Semileptonic Charm Decays

Doris Y Kim
University of Illinois

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Content

I: Why We Study Charm Semileptonic Decays.

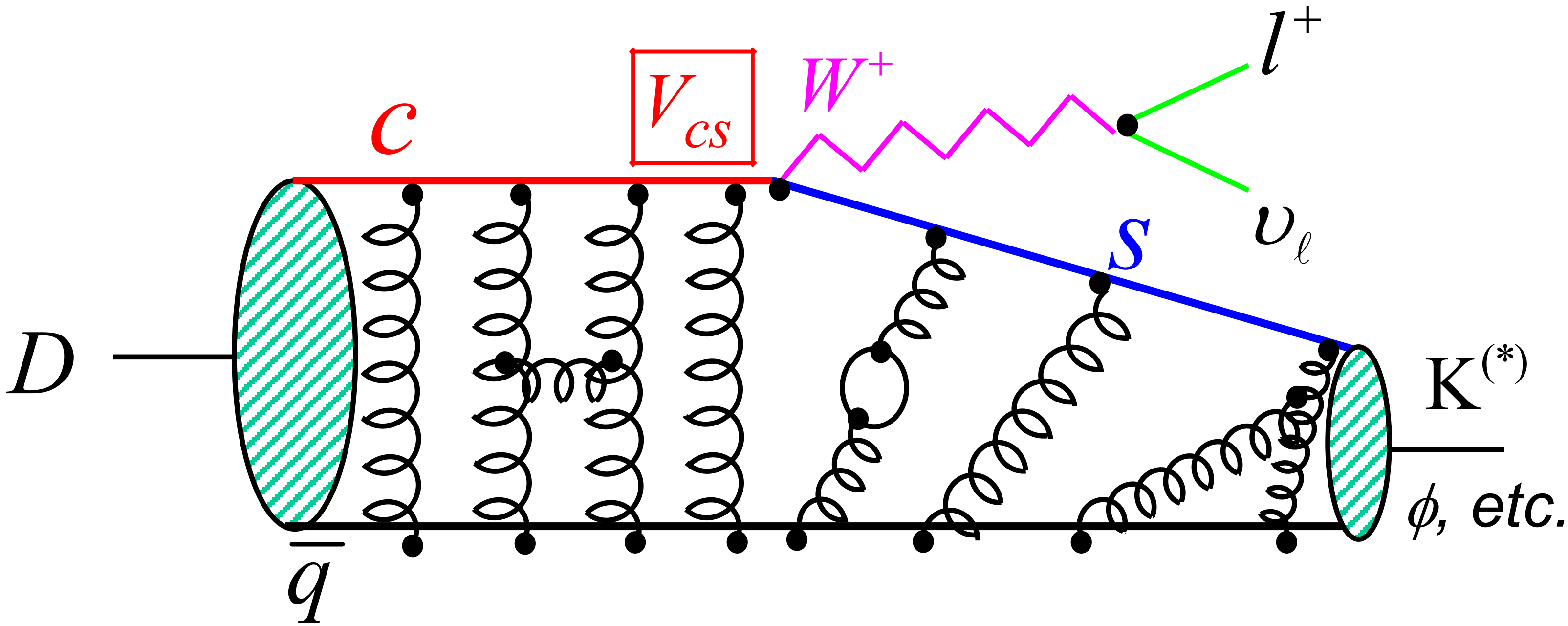
II: Recent Analyses on Semileptonic BF, from BES and CLEO-c.

III: Form Factors for PseudoScalar l ν, from BaBar, Belle, CLEO-c, & FOCUS.

IV: Vector l ν Form Factors from CLEO-c.

I. Charm Semileptonic Decays as Tests of QCD

BF (decay rate) study provides a measurement of $|V_{cq}|^2$



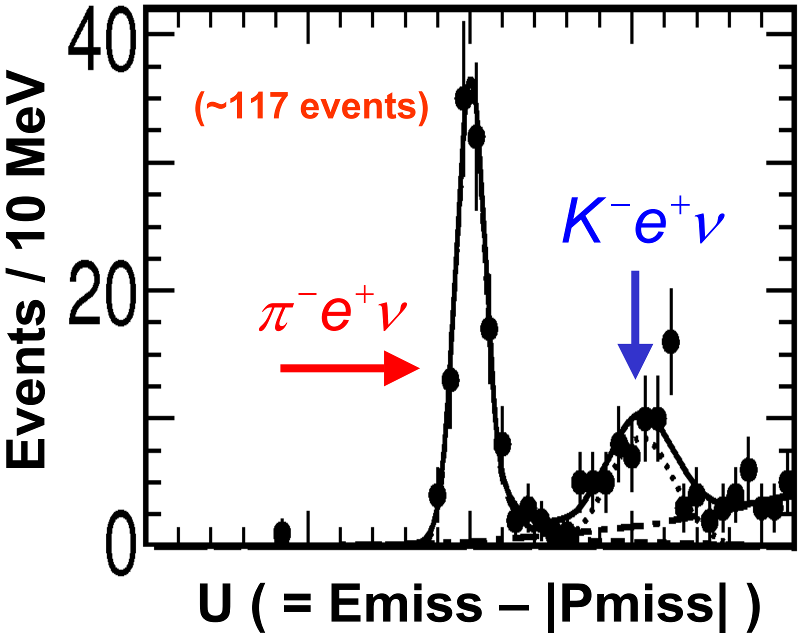
The hadronic complications are contained in the form factors, which can be calculated via non-perturbative lattice QCD, HQET, quark models, etc.

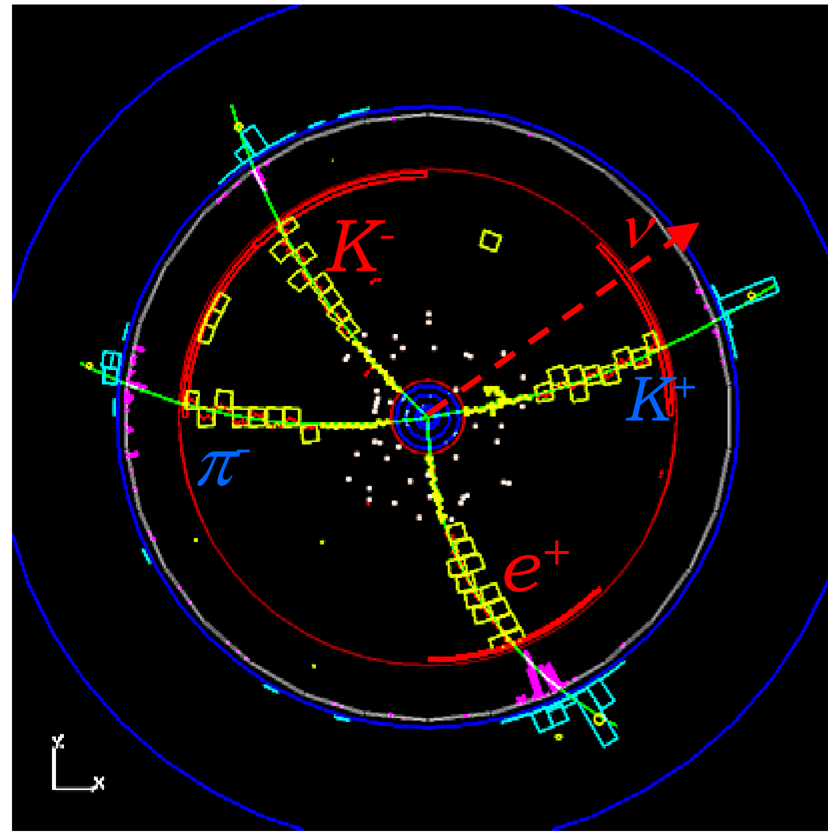
Charm SL decays provide a high quality lattice calibration, which is crucial in reducing systematic errors in the Unitarity Triangle. The techniques validated by charm decays can be applied to beauty decays.

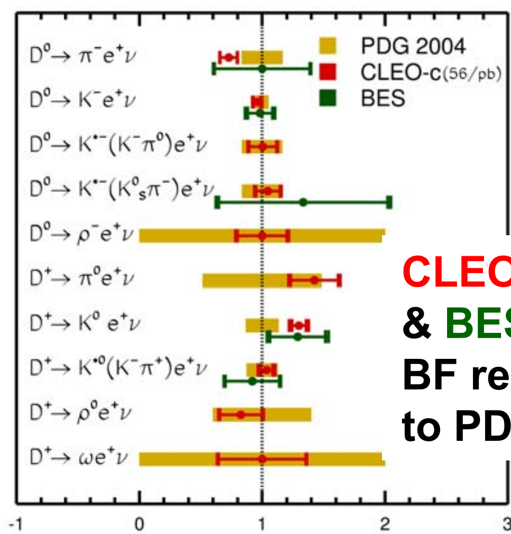
⇒ Improvement of CKM @ beauty sector.

An Example of Semileptonic Decays: CLEO-c

Example: $D^0 \to \pi^- e^+ \nu$







CLEO-c (56/pb)
& BES
BF relative
to PDG 04

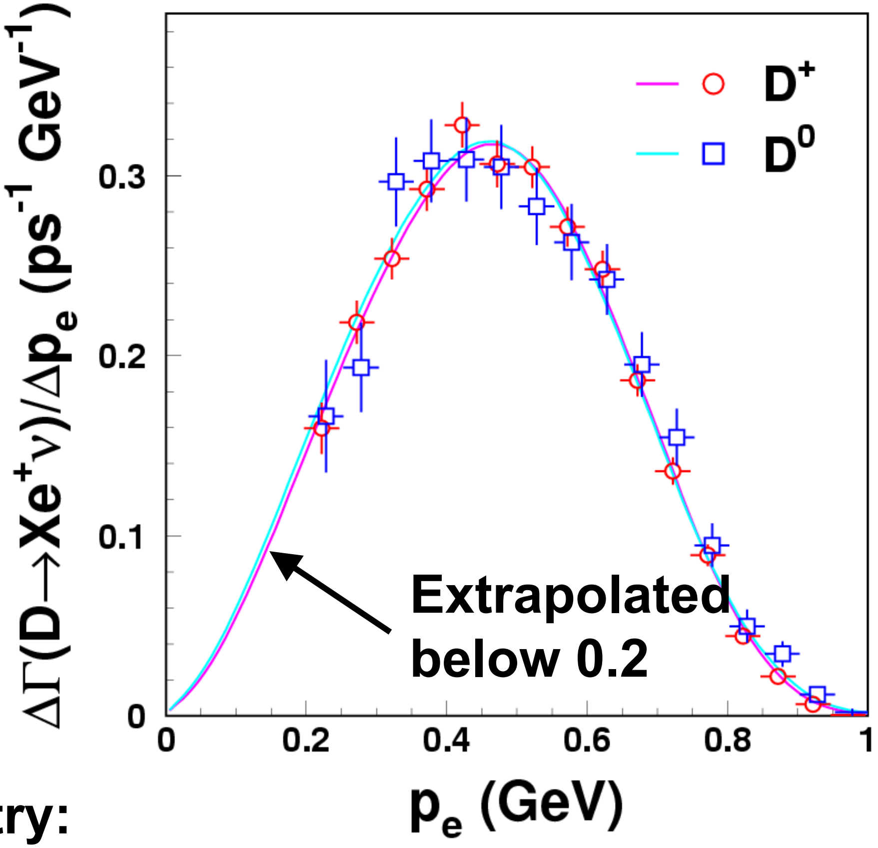
$$\psi(3770) \to D^0 \bar{D}^0$$
$$\bar{D}^0 \to K^+ \pi^-, \; D^0 \to K^- e^+ \nu$$

