Charm Semileptonic Decays

New Results from FOCUS

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Representing FOCUS

Outline

- Interference in $D^+ \to K\pi\mu\nu$
- BR $D^+ \to K^*\mu\nu/K2\pi$
- BR $D_s^+ \to \phi\mu\nu/\phi\pi$

BEACH2002

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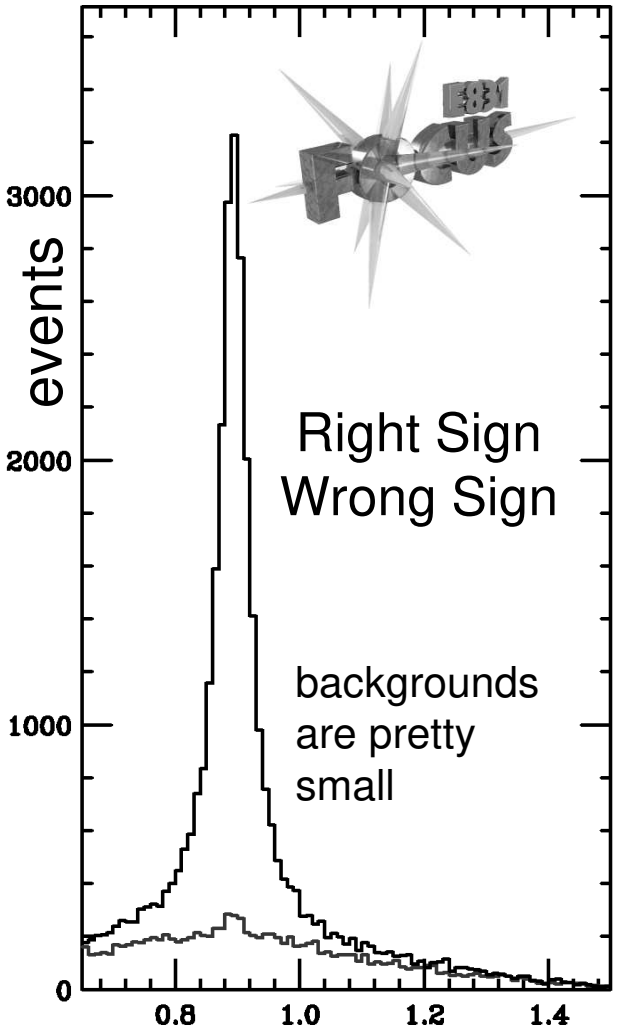
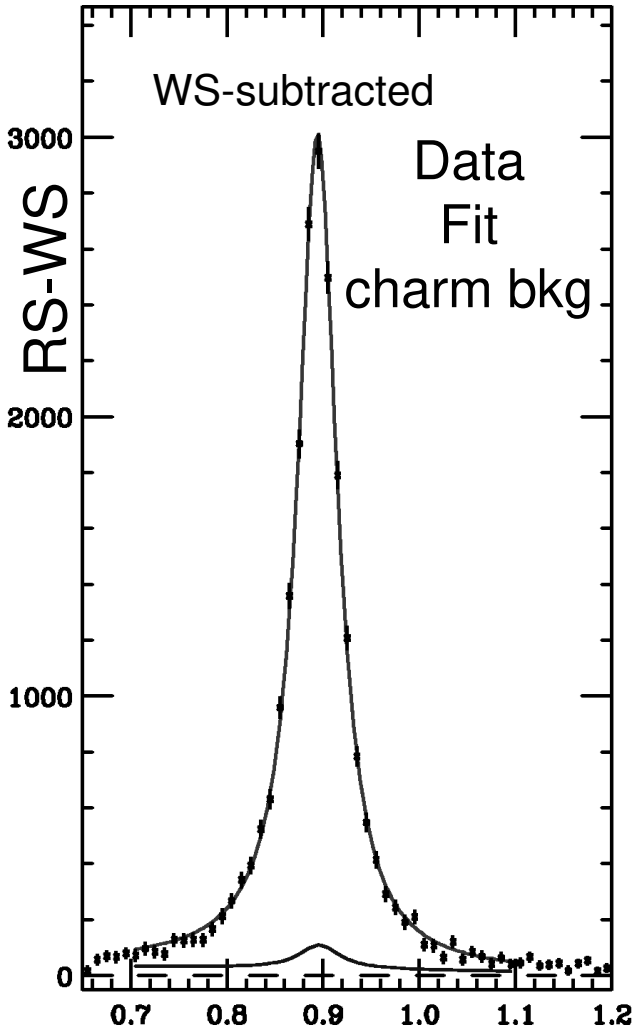
New results on $D^+ \to K\pi\mu\nu$





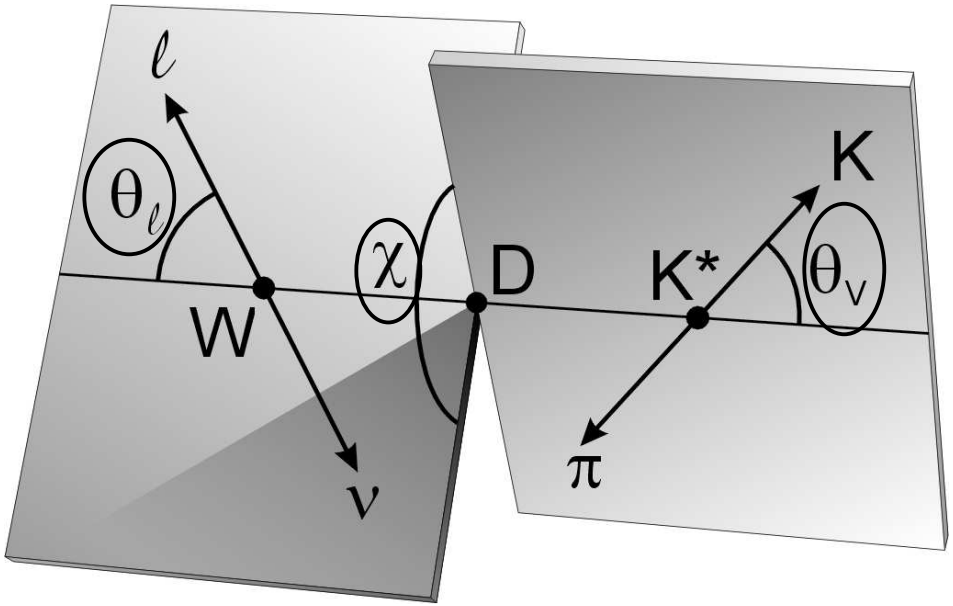
$M_{K\pi}$ (GeV/c^2)

Our $K\pi$ spectrum (like everyone else's) looks like 100% K*(890).

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 ...

Five observables are studied



A 4-body decay requires 5 kinematic variables: Three angles and two masses.

$M_{K\pi}$

$M_W^2 \equiv q^2 \equiv t$

Two amplitude sums over W polarization

$$|\mathrm{A}|^2 = \frac{1}{8}(t - m_l^2)\left\{ \left| \begin{array}{l} (1+\cos\theta_l)\sin\theta_V e^{i\chi} H_+ \\ -(1-\cos\theta_l)\sin\theta_V e^{-i\chi} H_- \\ -2\sin\theta_l \cos\theta_V H_0 \end{array} \right|^2 + \frac{m_\mu^2}{t} \left| \begin{array}{l} \sin\theta_l \sin\theta_V e^{i\chi} H_+ \\ +\sin\theta_l \sin\theta_V e^{-i\chi} H_- \\ +2\cos\theta_l \cos\theta_V H_0 \\ +2\cos\theta_V H_t \end{array} \right|^2 \right\}$$

