Semileptonic Charm Decays and QCD

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July 27, 2004

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    - Form factors of $D_s \to \phi\ \mu\ \nu$
- Part V: Future of Semileptonic decays.

BELLE

CLEO

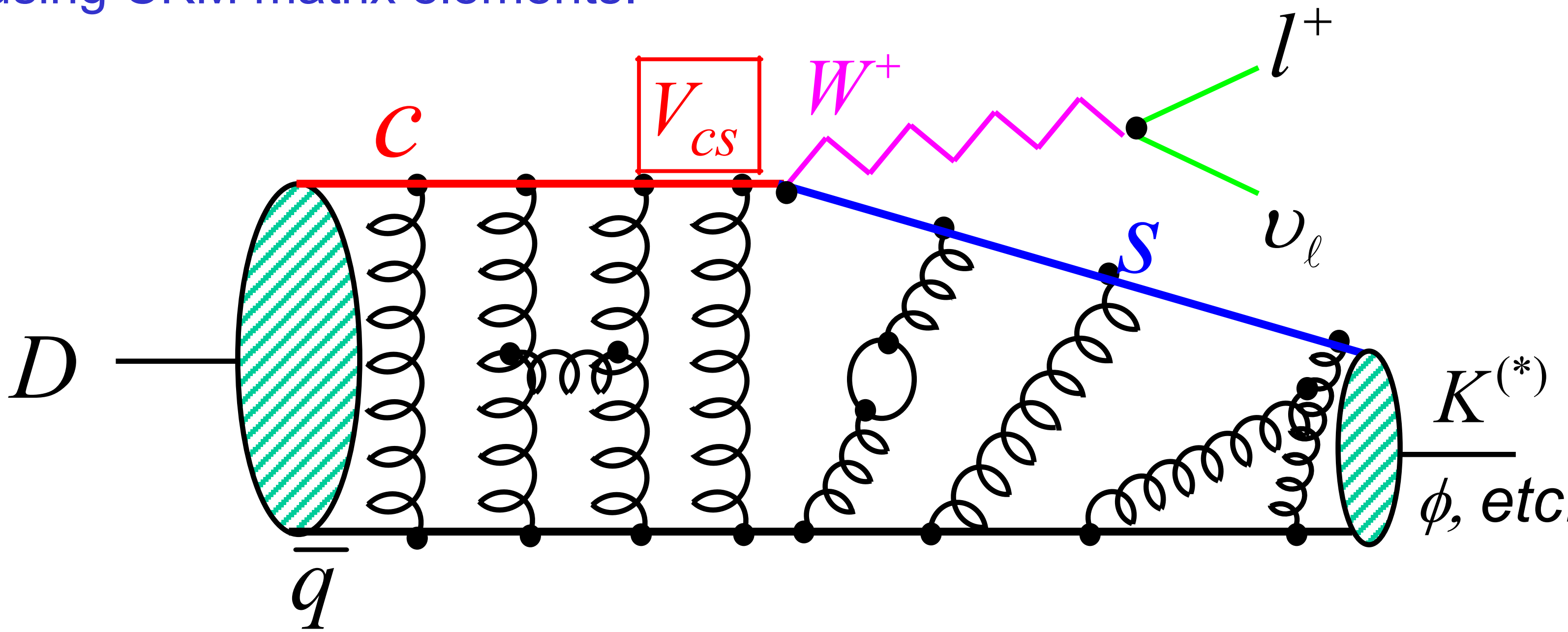
E831 FOCUS

E687

E791

I: Charm semileptonic decay as tests of LQCD

The decay rates are computed from first principles (Feynman diagrams) using CKM matrix elements.



The hadronic complications are contained in the form factors, which can be calculated via non-perturbative Lattice QCD, HQET or quark models.

Charm SL decays provide a high quality lattice calibration, which is crucial in reducing systematic errors in the Unitarity Triangle. The techniques validated by charm decays can be applied to beauty decays.

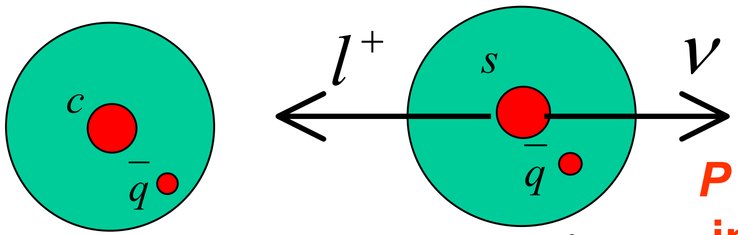
II: Pseudoscalar *l* ν decays

Simple kinematics → Easy to extract form factors.

$$\frac{d\Gamma\left(D \to P\ell\nu\right)}{dq^2} = \frac{G_F^2\left|V_{cq}\right|^2 P_P^3}{24\pi^3}\left\{\left|f_+(q^2)\right|^2 + O(m_l^2)\right\}$$

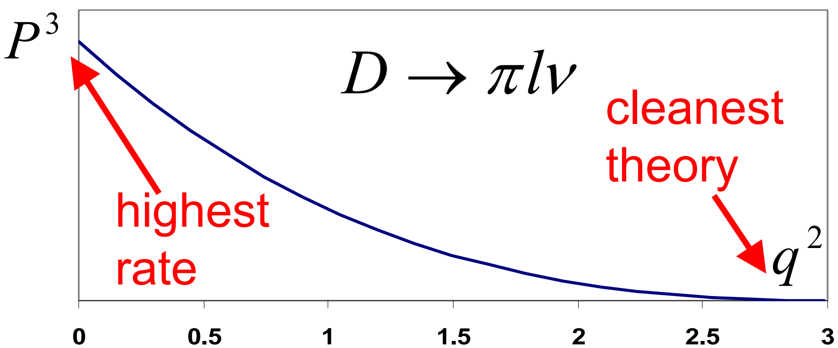
But a major disconnection exists between experiment and theory. In the past, theories worked best where experiments worked worst.

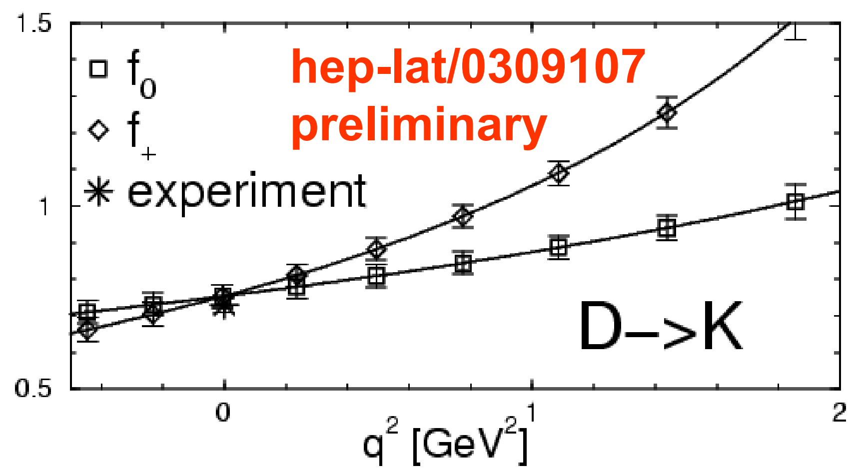
$q^2 = q^2_{\max}$ **is the easiest point for LQCD calculation.**



P at rest in D frame

$$a_{\text{lattice}} \ll \lambda_{\text{daughter}}$$

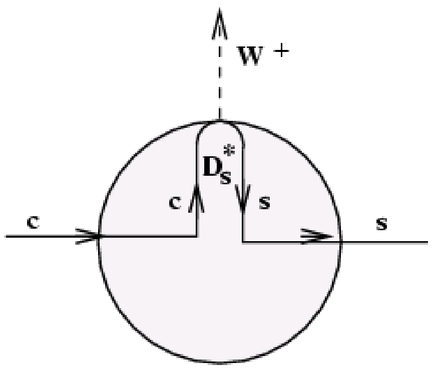




The lattice community is actively fixing the situation and calculating f+ as a function of q^2.

