Semileptonic and Leptonic D^0, D^+, and D_s^+ Decays at CLEO-c

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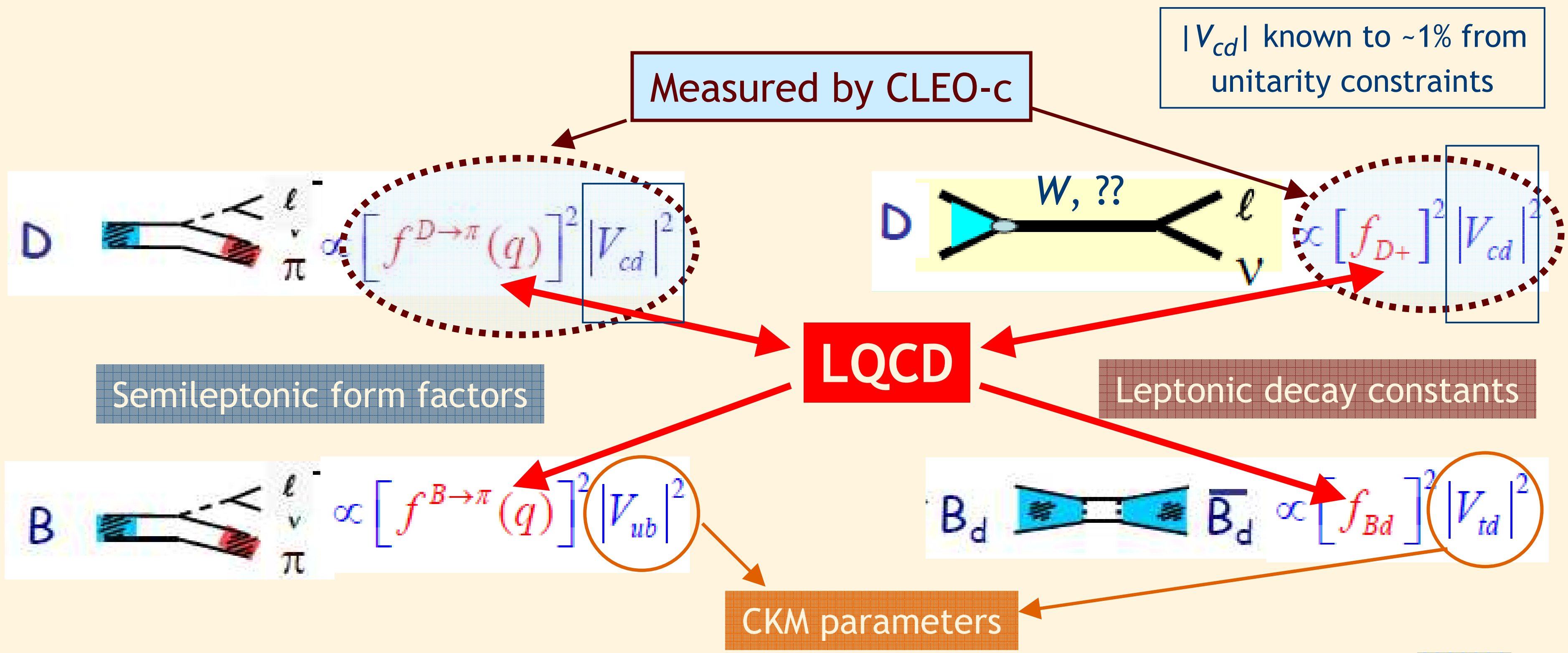
(Semi)leptonic decays, LQCD, and CKM
CLEO-c detector and dataset
CLEO-c results for:

$D \to \{K, \pi\} e^+\nu$ $\qquad D_s^+ \to X e^+\nu$

$D^+ \to \mu^+\nu$ $\qquad D_s^+ \to \{\mu^+, \tau^+\}\nu$

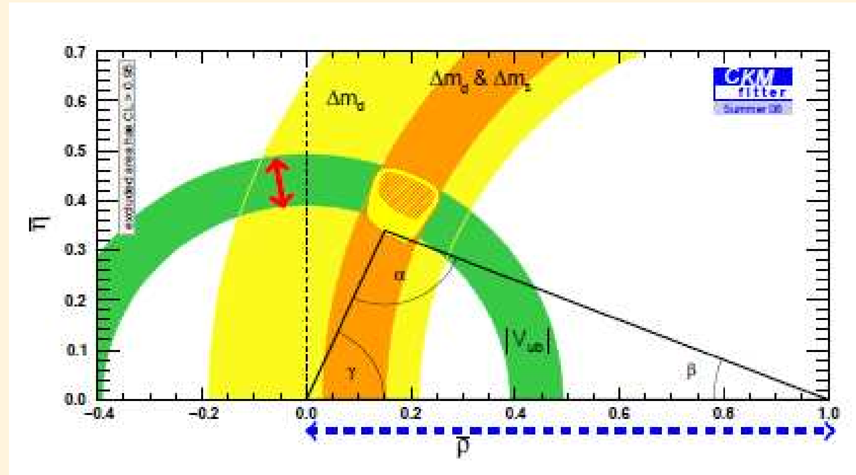
(Semi)leptonic Decays and QCD

- Charm semileptonic and leptonic decays probe non-perturbative QCD.
  - Measured form factors and decay constants ↔ Lattice QCD (LQCD) calculations.
  - Validation of LQCD in charm carries over to the *B* system.
  - If LQCD is correct, then comparison with experiment sensitive to new particles.

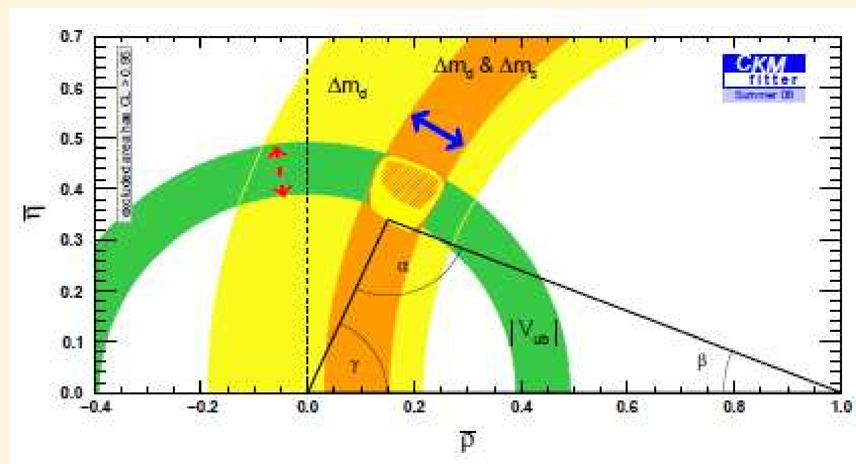


Impact on CKM Unitarity Triangle

- Validating LQCD in *B* system reduces theoretical uncertainty in CKM constraints.
  - Semileptonic form factors affect:
    - $|V_{ub}|$ from $b \to u l^- \nu$
    - $|V_{cd}V_{cb}^*|$: direct determination of $|V_{cd}|$

