Charm (meson) Semileptonic Decays

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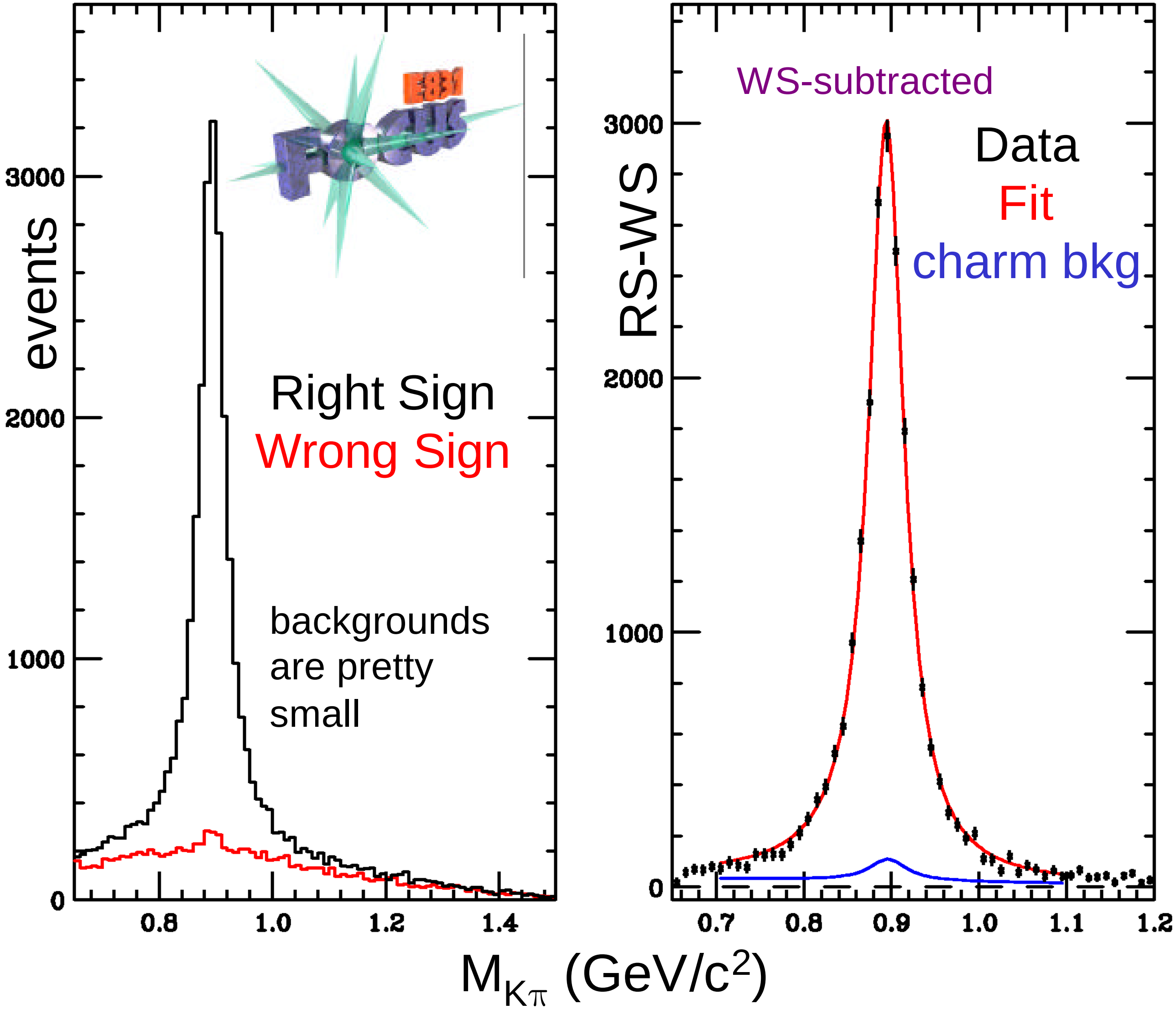
Representing FOCUS

Outline

- Interference in $D^+ \to K\pi\mu\nu$
  - FOCUS
- New $D^+ \to K^*\mu\nu / K2\pi$ BR
  - CLEO and FOCUS
- Prognosis for new SL results

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

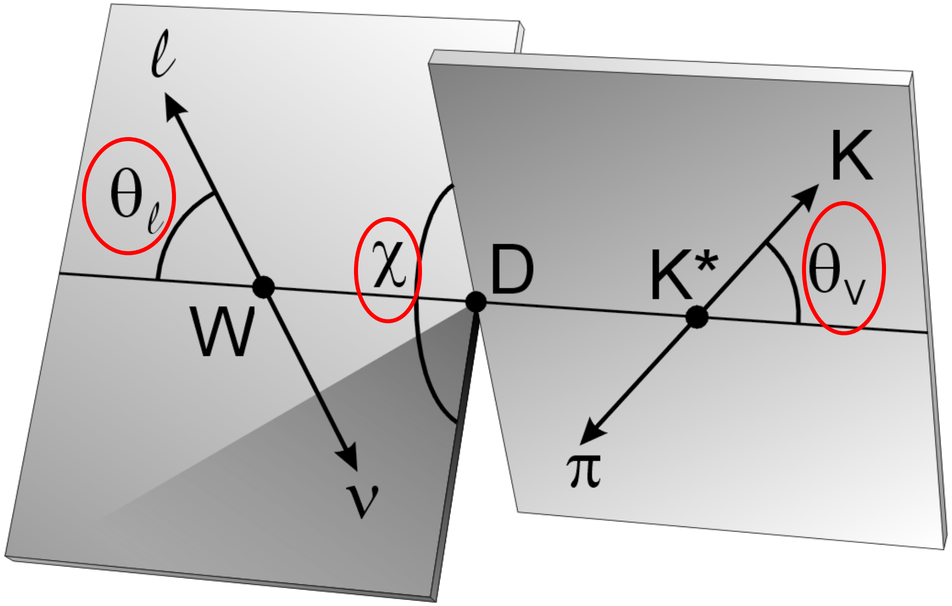


Our $K\pi$ spectrum like everyone else's looks like 100% K*(890)

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

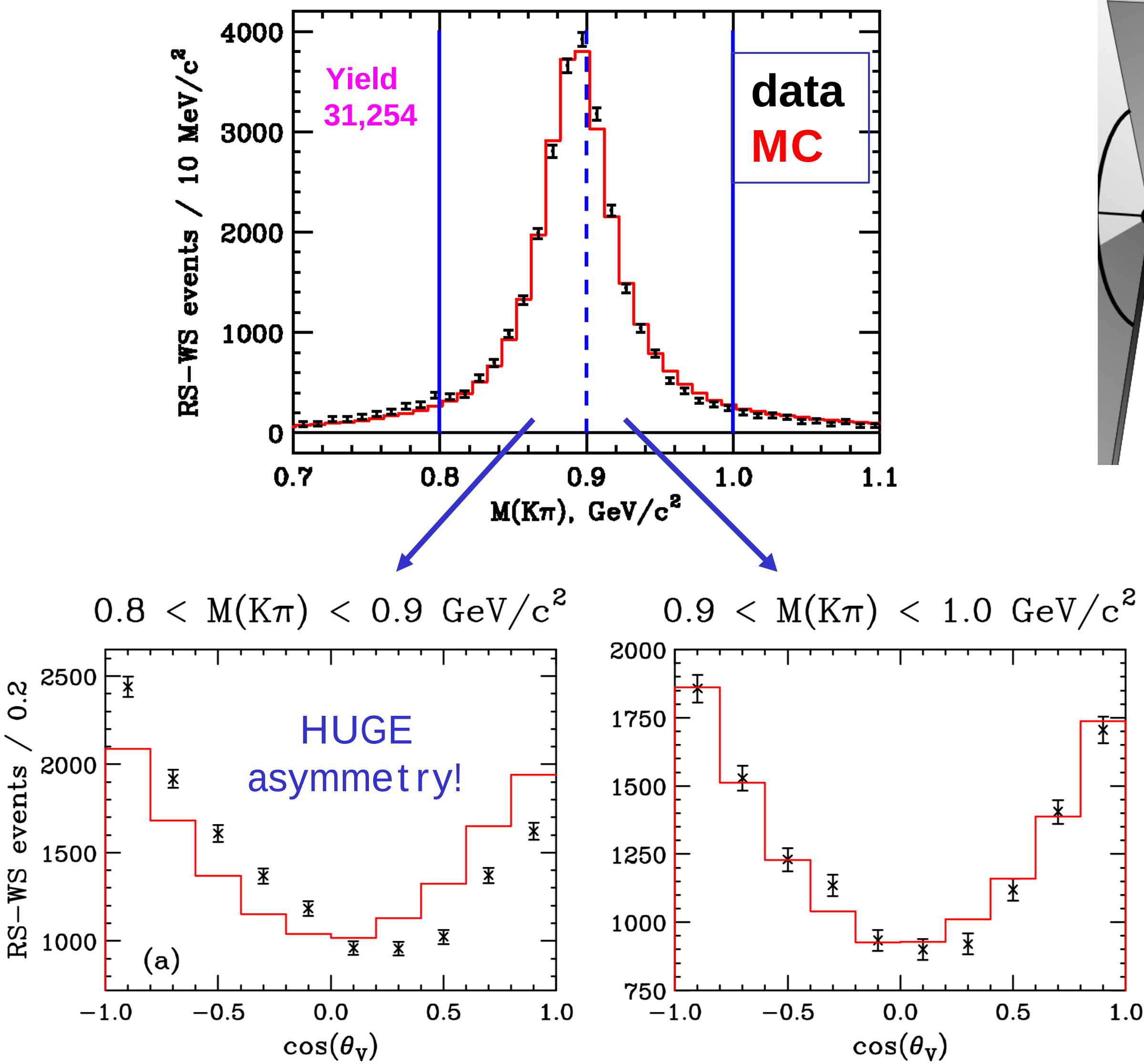
$$|A|^2 = \frac{1}{8}(t - m_l^2)\left\{ \underbrace{\left| \begin{array}{l} (1+\cos\theta_l)\sin\theta_V e^{i\chi} H_+ \\ -(1-\cos\theta_l)\sin\theta_V e^{-i\chi} H_- \\ -2\underbrace{\sin\theta_l \cos\theta_V}_{\text{Wigner D-matrices}} H_0 \end{array} \right|^2}_{} + \frac{m_\mu^2}{t} \left| \begin{array}{l}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

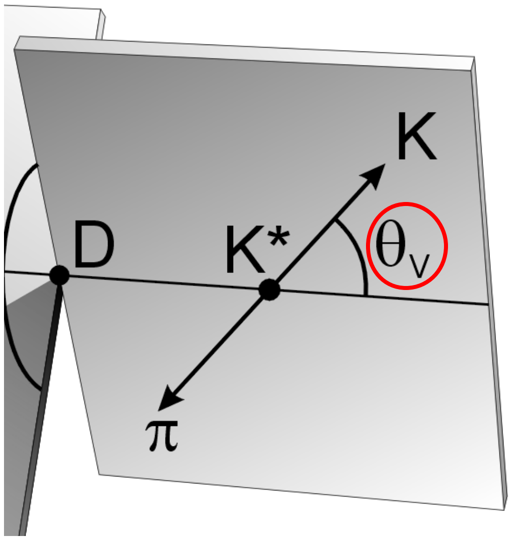
right-handed μ^+ — left-handed μ^+

("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 an forward-backward asymmetry in $\cos\theta_V$ below the K* pole, but almost none above the pole.

Sounds like QM interference

Simplest approach —
Try an interfering spin-0 amplitude

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

(plus mass terms)

$$\text{where } \mathrm{B} \equiv \frac{\sqrt{m_o\Gamma}}{m^2 - m_0^2 + im_0\Gamma}$$

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 an m=0 W^+
with amplitude H_0.

Since A << B, interference will dominate..