Comparing Pole versus ISGW forms in $D\to\pi l\nu$

Until <u>quite</u> recently one required a specific parameterized form to bridge the gap between a theory and an experiment, since neither an experiment nor a theory had clean $f_+(q^2)$ information.



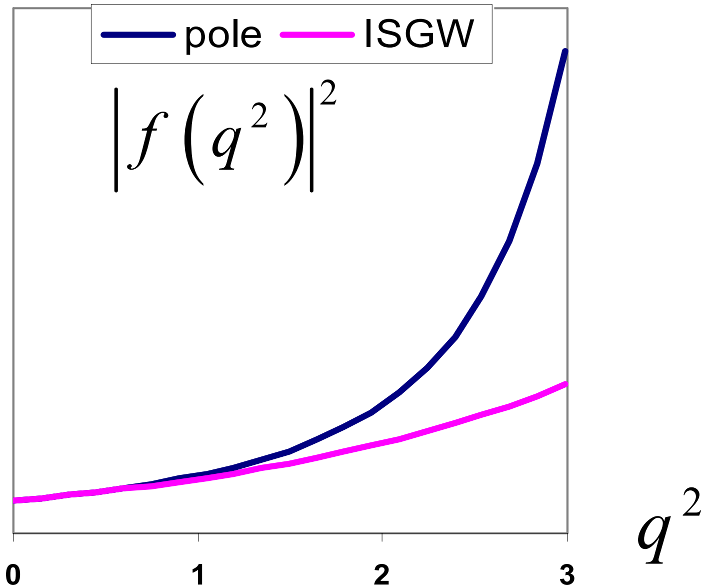
$f_+(q^2)$ parameterization

pole $\quad f_+ \propto \dfrac{1}{q^2 - m^2_{pole}}$

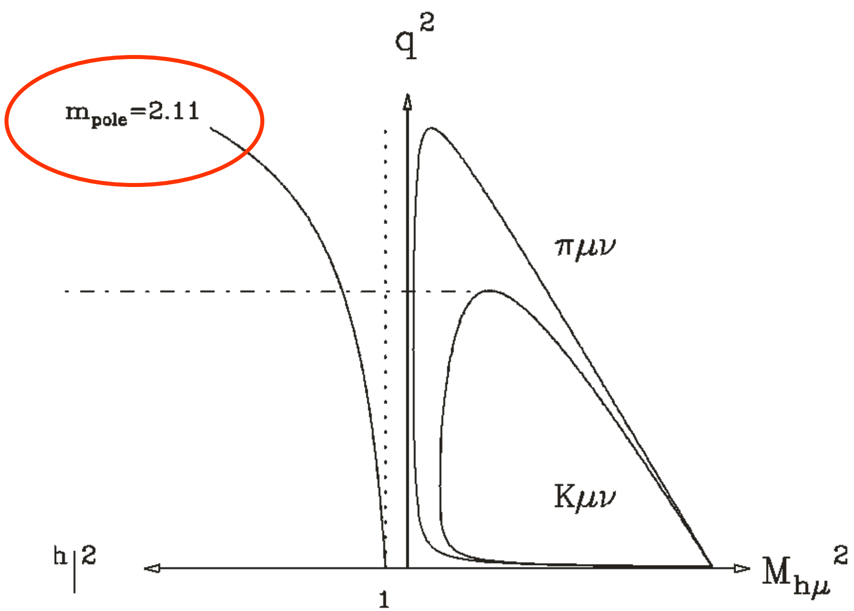
ISGW1 $\quad f_+ \propto \exp\left(\alpha q^2\right)$

ISGW2 **Updated one.**

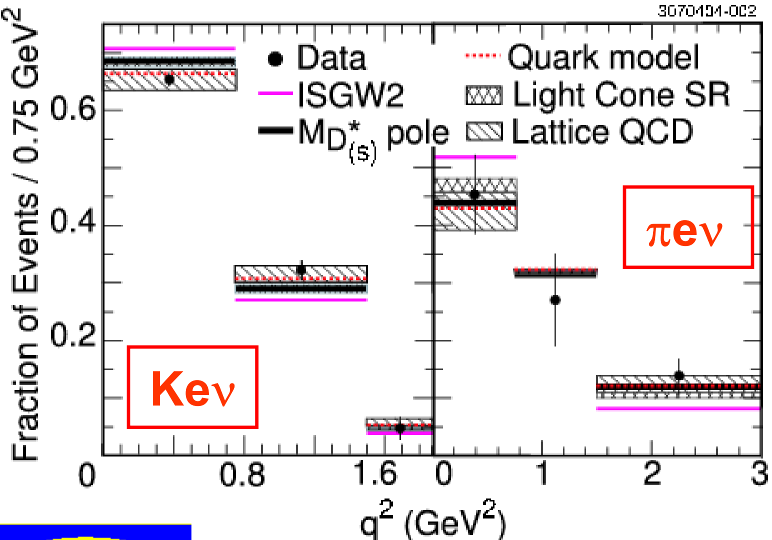
The difference between these forms can be quite dramatic in $\pi\mu\nu$ decays.



Especially since $\pi\mu\nu$ decay gets <u>quite</u> close to the D* pole.



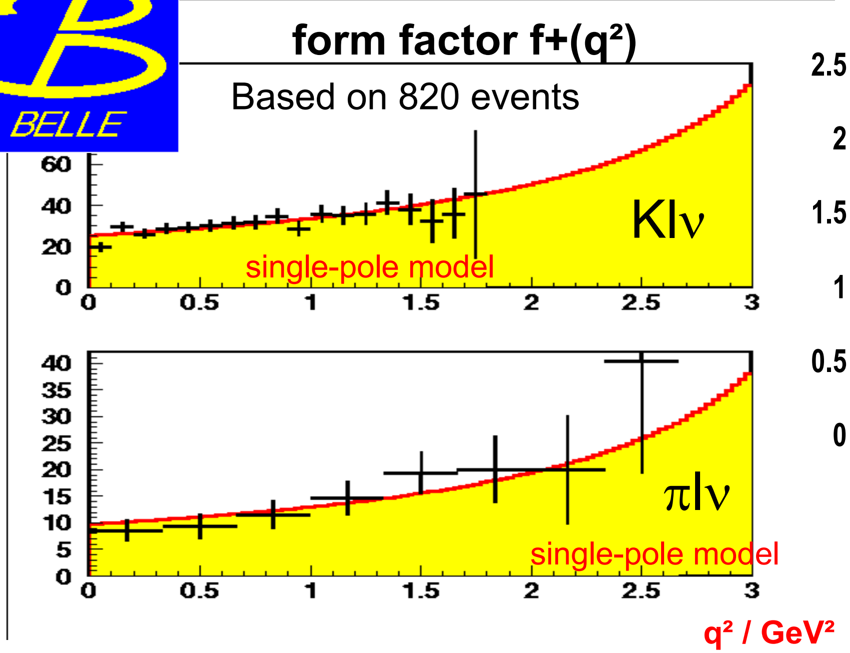
Brand new q^2 information in $D \to \pi l \nu / K l \nu$

