The Physics of Charm: Recent Experimental Results

Jim Napolitano
Rensselaer Polytechnic Institute
and the CLEO-c Collaboration

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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
BaBar
Belle
DO
CDF
E835
CLEO
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

- **D⁰ 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

$\tau(D_s) = 507.4 \pm 5.5 \pm 5.1$ 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!
ψ(3770) \rightarrow 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 ψ(3770)

hep-ex/0605105 and hep-ex/0605107

Find room for possible non-\( D\bar{D} \) contribution of \( \approx 16\pm8\% \).

Consistent with CLEO-c, worth more study.
$\bar{p}p \rightarrow \gamma \eta_c$

$\rightarrow \gamma \gamma \gamma$

$e^+ e^- \rightarrow \psi(2S) \rightarrow \pi^0 h_c$

$h_c \rightarrow \gamma \eta_c$

New States

$^{1}P_1$ Charmonium: The $h_c(3525)$

PRD 72(2005)032001

PRD 72(2005)092004
Radial $\chi_{cJ}$ Excitations?

$e^+e^- \rightarrow \jpsi + \chi_{c0}(3940)$

Consistent with $J^{PC}=0^{++}$

$\gamma\gamma \rightarrow \zeta(3930) \rightarrow D\bar{D}$

Consistent with $J^{PC}=2^{++}$
The Y(4260)

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ using "radiative return"

$\psi(3770)$  $\psi(4040)$  $\psi(4160)$  $\psi(4260)$  $\psi(4260)$

$\pi^+\pi^- J/\psi$

$\pi^0\pi^0 J/\psi$

$\eta J/\psi$

$\sigma (e^+e^- \rightarrow \pi\pi J/\psi)$

$\sigma (e^+e^- \rightarrow \psi (2S))$
**Ds Decay Constant**

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

*PRL 95(2005)122002*

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

Third error from branching ratio for \( D_s \to \varphi \pi \), recent from BaBar and which CLEO-c will measure to higher precision.

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

\[ \Delta M = M_{Ds^*} - M_{Ds} \]
**Example: D → μν**

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

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

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

\[ K_S \rightarrow \pi^+ \pi^- \]
D$^+$ Decay Constant

CLEO-c finds:

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

Lattice QCD calculates:

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

- 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**

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

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

**Lattice QCD**

*Nucl. Phys. Proc. Suppl.* 129 (2004) 334

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 $r_D < 1.0 \times 10^{-3}$
CDF: Wrong sign Kπ

hep-ex/0605027

$R_D = 0.405 \pm 0.021 \pm 0.011\%$

Tag flavor using $D^* \rightarrow \pi D$

$R_D = 0.377 \pm 0.008 \pm 0.005\%$
Limits on Mixing Parameters

D. Asner, Review in 2006 Particle Data Group compilation

Both the sign and magnitude of $x$ and $y$ may be measured using the time-dependent resonant substructure of $K^{+}\rightarrow\pi^{+}\pi^{0}\pi^{0}$.

$\delta_{K\pi} = 0^\circ$ assumed
95% C.L. Limits

$y' (\%)$ vs. $x' (\%)$
| Experiment   | Mode                      | $A_{CP}$ (%) | Notes                                      |
|--------------|---------------------------|--------------|--------------------------------------------|
| BaBar        | $D^+ \rightarrow K^+K^−\pi^+$ | $1.4\pm1.0\pm0.8$ | Exploits resonant substructure             |
| BaBar        | $D^+ \rightarrow \phi\pi^+$  | $0.2\pm1.5\pm1.6$ |                                            |
| BaBar        | $D^+ \rightarrow K^*0K^+$    | $0.9\pm1.7\pm0.7$ |                                            |
| CLEO II.V    | $D^0 \rightarrow \pi^+\pi^-\pi^0$ | $1.9^{+1.9}_{-1.6}$ | Dalitz plot                                |
| CDF          | $D^0 \rightarrow K^+K^−$     | $2.0\pm1.2\pm0.6$ | Direct CP                                  |
| CDF          | $D^0 \rightarrow \pi^+\pi^−$ | $1.0\pm1.3\pm0.6$ |                                            |
| FOCUS        | $D^0 \rightarrow K^+K^−\pi^+\pi^−$ | $1.0\pm5.7\pm3.7$ | Triple correlations to get at $T$-violation |
| FOCUS        | $D^+ \rightarrow K^0K^+\pi^+\pi^−$ | $2.3\pm6.2\pm2.2$ |                                            |
| FOCUS        | $D_s^+ \rightarrow K^0K^+\pi^+\pi^−$ | $−3.6\pm6.7\pm2.3$ |                                            |
**D^0 → K^* K:**

A Tool for B^± → D^0 K^±

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**D^0 → K^+ K^- π^0** Dalitz analysis

**Destructive interference:**

\[ \delta_D = 332^\circ \pm 8^\circ \pm 11^\circ \]

**Amplitude ratio:**

\[ |A(K^*-K^+)|/|A(K^+K^-)| = 0.52 \pm 0.05 \pm 0.04 \]

Submitted to Phys Rev D
Quantum Correlations

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

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!

Ref: D. Asner and W. Sun, Phys. Rev. D73(2006)034024
### D⁰ Mixing and CP

**Statistical errors only!**

|       | **K⁺K⁻** | **π⁺π⁻** | **Kₛπ⁰π⁰** | **Kₛπ⁰** |
|-------|-----------|-----------|-------------|----------|
| **K⁺K⁻** | 5.2±0.4  | 4.5±0.3  | 5.7±0.4  | 16.0±0.6 |
|       | -2.2±1.9 | 0.1±0.9  | 1.6±1.3  | 39.6±6.3 |
| **π⁺π⁻** | 1.1±0.2  | 2.2±0.2  | 5.8±0.4  |
|       | 0.2±1.4  | 1.6±1.3  | 14.0±3.7 |
| **Kₛπ⁰π⁰** |         | 1.2±0.2  | 7.3±0.4  |
|       |         | 1.0±1.0  | 19.0±4.4 |
| **Kₛπ⁰** | Product CP+ |         | 9.7±0.5  |
|       | Product CP− |         | 3.0±1.7  |

**No QC Data**

Statistical errors only!

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- CP+
- 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 $\approx 25 \times$ 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

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