There will only be three terms as $m_\mu \Rightarrow 0$

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

If we average over acoplanarity we only get the first term

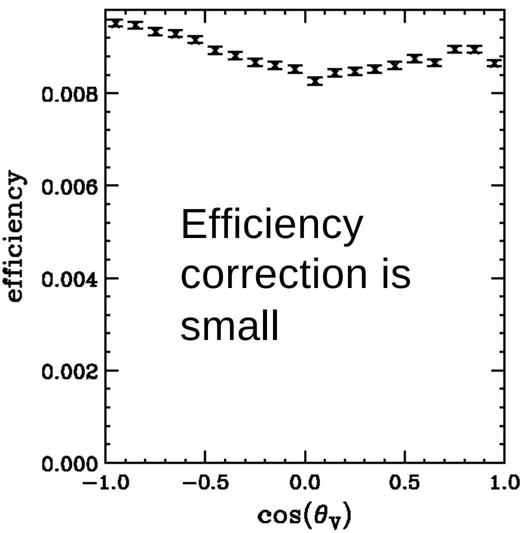
$$
8\underline{\cos\theta_V}\sin^2\theta_l A \,\mathrm{Re}\left(e^{-i\delta} B_{K^*}\right) H_0^2
$$

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



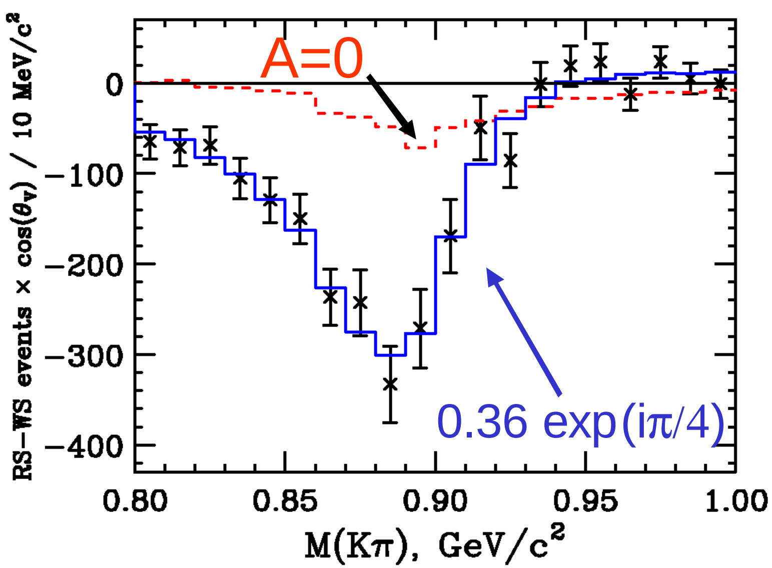
$$\boxed{+8\cos\theta_V\ \sin^2\theta_l A\,\mathrm{Re}\left(e^{-i\delta}B_{K^*}\right)H_0^2}$$

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

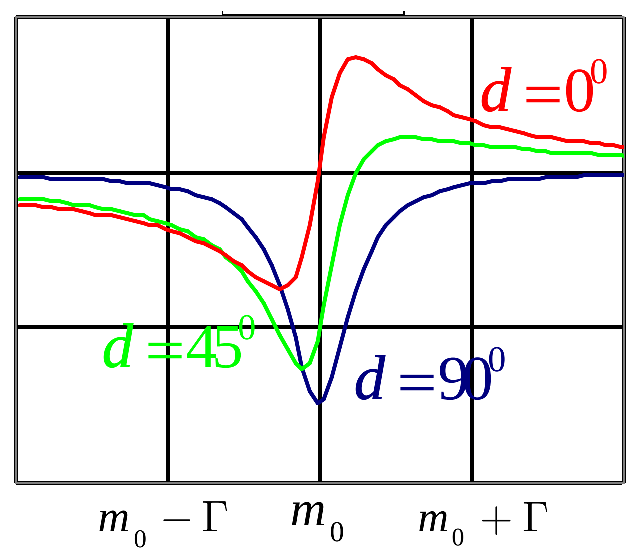
Since all other χ-averaged terms in the decay intensitty are constant or $\cos^2\theta_V$.

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

Our weighted mass distribution..



..looks just like the calculation.



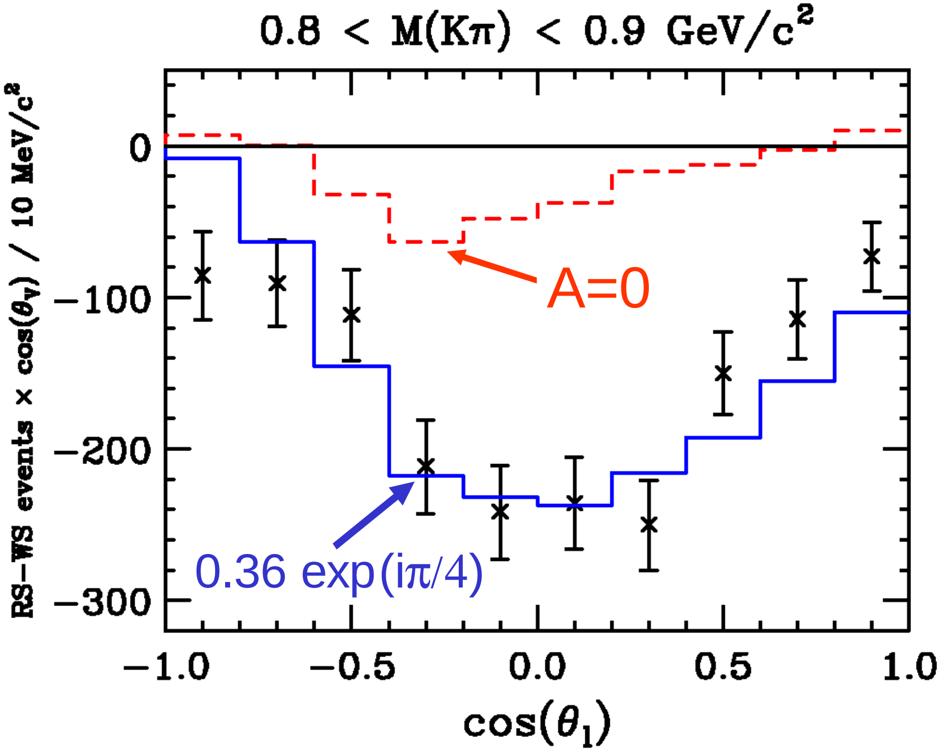
A constant 45^0 phase works great...

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

Dependence of asymmetry on cosθ_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 θ_l and expect a parabola in $\cos^2\theta_l$ since $\sin^2\theta_l = (1 - \cos^2\theta_l)$

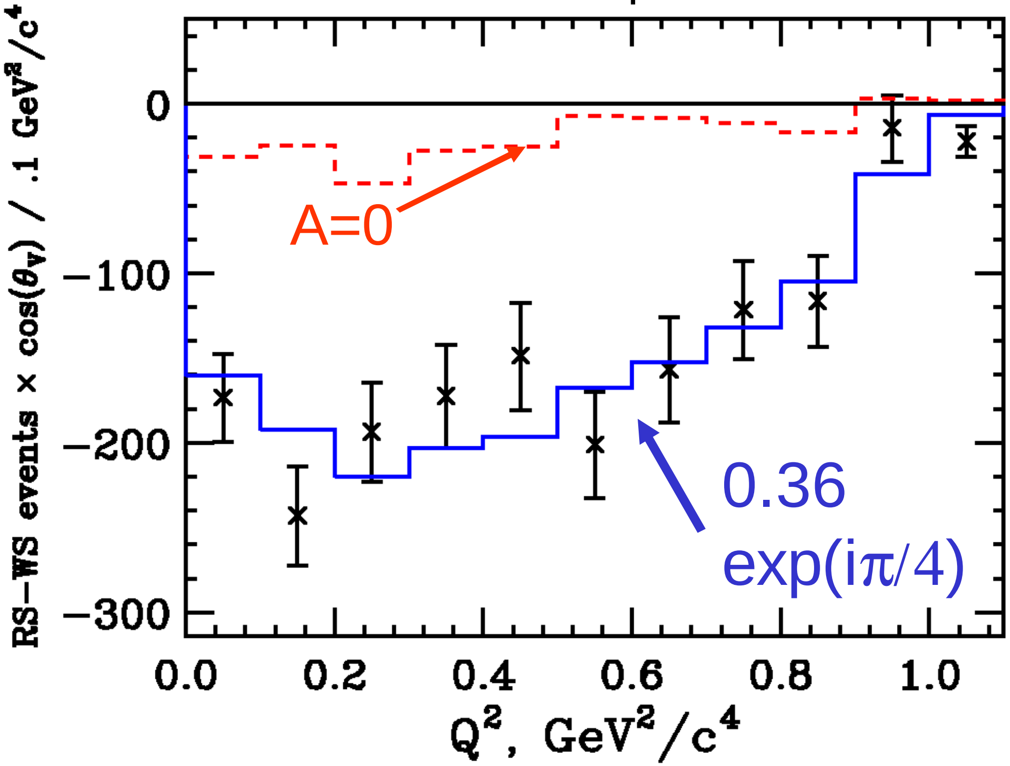


Looks $\propto -(1 - \cos^2\theta_l)$. Some modulation due to efficiency and resolution

q^2 dependence of asymmetry

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

Below the pole



Acoplanarity dependent interference terms

The interference adds two new terms to the acoplanarity dependence.

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

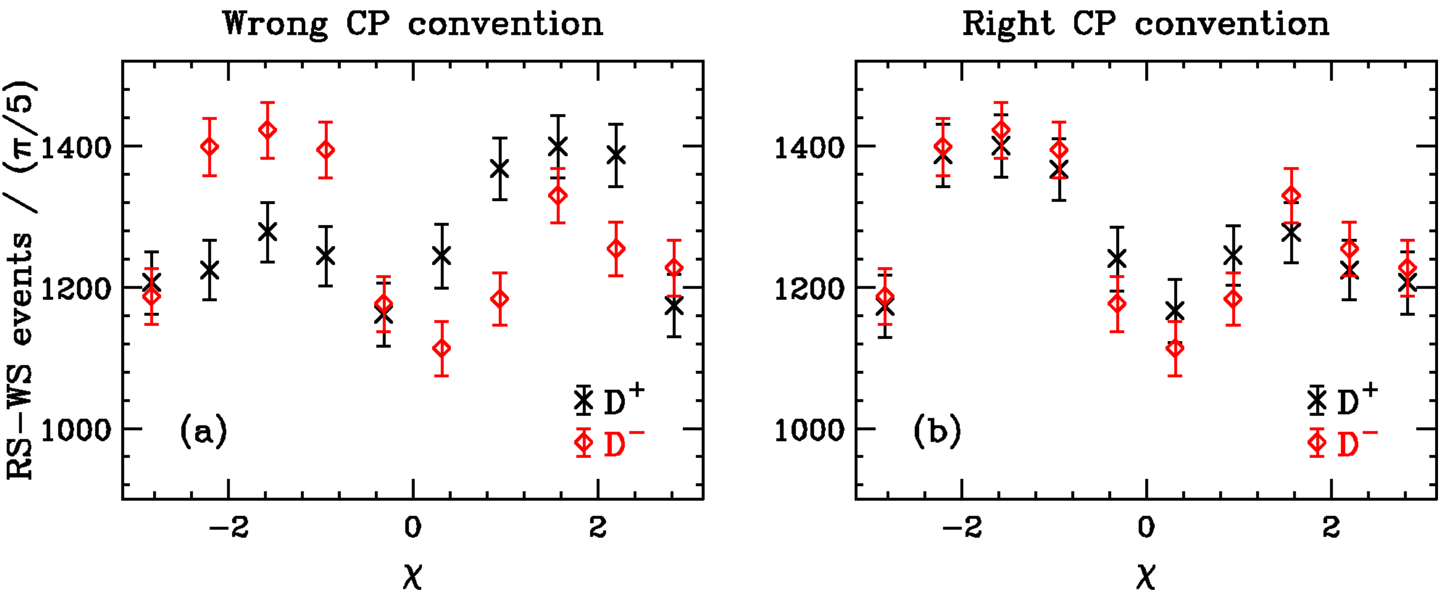
$$+4(1-\cos\theta_l)\sin\theta_l\,\sin\theta_V A\,\mathrm{Re}(B_{K^*}e^{-i(\chi+\delta)})H_-H_0$$

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 -**χ symmetry

Our first brush with sinχ was frightening!

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



$D^{+} \rightarrow K^{-} p^{+} m^{+} n$

$D^{-} \rightarrow K^{+} p^{-} m^{-} \overline{n}$

Same sign convention used for D+ and D-

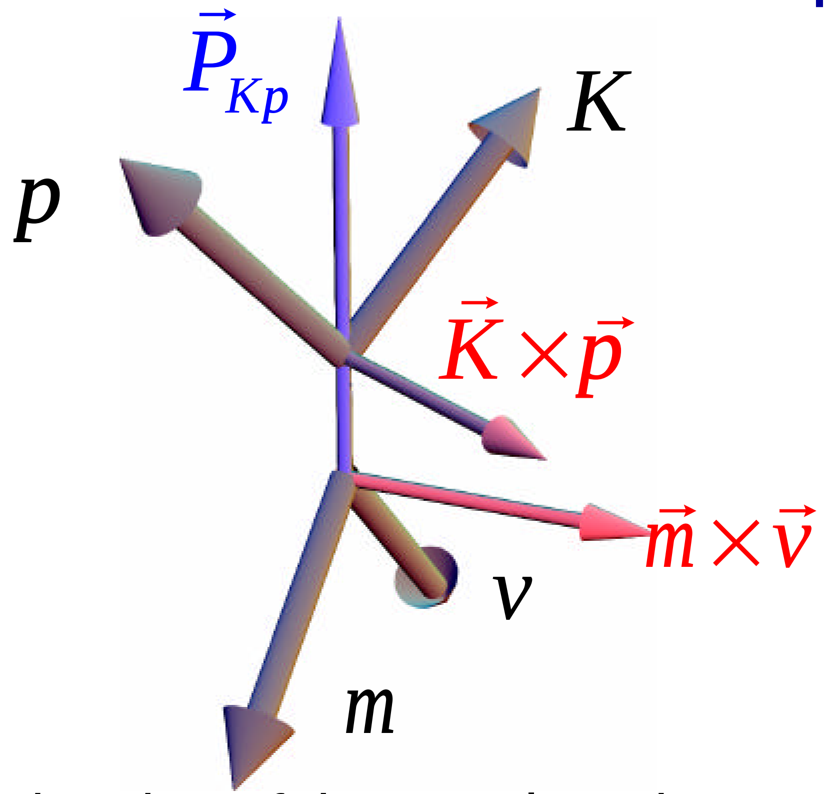
Yikes! CP violation?

