Absolute Hadronic $D^0$ and $D^+$ Branching Fractions at CLEO-c

Werner Sun, Cornell University
for the CLEO-c Collaboration

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Introduction to CLEO-c
Branching fraction measurement technique
Results
Future directions
The CLEO-c Program

- Run CESR at $\sqrt{s} = 3-5$ GeV to study $D$ and $D_s$ at threshold, search for exotics at $\psi$.
- Precise measurements of:
  - $D$, $D_s$ hadronic branching fractions:
    - Input to $V_{cb}$, 5% error.
    - For CLEO $V_{cb}$, 1.4% from $\sigma(B)$, total syst 4.3%
  - $D$ semileptonic $B$'s and form factors:
    - $V_{cs}$, $V_{cd}$ to ~ 1% (current errs. 16% and 7%).
    - $c\rightarrow u\nu$ FFs to test LQCD $V_{ub}$ (25% err. → 5%).
  - $D$ and $D_s$ decay constants:
    - Validate LQCD, use to predict $f_B$ & $f_{Bs} \rightarrow V_{td}$ & $V_{ts}$ (40% error → 5%).
- Improve understanding of strong and weak interactions (6 of 9 CKM matrix elements).
- Currently running at $\psi(3770) \rightarrow D\bar{D}$, no $D_s$.

Current analysis based on 60 pb$^{-1}$ pilot run from fall ’03–spring ‘04
CLEO-c and CESR-c

- **CESR III → CESR-c:**
  - Added 12 SC wiggler magnets to decrease emittance, damping time.
  - Only 6 were in place for the present dataset.

- **CLEO III → CLEO-c:**
  - Silicon vertex detector → stereo drift chamber.
  - B field 1.5 → 1.0 T

- **Tracking:** 93% of 4π
  - 53 layers.
  - $\sigma_p/p \approx 0.6\%$ at 1 GeV.

- **CsI calorimeter:** 93% of 4π
  - 7800 crystals.
  - $\sigma_E/E \approx 2.2\%$ at 1 GeV.

- **2 sources of particle ID:**
  - dE/dx in drift chamber.
  - RICH: 80% of 4π
  - Combined $\varepsilon$ (K or $\pi$) > 90%.
  - Fake rate < 5%.

- **Experimental features:**
  - Low multiplicity, bkgds.
  - Simple initial state: $e^+e^- \rightarrow \psi(3770) \rightarrow DD$, no extra fragmentation.
  - $D$ tagging—this analysis reconstructs 10% of all $D$ decays.
Overview of Technique

- Single tag (ST) = one $D$ reconstructed: $n_i = N_{DD}B_i \epsilon_i$
  - Identifies charge and flavor of other $D$.
  - Establishes well-defined subsample to search for other $D$.
- Double tag (DT) = both reconstructed: $n_{ij} = N_{DD}B_iB_j \epsilon_{ij}$
  \[
  B_i \approx \frac{n_{ij} \epsilon_j}{n_j \epsilon_{ij}} \quad N_{DD} \approx \frac{n_{ij} \epsilon_j}{n_{ij} \epsilon_i \epsilon_j}
  \]
- When all information combined, statistical $\sigma(B) \sim \sigma(N_{DD})$.
- Independent of $L$ and cross sections.
- Correlated systematic uncertainties cancel.
- Kinematics analogous to $Y(4S) \rightarrow \bar{B}B$: identify $D$ with
  \[
  M_{BC} = \sqrt{E_{beam}^2 - |P_D|^2} \quad \sigma(M_{BC}) \sim 1.3 \text{ MeV}, \text{x2 with } \pi^0
  \]
  \[
  \Delta E = E_{beam} - E_D \quad \sigma(\Delta E) \sim 7-10 \text{ MeV}, \text{x2 with } \pi^0
  \]
- Reference modes $D \rightarrow K^-\pi^+$ and $K^-\pi^+\pi^+$ normalize other $B$ measurements from other experiments.
- Same dataset as ICHEP04, but analysis updated.
Yield Fits

- Unbinned ML fits to $M_{BC}$ (1D for ST, 2D for DT)
  - Signal function includes ISR, $\psi(3770)$ line shape, beam energy smearing, and detector resolution.
  - Signal parameters from DT fits, then apply to ST.
  - Background: phase space (“ARGUS function”).
- $D$ and $\bar{D}$ yields and efficiencies separated.