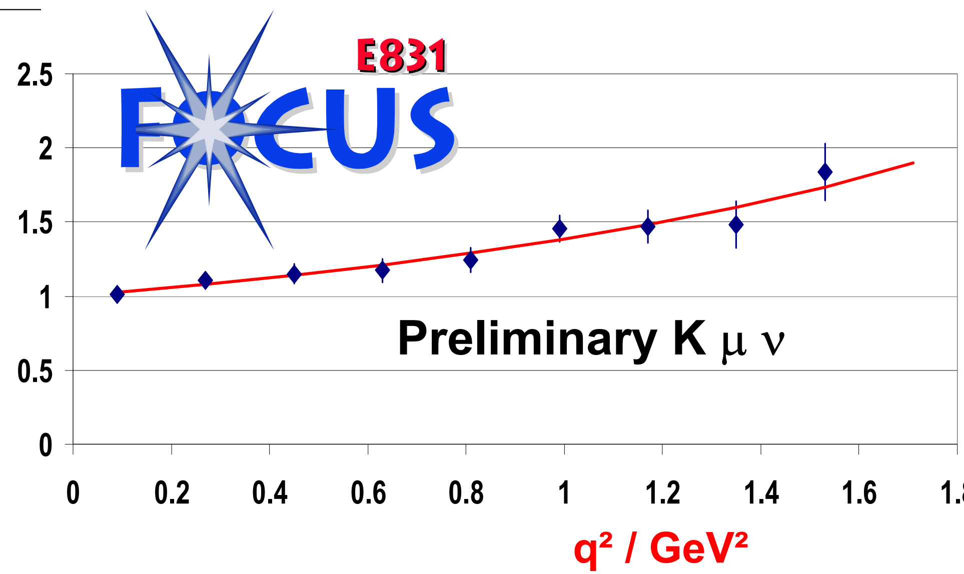


Preliminary Cleo 2004
πeν pole mass is

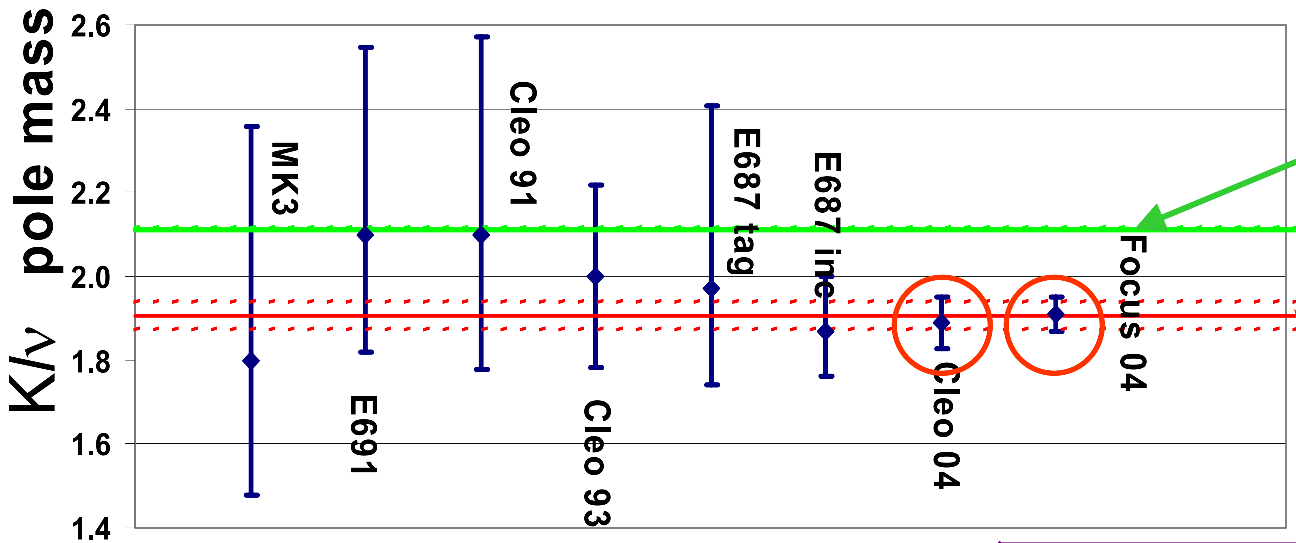
$$1.86^{+0.10+0.07}_{-0.06-0.03}\ \mathrm{GeV}$$

It disfavors ISGW2 form by ~4.2σ





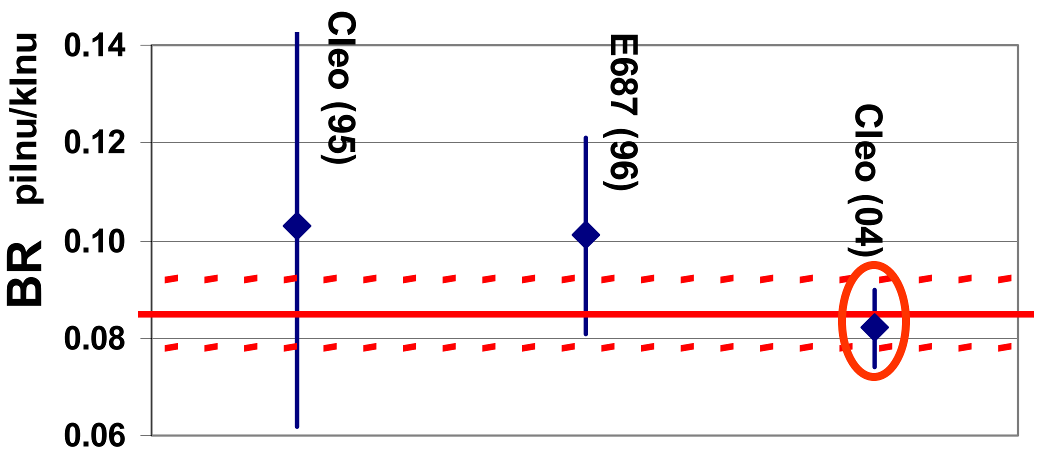
Summary of D→πlν/Klν Results



Clearly the data does not favor the simple Ds* pole

1.91 ± 0.03

$$\frac{d\Gamma(D \to P\ell\nu)}{dq^2} = \frac{G_F^2 |V_{cq}|^2 P_P^3}{24\pi^3} |f_+(q^2)|^2$$



A big advance in precision!

$$\frac{\Gamma(\pi e\nu)}{\Gamma(K e\nu)} = 0.082 \pm .006 \pm 0.005 \text{ CLEO}$$

$$\frac{|f_+^\pi(0)|}{|f_+^K(0)|} = 0.86 \pm 0.07 \pm 0.05 \pm 0.01$$

Consistent w/ SU(3) breaking

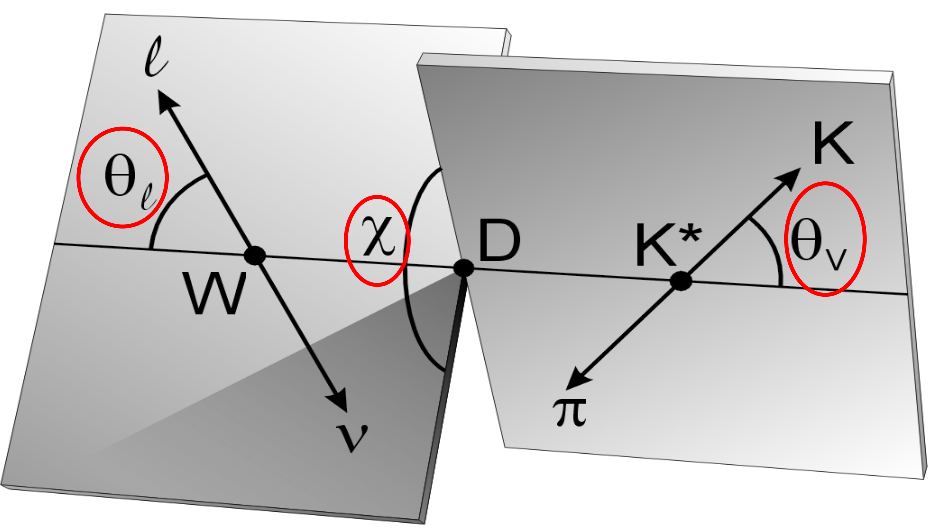
III: D→vector μ ν decays

Two amplitudes get sumed over W polarization using D-matrices

right-handed μ^+ **left-handed μ^+**

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

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



Helicity FF are combinations of one vector and two axial form factors.

