

Rencontres de Moriond EW 2008

{ CLEO-c Charm Leptonic & Semileptonic Decays }

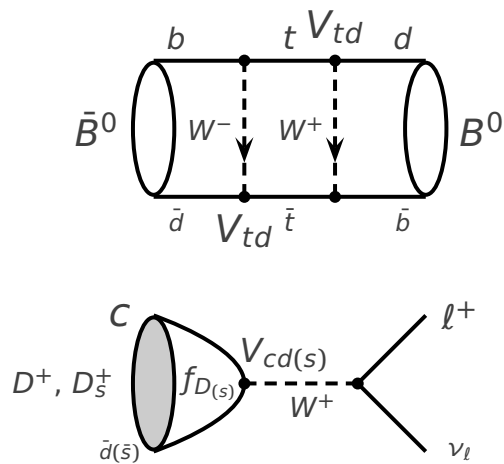
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Charm Leptonic and Semileptonic Decays

- Careful studies of charm leptonic and semileptonic decays calibrates theory, so more reliable values of V_{td} , V_{ub} , can be obtained from B factories.
- Leptonic decays



$$\text{Rate} \propto f_B^2 |V_{td}|^2$$

experiment \leftrightarrow LQCD

LQCD predicts f_B/f_D and f_B/f_{B_s} w/ small errors \Rightarrow

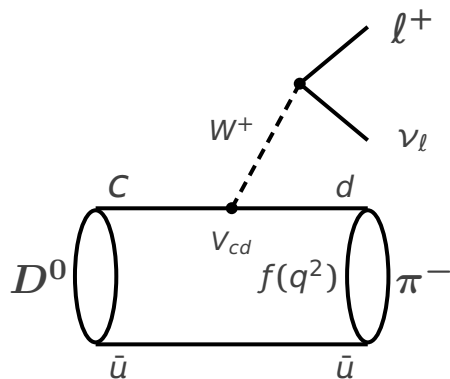
precise f_D gives precise f_B and $|V_{td}|$
 f_D/f_{D_s} checks f_B/f_{B_s}

$$\text{Rate} \propto f_{D(s)}^2 |V_{cd(s)}|^2$$

and allows precise $|V_{td}|/|V_{ts}|$

known to $< 1\%$ from the CKM unitarity

- Semileptonic decays



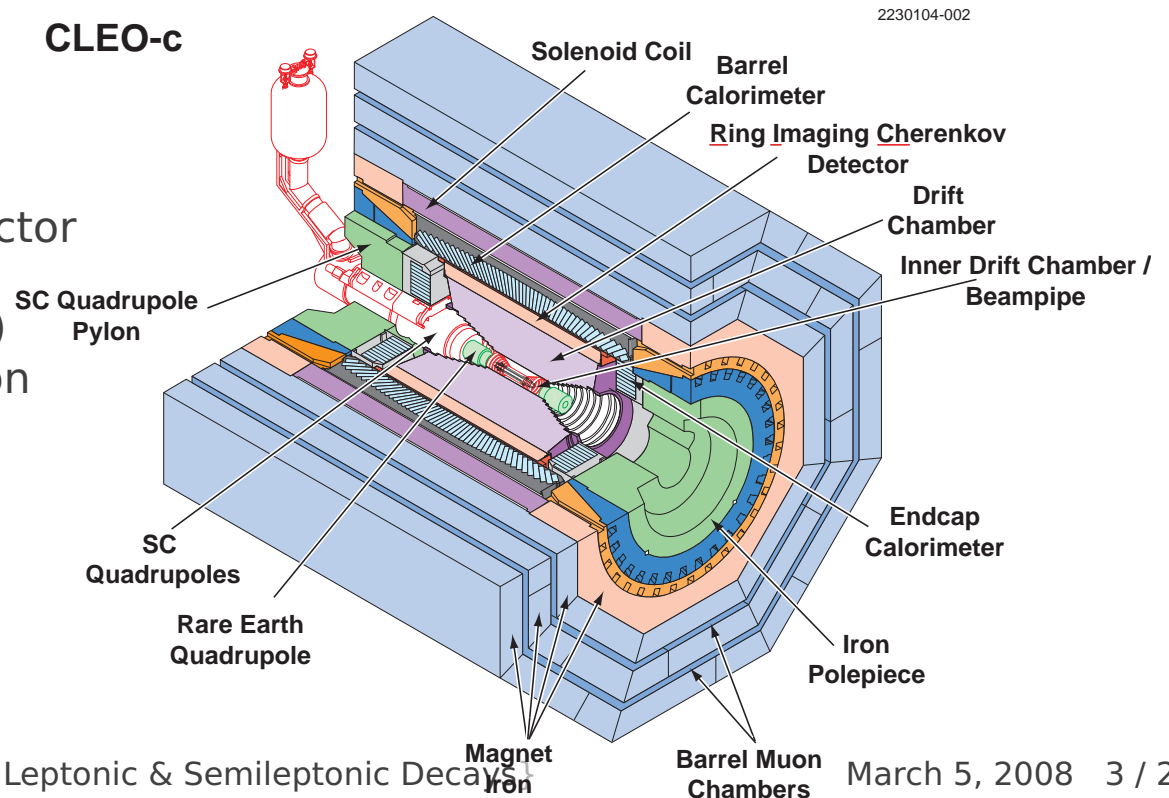
$$\text{Rate} \propto |V_{cd}|^2 |f_+(q^2)|^2$$

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

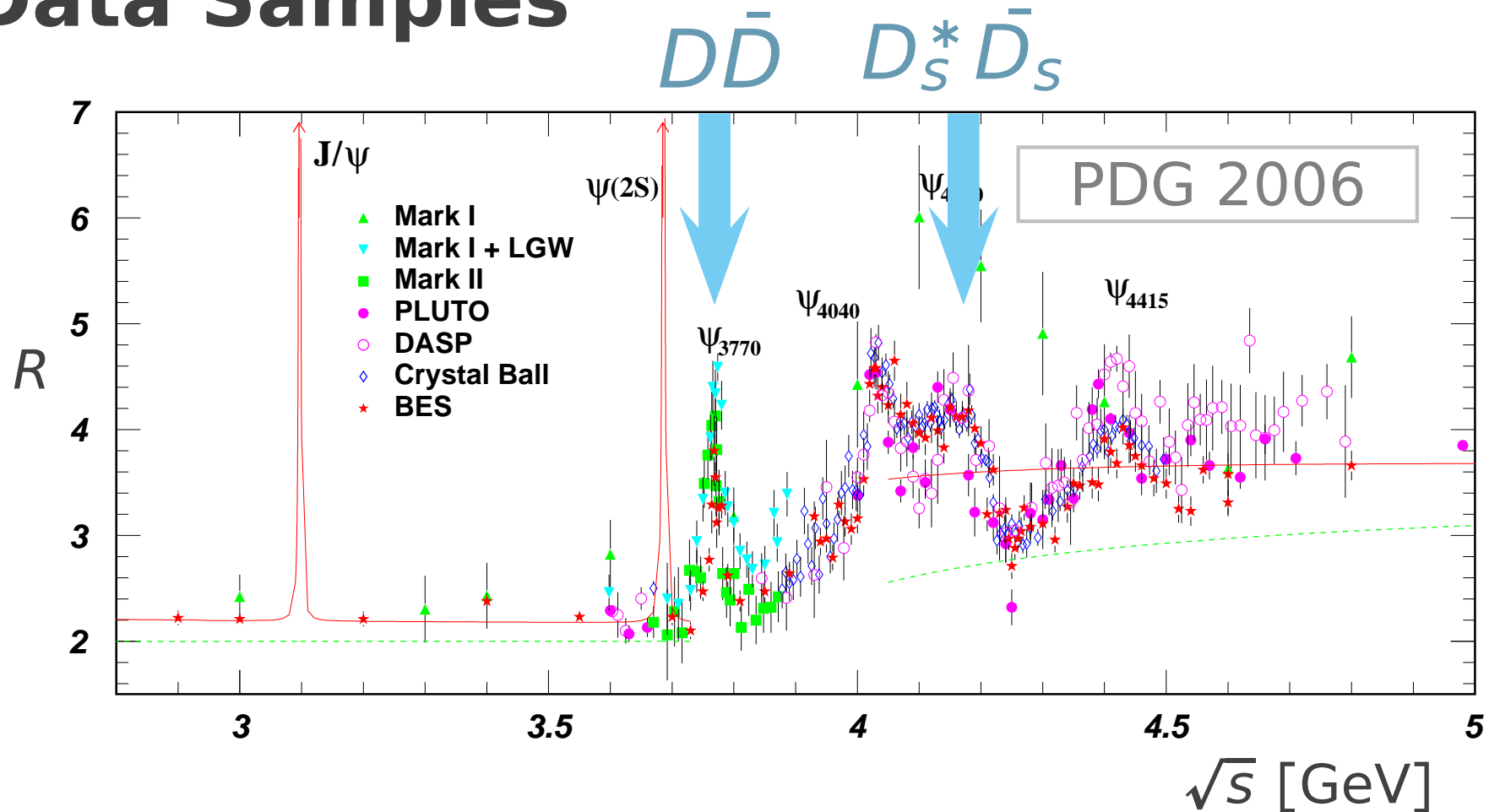
CLEO-c Open Charm Program

- Precision measurements of benchmark branching fractions of D^0 , D^+ , and D_s , i.e., those decay modes used by B factories and hadron colliders : $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D_s^+ \rightarrow \pi^+ K^+ K^-$, and others.
- Measurements to test, calibrate, validate Lattice QCD calculations, other calculations of strong interaction effects. D^+ , $D_s^+ \rightarrow \ell^+ \nu_\ell$, D exclusive semileptonic decays.

