Charm Decays from CLEO-c: Most Recent Results

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Presently running at $\approx 4 \text{pb}^{-1}$/day

**CLEO-c**

A Hermetic Detector

Wiggler Magnets (for damping)
Pair Production of D Mesons

Low Backgrounds and Quantum Correlations

Example:

\[ e^+e^- \rightarrow D^+D^- \]

\[ D^+ \rightarrow K_S\pi^+\pi^+\pi^- \]

\[ D^- \rightarrow \mu^-\bar{\nu}_\mu \]

\[ K_S \rightarrow \pi^+\pi^- \]
About CLEO-c ...

- The idea we call “D-Tagging” has proven to be a tremendously useful tool
- Production running is well underway
  - First $\psi(3770)$ run acquired 56pb$^{-1}$
  - Second $\psi(3770)$ run acquired 281pb$^{-1}$
  - First $D_s$ run to be completed this summer
  - Goal is $\approx 750$pb$^{-1}$ each for $\psi(3770)$ and $D_s$
- Research interests include B-factory input data, as well as charm in its own right
D Meson Decay Results

1. Leptonic: $D^+ \rightarrow \mu^+ \nu_\mu$ and $D^+ \rightarrow \tau^+ \nu_\tau$
2. Semileptonic exclusive branching ratios
3. Semileptonic inclusive lepton spectrum
4. Semileptonic $D \rightarrow K^*e^-\nu_e$ form factors
5. Hadronic branching ratios
   • Cross section at $\psi(3770)$
6. Cabibbo suppressed hadronic decays
7. Quantum interference phenomena
8. Preliminary results for $D_s$ mesons
   • Scan to find optimal production energy
Leptonic: $D^+ \rightarrow \mu^+ \nu_\mu$


**CLEO-c result:**

$$f_{D^+} = 222.6 \pm 16.7^{+2.8}_{-3.4} \text{ MeV}$$

**Theoretical models:**

<table>
<thead>
<tr>
<th>Model</th>
<th>$f_{D^+}$ (MeV)</th>
<th>$f_{D^+<em>s}/f</em>{D^+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice ($n_f=2+1$) [13]</td>
<td>$201 \pm 3 \pm 17$</td>
<td>$1.24 \pm 0.01 \pm 0.07$</td>
</tr>
<tr>
<td>QL (Taiwan) [14]</td>
<td>$235 \pm 8 \pm 14$</td>
<td>$1.13 \pm 0.03 \pm 0.05$</td>
</tr>
<tr>
<td>QL (UKQCD) [15]</td>
<td>$210 \pm 10^{+17}_{-16}$</td>
<td>$1.13 \pm 0.02^{0.04}_{-0.02}$</td>
</tr>
<tr>
<td>QL [16]</td>
<td>$211 \pm 14^{+0}_{-12}$</td>
<td>$1.10 \pm 0.02$</td>
</tr>
<tr>
<td>QCD Sum Rules [17]</td>
<td>$203 \pm 20$</td>
<td>$1.15 \pm 0.04$</td>
</tr>
<tr>
<td>QCD Sum Rules [18]</td>
<td>$195 \pm 20$</td>
<td></td>
</tr>
<tr>
<td>Quark Model [19]</td>
<td>$243 \pm 25$</td>
<td>$1.10$</td>
</tr>
<tr>
<td>Potential Model [20]</td>
<td>$238$</td>
<td>$1.01$</td>
</tr>
<tr>
<td>Isospin Splittings [21]</td>
<td>$262 \pm 29$</td>
<td></td>
</tr>
</tbody>
</table>

**Signal in Missing Mass**
Leptonic: $D^+ \rightarrow \tau^+ \nu_\tau$

Background contributions from various sources amount to five or six events. 

Upper limit (90% C.L.) on branching ratio is 1.8 times standard model prediction.

Note: $D^+ \rightarrow \mu^+ \nu_\mu$ analysis yields $B(D^+ \rightarrow e^+ \nu_\mu) < 2.4 \times 10^{-5}$
Semileptonic: Exclusive decays

- Needed to “climb the ladder” to $V_{ub}$
- Form factors are the main uncertainties
- CLEO-c form factors are on the way

The signal is cleanly separated from the background

$$D^+ \rightarrow \pi^0 e^+ \nu_e$$

$$D^+ \rightarrow K_{S} e^+ \nu_e$$

$U = E_{\text{miss}} - cP_{\text{miss}}$
Branching Ratios (%)

<table>
<thead>
<tr>
<th></th>
<th>$D \rightarrow \pi^+ e^+ \nu_e$</th>
<th>$D \rightarrow K^+ e^+ \nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+$</td>
<td>$0.44 \pm 0.06 \pm 0.03$</td>
<td>$8.71 \pm 0.38 \pm 0.37$</td>
</tr>
<tr>
<td>$D^0$</td>
<td>$0.262 \pm 0.025 \pm 0.008$</td>
<td>$3.44 \pm 0.10 \pm 0.10$</td>
</tr>
</tbody>
</table>