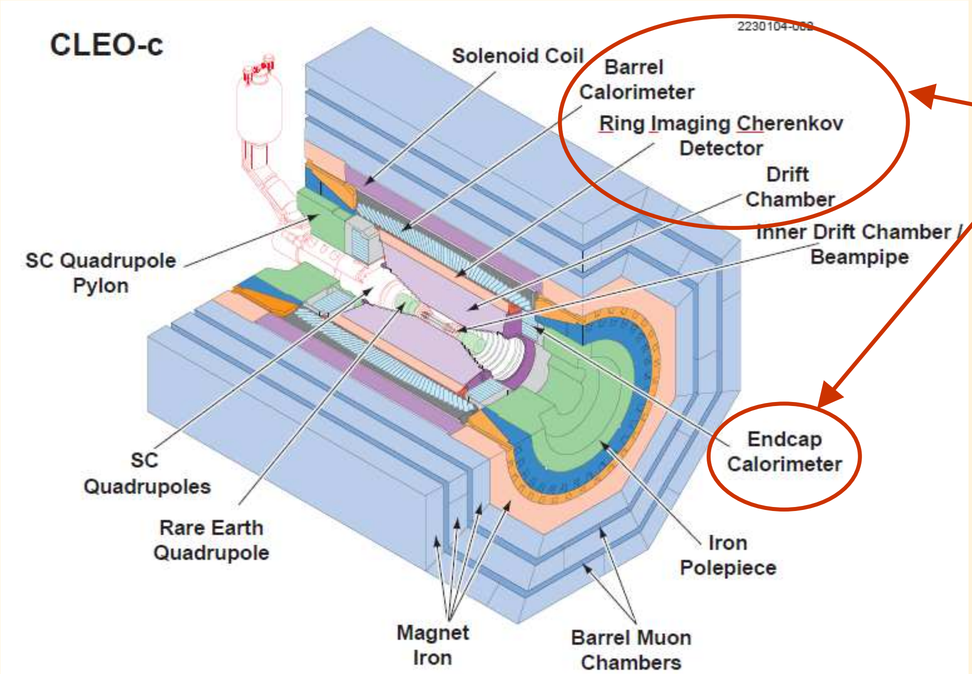


  - Leptonic decay constants affect:
    - $|V_{ub}|$ from $B^+ \to l^+ \nu$
    - $|V_{td}|$ from Δm_d in B^0 mixing
    - $|V_{ts}|$ from Δm_s in B_s mixing



CLEO-c Detector and Datasets

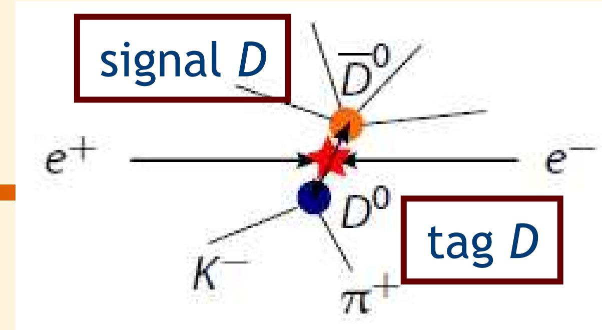
- CLEO-c detector is same as CLEO-III but with low-mass inner drift chamber and weaker magnetic field (1.0 T).



- Used for electron ID
  - E(calorimeter)/p(track)
  - dE/dx in drift chamber
  - RICH info
- Muons not explicitly identified.
  - Veto tracks with associated calorimeter deposits.
  - Veto identified kaons.

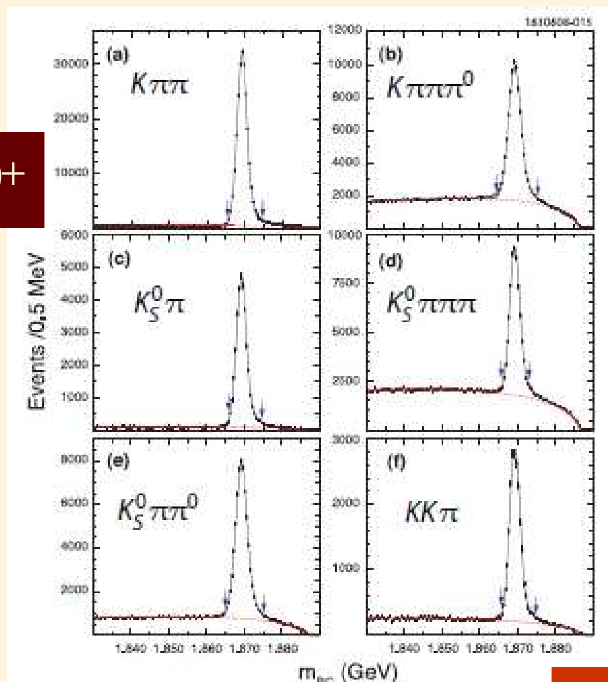
- Results shown here based on two datasets collected Oct. 2003 to Mar. 2008:
  - E_{cm} near 3770 MeV, on $\psi(3770)$: 818 pb^{-1} = 3.0M $D^0\overline{D}^0$ events, 2.4M D^+D^- events.
  - E_{cm} near 4170 MeV: 600 pb^{-1} = 5.8M $D_s^{*+}D_s^-$ events.
  - Data samples of unique quality and size.

D Tagging Technique



- Technique for most results presented today:
  - D's are pair produced; identify one D and study other D in the event.
- $e^+e^- \to \psi(3770) \to D\overline{D}$ produced at threshold, no extra particles.
  - 10-15% of all D^0/D^+ are fully reconstructed in clean modes.
- At 4170 MeV, $e^+e^- \to D_s^{*+}D_s^-$ produces extra γ or π^0 from D_s^{*+} decay.
  - 6% of all D_s^- are fully reconstructed in clean modes.