right-handed μ⁺

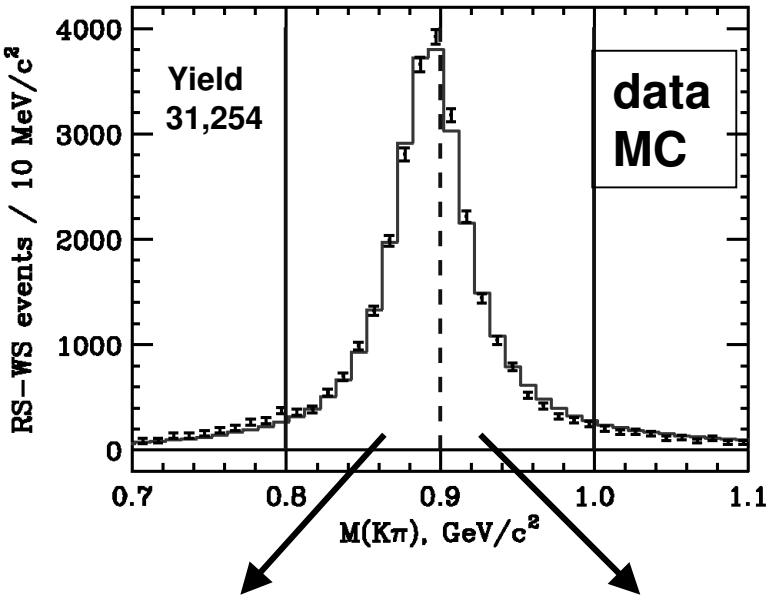
Wigner D-matrices

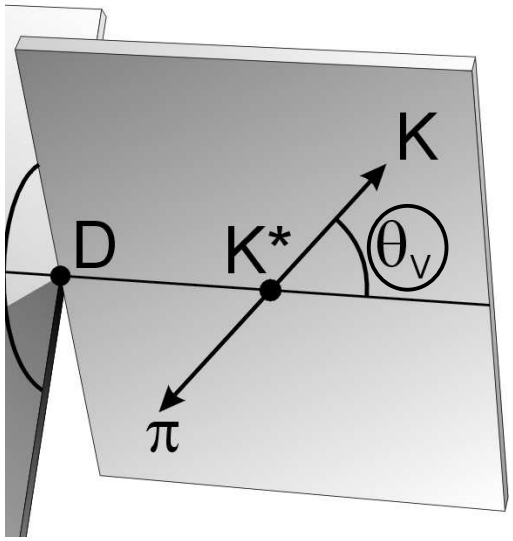
left-handed μ⁺

("mass terms")

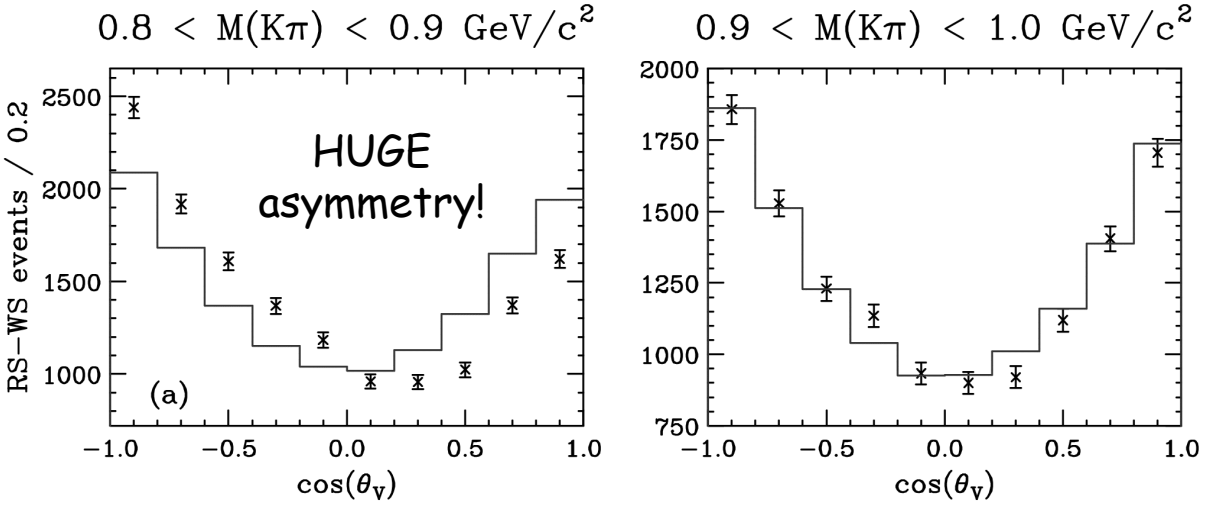
$H_0(q^2)$, $H_+(q^2)$, $H_-(q^2)$ are helicity-basis form factors computable by LGT

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.

Could it be QM interference?

Simplest approach — Try an interfering spin-0 amplitude

$$|\mathbf{M}|^2 \propto (t - m_\mu^2) \left| \begin{array}{l} \dfrac{(1+\cos\theta_l)}{2} \dfrac{\sin\theta_V}{\sqrt{2}} e^{i\chi} \mathrm{B} H_+ \\ + \dfrac{(1-\cos\theta_l)}{2} \dfrac{-\sin\theta_V}{\sqrt{2}} e^{-i\chi} \mathrm{B} H_- \\ + \dfrac{-\sin\theta_l}{\sqrt{2}} (\cos\theta_V \mathrm{B} \boxed{+ A e^{i\delta}}) H_0 \end{array} \right|^2$$

(plus mass terms)

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

A exp(iδ) will produce
3 interference terms

We simply add a new constant amplitude : A exp(iδ) in the place where the K* couples to a helicity=0 W^+ with amplitude H_0.

Since A << B, interference will dominate..

Ignoring the "mass terms",

$$\begin{aligned}\text{Intrf.} = & \; 8\cos\theta_V \sin^2\theta_l A \,\mathrm{Re}\left(e^{-i\delta} B_{K^*}\right) H_0^2 \\ & -4(1+\cos\theta_l)\sin\theta_l \sin\theta_V A \,\mathrm{Re}(B_{K^*} e^{i(\chi-\delta)}) H_+ H_0 \\ & +4(1-\cos\theta_l)\sin\theta_l \sin\theta_V A \,\mathrm{Re}(B_{K^*} e^{-i(\chi+\delta)}) H_- H_0\end{aligned}$$

If we average over acoplanarity we only get the first term

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

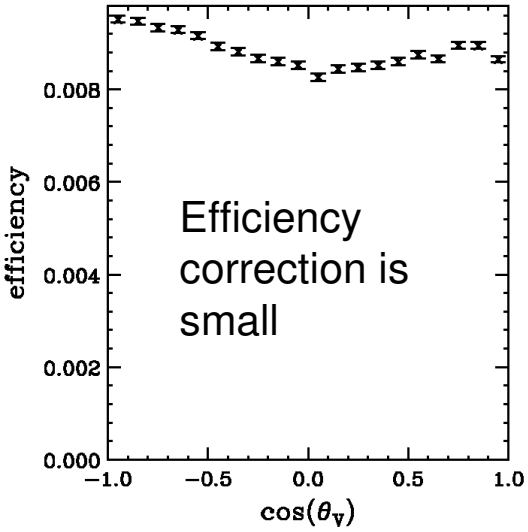
This is the term that created our forward-backward asymmetry!

If our model is right:

- The asymmetry will have a particular mass dependence: $\mathrm{Re}\left(e^{-i\delta} B_{K^*}\right)$
- The asymmetry should be proportional to $\sin^2\theta_l$
- The asymmetry should have a q^2 dependence given by $q^2 H_0^2(q^2)$

Studies of the acoplanarity-averaged interference

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

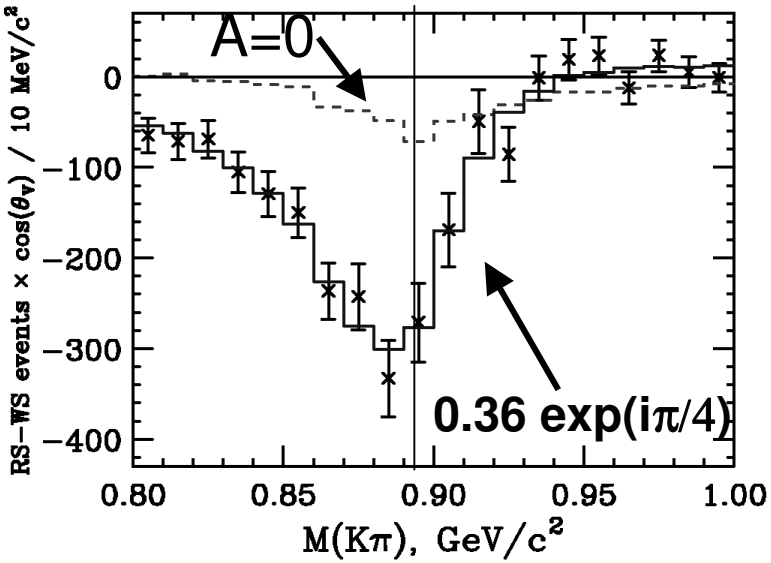


Extract this interference term by weighting data by $\cos\theta_V$.

