Charm Decays

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Outline

• Results from active experiments
  - BaBar, Belle, CLEO-c, (CDF, DØ), FOCUS
• Guiding principle: Charm’s role in flavor physics
• Hadronic Charm Decays
  - D and Ds branching fractions
• Leptonic Charm Decays
  - decay constants from $D_{(s)} \to \mu \nu$ and $D_s \to \tau \nu$
• Semileptonic Charm Decays
  - branching fractions
  - hadronic form factors and CKM $V_{cs}$ and $V_{cd}$
• Many interesting results not shown for lack of time
  - hadronic structure in multibody decays
  - rare D decays: CDF $D^0 \to \mu \mu$ search presented in session B14
Flavor physics:
- Overconstrain $V_{\text{CKM}}$
- Inconsistency → new physics

Unitarity Triangle Constraints
- $\sin 2\beta$ is theoretically clean
- $|V_{ub}|$ is not
- $B$ mixing is not
Hadronic uncertainties confound extraction of weak physics

Charm decay measurements can validate QCD corrections needed to extract weak physics parameters from experimental observables
$|V_{ub}|$ from semileptonic B decay

- Rate goes like $|V_{ub}|^2$
- But quarks always in hadrons
- QCD form factor $f_+(q^2)$ needed to extract weak interaction physics

\[
\Gamma(b \to u e \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{ub}|^2
\]

\[
\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 p_\pi^3 |f_+(q^2)|^2
\]
UT Constraint from $|V_{ub}|$

$|V_{ub}|$ from $B \rightarrow \pi \ell \nu$:

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 p_{\pi}^3 |f_+(q^2)|^2$$

Form factor $f(q^2)$:
- Hard to calculate
- Limits $|V_{ub}|$ precision
- Lattice QCD can do from first principles

- $D \rightarrow \pi \ell \nu$ to $B \rightarrow \pi \ell \nu$ are both “heavy to light” decays
- Precise measurement of $D \rightarrow \pi \ell \nu$ can calibrate LQCD and allow a precise extraction of $|V_{ub}|$ from $B \rightarrow \pi \ell \nu$
- Absolute rate and shape is a stringent test of theory
$|V_{td}|$ from $B^0$-$\bar{B}^0$ mixing

- Mixing rate depends on $|V_{td}|^2$
- QCD correction here is partly decay constant $f_B$
  - probability of wave function overlap $\psi(r=0)$
- Hard to calculate @ small $q^2$
  - low energy QCD
    - Lattice QCD to $\sim 15\%$
- Same for meson decay
- Can measure annihilation decay
    Evidence for $B^- \rightarrow \tau^- \nu$ (3.5 $\sigma$)
    $f_B = 229\pm36\pm37$ MeV (20%)
- But would like a precise measurement
**UT Constraint from B mixing**

- Lattice QCD predicts decay constants $f_D$ & $f_B$
- Charm sector measurements of $f_{D(s)}$ from $D(s) \rightarrow \mu \nu$ can increase our confidence in the non-perturbative QCD calculations of $f_B$ needed to interpret $\Delta m$ and $\Delta m_s$
  - direct measurement of $B \rightarrow \ell \nu$ is much harder!
- Better constraint on $|V_{ts}/V_{td}|$ from $\Delta m_s/\Delta m_d$
  - still want to check $f_{Ds}/f_D$

\[
\Delta M_d = 0.50 \text{ps}^{-1} \left[ \frac{\sqrt{B_{B_d}} f_{B_d}}{200 \text{MeV}} \right]^2 \left[ \frac{|V_{td}|}{8.8 \times 10^{-3}} \right]^2
\]

\[
\frac{\sigma(|V_{td}|)}{|V_{td}|} = 0.5 \left( \frac{\sigma(\Delta M_d)}{\Delta M_d} \right) \left( \frac{\sigma(f_B \sqrt{B_{B_d}})}{f_B \sqrt{B_{B_d}}} \right)
\]

0.8% ~15% (LQCD)
Current $V_{\text{CKM}}$ from direct measurements - no unitarity imposed.

charm decay measurements:
- direct access to 2nd generation elements
- enable improvements in 3rd generation elements
CLEO-c Hadronic D Decays