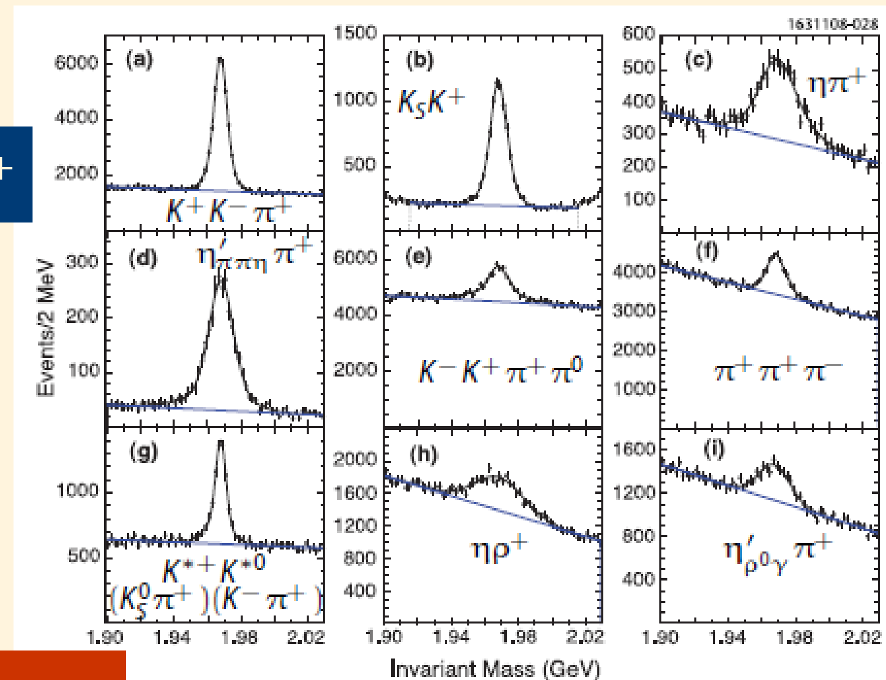
D^+



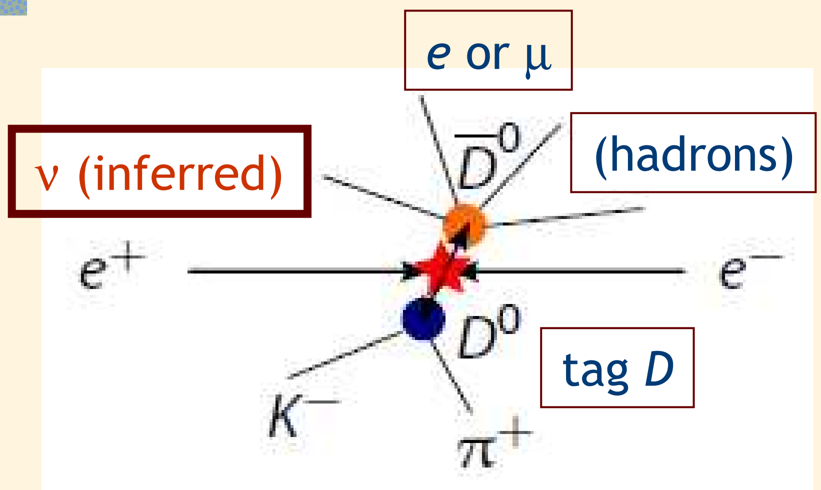
$$m_{BC} \equiv \sqrt{E_{beam}^2 - \vec{p}_D^{\,2}}$$

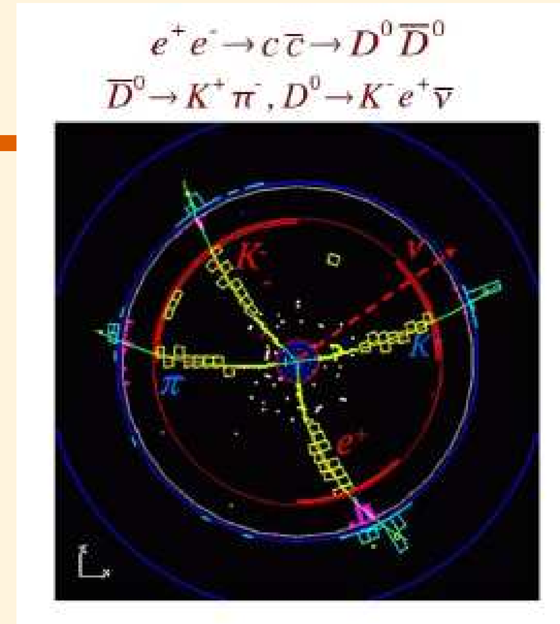
D^0 not shown

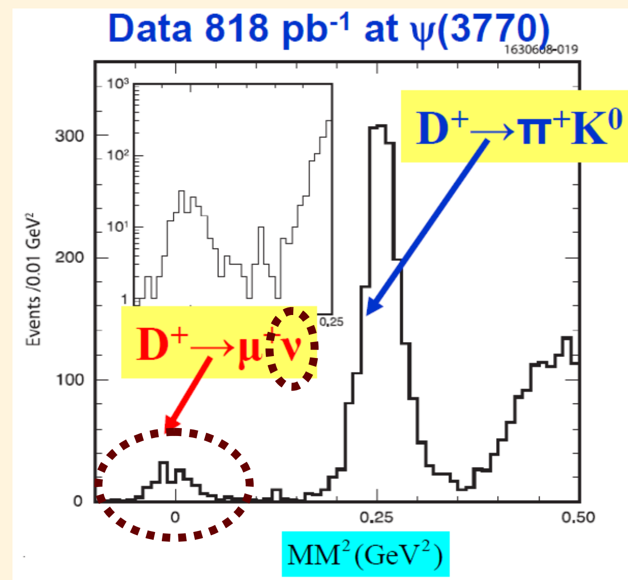
D_s^+



Detection of Neutrinos







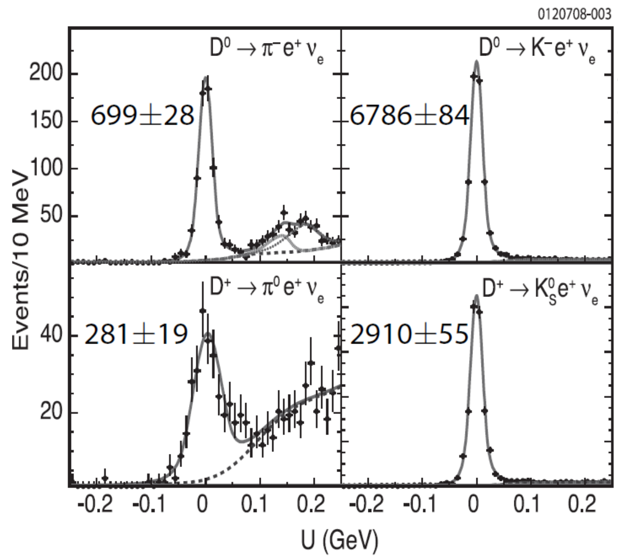
- Combine:
  - Knowledge of e^+e^- beam parameters (initial state)
  - Fully reconstructed *D* tag
  - Lepton candidate
  - [Hadron candidates from SL decay]
- Compute missing energy and missing momentum.
  - Require invariant mass consistent with zero = $m(\nu)$
  - Very clean signals!
- *Absolute* branching fractions from $N(\nu)/N(\text{tag})$.

