# Recent Results in Charm Mesons

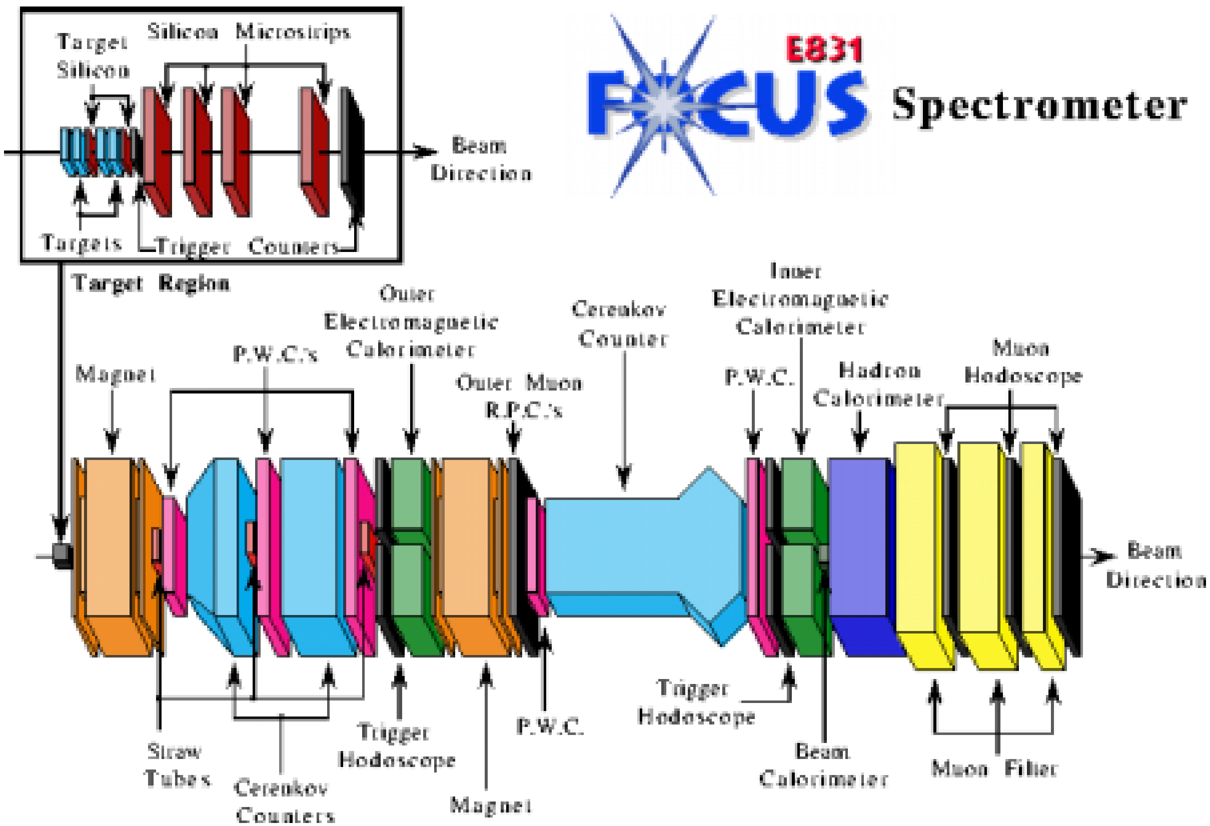
Jonathan Link

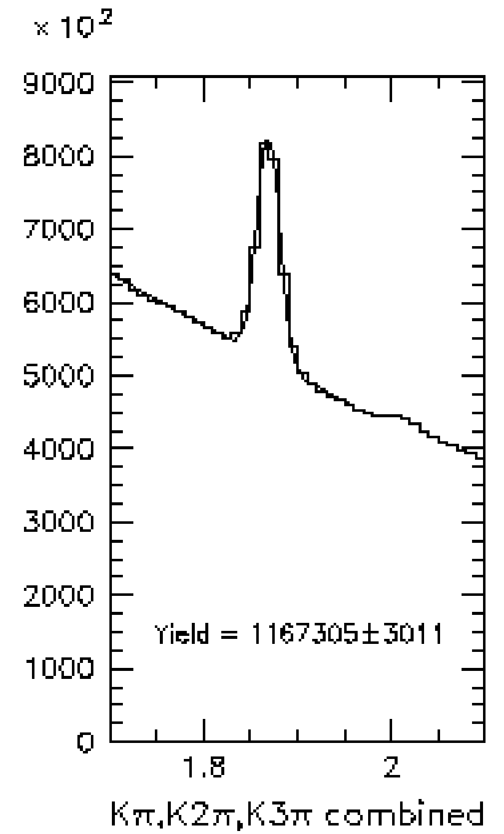
Columbia University

The 5th KEK Topical Conference –
Frontiers in Flavor Physics

November 20-22, 2001

# FOCUS is a Charm Photoproduction Experiment at Fermilab




This design facilitates excellent vertex resolution, particle identification and momentum resolution.

More than 1 million fully reconstructed *D* mesons!

# Collaborating Institutions

University of California, Davis

CBPF (Brazil)

CINVESTAV (Mexico)

University of Colorado, Boulder

Fermi National Accelerator Laboratory

Laboratori Nazionali di Frascatti dell'INFN (Italy)

University of Illinois, Urbana

Indiana University, Bloomington

Korea University, Seoul

INFN and University of Milano (Italy)

University of North Carolina, Asheville

INFN and University of Pavia (Italy)

University of Puerto Rico, Mayaguez

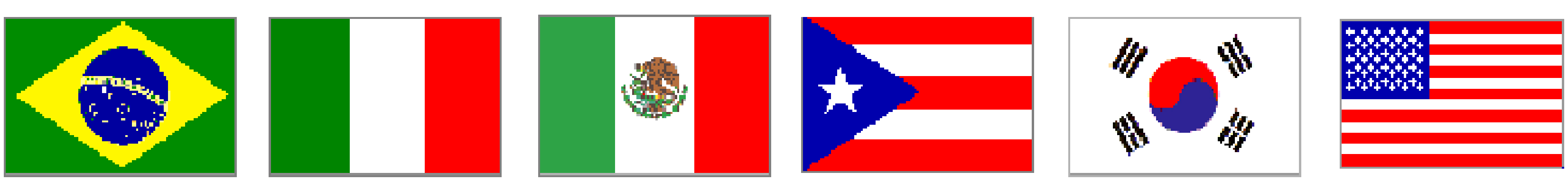
University of South Carolina, Columbia

University of Tennessee, Knoxville

Vanderbilt University

University of Wisconsin, Madison

**~ 100 Physicists**

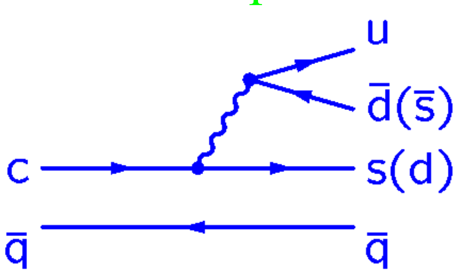


# Charm Branching Ratios

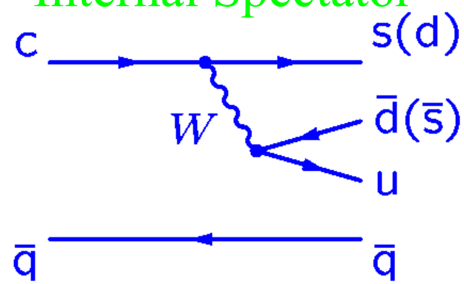
Deviations from naïve expectations leads to an improved understanding of

- charm quark decay dynamics
- and final state interactions

External Spectator

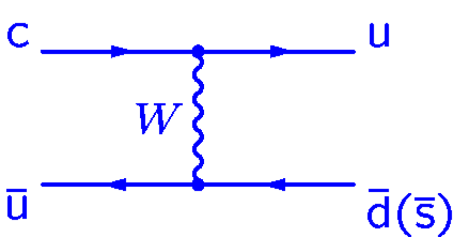



Internal Spectator

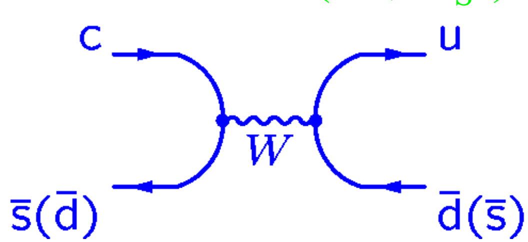



There are 4 tree level Feynman diagrams for charm meson decay.

