Recent results on charm from E831-FOCUS

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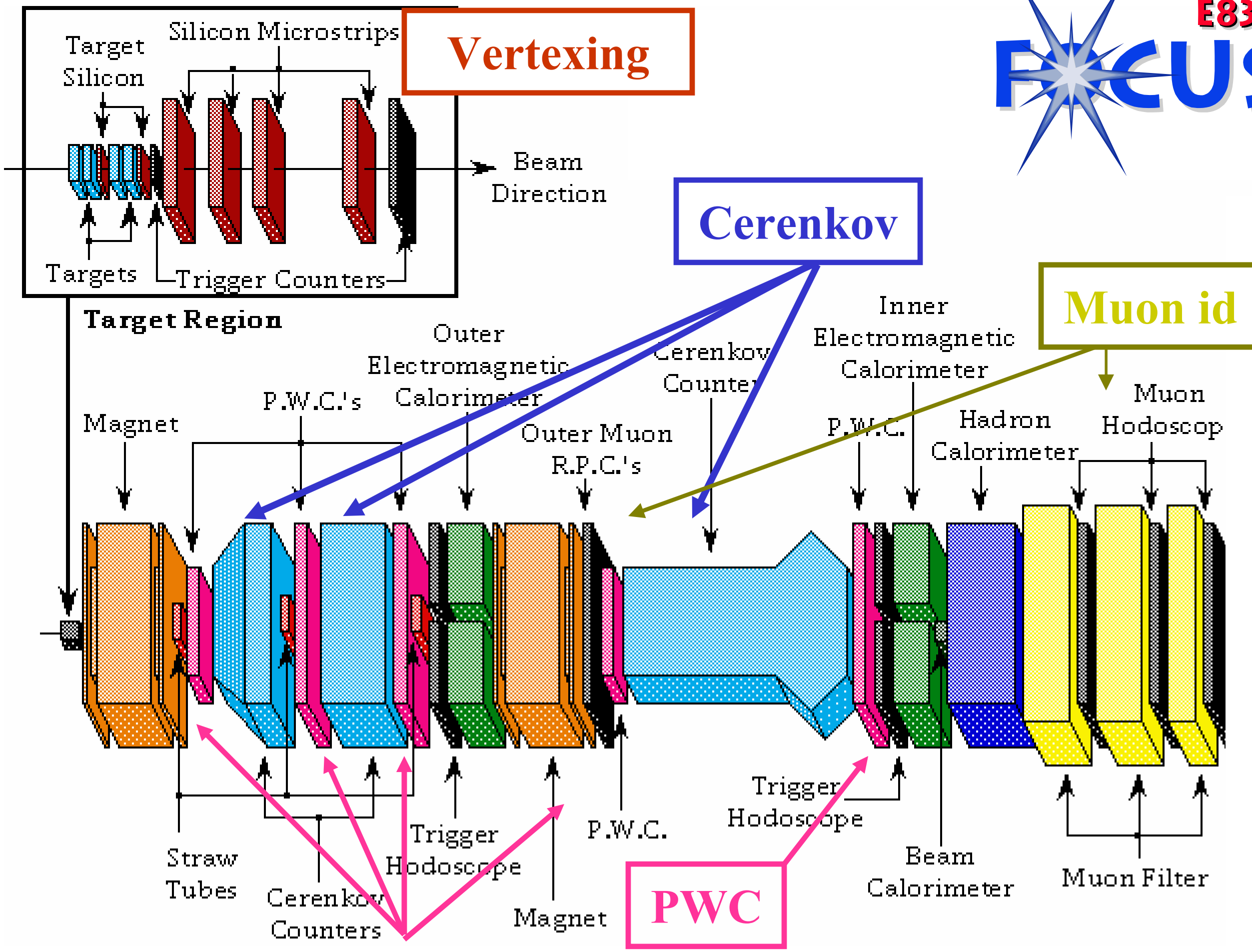
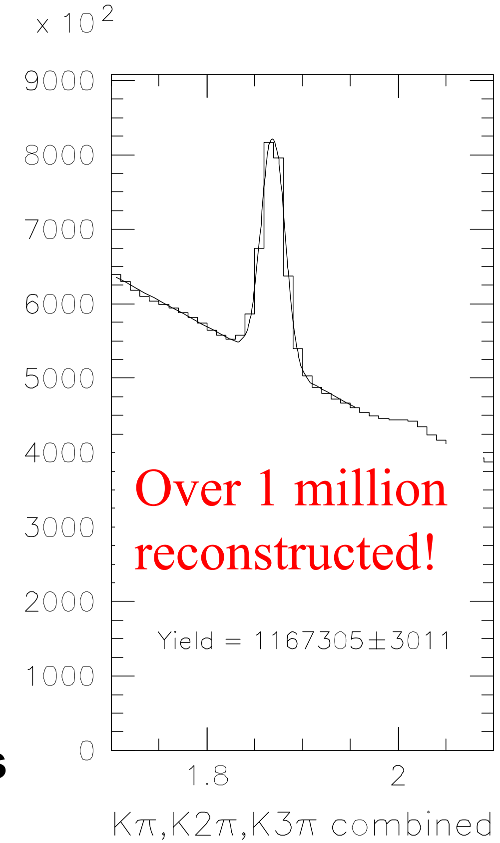
on behalf of the FOCUS collaboration

Outline

- Charm lifetimes
- Semileptonic decays
- Hadronic decays
- Conclusions

E831 FOCUS spectrometer





Successor to E687. Designed to study charm particles produced by ~200 GeV photons using a fixed target spectrometer with updated Vertexing, Cerenkov, EM Calorimeters, and Muon id capabilities. Member groups from USA, Italy, Brazil, Mexico, Korea.

