CLEO-c Inputs to B Physics

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CLEO Collaboration

Joint SLAC/INT Workshop on Flavor Physics and QCD
Seattle, WA
Friday the 13th of May, 2005
Outline

CLEO Datasets

Charm Meson Decays

*Leptonic*: Decay constant $f_D$ (test Lattice re: $f_B$)
*Hadronic*: Precision branching fractions (absolute!)
  Dalitz plots: flavor & CP-tagged ($\gamma$ from $B \Rightarrow DK$)
  Strong Phase in $D \Rightarrow K\pi$ (also needed…)
*Semi-lep*: Form-factors (D vs. $B \Rightarrow \pi\ell\nu$)
  Inclusive electron spectra (model secondaries)

Quarkonium Data (omit due to time)
Discovered $h_c$ $\Upsilon(1D)$ confirm/co-discover $\eta_c'$ (Belle)
Glueballs and other low-E spectroscopy
Onia decay topics:
  “PV puzzle” in $J/\psi$ vs. $\psi'$ decays (published)
  photon, dipion, omega (!) transitions…
  gluon vs. quark jets
  charm in bottomonium decay ($J/\psi$, $\Lambda_c$, $D$, …)
Summary Take-Home Message

CLEO has stopped running on the $\Upsilon(4S)$.  
(Moments & neutrino reconstruction perhaps most influential recent $B$ work)

**We now run as CLEO-c, a charm factory.**

**Our main physics output involves hadronic parameters needed for weak flavor physics.**

(I believe this may be of some relevance…)

*My charge:*
What are the short term results impacting measurements in B decays that we should expect from CLEO-C? What are your priorities among these measurements, and how long does CLEO-c need to run to achieve the precision required for a possible very high luminosity B-Factory?
**CLEO-c Datasets**

**ψ(3770) Data:**
Summer 2004 results & today: 55.8 pb\(^{-1}\) 356,000 \(\bar{D}D\) pairs
Ready for analysis now: \(\sim 275\) pb\(^{-1}\) \(\sim 1,750,000\) \(\bar{D}D\) pairs
(latest run just ended April 4th)

**Ds:** Need to scan for good running point; next on agenda

**ψ’:** have \(\sim 3 \times 10^6\) already (several papers: PV, \(h_c\), …)

**J/ψ:** in the future (glue-rich decays, etc.)

**ϒ(1S,2S,3S):** 10x previous CLEO data e.g., \(\sim 22 \times 10^6\) \(ϒ(1S)\)
many papers…

**Power of D Tagging:** Fully reconstruct one decay (tag), study other \(D\)
-- Know direction of other \(D\) fully constrained kinematics!
-- No combinatorics for other \(D\)
-- Can infer neutrinos
-- Suppress non-\(D\bar{D}\) events
D Tagging at CLEO-c

Clean events; high-efficiency for full reconstruction

Note: coarse yellow boxes are trigger-related, not for track reconstruction…
**D Tagging vs. B tagging**

\[ \psi(3770) \Rightarrow D\bar{D} \quad \text{cleo-c} \]

\[ \Upsilon(4S) \Rightarrow B\bar{B} \quad \text{cleo III} \]

**D-tagging vs. B tagging:**

Tagging efficiency (>100x) and cross-section (6x) both larger

Integrated luminosity smaller (~1000x)

so, #single tags similar… *but many more double tags for D’s!*

In 55.8pb\(^{-1}\):

- 32K \(D^+\) single tags in 155K pairs (\(~10\% / D^+\))
- 60K \(D^0\) single tags in 200K pairs (\(~15\% / D^0\))

\(~25\%\) of pairs have at least one \(D\) tagged
**B (D ⇒ μν) and f_D**

**Goal:** $f_{D^+}$, $f_{D^0}$ to check LQCD

$f_B$, $f_{B_s}$ rely on lattice

Needed to interpret mixing!

Plot missing-mass squared:

signal peaks at $M_\nu^2 = 0$

**CLEO-c Proposal**

- **Goal:**
  - $f_{D^+}$, $f_{D^0}$ to check LQCD
  - $f_B$, $f_{B_s}$ rely on lattice
  - Needed to interpret mixing!

- **Plot missing-mass squared:**
  - **Signal:** peaks at $M_\nu^2 = 0$

  **CLEO-c Proposal**

- **Clean, as predicted**
- **Used ~29K $D^+$ tags**

- **Key backgrounds:**
  - $\pi^+\pi^0$, $\tau\nu$
  - (ignored by BES?)

