Recent FOCUS results on charm mixing and CP violation

Luigi Moroni, INFN-Milano

Outline

- Mixing
  - Brief introduction on Mixing Phenomenology
    $x = \Delta M / \Gamma$ and $y = \Delta\Gamma / 2\Gamma$
  - Theory predictions
  - Experimental strategies and expected sensitivities
  - Present experimental status
  - Sensitivity to compete via
    $y = \tau(K\pi) / \tau(KK) - 1$

- New FOCUS result on y
  - **Kπ** & **KK** signals
  - CP eigenstate lifetimes
  - Impact of this result on the present experimental scenario
- Search for CP violation
  - New FOCUS limits
    Compare $D^0(\bar{D}^0) \to K^+K^-$
    and $D^\pm \to K^+K^-\pi^\pm$
- Summary & Conclusions

Mixing Review

$$i\frac{\partial}{\partial t}\begin{pmatrix} D \\ \overline{D} \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}\begin{pmatrix} D \\ \overline{D} \end{pmatrix} \text{where } H_{11} = M_{11} - i\,\Gamma_{11}/2 \text{ etc...}$$

If $H_{12}, H_{21} \neq 0$, the D and $\overline{D}$ are not mass eigenstates.

If CP conserved, $D_{1,2} = \frac{D \pm \overline{D}}{\sqrt{2}}$ are mass and CP eigenstates with $\Delta\Gamma, \Delta M \neq 0$

If $|x|, |y| << 1$:

$$A_{mix} \approx \frac{y + ix}{2} \times \Gamma t \times \exp\left(-\frac{\Gamma t}{2}\right) \text{where } x = \frac{\Delta M}{\Gamma} \text{ and } y = \frac{\Delta\Gamma}{2\Gamma} \equiv \frac{\tau^{+} - \tau^{-}}{\tau^{+} + \tau^{-}}$$

Measuring Mixing

In practice, one has to compare the transition rates to 2 particular CP - conjugate final states,

e.g. $$\Gamma(D^0 \to \bar{f}) \big/ \Gamma(D^0 \to f)$$

where the transition $D^0 \to \bar{f}$ is through mixing.

In D^0 hadronic decays, $D^0 \to \bar{f}$ can go through mixing as well as through a simple DCS process.

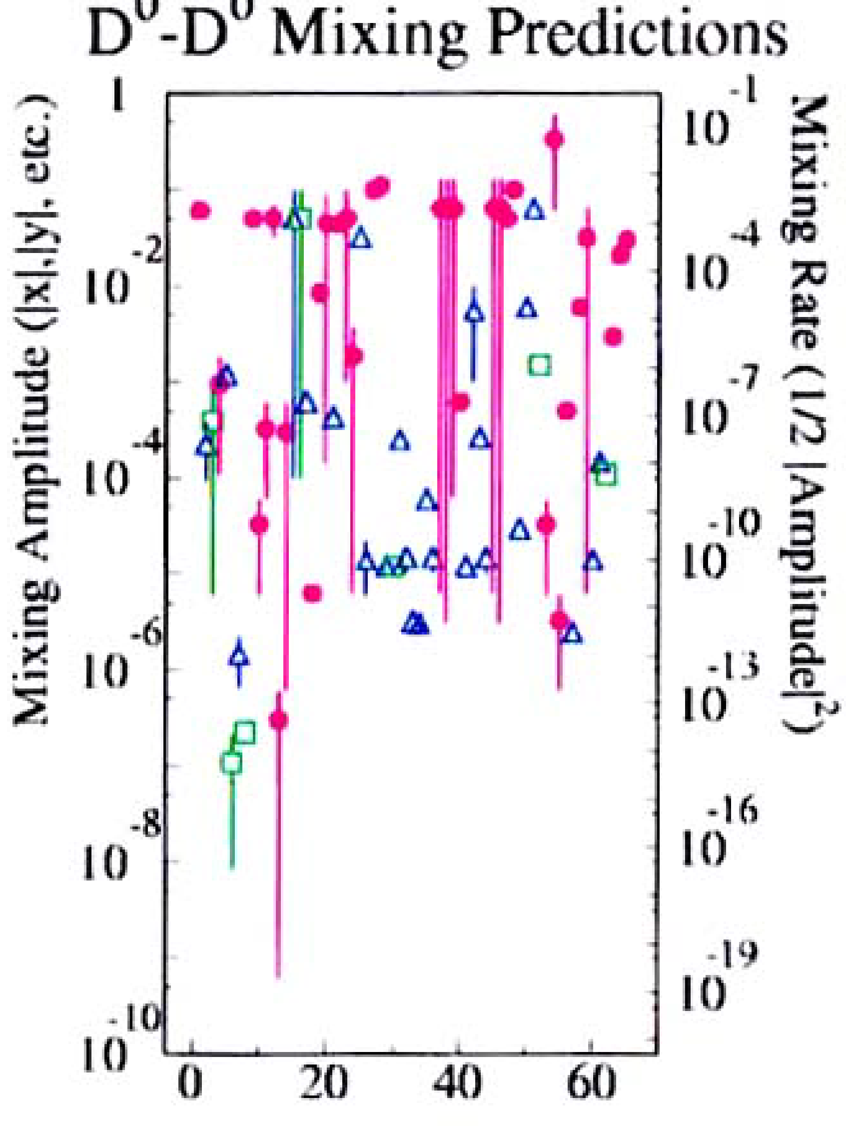
In this case: $$\frac{dN_{D\to\bar{f}}}{dt} \propto \left| A_{mix} + \sqrt{R_D} e^{-i\delta} e^{-\Gamma t/2} \right|^2 \approx$$

i.e. $x, y \overset{\delta}{\curvearrowright} x', y'$

$$\left(\left(\frac{x^2+y^2}{2} \right) \frac{\Gamma^2 t^2}{2} + \sqrt{R_D}(-x\sin\delta + y\cos\delta)\Gamma t + R_D \right) \exp(-\Gamma t)$$

On the other hand, processes such a semileptonic decay have no R_D terms!

Theoretical "guidance"



From compilation of H.N.Nelson hep-ex/9908021

Triangles are SM x

Squares are SM y

Circles are NSM x

Predictions encompass **15 orders magnitude** for R_{mix}

(but only 7 orders of x or y!)

Mixing Measurements

Pretend that $R_{mix} = \left(\frac{x^2 + y^2}{2} \right) = 0.05\%$.

How could one "see" it at 95% CL (2σ)?

One could observe $\approx$ 16 $D^{*+} \rightarrow \pi^+ (K^+ \mu^- \bar{\nu})$ decays
over a background of 10 among $\approx$ 12000 $D^{*+} \rightarrow \pi^+ (K^- \mu^+ \bar{\nu})$decays

If mixing is through x (ΔM)

One could try to measure CP mass differences to 25μeV

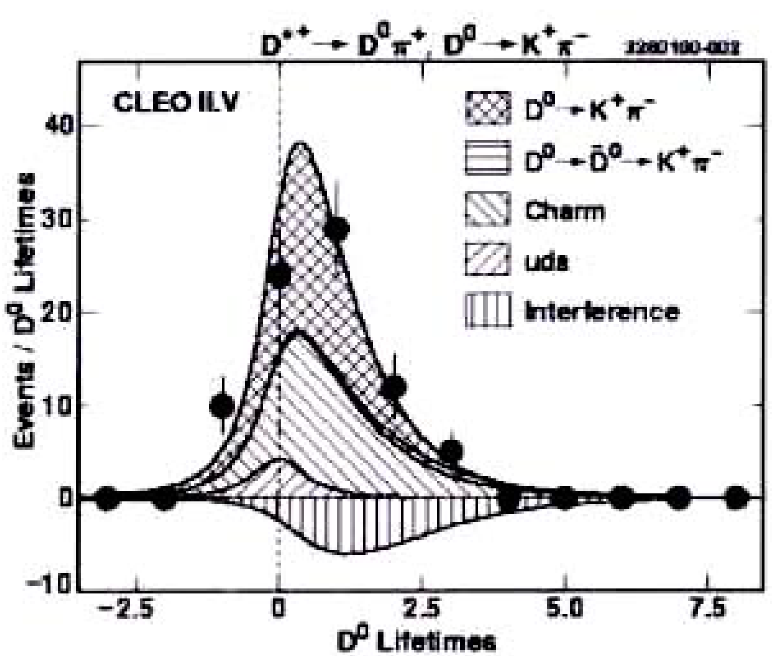
If mixing is through y ($\Delta\Gamma$)

