Charm Physics at CLEO

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Overview

Weak Physics at CLEO: “All notes from the same chord”

\[ B^b \quad D \quad F \]  
( this is a B\(^b\) major chord )

CLEO first concentrated with B mesons containing b quarks: \( B^b \)

After the asymmetric B factories came online, we moved to other notes in the same chord: \( D \quad F \)

For the younger crowd, note (sic) that the \( D_s \) was once called the “F” (Lincoln Wolfenstein often asked me how our “F Factory” was going)
Our Distinguished Cast

Seven Weakly-Decaying Ground States:

\[
\begin{align*}
& D^0 \quad D^+ \quad D_{s}^+ \\
& \Lambda_c \quad \Xi_c^0 \quad \Xi_c^+ \quad \Omega_c \\
\end{align*}
\]

Modes \quad K\pi \quad K\pi\pi \quad K\pi\pi \quad pK\pi \quad \Xi\pi \quad \Xi\pi\pi \quad \Omega\pi

Vector mesons, other L=0 baryons states:

very common

decays are a mix of pion and photon transitions

P-wave states:

a bit less common; pion and kaon decay transitions;

HQET guidance --> some narrow states due to D-wave decays
CAVEATS & OMISSIONS

Many other people could have been chosen to give this talk.

I’m sure I will say “we” sometimes when “CLEO” is more appropriate… I’ve been here for “only” 13 years, after all.

Charmonium was well-covered earlier in this Symposium…

STILL about 150 open-charm papers from CLEO !!!
( >30% through 2008 submissions )
So some things will of course be missed, e.g.:
  o Mapping out decay modes is under-covered
  o CLEO-c: a bit less emphasized since it’s more familiar

Finally, I only know some of the historical tales… take advantage of this gathering to talk to the Primary Sources among us!
Open Charm papers are 30% of total CLEO papers (1980 - 2007)

A bit slow at the start

Then...much interest in 1990’s
-- New university groups
-- Served by multiple PTAs

SURPRISE: Open Charm does NOT dominate CLEO-c era, due to quarkonia, other topics
Organizational Themes

Historical Ordering

CESR Upgrades and Data Size  (correlated)

Detector Upgrades
- CLEO1.5  DR2 tracking  0.43 fb⁻¹  1987-1988
- CLEOII  CsI calorimeter  4.8 fb⁻¹  1989-1995
- CLEOII.V  Silicon vertexing  9.0 fb⁻¹  1995-1999
- CLEOIII  RICH Particle ID  9.4 fb⁻¹  2000-2003

Techniques
- D* tags
- Vertixing
- Partial reconstruction

The CLEO-c era changed the whole landscape! 2003 - 2008

Physics
- CKM, CPV, DCSD, FCNC, FSI, HQET, LQCD,
- D Mixing, Spectator Model, Diagramology,
- Spectroscopy, Dalitz Plots, Fragmentation, …
Act I:
Charm Arrives at CLEO

Interest in Charm?
First $D^*$ Mesons Appear in CBX Land
Charm Fragmentation Papers
Earning an “F” Grade
First Lifetimes from CLEO
Tagging, 1988-style

CLEO1.5 on $D_s$ Decays and Charm Baryons
1981: Interest in Charm?

56% response rate

Points system:
10, 5, 2, 3, 1 for 1st-5th choice

Results:
B Physics 512.1
Upsilon 121.5
Other 103.4
New States 26.6
Continuum 38.6 **
Misc... 8.5
Higgs! 8.0
'Unexpected' 21.7

** 5.0 ccbar
** 2.0 charm baryons

Not clear that much interest is in charm itself; likely more in charm from B...
Charm at CLEO:
A Slow but Steady Start

First 10 CLEO papers:
-- 4 Upsilon, 5 B meson, and... 1 on D* fragmentation

Only 4 of first 37 CLEO papers from 1980-1985 are on charm
-- 3 on fragmentation plus the discovery of the F (now D_s)

13 of 75 total journal papers 1980-89 are on charm (17%)
-- 4 on D fragmentation (including 1 on the \Lambda_c)
-- 4 on Charm Baryons (note: 3 of the 4 from 1989!)
-- 3 on D_{(s)} decays (2 w/ observations, 1 w/ FCNC limits)
  best: \( B(c \rightarrow Xe^+e^-) < 2.2 \times 10^{-3} \)
-- 1 on the D^0/D^+/D_s meson lifetimes
-- 1 on the discovery of the F (= D_s) 2nd charm paper!
First D* at CLEO

All momenta

P > 3.5 GeV/c

Note: I'm skipping the work on D0, D+ from the ϒ(4S)

J. Rohlf
CBX82-19
(Feb.)

E/E_{bm} > 0.7

V. Thomas
P. Avery
CBX82-55
(Sept.)
First Fragmentation Papers

$D^0$ a) NO $Z$ CUT

$K^-\pi^+$

All $z$

$\Delta m$ cut

$D^0$ b) $Z > 0.7$

$K^-\pi^+$

$z > 0.7$

$\Delta m$ cut

$D^{*+}$

$\Delta m$

$z > 0.7$

Plot vs.

