Meson Lifetimes, Decays, Mixing and CPV in FOCUS

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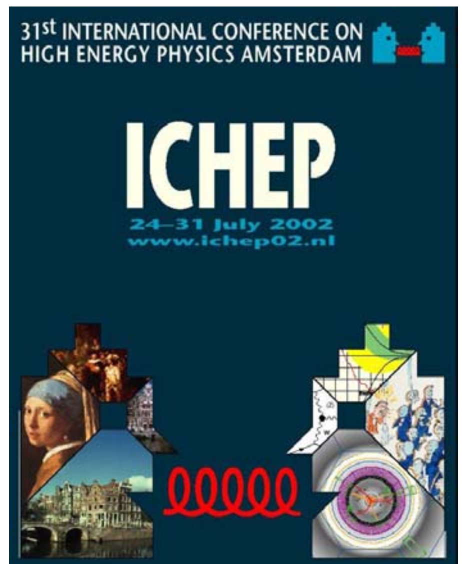


A new charm-physics era

The high statistics and excellent quality of data allow for unprecedented sensitivity & sophisticated studies

Investigation of decay dynamics both in the hadronic and semileptonic sector

- Phases and Quantum Mechanics interference
- FSI role & CP studies

Lifetime measurements @ better than 1%

- non-spectator processes

Mixing

- possible window on physics beyond SM

Outline

- Hadronic decays

$D^+ \to K^- K^+ K^+$ → **First clear evidence (DSCD)**

$D_s^+ \to K^- K^+ K^+$ → **First evidence (SCSD)**

- Amplitude Analysis of three pseudoscalar channels

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

$D_s^+ \to K^+ \pi^+ \pi^-$ → **First Dalitz analysis**

$D^+ \to K^- K^+ \pi^+$ → **New method for CPV**

- Semileptonic decays

Anomaly in $D^+ \to (K^- \pi^+) \mu^+ \nu$ decay → **s-wave interference**

New BR of $\dfrac{\Gamma(D^+ \to \overline{K^*}^0 \mu^+ \nu)}{\Gamma(D^+ \to K^- \pi^+ \pi^+)}$ and $\dfrac{\Gamma(D_s^+ \to \phi \mu^+ \nu)}{\Gamma(D_s^+ \to \phi \pi^+)}$

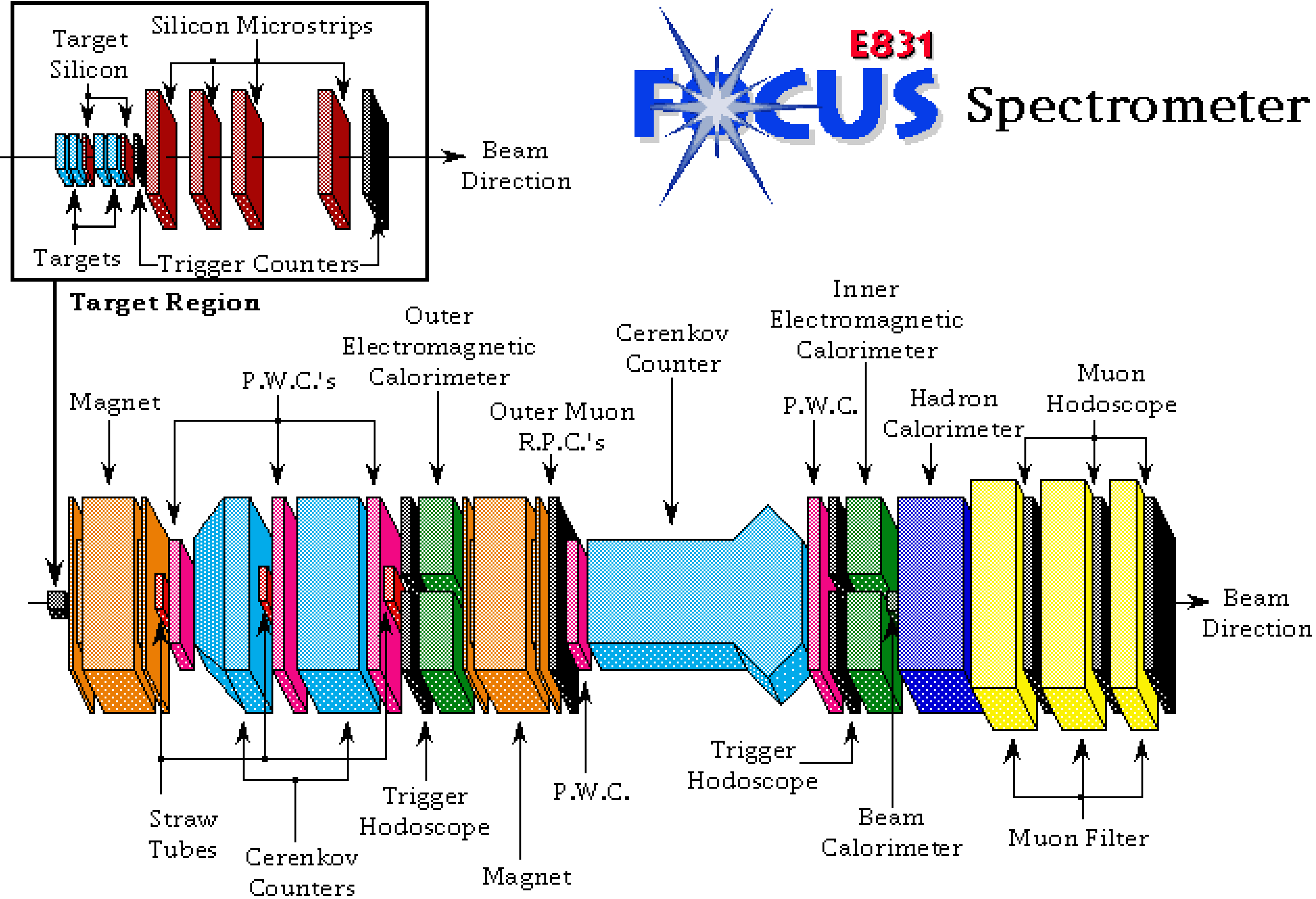
- Lifetimes

Precise measurements for D^+, D^0 and preliminary for D_s

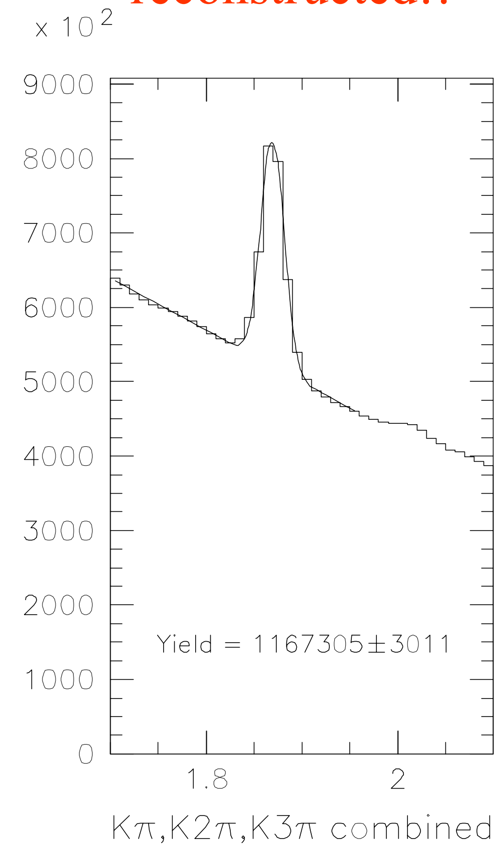
- Mixing

Prelimary results from $D^0 \to K^+ \pi^-$ and $D^0 \to K^+ \mu^- \nu$

E831 FOCUS Spectrometer



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 $D \rightarrow K\pi$, $K2\pi$, $K3\pi$

$D^+, D_s^+ \to K^-K^+K^+$

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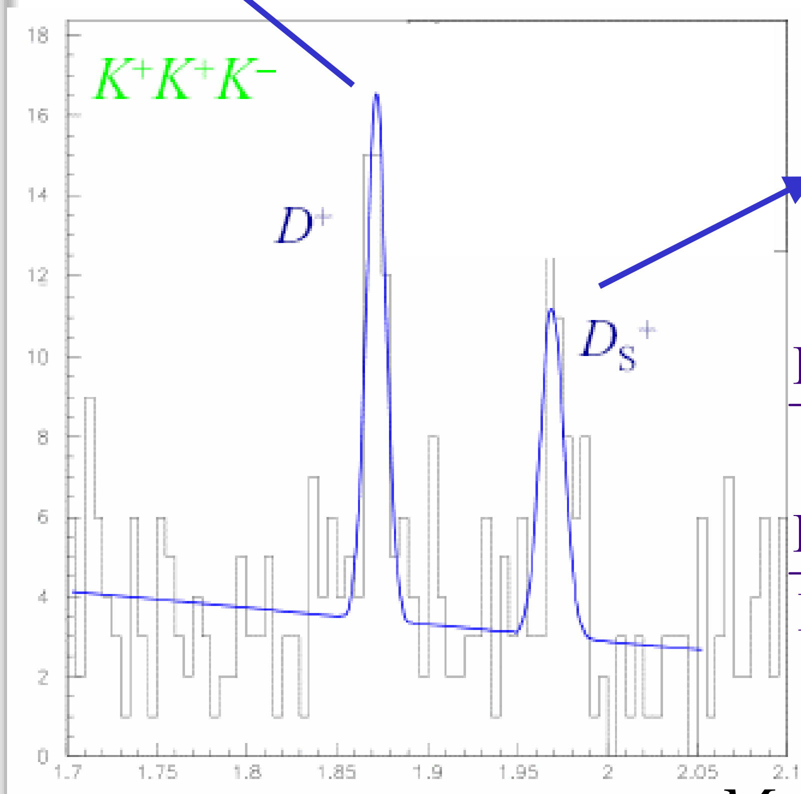
First clear observation