Semileptonic Results

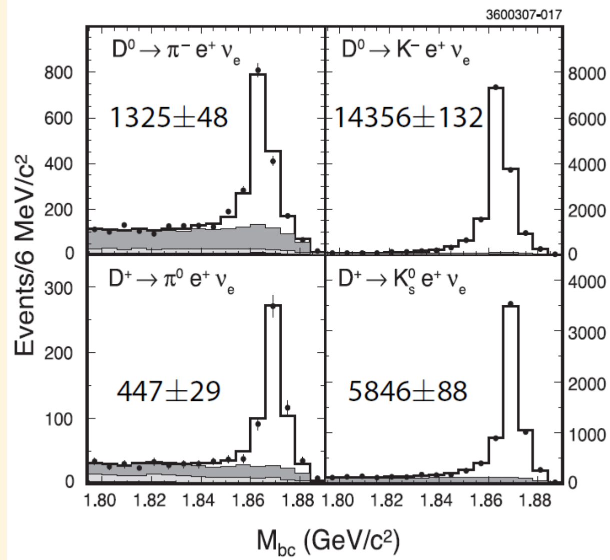
D^0 and D^+ Semileptonic (SL) Decays

- Two combined analyses using 281 pb^{-1} at 3770 MeV (one-third of full dataset)

Tagged
(arXiv:0810.3878, accepted by PRD)



Untagged
(PRL 100, 251802 (2008))



tag mode $\leftarrow \bar{D}$ $D \rightarrow \{K^-, \pi^-, K^0, \pi^0\}\ e^+\nu$

- Higher purity, lower efficiency.

generic $\leftarrow \bar{D}$ $D \rightarrow \{K^-, \pi^-, K^0, \pi^0\}\ e^+\nu$

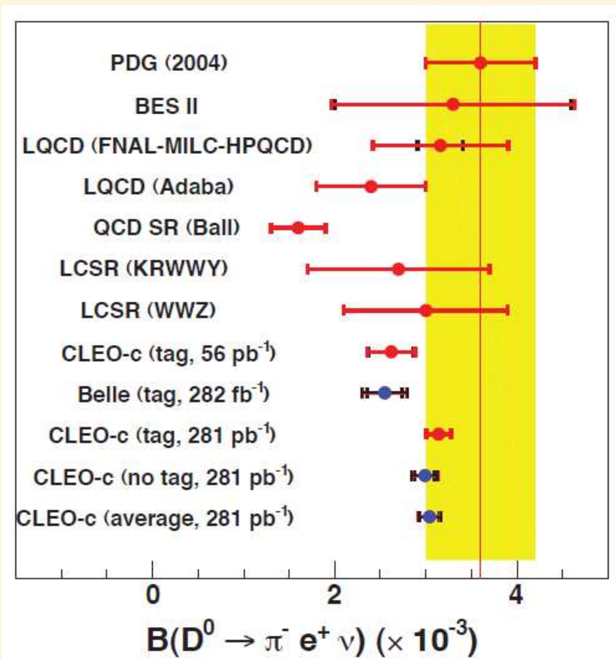
- No tag requirement, use detector hermeticity to infer ν 4-momentum.
- Lower purity, higher efficiency.

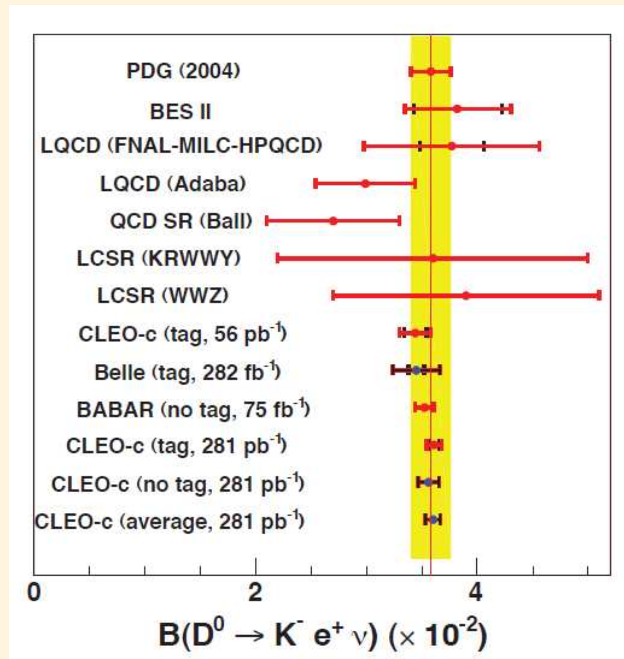
- Sample overlap accounted for in averages.
- Tagged analysis with full dataset in progress.

D^0/D^+ SL: Branching Fractions

- Absolute branching fractions (%):

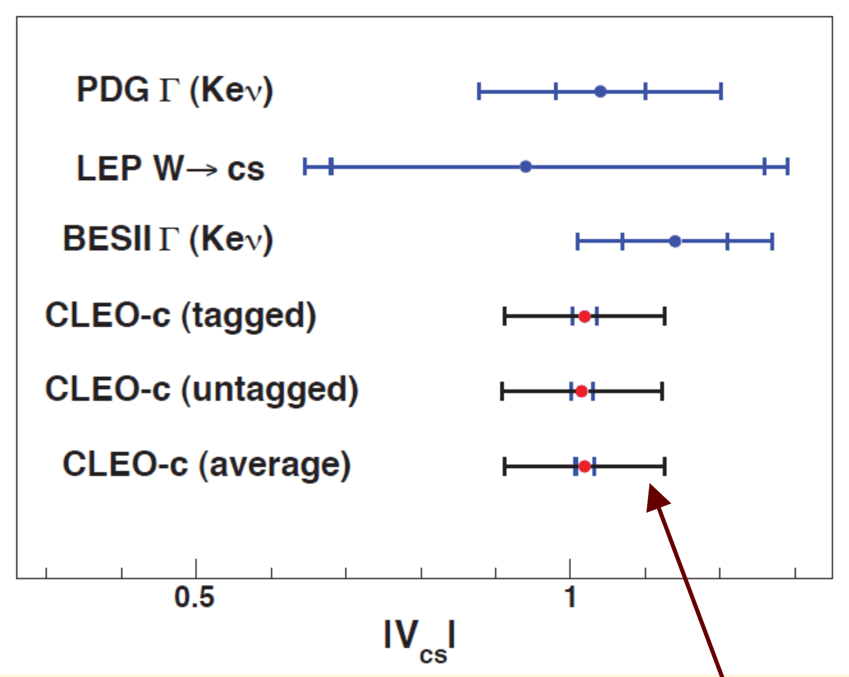
	Tagged	Untagged	Average
$\pi^- e^+ \nu_e$	0.308(13)(4)	0.299(11)(8)	0.304(11)(5)
$\pi^0 e^+ \nu_e$	0.379(27)(23)	0.373(22)(13)	0.378(20)(12)
$K^- e^+ \nu_e$	3.60(5)(5)	3.56(3)(9)	3.60(3)(6)
$\bar{K}^0 e^+ \nu_e$	8.87(17)(21)	8.53(13)(23)	8.69(12)(19)