- General-purpose symmetric detector
- Particle ID (dE/dx , Ring Imaging Cherenkov) excellent in our momentum region
- Tracking: $\delta p/p = 0.6\%$ at 1 GeV
- CsI calorimeter: $\delta E/E \sim 5\%$ at 100 MeV



Data Samples



- $D\bar{D}$ @ 3770 : 800 pb⁻¹ (56 & 281 pb⁻¹ in this talk);
281 pb⁻¹ $\sim 1.8 \times 10^6 D\bar{D}$
- $D_S^* \bar{D}_S$ @ 4170 : 314 pb⁻¹ (will double the sample)
314 pb⁻¹ $\sim 0.3 \times 10^6 D_S^* \bar{D}_S$

Charm at $\psi(3770)$

- $\psi(3770) \rightarrow D\bar{D}$:
just above threshold,
no additional particles

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

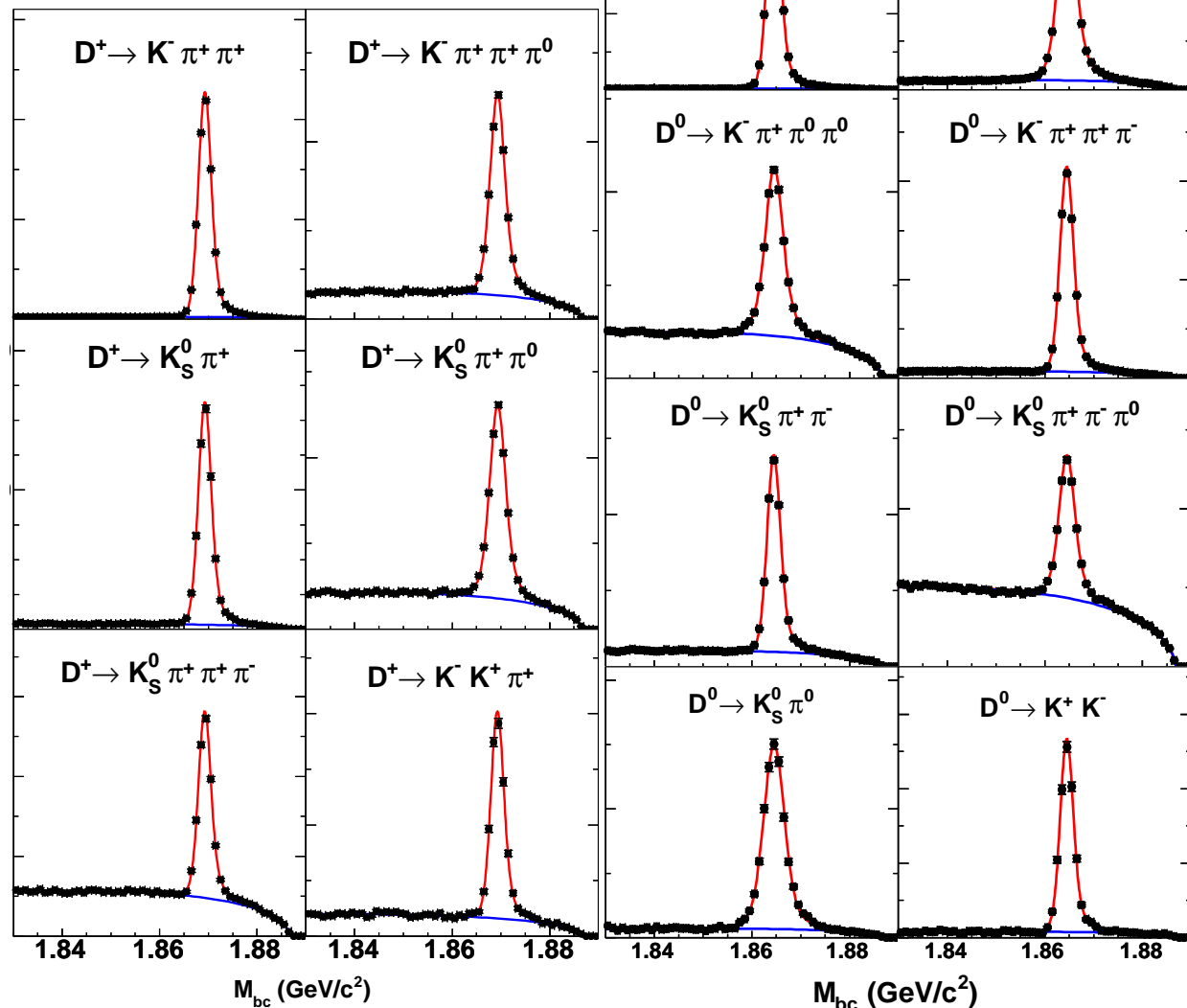
$$M_{bc} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_D^2|}$$

- D tagging efficiency:

$$\sim 10\% D^+$$

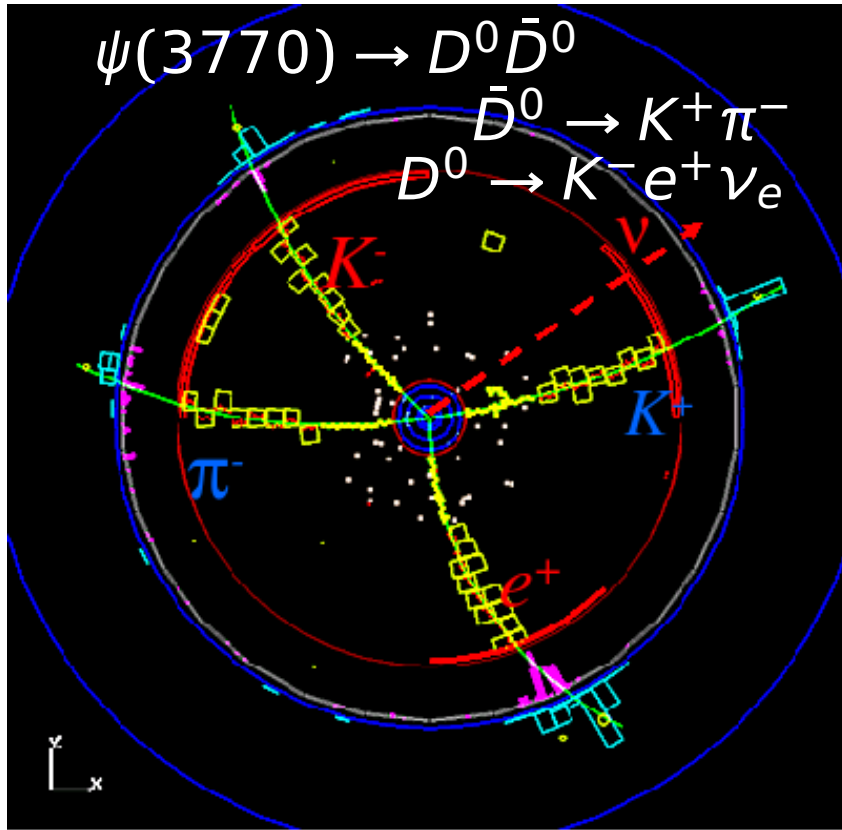
$$\sim 15\% D^0$$

- Clean experimental environment
(\Leftarrow low multiplicity
& D -tagging)



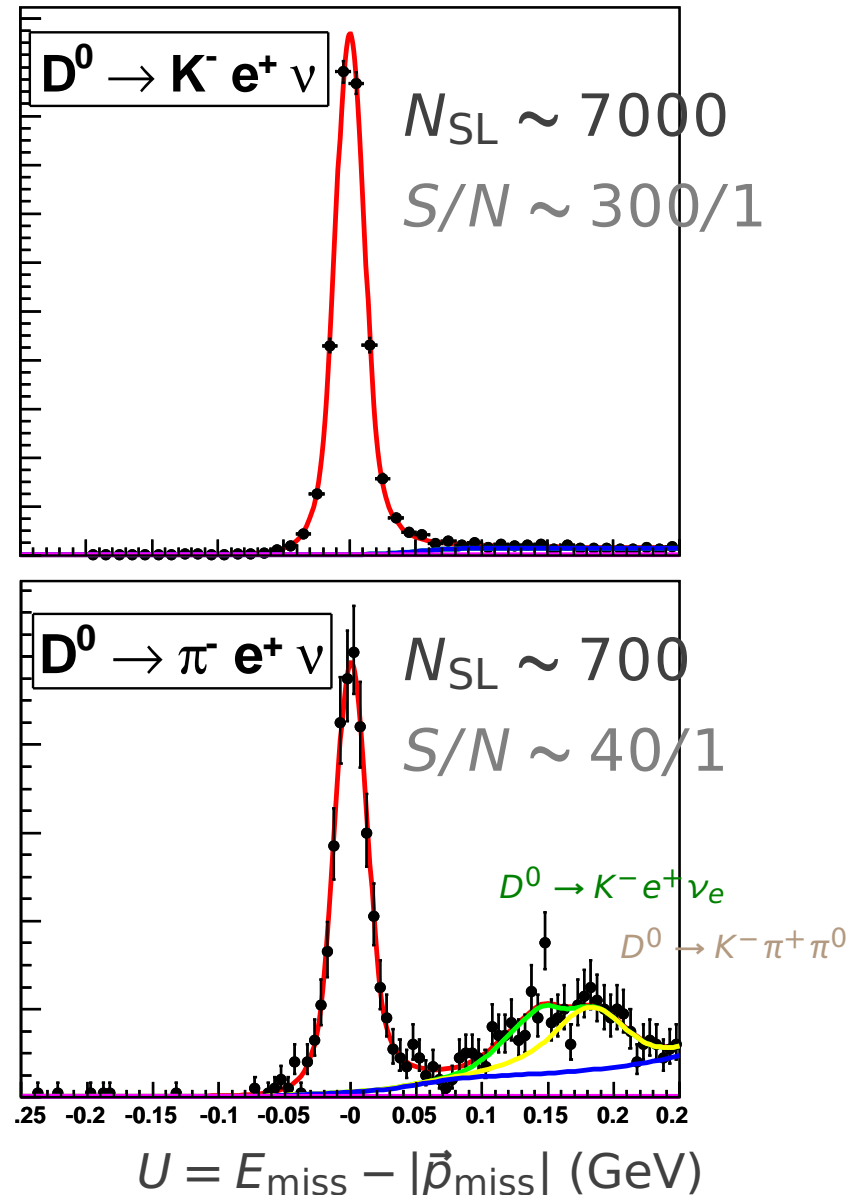
- Absolute branching fraction measurement ($\Leftarrow D$ tagging)
- CLEO-c has largest data set at 3770

Absolute Branching Fractions

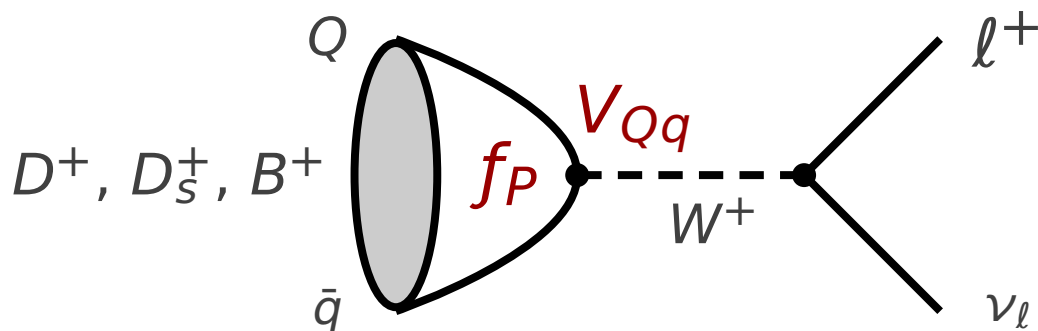


- Semileptonic event can be fully reconstructed (except neutrino)

- $$\mathcal{B}(D \rightarrow X e^+ \nu_e) = \frac{N_{SL}/\epsilon_{SL}}{N_{tag}}$$