II. Inclusive Semileptonic BF.

Inclusive BF vs sum of exclusive BF

CLEO-c 281 pb^{-1}

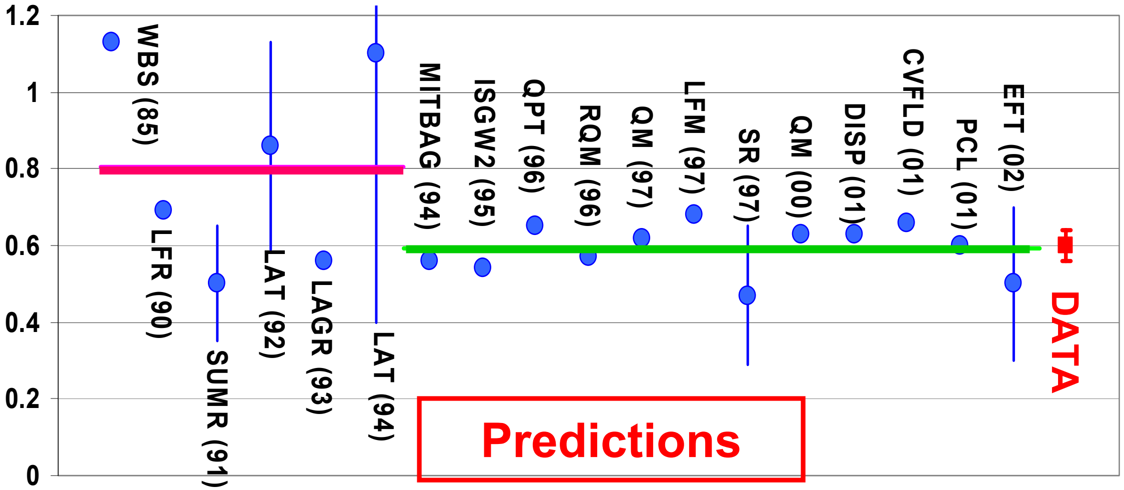
mode	$\mathcal{B}$
$D^0 \to X e^+ \nu$	$(6.46 \pm 0.17 \pm 0.13)\%$
$\Sigma_i \mathcal{B}_i (D^0 \to X e^+ \nu)$	$(6.1 \pm 0.2 \pm 0.2)\%$
$D^+ \to X e^+ \nu$	$(16.13 \pm 0.20 \pm 0.33)\%$
$\Sigma_i \mathcal{B}_i (D^+ \to X e^+ \nu)$	$(15.1 \pm 0.5 \pm 0.5)\%$

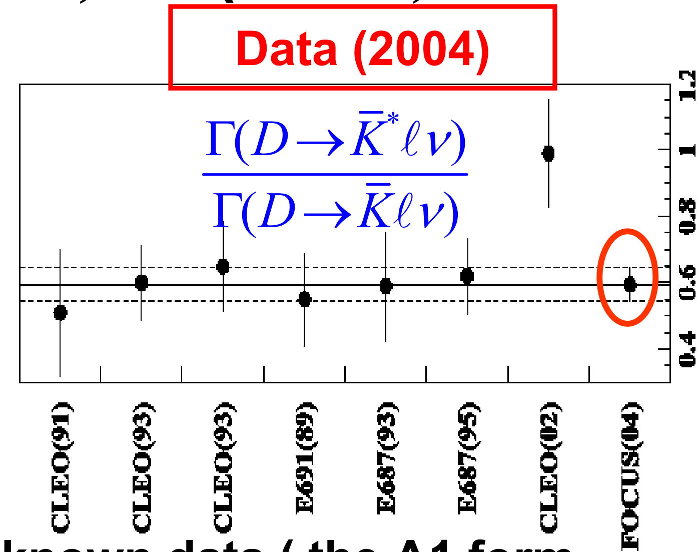


- Consistent with the known exclusive modes saturating the inclusive $\mathcal{B}$.
- Some room for new modes?
- Consistent with SL isospin symmetry:

$$\frac{\Gamma^{SL}_{D^+}}{\Gamma^{SL}_{D^0}} = \frac{B^{SL}_{D^+}}{B^{SL}_{D^0}} \times \frac{\tau_{D^0}}{\tau_{D^+}} = 0.985 \pm 0.028 \pm 0.015$$

V/PS Anomaly in $\Gamma(D \rightarrow K^* l\, \nu)$ / $\Gamma(K\, l\, \nu)$





• Early V/PS predictions were 1.5 – 2 × larger than known data (the A1 form factor problem).

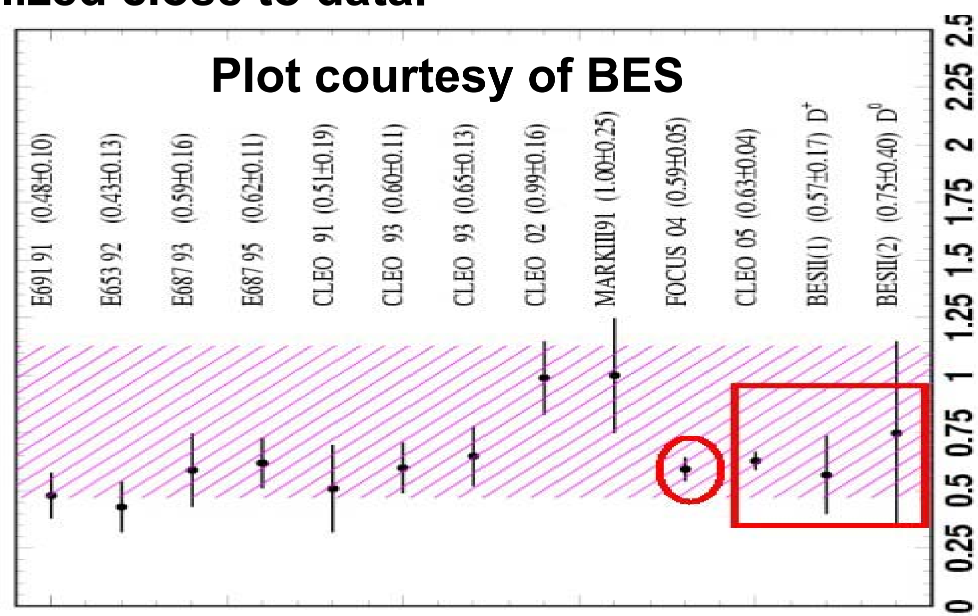
• Since 1995 predictions have stabilized close to data.

• Recent V/PS measurements are consistent:

FOCUS (04)

CLEO(05)

two new BES(06).

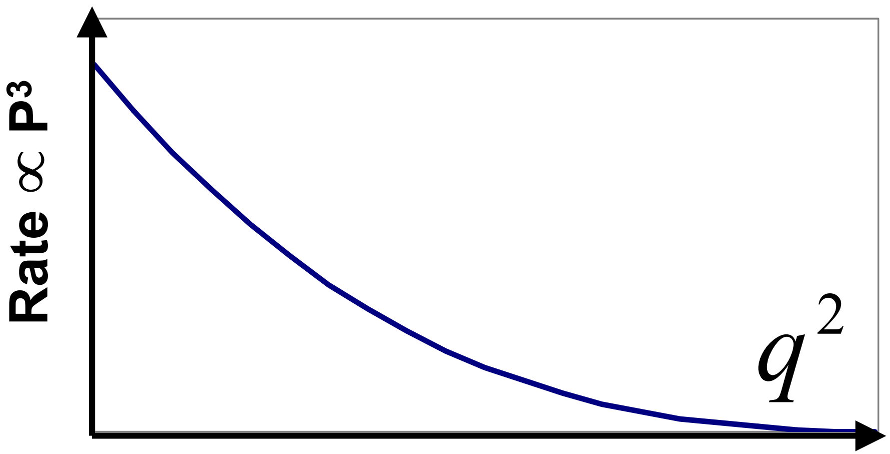


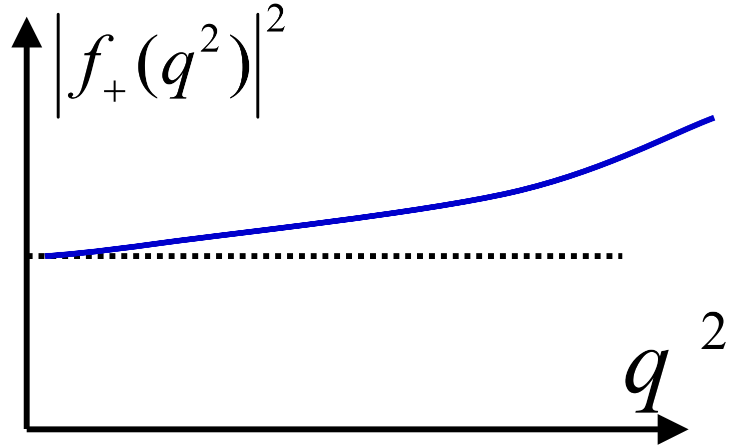
The V/PS anomaly is rapidly fading away.

III. D → Pseudoscalar $l\,\nu$ Form Factors

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

This process can give a clean measurement of CKM angles and powerful tests of LQCD.