Charm lifetimes

- lifetime determination allows conversion of relative BRs to partial decay rates
- FOCUS is the only experiment to have measured the lifetimes of all the charm particles
- most of the systematic errors cancel out in the ratio of lifetimes
- increasingly precise measurements of the heavy quarks lifetimes have stimulated the development of theoretical models able to predict this rich pattern (more than one order of magnitude from D^+ to Ω_c)
- charm lifetime hierarchy established
- crucial for meaningful measurements of lifetime difference

Charm lifetimes, technique

- proper time resolution ~ 35 ps

- use of reduced proper time

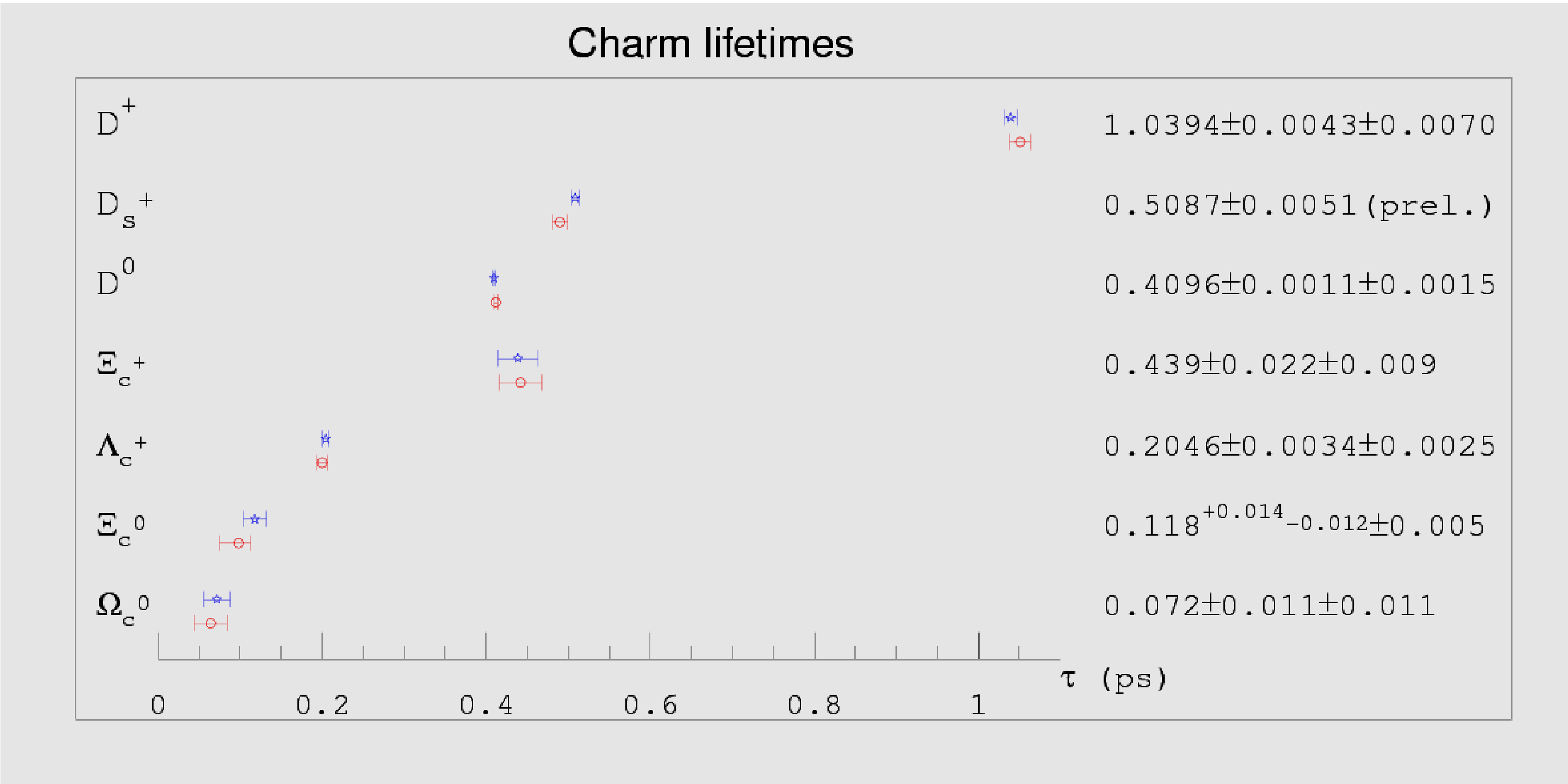
$$t' = (L - n\sigma_L)/\beta\gamma c$$

- f(t') from Monte Carlo

- binned maximum likelihood

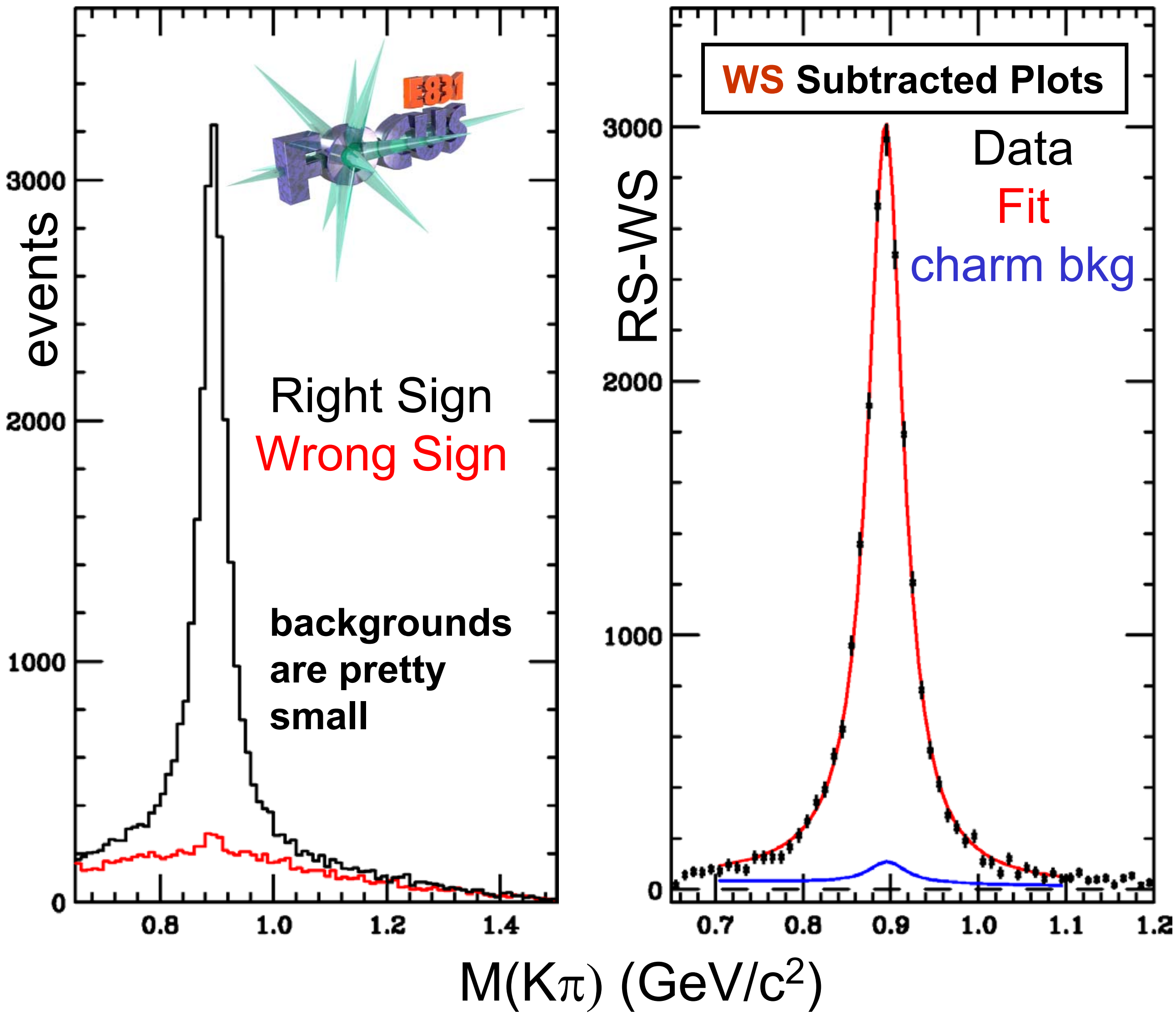
- this technique allows direct use of sidebands for the background (no background parametrization)

