CLEO-c *D* Semileptonic Decays

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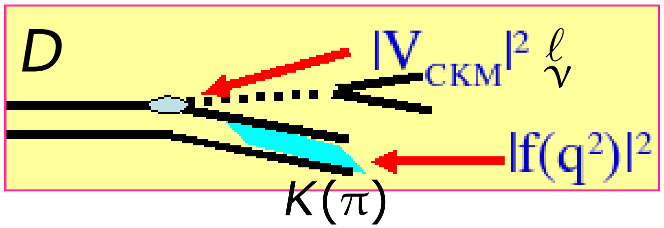
Introduction

- Cleanest (and simplest, both experimentally & theoretically) way to determine magnitudes of CKM elements

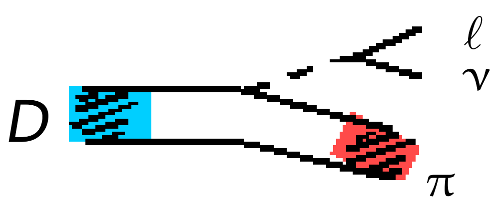


Experiment   Theory (LQCD)

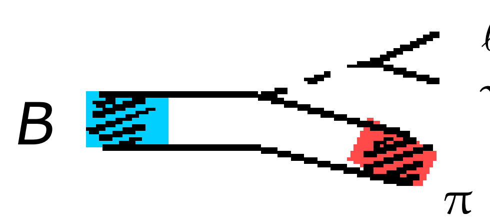
$$\frac{d\Gamma}{dq^2} \propto |V_{cs(d)}|^2 |f_+^{D\to K(\pi)}(q^2)|^2$$

  - Assuming theoretical form factor
    $\Rightarrow$ determine $|V_{cs}|$ and $|V_{cd}|$
  - Assuming $|V_{cs}|$ and $|V_{cd}|$
    $\Rightarrow$ we can check theoretical calculations of the form factors

- Test theory calculations (e.g. LQCD) of $f_+(q^2)$ in the D system and apply them to the B system, e.g. for $|V_{ub}|$.

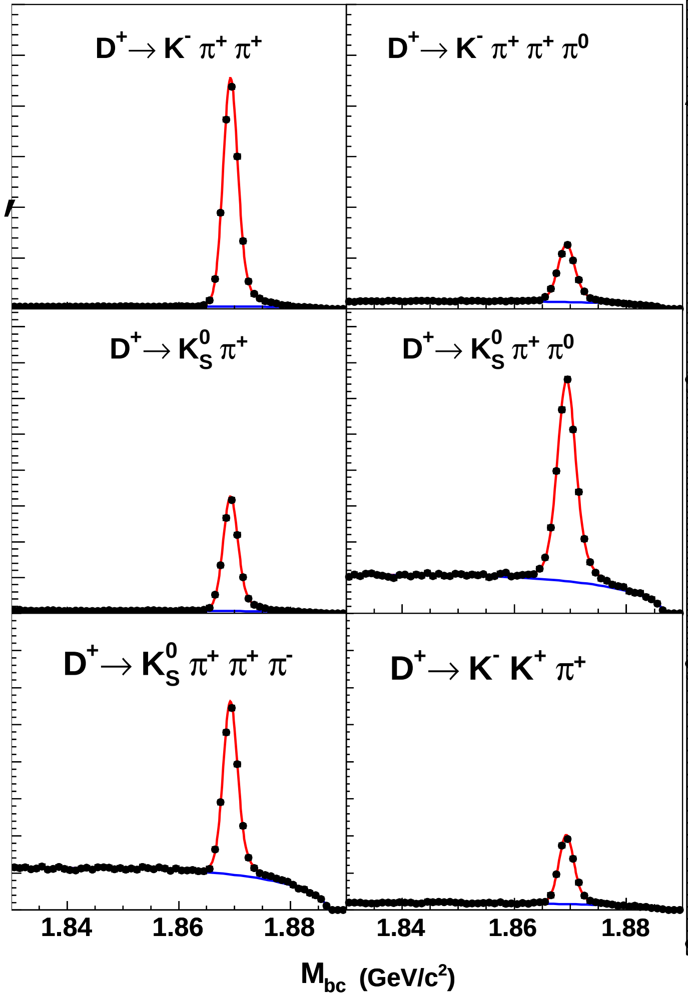


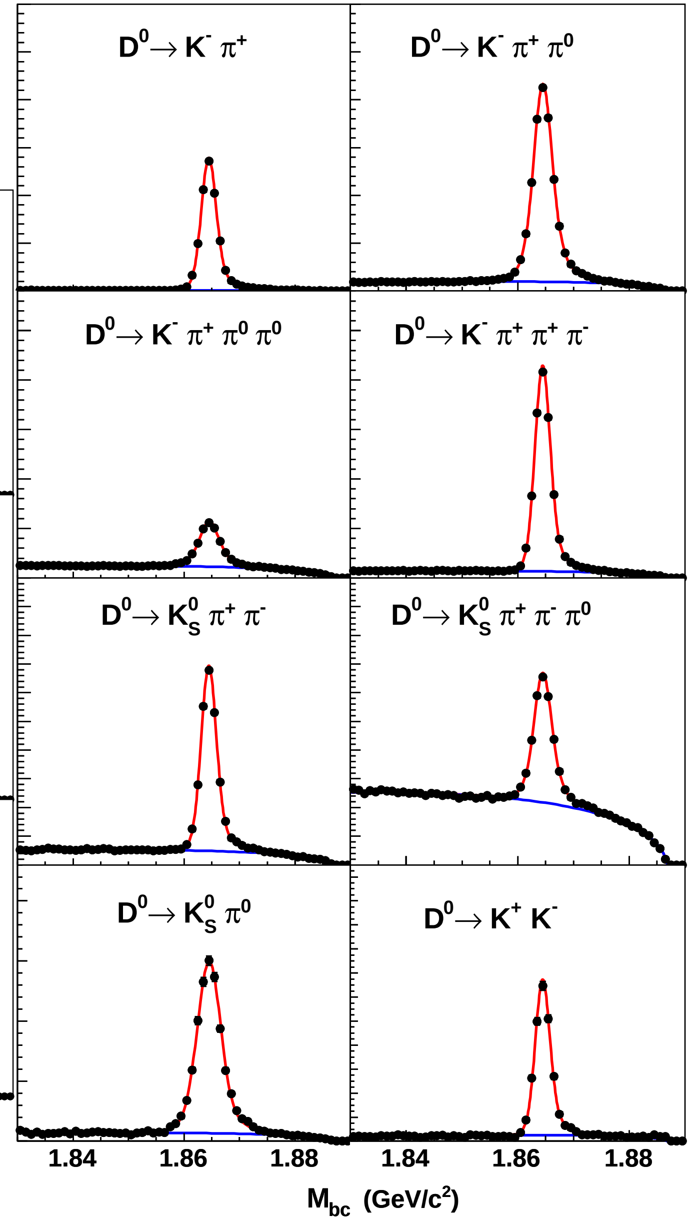
$\Rightarrow$ HQS $\Rightarrow$



Charm at $\psi(3770)$

- $\psi(3770) \to D\bar{D}$:
  just above threshold, no additional particles
- D tagging :
  $\sim 10\%\ D^+$
  $\sim 15\%\ D^0$
- Clean experimental environment ($\Leftarrow$ low multiplicity & D-tagging)
- Absolute branching fraction measurement ($\Leftarrow$ D tagging)
- CLEO-c has largest data set at 3770 (281pb^{-1} or $1.8 \times 10^6\ D\bar{D}$ in this talk)