M_{KKK}

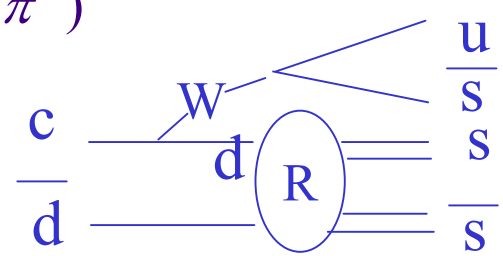
Yield D^+ = 65.5±15.0

Yield D_s = 31.4 ±7.4

First observation

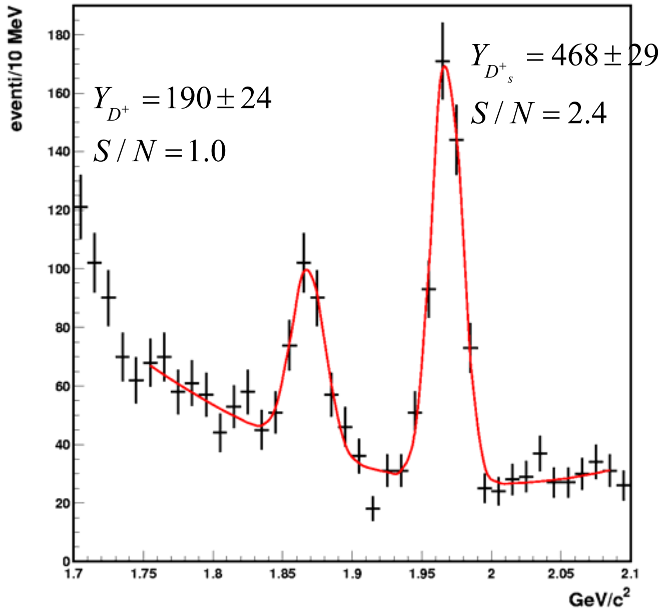
$$\frac{\Gamma(D^+ \to K^-K^+K^+)}{\Gamma(D^+ \to K^-\pi^+\pi^+)} = (9.49 \pm 2.17 \pm 0.22) \times 10^{-4}$$

$$\frac{\Gamma(D_s^+ \to K^-K^+K^+)}{\Gamma(D_s^+ \to K^-K^+\pi^+)} = (8.62 \pm 2.04 \pm 2.07) \times 10^{-3}$$

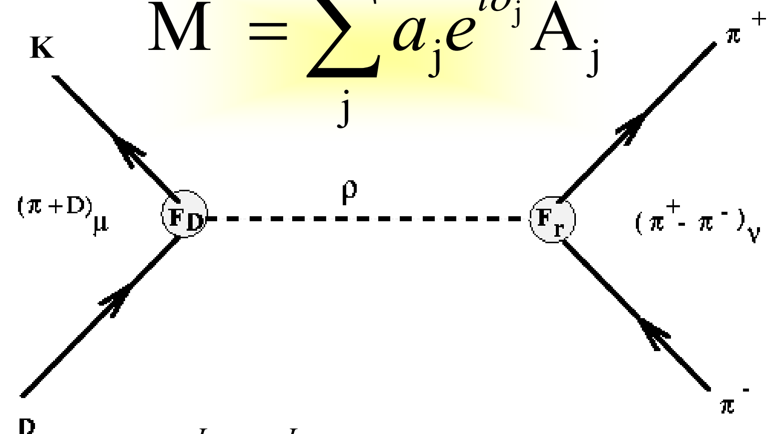


Intervention of resonances coupling both to ππ and KK or annihilation

Dalitz plot analysis of $D^+, D_s^+ \to K^+\pi^+\pi^-$



$$\mathrm{M} = \sum_j a_j e^{i\delta_j} \mathrm{A}_j$$



$$A = F_D F_r \times \left|\overrightarrow{p_1}\right|^J \left|\overrightarrow{p_3}\right|^J P_J(\cos\vartheta_{13}^r) \times BW(m_{12}^2)$$

Where

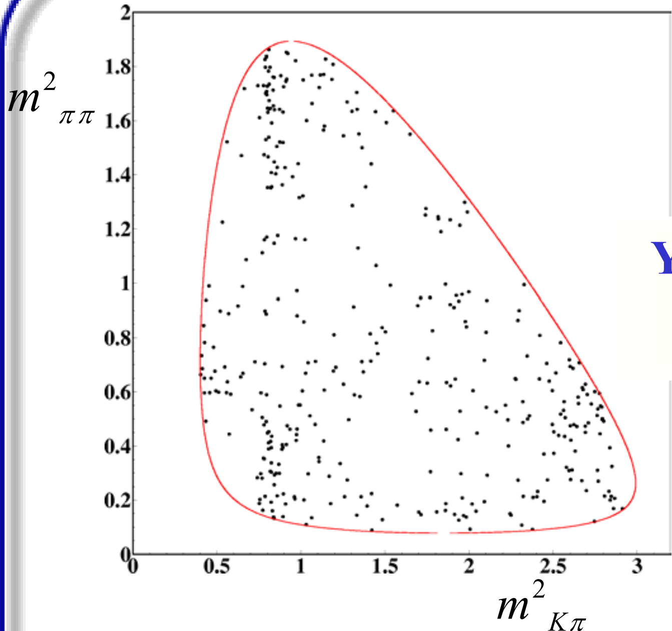
$F = 1$	**Spin 0**	$P_J = 1$
$F = (1 + R^2 p^2)^{-1/2}$	**Spin 1**	$P_J = (-2\overrightarrow{p_3} \cdot \overrightarrow{p_1})$
$F = (9 + 3R^2 p^2 + 3R^4 p^4)^{-1/2}$	**Spin 2**	$P_J = 2(p_3 p_1)^2 (3\cos^2\vartheta_{13} - 1)$

and

$$BW(12 \mid r) = \frac{F_D F_r}{M_r^2 - m_{12}^2 - i\Gamma M_r} \qquad \Gamma = \Gamma_r \left[\frac{p}{p_0}\right]^{2j+1} \frac{M_r}{m_{12}} \frac{F_r^2(p)}{F_r^2(p_0)}$$

DCS

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



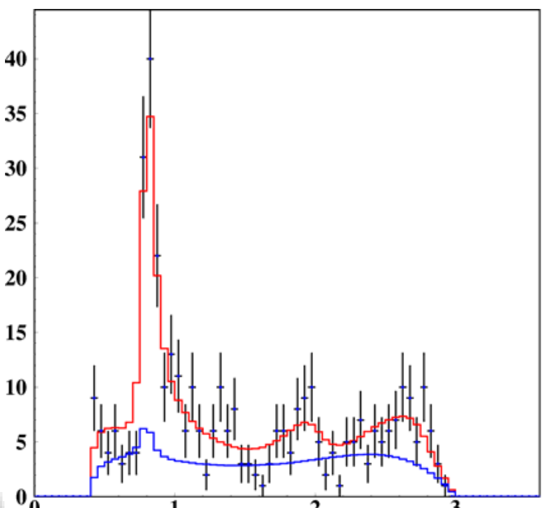
Yield D^+ = 190 ±24

S/N D^+ = 1.0

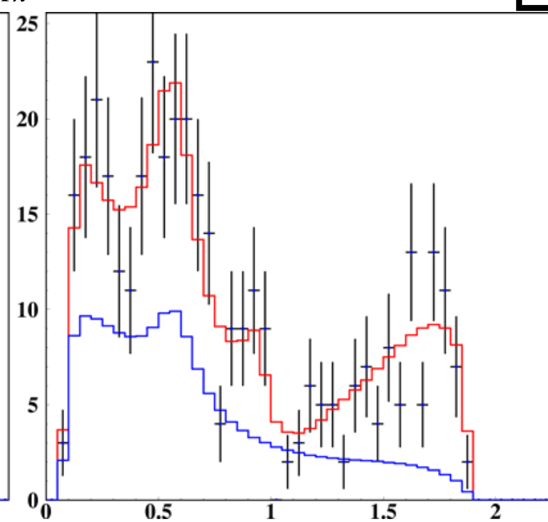
Preliminary

Decay fractions and phases

NR	= 9 ± 5 %	(-6 ± 16) °
K*(892)	= 43 ± 7 %	(208 ± 16) °
K*(1410)	= 12 ± 8 %	(133 ± 23) °
K_2(1430)	= 6 ± 3 %	(48 ± 27) °
K*(1680)	= 22 ± 10 %	(2 ± 20) °
ρ (770)	= 51 ± 10 %	(0 fixed)
f_0(980)	= 9 ± 5 %	(73 ± 31) °
ρ(1450)	= 10 ± 5 %	(-113 ± 15) °

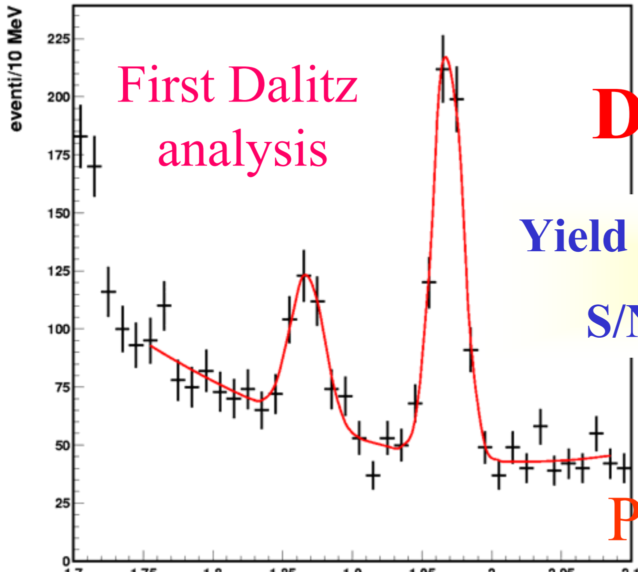


$K^+\pi^-$ projection



$\pi^+\pi^-$ projection

$$f_r = \frac{\int \left| a_r e^{i\delta_r} A_r \right|^2 dm_{12}^2\, dm_{13}^2}{\int \left| \sum_j a_j e^{i\delta_j} A_j \right|^2 dm_{12}^2\, dm_{13}^2}$$



