A Review of Charm Physics

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(& CLEO Collaboration)

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Outline

Introductory Observations

Bread & Butter Physics: 
  Lifetimes & Masses

Searches for New Physics:
  $D^0 - \bar{D}^0$ Oscillations & Rare Decays

QCD Effects & Heavy Flavor Physics: 
  Decay Constants, Form Factors, Absolute BF

Understanding the Charm Region: 
  Recent Work on $\psi(3770)$

The Future

Conclusions

Charm in Parallel talks:
  Bitenc: D mixing at B Factories
  Blusk: CLEO Ds scan, Y(4260)
  Cronin-Hennessy: CLEO Open Charm
  Hinz: States around 4 GeV
  Mallik: Y(4260) & other states
  Marton: Future PANDA Experiment
  Swanson: Charmonium Spectroscopy
  Tomaradze: BES+CLEO Charmonium
  Tsuboyama: Belle Charmed Baryons

What’s NOT included in this talk:
  Spectroscopy: see Jon Rosner’s plenary
  Charm Production
  Most of Charmonium is not covered
  ( and whatever else I couldn’t fit …
  apologies in advance ! )
**Favorite Reviews for Perspective**

**What we knew before Charm was discovered:**

Search for Charm
M.K. Gaillard, B.W. Lee & J.L. Rosner
Rev. of Mod. Phys. 47, 277 (1975)
written before the November Revolution**

**What we knew 30 years later:**

A Cicerone for the Physics of Charm
S Bianco, F.L. Fabbri, D. Benson & I. Bigi

*I’ll try to emphasize new results & interconnections to other sub-fields*

** Nov. 1974 marked the discovery of the J/ψ c ¯c state.
This “November Revolution” helped to solidify the Standard Model.
( Japanese emulsion experiments had good evidence before this… )
Building on a fine tradition:
E791, LEP/SLD, E687, E691, WA89, MARKIII, H1, ZEUS, E835, R704, etc.
Experimental Issues

**B Factories:**

- $\sim 120 \times 10^6$ ccbar pairs / 100 fb$^{-1}$
  - Substantial continuum rate ($B \Rightarrow DX$ rate $\sim$equal, but softer)
  - Hard fragmentation: higher momentum, lower combinatorics
  - Good with neutral daughters

**Charm Factories:**

- $\sim 640 \times 10^3$ ccbar pairs / 100 pb$^{-1}$
  - Modest Rates; low momentum: silicon not useful here
  - Constrained Kinematics: very clean
  - Good with neutral daughters & especially neutrinos

**Hadron colliders:**

- Very high rate
  - Need detached vertex & lepton triggers
  - Limited modes

**Fixed Target:**

- High rate
  - Most modes accessible
  - Large boosts good for lifetimes
Charm  vs.  Beauty

\[ \lambda = \sin \theta_C \sim 0.22 \quad \text{Cabibbo quark-mixing angle} \]

Decay rate:  \( \mathcal{O}(1) \quad \mathcal{O}(\lambda^4) \)

“Cabibbo”-suppression of \( b \) decay compensates \( \Gamma \sim m^5 \) behavior
Long \( B \) life inspired Wolfenstein’s famous CKM parameterization…
Advent of silicon vertex detectors revolutionizes \( b \) physics, as well as \( c \)

Mixing Ampl. :  \( \mathcal{O}(\lambda^2) \quad \mathcal{O}(\lambda^6) \times f(m_t) \)

Charm decays too fast to mix
\( B \) mixing enhanced by top mass  \( \quad \text{(actually, } B_s \text{ enhanced too much!)} \)

Fully Reconstruct:  \( 13\% \quad \sim 0.1\% \)

Factories produce \textbf{meson pairs}: A fully-reconstructed meson acts as a “\textbf{Tag}”
\( \quad \text{(more on tags later…)} \)

\textbf{Much larger }B\textbf{ factory luminosity:}
-- Compensates for smaller efficiency & cross-section for single tags
-- But high efficiency for charm allows for more “double tags”
Theory & Charm

Lattice QCD: e.g., CLEO-c program & Lepage’s talk
  Useful for charm & bottom
  Charmonia more relativistic…
  Good opportunities to test in charm sector

Spectator model, quark-hadron duality: NOT like a free quark!
  Factor of ~15x spread in lifetimes
    (Pauli interference, weak exchange/annihilation)
  Compare: ~30% for bottom (only 4 states, vs. 7 for charm)
  Large final-state interactions in charm

B vs. D decay & Penguin example: Long-distance effects common
  B decay: integrate out top quark ⇒ local 4-quark operator
  D decay: b ~decouples (CKM); dominant strange is light ⇒ not short-distance!