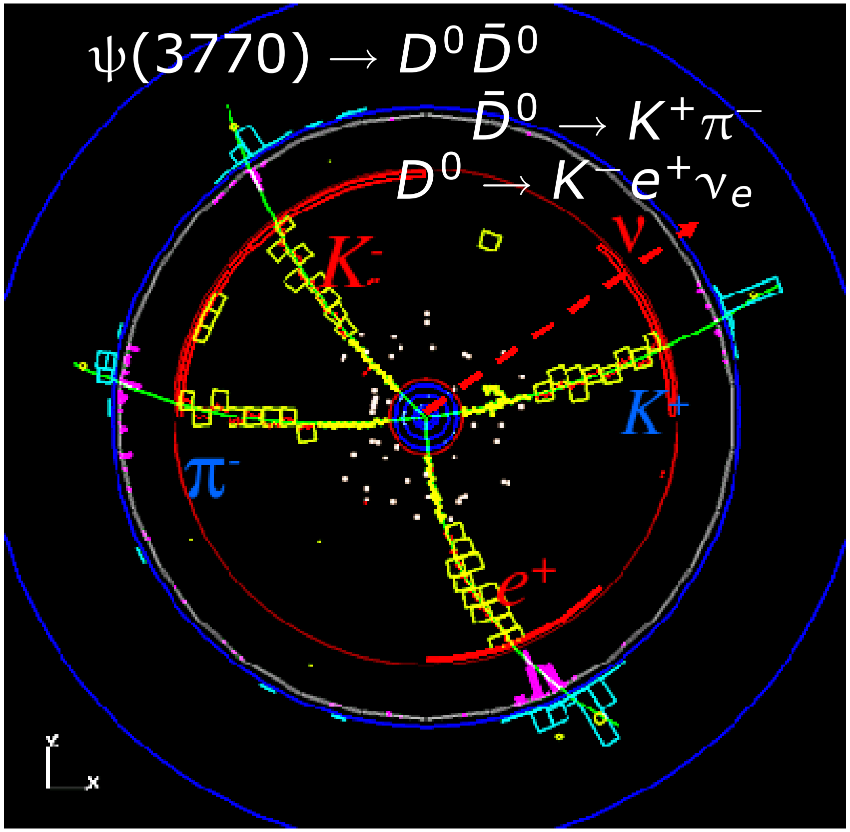


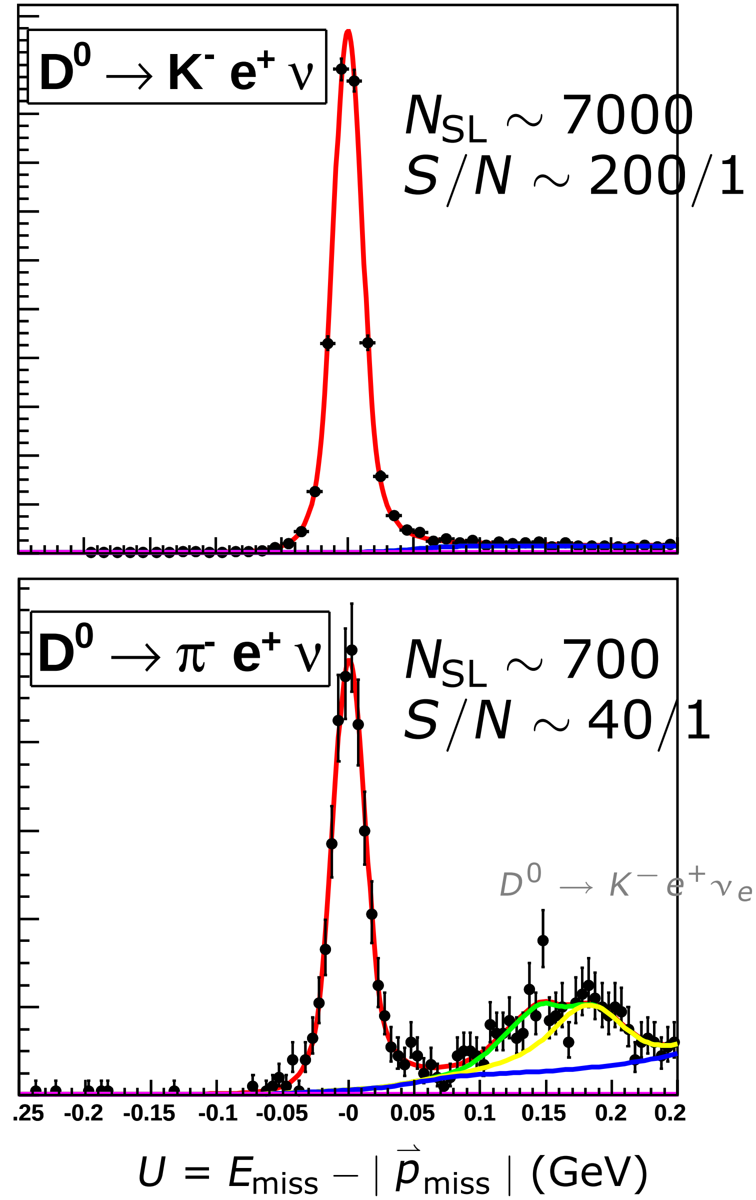


$$\Delta E = E_D - E_{\text{beam}}$$

$$M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_D|^2}$$

Absolute Semileptonic Branching Fractions





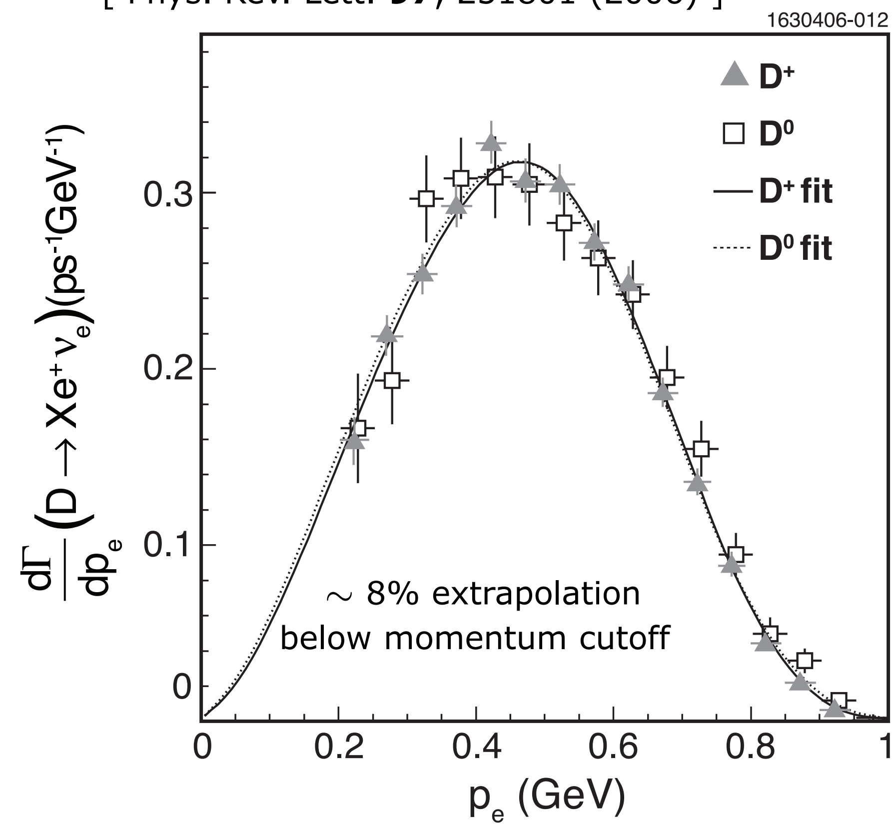
- Semileptonic event can be fully reconstructed (except neutrino)
- $\mathcal{B}(D \to X e^+ \nu_e) = \frac{N_{SL}/\epsilon_{SL}}{N_{tag}}$

Inclusive D Semileptonic Decays

- Historically : interesting due to the large difference in D^0 vs D^+ lifetimes (spectator model inadequate)
- Inclusive vs Sum of Exclusive : room for new modes?

Mode	Branching Fraction
$D^0 \to Xe^+\nu_e$	$(6.46 \pm 0.17 \pm 0.13)\%$
Sum of $\mathcal{B}_{\rm SL}(D^0)$	$(6.1 \pm 0.2 \pm 0.2)\%$
$D^+ \to Xe^+\nu_e$	$(16.13 \pm 0.20 \pm 0.33)\%$
Sum of $\mathcal{B}_{\rm SL}(D^+)$	$(15.1 \pm 0.5 \pm 0.5)\%$

[Phys. Rev. Lett. **97**, 251801 (2006)]



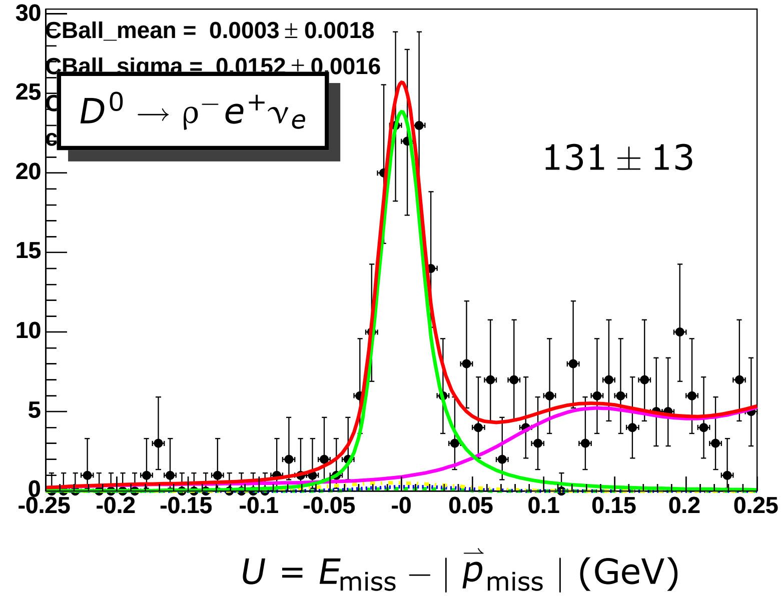
- Consistent with isospin symmetry : the lepton cannot interact strongly with the final-state hadrons and the two mesons are differ only in the isospin of the light quark

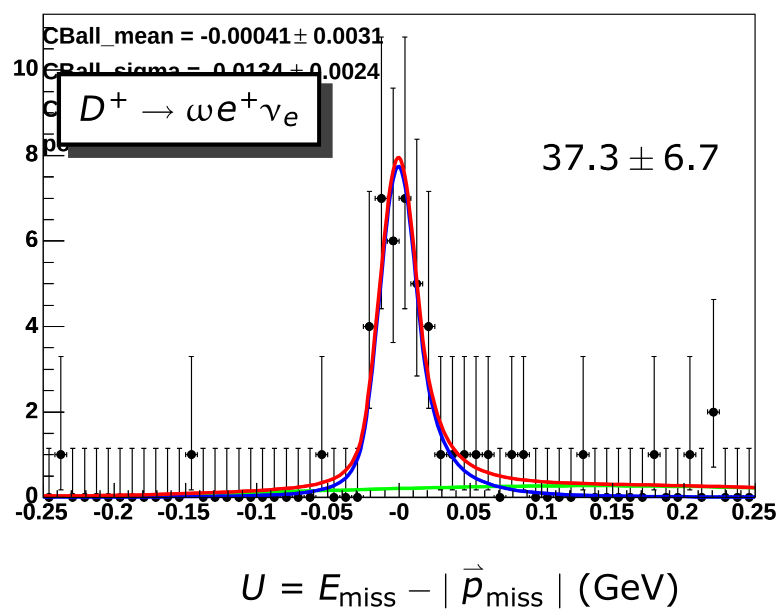
$$\frac{\Gamma^{\rm SL}_{D^+}}{\Gamma^{\rm SL}_{D^0}} = \frac{\mathcal{B}^{\rm SL}_{D^+}/\tau_+}{\mathcal{B}^{\rm SL}_{D^0}/\tau_0} = 0.985 \pm 0.028 \pm 0.015$$

