$D_{(s)}$ Hadronic Decays From CLEO-c

$e^+ e^- \rightarrow D_s^* D_s \rightarrow D_s^+ D_s^- \gamma$

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CLEO Collaboration

Charm 2006, June 5-7, 2006
Outline

- Scope of hadronic decay analyses (and this talk)
- Analysis techniques
- Results:
  - $D^0/D^+/D_s$ absolute branching fractions
  - $D^0/D^+ \rightarrow (m)\pi^\pm (n)\pi^0$
  - $D^+ \rightarrow K_{S,L}\pi^+$
  - $D^0/D^+/D_s \rightarrow (\phi, \eta, \eta')X$
The hadronic decays of charmed mesons are a very active field of study at CLEO-c — multiple talks are covering our results:

- The Quantum Correlation Analysis (D. Asner)
- Dalitz analyses (M. Dubrovin)
- High energy scan [3.97–4.26 GeV] (R. Poling)

This talk will cover branching fraction results.

Physics from branching fractions:

- Important as engineering numbers:
  - “Reference” modes, e.g. $D^0 \rightarrow K^-\pi^+$ and $D^+ \rightarrow K^-\pi^+\pi^+$, normalize many $D$ and $B$ decays
  - Inclusive rates help disentangle charm content

- Relative rates of decays measure various decay amplitudes, probe final state interactions
Detector slightly modified from $\Upsilon$ physics configuration: silicon vertex detector replaced with (all stereo) drift chamber

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. $J/\psi \rightarrow \mu^+\mu^-$)
Datasets

CLEO-c has accumulated:

- 281 pb\(^{-1}\) at \(\psi(3770)\)
  - \(D\bar{D}\) at 6 nb
  - The \(D^0/D^+\) absolute BFs use 56 pb\(^{-1}\) only, are being updated
- \(\approx 200\) pb\(^{-1}\) near 4.17 GeV
  - \(D_s^*D_s\) at 1 nb, \(DD + D^*D + D^*D^*\) at 7 nb
  - Only \(\approx 75\) pb\(^{-1}\) used for results here

Operating points

\(E_{cm}\) \(\rightarrow\) \(D\bar{D}\) \(\rightarrow\) \(D_s^*D_s\)
Analysis techniques

These analyses use “single tag” and “double tag” techniques:

▶ **Single tag** events reconstruct the signal in events without regard for the rest of the event

▶ **Double tag** events reconstruct the signal opposite a well-understood (flavor tagging) decay

**Single tags:**
- ✓ Full statistics available
- × Branching ratios only (ratios of ST yields)
- × $D^0$ BFs affected by quantum correlations, especially CP eigenstates

**Double tags:**
- ✓ Very clean
- ✓ Branching fractions from ratios of DT and ST yields
- ✓ Can infer $K_L^0$
- ✓ Flavor tags minimize quantum correlations
- × Tag efficiency $\sim O(10\%)$
Tagging at different energies

- At $\psi(3770)$, only open charm channels are $D^0\bar{D}^0$, $D^+D^-$
  - Cut on $\Delta E \equiv E_{\text{cand}} - E_{\text{beam}}$, fit in $m_{BC} \equiv \sqrt{E_{\text{beam}}^2 - |\vec{p}_{\text{cand}}|^2}$
- At $E_{cm} = 4.17$ GeV, multiple open channels. For $D_s$ we use $D_s^*D_s$
  - We use $m_{BC}$ as a proxy for momentum to choose the $D_s^*D_s$ two-body decay
  - Fits are in invariant mass
- 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
Kinematic Separation at $E_{cm} = 4.17$ GeV

$m_{inv}$ vs. $m_{BC}$ for $K^- K^+ \pi^+$ candidates

$\sqrt{E_{beam}^2 - \vec{p}_{cand}^2}$
Absolute Hadronic Branching Fractions: Overview

- $D^0/D^+$ reference decay modes are $D^0 \rightarrow K^-\pi^+$ and $D^+ \rightarrow K^-\pi^+\pi^+$
- The classic $D_s$ reference decay has been the exclusive mode $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$
- This causes problems since $\phi$ signal is ambiguous given the precision we will soon achieve. All results here are inclusive branching fractions only.

