Rencontres de Moriond EW 2008

{CLEO-c Charm Leptonic & Semileptonic Decays}

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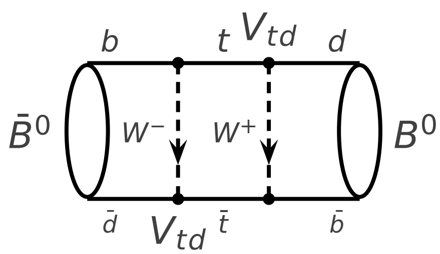
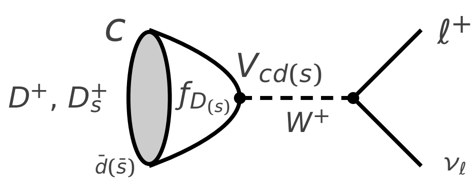
March 5, 2008

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





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

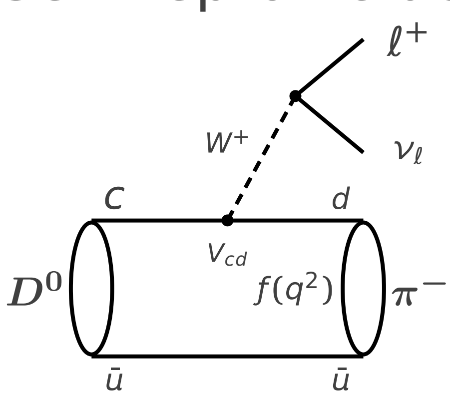
experiment LQCD

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

known to < 1% from the CKM unitarity

LQCD predicts f_B/f_D and f_B/f_{B_s} w/ small errors ⇒ precise f_D gives precise f_B and $|V_{td}|$ f_D/f_{D_s} checks f_B/f_{B_s} and allows precise $|V_{td}|/|V_{ts}|$

- Semileptonic decays

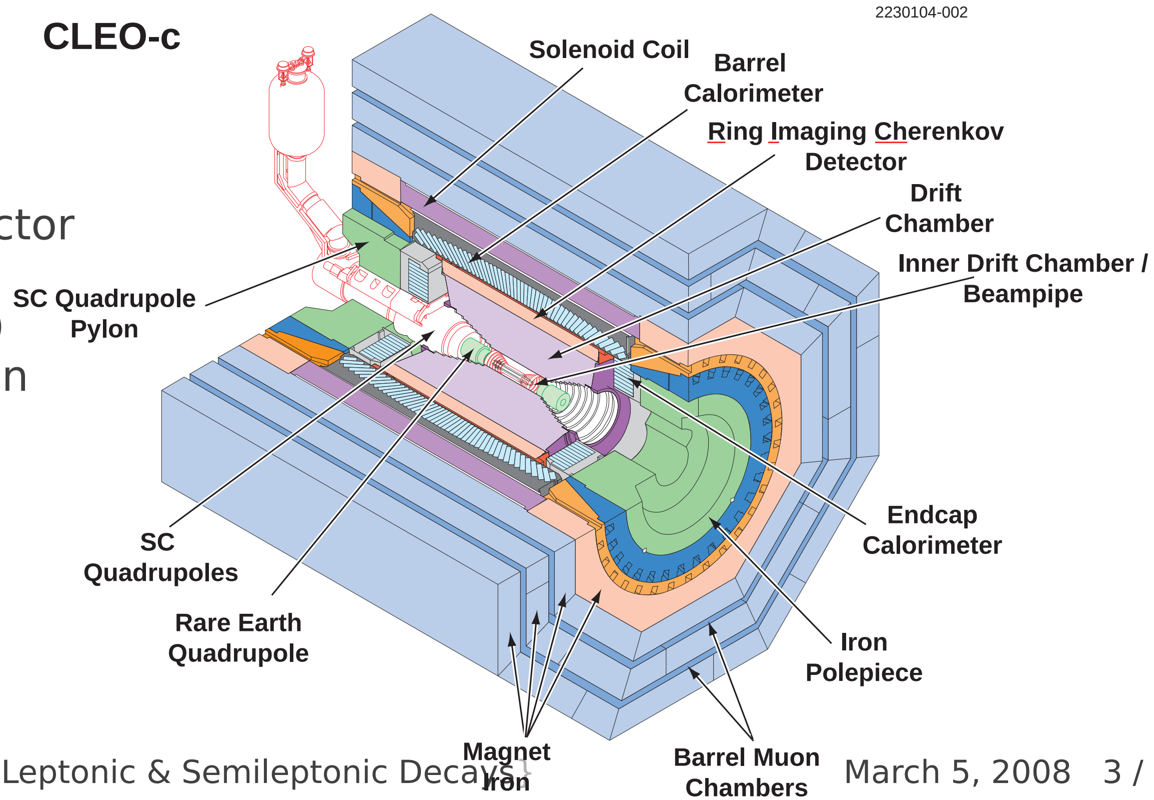


$$\text{Rate} \propto |V_{cd}|^2 |f_+(q^2)|^2$$

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

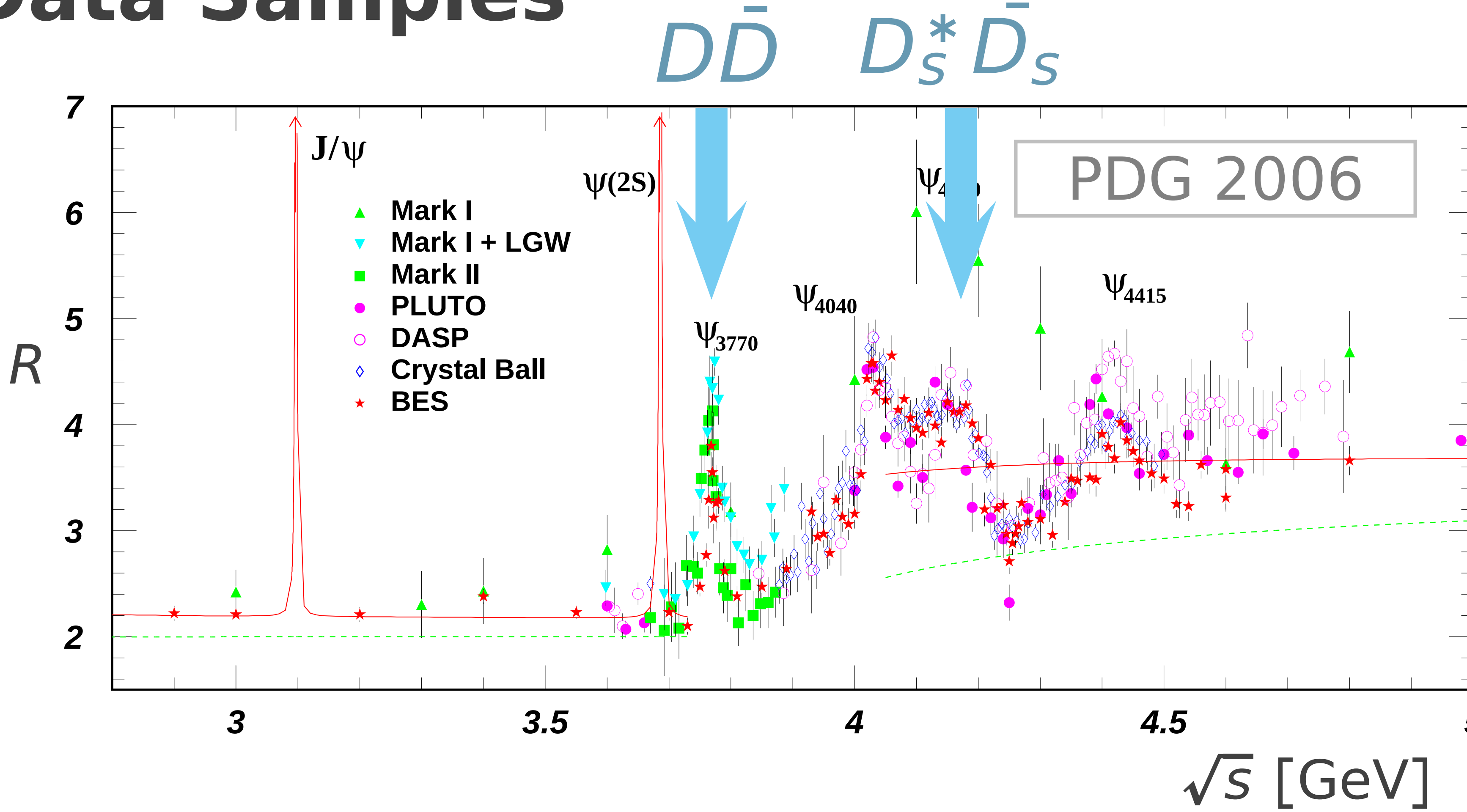
CLEO-c Open Charm Program

- 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 : $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to \pi^+K^+K^-$, and others.
- Measurements to test, calibrate, validate Lattice QCD calculations, other calculations of strong interaction effects. D^+, $D_s^+ \to \ell^+\nu_\ell$, 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



