CLEO-c: Progress and Future

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Outline

• Motivations
• CLEO-c and CESR-c
• Preliminary CLEO-c Results
• CLEO-c Gluonic Program
• Summary and Outlook

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Motivations for CLEO-c and CESR-c

CLEO made substantial progress in measuring nonperturbative parameters that relate observables to underlying parton-level processes and CKM matrix elements.

- Much remains to be accomplished since we are rapidly approaching a situation where theoretical uncertainties will dominate all experimental CKM uncertainties.
  - Theoretical uncertainties already totally dominate the uncertainty in $|V_{td}|$.
  - Theoretical uncertainties are still significant in measurements of $|V_{cb}|$ and $|V_{ub}|$.
  - Experimental uncertainties will decrease significantly when the enormous BaBar and Belle data samples are fully understood, evaluated, and utilized.
    - Of course, to some extent, more precise measurements from BaBar and Belle will provide further constraints on theoretical uncertainties.

- Development of reliable theoretical methods for calculating these nonperturbative parameters is essential for precise determination of CKM matrix elements.
  - Experimental verification is an essential element for ensuring reliability.
  - Precise data in the charm sector can motivate and validate theoretical progress in nonperturbative heavy quark physics that can then be applied to $b$ physics.
  - Lattice QCD (LQCD) is a candidate for a theory to calculate these parameters.

Providing precise charm data to motivate and validate theoretical progress in nonperturbative heavy quark physics is a major focus of the CLEO-c program.

Exhaustive searches for glue-rich states is the other major focus of CLEO-c.
Testing the quark mixing (CKM) matrix

For example, consider the parameters $\rho$ and $\eta$ in the CKM matrix, the fundamental matrix of weak couplings.

The extraction of constraints in the $\rho$--$\eta$ plane is limited by theory. Non-perturbative strong effects limit our ability to extract the fundamental parameters from the measurements.

CLEO-c can provide unique measurements that will address this current limitation.
CLEO-c and CESR-c

CLEO-c is a focused program of measurements and searches in $e^+e^-$ collisions in the $\sqrt{s} = 3 - 5$ GeV energy region, including:

- charm measurements
  - absolute charm branching fractions
  - the decay constants $f_D$ and $f_{Ds}$
  - semileptonic decay form factors
  - $|V_{cd}|$ and $|V_{cs}|$
- searches for new physics including
  - $CP$ violation in $D$ decay
  - $D\bar{D}$ mixing without DCSD
  - rare $D$ decays
- QCD studies
  - $c\bar{c}$ spectroscopy
  - searches for gluonic exotic states: glueballs
  - measurements of $R$
    - between 3 and 5 GeV – direct
    - between 1 and 3 GeV – indirect (Initial State Radiation)
- $\tau$ studies

The acceptance, resolution, and particle identification capability of the CLEO-c detector are substantially beyond those of any detector that has operated in the charm threshold region.
CLEO-c Run Plan

- 2002 – Prologue – \( \Upsilon \)'s \( \gtrsim 1.2 \text{ fb}^{-1} \) each
  - \( \Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \) – Completed
  - Matrix elements, \( \Gamma, \Gamma_{ee} \),
    spectroscopy (\( \eta_b, h_b, D \) states, ...)
  - \( \Upsilon(1D) \) already published
  - Compare with LQCD calculations
  - 10-20 \( \times \) the previous world’s data
- Act I – \( \psi(3770) \) 3 fb\(^{-1}\)
  - 30 M \( D\bar{D} \) events, 6 M tagged \( D \)
  - 310 \( \times \) MARK III
- Act II – \( \sqrt{s} \sim 4.1 \text{ GeV} \) – 3 fb\(^{-1}\)
  - 1.5 M \( D_s\bar{D}_s \) events, 0.3 M tagged \( D_s \)
  - 480 \( \times \) MARK III and 130 \( \times \) BES II
- Act III – \( J/\psi \) – 1 fb\(^{-1}\)
  - 1 G \( J/\psi \) decays
  - 170 \( \times \) MARK III and 20 \( \times \) BES II
- Plan a year for each Act
  - NSF support until Mar 31, 2008

The CESR-c Accelerator

Running at all energies from the \( J/\psi \) to above the \( \Upsilon(4S) \) is possible with existing superconducting IR quads.