<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>
<tr>
<td>$D_s^+ \rightarrow K_SK^+$</td>
<td>1.8%</td>
<td>31%</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^-K^+\pi^+$</td>
<td>4.3%</td>
<td>28%</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^-K^+\pi^+\pi^0$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \pi^+\pi^+\pi^-$</td>
<td>1.00%</td>
<td>28%</td>
</tr>
</tbody>
</table>

BaBar has a 2005 $\phi\pi^+$ measurement, 34% higher than the PDG, with 13% errors.
Absolute Hadronic Branching Fractions: General Method

(Follows pioneering analysis at $\psi(3770)$ by Mark III...)

▸ Exploit low-energy production processes:
  ▸ At 3.77 GeV, open charm only produced as $D^0\overline{D}^0$ and $D^+D^−$
  ▸ At 4.17 GeV, $D_s$ produced almost entirely as $D_{s}^*D_{s}$

▸ Single tags pin down ratios between modes, double tags establish absolute BF scale
  ▸ Use a $\chi^2 (D^0/D^+)$ or maximum likelihood ($D_s$) fit to the observed yields to extract maximum information

▸ For $D^0/D^+$, double tags reconstruct entire event. For $D_s$, we only reconstruct the $D_{s}^+D_{s}^−$ (the $\gamma$ or $\pi^0$ from the $D_{s}^* \rightarrow D_s$ transition is ignored)
$D^0/D^+$ Yield Extraction

DATA: Single tags

- $D^0 \to K^- \pi^+$
- $D^- \to K^- \pi^+ \pi^+$
- $D^0 \to K_S^0 \pi^+$
- $D^0 \to K^- \pi^+ \pi^0$
- $D^- \to K^- \pi^+ \pi^0$
- $D^0 \to K_S^0 \pi^+ \pi^0$
- $D^0 \to K^- \pi^+ \pi^+$
- $D^- \to K_S^0 \pi^+ \pi^-$
- $D^0 \to K^+ \pi^+$

DATA: Double tag projections

- 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. $M_{BC}(2)$

DT signal shape

Detector resolution

ISR & beam energy
### Systematic Uncertainties

(56 pb$^{-1}$ analysis)

<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>

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

For these, largest contributors are kaon PID and $\Delta E$ cut
### $D^0 / D^+$ Results

#### 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>

#### Cross sections from $55.8 \text{ pb}^{-1}$ (PRL 95 121801)

<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>
$D^0 / D^+$ Result Comparison

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

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

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

$\mathcal{B}(D^+ \rightarrow K^-\pi^+\pi^+)$
previous absolute measurements and PDG fit
$D_s$ Data Yields

**Single Tags**

$K_S K^+$ \(788 \pm 34\)

$K^- K^+ \pi^+$ \(3344 \pm 77\)

$K^- K^+ \pi^+ \pi^0$ \(709 \pm 54\)

$\pi^+ \pi^+ \pi^-$ \(539 \pm 41\)

**Double Tags**

All double tags

136 signal
28 sideband

Peter Onyisi
CLEO-c Charm Hadronic Decays
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### $D_s$ Systematic Uncertainties

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</tr>
<tr>
<td>Resonant substructure</td>
<td>0–6.0 correlated by decay</td>
</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>$\mathcal{B}(D_s^{*+} \rightarrow \pi^0 D_s^+)$</td>
<td>0.7 in $KK\pi\pi^0, \pi\pi\pi$</td>
</tr>
</tbody>
</table>
### $D_s$ Results