W Exchange ($D^0$)



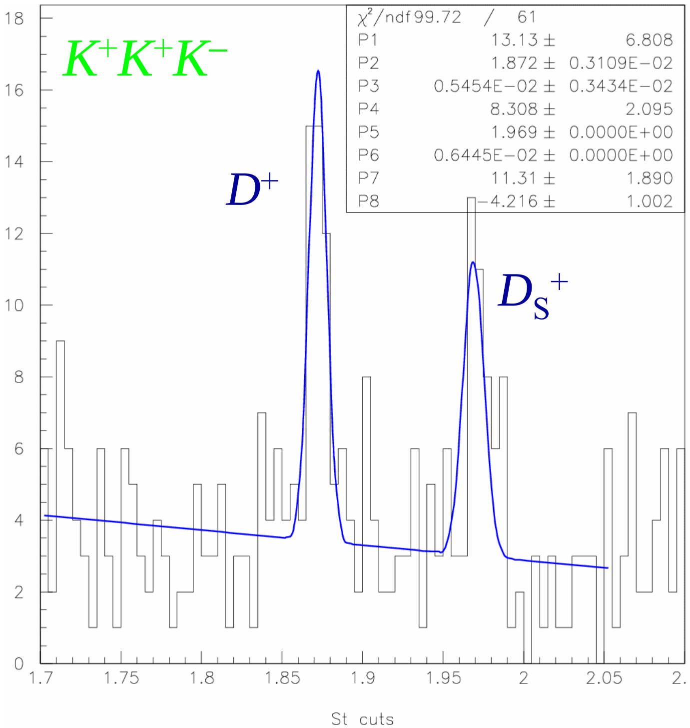

Annihilation ($D^+$, $D_S^+$)



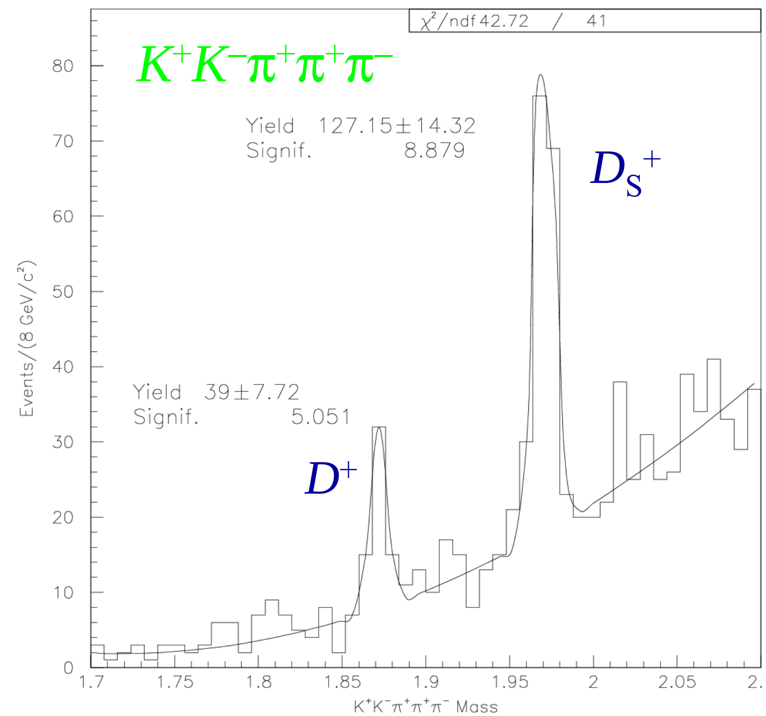

Each CS vertex leads to a suppression of $\sim\tan^2\theta_C$.

Quarks in () indicate Cabibbo suppression.

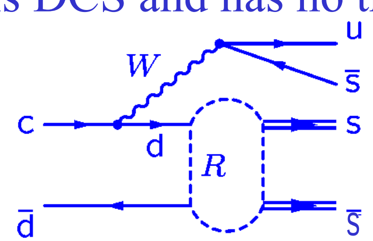
# Rare Hadronic Decays




$D^+ \to K^+K^-\pi^+\pi^+\pi^-$ is a SCS and is also a first observation.

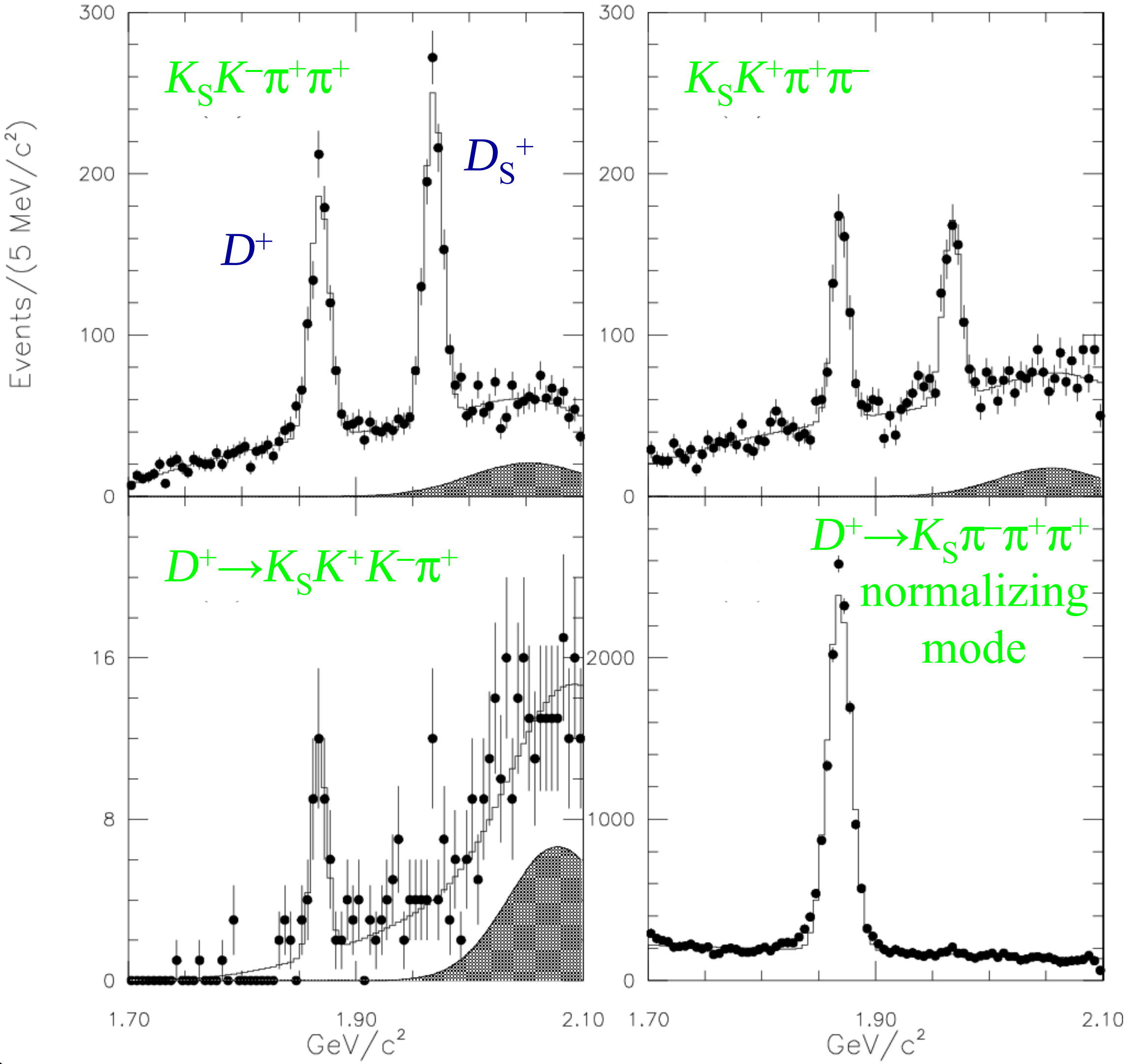



$D^+ \to K^+K^+K^-$ is DCS and has no trivial Feynman diagrams




∴ it is the smallest charm BF yet measured at $10^{-4}$.

# Four Body Decays with a $K_S$




Many of these modes have never been observed before.

Our ability to extract them from the data illustrates the power of our Čerenkov particle id system.