Charm lifetimes



FOCUS (*) produced new lifetimes results with precision better than the previous world average (○), PDG 2002

$D^+ \to K\pi\mu\nu$ events from FOCUS

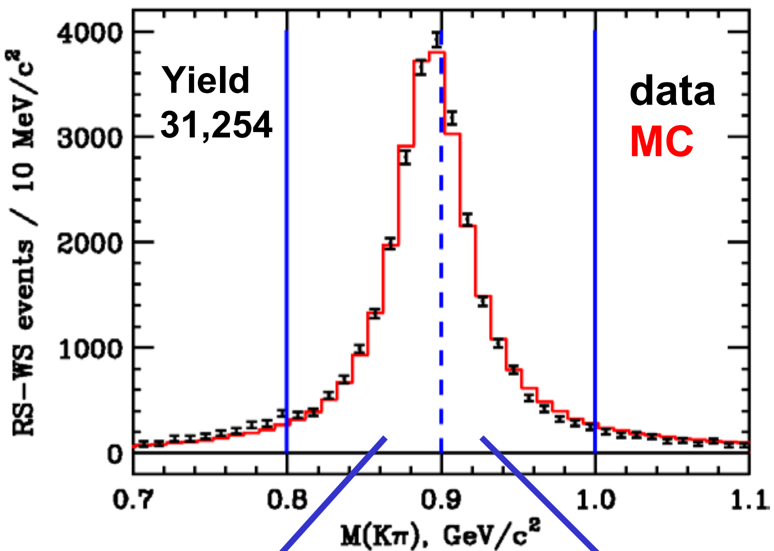


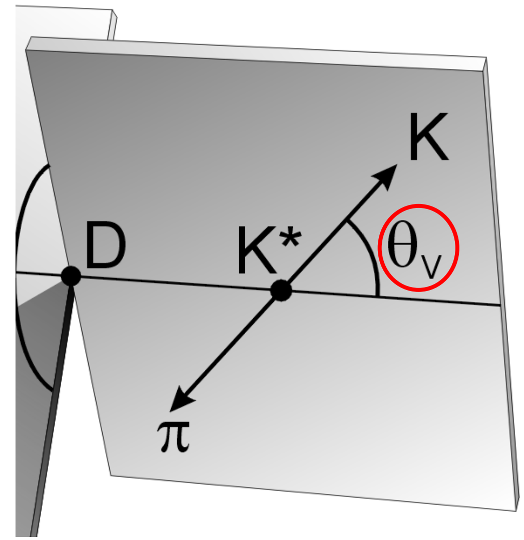
Our $K\pi$ spectrum looks like everyone else's, 100% K*(890), with much more data.

This has been so for last 20 years.

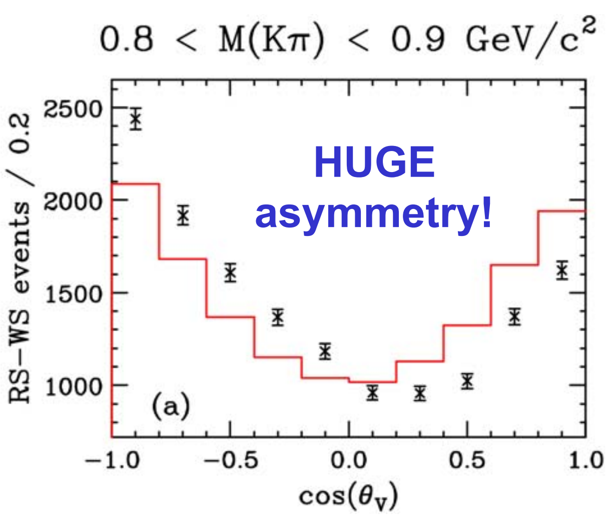
But *strange things* happen when we tried to measure form factors.

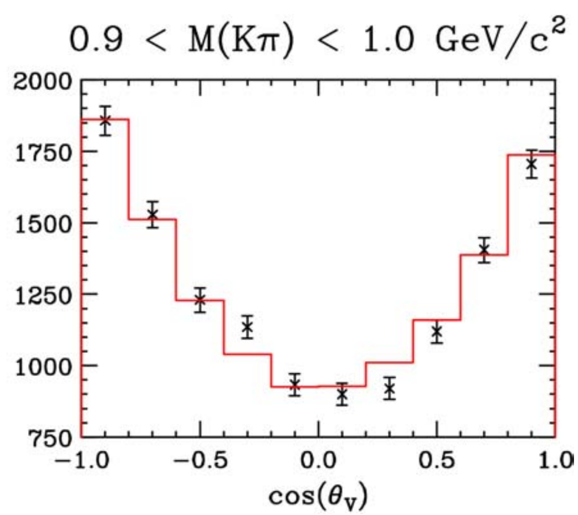
An unexpected asymmetry in the K* decay





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



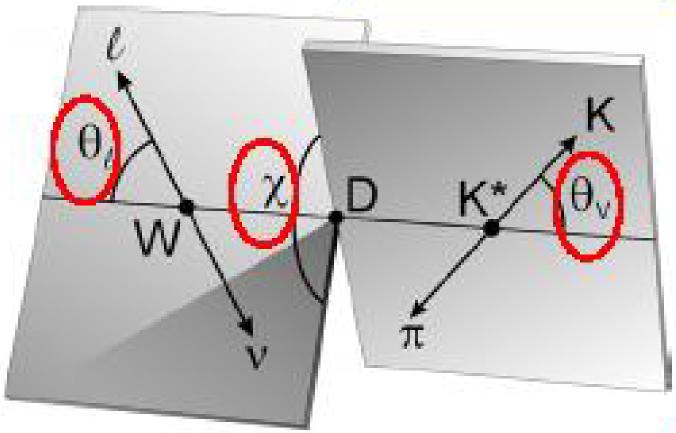


We noticed a forward-backward asymmetry in $\cos\theta_V$ below the K* pole, but almost none above the pole. → QM interference?