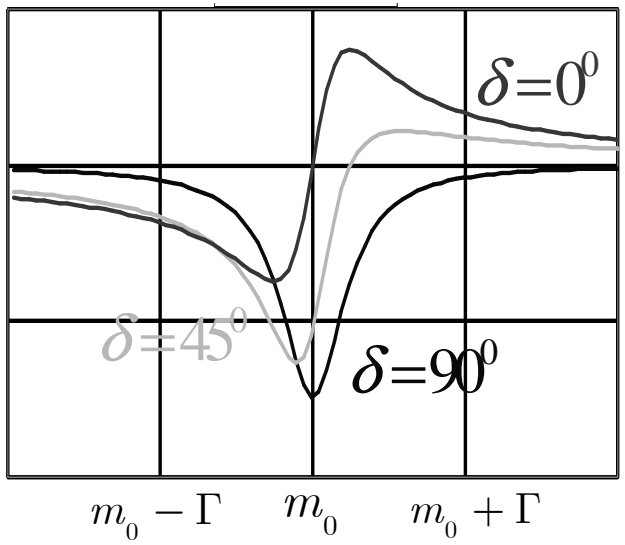
Since all other χ-averaged terms in the decay intensity are constant or $\cos^2\theta_V$, they do not contribute.

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

Our weighted mass distribution..



..looks just like the calculation.



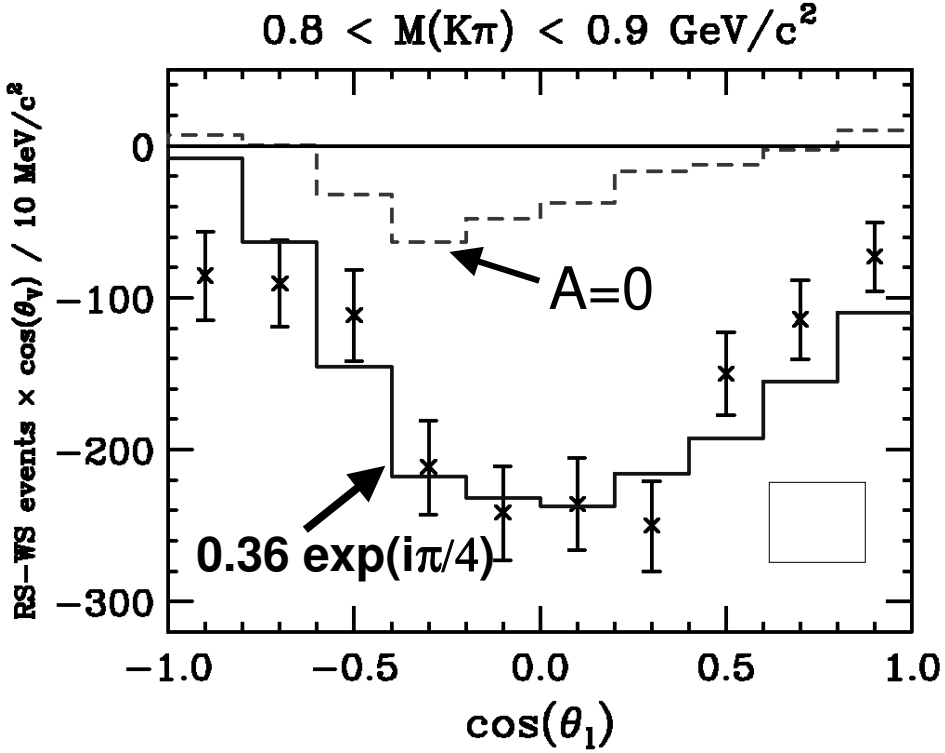
A constant 45^0 phase works great...

...but a broad resonance is fine as well.

Dependence of asymmetry on $\cos\theta_l$

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

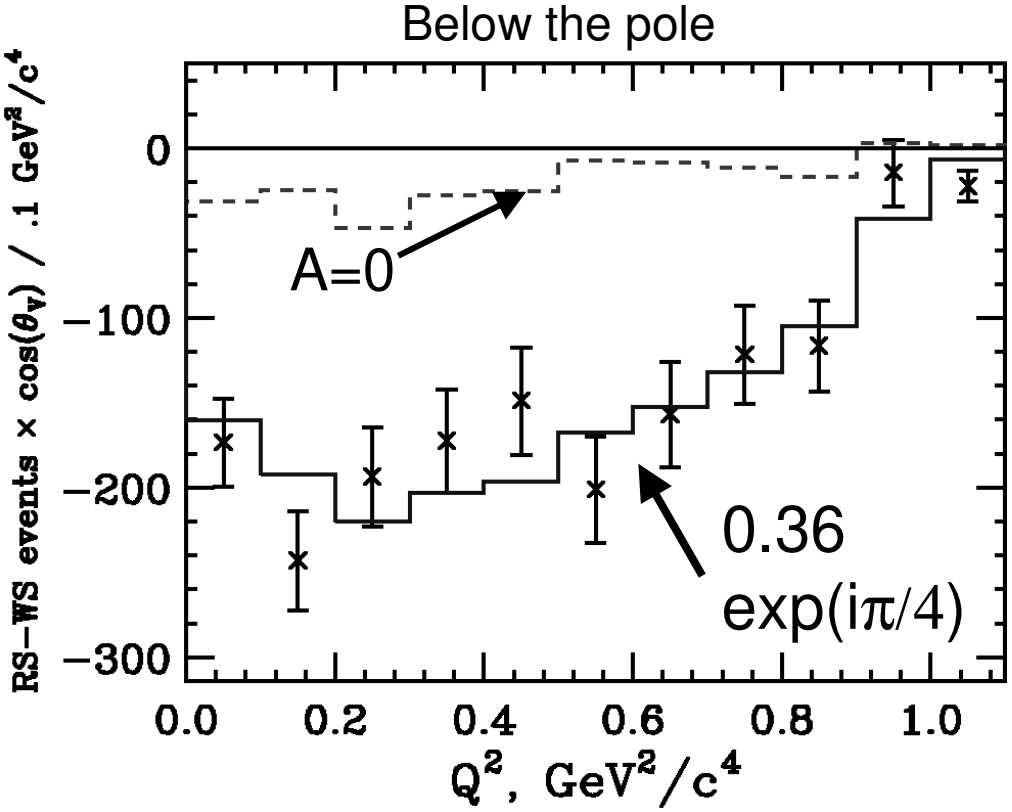
- We plot the asymmetry versus $\cos\theta_l$ and expect a parabola in $\cos^2\theta_l$ since $\sin^2\theta_l = (1 - \cos^2\theta_l)$



Looks $\propto -(1 - \cos^2\theta_l)$. Some modulation due to efficiency and resolution

q^2 dependence of asymmetry

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



Acoplanarity dependent interference terms

The interference adds two new terms to the acoplanarity dependence.

$$-4(1+\cos\theta_l)\sin\theta_l\sin\theta_V A\,\mathrm{Re}(B_{K^*}e^{i(\chi-\delta)})H_+H_0$$