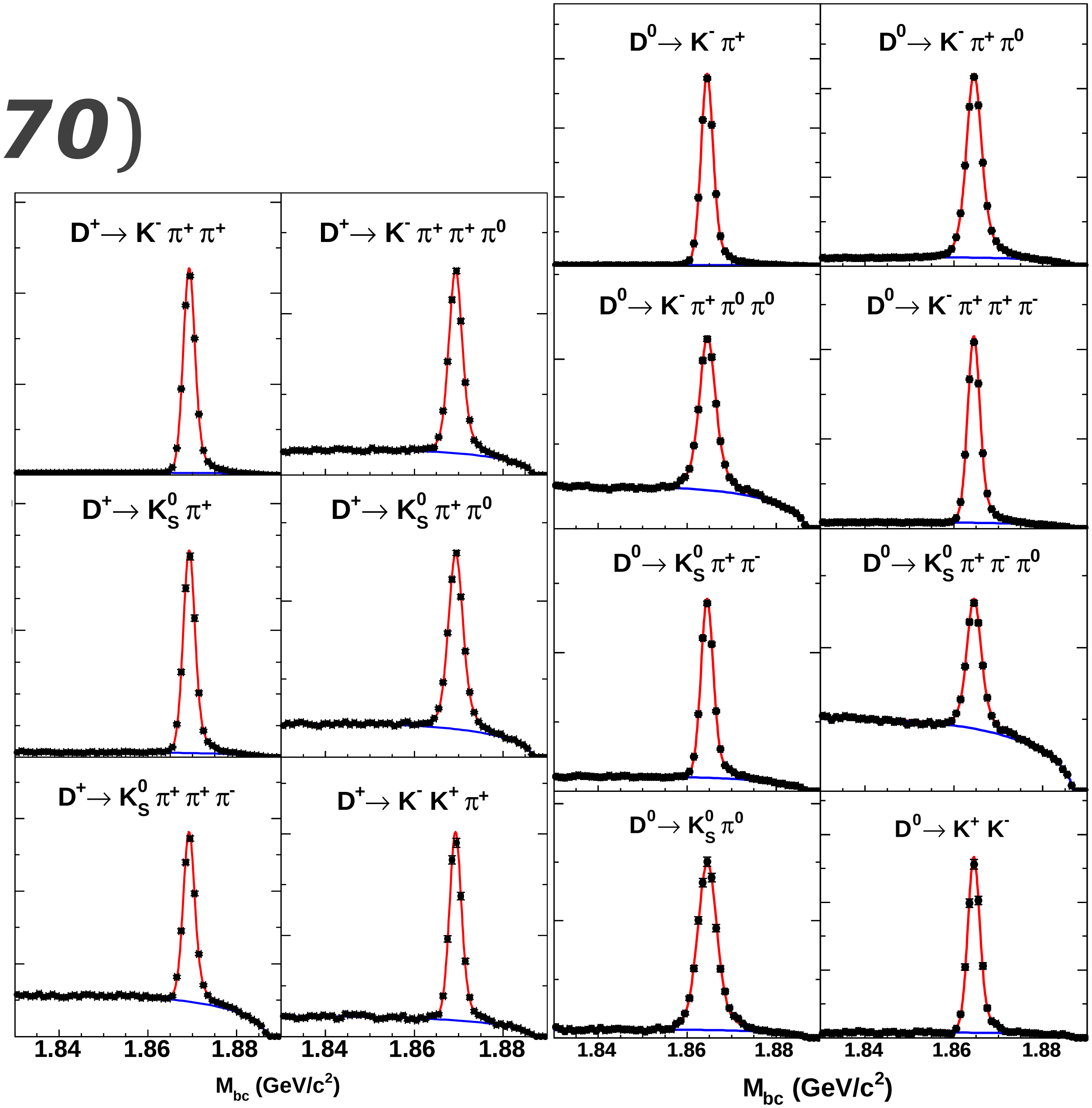
- $D\bar{D}$ @ 3770 : 800 pb^{-1} (56 & 281 pb^{-1} in this talk);
  281 $\mathrm{pb}^{-1} \sim 1.8 \times 10^6 D\bar{D}$
- $D_s^*\bar{D}_s$ @ 4170 : 314 pb^{-1} (will double the sample)
  314 $\mathrm{pb}^{-1} \sim 0.3 \times 10^6 D_s^*\bar{D}_s$

Charm at $\psi(3770)$

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

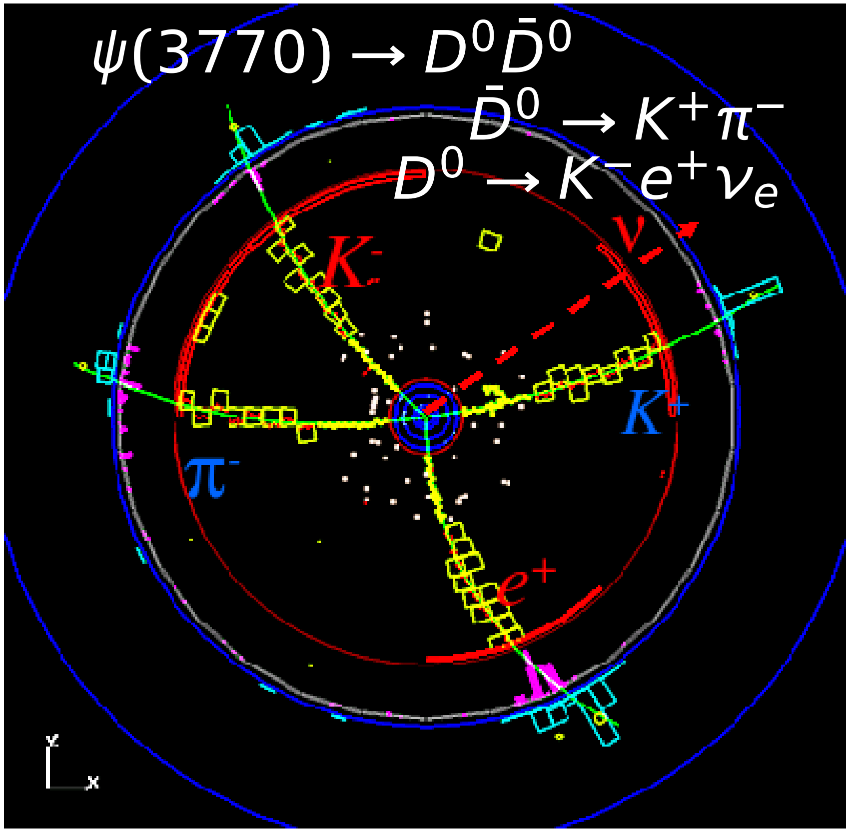
  $\Delta E = E_D - E_{\text{beam}}$

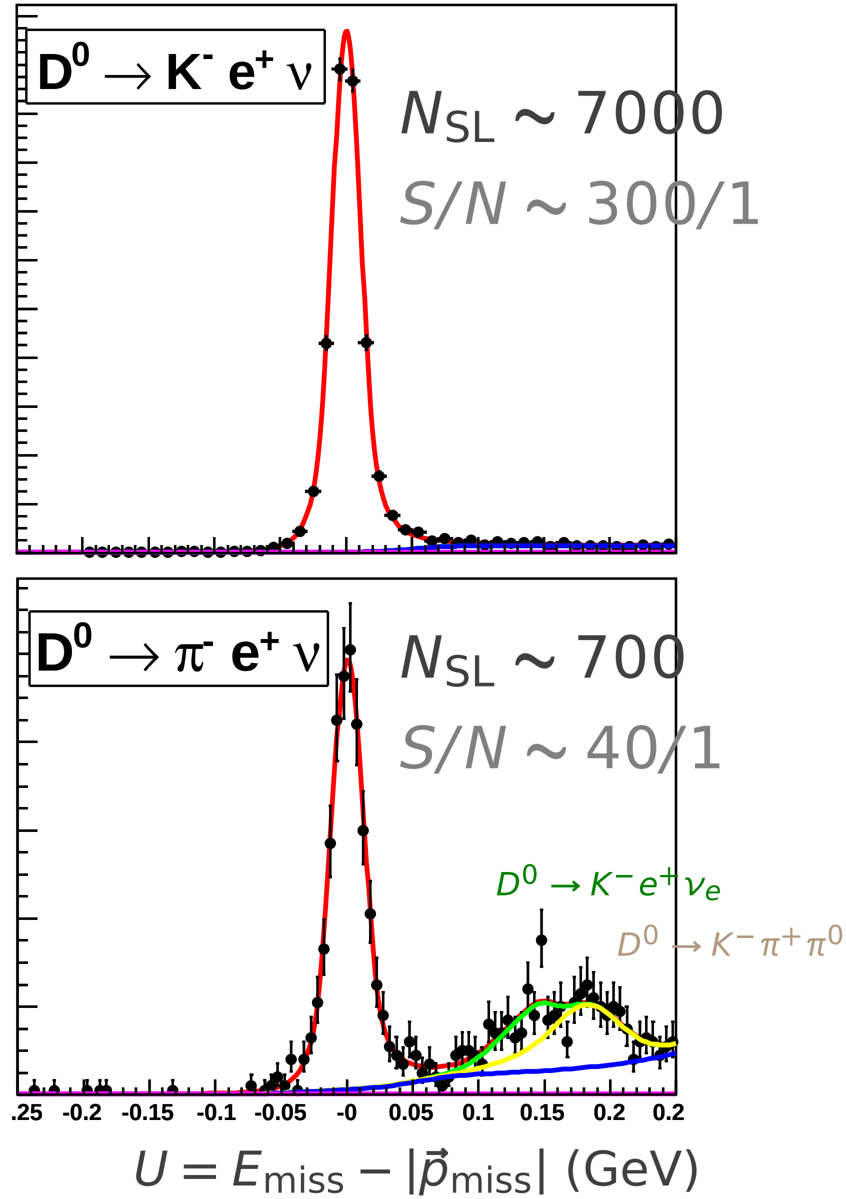
  $M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_D^{\,2}|}$
- D tagging efficiency:
  $\sim 10\%\ D^+$
  $\sim 15\%\ D^0$
- Clean experimental environment
  ($\Leftarrow$ low multiplicity & D-tagging)