SCS

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

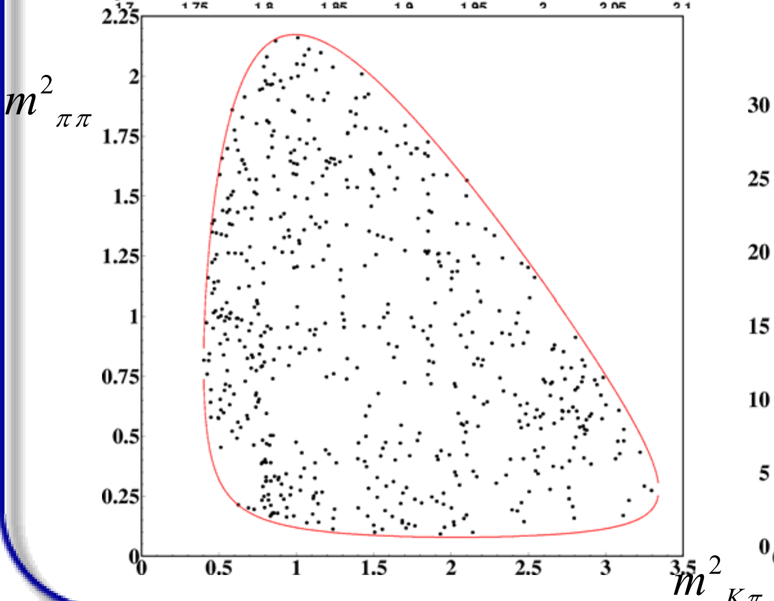
Yield D_s^+ = 468 ±29

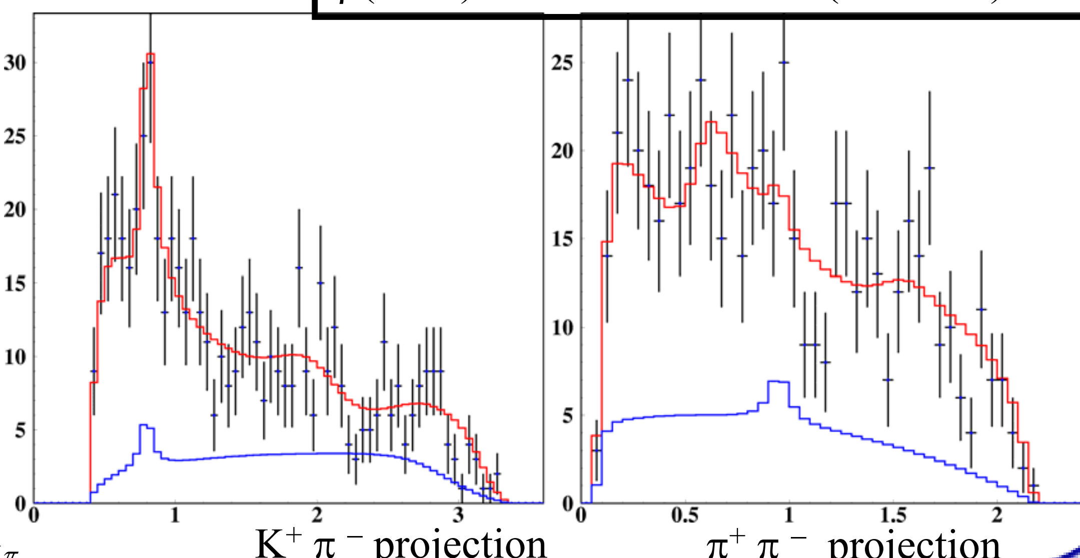
S/N D_s^+ = 2.4

Preliminary

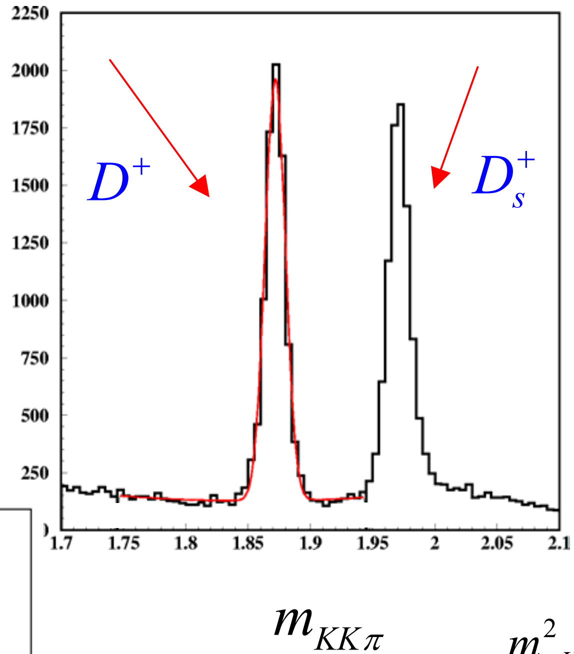
Decay fractions and phases

NR	=	18 ± 4	%	(34 ± 7)°
K*(892)	=	22 ± 3	%	(163 ± 7) °
K*(1410)	=	14 ± 5	%	(-10 ± 7) °
$K^*_0(1430)$	=	14 ± 6	%	(68 ± 7) °
ρ (770)	=	40 ± 4	%	(0 fixed)
$f_2(1270)$	=	2 ± 1	%	(33 ± 21) °
ρ(1450)	=	8 ± 2	%	(219 ± 14) °

