The Physics of Charm: Recent Experimental Results

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What is Special about Charm?

1) *Its mass.* The charm quark is “heavy”...

... but not “too” heavy.

*Most decay modes of hadrons with charm are “easy” to observe experimentally.*
2) *Its decays.* Charm is the only heavy quark that forms hadrons with CKM-allowed decays.
The Experiments

e^+e^- and Photon Beams

Hadroproduction

BES

CLEO

BABAR

Belle

CDF

E835
A Survey of Recent Results

My own selection! My apologies for not covering it all!

• “Precision” Measurements
  Small error bars, stringent limits, and tying up old loose ends

• New States  (Note: Talk tomorrow by R. Waldi)
  A resurgence in charmonium

• Confronting Lattice QCD
  Testing “high precision” lattice calculations

• D^0 Mixing and Tests of CP Violation
  Current status and future prospects
The $D_s$ Lifetime

$\gamma N \rightarrow (K^+ K^- \pi^\pm) X$

$D_s$ signal  Sidebands

$\tau(D_s) = 507.4 \pm 5.5 \pm 5.1 \text{ fs}$
**Limit: $D^+ \rightarrow \pi^+ \mu^+ \mu^-$**

Possible new physics in charm FCNC

**Observe:**

$D^+ \rightarrow \phi \pi^+$

with $\phi \rightarrow \mu^+ \mu^-$

**Put limits on:**

$D^+ \rightarrow \pi^+ \mu^+ \mu^-$ with anti-$\phi$ cut

$\Rightarrow \text{BR}(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 4.7 \times 10^{-6}$

Tevatron experiments make a lot of charm!
\[ \psi(3770) \rightarrow \text{hadrons} \]

**CLEO-c: Closing the gap**

\[
\sigma(e^+e^- \rightarrow D\bar{D}) = 6.39 \pm 0.10^{+0.17}_{-0.08} \text{ nb}
\]

\[
\sigma(e^+e^- \rightarrow \text{hadrons}) = 6.38 \pm 0.08^{+0.41}_{-0.30} \text{ nb}
\]

*Upper limit on gap is \( \approx 10\% \). Other observed modes \( \approx 2\% \).*

**BES III: Resonance scan of \( \psi(3770) \)**

*hep-ex/0605105 and hep-ex/0605107*

Find room for possible non-\( DD \) contribution of \( \approx 16 \pm 8\% \).

*Consistent with CLEO-c, worth more study.*

"Precision" Measurements

PRL 95(2005)121801

PRL 96(2006)092002
$^1P_1$ Charmonium: The $h_c(3525)$
Radial $\chi_{cJ}$ Excitations?

$e^+e^- \rightarrow J/\psi + X(3940)$
Consistent with $J^{PC}=0^{++}$

$\gamma\gamma \rightarrow Z(3930) \rightarrow D\bar{D}$
Consistent with $J^{PC}=2^{++}$
The $Y(4260)$

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ using “radiative return”
**D_s Decay Constant**

**Lattice QCD calculates:**
\[ f_{D_s} = 249 \pm 3 \pm 16 \text{ MeV} \]

**PRL 95(2005)122002**

Uses “charm tagging” to find leptonic decays of D_s from \( D_s^* \to \gamma D_s \)

**BaBar finds:**
\[ f_{D_s} = 279 \pm 17 \pm 6 \pm 19 \text{ MeV} \]

*Third error from branching ratio for \( D_s \to \phi \pi \), recent from BaBar and which CLEO-c will measure to higher precision.*
**Example:** $D \rightarrow \mu \nu$

$e^+ e^- \rightarrow D^+ D^-$

$D^+ \rightarrow K_s \pi^- \pi^+ \pi^+$

$D^- \rightarrow \mu^- \bar{\nu}_\mu$
D$^+$ Decay Constant

CLEO-c finds:

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

Lattice QCD calculates:

$$f_D = 201 \pm 3 \pm 17 \text{ MeV}$$

PRL 95(2005) 122002

- Important test of actions that use “staggered fermions.”
- Same for determinations of $f_{D_s}$.
- More results to come!
Semileptonic Form Factors

Belle: hep-ex/0604049

\[ D^0 \rightarrow K \nu \]

\[ D^0 \rightarrow \pi \nu \]

Lattice QCD


Pole model

ISGW2 prediction

Low background results from CLEO-c are on the way.
Semileptonic Decay

Look for “Wrong Sign” lepton using \( D^{*\pm} \rightarrow D^0 \pi^\pm \) to tag flavor

\[ \Delta M = M_{D^*} - M_{D^0} \]

