CLEO-c and CKM Physics

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Cornell University
WIN 2003
October 7, 2003
CLEO-c and CESR-c

What’s with the “-c”?
- CLEO detector
- Symmetric e^+e^- collider
  \( \sqrt{s} = 10.6 \text{ GeV} \)
- Add wigglers to improve damping and run at
  \( \sqrt{s} = 3-6 \text{ GeV} \)
- Access to charm threshold region
- Approved by National Science Board Feb 2003
- First Physics Run starts October 24, 2003
- 3+ year program
Context for CLEO-c

Flavor physics:
- Overconstrain $V_{CKM}$
- Inconsistency $\rightarrow$ new physics
- Interpretation limited by strong interaction effects
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- $\sin 2\beta$ is clean
- $|V_{ub}|$ is not
- $B$ mixing is not

Hadronic uncertainties confound the extraction of weak physics
- Non-perturbative QCD
- Perturbative QCD (on better ground)
Context for CLEO-c

Flavor physics:
- Overconstrain $V_{CKM}$
- Inconsistency → new physics
- Interpretation limited by strong interaction effects
- Measurements in Charm decays can validate QCD corrections needed to extract Weak physics from observables

$\sin 2\beta$ is clean
$|V_{ub}|$ is not
B mixing is not
Hadronic uncertainties confound the extraction of weak physics
- Non-perturbative QCD
- Perturbative QCD (on better ground)
UT Constraint from $B$ mixing

$$\Delta M_d = 0.50 \text{ ps}^{-1} \left[ \frac{\sqrt{B_{B_d}} f_{B_d}}{200 \text{ MeV}} \right]^2 \left[ \frac{|V_{td}|}{8.8 \times 10^{-3}} \right]^2$$

$$\frac{\sigma(|V_{td}|)}{|V_{td}|} = 0.5 \frac{\sigma(\Delta M_d)}{\Delta M_d} \oplus \frac{\sigma(f_B \sqrt{B_{B_d}})}{f_B \sqrt{B_{B_d}}}$$
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1.2% ~15% (LQCD)
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- Lattice QCD predicts decay constants \( f_{D(s)} / f_{B(s)} \)
- If precise measurements of \( f_D \) and \( f_{Ds} \) exist, then our confidence in non-perturbative QCD calculations needed to make constraints on the UT is increased.
- Even better if \( B_s \) mixing is observed!
UT Constraint from $|V_{ub}|$

$|V_{ub}|$ from $B \rightarrow \pi \ell \nu$:

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 p_\pi^3 |f_+(q^2)|^2$$

Form factor $f(q^2)$:
- Not well known
- Limits $|V_{ub}|$ precision
- Predicted by LQCD
|V_{ub}| from B → π l ν:

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Form factor \( f(q^2) \):
- Not well known
- Limits \(|V_{ub}|\) precision
- Predicted by LQCD

- Absolute rate and shape is a stringent test of theory
- Heavy quark symmetry relates D → π l ν to B → π l ν
- A precise measurement of D → π l ν can calibrate LQCD and allow a precise extraction of \(|V_{ub}|\) from B → π l ν
### Status of CKM Matrix

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<thead>
<tr>
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**CLEO-c** will redefine 2\textsuperscript{nd} generation elements and enable improvements in 3\textsuperscript{rd} generation.
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CESR-c

6/12 Wigglers     E=1.5-3 GeV
Installed Spring’03
6 more March-May’04
CESR-c Design Luminosity:

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>$L \left(10^{32} \text{ cm}^{-2} \text{s}^{-1}\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>2.0</td>
</tr>
<tr>
<td>3.77</td>
<td>3.0</td>
</tr>
<tr>
<td>4.1</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Machine performance: $\Delta E_{\text{beam}} \sim 1.6 \text{ MeV at } \psi' \text{ (6 wigglers)}$
CLEO-c Detector

State of Art Detector:
- Drift Chamber Tracking (1 Tesla)
- RICH Particle ID
- Crystal EM Calorimetry
- 93% of solid angle
- Only small changes from CLEO III
  - B field 1.5 → 1 T
  - Silicon → ZD
New Inner Detector

- Replaced Silicon Vertex Detector May 2003
- 6 stereo layers:
  - $r = 5.3 \text{ cm} - 10.5 \text{ cm}$
  - 12-15° stereo angle
  - $|\cos \theta| < 0.93$
- 300, 10 mm cells
- 1% $X_0$ inner Al tube .8mm
- Helium-Propane (60:40)
- 20 µm Au-W sense wires
- 110 µm Au-Al field wires
- Outer Al-Mylar skin