Simplest approach —
Try an interfering spin-0 amplitude

A 4-body decay requires 5 kinematic variables:

- $M_{K\pi}$
- $M_W^2 = q^2 = t$



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

+ muon mass terms

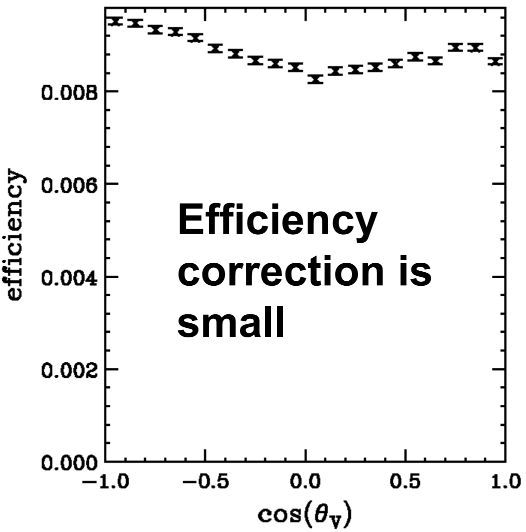
A exp(iδ) will produce 3 interference terms

where $B \equiv \dfrac{\sqrt{m_o \Gamma}}{m^2 - m_0^2 + i m_0 \Gamma}$

We simply add a new constant amplitude : A exp(iδ) in the place where the K* couples to an m=0 W^+ with amplitude H_0.
This assumes the q^2 dependence of the anomaly s-wave coupling is the same as the K* (could be challenged)

Studies of the acoplanarity-averaged interference

$$+8\cos\theta_V \sin^2\theta_l A\,\mathrm{Re}(e^{-i\delta}B_{K*})H_0^2$$

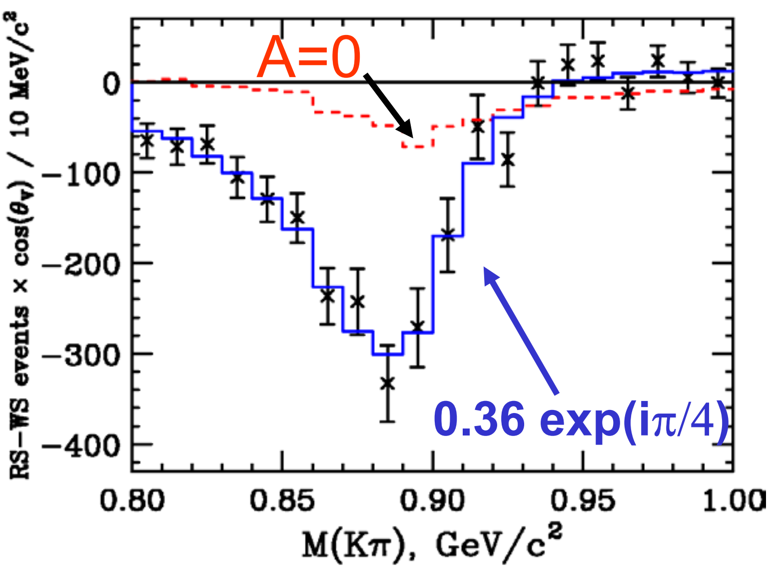


Extract this interference term by weighting data by cosθ_V,

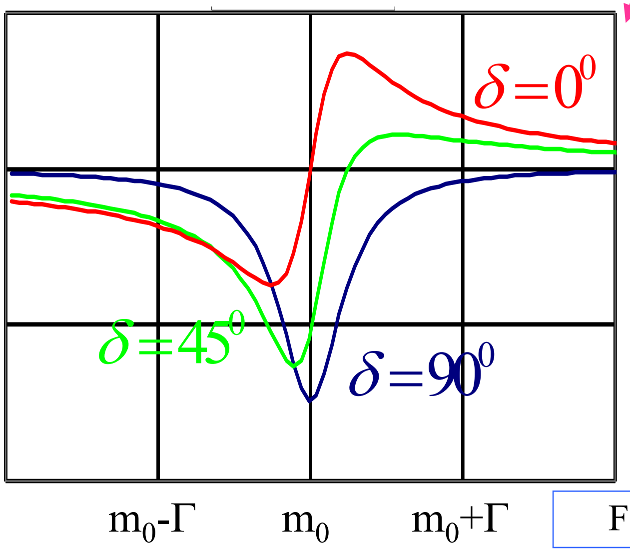
Since all other χ-averaged terms in the decay intensity are constant or cos$^2\theta_V$.

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

Our weighted mass distribution..



..looks just like the calculation..



A constant 45^0 phase works great…

…other options also possible.