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

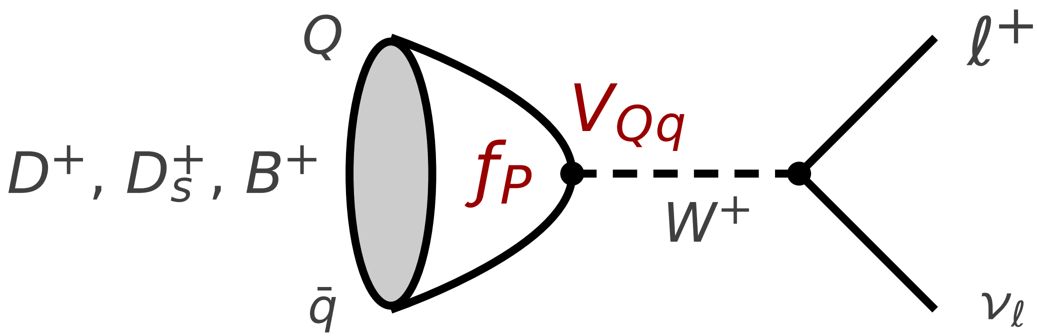
Absolute Branching Fractions





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

Introduction : Leptonic Decays

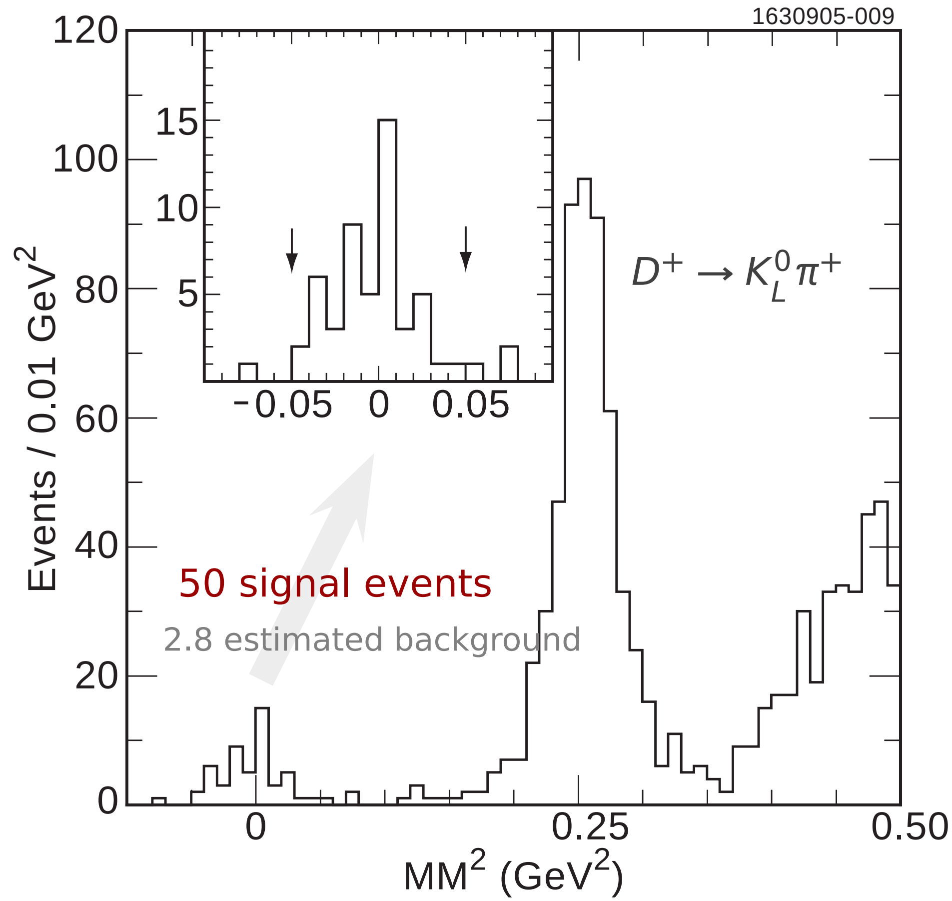


$$\Gamma(P_{Q\bar{q}} \to \ell^+\nu_\ell) = \frac{G_F^2 |V_{Qq}|^2 {f_P}^2}{8\pi} m_{Q\bar{q}} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{Q\bar{q}}^2}\right)^2$$

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

$D^+ \to \mu^+ \nu_\mu$

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

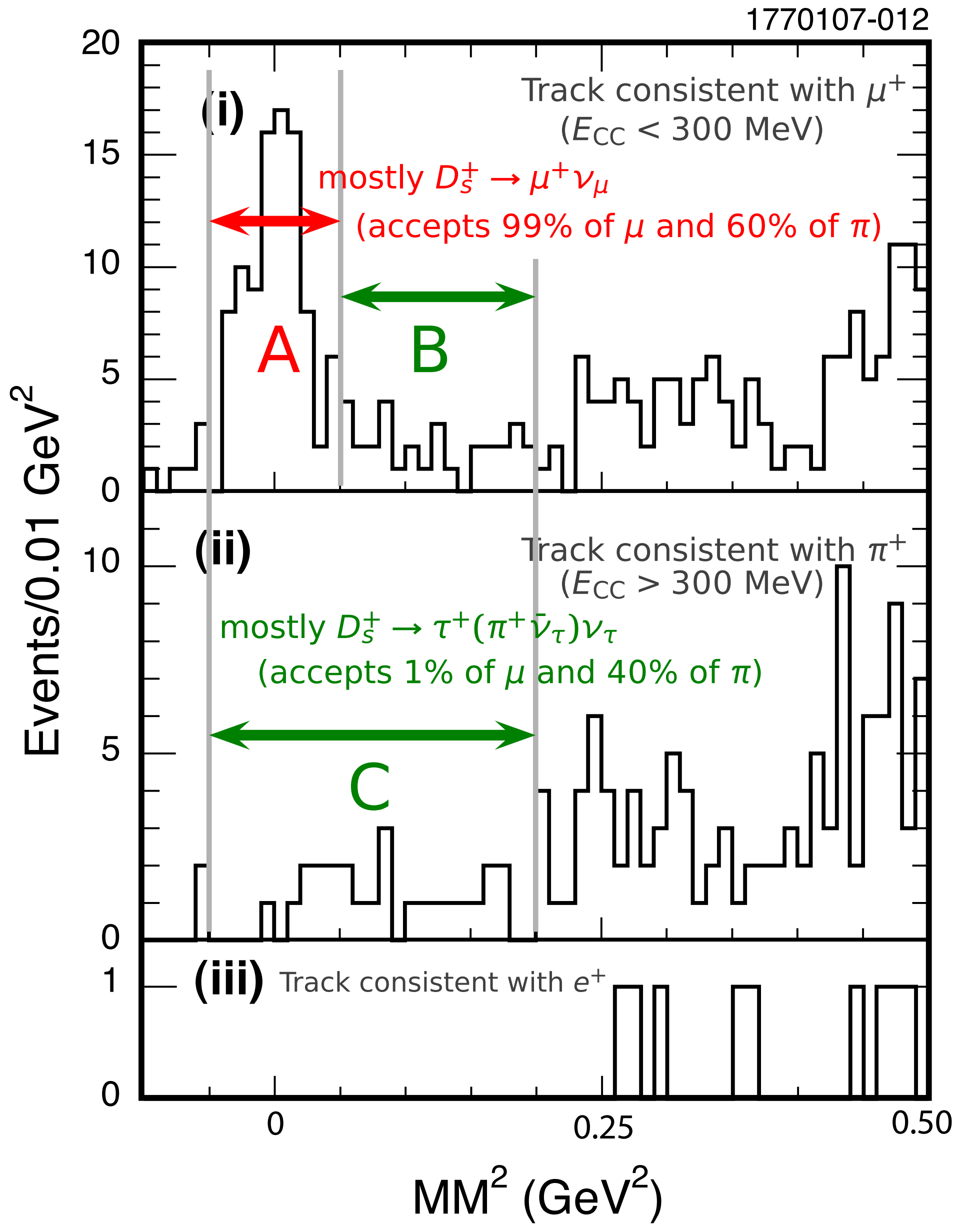


- Result: Phys. Rev. Lett. **95**, 251801 (2005)
  - $B(D^+ \to \mu^+ \nu_\mu) = (4.40 \pm 0.66^{+0.09}_{-0.12}) \times 10^{-4}$
  - $f_D = (222.6 \pm 16.7^{+2.8}_{-3.4})$ MeV (using $|V_{cd}| = 0.2238$)
- Unquenched LQCD $f_{D^+} = (201 \pm 3 \pm 17)$ MeV, Exp/Theory agree ∼ to 10%.

$$D_s^+ \to \mu^+ \nu_\mu$$
$$D_s^+ \to \tau^+ \nu_\tau \ (\tau^+ \to \pi^+ \bar{\nu}_\tau)$$

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 – $e^+e^- \to D_s D_s^*$
- Find a D_s (8 tag modes used), 31k tag candidates
- Now include a γ, looking for $D_s^* \to \gamma D_s$ 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)