- Loss of synchrotron radiation damping at low energies reduces luminosity
- Compensate with wiggler magnets
- Designed, built, and installed 12 superferric wigglers (Fe poles & SC coils)
- Excellent prototypes for Linear Collider damping ring wigglers.
- The only substantial hardware upgrade in the program

<table>
<thead>
<tr>
<th>( \sqrt{s} ) (GeV)</th>
<th>( \mathcal{L} ) ( (10^{33} \text{ cm}^{-2} \text{ s}^{-1}) )</th>
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<td>10</td>
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<tr>
<td>4.1</td>
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<tr>
<td>3.8</td>
<td>0.3</td>
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<tr>
<td>3.1</td>
<td>0.2</td>
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CESR-c Wiggler Magnets

- The 12 superferric wigglers are 7 pole, 1.3 m long, with $B_{max} = 2.1$ T
- Field quality and wiggler performance in CESR as predicted
- Lots to learn about the dynamics of a wiggler dominated storage ring
  - CESR-c is the first wiggler dominated storage ring.
The CLEO-c Detector and CLEO Collaboration

~ 140 Physicists in 14 Institutions

Determining $D$ Meson Decay Constants

The factor $f_{Dq} V_{cq}$ occurs in the decay amplitude for the $c\bar{q}W$ vertex

- The decay widths for leptonic $D^+$ and $D_s^+$ decays are:

$$\Gamma(D^+_q \to \ell^+ \nu_\ell) = \frac{1}{8\pi} G_F^2 M_{D_q} m_\ell^2 \left(1 - \frac{m_\ell^2}{M_{D_q}^2}\right) f_{Dq}^2 |V_{cq}|^2$$

- Measurements of $\mathcal{B}(D^+ \to \ell^+ \nu_\ell)$ and $\mathcal{B}(D_{s}^+ \to \ell^+ \nu_\ell)$
  - Determine $f_{D^+} |V_{cd}|$ and $f_{D_s} |V_{cs}|$
  - Conventionally measure $f_{Dq} |V_{cq}|$ and use unitarity for $|V_{cq}|$ to get $f_{Dq}$
  - We will also measure $|V_{cd}|$ and $|V_{cs}|$ accurately with semileptonic $D$ decays
  - Challenge theorists with values of $f_{D^+}$ and $f_{D_s}$ with errors $\mathcal{O}(1\%)$
  - Lead to understanding of the level of reliability of $f_{B^0}$ and $f_{B_s}$ calculations
  - $f_{B^0}$ uncertainty dominates error in $|V_{td}|$ from value of $\Delta m_d$ in $B^0\bar{B}^0$ mixing
We run at $E_{\text{cm}} = 3.77$ GeV, the $\psi(3770)$ resonance.

- Producing $D\bar{D}$ pairs and no other particles.
- Makes this a very clean experiment for studies of charm decays.
- Most analyses use a tagging technique
  - one of the produced $D$ mesons is fully reconstructed.
\[ D^+ \rightarrow \mu^+ \nu \mu \]

\[ Br(D^+ \rightarrow \mu^+ \nu) = (3.5 \pm 1.4 \pm 0.6) \times 10^{-4} \]

\[ f_{D^+} = (202 \pm 41 \pm 17) \text{ MeV} \]

Published:
PRD 70 112004, 2004
Semileptonic $D$ decays

$D^0 \rightarrow K^- e^+ \nu$

$D^0 \rightarrow \pi^- e^+ \nu$

**Decay modes**

1: $D^0 \rightarrow K^- e^+ \nu$
2: $D^0 \rightarrow K^*^- e^+ \nu$
3: $D^0 \rightarrow \pi^- e^+ \nu$
4: $D^0 \rightarrow \rho^- e^+ \nu$
5: $D^+ \rightarrow K_S^0 e^+ \nu$
6: $D^+ \rightarrow \bar{K}^{*0} e^+ \nu$
7: $D^+ \rightarrow \pi^0 e^+ \nu$
8: $D^+ \rightarrow \rho^0 e^+ \nu$
9: $D^+_S \rightarrow K_S^0 e^+ \nu$
10: $D^+_S \rightarrow \bar{K}^{*0} e^+ \nu$
11: $D_S^+ \rightarrow \phi e^+ \nu$

**PDG '04**

Projected CLEO-c data set

Not yet observed
Hadronic $D$ decays

$Br(D^+ \rightarrow K^- \pi^+ \pi^+)\quad Br(D^- \rightarrow K^+ \pi^- \pi^-)$

Data 57 pb$^{-1}$

CLEO-c already has the worlds best measurements!
Comparison with PDG 2004 (II)