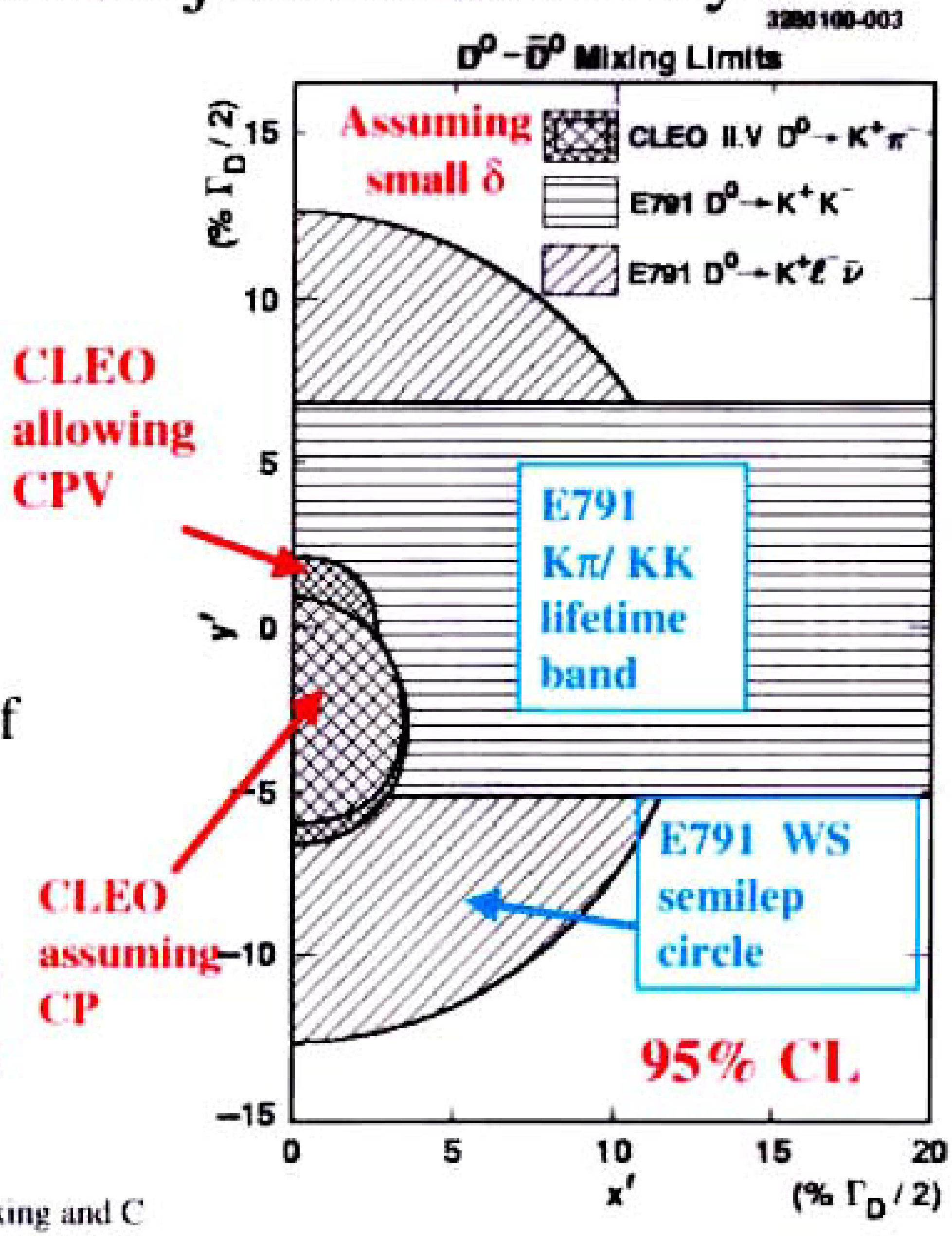
One could measure the KK/Kπ lifetime to 1.6%
$\rightarrow$ 4000 KK (background free) events.

NB: assuming $K^-\pi^+$ equal mix of CP^+ and CP^-

Or observe hadronic mixing interference (CLEO) with ~50 events...

CLEO enlivened this subject considerably...





CLEO studies time evolution of

$$D^{*+} \to \pi^+ D \to \pi^+ (K^+ \pi^-)$$

Required sensitivity to compete with CLEO

CLEO is obtaining an 95% allowed y' range of

-5.8% < y' < 1% (no CP assumption)

In FOCUS we would compare lifetime of KK to that of Kπ.

- **The errors on Kπ will be much smaller than KK**

$$y = \frac{\tau(D \to K\pi)}{\tau(D \to KK)} - 1 \quad \to \sigma_y \approx \frac{\sigma(\tau_{KK})}{\tau_{KK}} \approx \frac{1}{\sqrt{N^*}}$$

CLEO's 95% y range implies $\sigma_y \approx 1.73\%$

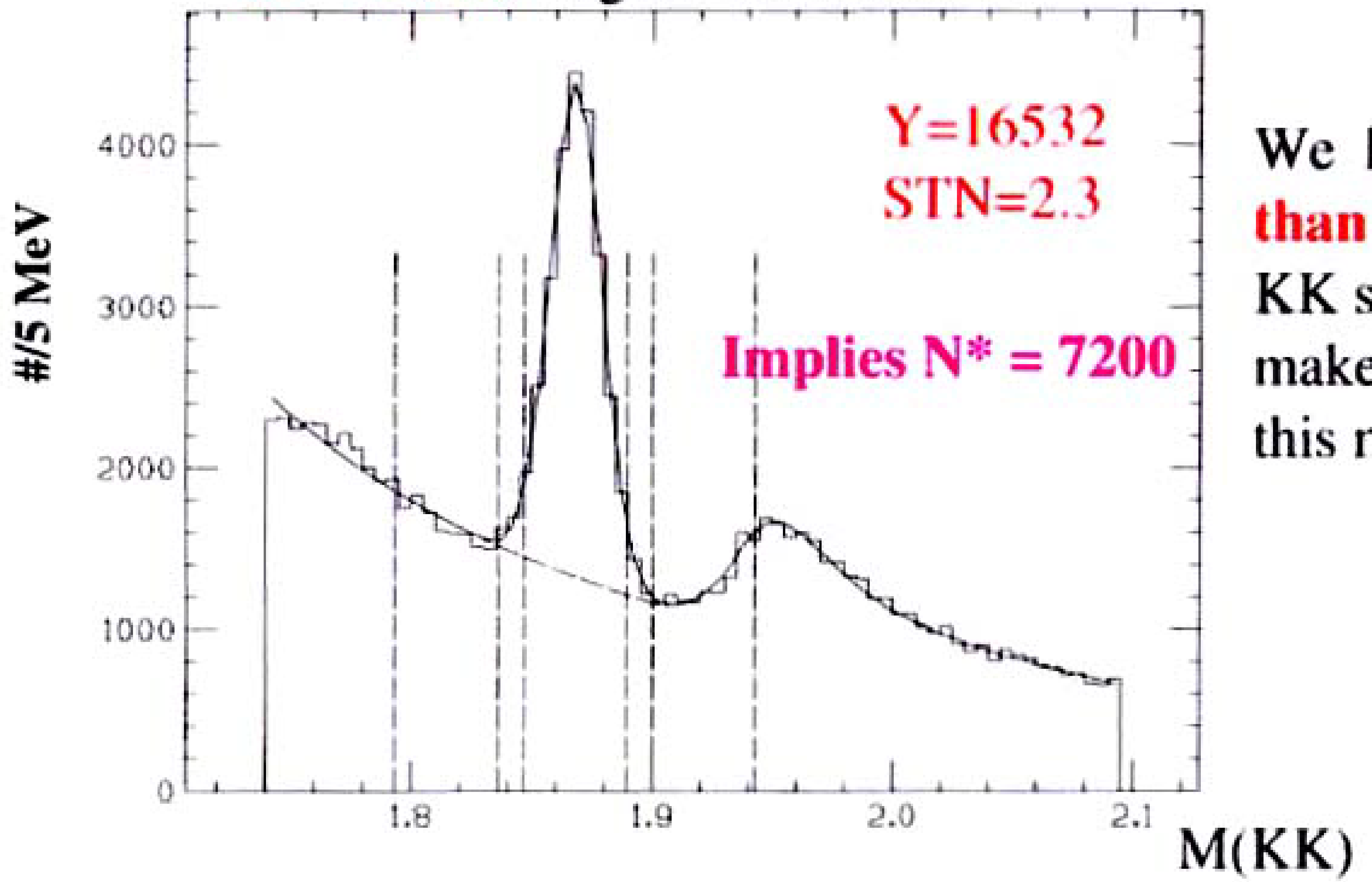
$$\sigma_y \approx \frac{1}{\sqrt{N^*}} \to N^* = \frac{1}{0.0173^2}$$