$$A_i(q^2) = \frac{A_i(0)}{1 - q^2/M_A^2}$$

$$V(q^2) = \frac{V(0)}{1 - q^2/M_V^2}$$

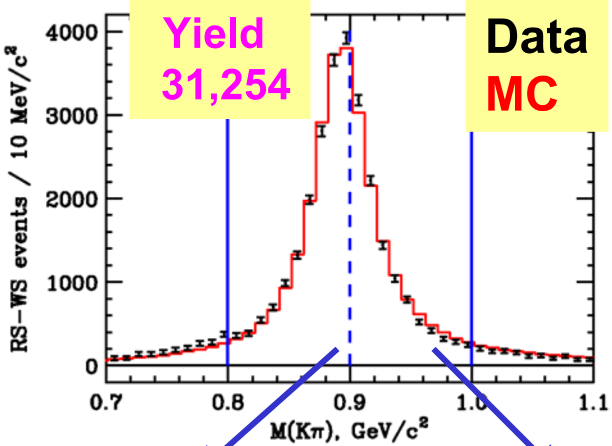
Two observables parameterize the decay

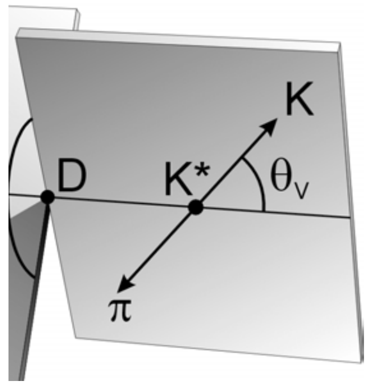
$$r_v \equiv V(0)/A_1(0)$$

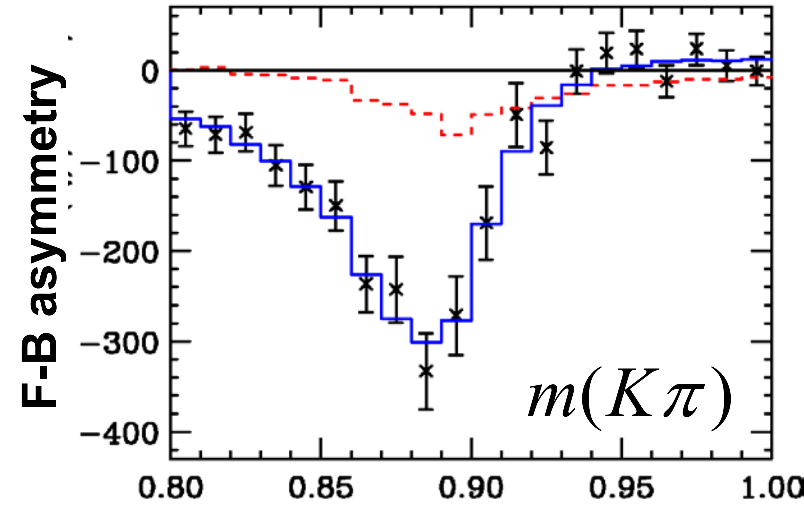
$$r_2 \equiv A_2(0)/A_1(0)$$

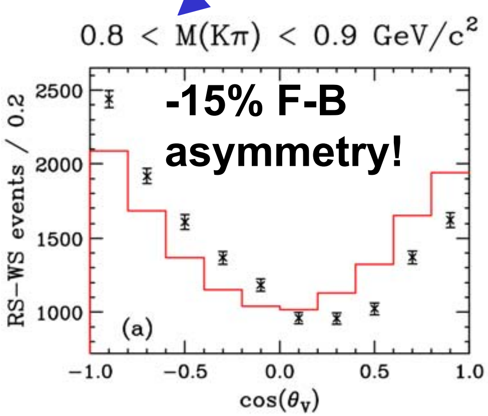
Interference in $D^+ \to K^* \mu\nu$

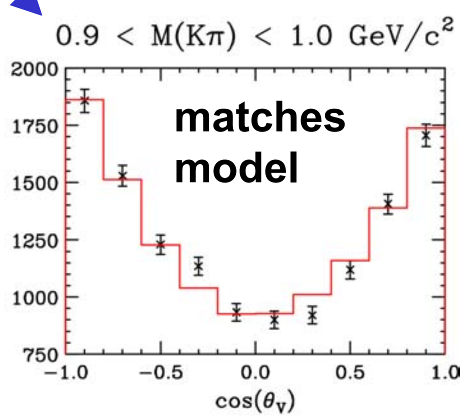
Focus "K*" signal











E831 FOCUS

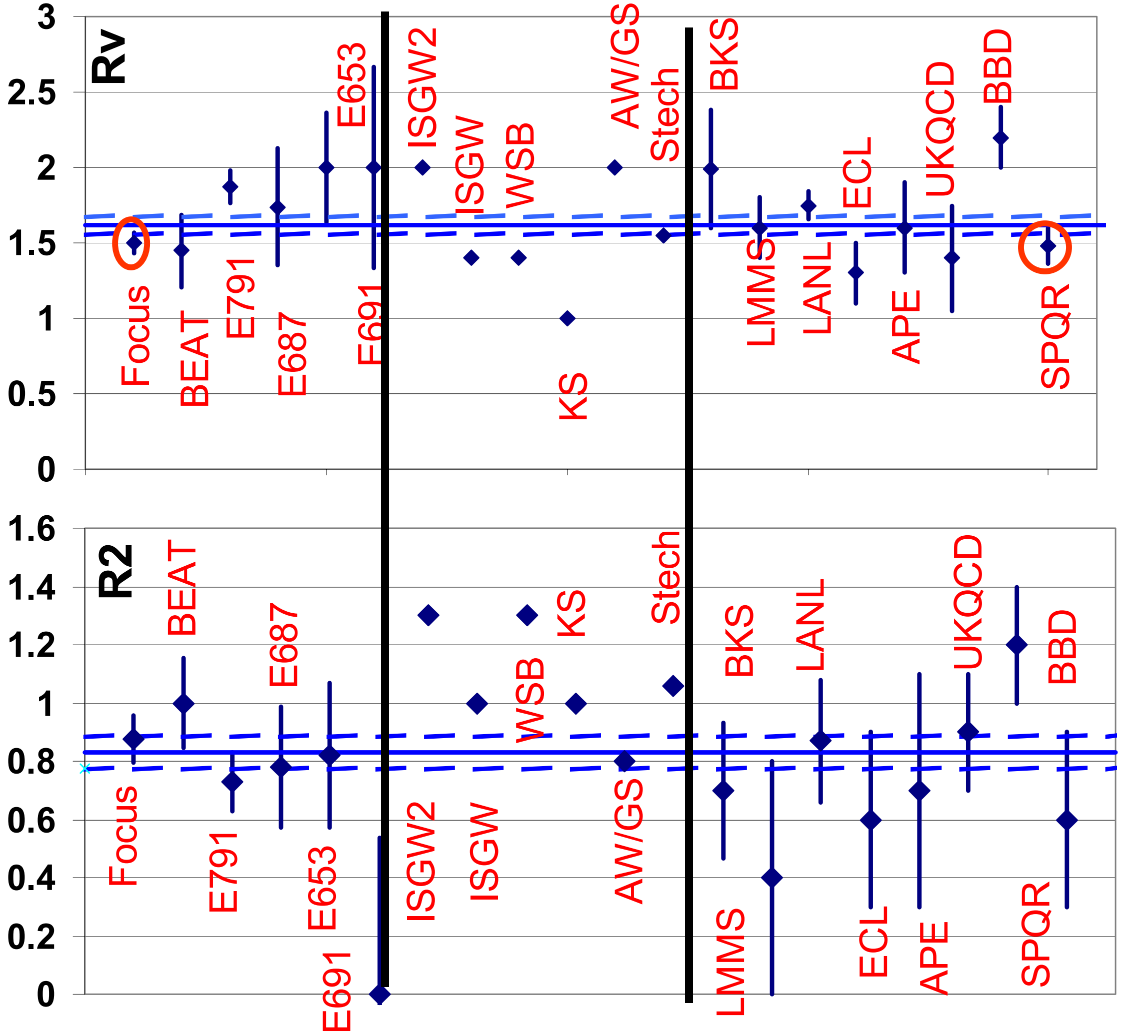
(2002)