# Summary of New *D* Meson Modes and Improved Branching Ratios

| Decay Mode | Norm | BR (%) | PDG 2K | Status |
|---|---|---|---|---|
| $D^+ \to \overline{K}^0 \pi^+$ | $K^- \pi^+ \pi^+$ | 30.60±0.46±0.32 | 32.1±2.5 | hep-ex/0109022 |
| $D^+ \to \overline{K}^0 K^+$ | $K^- \pi^+ \pi^+$ | 6.04±0.35±0.30 | 8.2±1.0 | hep-ex/0109022 |
| $D^+ \to K^+ K^- \pi^+ \pi^+ \pi^-$ | | seen | NA | Preliminary |
| $D^+ \to K_S K^- \pi^+ \pi^+$ | $K_S \pi^- \pi^+ \pi^+$ | 7.68±0.41±0.32 | 14±8 | PRL 87,162001 |
| $D^+ \to K_S K^+ \pi^+ \pi^-$ | $K_S \pi^- \pi^+ \pi^+$ | 5.62±0.39±0.40 | NA | PRL 87,162001 |
| $D^+ \to K_S K^+ K^- \pi^+$ | $K_S \pi^- \pi^+ \pi^+$ | 0.77±0.15±0.09 | NA | PRL 87,162001 |
| $D^+ \to K^+ K^+ K^-$ | $K^- \pi^+ \pi^+$ | 0.114±0.024 | <0.16 | Preliminary |
| $D^0 \to K^+ \pi^-$ | $K^- \pi^+$ | 0.404±0.085±0.025 | 0.38±0.08 | PRL 86,2955 |
| $D^0 \to K^+ K^- K^- \pi^+$ | $K^- \pi^+ \pi^+ \pi^-$ | 0.306±0.047 | 0.28±0.07 | Preliminary |
| $D_S^+ \to K^+ K^+ K^-$ | $K^- K^+ \pi^+$ | seen | NA | Preliminary |
| $D_S^+ \to K_S K^+ \pi^+ \pi^-$ | $K_S K^- \pi^+ \pi^+$ | 58.6±5.2±4.3 | NA | PRL 87,162001 |

Red indicates the mode is as first observation.

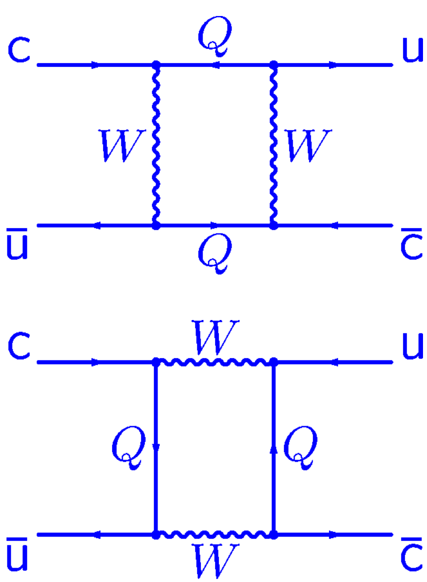
# Mixing Theory

Mixing is parameterized by two dimensionless amplitudes:

$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma}$$

$\Delta M$ and $\Delta\Gamma$ are the mass and width difference between $D^0$ weak eigenstates.

## Short Range Mixing:




The strength of the box diagram is driven by two factors:

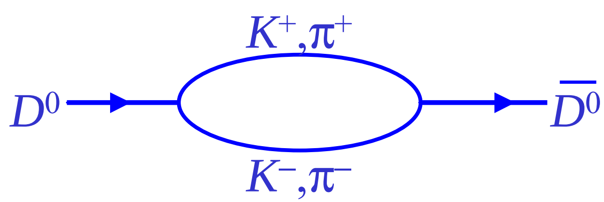
| System | Q | $m^2_Q/M^2_W$ | $(V_{Qq}V_{Qq'}^*)^2$ |
|---|---|---|---|
| $K^0$ | $c$ | $\sim 10^{-4}$ | $\sim\lambda^2$ |
| | $t$ | $\sim 5$ | $\sim\lambda^{10}$ |
| $D^0$ | $s$ | $\sim 10^{-6}$ | $\sim\lambda^2$ |
| | $b$ | $\sim 10^{-3}$ | $\sim\lambda^{10}$ |
| $B_d^0$ | $t$ | $\sim 5$ | $\sim\lambda^6$ |
| $B_s^0$ | $t$ | $\sim 5$ | $\sim\lambda^4$ |

$\lambda = \sin\theta_C \approx 0.23$

(from the Wolfenstein CKM Parameterization)

For the $D^0$ $R_{mix} \leq 10^{-10}$

## Long Range Mixing:

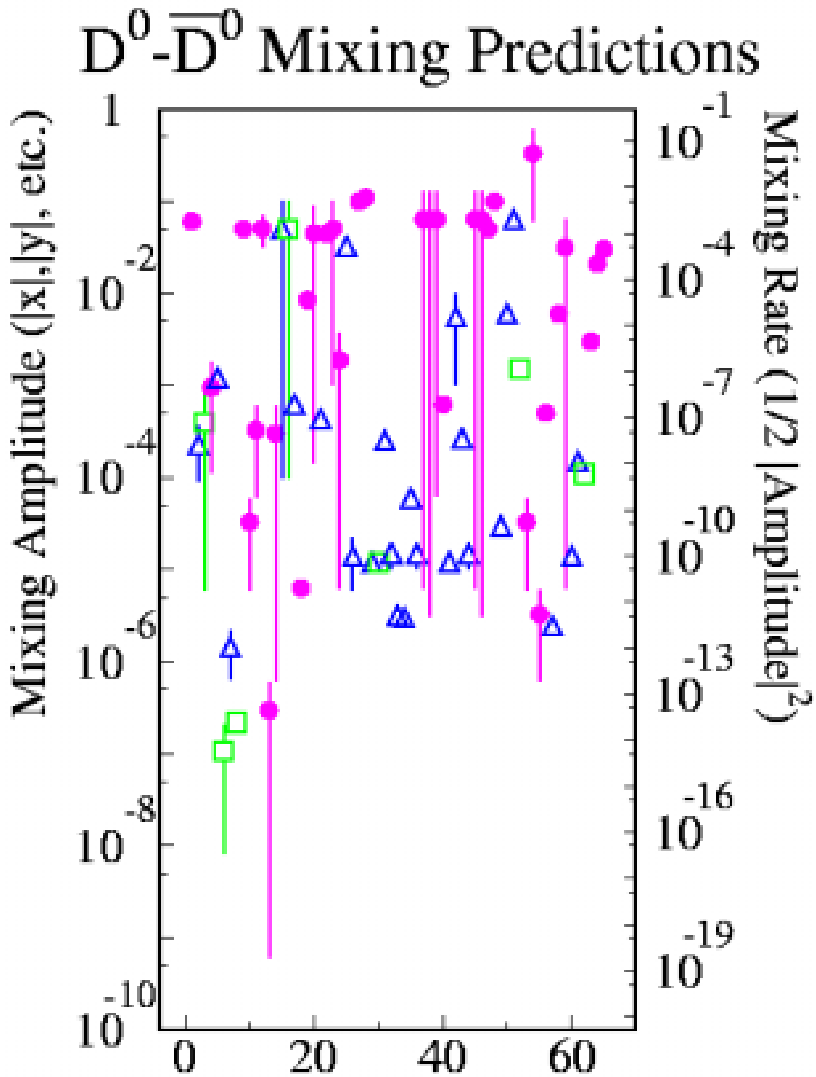



Naively, $\Delta C = 2$ so we expect $R_{mix} \leq \tan^4\theta_C$ but intermediate states interfere.

# Summary of Theoretical Predictions

From compilation of
H.Nelson hep-ex/9908021

- △ *x* Standard Model
- □ *y* Standard Model
- ● *x* Non-Standard Model



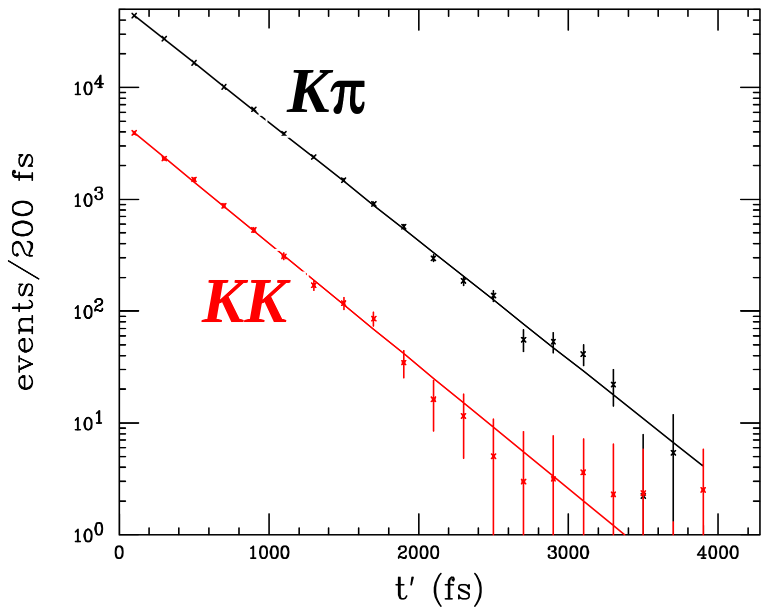

The predictions cover 7 orders of magnitude in *x* and *y*!