$Z = 2E/W$

(scaled $E$)

see hard

fragmentation

$D^0 \rightarrow K^-\pi^+$

$p_D > 2.5$ GeV

$D^0$

Switched to: $x = P/P_{max}$ (scaled $p$)

$D^{*+}$

$p_{D^*} > 3.0$ GeV

& $\Delta m$ cut
CLEO Earns an F
(that's really an A^+)

Evidence for the F Meson at 1970 MeV

Signal: 104 ± 19 Events
Mass: (1970 ± 5 ± 5) MeV
(calibrate w/ K→ππ D→Kπ)

Paper's "crude estimate" that:
B(D_s → φπ) ~ 4.4%,
is actually remarkably good!

Really a "discovery"? Yes, this seems fair!
Previous F discovery claims were "pathological"
Early CLEO D Lifetimes

Connects BF (experiment) to $\Gamma_i$ (theory)

Spectator model violations?

Precision: $\sim 15\%$ (50% $D_s$)

Competitive at the time

Also firms up unequal lifetimes:

$\tau(D^+)/\tau(D^0) = 2.3 \pm 0.5$

(quotes new world ave. as $2.3 \pm 0.3$)
Continuum Tags

Paper measures $\Delta R_{\text{had}}$ from charm, in two ways.

**Method 1 uses tags:**
- Uses inclusive reconstruction of a given charm mode
- Compares to same, with another anti-charm “tag”
- Get cross-section independent of BF
  (similar to CLEO-c, but with some assumptions & approximations)

\[ \Delta R_{\text{had}} = 1.13 \pm 0.17 - 0.13 \pm 0.09 \]

**Method 2 uses inclusive electrons:**
- Get cross-section for eX
- Estimate production rates and semileptonic BFs to get charm x-section

\[ \Delta R_{\text{had}} = 2.07 \pm 0.12 \pm 0.26 \]
Some $D_s$ Decay Modes

Still in "early days", investigate role of:
- color suppression
- $W$-exchange
- $W$ annihilation
- FSI

Note $D^+$ peaks to left...

<table>
<thead>
<tr>
<th>Mode</th>
<th># of events</th>
<th>Efficiency [%]</th>
<th>$B \cdot \sigma$(pb), $x_t \geq 0.5$</th>
<th>$B/B(D_s^+ \rightarrow \phi\pi^+)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_s^+ \rightarrow \phi\pi^+$</td>
<td>405 ± 27</td>
<td>14.3 ± 0.3</td>
<td>6.5 ± 0.5 ± 0.3</td>
<td>1.0</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^{*0}K^+$</td>
<td>149 ± 25</td>
<td>5.1 ± 0.4</td>
<td>6.8 ± 1.1 ± 0.7</td>
<td>1.05 ± 0.17 ± 0.12</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^{*+}K^0$</td>
<td>40 ± 7</td>
<td>1.2 ± 0.1</td>
<td>7.8 ± 1.4 ± 0.8</td>
<td>1.20 ± 0.21 ± 0.13</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^0K^+$</td>
<td>110 ± 19</td>
<td>4.0 ± 0.3</td>
<td>6.4 ± 1.1 ± 0.6</td>
<td>0.99 ± 0.17 ± 0.10</td>
</tr>
</tbody>
</table>
The story begins in 1989:

**Discovery of the Ξ_c^0**

- \( \Xi_c^0 \rightarrow \Xi^- \pi^+ \)
  - All \( x_p \)
  - \( x_p > 0.5 \)

- \( M(\Xi^- \pi^+) \)

**Confirmation of the Σ_c^{++} & Σ_c^0**

- \( \Sigma_c^{++} \rightarrow \Lambda_c^+ \pi^+ \)
- \( \Sigma_c^0 \rightarrow \Lambda_c^+ \pi^- \)
- \( M(\Sigma_c) - M(\Lambda_c) \)
Act II: Hitting Our Stride

The CLEOII Datasets:
Too many topics to be worth listing...

