CLEO-c Charm Semileptonic Decays

OUTLINE

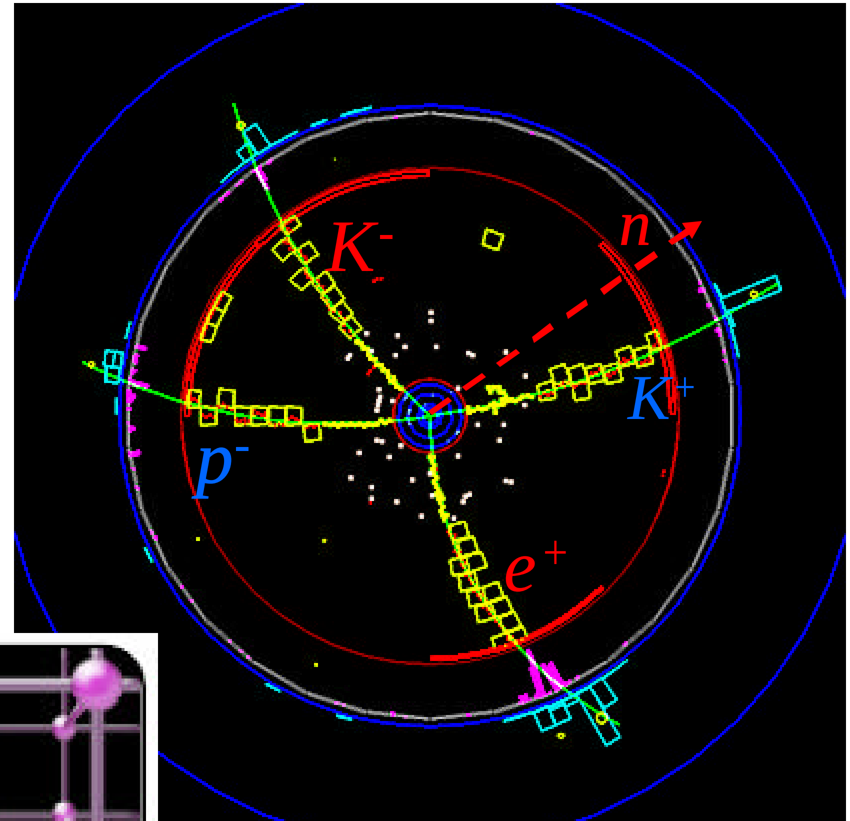
The role of charm semileptonic decays

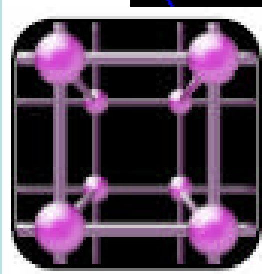
Reconstruction techniques

New modes

D→K/p ev
Determination of Vcs &Vcd

D → ?ev





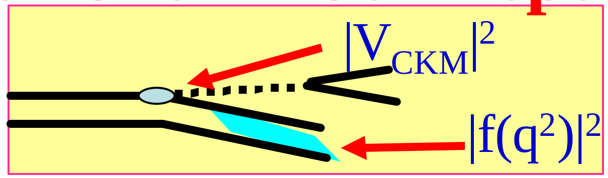
$$y\ (3770) \to D^0 \overline{D}^0$$

$$\overline{D}^0 \to K^+ p^-, D^0 \to K^- e^+ n$$

Ian Shipsey, Purdue University CLEO-c Collaboration

Edited and Presented by Marina Artuso, Syracuse University

Importance of Charm Semileptonic Decays

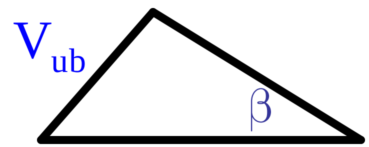


$$\frac{d\Gamma}{dq^2} \propto |V_{cs(d)}|^2 |f_+^{D\to(K)\pi}(q^2)|^2$$

1 Assuming th ff $\Rightarrow V_{cs}$ and V_{cd}

2 Assuming V_{cs} and V_{cd} known, we can check theoretical calculations of the form factors

3 Useful input to Vub from exclusive B semileptonic decays



$Br(B \to \pi l \nu)$ 6% precision

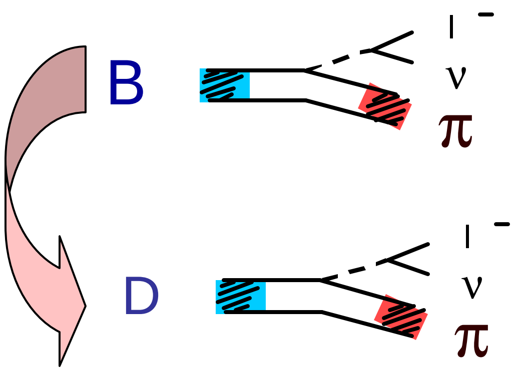
BABAR / Belle / CLEO

(HFAG (2006))

$$|V_{ub}| = (3.60 \pm 0.10 \pm 0.50) \times 10^{-3}$$
$$\pm \exp \pm \text{LQCD}$$

Expt. 3%

~14% HFAG average of form factor



HQS

$$\propto \left[f^{B\to\pi}(q) \right]^2 |V_{ub}|^2$$

$$\propto \left[f^{D\to\pi}(q) \right]^2 |V_{cd}|^2$$

V_{ub} is a Standard Model fundamental Parameter

Important to measure precisely AND to validate its errors

Analysis Technique @ CLEO-c D Tagging

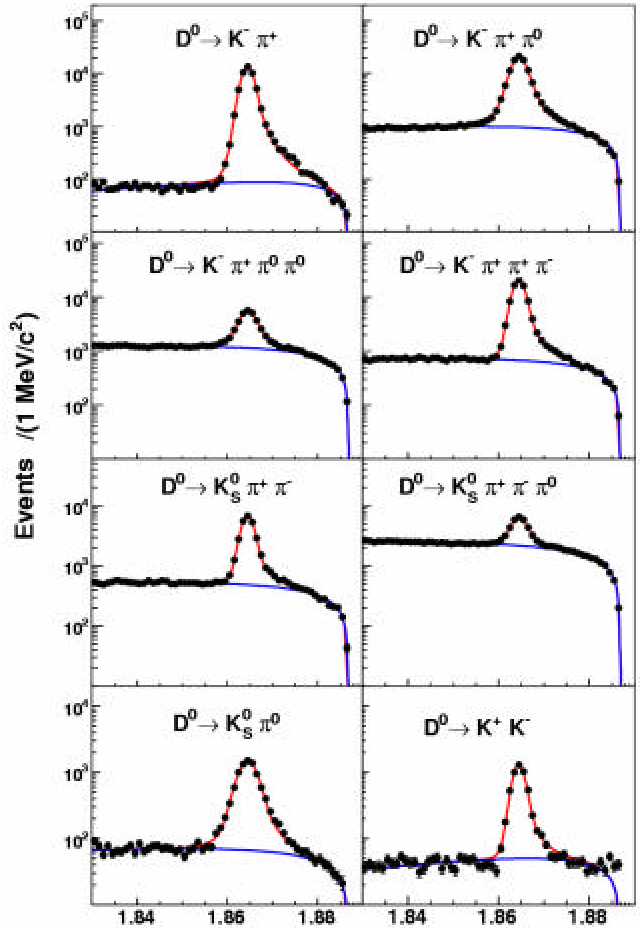
$y\,(3770) \rightarrow D\bar{D}$

- Just above threshold: no additional particles
- Fully reconstruct one D in the event in a hadronic mode: the tag using

$281\ \text{pb}^{-1}: 1.8\times10^{6}\,D\bar{D}$

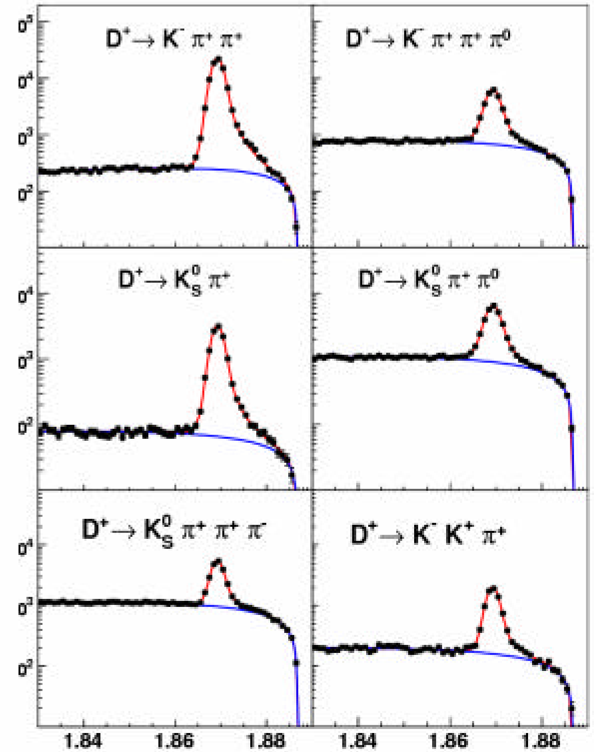
World's largest data set at 3770

Log scale!



M_{bc}

Log scale!