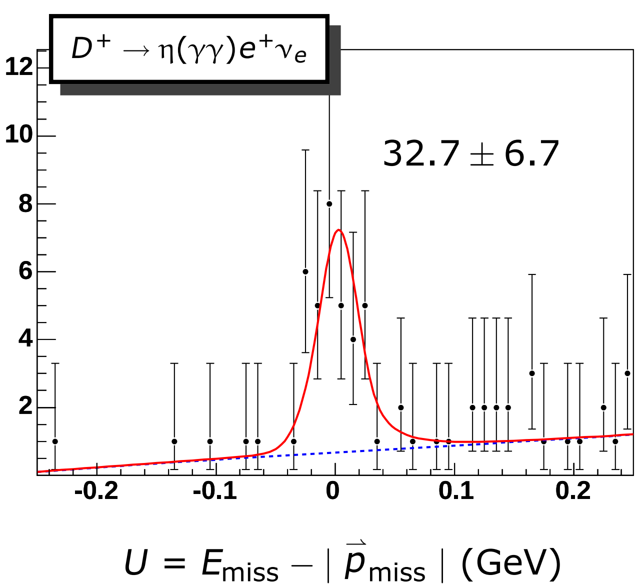
[Preliminary] First Observations : Cabibbo-suppressed

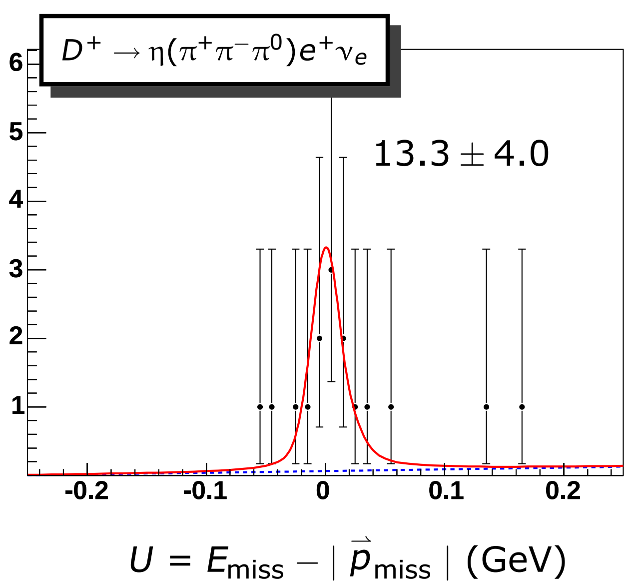
Mode	Branching Fraction ($\times 10^{-4}$)
$D^+ \to \eta e^+ \nu_e$	$12.9 \pm 1.9 \pm 0.7$
$D^+ \to \eta' e^+ \nu_e$	< 3 (90% U.L.)*
$D^+ \to \phi e^+ \nu_e$	< 2 (90% U.L.)*
$D^0 \to \rho^- e^+ \nu_e$	$15.6 \pm 1.6 \pm 0.9$
$D^+ \to \omega e^+ \nu_e$	$14.9 \pm 2.7 \pm 0.5$

$* \times 100$ improved upper limit

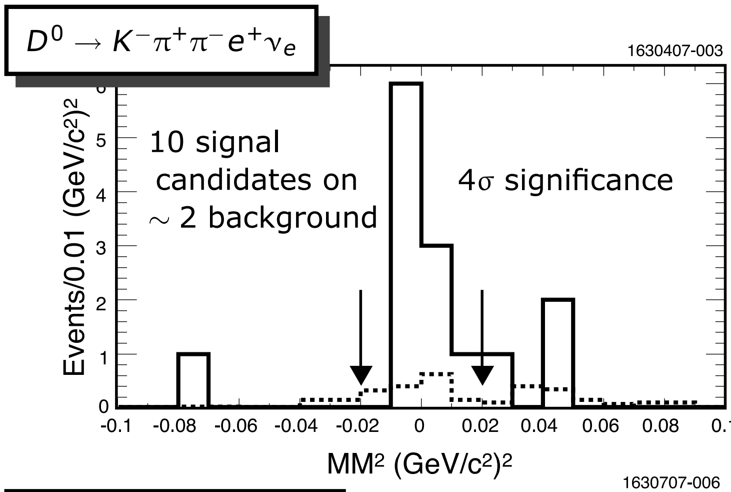


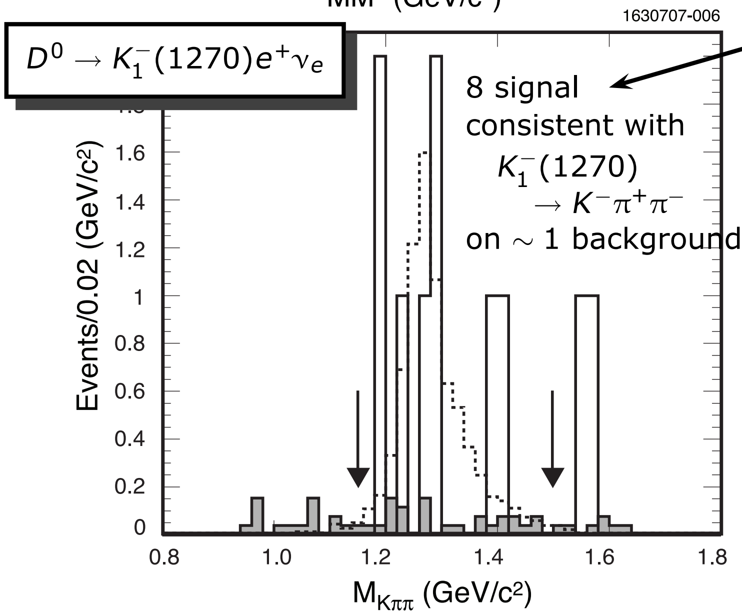


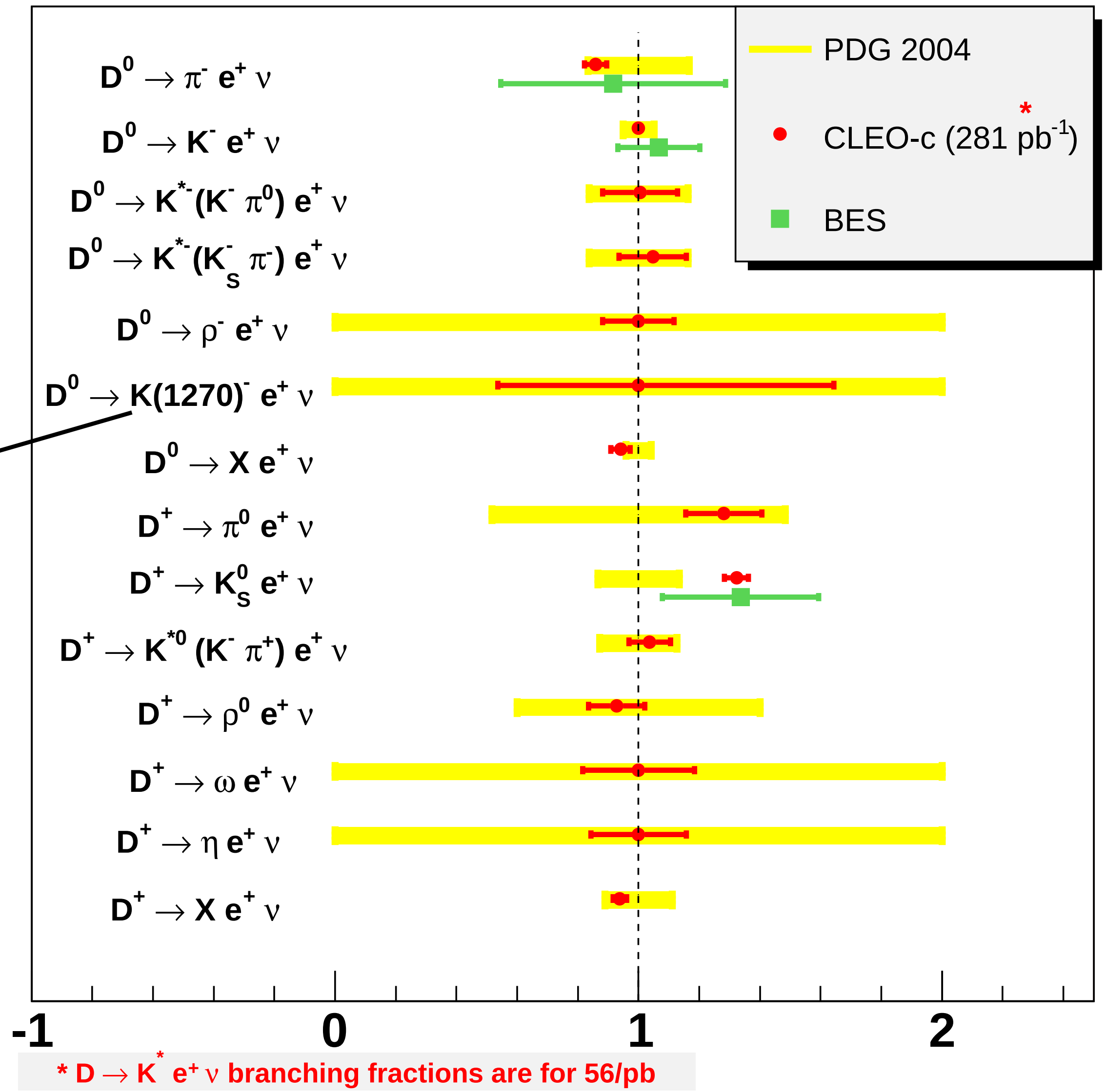




First Observations & Br Summary







[arXiv:0705.4276]