#### Preliminary

<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>

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**Diagrams:**

- **Left Diagram:**
  - Branching Fraction (%)
  - Modes: $K_S K^+$, $K^+ K^- \pi^+$, $K^+ K^- \pi^+ \pi^0$, $\pi^+ \pi^+ \pi^-$
  - Axes: Branching Fraction (%), PDG 2004 fit, CLEO Preliminary

- **Right Diagram:**
  - BF/PDG 2004 fit
  - Modes: $K_S K^+$, $K^+ K^- \pi^+$, $\pi^+ \pi^+ \pi^-$
  - Axes: BF/PDG 2004 fit, PDG 2004 fit, CLEO Preliminary
Absolute Branching Fractions Summary and Outlook

- $D^0/D^+$:
  - 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

- $D_s$:
  - 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 BFs 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
  - Have more than 120 pb$^{-1}$ additional data on tape
Motivations:

- Cabibbo-suppressed BF's badly known, in particular for modes with \( \pi^0 \)'s
- Isospin analysis from \( D \rightarrow \pi\pi \) probes final state interactions
- Find resonant contributions and tune MC

- Single tag analysis provides full reach for these low rate modes
- Branching ratios measured relative to \( D^0 \rightarrow K^-\pi^+ \) and \( D^+ \rightarrow K^-\pi^+\pi^+ \)
$D^0 / D^+ \rightarrow (m)\pi^\pm (n)\pi^0$

Shaded histogram is normalized sideband
Signals seen in all channels except $D^0 \rightarrow \pi^0 \pi^0 \pi^0$
$D^0 / D^+ \rightarrow (m)\pi^\pm (n)\pi^0$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\mathcal{B} \left(10^{-3}\right)$</th>
<th>PDG $\left(10^{-3}\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+ \pi^-$</td>
<td>$1.39 \pm 0.04 \pm 0.04 \pm 0.03 \pm 0.01$</td>
<td>$1.38 \pm 0.05$</td>
</tr>
<tr>
<td>$\pi^0 \pi^0$</td>
<td>$0.79 \pm 0.05 \pm 0.06 \pm 0.01 \pm 0.01$</td>
<td>$0.84 \pm 0.22$</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^0$</td>
<td>$13.2 \pm 0.2 \pm 0.5 \pm 0.2 \pm 0.1$</td>
<td>$11 \pm 4$</td>
</tr>
<tr>
<td>$\pi^+ \pi^+ \pi^- \pi^-$</td>
<td>$7.3 \pm 0.1 \pm 0.3 \pm 0.1 \pm 0.1$</td>
<td>$7.3 \pm 0.5$</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \pi^0 \pi^0$</td>
<td>$9.9 \pm 0.6 \pm 0.7 \pm 0.2 \pm 0.1$</td>
<td></td>
</tr>
<tr>
<td>$\pi^+ \pi^+ \pi^- \pi^- \pi^0$</td>
<td>$4.1 \pm 0.5 \pm 0.2 \pm 0.1 \pm 0.0$</td>
<td></td>
</tr>
<tr>
<td>$\omega \pi^+ \pi^-$</td>
<td>$1.7 \pm 0.5 \pm 0.2 \pm 0.0 \pm 0.0$</td>
<td></td>
</tr>
<tr>
<td>$\eta \pi^0$</td>
<td>$0.62 \pm 0.14 \pm 0.05 \pm 0.01 \pm 0.01$</td>
<td></td>
</tr>
<tr>
<td>$\pi^0 \omega \pi^0$</td>
<td>$&lt; 0.35 \text{ (90% CL)}$</td>
<td></td>
</tr>
<tr>
<td>$\omega \pi^0$</td>
<td>$&lt; 0.26 \text{ (90% CL)}$</td>
<td></td>
</tr>
<tr>
<td>$\eta \pi^+ \pi^-$</td>
<td>$&lt; 1.9 \text{ (90% CL)}$</td>
<td></td>
</tr>
<tr>
<td>$\pi^+ \pi^0$</td>
<td>$1.25 \pm 0.06 \pm 0.07 \pm 0.04$</td>
<td>$1.33 \pm 0.22$</td>
</tr>
<tr>
<td>$\pi^+ \pi^+ \pi^-$</td>
<td>$3.35 \pm 0.10 \pm 0.16 \pm 0.12$</td>
<td>$3.1 \pm 0.4$</td>
</tr>
<tr>
<td>$\pi^+ \pi^0 \pi^0$</td>
<td>$4.8 \pm 0.3 \pm 0.3 \pm 0.2$</td>
<td></td>
</tr>
<tr>
<td>$\pi^+ \pi^+ \pi^- \pi^0$</td>
<td>$11.6 \pm 0.4 \pm 0.6 \pm 0.4$</td>
<td></td>
</tr>
<tr>
<td>$\pi^+ \pi^+ \pi^+ \pi^- \pi^-$</td>
<td>$1.60 \pm 0.18 \pm 0.16 \pm 0.06$</td>
<td>$1.73 \pm 0.23$</td>
</tr>
<tr>
<td>$\eta \pi^+$</td>
<td>$3.61 \pm 0.25 \pm 0.23 \pm 0.12$</td>
<td>$3.0 \pm 0.6$</td>
</tr>
<tr>
<td>$\omega \pi^+$</td>
<td>$&lt; 0.34 \text{ (90% CL)}$</td>
<td></td>
</tr>
</tbody>
</table>

