Setting the Charm Decay Scale

\[ e^+ e^- \rightarrow D_s^* D_s \rightarrow D_s^+ D_s^- \gamma \]
Outline

- Intro to CLEO-c
- Open charm physics at CLEO-c
- Hadronic branching fraction analyses
  - $D^0/D^+$
  - $D_s$
CESR is a 768 m circumference $e^+e^-$ storage ring

Provides collisions for CLEO and beams for the Cornell High Energy Synchrotron Source

Originally designed to operate at $E_{cm} = 9$–$12$ GeV, ran mostly at $\gamma$ resonances with (at the time) world-record luminosities ($1.25 \times 10^{33}$)

Upgraded to provide collisions down to $E_{cm} = 3$ GeV
Old CESR could not cool the beams at low energy enough for good luminosity (synchrotron power $\propto E^4$)

- CLEO can no longer run simultaneously with CHESS

- Solution: 12 wiggler magnets installed

- “Anti-solenoids” cancel energy-dependent effects of CLEO field on beam
CLEO-c Upgrade

- CLEO-III silicon vertex detector replaced with (all stereo) drift chamber (typical $z_0$-resolution 700 $\mu$m)
- Solenoid magnetic field changed from 1.5T to 1.0T to compensate for lower-momentum tracks
- DAQ, trigger, software, etc. from CLEO-III with only minor changes
- Particle ID (from $dE/dx$, Čerenkov) better due to lower $p$ tracks
- Muon system now only useful for high momentum (e.g. $J/\psi \rightarrow \mu^+\mu^-$),

Peter Onyisi
Charm Hadronic BF's
Texas A&M, 21 Apr 2006
CLEO-c Missions

- **Enable** measurements at other experiments
  - Find branching fractions of reference modes
  - Test theoretical input to $B$-factories
  - Measure strong phases in $D$ system
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  ▶ Test theoretical input to $B$-factories
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**Explore** QCD dynamics in the charm region and below
  ▶ Charmonium
  ▶ $D$ Dalitz studies
  ▶ Light mesons in radiative decays
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- Explore QCD dynamics in the charm region and below
  - Charmonium
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  - Light mesons in radiative decays

- **Search** for new physics
  - $D^0 - \overline{D^0}$ mixing
  - CP violation
  - Rare decays
Leptonic decays:

- Probe wavefunction at origin (decay constants $f_D$, $f_{D_s}$)
  - Test lattice QCD and meson structure models

Semileptonic decays:

- Probe overlap of initial and final hadron states (form factors $f_+(q^2)$ ...)
  - Test LQCD and decay models

Hadronic decays:

- Reference modes normalize decays
- QCD dynamics
- Search for new phenomena: CP violation, $D^0-\bar{D}^0$ mixing
What is the problem?

- Measurements of decays to $c$ quarks depend on reconstructing decays of light charmed mesons and baryons.

- Branching fraction measurements can be limiting systematics.
  - Since $b \to c$ is a dominant decay mode, $B$ measurements often rely on knowing various $D_{(s)}$ BFs.
  - Affects precision measurements of $Z \to c\bar{c}$ ($H \to c\bar{c} \ldots$).

- Reference modes ($D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to \phi\pi^+$) normalize virtually all other branching fractions.
General Method

(Follows pioneering analysis by Mark III...)

- Exploit low-energy production processes:
  - At 3.77 GeV, open charm only produced as $D^0\bar{D}^0$ and $D^+D^-$
  - At 4.17 GeV, $D_s$ produced almost entirely as $D_s^*D_s$
- In the events we use, a meson of interest is always produced along with its antiparticle
- We choose a set of modes and reconstruct single tags (we reconstruct a decay) and double tags (we reconstruct both decays)
  - A double tag can count as single tags
  - For $N$ decay modes we have $2N$ single tags (separated by charge) and $N^2$ double tags
- Since the single tag yield in mode $i$ is proportional to $\mathcal{B}_i$, and the double tag yield for $i, j$ is proportional to $\mathcal{B}_i\mathcal{B}_j$, we can determine each of the branching fractions
Single tag yields: \( N_i = N_{DD} B_i \epsilon_i \)

Double tag yields: \( N_{ij} = N_{DD} B_i B_j \epsilon_{ij} \)

\[ \Rightarrow \text{Branching fractions: } B_j = \frac{N_{ij}}{N_i} \frac{\epsilon_i}{\epsilon_{ij}} \]

- In practice, we fit all the yields simultaneously
  - Maximizes power: limiting statistical uncertainty is \( \sqrt{\text{total double tags in every mode}} \)
  - Bad \( \chi^2 \rightarrow \) something wrong...