Two Popular Sample sizes:
- Early Results
  ~1.6-1.9 fb$^{-1}$
- Full Statistics
  4.7 fb$^{-1}$

René would be proud:
It is not enough to have a good mind detector.
The main thing is to use it well.

-- René Descartes in *Discours de la Méthode*
Charm Baryon Decays

Good at charged modes... & also with neutrals!

Observation of $\Lambda_c^+$ decays to $\Lambda\pi^+\pi^0, \Sigma^0\pi^+, \Sigma^0\pi^+\pi^0$, and $\Sigma^0\pi^-\pi^+\pi^+$.

CLEOI.5 tracking

CLEOII CsI
More Charm Baryons

$\Lambda_c^{+}\pi^{+}\pi^{-}$ final state

- $P$-wave $\Lambda_c$

$M(\Lambda_c^{+}\pi^{+}\pi^{-}) - M(\Lambda_c^+)$

Higher peak seen by ARGUS; lower peak is NEW

Still four more excited states from CLEO in 2001:
- PRL 86, 4243 & 4479 (2001)

At CLEO's peak dominance:
- 9 of first 10 $\Xi$
- 7 of first 11 $\Sigma$ & $\Lambda$

$\Lambda_c^{+}\pi^{+}$ & $\Lambda_c^{+}\pi^{-}$ final states

spin-3/2 $\Sigma_c^{*++}$ & $\Sigma_c^{*0}$

Lower peaks are spin-1/2

Masses useful to study hyperfine splittings...
Charmed Baryons from a 1998 Talk

Scoreboard:  CLEO = 10.5  Rest of World = 6.5

(later paper references added)

Charmed Baryons

Eight new states discovered since 1996 PDG!

- First $L = 1$ $\Xi_c$ states [top plots]  CLEO CONF 98-10; 5 fb$^{-1}$
- $\Xi'_c$ states [lower plots]

$\rightarrow$ PRL 83, 4390 (1999)

$L = 1$ $\Xi^0_{c1}$
$L = 1$ $\Xi^+_{c1}$

$\Xi'^+$
$\Xi'^0$

$\rightarrow$ PRL 82, 492 (1999)

Charmed Baryons

RED = CLEO discoveries 10.5
GREEN = not yet seen  $2L = 0 +$ ???
BLACK = All other experiments 6.5

$C = 1, L = 0$ States:

$J^P = 1/2^+$
$\Omega_c^0$

$\Xi_c^0$  $\Xi_c^+$  $\Xi_c^{0'}$  $\Xi_c^{+'}$
$\Lambda_c^+$  $\Sigma_c^0$  $\Sigma_c^+$  $\Sigma_c^{++}$

$J^P = 3/2^+$
$\Omega_c^{0*}$

$\Xi_c^{*0}$  $\Xi_c^{*+}$
$\Sigma_c^{*0}$  $\Sigma_c^{*+}$  $\Sigma_c^{*++}$

$C = 1, L = 1$ States:

$\Lambda_c(2593)$, $\Lambda_c(2625)$, $\Xi_c^+(\sim 2815)$, $\Xi_c^0(\sim 2820)$
**Λc Semileptonic**

1.6 fb⁻¹ PLB:
- $\Lambda_c \rightarrow \Lambda l \nu \sim 350$ events
- Measure $\sigma \cdot B$
- No significant of $\Lambda_c \rightarrow \Lambda X l \nu$
- Asymmetry parameter
- Some info on pKπ BF

3.0 fb⁻¹ PRL:
- $\Lambda_c \rightarrow \Lambda e \nu \sim 700$ events
- Concentrate on Form Factor
  \[ R = \frac{f_2}{f_1} = -0.25 \pm 0.14 \pm 0.08 \]
- Redo asymmetry parameter

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**PRL Plots**

- $M(\Lambda e)$

**PLB 323,219**
1994 1.6 fb⁻¹

**PRL 75,624**
1995 3.0 fb⁻¹
$D_s \rightarrow \phi l \nu$ & $D_s \rightarrow \phi \pi$

First, a CLEOI.5, then CLEOII analysis
Use theory for $\Gamma(D_s \rightarrow \phi l \nu) / \Gamma(D \rightarrow K^* l \nu)$
to get $B(D_s \rightarrow \phi l \nu)$

CLEOII result:
$B(D_s \rightarrow \phi e \nu) / B(D_s \rightarrow \phi \pi) = 0.54 \pm 0.05 \pm 0.04$

