The CLEO-c Experiment and its Impact

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Outline:
• The CLEO-c Physics Program
• Tests of Lattice QCD
• Some Recent CLEO-c Results:
  • Hadronic $D$ Decays
  • Leptonic $D$ and $D_s$ Decays
  • Semileptonic $D$ Decays
• Conclusions
Heavy Quark Physics

- Many experiments study decays of $b$-quarks:
  - B-factories: BABAR and Belle
  - Tevatron: CDF and D0
  - LHC: LHCb
- The CLEO-c experiment is making unique contributions to these studies

Leptonic decays

$D^+ \left\{ \begin{array}{cc} c & \bar{d} \\ \end{array} \right\} \rightarrow W^+ \ell^+ \nu$

Decay constant, $f_D$, describes overlap of $c$ and $d$ quark in the $D^+$.

Semileptonic decays

$D^0 \left\{ \begin{array}{cc} c \bar{u} \bar{d} & \bar{u} \\ d & \bar{u} \\ \end{array} \right\} \rightarrow \pi^+ \nu$

Form factors describe prob. to form final state: $f(p) = <\pi|H|D>$

QCD (Quantum ChromoDynamics) is a strongly interacting theory

CLEO-c will allow crucial tests of Lattice QCD
Lattice QCD

- At low energy QCD is strongly coupled
  - Calculations done on discrete lattice
  - Recent revolutionary progress in algorithms have allowed simulation of full QCD.
    - Can handle QCD vacuum polarization
  - Understanding strongly coupled systems is important.
    - LHC might uncover new strongly interacting physics.

This dramatic improvement in Lattice QCD needs to be validated in calculations of form factors and decay constants.

Before 2000

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<tr>
<th>Energy (GeV)</th>
<th>Coupling Strength</th>
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HPQCD+FERMILAB+MILC
PRL 92:022001,2004

~2004

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<th>Energy (GeV)</th>
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<tr>
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LQCD/Exp’t ($n_f = 0$) LQCD/Exp’t ($n_f = 3$)
CLEO-c detector is working very well. The detector capabilities are well matched to the physics.

- **New inner drift chamber**
- **Tracking in 1.0 T field**
  - $\sigma_p/p \approx 0.6\%$ at 1 GeV
- **Excellent E-M calorimeter**
  - $\sigma_E/E \approx 2\%$ at 1 GeV
- **Hadron PID from RICH**
  - Very good below 1 GeV
Absolute $D$ Branching Fractions

$D^+ \rightarrow K^- \pi^+ \pi^+$ Branching Fraction

Tag $D$ – fully reconstructed

Unique to CLEO-c:
Running near $c\bar{c}$ threshold

Data (281 fb$^{-1}$)

~80,000 $D \rightarrow K\pi\pi$

Very little background

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

$e^-$ $\rightarrow \pi^+ K^+$ $\rightarrow \pi^+ \pi^+$ $\rightarrow D^+$ $\rightarrow K^+ \pi^+ \pi^+$
$D^+ \rightarrow \mu^+ \nu_\mu$ and $f_{D^+}$

First significant measurement of $D^+ \rightarrow \mu^+ \nu_\mu$

$Br(D^+ \rightarrow \mu^+ \nu) = (4.40 \pm 0.66^{+0.09}_{-0.12}) \times 10^{-4}$

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

PRL 95, 251801 (2005)
Data vs. Lattice Calculations

- Similar technique used also to measure $f_{D_S}$ in $D_S \rightarrow \mu \nu$. 
- CLEO results consistent with most (recent) predictions.
- For precision comparisons we need the complete CLEO-c program.
  - Will allow tests at the 2-4% level.
An important goal of the CLEO-c program is to measure form factors to check lattice QCD calculations.

\[
D^0 \rightarrow \pi^{-} e^{+} \nu,
\]

\[
D^0 \rightarrow K e^{-} \nu,
\]

The \( c\bar{c} \) threshold operation of CLEO-c makes it unique.
Exclusive Signals (281 pb$^{-1}$)

$U = E_{\text{miss}} - |P_{\text{miss}}|$ (GeV)

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

$699\pm 28$

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

$6796\pm 84$

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

$295\pm 20$

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

$2910\pm 55$

B($D^0\rightarrow \pi^- e^+\nu$) x 10$^{-3}$

PDG (2004)

BES II

LQCD

CLEO–c (tag, 56 pb$^{-1}$)

Belle (tag, 282 fb$^{-1}$)

CLEO–c (tag, 281 pb$^{-1}$)

CLEO–c (no tag, 281 pb$^{-1}$)
CLEO-c measurements of semileptonic $D$ decays world's best.
Conclusion

• CLEO-c are producing unique results on charm decays
  · Very well understood detector and software
  · Small but dedicated and focused group
• For $D$ decays we are rewriting the books
  · Absolute branching fractions for $D$ and $D_s$ decays
  · Leptonic $D$ and $D_s$ decays
  · Semileptonic $D$ and $D_s$ decays
• These measurements allow precise tests of Lattice calculations.
  · Important to interpret $B$-physics data from the $B$-factories and the Tevatron.
• Many other important topics not discussed here, e.g., Dalitz studies for $\gamma$ measurements, strong phase in $D$ decays etc.
Backup Slides
Physics Motivation

- The CLEO-c program impacts many of the CKM parameters
- In particular, leptonic $D$ and $D_s$ decays allow measurements of the decay constants
- This will help the determination of $V_{td}$
- Semileptonic $D$ decays will check form factor calculations and improve $V_{ub}$
- Hadronic $D$ decays are important for normalization of $B$ decays

Determining the CKM Matrix

CLEO-c will directly measure D-decays
CLEO-c will measure D-decays constants

CLEO-c measurements of D-decays will have a significant impact on the determination of 6 of the CKM matrix elements.
- Directly by studying $D \rightarrow \pi e$ and $D \rightarrow K e$.
- Or indirectly be measuring quantities that can be used to validated calculations of the strong dynamics that binds the quarks to hadrons.

Form factors from D-decays and Lattice QCD and precision br. fr. From D decays will help improve
Testing Theories of Strong Interactions

- Measure form factors in $D \rightarrow \pi l\nu$ and validate theoretical calculations
  - Can then use this to extract $|V_{ub}|$ from $B \rightarrow \pi l\nu$

- $B$ mixing is well measured
  - $\Delta m_d = (0.502 \pm 0.007) \times 10^{-12}$ s
  - But $|V_{td}|$ from $\Delta m_d$ has large uncertainties from $f_B$
  - CLEO-c can measure $f_D$

\[ \Delta m_d = \frac{G_F^2}{6} M_B M_t^2 |V_{td} V_{tb}^*|^2 \eta_B S_0 (x_t) f_B^2 B_B \]
CLEO Collaboration

About 135 collaborators

- New groups are still joining CLEO-c