$K^* \mu\nu$ interferes with S- wave $K\pi$ and creates a forward-backward asymmetry in the K* decay angle with a mass variation due to the varying BW phase.

The S-wave amplitude is about 7% of the (H_0) K* BW with a 45° relative phase

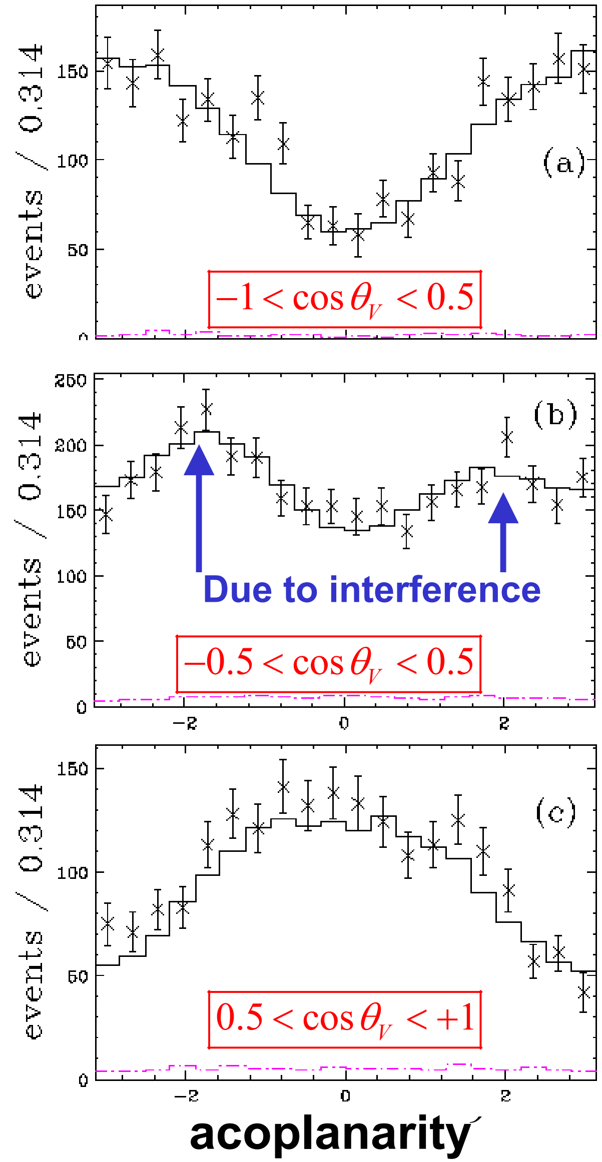
It's the same relative phase as the LASS (1988)

K*μν form factors

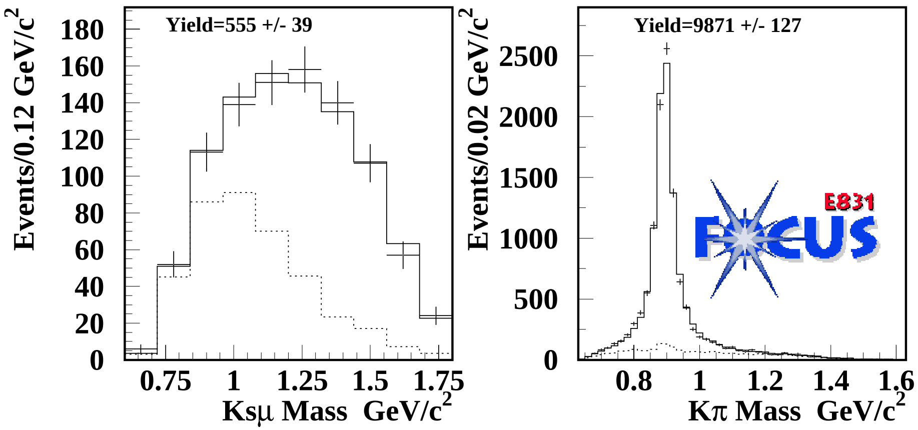


Results are getting very precise and unquenched calculations for incisive tests of the theory would be very desirable.

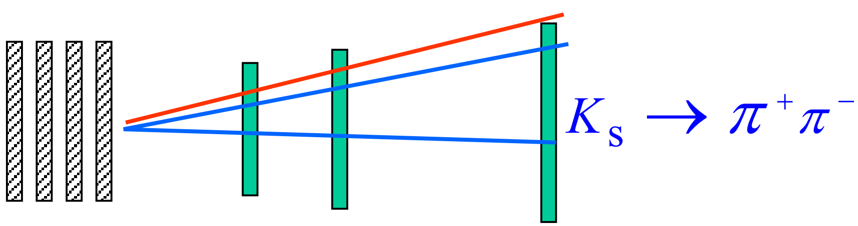
Precision tests of the model.