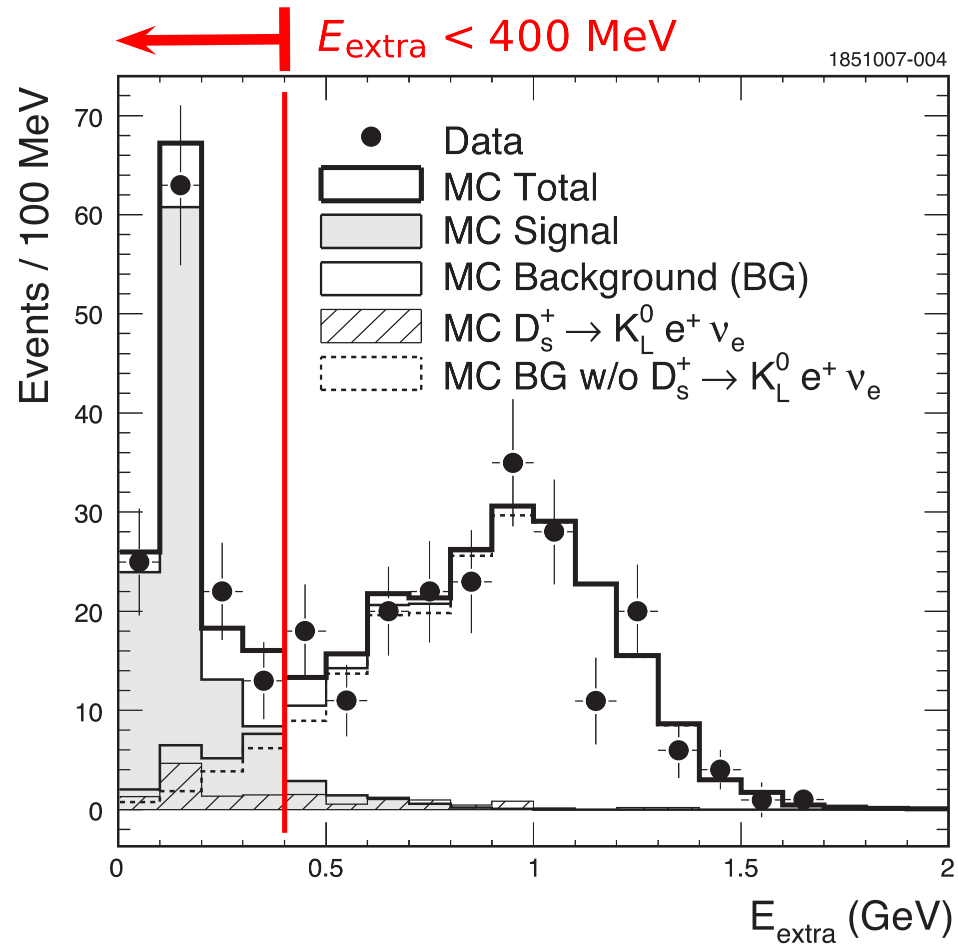


- A:
  $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.594 \pm 0.066 \pm 0.031)\%$
- B and C:
  $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (8.0 \pm 1.3 \pm 0.4)\%$
- A, B, and C: by summing all cases, w/ SM τ/μ ratio
  $\mathcal{B}^{\rm eff}(D_s^+ \to \mu^+\nu_\mu) = (0.638 \pm 0.059 \pm 0.033)\%$
  $f_{D_s}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

$D_s^+ \to \tau^+\nu_\tau\ (\tau^+ \to e^+\nu_e\bar{\nu}_\tau)$

- 298 pb^{-1} @ 4170 – $e^+e^- \to D_s D_s^*$
- 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
- $E_{\rm extra} < 400$ MeV is the signal region
- Extrapolate background from D_s semileptonic decays (mainly $D_s^+ \to \eta e^+\nu_e$) from region above 400 MeV
- $D_s^+ \to K_L^0 e^+\nu_e$ background from $D_s^+ \to K_S^0 e^+\nu_e$ measurement, $B(D_s^+ \to K_S^0 e^+\nu_e) = (0.14 \pm 0.06 \pm 0.01)\%$
- Background is $\sim$ 21% of yield in signal region
- **Result** : `arXiv:0712.1175`

- $B(D_s^+ \to \tau^+\nu_\tau) = (6.17 \pm 0.71 \pm 0.34)\%$
- This is the most precise determination of $B(D_s^+ \to \tau^+\nu_\tau)$
- $f_{D_s} = (273 \pm 16 \pm 8)$ 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 $D_s^+ \to \mu^+\nu_\mu$, $D_s^+ \to \tau^+(\pi^+\bar{\nu}_\tau)\nu_\tau$, and $D_s^+ \to \tau^+(e^+\nu_e\bar{\nu}_\tau)\nu_\tau$: Phys. Rev. Lett. **99**, 071802 (2007); arXiv:0712.1175

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

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

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

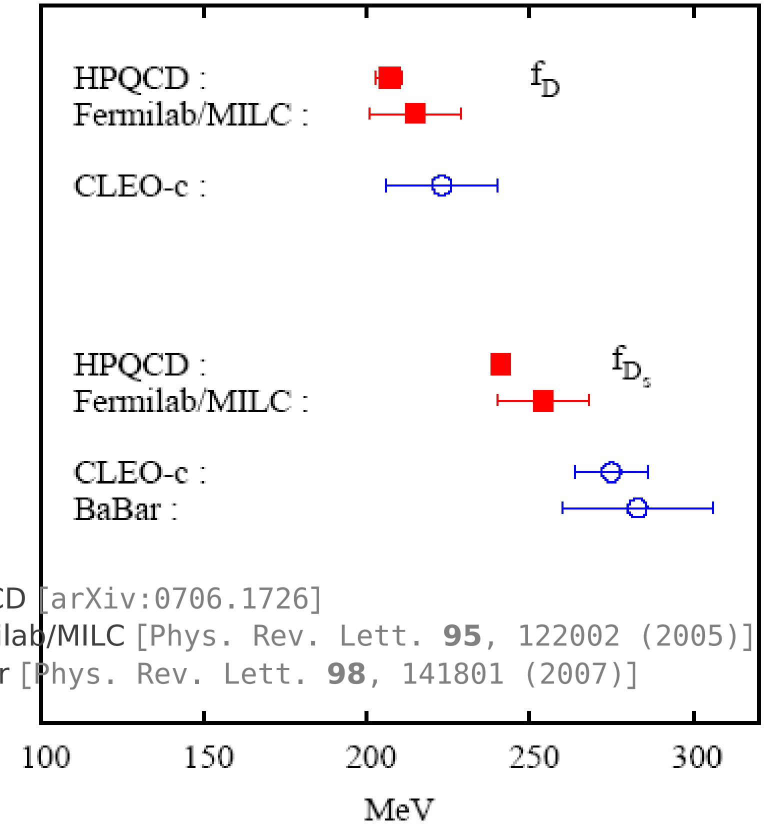
- CLEO-c is the most precise result to date for both f_D and f_{D_s} ([294 ± 27] MeV, PDG 2006).
- $R = \frac{\Gamma(D_s^+ \to \tau^+\nu_\tau)}{\Gamma(D_s^+ \to \mu^+\nu_\mu)} = 11.0 \pm 1.4 \pm 0.6$ (consistent with lepton universality, SM 9.72).

Comparison with Theory

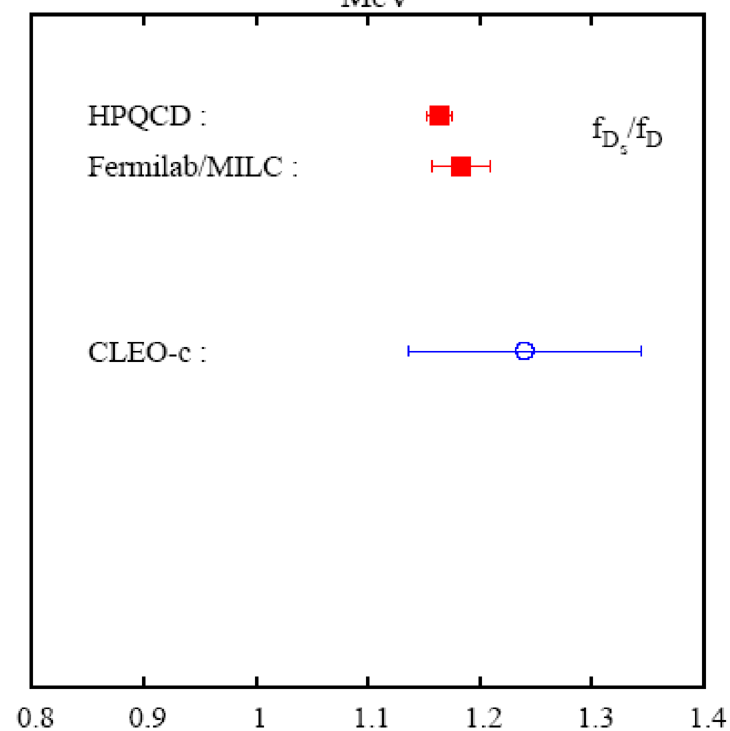
- CLEO f_D is consistent with LQCD calculations.
- CLEO f_{D_s} is $\sim 3\sigma$ above the most recent & precise LQCD calculation (HPQCD)
  - this discrepancy needs to be studied, LQCD or Exp error?
  - conflicts with the suppression expected from a 2HDM (Phys. Rev. D **75**, 075004 (2007))
  - there 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

  $|V_{cd}|/|V_{cs}| = 0.217 \pm 0.19_{\text{exp}} \pm 0.002_{\text{theory}}$

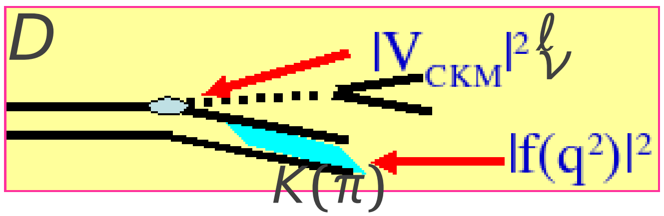


HPQCD [arXiv:0706.1726]
Fermilab/MILC [Phys. Rev. Lett. **95**, 122002 (2005)]
BaBar [Phys. Rev. Lett. **98**, 141801 (2007)]