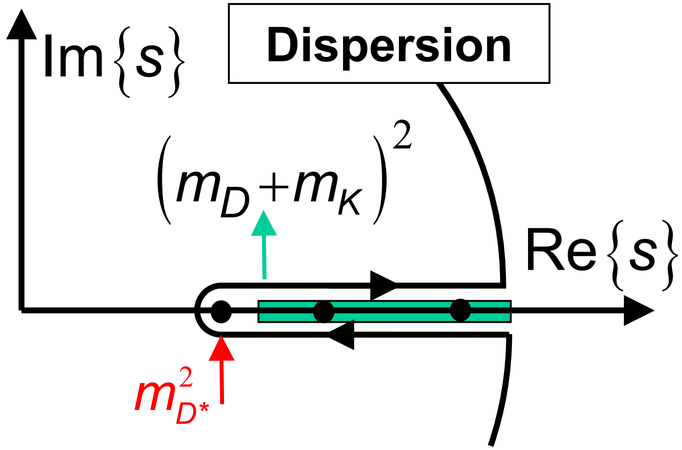


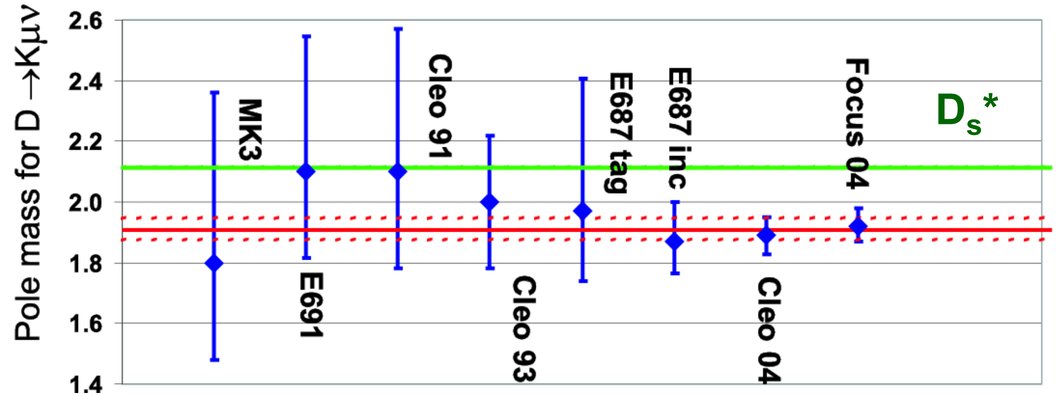


Unfortunately the rate vanishes at highest q^2 where sensitivity to the form of $f_+(q^2)$ is greatest. This is also the zero recoil limit where theory calculations are cleanest.

What do we know about $f_+(q^2)$? →

Pole Dominance Parameterization: D→ K *l* ν / π *l* ν





Fits to $f_+(q^2) \propto \dfrac{1}{m^2_{pole} - q^2}$

$$f_+(q^2) = \frac{\mathcal{R}}{m^2_{D^*} - q^2} + \boxed{\frac{1}{\pi}\int_{(m_D+K)^2}^{\infty} \frac{\mathrm{Im}\{f_+(s)\}}{s - q^2 - i\varepsilon} ds}$$

<Mpole> is 5.1 σ lower than D$_s$*

⇒ Integral term is important

Becirevic & Kaidalov write integral as effective pole with $m_{\mathrm{eff}} = \sqrt{\gamma}\, m_{D^*}$

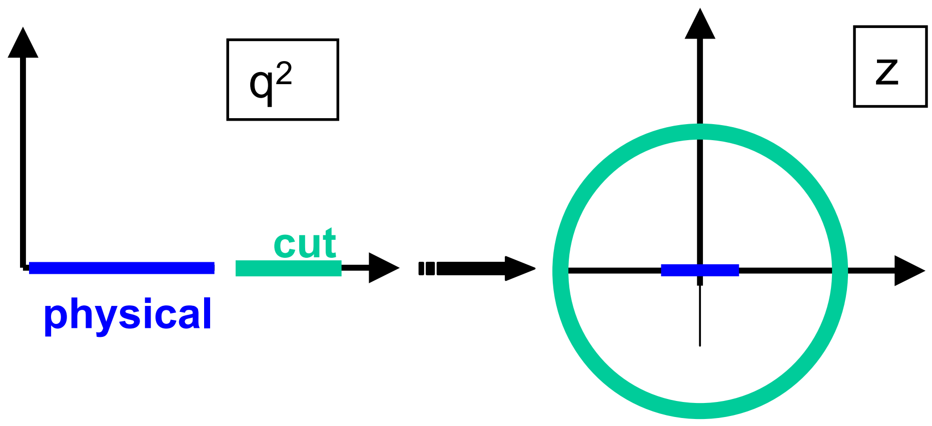
$$f_+(q^2) = \frac{c_D m^2_{D^*}}{m^2_{D^*} - q^2} - \boxed{\frac{\alpha\gamma c_D m^2_{D^*}}{\gamma m^2_{D^*} - q^2}}$$

HQET&SCET ⇒ Res & Pole $\alpha = 1/\gamma$

$$\Rightarrow f_+(q^2) = \frac{f_+(0)}{\left(1 - q^2/m^2_{D^*}\right)\left(1 - \alpha q^2/m^2_{D^*}\right)}$$

But there is a less model dependent way of dealing with f$_+$ singularities →

R.J. Hill's† New Approach to f (q²)



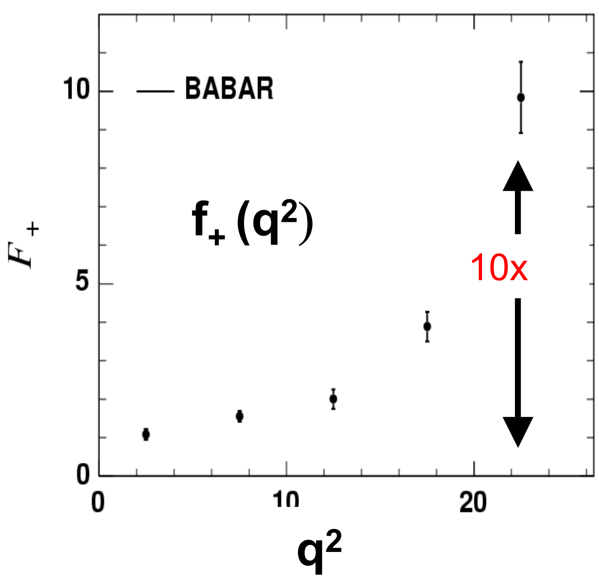
Hill makes a complex mapping that pushes the cut singularities far from maximum q².

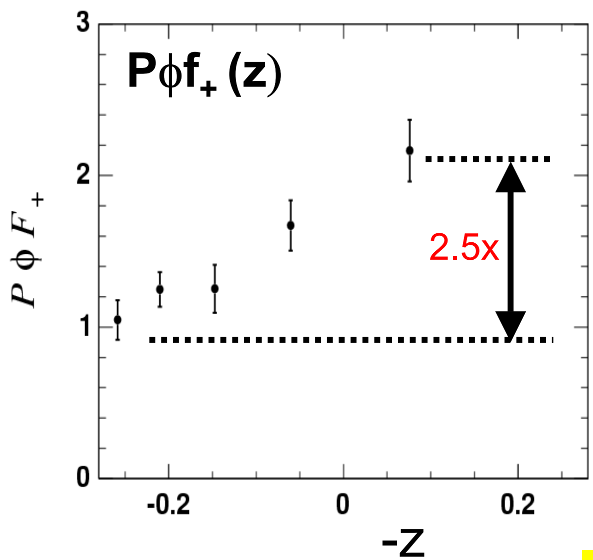
$$z(t, t_0) \equiv \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}$$

Form factors are given by a simple Taylor series for |z| << 1

$$P(t)\phi(t) \times f\left(z\right) = a_0 + a_1 z + \cdots$$

Illustrate with B→πeν data [Hill (06)]





For B→π: The cut is very close to the maximum q² and

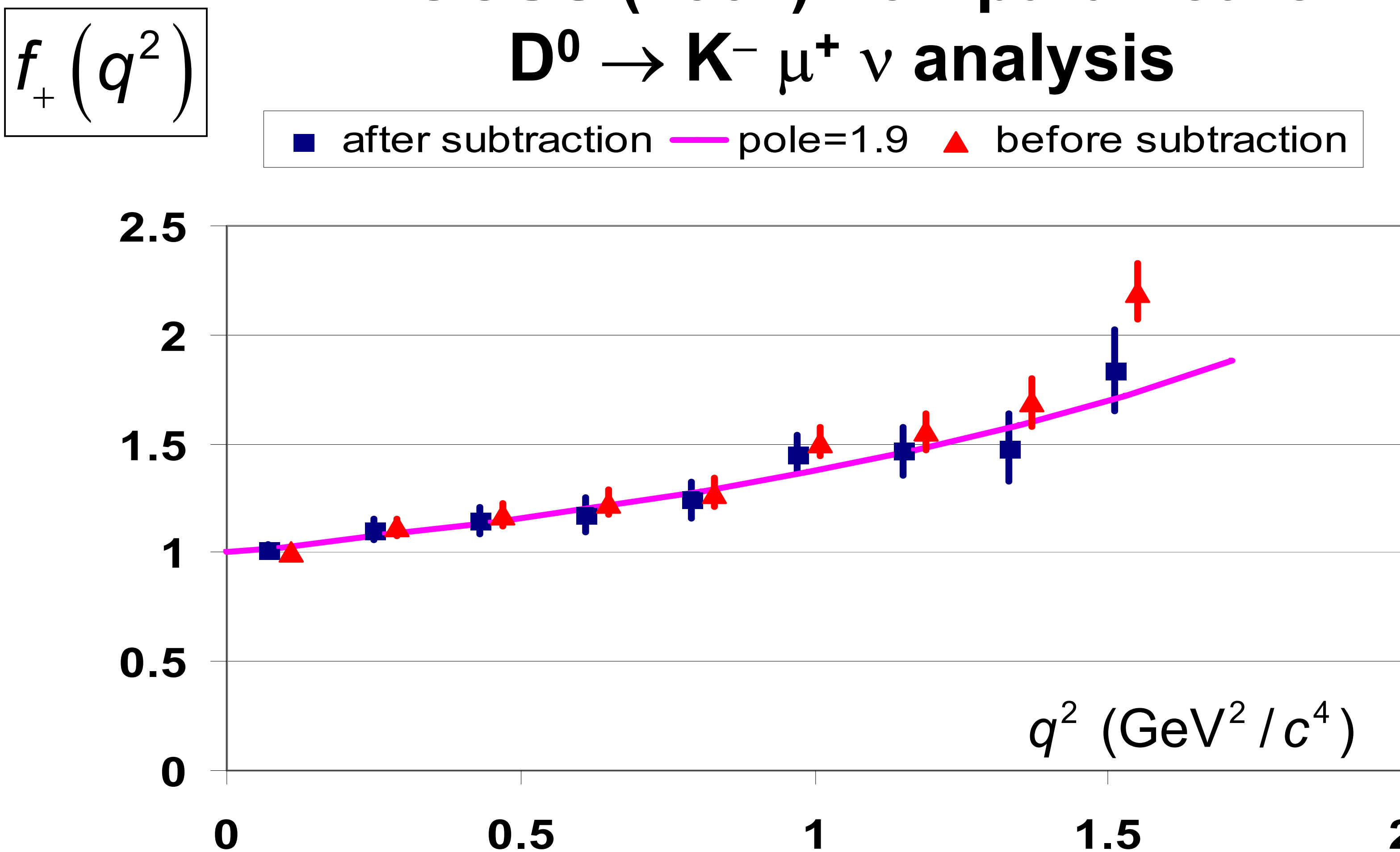
$f_+(q^2) \to \infty$ as $q^2 \to q^2_{max}$

After z mapping, the physical and cut region are far apart. The $f_+(z)$ data is well fit with just a straight line as a polynomial.