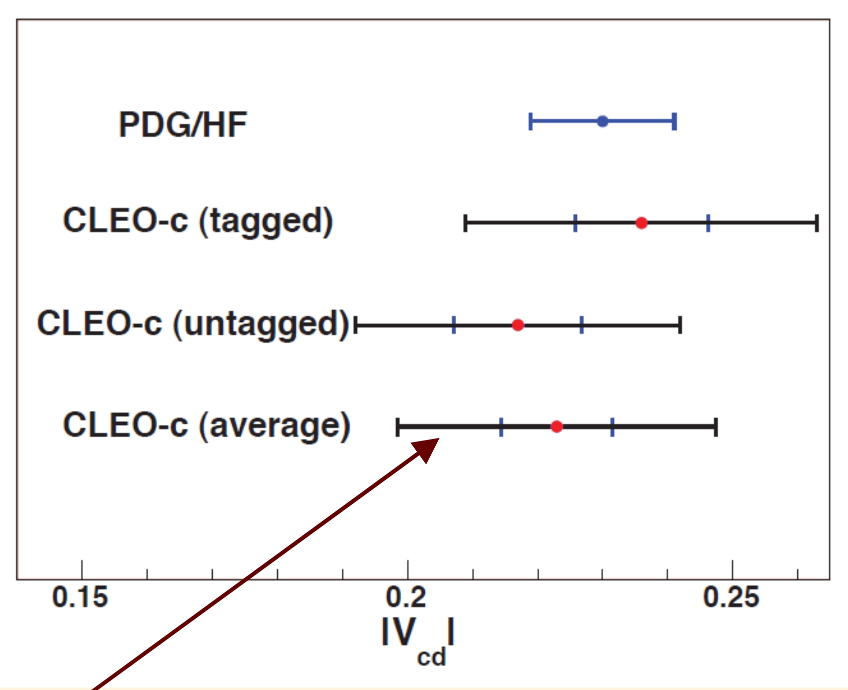




D^0/D^+ SL: V_{cs} and V_{cd}

- Direct determination of $|V_{cs}|$ and $|V_{cd}|$ using $f(0)$ from LQCD [PRL 100, 062002 (2008)].





Theory uncertainty

D^0/D^+ SL: Form Factors

- Form factor parametrizations:
  - Simple pole: $\alpha = 0$
  - Modified pole: $\alpha > 0$
    - Fits prefer unphysical pole masses.

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{M^2_{pole}}\right)\left(1 - \alpha\frac{q^2}{M^2_{pole}}\right)}$$

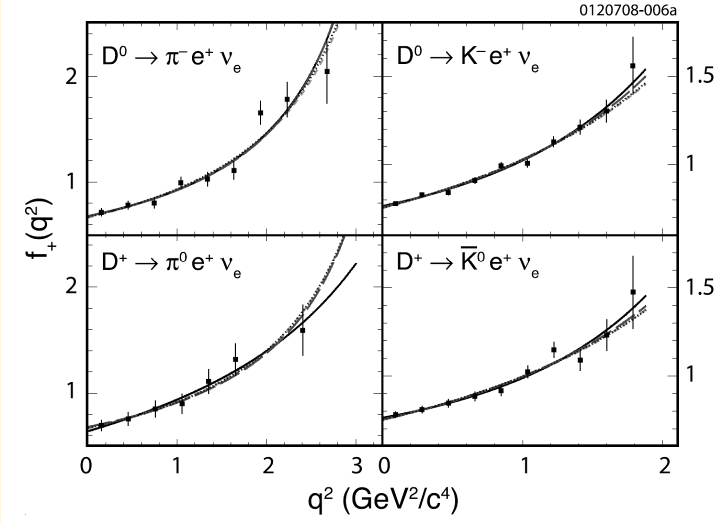
  - Series expansion:
    - Motivated by dispersion relation.
    - Considered 2- and 3- parameter fits.

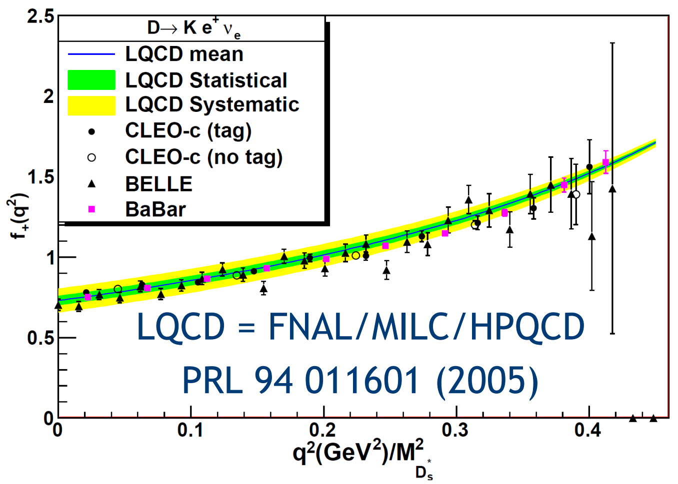
$$f_+(q^2) = \frac{a_0}{P(q^2)\phi(q^2,t_0)}\left(1 + \sum_{k=1}^{\infty} a_k(t_0)z(q^2,t^0)^k\right)$$

$$z(q^2,t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}},$$

$$t_\pm = \left(M_D \pm M_{K(\pi)}\right)^2,$$

- Fit results: all four fits displayed.