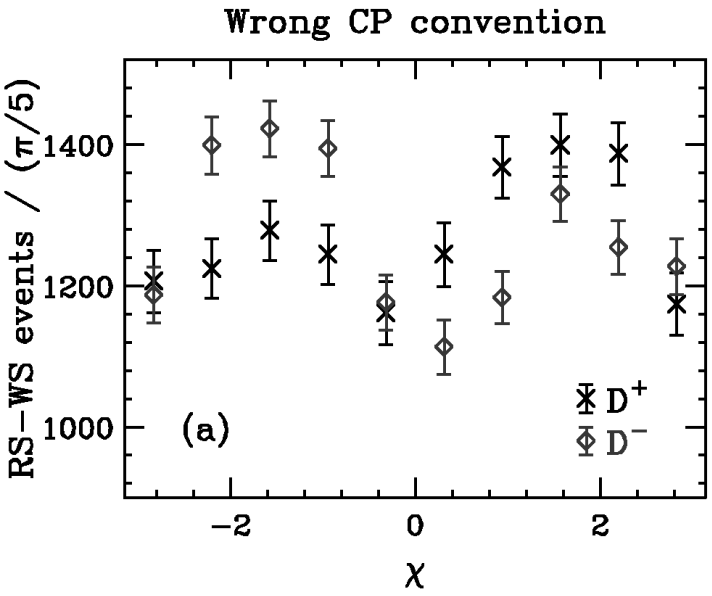
$$+4(1-\cos\theta_l)\sin\theta_l\sin\theta_V A\,\mathrm{Re}(B_{K^*}e^{-i(\chi+\delta)})H_-H_0$$

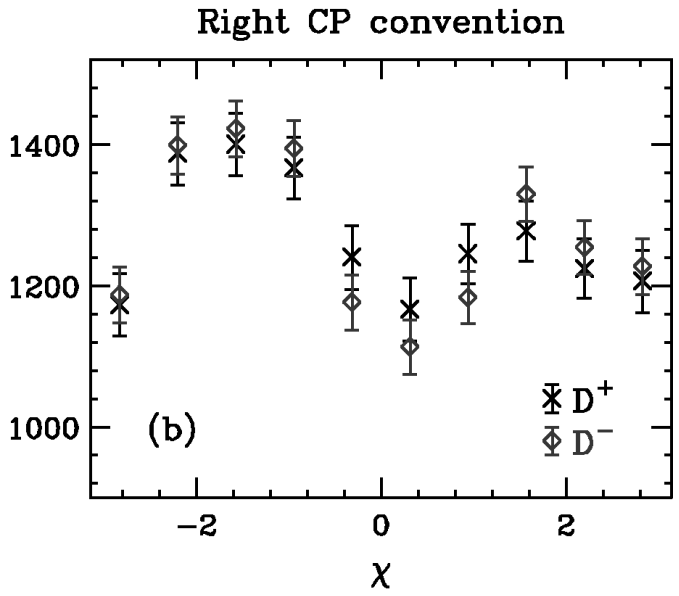
Without s-wave interference, the acoplanarity terms are even in χ: Only cos χ and cos 2χ dependencies are present

The interference produces sin χ terms which break χ **to** $-\chi$ symmetry

The loss of χ to -χ symmetry is seen in the data.

$$\chi\left(D^{+}\right) \rightarrow -\chi\left(D^{-}\right)$$





$$D^{+} \rightarrow K^{-}\pi^{+}\mu^{+}\nu$$

$$D^{-} \rightarrow K^{+}\pi^{-}\mu^{-}\bar{\nu}$$

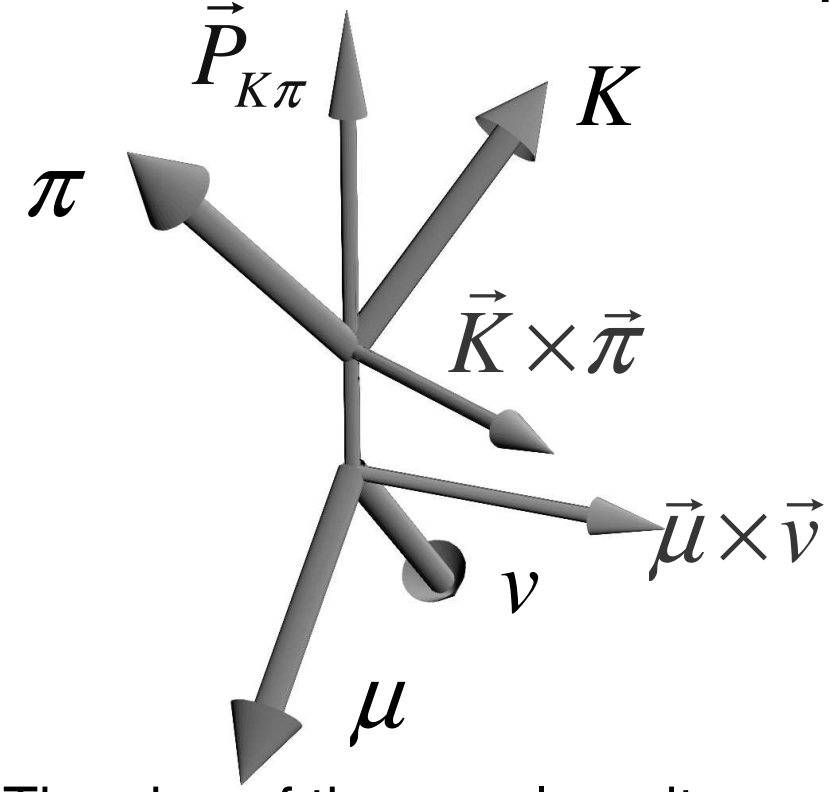
Same sign (incorrect) convention used for D+ and D-

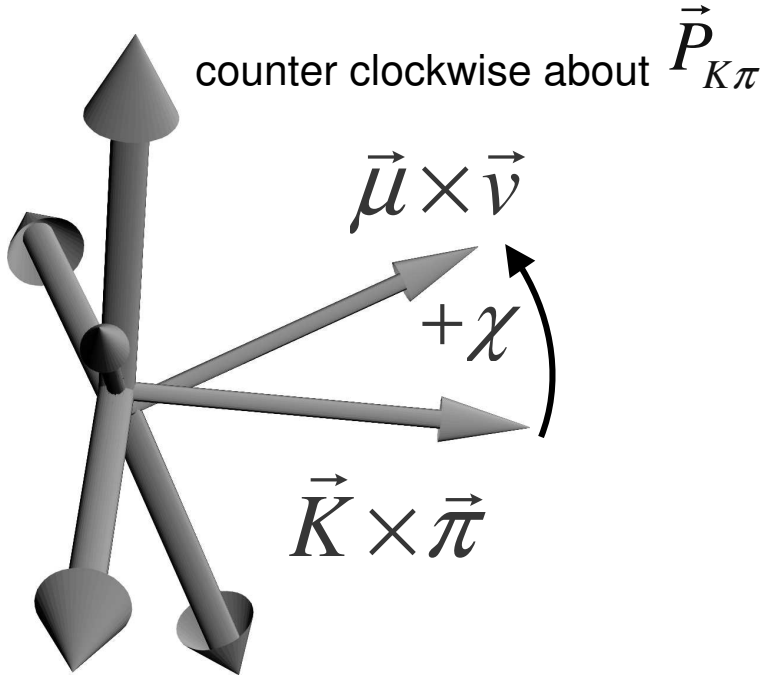
Opposite sign (correct) convention used for D+ versus D-

Can be mistaken for CP violation!

When sign of χ is handled properly, the D+ and D- acoplanarity distributions become consistent.