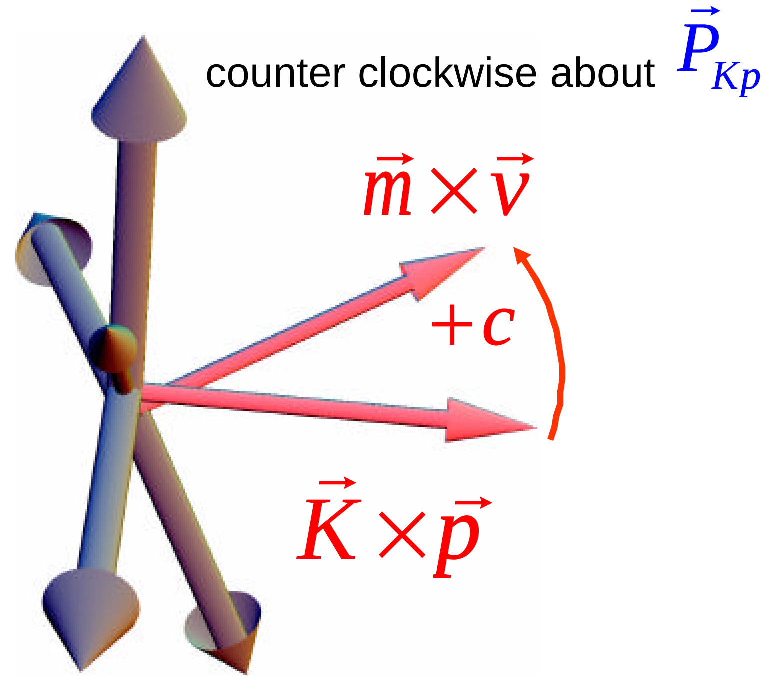
Opposite sign convention used for D+ versus D-

Interference with the new amplitude breaks χ to -χ symmetry.

When CP is handled properly, the D+ and D- acoplanarity distributions become consistent.

The correct acoplanarity convention



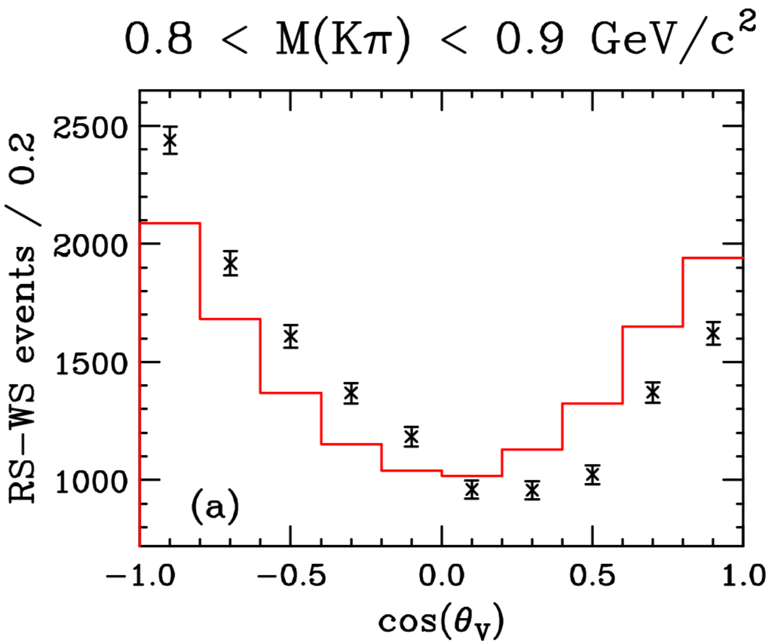


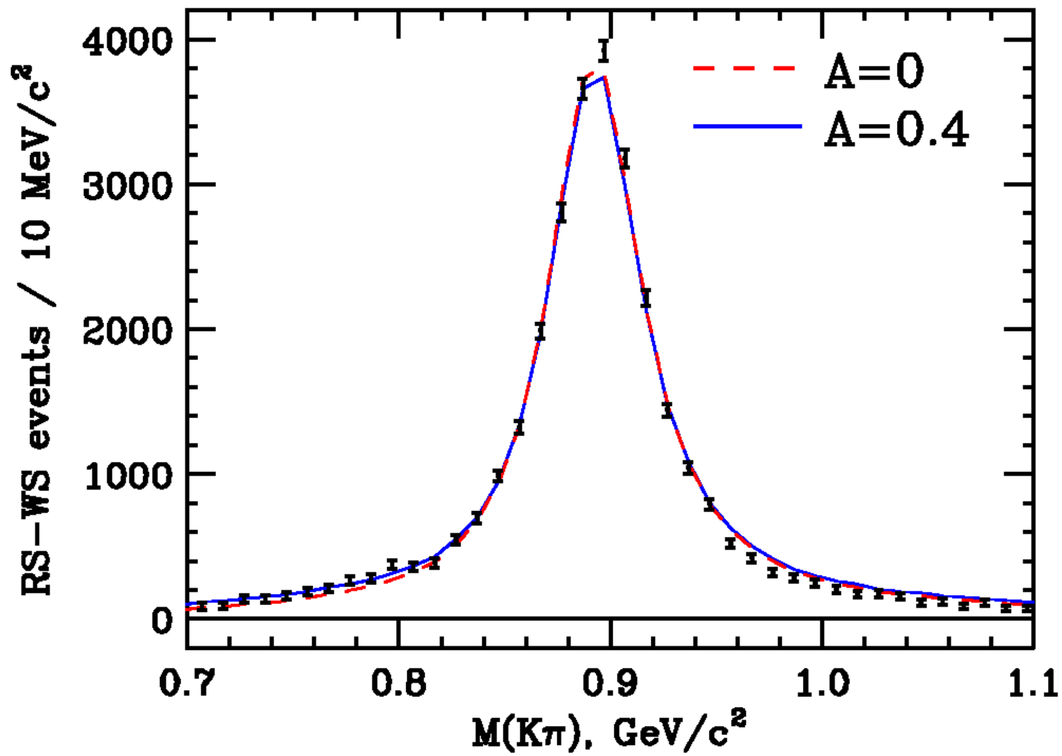
The sine of the acoplanarity requires 5 vectors to specify

$$\sin c = \frac{\vec{P}_{Kp} \cdot \left[\left(\vec{K}\times\vec{p}\right)\times\left(\vec{m}\times\vec{n}\right)\right]}{|\vec{P}_{Kp}|\,|\vec{K}\times\vec{p}|\,|\vec{m}\times\vec{n}|}$$

Under CP : D+ => D- , all 5 vectors will reverse as will sin χ under our convention. Interference produces a “false” CP violation between the acoplanarity distribution between D+ versus D- unless we explicitly take χ to $-\chi$

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





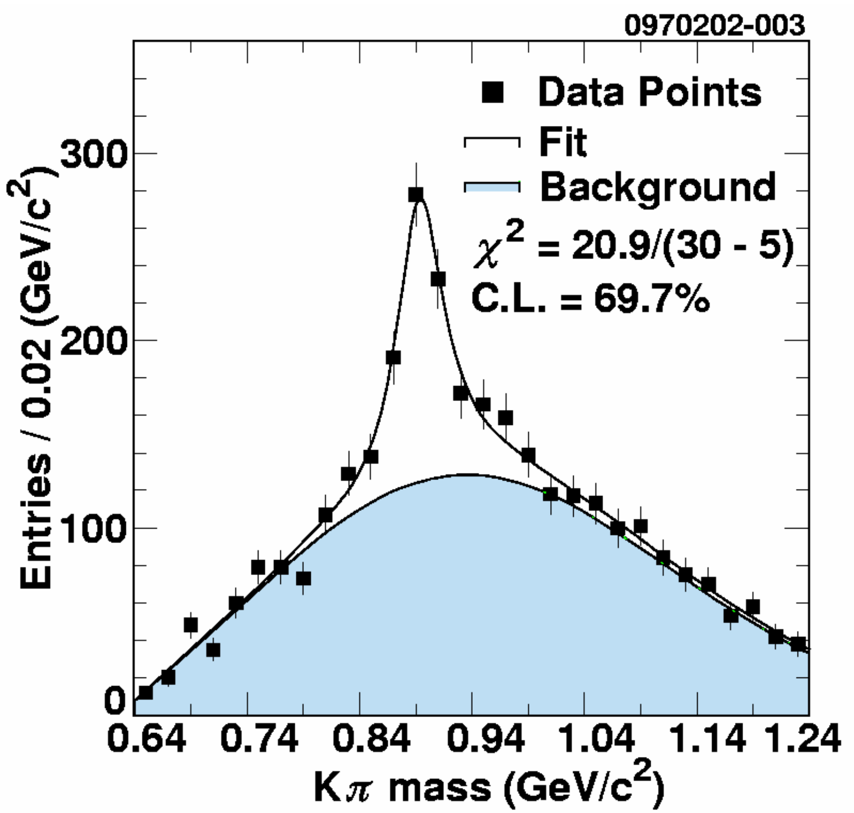
Although the interference *significantly* distorts the decay intensity....

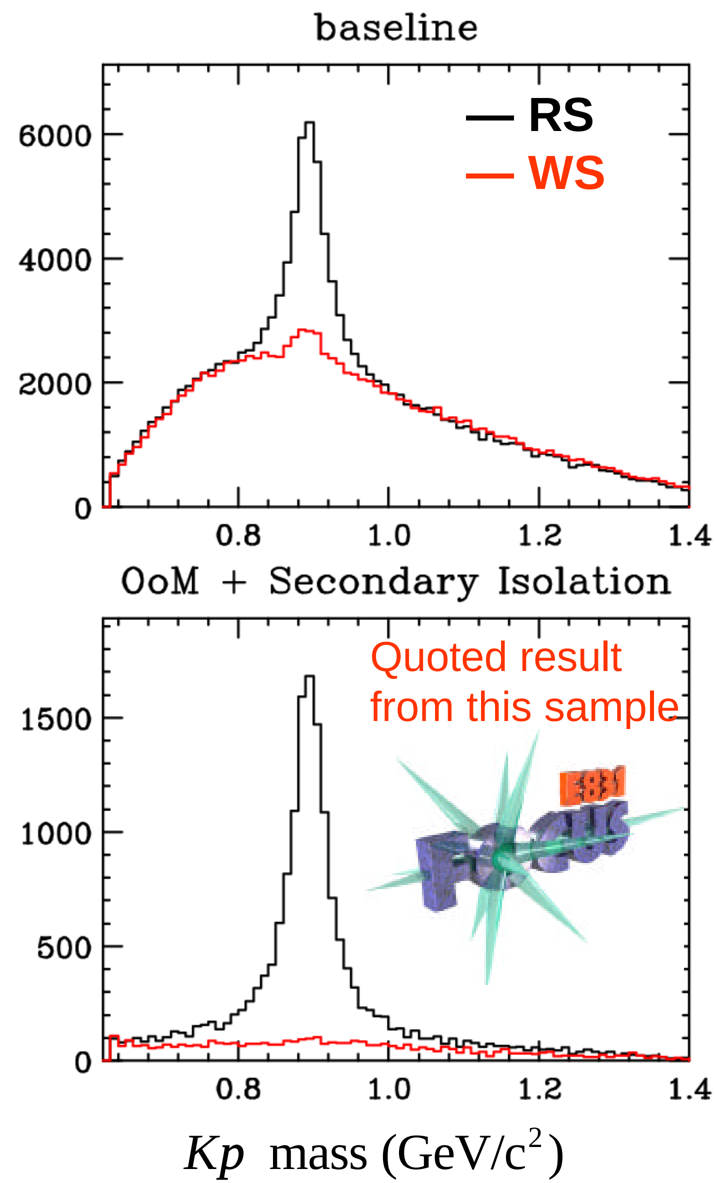
...the interference is nearly invisible in the Kp mass plot.

