Leptonic and Semileptonic Charm Decays at Threshold

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THE UNIVERSITY OF CHICAGO

(Semi-)leptonic Decays

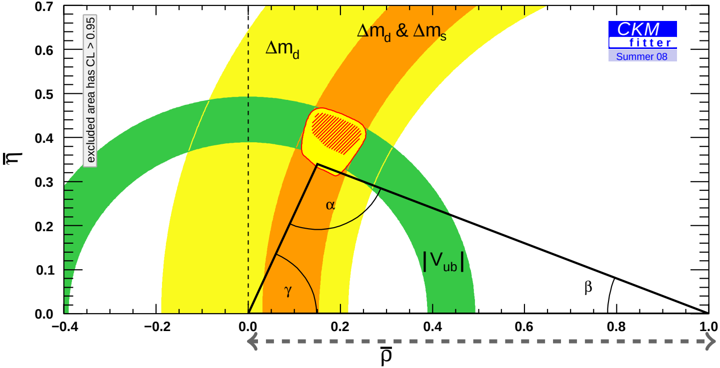
- Leptonic and semileptonic decays of mesons give clean access to hadronic currents
  - $\langle 0|\bar{q}\gamma_\mu\gamma_5 c|D\rangle$ for leptonic decays
  - $\langle X|\bar{q}\gamma_\mu(1-\gamma_5)c|D\rangle$ for semileptonic decays

$\longrightarrow$ Test our theoretical understanding of QCD in the hadronic regime & apply it elsewhere

Experimental Note:

- In recent years, "charm threshold" has meant "CLEO-c"
  - $\longrightarrow$ All results shown here are from CLEO
- I will also cover some prospects for BES-III

Access to CKM

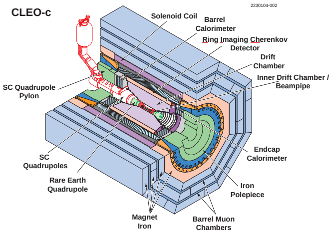


$D \to \ell\nu$

- $B^0_{d,s}$ mixing
- $B^+ \to \tau\nu$

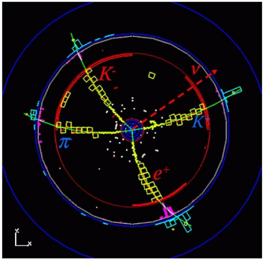
$D \to X\ell\nu$

- $|V_{ub}|$, $|V_{cb}|$ from exclusive $B \to X_{u,c}\ell\nu$



$e^+e^- \to c\bar{c} \to D^0\bar{D}^0$

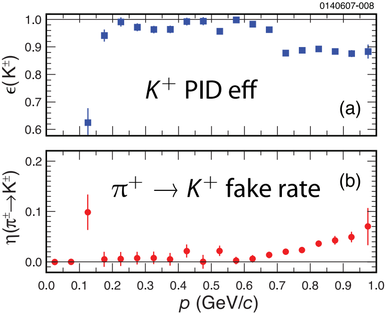
$\bar{D}^0 \to K^+\pi^-, D^0 \to K^-e^+\bar{\nu}$



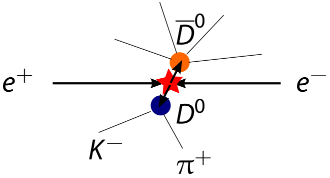
CLEO-c physics run ended in March 2008

- 818 pb^{-1} at $\psi(3770)$ (for D^0, D^+)
- 600 pb^{-1} near $E_{cm} = 4.17$ GeV (for D_s^+)
- 26 million $\psi(2S)$
- + small runs for $Y(4260)$, charm component of R, continuum, etc.

