Observation of interference in D+ semileptonic decay into $K\pi\mu\nu$

- I intended to measure several semileptonic form factors as a thesis
  - $D^+ \rightarrow K^{*0}\mu\nu$ was intended as training exercise for the more controversial $D_s^+ \rightarrow \phi\mu\nu$
- 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

Motivations for semileptonic charm physics

- Semileptonic decays are accessible to experiment...
  - Cabbibo-allowed decays have large branching ratios
  - and easily distinguishable signals

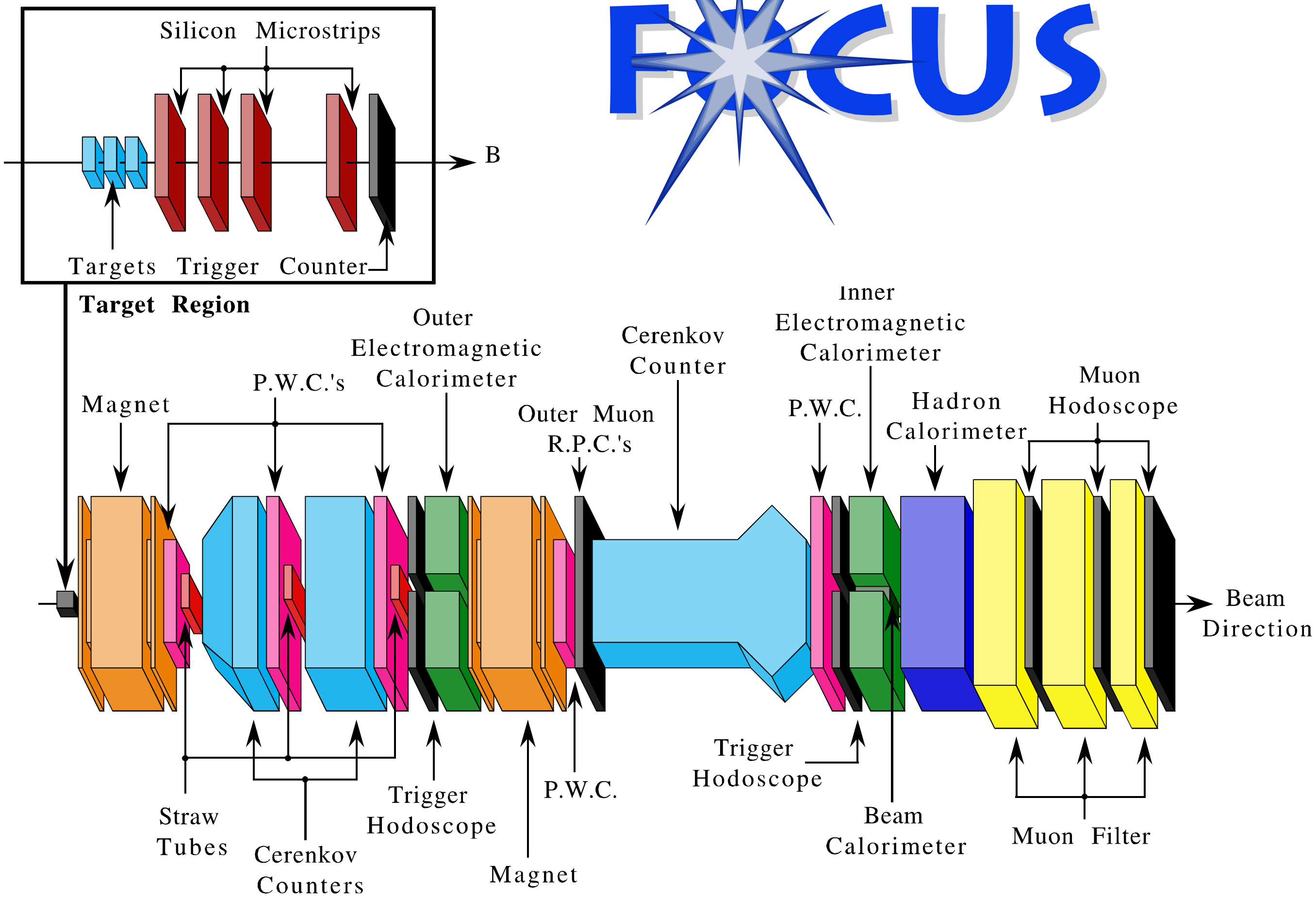
$$D^0 \to K^- l^+ \nu_l$$

$$D^+ \to \bar{K}^{*0} l^+ \nu_l \to (K^- \pi^+) l^+ \nu_l$$

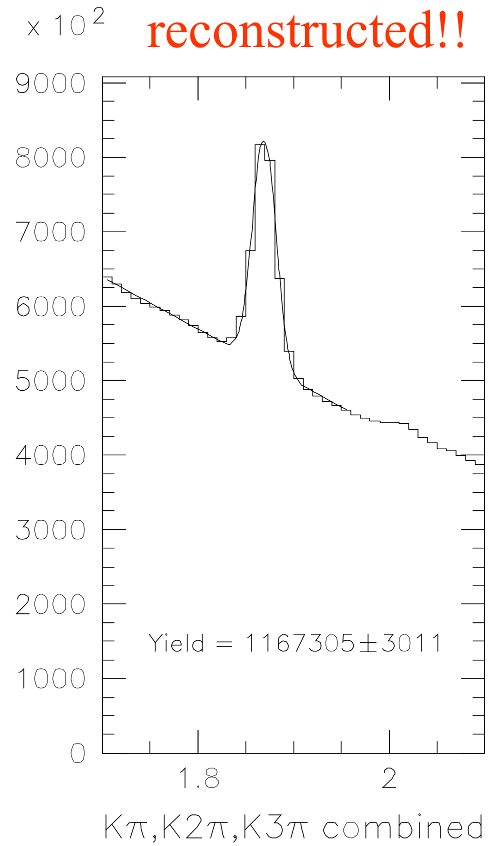
$$D_s^+ \to \phi l^+ \nu_l \to (K^- K^+) l^+ \nu_l$$

- And to theory.
  - Fully-explicit decay rate can be calculated from first principles (eg Feynman diagrams)
    - No final-state interactions to worry about!
  - QCD complications are contained in *form factors*
    - 1 (+1) for pseudoscalar-ℓ-ν
    - 3 (+1) for vector-ℓ-ν
  - Form factors can be predicted...
    - HQET, LGT, Quark models
  - And measured.
    - Shape measurement determines form factor ratios for vector-ℓ-ν
    - Branching ratio measures absolute FF scale times V_{CS}, V_{CD}
- Measurements + FF predictions can determine CKM matrix elements

E831 FOCUS



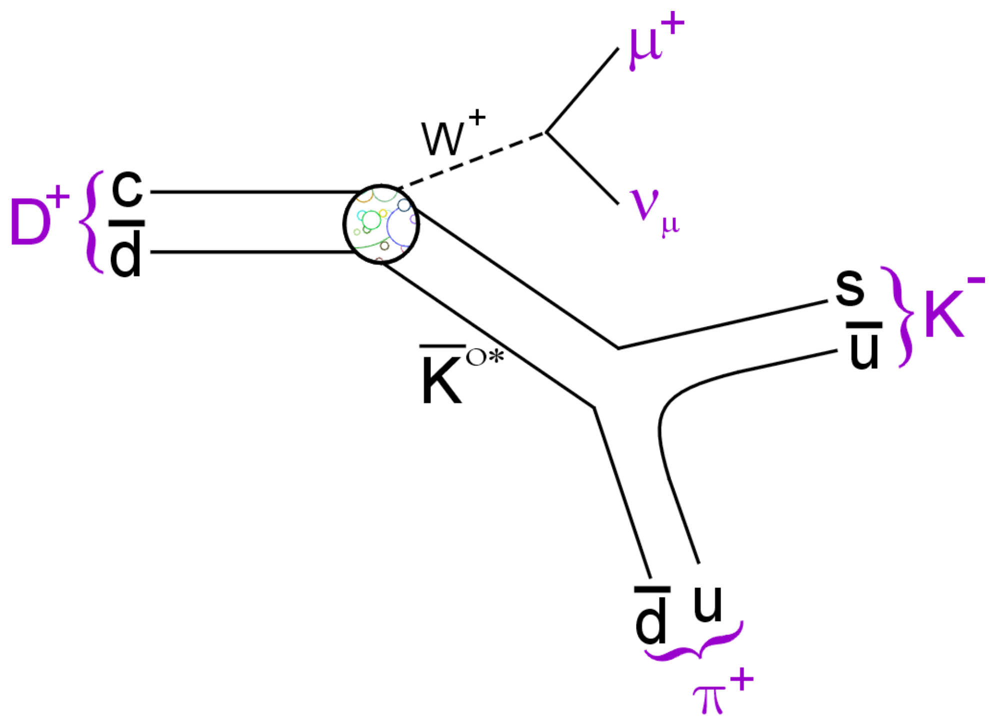
Over 1 million reconstructed!!