- Can correlate systematics
- Obtain cross-section as well
$D^0/D^+$ Analysis
(PRL 95 121801)
Data Used

- $\mathcal{L} = (55.8 \pm 0.6) \, \text{pb}^{-1}$ at $E_{cm} \approx 3.773 \, \text{GeV}$, at the peak of the $\psi(3770)$ resonance

- CLEO-c dataset as of end of 2004
  - We are updating to summer 2005 ($281 \, \text{pb}^{-1}$)

- Also exploit $\approx 3 \, \text{pb}^{-1}$ of CLEO-c $\psi'$ data for systematics studies

![Graph showing the operating point and threshold for charm hadronic BFs]
Hadronic Decay Overview

- Reference decay modes are $D^0 \rightarrow K^- \pi^+$ and $D^+ \rightarrow K^- \pi^+ \pi^+$
- 18 single tag, 45 double tag modes

<table>
<thead>
<tr>
<th>Decay</th>
<th>PDG 2004 fit</th>
<th>Rel uncert</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K^- \pi^+$</td>
<td>3.80%</td>
<td>2.4%</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^- \pi^+ \pi^0$</td>
<td>13.0%</td>
<td>6.2%</td>
</tr>
<tr>
<td>$D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$</td>
<td>7.46%</td>
<td>4.2%</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^- \pi^+ \pi^+$</td>
<td>9.2%</td>
<td>6.5%</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0$</td>
<td>6.5%</td>
<td>17%</td>
</tr>
<tr>
<td>$D^+ \rightarrow K_S \pi^+$</td>
<td>1.41%</td>
<td>6.7%</td>
</tr>
<tr>
<td>$D^+ \rightarrow K_S \pi^+ \pi^0$</td>
<td>4.85%</td>
<td>31%</td>
</tr>
<tr>
<td>$D^+ \rightarrow K_S \pi^+ \pi^+ \pi^-$</td>
<td>3.55%</td>
<td>14%</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^- K^+ \pi^+$</td>
<td>0.89%</td>
<td>9.0%</td>
</tr>
</tbody>
</table>
Charged $K$, $\pi$ distinguished using $dE/dx$ (all momenta) and Čerenkov (for high momentum)

Find $\pi^0$’s by combining pairs of isolated showers in the CsI calorimeter, requiring $3\sigma$ consistency with $\pi^0$ mass ($\sigma \sim 6$ MeV)

Find $K_S$’s by combining pairs of tracks that lie within a mass window

Two crucial kinematic variables:

- “Beam-constrained mass” $M_{BC} = \sqrt{E_{beam}^2 - p_D^2}$ tests that total momentum of candidate is right
- $\Delta E = E_D - E_{beam}$ tests particle ID, is sensitive to missing particles

“D Tagging will solve the world’s problems and make it sunny in Ithaca” - Anon.
Yield extraction

DATA: Single tags

- Fit signal with a priori function of physical parameters (detector momentum resolution, beam energy spread, $\Psi(3770)$ lineshape, ISR spectrum)
- Smooth backgrounds fit as combinatoric phase space ("ARGUS function")
- Peaking backgrounds estimated from known BFs and subtracted
- In double tags, fit 2D plane of $M_{BC}(1)$ vs. $M_{BC}(2)$

DATA: Double tag projections

DT signal shape

- Detector resolution
- ISR & beam energy

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Texas A&M, 21 Apr 2006
Clean decays $\psi' \rightarrow J/\psi \pi^+ \pi^-$ and $J/\psi \pi^0 \pi^0$ used to compare tracking and $\pi^0$ efficiencies in MC and data.