- **CLEO-c with ~56 pb$^{-1}$**
- **PRD 70, 112004 (2004)**

**Current full CLEO-c MC**
Future of $f_D$

Current published data:
8 events with $1.0 \pm 0.25$ expected background 
Reconstruction efficiency = 69.9%

$\mathcal{B} ( D \Rightarrow \mu \nu ) = (3.5 \pm 1.4 \pm 0.6) \times 10^{-4}$

$f_D = (202 \pm 41 \pm 17) \text{ MeV}$

5x more data being analyzed now for summer update:
$<10\%$ measurement soon.
1 fb$^{-1}$ = 18x published data; gives $< 5\%$

Systematics already improving 
(conservative before since stat. error so dominant…)
Study with data, some simple MC

We will also measure $f_{Ds}$ …
**Absolute Charm Branching Ratios**

**Method:**

\[ D_{ij} = 2N_{DD} B_i B_j \varepsilon_{ij} \]

\[ S_i = 2N_{DD} B_i \varepsilon_i \]

**Single Tags (S\_i)**

**Double Tags (D\_ij)**

**D/S Ratio independent of:**

\[ N_{DD}, \int \mathcal{L} dt, \text{ tag } B_j \]

(& tag \( \varepsilon_j \) almost cancels)

Systematics ~all from efficiency

(can study well with data; e.g. missing-mass for tracking efficiency, etc.)

Also get precision cross-section

**Note:** must be careful re: FSR at current accuracy…
Charm Branching Ratio Results

Systematics will improve with study and higher statistics, (5x available now)

Already surpass most world averages!

It’s just the “right technique”:
We cancel the difficult “denominator” of #D produced with algebra of S & D

submitted to PRL (hep-ex/0504003); final update of ICHEP04
**CLEO-c Inputs to $\phi_3/\gamma$**

1. Gronau-London-Wyler Method
   - $B^- \rightarrow D_{CP}K^-$
   - Statistics Limited so far
   - D mixing parameters can alter $\gamma$

2. Atwood-Dunietz-Soni Method
   - $B^- \rightarrow DK^-$
   - Requires very large $Ldt$
   - CLEO-c: measure $r_D$ & $\cos \delta_D$

3. Dalitz plot Method
   - $B^- \rightarrow DK^-$, $D \rightarrow K_s\pi^+\pi^-, \pi^+\pi^-\pi^0, K^+K^-K^0$
   - limited by uncertainty due to Dalitz plot model
   - CLEO-c: quantum correlated D’s reduce model dependence
**CLEO-c Measurement of Strong Phase**

*Key: Have CP-tags as well as flavor-tags with correlated D pairs*

--- ψ(3770) decays to a net CP– pair
  
  Good tag modes for both CP+ and CP– D⁰’s

--- also, K⁻ π⁺ vs. K⁻ π⁺ *cannot* be DCSD…

--- At higher E_{cm}, DDγ gives CP+ pairs; more fun & games…

*Reconstruct Double Tags: CP-tag vs. K⁻ π⁺*

Asymmetry in CP+ vs CP – related to \( \cos \delta \):

\[
A \equiv \frac{B(D_{CP+} \rightarrow K^-\pi^+) - B(D_{CP-} \rightarrow K^-\pi^+)}{B(D_{CP+} \rightarrow K^-\pi^+) + B(D_{CP-} \rightarrow K^-\pi^+)}
\]

\[
\cos \delta = \frac{A}{2\sqrt{R_D}}
\]

\( R_D \) is ratio of DCS to Cabibbo-favored rates

Input \( R_D \) from PDG2004 ± 8%, Belle 2005 ±5%
**Full Information Contained in Tag Rates**

Omitted dependence on $N(D^0\bar{D}^0) \times$ relevant branching fractions to elucidate the dependence on: $x, y, r = \sqrt{R_D}, z = 2\cos\delta$