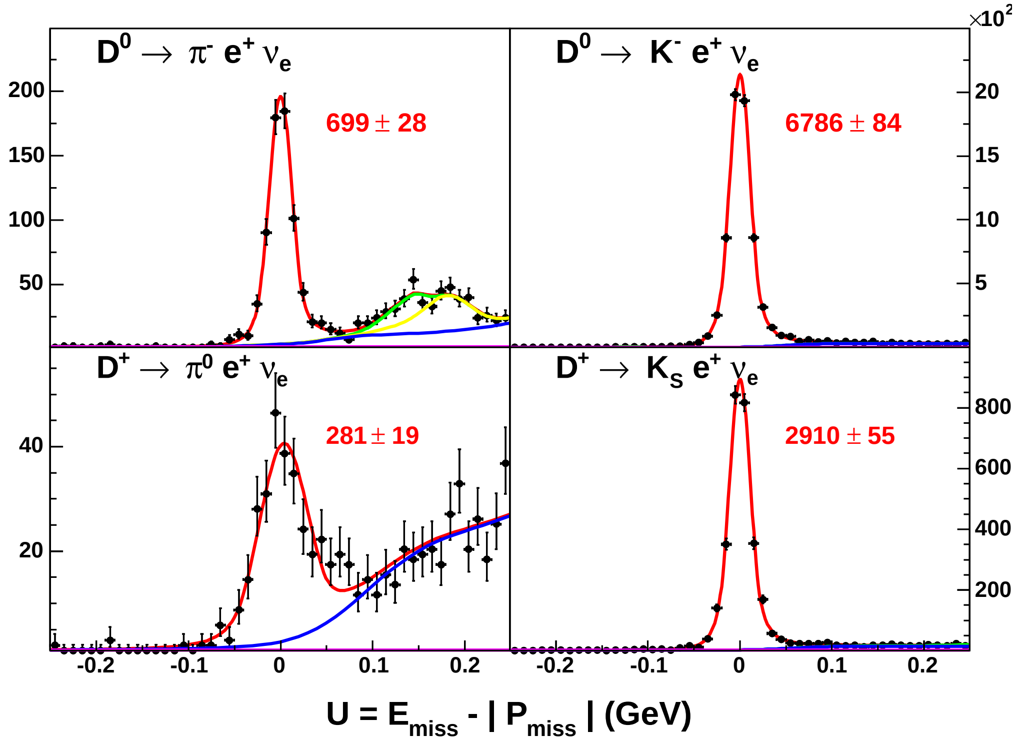
Normalized to PDG

$$\mathcal{B}(D^0 \to K^-\pi^+\pi^- e^+\nu_e) = [2.8^{+1.4}_{-1.1}(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-4}$$

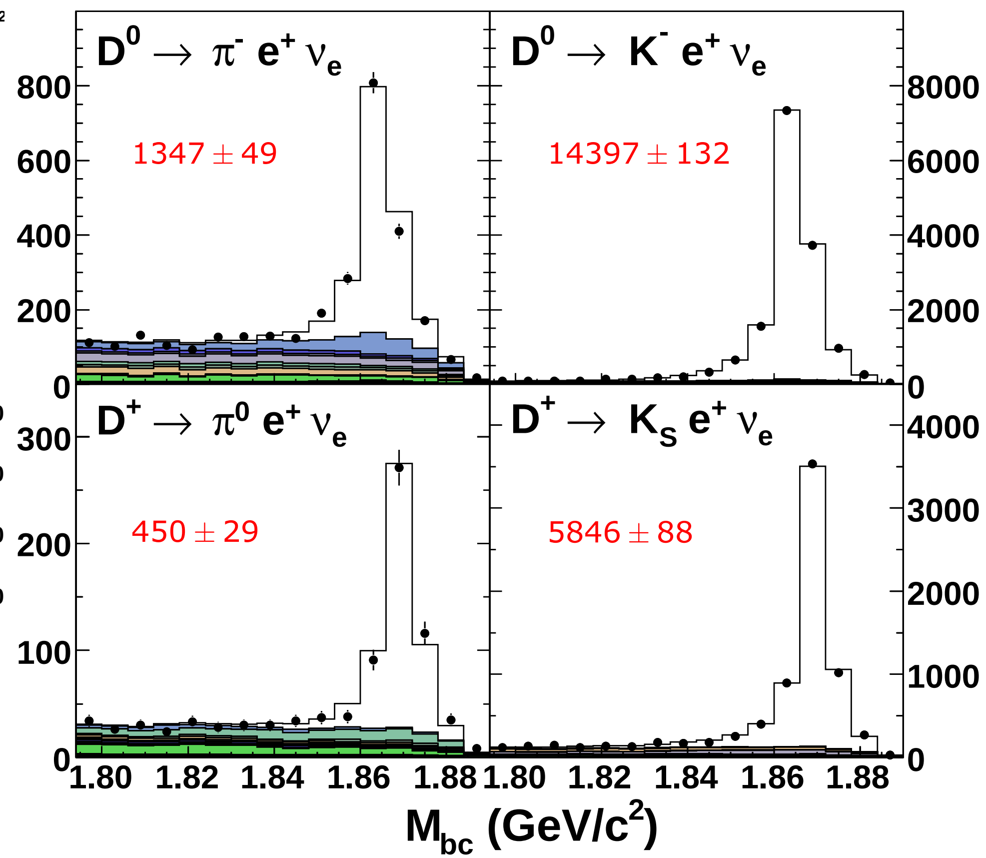
$$\mathcal{B}(D^0 \to K_1^-(1270) e^+\nu_e) = [7.6^{+4.1}_{-3.0}(\text{stat}) \pm 0.6(\text{syst}) \pm 0.7] \times 10^{-4}$$

$\mathbf{D} \rightarrow \mathbf{K}(\pi)\mathbf{e}\nu$

(1) Tagged Analysis :

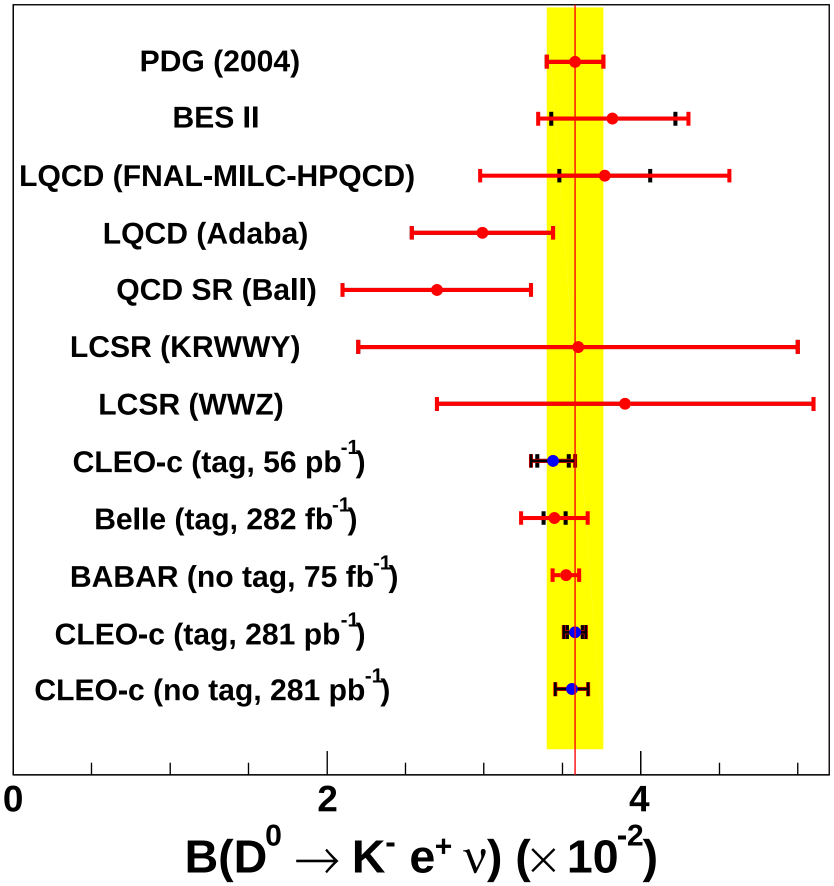


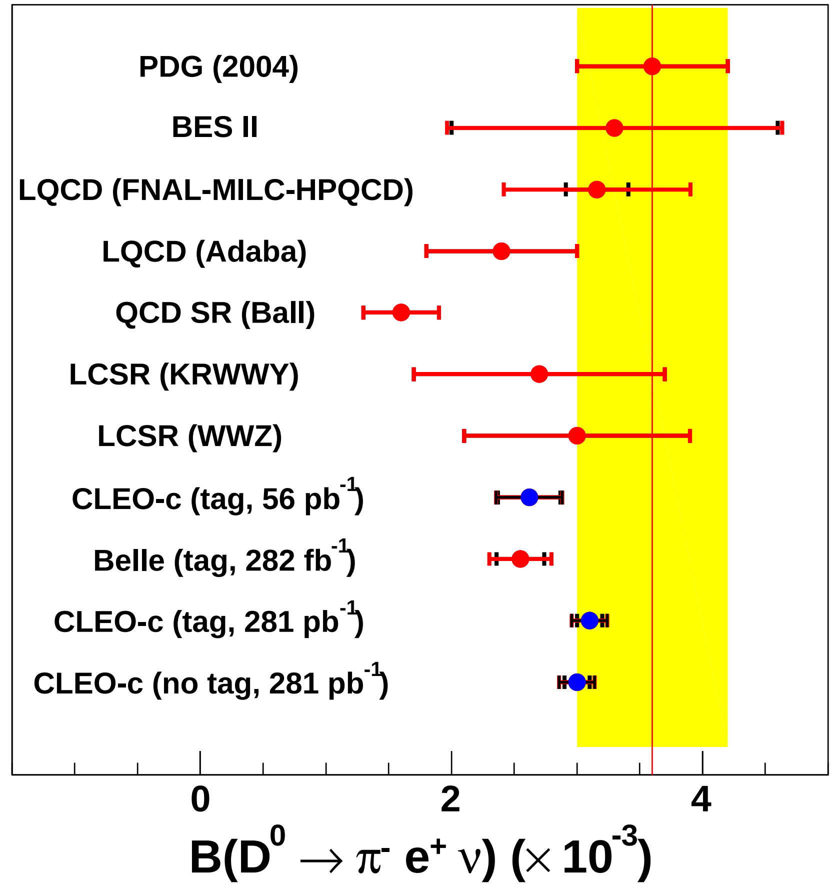
(2) Untagged Analysis :
[neutrino reconstruction]



- The untagged analysis has larger signal yields but larger backgrounds and systematic uncertainties.