†R.J. Hill hep-ph/0606023 (FPCP06)

Charm data?? →

FOCUS (2004) non-parametric $D^0 \to K^- \mu^+ \nu$ analysis



The background only affects the highest q^2 bins.

After subtracting known charm backgrounds, $f_+(q^2)$ is an excellent match to a pole form with $m_{pole} = 1.91 \pm 0.04 \pm 0.05$ GeV/c^2 or $\alpha = 0.32$ (CL 87%, 82%).

The New Results from Belle (2006)

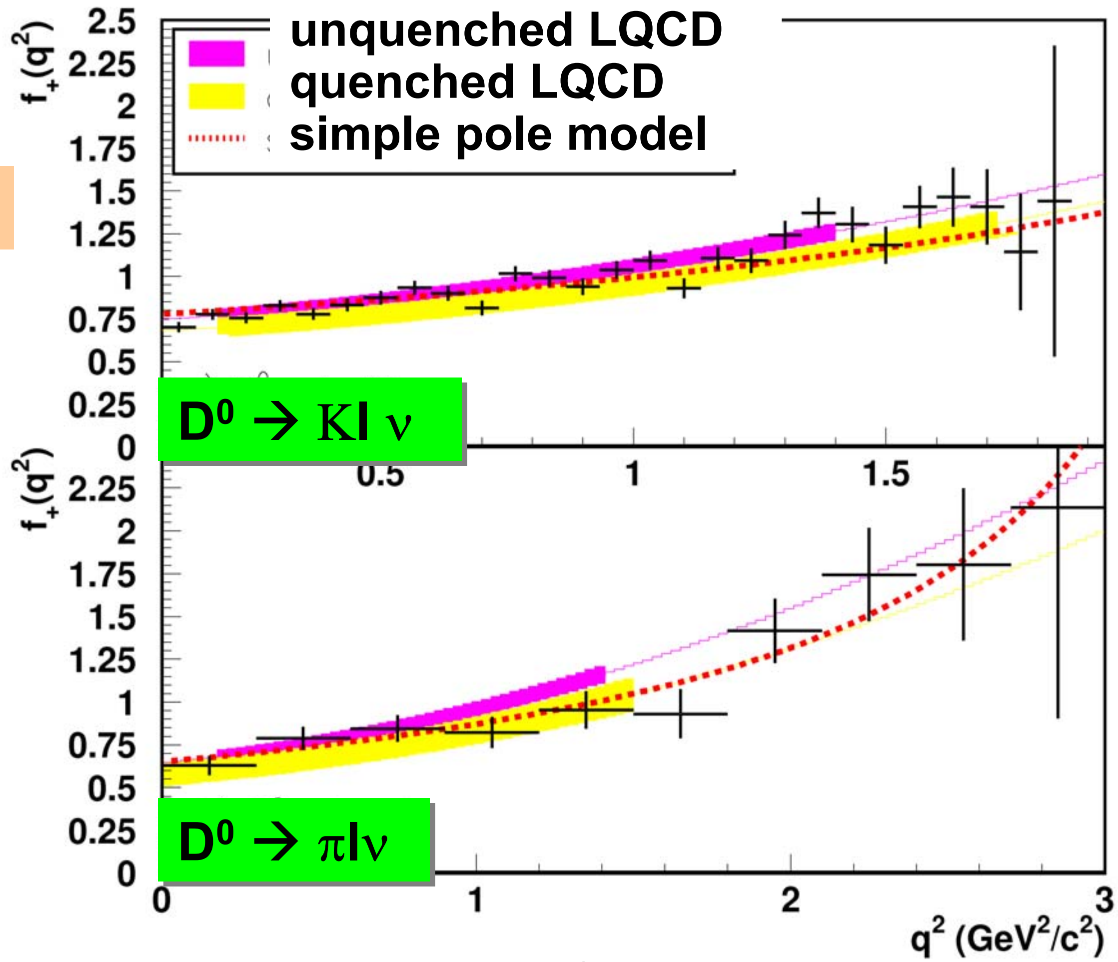
fit results

One “effective” pole

	pole mass (GeV)
$Kl\nu$	$1.82 \pm 0.04_{stat} \pm 0.03_{syst}$
$\pi l\nu$	$1.97 \pm 0.08_{stat} \pm 0.04_{syst}$

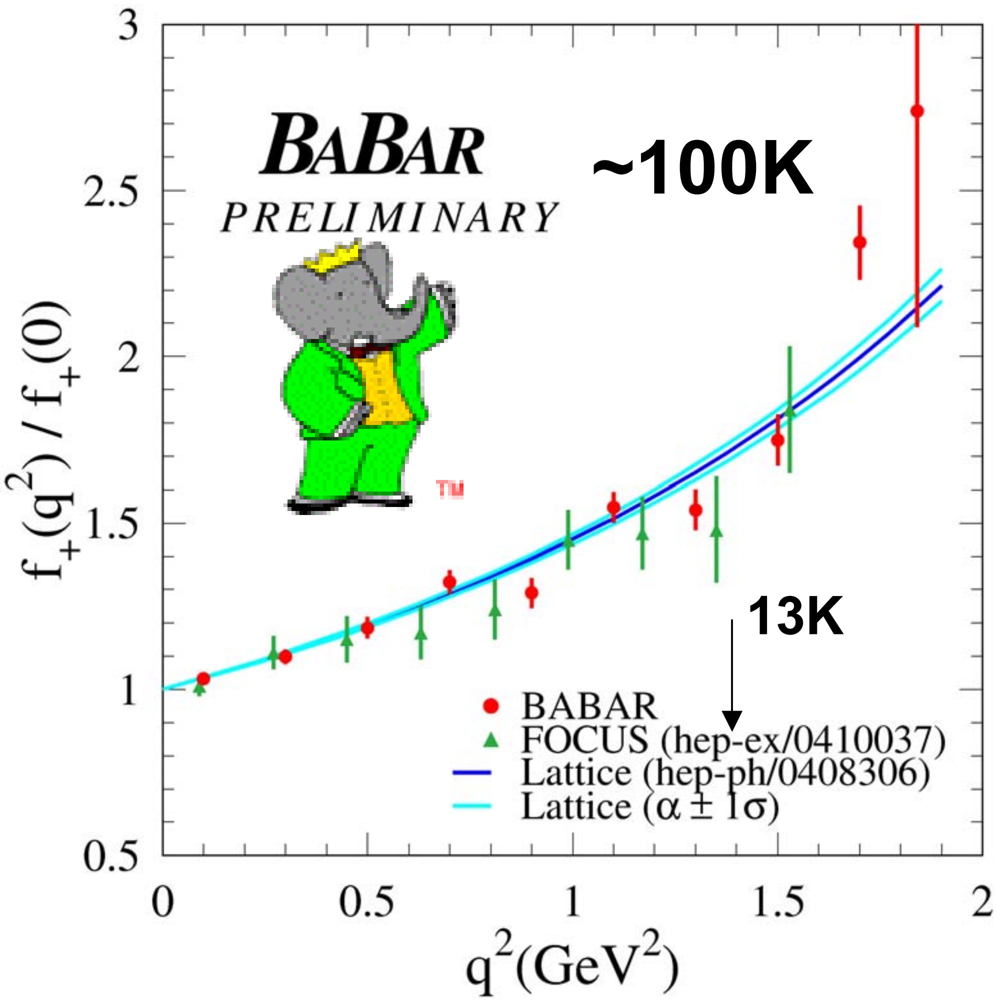
modified pole

	α
$Kl\nu$	$0.52 \pm 0.08_{stat} \pm 0.06_{syst}$
$\pi l\nu$	$0.10 \pm 0.21_{stat} \pm 0.10_{syst}$

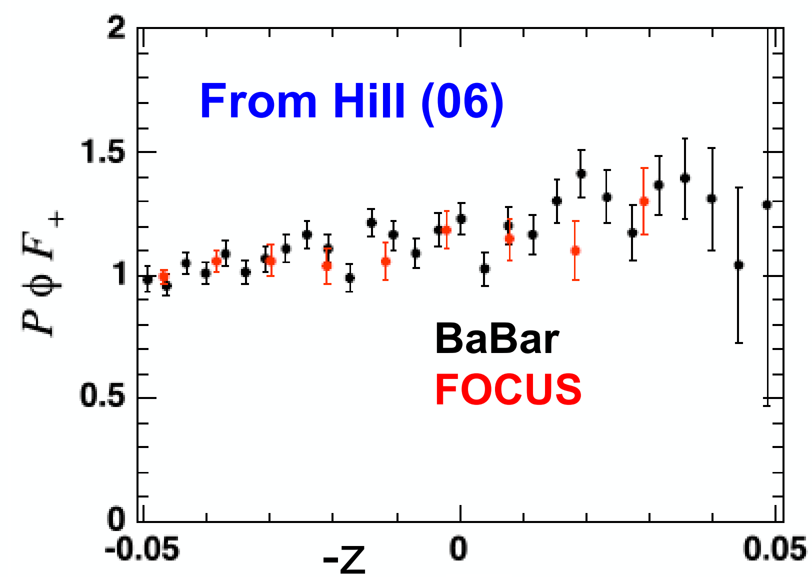


Plot courtesy of L. Widhalm

LQCD, FOCUS & BaBar: q^2 and z-trans



Hill transformation gives a nearly linear f(Z) for $D \rightarrow K$ data. The expansion should converge very rapidly since |z| << 1 in this decay



Plus some new results from CLEO-c→

Preliminary Untagged $D \to K/\pi\ e\ \nu$ from CLEO-c

	CKM info	Modified pole
Decay Mode	$\|V_{cx}\| f^{+}(0)$	α
$D^0 \to \pi^{\pm} e \nu$	$0.142 \pm 0.005 \pm 0.003$	$0.37 \pm 0.09 \pm 0.03$
$D^0 \to K^{\pm} e \nu$	$0.734 \pm 0.006 \pm 0.010$	$0.19 \pm 0.05 \pm 0.03$
$D^{\pm} \to \pi^0 e \nu$	$0.151 \pm 0.008 \pm 0.004$	$0.12 \pm 0.17 \pm 0.05$
$D^{\pm} \to K^0 e \nu$	$0.718 \pm 0.009 \pm 0.012$	$0.20 \pm 0.08 \pm 0.04$

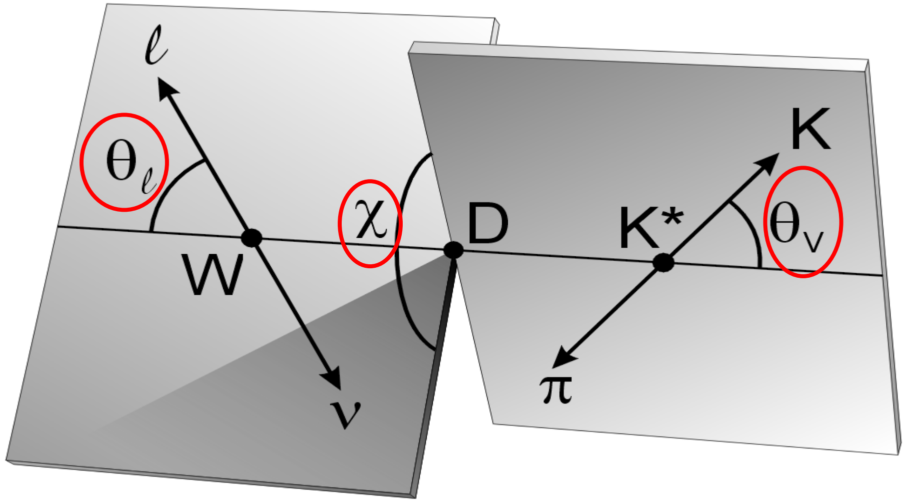
Neutrinos are determined by energy-momentum balance AND the recoil D tagging method is not used.