Extract: $B(D_s \rightarrow \phi \pi) = 5.1 \pm 0.4 \pm 0.4 \pm 0.7$
\( B(D_s \rightarrow \phi \pi) \) using \( B \) Decays

All candidates →

Partial reconstruction of:
\( B^0 \bar{B} \rightarrow D^{*+} D_s^{*-} \)

Compare:
1. partial \( D^{*+} \) & full \( D_s^{*-} \)
2. full \( D^{*+} \) & partial \( D_s^{*-} \)

Kinematics give "intersecting cones" characterized by an angle \( \phi \)

Background-subtracted →

\[ \cos \phi \]

Measure \( B(D_s \rightarrow \phi \pi) / B(D^0 \rightarrow K^- \pi^+) \)

Extract: \( B(D_s \rightarrow \phi \pi) = 3.59 \pm 0.77 \pm 0.48 \)
DCSD First Observed

\[ \frac{B(D^0 \rightarrow K^+\pi^-)}{B(D^0 \rightarrow K^-\pi^+)} = (0.77 \pm 0.25 \pm 0.25)\% \]

\(~\text{large re: } \tan^4 \theta_C \text{ & current PDG, but well within errors!}\)

**FIG. 1.** Mass difference in the \(D^0\) mass signal region for right sign and wrong sign. The solid lines are the fitted results.

**FIG. 2.** The \(D^0\) mass in \(\Delta M\) signal region after \(\Delta M\) sideband subtraction for right sign and wrong sign. The solid lines are the fitted results.
**D* Branching Fractions**

D*\( \rightarrow \) D\(^0\)\(\gamma\)  
D*\( \rightarrow \) D\(+\)\(\gamma\)  
D*\( \rightarrow \) D\(^0\)\(\pi^0\)  
D*\( \rightarrow \) D\(+\)\(\pi^0\)

Dominated PDG averages & led to significant shifts for D*+

D*+\( \rightarrow \) D+\(\gamma\) was a limit here, later observed later by CLEO; 
& also high-statistics updates of other D*+ BF

PRD 69, 2041  
1992 0.78 fb\(^{-1}\)  
PRL 80, 3919  
1998 4.7 fb\(^{-1}\)
Precision $D_s^* - D_s$ Mass

Calibration:

Use $D^{*0} \rightarrow D^0 \gamma$ decay:
compare to CLEO's precise $D^{*0} \rightarrow D^0 \pi^0$ result!
( low-$Q$ decay; $\pi^0$ mass well-known )

$M(D_s^*) - M(D_s) = 144.22 \pm 0.47 \pm 0.37$

Previous World Ave.: $142.4 \pm 1.7$
Observation of $D_s^* \rightarrow D_s\pi^0$

Interest: isospin-violating decay
Competes with dominant EM decay

$$\Gamma(D_s^* \rightarrow D_s\pi^0)/\Gamma(D_s^* \rightarrow D_s\gamma) = 0.062 \pm 0.022$$
Discovery of $D_{s2}^*(2573)$

2nd narrow P-wave $D_s$ state

( & the last narrow one, right??? Sigh...)

**FIG. 1.** $M^*$, “corrected” invariant mass, of $(K^-\pi^+[\pi^0])K^+$ combinations. Data points are for $K^-\pi^+[\pi^0]$ combinations in the $D^0$ signal region; the histogram shows $M^*$ for $(K^-\pi^+[\pi^0])K^+$ combinations where the $K^-\pi^+[\pi^0]$ combinations were chosen in $D^0$ sidebands.

**FIG. 2.** Histogram of $M^*(D^0K^+)$, with fit. The solid line shows the complete signal and background fitting functions. The sum of the background functions is shown by the dashed line. The dotted line shows just the polynomial used to represent the combinatoric background. The shape of the $D_S^*(2470)^+$ background function is shown at the bottom by the dash-dotted line, with the area scaled up by a factor of 5.

**Note:** known narrow $J=1$ state cannot decay to $DK$ (spin-parity)
**P-Wave D⁺ Mesons**

Neutral D better known

Study charged D here:
-- First full recon. of $D_1(2420)^+$
-- First obs'n of $D^*\pi$ mode of $D_2^*(2460)^+$

Use angular cut:

$D_1(2420)^+$ enhanced
\[ B(D^0 \rightarrow K^-\pi^+) \]

\[ D^*+ \rightarrow D^0 \pi^+ \]

**Analyze \( \sin^2 \alpha \): \( \alpha \) is the angle between thrust axis and slow pion**

\[ \sin^2 \alpha \text{ (in } p_\pi \text{ bins)} \]

\[ B(D^0 \rightarrow K^-\pi^+) = (3.95 \pm 0.08 \pm 0.17)\% \]
Partial reconstruction of: \( B_{\bar{b}} \rightarrow D^{*+}Xl\nu \)