Presented in session B14 X. Shi

e^+e^-\rightarrow\psi(3770) \rightarrow D \bar{D} \ (D^0\bar{D}^0 \ or \ D^+D^-)

• Just above threshold: no additional particles are produced
• Fully reconstruct one D in the event, e.g. \( D^0 \rightarrow K^-\pi^+ \)

Energy and Momentum Conservation:

\[
E_D = E_K + E_\pi \\
\vec{p}_D = \vec{p}_K + \vec{p}_\pi
\]

\[\Delta E = E_{\text{beam}} - E_D\]

\[M(D) = \sqrt{E_{\text{beam}}^2 - |\vec{p}_D|^2}\]

resolution:
7-10 MeV
1.3 MeV
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\[ \Delta E = E_{\text{beam}} - E_D \]
\[ M(D) = \sqrt{E_{\text{beam}}^2 - |p_D|^2} \]

resolution:

7-10 MeV
1.3 MeV
Double Tag Events

\[ D^+ \rightarrow K^-\pi^+\pi^+ \text{ & } D^- \rightarrow K^+\pi^-\pi^- \]

• Tagging effectively makes a single D beam
• Can tag \( \approx 22\% \) of D's produced!

\[ \mathcal{B}(D \rightarrow X_i) = \frac{N(D \rightarrow X_i)}{\text{Efficiency} \times N_{\text{tags}}} \]
\[ N_i = N_{DD} B_i \varepsilon_i \]
\[ N_{ij} = N_{DD} B_i B_j \varepsilon_{ij} \]

\[ B_i = \frac{N_{ij} \varepsilon_j}{N_j \varepsilon_{ij}} \]
\[ N_{DD} = \frac{N_i N_j}{N_{ij} \varepsilon_i \varepsilon_j} \]
\[ \varepsilon_{ij} \approx \varepsilon_i \varepsilon_j \]

\[ \varepsilon_i = 16\% - 65\% \]

9 modes, simultaneous $\chi^2$ fit including correlations on $N$, $\varepsilon$ to extract 9 $B_i$ & $N(DD)$

56 pb$^{-1}$: PRL 95 121801 (2005)
281 pb$^{-1}$: Preliminary results reported at this meeting (X. Shi)
Additional data in hand now (~280 pb$^{-1}$)
And from run through Mar’08 (~300 pb$^{-1}$)
CLEO-c hadronic decay results

Comparison to other measurements

\[ \text{BF}(D^0 \rightarrow K^\mp \pi^+) \]

Precision measurements of many \( D^0, D^+ \) decay modes
Leptonic $D_{(s)}$ Decay

- Measure rate to extract $f_D$ and $f_{Ds}$
- Useful to calibrate $V_{td}/V_{ts}$ from $B_{(s)}^0$ mixing

\[ \Gamma(D \rightarrow \mu\nu) = \frac{G_F^2}{8\pi} |V_{cd}|^2 f_D^2 m_\mu^2 M_D^2 \left(1 - \frac{m_\mu^2}{M_D^2}\right)^2 \]

\[ \mathcal{B}(D \rightarrow \mu\nu) = \Gamma \tau_D \approx 4 \times 10^{-4} \]

\[ \mathcal{B}(D \rightarrow \tau\nu) \approx 4 \times 10^{-3} \]

\[ \mathcal{B}(D_s \rightarrow \mu\nu) \approx 6 \times 10^{-3} \]

\[ \mathcal{B}(D_s \rightarrow \tau\nu) \approx 6 \times 10^{-2} \]

decay constant

measures overlap of quark wave functions
CLEO-c $D^+ \to \mu \nu$

281 pb$^{-1}$ PRL 95, 251801 (2005)

Use 158k tagged $D^-$ decays

Require

- one $\mu$ candidate with MIP-like shower
- no extra tracks
- no unmatched showers with $E_{CC} > 250$ MeV

$$B = (4.40 \pm 0.66 \pm 0.09 \pm 0.12) \times 10^{-4}$$

$$f_D = (222.6 \pm 16.7 \pm 2.8 \pm 3.4) \text{ MeV}$$

Signal region: 50 events

2.8 estimated background

Unquenched Lattice QCD

$201 \pm 3 \pm 17$ MeV

PRL 95, 122002 (2005)
BaBar $D_s \to \mu \nu$  

$e^+e^- \to D_s^* D_{tag} X$; $D_{tag}$ is fully reconstructed $D(s)^(*)$

Then look for $D_s^* \to D_s \gamma$; $D_s \to \mu \nu$:

$\Delta M = M(\mu \nu \gamma) - M(\mu \nu)$ signal peak at 143 GeV

- Measure also $D_s \to \phi \pi$ to normalize
- Detailed systematic understanding

\[
\frac{\Gamma(D_s^+ \to \mu^+ \nu)}{\Gamma(D_s^+ \to \phi \pi^+)} = 0.143 \pm 0.018 \pm 0.006
\]

$BF(D_s \to \mu \nu) = (6.74 \pm 0.83 \pm 0.26 \pm 0.66) \times 10^{-3}$

$f_{D_s} = (283 \pm 17 \pm 7 \pm 14)\text{MeV}$

Unquenched Lattice QCD
249\pm3\pm16 \text{MeV}

PRL 95, 122002 (2005)
CLEO-c $D_s \rightarrow \mu \nu$ & $D_s \rightarrow \tau \nu; \tau \rightarrow \pi \nu$

- $e^+ e^- \rightarrow D_s D_s^* \ @ \sqrt{s}=4170 \ MeV$
  - 314 \ pb^{-1}$
- Fully Reconstruct
  - 19k $D_s$ tags (8 modes)
  - Recoil Mass peaks at $D_s^*$
    - count tags by fit
- Add a single track
  - $\mu$: MIP-like in Calorimeter
  - $\pi$: sometimes $E_{CC}>200 \ MeV$
  - $MM^2$ peaks at 0 for $\mu \nu$
  - and near 0 for $\tau \nu; \tau \rightarrow \pi \nu$
- Veto events with
  - extra tracks
  - extra neutral energy
- Kinematic Fit
  - improved resolution
  - resolve ambiguity: $D_s^* \rightarrow D_s \gamma$
  on tag or signal side
CLEO-c $f_{D_s}$ Results

<table>
<thead>
<tr>
<th>Case</th>
<th>Region (GeV$^2$)</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>-0.05&lt;MM$^2$ &lt; 0.05</td>
<td>92</td>
<td>3.5±1.4</td>
</tr>
<tr>
<td>i</td>
<td>0.05&lt;MM$^2$ &lt; 0.20</td>
<td>31</td>
<td>2.5±1.1</td>
</tr>
<tr>
<td>ii</td>
<td>-0.05&lt;MM$^2$ &lt; 0.20</td>
<td>25</td>
<td>3.0±1.3</td>
</tr>
<tr>
<td>Sum</td>
<td>-0.05&lt;MM$^2$ &lt; 0.20</td>
<td>148</td>
<td>9.0±2.3</td>
</tr>
</tbody>
</table>

$B=(0.638±0.059±0.033)\%$

$f_{D_s}=(274±13±7)$ MeV

Unquenched Lattice QCD
249±3±16 MeV
PRL 95, 122002 (2005)

\[
\frac{f_{D_s}}{f_D} = 1.23 ± 0.11 ± 0.04
\]

ULQCD
1.24±0.01±0.07
2nd Complementary Analysis with $\tau^+ \to e^+\nu\nu$

- Signal production of $e^+$: $B(D_s^+ \to \tau^+\nu)B(\tau^+ \to e^+\nu\nu) \sim 1.3\%$
- Background: $B(D_s^+ \to Xe^+\nu) \sim 8\%$

Technique:
- Use $D_s^-$ tags and $e^+$
- Suppress background
  - no additional tracks and
  - $\Sigma$ Ecal < 400 MeV
- No need to find $\gamma$ from $D_s^*$
- $B(D_s^+ \to \tau^+\nu) = (6.29\pm0.78\pm0.52)\%$
- $f_{D_s} = 278\pm17\pm12$ MeV

Preliminary @ ICHEP 06
195 pb$^{-1}$ near $\sqrt{s} = 4170$ MeV
$f_{D(s)}$: Comparison to Theory

**CLEO results**

- Good agreement with unquenched LQCD

**Calculations**

- Comparable uncertainties already!