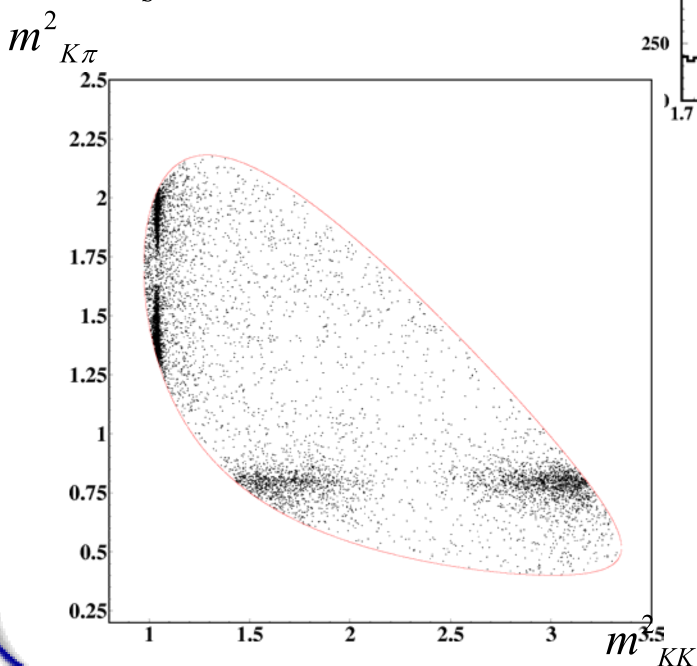




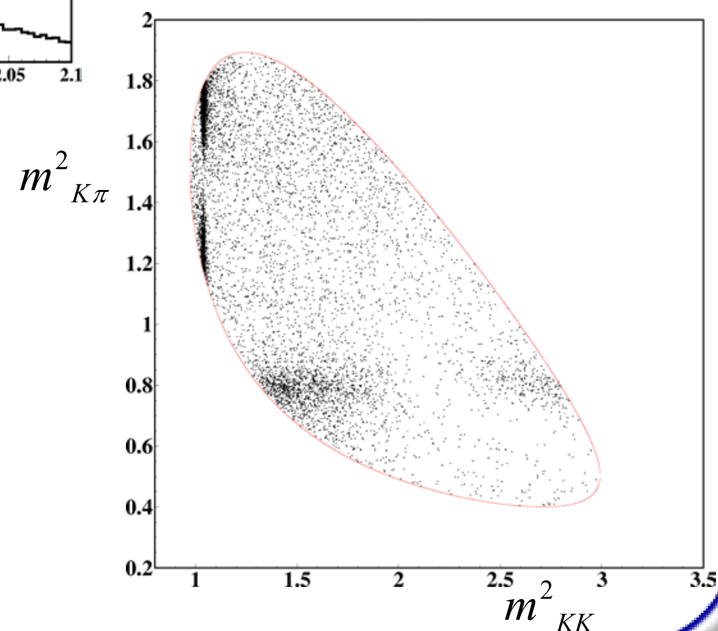
$D_s, D^+ \rightarrow KK\pi$



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



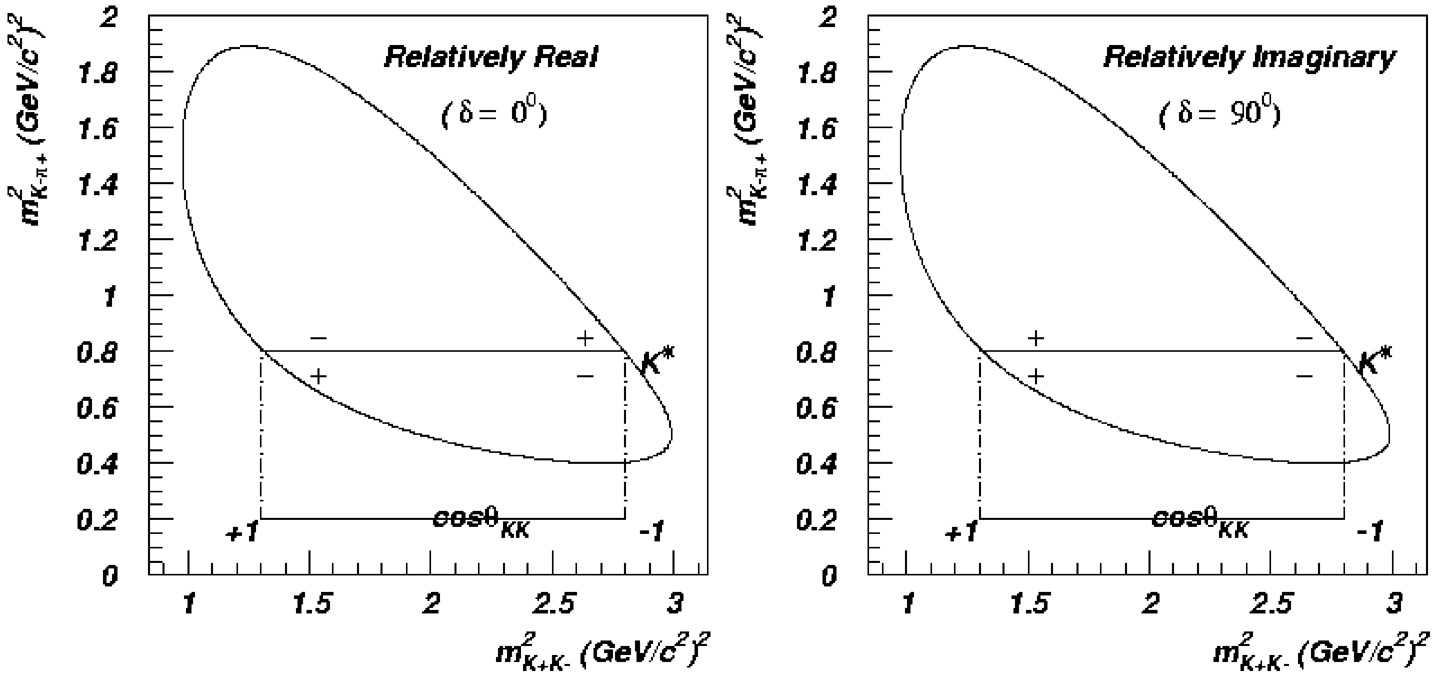
$D^+ \rightarrow K^+ K^- \pi^+$

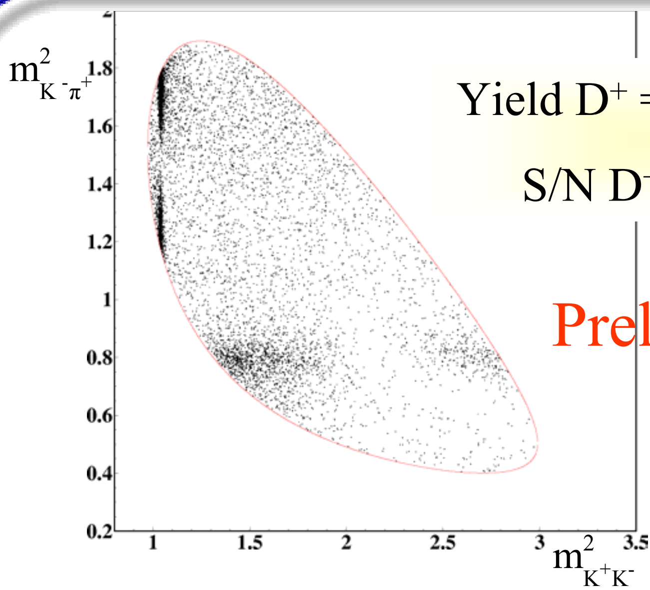


Interference term

$$2Re\left[(\cos\delta + i\sin\delta)^* \frac{\cos\theta_{KK}}{m_r^2 - m_{K\pi}^2 - i\Gamma m_r}\right] =$$

$$= 2\frac{(m_r^2 - m_{K\pi}^2)\cos\theta_{KK}\cos\delta}{(m_r^2 - m_{K\pi}^2)^2 + \Gamma^2 m_r^2} + 2\frac{\Gamma M_r \cos\theta_{KK}\sin\delta}{(m_r^2 - m_{K\pi}^2)^2 + \Gamma^2 m_r^2}$$





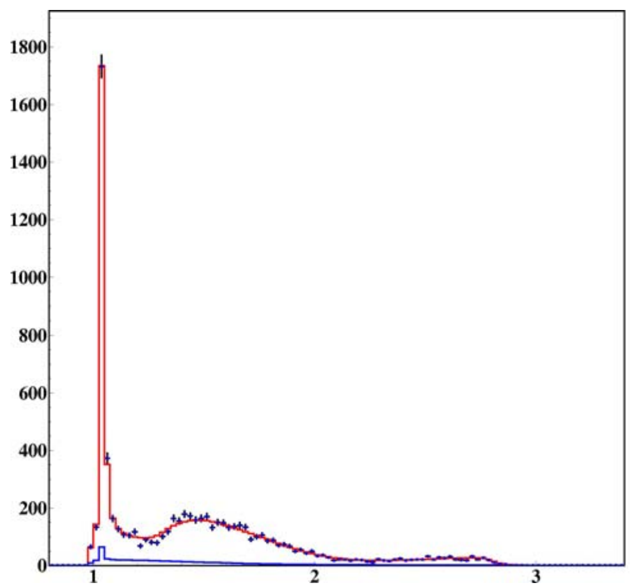
Yield D^+ = 7106 ±92

S/N D^+ = 8.62

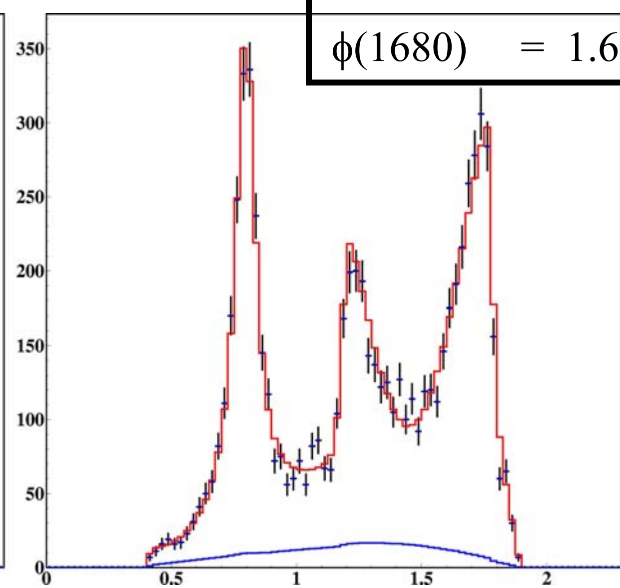
Preliminary

Decay Fraction and phases

$\overline{K}^*(892)$	= 20.7 ± 1.0	%	(0 fixed)
$\phi(1020)$	= 27.8 ± 0.7	%	(243.1 ±5.2)°
$\overline{K}^*(1410)$	= 10.7 ± 1.9	%	(-47.4 ± 4.9) °
$\overline{K}^*(1430)$	= 66.5 ± 6.0	%	(61.8 ± 3.8)°
$f_0(1370)$	= 7.0 ± 1.1	%	(60.0 ± 5.3) °
$a_0(980)$	= 27.0 ± 4.8	%	(145.6 ± 4.3)°
$f_2(1270)$	= 0.8 ± 0.2	%	(11.6 ± 7.0) °
$\phi(1680)$	= 1.6 ± 0.4	%	(-74.3 ± 7.5) °



K^+K^- projection



$K^-\pi^+$ projection

CP violation

For a two amplitude decay

$$A_{tot} = g_1 M_1 e^{i\delta_1} + g_2 M_2 e^{i\delta_2}$$

CP conjugate

$$\bar{A}_{tot} = g_1^* M_1 e^{i\delta_1} + g_2^* M_2 e^{i\delta_2}$$

δ_i = strong phase

CP asymmetry:

$$a_{CP} = \frac{|A_{tot}|^2 - |\bar{A}_{tot}|^2}{|A_{tot}|^2 + |\bar{A}_{tot}|^2} = \frac{2\mathrm{Im}(g_2 g_1^*)\sin(\delta_1 - \delta_2) M_1 M_2}{|g_1|^2 M_1^2 + |g_2|^2 M_2^2 + 2\mathrm{Re}(g_2 g_1^*)\cos(\delta_1 - \delta_2) M_1 M_2}$$

2 different amplitudes ← $(g_2 g_1^*)$

strong phase-shift ← $(\delta_1 - \delta_2)$

CP violation:Dalitz analysis

Dalitz plot = FULL OBSERVATION of the decay

COEFFICIENTS and **PHASES** for each amplitude

Measured phase: $\theta = \delta + \phi$

CP conserving (δ) — CP violating (ϕ)

CP conjugate: $\bar{\delta} = \delta \quad \bar{\phi} = -\phi$

$\Rightarrow \bar{\theta} = \delta - \phi$

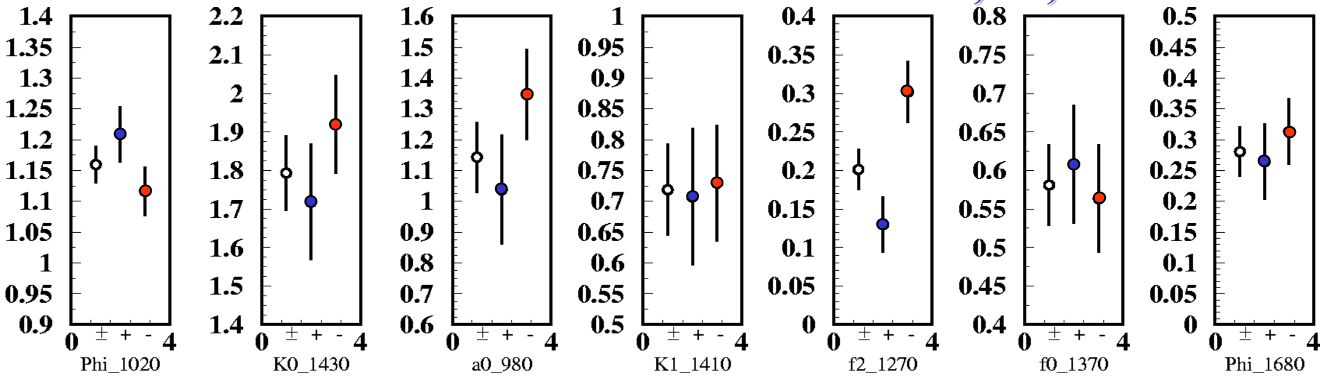
E831 → Measure of direct CP violation: asymmetrys in decay rates of $D^{\pm} \rightarrow K^{\mp} K \pi^{\pm}$