Use \( \pi \) & lepton

\[
B(D^0 \rightarrow K^-\pi^+) = (3.81 \pm 0.15 \pm 0.16)\%
\]

A tagged \( b \rightarrow c,c\bar{c} \) paper also obtained a BR:

\[
B(D^0 \rightarrow K^-\pi^+) = (3.69 \pm 0.11 \pm 0.16)\%
\]

New CLEO Average (All three results):

\[
B(D^0 \rightarrow K^-\pi^+) = (3.82 \pm 0.07 \pm 0.12)\%
\]
Semileptonic D Decays
All four Cabibbo-allowed $K^{(*)}l\nu$

Use $\delta m$: like $\Delta m$, but w/o neutrino

\[ \frac{\Gamma(D \rightarrow K^*e\nu)}{\Gamma(D \rightarrow K\nu)} = 0.62 \pm 0.08 \]

Note: $K$ modes are higher
Statistics than $K^*$ shown...
can look at form-factor

2700 events

$D^0 \rightarrow K^- l^+ \nu$
\[ \frac{B(D^0 \rightarrow \pi^- l^+ \nu)}{B(D^0 \rightarrow K^- l^+ \nu)} \]

Cabibbo-suppressed

Use D*+ tag
2-D fit to $\delta m M(\pi e)$

Later improvements will come from:
- RICH PID
- CLEO-c kinematics

\[ \frac{B(D^0 \rightarrow \pi^- l^+ \nu)}{B(D^0 \rightarrow K^- l^+ \nu)} = (10.3 \pm 3.9 \pm 1.3)\% \]

or \(< 15.6\% \) 90\%CL
$D^0$: Inclusive Electrons

Use slow $\pi$ from $D^{**}$ tag

Inclusive slow $\pi$

$\sin^2\alpha$

Analyze $\sin^2\alpha$: $\alpha$ is the angle between thrust axis and slow pion

$P_{\text{elec}} > 0.7 \text{ GeV}/c$

Electron Spectrum

$B(D^0 \rightarrow X\nu) = 6.64 \pm 0.18 \pm 0.29$

Prev. World Ave.: 7.01 $\pm$ 0.62
**D_s Decay Constant**

\[ B(D_s \rightarrow \mu \nu) / B(D_s \rightarrow \phi \pi) = 0.245 \pm 0.052 \pm 0.074 \]

\[ B(D_s \rightarrow \mu \nu) / B(D_s \rightarrow \phi \pi) = 0.173 \pm 0.023 \pm 0.035 \]

\[ f_{D_s} = (280 \pm 19 \pm 28 \pm 34) \text{ MeV} \]

Clever use of electrons for background, plus e-mu differences

State-of-the-art for quite some time…
$D^0 \rightarrow K\pi\pi^0$ Dalitz Plot

Previous 4 experiments: <1000 events
CLEOII: 7070 events 97% signal

Classic structure:
3 bands with long. Polarization
but lots more detailed structure!
$B(\Lambda_c \rightarrow pK\pi)$

Tag: anti-proton and anti-D

( D: slow $\pi$ from $D^*$, electrons, $K\pi$ )

Reconstruct $\Lambda_c$ opposite this tag

Result: $(5.0 \pm 0.5 \pm 1.2)\%$
Act II.V:
Silicon arrives at the 4S

Lifetimes & $D^*$ Width
DCSD & D mixing?
Charm Baryon Work
Fragmentation
More Narrow $D_{sJ}$ !?!
D Meson Lifetimes

Partial II.V statistics

Note nice fits for $t<0$:
good resolution modeling

Different systematics than fixed target, very competitive

$D^0$, $D^+$, and $D_s^+$ mesons are $408.5 \pm 4.1^{+3.5}_{-3.4}$ fs, $1033.6 \pm 22.1^{+9.9}_{-12.7}$ fs, and $486.3 \pm 15.0^{+4.9}_{-5.1}$ fs.
Natural Extension of other D lifetime work...
Full CLEOII.V statistics

\[ B(KK)/B(\pi\pi) = 2.96 \pm 0.16 \pm 0.15 \]

CP asymmetries limited

Mixing parameter, w/ no CPV:
\[ \gamma_{CP} = -0.012 \pm 0.025 \pm 0.044 \]
**D**^{**+**} Total Width