HQET:
  Useful, but larger \((1/m)^N\) corrections,
  & no heavy-to-heavy decays like \(b \Rightarrow c l \nu\)
  Good for basic properties of P-wave mesons

SCET, OPEs, QCD Sum Rules, Dispersion Relations, Potential Models, Bag Models, …
## Charm Lifetimes (~PDG 04)

<table>
<thead>
<tr>
<th></th>
<th>PDG ave</th>
<th>Best; error (fs)</th>
<th>#events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+$</td>
<td>1040 ± 7 fs</td>
<td>FOCUS’02 ±8</td>
<td>110,000</td>
</tr>
<tr>
<td>$D_s^+$</td>
<td>501 ± 6 fs*</td>
<td>FOCUS’05 ±8</td>
<td>13,641</td>
</tr>
<tr>
<td>$D^0$</td>
<td>410.3 ± 1.5 fs</td>
<td>FOCUS’02 ±2</td>
<td>210,000</td>
</tr>
<tr>
<td>$\Lambda_c$</td>
<td>200 ± 6 fs*</td>
<td>FOCUS’02 ±4, CLEO’01 ±8</td>
<td>8034</td>
</tr>
<tr>
<td>$\Xi_c^0$</td>
<td>112 $^{+13}_{-10}$ fs</td>
<td>FOCUS’02 $^{±14*}<em>{±22*}$ E687 '93 $^{±22*}</em>{±22*}$</td>
<td>110, 42</td>
</tr>
<tr>
<td>$\Xi_c^+$</td>
<td>442 ± 26 fs</td>
<td>FOCUS’01 ±24</td>
<td>532</td>
</tr>
<tr>
<td>$\Omega_c$</td>
<td>69 ± 12 fs</td>
<td>FOCUS’03 ±16, WA89 ’95 ±24</td>
<td>64, 86</td>
</tr>
</tbody>
</table>

*I’ve adeed FOCUS’05, *scale factor 1.6; CLEOII ~low, *asymmetric errors quoted

### Low phase-space $\pi$ & $\gamma$ transitions:

CLEO ’02: $\Gamma(D^{*+}) = 96 ± 4 ± 22 keV$ (syst. limited, no other attempts since…)

$D^{*0}, D_s^+, \Xi_c^+, \Xi_c^{0'}$: too narrow to see width, too short-lived to see lifetime
Recent Mass & Lifetime Work

**$D_s$ lifetime:** 507.4 ± 5.5 ± 5.1 fs
PRL 95, 052003 (2005)

**$\Lambda_c^+$ mass:** 2286.46 ± 0.14 MeV
4627+264 events of $\Lambda K_S K^+$ & $\Sigma^0 K_S K^+$
PRD 72, 052006 (2005)

**Preliminary $\Omega_c$ lifetime:**
69.3 ± 14.4 ± 8.6 fs
83 events in 2 channels

**Preliminary $\Xi_c^0$ lifetime:**
430 ± 22 ± 9 fs
301 events in 3 channels

*Sidebands demonstrate good understanding of backgrounds*
Charm Baryon Overview

Lifetimes less precise than for the mesons

Mesons: 0.4 - 1.3%  Baryons: 3% - 17%

-- Limited statistics & shorter lifetimes

Need absolute branching fractions:

-- $B(\Lambda_c \Rightarrow pK\pi) = (5.0 \pm 0.5 \pm 1.2) \%$  CLEO, with assumptions

-- Nothing at all to set absolute scale for $\Xi_c^0$, $\Xi_c^+$, $\Omega_c$ !!!

BaBar, Belle, CLEO, FOCUS, SELEX all active:

-- New decay modes, semileptonic form-factors, masses, …

-- Many more results to extract from B-factory datasets

Spectroscopy also still quite active…
Mixing: Intro & Lifetime Differences

D⁰ mixes very little in Standard Model: (and small CP violation)
-- An opportunity to see new physics effects in loops!
-- But… long-distance effects make SM prediction imprecise

Mixing parameters:   \[ \Delta s \text{ are between } \sim \text{CP-eigenstates}: \]
\[ x = \Delta m / \Gamma \quad y = \Delta \Gamma / 2 \Gamma \quad D_{CP\pm} = (D^0 \pm D^{0\text{bar}}) / \sqrt{2} \]