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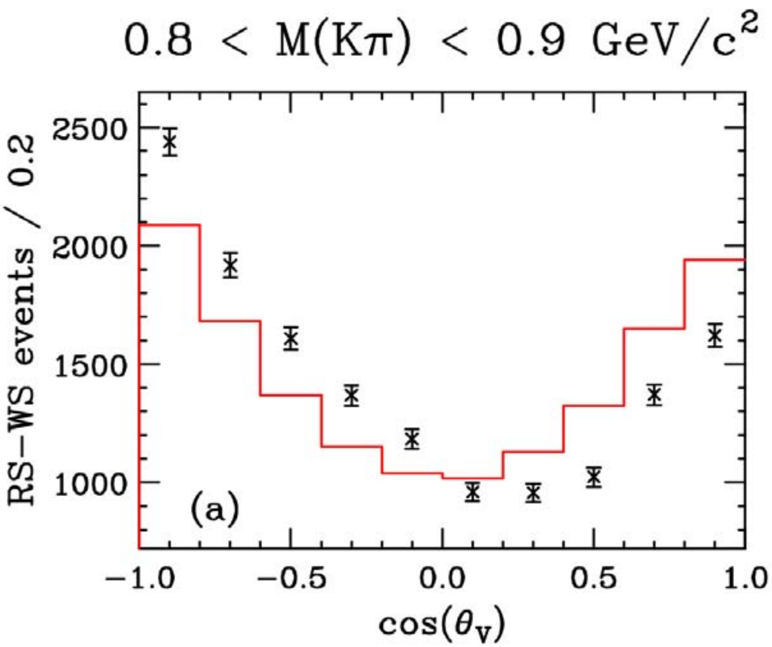
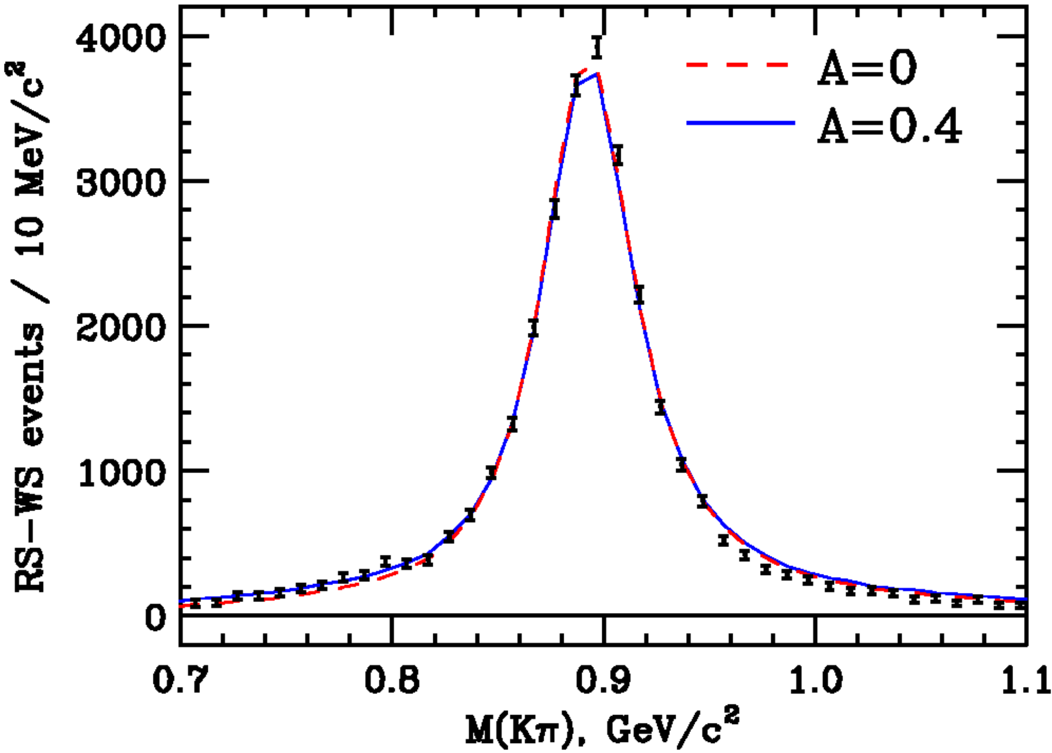
But surely an effect this large must have been observed before?





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

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

The FOCUS result on BR($D^+ \to K^*\mu\nu/K2\pi$)

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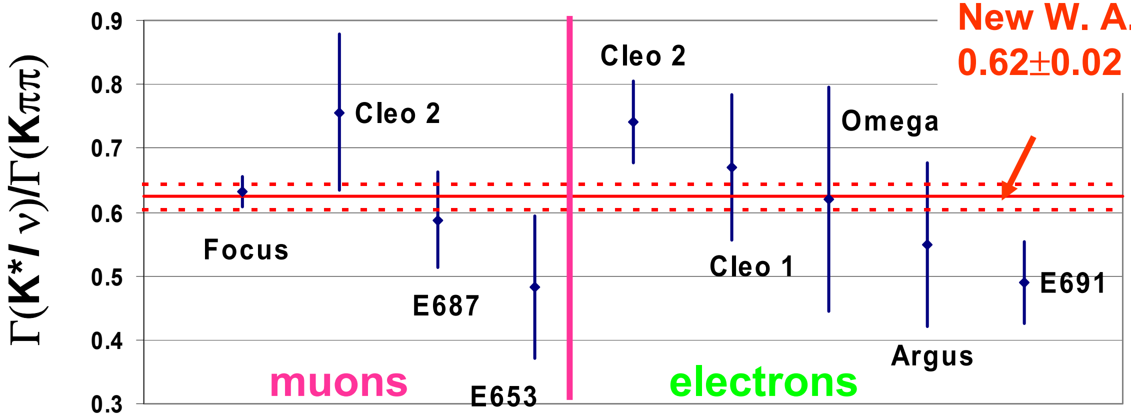
11,698 events

$$\frac{\Gamma(D^+ \to \overline{K}^{*0}\mu^+\nu)}{\Gamma(D^+ \to K^-\pi^+\pi^+)} = 0.602 \pm 0.010\ (\mathrm{stat}) \pm 0.021\ (\mathrm{sys})$$

65,421 events

With the correction factor applied,

$$f_{K*} \equiv \frac{\int dLIPS\ |\mathcal{M}(r_v, r_2, A=0)|^2}{\int dLIPS\ |\mathcal{M}(r_v, r_2, A=0.36)|^2} = 0.945$$



All muon results multiplied by 1.05 to be compared to electron results

Our number, the only one to consider an s-wave contribution explicitly, is 1.6 σ below CLEO and 2.1 σ above E691.