M_{bc}

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

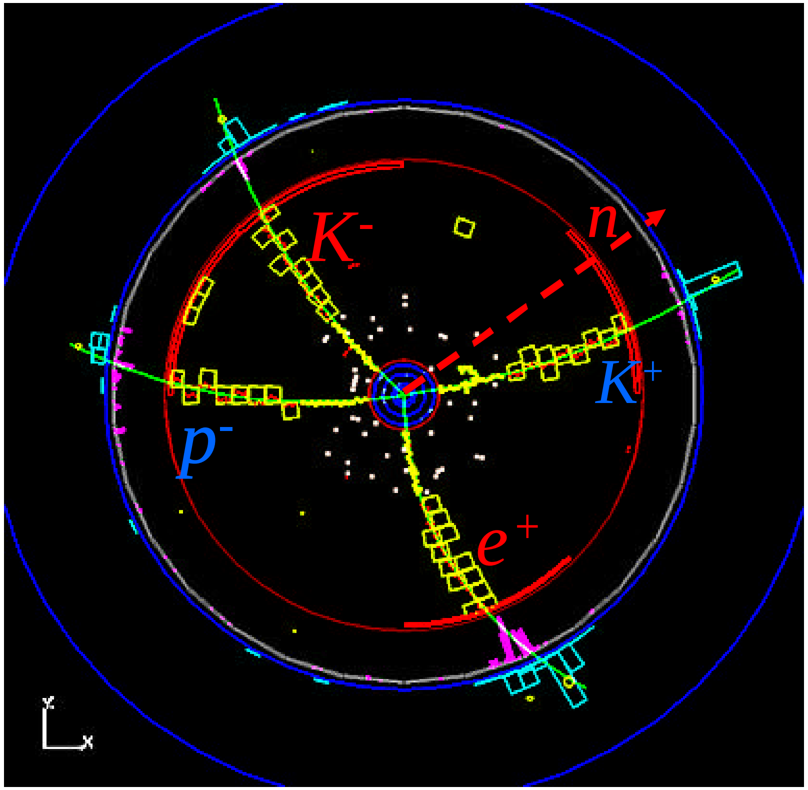
$$M_{bc} = \sqrt{E_{\text{beam}}^2 - |p_D|^2}$$

Can tag ~25% of events

Absolute Semileptonic Branching Fractions

The neutrino direction is determined to 1^0

no kinematics ambiguity

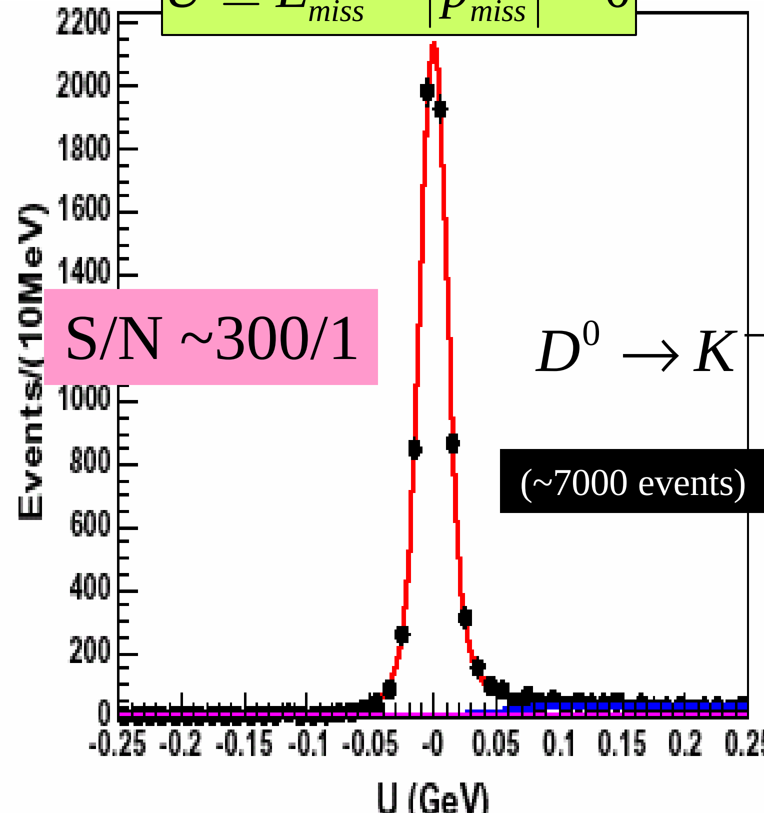


$$y\ (3770) \to D^0\, \overline{D}^0$$

$$\overline{D}^0 \to K^+ p^-,\ D^0 \to K^- e^+ n$$

Tagging creates a single D beam of known 4-momentum

$$U \equiv E_{miss} - \left|\vec{p}_{miss}\right| = 0$$

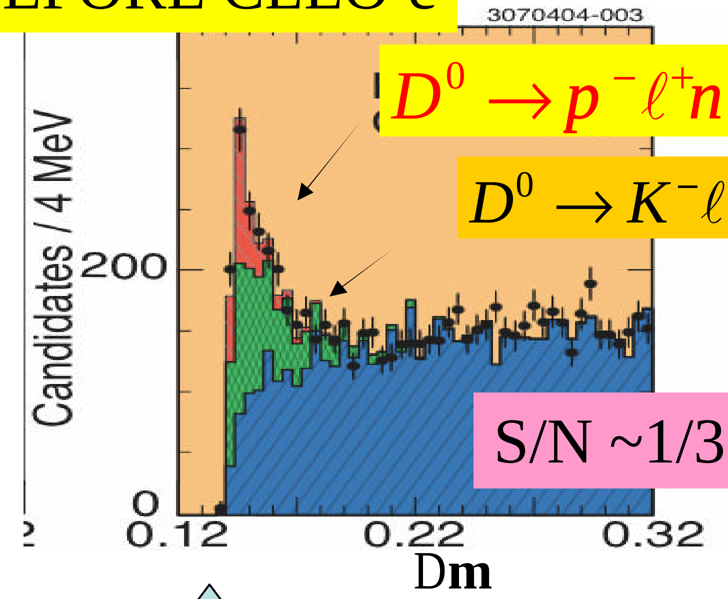


(Belle 282/fb (x1,000 CLEOc) 2700 events S/N 20/1)

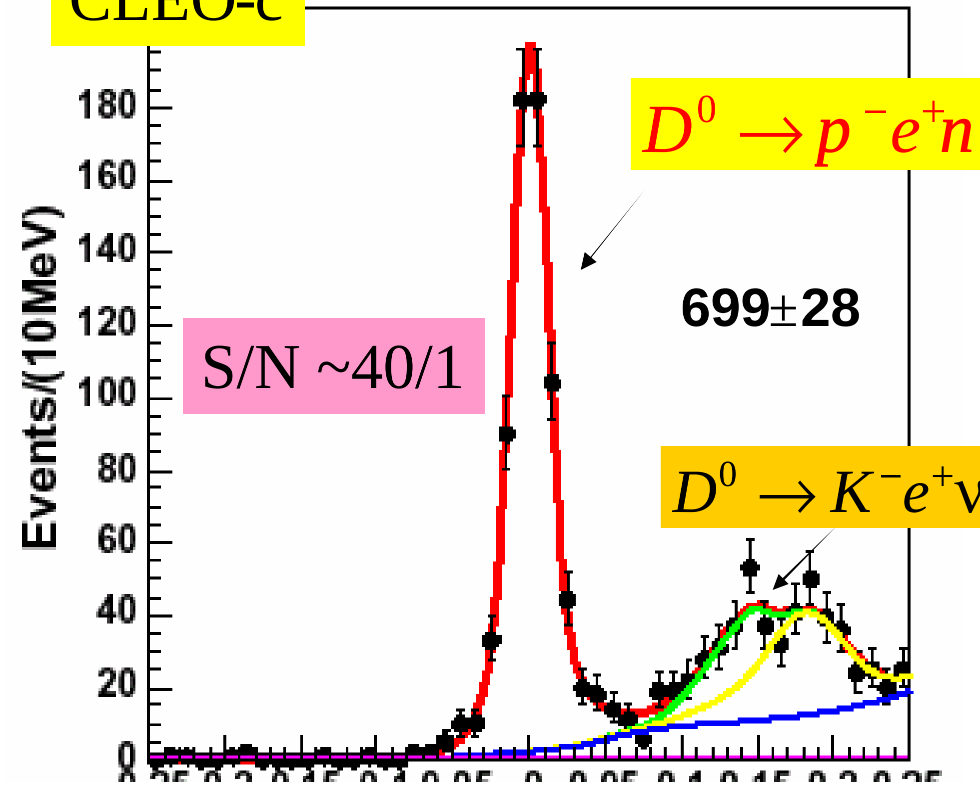
$$\mathrm{B}(D \to Ken) = \frac{N(D \to Ken)}{\text{Efficiency} \times N_{\text{tags}}}$$

$D^0 \to p^- e^+ n$

BEFORE CLEO-c



CLEO-c



Tag with $D^{*+} \to D^0 p_s$

$D^0 \to p^- \ell^+ n$

observable:

$\Delta m = m(p_s p \ell) - m(p \ell)$

$U = E_{miss} - |P_{miss}|$ (GeV)

Compare to:
state of the
art measurement
at 10 GeV (CLEO III)
PRL 94, 11802

Note:
kinematic
separation.

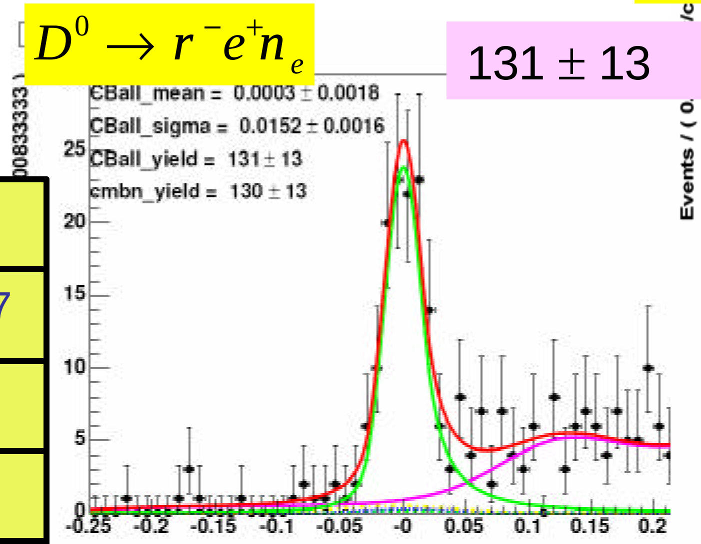
Only other high statistics measurement is from Belle
282/fb (x1,000 CLEOc) 222± 17 events S/N 4/1

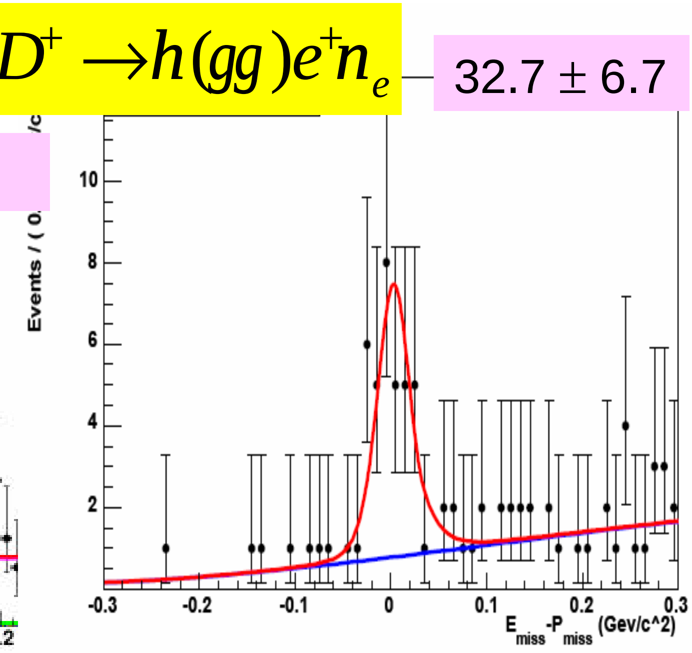
1st Observations:

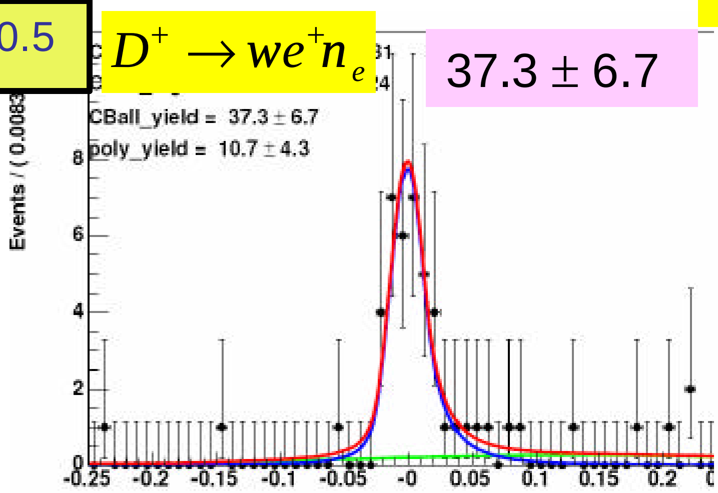
Mode	BR (10^{-4})
$\eta e^+\nu$	12.9±1.9±0.7
*$\eta' e^+\nu$	<3 (90%CL)
*$\phi e^+\nu$	<2 (90%CL)
?$e^+\nu$	15.6±1.6±0.9
$\omega e^+\nu$	14.9±2.7±0.5

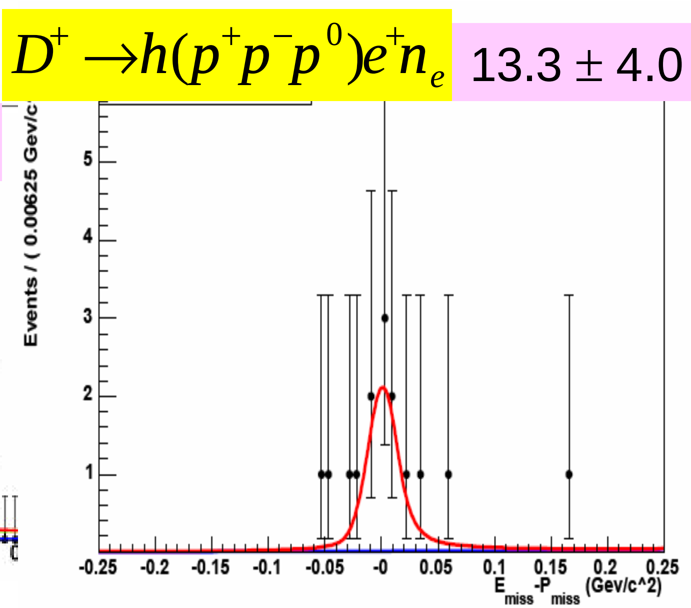
* x100 improved UL

D-tagged, 281/pb







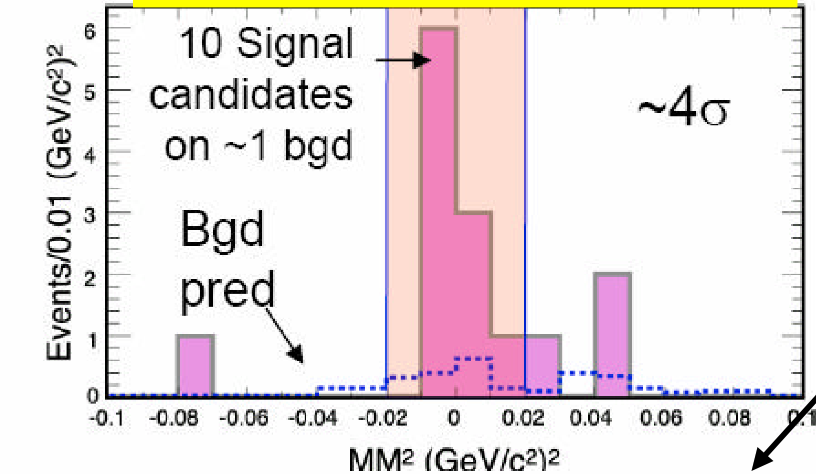


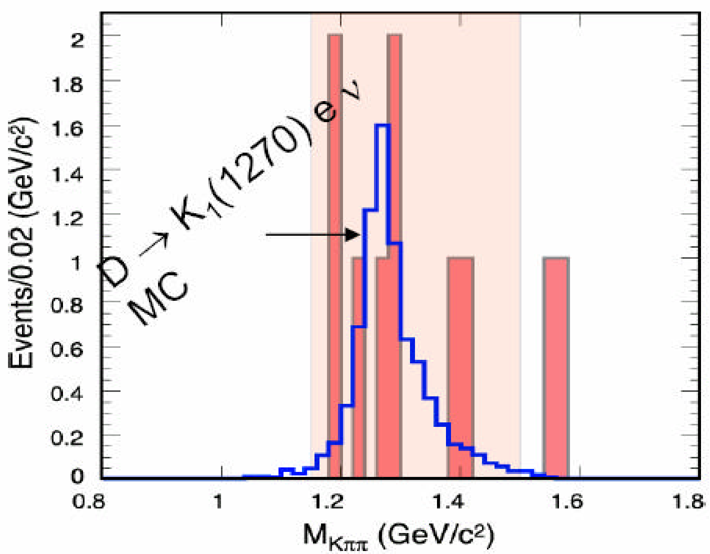
PRELIMINARY

1[st] Observations:

arXiv0705.4276 [hep-ex] subm PRL

$D^0 \to K^- \pi^+ \pi^- e^+ \nu_e$ 281pb^{-1}

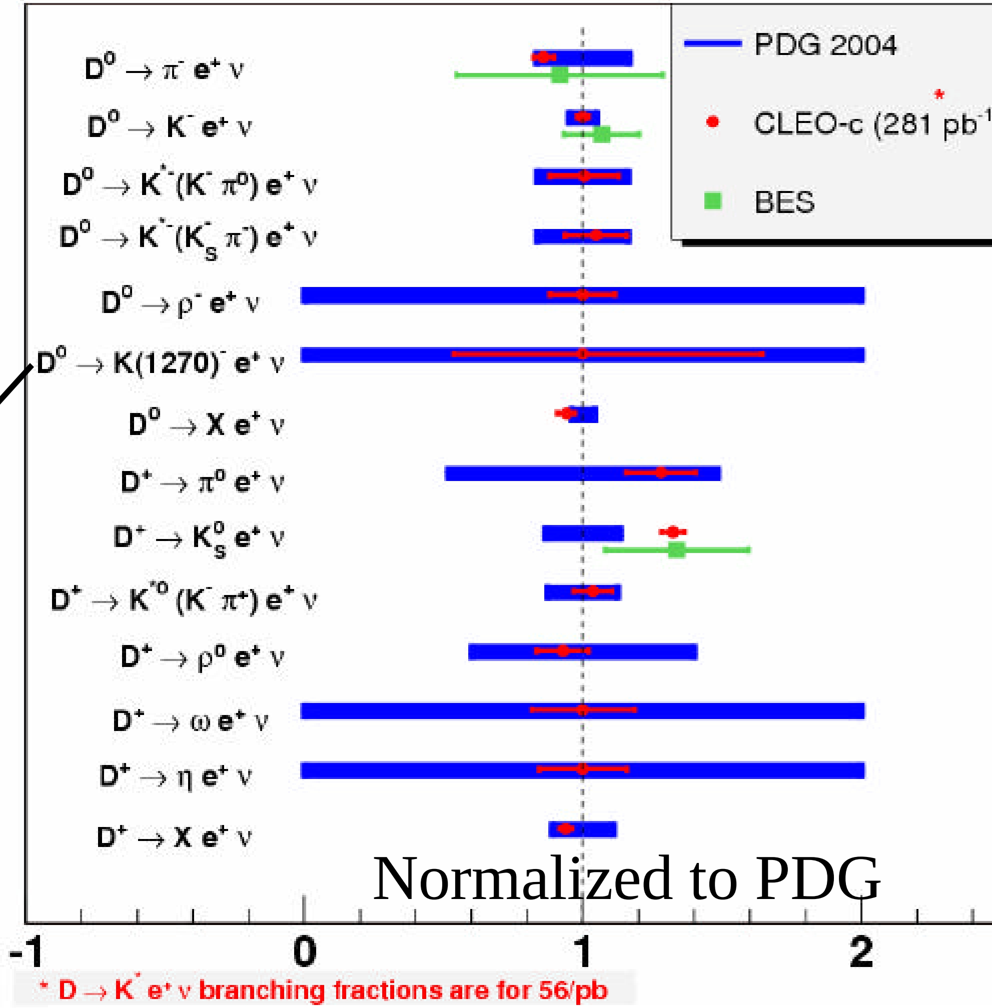




$$\mathcal{B}(D^0 \to K^-\pi^+\pi^-e^+\nu_e) = [2.8^{+1.4}_{-1.1}(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-4}$$

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

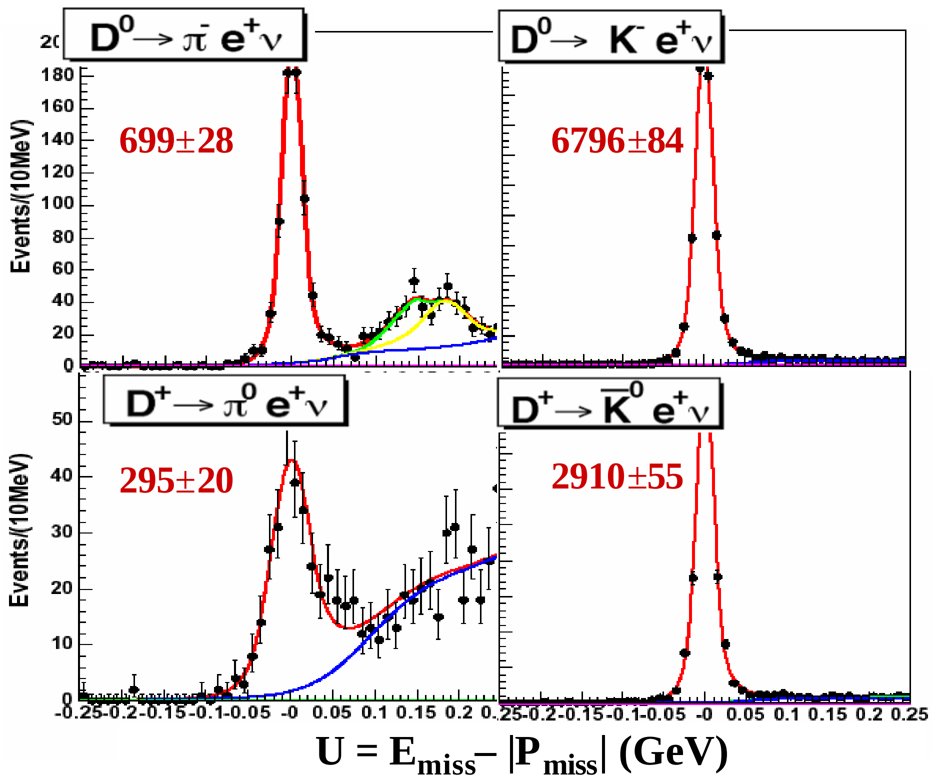
CLEO-c semileptonic BF summary



CLEO's measurements the most precise for ALL modes; *4 modes* observed for the first time