Measure lifetime difference \( y \) via :
-- CP-eigenstates:   KK, \( \pi\pi \)
-- “CP-average” state:   K\( \pi \)

Best results on \( y \) are from 2003:
Belle:   \((1.15 \pm 0.69 \pm 0.38)\% \quad 158\text{ fb}^{-1}\)  hep-ex/0308034
BaBar:   \((0.8 \pm 0.4\, +0.5\, -0.4)\% \quad 91\text{ fb}^{-1}\)  PRL 91, 121801(2003)

Pro: direct linear sensitivity to \( y \); measuring a lifetime difference
Con: systematic error improvement is still tough!
**Semileptonic Mixing Limits**

**Tag initial flavor** \((D^0 \text{ vs. } D^{0\text{bar}})\) **with** \(D^{*+} \Rightarrow D^0 \pi^+\)

**Result:** \(R_M = (x^2 + y^2)/2 < 0.10\% \quad 90\% \text{ CL}\)

---

**Unpublished FOCUS’02:**

\[ r_M < 0.101\% \quad (90\%\text{CL}) \]

(from Ph.D. Thesis + APS’03)
**Mixing: Hadronic Final States**

\[ D^0 \Rightarrow K^- \pi^+ : \text{Common decay} \quad \quad D^0 \Rightarrow K^+ \pi^- : \text{rarer, DCSD decay} \]

DCSD = Doubly-Cabibbo Suppressed Decay

\[
\begin{align*}
&c \bar{u} \Rightarrow s \bar{u} W^+ \Rightarrow s \bar{u} u \bar{d} & A \sim O(1) \\
&c \bar{u} \Rightarrow d \bar{u} W^+ \Rightarrow d \bar{u} u \bar{s} & A \sim O(\lambda^2)
\end{align*}
\]

So... DCSD final states look just like a mixing signal

Kaon charge is an imperfect flavor tag

**Wrong-sign \( K^+ \pi^- \) rate vs. time:**

\[
r(t) = e^{-t} \left( R_D + \sqrt{R_D} y' t + R_M t^2 / 2 \right)
\]

Integrates to: \( R_D + \sqrt{R_D} y' + R_M \)

\( R_D \) : DCSD rate \quad \( y', R_M \) : Mixing

\( x', y' \) time-dependent analyses \quad (\text{contours})

**Primes:** \( x, y \) are rotated by strong phase \( \delta_{K\pi} \)

D. Asner in ‘06 PDG Review:

\[
\begin{array}{c}
\text{D}^0 - \overline{\text{D}}^0 \text{ Mixing Limits}
\end{array}
\]
**Mixing: \( K\pi \) time-dependence**

Tag flavor with \( D^* \):
Use time-dependence
to separate DCSD
from possible mixing...

\[ M(K\pi) = M(K\pi \pi) - M(K\pi) - M_\pi \]

\( K^-\pi^+ \)
Right-sign
\((\log y)\)

\( K^+\pi^- \)
Wrong-sign
DCSD
\(+ ?\text{mixing?} \)
\((\text{linear } y)\)

Assuming no mixing:
\[ R_D = (0.377 \pm 0.008 \pm 0.005) \% \]

Mixing Limits:
green contour in \( x-y \) plot;
current best

\[ Q = \frac{M(K\pi \pi)}{D^*} - D^0 - \pi \]

Consistency with no-mixing: 3.9%
Mixing: $K\pi\pi^0$ Dalitz Plot

Use parts of Dalitz plot where Cabibbo-Favored is large relative to Doubly-Cabibbo Suppressed!

$R_M < 0.54 \times 10^{-3}$ (95% CL)  
Consistency with no-mixing: 4.5%  
New Dalitz technique is a very welcome addition!
Wrong-sign $K\pi$ "Warm-up"

Exploits detached vertex trigger

Assuming no mixing:

$$R_D = (0.405 \pm 0.021 \pm 0.011) \%$$

Plan is to update to 1 fb$^{-1}$ for ICHEP 2006

& then move on to the full time-dependent analysis…
Rare Charm Decays

Rare decays can be important to constrain new physics

Superficially analogous to many familiar B decays
-- But… long-distance effects important in general
-- Limits are generally still far from SM rates

Lots of activity at many experiments
-- Good:  More luminosity to come everywhere
-- Bad:   All results have background, so sqrt(lumi) improvement
-- Envy:  One CDF result has huge lumi gain to come soon…

h⁺ l⁺ l⁻ modes are popular
Di-leptons, di-photon and radiative modes are also explored