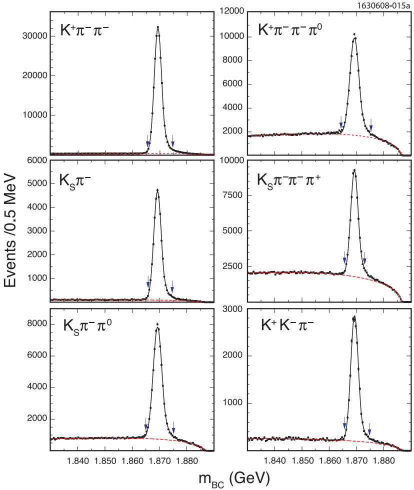
Great tracking, calorimetry, particle ID



Reconstruction — 3.77 GeV



- Open charm threshold: only $D^0\overline{D}^0$, D^+D^- possible
- Fully reconstruct 10–15% of D decays in clean hadronic "tagging" modes



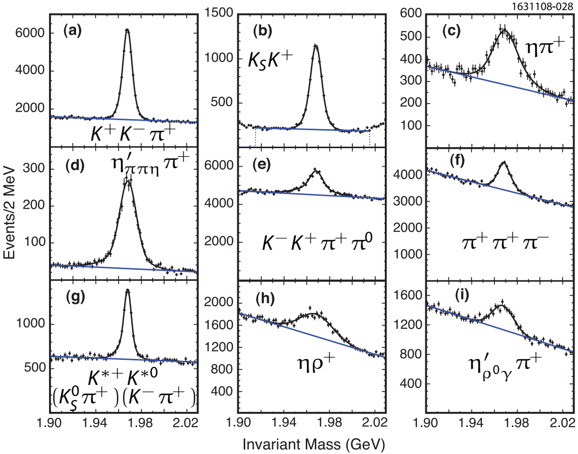
$$m_{BC} \equiv \sqrt{E^2_{beam} - \vec{p}^{\,2}_D}$$

4.6×10^5 D^+ tags in 6 modes, 818 pb^{-1}

4.17 GeV data is used for its large sample of $D_s D_s^*$ events

A $D_s^\pm$ tag implies $D_s^\mp$ on the other side; γ (or π^0) from the $D_s^* \to D_s$ transition is also present

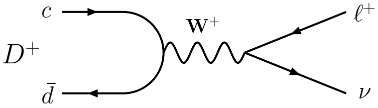
Tagging efficiency for D_s is $\sim 6\%$

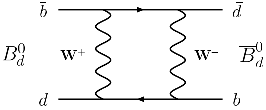


70.5k tags in 9 modes, 600 pb^{-1}

Leptonic Decays

Leptonic Decays





- D leptonic decay rate depends on wave function at zero separation $f_{D_{(s)}}$:

$$\Gamma(D_{(s)} \to \ell\nu) = f^2_{D_{(s)}} |V_{cq}|^2 \frac{G_F^2}{8\pi} m_{D_{(s)}} m_\ell^2 \left(1 - \frac{m_\ell^2}{m^2_{D_{(s)}}}\right)^2$$

- Analogous equation for $B^+ \to \tau\nu$
- $B^0_{d,s}$ mixing happens at short distance and depends on f_B:

$$\Delta m_{d,s} \propto f^2_{B_{d,s}} |V_{t(d,s)} V^*_{tb}|^2$$

- Precision test of lattice QCD predictions of $f_{D_{(s)}}$, $f_{D_s}/f_D \Rightarrow$ more confidence in expectations for B systems

D Leptonic Decays at CLEO

- Measure f_D and f_{D_s} using leptonic decays
  - Constrain $|V_{cd}|$ and $|V_{cs}|$ with CKM unitarity
- $D_s^+ \to \ell\nu$ not Cabibbo-suppressed so $\mathcal{B}$ much larger
- Measurement modes are
  - $D^+ \to \mu^+\nu$
  - $D_s^+ \to \mu^+\nu$
  - $D_s^+ \to \tau^+\nu$ $(\tau^+ \to \pi^+\nu)$
  - $D_s^+ \to \tau^+\nu$ $(\tau^+ \to e^+\nu\bar{\nu})$.
- Relative branching ratios for $D_{(s)}^+ \to \ell^+\nu$ set by lepton mass
  - Competing effects of helicity suppression and phase space
- Combine the D_s^+ results for a single f_{D_s}