Direct measurement of Γ (D+→K*μν / Kμν)



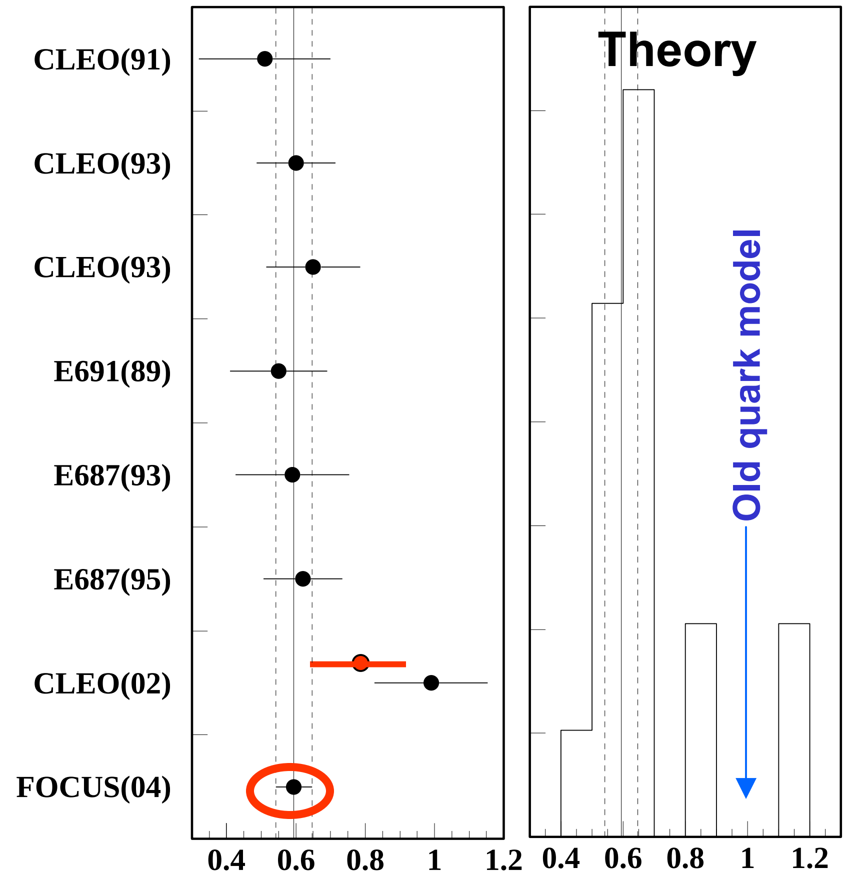
Use upstream K_s (~10%) so that both the numerator ($K\pi\mu\nu$) and denominator ($K_s\,\mu\nu$) leave 3 tracks in FOCUS μ-strip



$$\frac{D^+ \to \bar{K}^{*0}\mu^+\nu}{D^+ \to \bar{K}^0\mu^+\nu} = 0.594 \pm 0.043 \pm 0.033$$

S-wave corrected

$D^+ \to \bar{K}^{*0} l^+ \nu / \bar{K}^0 l^+ \nu$



using B($D^0 \to K^-\mu^+\nu$)

CLEO(02) partially reflects an inconsistency in $\Gamma\ (D^+ \to \bar{K}^0 e^+\nu)$

$$\Gamma_{\bar{K}^0\mu^+\nu}(D^+) - \Gamma_{K^-\mu^+\nu}(D^0) = (11 \pm 11)/ns$$

$$\Gamma_{\bar{K}^0 e^+\nu}(D^+) - \Gamma_{K^- e^+\nu}(D^0) = (-25 \pm 9.7)/ns$$

The $D_s \to \phi\mu\nu$ form factor enigma

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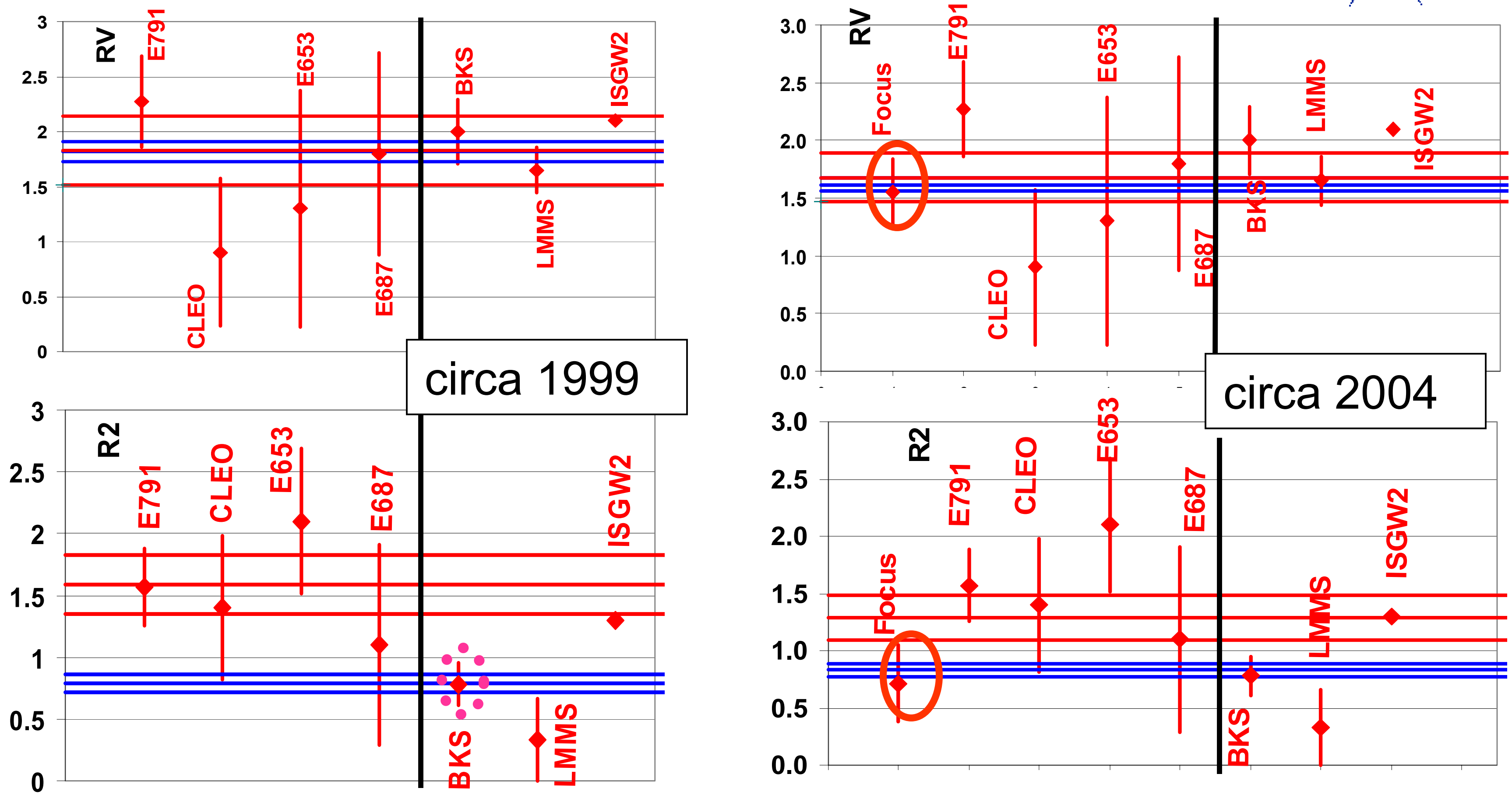
$D_s \to \phi\mu\nu$ versus $D^+ \to K^*l\nu$



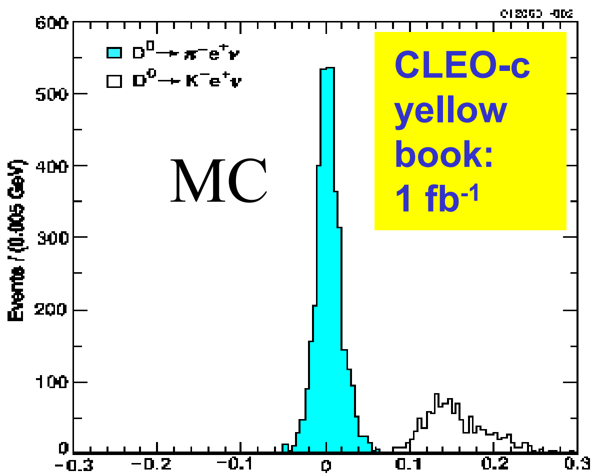
Theoretically, the $Ds \to \phi l\nu$ form factors should be within 10% of $D^+ \to K^*l\nu$. The r_V values were consistent, but r_2 for $Ds \to \phi l\nu$ was $2 \otimes$ higher than $D^+ \to K^*l\nu$.