Introduction : Semileptonic Decays

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

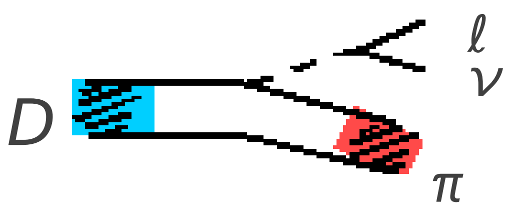


Experiment Theory (LQCD)

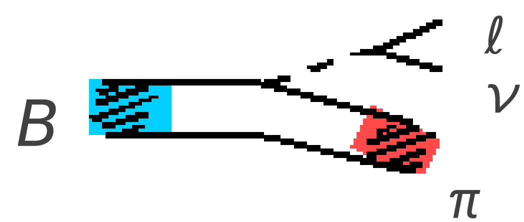
$$\frac{d\Gamma}{dq^2} \propto |V_{cs(d)}|^2 |f_+^{D\to K(\pi)}(q^2)|^2$$

  - 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 $\Rightarrow$

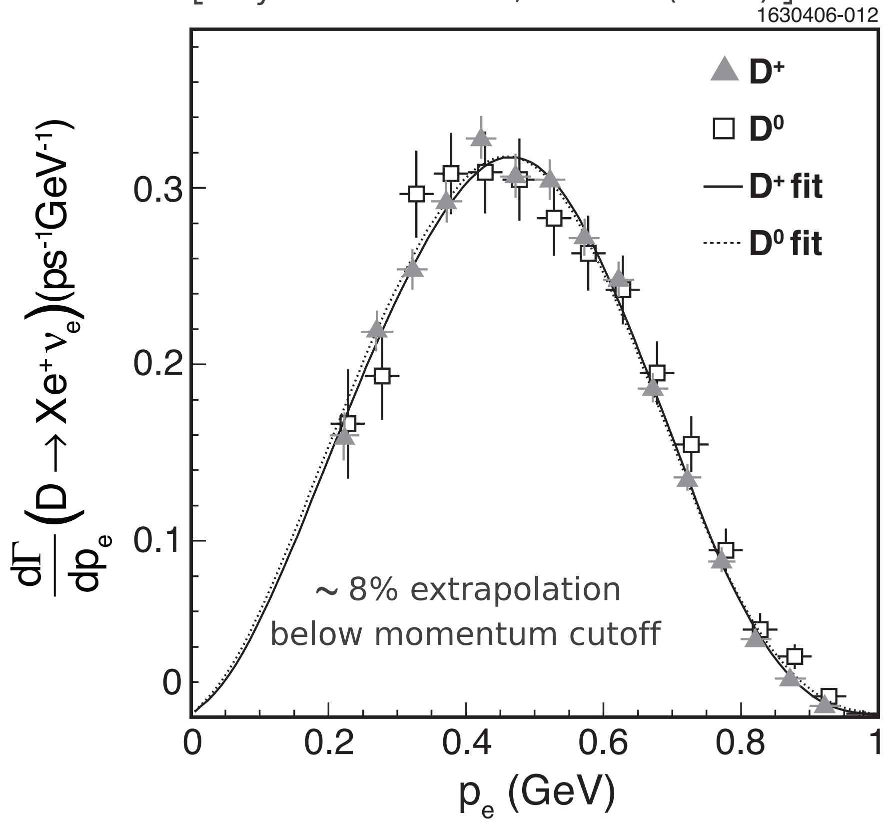


Inclusive *D* Semileptonic Decays

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

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

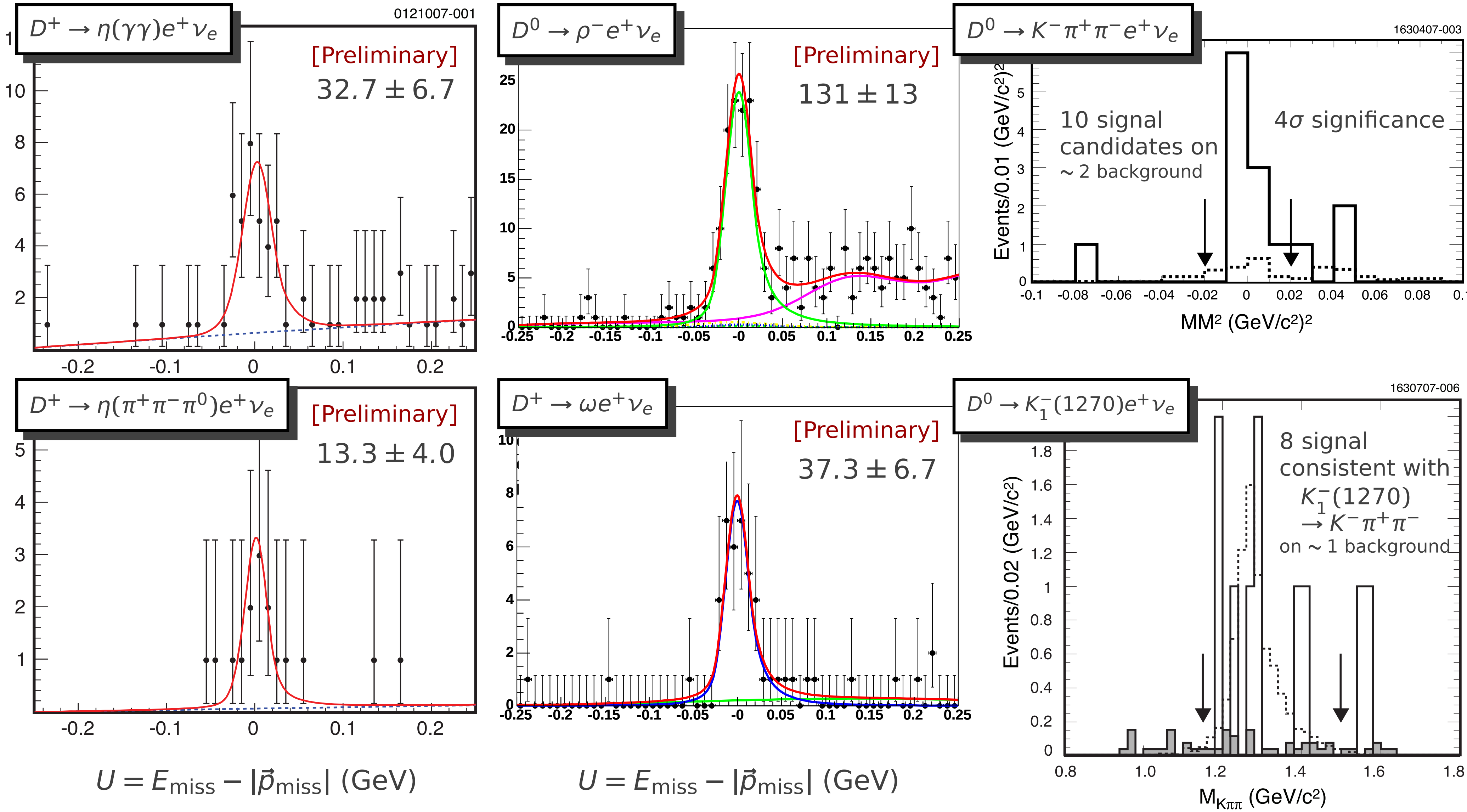


- Consistent with isospin symmetry : the lepton cannot interact strongly with the final-state hadrons and the two mesons differ only in the isospin of the light quark

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

First Observations

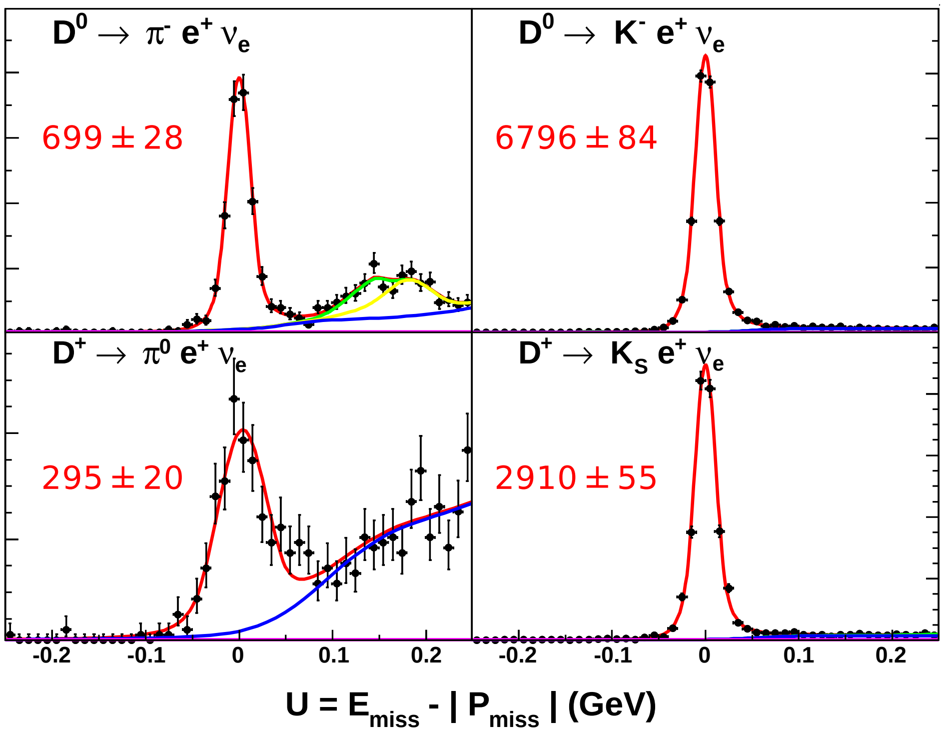
[Phys. Rev. Lett. **99**, 191801 (2007)]