New results on D⁺ → K∗μν/K2π branching ratio

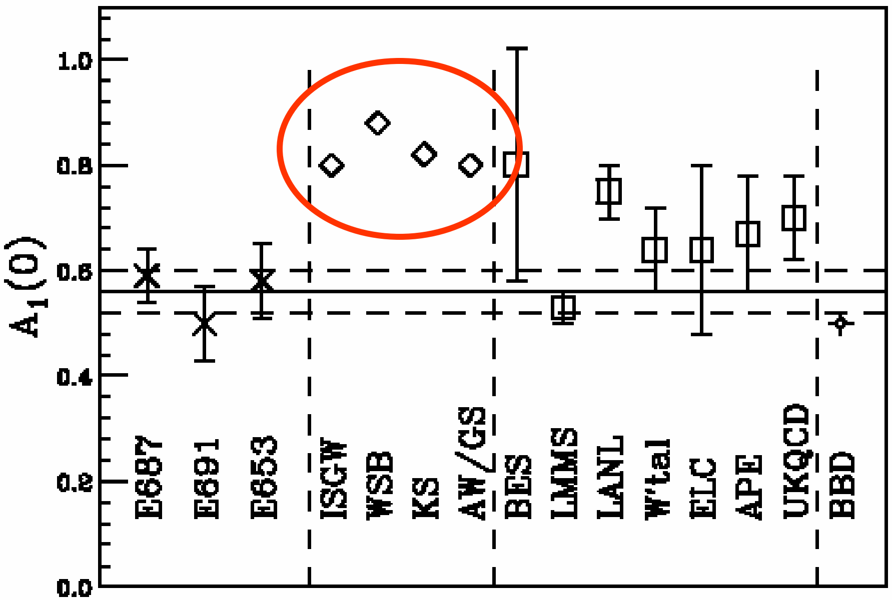
CLEO (partial) signal for

$$D^{*+} \rightarrow p^0 D^+ \rightarrow p^0(\bar{K}^{*o} e^+ n)$$





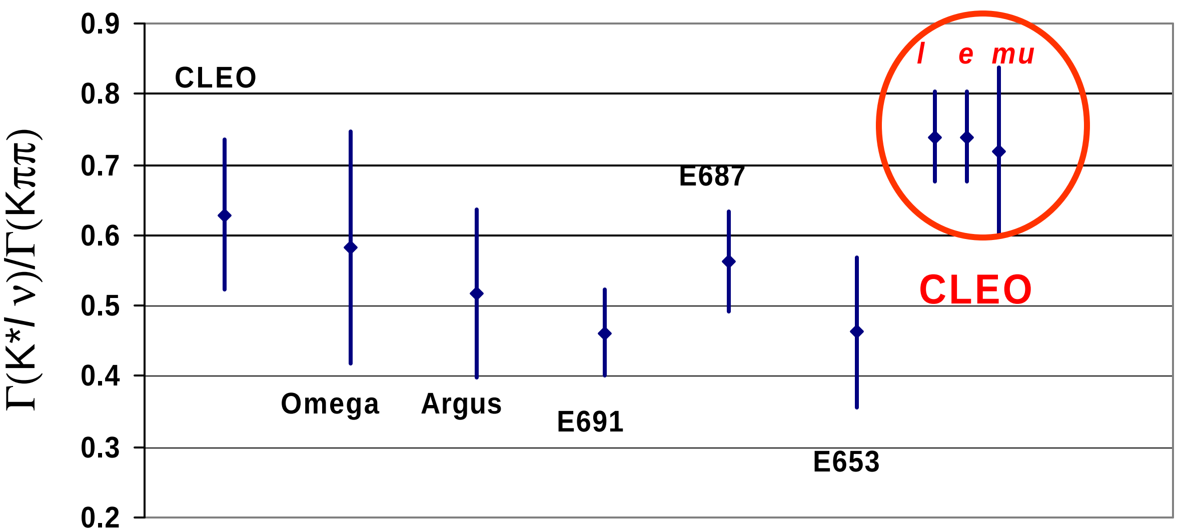
The CLEO result might resolve an old problem



Quark models predicted a

$$\Gamma\left(D^{+} \rightarrow \bar{K}^{*o} m^{+} n\right) \propto \left|A_{1}(0)\right|^{2}$$

≈ twice as high as existing data.

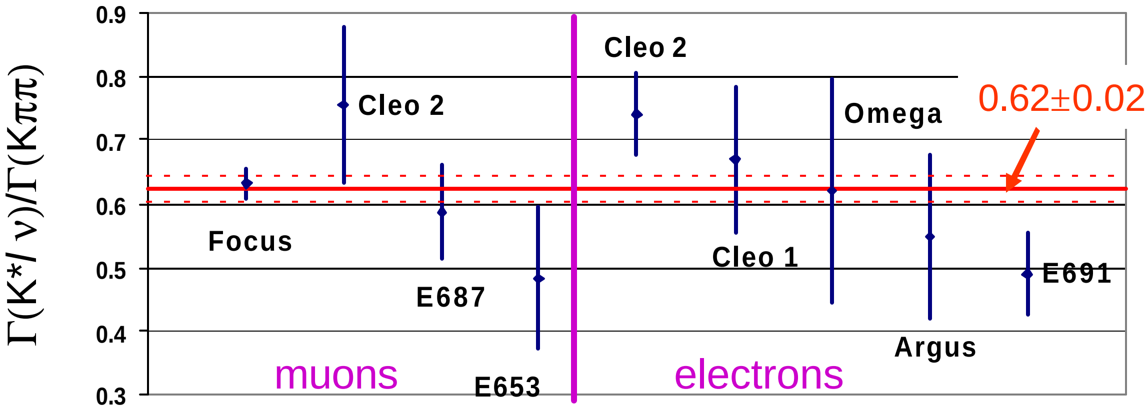


The recent CLEO number raises this width considerably .. thus partially resolving this long standing problem.

The preliminary FOCUS result

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

Still under study!



We multiply muon results by 1.05 to compare to electron results

Our preliminary number is 1.59 standard deviations below CLEO and 2.1 standard deviations above E691

PRELIMINARY

Summary

(1) S-wave interference in **D⁺ ® K**pmn of form

$$|H_0|^2 \left| 0.36\exp\left(i\frac{p}{4} \right) + \frac{\cos q_{\mathrm{v}} \sqrt{\mathrm{m}_0 \Gamma}}{(m - m_o)^2 + i m_0 \Gamma} \right|^2$$

The new amplitude is <u>small:</u>
≈7% of BW peak amplitude in the H_0 part.
≈ 6% of all Kπμν over the full Kπ range

(2) New results on **D⁺ ® K***mn**/K2**p

- CLEO value 0.74 ± 0.04 ± 0.05 (is higher than previous data)
- FOCUS <u>preliminary</u> value is 0.60 ± 0.01 ± 0.02 (1.57σ lower than CLEO)

(3) Many interesting results are on the way:

- New measurements of $\mathbf{D_s^+}$ ® fmn/ fp
- New $\mathbf{r_v}$ and $\mathbf{r_2}$ form factor measurements for K*μν and ϕμν
- f(q²) measurement for **D⁰ ® K**mn
- Cabibbo suppressed ratios: **D⁺ ®** rmn**/K***mn **& D⁰ ®** pmn**/K**mn

$\phi\mu\nu$ BR — work in progress

— data

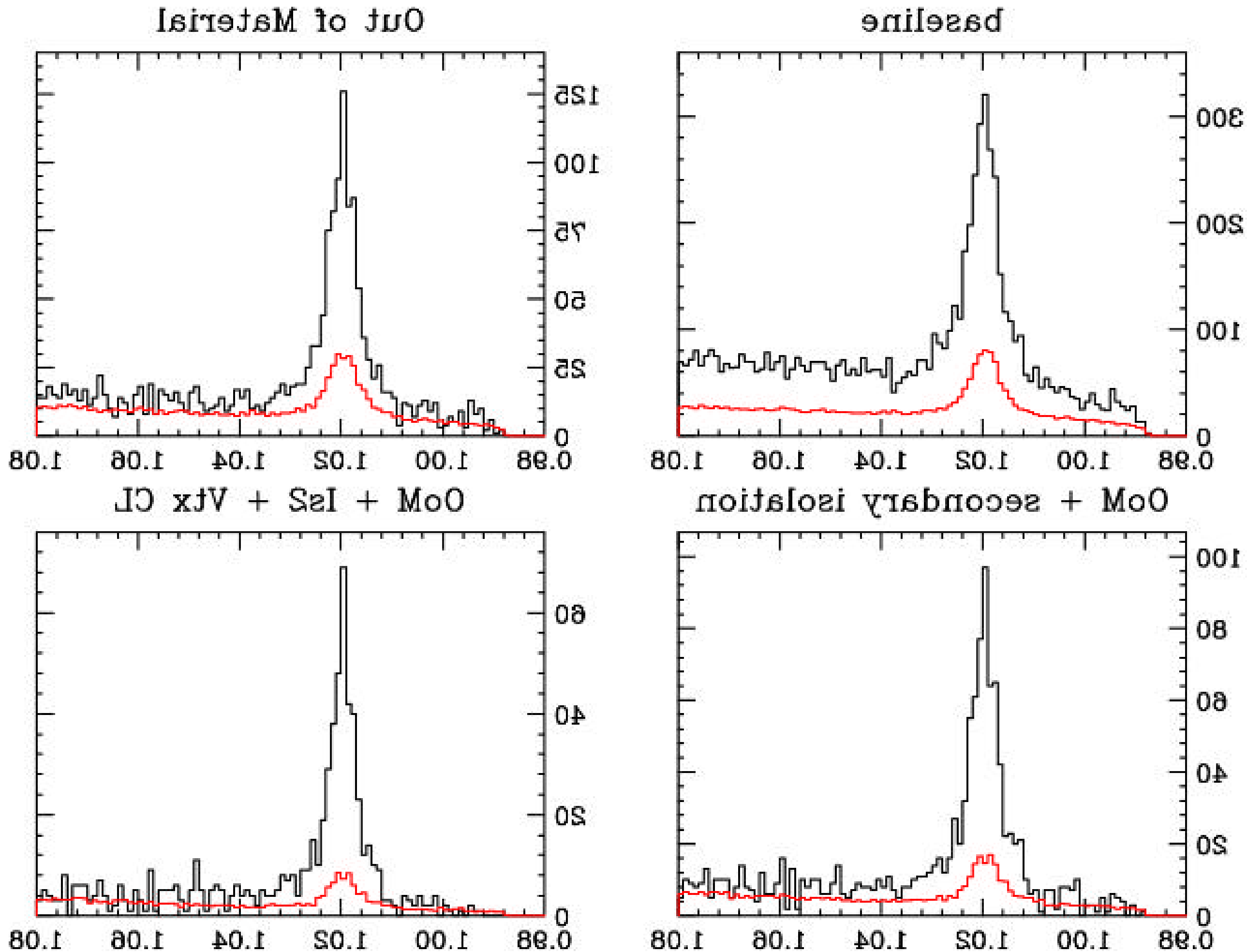
— charm background MC

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

This is a "c,cbar" MC with events containing a $\phi\mu\nu$ decay excluded.

Work is being done on the branching ratio measurement, and I hope to work on the form factor measurement.

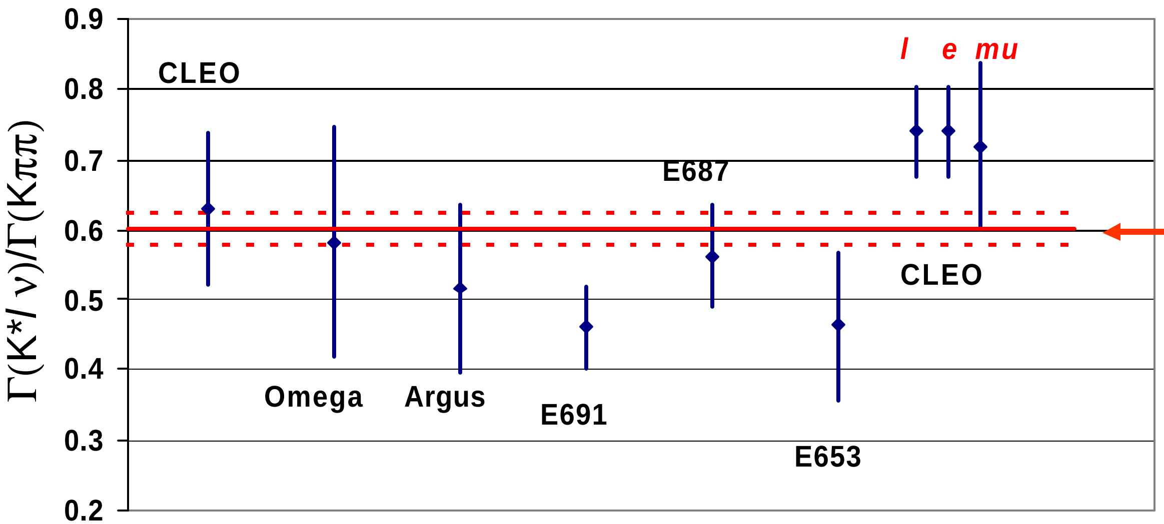
Perhaps we will see interference with the $f_0(980)$?