<table>
<thead>
<tr>
<th>$M_{BC}$ (log scale) for ST modes: D+$\bar{D}$</th>
<th>Mode</th>
<th>$N_D$ (10^3)</th>
<th>$\bar{N}_D$ (10^3)</th>
<th>$\langle \varepsilon_D \rangle$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \to K\pi^+$</td>
<td>$K\pi$</td>
<td>5.11±0.07</td>
<td>5.15±0.07</td>
<td>65.1±0.2</td>
</tr>
<tr>
<td>$D^0 \to K\pi\pi^0$</td>
<td>$K\pi\pi^0$</td>
<td>9.51±0.11</td>
<td>9.47±0.11</td>
<td>31.6±0.1</td>
</tr>
<tr>
<td>$D^0 \to K\pi\pi\pi$</td>
<td>$K\pi\pi\pi$</td>
<td>7.44±0.09</td>
<td>7.43±0.09</td>
<td>43.8±0.1</td>
</tr>
<tr>
<td>$D^0 \to K\pi\pi\pi\pi$</td>
<td>$K\pi\pi\pi\pi$</td>
<td>7.56±0.09</td>
<td>7.56±0.09</td>
<td>51.0±0.1</td>
</tr>
<tr>
<td>$D^0 \to K\pi\pi\pi\pi\pi$</td>
<td>$K\pi\pi\pi\pi\pi$</td>
<td>2.45±0.07</td>
<td>2.39±0.07</td>
<td>25.7±0.1</td>
</tr>
<tr>
<td>$D^0 \to K\pi\pi\pi\pi\pi\pi$</td>
<td>$K\pi\pi\pi\pi\pi\pi$</td>
<td>1.10±0.04</td>
<td>1.13±0.04</td>
<td>45.7±0.3</td>
</tr>
<tr>
<td>$D^0 \to K\pi\pi\pi\pi\pi\pi\pi$</td>
<td>$K\pi\pi\pi\pi\pi\pi\pi$</td>
<td>2.59±0.07</td>
<td>2.50±0.07</td>
<td>22.4±0.1</td>
</tr>
<tr>
<td>$D^0 \to K\pi\pi\pi\pi\pi\pi\pi\pi$</td>
<td>$K\pi\pi\pi\pi\pi\pi\pi\pi$</td>
<td>1.63±0.06</td>
<td>1.58±0.06</td>
<td>31.2±0.1</td>
</tr>
<tr>
<td>$D^0 \to K\pi\pi\pi\pi\pi\pi\pi\pi\pi$</td>
<td>$K\pi\pi\pi\pi\pi\pi\pi\pi\pi$</td>
<td>0.64±0.03</td>
<td>0.61±0.03</td>
<td>41.1±0.4</td>
</tr>
</tbody>
</table>

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Branching Fraction Fitter

- $\mathcal{B}$ and $N_{DD}$ extracted from $\chi^2$ fit.
- Include both statistical and systematic errors (with correlations):
  - All experimental inputs treated consistently.
  - $\mathcal{B}(D^0)$ and $\mathcal{B}(D^+)$ statistically independent, but correlated by common systematics.
- Efficiency, crossfeed, background corrections performed directly in fit.
  - Predicted DCSD explicitly removed as background.

Fit Inputs:

\[ c = E^{-1} \left( n - F_b \right) \]

<table>
<thead>
<tr>
<th>Yields</th>
<th>( n )</th>
<th>( V_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>((n))</td>
<td>((n \times n))</td>
</tr>
<tr>
<td>Bkgnds</td>
<td>( b )</td>
<td>( V_b )</td>
</tr>
<tr>
<td></td>
<td>((b))</td>
<td>((b \times b))</td>
</tr>
<tr>
<td>Signal effs</td>
<td>( E )</td>
<td>( V_E )</td>
</tr>
<tr>
<td></td>
<td>((n \times n))</td>
<td>((n^2 \times n^2))</td>
</tr>
<tr>
<td>Bkgnd effs</td>
<td>( F )</td>
<td>( V_F )</td>
</tr>
<tr>
<td></td>
<td>((n \times b))</td>
<td>((nb \times nb))</td>
</tr>
</tbody>
</table>
Systematic Uncertainties

- Dominant error: MC simulation of tracking, $K^0_S$, and $\pi^0$ efficiencies.
  - Correlated among all particles of a given type—adds up quickly.
  - Missing mass technique to compare data and MC.
  - Fully reconstruct entire event, but deliberately leave out one particle.
  - Fraction of MM peak where the last particle is found = efficiency.
  - Depends on event cleanliness.