But the (2004) FOCUS measurement obtained a consistent r_2 value as well!

The future of charm SL physics

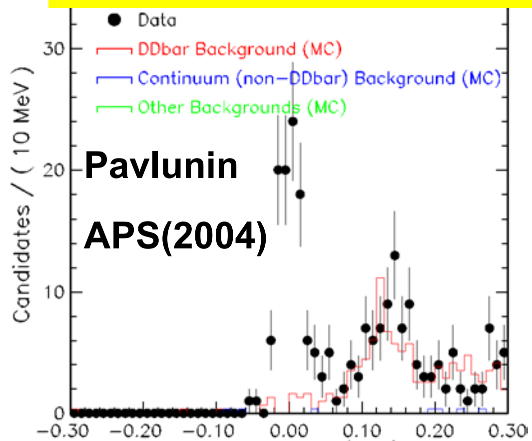
Cleo-c and Bes III: Run at Ψ(3770) with high luminosity and modern detectors.

Precision neutrino closure in $D \to \pi e \nu$.



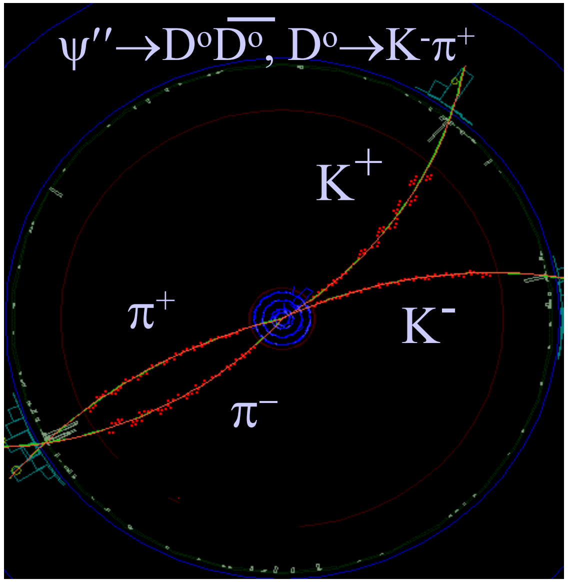
$U = E_{miss} - P_{miss}$

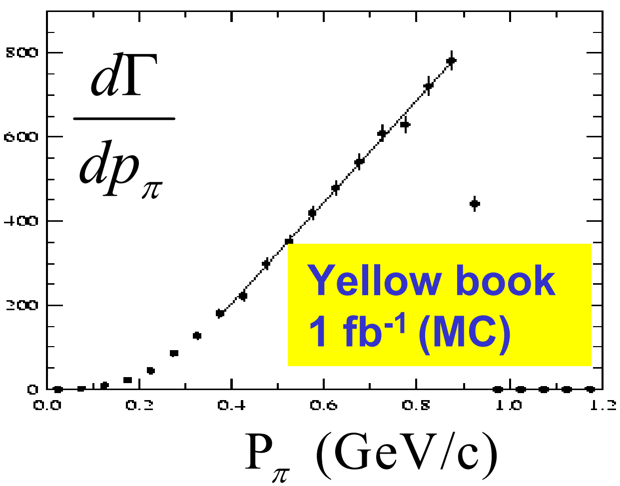
Prelim. data (60 pb^{-1})

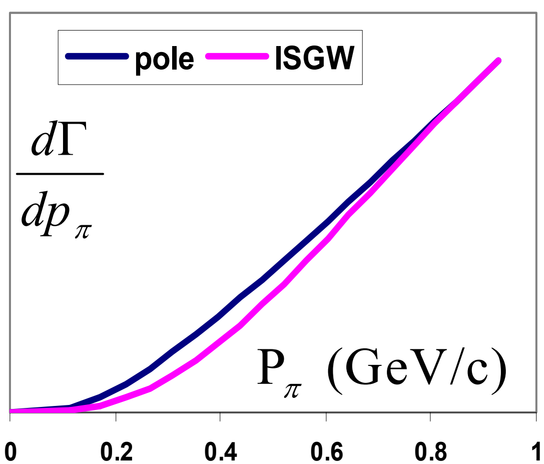


$U = E_{miss} - P_{miss}$

Extremely clean events!







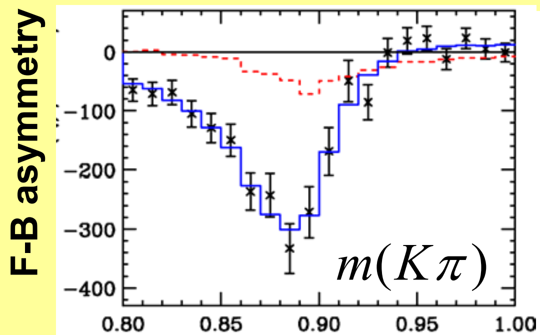
The q^2 impasse afflicting SL data for the last 20 years shall be solved, finally.

Summary

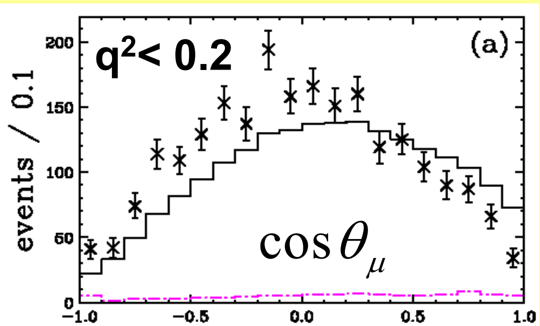
New CLEO 2004 D→πeν/Keν result

$$\frac{\Gamma(\pi e\nu)}{\Gamma(Ke\nu)} = 0.082 \pm .006 \pm 0.005 \qquad \frac{|f_+^\pi(0)|}{|f_+^K(0)|} = 0.86 \pm 0.07 \pm 0.05$$

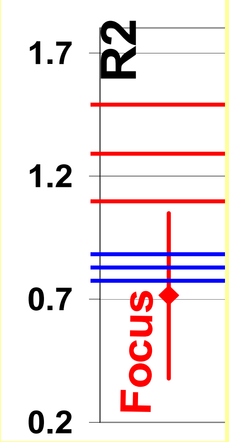
$$m_{\rm pole}^{D\to K} = 1.89^{+0.05+0.04}_{-0.05-0.03}\ {\rm GeV} \quad < m(D_s^*)$$

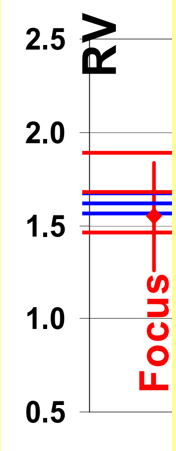


s-wave interference in $D^+ \to K^* \mu\nu$



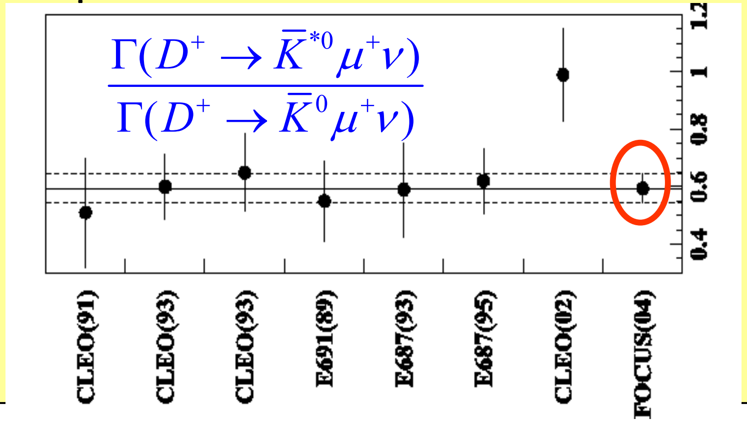
V($q^2 \to 0$) problem $D^+ \to K^* \mu\nu$