$\approx$ 3300 background free KK events

E831 FOCUS

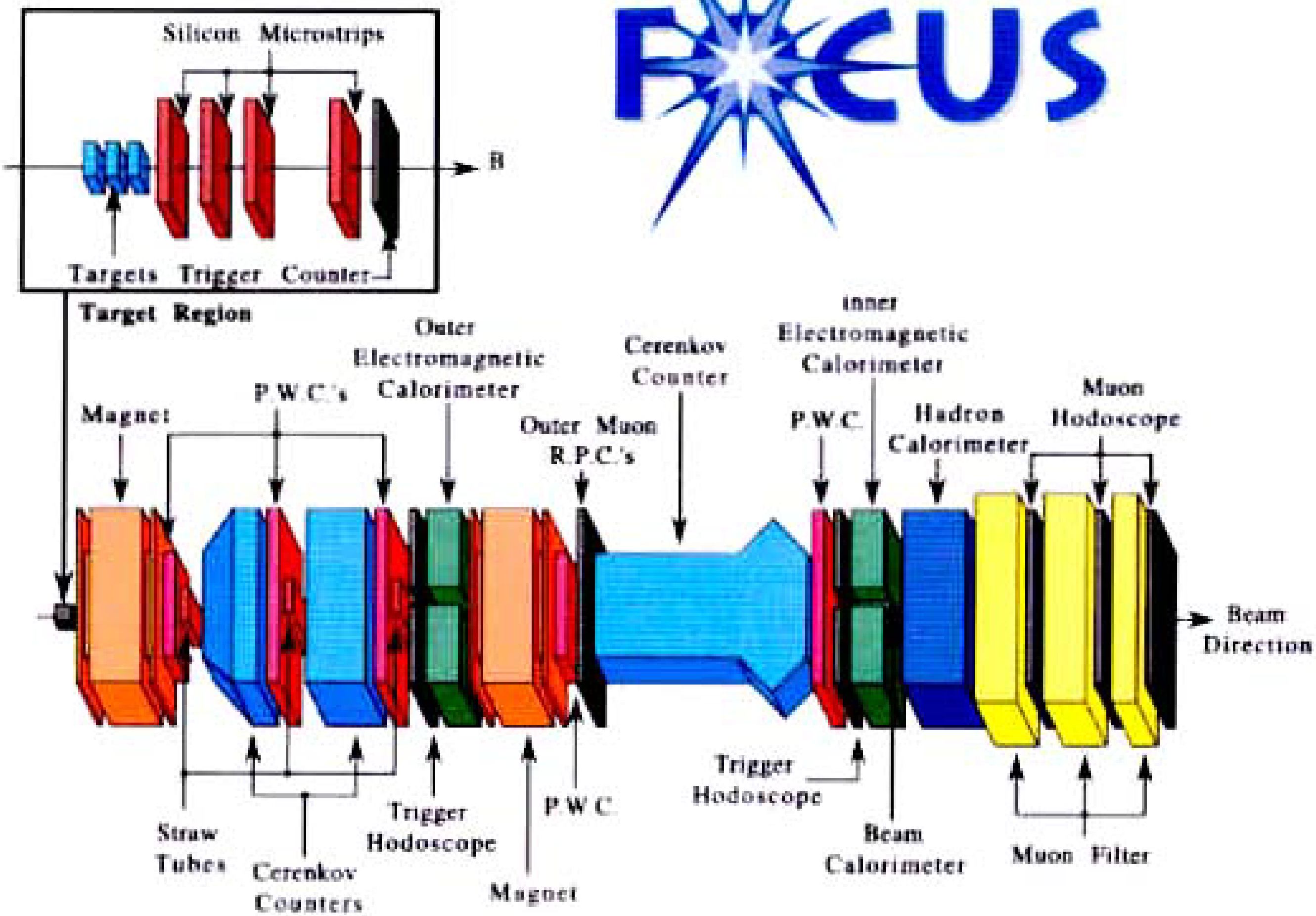
FOCUS has adequate statistics to do this!

$D^0 \to K^+K^-$ signal from FOCUS

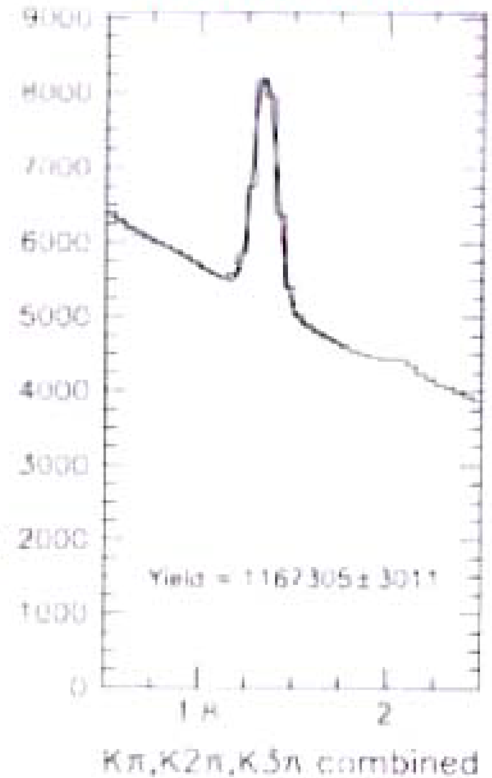


We have **more than adequate** KK statistics to make an impact on this measurement