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

(1) Tagged Analysis :

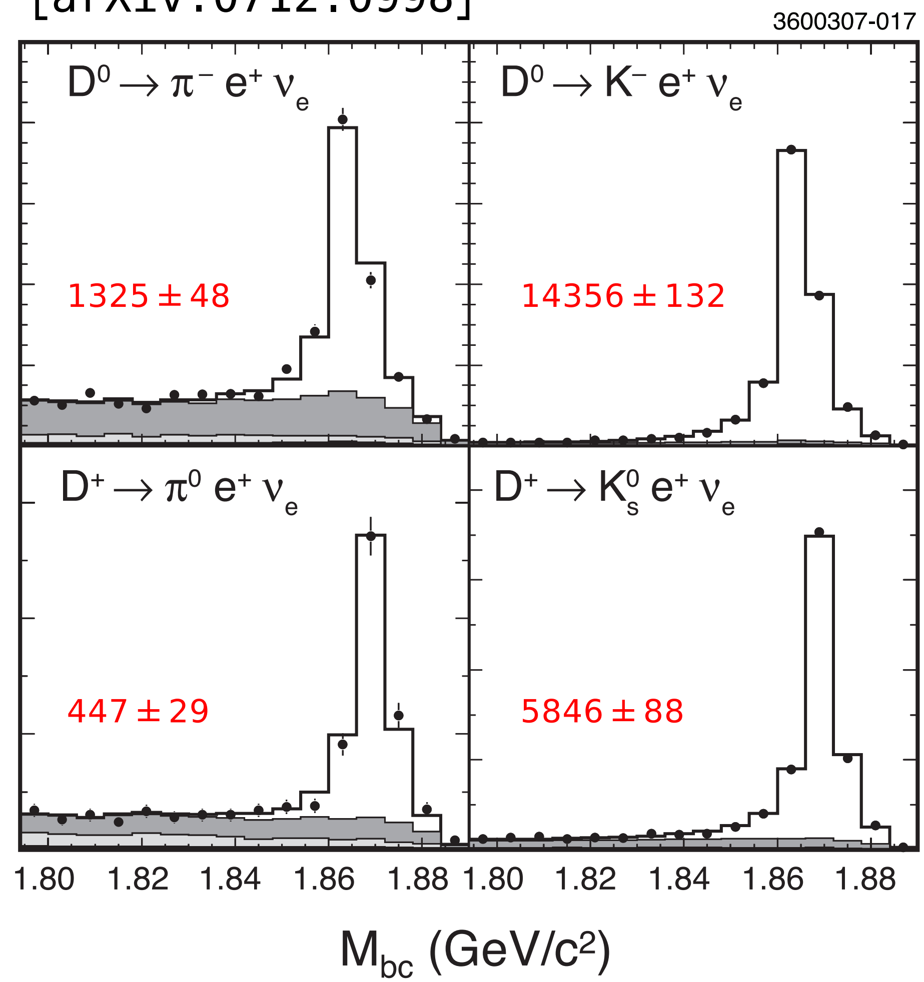
[Preliminary]



(2) Untagged Analysis :

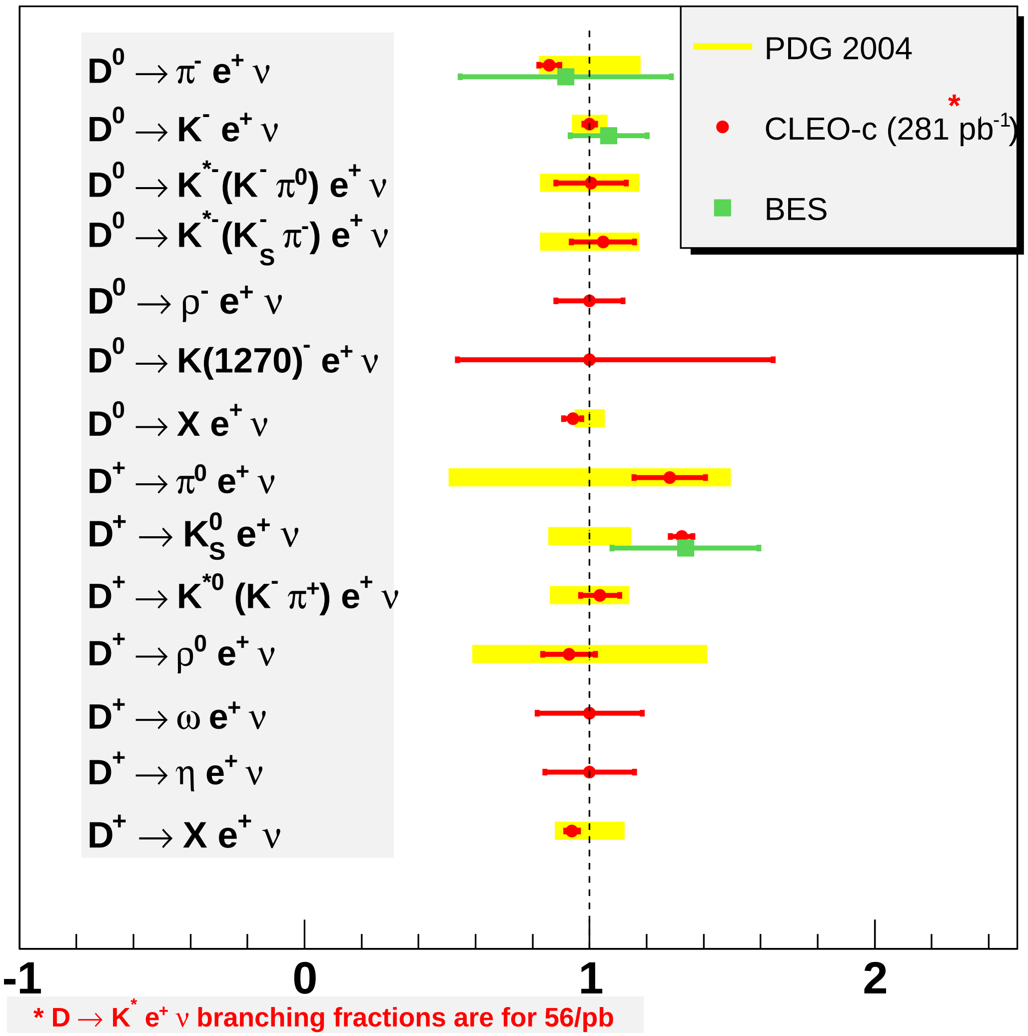
neutrino reconstruction

[arXiv:0712.0998]



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

Branching Fraction Summary

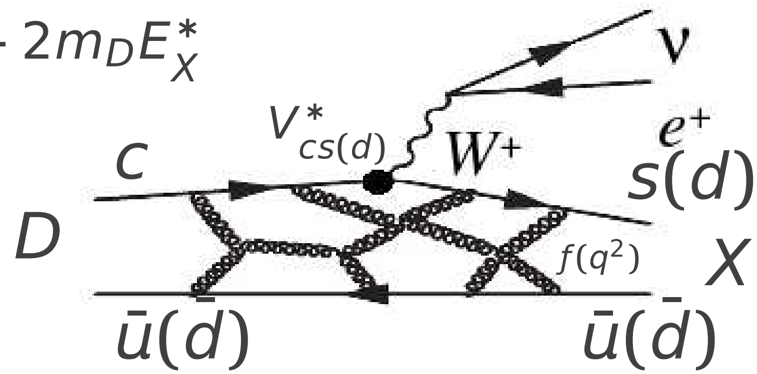


L (pb^{-1})		$B(D^0)_{SL}$ (%)	$B(D^+)_{SL}$ (%)
		$K^- e^+ \nu_e$	$\bar{K}^0 e^+ \nu_e$
281	tagged	$3.58 \pm 0.05 \pm 0.05$	$8.86 \pm 0.17 \pm 0.20$
281	ν-recon	$3.56 \pm 0.03 \pm 0.09$	$8.53 \pm 0.13 \pm 0.23$
		$K^*(892)^- e^+ \nu_e$	$\bar{K}^*(892)^0 e^+ \nu_e$
56		$2.16 \pm 0.15 \pm 0.08$	$5.56 \pm 0.27 \pm 0.23$
		$\pi^- e^+ \nu_e$	$\pi^0 e^+ \nu_e$
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	$0.076^{+0.041}_{-0.030} \pm 0.006 \pm 0.007$	
$\sum_{\text{exclusive}}$		$6.28 \pm 0.16_{\text{stat}}$	$15.33 \pm 0.42_{\text{stat}}$
		$X e^+ \nu_e$	$X e^+ \nu_e$
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 $Xe\nu$, $K_1^-(1270)e\nu$, 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

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

- Hadronic currents : in the limit $m_\ell \to 0$
  - $P \to P'\ell^+\nu_\ell$: 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 $\frac{d\Gamma(D\to Ke\nu_e)}{dq^2} = \frac{G_F^2 |V_{cs}|^2 p_K^3}{24\pi^3} |f_+(q^2)|^2$.
- 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 : $f_+(q^2) = \frac{f_+(0)}{1-\alpha} \frac{1}{1-q^2/m^2_{\rm pole}} + \sum_{k=1}^{N} \frac{\rho_k}{1-\frac{1}{\gamma_k}\frac{q^2}{m^2_{\rm pole}}}$
- Single pole : $f_+(q^2) = \frac{f_+(0)}{1-q^2/m^2_{\rm pole}}$
- Modified pole : $f_+(q^2) = \frac{f_+(0)}{(1-q^2/m^2_{\rm pole})(1-\alpha q^2/m^2_{\rm pole})}$