The correct acoplanarity convention



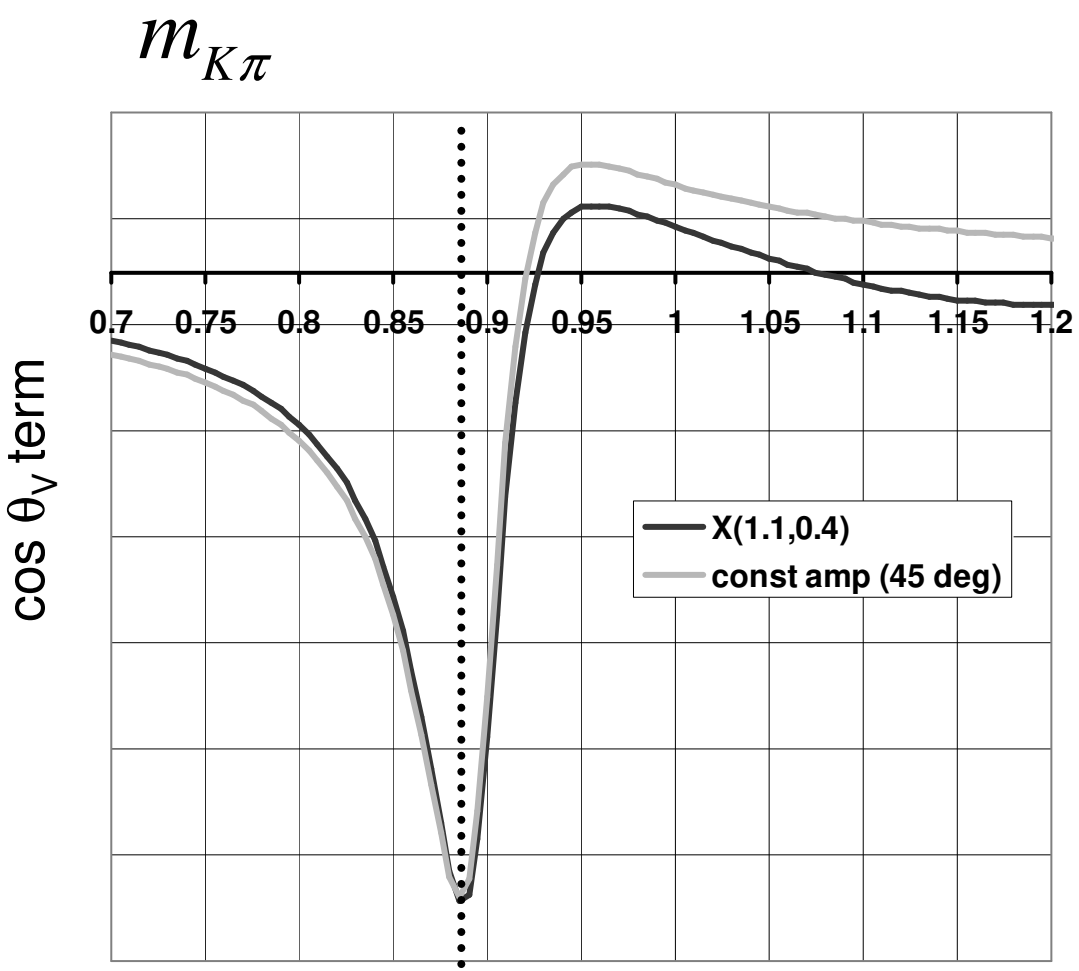


The sine of the acoplanarity is a product of five vectors.

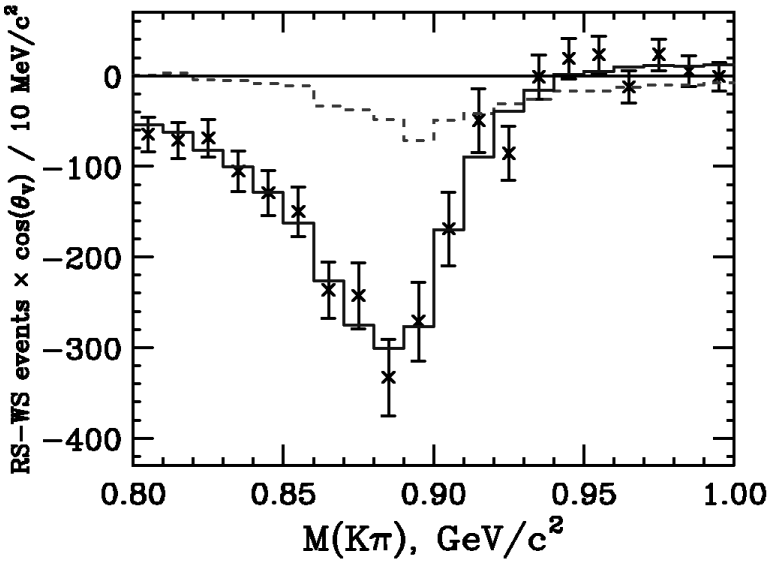
$$\sin\chi = \frac{\vec{P}_{K\pi}\cdot\left[\left(\vec{K}\times\vec{\pi}\right)\times\left(\vec{\mu}\times\vec{\nu}\right)\right]}{|\vec{P}_{K\pi}||\vec{K}\times\vec{\pi}||\vec{\mu}\times\vec{\nu}|}$$

Under CP, D+ => D-. We want χ to have the same value for CP transformed states but the formula above changes sign when all 5 vectors reverse. Thus we must take the opposite sign for D+ versus D- decays.

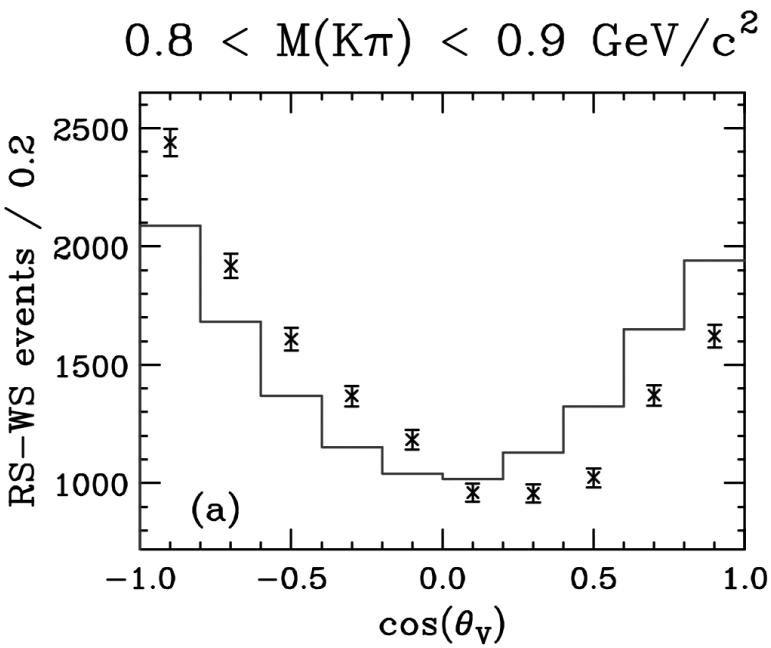
The model is not a unique solution. A broad resonant amplitude also works well.



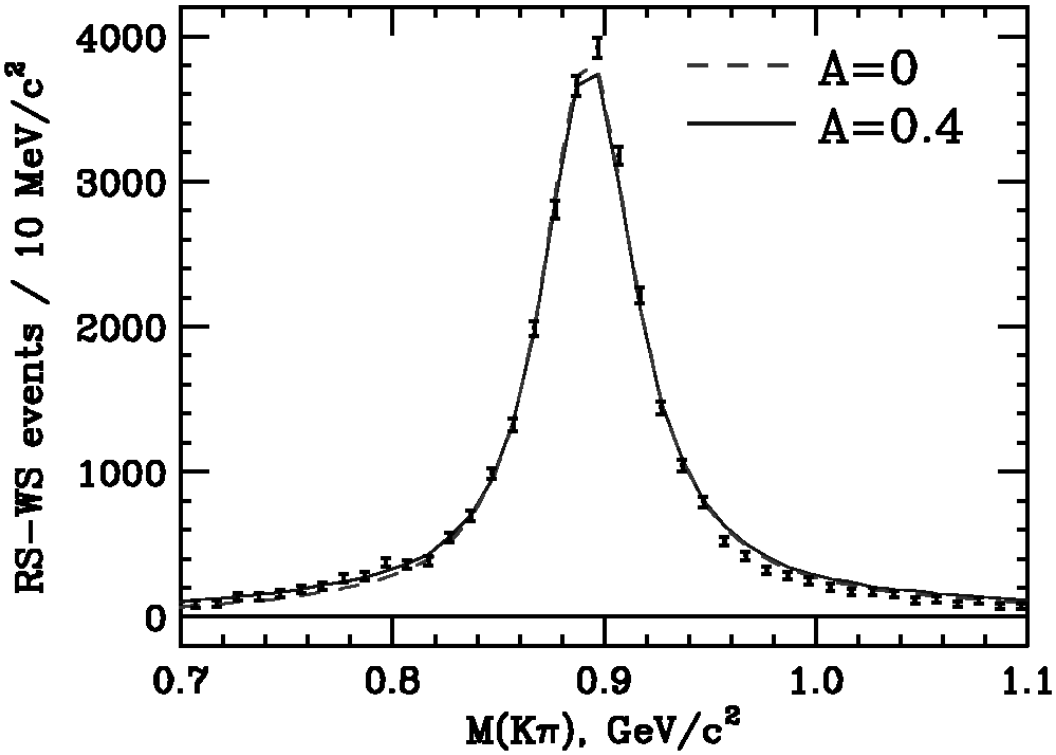
We can mimic the cosV dependence for a **constant amplitude** using a BW put in with a relatively real phase. For example use a wide width (400 MeV) and center it above the K* pole (1.1 GeV).