$BR(D_s^+ \rightarrow \phi\mu\nu/\phi\pi)$

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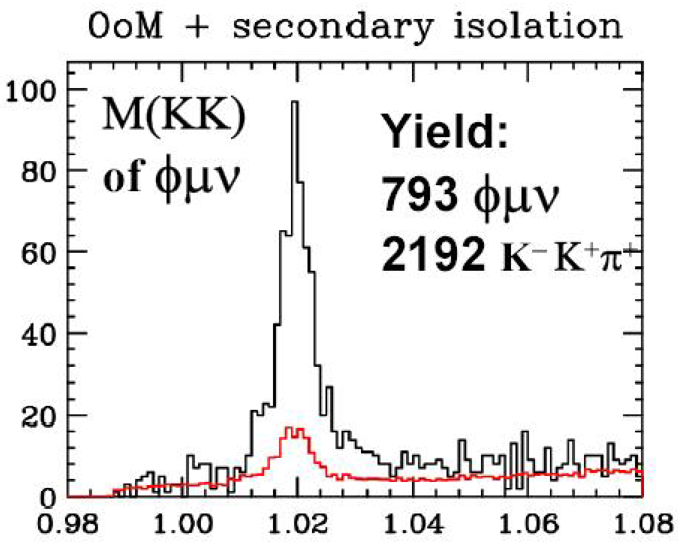
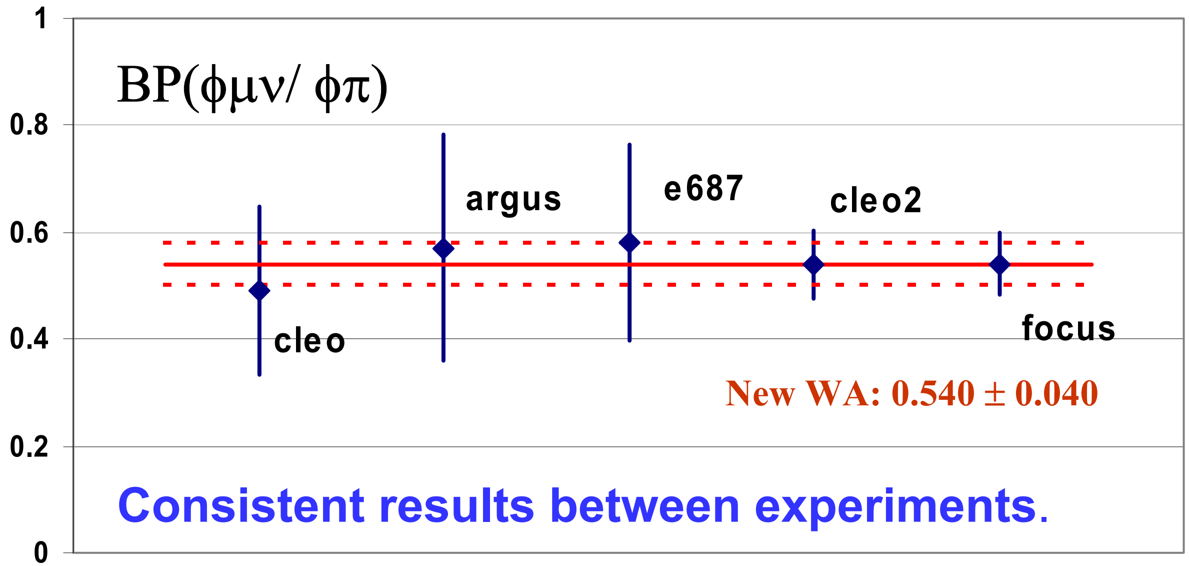


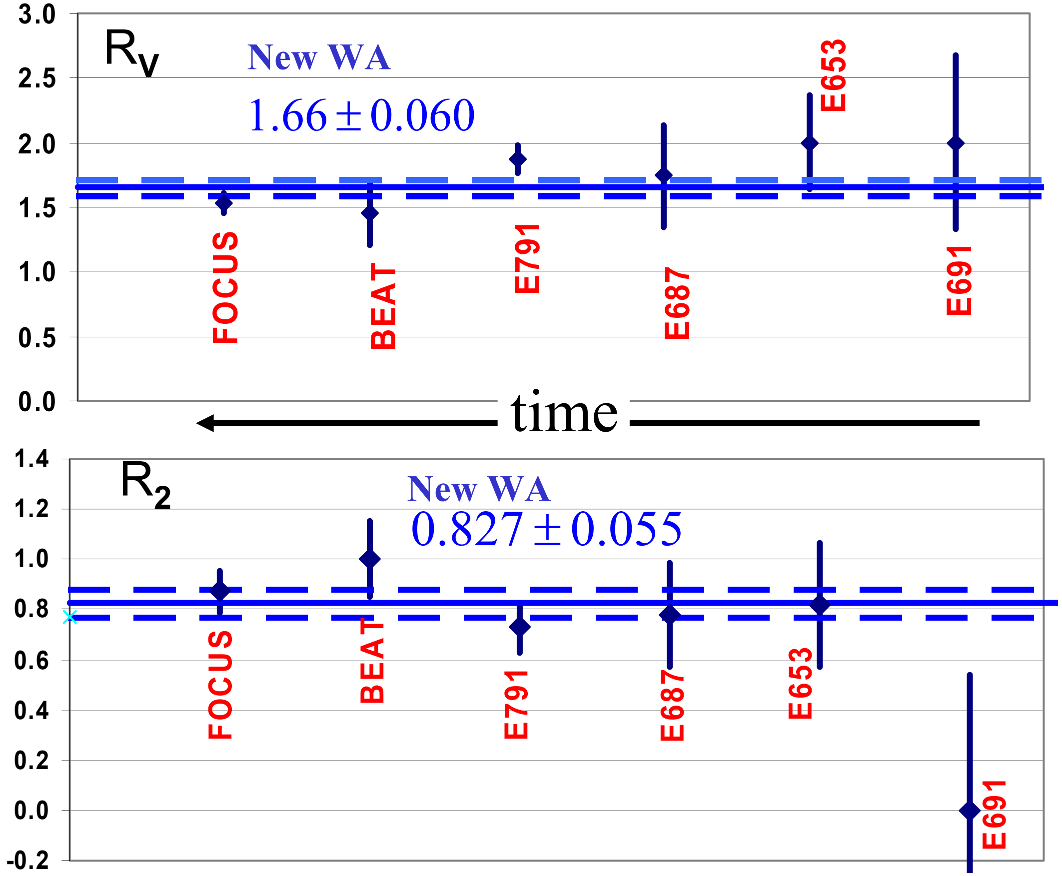


	br	stat	sys	stat+sys
cleo	0.49	0.1	0.12	0.156
argus	0.57	0.15	0.15	0.212
e687	0.58	0.17	0.07	0.184
cleo2	0.54	0.05	0.04	0.064
focus	0.540	0.033	0.048	0.058

This branching ratio is traditionally used to set the scale for D_s^+ branching fractions
by assumptions such as:

$$\Gamma(\phi\mu\nu) = (0.8 \rightarrow 1.0) \times \Gamma(\bar{K}^* \mu\nu)$$

Form Factor Measurements, $D^+ \to \overline{K}^*\mu\nu$



The experimental R_V value is getting smaller with the passing years. The new Focus value is 2.9 σ below E791. We were consistent before charm background correction.