Example: $K^-$ efficiency from $D^0 \rightarrow K^-\pi^+$

$\varepsilon \approx 91\%$ in fiducial volume

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking/$K^0_S/\pi^0$</td>
<td>0.7/3.0/2.0</td>
</tr>
<tr>
<td>Particle ID</td>
<td>0.3 $\pi$ / 1.3 $K$</td>
</tr>
<tr>
<td>Trigger $\varepsilon$</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>$\Delta E$ cut</td>
<td>1.0–2.5 per $D$</td>
</tr>
<tr>
<td>FSR</td>
<td>0.5 ST / 1.0 DT</td>
</tr>
<tr>
<td>$\psi(3770)$ width</td>
<td>0.6</td>
</tr>
<tr>
<td>Resonant substructure</td>
<td>0.4–1.5</td>
</tr>
<tr>
<td>Event environment</td>
<td>0.0–1.3</td>
</tr>
<tr>
<td>Yield fit functions</td>
<td>0.5</td>
</tr>
<tr>
<td>Misc. event selection</td>
<td>0.3</td>
</tr>
<tr>
<td>Double DCSD</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Neutral DT: interference between Cabibbo-favored and DCSD on both sides.
Fit Results

- Precision comparable to PDG WA.
- Statistical errors: ~2.0% neutral, ~2.5% charged from total DT yields.
- \( \sigma \) (systematic) ~ \( \sigma \) (statistical).
  - Many systematics measured in data, will improve with time.
- Simulation includes FSR, so we measure \( B \) (final state + \( n_{\gamma} \)).
  - Using efficiencies without FSR correction would lower \( B \).
- \( N_{DD} \) includes continuum and resonant production.
- \( L \) determination being updated; no new cross sections since ICHEP, yet.
- \( N_{D^+D^-} / N_{D^0D^0} = 0.78 \pm 0.02 \pm 0.02 \).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>no FSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{D^0D^0} )</td>
<td>(2.01\pm0.04\pm0.02)\times10^5</td>
<td>-0.2%</td>
</tr>
<tr>
<td>( R^0 = K^-\pi^+ )</td>
<td>(3.91\pm0.08\pm0.09)%</td>
<td>-2.0%</td>
</tr>
<tr>
<td>( K^-\pi^+\pi^0 )</td>
<td>(14.9\pm0.3\pm0.5)%</td>
<td>-0.8%</td>
</tr>
<tr>
<td>( K^-\pi^+\pi^- )</td>
<td>(8.3\pm0.2\pm0.3)%</td>
<td>-1.7%</td>
</tr>
<tr>
<td>( N_{D^+D^-} )</td>
<td>(1.56\pm0.04\pm0.01)\times10^5</td>
<td>-0.2%</td>
</tr>
<tr>
<td>( R^+ = K^-\pi^+\pi^+ )</td>
<td>(9.5\pm0.2\pm0.3)%</td>
<td>-2.2%</td>
</tr>
<tr>
<td>( K^-\pi^+\pi^-\pi^0 )</td>
<td>(6.0\pm0.2\pm0.2)%</td>
<td>-0.6%</td>
</tr>
<tr>
<td>( K_s^0\pi^+ )</td>
<td>(1.55\pm0.05\pm0.06)%</td>
<td>-1.8%</td>
</tr>
<tr>
<td>( K_0^0\pi^+\pi^0 )</td>
<td>(7.2\pm0.2\pm0.4)%</td>
<td>-0.8%</td>
</tr>
<tr>
<td>( K^0\pi^+\pi^- )</td>
<td>(3.2\pm0.1\pm0.2)%</td>
<td>-1.4%</td>
</tr>
<tr>
<td>( K^+K^-\pi^+ )</td>
<td>(0.97\pm0.04\pm0.04)%</td>
<td>-0.9%</td>
</tr>
<tr>
<td>( K^-\pi^+\pi^- / R^0 )</td>
<td>3.65\pm0.05\pm0.011%</td>
<td>+1.2%</td>
</tr>
<tr>
<td>( K^-\pi^+\pi^- \pi^0 / R^0 )</td>
<td>2.10\pm0.03\pm0.06%</td>
<td>+0.3%</td>
</tr>
<tr>
<td>( K^-\pi^+\pi^-\pi^0 / R^+ )</td>
<td>0.61\pm0.01\pm0.02%</td>
<td>+1.7%</td>
</tr>
<tr>
<td>( K_s^0\pi^+ / R^+ )</td>
<td>0.165\pm0.004\pm0.006%</td>
<td>+0.4%</td>
</tr>
<tr>
<td>( K_0^0\pi^+\pi^0 / R^+ )</td>
<td>0.75\pm0.02\pm0.03%</td>
<td>+1.4%</td>
</tr>
<tr>
<td>( K^0\pi^+\pi^- \pi^+ / R^+ )</td>
<td>0.34\pm0.009\pm0.014%</td>
<td>+0.8%</td>
</tr>
<tr>
<td>( K^+K^-\pi^+ / R^+ )</td>
<td>0.101\pm0.004\pm0.002%</td>
<td>+1.3%</td>
</tr>
</tbody>
</table>
Comparison with PDG 2004

