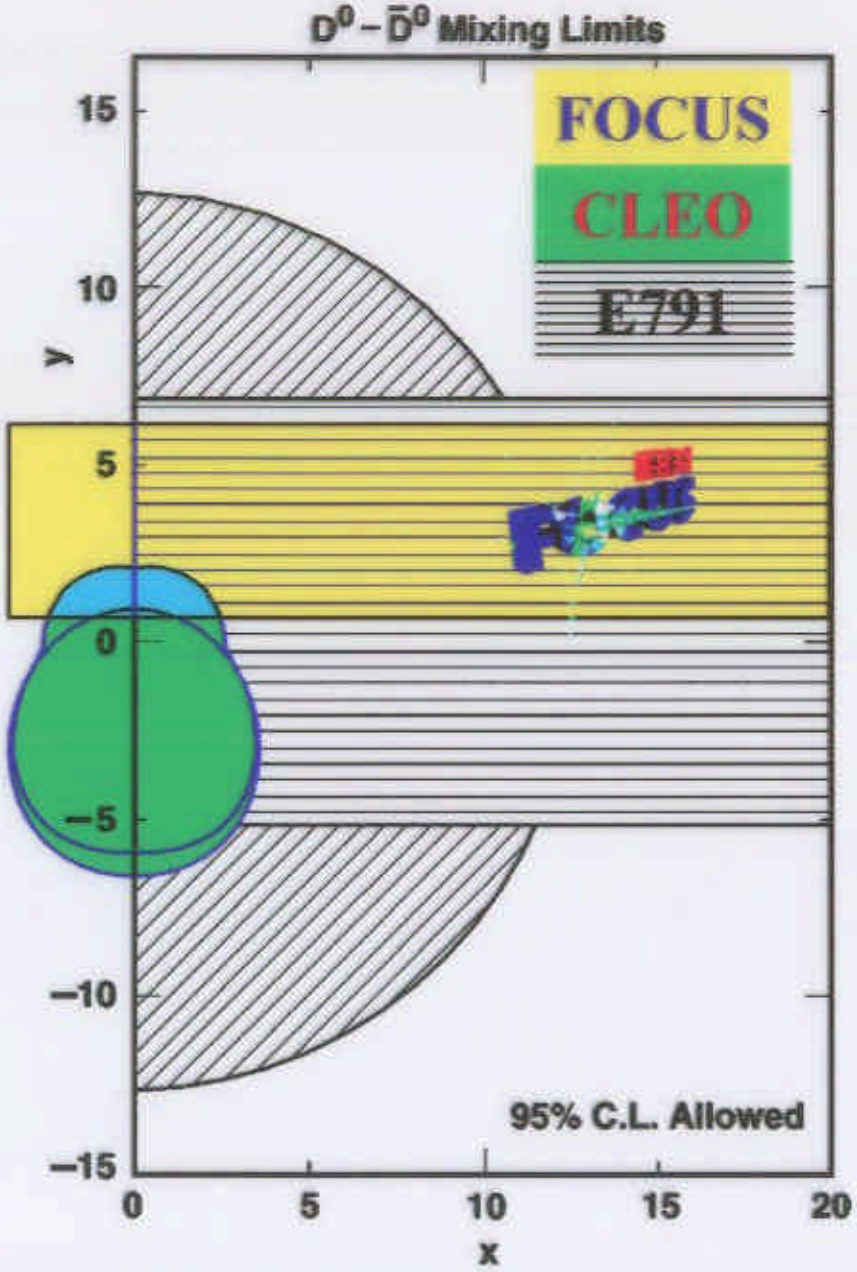
Could curvature in reflection line shapes cause the sideband Background to fail

Results are nearly identical to standard fits



f(t')=1 Tests

How important is the f(t') correction?



Comparisions

- The comparison to CLEO **is vaild only if** one assumes a small strong phase difference δ.
- About the same sensitivity to the CLEO CP constrained fit, but the **opposite sign!**

$$y_{CP} = 3.42 \pm 1.39 \pm 0.74\ \%$$

Previous Measurements

E791: $y_{CP} = 0.8 \pm 2.9 \pm 1\ \%$

CLEO: $-5.8\ \% < y' < 1\%$ **(95% CL)**

CP Violation

• SM predicts "direct CP violation in D decay rates" largest in singly Cabbibo-suppressed decays. (0.002 ~ 0.14%, Buccella et al.)