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

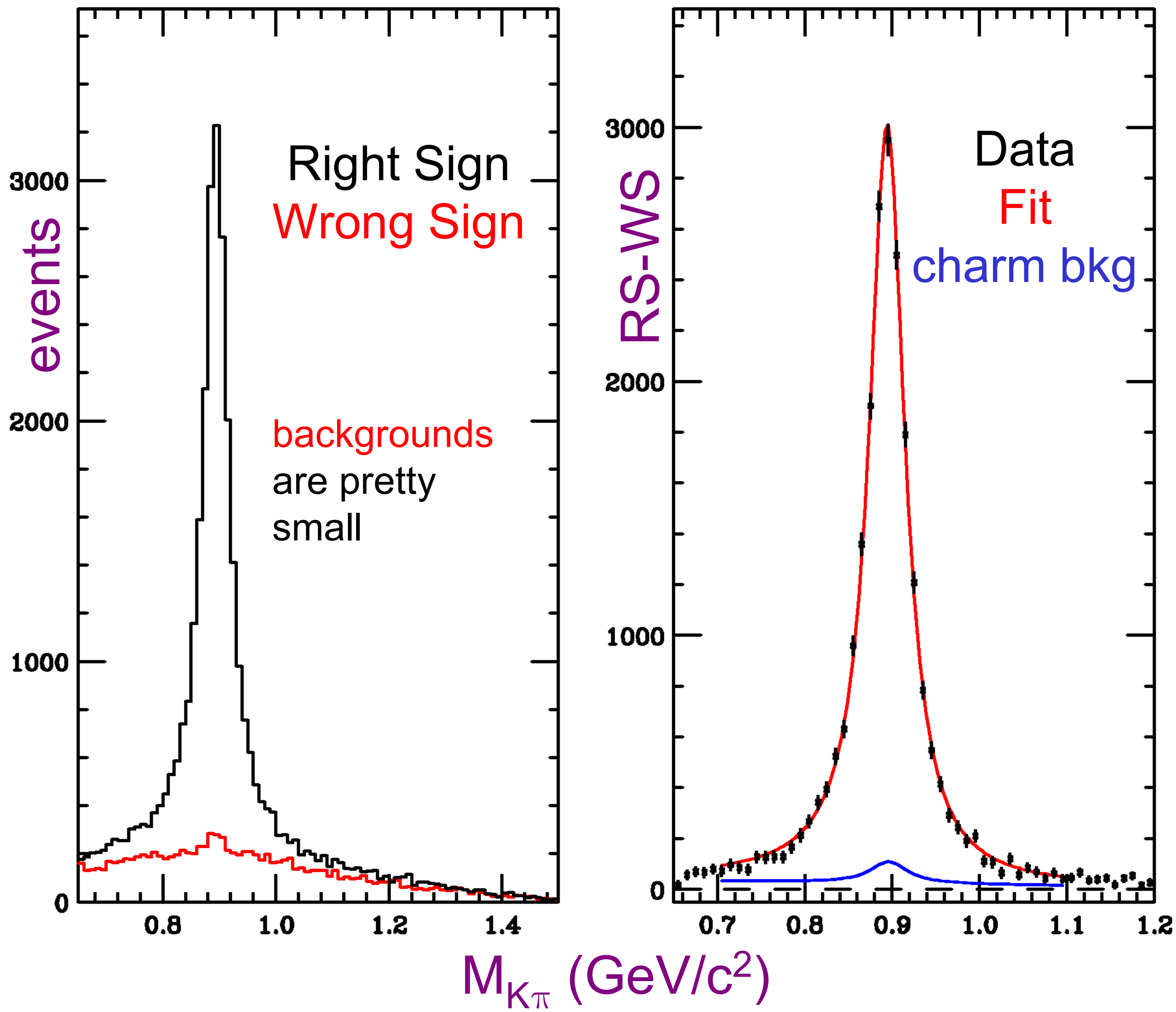
1 million charm particles reconstructed into $D \to K\pi$, $K2\pi$, $K3\pi$

The $(K\pi)\mu\nu$ is very accessible to experiment…



- The BR is large
- The $K^- \pi^+ \mu^+$ topology forms forms an easy to isolate 3 track vertex
- The strangeness of the kaon is coupled to the charge of the lepton
  - Nature provides a wrong-sign sample to gauge backgrounds
- The $K\pi$ spectra is dominated by a relatively narrow K^* landmark

The FOCUS $(K\pi)\mu\nu$ signal



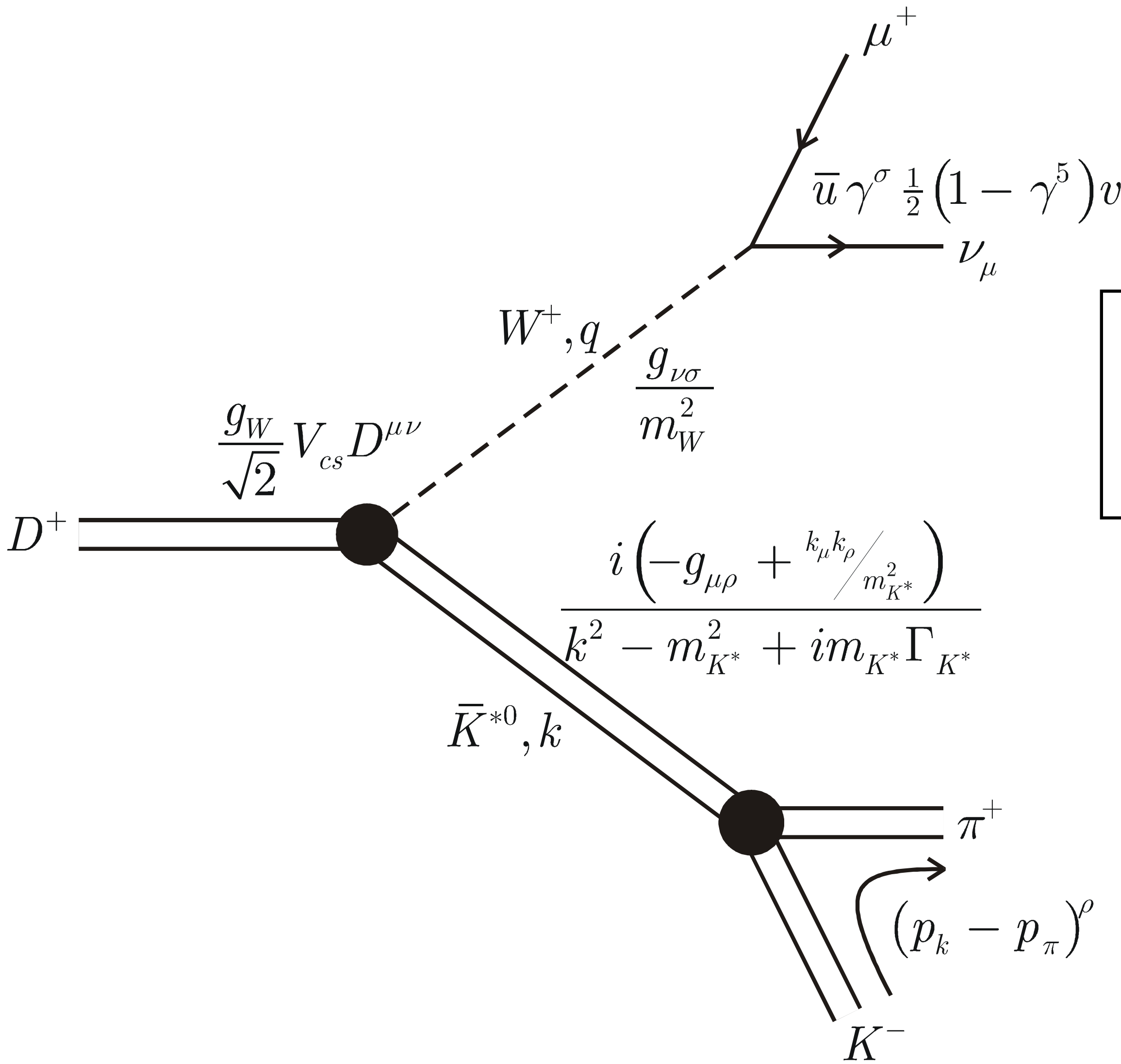
After accounting for charm backgrounds from Monte Carlo, the WS-subracted $K\pi$ spectrum seems to be essentially 100% K*(890) !!

This has been "known" for about 20 years.

We will challenge this!

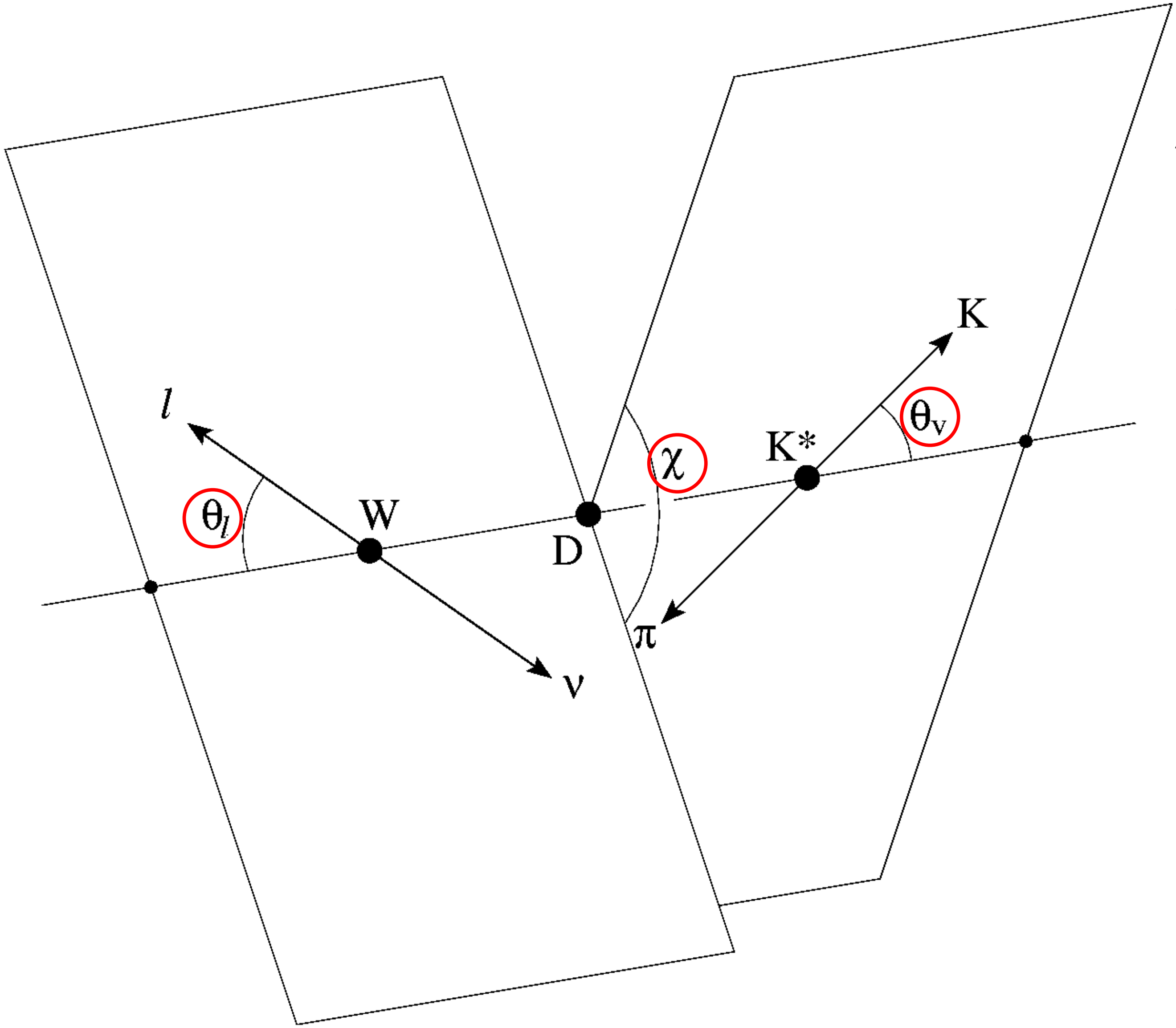
This decay is also very accessible to theory