Combinations

$$\frac{B(D^0 \rightarrow \pi^- e^+ \nu_e)}{B(D^0 \rightarrow K^- e^+ \nu_e)} = 0.076 \pm 0.008 \pm 0.002$$

$$\frac{\Gamma(D^0 \rightarrow K^- e^+ \nu_e)}{\Gamma(D^+ \rightarrow \bar{K}^0 e^+ \nu_e)} = 1.00 \pm 0.05 \pm 0.04$$

$$\frac{\Gamma(D^0 \rightarrow \pi^- e^+ \nu_e)}{2 \times \Gamma(D^+ \rightarrow \pi^0 e^+ \nu_e)} = 0.75^{+0.14}_{-0.11} \pm 0.04$$

All results based on early sample of 56 $\text{pb}^{-1}$ at $\psi(3770)$
Semileptonic: Inclusive lepton spectrum

hep-ex/0604044 (Submitted to Phys.Rev.Lett.)

\[ BR(D^0 \rightarrow X e^+ \nu_e) = (6.16 \pm 0.17 \pm 0.13) \times 10^{-2} \]

\[ BR(D^+ \rightarrow X e^+ \nu_e) = (16.13 \pm 0.20 \pm 0.33) \times 10^{-2} \]

Note: These are nearly saturated by measured exclusive semileptonics!
Semileptonic: $D \rightarrow K^* e \nu$ form factors

Model Independent Analysis: hep-ex/0606010

Very clean signal

Use all kinematic information to extract form factors as a function of $q^2 = M(l\nu)^2$
Results (Submitted to Phys Rev D)

**P-Wave Dominant**

*(Nominal and tight cuts included)*

**S-Wave Apparent**

\[-h_0(q^2)H_0(q^2)\text{Re}\{Ae^{i\delta(BW)}\}\]

Below $K^*$

Above $K^*$

**Little D-wave or F-Wave**

Lines are fit to FOCUS data
D⁺,D⁰ Hadronic Branching Ratios

Double tag technique used to get branching ratios and total cross sections.

Note: These are log plots!
Hadronic Decay

Results from $56^{-1}_{\text{pb}}$: Phys.Rev.Lett.95(2005)121801

CLEO-c $\div$ PDG

$D^0 \rightarrow K^-\pi^+$

CLEO II average
ALEPH 97
ARGUS (D^{**})
ARGUS (B)
ALEPH 91
HRS
Mark III
Mark II
Mark I
BES II

CLEO-c
Cabibbo Suppressed Hadronic Decays

Cabibbo allowed decays used for reference.
Results and comparison to PDG...

Errors are a significant improvement, and often a “first measurement”

<table>
<thead>
<tr>
<th>Mode</th>
<th>(B_{\text{mode}} / B_{\text{ref}}) (%)</th>
<th>(B_{\text{mode}}) (10^{-3})</th>
<th>(B) (PDG) (10^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D^0 \rightarrow \pi^+\pi^-)</td>
<td>3.62 ± 0.10 ± 0.07 ± 0.04</td>
<td>1.39 ± 0.04 ± 0.04 ± 0.03 ± 0.01</td>
<td>1.38 ± 0.05</td>
</tr>
<tr>
<td>(D^0 \rightarrow \pi^0\pi^0)</td>
<td>2.05 ± 0.13 ± 0.16 ± 0.02</td>
<td>0.79 ± 0.05 ± 0.06 ± 0.01 ± 0.01</td>
<td>0.84 ± 0.22</td>
</tr>
<tr>
<td>(D^0 \rightarrow \pi^+\pi^-\pi^0)</td>
<td>34.4 ± 0.5 ± 1.2 ± 0.3</td>
<td>13.2 ± 0.2 ± 0.5 ± 0.2 ± 0.1</td>
<td>11 ± 4</td>
</tr>
<tr>
<td>(D^0 \rightarrow \pi^+\pi^-\pi^-)</td>
<td>19.1 ± 0.4 ± 0.6 ± 0.2</td>
<td>7.3 ± 0.1 ± 0.3 ± 0.1 ± 0.1</td>
<td>7.3 ± 0.5</td>
</tr>
<tr>
<td>(D^0 \rightarrow \pi^+\pi^-\pi^0\pi^0)</td>
<td>25.8 ± 1.5 ± 1.8 ± 0.3</td>
<td>9.9 ± 0.6 ± 0.7 ± 0.2 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>(D^0 \rightarrow \pi^+\pi^+\pi^-\pi^-)</td>
<td>10.7 ± 1.2 ± 0.5 ± 0.1</td>
<td>4.1 ± 0.5 ± 0.2 ± 0.1 ± 0.0</td>
<td></td>
</tr>
<tr>
<td>(D^0 \rightarrow \omega\pi^+\pi^-)</td>
<td>4.1 ± 1.2 ± 0.4 ± 0.0</td>
<td>1.7 ± 0.5 ± 0.2 ± 0.0 ± 0.0</td>
<td></td>
</tr>
<tr>
<td>(D^0 \rightarrow \eta\pi^0)</td>
<td>1.47 ± 0.34 ± 0.11 ± 0.01</td>
<td>0.62 ± 0.14 ± 0.05 ± 0.01 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>(D^0 \rightarrow \pi^0\pi^0\pi^0)</td>
<td>&lt; 0.35 (90% CL)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(D^0 \rightarrow \eta\pi^+\pi^-)</td>
<td>&lt; 1.9 (90% CL)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(D^+ \rightarrow \pi^+\pi^-)</td>
<td>1.33 ± 0.07 ± 0.06</td>
<td>1.25 ± 0.06 ± 0.07 ± 0.04</td>
<td>1.33 ± 0.22</td>
</tr>
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<td>(D^+ \rightarrow \pi^+\pi^+\pi^-)</td>
<td>3.52 ± 0.11 ± 0.12</td>
<td>3.35 ± 0.10 ± 0.16 ± 0.12</td>
<td>3.1 ± 0.4</td>
</tr>
<tr>
<td>(D^+ \rightarrow \pi^+\pi^0\pi^0)</td>
<td>5.0 ± 0.3 ± 0.3</td>
<td>4.8 ± 0.3 ± 0.3 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>(D^+ \rightarrow \pi^+\pi^+\pi^-\pi^0)</td>
<td>12.4 ± 0.5 ± 0.6</td>
<td>11.6 ± 0.4 ± 0.6 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>(D^+ \rightarrow \pi^+\pi^+\pi^-\pi^-)</td>
<td>1.73 ± 0.20 ± 0.17</td>
<td>1.60 ± 0.18 ± 0.16 ± 0.06</td>
<td>1.73 ± 0.23</td>
</tr>
<tr>
<td>(D^+ \rightarrow \eta\pi^+)</td>
<td>3.81 ± 0.26 ± 0.21</td>
<td>3.61 ± 0.25 ± 0.23 ± 0.12</td>
<td>3.0 ± 0.6</td>
</tr>
<tr>
<td>(D^+ \rightarrow \omega\pi^+)</td>
<td>-</td>
<td>&lt; 0.34 (90% CL)</td>
<td></td>
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</table>
Quantum Interference Phenomena