$D^+ \to K^-K^+\pi^+$

$D^0 \to K^-K^+, \pi^-\pi^+$

$$\eta(D) = \frac{N(D^+ \to K^-K^+\pi^+)}{N(D^+ \to K^-\pi^+\pi^+)}$$

$$\eta(D) = \frac{N(D^0 \to K^-K^+)}{N(D^0 \to K^-\pi^+)}$$

C.F.

• Charge of D^0 is determined by the bachelor π from $D^{*+} \to D^0 \pi^+$. Note: FOCUS has production asymmetry between D and Dbar Rather measure normalized asymmetry to Cabbibo favored.

CP asymmetry:

$$A_{CP} = \frac{\eta(D) - \eta(\bar{D})}{\eta(D) + \eta(\bar{D})}$$

CP violation search (D→KKπ)

- Cabbibo suppressed mode.

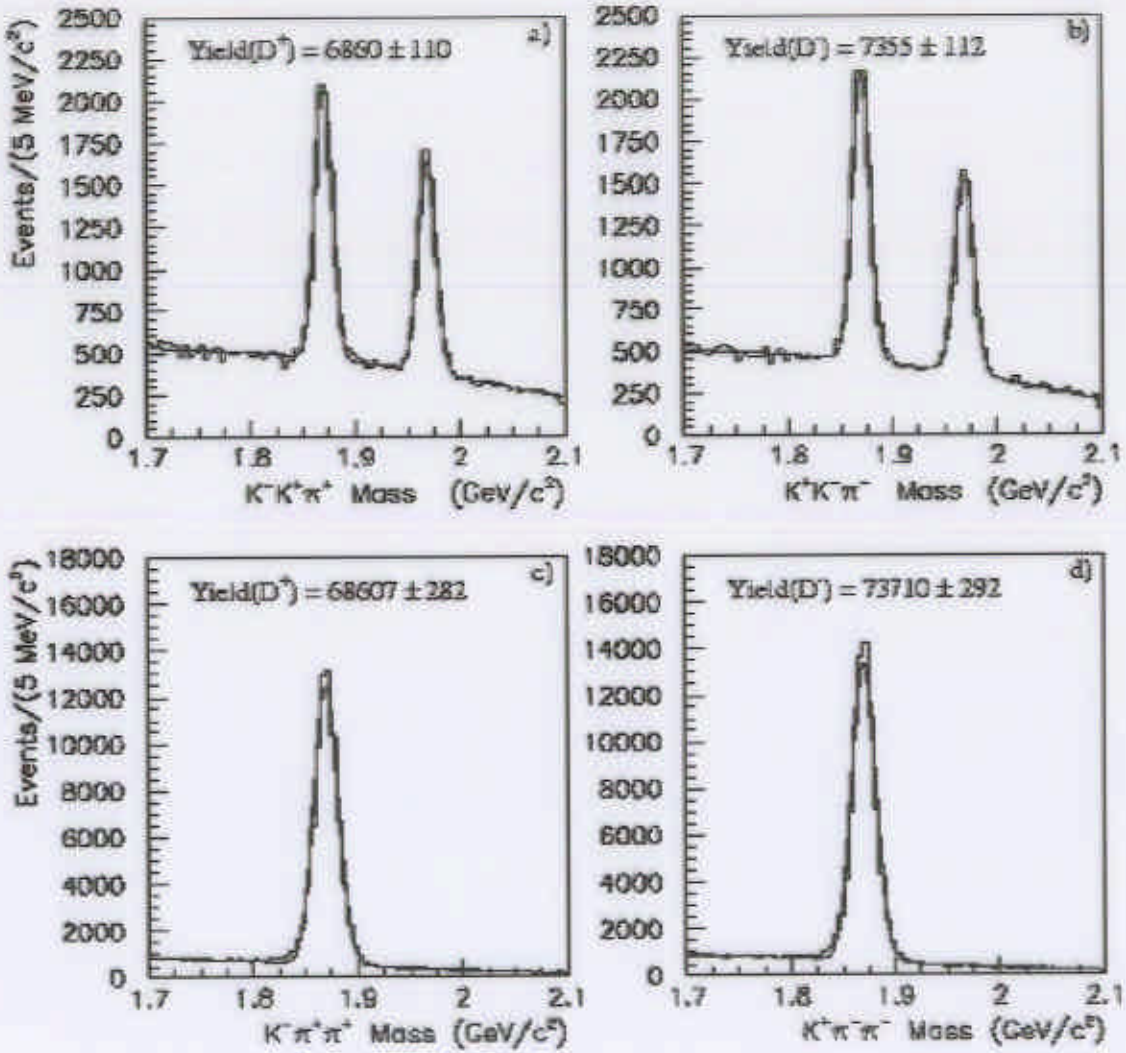
$D^+ \rightarrow K^-K^+\pi^+$

$D^- \rightarrow K^-K^+\pi^-$

- Cabbibo favored mode.

