“Heavy and Light”: Hadron Spectroscopy and Strong Interaction Dynamics from CLEO III and CLEO-c

Jim Napolitano, Rensselaer Polytechnic Institute for the CLEO Collaboration
Topics Covered in this Talk

New (and Developing) Results

• Color Singlet vs Octet in $\Upsilon(1S) \rightarrow J/\psi + X$
• Branching Ratios for $\Upsilon(nS) \rightarrow \mu^+\mu^-$
• Decays of the $\psi(2S)$
• Strong Physics from Weak Decays of $D^+, D^0$
• Measuring the Scalar Meson Mass Matrix

There is a lot that I’m leaving out!!
Color Singlet vs Octet in $\Upsilon(1S) \rightarrow J/\psi + X$

hep-ex/0407030 (Accepted for Phys.Rev.D)

Color Singlet

Color Octet

Color singlet mechanism predicts a softer $J/\psi$ momentum spectrum because of additional charmed particles

Note: $J/\psi$ Production mechanism important for RHIC physics (See M. Leitch talk yesterday, Session D.)
Result

Mechanism is still not understood!

Find branching ratio \((6.4\pm0.4\pm0.6)\times10^{-4}\) consistent with either color singlet or octet.

CLEO plans to search for open charm in these decays.
Results: Other Charmonium States

ψ(2S)

χ_{cj}

$$\tau(1S) \rightarrow \psi(2S) + X$$

Signal: 56 ± 11

$${\mathcal B}/B_{J/\psi} = 0.41 \pm 0.11 \pm 0.08$$

$${\mathcal B}(j=1)/B_{J/\psi} = 0.35 \pm 0.08 \pm 0.06$$

$${\mathcal B}(j=2)/B_{J/\psi} = 0.52 \pm 0.12 \pm 0.09$$
Branching Ratios for $\Upsilon(nS) \rightarrow \mu^+ \mu^-$

hep-ex/0409027 (Submitted to Phys.Rev.Lett.)

The total widths $\Gamma_{\text{tot}}$ of the narrow upsilon resonances are *too small* to measure directly.

We instead use two separate measurements (and lepton universality) to extract $\Gamma_{\text{tot}} = \Gamma_{ee}/B_{\mu\mu}$:

- Branching ratios $B_{\mu\mu}$ from $\Upsilon(nS) \rightarrow \mu^+ \mu^-$
  
  *New results presented here*

- $\Gamma_{ee}$ from cross section for $e^+e^- \rightarrow \Upsilon(nS) \rightarrow \text{hadrons}$
  
  *Analysis in progress*

*Our goal is to match the precision of LQCD predictions!*
Results

Branching ratios (%):

<table>
<thead>
<tr>
<th></th>
<th>Branching Ratio</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Υ(1S)</td>
<td>52.8±1.8</td>
<td></td>
</tr>
<tr>
<td>Υ(2S)</td>
<td>29.0±1.6</td>
<td></td>
</tr>
<tr>
<td>Υ(3S)</td>
<td>20.3±2.1</td>
<td></td>
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</tbody>
</table>

Total widths (keV):

Errors dominated by $\sigma(e^+e^-)$
Decays of the $\psi(2S)$

Various Measurements Just Completed or In Progress

- **Inclusive Photon Spectrum**
  hep-ex/0408133 (*Submitted to Phys.Rev.Lett.*)

- **$\psi(2S) \rightarrow$ Vector + Pseudoscalar**
  hep-ex/0407028 (*Submitted to Phys.Rev.Lett.*)

- **Multibody Decays**
  hep-ex/0408084 (*Preliminary*)

- **Search for the $h_C$**
  Several analyses (*inclusive and exclusive*) in progress
Results: $\psi(2S) \rightarrow \text{Vector + Pseudoscalar}$

Data Taken On and Off Resonance

Dashes = Monte Carlo
Results: $\psi(2S) \rightarrow \text{Vector + Pseudoscalar}$

Focus on $\pi^+\pi^-\pi^0$ including $\rho\pi$

On Resonance

Off Resonance

Note: Data taken off resonance is important and is a measurement in its own right!
Strong Physics from Weak Decays of $D^0, D^+$

Three Pieces of Physics:

1) Three body decays of $D$ mesons

   Evidence (or not) for low mass scalar mesons

2) Form Factors in $D^0 \rightarrow \{K^-, \pi^- \} e^+ \nu_e$

   CLEO-c: hep-ex/0408077 (*Preliminary*)

3) $D^+$ Decay Constant in $D^+ \rightarrow \mu^+ \nu_{\mu}$

   CLEO-c: hep-ex/0408071 (*Preliminary*)
1) Three body decays of D mesons

*Example:* $\kappa \to K^-\pi^+$ in $D^+ \to K^-\pi^+\pi^+$ ??

Fermilab E791

CLEO-c
2) Form Factors in $D^0 \rightarrow \{K^-, \pi^-\} e^+ \nu_e$

Various techniques (including Lattice QCD) used to calculate the form factor as a function of $q^2$.