# Mixing from $D^0$ Lifetime Differences
(PLB 495, 62)

Look for a lifetime difference between CP even and CP odd states.

We use $K^+K^-$, which is pure CP even, and $K^-\pi^+$, which has mixed CP (we assume an even mixture) then:

$$y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_{\mathrm{even}} - \Gamma_{\mathrm{odd}}}{\Gamma_{\mathrm{even}} + \Gamma_{\mathrm{odd}}} = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^-K^+)} - 1$$




$\tau(KK) = 395.7 \pm 5.5$ fs

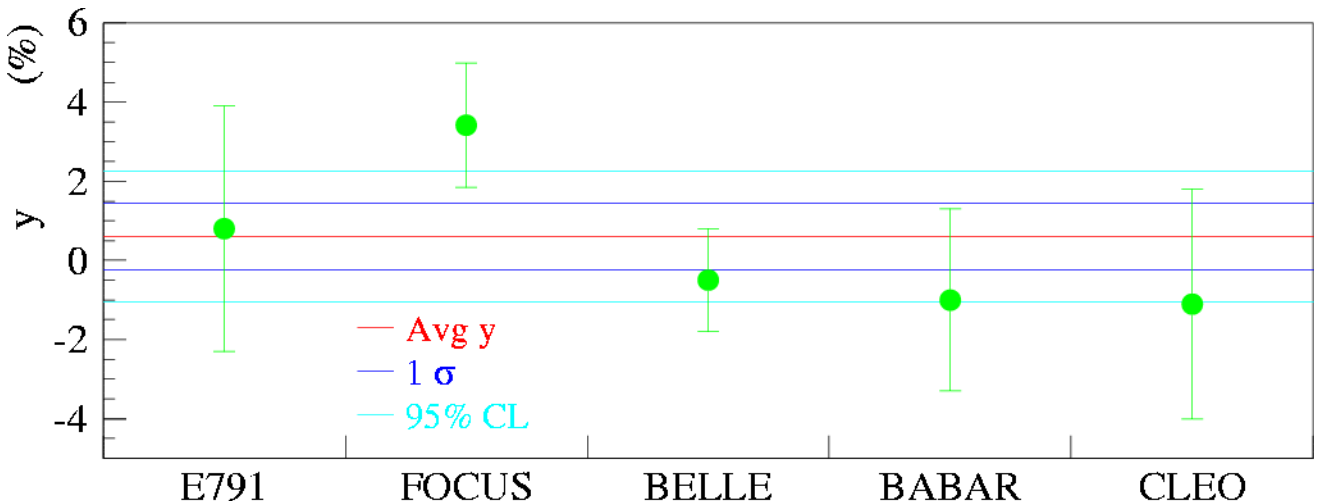
$\tau(K\pi) = 409.2 \pm 1.3$ fs

and

$y = (3.42 \pm 1.39 \pm 0.74)\%$

# Comparison of *y* Results

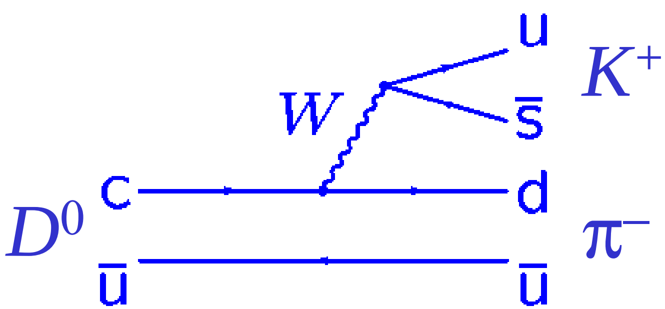
| Experiment | $y$ (%) | Lifetime $D^0 \to K\pi$ (*fs*) |
|---|---|---|
| E791 | 0.8 ± 2.9 ± 1.0 | 413 ± 11 ± 6 |
| FOCUS | 3.42 ±1.39 ± 0.74 | 409.2 ± 1.3 (Stat. Only) |
| BELLE (Preliminary) | $-0.5 \pm 1.0 ^{+0.7}_{-0.8}$ | 416.2 ± 1.1 (Stat. Only) |
| BABAR (Preliminary) | –1.0 ± 2.2 ± 1.7 | 412 ± 2 (Stat. Only) |
| CLEO (Preliminary) | –1.2 ± 2.5 ± 1.4 | 404.6 ± 3.6 (Stat. Only) |
| World Average | 0.60 ± 0.84 | 412.6 ± 2.8 (PDG 2K) |

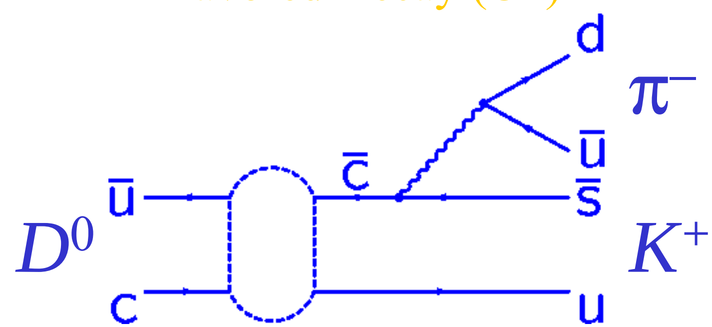


# Mixing Search with $D^0 \rightarrow K^+\pi^-$

$D^0 \rightarrow K^+\pi^-$ may occur through two processes:

Double Cabibbo Suppression (DCS) **or** Mixing Followed by a Cabibbo Favored Decay (CF)




Predicted contributions to the relative branching ratio (Standard Model):

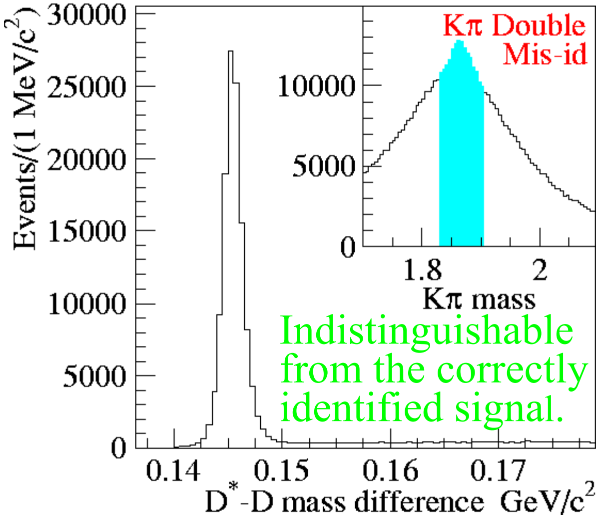
$R_{DCS} \sim \tan^4\theta_C = 0.25\%$ $R_{mix} \sim 10^{-7}$ to $10^{-3}$

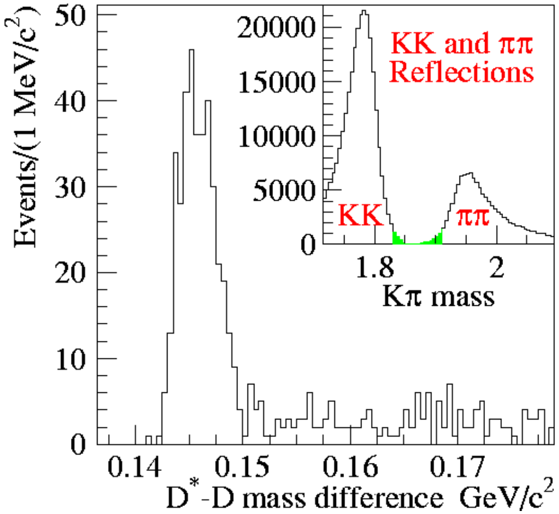
Only the decay time evolution can distinguish between DCS and mixing.