[Preliminary] $\mathcal{B}(D \to K(\pi)e\nu)$

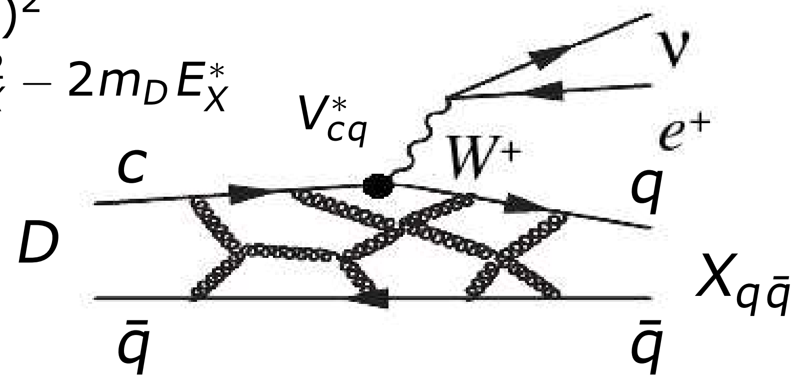




- Significant recent increase in precision (BaBar, Belle, and CLEO-c) measurements.
- Theoretical precision lags experiment

Semileptonic Decay Form Factor

$$q^2 = (p_D - p_X)^2 = m_D^2 + m_X^2 - 2m_D E_X^*$$



Amplitude factorizes

$$\mathcal{M}(D \to X\ell^+\nu_\ell) = -i\frac{G_F}{\sqrt{2}}V_{cq}^* L_\mu H^\mu$$

- Hadronic currents : in the limit $m_\ell \to 0$
  - $P \to P'\ell^+\nu_\ell$: 1 form factor, $H^\mu = f_+(q^2)(p_P + p_{P'})^\mu$ (gold-plated for both theory and experiment)
  - $P \to V\ell^+\nu_\ell$: 3 form factors
    $H^\mu = \frac{2i\epsilon^{\mu\nu\alpha\beta}}{m_P+m_V}\epsilon_\nu^* p_{P'\alpha} p_{P\beta} V(q^2) - (m_P + m_V)\epsilon^{*\mu} A_1(q^2) + \frac{\epsilon^* \cdot q}{m_P+m_V}(p_P + p_V)^\mu A_2(q^2)$
- Form factors describe the non-perturbative QCD physics : probability final state hadron will be formed.
- Theory (i) calculates at fixed q^2 (ii) uses parametrization to evolve to full q^2 range.

Form Factor : parameterizations

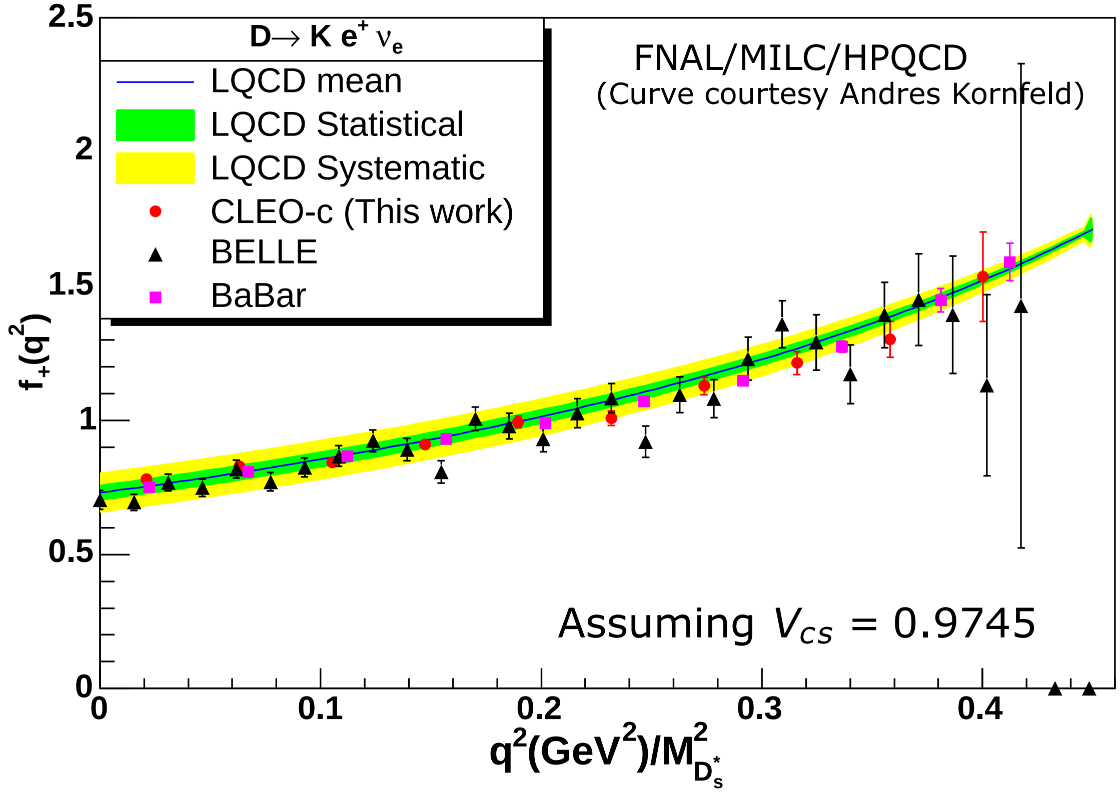
- In general : $f_+(q^2) = \frac{f_+(0)}{1-\alpha} \frac{1}{1-q^2/m^2_{\rm pole}} + \sum_{k=1}^{N} \frac{\rho_k}{1-\frac{1}{\gamma_k}\frac{q^2}{m^2_{\rm pole}}}$
- Single pole : $f_+(q^2) = \frac{f_+(0)}{1-q^2/m^2_{\rm pole}}$
- Modified pole : $f_+(q^2) = \frac{f_+(0)}{(1-q^2/m^2_{\rm pole})(1-\alpha q^2/m^2_{\rm pole})}$
  (allows for additional poles).
- Series expansion : [T. Becher and R. J. Hill, Phys. Lett. B **633**, 61 (2006)]

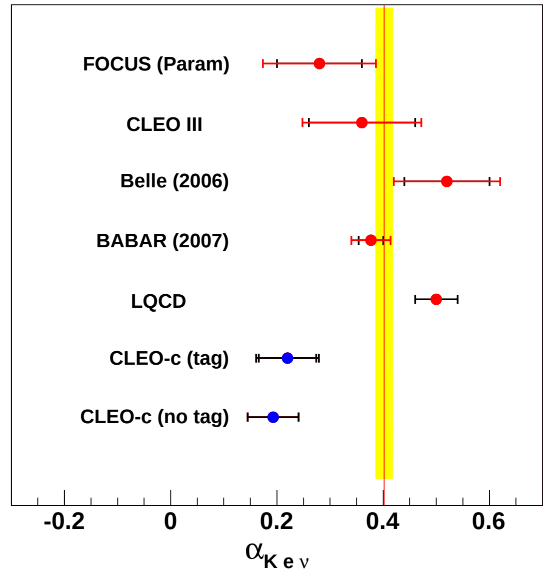
  $$f_+(q^2) = \frac{1}{P(q^2)\phi(q^2,t_0)} \sum_{k=0}^{\infty} a_k(t_0)[z(q^2,t_0)]^k,$$

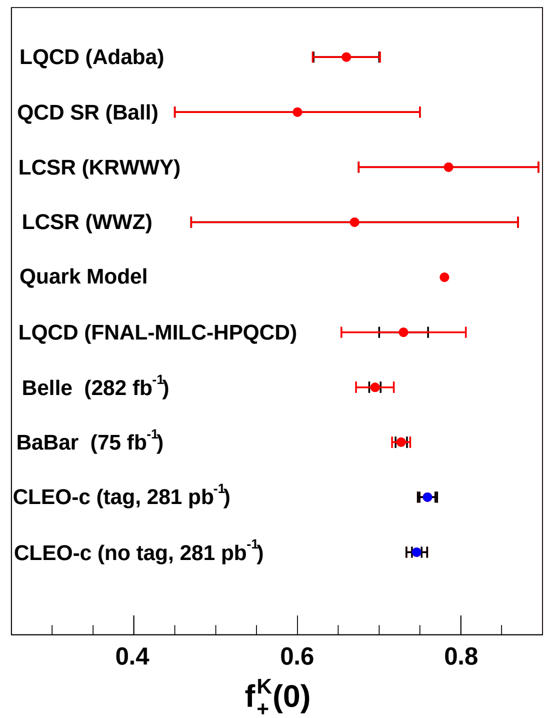
  with $z(q^2,t_0) = \frac{\sqrt{t_+-q^2}-\sqrt{t_+-t_0}}{\sqrt{t_+-q^2}+\sqrt{t_+-t_0}}$, $t_\pm \equiv (M_D \pm m_P)^2$, and $P(q^2) \equiv 1$ $(D \to \pi)$ or $z(q^2, M^2_{D_s^*})$ $(D \to K)$.

  With current CLEO-c data we only resolve the first 2–3 terms in the series expansion.
- Experiment probes both the form factor magnitude & parametrization.