Slightly lower than previous measurements

Experiment	α_{pole}
CLEO III [7]	$0.36 \pm 0.10^{+0.08}_{-0.07}$
FOCUS [8]	$0.28 \pm 0.08 \pm 0.07$
BELLE [9]	$0.40 \pm 0.12 \pm 0.09$ e sample $0.66 \pm 0.11 \pm 0.09$ μ sample
BaBar	$0.43 \pm 0.03 \pm 0.04$

charm vector semileptonic decays→

IV. D $\to$ Vector l ν Decay



$$\int |A|^2 d\chi = \frac{1}{8} q^2 \left\{ \begin{array}{l} \left((1+\cos\theta_l)\sin\theta_V\right)^2 \left|H_+(q^2)\right|^2 |BW|^2 \\ +\left((1-\cos\theta_l)\sin\theta_V\right)^2 \left|H_-(q^2)\right|^2 |BW|^2 \\ +\left(2\sin\theta_l\cos\theta_V\right)^2 \left|H_0(q^2)\right|^2 |BW|^2 \\ +8\left(\sin^2\theta_l\cos\theta_V\right) H_0(q^2) h_o(q^2) \mathrm{Re}\left\{Ae^{-i\delta} BW\right\} \\ +O(A^2) \end{array} \right\}$$

Korner+Schuler (1990)

Present in K* l nu

$H_0(q^2)$, $H_+(q^2)$, $H_-(q^2)$ are **helicity-basis form factors** computable by LQCD
A new factor **h_0** (q^2) is needed to describe **s-wave interference piece**.

KS / GS model for $H_\pm$ and H_0

K&S write $H_\pm$ and H_0 as linear combinations of two axial and one vector form factors.

Two approaches are used to parameterize them:

Spectroscopic pole dominance **Versus** **B&K style "effective" poles**

The traditional method.

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

$M_V = 2.1$ GeV $\quad M_{A1} = M_{A2} = 2.5$ GeV

Only 2 shape parameters needed in spectroscopic pole dominance fit

$$R_V = \frac{V(0)}{A_1(0)} \qquad R_2 = \frac{A_2(0)}{A_1(0)}$$

But spectroscopic pole dominance should work poorly at high $q^2 \rightarrow$ Need for alternative…

Fajfer & Kamenik (2005)

$$V(q^2) = \frac{c_{H'}(1-a)}{(1-x)(1-ax)} \quad \text{where } x \equiv \frac{q^2}{m^2_{Ds*}}$$

$$A_1(q^2) = \xi \frac{c_{H'}(1-a)}{1-b'x} \quad \text{where } \xi = \left(\frac{m_D}{m_D + m_{K*}}\right)^2$$

$$A_2(q^2) = \frac{(m_D + m_{K*})\xi c_H'(1-a) + 2m_{K*}c_{H''}(1-a')}{(m_D - m_{K*})(1-b'x)(1-b''x)}$$

- **$V(q^2)$ essentially same as B&K with one physical and one effective 1- poles.**
- **$A_1(q^2)$ forced to be one effective 1+ pole**
- **$A_2(q^2)$ has two effective 1+ poles**

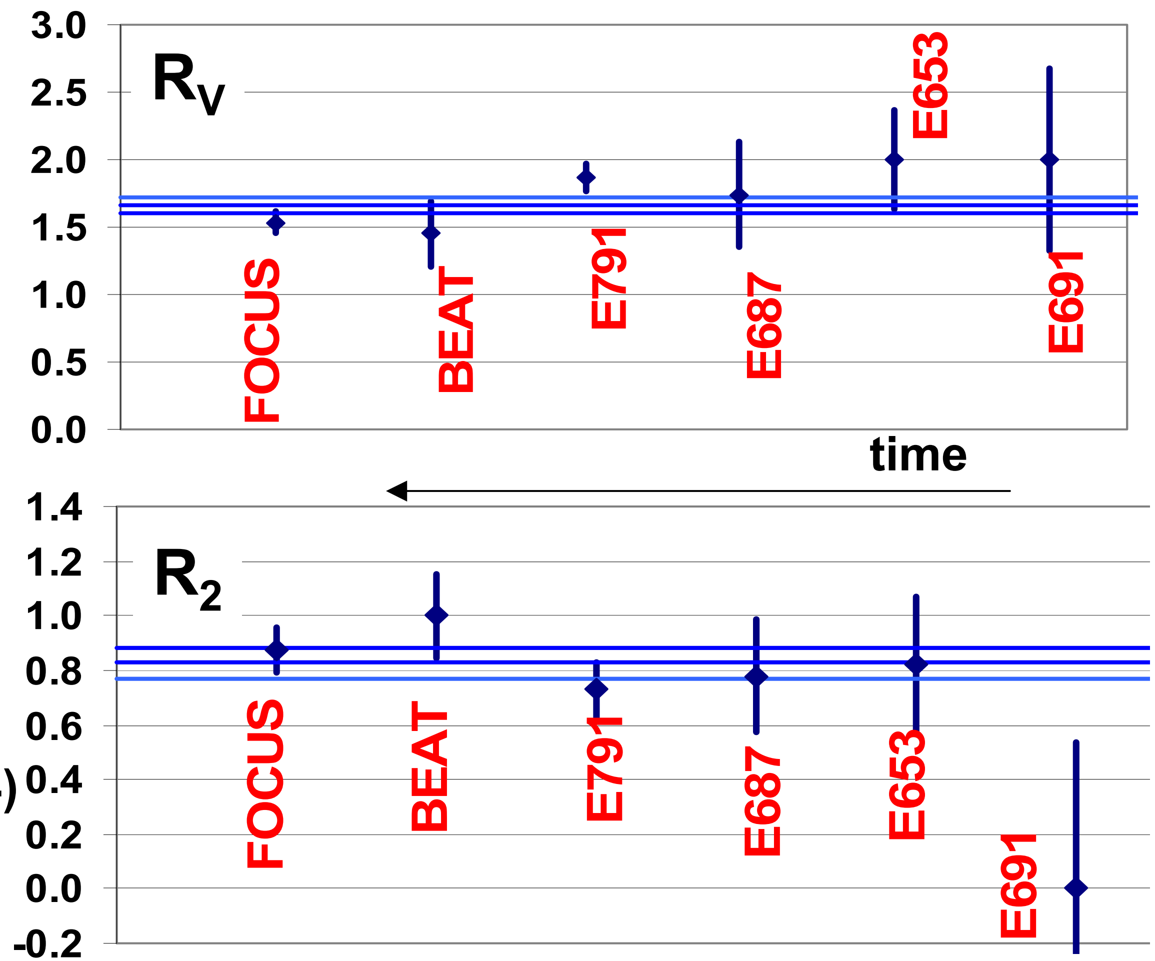
Spectroscopic Pole Dominance $D \to V\, l\, \nu$ Fits

$D^+ \to K^* l^+ \nu$

$R_V \quad 1.66 \pm 0.060$

$R_2 \quad 0.827 \pm 0.055$

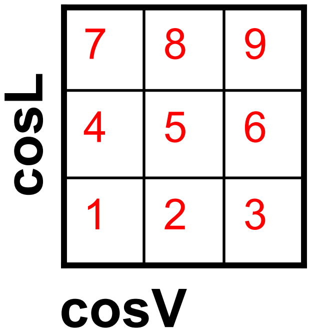
$$R_V = \frac{V(0)}{A_1(0)} \qquad R_2 = \frac{A_2(0)}{A_1(0)}$$



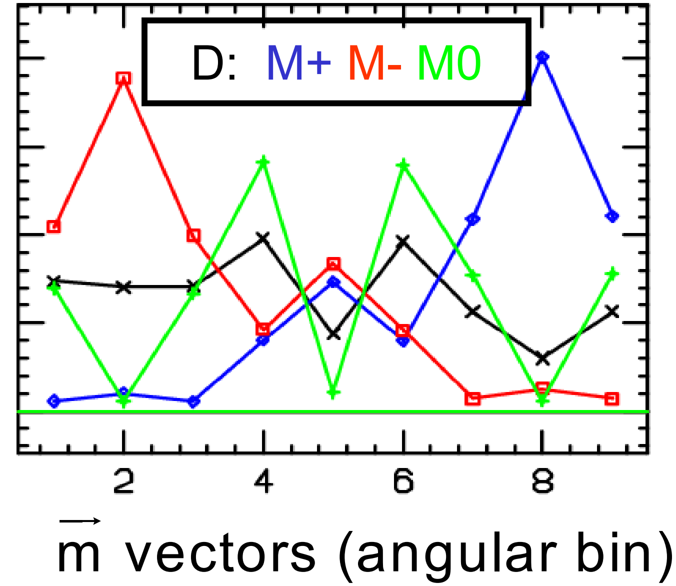
The latest results FOCUS (2004) on $D_s \to \phi\, \mu\, \nu$ form factors are consistent with those for D^+.

Experimental results are very consistent with small errors. But must we trust/rely on spectroscopic pole dominance? →

A non-parametric Approach



Disentangle helicity form factors based on their different angular bin populations.



Each $K\pi e\nu$ candidate is given four weights based on its decay angles.