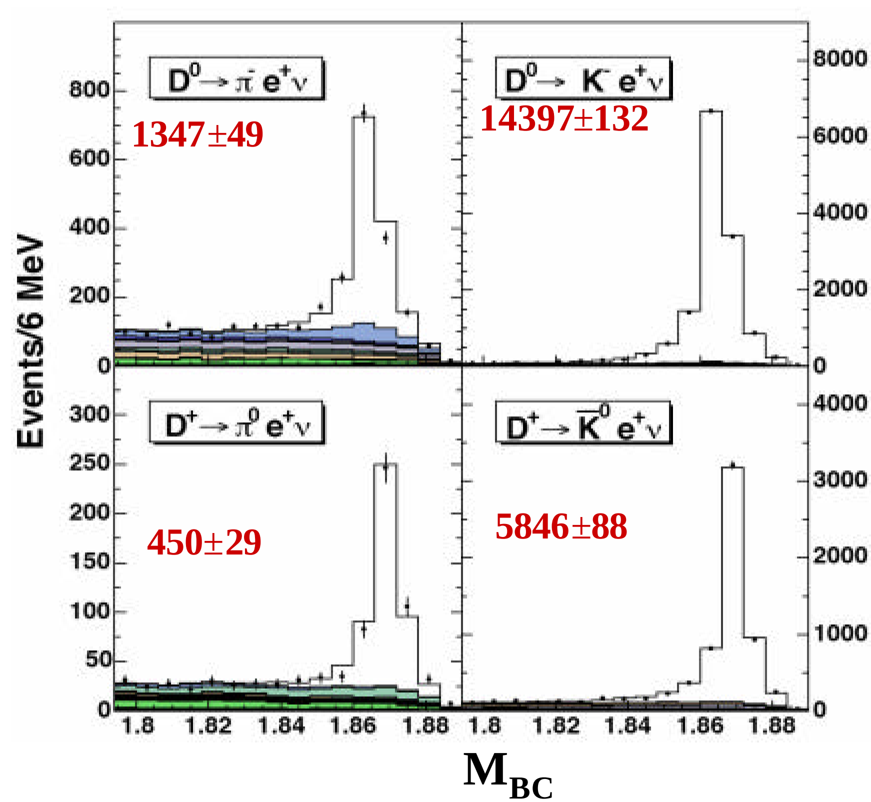
$D \to K/\pi e^+\nu$ without tagging

1) Tagged CLEO-c analysis:



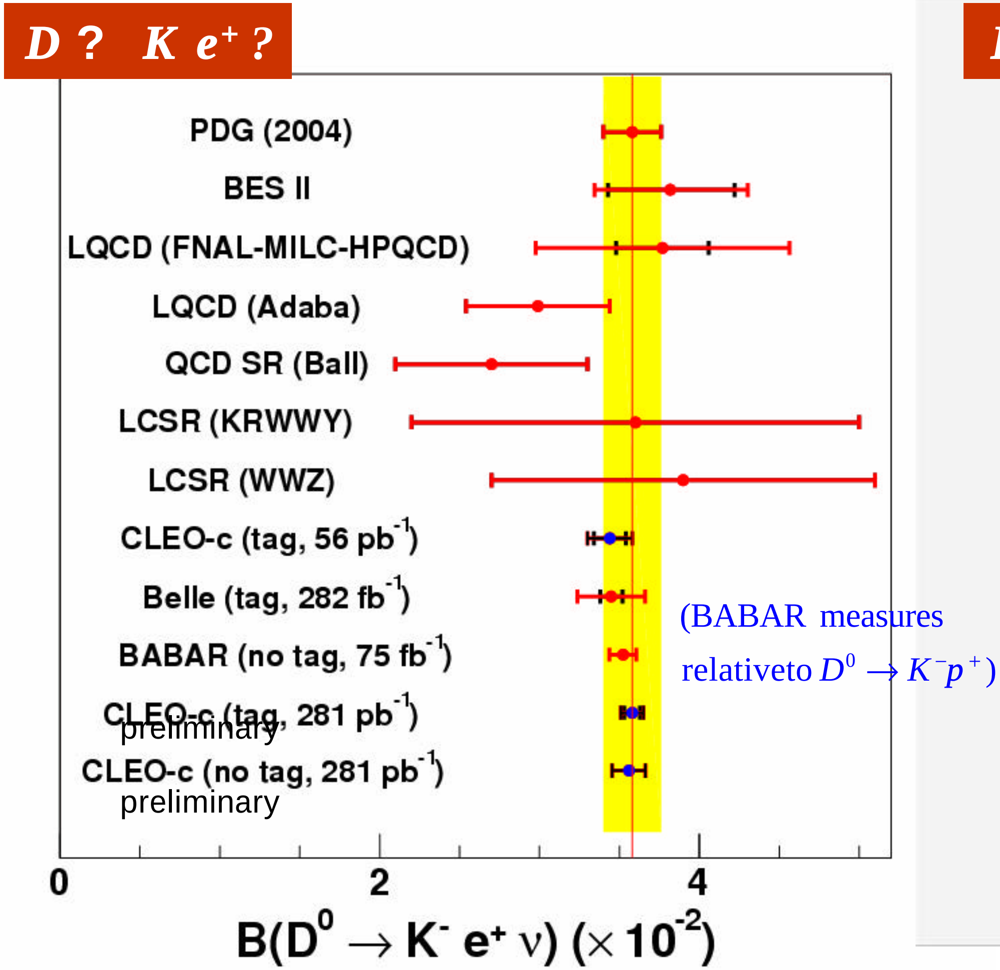
2) Untagged CLEO-c analysis:

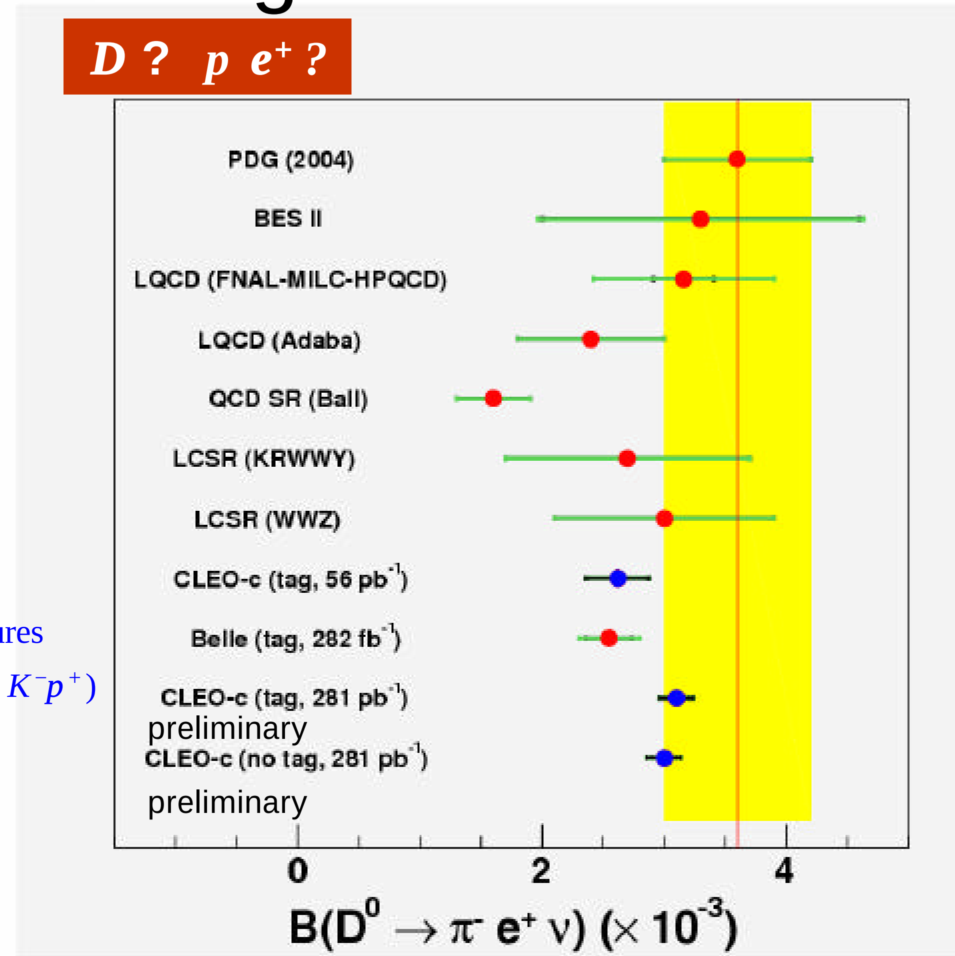
[analogous to neutrino reconstruction @ Y(4S)]



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

D →K, π eν Branching Fractions





Shipsey's averages:

$$B(D \to K^- e^+ n) = (3.555 \pm 0.050)\%$$

$$B(D^0 \to p^- e^+ n) = (2.99 \pm 0.12) \times 10^{-3}$$

Significant recent increase in precision (BABAR/Belle/CLEO-c) measurements

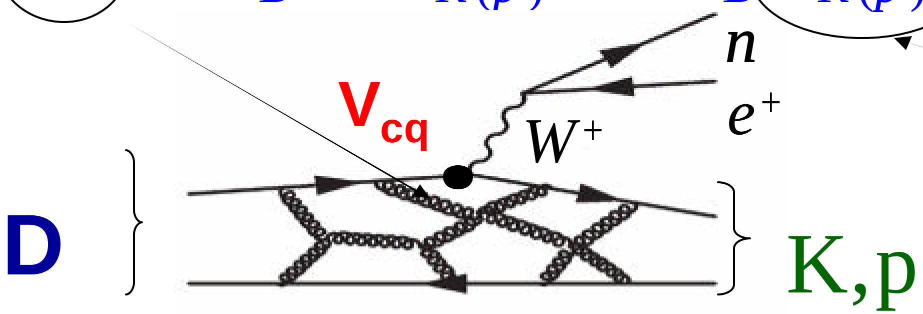
Consistent, CLEO-c most precise

Theoretical precision lags experiment

Semileptonic Decay Form Factors

Example: $D^0 \to \pi^- l^+ \nu$ $\qquad M(D^0 \to \pi^- l^+ \nu) = -i \frac{G_{Fermi}}{\sqrt{2}} V_{cd} \, L_\mu \, H^\mu$

$$q^2 = m_D^2 + m_{K(\pi)}^2 - 2m_D E_{K(\pi)}$$



In D rest frame

Matrix element expressed as form-factors (for D→Pseudoscalar $\ell^+\nu$) simplest case for experiment. and theory

$$H^\mu = \langle P(P_D) | J_\mu | D(P_{K,\pi}) \rangle = f_+(q^2)(P_{K,\pi} + P_D)_\mu + f_-(q^2)(P_{K,\pi} - P_D)_\mu$$

For ℓ = e, effect of $f_-(q^2) \to 0$ negligible: $\frac{d\Gamma(D^+ \to K,\pi \, e\nu)}{dq^2} = \frac{G_F^2}{24\pi^3} P_{K,\pi}^3 \left| f_+(q^2) \right|^2 \left| V_{cs,d} \right|^2$

Form factor measures probability final state hadron will be formed

Theory (i) calculates at fixed q^2 (ii) uses parameterization to evolve to full q^2 range

(i) Theoretical approaches: phenomenological models, QCD sum rules, LQCD.