Study $Q = $ energy release

Good MC & careful cross-checks

\[
\Gamma(D^{**+}) = 96 \pm 4 \pm 22 \text{ keV}
\]

\[
M(D^{**+}) - M(D^0) = 145.412 \pm 0.002 \pm 0.012 \text{ MeV}
\]
Note: Analysis also spawned new dE/dx calibration ideas...
More $D^0$ DCSD Modes

$K^+\pi\pi^0$  

$K^+\pi\pi\pi^+$

DCSD/Cabibbo-allowed ratios:

\[ R = 0.0043 \pm 0.0007 \]

\[ R = 0.0041 \pm 0.0004 \times \text{phase-space factor} \]
\[ D^0 \rightarrow K_s \pi^0 \pi^0 \text{ Dalitz Plot} \]

5299 events
~98% signal

10 components in fit

See \( K^{*+}\pi^- \) component:
DCSD and/or mixing

First paper of set:
followed by searches
for CP-violation
and D mixing:

PRD 70, 091101
PRD 72, 012001
2004 9.0 fb\(^{-1}\) 2005 9.0 fb\(^{-1}\)
\( \Lambda_c & \Xi_c^+ \) Lifetime

\( \Lambda_c \): Short lifetime!

Result: \( 179.6 \pm 6.9 \pm 4.4 \) fs

World average of \( 200 \pm 6 \) fs

\( \Xi_c^+ \)

Result: \( 503 \pm 47 \pm 18 \) fs

World average of \( 442 \pm 26 \) fs
**$\Omega_c$: Finding & Beta Decay**

*Both use all II + II.V data*

**Establish $\Omega_c$ at CLEO:**

- **5 hadronic modes summed**
  - **40.4 ± 9.0 events**

**Semileptonic**

- **$\Omega_c \rightarrow \Omega e \nu$**
  - **11.4 ± 3.8 events**

**Right-sign**  
**Wrong-sign**

**First baryonic beta-decay w/o u,d quarks at vertex**

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**FIG. 2.** The invariant mass distribution for the sum of $\Omega^{-}\pi^+$, $\Omega^{-}\pi^+\pi^0$, $\Omega^{-}\pi^+\pi^+\pi^-$, $\Xi^0K^-\pi^+$, and $\Xi^-K^-\pi^+\pi^+$ combinations. The fit function is a sum of the fit functions from Fig. 1.
**D(*) Fragmentation**

**CLEO's definitive result**
Full II+II.V data

**Great care w/ efficiency & yield systematics**
Search for a Narrow Charmed Strange Meson Near $D^*K$ Threshold

J. Bartelt
Vanderbilt University, Nashville, Tennessee 37235

A search has been carried out for a narrow state decaying to $D_s^+ \pi^+ \pi^-$ or $D_s^{*-} \pi^0$. It has been suggested that the “broad” $1^+ D_s^{*-}$ state, if below $D^*K$ threshold, might be narrow and might decay to these modes. No evidence is found for such a state. Upper limits are also set on the decays of the $D_{s1}(2536)^+$ and $D_{s2}^*(2573)^+$ to these modes.

Real 2460 peak in latter?
But fit to former...
Rapid Response Team: Snagging the $D_{sJ}(2460)$

BaBar finds an unexpected (huge) $D_{sJ}(2317)$, and sees a “structure” at 2460 MeV as well: but it is clearly partly feed-across.

Various CLEOons believe the 2460 may be real, and prove it! Leverages our very well-understood detector & well-tuned MC

$D^*_s(2317)$

$D_{s1}(2460)$

$M(D_s\pi^0) - M(D_s)$

$M(D_{sJ}\pi^0) - M(D_{sJ})$
Decays with $K$ are 10x more common than $\pi$:
Separation via “particle ID” alone is hard!

Soon, CLEO-c: has excellent kinematic separation

World’s best when done…
But note Kaons under pion peak!
(even w/ RICH…)

CLEOIII $D^0 \rightarrow \pi^- l^+ \nu$, $K^- l^+ \nu$

PRL 94, 011802 (2005) 6.7/8.0 fb$^{-1}$
Act IV:  
The CLEO-c Era

The Three Pillars of CLEO-c
- Leptonic modes and Decay Constants
- Semileptonic modes and Form Factors
- Hadronic modes and Golden-Mode BF

Quantum Coherence & other fun modes

This history is still being written...

God grant me the Serenity to accept
the things I cannot change,
the Courage to change the things I can,
and the Wisdom to know the difference.

-- attributed to St. Francis of Assisi
D Tagging at CLEO-c

Clean: high-efficiency for full reconstruction & low background
Don’t forget the use of data for efficiency & resolution systematics!