E831 FOCUS



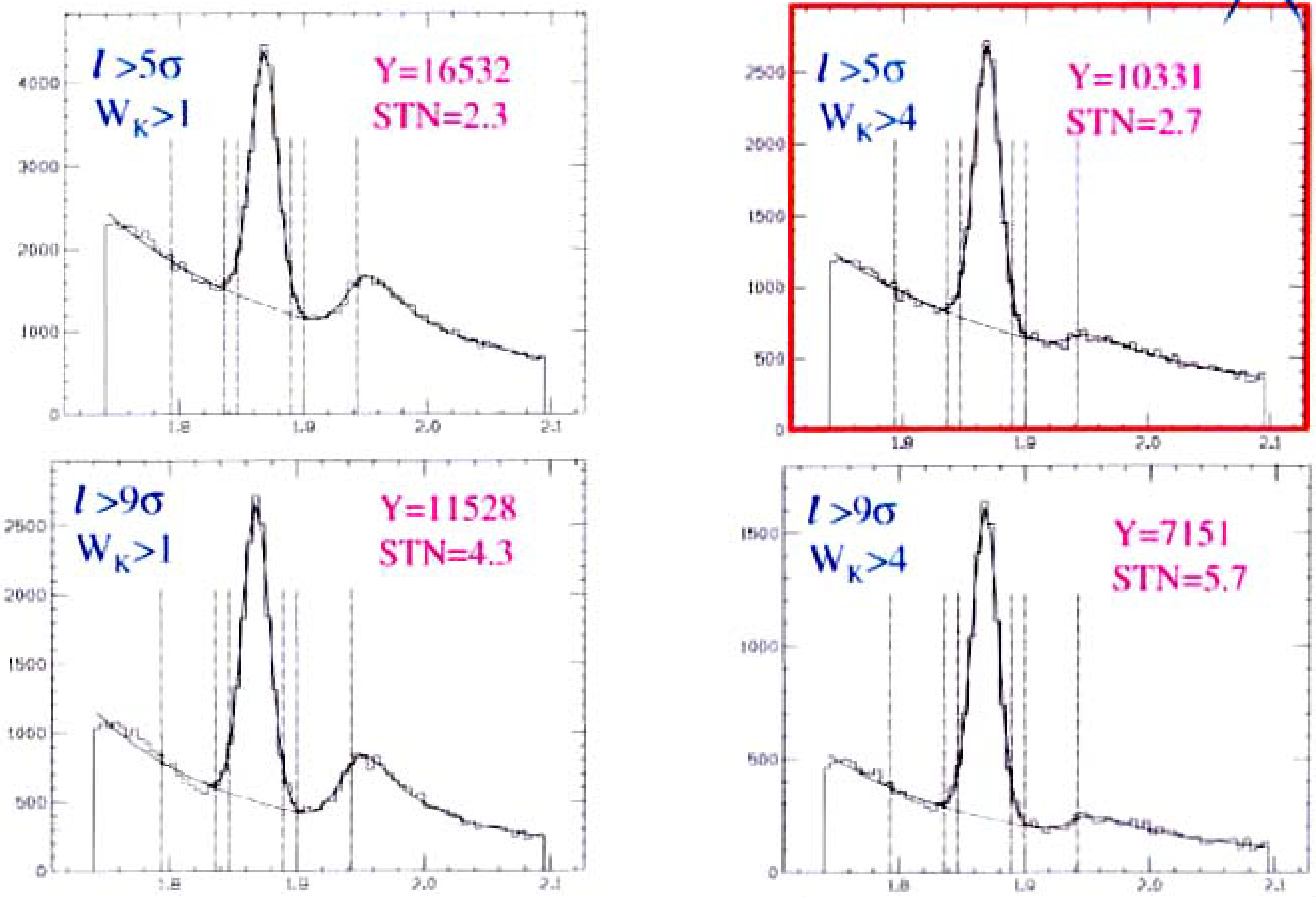
Over 1 million reconstructed!!



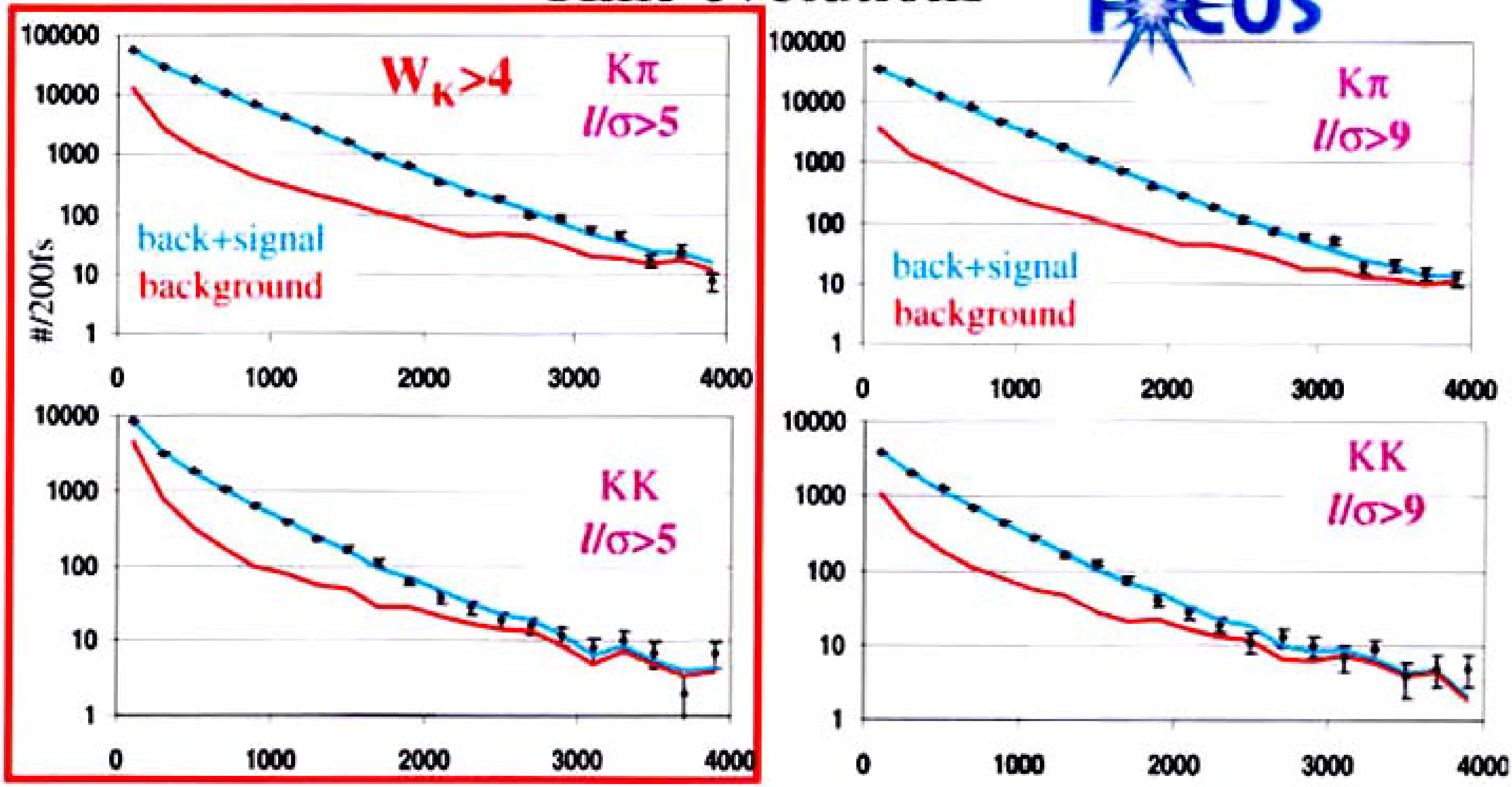
Successor to E687. Designed to study charm particles produced by ~200 GeV photons using a fixed target spectrometer with upgraded Vertexing, Cerenkov, E+M Calorimetry, and Muon id capabilities. Includes groups from USA, Italy, Brazil, Mexico, Korea

1 million charm particles reconstructed into $D \rightarrow K\pi$, $K2\pi$, $K3\pi$