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



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

Five observables are studied



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

$M_{K\pi}$
$M_W^2 \equiv Q^2 \equiv t$

Decay rate details

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

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

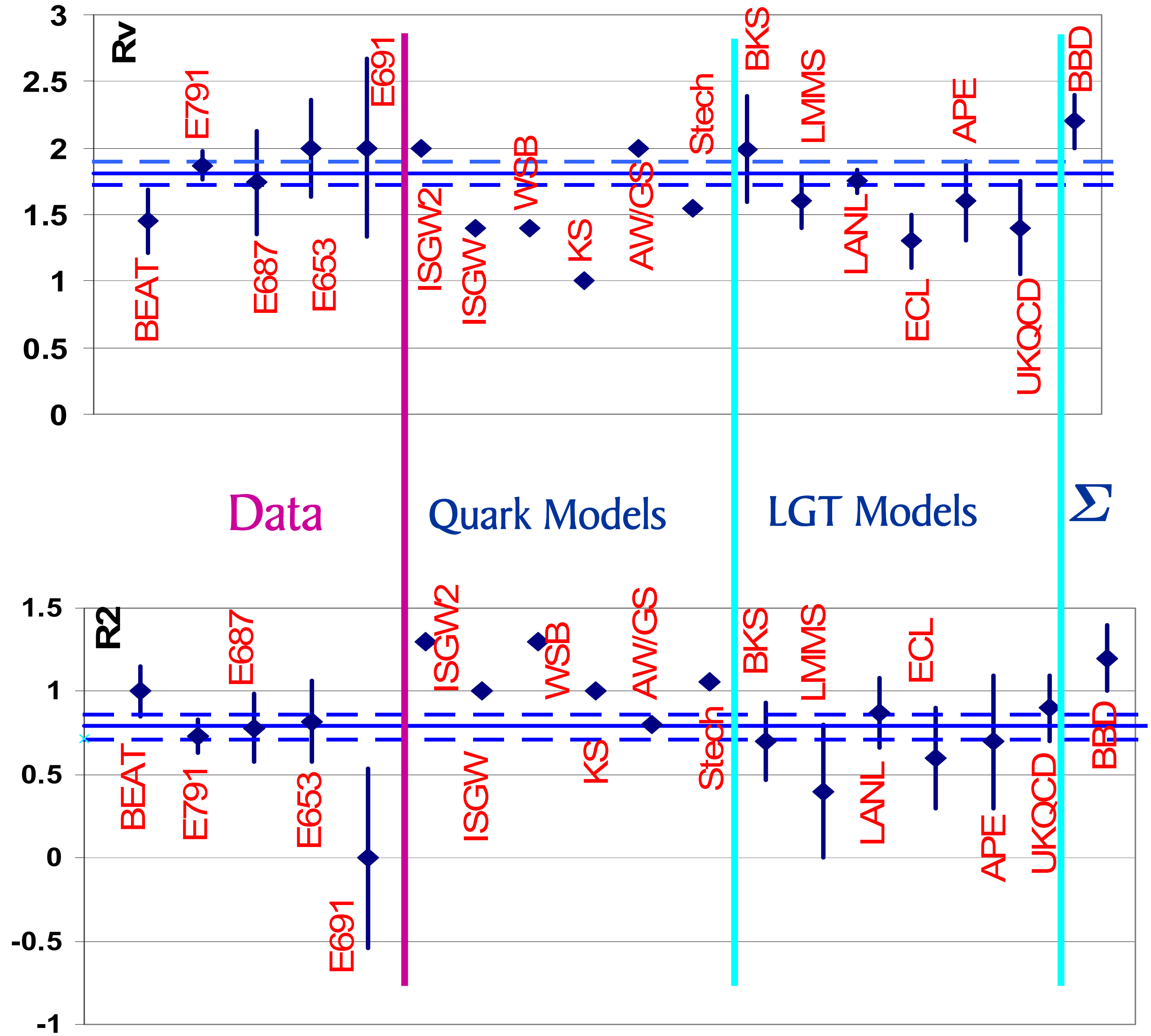
$$\begin{aligned} H_\pm(t) &= (M_D+M_{K\pi})A_1(t)\mp 2\frac{M_D K}{M_D+M_{K\pi}}V(t) \\ H_0(t) &= \frac{1}{2M_{K\pi}\sqrt{t}}\left[(M_D^2-M_{K\pi}^2-t)(M_D+M_{K\pi})A_1(t)-4\frac{M_D^2K^2}{M_D+M_{K\pi}}A_2(t)\right]\end{aligned}$$

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

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

Form factor ratios as tests of LGT

- A 20-year history of measurements!
- Experiments are self-consistent and slightly higher than present LGT calculations.
- Much more potential accuracy w/ FOCUS



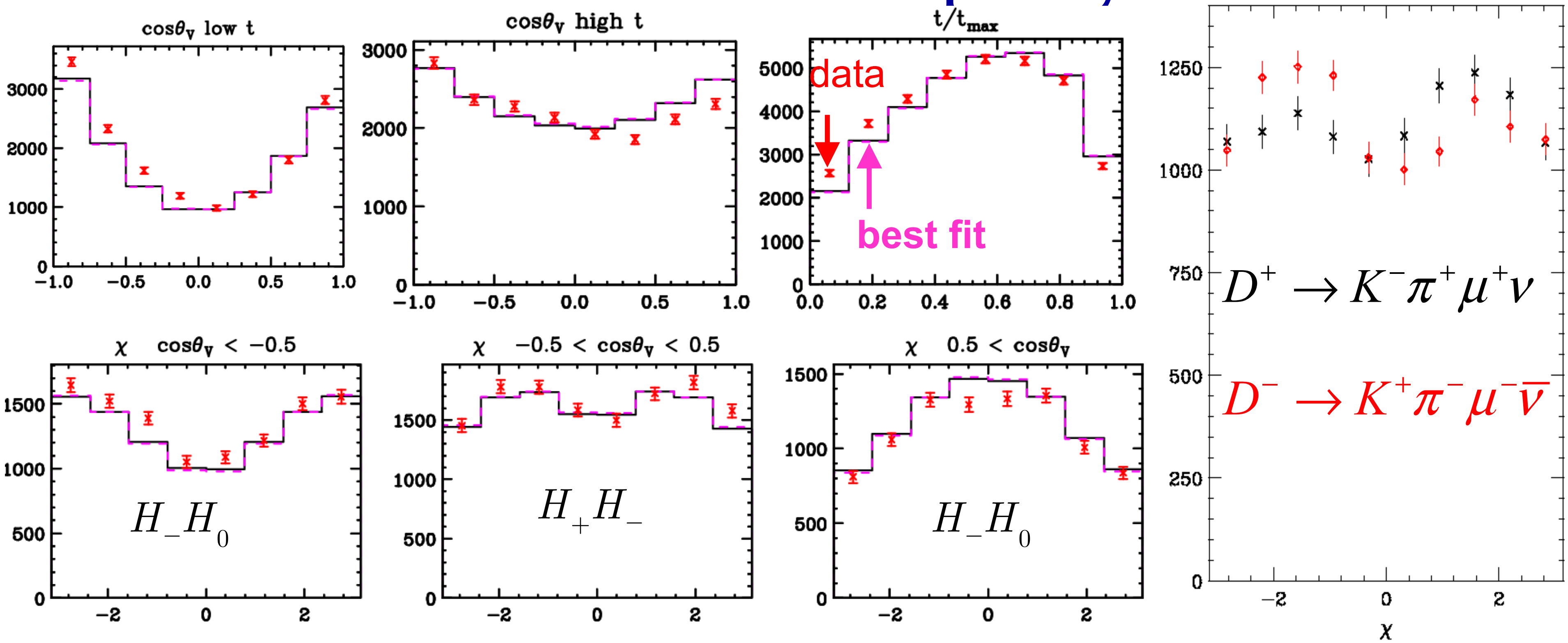
What happened when we fit $K^*\mu\nu$?

- We tried to measure the form factor ratios for $K^*\mu\nu$, but we could never get a good fit!
- We tried various cuts that varied the yield by a factor of 2 and the S/N by a factor of 3 but could never achieve a fit confidence level in excess of 10^{-12}
- We compared the data to the model for a large number of distributions searching for problems....

Cut	Yield	RS/WS	χ^2/DOF
baseline	27861	4.84	3.73
DCL $> .01$	30036	4.35	3.29
DCL $> .25$	22040	5.34	3.55
ISOP $< .1$, no $M(D^{*+} - D^0)$ cut	24795	5.26	4.15
ISOP $< .1$	24701	5.29	4.16
ISO2ex $< .01$	28853	4.58	3.68
ISO2inc $< .0001$	20587	7.84	4.21
Kaonicity > 6	20420	5.99	3.54
no Pionicity cut	28530	3.78	3.66
Pionicity > 2	20204	5.22	3.52
no $M(K\pi\pi)$ cut	28060	4.83	3.69
μ TRKFIT CL $> 1\%$	23606	7.48	3.41
mu1, CL$\mu_{(\mathrm{new})} > .15$	20948	8.06	3.19
mu1, CL$\mu_{(\mathrm{new})} > .20$, $\lvert P_\mu \rvert > 12$ GeV$/c^2$	17907	9.07	2.65
$L/\sigma > 12$	23851	5.97	4.05
$L/\sigma > 16$	20441	6.57	3.87
$L/\sigma > 20$	17570	6.87	3.82
$1.4 <$ min D mass < 2.2 GeV$/c^2$	23139	8.17	4.17
$1.6 <$ min D mass < 2.0 GeV$/c^2$	17612	11.17	3.59
no M(charged daughters) cut	27897	4.75	3.70
no $\lvert P_{K\pi\mu} \rvert$ cut	28173	4.48	3.72
$\lvert P_{K\pi\mu} \rvert > 50$ GeV$/c$	23444	6.34	3.67

81 dof!