Reconstruct $J/\psi$ and one pion; compute recoil mass: peaks at pion mass

Find fraction of such events with other pion reconstructed

Right: Plots for $J/\psi \pi^+ \pi^-$, $0.15 < \cos \theta_{\pi} < 0.55$

$\epsilon = (95.89 \pm 0.20)\%$; agrees with MC within statistics.
Consider double tags with $D^0 \to K\pi$:

- Dominant decay is $D^0 \to K^-\pi^+$ ($\bar{D}^0 \to K^+\pi^-$). However there are doubly Cabibbo-suppressed decays $D^0 \to K^+\pi^-$ and vice versa.
- The ratio of amplitudes is the complex number $A$, which encodes both the suppression and a relative strong interaction phase $\delta$.
- The *direct contribution* of the double DCSD amplitude in double tags is negligible.
- But you have *interference* between $D^0\bar{D}^0$ going Cabibbo-allowed to both modes and double DCSD:

  $$ J = |1 + A^2|^2 = 1 + 2|A|^2 \cos 2\delta + O(|A|^4) $$

- $|A|^2 \sim 0.4\%$; we don't know $\cos 2\delta$: 0.8% uncertainty on $D^0$ double tag rates!

(We expect $\cos \delta \sim 1$; we're doing analyses to test this...)
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Fractional uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking/$K_S /\pi^0$</td>
<td>0.7/3.0/2.0 per particle</td>
</tr>
<tr>
<td>Particle ID</td>
<td>0.3 per $\pi$, 1.3 per $K$</td>
</tr>
<tr>
<td>Trigger efficiency</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 modeling</td>
<td>0.5 per single tag</td>
</tr>
<tr>
<td>$\psi''$ 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 interference</td>
<td>0.8 in neutral double tags</td>
</tr>
</tbody>
</table>

$D^0 \rightarrow K^-\pi^+$ uncert 2.3%, $D^+ \rightarrow K^-\pi^+\pi^+$ uncert 2.8%

For these, largest contributors are kaon PID and $\Delta E$ cut
Branching fractions ...

<table>
<thead>
<tr>
<th>Mode</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(D^0 \to K^-\pi^+)$</td>
<td>$(3.91 \pm 0.08 \pm 0.09)%$</td>
</tr>
<tr>
<td>$\mathcal{B}(D^0 \to K^-\pi^+\pi^0)$</td>
<td>$(14.9 \pm 0.3 \pm 0.5)%$</td>
</tr>
<tr>
<td>$\mathcal{B}(D^0 \to K^-\pi^+\pi^+\pi^-)$</td>
<td>$(8.3 \pm 0.2 \pm 0.3)%$</td>
</tr>
<tr>
<td>$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$</td>
<td>$(9.5 \pm 0.2 \pm 0.3)%$</td>
</tr>
<tr>
<td>$\mathcal{B}(D^+ \to K^-\pi^+\pi^+\pi^0)$</td>
<td>$(6.0 \pm 0.2 \pm 0.2)%$</td>
</tr>
<tr>
<td>$\mathcal{B}(D^+ \to K_S\pi^+)$</td>
<td>$(1.55 \pm 0.05 \pm 0.06)%$</td>
</tr>
<tr>
<td>$\mathcal{B}(D^+ \to K_S\pi^+\pi^0)$</td>
<td>$(7.2 \pm 0.2 \pm 0.4)%$</td>
</tr>
<tr>
<td>$\mathcal{B}(D^+ \to K_S\pi^+\pi^+\pi^-)$</td>
<td>$(3.2 \pm 0.1 \pm 0.2)%$</td>
</tr>
<tr>
<td>$\mathcal{B}(D^+ \to K^+K^-\pi^+)$</td>
<td>$(0.97 \pm 0.04 \pm 0.04)%$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\sigma_{D^+D^-}$ (nb)</th>
<th>$\sigma_{D^0\bar{D}^0}$ (nb)</th>
<th>$\sigma_{D\bar{D}}$ (nb)</th>
<th>$\sigma_{D^+D^-}/\sigma_{D^0\bar{D}^0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.79 \pm 0.07^{+0.10}_{-0.04}$</td>
<td>$3.60 \pm 0.07^{+0.07}_{-0.05}$</td>
<td>$6.39 \pm 0.10^{+0.17}_{-0.08}$</td>
<td>$0.776 \pm 0.024^{+0.014}_{-0.006}$</td>
</tr>
</tbody>
</table>

... and cross sections from $55.8$ pb$^{-1}$
Result comparison

\[ \frac{\mathcal{B}(\text{CLEO-c})}{\mathcal{B}(\text{PDG})} \]

\[ \frac{\text{Br. Ratio(\text{CLEO-c})}}{\text{Br. Ratio(\text{PDG})}} \]

\[ \mathcal{B}(D^0 \rightarrow K^- \pi^+) \]
previous absolute measurements and PDG fit

\[ \mathcal{B}(D^+ \rightarrow K^- \pi^+ \pi^+) \]
previous absolute measurements and PDG fit
Branching fractions from 56 pb$^{-1}$ have precision comparable to world averages.