Apart from E691 the R_2 values have been pretty consistent.

Latest form factor calculation Damir Becirevic (ICHEP02)

$R_V = 1.55 \pm 0.11$

which is remarkably close to

$R_V = 1.504 \pm 0.087$(FOCUS)

New FOCUS Results:

$R_V = 1.504 \pm 0.057 \pm 0.039$

$R_2 = 0.875 \pm 0.049 \pm 0.064$

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Summary on semileptonic

(1) S-wave interference in $D^+ \to K\pi\mu\nu$ of the form

$$|H_0|^2 \left| 0.36 \exp\left(i\frac{\pi}{4}\right) + \frac{\cos\theta_v \sqrt{m_0\Gamma}}{(m-m_o)^2 + i m_0 \Gamma} \right|^2$$

The new amplitude is **small:**
$\approx$ **7% of BW** peak amplitude in the H_0 part.
$\approx$ **6% of all $K\pi\mu\nu$** over the full $K\pi$ range

(2) New results on BR $D^+ \to K^*\mu\nu/K2\pi$

- CLEO value $0.74 \pm 0.04 \pm 0.05$ (is higher than previous data)
- FOCUS value is $0.60 \pm 0.01 \pm 0.02$ ($1.6\ \sigma$ lower than CLEO)

(3) New measurements of BR $D_s^+ \to \phi\mu\nu/\phi\pi$

- Data from all experiments remarkably consistent one another.

(4) New measurements of $D^+ \to K^*\mu\nu$ form factors

- Charm backgrounds artificially raise R_V significantly ($\sim 3\sigma$)
- Our R_V measurement is 3σ lower than E791 but very much in line with most recent Lattice Gauge Calculation by Rome group.
- (S-wave helps fit but we have a $V(q^2)$ problem for $q^2 < 0.2\ \text{GeV}^2$)

Summary on semileptonic

(5) Will there be similar effects (interference) in other charm semileptonic or beauty semileptonic channels?

Good question.

Hadronic decays

- the correct interpretation of the hadronic decays is complicated
- FSI play a central role (in the B decays they are supposed to be small, is it true?)
- amplitude analysis (Dalitz plot) is the correct tool to determine the resonant substructure

FSI, an example the $BR(D^0 \to K^- K^+)/(D^0 \to \pi^- \pi^+)$

Elastic FSI - rotation in Isospin space

$\pi^- \pi^+ \xrightarrow[\text{FSI}]{\text{Elastic}} \pi^0 \pi^0$ $\quad$ $K^- K^+ \xrightarrow[\text{FSI}]{\text{Elastic}} K^0 \bar{K}^0$

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(BR and Isospin analysis)

$$\frac{\Gamma(D^0 \to K^- K^+)}{\Gamma(D^0 \to \pi^- \pi^+)} = 2.81 \pm 0.12$$

$$\frac{\Gamma(D^0 \to K^+ K^-) + \Gamma(D^0 \to K^0 \bar{K}^0)}{\Gamma(D^0 \to \pi^- \pi^+) + \Gamma(D^0 \to \pi^0 \pi^0)} = 2.06 \pm 0.24$$

Large SU(3) breaking

Not affected by elastic FSI

SU(3) breaking is reduced

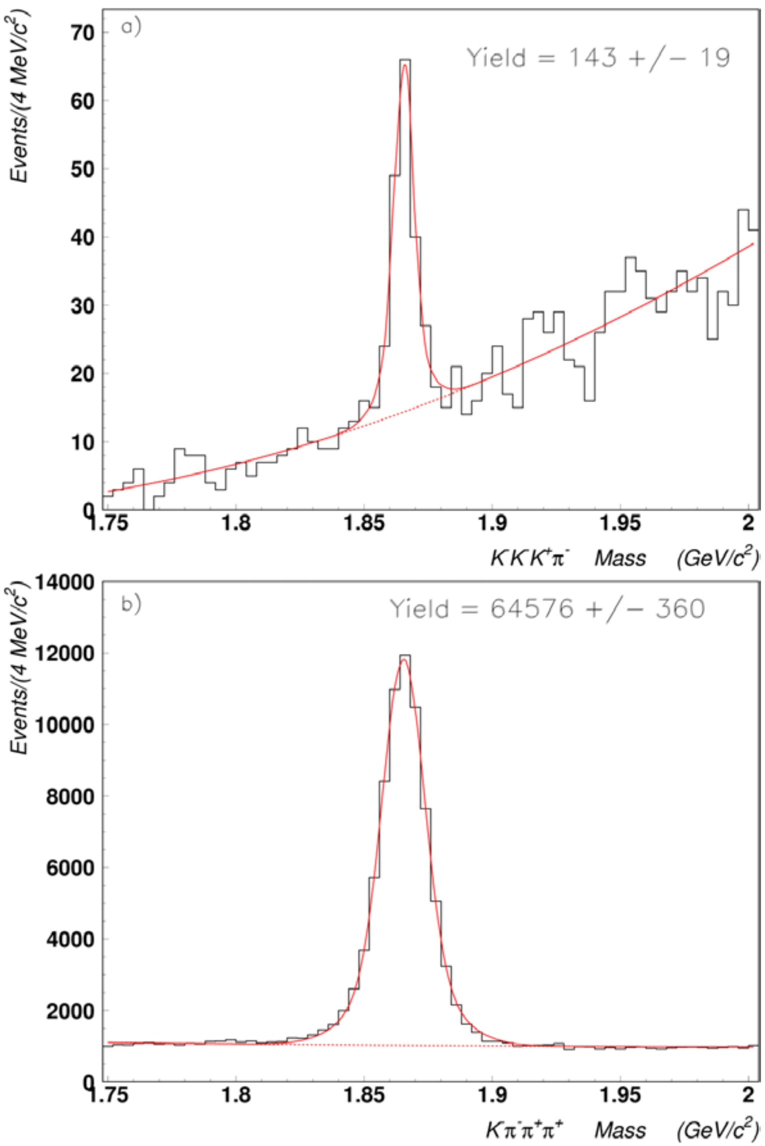
Conclusions:

- Summing over Isospin rotated channels, SU(3) breaking is reduced.
- The effect of elastic FSI on BR $(K^- K^+)/(\pi^- \pi^+)$ is significant, but is unable to explain the discrepancy between experimental results and theoretical predictions $(\Gamma(K^- K^+)/\Gamma(\pi^- \pi^+) \leq 1.4)$

Most reasonable explanation : inelastic FSI

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

Preliminary



- **$D^0 \rightarrow K^+K^-K^-\pi^+$ is Cabibbo favored but it is strongly suppressed by phase space**

- **This decay mode requires the production of a couple *$s\bar{s}$* either from the vacuum or via FSI**

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

Preliminary

Experiment	$\Gamma(D0 \to K^+K^-K^-\pi^+) / \Gamma(D0 \to K^-\pi^-\pi^+\pi^+)$	Events
E687	0.0028±0.0007±0.0001	20 ± 5
E791	0.0054±0.0016±0.0008	18.4 ± 5.3
FOCUS (this result)	0.00257±0.00034±0.00023	143 ± 19

Mode	phase(deg)	magnitude	fraction(%)
$\phi K^{*0}(890)$	0	1.	48±6±1
$\phi K^-\pi^+$	194±24	0.60±0.12	18±6±3
$K^{*0}(890)K^+K^-$	255±15	0.65±0.13	20±7±2
Non-resonant	278±16	0.55±0.14	15±6±2

Amplitude analysis

Can we get a pure $K_s\,\phi$ CP odd from $D^0 \to K_s K^+K^-$?

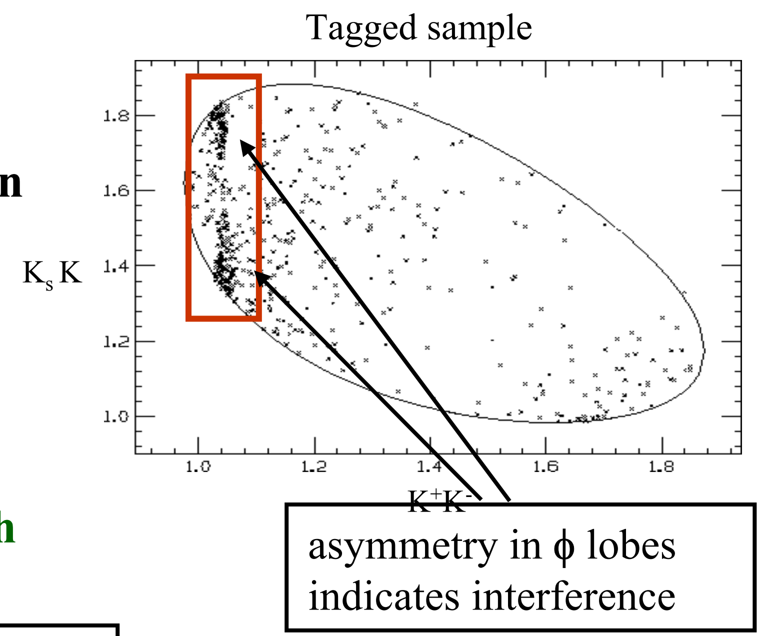
$K_s\,\phi$ is a CP odd state: Ks and ϕ are CP even

- **$K_s\,\phi$ is in a relative p-wave with parity -1**

$K_s\ f_0(980)$ is a CP even state: Ks and f_0 are CP even

- **$K_s\ f_0(980)$ is relative s-wave with parity +1**

Two states interfere in same region in Dalitz plot:



Is there a pure CP odd eigenstate near the ϕ ?

- **No. A CP even eigenstate will be present with a non-negligible fraction.**

Fraction of events in the ϕ region due to ϕK_s is:

$$\frac{\int_{\phi\ region} A_\phi A_\phi}{\int_{\phi\ region} A^*_{total} A_{total}} = 62 \pm 3\%$$

Resonance	Fraction in the ϕ region $(M^2_{k^+K^-} < 1.1(MeV/c^2)^2)$
$f_0(980)$	$37.8 \pm 3.0\%$
$a_0^+(980)$	$0.5 \pm 0.1\%$
ϕ	$62.2 \pm 2.8\%$

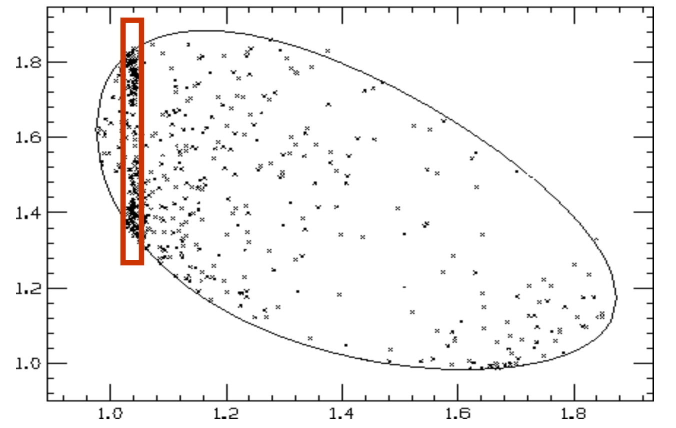
Suggests $D^0 \to "\phi" K_s$ is 62% CP odd and 38% CP even

But $D^o \to K^-\pi^+$ is 50% CP odd + 50 CP even

$K_s\,\phi$ CP odd purity can be improved with a tighter cut

The contaminating f_0 fraction rapidly reduces as we narrow the phi region from 50 MeV to 4 MeV

Tagged sample



Resonance	Fraction in the ϕ region $((MeV/c^2)^2)$ $1.034 < M^2_{K^+K^-} < 1.042$
$f_0(980)$	$7.7 \pm 1.0 \pm 0.4\%$
$a_0^+(980)$	$0.05 \pm 0.01 \pm 0.1\%$
ϕ	$93.0 \pm 0.9 \pm 0.3\%$

Fraction of events in the ϕ region due to ϕK_s is:

$$\frac{\int_{\phi\ region} A_\phi^* A_\phi}{\int_{\phi\ region} A_{total}^* A_{total}} = 93 \pm 2 \pm 1\%$$

Now $D^0 \rightarrow "\phi" K_s$ is 93% CP odd and 7% CP even

Conclusions

- At 30 years from the discovery of the *c* quark the physics analysis of the first *heavy* quark has reached a complete maturity

- With the large statistics now available in the charm sector, we start to see strange effects which complicate the explanation of the decay processes

- FSI play a crucial role
- *Light* hadron physics is important in charm decays

- Lessons for the *b* sector?