Only the latter is systematically improvable; aims for several %

(ii) Form Factor Parameterizations

In general: $$f_+(q^2) = \frac{f_+(0)}{1-a}\frac{1}{\left(1-q^2/m_{pole}^2\right)} + \sum_{k=1}^{N}\frac{r_K}{1-\frac{1}{g_K}\frac{q^2}{m_{pole}^2}}$$

Models

- Single pole $$f_+(q^2) = \frac{f_+(0)}{\left(1-q^2/m_{pole}^2\right)}$$

$D \to Ke\nu$

$m_{pole} = m(D_S^*)$

- Modified Pole $$f_+(q^2) = \frac{f_+(0)}{\left(1-q^2/m_{pole}^2\right)\left(1-a\, q^2/m_{pole}^2\right)}$$

(Allows for additional poles)

Model independent

- Series Expansion *Hill & Becher, Phys. Lett. B 633, 61 (2006)*

the function $z(q^2,t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$ $t \equiv q^2 = (P_D - P_K)^2$ $t_+ \equiv \left(M_D + m_K\right)^2$,

t_0: arbitrary q^2 value that maps to z=0

maps the physical q^2 region into $0<z<0.1$: $D \to Ke\nu$

form factors can be written as: $$f_+(q^2) = \frac{1}{P(q^2)\phi(q^2)}\sum_{k=0}^{\infty} a_k(t_0)[z(q^2,t_0)]^k$$

accounts for D_S^* pole →

calculable function to make a_K's look simple

zsmall, converges rapidly → linear or quadratic sufficient

Experiment probes both the form factor magnitude & parameterization

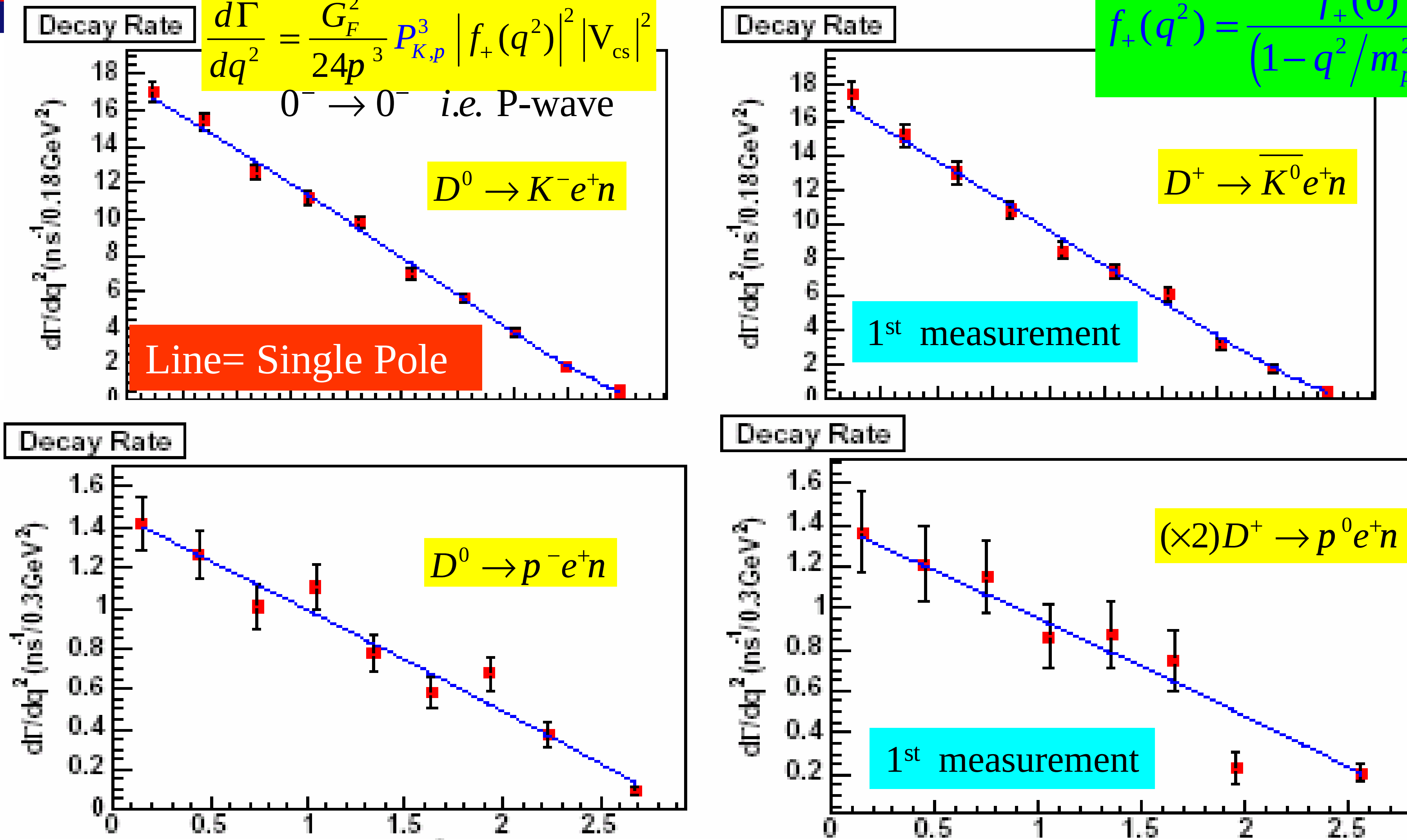
PRELIMINARY

Absolute $d\Gamma/dq^2$ distributions

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} P_{K,\pi}^3 \left| f_+(q^2) \right|^2 \left| V_{cs} \right|^2$$

$0^- \to 0^-$ *i.e.* P-wave

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - q^2/m_{pole}^2\right)}$$



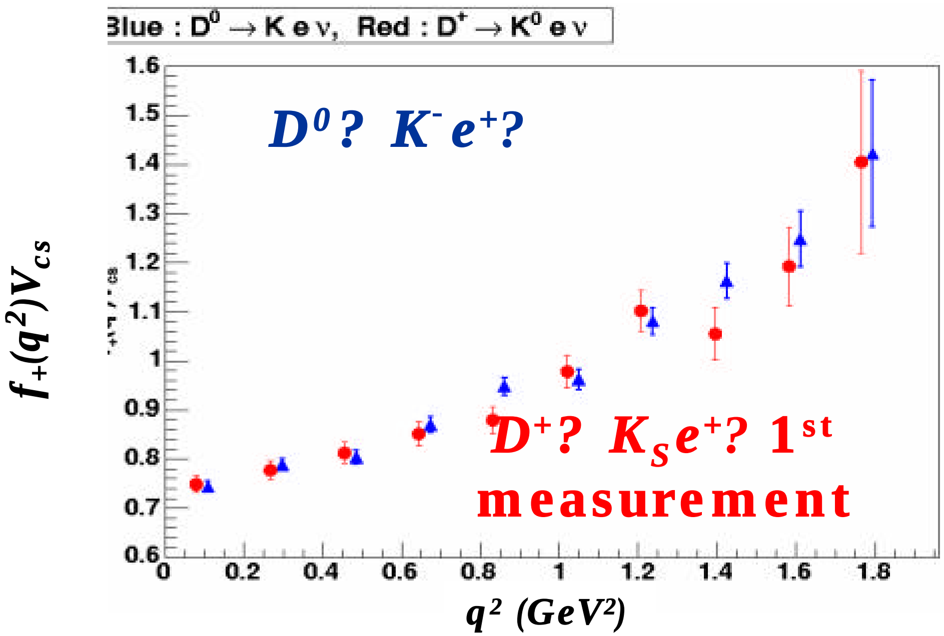
Background subtracted efficiency corrected absolute $d\Gamma/dq^2$ distributions. are simultaneously fit for sospin conjugate pairs

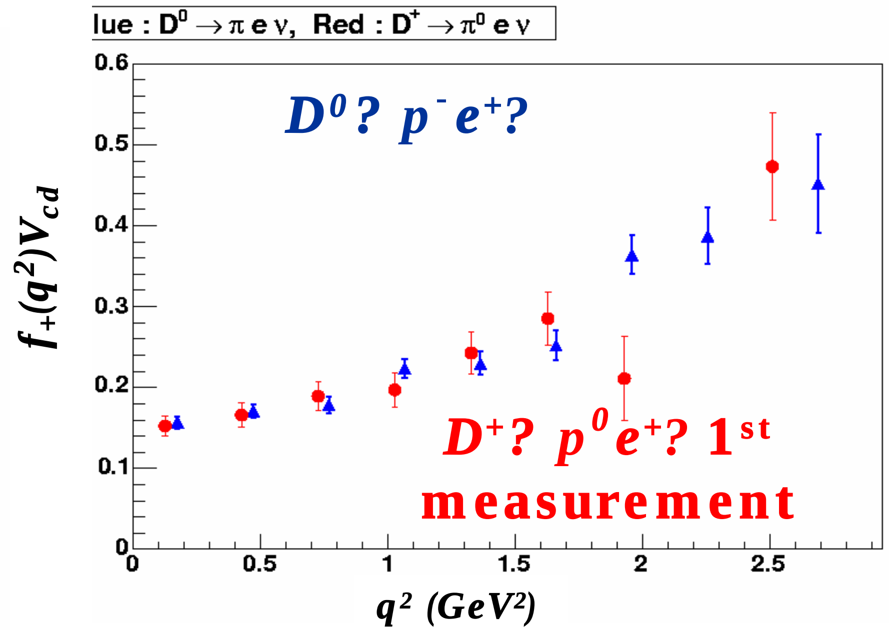
PRELIMINARY

$|V_{cs(cd)}||f_+(q^2)|$

Removing the kinematic terms
reveals the form factor
(which varies by only a factor ~2 (~3)
across phase space for $K e \nu$ ($\pi e \nu$))