$D^+ \rightarrow K^-\pi^+\pi^+$

$D^- \rightarrow K^+\pi^-\pi^-$



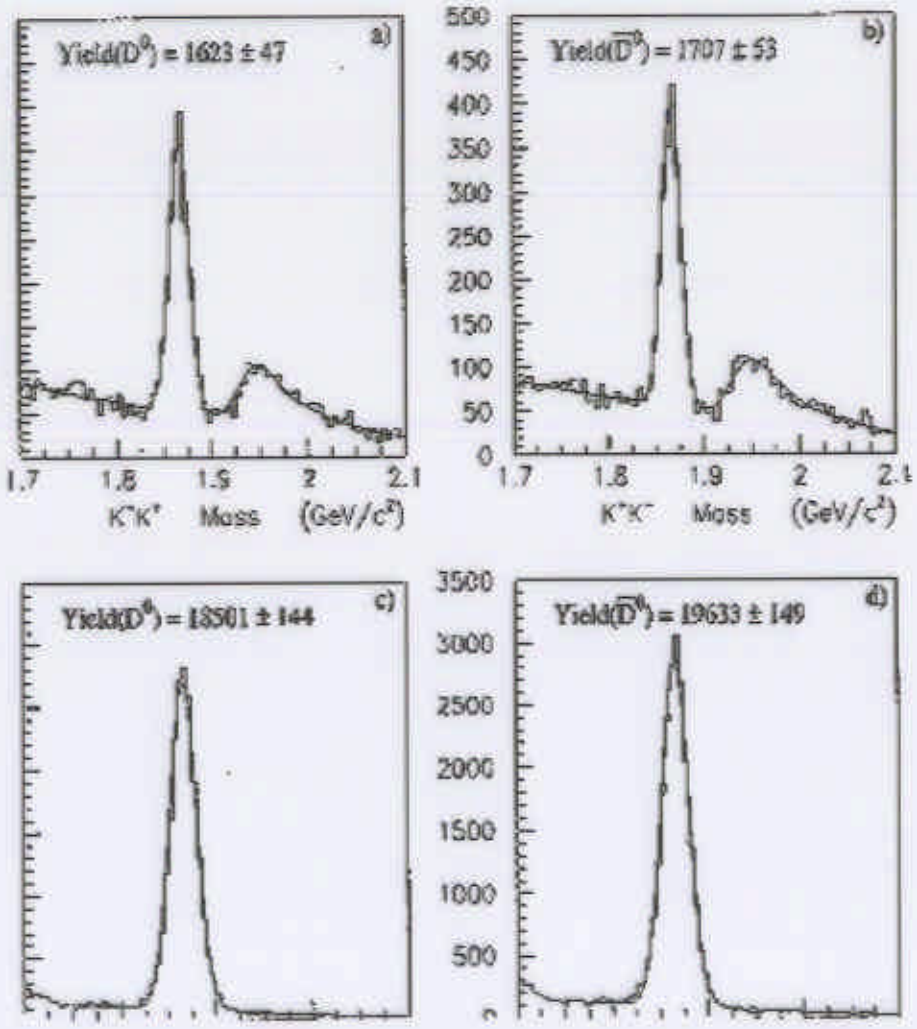
CP violation search (D→KK)

• Cabbibo suppressed mode.

$D^* \rightarrow D0(K^- K^+)\pi$

• Cabbibo favored mode.