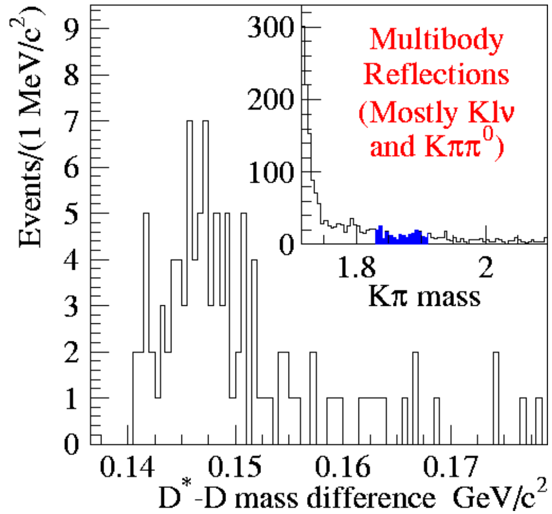
Useful Notation → Right Sign (RS): Cabibbo Favored Path
Wrong Sign (WS): DCS or Mixed Path

# Monte Carlo Background Studies

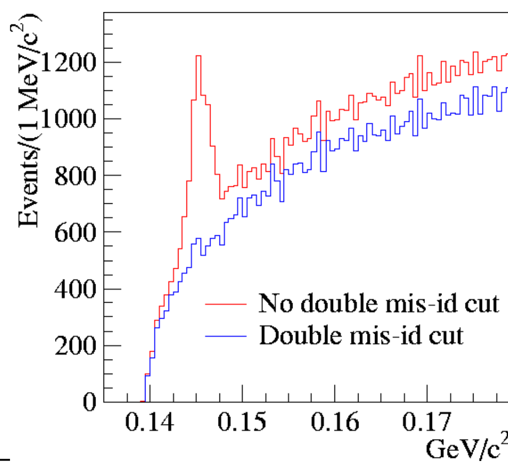
Backgrounds from other $D^0$ decays peak in the $D^*$ signal region!




If not dealt with these backgrounds could seriously bias the analysis.



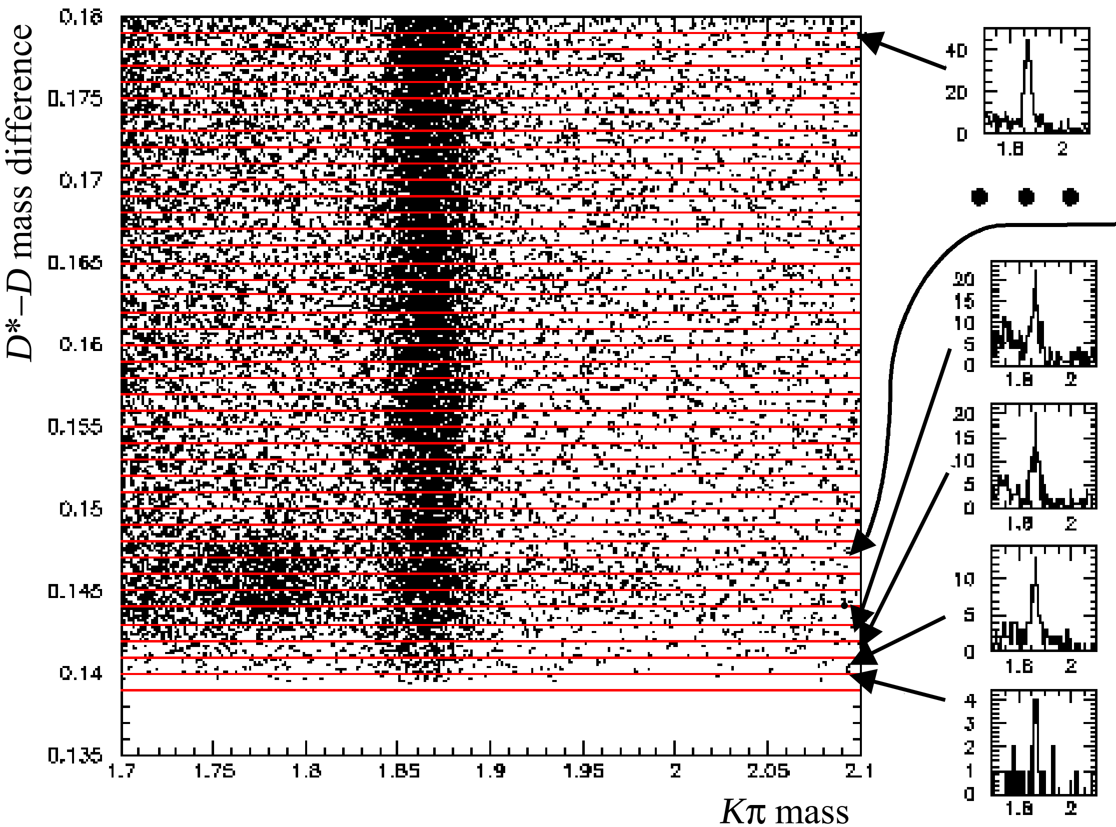

## To Deal With Double Mis-id

We use a tight Čerenkov id cut in an 8σ window about the $D^0$ mass with $K\pi$ reconstructed as $\pi K$.

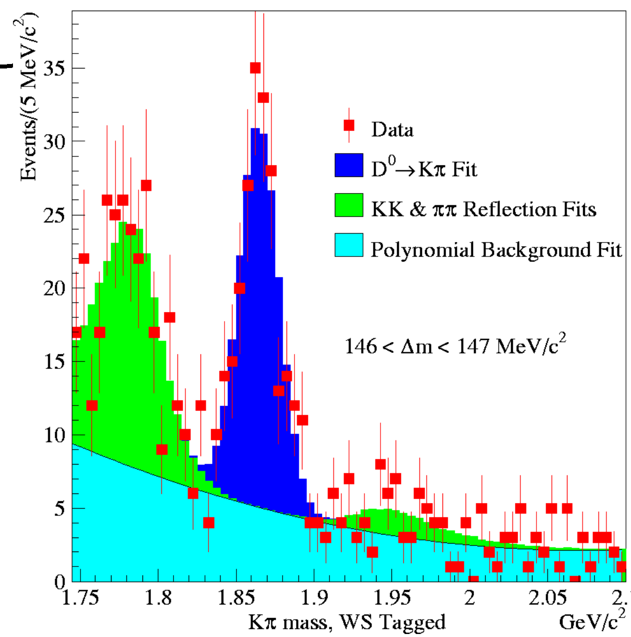
E831 FOCUS

# A New Background Suppressing Fit Method

- Divide the data into 1 MeV wide bins in $\Delta m$, and fit the $D^0$ in each bin.
- Fit the *KK* and $\pi\pi$ reflections to Monte Carlo line shapes.



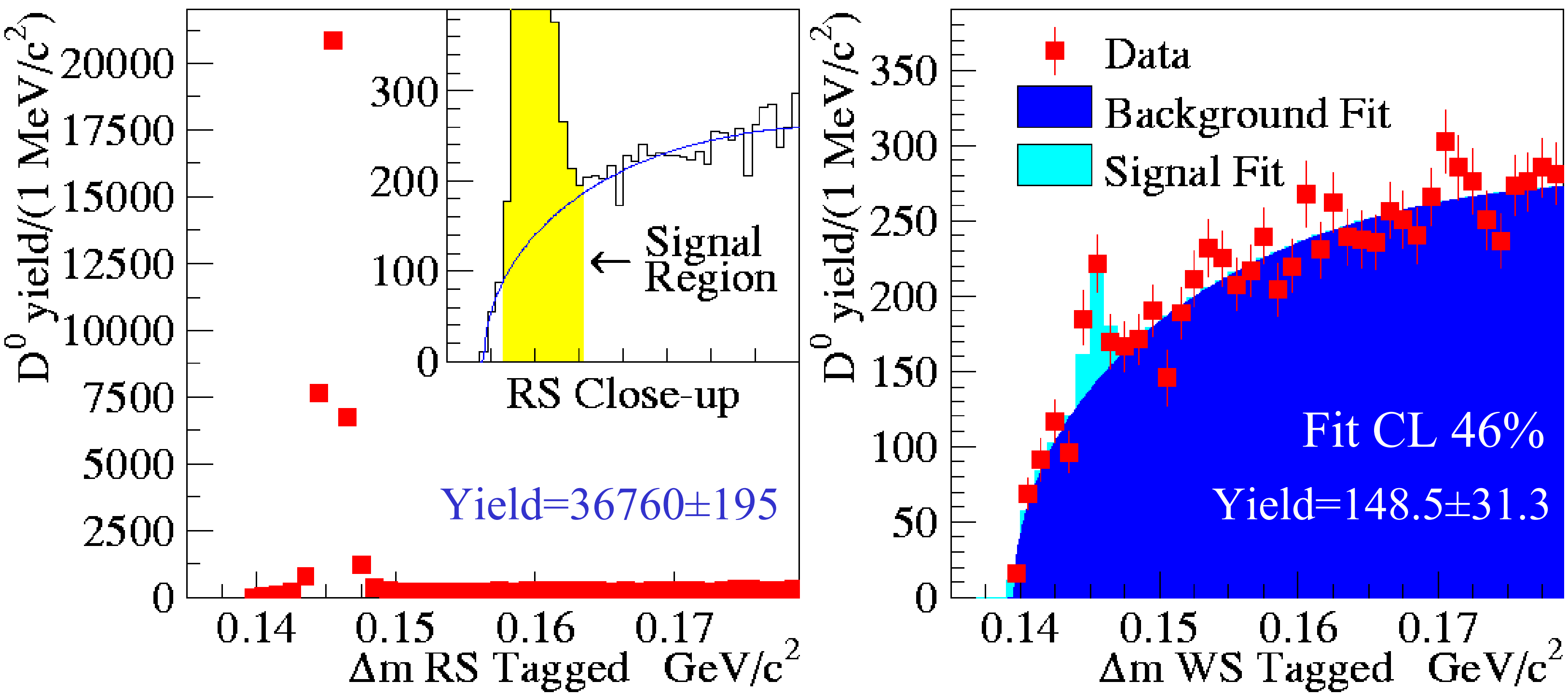

- Fit BG to a polynomial.
- Fit $D^0$ to a Gaussian.