Introduction : Leptonic Decays

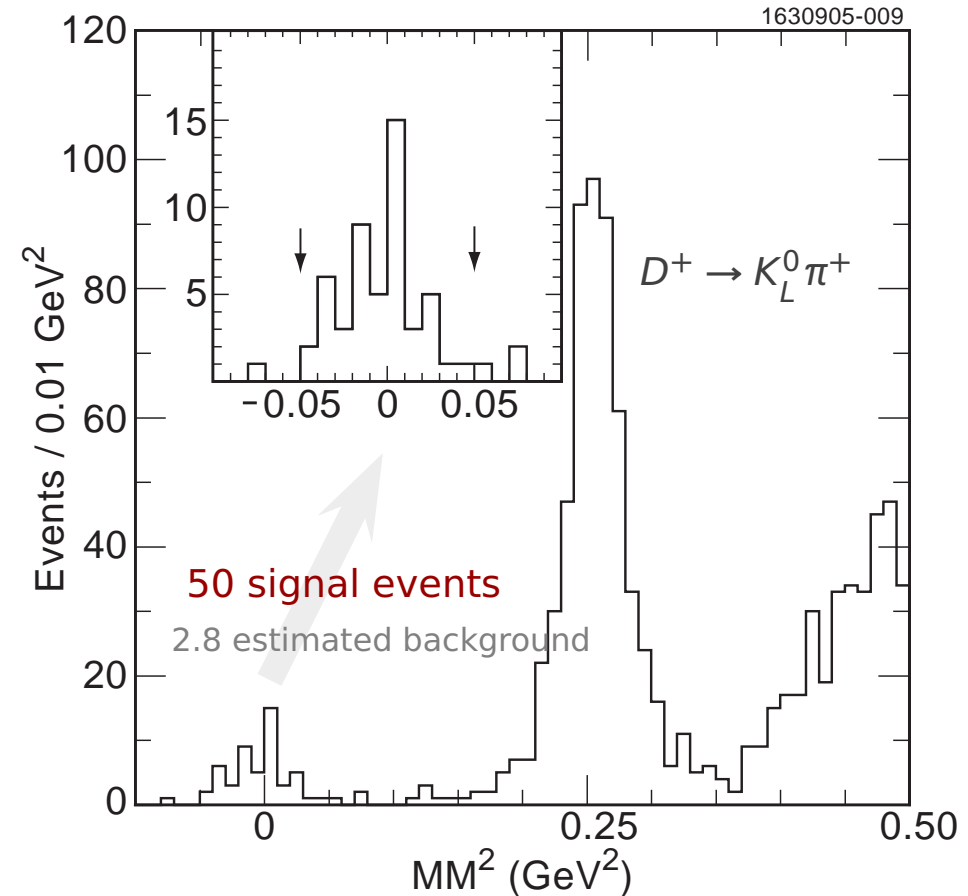


$$\Gamma(P_{Q\bar{q}} \rightarrow l^+ \nu_l) = \frac{G_F^2 |V_{Qq}|^2 f_P^2}{8\pi} m_{Q\bar{q}} m_l^2 \left(1 - \frac{m_l^2}{m_{Q\bar{q}}^2}\right)^2$$

- Measure rates to extract decay constant f_P (V_{Qq}).
- Check lattice calculations of decay constants.
 - ◆ f_D at CLEO-c and $(f_B/f_D)_{\text{LQCD}} \Rightarrow f_B$ for precise $|V_{td}|$.
 - ◆ f_D/f_{D_s} checks $(f_B/f_{B_s})_{\text{LQCD}}$ for $|V_{td}|/|V_{ts}|$.
- Sensitive to new physics, e.g. H^+ can mediate.

$$D^+ \rightarrow \mu^+ \nu_\mu$$

- Use 158k D^- tags (281 pb⁻¹ @3770)
- Require only one additional track, μ^+
- Reject event if substantial energy in calorimeter
- Compute missing mass

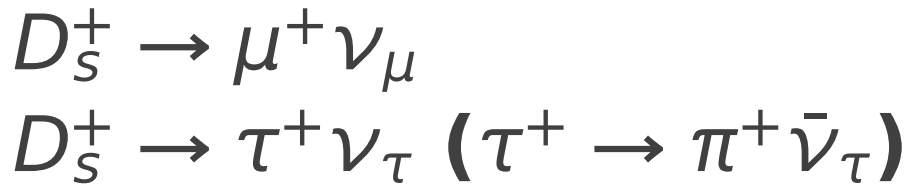


- Result: Phys. Rev. Lett. **95**, 251801 (2005)

◆ $B(D^+ \rightarrow \mu^+ \nu_\mu) = (4.40 \pm 0.66_{-0.12}^{+0.09}) \times 10^{-4}$

◆ $f_D = (222.6 \pm 16.7_{-3.4}^{+2.8})$ MeV (using $|V_{cd}| = 0.2238$)

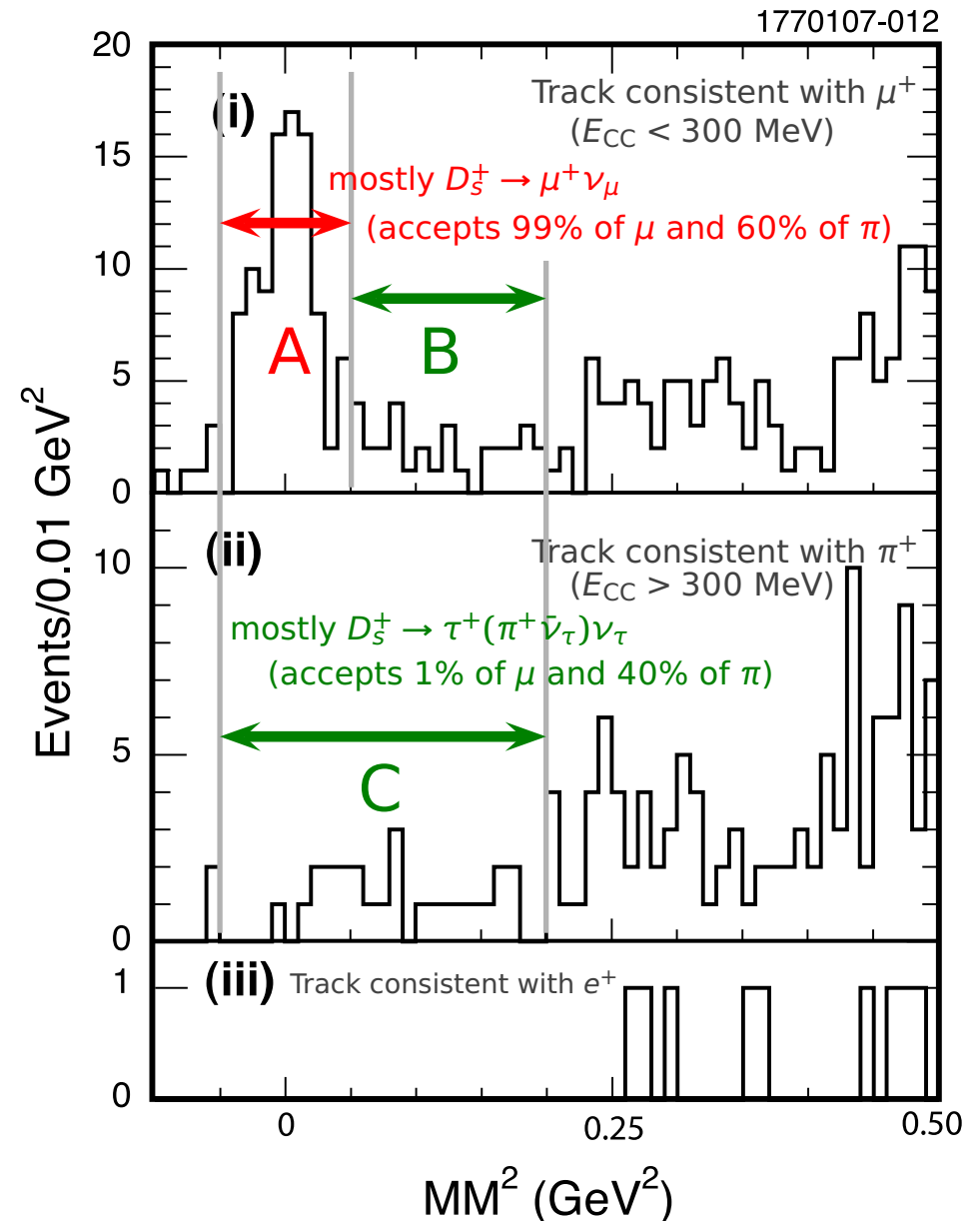
- Unquenched LQCD $f_{D^+} = (201 \pm 3 \pm 17)$ MeV, Exp/Theory agree ~ to 10%.



Case	Region (GeV^2)	Signal	Background
A	$-0.05 < MM^2 < 0.05$	92	3.5 ± 1.4
B	$0.05 < MM^2 < 0.20$	31	2.5 ± 1.1
C	$-0.05 < MM^2 < 0.20$	25	3.0 ± 1.3
Sum	$-0.05 < MM^2 < 0.20$	148	9.0 ± 2.3

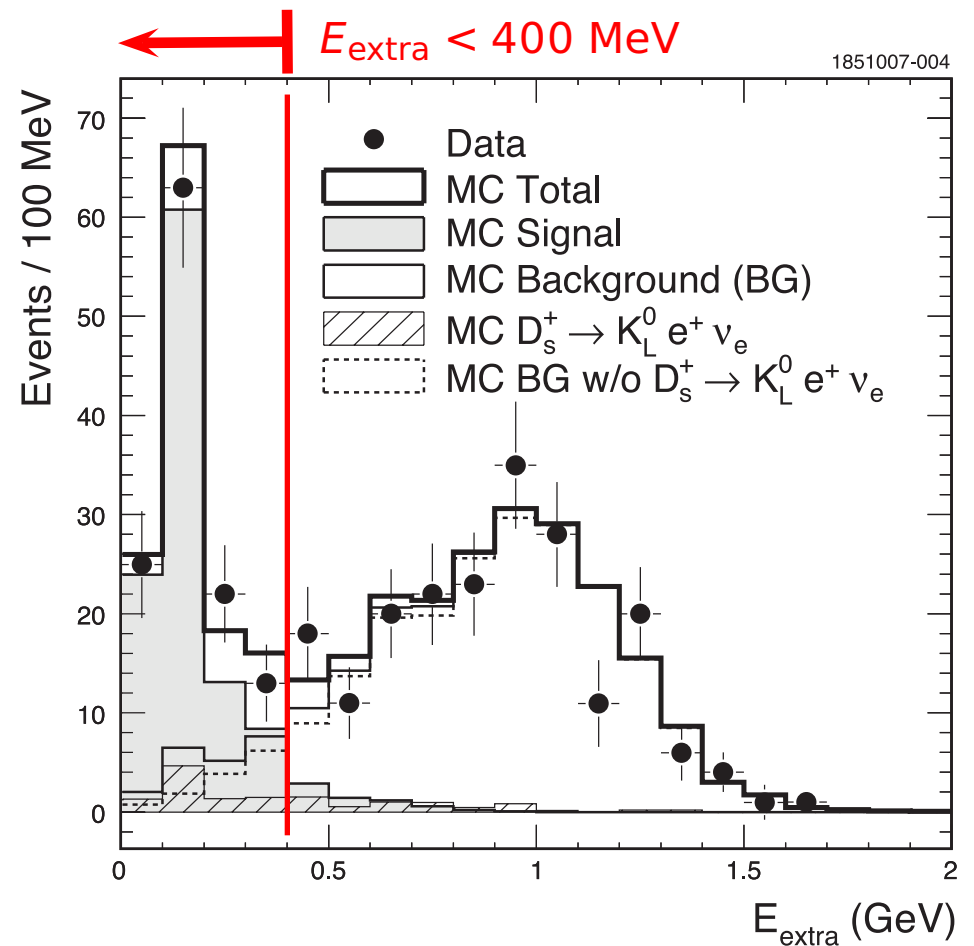
- 314 pb^{-1} @ 4170 – $e^+e^- \rightarrow D_S D_S^*$
- Find a D_S (8 tag modes used), 31k tag candidates
- Now include a γ , looking for $D_S^* \rightarrow \gamma D_S$ decay γ
- Calculate mass recoiling against D_S -tag + γ , to find events with detected decay γ
- Select events with only one additional track, oppositely charged, consistent with μ or π
- Reject events with energetic neutral energy clusters
- Calculate missing mass.
- **Results** : Phys. Rev. Lett. **99**, 071802 (2007)