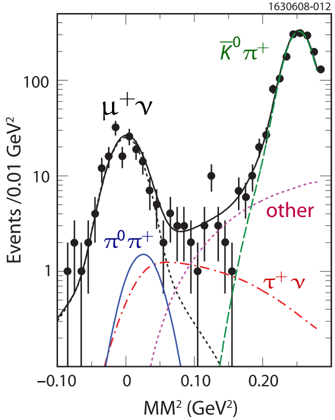
Quoted lattice QCD results: PRL **100**, 062002 (2008) [HPQCD-UKQCD]

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

- Find D^- tag and muon candidate (track leaves < 300 MeV in calorimeter and is not a kaon candidate)
- Veto extra tracks and extra calorimeter energy
- Compute missing mass from four-vectors

$$MM^2 = (p_{CM} - p_{D^-} - p_{\mu^+})^2$$

and fit distribution



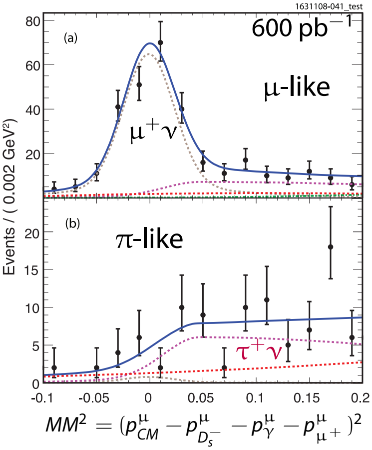
$$f_{D^+} = (205.8 \pm 8.5 \pm 2.5)\ \text{MeV}$$

PRD **78** 052003 (2008) (818 pb^{-1})

Lattice: $f_{D^+} = 207 \pm 4$ MeV

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

- Find D_s^- tag, transition photon, and additional track candidate
- Veto extra tracks and extra calorimeter energy
- Two types of event:
  - (a) μ-like tracks: $E_{cal} < 300$ MeV
  - (b) π-like tracks: $E_{cal} > 300$ MeV, fail electron ID

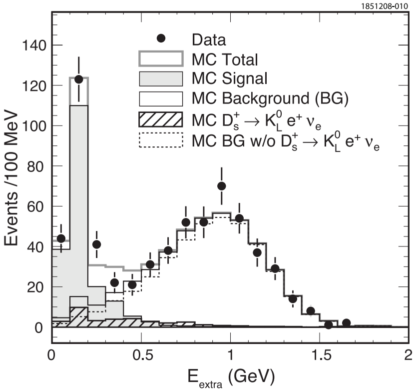


$$\mathcal{B}(D_s^+ \to \mu^+\nu) = (5.65 \pm 0.45 \pm 0.17) \times 10^{-3}$$
$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (6.42 \pm 0.81 \pm 0.18)\%$$

PRD 79, 052001 (2009)

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

- Find hadronic D_s tag and electron candidate
- Veto extra tracks
- Signal candidates have extra calorimeter energy < 400 MeV
  - Peaks above zero due to $D_s^* \to \gamma D_s$ photon
- Dominant systematic uncertainty is $\mathcal{B}(D_s^+ \to K_L^0 e^+\nu)$



$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (5.30 \pm 0.47 \pm 0.22)\%$$

PRD 79, 052002 (2009)

[$\tau \to \pi\nu$ result: $(6.42 \pm 0.81 \pm 0.18)\%$]

Combined Leptonic Results

$D_s^+ \to \mu^+\nu$ and two $D_s^+ \to \tau^+\nu$ measurements statistically independent: combine