Question slides

The preliminary FOCUS result

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



FOCUS preliminary (uses the S-wave MC)

If we were to multiply the FOCUS muon result by 1.05 to compare with CLEO electrons, CLEO would still lie 1.59 standard deviations above FOCUS

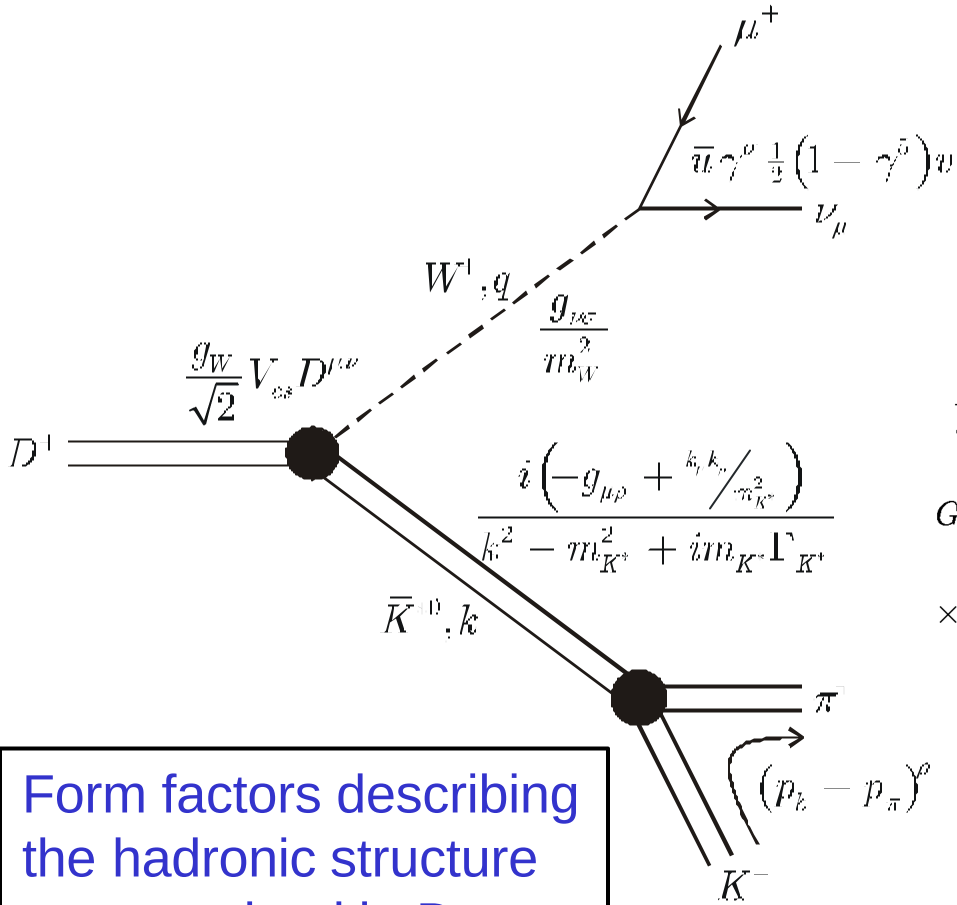
PRELIMINARY

Observation of interference in D+ semileptonic decay into K* μ ν

- I intended to measure several semileptonic form factors as a thesis
  - $D^+ \to K^{*0} \mu \nu$ was intended as training exercise for the more controversial $D_s^+ \to \phi \mu \nu$
- We could *not* get good confidence level fits on $K^{*0} \mu \nu$, even after exhaustive checks of MC and possible backgrounds
  - Known backgrounds were small and benign (in form factor variables)
  - The Monte Carlo simulated both resolution and acceptance well.
- We then made a crucial observation that led to an explicit interference model
  - The model is described by only a single amplitude and phase
  - The model explained the discrepancies between the data and the fit.
  - And suggested numerous new places to search for interference

The decay rate via Feynman rules

- Assuming the Kπ spectrum contains nothing but K*, the decay rate is straight-forward



H$_+$, H$_0$, H$_-$ are helicity-basis form factor amplitudes.

Form factors describing the hadronic structure are contained in $D^{\mu\nu}$

$$\frac{d^4\Gamma}{dM_{K\pi}^2\ dt\ dcos\theta_v\ dcos\theta_\mu} =$$

$$G_F^2|V_{cs}|^2 \frac{3}{2(4\pi)^5} \frac{M_{K^*}}{M_D^2 M_{K\pi}} \frac{M_{K^*}\Gamma}{(M_{K\pi}^2 - M_{K^*}^2)^2 + M_{K^*}^2\Gamma^2} Kt\left(1 - \frac{m_\mu^2}{t}\right)^2$$
$$\times \left[\text{diagonal terms} + \text{cross terms} + \frac{m_\mu^2}{t}(\text{mass terms})\right]$$

$$\text{diagonal terms} = \sin^2\theta_v \ \left((1+\cos\theta_\mu)^2\ |H_+(t)|^2 + (1-\cos\theta_\mu)^2\ |H_-(t)|^2\right) + 4\cos^2\theta_v \sin^2\theta_\mu\ |H_0(t)|^2$$

$$\begin{aligned}\text{cross terms} = \ & -2\sin^2\theta_v \sin^2\theta_\mu \cos 2\chi\ \mathcal{R}\mathrm{e}(H_+^* H_-) \\ & -4\sin\theta_v\cos\theta_v\sin\theta_\mu(1+\cos\theta_\mu)\cos\chi\ \mathcal{R}\mathrm{e}(H_+^* H_0) \\ & +4\sin\theta_v\cos\theta_v\sin\theta_\mu(1-\cos\theta_\mu)\cos\chi\ \mathcal{R}\mathrm{e}(H_-^* H_0)\end{aligned}$$

Decay rate as an amplitude

Written as an |amplitude|^2, the decay rate is much more simple and intuitive:

$$\frac{d^4\Gamma}{dM^2_{K\pi}\ dt\ dcos\theta_v\ dcos\theta_\mu} = G_F^2|V_{cs}|^2 \frac{3}{2(4\pi)^5}\frac{M_{K^*}}{M_D^2 M_{K\pi}}\frac{M_{K^*}\Gamma}{(M^2_{K\pi}-M^2_{K^*})^2+M^2_{K^*}\Gamma^2} K|A|^2$$

right-handed μ^+

left-handed μ^+ ("mass terms")

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

~2%

Wigner D-matrices

internal sum over W polarization

$$H_\pm(t) = (M_D+M_{K\pi})A_1(t) \mp 2\frac{M_D K}{M_D+M_{K\pi}}V(t)$$

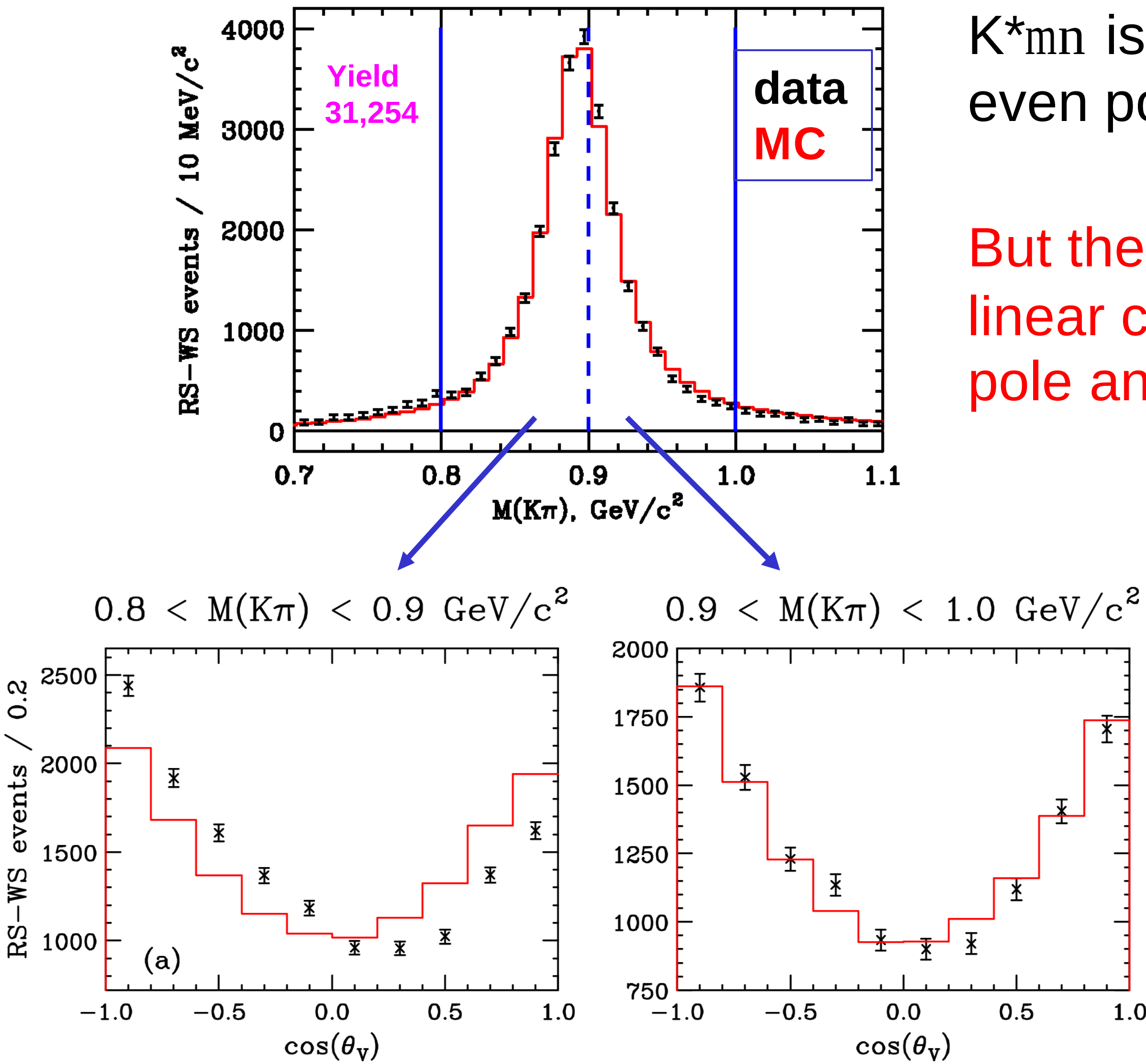
$$H_0(t) = \frac{1}{2M_{K\pi}\sqrt{t}}\left[(M_D^2-M_{K\pi}^2-t)(M_D+M_{K\pi})A_1(t) - 4\frac{M_D^2K^2}{M_D+M_{K\pi}}A_2(t)\right]$$

$$A_i(t) = \frac{A_i(0)}{1-t/M_A^2} \qquad V(t) = \frac{V(0)}{1-t/M_V^2} \qquad r_v \equiv V(0)/A_1(0),\ r_2 \equiv A_2(0)/A_1(0)$$

Form factor details from Feynman calculus

Rich + detailed kinematic structure! Angular distributions are highly correlated.

A problem with K*lν form factor fits!

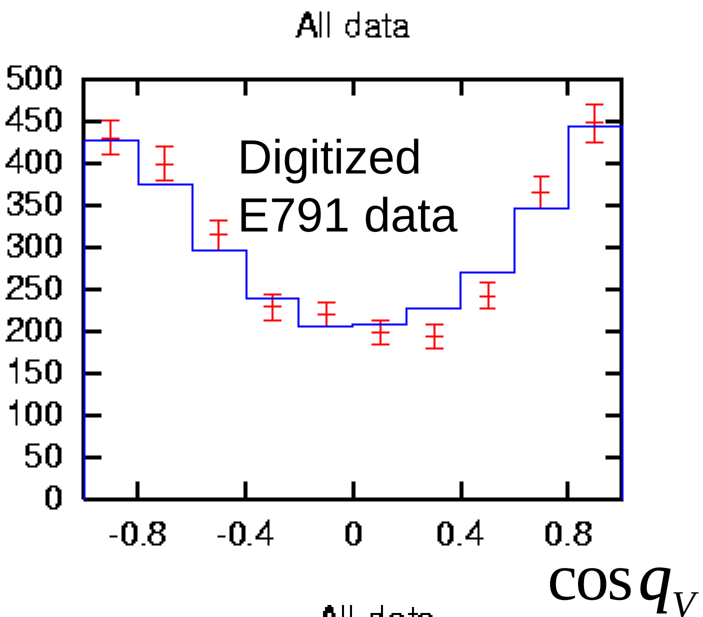


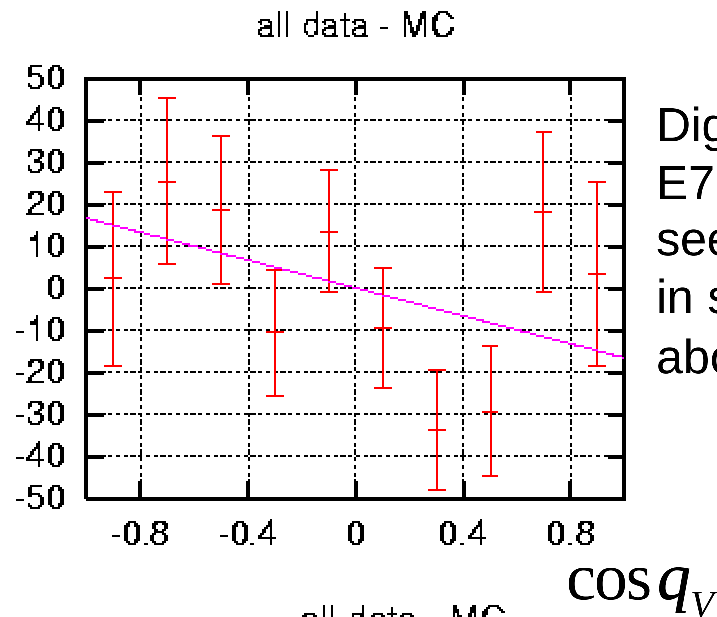
K*mn is supposed to have just even power terms of cos θ_v

But the data seemed to require a linear cos θ_v term below the K* pole and none above the pole.