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



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

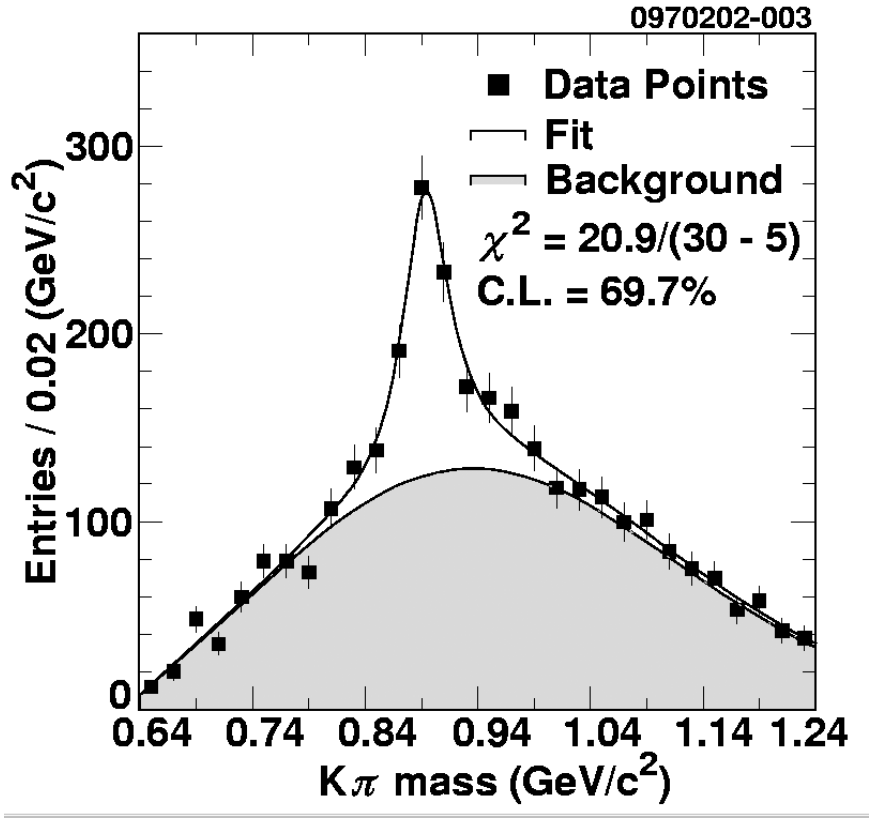


...the interference is nearly invisible in the Kπ mass plot.

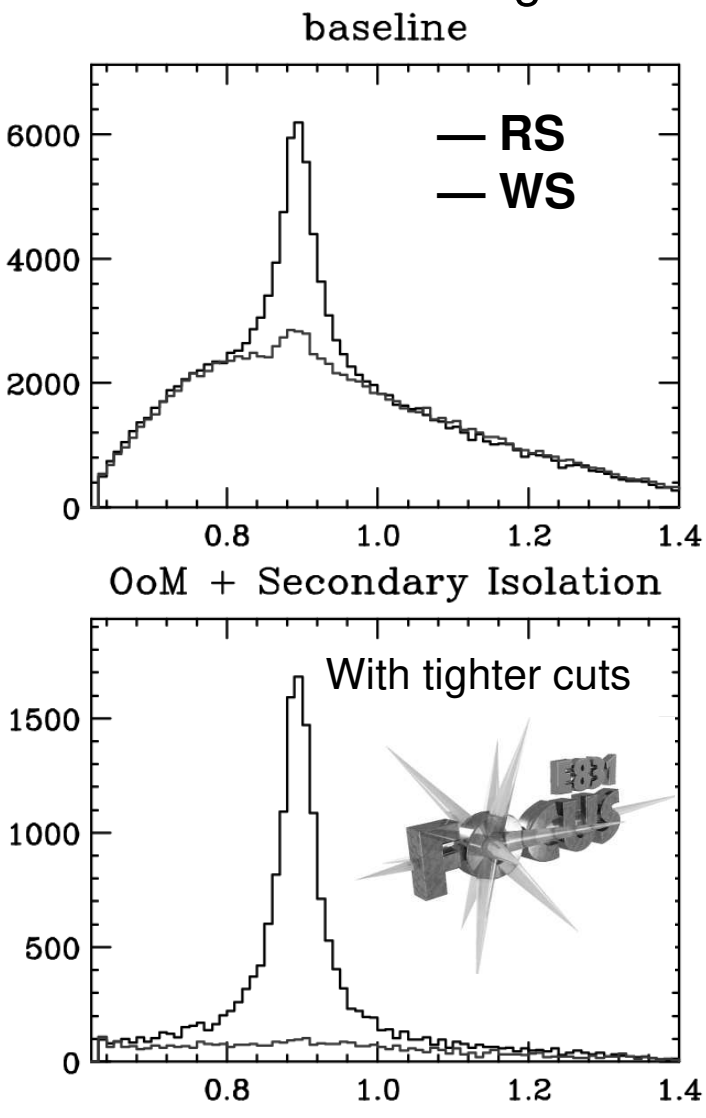
New results on $D^+ \to K^* l\nu / K2\pi$ branching ratio

CLEO (partial) signal for

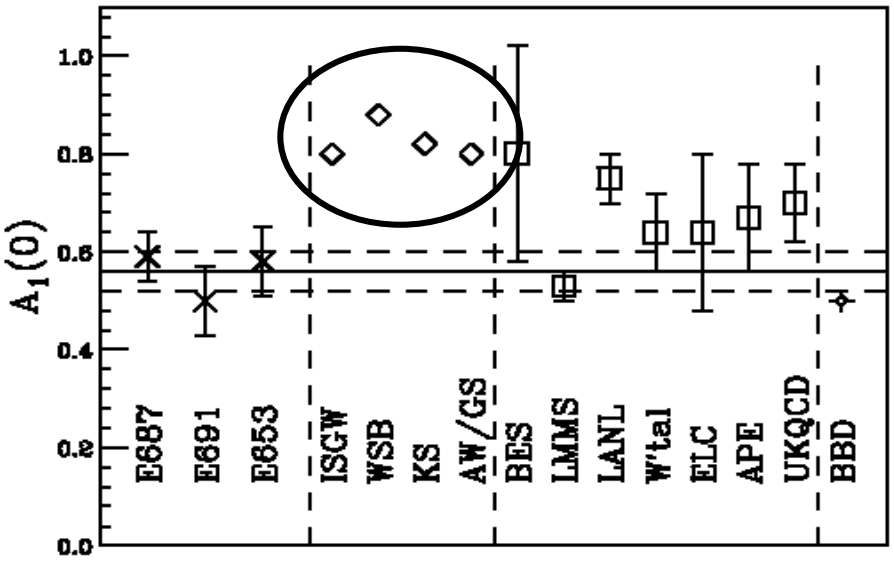
$D^{*+} \to \pi^0 D^+ \to \pi^0 (\bar{K}^{*o} e^+ \nu)$