a_{CP}=0.006±0.011±0.005

D^+/D^- split sample analysis

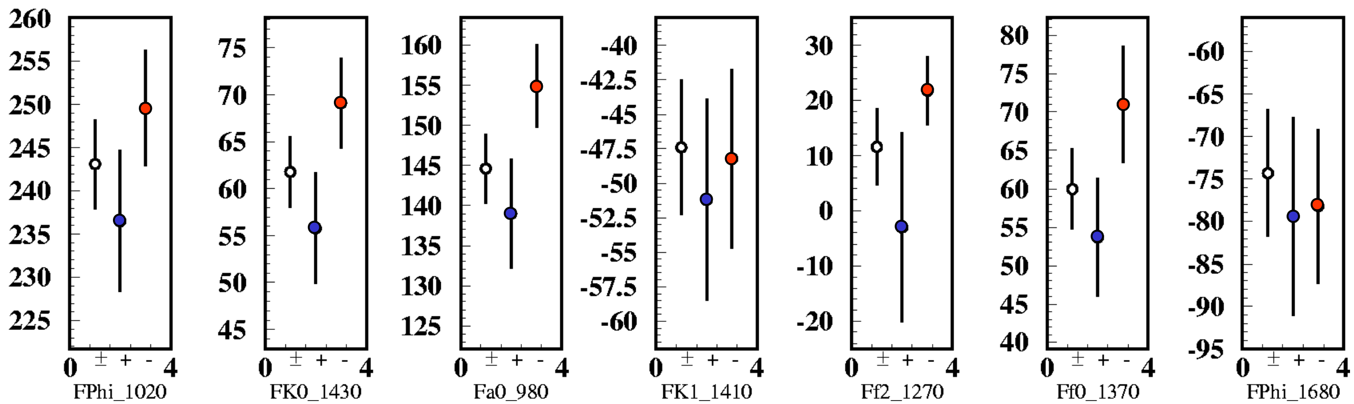
Coefficients: $D^{\pm}$, D^+, D^-

Preliminary!



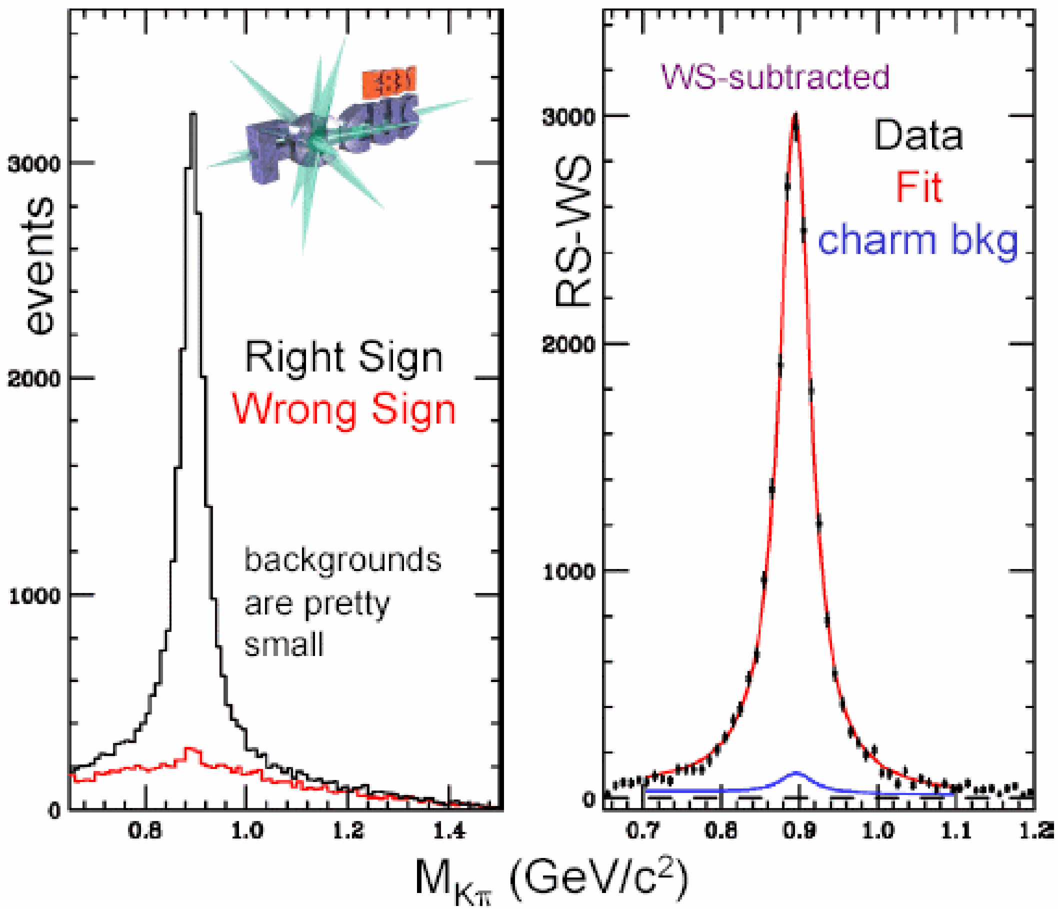
Phases: $D^{\pm}$, D^+, D^-

No evidence of CPV



K-matrix approach to improve the quality of the analysis

New results on $D^+ \to K\pi\mu\nu$

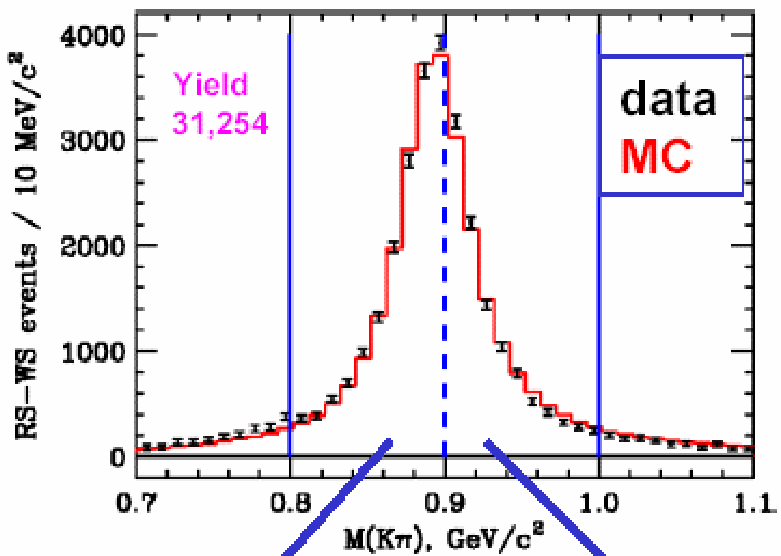


Our Kπ spectrum looks like 100% K*(892)

This has been known for about 20 years

...but a funny thing happened when we tried to measure the form factor ratios by fitting the angular distributions

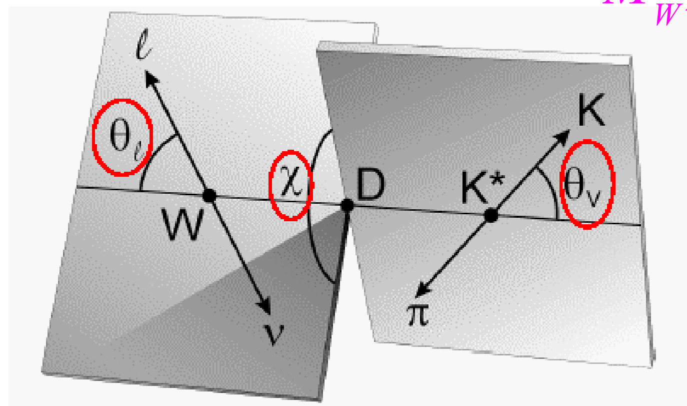
An unexpected asymmetry in the K* decay



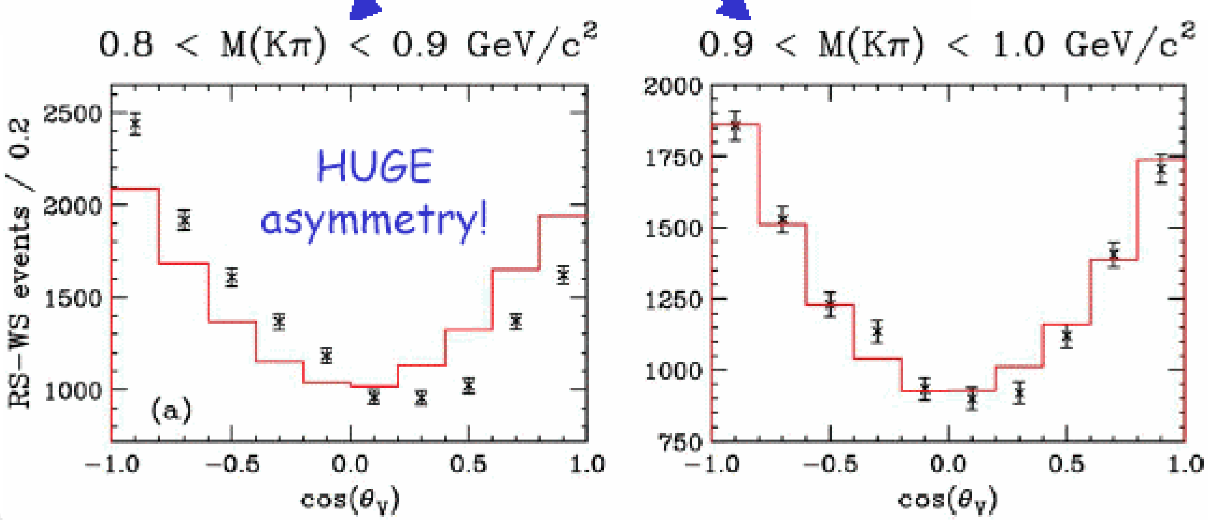
A 4-body decays requires 5 kinematics variables: 3 angles and 2 masses

$$M_{W^2} \equiv q^2 \equiv t$$

$$M_{K\pi}$$



$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha \cos^2 \theta_V$$



forward-backward asymmetry in $\cos \theta_V$ below the K* pole but almost none above the pole