For $\pi\pi$ decays, obtain amplitude ratios for $A_2 \left(\Delta I = 3/2\right)$ and $A_0 \left(\Delta I = 1/2\right)$:

$$\left| \frac{A_2}{A_0} \right| = 0.420 \pm 0.014 \pm 0.016$$

$$\arg\left(\frac{A_2}{A_0}\right) = (86.4 \pm 2.8 \pm 3.3)^\circ$$

(Erros: stat, syst, normalizing mode, [CP correlation])

PRL 96, 081802
$D^+ \rightarrow K_{S,L} \pi^+ \ (281 \text{ pb}^{-1})$

Usually assume $\mathcal{B}(D \rightarrow K_L X) = \mathcal{B}(D \rightarrow K_S X)$ — but this is not strictly true...

Can produce both Cabibbo-allowed $\bar{K}^0$ and doubly-Cabibbo-suppressed $K^0$, and their amplitudes for producing $K_L$ and $K_S$ interfere with opposite signs; thus we expect $K_L$ and $K_S$ decays to have unequal rates (Bigi & Yamamoto, PL B349, 363)

Interference $\Rightarrow$ effect $\propto \tan^2(\theta_C)$

Expect $\mathcal{B}(D^+ \rightarrow K_S \pi^+) \neq \mathcal{B}(D^+ \rightarrow K_L \pi^+)$ by up to $\sim 10\%$
$D^+ \rightarrow K_{S,L}\pi^+$

- Double tag analysis
  - Tag $D^+$, find extra pion
  - Form missing mass of rest of system: fit for peak at kaon mass $-\text{independent of whether it's } K_L \text{ or } K_S$

- Careful understanding of background shapes required

- Combine with absolute $D^+ \rightarrow K_S\pi^+$ BF to form asymmetry

![Diagram showing $D^+$ decay modes](image)
$D^+ \rightarrow K_{S,L} \pi^+$

\[
\mathcal{B}(K_S \pi^+) + \mathcal{B}(K_L \pi^+) = (3.055 \pm 0.057 \pm 0.158)\% \\
\frac{\mathcal{B}(K_L \pi^+) - \mathcal{B}(K_S \pi^+)}{\mathcal{B}(K_L \pi^+) + \mathcal{B}(K_S \pi^+)} = -0.01 \pm 0.04 \pm 0.07 \\
\mathcal{B}(D^+ \rightarrow \eta \pi^+) = (0.391 \pm 0.031 \pm 0.033)\% 
\]
$D^0/D^+/D_s \rightarrow (\phi, \eta, \eta')X$