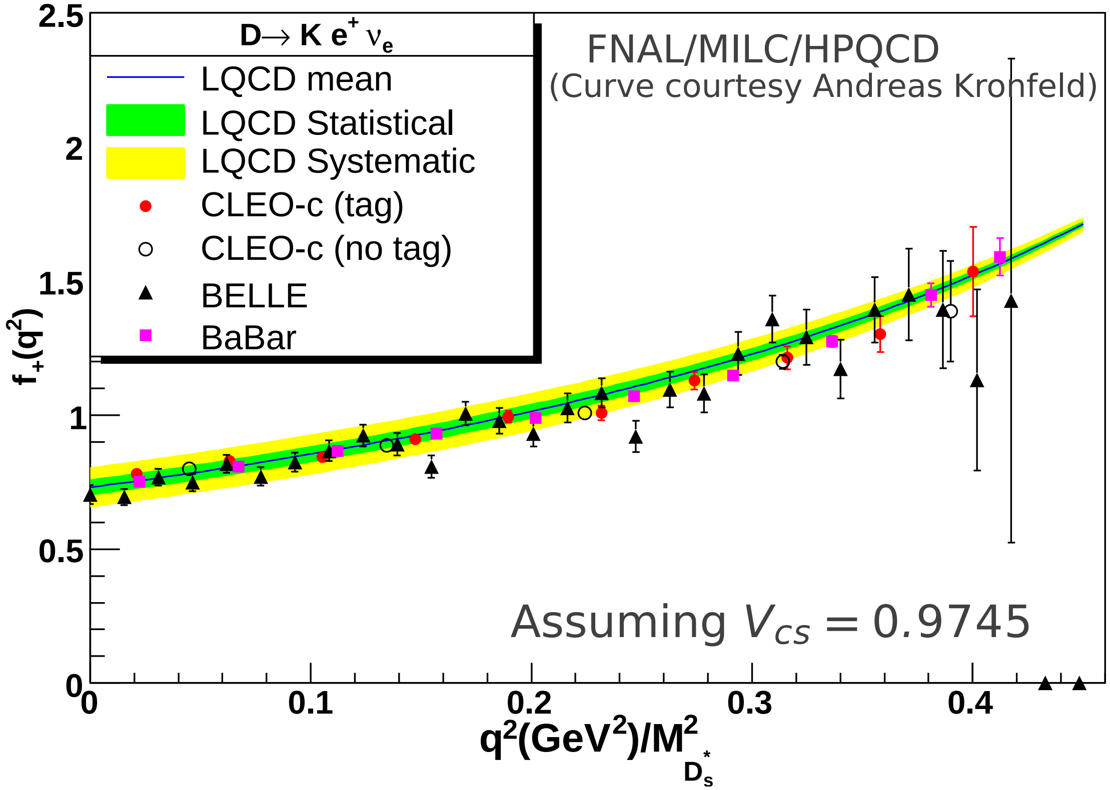
  (allows for additional poles).
- Series expansion : [T. Becher and R. J. Hill, Phys. Lett. B **633**, 61 (2006)]

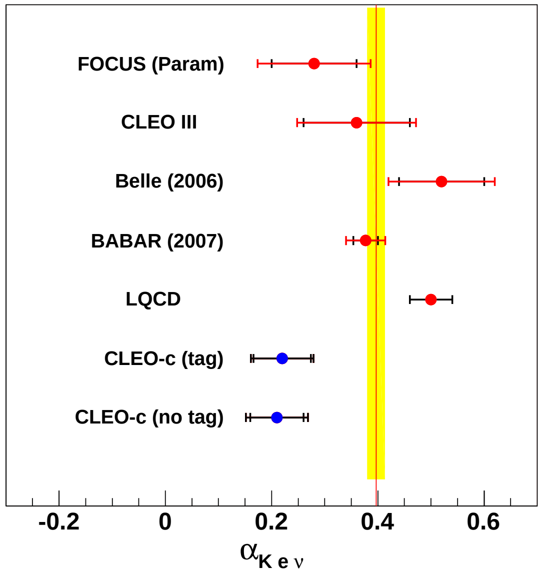
  $$f_+(q^2) = \frac{1}{P(q^2)\phi(q^2,t_0)} \sum_{k=0}^{\infty} \alpha_k(t_0)[z(q^2,t_0)]^k,$$

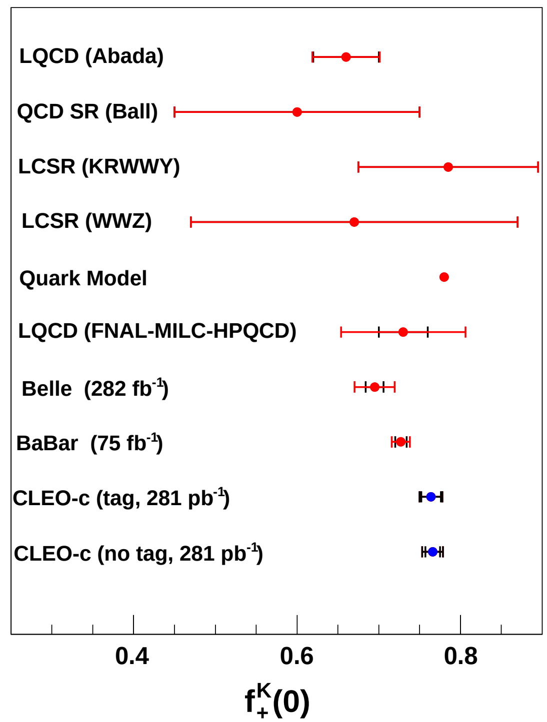
  with $z(q^2,t_0) = \frac{\sqrt{t_+-q^2}-\sqrt{t_+-t_0}}{\sqrt{t_+-q^2}+\sqrt{t_+-t_0}}$, $t_\pm \equiv (M_D \pm m_P)^2$, and $P(q^2) \equiv 1$ $(D\to\pi)$ or $z(q^2, M^2_{D_s^*})$ $(D \to K)$.

  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.

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



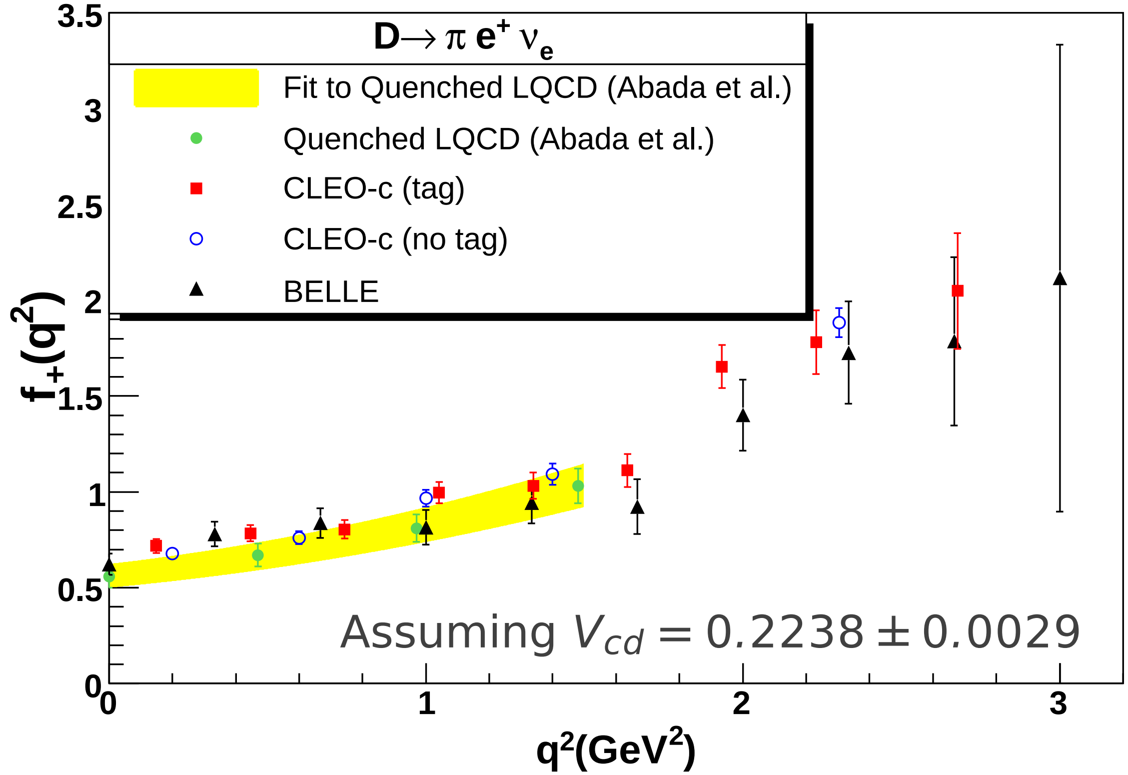


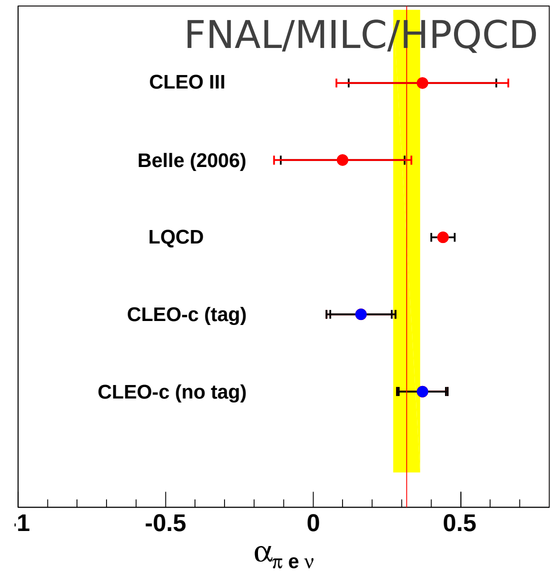


- Modified pole model used for comparison :
  $$f_+(q^2) = \frac{f_+(0)}{(1-q^2/m^2_{\text{pole}})(1-\alpha q^2/m^2_{\text{pole}})}$$
- Shape parameter: CLEO-c prefers smaller value
- Normalization:
  experiment (2%) consistent with LQCD (10%)