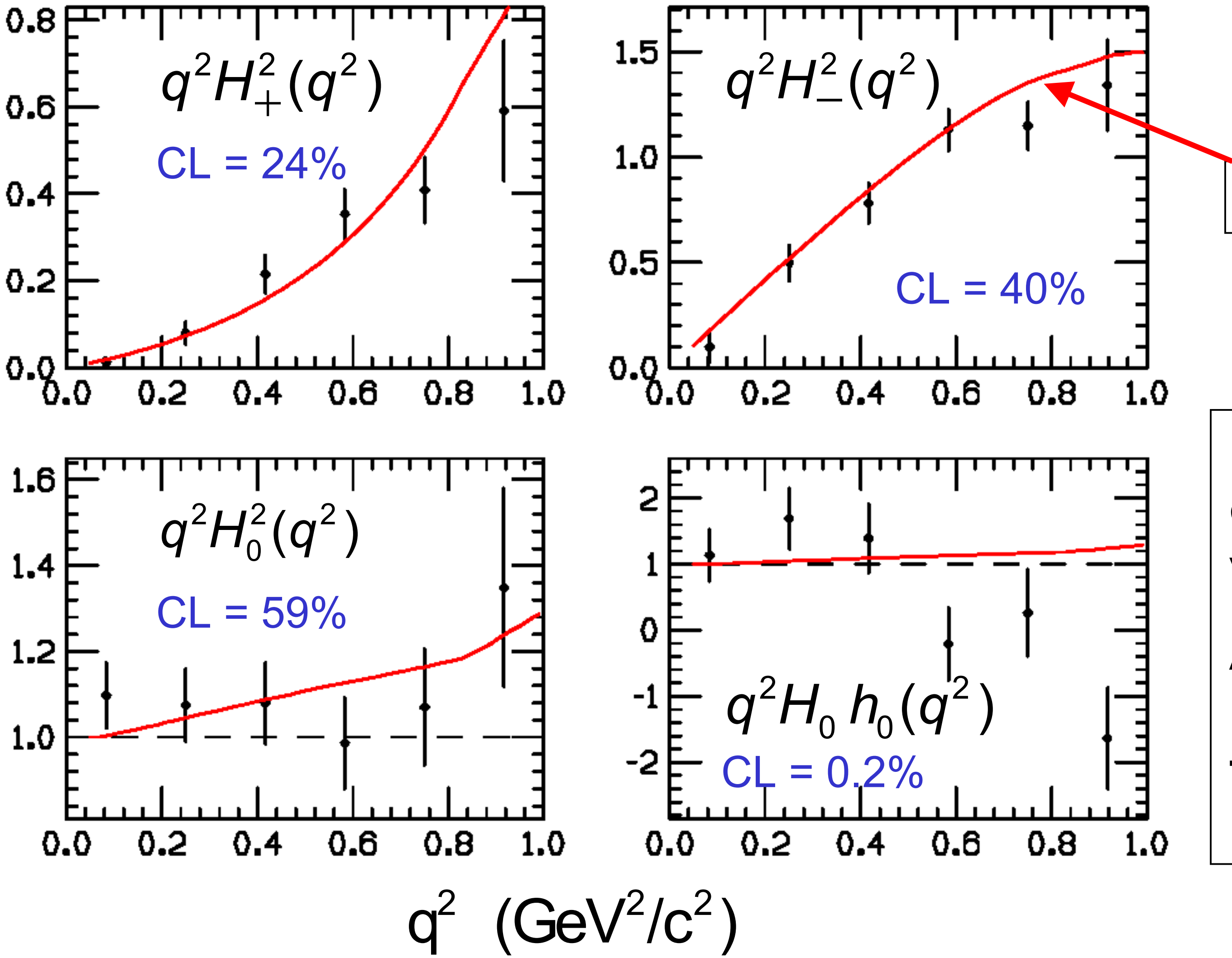
These weights project out $H_+^2(q^2)$, $H_-^2(q^2)$, $H_0^2(q^2)$ & $H_0 \times h_0(q^2)$

Results appear as just 4 weighted histograms.

The projection weights can be computed directly from the MC bin populations using linear algebra

$$\begin{pmatrix} \vec{P}_+ \\ \vec{P}_- \\ \vec{P}_0 \\ \vec{P}_l \end{pmatrix} = \begin{pmatrix} \vec{m}_+ \cdot \vec{m}_+ & \vec{m}_+ \cdot \vec{m}_- & \vec{m}_+ \cdot \vec{m}_0 & \vec{m}_+ \cdot \vec{m}_l \\ \vec{m}_- \cdot \vec{m}_+ & \vec{m}_- \cdot \vec{m}_- & \vec{m}_- \cdot \vec{m}_0 & \vec{m}_- \cdot \vec{m}_l \\ \vec{m}_0 \cdot \vec{m}_+ & \vec{m}_0 \cdot \vec{m}_- & \vec{m}_0 \cdot \vec{m}_0 & \vec{m}_0 \cdot \vec{m}_l \\ \vec{m}_l \cdot \vec{m}_+ & \vec{m}_l \cdot \vec{m}_- & \vec{m}_l \cdot \vec{m}_0 & \vec{m}_l \cdot \vec{m}_l \end{pmatrix}^{-1} \begin{pmatrix} \vec{m}_+ \\ \vec{m}_- \\ \vec{m}_0 \\ \vec{m}_l \end{pmatrix}$$

Non-parametric $D^+ \to K^-\pi^+e^+\nu$ Form Factors (281 pb^{-1})

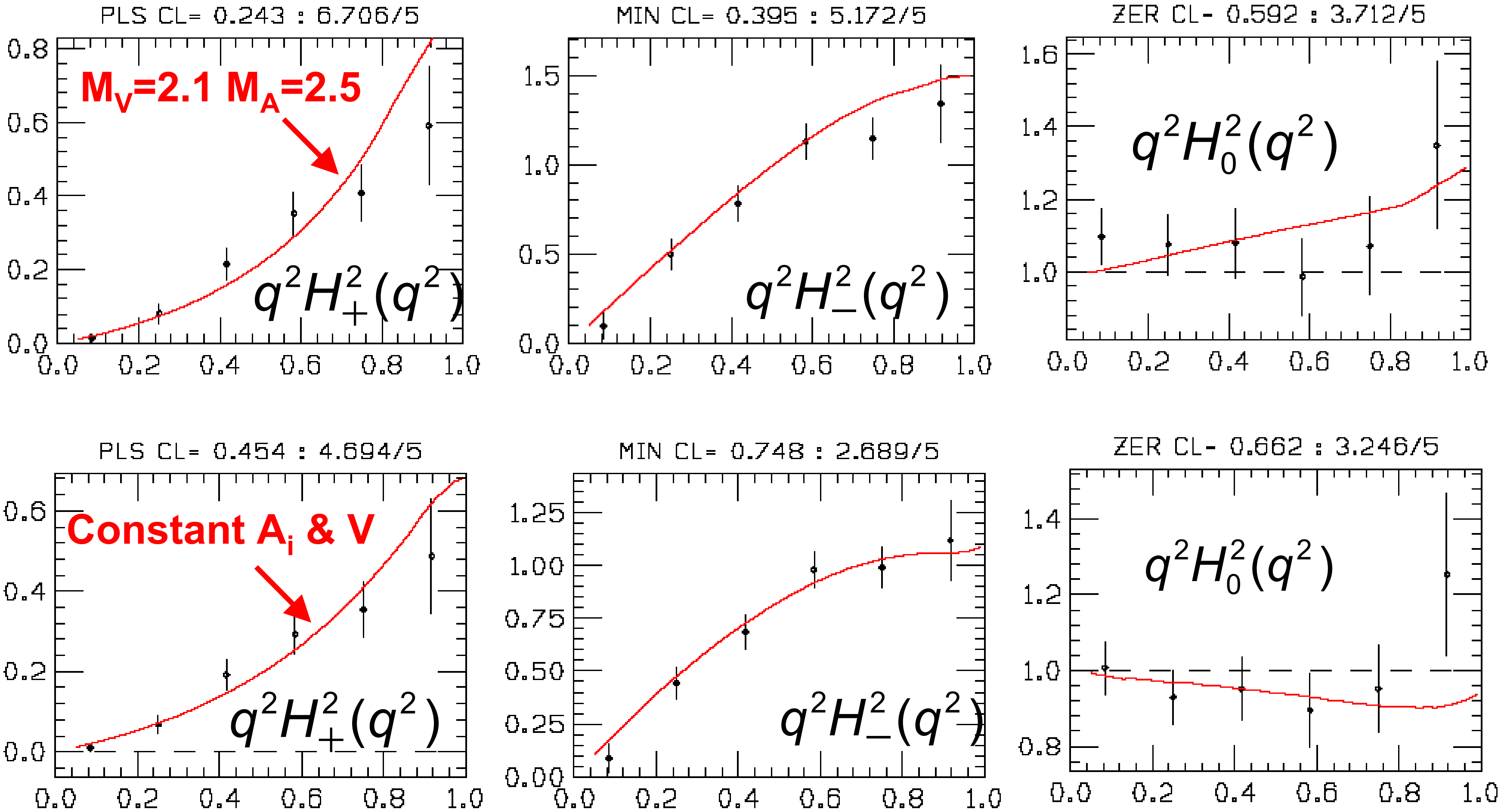


Low q^2 peaking of H_0 and h_0 is very apparent.

Apart from interference term the CL are rather good.

Pole Mass Sensitivity in Data

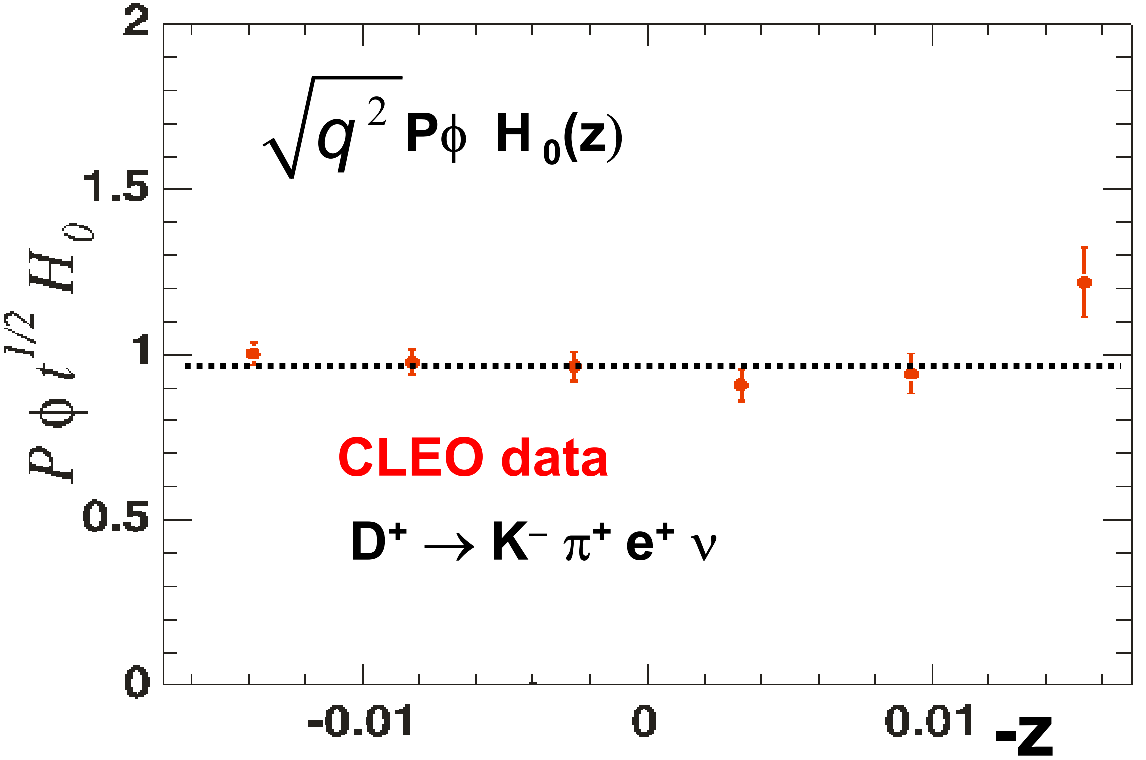
$$A_i(q^2) = \frac{A_i(0)}{1 - q^2/M_A^2} \qquad V(q^2) = \frac{V(0)}{1 - q^2/M_V^2}$$



Data fits spectroscopic poles and constant form factors equally well.