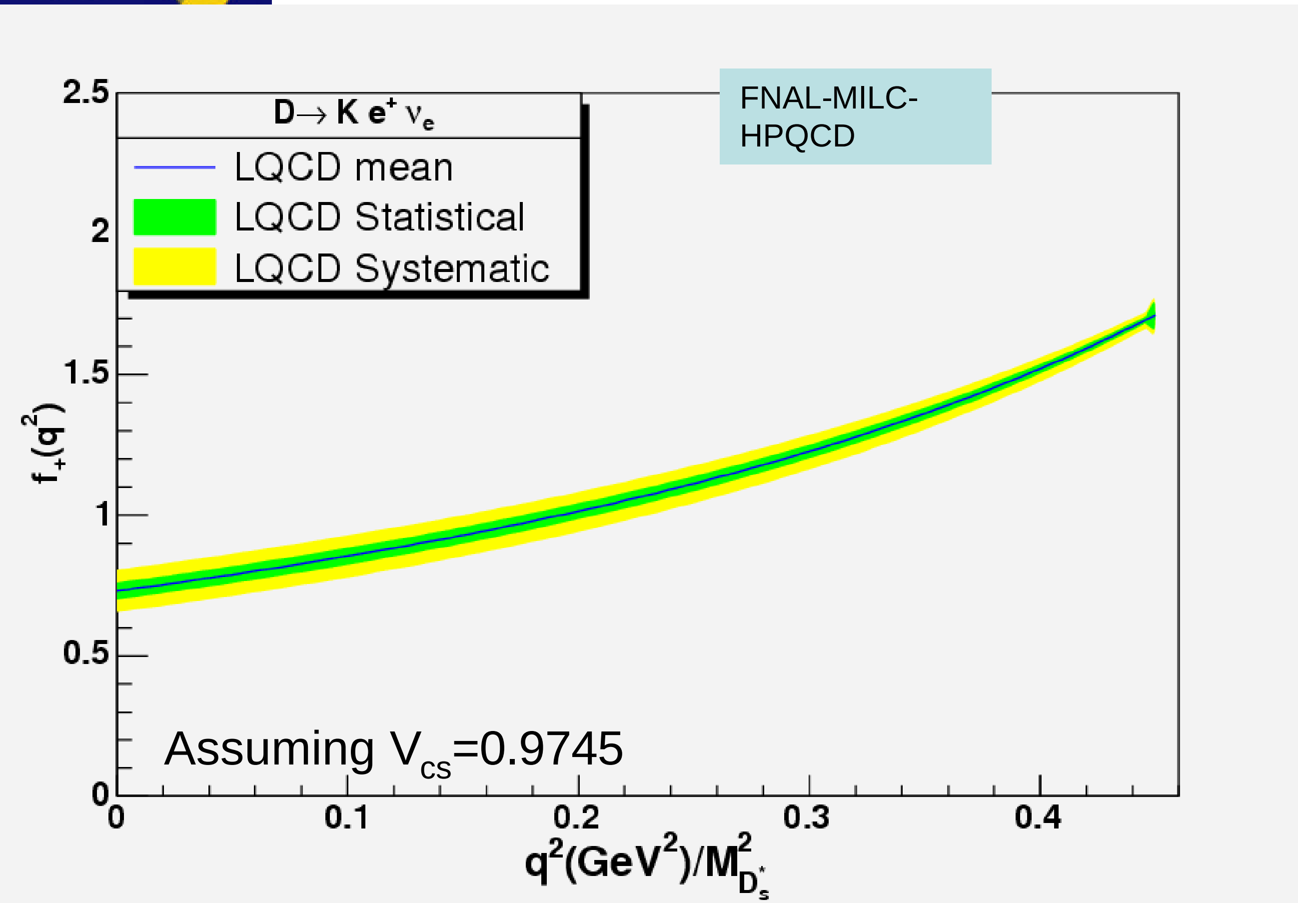
$$|V_{cs(cd)}||f_+(q^2)| \sim \left[\frac{\Delta\Gamma_i(D \to K(\pi) e\nu)}{\Delta q_i^2} / P^3_{K(\pi)i} \right]^{1/2}$$





The q^2 spectra for isospin conjugate pairs are consistent which provides a, *unique* to CLEO-c, powerful cross check

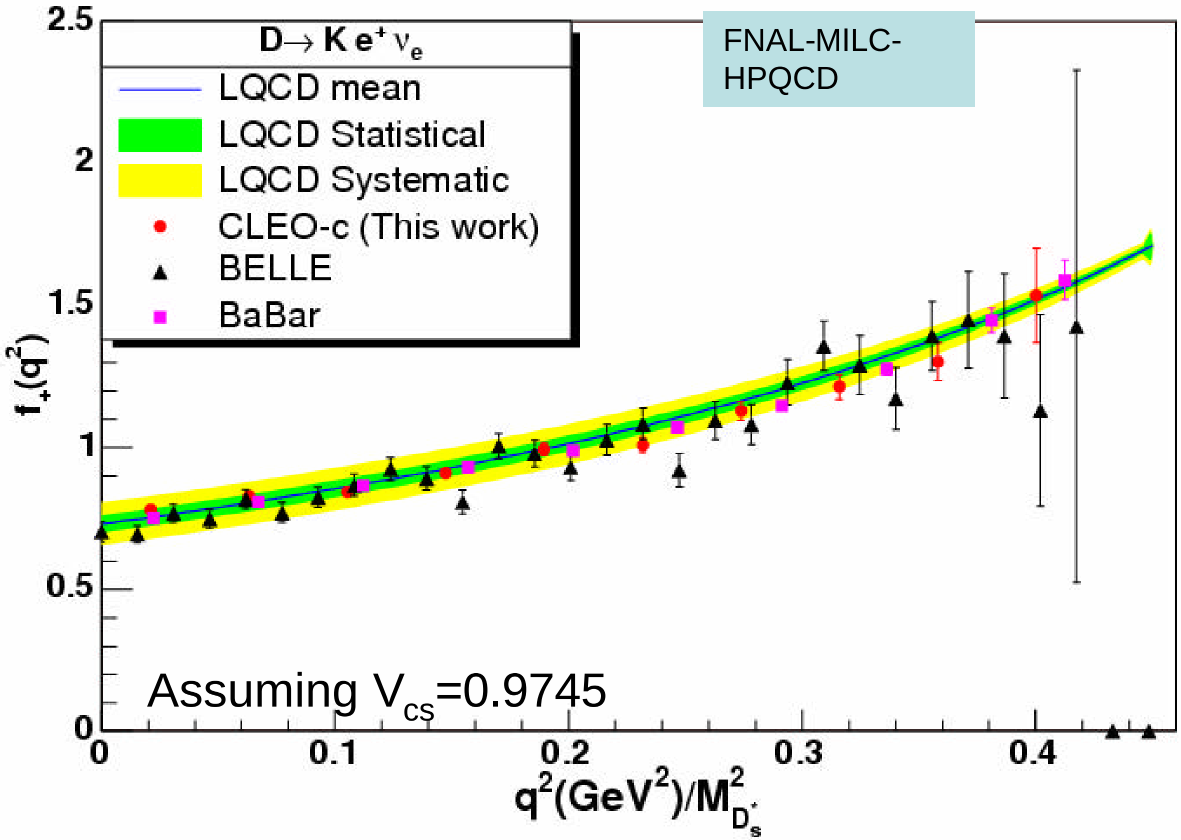
Lattice Prediction shape *and* absolute normalization



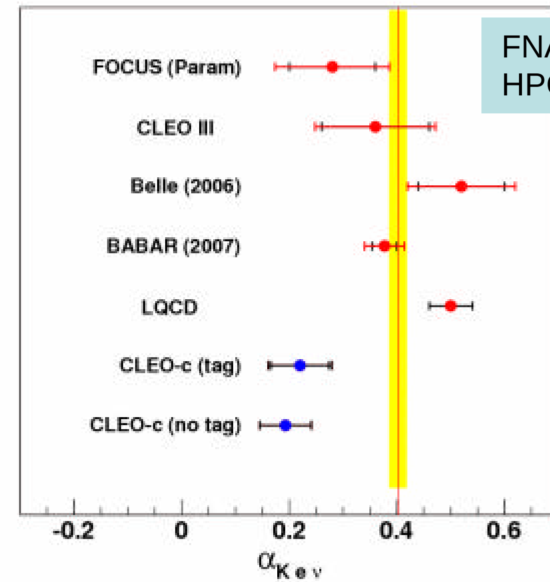
Curve courtesy Andreas

Kronfeld

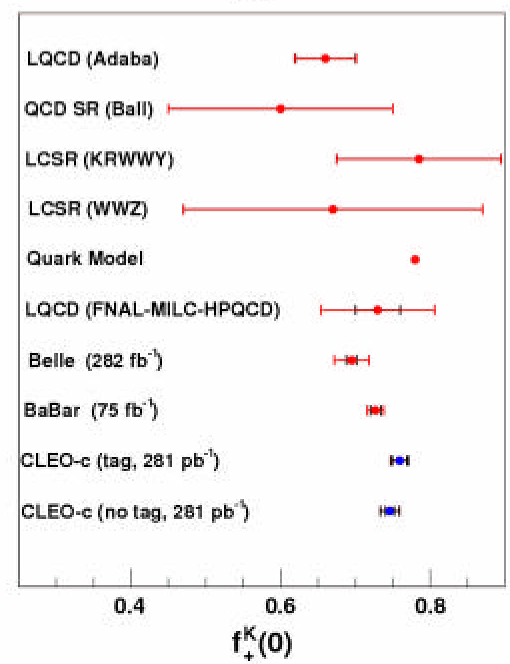
High Statistics test of shape *and* absolute normalization $f_+(q^2)$