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

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

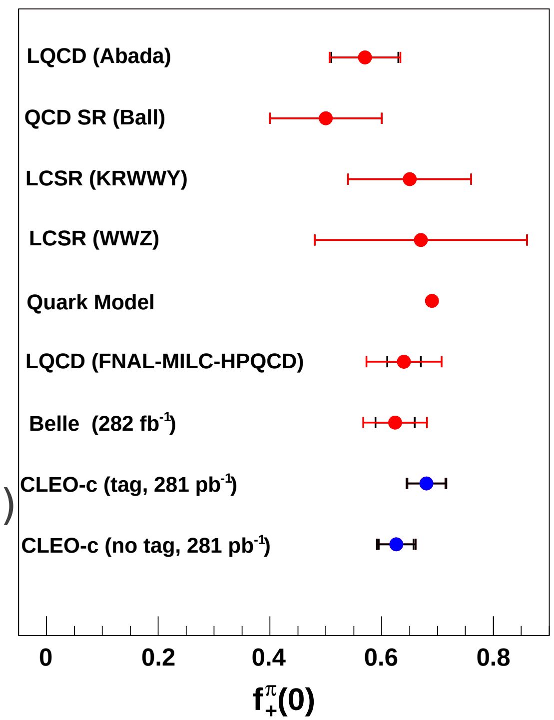




- Modified pole model used for comparison :

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

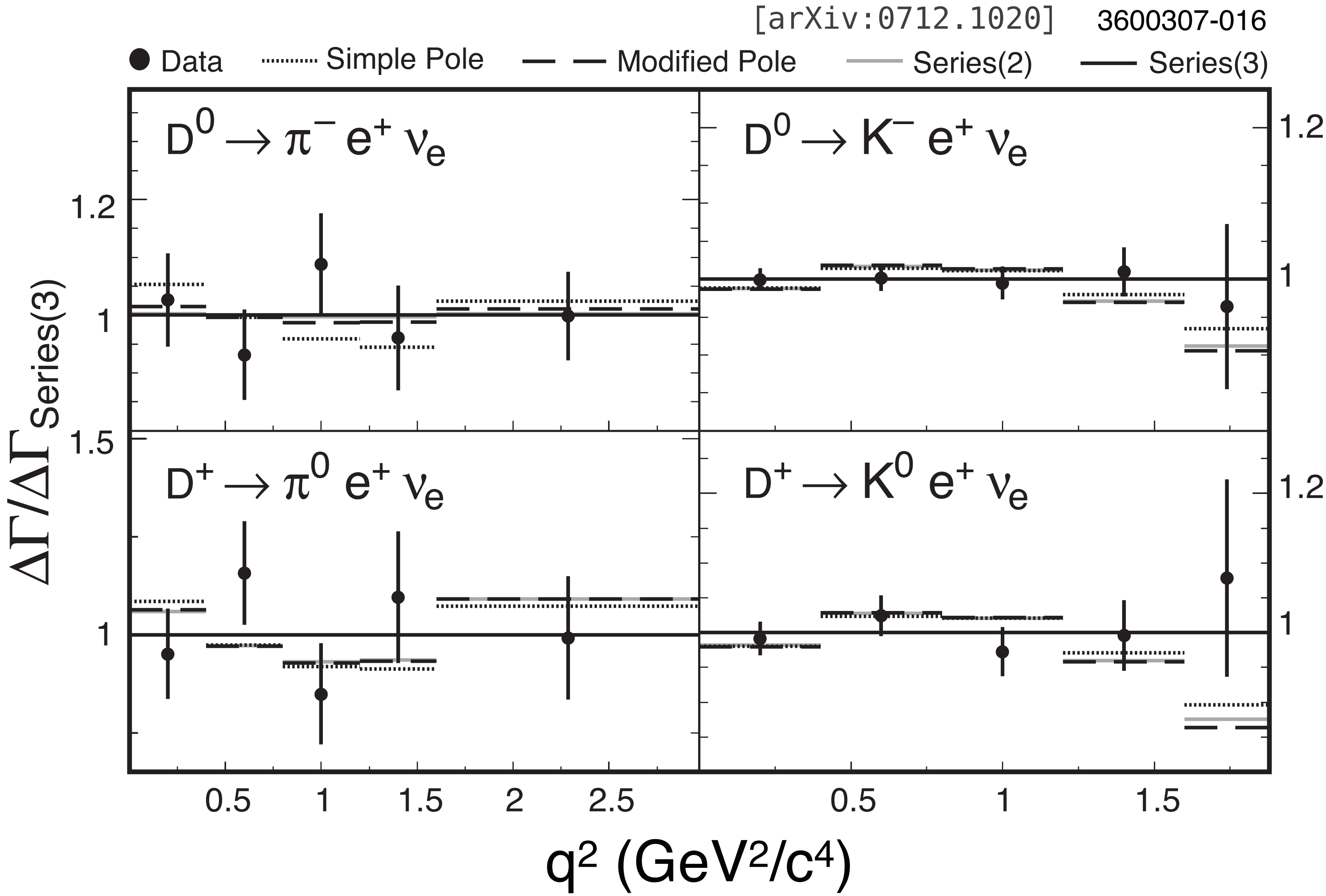
- Shape parameter: experiments compatible with LQCD
- Normalization: experiment (4%) consistent with LQCD (10%)



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

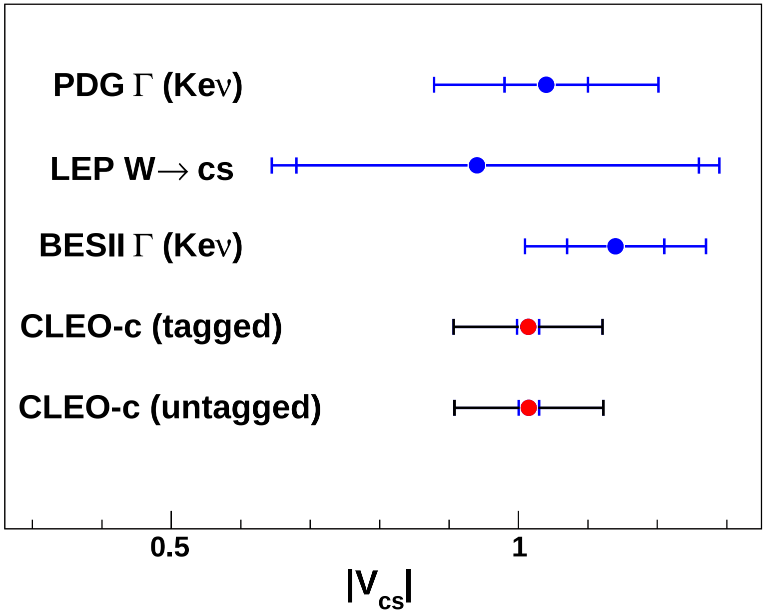
Form Factor : $D \to Pe\nu$ which parametrization?

[arXiv:0712.1020]



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

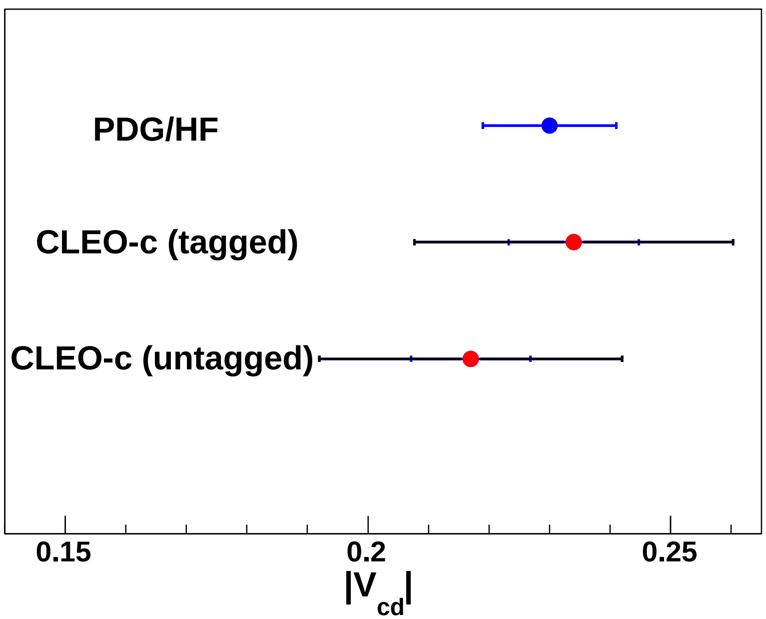
$|V_{cs}|$ & $|V_{cd}|$ Results



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)	$1.014 \pm 0.013 \pm 0.009 \pm 0.106$
(untagged)	$1.015 \pm 0.010 \pm 0.011 \pm 0.106$
	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)	$0.234 \pm 0.010 \pm 0.004 \pm 0.024$
(untagged)	$0.217 \pm 0.009 \pm 0.004 \pm 0.023$
	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.
  - $B(D_s^+ \to \tau^+\nu_\tau)/B(D_s^+ \to \mu^+\nu_\mu)$ 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.
  - $D \to Ke\nu$, $\pi e\nu$ 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 $D \to K(\pi)e^+\nu_e$ form factor $f_+(0)$ & shape.