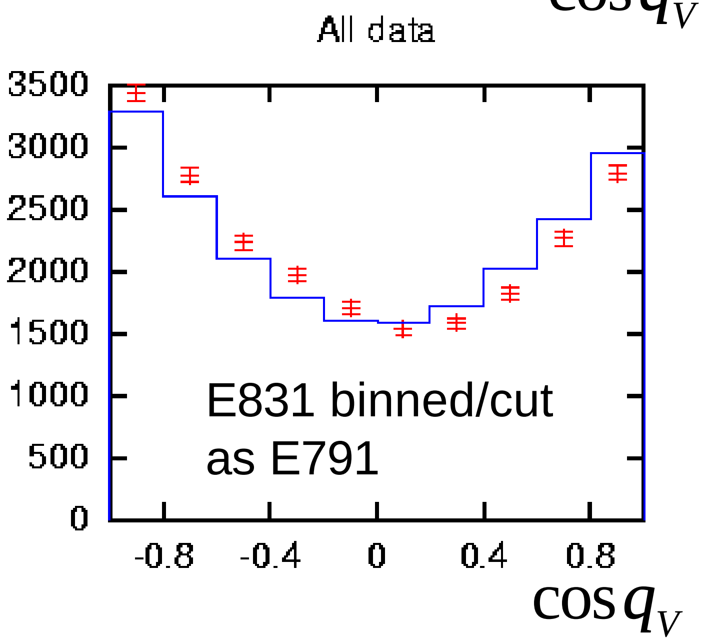
We hit upon an interference explanation for a linear cos θ_v with a dramatic mass dependence.

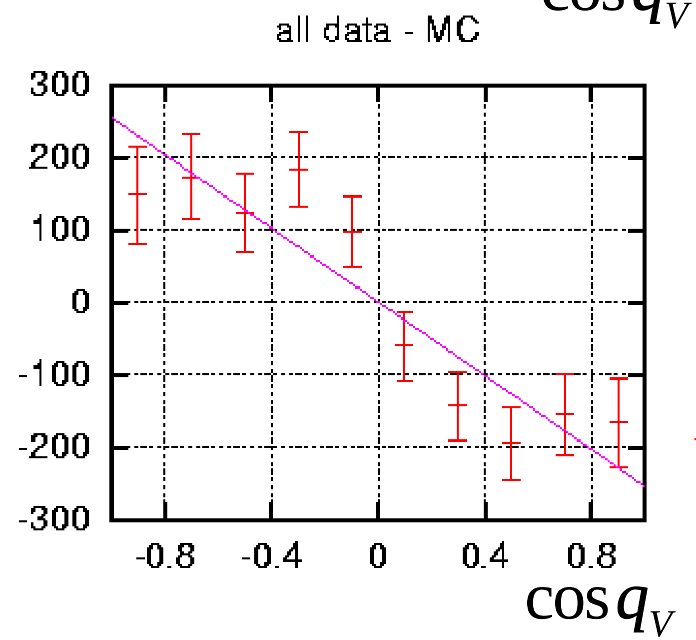
Did E791 see it?





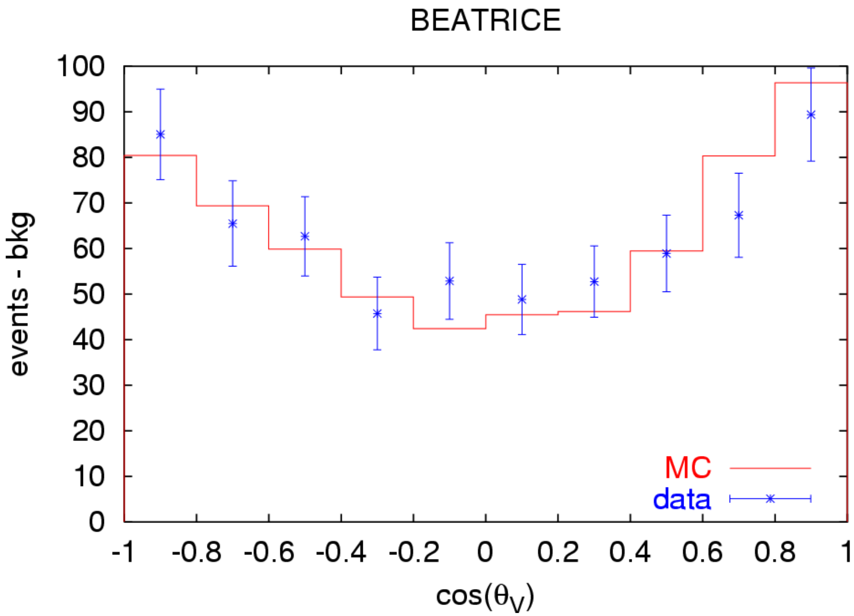
Digitized data from E791 paper. They see an asymmetry in same direction at about 1.5 σ level.

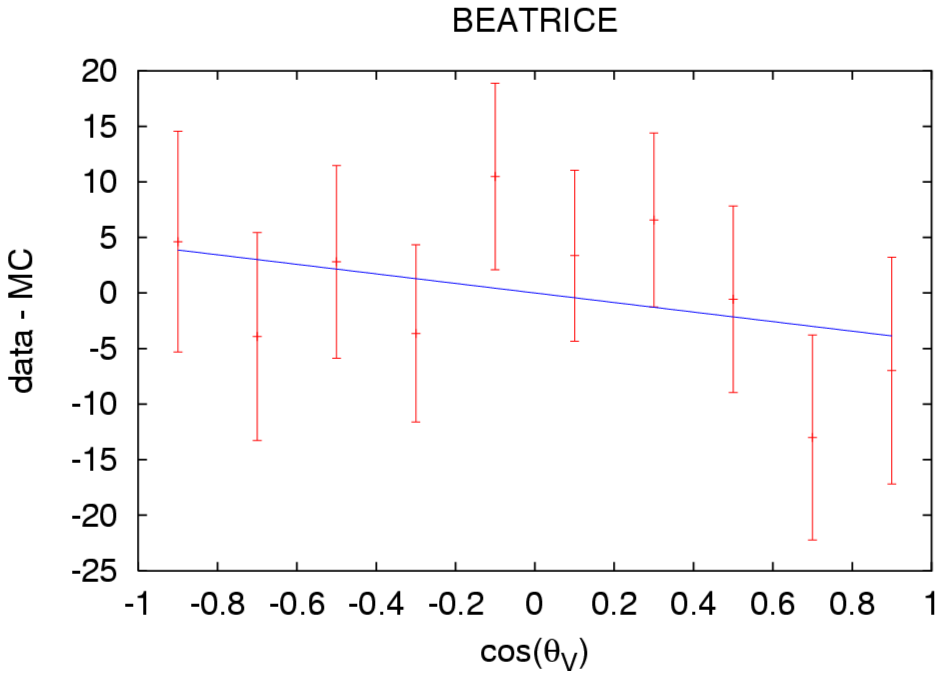




If we bin our data like E791 we see a 6σ asymmetry with a consistent slope. But even with our <u>huge</u> data sample the effect looks rather subtle.

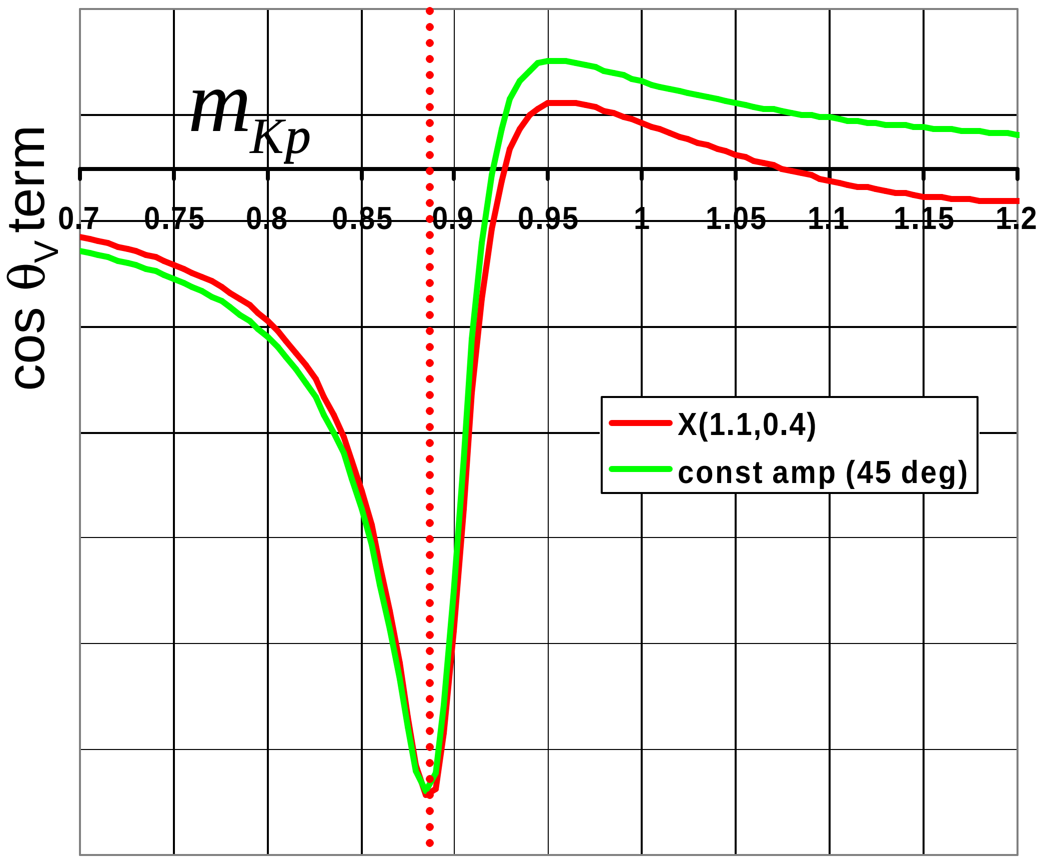
BEATRICE??



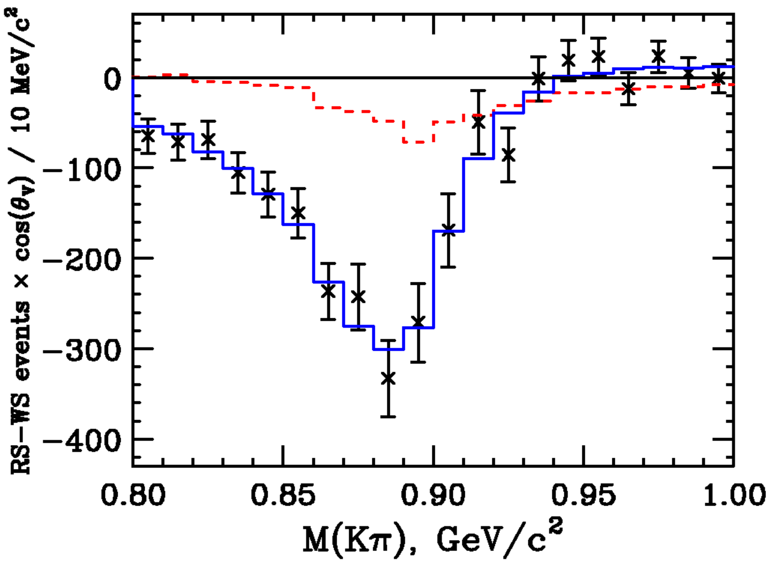


BEATRICE also uses a narrow Kπ mass cut, and here the slope of the residuals is 1.2σ, in the direction of our effect. So BEATRICE seems to see a hint of this effect as well.

..but a broad resonant amplitude works just fine.



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).