FNAL-MILC-HPQCD



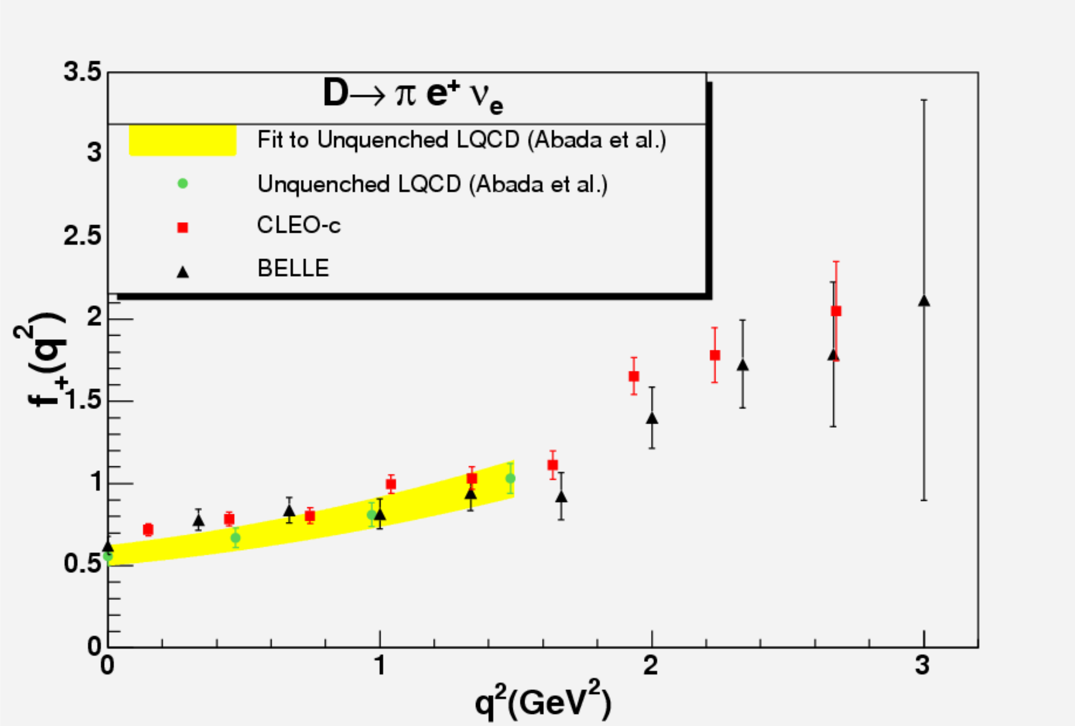
FNAL-MILC-HPQCD



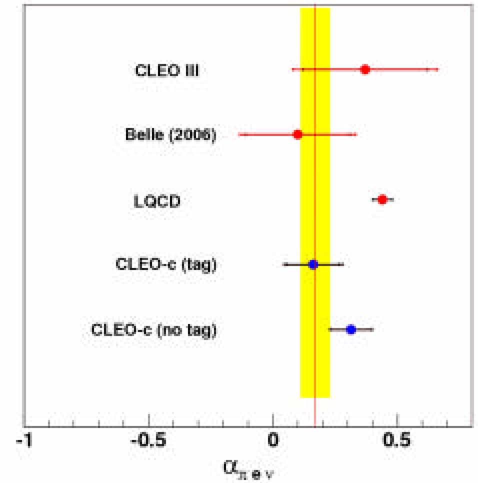
CLEO prefers smaller slope a
Normalization: experiments (2%) consistent with LQCD (10%)
Theoretical precision lags

Curve courtesy Andreas Kronfeld

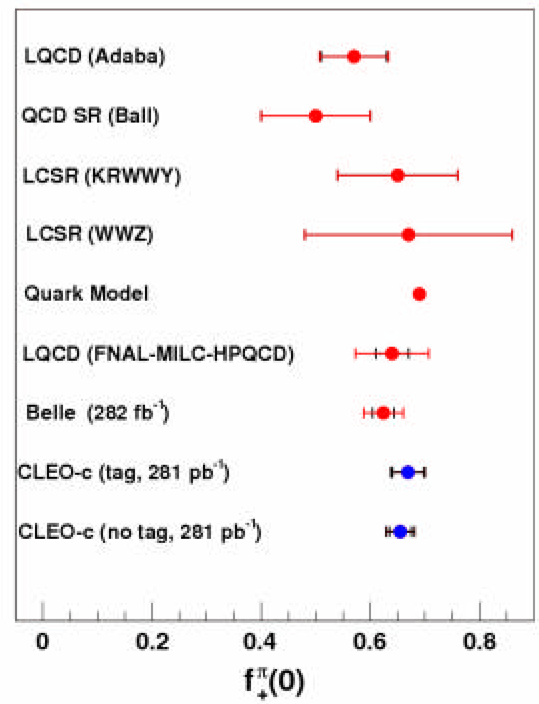
High Statistics test of shape *and* absolute normalization $f_+(q^2)$



Assuming V_{cd} = 0.2238±0.0029



FNAL-MILC-HPQCD

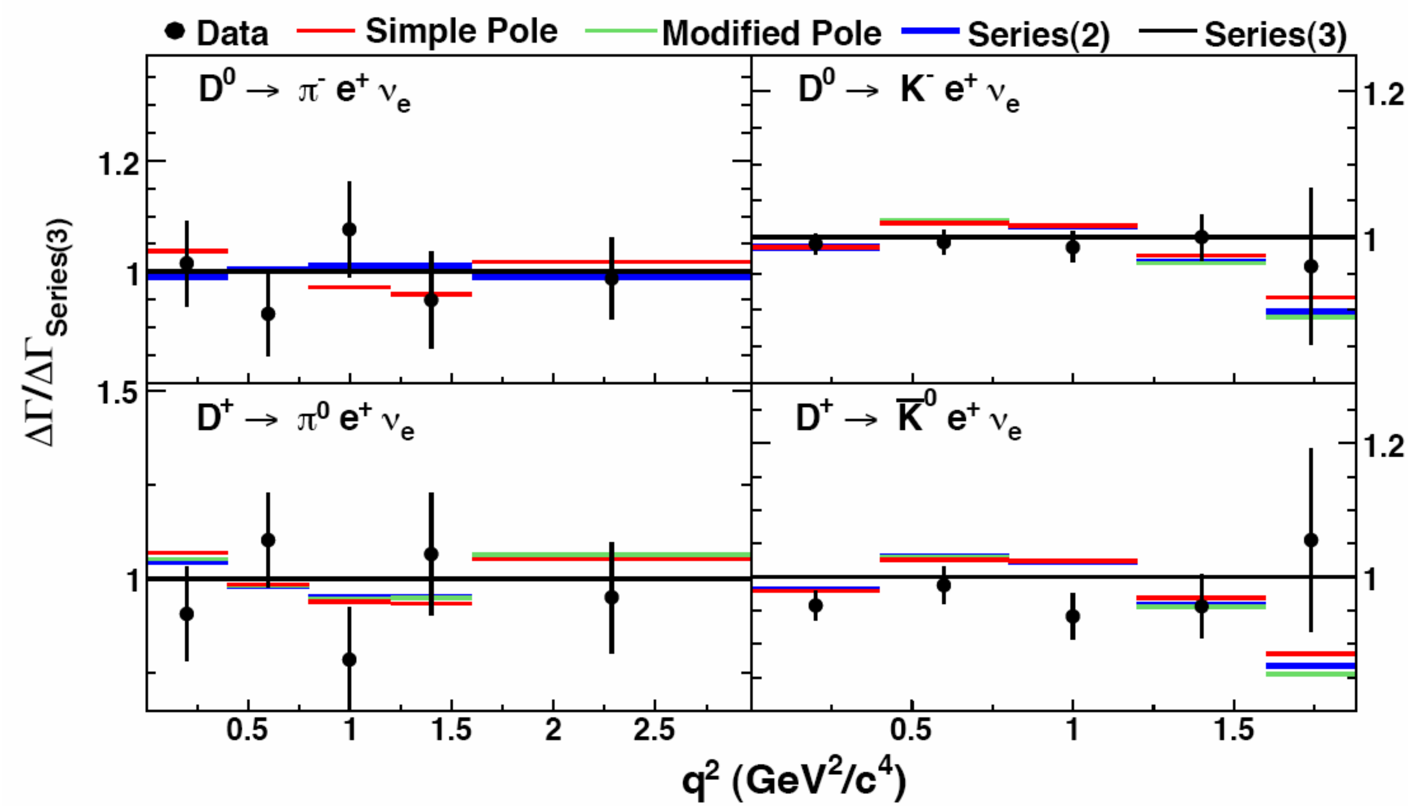


Shape: Experiments compatible with LQCD
Normalization: experiments (4%)
consistent with LQCD (10%)
Theoretical precision lags

PRELIMINARY

$D \to \pi/K e\nu$ Which Form Factor Parameterization?

Need to select 1 parameterization to measure intercept & determine $f_+(0)V_{cx}$, then use theory value of $f_+(0)$ to obtain V_{cx}



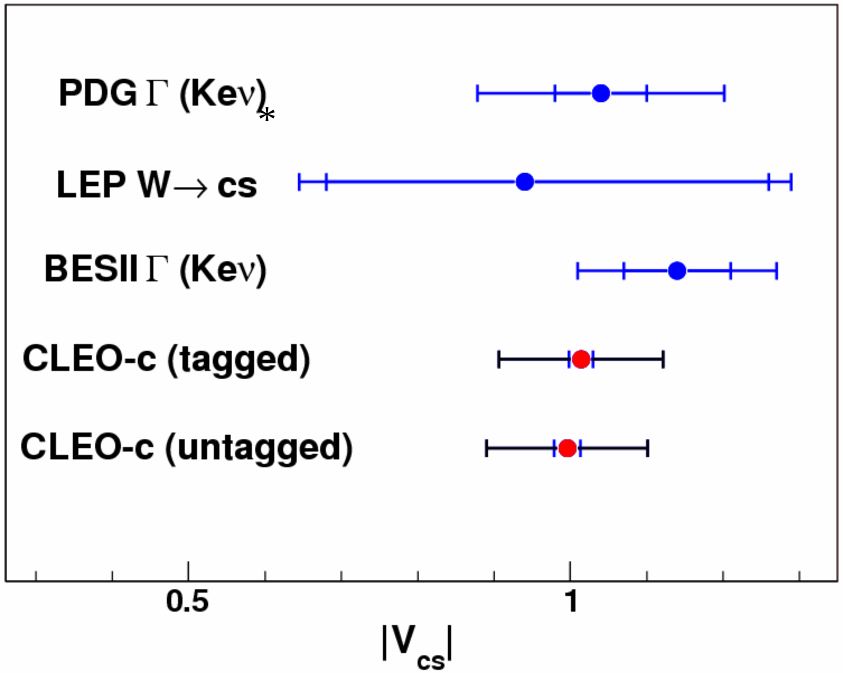
Form factor fits to partial branching fraction results in five q^2 ranges normalized to Hill series parameterization (Untagged shown)

- The confidence levels for all parameterizations are good, when shape parameters are not fixed to their model values
- We will use the *model independent* Becher-Hill series parameterization for Vcx

V_{cs} Result

PRELIMINARY

Combine measured $|V_{cx}|f_+(0)$ values using Becher-Hill parameterization *with (FNAL_MILC-HPQCD) for* $f_+(0)$