[Preliminary] D $\to$ Keν : high statistics test of shape & absolute normalization of $f_+(q^2)$

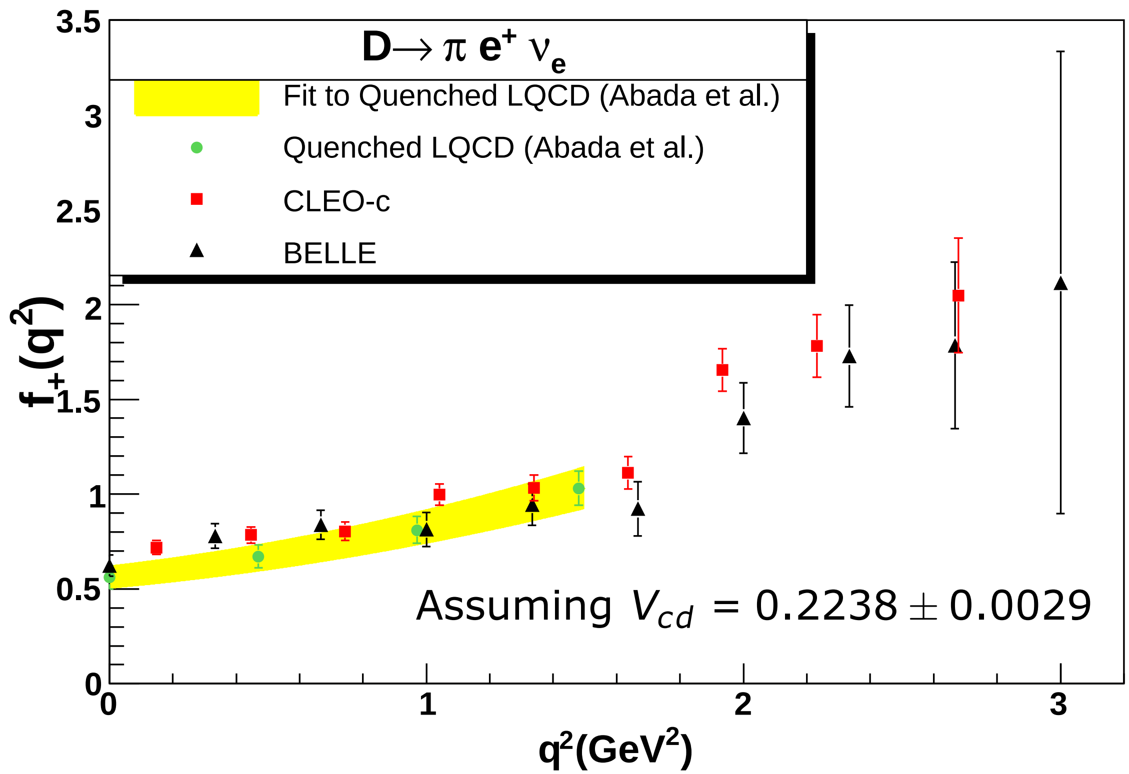


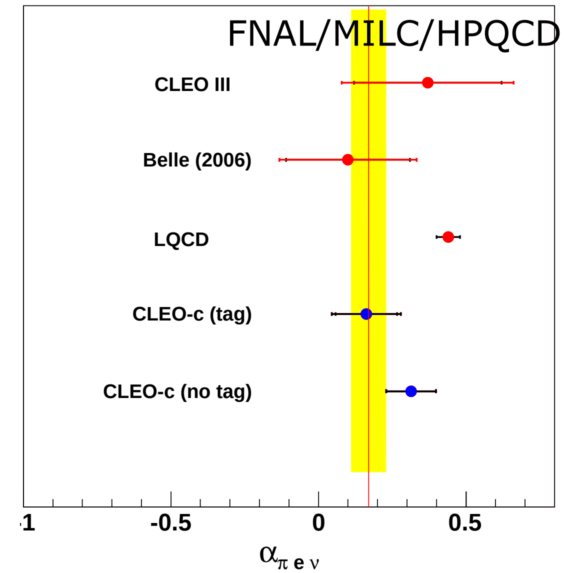


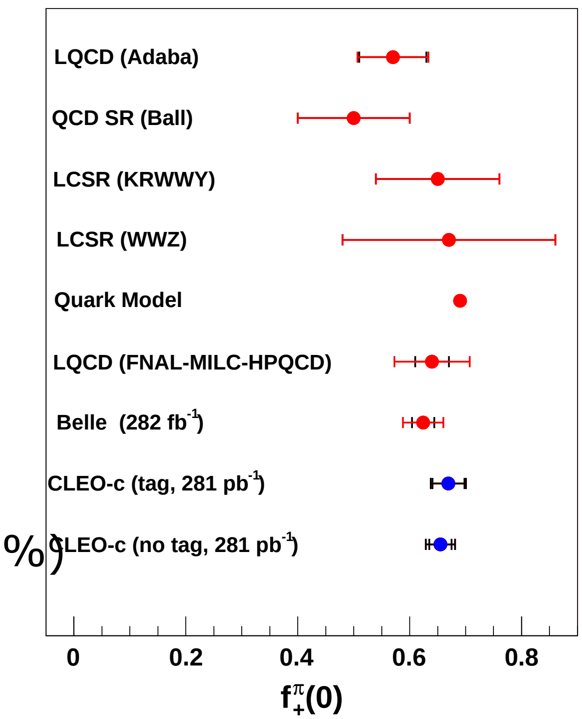


- Modified pole model used for comparison :
  $$f_+(q^2) = \frac{f_+(0)}{(1-q^2/m^2_{\rm pole})(1-\alpha q^2/m^2_{\rm pole})}$$
- Shape parameter: CLEO-c prefers smaller value
- Normalization:
  experiment (2%) consistent with LQCD (10%)

[Preliminary] $D \to \pi e \nu$: high statistics test of shape & absolute normalization of $f_+(q^2)$





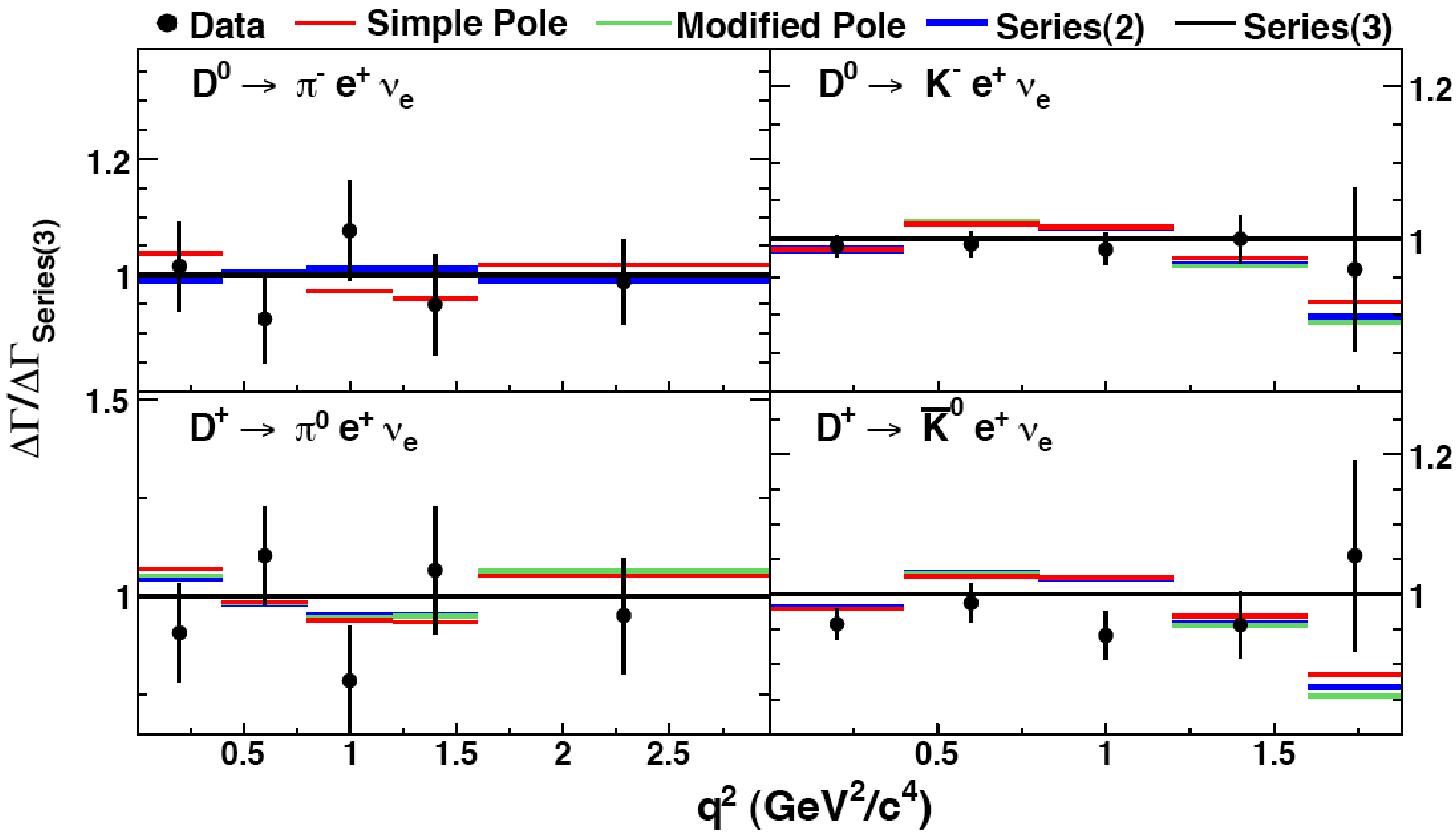


- Modified pole model used for comparison :

$$f_+(q^2) = \frac{f_+(0)}{(1-q^2/m^2_{\text{pole}})(1-\alpha q^2/m^2_{\text{pole}})}$$

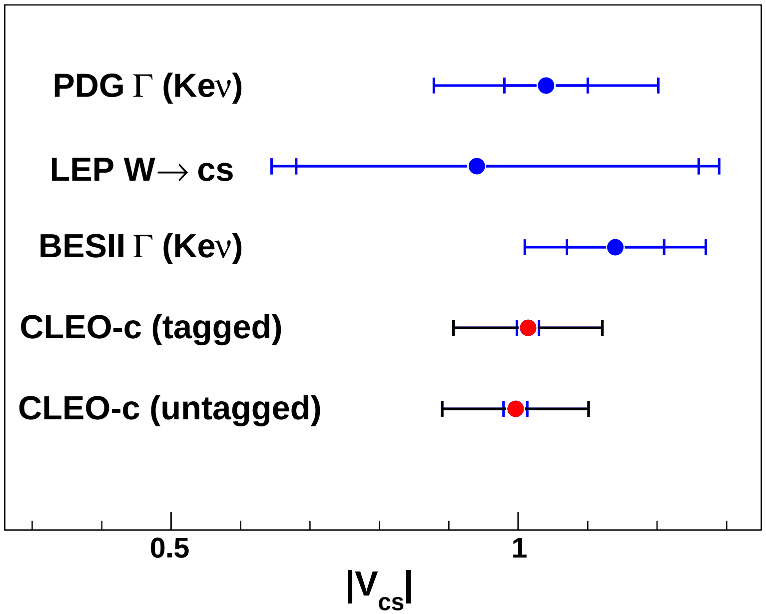
- Shape parameter: experiments compatible with LQCD
- Normalization: experiment (4%) consistent with LQCD (10%)

Form Factor : D $\to$ Peν which parametrization?