Continuous tracking volume
Low mass ($\sigma_p$ is MS limited)
Nothing to vertex at charm threshold!
CLEO III

Y(4S)

Typical Hadronic Event

Average:
- 10 tracks
- 10 showers
CLEO-c
ψ(3770)
Typical Hadronic Event

Average:
- 5 tracks
- 5 showers

Event Recorded September 29, 2003
Charm Threshold Region

- $D^+D^-, D^0\bar{D}^0$ at $\psi(3770)$
- $D_s^+D_s^-$ at $\sqrt{s}=4140$ MeV
- Potential for $\Lambda_c^+\Lambda_c^-$
- Will also run on $J/\psi$ and possibly $\psi'$

$DD$ cross section at $\psi(3770) \sim 5$ nb (Mark III)
$D_s\bar{D}_s$ cross section $\sim 0.5$ nb
CLEO-c Run Plan

Phase I: $\psi(3770) - 3$ fb$^{-1}$ ($\psi(3770) \rightarrow \bar{D}D$)
- 30 million DD events, 6 million tagged D decays
  (310 times MARK III)

Phase II: $\sqrt{s}=4140$ MeV - 3 fb$^{-1}$
- 1.5 million $D_s\bar{D}_s$ events, 0.3 million tagged $D_s$ decays
  (480 times MARK III, 130 times BES)

Phase III: $\psi(3100) - 1$ fb$^{-1}$
- 1 Billion J/$\psi$ decays
  (170 times MARK III, 20 times BES II)

Now: Dec'02
- 5 pb$^{-1}$ at $\psi(3770)$

Oct'03-Jan'04
- 50 pb$^{-1}$ on $\psi(3770)$
Tagging Technique - Tag Purity

\[ \psi(3770) \rightarrow D \bar{D} \]

\[ \sqrt{s} \sim 4140 \rightarrow D_s \bar{D}_s \]

- Charm mesons have many large branching ratios (~1 - 15%)
- High reconstruction efficiency

\[ \Rightarrow \text{High net tagging efficiency} \sim 20\% \]

Anticipate 6M D tags and 0.3M \( D_s \) tags

- \( D \rightarrow K\pi \) tag: \( S/B \sim 5000/1 \)
- \( D_s \rightarrow \phi\pi (\phi \rightarrow KK) \) tag: \( S/B \sim 100/1 \)

Log Scale!
## Absolute Charm Branching Ratios

### Double tag technique:

Almost zero background in hadronic tag modes

Measure absolute $B(D \to X)$ with double tags

$$B = \frac{\text{# of } X}{\text{# of D tags}}$$

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\sqrt{s}$</th>
<th>$L$ (fb$^{-1}$)</th>
<th>Double tags</th>
<th>$\delta B / B$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \to K^- \pi^+$</td>
<td>3770</td>
<td>3</td>
<td>53,000</td>
<td>2.4</td>
</tr>
<tr>
<td>$D^+ \to K^- \pi^+ \pi^+$</td>
<td>3770</td>
<td>3</td>
<td>60,000</td>
<td>7.2</td>
</tr>
<tr>
<td>$D_s \to \phi \pi$</td>
<td>4140</td>
<td>3</td>
<td>6,000</td>
<td>25</td>
</tr>
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</table>

**CLEO-c**: potential to set absolute scale for heavy quark measurements

50 pb$^{-1} \to \sim 1,000$ events $\Rightarrow$ x2 improvement (stat) on $D^+ \to K^- \pi^+ \pi^+$ PDG $dB/B$
$f_{D_s}$ from Absolute $B(D_s \rightarrow \mu^+\nu)$

- Measure absolute $B(D_s \rightarrow \mu\nu)$
- Fully reconstruct one $D$ (tag)
- Require one additional charged track and no additional photons
- Compute $MM^2$
- Peaks at zero for $D_s^+ \rightarrow \mu^+\nu$ decay
- Expect resolution of $\sim O(M_{\pi^0})$

$V_{cs}$ ($V_{cd}$) known from unitarity to 0.1% (1.1%)

<table>
<thead>
<tr>
<th>Decay Constant</th>
<th>Reaction</th>
<th>Energy (MeV)</th>
<th>$L$ (fb$^{-1}$)</th>
<th>$\delta f / f$ (%)</th>
<th>PDG</th>
<th>CLEO-c</th>
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<td>$f_{D_s}$</td>
<td>$D_s^+ \rightarrow \mu \nu$</td>
<td>4140</td>
<td>3</td>
<td>17</td>
<td>1.9</td>
<td></td>
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<tr>
<td>$f_{D_s}$</td>
<td>$D_s^+ \rightarrow \tau \nu$</td>
<td>4140</td>
<td>3</td>
<td>33</td>
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Semileptonic Decays: $|V_{CKM}|^2 |f(q^2)|^2$

Measurement of complete set of charm $P \rightarrow P l\nu$ and $P \rightarrow V l\nu$ absolute form factor magnitudes and slopes to a few %:

- almost no background
- one experiment

Stringent test of theory!

