Heavy Flavor at CLEO-c

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La Thuile, 4 March 2009
CLEO-c’s extensive program in charm and light flavor physics:

- Leptonic and semileptonic decays for CKM magnitudes
- Strong phase measurements for CKM angles and $D$ mixing
- Precise normalization branching fraction measurements
- $D$ hadronic decay dynamics
- Charmonia and light hadrons
- Rare decay + new physics searches
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Only have time for first two topics — can’t do justice to full range of work...
Overconstrain unitarity triangle to validate Standard Model/find new physics in CP violation
Weak physics must be extracted from strongly-interacting objects
Theoretical understanding of nonperturbative QCD can limit precision
CLEO-c aims to validate theoretical tools in the charm system
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 $\gamma(4260)$, charm component of $R$, continuum, etc.

Great tracking, calorimetry, particle ID

\[ e^+ e^- \rightarrow c \bar{c} \rightarrow D^0 \bar{D}^0 \]
\[ \bar{D}^0 \rightarrow K^+ \pi^-, D^0 \rightarrow K^- e^+ \nu \]

(a) $K^+$ PID eff

(b) $\pi^+ \rightarrow K^+$ fake rate

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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

\[ m_{BC} = \sqrt{E_{beam}^2 - \vec{p}_D^2} \]

$4.6 \times 10^5 D^+$ tags in 6 modes, 818 pb$^{-1}$
4.17 GeV data is used for its large sample of $D_sD_s^*$ events

A $D_s^\pm$ tag implies $D_s^{\mp}$ on the other side; $\gamma$ (or $\pi^0$) from the $D_s^* \rightarrow D_s$ transition is also present

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

70.5k tags in 9 modes, 600 pb$^{-1}$
Decay Constant Measurements

![Graph showing decay constant measurements](image)
$B_{d,s}^0$ mixing proceeds through box diagrams (short distance interactions).

Rate depends on wave function near zero separation $f_B$: \[ \Delta m_{d,s} \propto f_{B_{d,s}}^2 |V_{t\,d,s}V_{tb}^*|^2 \]

Analogous quantity appears in $D$ leptonic decays:

\[ \Gamma(D_{(s)} \to \ell\nu) = f_{D_{(s)}}^2 |V_{cq}|^2 \frac{G_F^2}{8\pi} m_{D_{(s)}} m_\ell^2 \left( 1 - \frac{m_\ell^2}{m_{D_{(s)}}^2} \right)^2 \]

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

(Also affects $B^+ \to \tau\nu...$)
Leptonic Decays

- Measure $f_D$ and $f_{D_s}$ using leptonic decays
  - Constrain $|V_{cd}|$ and $|V_{cs}|$ with CKM unitarity
- $D_s^+ \rightarrow \ell \nu$ not Cabibbo-suppressed so $B$ much larger
- Measurement modes are
  - $D^+ \rightarrow \mu^+ \nu$
  - $D_s^+ \rightarrow \mu^+ \nu$
  - $D_s^+ \rightarrow \tau^+ \nu$ ($\tau^+ \rightarrow \pi^+ \nu$)
  - $D_s^+ \rightarrow \tau^+ \nu$ ($\tau^+ \rightarrow e^+ \nu \bar{\nu}$).
- Relative branching ratios for $D_s^{(s)} \rightarrow \ell^+ \nu$ 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]
$D^+ \rightarrow \mu^+\nu$

- Find $D^-$ tag and muon candidate ($< 300$ MeV in calorimeter, 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
$D_s^+ \rightarrow \mu^+ \nu, \tau^+ \nu (\tau^+ \rightarrow \pi^+ \bar{\nu})$

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

$$MM^2 = (p_{CM} - p_{D_s} - p_\gamma - p_\mu)^2$$

$$\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu) = (5.65 \pm 0.45 \pm 0.17) \times 10^{-3}$$

$$\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu) = (6.42 \pm 0.81 \pm 0.18)\%$$

arxiv:0901.1216, accepted by PRD
$D_s^+ \rightarrow \tau^+ \nu$ ($\tau^+ \rightarrow e^+ \nu \bar{\nu}$)

- Find hadronic $D_s$ tag and electron candidate
- Veto extra tracks
- Signal candidates have extra calorimeter energy $< 400$ MeV
  - Peaks above zero due to $D_s^* \rightarrow \gamma D_s$ photon
- Dominant systematic uncertainty is $\mathcal{B}(D_s^+ \rightarrow K^0_L e^+ \nu) = (5.30 \pm 0.47 \pm 0.22)\%$