- Data fits are normalized to the three-parameter series fit result.
- All parameterizations are consistent with data, when shape parameters are not fixed to their model values.
- We use the model independent Becher-Hill series parametrization for V_{cx} (determine $f_+(0)|V_{cx}|$ then use theory value of $f_+(0)$).

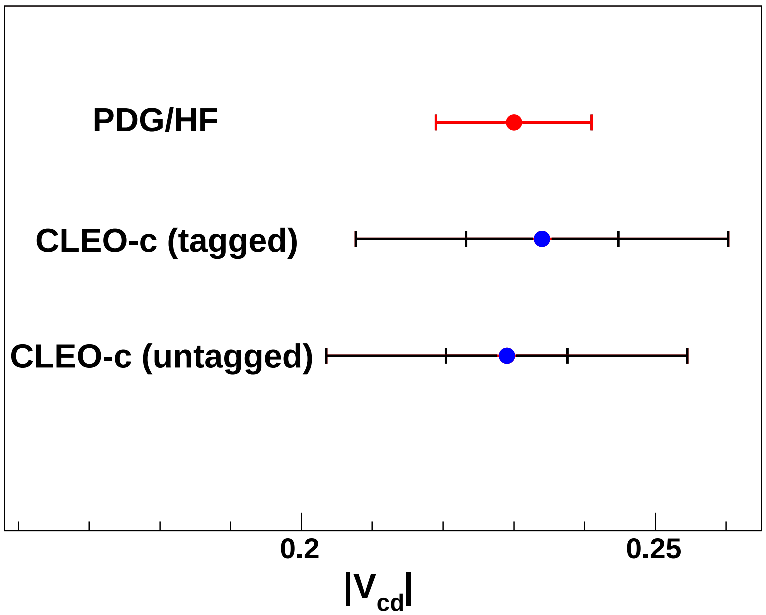
[Preliminary] V_{cs} & V_{cd} Results



Combined measured $|V_{cx}|f_+(0)$ values
using Becher-Hill parameterization
with FNAL/MILC/HPQCD for $f_+(0)$.

- CLEO-c : the most precise direct determination of V_{cs}
- Dominant uncertainty : LQCD

CLEO-c	V_{cs}
(tagged)	$1.014 \pm 0.013 \pm 0.009 \pm 0.106$
(untagged)	$0.996 \pm 0.008 \pm 0.015 \pm 0.104$
	stat syst theory

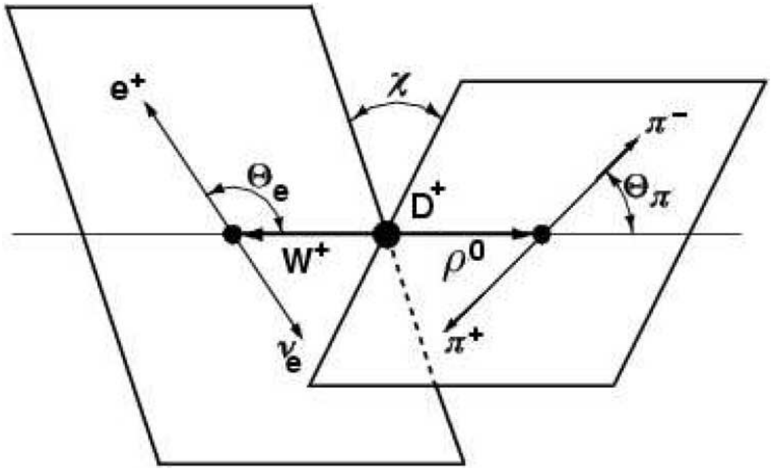


- CLEO-c : dominant uncertainty LQCD
- νN remains most precise determination for now

CLEO-c	V_{cd}
(tagged)	$0.234 \pm 0.010 \pm 0.004 \pm 0.024$
(untagged)	$0.229 \pm 0.007 \pm 0.005 \pm 0.024$
	stat syst theory

- Tagged and untagged are consistent.
- 40% overlap, DO NOT AVERAGE.

$D \to \rho e^+ \nu_e$



- Kinematic variables describe the decay rate : q^2, $\cos\theta_e$, $\cos\theta_\pi$, χ, and $m(\pi\pi)$
- We fit to the decay rate

$$\frac{d\Gamma(D \to \rho e^+ \nu_e,\ \rho \to \pi\pi)}{dq^2 d\cos\theta_\pi d\cos\theta_e d\chi dm(\pi\pi)} = \frac{3G_F^2}{8(4\pi)^4}|V_{cd}|^2 \frac{p_\rho q^2}{M_D^2} \mathcal{B}(\rho \to \pi\pi)|BW|^2(m(\pi\pi)) \times$$

$$\{(1+\cos\theta_e)^2 \sin^2\theta_\pi |H_+(q^2)|^2$$

$$(1-\cos\theta_e)^2 \sin^2\theta_\pi |H_-(q^2)|^2$$

$$+4\sin^2\theta_e \cos^2\theta_\pi |H_0(q^2)|^2$$

$$+4\sin\theta_e(1+\cos\theta_e)\sin\theta_\pi\cos\theta_\pi\cos\chi H_+(q^2)H_0(q^2)$$

$$-4\sin\theta_e(1-\cos\theta_e)\sin\theta_\pi\cos\theta_\pi\cos\chi H_-(q^2)H_0(q^2)$$

$$-2\sin^2\theta_e\sin^2\theta_\pi\cos 2\chi H_+(q^2)H_-(q^2)\}$$

- $H_\pm(q^2) = (M_D + m_{\pi\pi})A_1(q^2) \mp 2\frac{M_D P_{\pi\pi}}{M_D + m_{\pi\pi}} V(q^2)$

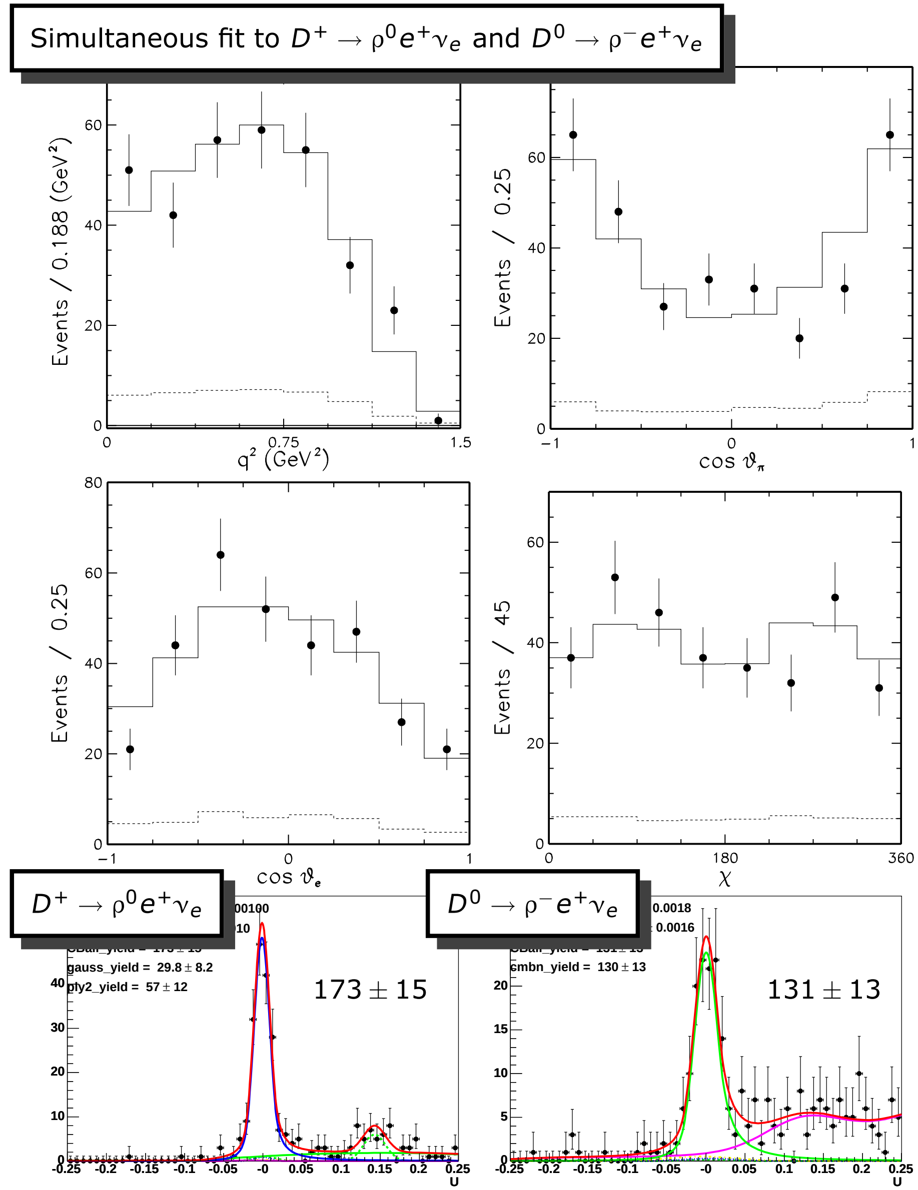
  $H_0(q^2) = \frac{1}{2m_{\pi\pi}\sqrt{q^2}}\left[(M_D^2 - m_{\pi\pi}^2 - q^2)(M_D + m_{\pi\pi})A_1(q^2) - 4\frac{M_D^2 P_{\pi\pi}^2}{M_D + m_{\pi\pi}} A_2(q^2)\right]$
- Traditionally spectroscopic pole model is used : $A_i(q^2) = \frac{A_i(0)}{1 - q^2/M_A^2}$ and $V(q^2) = \frac{V(0)}{1 - q^2/M_V^2}$
- Only two shape parameters needed : $R_V = \frac{V(0)}{A_1(0)}$ and $R_2 = \frac{A_2(0)}{A_1(0)}$