D→KK signal for several cleanups

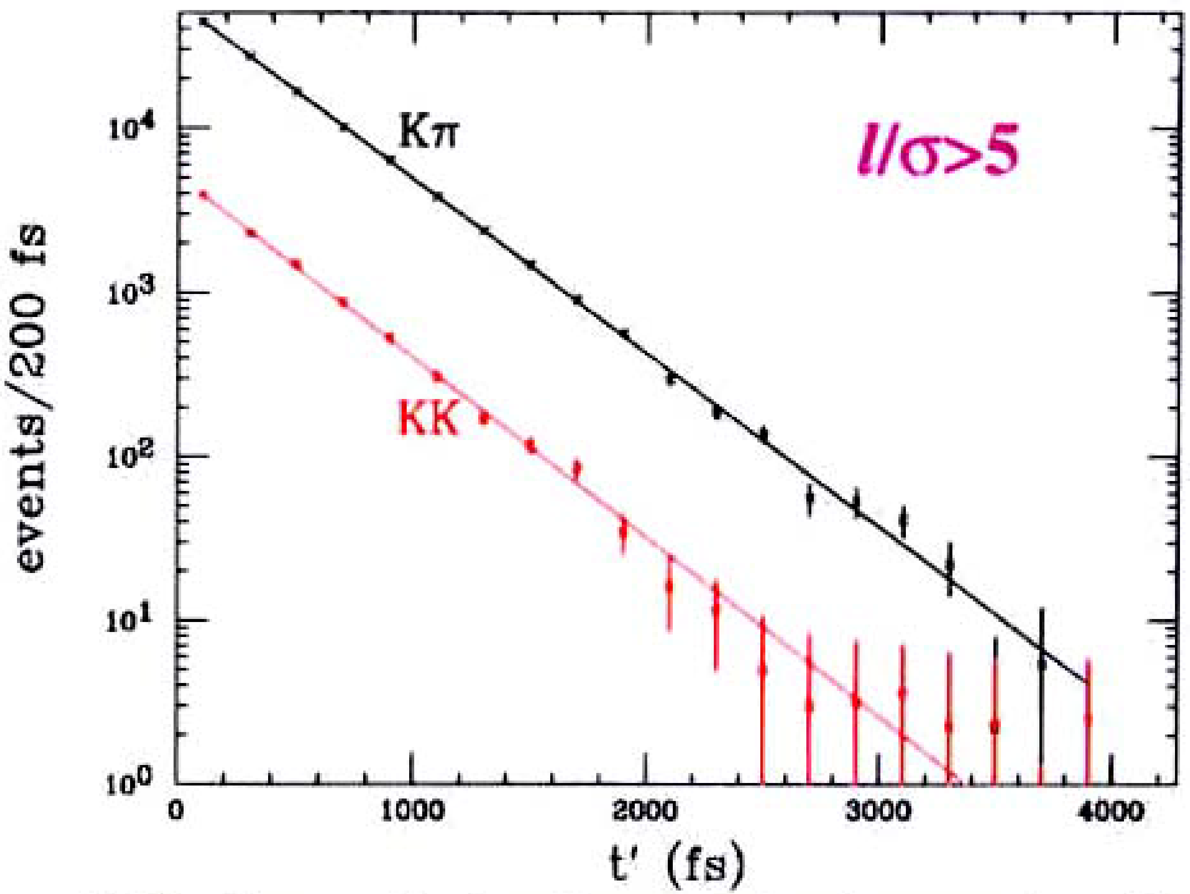


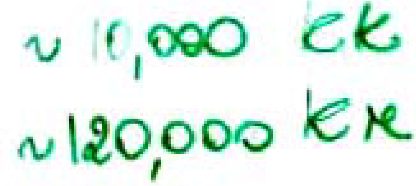
Time evolutions



We illustrate a low and high l/σ detachment with tight kaonicity. Fits cover ~3.5 orders of magnitude and about 10 lifetimes. Fit quality is very good. Backgrounds have a short as well as long component. Detachment dramatically reduces the background level at low detachment

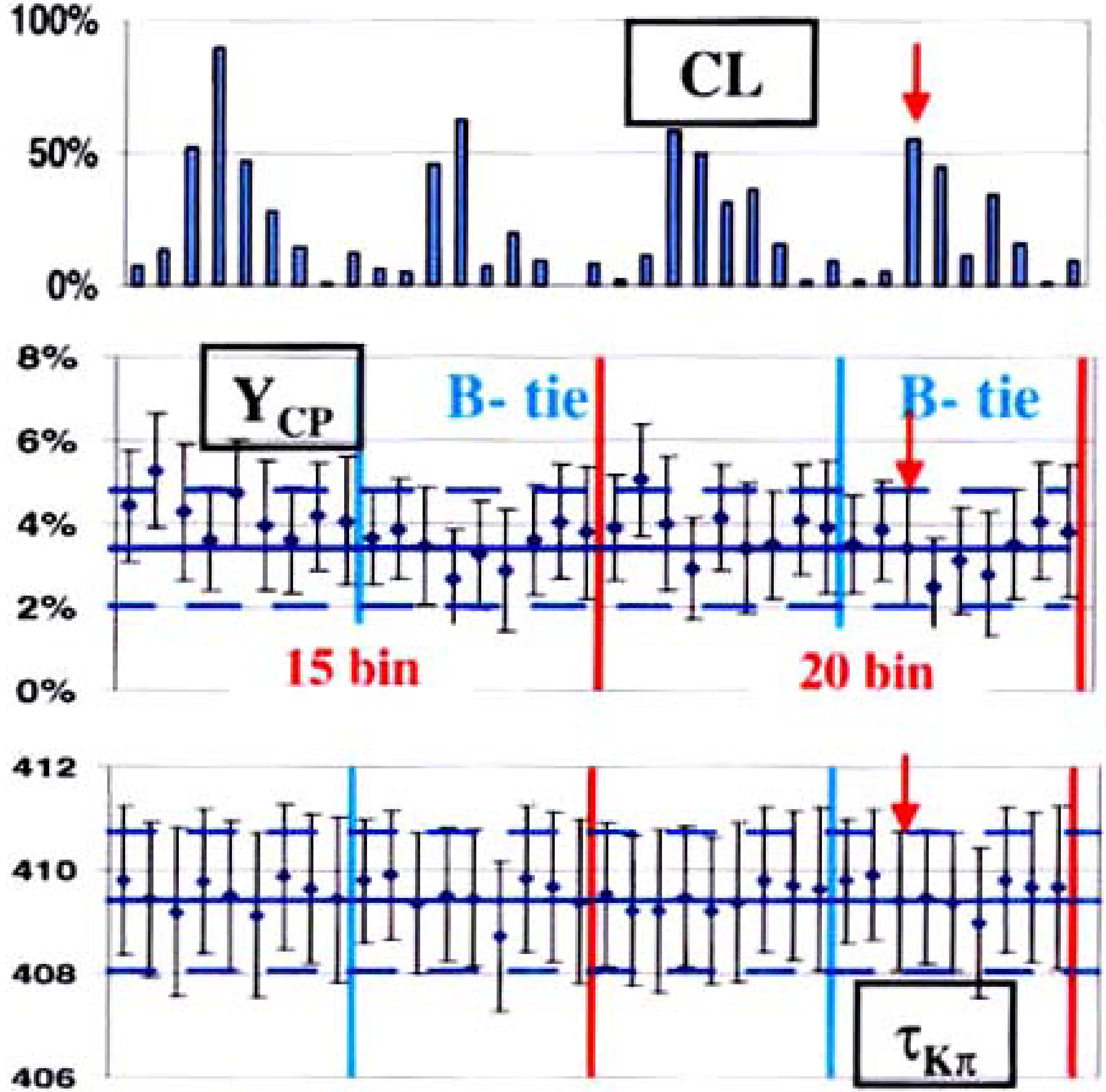
Subtracted time evolution





This shows the background subtracted and (very slight) MC corrected KK and Kπ yields versus t' for our "official" fit.