- A: $B(D_S^+ \rightarrow \mu^+ \nu_\mu) = (0.594 \pm 0.066 \pm 0.031)\%$
- B and C: $B(D_S^+ \rightarrow \tau^+ \nu_\tau) = (8.0 \pm 1.3 \pm 0.4)\%$
- A, B, and C: by summing all cases, w/ SM τ/μ ratio
 $B^{\text{eff}}(D_S^+ \rightarrow \mu^+ \nu_\mu) = (0.638 \pm 0.059 \pm 0.033)\%$
 $f_{D_S} = (274 \pm 13 \pm 7) \text{ MeV}$ ($|V_{cs}| = 0.9738$)



$$D_S^+ \rightarrow \tau^+ \nu_\tau \quad (\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau)$$

- 298 pb⁻¹ @ 4170 – e⁺e⁻ → D_SD_S^{*}
- Find a D_S (3 cleanest tag modes used), 13k tag candidates
- Find an electron on *the other side*
- Require no other charged tracks on *the other side*
- Plot the energy in the calorimeter, not due to tag side or the electron
- E_{extra} < 400 MeV is the signal region
- Extrapolate background from D_S semileptonic decays (mainly D_S⁺ → ηe⁺ν_e) from region above 400 MeV
- D_S⁺ → K_L⁰e⁺ν_e background from D_S⁺ → K_S⁰e⁺ν_e measurement, B(D_S⁺ → K_S⁰e⁺ν_e) = (0.14 ± 0.06 ± 0.01)%
- Background is ~ 21% of yield in signal region
- **Result** : arXiv:0712.1175
 - B(D_S⁺ → τ⁺ν_τ) = (6.17 ± 0.71 ± 0.34)%
 - This is the most precise determination of B(D_S⁺ → τ⁺ν_τ)
 - f_{D_S} = (273 ± 16 ± 8) MeV (|V_{CS}| = 0.9738)



$$N_{DT} = 123 \pm 11.3$$

$$N_S = 101.6 \pm 11.5$$

$$N_B = 21.4 \pm 1.0$$

f_{D_s} & f_{D_s}/f_D

- Combining $D_s^+ \rightarrow \mu^+ \nu_\mu$, $D_s^+ \rightarrow \tau^+ (\pi^+ \bar{\nu}_\tau) \nu_\tau$, and $D_s^+ \rightarrow \tau^+ (e^+ \nu_e \bar{\nu}_\tau) \nu_\tau$: Phys. Rev. Lett. **99**, 071802 (2007); arXiv:0712.1175

$$f_{D_s} = (274 \pm 10 \pm 5) \text{ MeV}$$

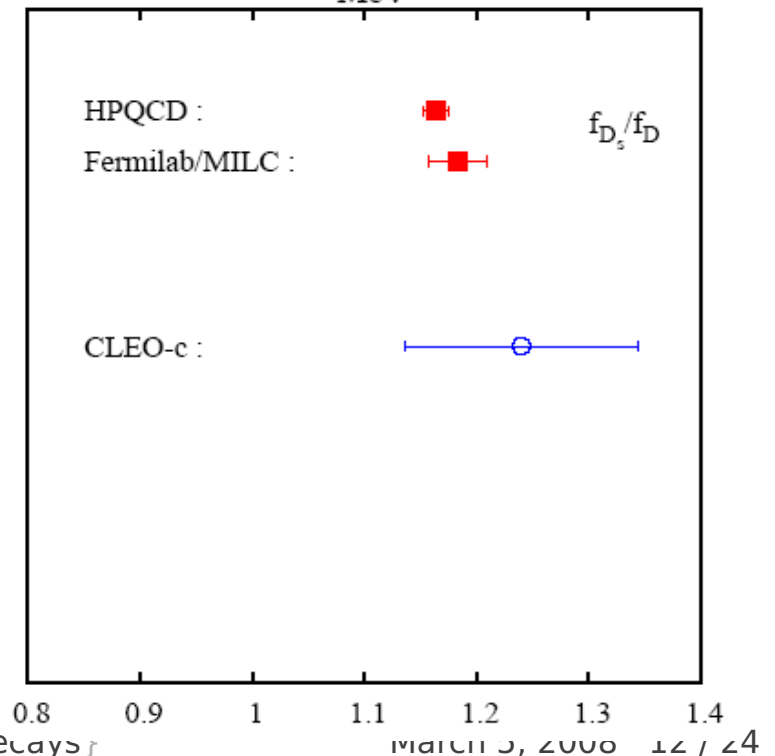
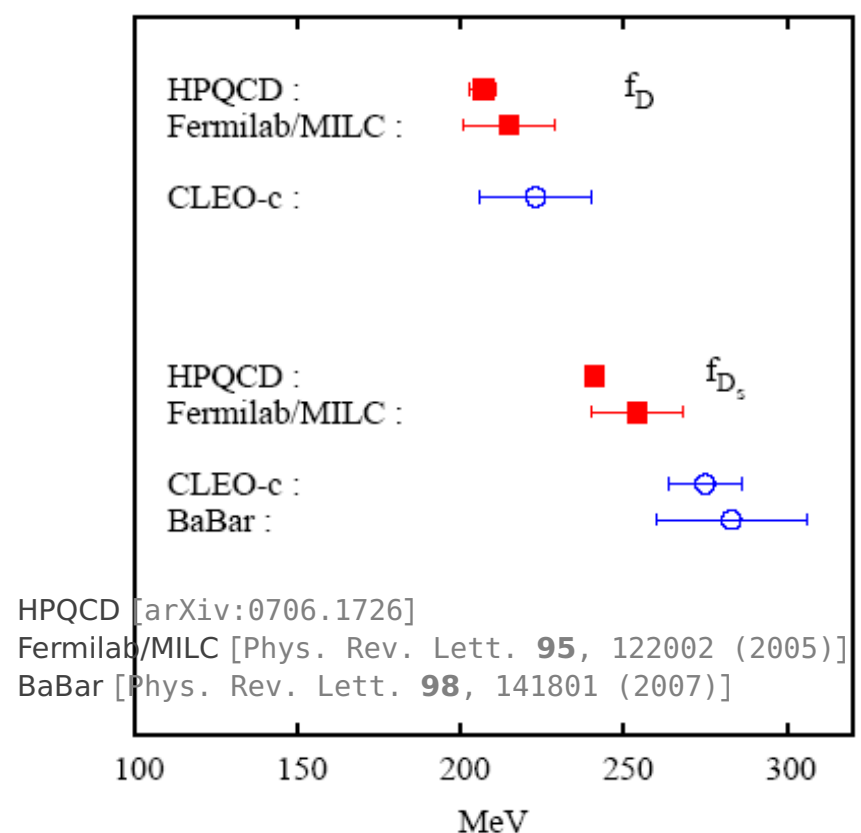
- Using $f_D = (222.6 \pm 16.7^{+2.8}_{-3.4}) \text{ MeV}$

$$\frac{f_{D_s}}{f_D} = 1.23 \pm 0.10 \pm 0.03$$

- CLEO-c is the most precise result to date for both f_D and f_{D_s} ($[294 \pm 27] \text{ MeV}$, PDG 2006).
- $R = \frac{\Gamma(D_s^+ \rightarrow \tau^+ \nu_\tau)}{\Gamma(D_s^+ \rightarrow \mu^+ \nu_\mu)} = 11.0 \pm 1.4 \pm 0.6$
(consistent with lepton universality, SM 9.72).

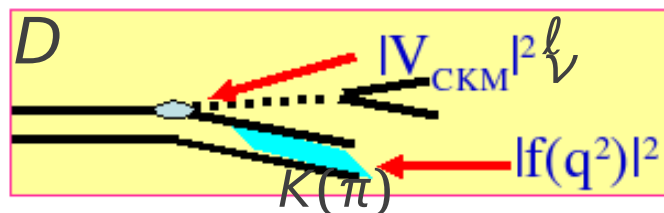
Comparison with Theory

- CLEO f_D is consistent with LQCD calculations.
- CLEO f_{D_s} is $\sim 3\sigma$ above the most recent & precise LQCD calculation (HPQCD)
 - ◆ this discrepancy needs to be studied, LQCD or Exp error?
 - ◆ conflicts with the suppression expected from a 2HDM (Phys. Rev. D **75**, 075004 (2007))
 - ◆ there is new physics that interferes constructively with the SM?
- Comparing measured f_{D_s}/f_D with HPQCD
 - $M_{H^+}/\tan\beta > 2.2$ GeV at 90% C.L.
- Using HPQCD f_{D_s}/f_D
 - $|V_{cd}|/|V_{cs}| = 0.217 \pm 0.19_{\text{exp}} \pm 0.002_{\text{theory}}$



Introduction : Semileptonic Decays

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

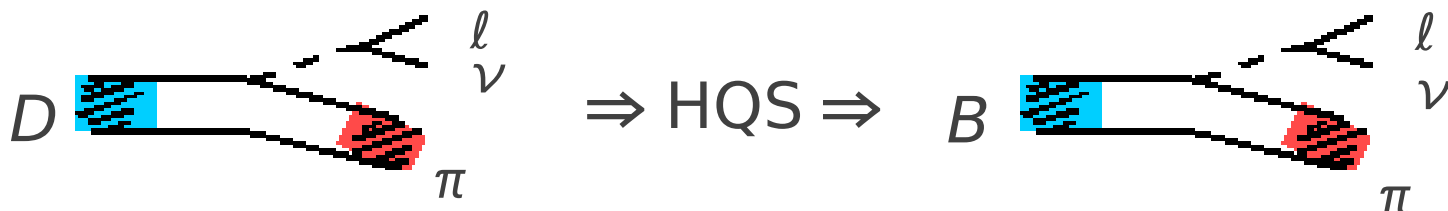


Experiment

Theory (LQCD)