FOCUS total signal



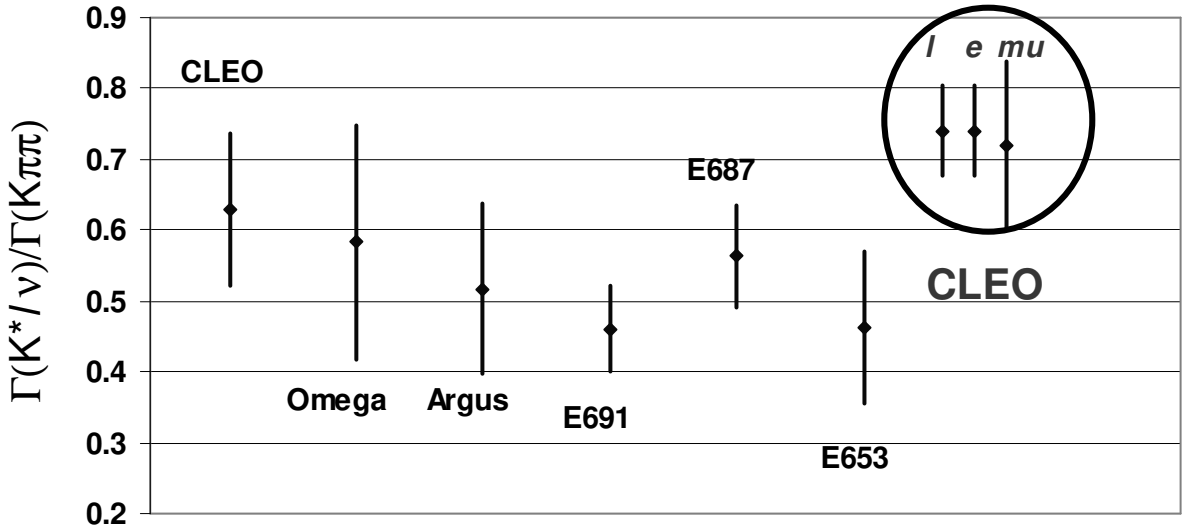
This rate is very much an open experimental and theoretical question.



Quark models predicted a

$$\Gamma\left(D^+ \to \bar{K}^{*o}\mu^+\nu\right) \propto \left|A_1(0)\right|^2$$

$\approx$ twice as high as existing data.

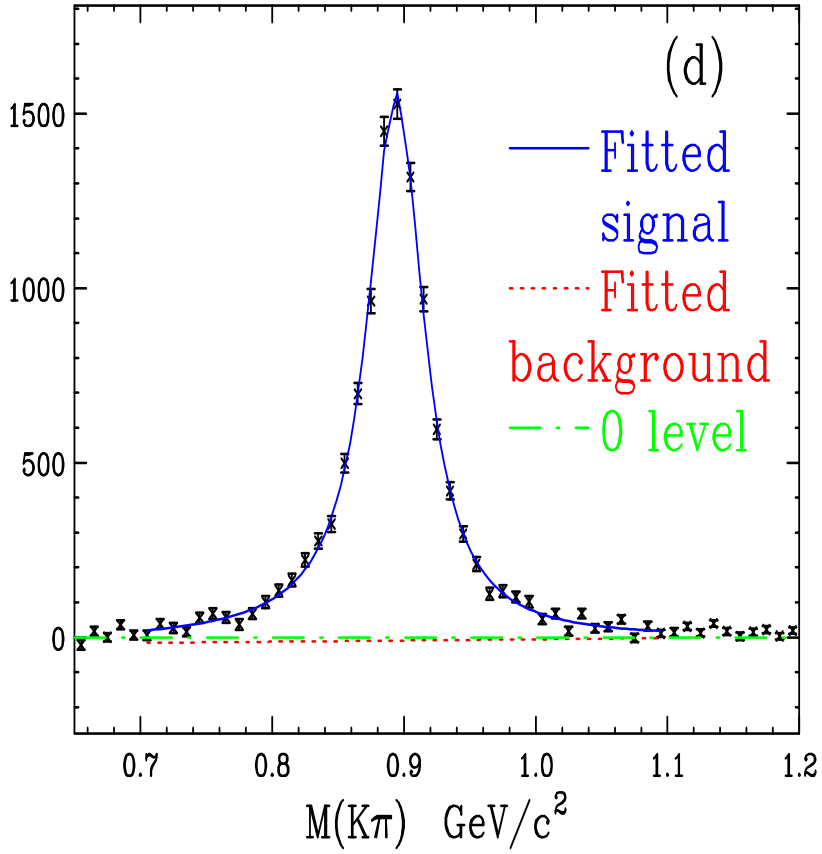


The recent CLEO numbers are higher than previous measurements.

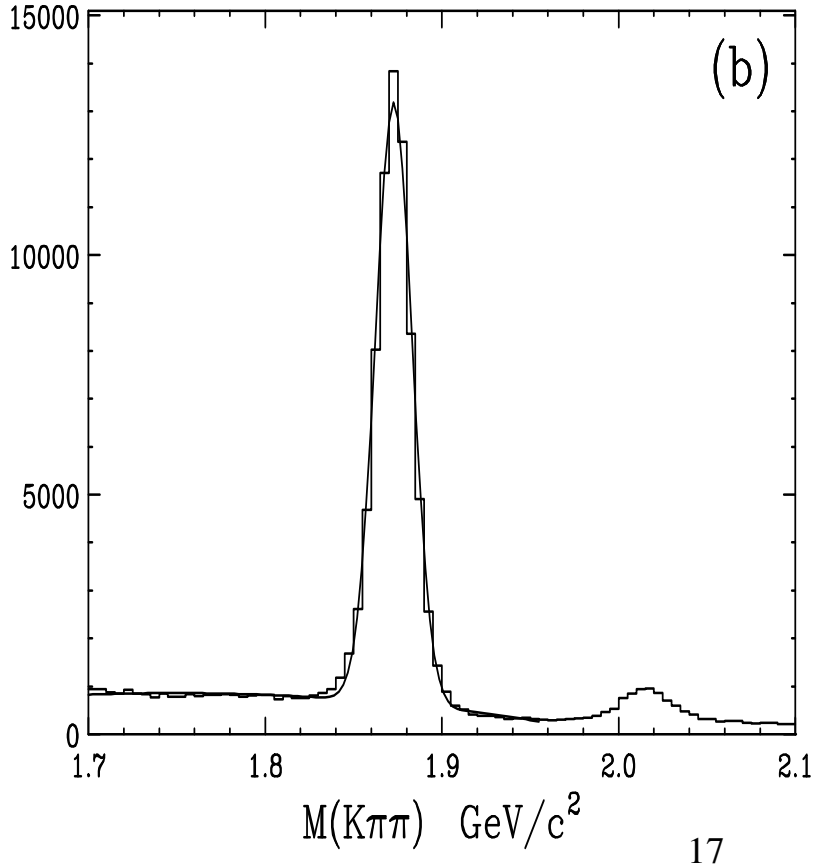
Fitted Mass Histograms for the FOCUS Data

Samples with baseline + out-of-material + secondary vertex isolation cuts.

K∗μν after subtracting wrong-sign and charm background (from MC). Backgrounds are well understood!

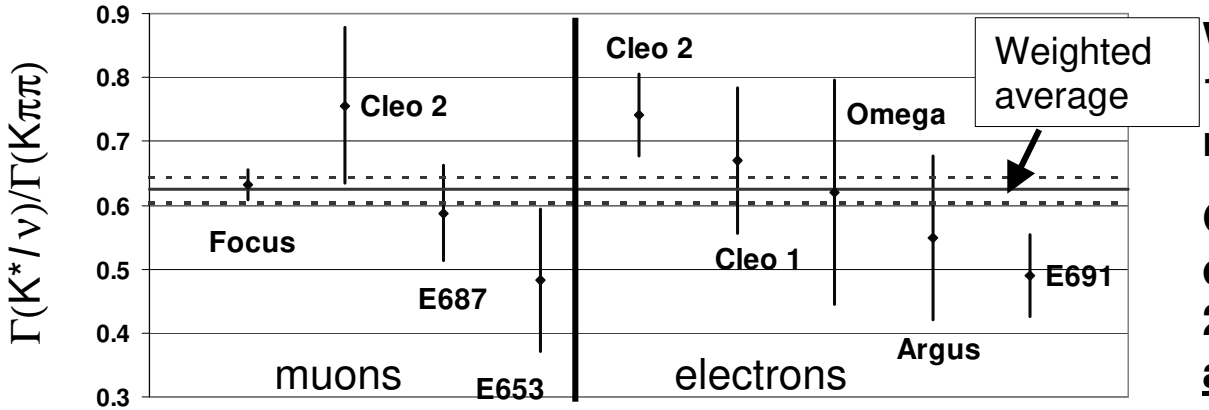


For the Kππ normalization channel it is sufficient to fit a Gaussian peak over a polynomial background.