$D^* \rightarrow D0(K^- \pi^+)\pi$

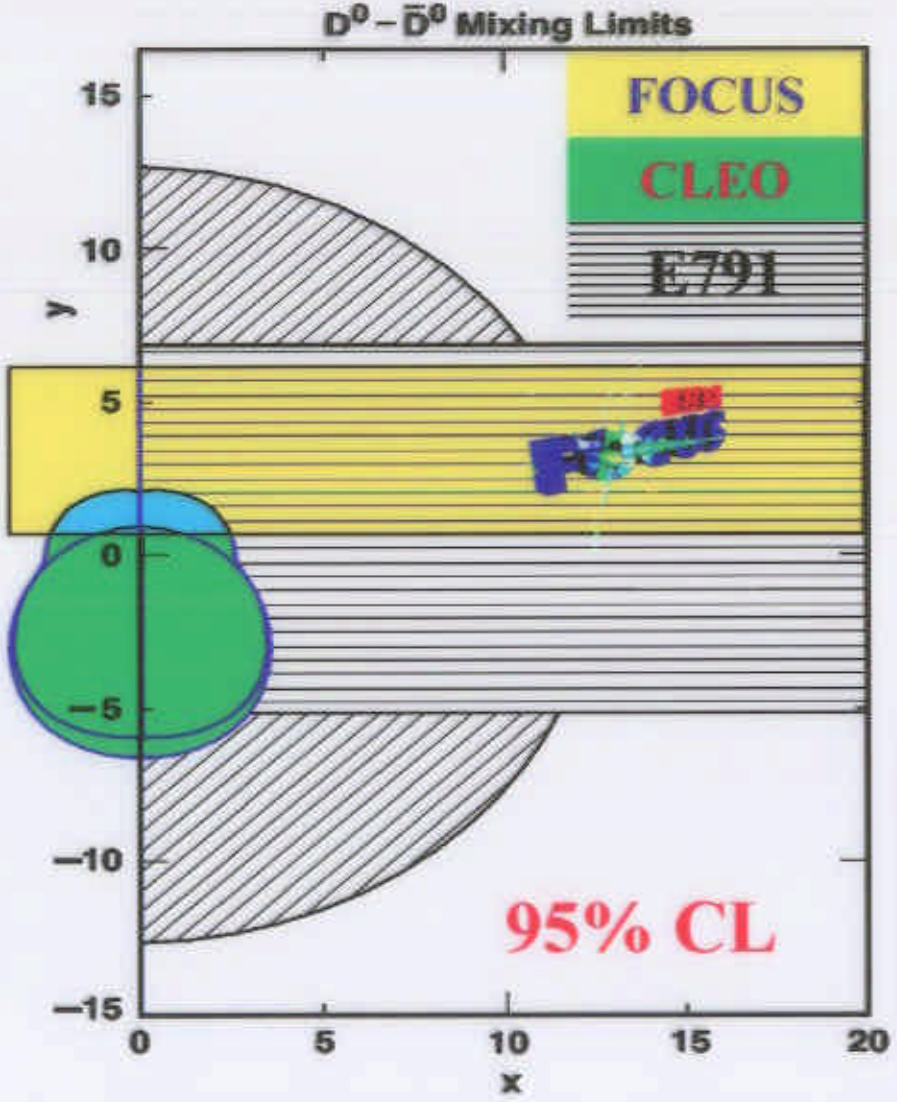


CP asymmetry results

Decay Mode	FOCUS	E791 (previous best)
$D^+ \to K^- K^+ \pi^+$	$+0.006 \pm 0.011 \pm 0.005$	-0.014 ± 0.029
$D^0 \to K^- K^+$	$-0.001 \pm 0.022 \pm 0.015$	$-0.010 \pm 0.049 \pm 0.012$
$D^0 \to \pi^- \pi^+$	$+0.048 \pm 0.039 \pm 0.025$	$-0.049 \pm 0.078 \pm 0.025$

- No evidence for CP violation.
- Our limits on
  - Need to use tagged D^o sample which cuts our sample by 80%.
- 2~3 times better limit than the previous measurements.

Summary of FOCUS E831 Results



Mixing parameter y_{cp}:

$$y_{CP} = 3.42 \pm 1.39 \pm 0.74\ \%$$

Previous Measurements

E791: $y_{CP} = 0.8 \pm 2.9 \pm 1\ \%$

CLEO: $-5.8\ \% < y' < 1\%$ (95% CL)

CP Asymmetry A_{CP}:

Decay Mode	Acp
$D^+ \to K^- K^+ \pi^+$	$+0.006 \pm 0.011 \pm 0.005$
$D^0 \to K^- K^+$	$-0.001 \pm 0.022 \pm 0.015$
$D^0 \to \pi^- \pi^+$	$+0.048 \pm 0.039 \pm 0.025$

Phase ambiguity

What if $\delta = 40°$, the estimated maximum of the model of *Falk, Nir & Petrov (99)?* We see **some overlap...**

CLEO and FOCUS would be more consistent if $\delta > 90°$...

Bergmann, Grossman et al(00).