Note: coarse yellow boxes are trigger cells, not for track reconstruction!
Tagging Techniques

CLEO-c uses Tagging:
\[ \psi(3770) \rightarrow D^0D^0, D^+D^- \]
@4170 MeV: \( D_s^+D_s^- \) + c.c. creates ONLY D pairs

Fully reconstruct one \( D_{(s)} \)
- Can then infer neutrinos (constrained kinematics)
- or get absolute hadronic BF's (algebra eliminates \#D's)
The Three Pillars of CLEO-c

The core open-charm program at CLEO-c features:

**Leptonic Decays** $D_{(s)} \Rightarrow \mu \nu$, to extract decay constants.

$D \Rightarrow Kl\nu, \pi l\nu$; to measure form factors.

$D^0 \Rightarrow K\pi$, $D^+ \Rightarrow K\pi\pi$, $D_s \Rightarrow KK\pi$, to provide golden-mode branching ratios.

...and many other nice open-charm topics.
$D^+ \Rightarrow \mu^+ \nu$

Clean, isolated signal peak: Power of D-tagging:
Recall that the signal is one track + neutrino!

Fit components

$K^0 \pi^+$ peak

$\mu^+ \nu$ peak

$\tau^+ \nu, \tau^+ \rightarrow \pi^+ \nu$ region

$f_{D^+} = (206.7 \pm 8.5 \pm 2.5) \text{ MeV}$

Good agreement w/ LQCD

$(207 \pm 4) \text{ MeV}$
\[ D_s \Rightarrow \mu^+\nu \& \tau^+\nu (\tau^+ \Rightarrow \pi\nu) \]

\[ f_D = (268.2 \pm 9.6 \pm 4.4) \text{ MeV} \]

Higher than recent LQCD ?!

\[ (241 \pm 3) \text{ MeV} \]
$D_s \rightarrow \tau^+\nu \ (\tau^+ \rightarrow e^+\nu\nu)$

**PRL100, 161801**
*(2007) 298 pb$^{-1}$*

**Uses only cleanest tags**

Can’t use $M M^2$ with >1 neutrino...

Semileptonic events tend to have hadronic Energy in CsI
( but careful re: $K_L$! )

Plot $E_{extra}$ in Calorimeter
( Extra = not tag $D$ or $e$ )

$E_{extra}$ can include $\gamma$ from $D_s^*$ decay

$f_{Ds} = (273 \pm 16 \pm 8 \text{ MeV}$

Consistent w/ other CLEO result
Inclusive Semileptonic

Results for $B (D \Rightarrow X e\nu)$:

$D^+$: $\mathcal{B} = (16.13 \pm 0.20 \pm 0.33)\%$

$D^0$: $\mathcal{B} = (6.46 \pm 0.17 \pm 0.13)\%$

Better than prior PDG world averages:

$D^+$: $\mathcal{B} = (17.2 \pm 1.9)\%$ (electrons)

$D^0$: $\mathcal{B} = (6.87 \pm 0.28)\%$ (electrons)

$D^0$: $\mathcal{B} = (6.5 \pm 0.8)\%$ (muons)

Most exclusives known (use CLEO-c BF’s):

$\Sigma \mathcal{B} (D^+ \Rightarrow X e\nu)_{excl} = (15.1 \pm 0.5 \pm 0.5)\%$

$\Sigma \mathcal{B} (D^0 \Rightarrow X e\nu)_{excl} = (6.1 \pm 0.2 \pm 0.2)\%$

Combine with lifetimes:

$D^+$: $\Gamma_{SL} = 0.1551 \pm 0.0020 \pm 0.0031 \text{ ps}^{-1}$

$D^0$: $\Gamma_{SL} = 0.1574 \pm 0.0041 \pm 0.0032 \text{ ps}^{-1}$

$\Gamma_{SL} (D^+) / \Gamma_{SL} (D^0) = 0.985 \pm 0.28 \pm 0.15$

Only “golden” tags:

$D^+ \Rightarrow K^-\pi^+\pi^+ \& D^0 \Rightarrow K^-\pi^+$
\[ U_{\text{miss}} = E_{\text{mis}} - |p_{\text{mis}}| \text{ (GeV)} \]

**Excellently background suppression**

**Small K-\pi feed-across due to threshold kinematics**
Tagged πeν, Kν

**Cabibbo suppressed**

\[ D^0 \rightarrow \pi^- e^+ \nu_e \]