Updating to 281 pb$^{-1}$: we will be systematics-limited.

Aiming for $< 1.5\%$ uncertainty on reference modes.
$D_s$ Analysis
(In Progress)
The classic reference decay has been the exclusive mode $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$

Essentially all other decays have branching ratios to this mode.

This causes problems since $\phi$ signal is ambiguous given the precision we will soon achieve.

We instead measure inclusive branching fractions.

### Modes used

<table>
<thead>
<tr>
<th>Decay</th>
<th>PDG 2004 BF (%)</th>
</tr>
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<tbody>
<tr>
<td>$D_s^+ \rightarrow K_S K^+$</td>
<td>1.8 ± 0.55</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^- K^+ \pi^+$</td>
<td>4.3 ± 1.2</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^- K^+ \pi^+ \pi^0$</td>
<td>—</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \pi^+ \pi^+ \pi^-$</td>
<td>1.00 ± 0.28</td>
</tr>
</tbody>
</table>

Relative uncertainties are roughly 25–30%, limited by the $\phi \pi^+$ BF in PDG 2004. BaBar has a 2005 $\phi \pi^+$ measurement, 34% higher than the PDG, with 13% errors.
The $\phi\pi^+$ problem

- Expect $(f_0(980) \rightarrow K^- K^+)\pi^+$ to contribute to any $\phi$ mass region, with badly controlled parameters.

- Correction might be on the order of 5% or more — but depends on experiment’s mass window, resolution, angular distribution requirements!

Looking at low-mass $KK$ pairs ($m(KK) < 1.005$ GeV) we see evidence for scalar production by looking at helicity angle.
Dataset and Landscape

- Use 76 pb$^{-1}$ of data collected at $E_{cm} \sim 4170$ MeV as part of the recent (Aug.–Jan.) $D_s$ energy scan and data run
  - Chose running point for maximal $D_s$ production
- Dominant $D_s$ production channel in this region is $D_s^* D_s$, $\approx 1$ nb
- $D^0$, $D^+$ events produced at $\approx 7$ nb, are the major background

![Operating point diagram]
We use events with the topology
\( e^+ e^- \rightarrow D_s^{*\pm} D_s^{\mp} \rightarrow D_s^+ D_s^- (\gamma, \pi^0) \).

We do not reconstruct the \( \gamma \) or \( \pi^0 \).

We use the momentum of the \( D_s \) candidates to select for events with an intermediate \( D_s^* \). (The quantity \( m_{BC} = \sqrt{E_{beam}^2 - \vec{p}_D^2} \) is a proxy for momentum.)

We can use a loose cut to include the daughters of \( D_s^* \), or a tight cut for the directly produced \( D_s \).
$m_{\text{inv}}$ vs. $m_{\text{BC}}$ for $K^- K^+ \pi^+$ candidates

$\sqrt{E_{\text{beam}}^2 - p_{\text{cand}}^2}$
We do a binned maximum likelihood fit for all the observed yields (utilizing Poisson statistics for double tags)

Maximizing statistical power important given relatively low $D_s$ cross-section

The $KK\pi$ mode is 62% of all single tags, but $KK\pi/KK\pi$ is only 26% of the double tag yield
Crossfeed between $D_s$ modes from $K_S \leftrightarrow \pi^+\pi^-$ is Cabibbo-suppressed.

- Use vetoes and sidebands

Peaking structure can arise from reflections: for example, the decay chain $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-K^+\pi^+$ has correct $m_{BC}$, peaks at 2.06 GeV.

- We veto certain mass regions; e.g. for $KK\pi$ we reject events consistent with $D^0 \rightarrow KK$.