Results



3 Wk × 3 l/σ ×2 options ×2 bin

y_{CP} = 3.42±1.39±0.74 %

Sample standard deviation of fit variants is **±0.61**

$\tau(K\pi)$ = 409.4±1.34±?? fs

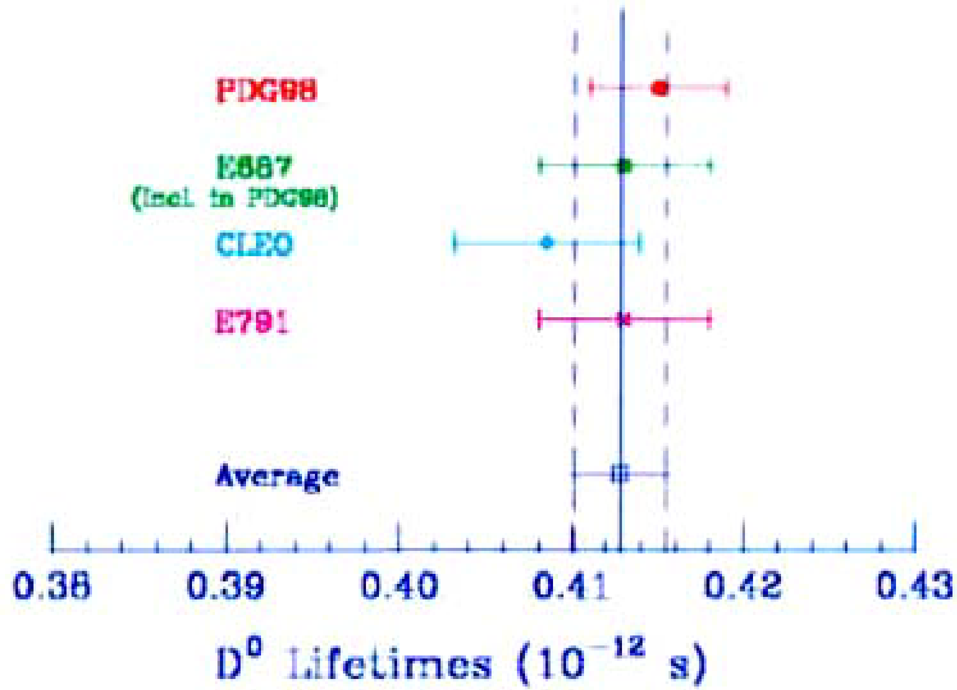
Sample standard deviation of fit variants **±0.3**

Absolute lifetime systematics not shown until we analyze $K3\pi$ etc

D° lifetimes

D⁰ lifetime update

Average $\tau(D^0) = 0.4128 \pm 0.0027$ psec

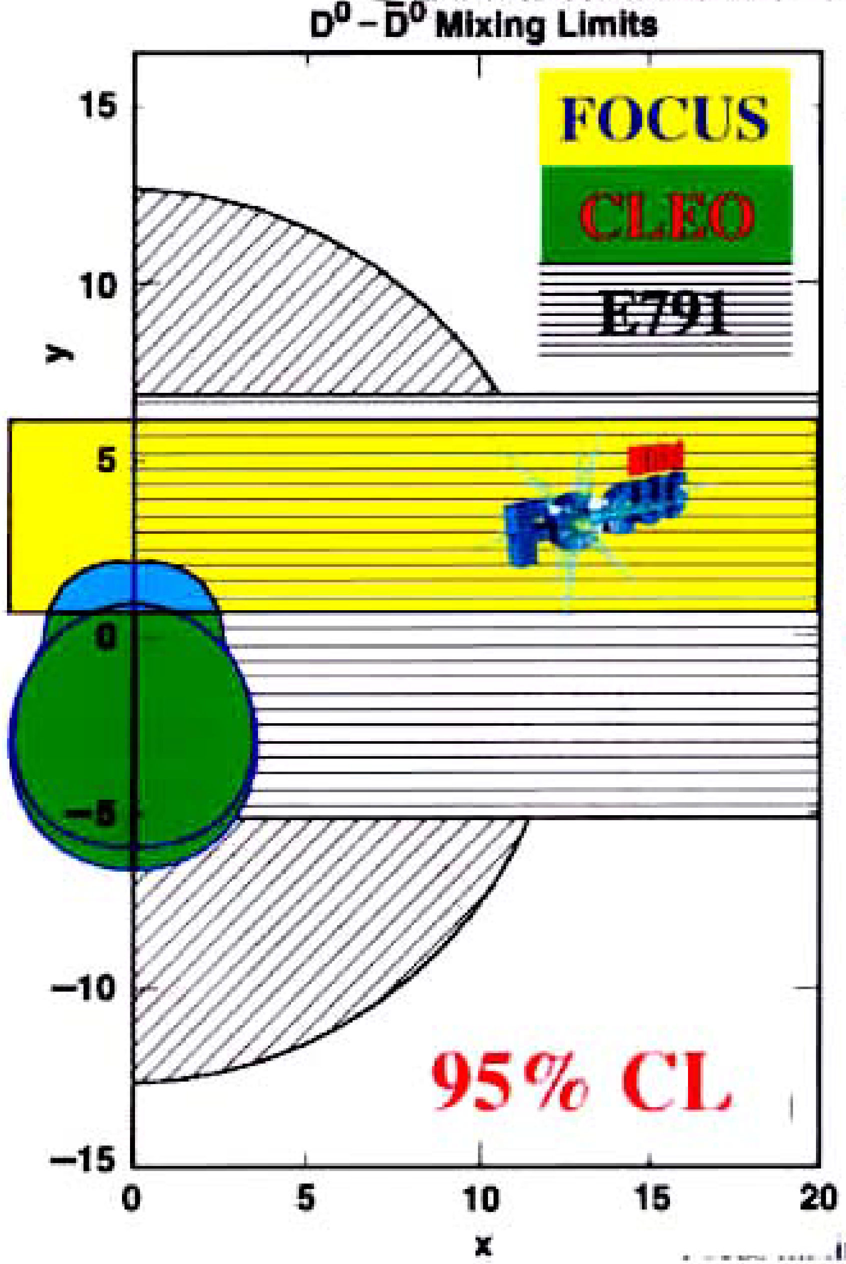


- Harry W. K. Cheung

HEAVY FLAVOURS 8

Experiment	pub order	D° lifetime fs
E691	1	422 ± 8 ± 10
E687	2	413 ± 4 ± 3
E791	3	413 ± 3 ± 4
CLEO	4	408.5 ± 4.1 ± 3.5
FOCUS *Kπ only	**5**	**409.4 ± 1.34 ± x***
Average of 3 recent values		409.6 ± 1.3
		χ^2=0.52 for 2

Comparisons to CLEO and E791



The comparison to CLEO **is only valid if** one assumes a small strong phase difference δ

We have essentially the same sensitivity to the CLEO CP constrained fit but are getting the opposite sign!