<table>
<thead>
<tr>
<th>$C = -1$</th>
<th>$f$</th>
<th>$\bar{f}$</th>
<th>$\ell^+$</th>
<th>$\ell^-$</th>
<th>$S_+$</th>
<th>$S_-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{f}$</td>
<td>$1 + r^2(2 - z^2)$</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\ell^+$</td>
<td>$r^2$</td>
<td>1</td>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\ell^-$</td>
<td>1</td>
<td>$r^2$</td>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_+$</td>
<td>$1 + r(r + z)$</td>
<td>$1 + r(r + z)$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>$S_-$</td>
<td>$1 + r(r - z)$</td>
<td>$1 + r(r - z)$</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>$X$</td>
<td>$1 + r^2 - rz(B_f rz - y)$</td>
<td>1</td>
<td>2</td>
<td>$[1 \pm (\hat{B}_f rz - y)]$</td>
<td></td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>$C = +1$</th>
<th>$f$</th>
<th>$\bar{f}$</th>
<th>$\ell^+$</th>
<th>$\ell^-$</th>
<th>$S_+$</th>
<th>$S_-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>$2r(2r + zy - wz)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{f}$</td>
<td>$1 - r^2(2 - z^2) + 2r(zy + wx)$</td>
<td>$2r(2r + zy - wz)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\ell^+$</td>
<td>$r(ry + wy)$</td>
<td>$1 + r(zy + wx)$</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\ell^-$</td>
<td>$1 + r(zy + wx)$</td>
<td>$r(ry + wy)$</td>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_+$</td>
<td>$1 + r(r - z) - 2y$</td>
<td>$1 + r(r - z) - 2y$</td>
<td>$1 - 2y$</td>
<td>$1 - 2y$</td>
<td>$4(1 - 2y)$</td>
<td></td>
</tr>
<tr>
<td>$S_-$</td>
<td>$1 + r(r + z) + 2y$</td>
<td>$1 + r(r + z) + 2y$</td>
<td>$1 + 2y$</td>
<td>$1 + 2y$</td>
<td>0</td>
<td>$4(1 + 2y)$</td>
</tr>
<tr>
<td>$X$</td>
<td>$1 - \hat{B}_f r^2(1 - z^2) - \hat{B}_f rzy$</td>
<td>$1 + 2\hat{B}_f rzy$</td>
<td>2</td>
<td>$[1 + 2\hat{B}_f rzy + (\hat{B}_f rz + y)]$</td>
<td></td>
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</tbody>
</table>
“$K\pi$ physics” Sensitivity Estimates

Uncertainty dominated by double tag statistics.
Use yields in $56\ \text{pb}^{-1}$ to determine sensitivity
44000 single hadronic flavor tags.
13000 “single” semileptonic flavor tags.
CP+: $K^+ K^-, \pi^+ \pi^-, K^0_S \pi^0 \pi^0$, 1/3 of $K^0_S \pi^+ \pi^-$: 470 DTs.
CP−: $K^0_S \pi^0, K^0_S \omega, K^0_S \phi$, 1/3 of $K^0_S \pi^+ \pi^-$: 570 DTs.

<table>
<thead>
<tr>
<th>Relative 1σ error</th>
<th>PDG(2004)</th>
<th>$285\ \text{pb}^{-1}$ C=−1</th>
<th>$3\ \text{fb}^{-1} \ @ψ(3770)$ &amp; $3\ \text{fb}^{-1} \ ~4\text{GeV}$</th>
</tr>
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<tbody>
<tr>
<td>$R_D$</td>
<td>0.08</td>
<td>~0.2</td>
<td>~0.05</td>
</tr>
<tr>
<td>$\cos \delta$</td>
<td>–</td>
<td>~0.3</td>
<td>~0.08</td>
</tr>
<tr>
<td>$y$</td>
<td>0.005</td>
<td>~0.02</td>
<td>~0.003</td>
</tr>
<tr>
<td>$x$</td>
<td>0.01</td>
<td>–</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

More refined estimate soon - Preliminary results in summer
**CLEO-c Data: Single Tag \(D^0 \rightarrow K_S \pi^+ \pi^-\)**

Phase difference between \(D^0\) & \(\bar{D}^0\) varies across Dalitz plot – model dependent. Simultaneously analyze Dalitz plot vs flavor tag and Dalitz plot vs CP tag; direct measurement of phase difference ⇒ less model dependence on \(\gamma\)

- **Single Tag Dalitz plot of**
  \(D^0 \rightarrow K_S \pi^+ \pi^-\) (pilot run 56 pb\(^{-1}\))

- **Construct Double Tags with**
  - \(\text{CP}^+ \ K^+K^-\), \(\pi^+\pi^-\), \(K_S\pi^0\pi^0\)
  - \(\text{CP}^-\) \(K_S\pi^0\), \(K_S\omega\), \(K_S\eta\), \(K_S\phi\)
  - Double Dalitz plot \((D \rightarrow K_S \pi^+ \pi^-)^2\)

- **Dalitz plot has CP content**
  - 1/3 CP+ \(K_Sf_0\)
  - 1/3 CP- \(K_S\rho\), \(K_S\omega\)
  - Significantly augments statistics of 2-body & pseudo-2-body CP modes
**CP-Tagged $K_S\pi^+\pi^-$ Dalitz Plot**

(Belle simulation of CLEO-c data)

**Double Tags have very low backgrounds**
- $\sim 10^{-4}$ for all tracks modes such as $K^+K^-$ vs $K_S\pi^+\pi^-$
- $\sim 10^{-3}$ for modes with a $\pi^0$ such as $K_S\pi^0$ vs $K_S\pi^+\pi^-$

syst. on $\gamma : 7^\circ$ with data in hand; 1-2$^\circ$ later?