$CLEO-c$	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

Tagged/untagged consistent, 40% overlap
DO NOT AVERAGE

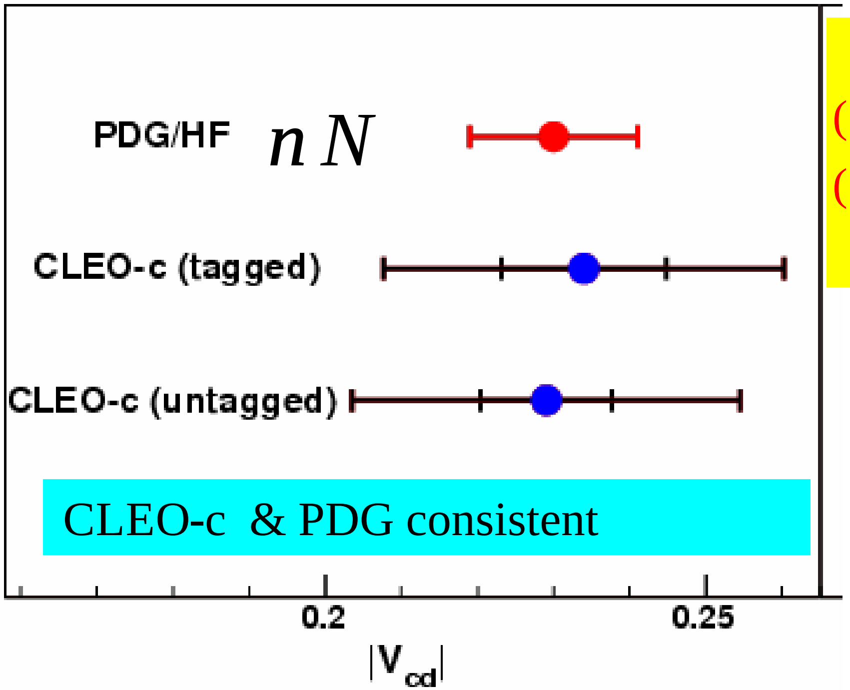
		Uncertainty (%)		
	V_{cs}	exp.	thy.	tot.
$PDG\ \Gamma(Ke\nu)$*	1.04 ± 0.16	6	14.2	15.4
$W \to cs$	$0.94^{+0.32}_{-0.26} \pm 0.14$			31
$BESII\ \Gamma(Ke\nu)$	$1.14 \pm 0.07 \pm 0.11$	6.5	10.4	12.8
$CLEO-c$	$1.014\ \pm 0.016 \pm 0.106$	1.6	10.4	10.5

(* I used PDG02 to remove CLEO-c and BES II from the average)

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

V_{cd} Result PRELIMINARY

Combine measured $|V_{cx}|f_+(0)$ values using Becher-Hill parameterization *with (FNAL_MILC-HPQCD) for* $f_+(0)$



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/untagged consistent, 40% overlap
DO NOT AVERAGE

	V_{cd}	Uncertainty (%)
PDG n d → cu	0.22 ± 0.011	5%
CLEO − c	$0.229 \pm 0.08 \pm 0.024$	$3.5\% \oplus 10.5\%$

CLEO-c: dominant uncertainty LQCD
?N remains most precise determination (for now)

Full CLEO-c data set
→Vcd stat. limited

$$D \to p e^+ u \quad \frac{dVcd}{Vcd} = 1.6\% \oplus \frac{dTheory}{Theory}$$

$D \to \quad e$ BF +FF

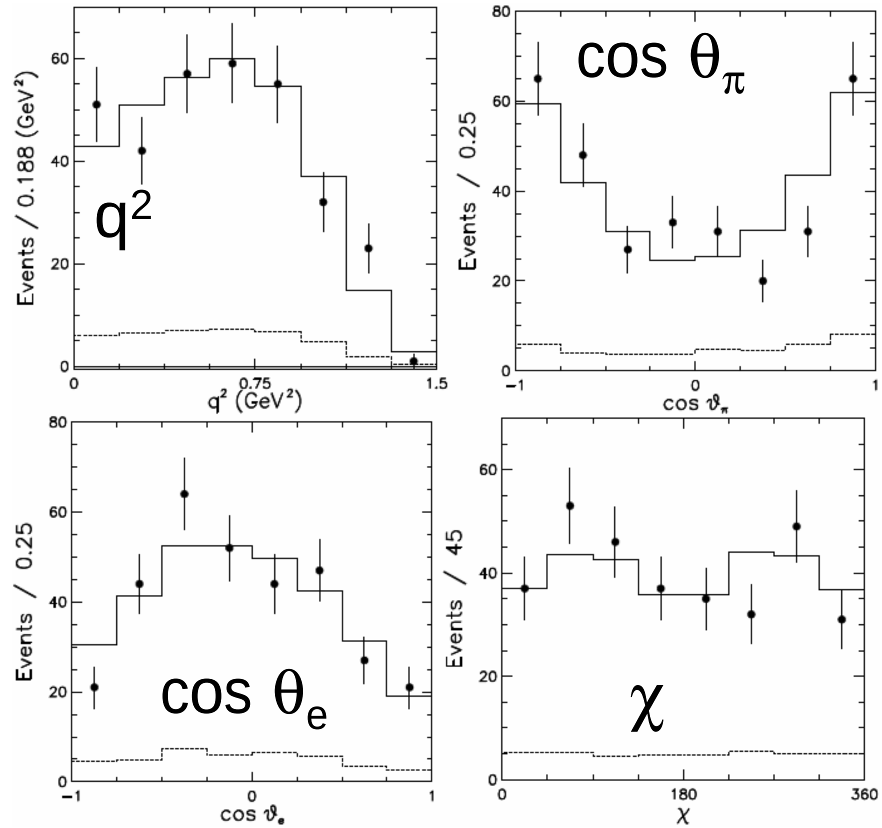
Dtagged, 281/pb

Interest: 1st measurement of FF in Cabibbo suppressed charm PS→ V decay +

$$\frac{d\Gamma(B \to \quad e^{+} \quad)/dq^2}{d\Gamma(B \to K^{*}\ell\ell)/dq^2} \propto \frac{|V_{ub}|^2}{|V_{cb}|^2}$$

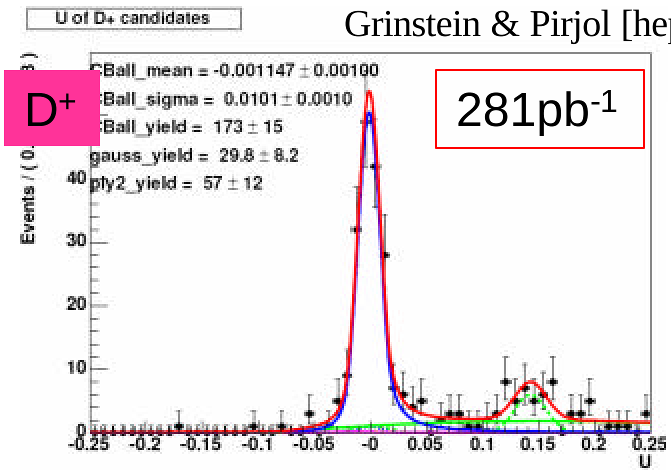
Need $D \to K^{*} e$, $D \to \quad e$ FF

Grinstein & Pirjol [hep-ph/0404250]

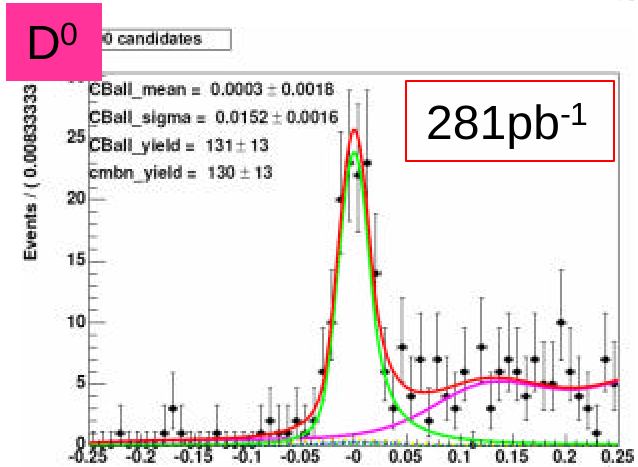


Line is projection for fitted R_V, R_2

D+



D0



Fixed background shape and signal tails from MC

$B(D^0 \to \rho^- e^+ \nu) = (1.56 \pm 0.16 \pm 0.09) \times 10^{-3}$

$B(D^+ \to \rho^0 e^+ \nu) = (2.32 \pm 0.20 \pm 0.12) \times 10^{-3}$

Isospin average:

$\Gamma(D^0 \to \rho^- e^+ \nu) = (0.41 \pm 0.03 \pm 0.02) \times 10^{-2}\ \mathrm{ps}^{-1}$

Simultaneous fit to $D^+ \to \rho^0 e\nu$, $D^0 \to \rho^- e\nu$

$R_V = 1.40 \pm 0.25 \pm 0.03$

$R_2 = 0.57 \pm 0.18 \pm 0.06$

PRELIMINARY

Summary of CLEO-c Semileptonic Decay Results

1st observations of 4 modes

$$D^0 \to \;{}^-e^+ \;, D^+ \to \; e^+ \;, D^+ \to \; e^+ \;, D^0 \to K(1270)e^+$$

1st form factors in a Cabibbo suppressed P→Vlv decay

B(D→ Kev) pre-CLEO-c dB/B=6% now 2%,

$$|V_{cs}| = 1.014 \pm 0.013 \pm 0.009 \pm 0.106_{\text{theory}} \quad (\text{tag})$$

$$|V_{cs}| = 0.996 \pm 0.008 \pm 0.015 \pm 0.104_{\text{theory}} \quad (\text{notag})$$

Best *direct* determination of Vcs

B(D→ pev) pre-CLEO-c dB/B=45% now 4%, most precise f+(0) & shape

$$|V_{cd}| = 0.234 \pm 0.010 \pm 0.004 \pm 0.024_{\text{theory}} \quad (\text{tag})$$

$$|V_{cd}| = 0.229 \pm 0.007 \pm 0.005 \pm 0.024_{\text{theory}} \quad (\text{notag})$$

(most precise determination of Vcd from semileptonic decay)

CLEO-c baseline plan 800/pb @ 3770 & 600/pb at 4170.

→more stringent tests of theory for D→ K/pev f+(0) & shape

→CKM Precision expected: Vcs (syst. limited) Vcd (stat limited)

$$D \to Ke^+u \quad \frac{dVcs}{Vcs} = 0.8\% \oplus \frac{dTheory}{Theory}$$

$$D \to pe^+u \quad \frac{dVcd}{Vcd} = 1.6\% \oplus \frac{dTheory}{Theory}$$

Results on D_S semileptonic decays @E_{CM} = 4.170 GeV coming soon