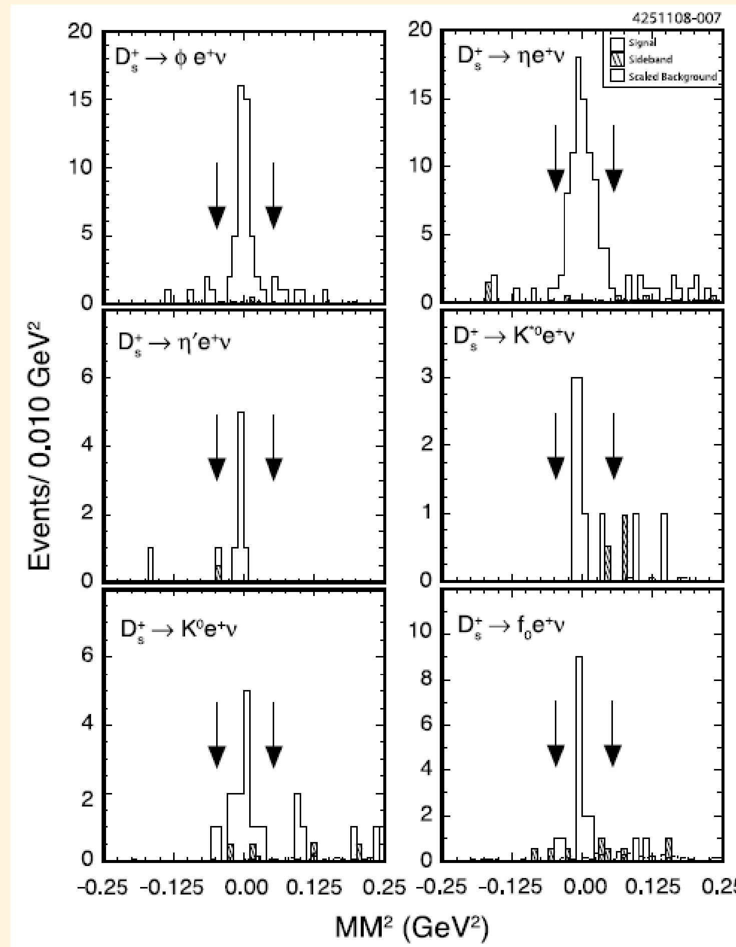
D_s^+ Semileptonic Decays

tag mode $\leftarrow D_s^-$ $D_s^+ \rightarrow Xe^+\nu$

- 310 pb^{-1} at 4170 MeV [arXiv:0903.0601]
  - Half of full dataset, tagging technique
  - First measurements of absolute branching fractions.
  - First observation of
    - Cabibbo-suppressed modes
    - $f_0(980)$ mode
  - Ratio of η to η' sensitive to mixing angle.

$D_s^+ \rightarrow Xe^+\nu$:

X	$\mathcal{B}(\%)$
ϕ	$2.29 \pm 0.37 \pm 0.11$
η	$2.48 \pm 0.29 \pm 0.13$
η'	$0.91 \pm 0.33 \pm 0.05$
K^0	$0.37 \pm 0.10 \pm 0.02$
K^{*0}	$0.18 \pm 0.07 \pm 0.01$
$f_0 \rightarrow \pi^+\pi^-$	$0.13 \pm 0.04 \pm 0.01$

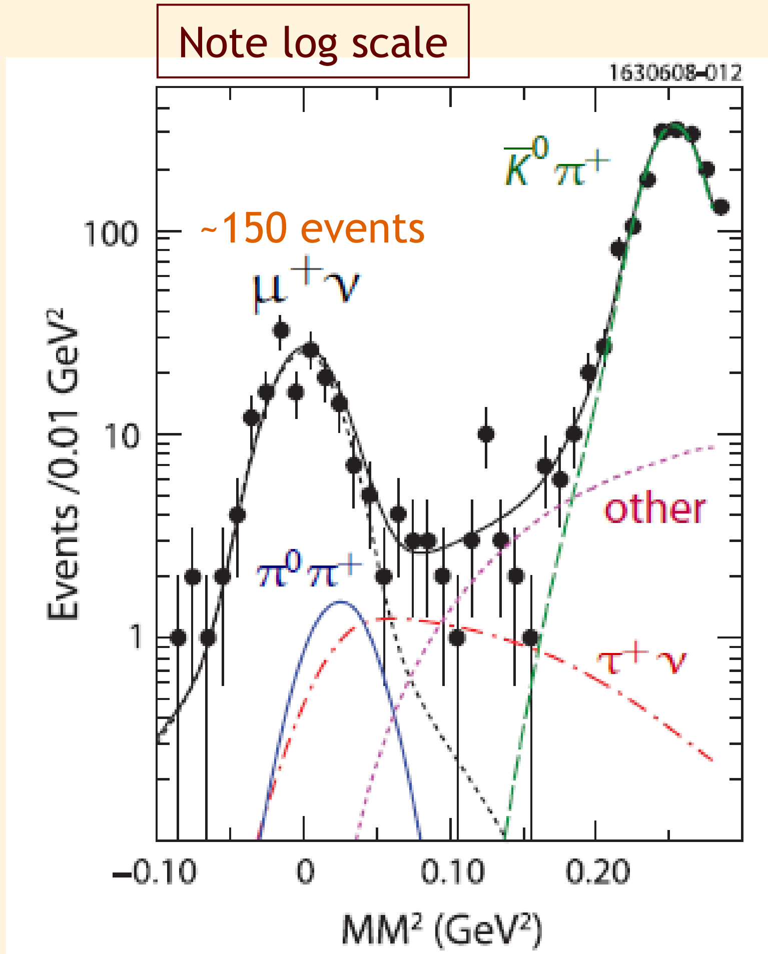


Leptonic Results

$D^+ \to \mu^+\nu$

tag mode $\leftarrow D^- \; D^+ \rightarrow \mu^+\nu$

- Cabibbo- and helicity-suppressed.
- 818 pb^{-1} at 3770 MeV
  - Combine D^- tag with μ^+ candidate.
  - Veto extra tracks and calorimeter energy deposits.
  - Compute missing mass distribution.
    - Recoil against D^- tag and μ^+.
  - Fit results [PRD 78 052003 (2008)]:
    - $B(D^+ \to \mu^+\nu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$,
    - $f_{D+} = (\, 205.8 \pm 8.5 \pm 2.5\,)$ MeV
    - Unique measurement.
  - Good agreement with LQCD [PRL 100, 062002 (2008)]
    - $f_{D+} = (\, 207 \pm 4\,)$ MeV



$D_s^+ \to \{\mu^+, \tau^+\}\nu$

- Cabibbo-favored, less helicity suppression (τ).
- Two combined analyses, 600 pb^{-1} at 4170 MeV:

tag mode $\longleftarrow D_s^-$ $D_s^+ \longrightarrow$ $\tau^+\nu$

$\tau^+ \to e^+\nu\bar{\nu}$

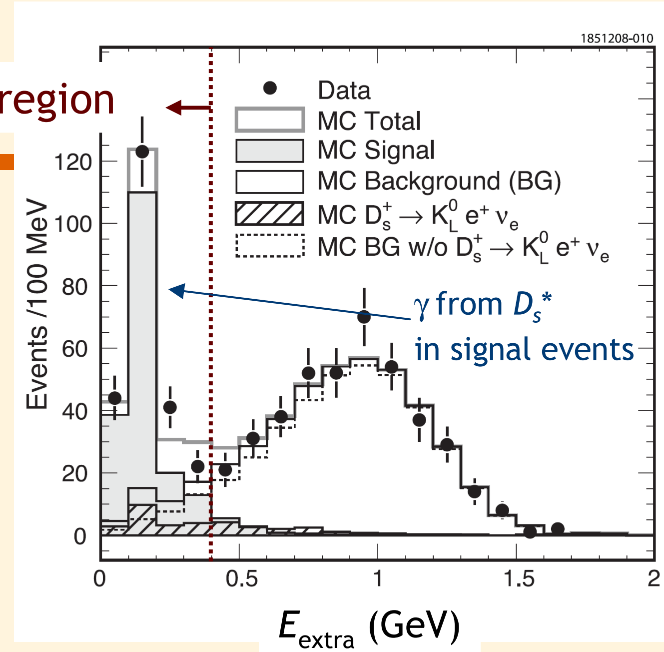
  - Combine D_s tag with electron candidate.
  - Veto extra tracks.
  - Study extra calorimeter energy in event.