A total of 80 $K\pi$ fits!

# Fit the Mass Difference Distributions

- Fitted $D^0$ yields are plotted in the appropriate mass difference bins.
- WS signal is fit directly to the RS histogram above BG in the signal region.
- Background is fit to: $f(\Delta m) = a(\Delta m - m_\pi)^{1/2} + b(\Delta m - m_\pi)^{3/2}$.




$$R_{WS} = (0.404 \pm 0.085 \pm 0.025)\%$$

# Other Measurements

Four groups have published measurements of this branching ratio (which in the limit of no mixing is just $R_{DCS}$). Also Belle and BaBar have preliminary measurements

| Experiment | $R_{DCS}$ (%) | Events |
|---|---|---|
| CLEO | 0.77±0.25±0.25 | 19.1 |
| E791 | 0.68 ±0.33 ±0.07 | 34 |
| Aleph | 1.77 ±0.58 ±0.31 | 21.3 |
| CLEO II.V | 0.332±0.064±0.040 | 44.8 |
| FOCUS, this study | 0.404±0.085±0.025 | 148.5 |
| BaBar, preliminary | 0.38±0.04±0.02 | 207 |
| BELLE, preliminary | 0.30±0.06±0.08 | |

All the high statistics measurements are in good agreement.

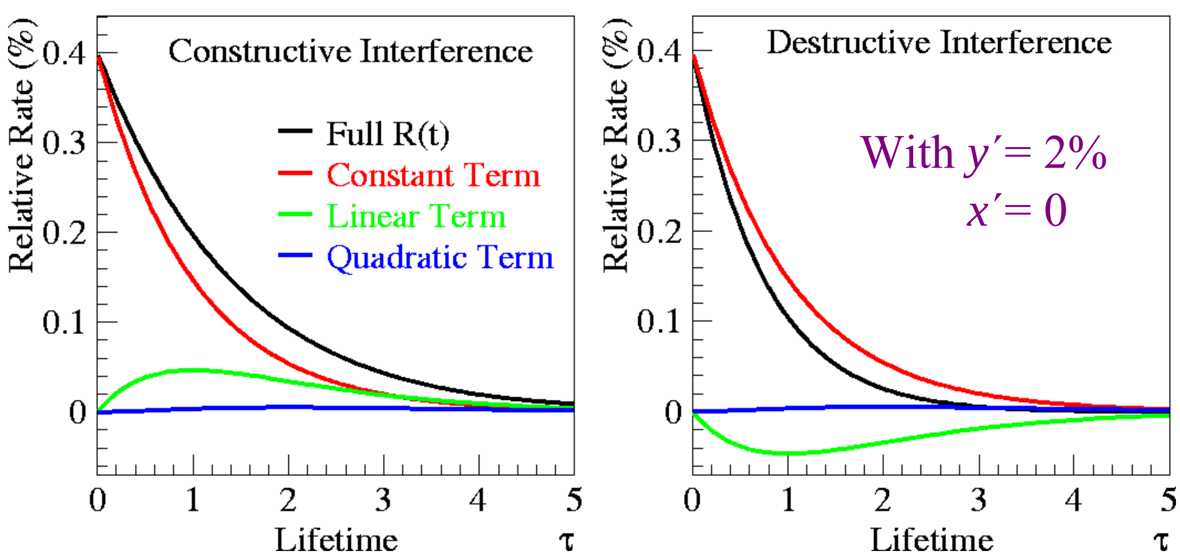
# Effect of Mixing on the Time Evolution

$$R(t) = e^{-t}\left( R_{\mathrm{DCS}} + \sqrt{R_{\mathrm{DCS}}}\, y' t + \frac{x'^2 + y'^2}{4} t^2 \right)$$

Pure DCS | Interference | Pure Mixing

Where $x'$ and $y'$ are strong phase rotations of $x$ and $y$ ($y' = y\cos\delta + x\sin\delta$ and $x' = x\cos\delta - y\sin\delta$).

And $t$ is defined in units of the $D^0$ lifetime ($\tau = 1/\Gamma = 413\ fs$).




If the acceptance or analysis have any systematic dependence on lifetime then the measured branching ratio depends on the lifetime acceptance of the analysis.

# Effects of Mixing

We use a large RS Monte Carlo to study the effects of mixing on $R_{\mathrm{WS}}$

$$\left(D^0 \to K^+\pi^-\right)^{expected}_{data} = \sum_i^{MC\ accepted} W\left(t_i, x', y', R_{\mathrm{DCS}}\right)$$

Where

$$W\left(t, x', y', R_{\mathrm{DCS}}\right) = \frac{N_{data}}{N_{MC}}\left(R_{\mathrm{DCS}} + \sqrt{R_{\mathrm{DCS}}}\,y't + \frac{x'^2+y'^2}{4}t^2\right)$$

Summing and solving for $R_{\mathrm{DCS}}$ we find…

$$R_{\mathrm{DCS}} = \frac{y'^2}{2}\langle t\rangle^2 - \frac{x'^2+y'^2}{4}\left\langle t^2\right\rangle + R_{\mathrm{WS}} - \frac{y'}{2}\langle t\rangle\sqrt{y'^2\langle t\rangle^2 - \left(x'^2+y'^2\right)\left\langle t^2\right\rangle + R_{\mathrm{WS}}}$$

Where $\langle t\rangle$ and $\langle t^2\rangle$ are in units of the $D^0$ lifetime.

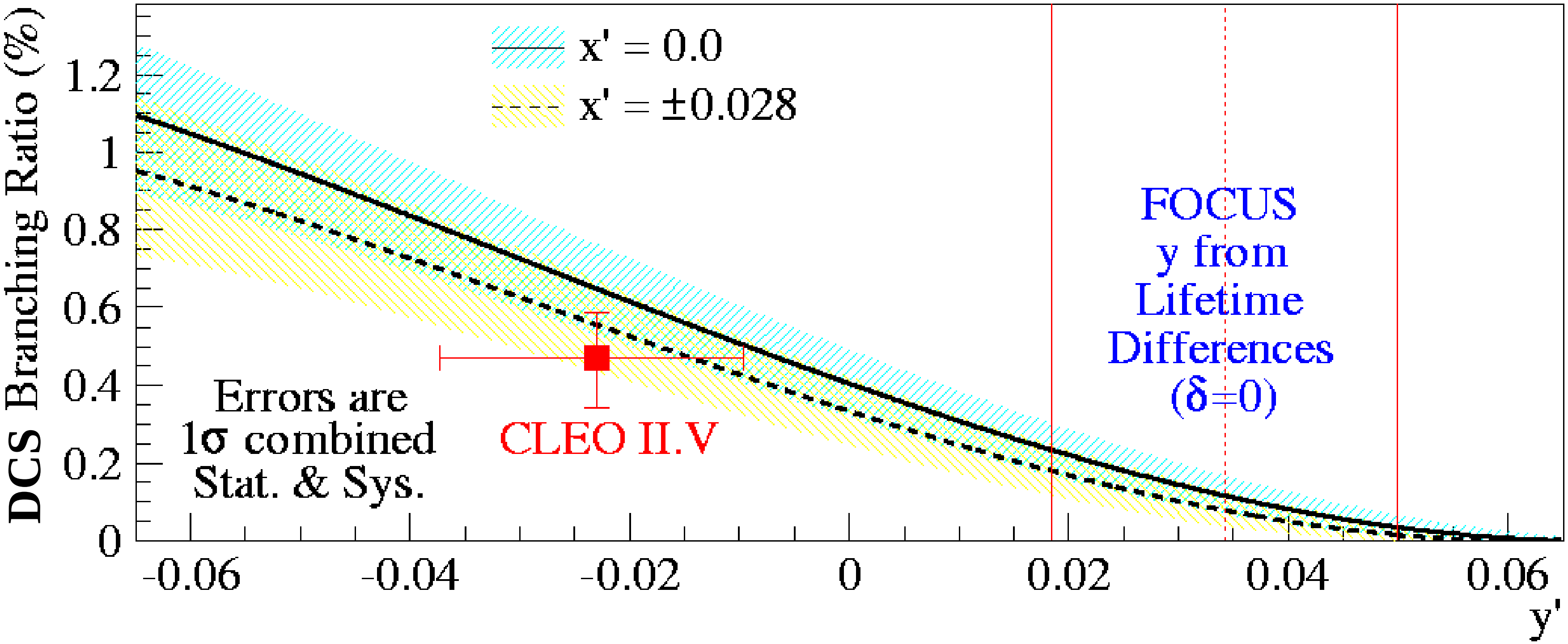
From the Monte Carlo:

$$\langle t\rangle = 1.578 \pm 0.008 \quad \text{and} \quad \left\langle t^2\right\rangle = 3.61 \pm 0.03$$