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

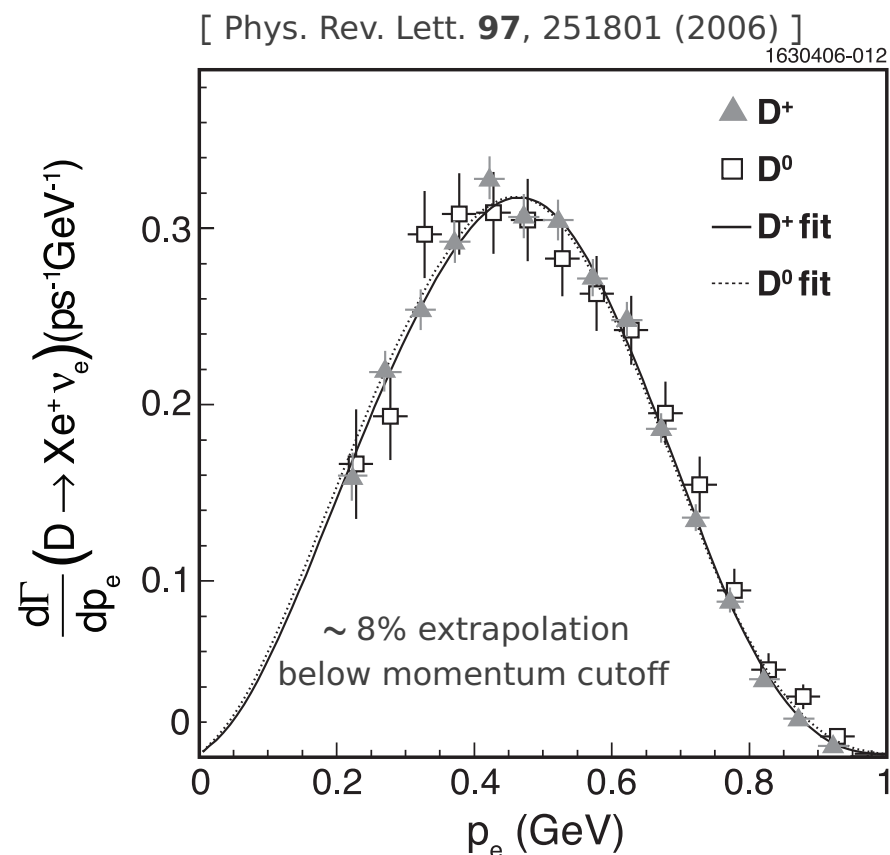
- ◆ Assuming theoretical form factor \Rightarrow determine $|V_{cs}|$ and $|V_{cd}|$
- ◆ Assuming $|V_{cs}|$ and $|V_{cd}| \Rightarrow$ we can check theoretical calculations of the form factors
- Test theory calculations (e.g. LQCD) of $f_+(q^2)$ in the D system and apply them to the B system, e.g. for $|V_{ub}|$.



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

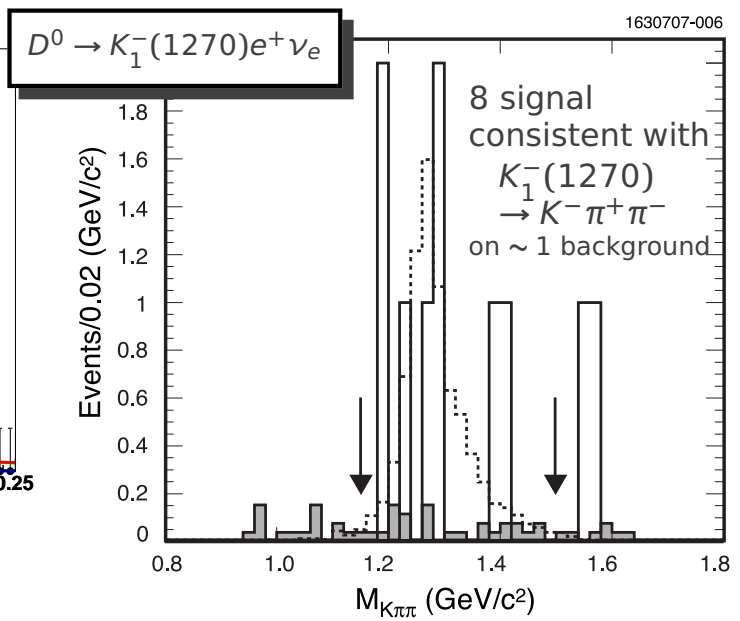
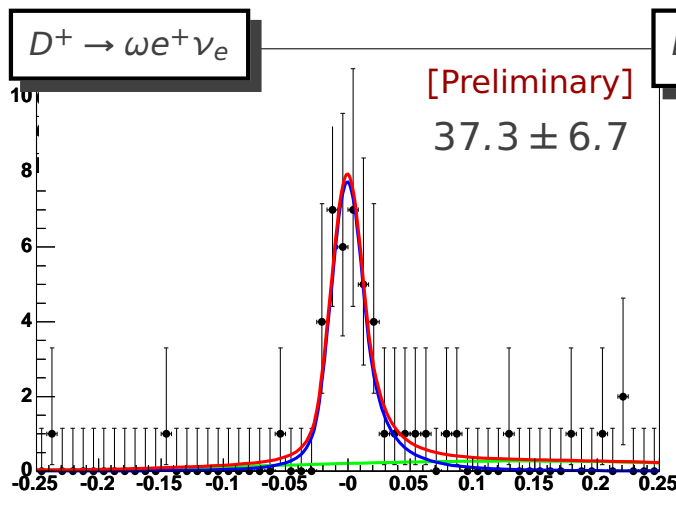
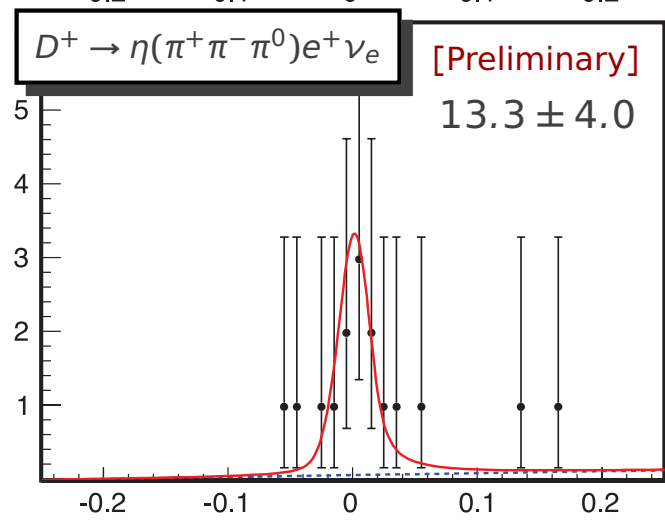
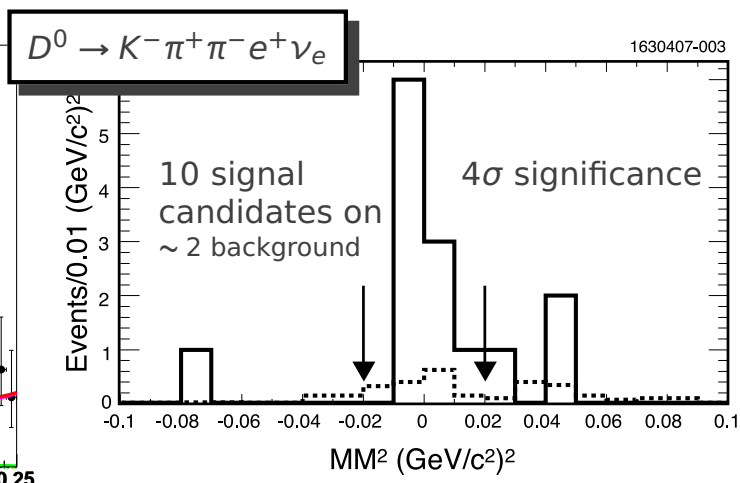
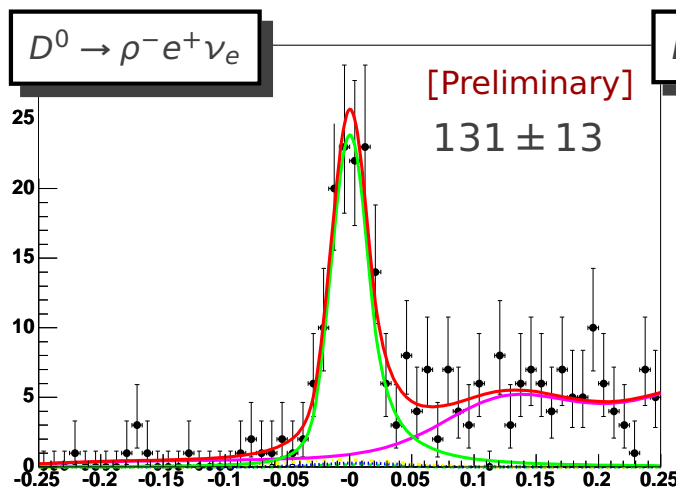
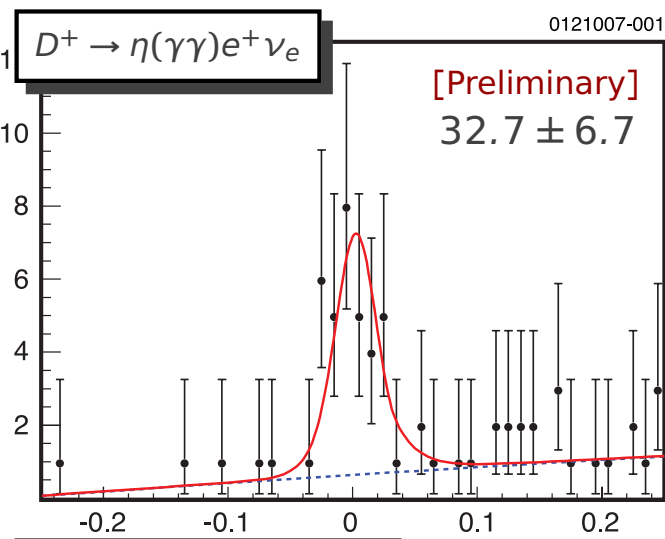


- Consistent with isospin symmetry : the lepton cannot interact strongly with the final-state hadrons and the two mesons differ only in the isospin of the light quark