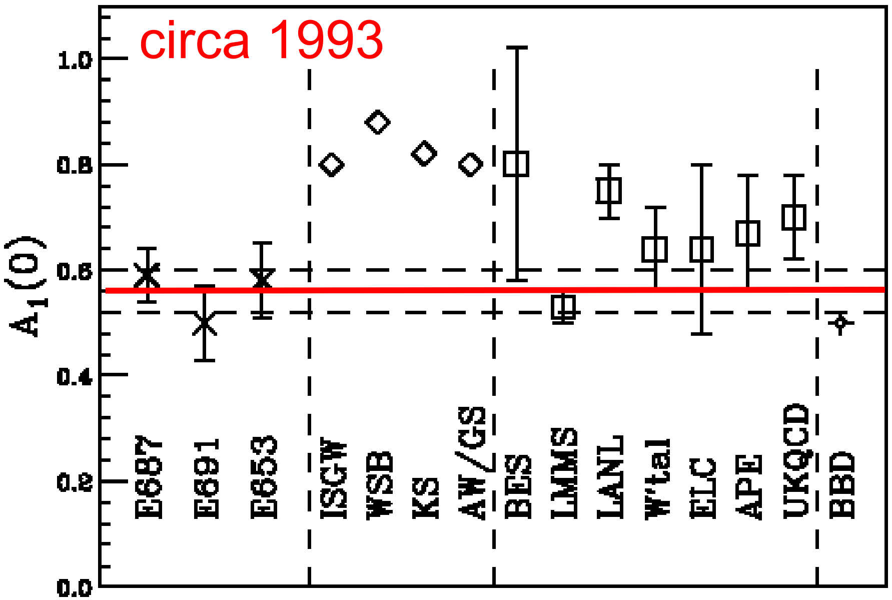


Consistent FF for $D^+ \to K^* \mu\nu$ & $D_s^+ \to \phi\,\mu\nu$

V/PS ratio

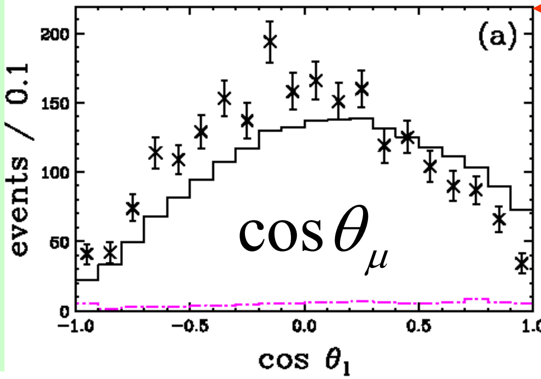


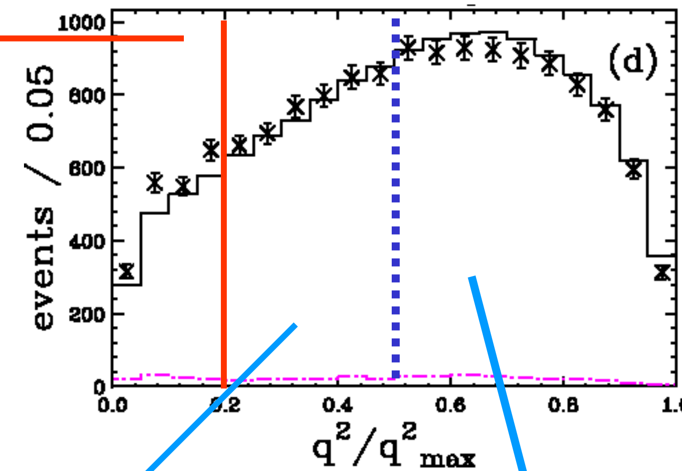
Γ (D+→K*μν / Kμν) circa 1993



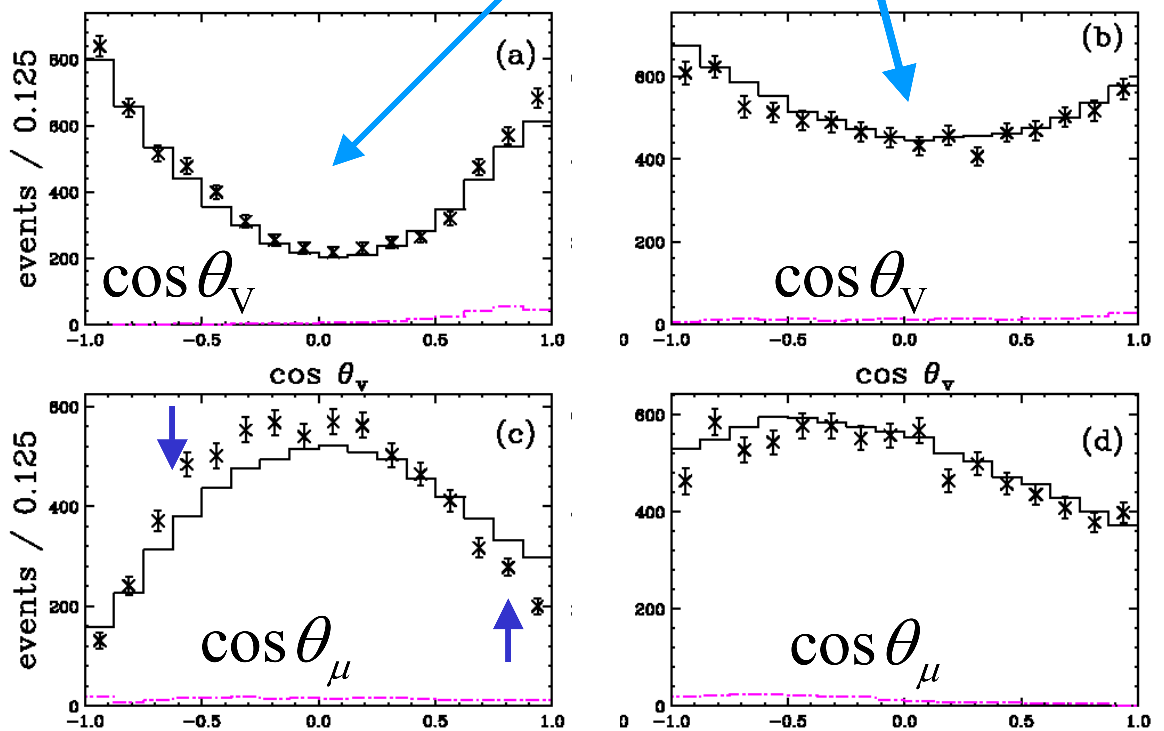
Some more tests of the K*μν model

A **dramatic** mismatch is seen at very low q^2 suggesting a $V(q^2 \rightarrow 0)$ problem





Generally the model tracks the data rather well…



Focus has a preliminary analysis of the K^{*0} line shape. $\Gamma(K^{*0})$ is seen as less than PDG by ~1.6 MeV.