...and we found plenty

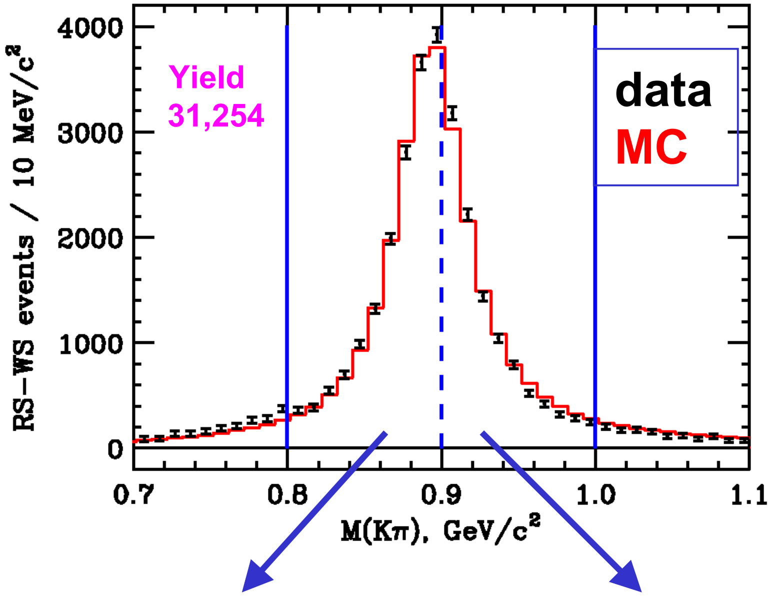


The $K^*\mu\nu$ model roughly tracked the data. But in data we saw:

- Significant backward peaking in cos θ_V (primarily at low t)
- A significant excess at low "t"
- A significant difference between the D+ and D- in acoplanarity

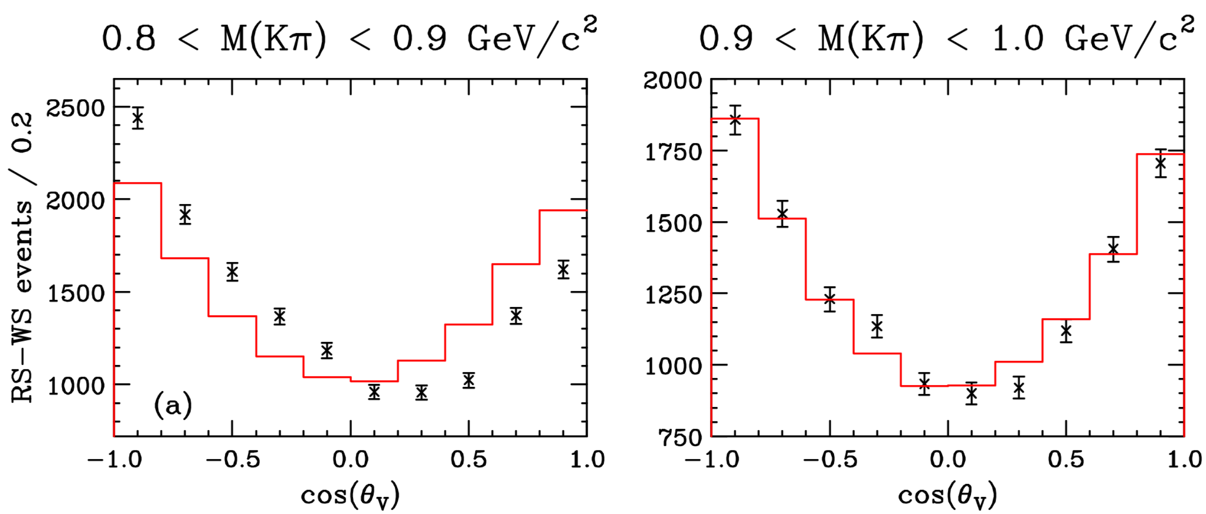
After additional searching for possible acceptance problems or backgrounds, we stumbled upon something really dramatic...

Nearly all the θ_v asymmetry was below the K* pole!



K*μν is supposed to have just even power terms of cos $\theta_{\mathbf{v}}$

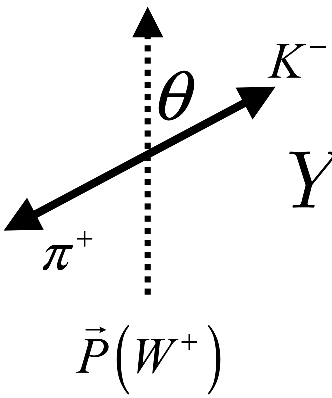
But the data seemed to require a linear cos $\theta_{\mathbf{v}}$ term below the K* pole and none above the pole.



We hit upon an interference explanation for a linear cos $\theta_{\mathbf{v}}$ with a dramatic mass dependence.

Developing an asymmetry through interference...

- The θ_V dependence of the decay is easy to understand:
  Consider the wave function of the $K\pi$ final state in the K^* rest frame.



$$Y_1^{\,0} \Rightarrow \cos\theta$$

$$Y_1^{\pm 1} \Rightarrow \sin\theta \exp(\pm i\phi)$$

$$\left|\alpha\cos\theta\right|^2 + \left|\beta\sin\theta\right|^2$$

$$= \beta^2 + (\alpha^2 - \beta^2)\cos^2\theta$$

$\left|\alpha Y_1^0 + \beta Y_1^{\pm 1}\right|^2$ and averaging over ϕ

No linear cos θ term

- A *scalar amplitude* could interfere with the Y_1^0 piece of the K*

$$\Downarrow Y_0^{\,0}$$

averaging over ϕ

$$Y_1^{\,0} \Rightarrow \cos\theta + A$$

$$Y_1^{\pm 1} \Rightarrow \sin\theta \exp(\pm i\phi)$$

$$\left|\alpha\cos\theta + A\right|^2 + \left|\beta\sin\theta\right|^2$$

$$= a + b\cos\theta + c\cos^2\theta$$

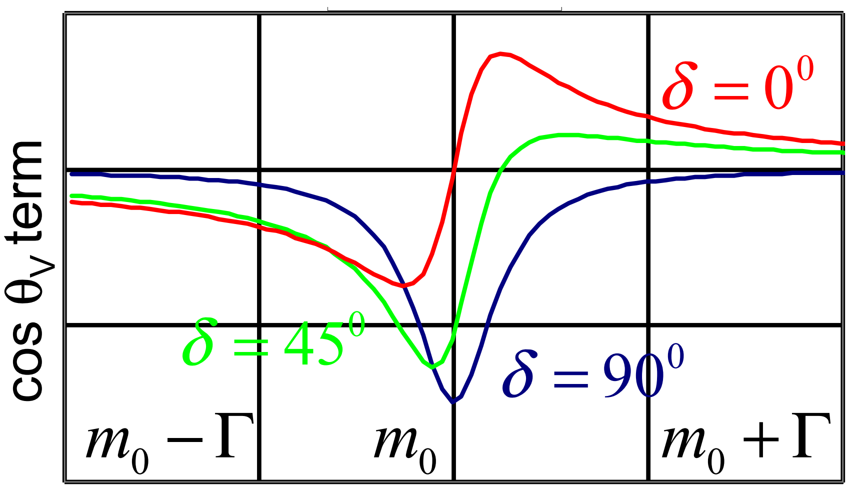
Linear cos θ term through interference

The Breit-Wigner interference would give the asymmetry a distinctive mass dependence

As a first guess we try a constant amplitude with an adjustable phase.

$$\cdots\left|\frac{\cos\theta_V}{m^2-m_0^2+im_0\Gamma}+Ae^{-i\delta}\right|^2\cdots\propto$$

$$A^2+2A\cos\theta_V\left[\frac{\left(m^2-m_0^2\right)\cos\delta-\Gamma m_0\sin\delta}{\left(m^2-m_0^2\right)^2+\left(\Gamma m_0\right)^2}\right]+\frac{\cos^2\theta_V}{\left(m^2-m_0^2\right)^2+\left(\Gamma m_0\right)^2}$$



We can get a large asymmetry below the K* pole and almost no asymmetry above the pole with phase choice of 45^0 to match the observed cos θ_V vrs $m_{K\pi}$. But how can we insert this new amplitude to get a fully explicit decay intensity?

Angular momentum makes the prescription unique

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

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

- We simply add a new constant amplitude : A exp(iδ) to the standard amplitude in the three places where the K* couples to an m=0 W+ .
- You can see the Wigner D- matrices describing the amplitudes for the μν and Kπ to be in their respective m = +1 , -1 , 0 spin states.

For a small amplitude 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

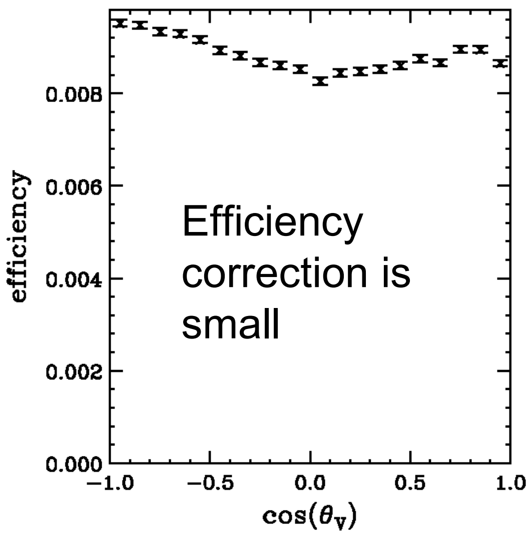
$$8\,\underline{\cos\theta_V}\,\sin^2\theta_l A\,\mathrm{Re}\left(e^{-i\delta}B_{K^*}\right)H_0^2$$

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

If our model is right:

- The asymmetry should be proportional to $\sin^2\theta_\ell$
- The asymmetry should have a Q^2 dependence given by $Q^2\, H_0^2(Q^2)$

Studies of the acoplanarity-averaged interference

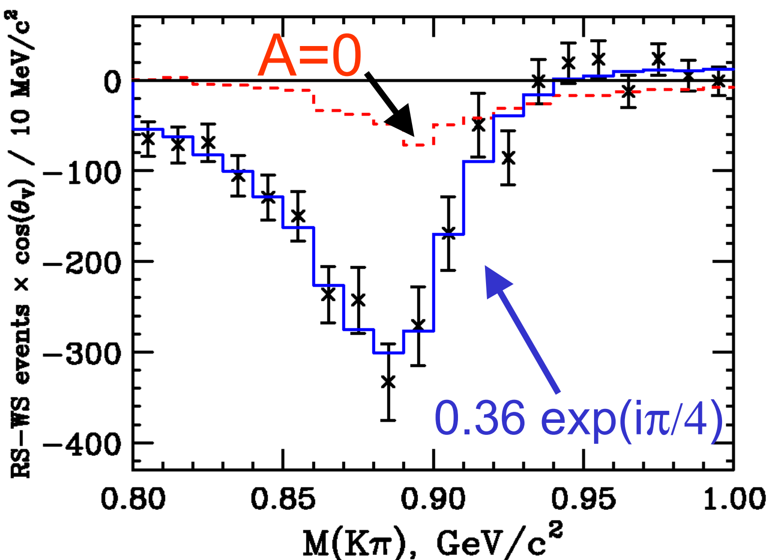


$$\boxed{+8\cos\theta_V \sin^2\theta_l A\,\mathrm{Re}\left(e^{-i\delta}B_{K^*}\right)H_0^2}$$