“Right” Sign

“Wrong” Sign as a function of decay time

Upper limit on mixing rate \( r_D < 1.0 \times 10^{-3} \)
D⁰ → Kπ DCS & Mixing

Belle: Time Dependence

PRL 96(2006)151801

CDF: Wrong sign Kπ

hep-ex/0605027

R_D = 0.405 ± 0.021 ± 0.011%

Tag flavor using D* → πD

R_D = 0.377 ± 0.008 ± 0.005%
Limits on Mixing Parameters

D. Asner, Review in 2006 Particle Data Group compilation
### CPV Summary: S. Stone, FPCP 06

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mode</th>
<th>$A_{CP}$ (%)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>$D^+ \rightarrow K^+K^-\pi^+$</td>
<td>$1.4\pm1.0\pm0.8$</td>
<td>Exploits resonant substructure</td>
</tr>
<tr>
<td>BaBar</td>
<td>$D^+ \rightarrow \phi\pi^+$</td>
<td>$0.2\pm1.5\pm1.6$</td>
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<tr>
<td>BaBar</td>
<td>$D^+ \rightarrow K^{*0}K^+$</td>
<td>$0.9\pm1.7\pm0.7$</td>
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<tr>
<td>CLEO II.V</td>
<td>$D^0 \rightarrow \pi^+\pi^-\pi^0$</td>
<td>$1^{+9}_{-7}\pm8$</td>
<td>Dalitz plot</td>
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<tr>
<td>CDF</td>
<td>$D^0 \rightarrow K^+K^-$</td>
<td>$2.0\pm1.2\pm0.6$</td>
<td>Direct CP</td>
</tr>
<tr>
<td>CDF</td>
<td>$D^0 \rightarrow \pi^+\pi^-$</td>
<td>$1.0\pm1.3\pm0.6$</td>
<td></td>
</tr>
<tr>
<td>FOCUS</td>
<td>$D^0 \rightarrow K^+K^-\pi^+\pi^-$</td>
<td>$1.0\pm5.7\pm3.7$</td>
<td>Triple correlations to get at $T$-violation</td>
</tr>
<tr>
<td>FOCUS</td>
<td>$D^+ \rightarrow K^0K^+\pi^+\pi^-$</td>
<td>$2.3\pm6.2\pm2.2$</td>
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<tr>
<td>FOCUS</td>
<td>$D_s^+ \rightarrow K^0K^+\pi^+\pi^-$</td>
<td>$-3.6\pm6.7\pm2.3$</td>
<td></td>
</tr>
</tbody>
</table>
D^0 \rightarrow K^*K: A Tool for B^\pm \rightarrow D^0 K^\pm

D^0 \rightarrow K^+K^-\pi^0 Dalitz analysis

\textit{Destructive interference:}
\[ \delta_D = 332^\circ \pm 8^\circ \pm 11^\circ \]

\textit{Amplitude ratio:}
\[ \frac{|A(K^*^-K^+)|}{|A(K^{*+}K^-)|} = 0.52 \pm 0.05 \pm 0.04 \]
Quantum Correlations

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.

BES III will be in an excellent position to capitalize!

### D⁰ Mixing and CP

#### Statistical errors only!

<table>
<thead>
<tr>
<th></th>
<th>K⁺K⁻</th>
<th>π⁺π⁻</th>
<th>Kₛπ⁰π⁰</th>
<th>Kₛπ⁰</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>
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<td>-2.2±1.9</td>
<td>0.1±0.9</td>
<td>1.6±1.3</td>
<td>39.6±6.3</td>
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<td>π⁺π⁻</td>
<td>1.1±0.2</td>
<td>2.2±0.2</td>
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<tr>
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<td>0.2±1.4</td>
<td>1.6±1.3</td>
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<td>Kₛπ⁰π⁰π⁰</td>
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<td>1.0±1.0</td>
<td>19.0±4.4</td>
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<td>Kₛπ⁰</td>
<td>9.7±0.5</td>
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<tr>
<td></td>
<td>3.0±1.7</td>
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Preliminary CP+ No QC Data

Product CP+

Product CP−
The Future

• Expect more from Belle, BaBar, CDF, and D0
  They produce lots of charm!

• CLEO-c will run through March 2008
  Expect ≈3M D-pairs (charged and neutral)
  Also “thousands” of tagged $D_s$ Sneak Peek!

• BES III coming on line in the next few years
  Data samples to be ≈25× CLEO-c

• Don’t forget about LHCb, PANDA, ...

Obrigado!

Also, thanks to all the experiments, and especially to R. Briere!
**CLEO-c Preliminary: $D_s$ Hadronic Decays**

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<th>Mode</th>
<th>CLEO-c (%)</th>
<th>PDG 2004 fit (%)</th>
</tr>
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<tbody>
<tr>
<td>$\mathcal{B}(K_S K^+)$</td>
<td>$1.28^{+0.13}_{-0.12} \pm 0.07$</td>
<td>$1.8 \pm 0.55$</td>
</tr>
<tr>
<td>$\mathcal{B}(K^- K^+ \pi^+)$</td>
<td>$4.54^{+0.44}_{-0.42} \pm 0.25$</td>
<td>$4.3 \pm 1.2$</td>
</tr>
<tr>
<td>$\mathcal{B}(K^- K^+ \pi^+ \pi^0)$</td>
<td>$4.83^{+0.49}_{-0.47} \pm 0.46$</td>
<td>—</td>
</tr>
<tr>
<td>$\mathcal{B}(\pi^+ \pi^+ \pi^-)$</td>
<td>$1.02^{+0.11}_{-0.10} \pm 0.05$</td>
<td>$1.00 \pm 0.28$</td>
</tr>
</tbody>
</table>