Sounds like QM interference

Try an interfering spin-0 amplitude

Phys.Lett.B535,43,2002

$$|M|^2 \propto (t - m^2{}_\mu) \left| + \frac{(1+\cos\theta_l)\sin\theta_V}{2\sqrt{2}} e^{i\chi} B H_+ + \frac{(1-\cos\theta_l)-\sin\theta_V}{2\sqrt{2}} e^{-i\chi} B H_- + \frac{-\sin\theta_l(\cos\theta_V B + Ae^{i\delta})H_0}{\sqrt{2}} \right|^2$$

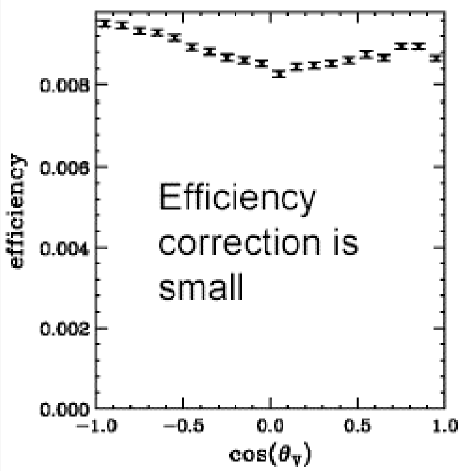
(plus mass terms)

$Ae^{i\delta}$ will produce
3 interference terms

$$B \equiv \frac{\sqrt{m_0\Gamma}}{m^2 - m^2{}_0 + i m_0 \Gamma}$$

We simply add a constant amplitude $Ae^{i\delta}$ in the place where the K* couples to an m=0 W+ with amplitude H_0

Studies of the acoplanarity-averaged interference



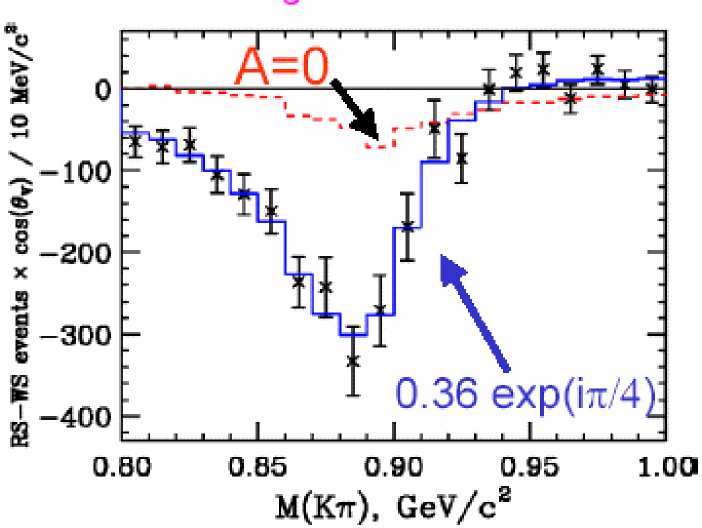
$$8\cos\theta_V \sin^2\theta_V A\,\mathrm{Re}(e^{-i\delta}B_{K^*})H^2{}_0$$

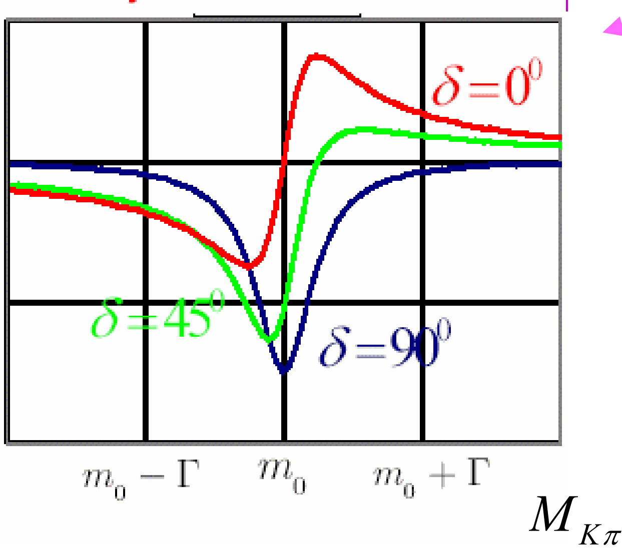
Extract this interference term by weighting data by $\cos\theta_V$

Since all other χ–averaged terms in the decay intensity are constant or $\propto \cos^2\theta_V$

We begin with the mass dependence: $\mathrm{Re}(e^{-i\delta}B_{K^*})$

Our weighted mass distribution.. ..looks just like the calculation

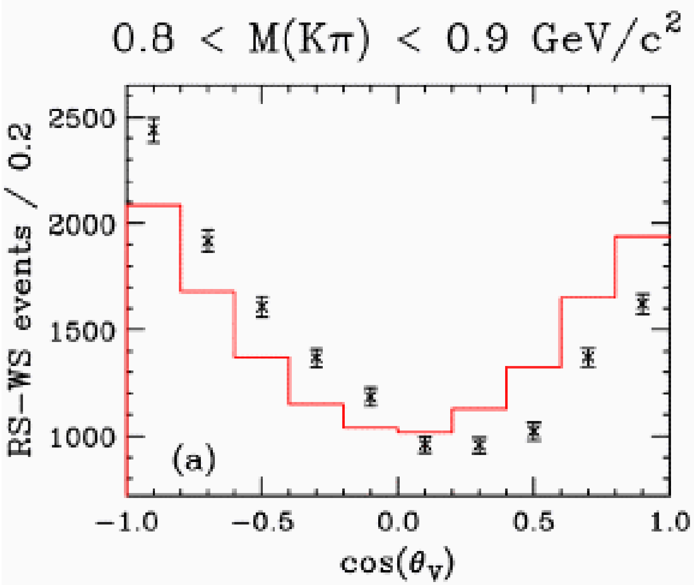


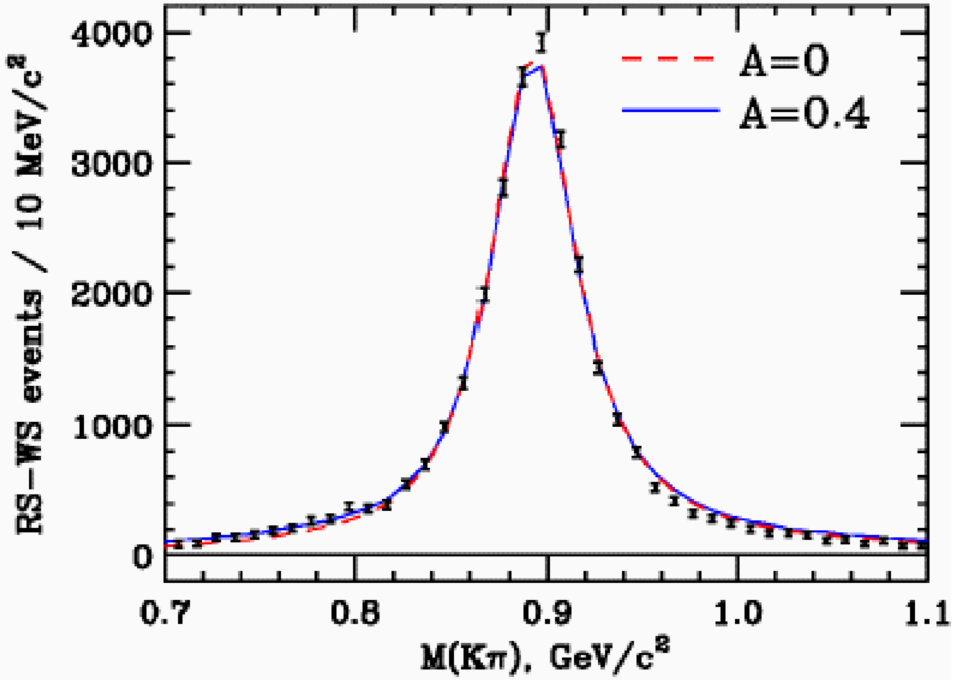


A constant 45° phase works great....

...but the solution is not unique

But surely an effect this large must have been observed before?



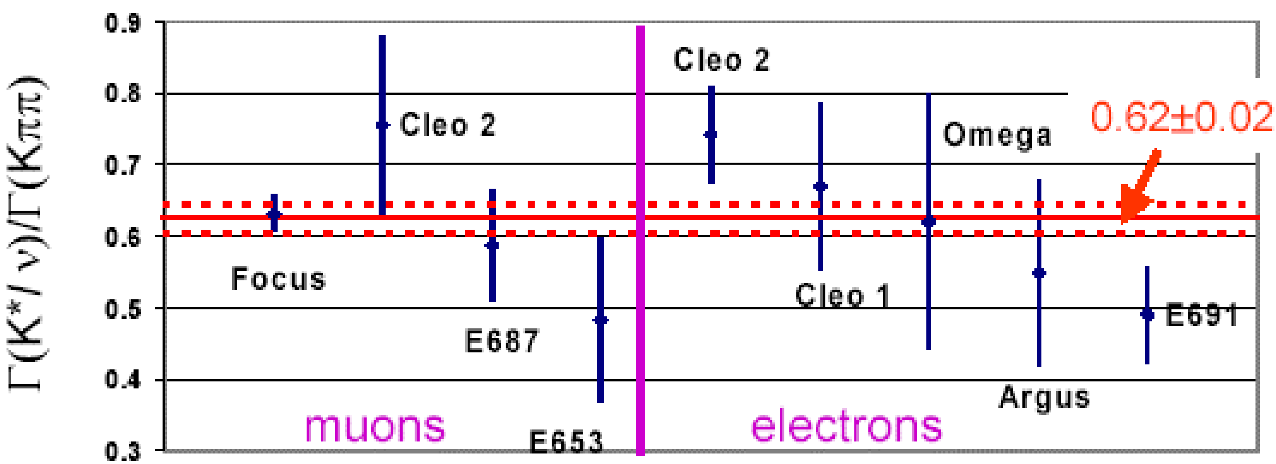


Although the interference *significantly* distorts the decay intensity....