CP & T violation searches are also important for new physics
Rare Charm Decays

Recent BaBar analysis and compilation:

Winter Conf’s
288 fb⁻¹

CLEO also reported:

\[ \mathcal{B}(D^+ \rightarrow \pi^- e^+ e^+) < 3.6 \times 10^{-6} \]
\[ \mathcal{B}(D^+ \rightarrow K^- e^+ e^+) < 4.5 \times 10^{-6} \]

Tevatron Activity with Muon Triggers:

\[ D\Phi \ (1 \text{ fb}^{-1}): \mathcal{B}(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 4.7 \times 10^{-6} \] Moriond EW

\[ CDF \ (65 \text{ pb}^{-1}): \mathcal{B}(D^0 \rightarrow \mu^+ \mu^-) < 2.5 \times 10^{-6} \] PRD 68, 091101 (2003)
$D^+ \Rightarrow \pi^+ \mu^+ \mu^-$

Dimuon trigger
Global event topology + detached vertex

Short distance: Z penguin, W box
Long distance: phi, omega $\Rightarrow \mu^+ \mu^-$

Results:

$\mathcal{B} \left( D^+ \Rightarrow \phi \pi^+ \Rightarrow \pi^+ \mu^+ \mu^- \right) = \left(1.75 \pm 0.70 \pm 0.50\right) \times 10^{-6}$

Consistent w/ previous...check.

Look away from $\phi$ mass region...

$\mathcal{B} \left( D^+ \Rightarrow \pi^+ \mu^+ \mu^- \right) < 4.7 \times 10^{-6}$
## CP/T Violation: Survey of Results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Decay mode</th>
<th>$A_{CP} (%)$</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>$D^+ \rightarrow K^- K^+ \pi^+$</td>
<td>$1.4 \pm 1.0 \pm 0.8$</td>
<td></td>
</tr>
<tr>
<td>BaBar</td>
<td>$D^+ \rightarrow \phi \pi^+$</td>
<td>$0.2 \pm 1.5 \pm 0.6$</td>
<td>Resonant substructure of $D^+ \rightarrow K^- K^+ \pi^+$</td>
</tr>
<tr>
<td>BaBar</td>
<td>$D^+ \rightarrow K^{*0} K^+$</td>
<td>$0.9 \pm 1.7 \pm 0.7$</td>
<td></td>
</tr>
<tr>
<td>CLEO II.V</td>
<td>$D^0 \rightarrow \pi^+ \pi^- \pi^0$</td>
<td>$1 \pm 9_{-7} \pm 8$</td>
<td>Dalitz plot analysis</td>
</tr>
<tr>
<td>CDF</td>
<td>$D^0 \rightarrow K^+ K^-$</td>
<td>$2.0 \pm 1.2 \pm 0.6$</td>
<td>Direct CPV</td>
</tr>
<tr>
<td>CDF</td>
<td>$D^0 \rightarrow \pi^+ \pi^-$</td>
<td>$1.0 \pm 1.3 \pm 0.6$</td>
<td>Direct CPV</td>
</tr>
<tr>
<td>FOCUS</td>
<td>$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$</td>
<td>$1.0 \pm 5.7 \pm 3.7$</td>
<td>T violation through triple product correlations</td>
</tr>
<tr>
<td>FOCUS</td>
<td>$D^+ \rightarrow K^0 K^+ \pi^+ \pi^-$</td>
<td>$2.3 \pm 6.2 \pm 2.2$</td>
<td></td>
</tr>
<tr>
<td>FOCUS</td>
<td>$D_S \rightarrow K^0 K^+ \pi^+ \pi^-$</td>
<td>$-3.6 \pm 6.7 \pm 2.3$</td>
<td></td>
</tr>
</tbody>
</table>

as compiled by Sheldon Stone for FPCP06
Charmonium Spectrum

Rich Spectroscopy, discussed elsewhere.

Main point for us: $\psi(3770)$ is a good source of $D$ mesons.