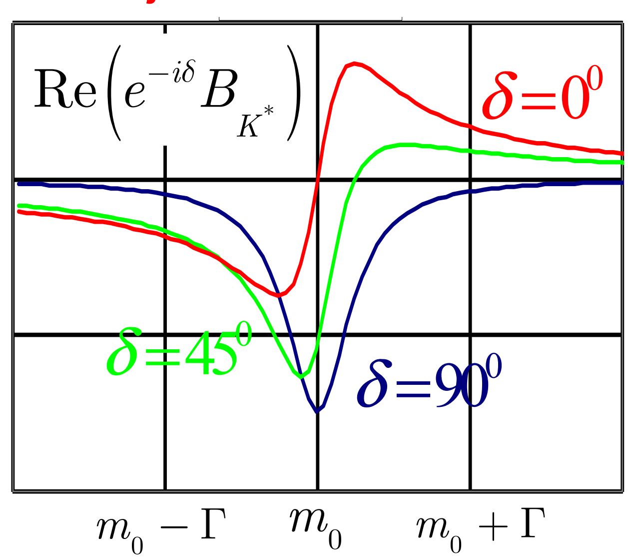
- All other χ-averaged terms in the decay intensity are even powers of $\cos\theta_V$.
- We extract a linear $\cos\theta_V$ term by weighting data by $\cos\theta_V$

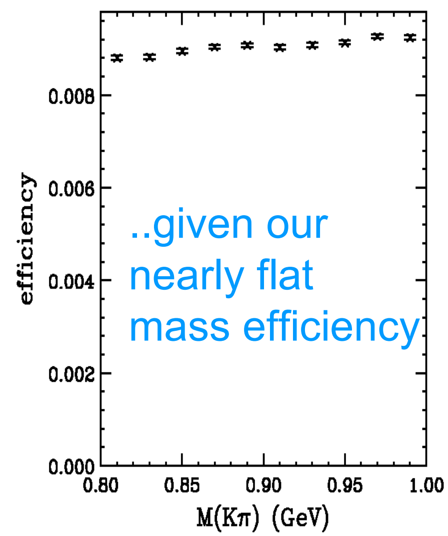
We begin with the mass dependence: $\boxed{\mathrm{Re}\left(e^{-i\delta}B_{K^*}\right)}$

Our weighted mass distribution..



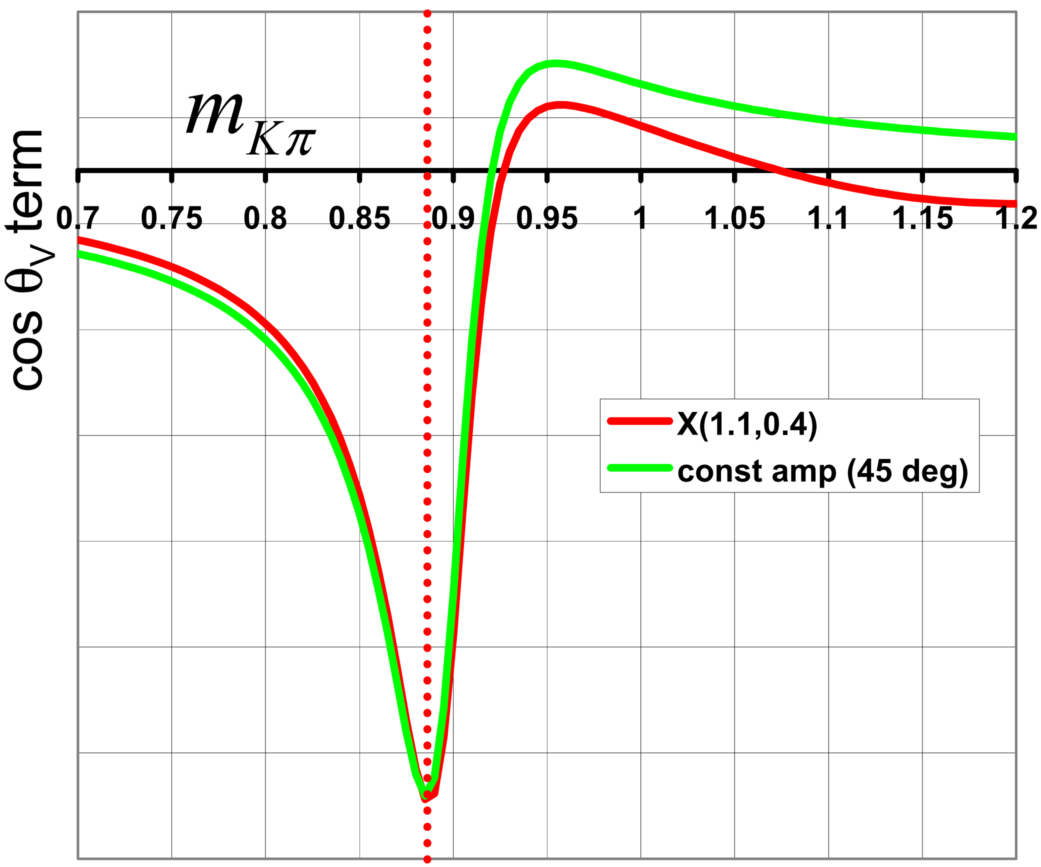
..looks just like the calculation..



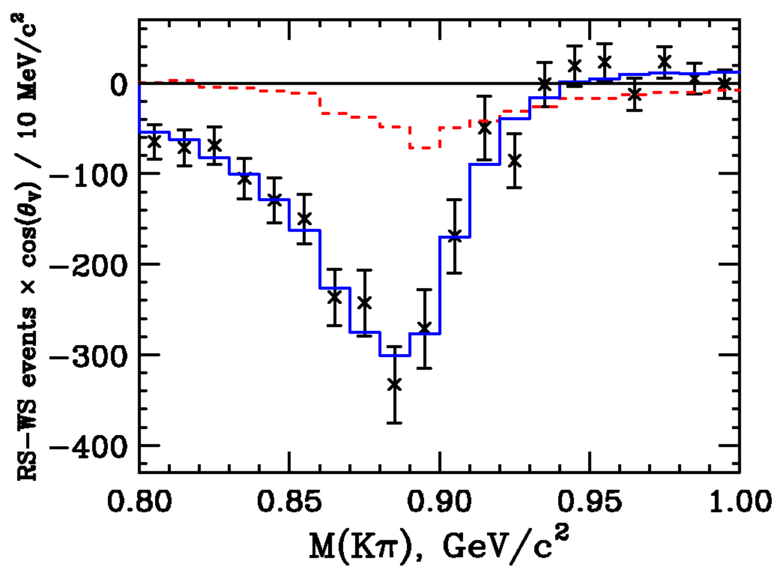


A constant 45^0 phase works great...

..but a broad resonant amplitude works just fine.



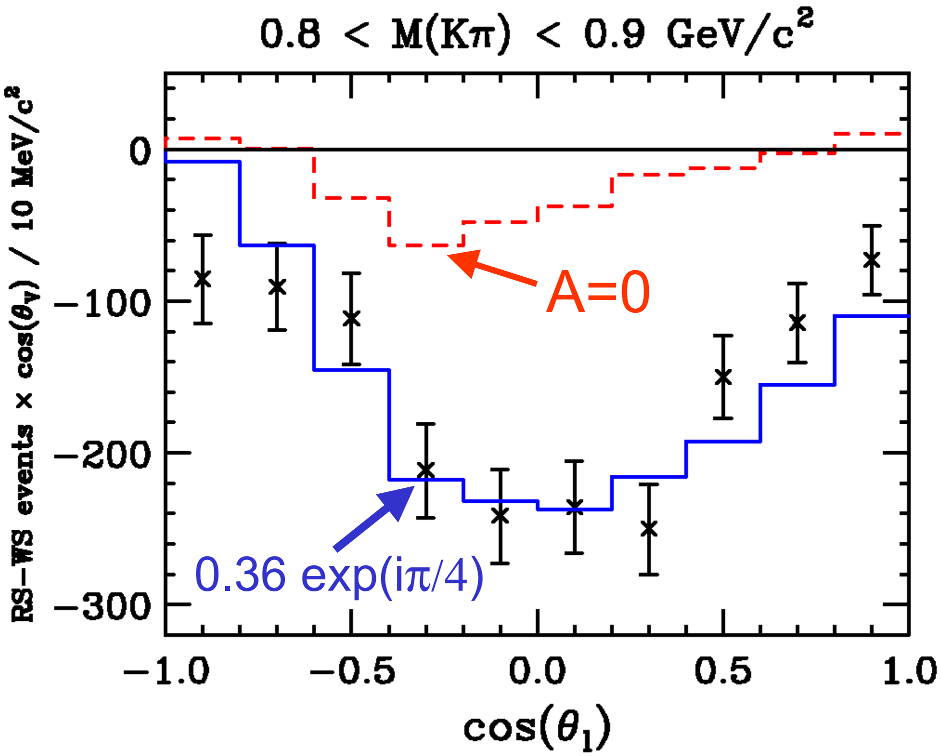
We can mimic the cosV dependence for a **constant amplitude** using a BW put in with a <u>relatively real phase</u>. For example use a wide width (400 MeV) and center it above the K* pole (1.1 GeV).