---

**Diagrams:**
- $K^+K^-$ vs $K_S\pi^+\pi^-$
- $K_S\pi^0$ vs $K_S\pi^+\pi^-$

**Marked Points:**
- $K^*(892)$
- $\rho(770)$
- $f_0(980)$

**CP+ and CP-**

---

**Notes:**
- MC
- C=-1
- MC
- C=+1
Exclusive Semileptonic Summary

Final results from 56 pb$^{-1}$:

D$^0$ excl. semileptonic BR’s: CLNS 05/1906, CLEO 05-1 (update of ICHEP04)

D$^+$ excl. semileptonic BR’s: CLNS 05/1915, CLEO 05-7 (new since ICHEP04)

Both as hep-ex very soon….

Like hadronic BR’s, already surpass world averages!

(Plot: BR’s norm’d to PDG; so, “0-2” = 100% error = no info. now)

Use D Tag + E$_{bm}$ to infer neutrino

Plot data as $U = E_{miss} - p_{miss}$

signal peaks at $U = 0$

(similar to missing-mass…)

K-pi are kinematically separated
Cabibbo-Allowed Modes

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

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

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

$D^+ \rightarrow K^{*0} e^+ \nu$

$K^{*0} \rightarrow K^- \pi^0$

$K^{*0} \rightarrow K^- \pi^+$

$U = E_{\text{miss}} - |P_{\text{miss}}| \ (\text{GeV})$
Cabibbo-Suppressed $D \Rightarrow \pi l\nu$

**CLEOIII**

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

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

Tag with $D^* \rightarrow D\pi$

Observable: $\Delta m = m_{D^*} - m_D$.

Compare to:

state of the art measurement

at 10 GeV (CLEO III)

PRL 94, 11802

**CLEO-c**

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

(\textasciitilde 110 events)

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

Note: kinematic separation.

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

(\textasciitilde 65 events)
FYI: prelim. form-factor plots not yet efficiency corrected, background subtracted, or boosted to D rest-frame…
More Cabibbo-Suppressed Modes


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

S/N $\sim 1/2$

First Observation.

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

First Observation.

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

($\sim 30$ events)

$E_{\text{miss}} - |P_{\text{miss}}|$ (GeV)
Inclusive Electron Spectra

Analysis not yet complete for first 56 pb$^{-1}$ of data; expected precision will already improve on PDG.

$D^0 \rightarrow e^+ X$:
- CLEO-c: $\sigma_{BR}$ (stat) $\approx 0.2\%$
- PDG: $\sigma_{BR}$ (stat $\oplus$ sys) $\approx 0.3\%$

$D^+ \rightarrow e^+ X$:
- CLEO-c: $\sigma_{BR}$ (stat) $\approx 0.3\%$
- PDG: $\sigma_{BR}$ (stat $\oplus$ sys) $\approx 1.9\%$
Precision theory + charm = dramatic increase in the potential of quark flavor physics to discover new physics

Theoretical errors dominate width of bands

Precision QCD calculations tested with precision charm data from CLEO-c ➔ theory errors of a few % on B system decay constants & semileptonic form factors

500 fb-1 @ BABAR/Belle

NOTE: no gamma constraint
**Future of Precision CKM & CLEO-c**

**The Goal:** Measure all CKM matrix elements and associated phases in order to over-constrain the unitary triangles.
Extras
Observation of $h_c$ Charmonium

$\psi' \rightarrow h_c \pi^0$  $h_c \rightarrow \eta_c \gamma$

exclusive

inclusive

E835 has weaker evidence as well
Details of $h_c$ Exclusive Analysis
CLEO-c 6-layer, all-stereo inner chamber
CLEO Dataset Overview

**CLEO detector at CESR e^+ e^- collider -- Ithaca, New York, USA**

**CLEO II, II.V, III: High-Energy Data**  \( b\bar{b} \) resonances
\( \Upsilon(4S) \) and continuum \( \Rightarrow \) years of quality B, D, \( \tau \), 2-\( \gamma \) physics
New \( \Upsilon(1S,2S,3S) \), continuum \( \Rightarrow >10x \) older CLEO samples
\( \Lambda_B \) scan; \( \Upsilon(5S) \); \( R_{had} \) scans \( \Rightarrow \) more unique physics!

**CLEO-c: Low-Energy Data**  (‘c’ = charm)  \( c\bar{c} \) resonances
\( \psi(3770) \), \( \psi(4140) \), J/\( \psi \), \( \psi(2S) \), ...