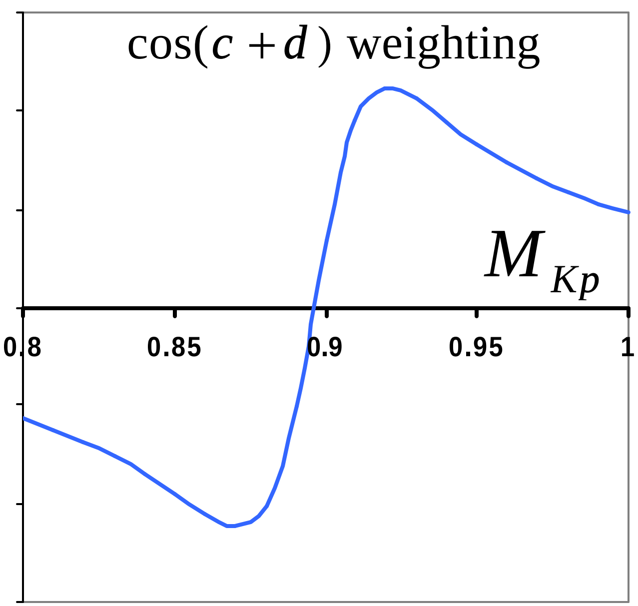


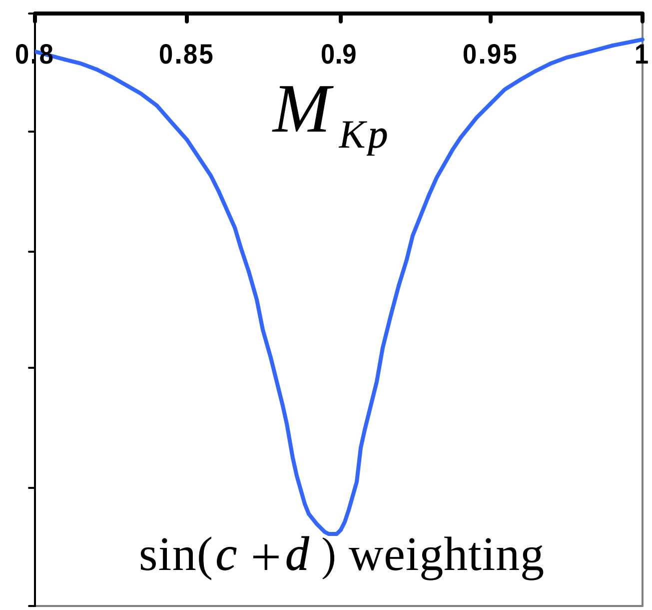
Mass dependence of this interference term

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

To study the χ dependence of interference term we use a Fourier weighting of $\cos(\chi+\delta)$ and $\sin(\chi+\delta)$ of the $K\pi$ mass distribution. This picks out pure interference terms that vary sinusoidally as χ and that do not change sign with $\cos\theta_v$. Given the form of the dominant term, we expect:

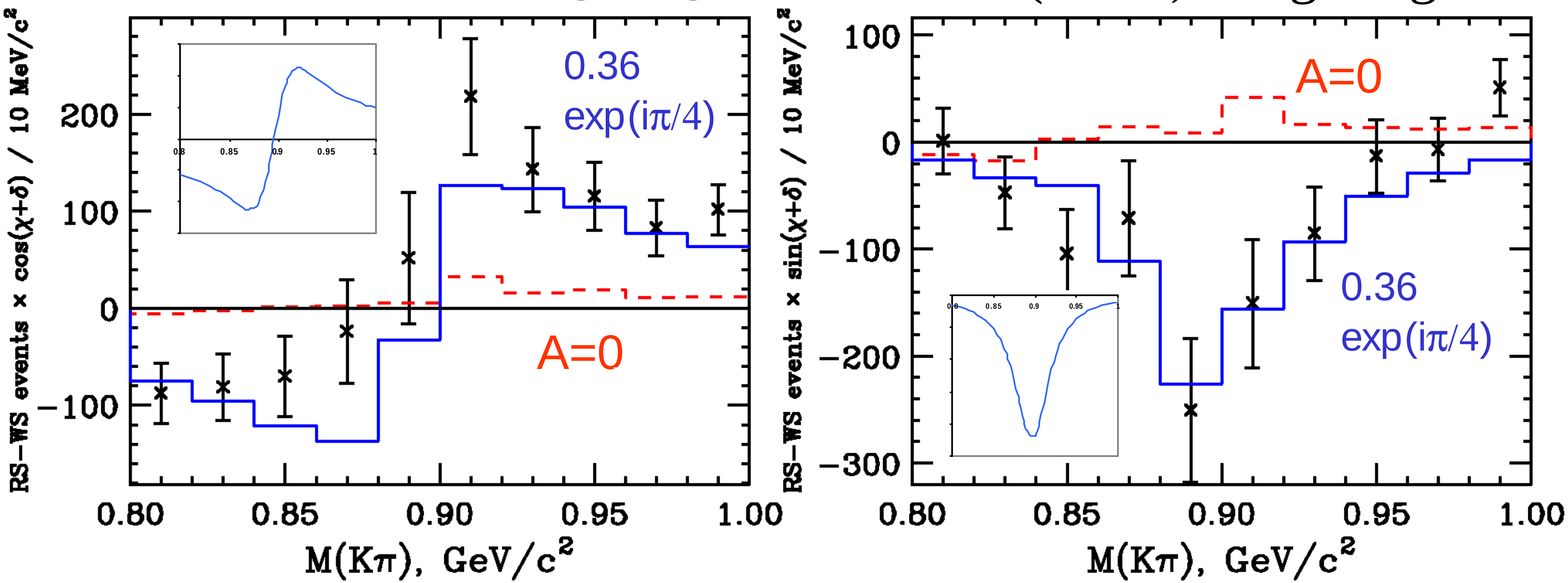
- $\cos(\chi+\delta)$ weighting will pick out the real part of the K* BW
- $\sin(\chi+\delta)$ weighting will pick out the imaginary part of the K* BW





Mass dependence of the acoplanarity interference.

$\cos(c+d)$ weighting $\qquad$ $\sin(c+d)$ weighting

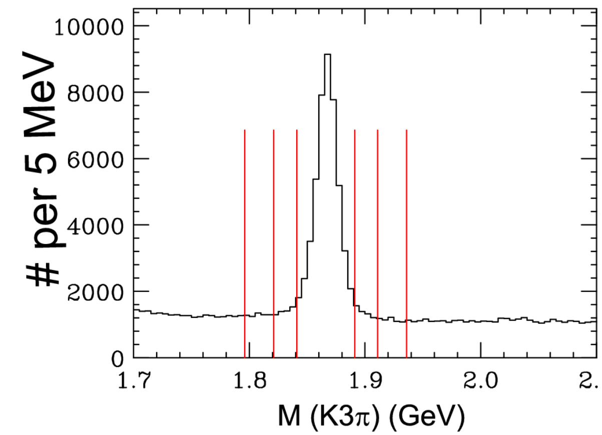


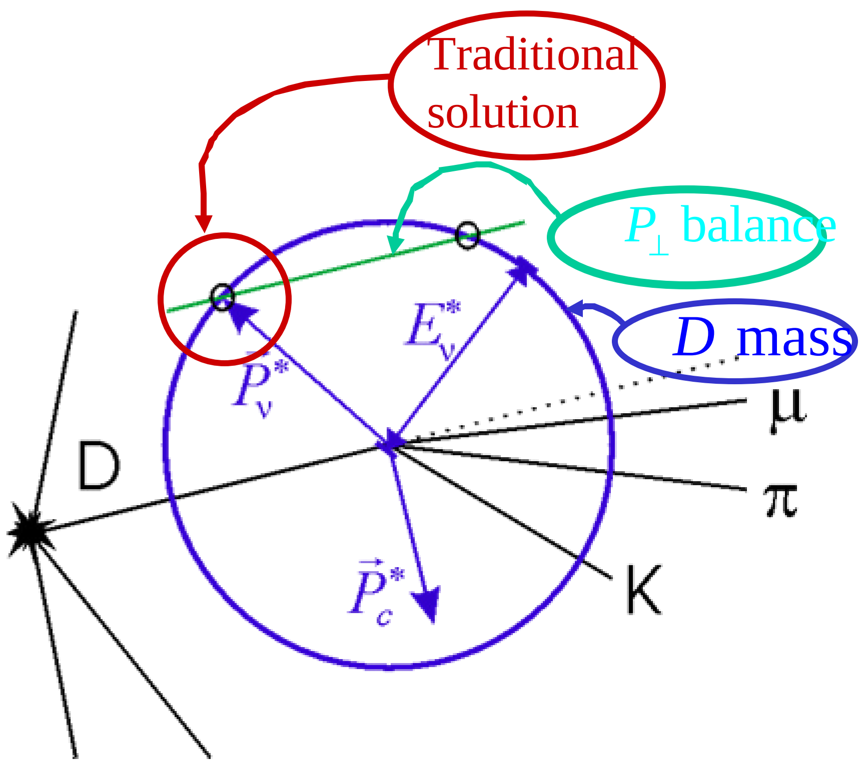
The data is in fair agreement with our model and resemble our naive expected shapes. Fractional error bars are large due to the smallness of the sin χ and cos χ Fourier components that are even in cos θ_v

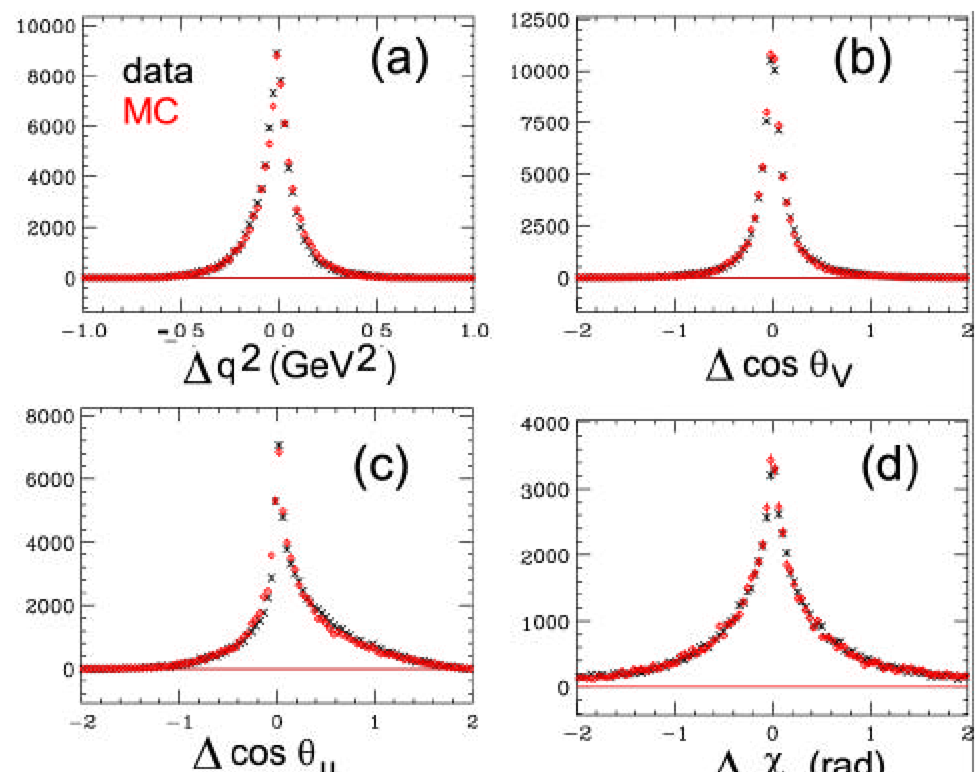
Resolution study

- Blank out the softest pion in $D \rightarrow K3\pi$ and reconstruct it like a neutrino using DVFREE upstream vertex.
- Compare with "right" answer from reconstructed pion.