$\psi(3770)$ decays:
-- mostly to $D$ pairs
-- analogous to $\Upsilon(4S)$ & $B$ pairs

$\psi(2S)$, $J/\psi$ decays:
-- ggg+ggγ; other charmonia;
dileptons; radiative
Charm Factory Datasets

14 x 10⁶ \( \psi(2S) \)
58 x 10⁶ \( J/\psi \)
6.4 pb\(^{-1}\) cont’m @ 3.65 GeV
Dedicated \( R_{\text{had}} \) scans
33 pb\(^{-1}\) \( \psi(3770) \)

3.1 x 10⁶ \( \psi (2S) \)
No \( J/\psi \) (access via \( \psi(2S) \Rightarrow J/\psi X \))
21 pb\(^{-1}\) cont’m @ 3.67 GeV
60 pb\(^{-1}\) \( D_s \) scan; included \( Y(4260) \)
281 pb\(^{-1}\) \( \psi(3770) \)
180 pb\(^{-1}\) @ 4170 MeV for \( D_s \)

CLEO-c detector is superior to BESII…
But, BESIII upgrade is well underway!
More on this later…

Only few days @ current lumi!
~10x this summer
CLEO-c Program: Precision Charm

Provides important tests of Lattice QCD

Necessary for overall Heavy Flavor program: helps B factories

Started with $D^0, D^+$, now extending to $D_s$ mesons

$\psi(3770) \rightarrow D^0 \bar{D}^0$

$D^0 \rightarrow K^-e^+\nu$ & $\bar{D}^0 \rightarrow K^+\pi$

Semileptonic decay

opposite

a fully reconstructed hadronic “Tag”

Cleanly infer neutrinos!

Almost all first results more precise than prior world averages
Reconstructing D Tag Samples

\( D^+ \) Tags Used for \( D^+ \rightarrow \mu^+ \nu \)

( similar for other analyses & \( D^0 \) )

\( \psi(3770) \):

-- \( D \bar{D} \) pair + \( \sim 35 \text{ MeV} \) extra energy

-- Not enough \( E \) for extra pions, etc.

All Tags Use:

Momentum Conservation:

\[ M_{bc} = (E_{\text{beam}}^2 - p_D^2)^{1/2} \]

-- “beam constrained mass”

-- Better resolution than 4-vector mass

\( \sim 1.5 \text{ MeV} \); mostly beam energy spread

Energy conservation:

\[ \Delta E = E_{\text{cand}} - E_{\text{beam}} \]

-- Peaks at 0

-- sensitive to Particle ID, missing particles
Charm as a QCD Lab I

Leptonic D Decays

\[ f_D \text{ LQCD} = \text{exp't ?} \]

\[ f_D \text{ is a “decay constant”:} \]

- chance that quarks are at same place
- \( \sim |\psi(0)|^2 \) : square of wavefunction at origin
- (weak interaction is short-range)

Lattice QCD: Calculate strong force on computers

\[ \text{for } V_{td}, V_{ts} \]
$D^+ \Rightarrow \mu^+ \nu_\mu$: Extracting $f_D$

50 candidates; $2.81 \pm 0.30^{+0.84}_{-0.27}$ background

Rely on data for systematic errors;

**Background** from data & MC

-- Key backgrounds: $D^+ \Rightarrow \pi^+\pi^0$, $\tau\nu$, $K^0\pi^+$

**Missing-mass$^2$: Data**

![Signal zoom](chart.png)

**Result:**

$f_D = (222.6 \pm 16.7^{+2.8}_{-3.4})$ MeV

**Also limit:**

$\mathcal{B} (D^+ \rightarrow e^+\nu) < 2.4 \times 10^{-5}$ @ 90% c.l.

and

$\mathcal{B} (D^+ \rightarrow \tau^+\nu) < 1.8 \times \text{Std. Model} @ 90\%$ c.l.
**Theory Comparison for \( f_D \)**

Will use \( f_D, f_{Ds}, \) & ratio to test lattice calculations

⇒ confidence in \( f_B, f_{Bs} \) to interpret \( B \) mixing.

---

**Sample Lattice Calculations:**

FNAL/MILC PRL 95, 122002 (2005)

**Unquenched LQCD:** \( m_{u,d} \ll m_s \)
   (but “fourth root” trick)

\[
\begin{align*}
  f_D &= (201 \pm 3 \pm 17) \text{ MeV} \\
  f_{D_s} &= (249 \pm 3 \pm 16) \text{ MeV}
\end{align*}
\]

Chiu et al. PLB 624, 31 (2005)

**Exact chiral symmetry,**

\( BUT \) quenched LQCD

\[
\begin{align*}
  f_D &= (235 \pm 8 \pm 14) \text{ MeV} \\
  f_{D_s} &= (266 \pm 10 \pm 18) \text{ MeV}
\end{align*}
\]

Comparable experimental & theory errors; working to improve both

---
\[ D_s^+ \Rightarrow \mu^+ \nu_\mu: Extracting f_{Ds} \]

**High statistics B factory data:**
allows “continuum tagging” of opposite-side charm jet

**BaBar**

\[ D_s^+ \Rightarrow \mu^+ \nu_\mu \]