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CLEO-c Impact on Semileptonic $\delta B/B$

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: $D^+ \rightarrow K^0 e^+ \nu$
6: $D^+ \rightarrow K^{*0} e^+ \nu$
7: $D^+ \rightarrow \pi^0 e^+ \nu$
8: $D^+ \rightarrow \rho^0 e^+ \nu$
9: $D_s \rightarrow K^0 e^+ \nu$
10: $D_s \rightarrow K^{*0} e^+ \nu$
11: $D_s \rightarrow \phi e^+ \nu$

CLEO-c will make significant improvements in precision for each absolute charm semileptonic branching ratio.
Determining $|V_{cs}|$ and $|V_{cd}|$

Combine semileptonic and leptonic decays - eliminating $V_{CKM}$

$\Gamma(D^+ \to \pi l \nu) / \Gamma(D^+ \to l \nu)$ independent of $|V_{cd}|$

Test rate predictions at ~4% level

$\Gamma(D_s \to \phi l \nu) / \Gamma(D_s \to l \nu)$ independent of $|V_{cs}|$

Test rate predictions at ~4.5% level

Test amplitudes at 2% level

Stringent test of theory - If theory passes test ... 

$D^0 \to K^- e^+ \nu$ \hspace{1cm} $\delta V_{cs}/V_{cs} = 1.6\%$ (now: 11\%)

$D^0 \to \pi^- e^+ \nu$ \hspace{1cm} $\delta V_{cd}/V_{cd} = 1.7\%$ (now: 7\%)

Use CLEO-c validated lattice to calculate $B$ semileptonic form factor

$B$ factories can use $B \to \rho/\pi/\eta/l\nu$ for precise $|V_{ub}|$ determination.
Inclusive Semileptonic Decays

- Significantly improved $D \rightarrow X e$ spectrum possible using tagged $D$'s
- Backgrounds in $B \rightarrow X l \nu$ analyses ($b \rightarrow c \rightarrow l$)
- Test of HQET: $D^0$, $D^+$, $D_s^+$ same to few %
  - $D_s$ and $D^+$ weak annihilation contribution - a concern for $|V_{ub}|$ from $E_1$ endpoint
  - Inclusive spectra + HQET used for $|V_{cb}|$ from $b \rightarrow c l \nu$

Also can measure $B_{SL}$ to get $\Gamma_{SL}$
- currently no measurement for $D_s$

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**Strong Phases in Hadronic D**

- **Methods to measure** $\gamma$ in $B^{\pm} \rightarrow (B^0 K^{\pm}; (B^0 \rightarrow f$

- **Aided by measurements of strong phases in hadronic D decays:**
  - $D \rightarrow$ many Atwood & Soni
    PRD 68, 033003
  - $D^0 \rightarrow K^{*\pm} K$ Rosner & Suprun
    PRD 68, 054010

- **CLEO-c:** advantage of quantum coherence:
  $\psi(3770) \rightarrow D\bar{D} ; J^P=1^-$

Interference of $K^{*+}$ & $K^{*-}$ bands
Potential Impact

- Top: current experimental and theoretical uncertainties

- Bottom: current experiment with 2% theory uncertainties – perhaps possible with LQCD calibrated with CLEO-c data
Potential Impact on $V_{CKM}$

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Potential Impact on $V_{CKM}$

Current $V_{CKM}$

From direct Measurements
-no unitarity imposed

Future $V_{CKM}$

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$\delta V_{cd}/V_{cd}$ 2%
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$\delta V_{us}/V_{us}$ 1%
$\delta V_{cs}/V_{cs}$ 2%
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$\delta V_{ub}/V_{ub}$ 5%
$\delta V_{cb}/V_{cb}$ 3%
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Summary

• The CLEO detector is state of the art, understood at a precision level, and collecting data in the cc resonance region.

• CLEO has a long history of weak decay and CKM physics interests that will carry over to the CLEO-c program
  - CKM physics
    • semileptonic D decays: spectra, form factors, $|V_{cs}|$ & $|V_{cd}|$
    • Leptonic decays: $f_D$, $f_{Ds}$ informing B mixing interpretation
  - Enabling measurements of Hadronic D decays
    • Strong Phases to inform $\gamma$ determinations in $B \to DK$
    • Measurement of absolute branching fractions