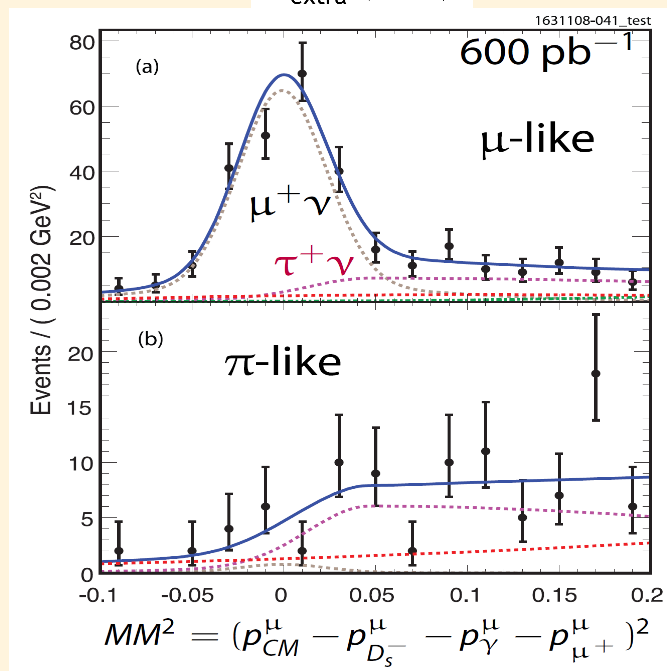
$\mu^+\nu$

tag mode $\longleftarrow D_s^-$ $D_s^+ \longrightarrow$ $\tau^+\nu$

$\tau^+ \to \pi^+\bar{\nu}$

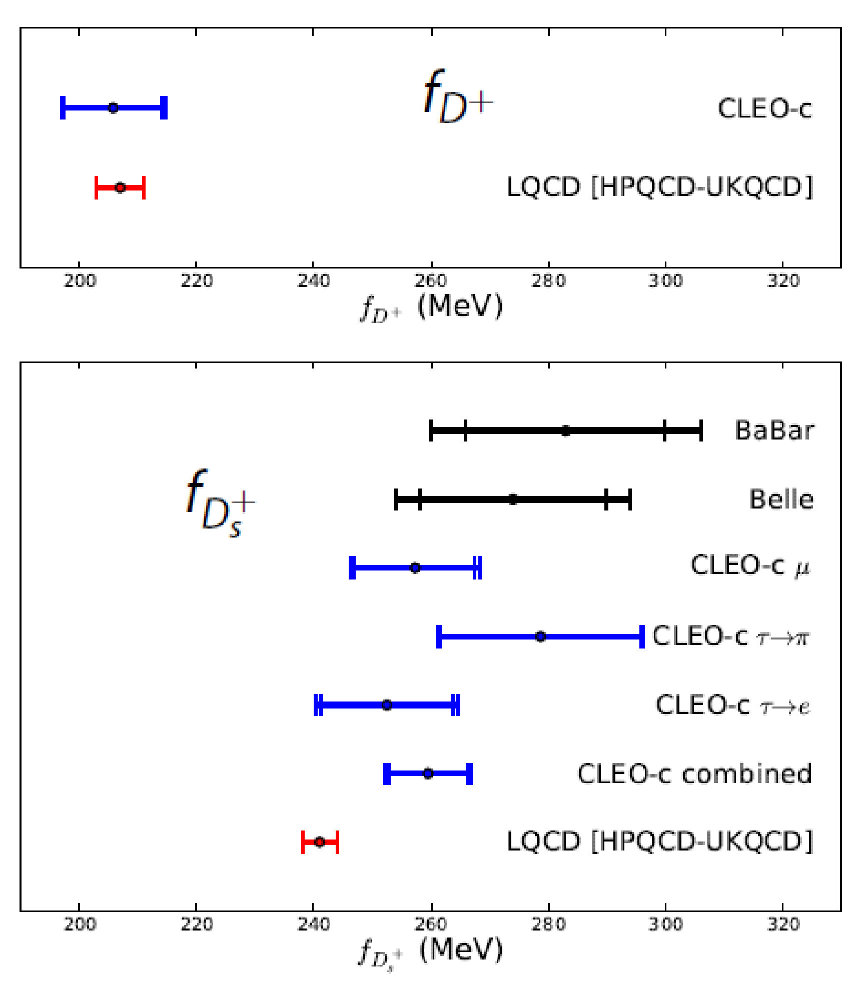
  - Combine D_s tag with track and γ from D_s^*.
  - Veto extra tracks and calorimeter energy.
  - Sort events by energy matched to track:
    - E < 300 MeV μ-like / E > 300 MeV π-like





$D_s^+ \to \{\mu^+, \tau^+\}\nu$ Results

- Branching fractions:
  - $B(D_s^+ \to \tau^+\nu)$ from $\tau^+ \to e^+\nu\bar{\nu}$ = (5.30 ± 0.47 ± 0.22)%
    - PRD 79, 052022 (2009)
  - $B(D_s^+ \to \tau^+\nu)$ from $\tau^+ \to \pi^+\bar{\nu}$ = (6.42 ± 0.81 ± 0.18)%
  - $B(D_s^+ \to \mu^+\nu)$ = (5.65 ± 0.45 ± 0.17) x 10^{-3}
    - PRD 79, 052009 (2009)
- Average decay constant:
  - f_{Ds+} = (259.5 ± 6.6 ± 3.1) MeV
- 2.3σ higher than LQCD [PRL 100, 062002 (2008)]:
  - f_{Ds+} = (241 ± 3) MeV
- Decay constant ratio f_{Ds} / f_{D+}:
  - CLEO-c: 1.26 ± 0.06 ± 0.02
  - LQCD: 1.164 ± 0.011