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

First Observations

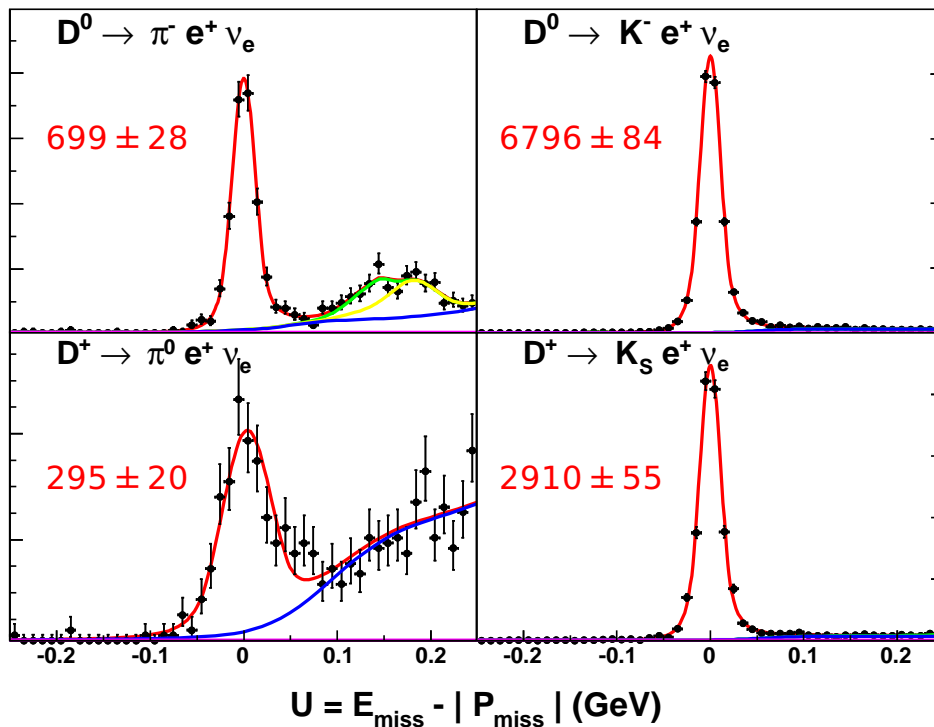
[Phys. Rev. Lett. **99**, 191801 (2007)]



$D \rightarrow K(\pi)e\nu$

(1) Tagged Analysis :

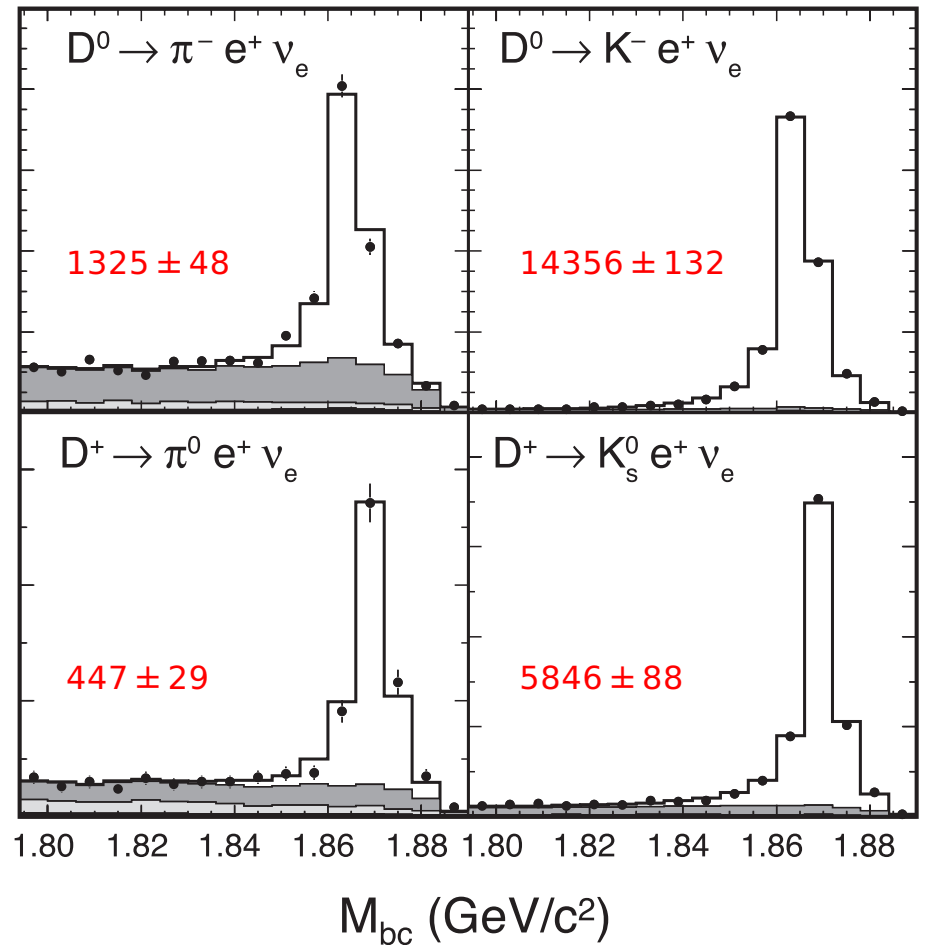
[Preliminary]



(2) Untagged Analysis :
neutrino reconstruction

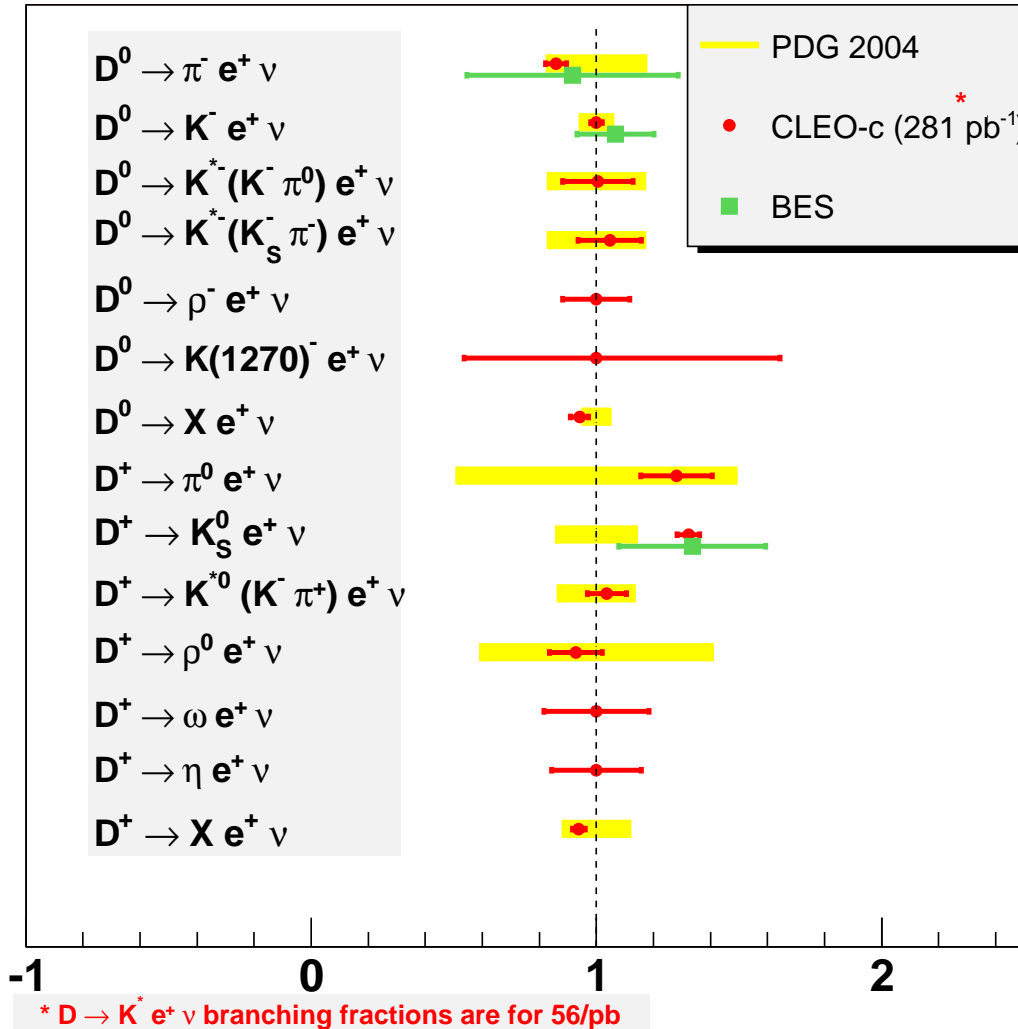
[arXiv:0712.0998]

3600307-017



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

Branching Fraction Summary

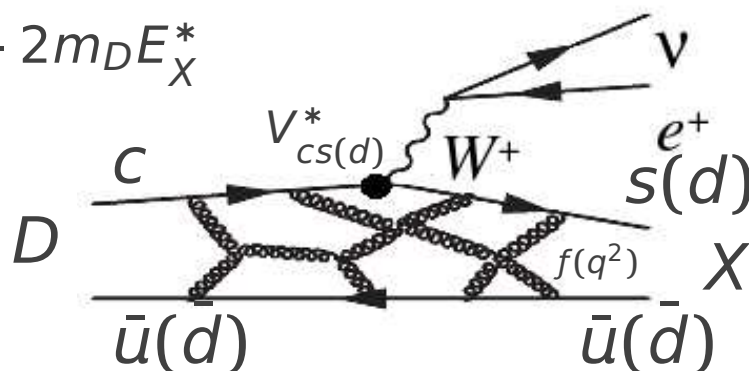


L (pb^{-1})	$B(D^0)_{\text{SL}}$ (%)	$B(D^+)_{\text{SL}}$ (%)
	$K^- e^+ \nu_e$	$\bar{K}^0 e^+ \nu_e$
281 tagged	$3.58 \pm 0.05 \pm 0.05$	$8.86 \pm 0.17 \pm 0.20$
281 ν -recon	$3.56 \pm 0.03 \pm 0.09$	$8.53 \pm 0.13 \pm 0.23$
	$K^*(892)^- e^+ \nu_e$	$\bar{K}^*(892)^0 e^+ \nu_e$
56	$2.16 \pm 0.15 \pm 0.08$	$5.56 \pm 0.27 \pm 0.23$
	$\pi^- e^+ \nu_e$	$\pi^0 e^+ \nu_e$
281 tagged	$0.309 \pm 0.012 \pm 0.006$	$0.397 \pm 0.027 \pm 0.029$
281 ν -recon	$0.299 \pm 0.011 \pm 0.009$	$0.373 \pm 0.022 \pm 0.013$
	$\rho^- e^+ \nu_e$	$\rho^0 e^+ \nu_e$
281 tagged	$0.156 \pm 0.016 \pm 0.009$	$0.232 \pm 0.020 \pm 0.012$
		$\omega e^+ \nu_e$
281 tagged		$0.149 \pm 0.027 \pm 0.005$
		$\eta e^+ \nu_e$
281 tagged		$0.133 \pm 0.020 \pm 0.006$
	$K_1^-(1270) e^+ \nu_e$	
281 tagged	$0.076^{+0.041}_{-0.030} \pm 0.006 \pm 0.007$	
	$\Sigma_{\text{exclusive}}$	
	$6.28 \pm 0.16_{\text{stat}}$	$15.33 \pm 0.42_{\text{stat}}$
	$X e^+ \nu_e$	$X e^+ \nu_e$
281 tagged	$6.46 \pm 0.17 \pm 0.13$	$16.13 \pm 0.20 \pm 0.33$
281 tagged		$\eta' e^+ \nu_e < 3.5 \times 10^{-4}$
281 tagged		$\phi e^+ \nu_e < 1.6 \times 10^{-4}$

- 281 pb^{-1} numbers are preliminary, except $X e \nu$, $K_1^-(1270) e \nu$, and $K/\pi e \nu$ (ν -recon).
- 40% overlap, do not average tagged/ ν -recon $K/\pi e \nu$.