FOCUS

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

Previous Measurements

E791: y_{CP} =(+0.8 ± 2.9 ±1)%

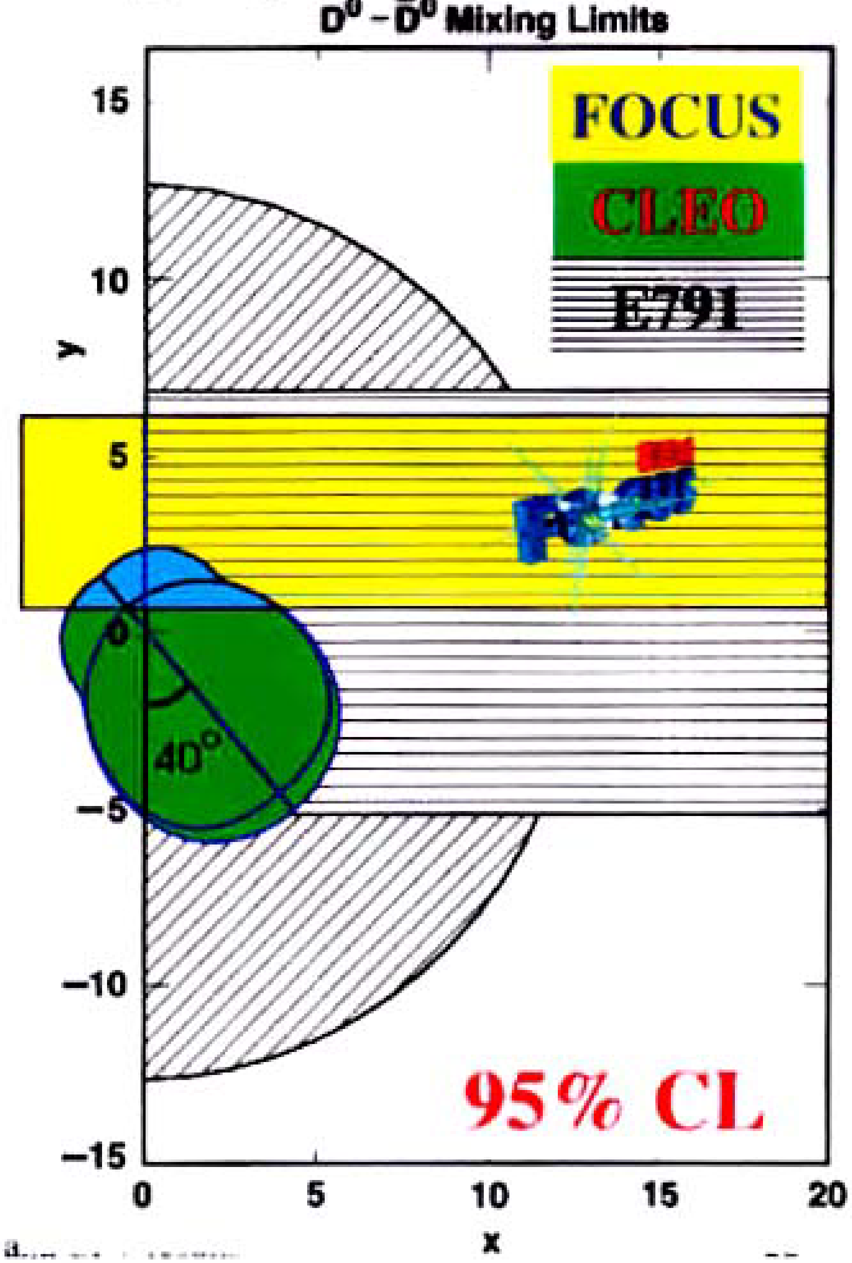
CLEO -5.8 % < y' < 1% (95% CL)

Phase ambiguity

We also show results under a 40° phase rotation for CLEO which is roughly the estimated maximum of the model of Falk, Nir & Petrov (99)

CLEO and FOCUS would be more consistent if δ> 90°...

but FOCUS has some overlap even with CLEO's most restrictive fit at δ= 40°.



Focus mixing a...

Search for CP asymmetry in charm decay

Ideally we would measure:

$$\alpha_{CP}(D^+ \to K^- K^+ \pi^+) = \frac{\Gamma(D^+ \to K^- K^+ \pi^+) - \Gamma(D^- \to K^- K^+ \pi^-)}{\Gamma(D^+ \to K^- K^+ \pi^+) + \Gamma(D^- \to K^- K^+ \pi^-)}$$

or: $$\alpha_{CP}(D^o \to K^- K^+) = \frac{\Gamma(D^0 \to K^- K^+) - \Gamma(\bar{D}^o \to K^- K^+)}{\Gamma(D^0 \to K^- K^+) + \Gamma(\bar{D}^o \to K^- K^+)}$$

- In the first case, would search for direct CP violation:
  - –need for CS decays
- In the latter case, D^o asymmetry is complicated by a direct as well mixed contribution.

Buccella et al predict state specific asymmetries in the range of $0.002 \to 0.14$ %

Tagging and asymmetry ratios

We ratio to a Cabibbo allowed reference states to correct for known production asymmetries: ~ -3% for photoproduced mesons.

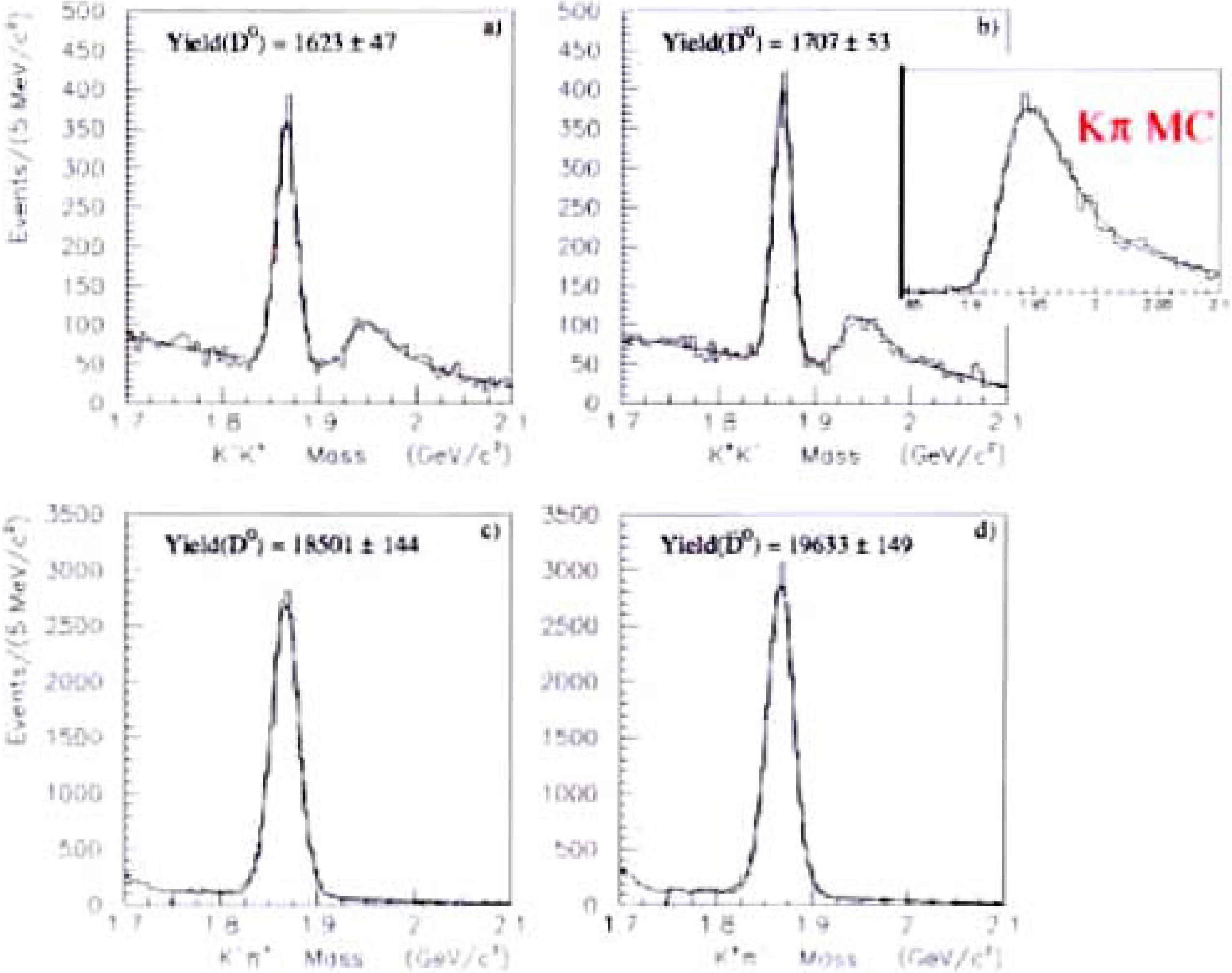
$$A_{CP} = \frac{\eta(D) - \eta(\bar{D})}{\eta(D) + \eta(\bar{D})}$$

For the D^+ we use: $\eta(D) = \frac{N(D^+ \to K^- K^+ \pi^+)}{N(D^+ \to K^- \pi^+ \pi^+)}$