...the interference is nearly invisible in the Kπ mass plot.

New FOCUS semileptonic BRs & Form Factors

$$\frac{\Gamma(D^+ \to \overline{K^{*0}}\mu^+\nu)}{\Gamma(D^+ \to K^-\pi^+\pi^+)} = 0.602 \pm 0.01(stat) \pm 0.021(sys)$$



Our number is 1.59 standard deviation below CLEO and 2.1 standard deviation above E691

All values consistent with their average value with a CL of 19%

$\Gamma(D^+ \to \overline{K^{*0}} \mu^+ \nu)$ Form Factors

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The vector and axial form factors are generally parametrized by a pole dominance form

$$A_i(q^2) = \frac{A_i(0)}{1 - q^2 / M^2_A} \quad V(q^2) = \frac{V(0)}{1 - q^2 / M^2_V}$$

$M_A = 2.5 \quad GeV/c^2$

$M_V = 2.1 \quad GeV/c^2$

Nominal spectroscopic pole masses

Decay intensity (including s-wave amplitude) parametrized by

$$r_v \equiv V(0)/A_1(0) \qquad r_2 \equiv A_2(0)/A_1(0) \qquad r_3 \equiv A_3(0)/A_1(0)$$

New FOCUS results →

$$r_v = 1.504 \pm 0.057 \pm 0.039$$

$$r_2 = 0.875 \pm 0.049 \pm 0.064$$

Form Factor Ratios

Group	r_v	r_2
FOCUS	$1.504 \pm 0.057 \pm 0.039$	$0.875 \pm 0.049 \pm 0.064$
BEATRICE	$1.45 \pm 0.23 \pm 0.07$	$1.00 \pm 0.15 \pm 0.03$
$E791(e)$	$1.90 \pm 0.11 \pm 0.09$	$0.71 \pm 0.08 \pm 0.09$
$E791(\mu)$	$1.84 \pm 0.11 \pm 0.09$	$0.75 \pm 0.08 \pm 0.09$
$E687$	$1.74 \pm 0.27 \pm 0.28$	$0.78 \pm 0.18 \pm 0.11$
$E653$	$2.00 \pm 0.33 \pm 0.16$	$0.82 \pm 0.22 \pm 0.11$
$E691$	$2.0 \pm 0.6 \pm 0.3$	$0.0 \pm 0.5 \pm 0.2$

Our analysis is the first to include the effects on the acceptance due to changes in the angular distribution brought about the s-wave interference

$$A = 0.330 \pm 0.022 \pm 0.015 \quad GeV^{-1}$$

$$\delta = 0.68 \pm 0.07 \pm 0.05 \quad \text{rad}$$

$D_s^+ \to \phi\mu^+\nu$

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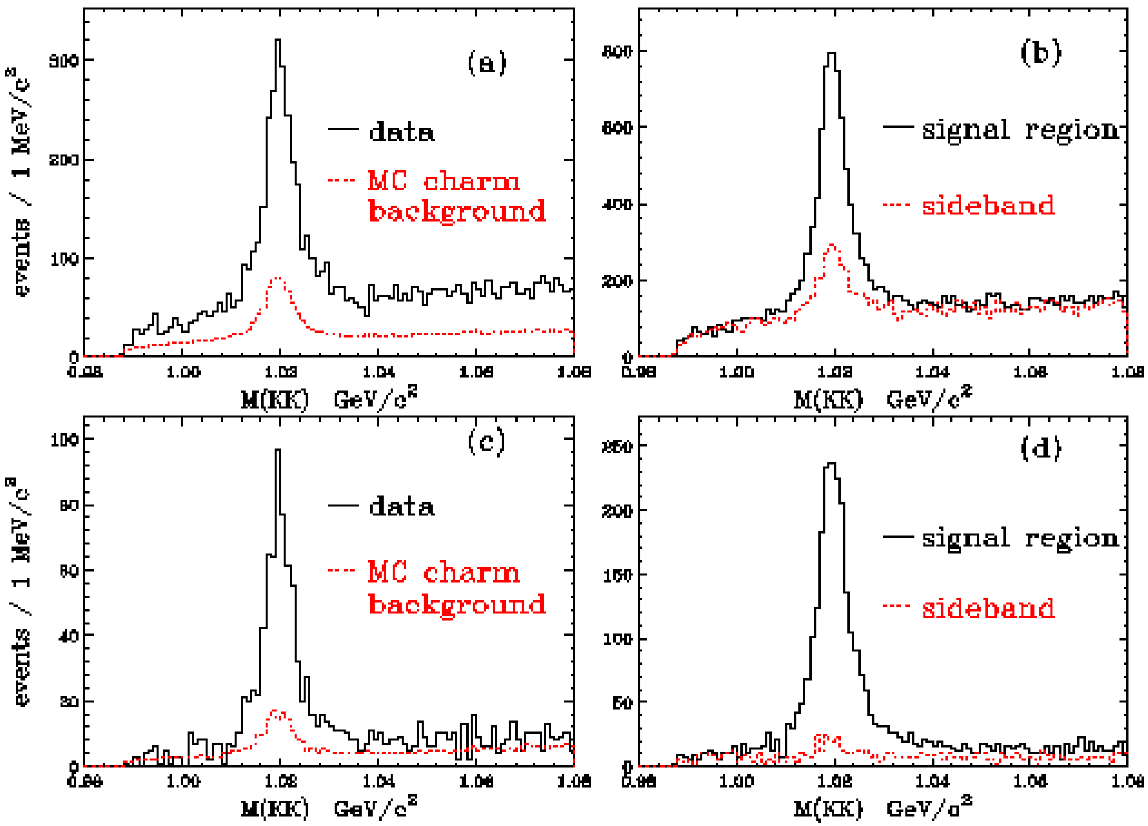
$D_s^+ \to \phi\mu^+\nu$ $D_s^+ \to \phi\pi^+$



Baseline cuts

a) 2682 evts
b) 4695 evts

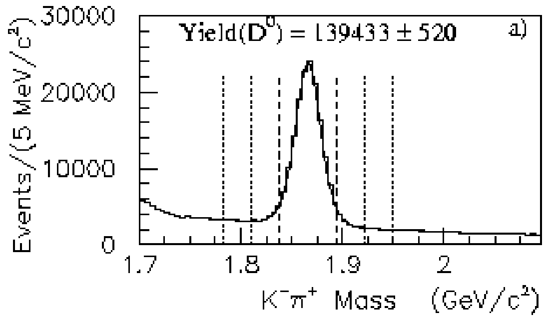
Baseline, out-of-material. isolation cuts

c) 793 evts
d) 2192 evts

$$\frac{\Gamma(D_s^+ \to \phi\mu^+\nu)}{\Gamma(D_s^+ \to \phi\pi^+)} = 0.54 \pm 0.033(stat) \pm 0.048(sys)$$

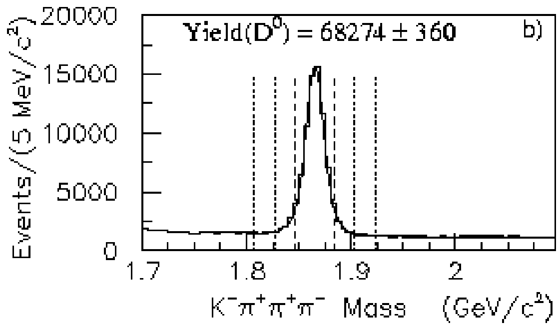
Charm Meson Lifetimes

D^0, D^+ Signal



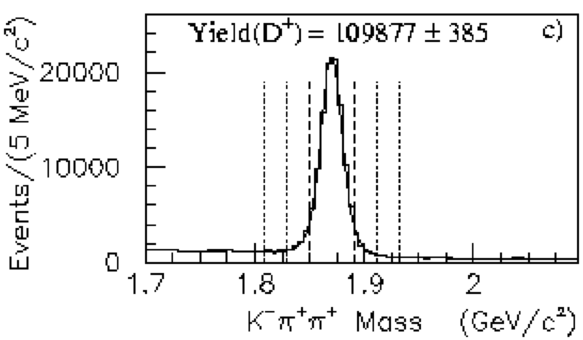
$D^0 \rightarrow K^- \pi^+$

139433 ±520 evts



$D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$

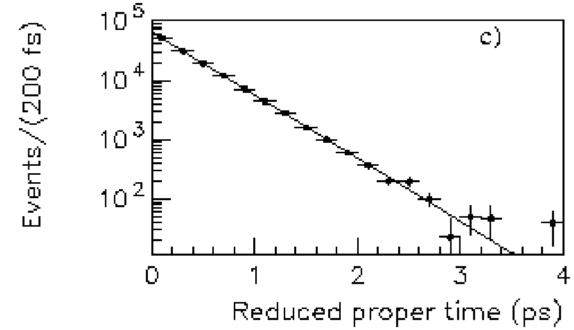
68274 ±360 evts

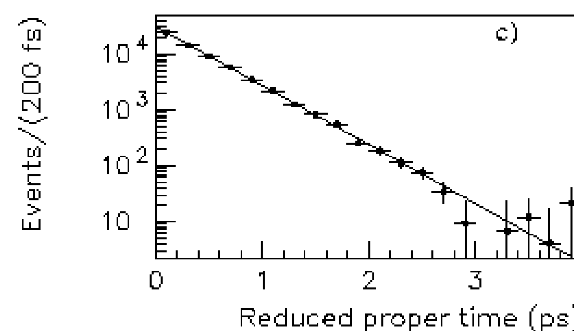


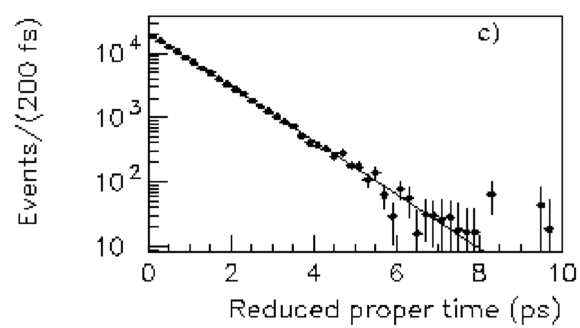
$D^+ \rightarrow K^- \pi^+ \pi^+$

109877 ±385 evts

D^0, D^+ Lifetime fits







$$\tau(D^0) = 409.6 \pm 1.1(stat) \pm 1.5(sys) \quad \text{fs}$$

$$\tau(D^+) = 1039.4 \pm 4.3(stat) \pm 7.0(sys) \quad \text{fs}$$

Phys.Lett.B537,192 ,2002

$$\frac{\tau(D^+)}{\tau(D^0)} = 2.538 \pm 0.023$$

Exp	$D^0 (\times 10^{-12} s)$	$D^+ (\times 10^{-12} s)$
E687	$0.413 \pm 0.004 \pm 0.003$	$1.048 \pm 0.015 \pm 0.011$
CLEOII	$0.4085 \pm 0.0041^{+0.0035}_{-0.0034}$	$1.0336 \pm 0.0221^{+0.0099}_{-0.0127}$
E791	$0.413 \pm 0.003 \pm 0.004$	
FOCUS	$0.4096 \pm 0.0011 \pm 0.0015$	$1.0394 \pm 0.0043 \pm 0.0070$

$$\frac{\Gamma(D^0 \to eX)}{\Gamma(D^+ \to eX)} = \frac{B(D^0 \to eX)}{B(D^+ \to eX)} \times \frac{\tau(D^+)}{\tau(D^0)} = 1.01 \pm 0.13$$