For \( e^+ e^- \rightarrow \bar{D}^0 D^0 \) expect \( CP(\bar{D}^0 D^0) = -1 \)

This can be exploited in a number of ways, including extract CP content for multibody charm decays and searching for CP violation.

CLEO-c is studying the ways we can use this in our data, and looking forward to applying these ideas to new data samples.

**Example:** Pure CP eigenstate final states

> Statistical errors only!

<table>
<thead>
<tr>
<th></th>
<th>$K^+K^-$</th>
<th>$\pi^+\pi^-$</th>
<th>$K_S\pi^0\pi^0$</th>
<th>$K_S\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+K^-$</td>
<td>5.2±0.4</td>
<td>4.5±0.3</td>
<td>5.7±0.4</td>
<td>16.0±0.6</td>
</tr>
<tr>
<td></td>
<td>-2.2±1.9</td>
<td>0.1±0.9</td>
<td>1.6±1.3</td>
<td>39.6±6.3</td>
</tr>
<tr>
<td>$\pi^+\pi^-$</td>
<td>1.1±0.2</td>
<td>2.2±0.2</td>
<td>5.8±0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2±1.4</td>
<td>1.6±1.3</td>
<td></td>
<td>14.0±3.7</td>
</tr>
<tr>
<td>$K_S\pi^0\pi^0$</td>
<td>1.2±0.2</td>
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<td>$K_S\pi^0$</td>
<td></td>
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<td>9.7±0.5</td>
<td>3.0±1.7</td>
</tr>
</tbody>
</table>
Preliminary results for $D_s$ mesons

First: Conduct energy scan to find optimum cross section
D meson exclusive cross sections (preliminary)

Resonance structure?

Plateau

Very small cross section for DD
$D_s$ meson exclusive cross sections (preliminary)

Resonance structure?

CLEO-c running point

Tricky! There is an extra photon

$E_{cm}$ (GeV)
Ds Hadronic Decays

$$K_S K^+ \quad 788 \pm 34$$

$$K^- K^+ \pi^+ \quad 3344 \pm 77$$

$$K^- K^+ \pi^+ \pi^0 \quad 709 \pm 54$$

$$\pi^+ \pi^+ \pi^- \quad 539 \pm 41$$

More data will be taken this summer.
Future CLEO-c Run Plan

- Increase $\psi(3770)$ sample to $\approx 750 \text{ pb}^{-1}$
  
  Primary goal is to triple D samples

- Increase 4170 sample to $\approx 750 \text{ pb}^{-1}$
  
  Multiply $D_s$ sample by about four, and investigate aspects of a resonance at 4170

- Acquire 30M $\psi(2S)$ (Summer 2006)
  
  Large charmonium program ready to go

**CLEO-c slated for turn-off in March 2008!**
Conclusion

CLEO has had a long and fruitful life, running at CESR at Cornell for more than 25 years.

CLEO-c has produced many new results on charm physics, and many more results are on the way.

Many in our collaboration believe that charm physics still has many secrets yet to be revealed.

BES III has a very bright future!