Average:

$$f_{D_s} = 259.5 \pm 6.6 \pm 3.1 \text{ MeV}$$

Lattice: 241 ± 3 MeV

Recall

$$f_D = 205.8 \pm 8.5 \pm 2.5 \text{ MeV}$$

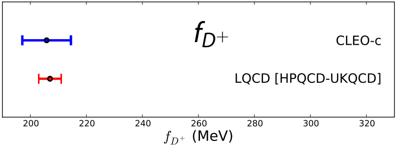
Lattice: 207 ± 4 MeV

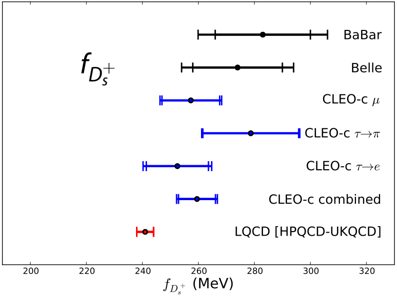
So

$$f_{D_s}/f_D = 1.26 \pm 0.06 \pm 0.02$$

Lattice: 1.162 ± 0.009

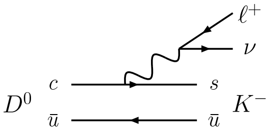
PRD 79, 052001 (2009)





Semileptonic Decays

Semileptonic Decays



For X, X' pseudoscalars:

$$\frac{d\Gamma(X \to X'\ell\nu)}{dq^2} = \left[f_+^{X\to X'}(q^2)|V_{Qq}| \right]^2 \frac{G_F^2}{24\pi^3} p_{X'}^3$$

Pseudoscalars:

- Rate depends on a form factor $f_+(q^2 = m_{\ell\nu}^2)$ times a CKM matrix element $|V_{Qq}|$.
- Γ from experiment and $f_+(q^2)$ from theory $\Rightarrow |V_{Qq}|$
  - Test lattice $f_+(q^2)$, or extract $|V_{cs}|$, $|V_{cd}|$

Also:

- Vectors have more degrees of freedom $\Rightarrow$ longitudinal, transverse form factors
- Clean source of hadrons $\Rightarrow$ insight into hadronic properties
- Inclusive semileptonic width tests SU(3), HQET, weak annihilation effects

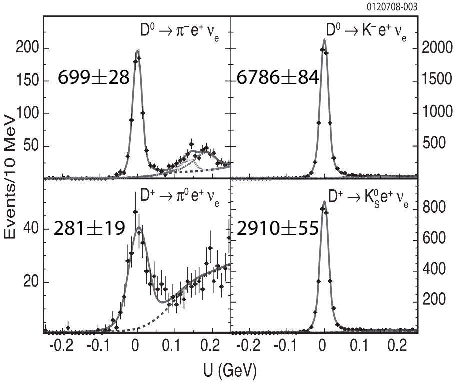
Exclusive D Semileptonic Decays

- Only electrons used for CLEO-c results shown here
- Results for:
  - $D^0 \to K^- e^+ \nu$
  - $D^+ \to \overline{K}^0 e^+ \nu$
  - $D^0 \to \pi^- e^+ \nu$
  - $D^+ \to \pi^0 e^+ \nu$
- Two methods:
  - Reconstruct hadronic $\overline{D}$ tag + hadron + lepton, see if missing four-momentum is consistent with neutrino ("tagged analysis")
  - Use detector hermeticity to reconstruct neutrino four-momentum with no tag, then combine with hadron and lepton to make a D candidate ("ν reconstruction")
- Tagged analysis has better systematics
- ν reconstruction has better statistics
- Following results use 281 pb^{-1}
  - Expect update to 818 pb^{-1} a week from now

D Semileptonics: Reconstruction

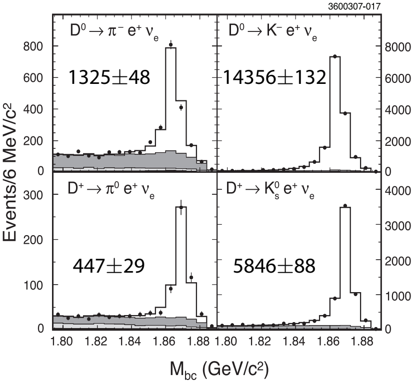
Tagged

(PRD 79, 052010 (2009))