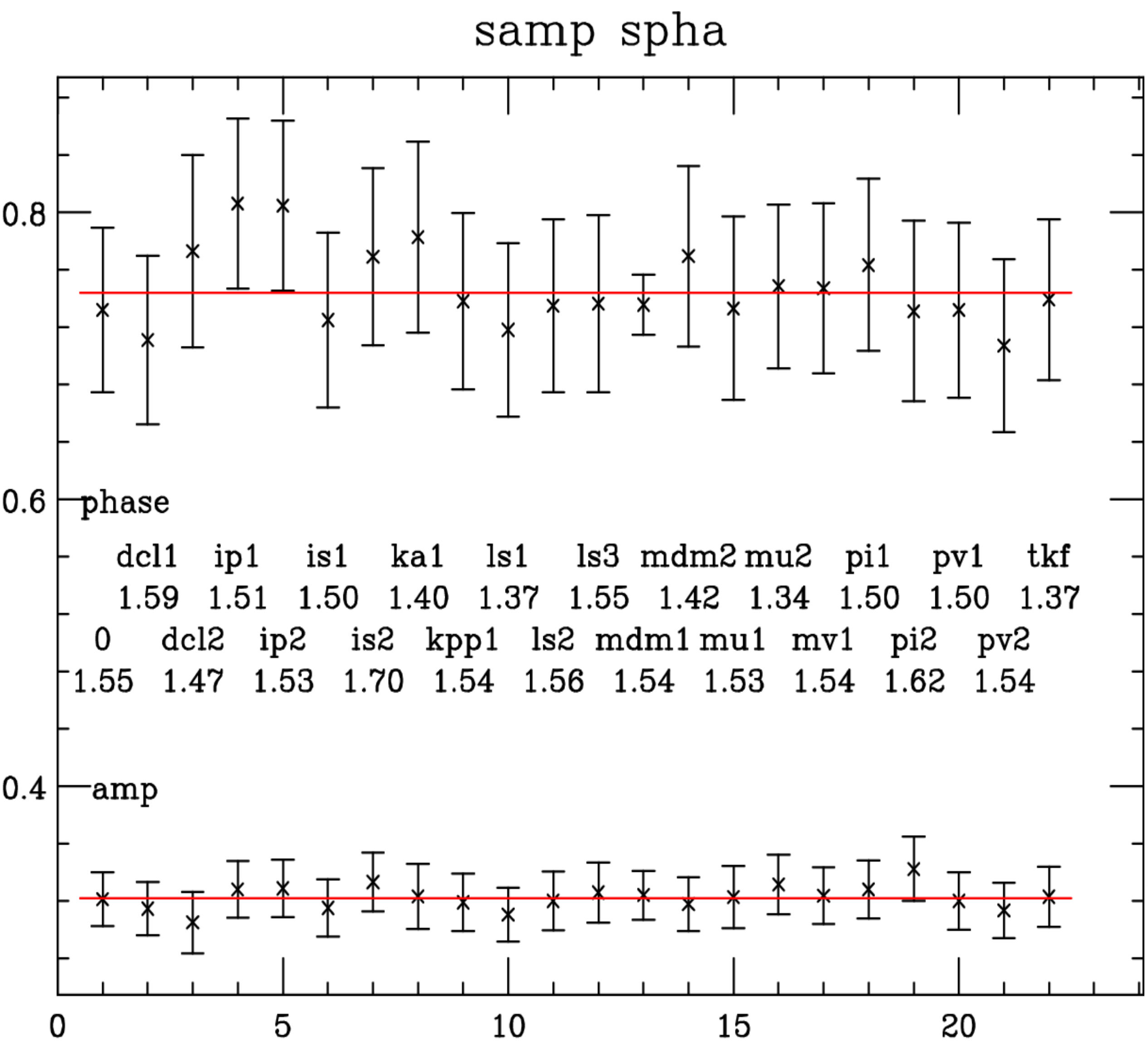
Blanking sample







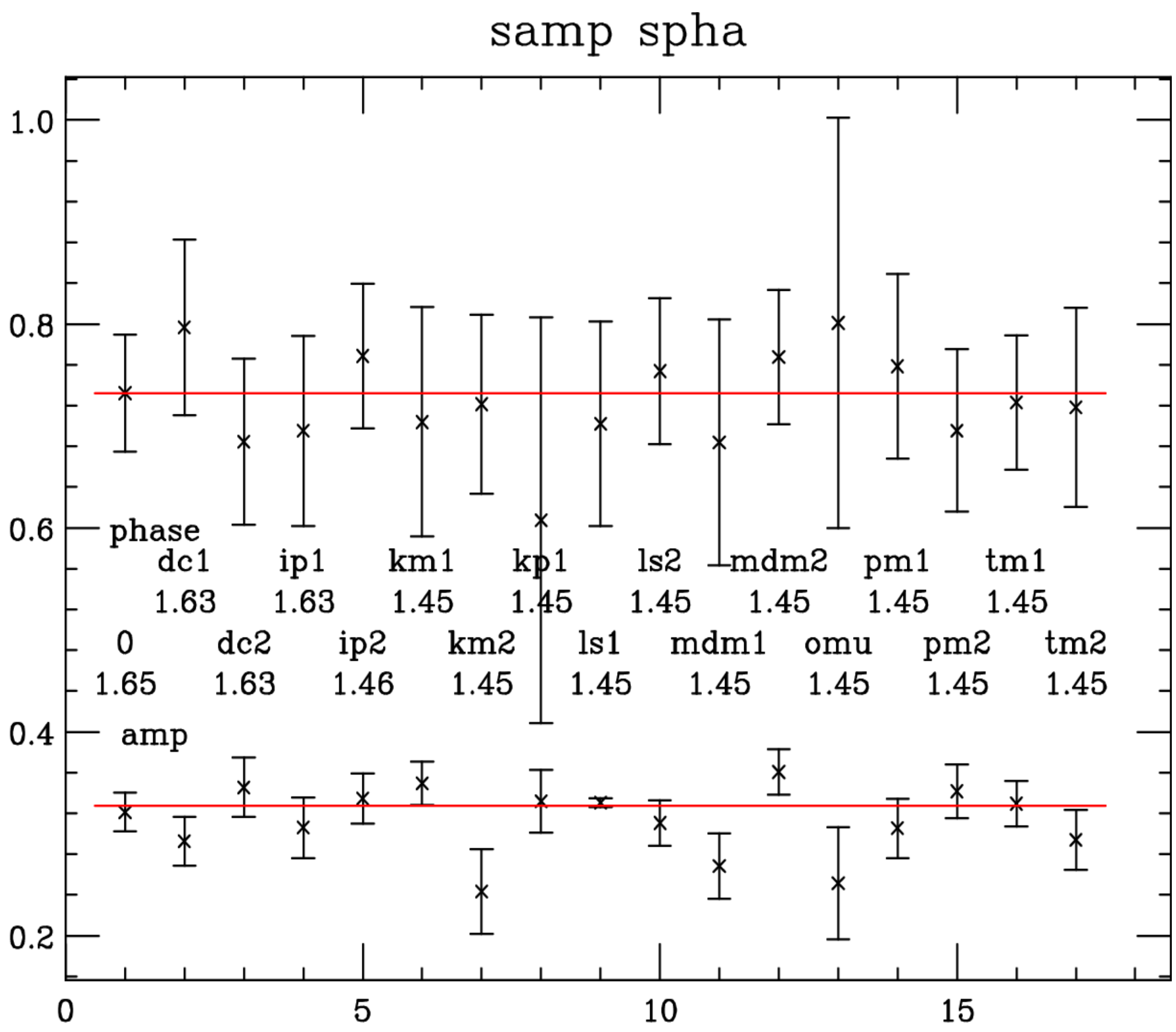
Cut Variants



Label	Cut
0	baseline
dcl1	DCL > .01
dcl2	DCL > .25
ip1	ISOP < .1, no $M(D^{*+} - D^0)$ cut
ip2	ISOP < .1
is1	ISO2ex < .01
is2	ISO2inc < .0001
ka1	Kaonicity > 6
pi1	no Pionicity cut
pi2	Pionicity > 2
kpp1	no $M(K\pi\pi)$ cut
mu1	μ TRKFIT CL > 1%
mu2	mu1, $\mathrm{CL}\mu_{(\mathrm{new})} > .15$
mu3	~~mu1, $\mathrm{CL}\mu_{(\mathrm{new})} > .20$, $\lvert P_\mu \rvert > 12$ GeV/c^2~~
ls1	$L/\sigma >$ 8
ls2	$L/\sigma > 16$
ls3	$L/\sigma > 20$
mdm1	$1.4 <$ min D mass < 2.2 GeV/c^2
mdm2	$1.6 <$ min D mass < 2.0 GeV/c^2
mv1	no M(charged daughters) cut
pv1	no $\lvert P_{K\pi\mu} \rvert$ cut
pv2	$\lvert P_{K\pi\mu} \rvert > 50$ GeV/c

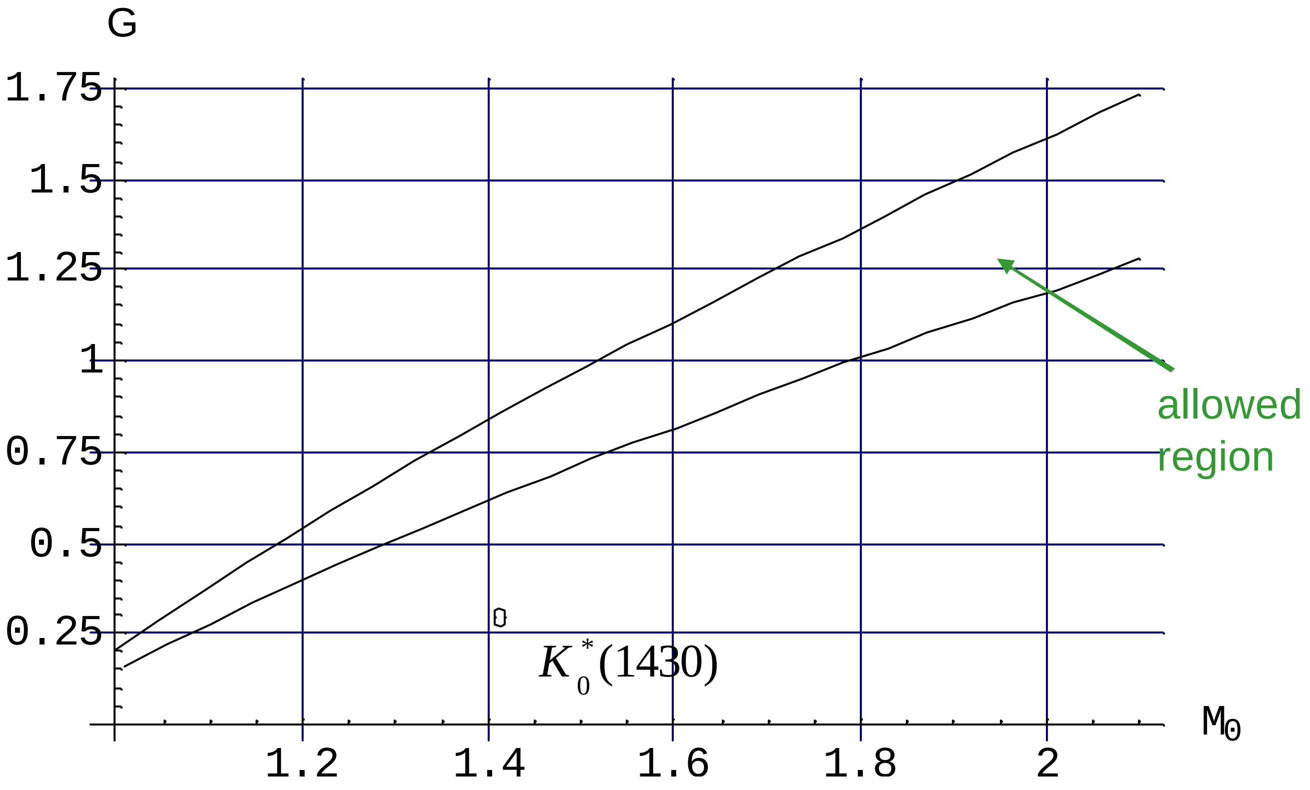
tkf — TRKFIT CL > 1%

Split Samples



Label	Cut
0	baseline
dc1	D^- only
dc2	D^+ only
ip1	min (of K,π,μ tracks) $\lvert X \rvert$ P2 > 5 cm
ip2	min (of K,π,μ tracks) $\lvert X \rvert$ P2 < 5 cm
km1	$M(K\pi) < .9\,\mathrm{GeV}/c^2$
km2	$M(K\pi) > .9\,\mathrm{GeV}/c^2$
kp1	$M(K\pi) < .87\,\mathrm{GeV}/c^2$ (incomplete series — ignore)
ls1	$12 < L/\sigma < 25$
ls2	$L/\sigma > 25$
mdm1	$1.4 <$ Min. D mass < 1.8
mdm2	$1.8 <$ Min. D mass < 2.2
omu	OMU only
pm1	$8 < P_\mu < 25$
pm2	$p_\mu > 25$
tm1	$Q^2/Q^2_{\mathrm{max}} < 0.5$
tm2	$Q^2/Q^2_{\mathrm{max}} > 0.5$

Phase of 45^0: mass versus width of s-wave



Implications

Our data is consistent with an interference of the (approximate) form:

$$|H_0|^2 \left| 0.36\exp\left(i\frac{p}{4}\right) + \frac{\cos q_{\mathrm{v}}\sqrt{\mathrm{m}_0\Gamma}}{(m-m_o)^2 + im_0\Gamma} \right|^2$$

The new amplitude is <u>small:</u> About 7% of the BW peak amplitude in the H_0 piece.

How would an interfering amplitude affect form factor measurements?

-in process of evaluating this but fit quality improves dramatically

-might effect the overall scale of the form factors derived from the branching fraction $K\pi\mu\nu/K2\pi$

What could be the strength of an s-wave amplitude according to theory?

-a small NR-K* interference (~10%) has been predicted by

B. Bajc, S. Fajfer, R.J. Oakes, T.N. Pham (1997) hep-ph/9710422

Amundson and Rosner, Phys. Rev. D47, (1993) 1951

Will there be similar effects in other charm semileptonic or beauty semileptonic channels?

-Good question!

Cuts to eliminate non-charm backgrounds