FOCUS

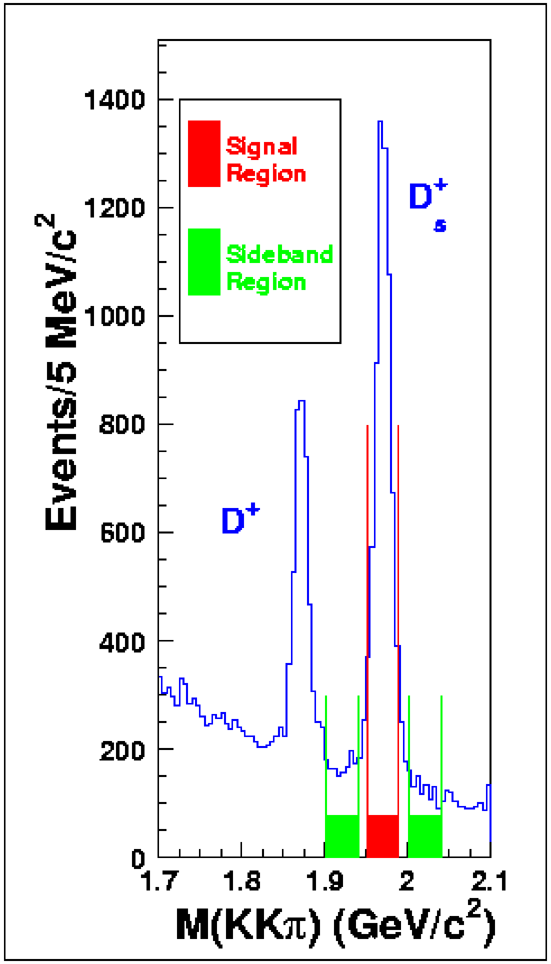
$$D^+ \to eX = (17.2 \pm 1.9)\%$$

$$D^0 \to eX = (6.87 \pm 0.28)\%$$

PDG2002

........difference in the hadronic sector

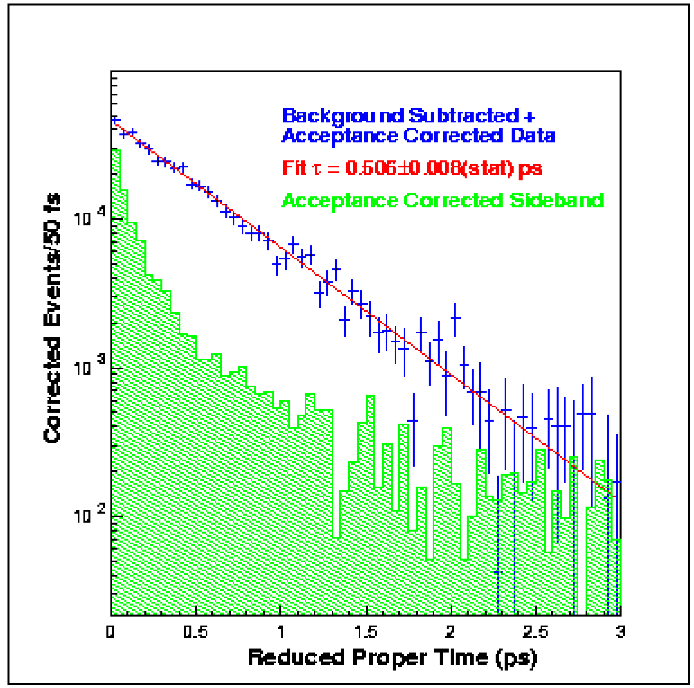
$D_s \to \phi\pi$ signal



Lifetime 506 ±8 fs

PDG 2002 490±9 fs

5668 ± 95 events (50% FOCUS data)



Preliminary

$$\frac{\tau(D_s)}{\tau(D^0)} = 1.23 \pm 0.02$$

4 x statistics including $\overline{K^{*0}}K$

Theoretical prediction (Bigi Uraltsev)

1.00-1.07 (no WA/WX)

0.8-1.27 (different process interference)

Mixing

- Neutral charm mesons:

$$D^0 = c\bar{u}, \bar{D}^0 = \bar{c}u$$

- If $H_{12}, H_{21} \neq 0$, they are not eigenstates.

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}\begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix}$$

where $H_{ij} = M_{ij} - i\Gamma_{ij}/2$.

- If CP is conserved,

$$D_{1,2} = \left(D^0 \pm \bar{D}^0\right)/\sqrt{2}$$

with mass and lifetime as

$$M_{1,2} = M \pm \Re[H_{12}H_{21}]^{1/2} = M \pm 1/2\,\Delta M$$

$$\Gamma_{1,2} = \Gamma \mp 2\Im[H_{12}H_{21}]^{1/2} = \Gamma \mp \Delta\Gamma$$

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

Direct comparison of CP final state lifetime

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

$$D^0 \to K^-\pi^+(\frac{1}{2}CP + \&\frac{1}{2}CP-)$$

$$\to \Gamma(K^-\pi^+) \approx \frac{1}{2}(\Gamma_1 + \Gamma_2)$$

$$y_{CP} = \frac{\tau(D^0 \to K\pi)}{\tau(D^0 \to KK)} - 1$$

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

Phys.Lett.B485,62,2000

New Mixing Results

Preliminary

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

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

$$x' \equiv x\cos\delta + y\sin\delta$$
$$y' \equiv y\cos\delta - x\sin\delta$$

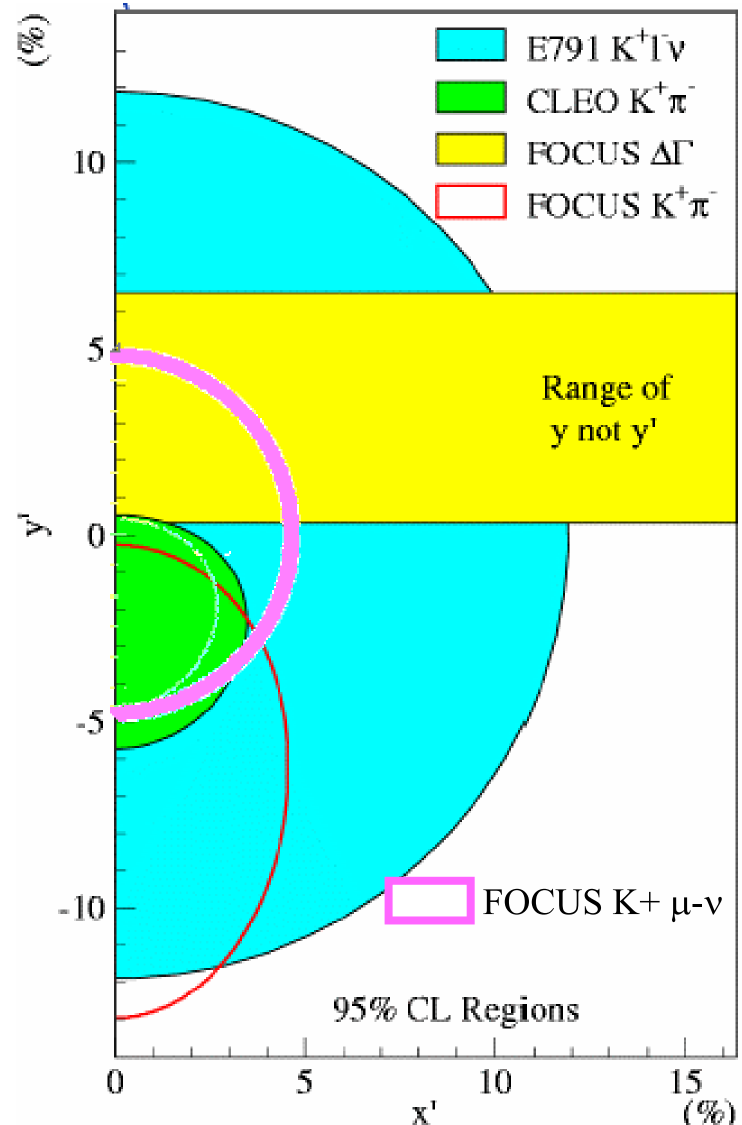
δ is the relative strong phase

$D^0 \to K^+\mu^-\nu_\mu$

$r_{mix} < 0.0012$ @ 95% C.L.

only statistical error !

....towards CLEO & a big relative phase



Conclusion

Charm physics is revealing itself a rich source of new results

FOCUS is playing a crucial role in understanding the charm phenomenology

new suppressed decay modes

decay dynamics of

three-body hadronic channels via quasi two-body decays

semileptonic sector

very precise lifetime measurements (will dominate PDG)

mixing $D^0 \to K^+\pi^-$ $D^0 \to K^+\mu^-\nu$