Preliminary Z transform of PS-V decay by Hill

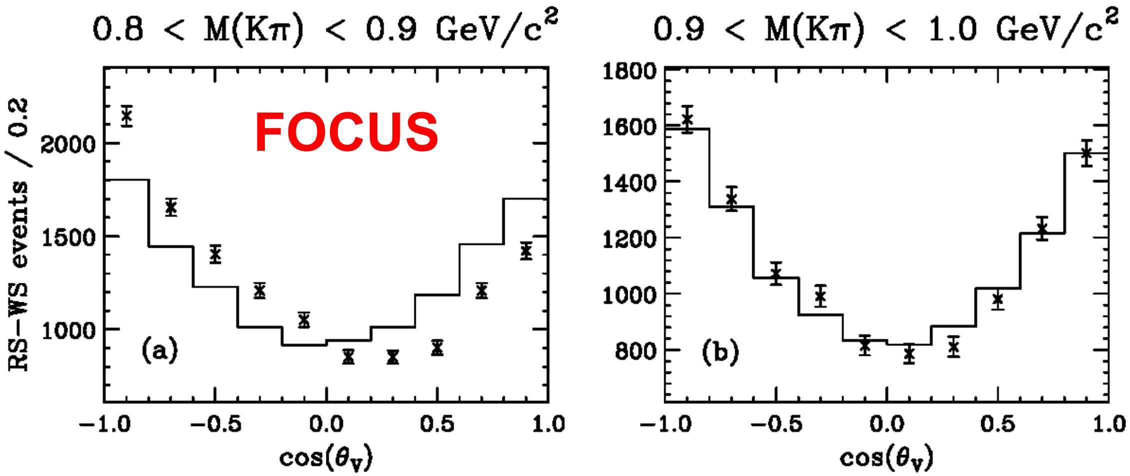
Analysis of CLEO non-parametric data by R.J. Hill (private communication)



The Hill- transformed CLEO non-parametric H_0 data seems nearly constant.

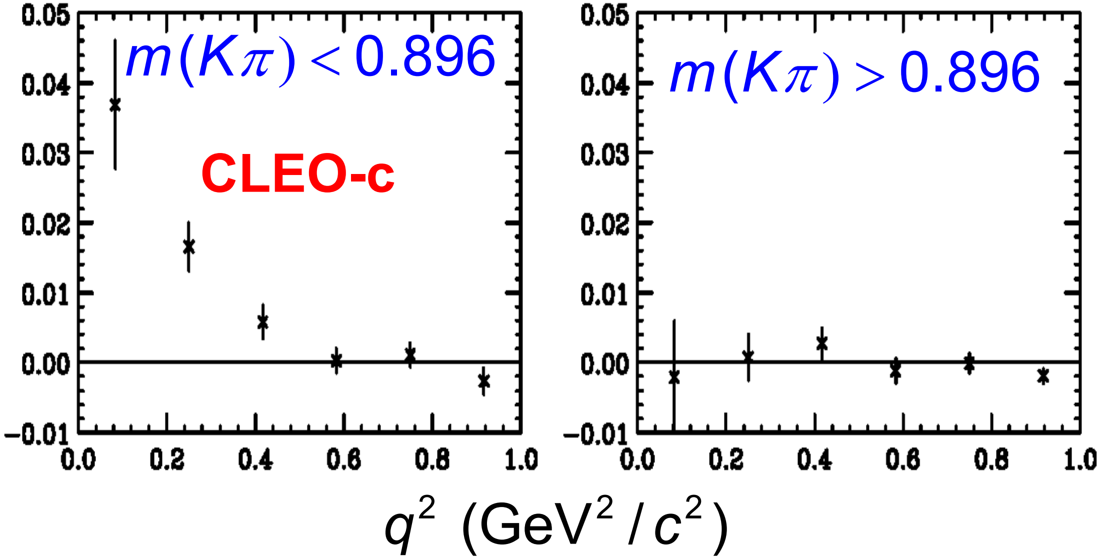
For D→K* decays, the z range is 4× small than for D→K. Hence, one expects that the H_0 data is nearly constant after transformation, which is confirmed in data

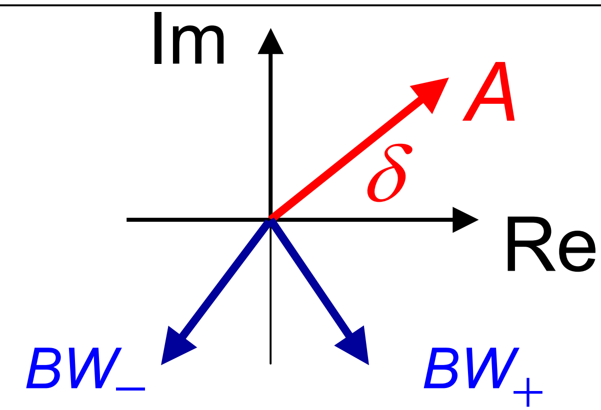
Confirming the s-wave in $D^+ \to K^- \pi^+ e^+ \nu$



Focus (2002) saw $\cos\theta_V$ asym for $m(K\pi) <$ K* pole from term : $\mathrm{Re}\left\{Ae^{-i\delta}\langle BW\rangle\right\}\cos\theta_V$

$$H_0 \times h_0\left(q^2\right)\mathrm{Re}\{A\exp(-i\delta)\langle BW\rangle\}$$





The disappearance of the interference above the pole implies the above phase relationships between the BW and the s-wave amplitude.

Summary

(1) Inclusive BF of semileptonic decays from CLEO-c.

- From 281/pb at $\psi(3770)$, much better than the PDG 04.
  Γ SL(D^0)/Γ SL(D^+) = 1. Known decay modes almost saturating.

(2) Active Form factor analyses for D $\rightarrow$Pseudoscalar l ν by several experiments are compared to the latest unquenched light-flavor LQCD results, B&K model & Hill transformation.

(3) Form Factor measurements for D $\rightarrow$V l ν from CLEO-c 281/pb and FOCUS.

- H_+, H_-, H_0 appear consistent with the spectroscopic pole dominance model and consistent with Hill.

(4) Not covered here & Coming soon: Exclusive BF decays, rare decays, Ds semileptonic decays, more form factors, etc.

(5) Looking forward to new data from B factories, CLEO-c, BES III, and next-next-generation charm experiments.

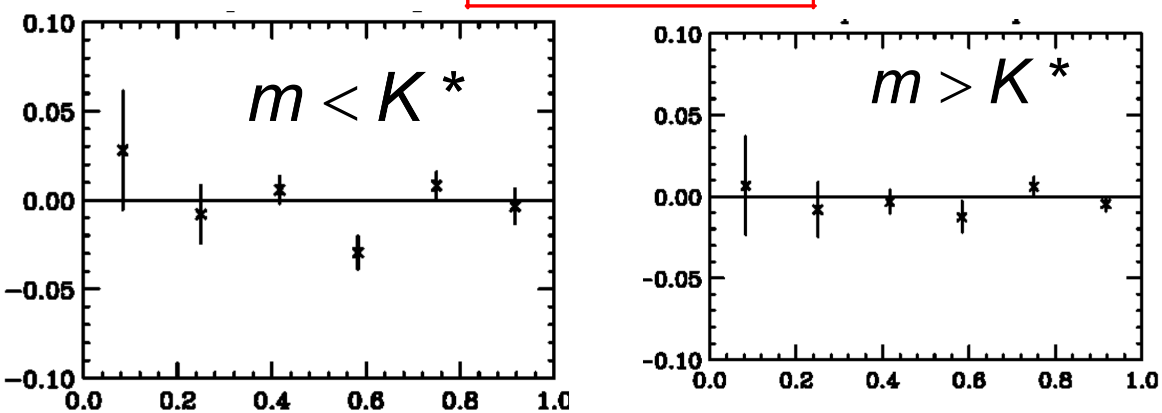
Question slides

Search for D-wave Kπ

Add a D-wave projector

$$\int |A|^2 d\chi = \frac{q^2 - m_\ell^2}{8} \left\{ \begin{array}{l} ((1+\cos\theta_\ell)\sin\theta_V)^2 |H_+(q^2)|^2 |BW|^2 \\ +((1-\cos\theta_\ell)\sin\theta_V)^2 |H_-(q^2)|^2 |BW|^2 \\ +(2\sin\theta_\ell\cos\theta_V)^2 |H_0(q^2)|^2 |BW|^2 \\ +8\sin^2\theta_\ell\cos\theta_V H_0(q^2) h_o(q^2) \mathrm{Re}\{Ae^{-i\delta} BW\} \\ \boxed{+4\sin^2\theta_\ell\cos\theta_V(3\cos^2\theta_V - 1) H_0(q^2) h_o^{(d)}(q^2) \mathrm{Re}\{A_d e^{-i\delta_d} BW\}} \end{array} \right\}$$

$$H_0 \times h_D(q^2)$$



q^2 GeV^2

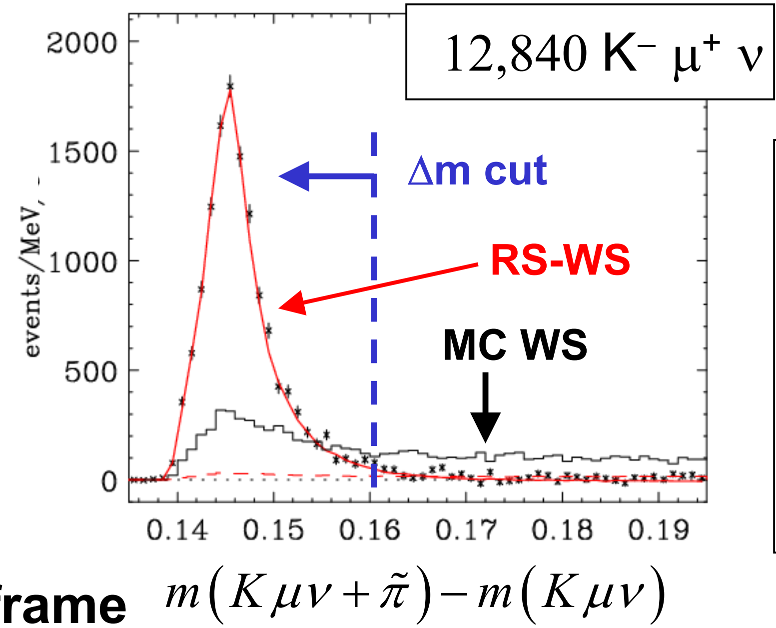
Guard against "phase cancellation" by showing above and below the K*