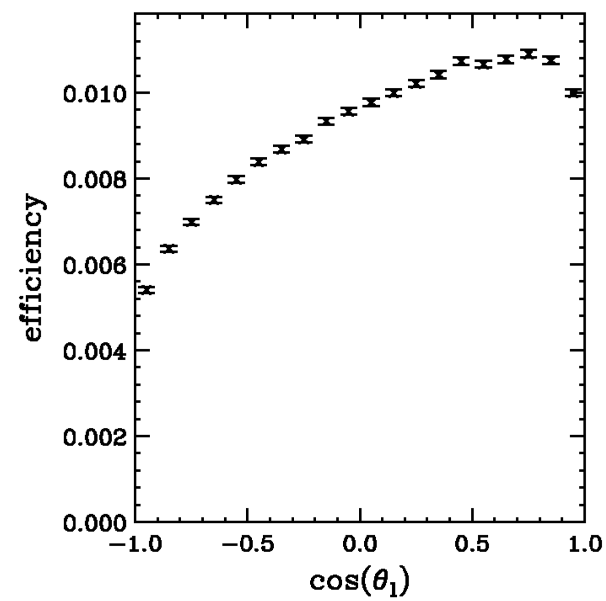


Dependence of asymmetry on cosθ_ℓ

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

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

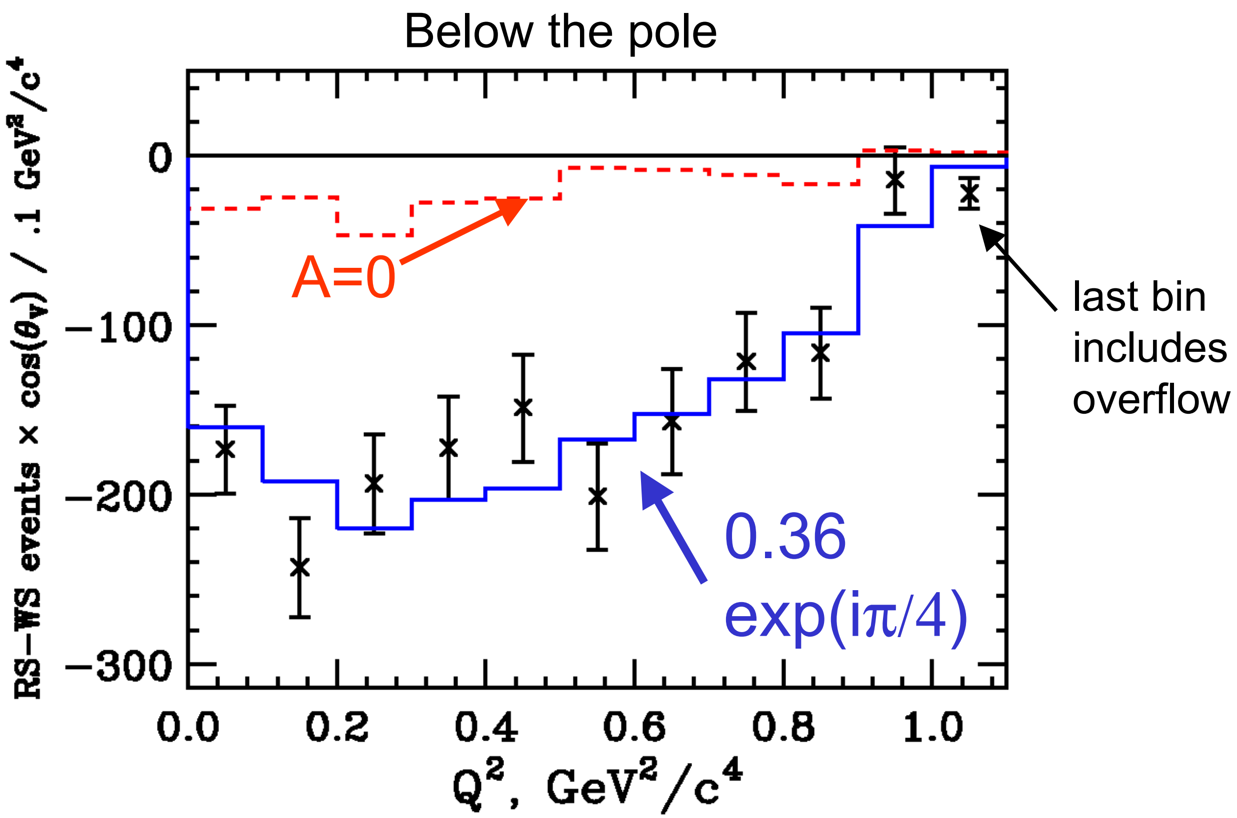




Looks $\propto$ - (1 - cos$^2\theta_\ell$). Some modulation due to efficiency and resolution

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 s-wave interference adds two new terms to the acoplanarity dependence.

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

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

In the absence of s-wave interference:

•Acoplanarity dependent terms are odd functions of cos θ_v

•The s-wave interference gives even functions of cos θ_v

•Acoplanarity terms are functions of cos χ and cos 2 χ only

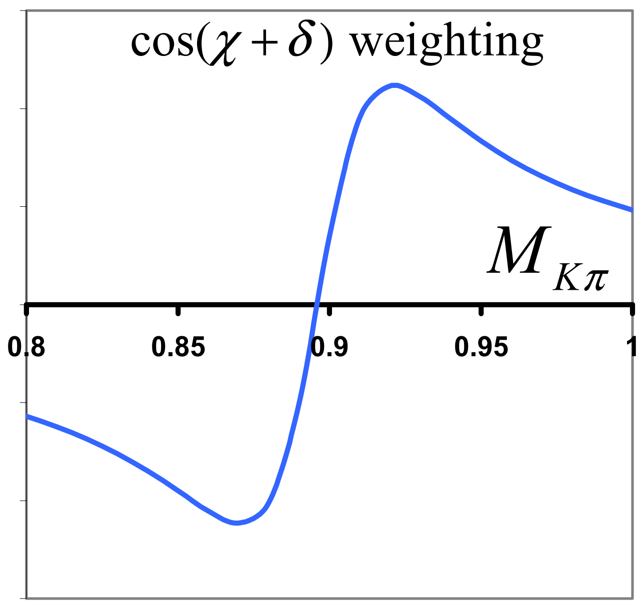
•The s-wave interference gives <u>both</u> cos χ and sin χ terms and thereby breaks χ to -χ symmetry

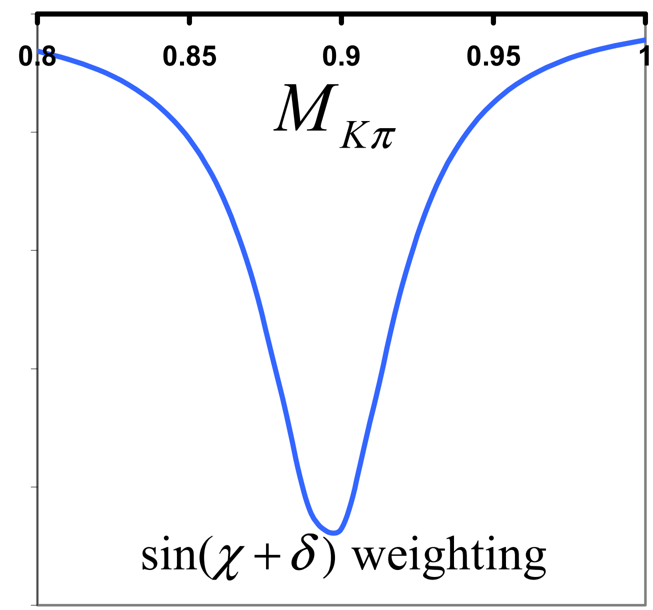
Acoplanarity dependence of the interference term

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

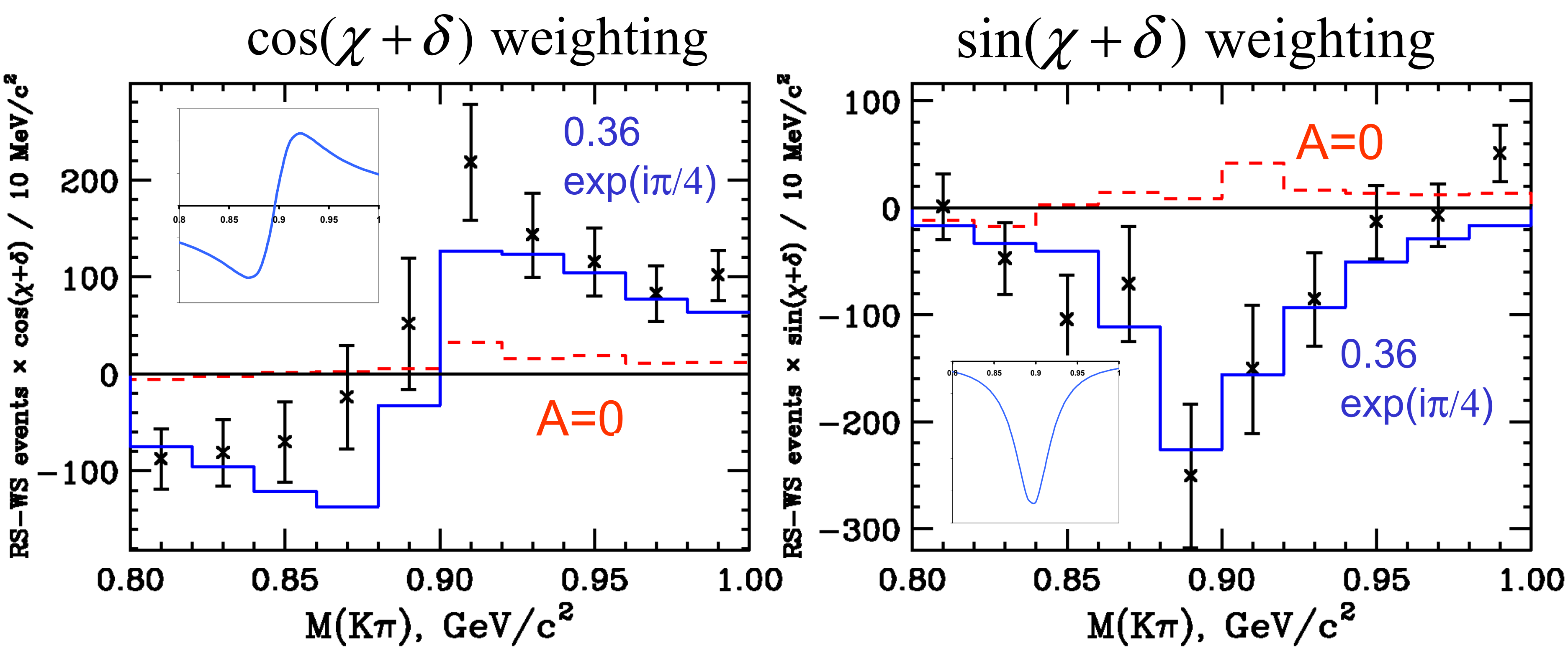
To study the χ dependence of interference term we use a Fourier weighting of cos(χ+δ) and sin(χ+δ) of the Kπ mass distribution. This picks out pure interference terms that vary sinusoidally as χ and that do not change sign with cos θ_v . Given the form of the dominant term, we expect:

- cos(χ+δ) weighting will pick out the real part of the K* BW
- sin(χ+δ) weighting will pick out the imaginary part of the K* BW