1325±48 events

**Cabibbo favored**

\[ D^0 \rightarrow K^- e^+ \nu_e \]

14356±132 events

\[ D^+ \rightarrow \pi^0 e^+ \nu_e \]

447±29 events

\[ D^+ \rightarrow K_S e^+ \nu_e \]

5846±88 events

Factor ~2 increase in the signal statistics compared to the tagged analysis

\[ arXiv:0712.1012 \]
\[ arXiv:0712.0998 \]
(accepted by PRD)

281 pb⁻¹
Significant improvement in precision by recent measurements
(CLEO-c most precise)
Pseudoscalar Form Factors

Good agreement with Lattice QCD
$D^0$ & $D^+$: Some Comparisons

"Golden Modes" are now systematics limited

$D^0$ & $D^+$: Some Comparisons

"Golden Modes" are now systematics limited

$\mathcal{B}(D^0 \to K^+\pi^-)$ (%)

Use PDG04 since PDG06 included 56 pb$^{-1}$ CLEO-c

PRD 76, 112001
(2007) 281 pb$^{-1}$
D_s Branching Ratios

Tougher than D
But solid results
Correlated D pairs are produced at the $\psi(3770)$: Allows a measurement of strong $K\pi$ FSI phase, of great interest for D mixing results!

Simultaneous fit to many hadronic & semileptonic modes & some external input

$$\cos \delta = 1.10 \pm 0.35 \pm 0.07$$

$$\delta = (22^{+11}_{-12} ^{+9}_{-11})^\circ$$
\[ D^0 \rightarrow K_L^0 \pi \]

\[ D^+ \rightarrow K_S^0 \pi^+ \]

\[ D^+ \rightarrow K_L^0 \pi^+ \]

\[ D^+ \rightarrow \pi^0 \pi^+ \], \( \mu^+ \nu \)

\[ M^2_{\text{missing}} \] (Monte Carlo)

\[ M^2_{\text{missing}} \] (Data)

\[ R_D = \frac{[ B(D \rightarrow K_S \pi) - B(D \rightarrow K_L \pi) ]}{[ B(D \rightarrow K_S \pi) + B(D \rightarrow K_L \pi) ]} \]

\[ D^0: \ R_D = 0.122 \pm 0.024 \pm 0.030 \]

(consistent with \( 2 \tan^2 \theta_C \))

\[ D^+: \ R_D = 0.030 \pm 0.023 \pm 0.025 \]

Dao-Neng Gao predicts:
\[ R(D^+) = 0.035 \text{ to } 0.044 \]
(\( \text{arXiv:hep-ph/0610389v2} \))

J. Rosner, CHARM2007:
\[ R(D^+) = 0.067 \pm 0.007 \]
“$D_s$ Scan” Cross-Sections

Spin-off from energy scan used to find $D_s$ running point...

MUCH more detailed than all previous measurements...
Precision $D^0$ Mass

$K_S \rightarrow \pi \pi$

$D^0 \rightarrow K_S \phi$

$\phi \rightarrow KK$

Inclusive $K_S \rightarrow \pi \pi$ resolution check

Final state: all charged & large rest-mass

$M(D^0) = 1864.847 \pm 0.150 \pm 0.095$ (very precise for absol. mass!)

$M(D^0) = 1864.847 \pm 0.150 \pm 0.095$
$D^+ \rightarrow K^-\pi^+\pi^+$ Dalitz Plot

141K events 99% signal!

(9x E791 sample)

Isobar models, and also:
- Improve some isobars
- Use a “quasi-model-independent” partial-wave analysis
Conclusions

Both the “CLEO-b” and CLEO-c phases made HUGE contributions to the world’s knowledge of open charm physics.

CLEO also pioneered many techniques, even while borrowing and extending others.

The physics results are of course very important, but perhaps even more so are the physicists trained here that have continued onward with both the knowledge and spirit of CLEO Physics!
Some Charm Reviews

Predictions:
Gaillard, Lee, & Rosner
Rev. Mod. Phys. 47, 277 (1975)

Selected Reviews:
Morrison & Witherall                  D Mesons
Richman & Burchat                    D & B LSL Decays
Browder, Honscheid, & Pedrini        D & B non-Lept Decays and Lifetime
Burdman & Shipsey                    D Mixing and Rare Decays
Bianco, Fabbri, Benson, & Bigi       A “Cicerone” for Charm

Forthcoming:
Artuso, Meadows, & Petrov            Charm Meson Decays
Asking *me* questions is fine, but…

Better to use the collective historical and physics knowledge of the audience!

so…

? Comments & Discussion ?