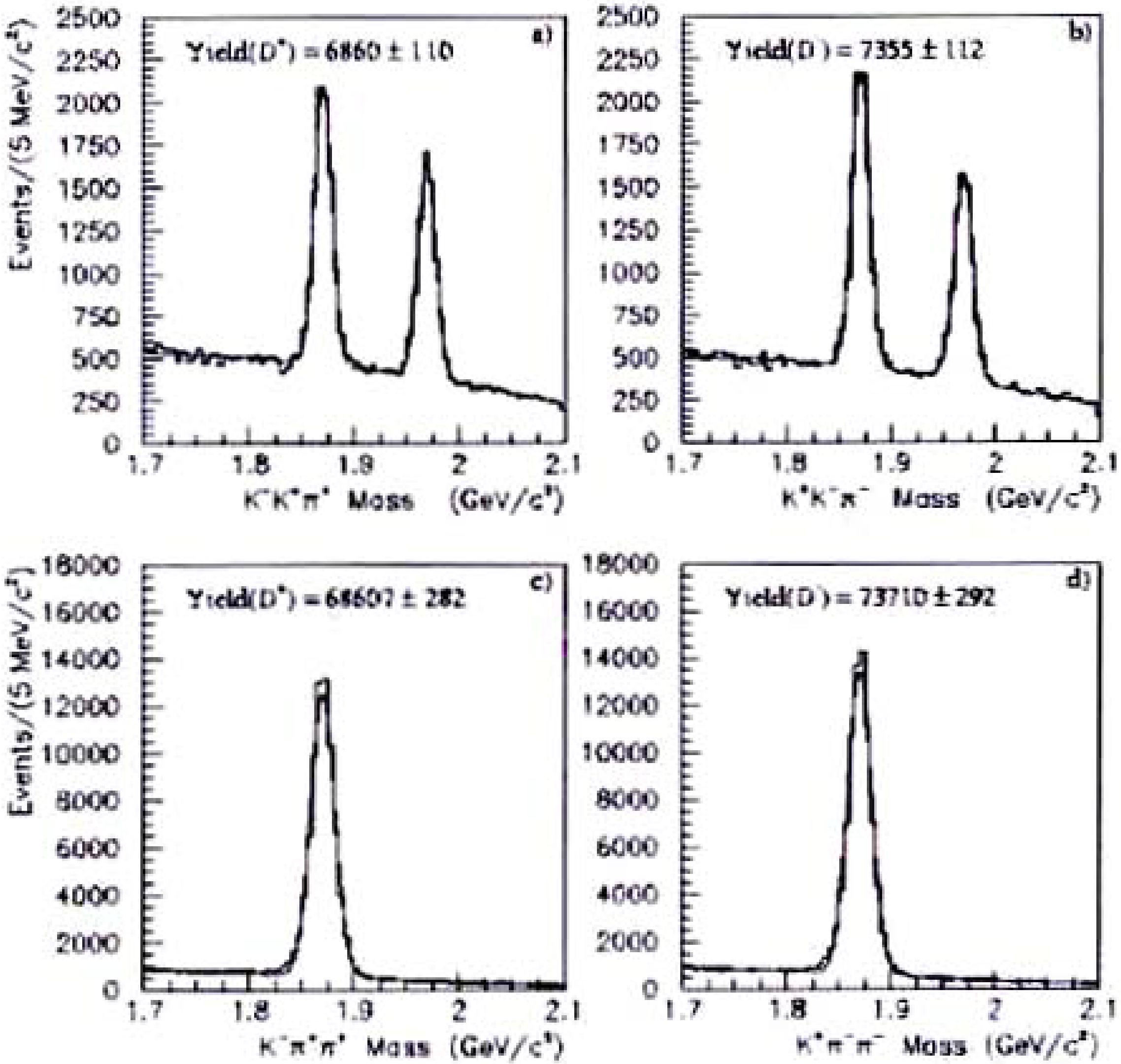
For the D^o we use: $\eta(D) = \frac{N(D^o \to K^- K^+)}{N(D^o \to K^- \pi^+)}$

For the D^o, we determine the charm by tagging the charge of the batchelor pion from $D^{*+} \to D^o \pi^+$

CP violation search (D→KK)



CP violation search (D⁺→KKπ)



CP asymmetry results

Decay mode	FOCUS	Previous best (E791)
$D^+ \to K^- K^+ \pi^+$	+0.006 ± 0.011 ± 0.005	-0.014 ± 0.029
$D^0 \to K^- K^+$	-0.001 ± 0.022 ± 0.015	-0.010 ± 0.049 ± 0.012
$D^0 \to \pi^+ \pi^-$	+0.048 ± 0.039 ± 0.025	-0.049 ± 0.078 ± 0.030

•No evidence for CP violation.

•Our limits on $K^+ K^- \pi^\pm$ are much better than $K^+ K^-$

•Need to use tagged D° sample which cuts our sample by 80%

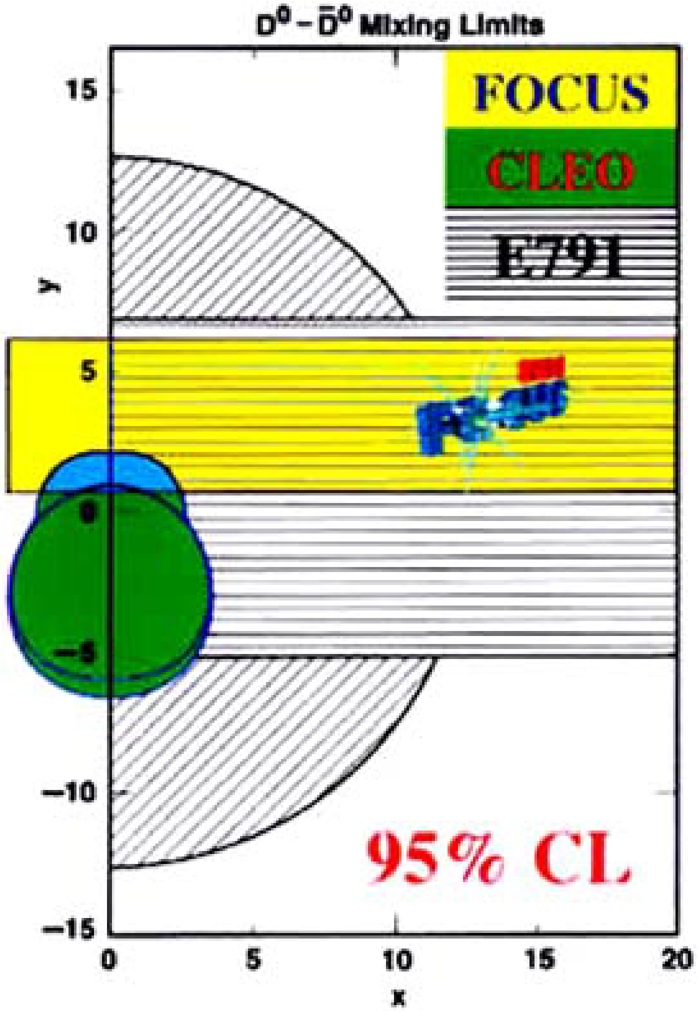
•Our limits are ~2→3 × more stringent than E791 reflecting our larger statistics.

Summary

$y_{CP} = 3.42 \pm 1.39 \pm 0.74\ \%$
$\tau(K\pi) = 409.4 \pm 1.34 \pm ??\ \text{fs}$

Decay mode	FOCUS	Previous best (E791)
$D^+ \to K^- K^+ \pi^+$	$+0.006 \pm 0.011 \pm 0.005$	-0.014 ± 0.029
$D^0 \to K^- K^+$	$-0.001 \pm 0.022 \pm 0.015$	$-0.010 \pm 0.049 \pm 0.012$
$D^0 \to \pi^+ \pi^-$	$+0.048 \pm 0.039 \pm 0.025$	$-0.049 \pm 0.078 \pm 0.030$

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



3 principal results presented

- A value for KK and Kπ lifetime ratio

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

- A new value for Kπ lifetime but without full systematics
- Much more stringent CPV asym limits