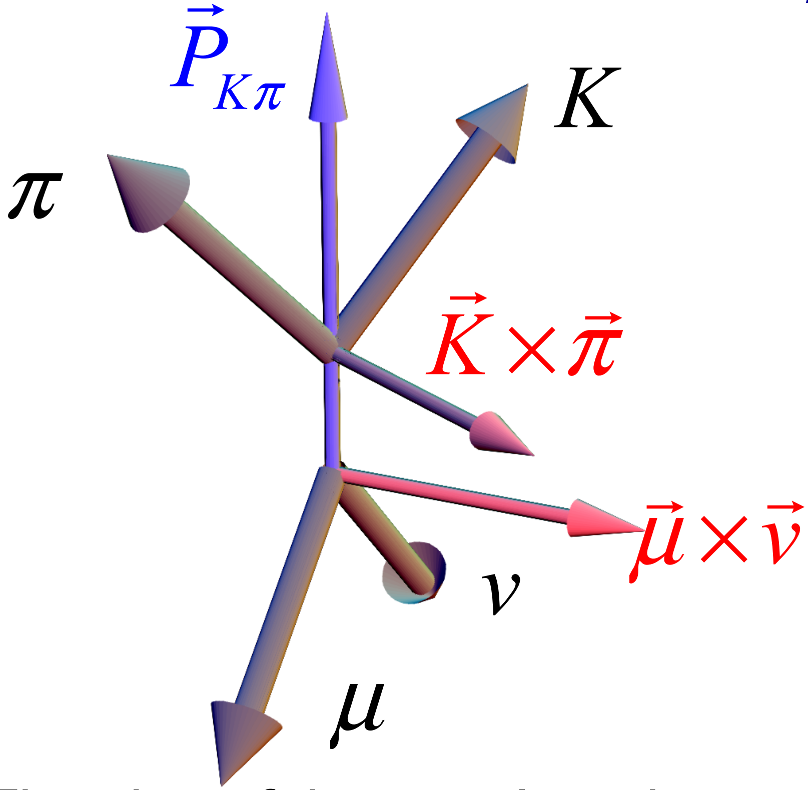


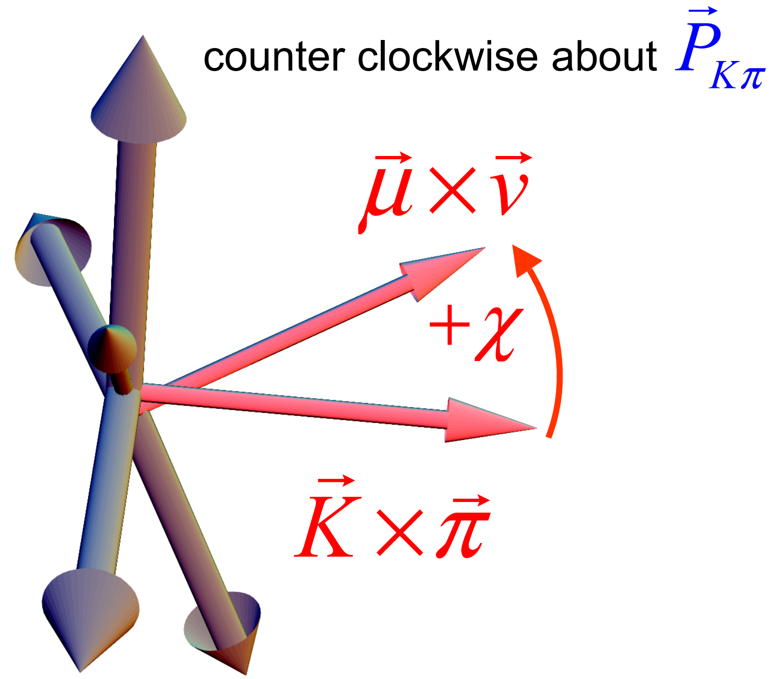
Mass dependence of the acoplanarity interference.



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

A note on our acoplanarity conventions





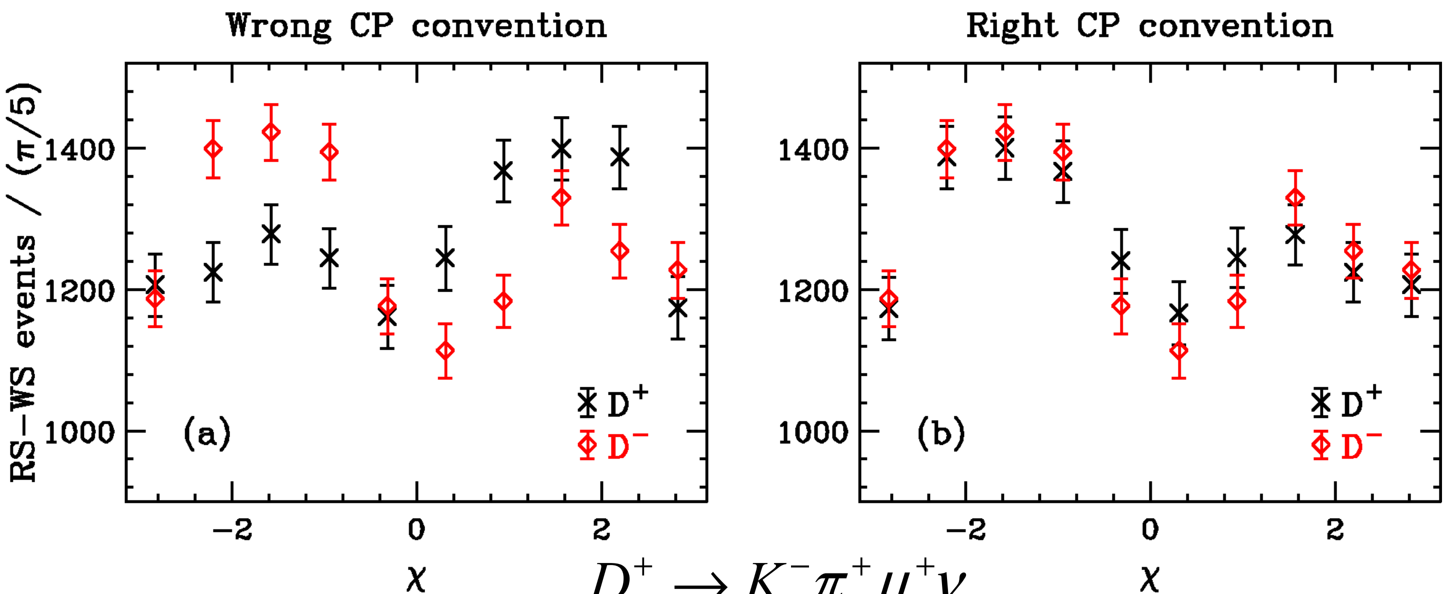
The sine of the acoplanarity requires 5 vectors to specify

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

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 $-\chi$

Saw apparent CP violation earlier. Was this it?

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

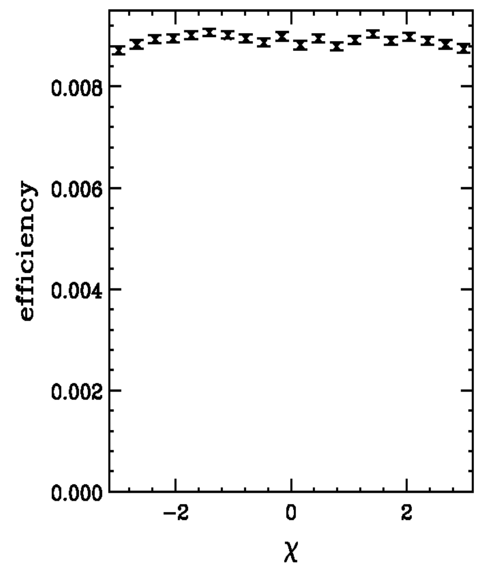


$$D^{+} \rightarrow K^{-}\pi^{+}\mu^{+}\nu$$

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

Same sign convention used for D+ and D-

Opposite sign convention used for D+ versus D-

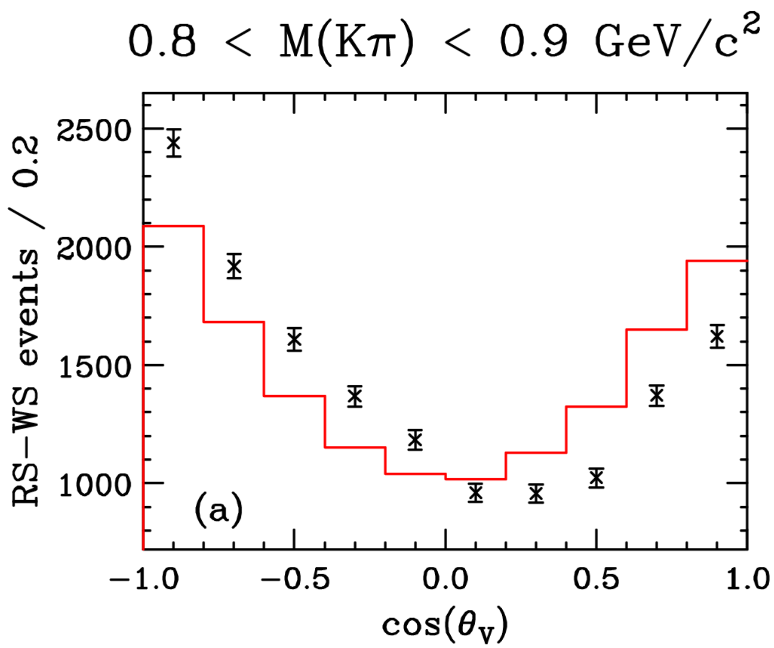


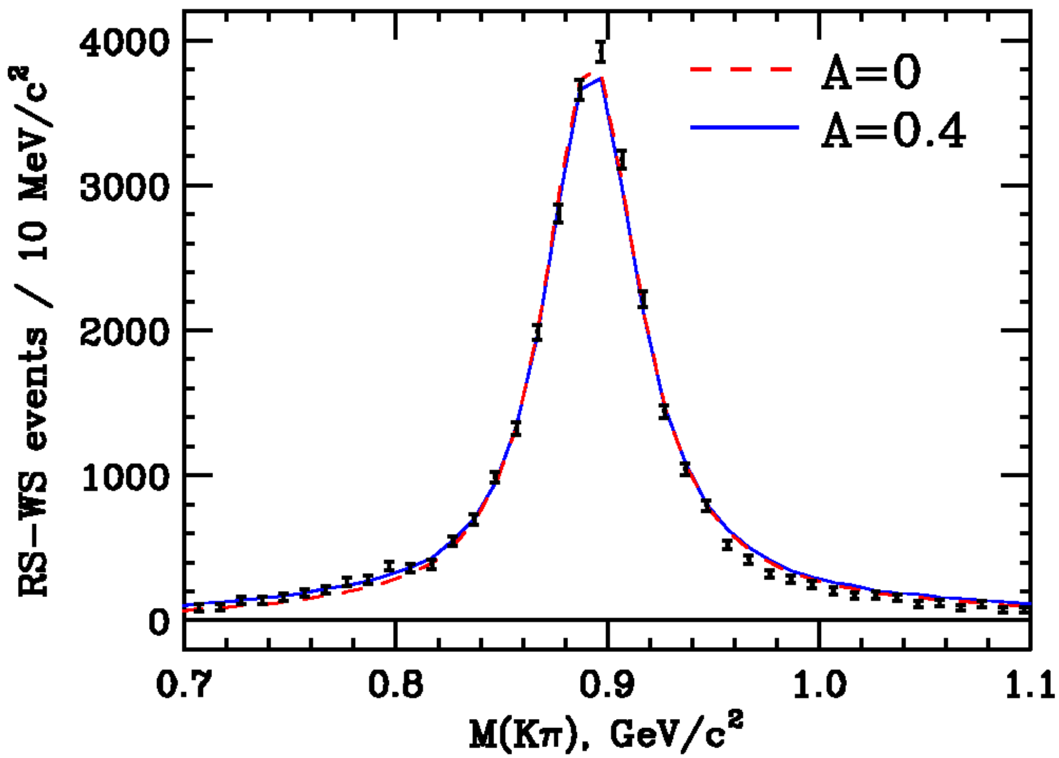
We have uniform χ efficiency.