The FOCUS Result

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



We multiply muon results by 1.05 to compare to electron results.

Our number is 1.59 standard deviations <u>below</u> CLEO and 2.1 standard deviations <u>above</u> E691.

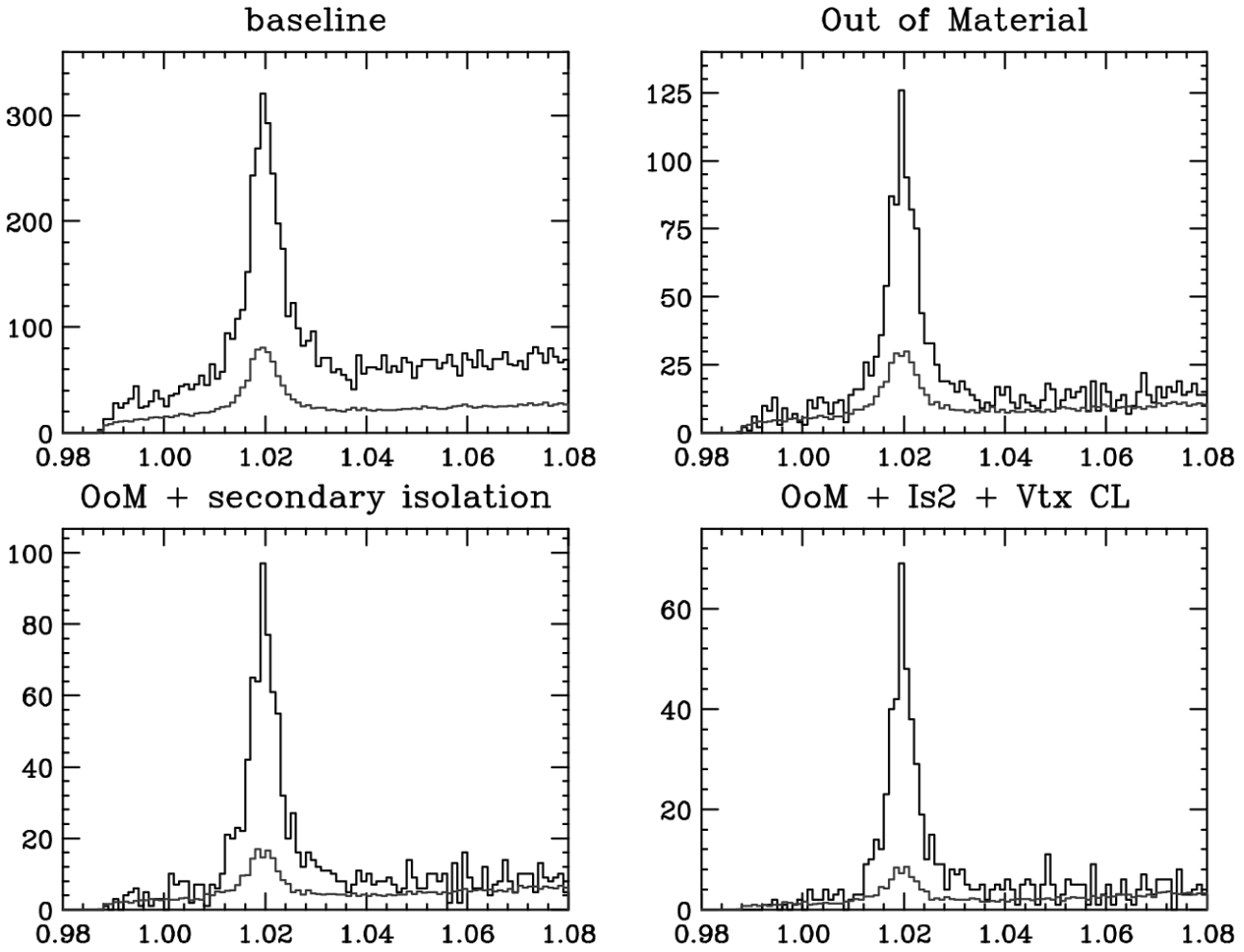
This result takes into consideration the interference phenomenon which affects the reconstruction efficiency.

New FOCUS $D_s^+ \to \phi\mu\nu/\phi\pi$ Branching Ratio

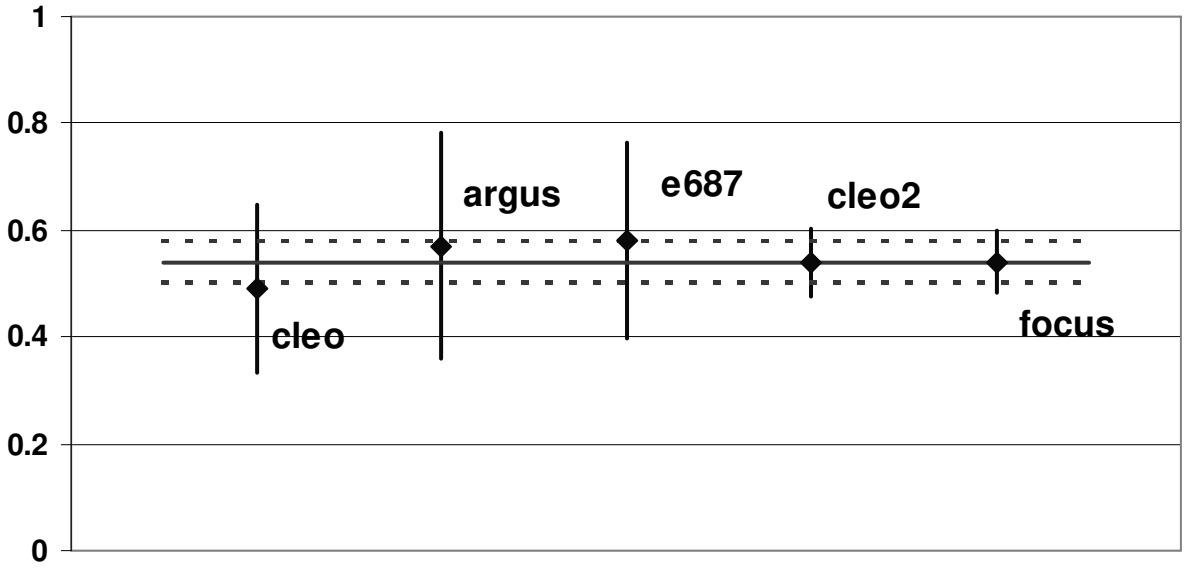
— data
— charm background MC

Once we demand a decay out of the target segments, the backgrounds are matched by our Monte Carlo.

This is a “c,cbar” MC excluding events that contain a $\phi\mu\nu$ decay.



Comparison of Results



FOCUS value is $0.54 \pm 0.033 \pm 0.048$.

There is very good agreement among experiments.

Summary

(1) S-wave interference in $\mathbf{D^+ \to K\pi\mu\nu}$ of 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 <u>small:</u>
≈7% of BW peak amplitude in the H_0 part.
≈ 6% of all $K\pi\mu\nu$ over the full $K\pi$ range

(2) $\mathbf{D^+ \to K^*\mu\nu / K2\pi}$ Branching Ratio

- New FOCUS value is $0.602 \pm 0.010 \pm 0.021$ (1.57σ lower than CLEO)

(3) $\mathbf{D_s^+ \to \phi\mu\nu / \phi\pi}$ Branching Ratio

- New FOCUS value is $0.54 \pm 0.033 \pm 0.048$

Many interesting FOCUS results are on the way

(1) $\mathbf{r_v}$ and $\mathbf{r_2}$ form factor measurements for $K^*\mu\nu$ and $\phi\mu\nu$

(2) $f(q^2)$ measurement for $\mathbf{D^0 \rightarrow K\mu\nu}$

(3) Cabibbo suppressed ratios: $\mathbf{D^+ \rightarrow \rho\mu\nu / K^*\mu\nu}$ **&** $\mathbf{D^0 \rightarrow \pi\mu\nu / K\mu\nu}$

There are probably still many surprises (such as the interference in $K\pi\mu\nu$) to be discovered in charm and beauty physics even in places where we least expect it.