Semileptonic Decay Form Factor

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



Amplitude factorizes

$$\mathcal{M}(D \rightarrow X l^+ \nu_l) = -i \frac{G_F}{\sqrt{2}} V_{cs}^* L_\mu H^\mu$$

- Hadronic currents : in the limit $m_\ell \rightarrow 0$
 - ◆ $P \rightarrow P' l^+ \nu_\ell$: single form factor, $H^\mu = f_+(q^2)(p_P + p_{P'})^\mu$ (gold-plated for both theory and experiment)
 - ◆ e.g. D semileptonic decays to a pseudoscalar can be written as $\frac{d\Gamma(D \rightarrow K e \nu_e)}{dq^2} = \frac{G_F^2 |V_{cs}|^2 p_K^3}{24\pi^3} |f_+(q^2)|^2$.
- The messy hadronic physics is contained in the form factor. The full test of LQCD is its ability to calculate $f(q^2)$, both the shape vs q^2 , and the absolute value.

Form Factor : parametrizations

- In general : $f_+(q^2) = \frac{f_+(0)}{1-\alpha} \frac{1}{1-q^2/m_{\text{pole}}^2} + \sum_{k=1}^N \frac{\rho_k}{1-\frac{1}{\gamma_k} \frac{q^2}{m_{\text{pole}}^2}}$

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

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

(allows for additional poles).

- Series expansion : [T. Becher and R. J. Hill, Phys. Lett. B **633**, 61 (2006)]

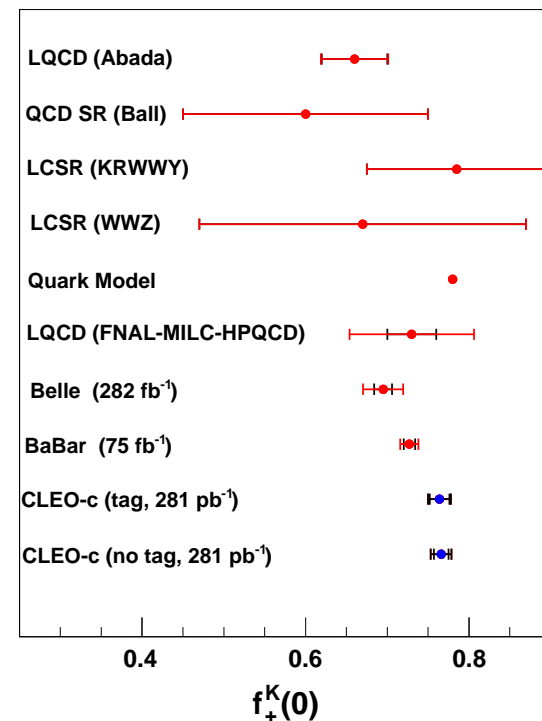
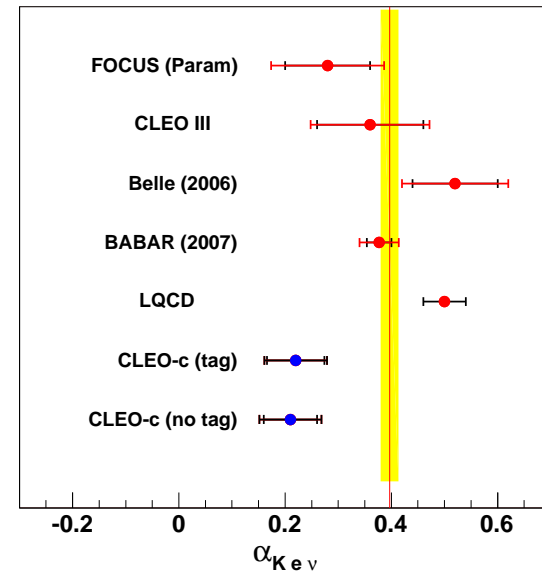
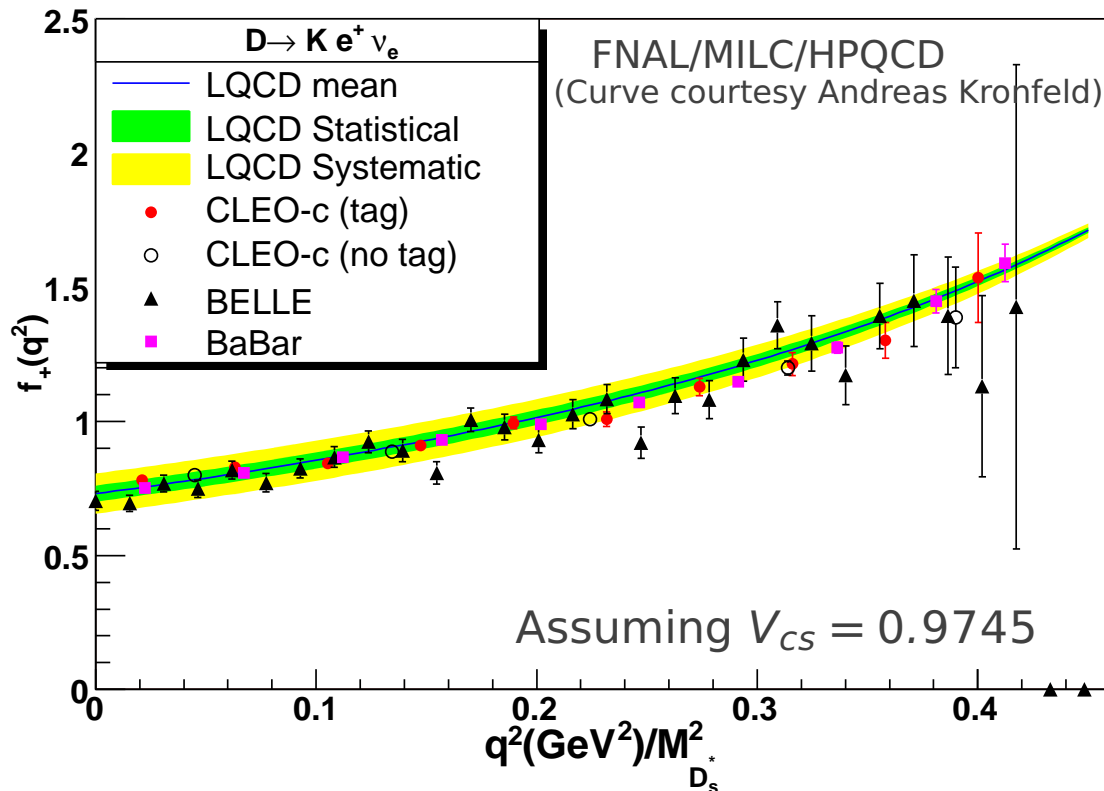
$$f_+(q^2) = \frac{1}{P(q^2)\phi(q^2, t_0)} \sum_{k=0}^{\infty} a_k(t_0) [z(q^2, t_0)]^k,$$

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 $P(q^2) \equiv 1$ ($D \rightarrow \pi$) or $z(q^2, M_{D_s^*}^2)$ ($D \rightarrow K$).

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.

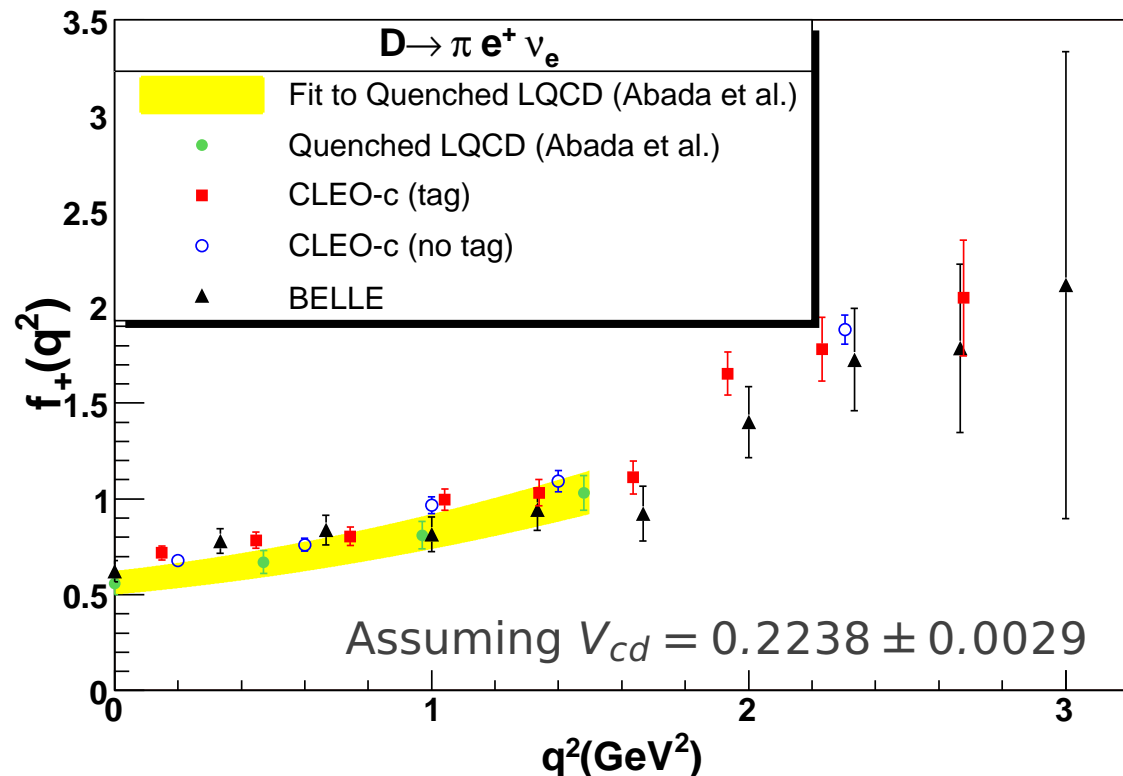
$D \rightarrow Ke\nu$: high statistics test of shape & absolute normalization of $f_+(q^2)$



- Modified pole model used for comparison :

$$f_+(q^2) = \frac{f_+(0)}{(1 - q^2/m_{\text{pole}}^2)(1 - \alpha q^2/m_{\text{pole}}^2)}$$
- Shape parameter: CLEO-c prefers smaller value
- Normalization:
 experiment (2%) consistent with LQCD (10%)
- CLEO-c (tag) – Preliminary
- CLEO-c (no tag) – arXiv:0712.0998