**Detector Highlights:**
1989 -- CLEOII: CsI EM calorimeter
1995 -- CLEOII.V: SVX, Helium-Propane drift-chamber gas
2000 -- CLEOIII: TOF \( \Rightarrow \) RICH, new drift chamber
2003 -- CLEO-c: SV3 \( \Rightarrow \) “ZD” all-stereo inner drift chamber
Current Results from Belle and BaBar

- Belle and BaBar have studied the dependence of $\gamma$ on the D decay model
    $\phi_3 = (77^{+17}_{-19} \pm 13 \pm 11)^\circ$
  - BaBar – ICHEP04 paper hep-ex/0408088
    $\gamma = (70 \pm 26 \pm 10 \pm 10)^\circ$

- Monte Carlo studies with D decay models containing only known resonances lead to assigned modeling systematic error
- Models with arbitrary Breit-Wigners provide a better fit to data and smaller systematic uncertainty ($\pm 1^\circ$)
Belle Monte Carlo Study

- Belle studied relationship between systematic error on $\gamma$ and # of CP± vs $K_S\pi^+\pi^-$ events at CLEO-c
- CLEO Model – minus $f_2(1270)$, $K_2(1430)$, $K^*(1680)$

<table>
<thead>
<tr>
<th>#D$^0$</th>
<th>#D$_{CP+}$</th>
<th>#D$_{CP-}$</th>
<th>$\Delta\phi_3$ (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>100</td>
<td>100</td>
<td>15.2 ± 5.4</td>
</tr>
<tr>
<td>5000</td>
<td>500</td>
<td>500</td>
<td>7.0 ± 2.5</td>
</tr>
<tr>
<td>20000</td>
<td>2000</td>
<td>2000</td>
<td>1.6 ± 0.6</td>
</tr>
</tbody>
</table>

$$\Delta\phi_3(\delta, \theta) = \frac{\Delta\theta(\delta + \phi_3) - \Delta\theta(\delta - \phi_3)}{2}$$

- Recall that measured phase in $B^\pm$ decay is $\theta_\pm = \delta \pm \phi_3$
- Scan $(\delta, \phi_3)$, Determine RMS $\Delta\phi_3(\delta, \phi_3)$
- Worst case taken as $\Delta\phi_3$(max)
Sensitivity Estimate from CLEO-c

- Projected number of reconstructed events

<table>
<thead>
<tr>
<th></th>
<th>( #D^0 \to K_S \pi^+ \pi^- )</th>
<th>( #D_{CP+} )</th>
<th>( #D_{CP-} )</th>
<th>( (K_S \pi^+ \pi^-)^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>285 pb(^{-1})</td>
<td>(~25000)</td>
<td>(~115)</td>
<td>(~135)</td>
<td>(~240)</td>
</tr>
<tr>
<td>1 fb(^{-1})</td>
<td>(~87500)</td>
<td>(~400)</td>
<td>(~470)</td>
<td>(~840)</td>
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<table>
<thead>
<tr>
<th></th>
<th>( #D^0 \to \pi^+ \pi^- \pi^0 )</th>
<th>( #D_{CP+} )</th>
<th>( #D_{CP-} )</th>
<th>( (\pi^+ \pi^- \pi^0)^2 )</th>
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<td>285 pb(^{-1})</td>
<td>(~9200)</td>
<td>(~40)</td>
<td>(~50)</td>
<td>(~35)</td>
</tr>
<tr>
<td>1 fb(^{-1})</td>
<td>(~32200)</td>
<td>(~150)</td>
<td>(~175)</td>
<td>(~115)</td>
</tr>
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</table>

- Few degrees? (there are other syst. to lower!)
Comparison with PDG 2004

**THEN:**

CLEO & ALEPH

\[ D^{*+} \to \pi^+ D^0, \quad D^0 \to \pi^- \pi^+ \]

compare to:

\[ D^{*+} \to \pi^+ D^0, \quad D^0 \to \text{unobserved} \]

(Q~6MeV)

**NOW:**

\[ D^0 \to K^- \pi^+ \]

<table>
<thead>
<tr>
<th>Source</th>
<th>Error(%)</th>
<th>Source</th>
</tr>
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<tbody>
<tr>
<td>CLEO</td>
<td>3.6</td>
<td>CLEO</td>
</tr>
<tr>
<td>ALEPH</td>
<td>3.8</td>
<td>PDG</td>
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<tr>
<td></td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>CLEO-c</td>
<td>3.1</td>
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</table>

CLEO-c as precise as any previous measurement.