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

arxiv:0901.1147, accepted by PRD

[$\tau \rightarrow \pi \nu$ result: $(6.42 \pm 0.81 \pm 0.18)\%]$
Combined Leptonic Results

\[ D_s^+ \rightarrow \mu^+\nu \] and two \( D_s^+ \rightarrow \tau^+\nu \) 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: 201 ± 3 ± 17 MeV

So

\[
f_{D_s}/f_D = 1.26 \pm 0.06 \pm 0.02
\]
Lattice: 1.162 ± 0.009

arxiv:0901.1216
Semileptonic Form Factor Measurements

\[
\begin{align*}
\Delta m_d & \quad \Delta m_s \\
\text{excluded area has CL > 0.95} & \\
\text{Summer 08 CKM fitter}
\end{align*}
\]
QCD in CKM — Semileptonic Decays

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

- Rate depends on a form factor \( f_+(q^2 = m_{\ell\nu}^2) \) times a CKM matrix element \( |V_{Qq}| \).
- \( \Gamma \) from experiment and \( f_+(q^2) \) from theory \( \Rightarrow |V_{Qq}| \)
- CLEO-c: test lattice \( f_+(q^2) \), or extract \( |V_{cs}|, |V_{cd}| \)
Only electrons used ($\pi \rightarrow \mu$ fake rate too high)

Results for:

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

Two methods:

- Reconstruct hadronic $\bar{D}$ 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 (“$\nu$ reconstruction”)

Tagged analysis has better systematics

$\nu$ reconstruction has better statistics

Following results use 281 pb$^{-1}$
Not statistically independent!
Results combined with proper correlations in arXiv:0810.3878
D Semileptonics: Absolute $B_s$, CKM Magnitudes

\[ B(D^0 \rightarrow K^- e^+ \nu) \times 10^2 \]

\[ B(D^0 \rightarrow \pi^- e^+ \nu) \times 10^3 \]

\[ |c_s|V \times 10^2 \]

\[ |c_d|V \times 10^2 \]

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18
Semileptonics: Form Factors

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

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

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

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

All shapes fit data if parameters allowed to float

“Physical” pole masses highly disfavored

(LQCD: FNAL-MILC-HPQCD
PRL 94 011601 (2005))
$D_s^+$ Semileptonic Decays

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

<table>
<thead>
<tr>
<th>$\chi$</th>
<th>$B(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$</td>
<td>$2.29 \pm 0.37 \pm 0.11$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>$2.48 \pm 0.29 \pm 0.13$</td>
</tr>
<tr>
<td>$\eta'$</td>
<td>$0.91 \pm 0.33 \pm 0.05$</td>
</tr>
<tr>
<td>$K^0$</td>
<td>$0.37 \pm 0.10 \pm 0.02$</td>
</tr>
<tr>
<td>$K^{*0}$</td>
<td>$0.18 \pm 0.07 \pm 0.01$</td>
</tr>
<tr>
<td>$f_0 \rightarrow \pi^+ \pi^-$</td>
<td>$0.13 \pm 0.04 \pm 0.01$</td>
</tr>
</tbody>
</table>

- Absolute branching fractions
- First observation of Cabibbo-suppressed and $f_0(980)$ modes
- Gives information on $\eta/\eta'/\text{glueball mixing angles}$

310 pb$^{-1}$ Preliminary
$D^0$ Decay Strong Phases for $\gamma$
CKMFitter, Summer 2008

Direct measurements

\[ \alpha \quad 88.2^{+6.1}_{-4.8} \]
\[ \beta \quad 21.11^{+0.94}_{-0.92} \]
\[ \gamma \quad 70^{+27}_{-29} \]

\( \gamma/\phi_3 \) is the poorest directly measured angle of the unitarity triangle

Tree measurements of \( \gamma \) complement loop measurements of \( |V_{td}| \)
QCD in CKM — $\gamma$ Extraction

- Can obtain $\gamma$ from interference between $b \rightarrow c(\bar{u}s)$ and $b \rightarrow u(\bar{c}s)$
- Use final states common to $D^0$ and $\bar{D}^0$
- Must know relative phase of $D^0$ and $\bar{D}^0$ amplitudes to same final state
  - This strong phase $\delta_D$ comes from intermediate resonances
  - $\delta_D$ depends on daughter momenta (hence resonant structure)
- $r_B$, $\delta_B$ from $B$-factories, $\delta_D$ from CLEO-c
  - Charm threshold gives unique access to $CP$-coherent $D^0\bar{D}^0$ pairs, giving $\delta_D$ from from data
  - Elsewhere, mesons tagged as definitely $D^0$ or $\bar{D}^0$ (“flavor tag”); phase information lost, $\delta_D$ only from Dalitz plot modeling
CP Correlation Studies

Studying:

- $\delta_D$ for $D^0 \rightarrow K^- \pi^+$
  (PRL 100 221801 (2008))

- Dalitz plot-dependent phases for $D^0 \rightarrow K_{S,L}^0 \pi^+ \pi^-$ and $K_{S,L}^0 K^+ K^-$ (arxiv:0810.3666)

- Coherence factor and average strong phase for $D^0 \rightarrow K^- \pi^+ \pi^0$ and $K^- \pi^+ \pi^+ \pi^-$ (arXiv:0805.1722)

Statistically limited by CP tag yields

818 pb$^{-1}$ Preliminary
\( K_{S,L}^{0} \pi^{+} \pi^{-} \) only:

BaBar: \( (63^{+30}_{-28} \pm 8 \pm 7)^{\circ} \)  
(PRD 78 034023 (2008))

Belle: \( (76^{+12}_{-13} \pm 4 \pm 9)^{\circ} \)  
(arxiv:0803.3375)

model uncertainty \( \Rightarrow \approx 2^{\circ} \) CLEO-c statistical uncertainty (Preliminary)
CLEO-c has had a significant impact across a broad range of topics, only a few of which are covered here:

- CKM measurements are a key focus area
- $D^+$ and $D_s^+$ leptonic decays test lattice predictions
  - Results shown here use full CLEO-c dataset
- $D^0$ and $D^+$ semileptonic decays test the lattice, probe $|V_{cs}|$ and $|V_{cd}|$
  - Update to full CLEO-c dataset (3× data shown here) nearing completion
- $D_s^+$ semileptonic decays are a new frontier
- Strong phase measurements in various $D$ decays have a large impact on the systematic uncertainty in $\gamma$
  - Technique unique to charm threshold
  - Multiple modes being studied
  - Great symbiosis with LHCb and $B$-factory programs
The End
The $\psi(3770)$ has $CP = +$; daughter $D^0$ mesons have opposite $CP$ to each other ($P$-wave decay)

Tag modes like $D^0 \rightarrow K_S^0 \pi^0$ ($CP = -$) or $\pi^+ \pi^-$ ($CP = +$) fix $CP$ content of the other side decay:

$$D_{CP=\pm}^0 = \frac{D^0 \mp D^0}{\sqrt{2}}$$

Tag modes like $K^- \pi^+$ determine if the other side is $D^0$ or $\bar{D}^0$

<table>
<thead>
<tr>
<th>Decay:</th>
<th>$D^0$</th>
<th>$\bar{D}^0$</th>
<th>$CP = +$</th>
<th>$CP = -$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measures</td>
<td>$</td>
<td>f_D</td>
<td>^2$</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$-</td>
<td>f_D</td>
</tr>
</tbody>
</table>

For 2-body decays (e.g. $K^- \pi^+$) there’s only one $\delta_D$, otherwise it varies over the Dalitz plot

Can also measure a weighted average phase whose effect is diluted by a “coherence factor” $R$
A Note On $f_{D_s^+}$

- CLEO-c discrepancy from HPQCD-UKQCD prediction is $2.3\sigma$
  - rises to $2.6\sigma$ when combined with Belle measurement
- Not particularly significant
- From new physics perspective: theoretically unpleasant to modify $f_{D_s^+}$ but not $f_{D^+}$
- We leave it to our colleagues on BES-III to constrain $f_{D_s^+}$ more tightly...

![Graph showing measurements of $f_{D_s^+}$](image_url)
Modified Pole Fits

-0.2 0 0.2 0.4 0.6
CLEO-c (no tag) 
CLEO-c (tag) 
LQCD         
BABAR (2007) 
Belle (2006) 
CLEO III      
FOCUS (Param)

-1 -0.5 0 0.5
CLEO-c (no tag)  
CLEO-c (tag)  
LQCD          
Belle (2006)  
CLEO III
Modified Pole Fits

\[ f^K_+(0) \]

\[ f^\pi_+(0) \]

LQCD (Abada)
QCD SR (Ball)
LCSR (KRWWY)
LCSR (WWZ)
Quark Model
LQCD (FNAL-MILC-HPQCD)
Belle (282 fb^{-1})
BaBar (75 fb^{-1})
CLEO-c (tag, 281 pb^{-1})
CLEO-c (no tag, 281 pb^{-1})
CLEO-c (average, 281 pb^{-1})

CLEO-c (average, 281 pb^{-1})
CLEO-c (no tag, 281 pb^{-1})

Belle (282 fb^{-1})

LQCD (Abada)
QCD SR (Ball)
LCSR (KRWWY)
LCSR (WWZ)
Quark Model
LQCD (FNAL-MILC-HPQCD)

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