# $R_{DCS}$ Dependence on $y'$

## and comparison to other mixing measurements

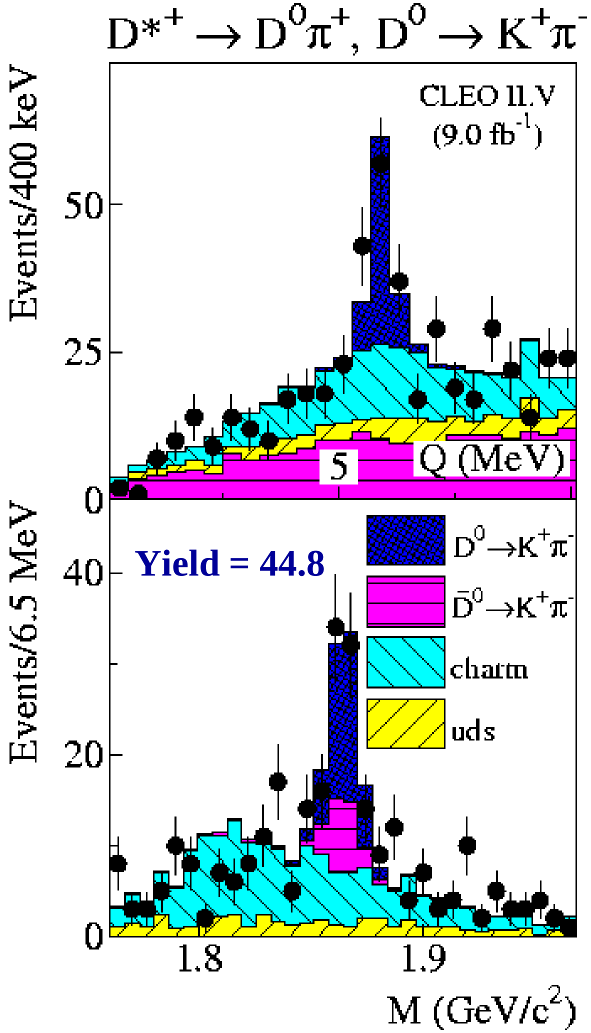
## (PRL 86,2955)

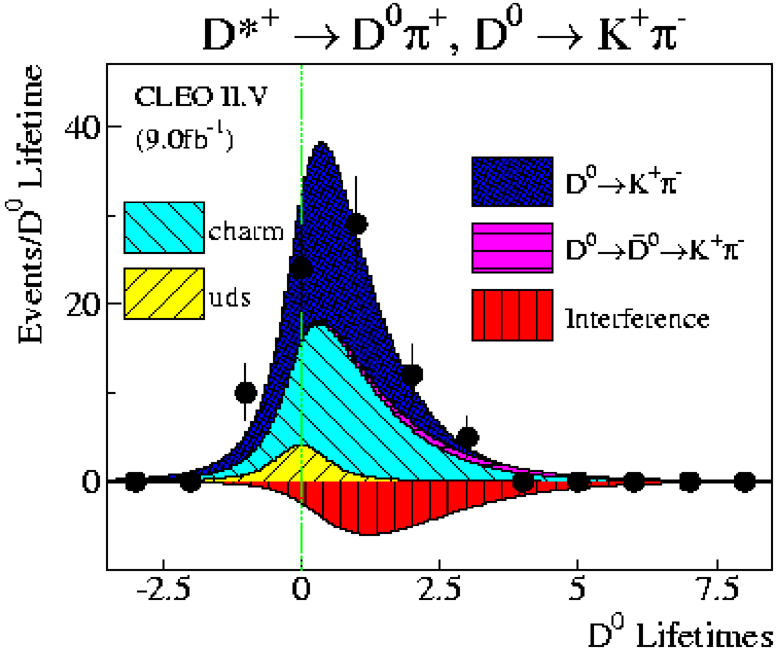



The FOCUS *y* measurement is only directly comparable to the $y'$ measurements if the strong phase δ is zero!


# CLEO II.V Mixing Study

Measure mixing and $R_{DCS}$ by fitting the lifetime distribution.




In the CP conserving case they finds:

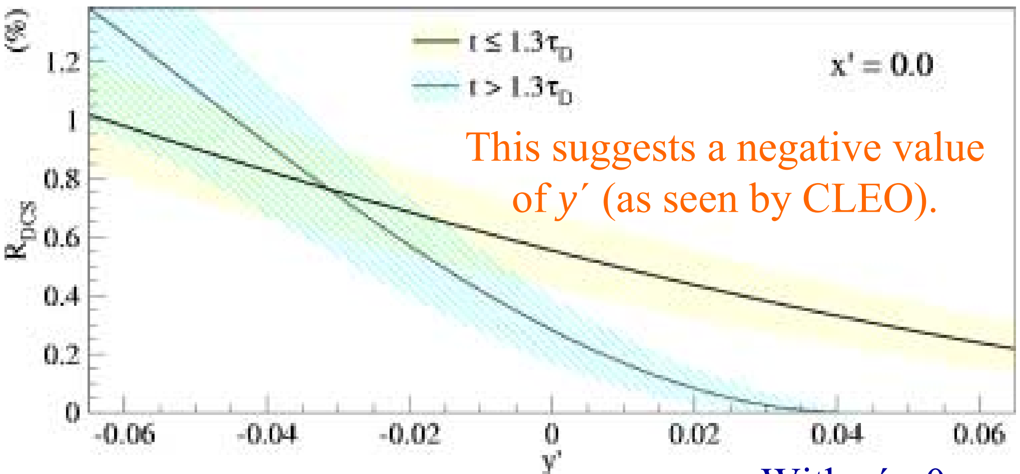
$R_{DCS} = (0.47 \pm 0.11 \pm 0.04)\%$

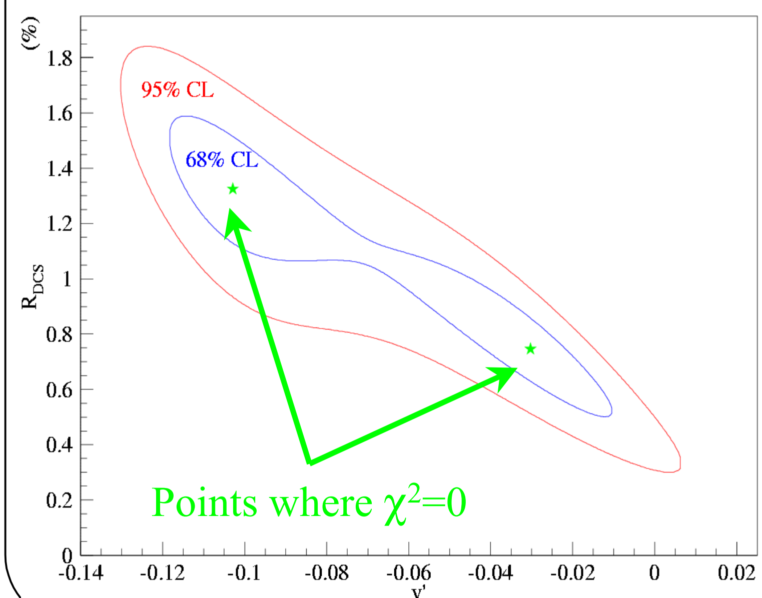
$y' = (-2.3 \pm 1.3 \pm 0.3)\%$

$x' = (0.0 \pm 1.5 \pm 0.2)\%$

# Determining Limits on $x'$ & $y'$ (Preliminary!)

## Split the data into long and short lifetime samples.




With $x' = 0$ we get the 95% CL Bayesian limits

$-12.4\% < y' < -0.6\%$

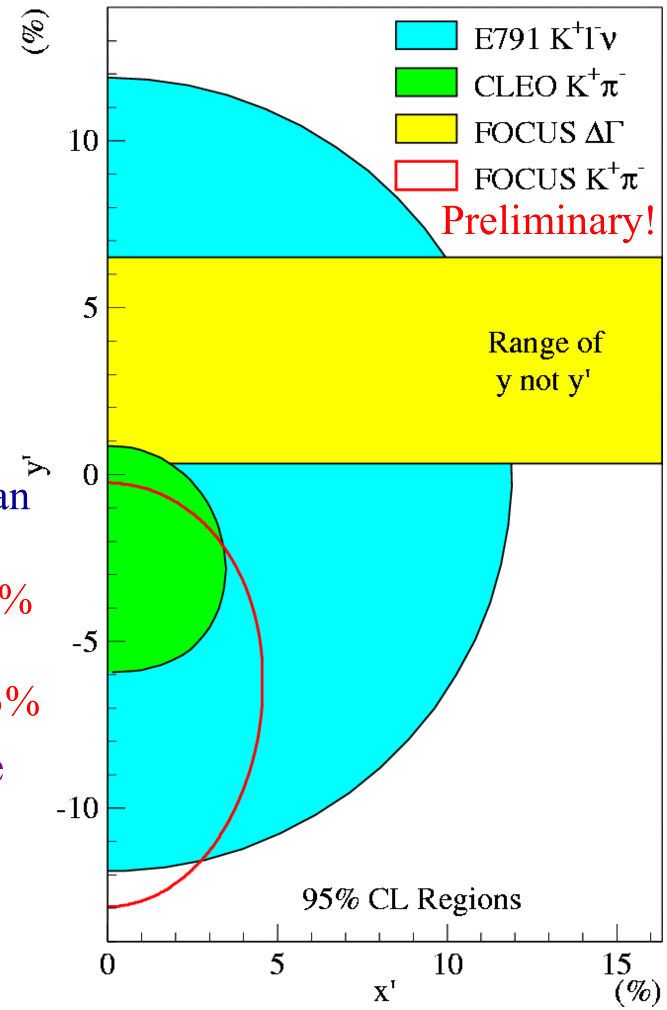
&

$0.43\% < R_{DCS} < 1.73\%$

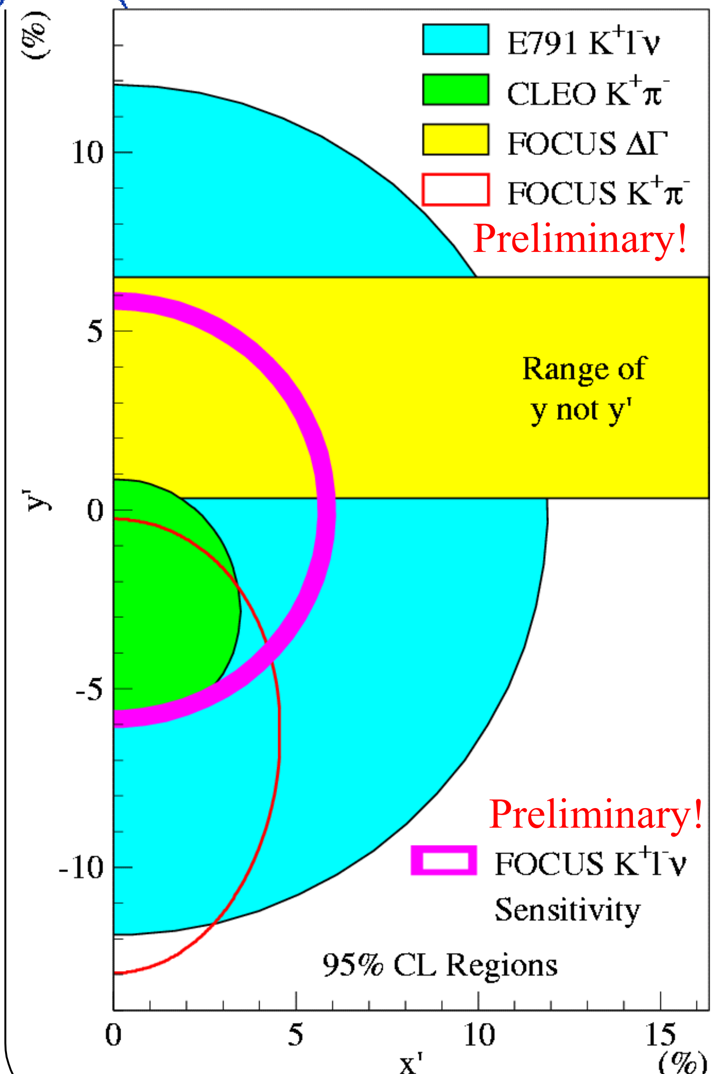
By integrating the likelihood over $y'$ and $R_{DCS}$, we find

$|x'| < 3.9\%$

at the 95% CL.



# Future of Charm Mixing Studies




Belle and BaBar have large $D^0$ samples and should be able to resolve these charm mixing questions.

- Semileptonic Wrong Sign Decays.

  No DCS backgrounds, but no interference enhancement. Expect $R_{mix}$ sensitivity around $1.6\times10^{-3}$.

- Full Lifetime Analysis on DCS Decays.

  Study more $D^0$ modes like $K\pi\pi^0$ and $K3\pi$.

- Lifetime Difference with CP odd States.

  Involve decays that interfere with CP even states on the Dalitz surface. Experimentally more difficult ($K_S$ and $\pi^0$) or rare processes.

# CP Violation Searches

For CP asymmetry to occur requires two independent amplitudes to the same final state with different strong phases.

In the Standard Model, charm CP asymmetry predictions are $10^{-3}$ or less.

Therefore any observed CP Violation is likely to be New Physics!

We define the CP asymmetry ($A_{CP}$) as

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

Where we use

$$\eta(D \to f) = \frac{N(D \to f)}{N(D \to f_{\text{norn}})}$$

to account for any $D$–$\overline{D}$ production asymmetry.

E831 FOCUS

# Summary of CP Asymmetry Measurements

| Decay Mode | E791 | CLEO | FOCUS |
|---|---|---|---|
| $D^0 \to K^- K^+$ | $-1.0 \pm 4.9 \pm 1.2$ | $0.05 \pm 2.18 \pm 0.84$ | $-0.1 \pm 2.2 \pm 1.5$ |
| $D^0 \to \pi^- \pi^+$ | $-4.9 \pm 7.8 \pm 3.0$ | $1.94 \pm 3.22 \pm 0.84$ | $4.8 \pm 3.9 \pm 2.5$ |
| $D^0 \to K_S \pi^0$ | | $0.1 \pm 1.3$ | |
| $D^0 \to \pi^0 \pi^0$ | | $0.1 \pm 4.8$ | |
| $D^0 \to K_S K_S$ | | $-23 \pm 19$ | |
| $D^+ \to K^- K^+ \pi^+$ | $-1.4 \pm 2.9$ | | $0.6 \pm 1.1 \pm 0.5$ |
| $D^+ \to \pi^- \pi^+ \pi^+$ | $-1.7 \pm 4.2 \pm 0.5$ | | |
| $D^+ \to K_S \pi^+$ | | | $-1.6 \pm 1.5 \pm 0.9$ |
| $D^+ \to K_S K^+$ | | | $6.9 \pm 6.0 \pm 1.5$ |

PLB 491, 232 (FOCUS results for $D^0 \to K^- K^+$, $D^0 \to \pi^- \pi^+$, $D^+ \to K^- K^+ \pi^+$)

hep-ex/0109022 (FOCUS results for $D^+ \to K_S \pi^+$, $D^+ \to K_S K^+$)

1% CP violation sensitivity level reached for some decays.

All measured CP asymmetries are consistent with zero to within errors.

# Conclusions

## We saw…

- Nine new branching ratios and six new decay modes.
- Results of two independent $D^0$–$\bar{D}^0$ mixing studies each with 2σ deviations from zero that need to be addressed by the *B* factories.
- Five new or improved CP asymmetry limits with sensitivities approaching the 1% level

## We did not see…

- Dalitz Analyses (We have at least 6 modes currently under study).
- Baryons ($\Sigma_C$ mass splitting PLB 488, 218, $\Xi_C^+$ SCSD PLB 512, 277).
- Lifetimes ($D^+$, $D^0$, $D_S^+$, $\Lambda_{C}$, $\Xi_C^+$ hep-ex/0110002, and $\Xi_C^0$).
- Semileptonic studies (such as form factors and branching ratios)
- *D* meson spectroscopy ($D_2^{*+}$, $D_2^{*0}$, $D_1^0$, $D_{S1}$, and $D_{S2}$).