ν reconstruction

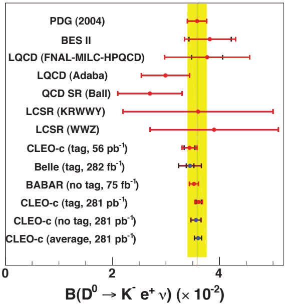
(PRL 100, 251802 (2008))

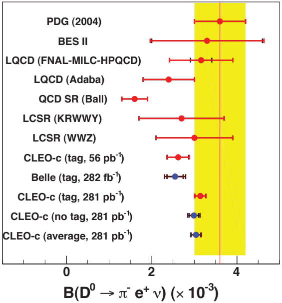


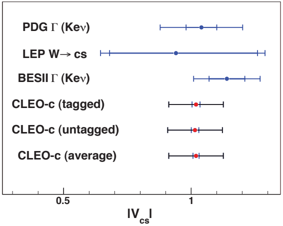
Not statistically independent!

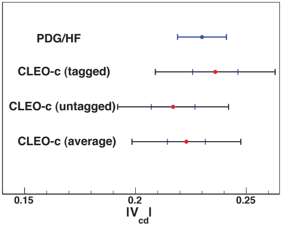
Results combined with proper correlations in PRD 79, 052010

D Semileptonics: Absolute $\mathcal{B}$s, CKM Magnitudes









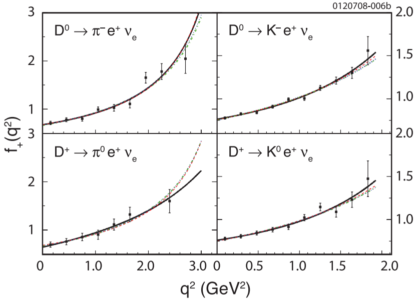
D Semileptonics: Form Factors

Simple pole: $f_+(q^2) = \dfrac{f_+(0)}{1 - \frac{q^2}{M^2_{pole}}}$

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

Series expansion (PLB **633**, 61 (2006)):

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

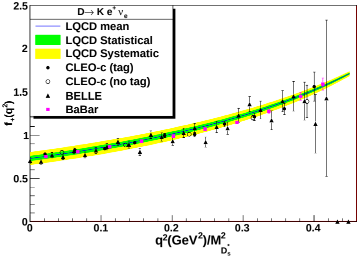


All shapes fit data if parameters allowed to float

"Physical" pole masses highly disfavored

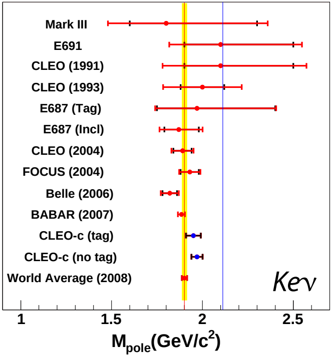
(LQCD: FNAL-MILC-HPQCD

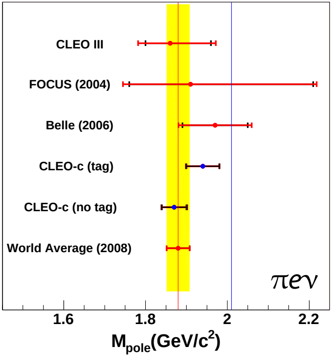
PRL **94** 011601 (2005))



Modified Pole Fits: Pole Mass

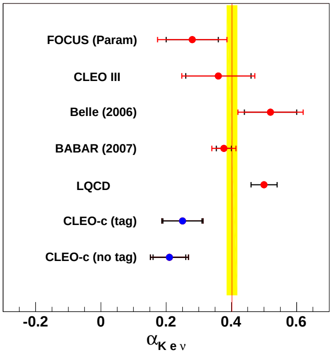
$$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{M^2_{pole}}\right)\left(1 - \alpha\frac{q^2}{M^2_{pole}}\right)}$$