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

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

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



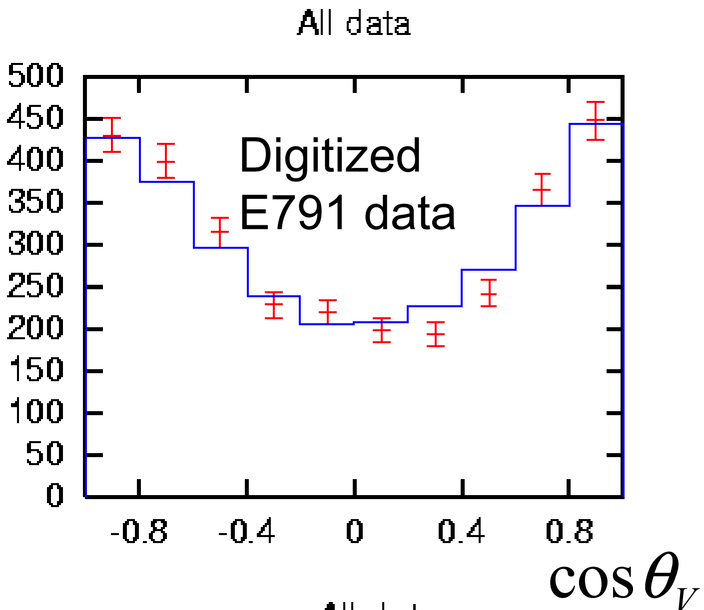


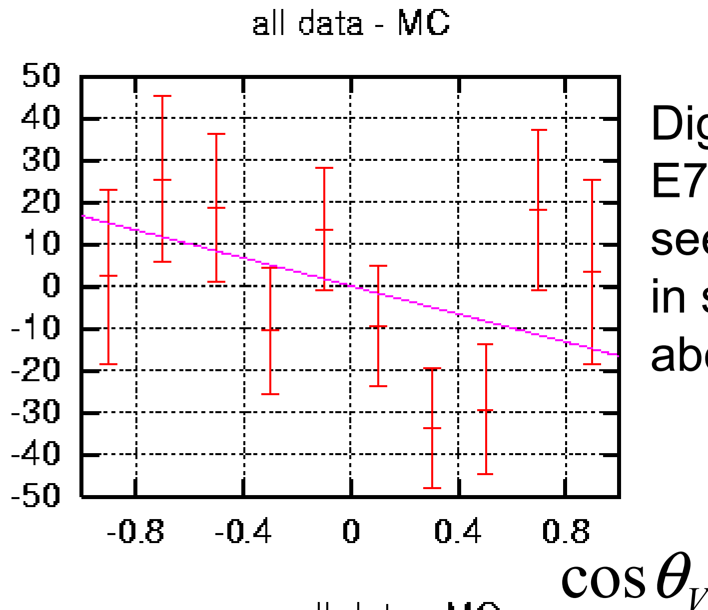
Although the interference significantly distorts the decay intensity....

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

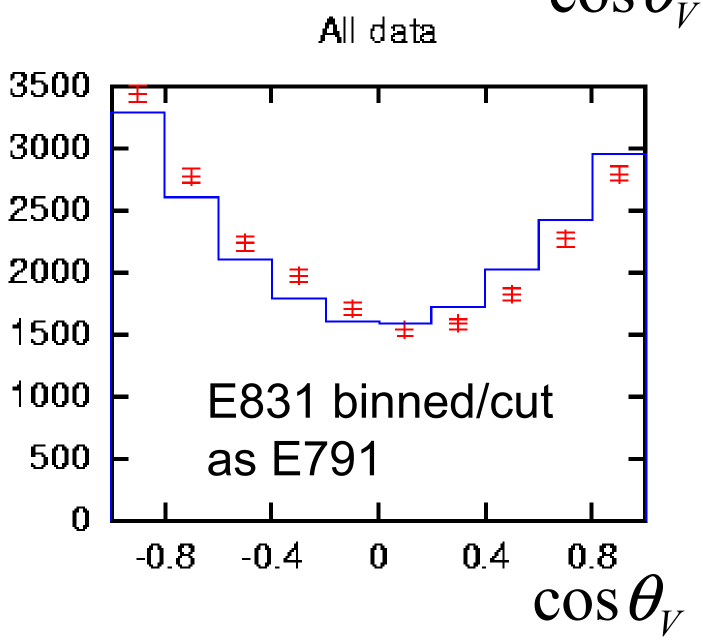
Can we find hints in previously published data?

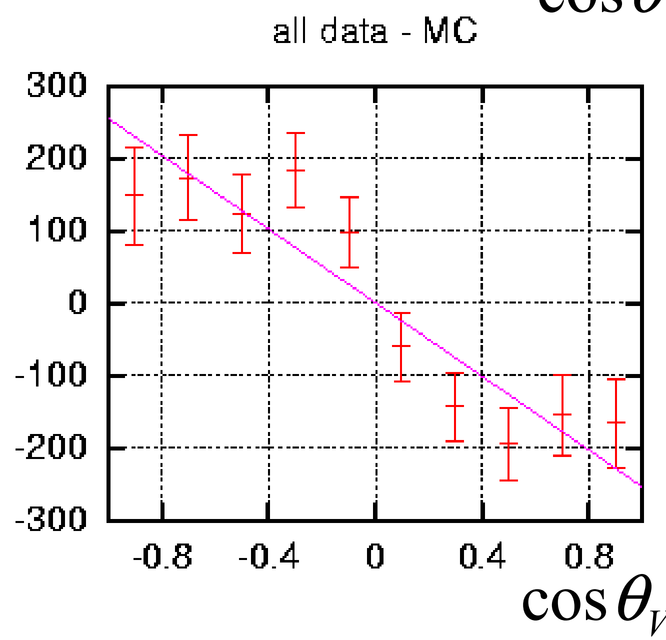
Did E791 see it?





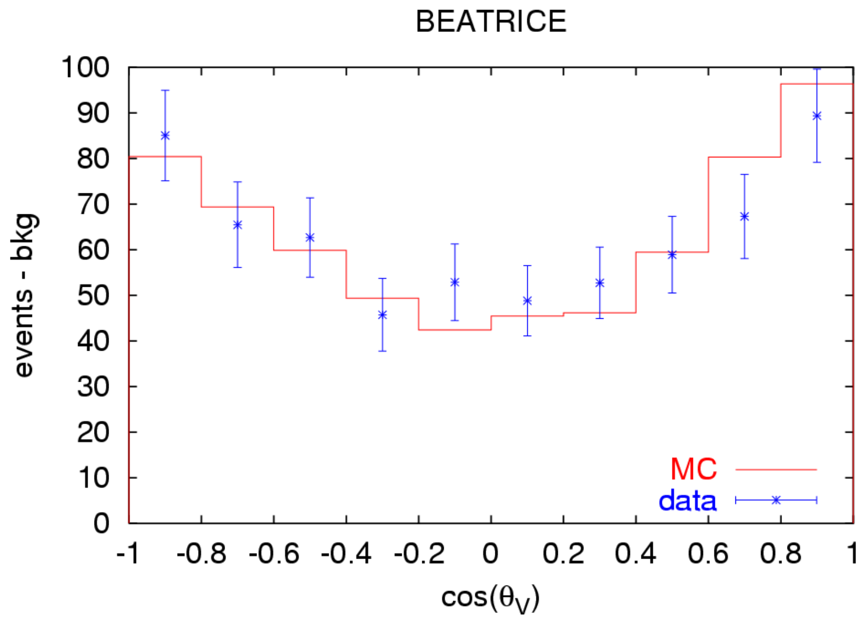
Digitized data from E791 paper. They see an asymmetry in same direction at about 1.5 σ level.

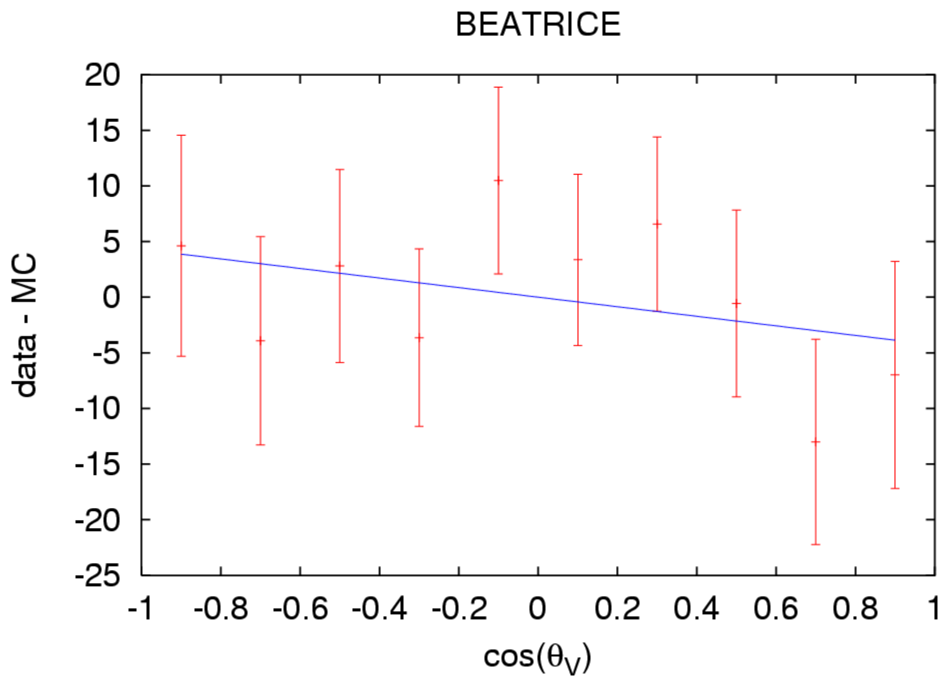




If we bin our data like E791 we see a 6σ asymmetry with a consistent slope. But even with our huge data sample the effect looks rather subtle.

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.

Implications

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

The moral of the story....

The spookiest things might be lurking just around the corner...

You just need to know where to look.

Question slides

Resolution study

- Blank out the softest pion in D→K3π and reconstruct it like a neutrino using DVFREE upstream vertex.
- Compare with "right" answer from reconstructed pion.