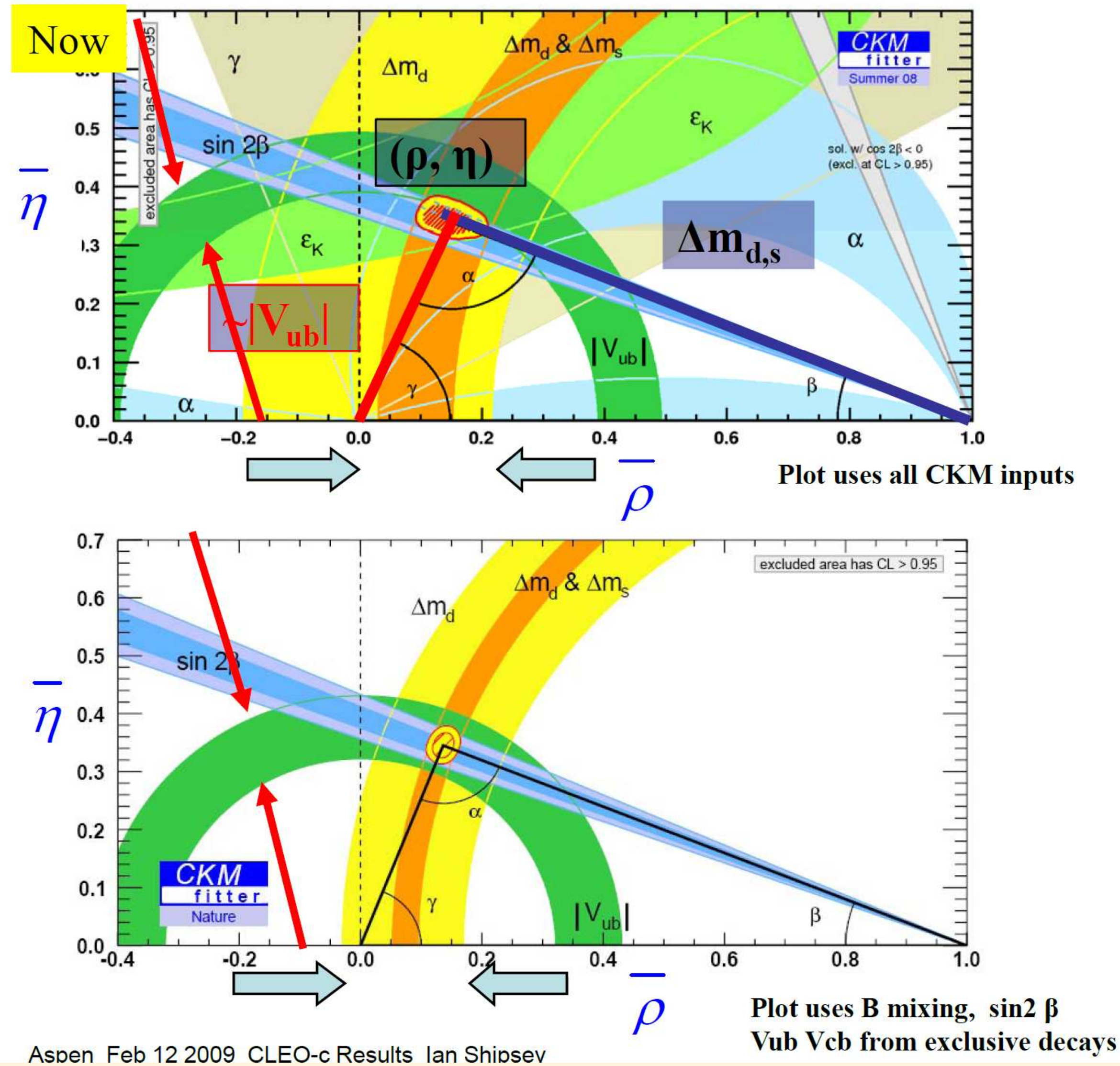


Summary

- Charm threshold and CLEO-c:
  - Clean environment and kinematic constraints.
  - Superb detector and large sample size.
  - $\Rightarrow$ Unique opportunities to study non-perturbative QCD.
- Theory and experiment are both making great strides in precision.
  - Uncertainties of a few percent.
  - Allows for stringent test of LQCD.
  - Important if LHC discovers strongly-coupled new physics.
- More to come from CLEO-c and BES-III!

BACKUP SLIDES

Theoretical Errors in CKM Constraints



Theoretical errors dominate width of bands

Few % precision QCD Calculations tested with few % *precision* charm data
➔theory errors of a few % on B system decay constants & semileptonic form factors

I. Shipsey

$D \to \{K, \pi\} e^+\nu$ Pole Models

- Simple pole model

	M^K_{pole} GeV/c^2
Mark III [42]	$1.80^{+0.50}_{-0.20}(25)$
E691 [43]	$2.10^{+0.40}_{-0.20}(20)$
CLEO [44]	$2.10^{+0.40}_{-0.20}(25)$
CLEOII [45]	2.00(12)(18)
E687 (Tag) [46]	$1.97^{+0.43}_{-0.22}(7)$
E687 (Incl) [46]	$1.87^{+0.11}_{-0.08}(7)$
CLEO [11]	$1.89(5)^{+0.04}_{-0.03}$
FOCUS [12]	1.93(5)(3)
Belle [13]	1.82(4)(3)
BABAR [9]	1.884(12)(15)
CLEO-c (tagged)	1.97(3)(1)
CLEO-c (untagged) [3]	1.97(3)(1)

  - $M(D_s^{*+})$ = 2112.0 ± 0.6 MeV

	M^π_{pole} GeV/c^2
CLEO (2004) [11]	$1.86^{+0.10}_{-0.06}(5)$
FOCUS (2004 [12])	$1.91^{+0.30}_{-0.15}(7)$
Belle (2006) [13]	1.97(8)(4)
CLEO-c (tagged)	1.95(4)(2)
CLEO-c (untagged) [3]	1.87(3)(1)

  - $M(D^{*+})$ = 2010.0 ± 0.4 MeV

- Modified pole model

	α^K	α^π
FOCUS [12]	0.28(8)(7)	–
CLEO III [11]	0.36(10)(5)	0.37(25)(15)
Belle [13]	0.52(8)(6)	0.10(21)(10)
BABAR [9]	0.377(23)(29)	–
LQCD [23]	0.50(4)	0.44(4)
LCSR [18]	$0.07^{+0.15}_{-0.07}$	$0.01^{+0.11}_{-0.07}$
CQM [47]	0.24	0.30
CLEO-c (tagged)	0.21(5)(2)	0.16(10)(5)
CLEO-c (untagged) [3]	0.21(5)(3)	0.37(8)(3)

  - Expect α ~ 1.75