- Measurements and errors normalized to PDG.
- PDG global fit includes ratios to $K\pi^+$ or $K^-\pi^+\pi^+$.
- No FSR corrections in PDG measurements.
- Our measurements also correlated (statistics and efficiency systematics).

Other direct meas.

$B(D^0 \rightarrow K\pi^+)$

$B(D^+ \rightarrow K^+\pi^+\pi^+)$

Overall C.L 25.9%
Future Directions

- Improve measurements with more data (goal 3 fb\(^{-1}\)).
  - 285 pb\(^{-1}\) projected for this summer.
  - Will lower both statistical and systematic uncertainties.
  - With 1 fb\(^{-1}\), < 2% errors on \(K^{-}\pi^{+}\) and \(K^{-}\pi^{+}\pi^{+}\)—systematics limited.

- \(D^{0}\bar{D}^{0}\) quantum coherence negligible: only flavored final states.
- But with \(CP\) eigenstates, exploit coherence to probe mixing.
  - \(x = \Delta M/\Gamma, y = \Delta \Gamma/2\Gamma, r = \text{DCS-CF amp. ratio, } \delta = \text{DCS-CF phase diff.}\)
  - \(Time\text{-}integrated\) yields sensitive to mixing, e.g. \(\Gamma(D\rightarrow CP^{\pm}) \sim 1\pm y\).
  - Mixing entangled with DCSD, separate with semileptons.

- Simultaneous fit for hadronic and semileptonic \(B_s + x, y, r, \delta\).
- With 1 fb\(^{-1}\): \(\sigma(y) \sim 1\%\) (same as current WA)
  - \(\sigma(x \sin \delta) \sim 1.5\%\) (current: \(x\cos \delta + y\sin \delta < 1.8\%\) at 95% C.L.).
- CLEO-c also sensitive to new physics through rare phenomena.
- See also D. Asner in WG5.
Summary

- One major goal of CLEO-c: measure hadronic $D$ branching fractions (preprint to appear as CLNS 05-1914, CLEO 05-6).
- Three more years of data taking.
- Branching fractions in 60 pb$^{-1}$ competitive with world averages.
  - $\mathcal{B}(D^0 \to K^-\pi^+)$ measured to 3.1% (PDG 2.4%).
  - $\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$ measured to 3.9% (PDG 6.5%).
- Over 4x more data for this summer.
  - Will lower statistical and systematic errors.
- $D_s$ branching fractions with $\sqrt{s} \sim 4.14$ GeV running.
- Reduce error on $V_{cb}$.
- Contribute to stringent test of CKM unitarity.