CLEO-III: Use "continuum" inclusive $D^0$ production
CLEO-c: Use "tagged" exclusive $D^0$ production

Note: $V_{cs} \gg V_{cd}$ so $\Gamma(D^0 \rightarrow K^- e^+ \nu_e) \gg \Gamma(D^0 \rightarrow \pi^- e^+ \nu_e)$

$\Rightarrow$ The $\pi$’s have a potentially large background from $K$’s!
CLEO III $D^0 \rightarrow \{K^-, \pi^-\} e^+ \nu_e$

**Difficult Analysis**

Mid $q^2$ Bin
C.L. = 28%

Mid $q^2$ Bin
C.L. = 52%
Results: Form Factors

\((\text{CLEO III } D^0 \rightarrow \{K^-, \pi^-\} e^+ \nu_e)\)
Cleaner Analysis in CLEO-c

\[ D^0 \rightarrow K^- e^+\nu \]
- data
- \[ D^0 \rightarrow K^- e^+\nu \] MC
- \[ D^0 \] other decays MC
- \[ D^0 \rightarrow K^- e^+\nu \] MC
- \[ D^0 \rightarrow \pi^- e^+\nu \] MC
- \[ D^+ \] MC
- Rad. Ret. MC
- cont. MC

\[ D^0 \rightarrow \pi^- e^+\nu \]
- data
- \[ D^0 \rightarrow \pi^- e^+\nu \] MC
- \[ D^0 \rightarrow K^- e^+\nu \] MC
- \[ D^0 \] other decays MC
- \[ D^0 \rightarrow \rho^- e^+\nu \] MC
- \[ D^+ \] MC
- Rad. Ret. MC
- cont. MC

Events/4 MeV

Events/5 MeV

\[ U=E_{\text{miss}}-p_{\text{miss}} \text{ (GeV)} \]
Preliminary Results

CLEO-c $D^0 \rightarrow \{K^-, \pi^-\} e^+ \nu_e$ Uncorrected Spectra

Expect $\approx 50$ times as much data in upcoming runs!
3) $D^+$ Decay Constant in $D^+ \rightarrow \mu^+ \nu_{\mu}$

$f_{D^+}$ can be calculated in Lattice QCD and in models.

However, $B(D^+ \rightarrow \mu^+ \nu_{\mu}) \sim 10^{-4}$ is small.

Therefore, backgrounds can be a severe problem.

*Measurement is very well suited to CLEO-c!*
Example: Data from $\psi(3770) \rightarrow D^+D^-$

Event: 98595

Tag the event using $D^+ \rightarrow K_S \pi^+\pi^+\pi^-$

Look opposite for $D^- \rightarrow \mu^-\nu_\mu$ with “missing” neutrino

Similar event topology from $D^- \rightarrow \pi^-K^0$
Preliminary Results \((\text{CLEO-c } D^+ \rightarrow \mu^+ \nu_\mu)\)

Background estimate:

<table>
<thead>
<tr>
<th>Mode</th>
<th>(\mathcal{B}) (%)</th>
<th># of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi^+\pi^0)</td>
<td>0.13(\pm 0.02)</td>
<td>0.31(\pm 0.04)</td>
</tr>
<tr>
<td>(K^0\pi^+)</td>
<td>2.77(\pm 0.18)</td>
<td>0.06(\pm 0.05)</td>
</tr>
<tr>
<td>(\tau^+\nu)</td>
<td>3.2(\times) (\mu^+\nu)</td>
<td>0.36(\pm 0.08)</td>
</tr>
<tr>
<td>(\pi^0\mu^+\nu)</td>
<td>0.31 (\pm 0.15)</td>
<td>negligible</td>
</tr>
</tbody>
</table>

Find eight events with an estimated background of one

\[ \mathcal{B} = (3.5 \pm 1.4 \pm 0.6) \times 10^{-4} \]

\[ f_{D^+} = (201 \pm 41 \pm 17) \text{ MeV} \]

Consistent with LQCD

 Plenty more data to come!
Measuring the Scalar Meson Mass Matrix

Establishing the lightest glueball using CLEO-c

QCD predicts three light isoscalar $J^{PC}=0^{++}$ mesons:

$$\frac{1}{\sqrt{2}} \left[ u\bar{u} + d\bar{d} \right] s\bar{s} \text{ glueball}$$

Three states are observed in nature:

$$f_0(1370) \quad f_0(1500) \quad f_0(1710)$$

How are these states mixed?

The answer should give us insight into hadron dynamics
Mixing is described by a mass matrix

\[
\begin{bmatrix}
M_{n\bar{n}} & \Delta_{ns} & \Delta_{ng} \\
\Delta^*_{\bar{n}s} & M_{s\bar{s}} & \Delta_{sg} \\
\Delta^*_{ng} & \Delta^*_s & M_g
\end{bmatrix}
\]

Lattice QCD calculations of $M_g$ are well known.

What are the prospects for calculating other matrix elements, in particular the off-diagonal ones?

Plans for CLEO-c: $J/\psi$ Radiative Decay

Populate states using $J/\psi \rightarrow \gamma f_0$

Measure decay rates for $f_0 \rightarrow \gamma V$


<table>
<thead>
<tr>
<th>State</th>
<th>$f_0 \rightarrow \gamma\rho(770)$</th>
<th>$f_0 \rightarrow \gamma\phi(1020)$</th>
<th>$\Gamma_{Tot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L</td>
<td>M</td>
<td>H</td>
</tr>
<tr>
<td>$f_0(1370)$</td>
<td>443</td>
<td>1121</td>
<td>1540</td>
</tr>
<tr>
<td>$f_0(1500)$</td>
<td>2519</td>
<td>1458</td>
<td>476</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>42</td>
<td>94</td>
<td>705</td>
</tr>
</tbody>
</table>

Goal for CLEO-c: $10^9 J/\psi$
Conclusions

• CLEO is enjoying life after B physics, with much of our research program aimed at hadronic spectroscopy and dynamics.

• Many new results are out now, based on our first low energy data sets.

• Much more data to come, to increase our statistics and to explore new ground.

Thank You!