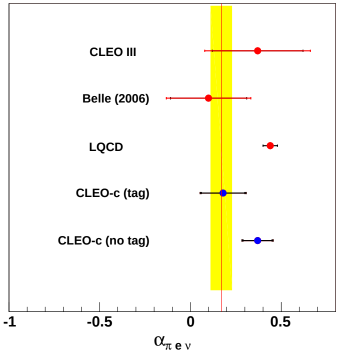




Modified Pole Fits: α

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

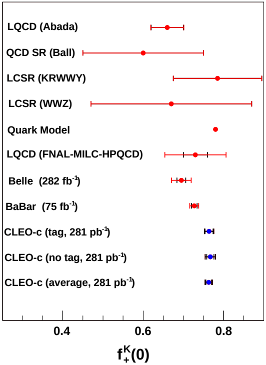


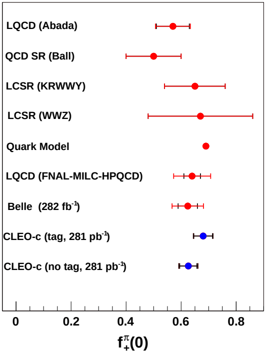


(WA = fit to points from all expts)

Modified Pole Fits: $|f_+(0)|$

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





Observation of $D^+ \to \eta e^+ \nu$

Search for $D^+ \to X e^+ \nu$, $X = \eta, \eta', \phi$

- Get information on $\eta/\eta'/$glueball mixing angles

  (Bianco, Fabbri, Benson, Bigi, hep-ex/0309021)
- $D^+ \to \phi \ell \nu$ signal not expected

Tagged analysis, 281 pb^{-1}

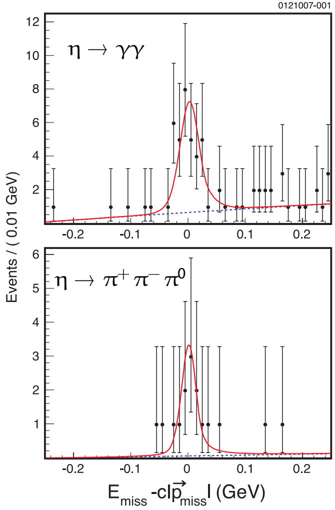
Branching fractions $\times 10^4$

X	CLEO	PDG 08	ISGW2	FK
η	$13.3 \pm 2.0 \pm 0.6$	< 70	11	10
η'	< 3.5	< 110	5	1.6
ϕ	< 1.6	< 201	—	—

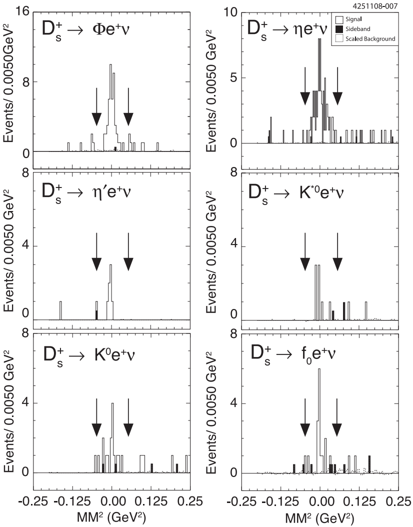
CLEO: PRL 102, 081801 (2009)

ISGW2: PRD 52, 2783 (1995)

FK: Fajfer & Kamenik, PRD 71, 014020 (2005)



D_s^+ Exclusive Semileptonic Decays



$310\ \text{pb}^{-1}$

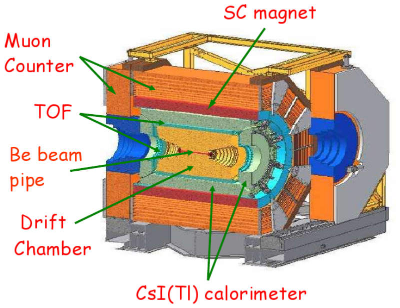
arXiv:0903.0601 (submitted to PRD)