[Preliminary] $D \to \rho e^+ \nu_e$ Results

- First measurement of form factor in Cabibbo suppressed charm $P \to V e \nu$ decay
- Can be used to determine V_{ub} along with $B \to \rho \ell \nu$, $D \to K^* \ell \nu$, and $B \to K^* \ell \ell$; B. Grinstein and D. Pirjol, [Phys. Rev. D **70**, 114005 (2004)].
- Simultaneous fit to $D^+ \to \rho^0 e^+ \nu_e$ and $D^0 \to \rho^- e^+ \nu_e$

$$R_V = 1.40 \pm 0.25 \pm 0.03$$
$$R_2 = 0.57 \pm 0.18 \pm 0.06$$

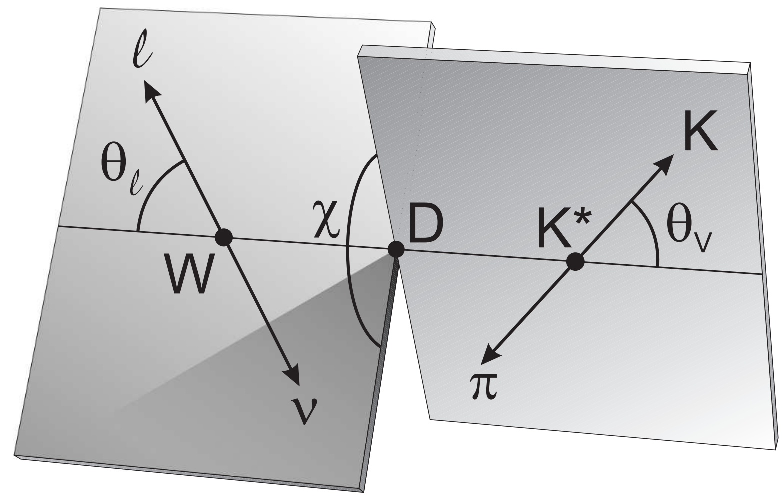
✥ $\mathcal{B}(D^0 \to \rho^- e^+ \nu_e) = (1.56 \pm 0.16 \pm 0.09) \times 10^{-3}$
✥ $\mathcal{B}(D^+ \to \rho^0 e^+ \nu_e) = (2.32 \pm 0.20 \pm 0.12) \times 10^{-3}$
✥ Isospin average :
$\Gamma(D^0 \to \rho^- e^+ \nu_e) = (0.41 \pm 0.03 \pm 0.02) \times 10^{-2} \text{ps}^{-1}$



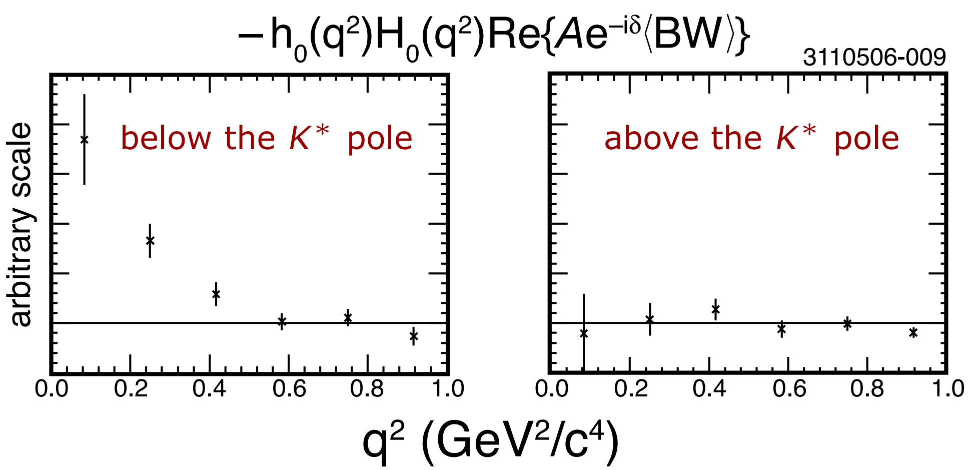
$U = E_{\text{miss}} - |\vec{p}_{\text{miss}}|$ (GeV)

$D^+ \to K^-\pi^+e^+\nu_e$

- For $D \to Ve\nu$, use 3 helicity amplitudes $H_+(q^2)$, $H_-(q^2)$, and $H_0(q^2)$.
- FOCUS : additional form factor $h_0(q^2)$ for s-wave amplitude. Confirmed by CLEO-c using 281pb^{-1}.



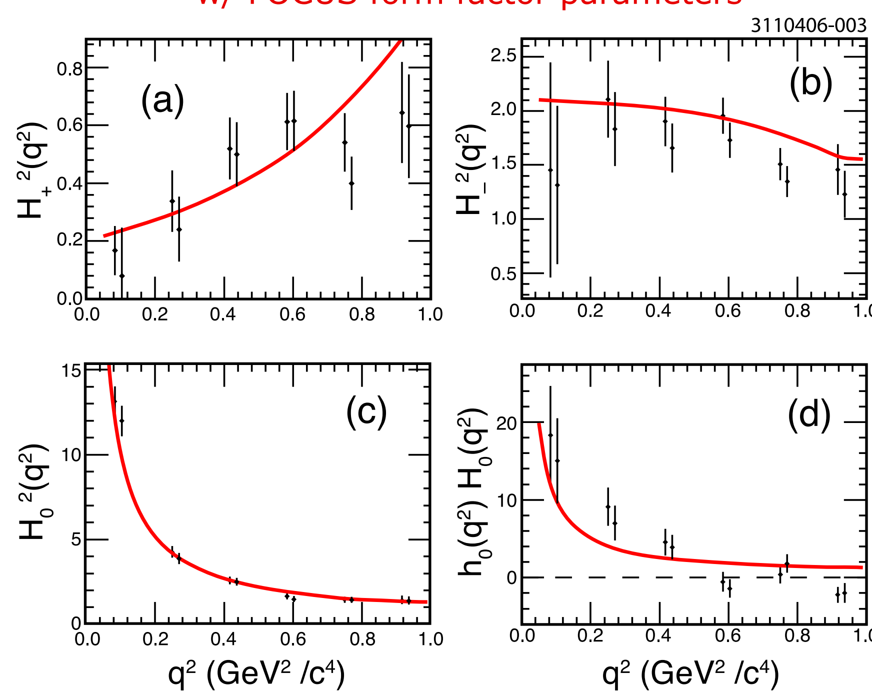
The *s*-wave interference term



For $\delta \approx 40^\circ$ the high mass BW is nearly orthogonal to the FOCUS *s*-wave phase. Our interference term should vanish above the pole and it does!

[Phys. Rev. D **74**, 052001 (2006)]

— w/ FOCUS form factor parameters



Summary (results are Preliminary)

- First observations of four modes
  $D^0 \to \rho^- e^+\nu_e$, $D^+ \to \omega e^+\nu_e$, $D^+ \to \eta e^+\nu_e$, and $D^0 \to K_1^-(1270)e^+\nu_e$
- First form factors in a Cabibbo suppressed $P \to Ve\nu$
- $\mathcal{B}(D \to Ke^+\nu_e)$ pre-CLEO-c $\delta\mathcal{B}/\mathcal{B}$ = 6% now 2%,
  $|V_{cs}| = 1.014 \pm 0.013 \pm 0.009 \pm 0.106_{\text{theory}}$ (tag)
  $|V_{cs}| = 0.996 \pm 0.008 \pm 0.015 \pm 0.104_{\text{theory}}$ (notag)
  (best direct determination of V_{cs})
- $\mathcal{B}(D \to \pi e^+\nu_e)$ pre-CLEO-c $\delta\mathcal{B}/\mathcal{B}$ = 45% now 4%, most precise $f_+(0)$ & shape
  $|V_{cd}| = 0.234 \pm 0.010 \pm 0.004 \pm 0.024_{\text{theory}}$ (tag)
  $|V_{cd}| = 0.229 \pm 0.007 \pm 0.005 \pm 0.024_{\text{theory}}$ (notag)
  (most precise determination of V_{cd} from semileptonic decay)
- CLEO-c baseline plan 750/pb @ 3770
  - more stringent tests of theory for $D \to K(\pi)e^+\nu_e$ form factor $f_+(0)$ & shape
  - CKM precision expected : V_{cs} (syst limited), V_{cd} (stat limited)
    $D \to Ke^+\nu_e$ $\frac{\delta V_{cs}}{V_{cs}} = 0.8\% \oplus \frac{\delta\text{theory}}{\text{theory}}$ and $D \to \pi e^+\nu_e$ $\frac{\delta V_{cd}}{V_{cd}} = 1.6\% \oplus \frac{\delta\text{theory}}{\text{theory}}$