- This doesn’t affect signal but makes the background easier to model.
Fit single tag signals with double Gaussian or Crystal Ball function (parameters fixed from Monte Carlo) plus a linear background

- Each charge done separately

- In double tags, count events in signal and sideband boxes

  - Combinatoric background is flat in $m(D_s^+) - m(D_s^-)$, has structure in $m(D_s^+) + m(D_s^-)$
Data Results

### m(D), D^+ → K_s K^+

- 788 ± 34

### m(D), D^+ → K^+ K^-

- 3344 ± 77

### m(D), D^+ → K^+ π^+

- 709 ± 54

### m(D), D^+ → π^+ π^- π^0

- 539 ± 41

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136 signal
28 sideband
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</tr>
<tr>
<td>Fit procedure</td>
<td>3.5 in fit result</td>
</tr>
<tr>
<td>Event environment</td>
<td>3.5 in $KK\pi\pi^0$</td>
</tr>
<tr>
<td>Initial state radiation correction</td>
<td>0–5 per single tag</td>
</tr>
<tr>
<td>$\mathcal{B}(D_{s}^{\ast+} \rightarrow \pi^0 D_{s}^+)$</td>
<td>0.7 in $KK\pi\pi^0$, $\pi\pi\pi$</td>
</tr>
</tbody>
</table>
### Preliminary Results for $D_s$

<table>
<thead>
<tr>
<th>Mode</th>
<th>CLEO-c (%)</th>
<th>PDG 2004 fit (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(K_S K^+)$</td>
<td>$1.28^{+0.13}_{-0.12} \pm 0.07$</td>
<td>$1.8 \pm 0.55$</td>
</tr>
<tr>
<td>$\mathcal{B}(K^- K^+ \pi^+)$</td>
<td>$4.54^{+0.44}_{-0.42} \pm 0.25$</td>
<td>$4.3 \pm 1.2$</td>
</tr>
<tr>
<td>$\mathcal{B}(K^- K^+ \pi^+ \pi^0)$</td>
<td>$4.83^{+0.49}_{-0.47} \pm 0.46$</td>
<td>—</td>
</tr>
<tr>
<td>$\mathcal{B}(\pi^+ \pi^+ \pi^-)$</td>
<td>$1.02^{+0.11}_{-0.10} \pm 0.05$</td>
<td>$1.00 \pm 0.28$</td>
</tr>
</tbody>
</table>

### Graphs

- **Left Graph**: Branching Fraction (%) vs. Mode: $K_S K^+$, $K^+ K^- \pi^+$, $K^+ K^- \pi^+ \pi^0$, $\pi^+ \pi^+ \pi^-$
  - PDG 2004 fit
  - CLEO Preliminary, 76 pb$^{-1}$

- **Right Graph**: BF/PDG 2004 fit vs. Mode: $K_S K^+$, $K^+ K^- \pi^+$, $K^+ K^- \pi^+ \pi^0$, $\pi^+ \pi^+ \pi^-$
  - PDG 2004 fit
  - PDG 2004 fit, BR error only
  - CLEO Preliminary, 76 pb$^{-1}$
Comparison with BaBar $\phi\pi^+$

Can we compare with the BaBar $\mathcal{B}(D_s^+ \to \phi\pi^+)$ result?

- We can use the PDG fit branching ratios...

- We are more consistent with 3.6% than 4.8%
We have preliminary absolute branching fractions for four $D_s$ decay modes from 76 pb$^{-1}$ of data
- Precision about 11% for all-charged modes
- Inclusive $K^- K^+ \pi^+ \pi^0$ is a first measurement
The measured BF$s$ are consistent with the PDG 2004 fit
- We are actively working on adding more modes (especially decays with $\eta$, $\eta'$)
- We are aiming for $< 4\%$ uncertainties with full CLEO-c dataset
- Already have more than 100 pb$^{-1}$ additional data on tape!
Non-peaking backgrounds removed in the yield fit

Peaking backgrounds are from crossfeed between modes we consider, and contamination from other modes

- Latter dominated by Cabibbo-suppressed decays in $K_S$ modes, e.g. prompt $D^+ \rightarrow 5\pi$ fakes $D^+ \rightarrow K_S 3\pi$; in some modes up to 3% correction

Estimate backgrounds to single and double tags with PDG branching fractions and efficiencies from MC, subtract from measured yields.

MC 30x data

DCSD decay $\bar{D}^0 \rightarrow K^- \pi^+$ faking $D^0 \rightarrow K^- \pi^+$ in 30x MC sample. In data, contributes $\approx 0.15\%$ of observed peak.
Resonant Substructure

- Our Monte Carlo has some reasonable mixture of intermediate resonances
- Our efficiencies depend on the intermediate state
- We reweight the expected efficiencies by comparing data yields with MC expectations
  - Size of correction is largest systematic for $K^- K^+ \pi^+ \pi^0$
- The correction for a given mode affects that mode’s BF only