$D_s^+ \to X e^+ \nu$:

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}	$0.18 \pm 0.07 \pm 0.01$
$f_0 \to \pi^+\pi^-$	$0.13 \pm 0.04 \pm 0.01$

- Absolute branching fractions
- First observation of Cabibbo-suppressed modes

Future: BES-III



- Experimental capabilities comparable to CLEO-c
  - $\longrightarrow$ but with muon ID
- BEPC-II design luminosity 10^{33} cm^{-2} s^{-1} is $\sim$ 20$\times$ CESR-c
  - $\longrightarrow$ has reached 3 $\times$ 10^{32} at ψ'
- Will push precision & rarer decays will be accessible

For 20 fb^{-1}:

- $D^{0,+} \rightarrow (K/\pi)\ell\nu$ systematics dominated
- $|V_{c(s,d)}|$ limited by theory — or, $|f_+^{K,\pi}(0)|$ limited by $|V_{c(s,d)}|$
- Extra statistics for $f_+^{\pi}(q^2)$ *always* welcome
- Stat, syst comparable for $f_{D_{(s)}}$

Expected statistical uncertainties

Quantity	CLEO-c	BES-III
$\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu)$	3.6%	0.7%
f_{D_s}	2.5%	0.7%

Based on BES-III physics book (arXiv:0809.1869)

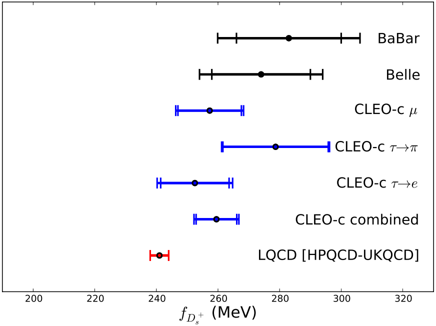
Summary and Outlook

- Leptonic and semileptonic *D* decays are an important laboratory for understanding QCD
- Threshold operation gives very clean environment
- CLEO-c's well-understood detector and dataset have provided many important results
- BES-III will take us further into the precision frontier

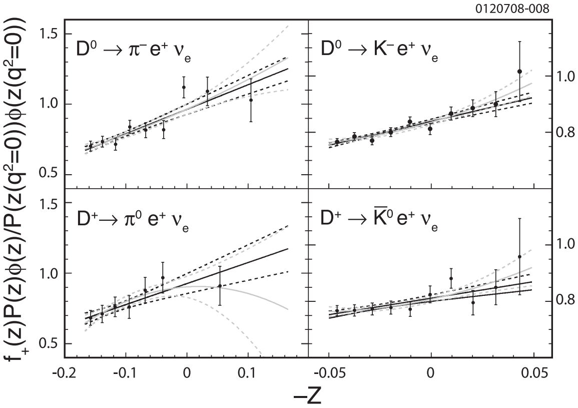
The End

A Note On $f_{D_s^+}$

- CLEO-c discrepancy from HPQCD-UKQCD prediction is 2.3σ
  - rises to 2.6σ when combined with Belle measurement
- Not particularly significant
- From new physics perspective: theoretically unpleasant to modify $f_{D_s^+}$ but not f_{D^+}
- Needs BES-III input



Series Fit



0120708-008
$D^0 \to \pi^- e^+ \nu_e$
$D^0 \to K^- e^+ \nu_e$
$D^+ \to \pi^0 e^+ \nu_e$
$D^+ \to \bar{K}^0 e^+ \nu_e$
$f_+(z)P(z)\phi(z)/P(z(q^2=0))\phi(z(q^2=0))$
$-z$
1.5
1.0
0.5
0.8
-0.2
-0.1
0
0.1
-0.05
0.05