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



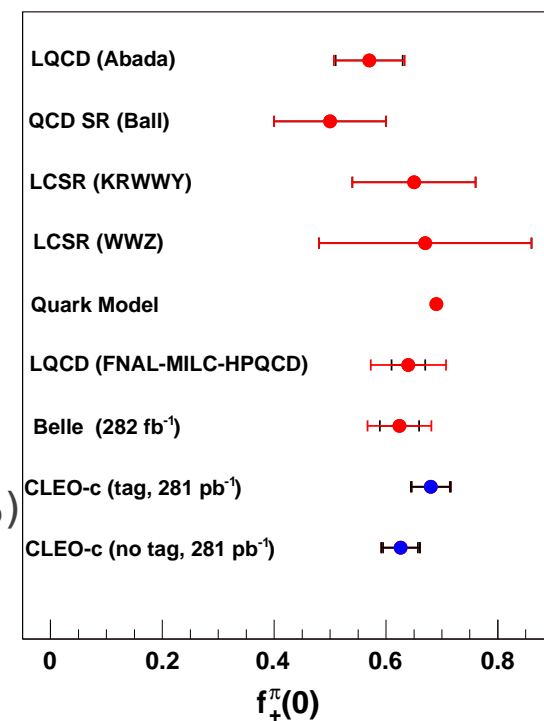
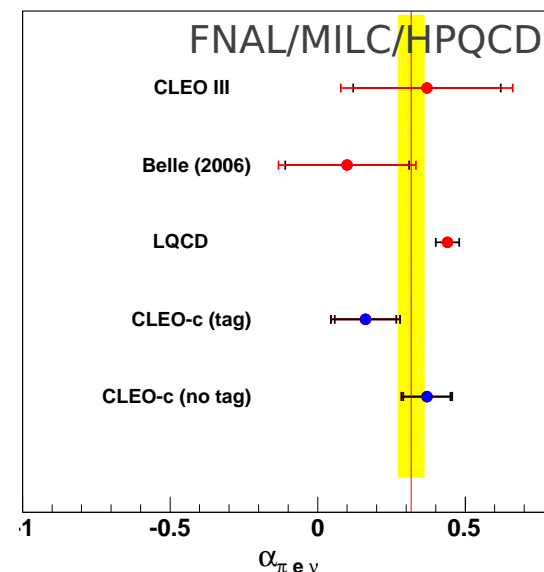
Modified pole model used for comparison :

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

Shape parameter: experiments compatible with LQCD

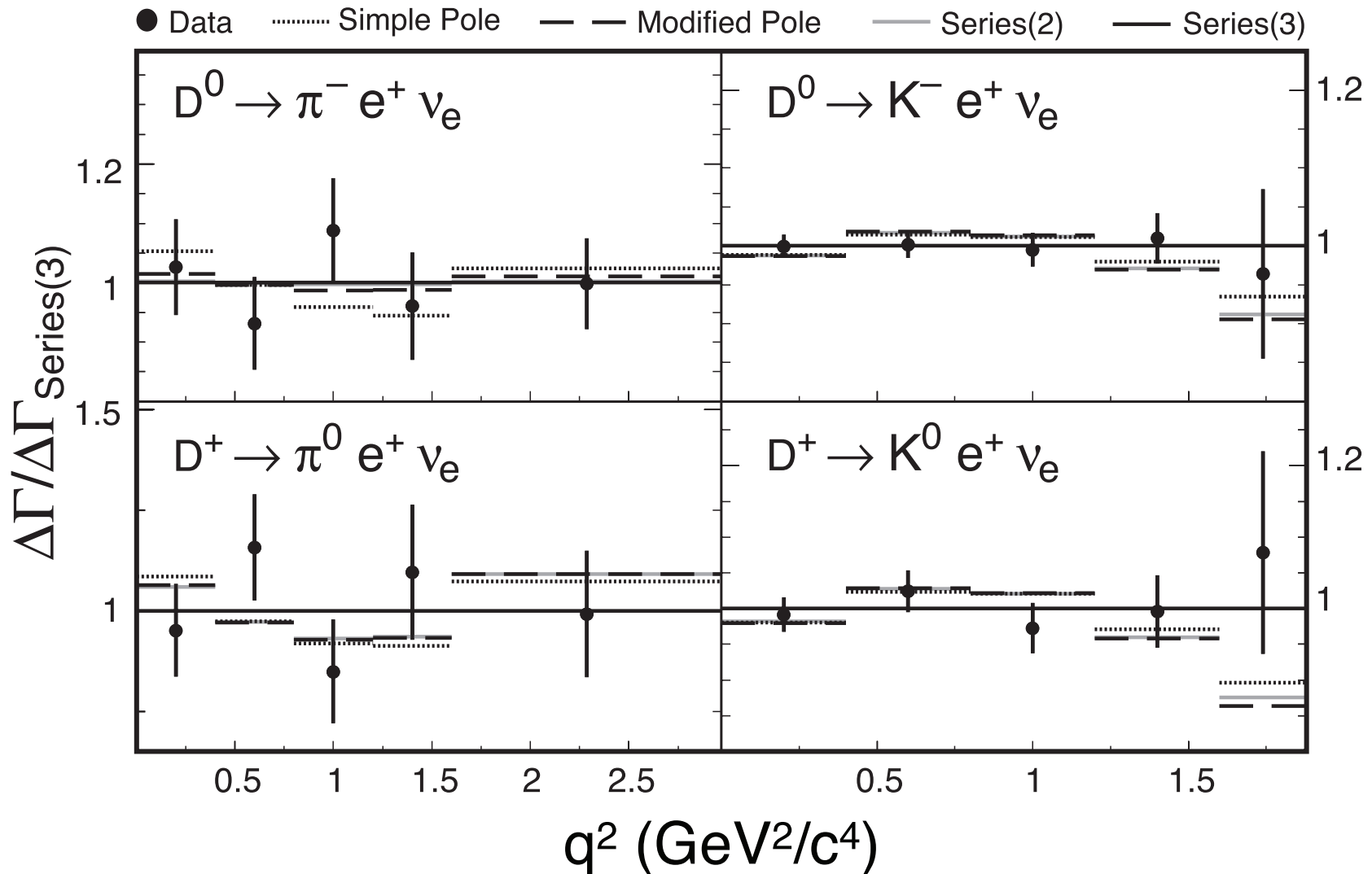
Normalization: experiment (4%) consistent with LQCD (10%)

- CLEO-c (tag) – Preliminary
- CLEO-c (no tag) – arXiv:0712.0998



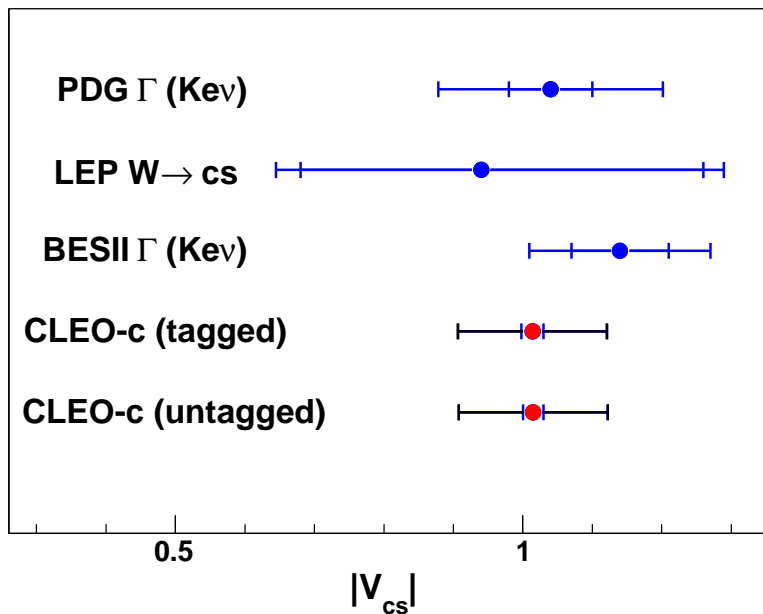
Form Factor : $D \rightarrow Pe\nu$ which parametrization?

[arXiv:0712.1020] 3600307-016



- We use the model independent Becher-Hill series parametrization for V_{cX} (determine $f_+(0)|V_{cX}|$ then use theory value of $f_+(0)$).

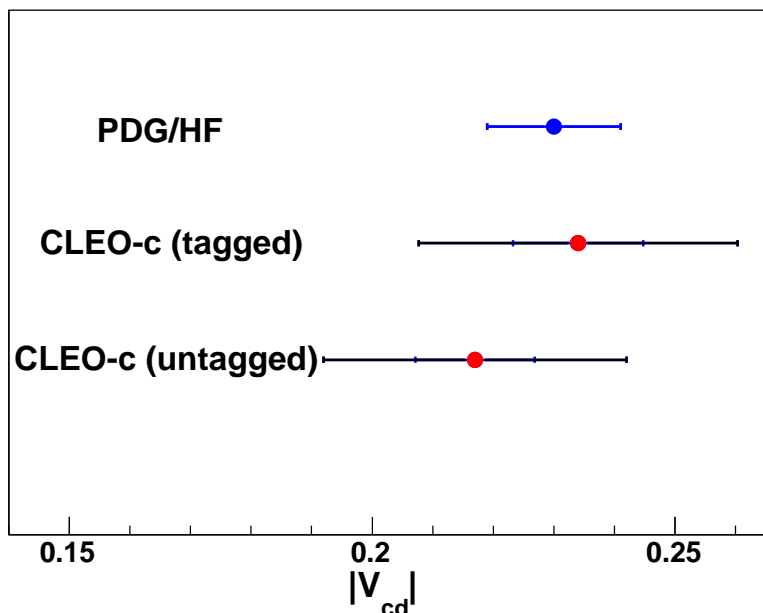
$|V_{cs}|$ & $|V_{cd}|$ Results



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 $|V_{cs}|$
- ◆ $\sigma(|V_{cs}|)/|V_{cs}| \sim 1.5\%$ (exp) $\oplus 10\%$ (theory)

CLEO-c	$ V_{cs} $		
(tagged)	1.014 ± 0.013	± 0.009	± 0.106
(untagged)	1.015 ± 0.010	± 0.011	± 0.106
	stat	syst	theory



- ◆ CLEO-c : $\sigma(|V_{cd}|)/|V_{cd}| \sim 4.5\%$ (exp) $\oplus 10\%$ (theory)
- ◆ νN remains most precise determination (for now).

CLEO-c	$ V_{cd} $		
(tagged)	0.234 ± 0.010	± 0.004	± 0.024
(untagged)	0.217 ± 0.009	± 0.004	± 0.023
	stat	syst	theory

- Tagged and untagged are consistent.
- 40% overlap, DO NOT AVERAGE.
- CLEO-c (tag) – Preliminary
- CLEO-c (no tag) – arXiv:0712.0998

Summary

■ D Leptonic :

- ◆ f_D measured to $\pm 7.6\%$, statistical error dominates.
- ◆ f_{D_s} measured to $\pm 4.1\%$, statistical error dominates.
- ◆ $B(D_S^+ \rightarrow \tau^+ \nu_\tau)/B(D_S^+ \rightarrow \mu^+ \nu_\mu)$ consistent with theory.
- ◆ For f_{D_s} , a suggestion of a disagreement with LQCD $\sim 3\sigma$.

■ D Semileptonic :

- ◆ Inclusive D^0, D^+ semileptonic widths \sim equal.
- ◆ Sum of measured exclusives almost saturates inclusives.
- ◆ $D \rightarrow Ke\nu, \pi e\nu$ form factors in general agreement with LQCD.

■ With CLEO-c full data : 800 pb^{-1} @3770 & 600 pb^{-1} @4170

- ◆ Expect errors in f_D & f_{D_s} decreased to a few % level.
- ◆ More stringent tests of theory for $D \rightarrow K(\pi)e^+ \nu_e$ form factor $f_+(0)$ & shape.