- Inclusive $D^0/D^+$ branching fractions to mesons with large $s\bar{s}$ content extremely poorly known
- $D_s$ final states have more $s\bar{s}$ content, hence expect larger $\eta$, $\eta'$, $\phi$ branching fractions
- Inclusive rates help disentangle decay chains through open charm ($\rightarrow$ e.g. understand $B_s$ from $\Upsilon(5S)$)
- Uses 281 pb$^{-1}$ for $D^0/D^+$ and 71 pb$^{-1}$ for $D_s$
$D^0/D^+/D_s \rightarrow (\phi, \eta, \eta')X$

- Double tag: find $D^0/D^+/D_s$; reconstruct $\phi$, $\eta$, $\eta'$ with remaining showers and tracks
  - Use $\phi \rightarrow K^-K^+$, $\eta \rightarrow \gamma\gamma$, $\eta' \rightarrow \pi^+\pi^-\eta \rightarrow \pi^+\pi^-\gamma\gamma$
- Use sidebands in $\Delta E (D^0/D^+)$ and $m_{BC} (D_s)$ of the tag side to get the background spectrum
- Fit invariant mass of $\phi$ and $\eta$, and $\eta'-\eta$ mass difference

![Histograms showing signal and sideband tags for $D_s \rightarrow \eta'X$](image)

**Signal tags**: 19.1 ± 5.3

**Sideband tags**: no events
\[ D^0 / D^+ / D_s \rightarrow (\phi, \eta, \eta') X \]

Preliminary

<table>
<thead>
<tr>
<th></th>
<th>$\mathcal{B}(\phi X)$ (%)</th>
<th>$\mathcal{B}(\eta X)$ (%)</th>
<th>$\mathcal{B}(\eta' X)$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0$</td>
<td>1.0 ± 0.1 ± 0.1</td>
<td>9.4 ± 0.4 ± 0.6</td>
<td>2.6 ± 0.2 ± 0.2</td>
</tr>
<tr>
<td>$D^+$</td>
<td>1.1 ± 0.1 ± 0.2</td>
<td>5.7 ± 0.5 ± 0.5</td>
<td>1.0 ± 0.2 ± 0.1</td>
</tr>
<tr>
<td>$D_s$</td>
<td>15.1 ± 2.1 ± 1.5</td>
<td>32.0 ± 5.6 ± 4.7</td>
<td>11.9 ± 3.3 ± 1.2</td>
</tr>
</tbody>
</table>

- $\eta$ signals include feeddown from $\eta'$$ \quad ▶$
- All except $D^0 / D_s \rightarrow \phi X$ are first measurements$$ \quad ▶$
- Known $D_s$ exclusive modes essentially saturate inclusive measurements
Excellent detector, clean events, and large data sample ⇒ branching fractions for open charm decays with precision ≥ world averages

BF measurements help normalize $D$ and $B$ physics, probe strong interaction physics

CLEO-c plans on taking 1.5 fb$^{-1}$ of open charm data over the next two years, aims for absolute BF precision of 1.5% for $D^0$, $D^+$ and 4% for $D_s$
Backup Slides
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
Yield extraction

DATA: $KK\pi$ Single Tags

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 $m(D_s^+) + m(D_s^-)$
Backgrounds

- 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

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
Systematics studies using $\psi'$

- **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

---

**DATA**

- 2nd $\pi$ found

**DATA**

- 2nd $\pi$ not found
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 $D_s$.
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
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...

![Graphs comparing branching fractions of $K_S K^+$, $K^+ K^- \pi^+$, $K^+ K^- \pi^+ \pi^0$, and $\pi^+ \pi^+ \pi^-$ with PDG 2004 fit and BaBar 2005 results.]

- We are more consistent with 3.6% than 4.8%