- Compare with other *direct* measurements in PDG.
- PDG band = average of direct meas., not global fit.

\[ \mathcal{B}(D^0 \to K^-\pi^+) \]

\[ \mathcal{B}(D^+ \to K^-\pi^+\pi^+) \]
Searching for Gluonic Matter

Since gluons carry color charge, they self-interact and should bind

• A rich spectrum of glueballs or glue-rich states is expected in the few-GeV region
• $J/\psi \rightarrow \gamma X$ decays are an ideal hunting ground
• Caveat – glueballs may mix with nearby conventional $q\bar{q}$ mesons

The hermetic CLEO-c detector with its excellent $\gamma$, $\pi^\pm$, and $K^\pm$ detection and resolution is nearly ideal

• Observe glueballs in many different modes (signature)
• Facilitates angular analysis to establish $J^P$
The $f_J(2220)$ candidate for a glue-rich meson has been rather elusive:

- Observed by MARK III
- Most robust signals came from BESI from $8 \times 10^6 J/\psi$ events
- Not observed by Crystal Barrel
- Most other sightings have disappeared
- If BESI branching fractions were correct CLEO-c rates would be enormous

<table>
<thead>
<tr>
<th>$f_J(2220)$ Decay Mode</th>
<th>BESI Yield</th>
<th>CLEO-c Yield</th>
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<tbody>
<tr>
<td>$\pi^+\pi^-$</td>
<td>74</td>
<td>23,000</td>
</tr>
<tr>
<td>$\pi^0\pi^0$</td>
<td>18.4</td>
<td>13,000</td>
</tr>
<tr>
<td>$K^+K^-$</td>
<td>46</td>
<td>15,600</td>
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<tr>
<td>$K_S^0K_S^0$</td>
<td>23</td>
<td>4,500</td>
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<tr>
<td>$p\bar{p}$</td>
<td>32</td>
<td>8,500</td>
</tr>
</tbody>
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BESI $f_J(2220)$ Signals
Search for the $f_J(2220)$

In the CLEO-c detector $f_J(2220)$ signals would stand out clearly above backgrounds in many modes.

Monte Carlo studies with 150 M $J/\psi$ decays ($\lesssim 1/6$ of the projected CLEO-c data sample) show clear signals.
Glueball search and study at BESII (58M J/ψ)

- PWA of J/ψ → γKK shows a dominant 0++ in 1.7 GeV mass region.
- PWA of J/ψ → γππ and γππππ to study 0++ glueball candidates.
- PWA of J/ψ → γηππ and γK Kıπ to study 0−+ structures around 1.44 GeV.
- ξ(2230) was observed by MARKIII, BESI etc..
  Not seen in the mass spectra of KK, ππ and p̅p̅ by BESII. Careful PWA is being performed by BESII.
BESII $J/\psi \rightarrow \gamma K^+K^-$ and $\gamma K_S^0K_S^0$

After acceptance and isospin corrections
\[ J/\psi \rightarrow \gamma \pi^0 \pi^0 \]

\[ J/\psi \rightarrow \gamma \pi^+ \pi^- \]

\[ J/\psi \rightarrow \gamma K^+ K^- \pi^0 \]
Inclusive $J/\psi \rightarrow \gamma X$ Measurements

The inclusive $J/\psi \rightarrow \gamma X$ spectrum is also a hunting ground for new states:

- Monte Carlo studies with only 60 M $J/\psi$ decays show a clear $f_J(2220)$ signal if $\mathcal{B}(J/\psi \rightarrow \gamma f_J) = 8 \times 10^{-4}$.

- With the full 1 G $J/\psi$ CLEO-c data sample, $\mathcal{B}(J/\psi \rightarrow \gamma X) \gtrsim 10^{-4}$ should be observable for any $X$ with reasonable width.
Summary and Outlook

- CLEO-c is working very well and preliminary $D$ decay results from $\sim 60 \text{ pb}^{-1}$ are already competitive with or better than world averages.
- CESR-c has not yet reached its luminosity goals and massive efforts are underway.
- The CLEO-c detector is an excellent venue for studying glueballs produced in radiative $J/\psi$ decays.
- With the demise of the BESI $f_J(2220)$ signals, CLEO-c needs crisp objectives for glueball searches!
  - Jim Napolitano and Anders Ryd will discuss more hopeful prospects.
  - Perhaps interactions among us in this workshop can help to provide clear crisp objectives for the CLEO-c gluonic program.