More data to come!
Semileptonic Decays

Focus on recent results in Pseudoscalar final states: \( K, \pi \)

Will not show:
- \( D \to \eta_{en}/\eta_{en}'/\phi_{en} \) (J.Ge)
  - presented in session B14
- \( D \to V \nu_e; V = K^*,\rho \)

\[
\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cx}|^2 p_X^3 |f_+(q^2)|^2
\]

\[
q^2 = (p_D - p_X)^2 = M_D^2 + M_X^2 - 2E_X M_D + \vec{p}_D \cdot \vec{p}_X
\]
Fully reconstructed $e^+e^- \rightarrow D(\ast)D\ast X$ events
$\sqrt{s}=10.6$ GeV
Allows count of $D^0$ independent of decay
Neutrino inferred from missing $E,p$
$D^\ast+ \rightarrow D^0\pi^+$ used to improve S/N
Excellent $q^2$ resolution: $\sigma(q^2)=0.017$ GeV$^2$
Measure rate directly

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cx}|^2 p_X^3 |f_+(q^2)|^2$$
$e^+e^- \rightarrow c\bar{c}$ at $\sqrt{s}=10.6$ GeV

- Reconstruct $D^{*+} \rightarrow \pi^+ D^0$ and signal $D^0 \rightarrow K e^+\nu$
- Estimate $p_D$ and $E_\nu$ with remaining event & kinematic fits
- Use Neural Nets to suppress backgrounds

- high statistics
- good S/N
BaBar $f_+(q^2) \ D^0 \rightarrow K^- e^+ \nu$

$85k$ signal/$11k$ background

$q^2 = (p_D - p_X)^2$

- Corrected spectrum compared to LQCD$^1$, FOCUS$^2$

$^1$ Aubin et al. PRL 94, 011601 (2005)

$^2$ PLB607, 233 (2005)
CLEO-c $D \rightarrow \pi e^+ \nu$ & $D \rightarrow K e^+ \nu$

Presented by B. Xin Session B14

Tagged Analysis

281 pb$^{-1}$

Neutrino Reconstruction

U = $E_{\text{miss}} - |P_{\text{miss}}|$ (GeV)

- extremely clean
- well separated backgrounds
- $q^2$ resolution: $\sigma = 0.012$ GeV$^2$

- better statistics
- larger systematic uncertainty
~40% overlap in event samples
**D^0 → K^- e^+ v** Form Factor Comparisons

High statistics test of shape
CLEO prefers smaller slope $\alpha$


Single parameter fit
“modified pole”

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14 Apr 2007 K. Ecklund: Charm Decays @ APS Meeting
D^0 \rightarrow \pi^- e^+ \nu \text{ Form Factor Comparisons}

CLEO & Belle agree well
Compatible with LQCD

14 Apr 2007 K. Ecklund: Charm Decays @ APS Meeting
Summary & Conclusions

• Charm decays are measured with precision
• Charm measurements complement flavor physics investigations in the b sector
  - aid interpretation of B mixing
  - assist extraction of $V_{CKM}$ especially $V_{ub}$
  - by constraining QCD effects
• Unquenched Lattice QCD decay constant results appear trustworthy but...
  - experimental precision exceeds current LQCD
  - hints of differences for semileptonic Form factors
    - $\text{Kev}$ experimental discrepancy?
  - normalization of form factor $\Rightarrow$ 10% uncertainty on $V_{cx}$
• Additional data from BaBar, Belle, CLEO
  - more precise results to come!
Additional Slides
CLEO-c $D_s$ Hadronic results

- Tagging with $D_sD_s^*$
- $D_s^* \rightarrow D_s \gamma$

Partial BF for $D_s \rightarrow \phi \pi$
interference with $f_0(980)$

$M(KK)=M_\phi\pm10$ MeV
$BF=(1.98 \pm 0.12 \pm 0.09)\%$

$M(KK)=M_\phi\pm20$ MeV
$BF=(2.25 \pm 0.13 \pm 0.12)\%$
CLEO-c $D_s$ Hadronic Decays

$M_{inv}$ vs. $M_{bc}$ for $K^- K^+ \pi^+$ candidates in MC

Cut on $M_{bc}$ and use $M_{inv}$ to extract $D_s^* D_s$ events
Additional Hadronic Decays

- Additional modes from CLEO-c
  - PRL 96, 081802 (2006)
  - Single Tag Measurement

D^0 modes shown on left