No evidence for $h_D(q^2) \propto \frac{1}{\sqrt{q^2}}$ or $h_F(q^2) \propto \frac{1}{\sqrt{q^2}}$

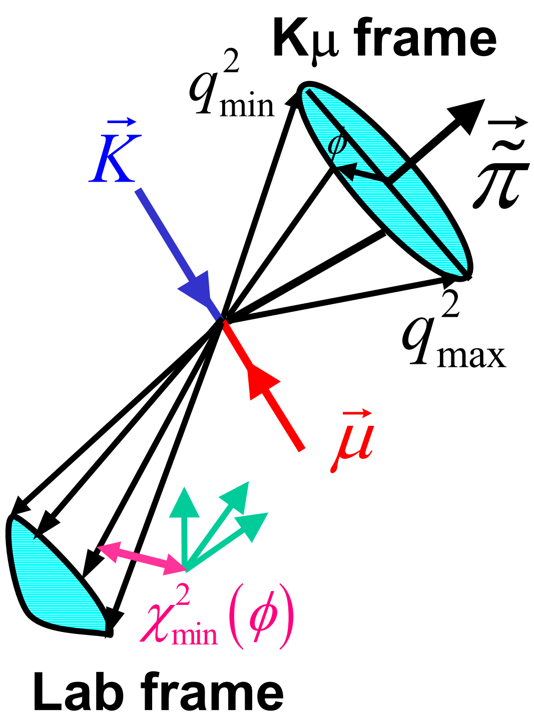
FOCUS $D^0 \to K^- \mu^+ \nu$ analysis

Select decay chain

$$D^{*+} \to D^0 \tilde{\pi}^+$$
$$\downarrow$$
$$K^- \mu^+ \nu$$

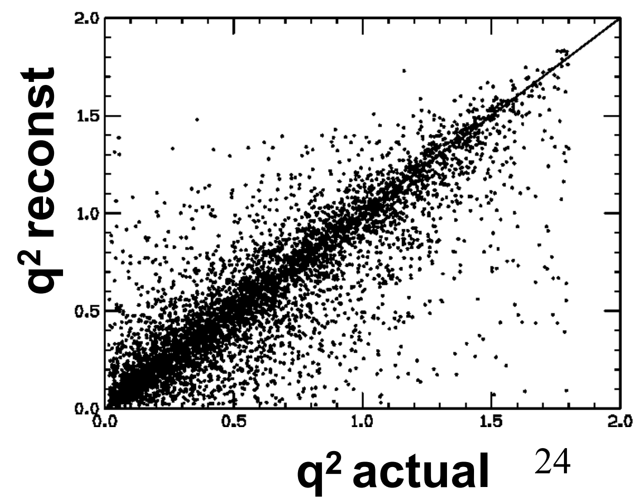


- **A good muon candidate.**
- **Cerenkov ID for K/π candidates.**
- **$L/\sigma > 5$ between two good vertices.**
- **D* tag required, and wrong sign soft π^- subtraction.**

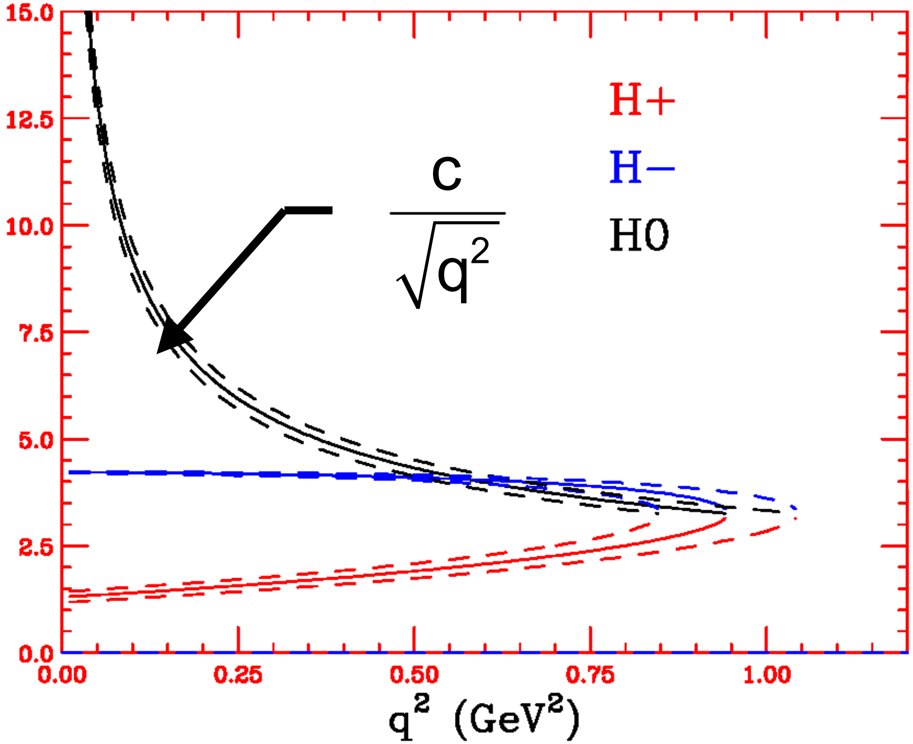


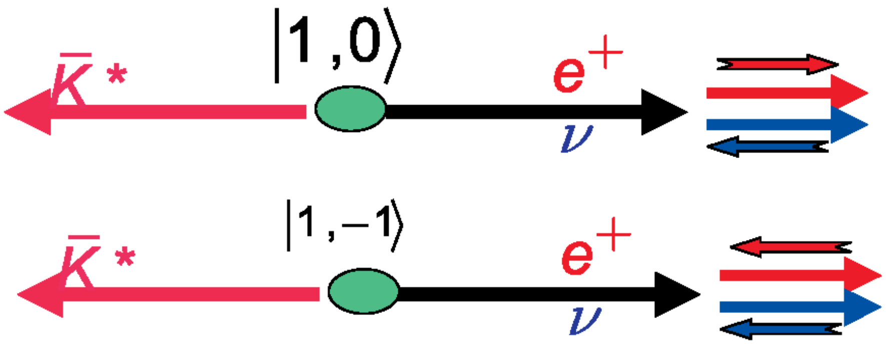
Fixed Target Neutrino closure

- Jump to Kμ rest frame
- The D and D* mass constraints→ the neutrino lies on a cone around the soft pion.
- Pick the φ that points the D closest to the primary vertex.



Expected q^2 Dependence of Helicity FF





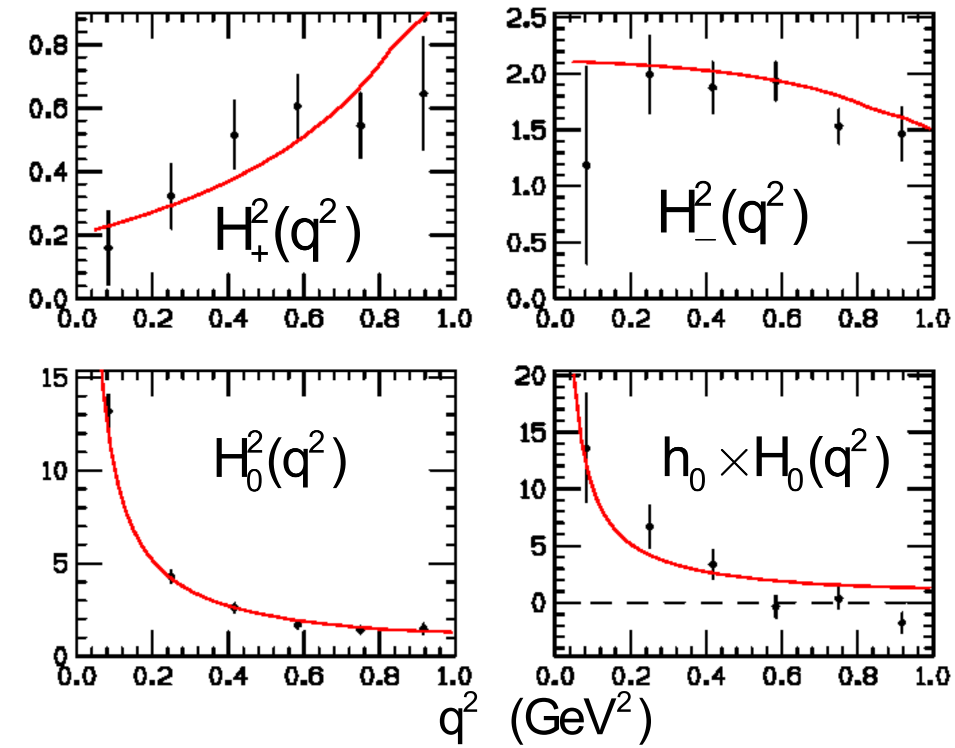
Only 0 helicity components can survive at $q^2 \to 0$ because of V-A helicity laws.

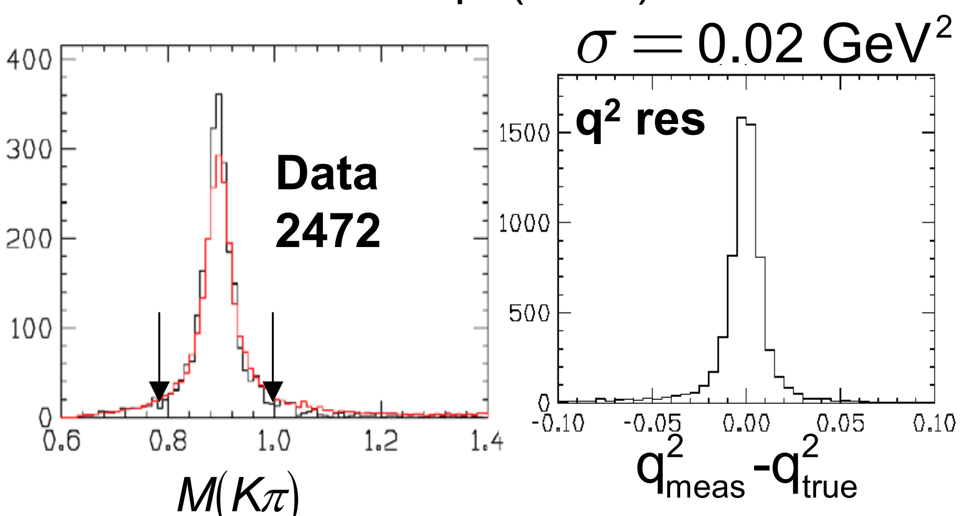
Since $\int |A|^2 d\chi \propto q^2 \sum_\alpha |H_\alpha(q^2)|^2 f_\alpha(\theta_V, \theta_\ell)$

$$H_\pm(q^2 \to 0) \to \text{constant or } H_0(q^2 \to 0),\ h_0(q^2 \to 0) \to \frac{c}{\sqrt{q^2}}$$

Comparing CLEO-c & FOCUS Results

Preliminary CLEO $D^+ \to K\pi e\nu$





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