LaThuile 230 fb\(^{-1}\)

\[ f_{Ds} = 279 \pm 17 \pm 6 \pm 19 \text{ MeV} \]

\[ \Delta M = M( D_s^*) - M( D_s) \]

\[ \mu^- \nu_\mu \text{ candidates opposite a } D^0, D^+, D^{*+}, \text{ or } D_s^+ \text{ tag} \]

**Last error from } \phi \pi \text{ BF**}

( CLEO-c will improve )

Bumps in dashed background are due to lower: \( \gamma \) from \( \pi^0 \) in \( D_s^* \Rightarrow D_s \pi^0 \)
higher: \( \mu \) is mis-id \( \pi \) from \( \tau \) decay in \( D_s \Rightarrow \tau \nu \)
Charm as a QCD Lab II

Semileptonic D Decays

Form factors, CKM
FF help w/ B decays

"Form Factor":
~ Chance that quarks bind into a given final state
Relate $B \rightarrow \pi e\nu$ to $D \rightarrow \pi e\nu$

Also, ratios of $D \rightarrow \pi e\nu$ to $D \rightarrow \mu\nu$
and $D \rightarrow K e\nu$ to $D_s \rightarrow \mu\nu$
cancel CKM elements: Pure LQCD tests...
Exclusive Semileptonic

All with electrons: muons are too soft at \(\psi(3770)\)

\[ D^0 \rightarrow K^- e^+ \nu \]
\[ D^0 \rightarrow \pi^- e^+ \nu \]

117 events

\[ U = E_{\text{miss}} - p_{\text{miss}} \, \text{GeV} \]

Great kinematic \(K/\pi\) separation
(in addition to particle ID)

Very clean, especially given the neutrino…

Ratios of new CLEO-c to PDG World Ave
(two first observations!)

Also new BES results:
hep-ex/0606103

Form-factors with 5x data later this summer…
But CLEO-c also has \(\Rightarrow\)
**Semileptonics w/o Tags**

*Uses neutrino reconstruction: an alternative to tagging w/ higher efficiency*  
(q\(^2\) resolution still more than sufficient)

---

**Preliminary form-factor results from this analysis shown at FPCP.**

-- Also analyze the $\pi^0$ e$^+\nu$ and $K_S$ e$^+\nu$ modes as well.

---

**Preliminary**

281 pb\(^{-1}\)

FPCP06
**Current Form Factors**

FOCUS: ~13,000 $K\ell\nu$ events

CLEO-c: ~6,500 $K\ell\nu$ events (tagged) in current 281 pb$^{-1}$ sample

Big interest: use $D^0 \Rightarrow \pi^- \ell^+ \nu$ to understand $B^0 \Rightarrow \pi^- \ell^+ \nu$

CLEO-c sample is very clean!
Form Factors: B Factories

High statistics B factories: “continuum tagging”

\[ \text{Belle } D^0 \rightarrow K \, l \, \nu, \pi l \, \nu \]
\[ \pi l \nu: 232 \text{ sig + 61 bkg} \]

\[ \text{BaBar } D^0 \rightarrow K \, l \, \nu \]

Winter conf’s (2006) 75 fb\(^{-1}\)

hep-ex/0604049 (to PRL) 282 fb\(^{-1}\)
Absolute Branching fractions (decay rates) for normalization

Cannot calculate

B decays most often to Charm:
Form factors less of an issue for $B \Rightarrow D^* l \nu$
(use HQET methods...)

But B decay is normalized to charm for $V_{cb}$
Absolute Branching Fractions

Method:
Double Tags: \( D_{ij} = 2N_{DD} B_i B_j \varepsilon_{ij} \)
Single Tags: \( S_i = 2N_{DD} B_i \varepsilon_i \)

D/S Ratio independent of:
\( N_{DD}, \int \mathcal{L} dt, \text{ tag } B_j \)
(& tag \( \varepsilon_j \) almost cancels)

Compare PDG to CLEO errors:

Ratios to PDG World Ave
(to keep modes on same scale…)
⇒ most precise already
(NOTE: includes final-state radiation; will make systematically higher…)

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

Also get precision cross-sections
(more on these later…)

Very Preliminary
from 281 pb\(^{-1}\)
See PRL95, 121801 (2005) for 56 pb\(^{-1}\)
\( D_s \) Absolute Branching Fractions

**Scan:** Preliminary

- BF scan: Preliminary
  - 60 pb\(^{-1}\)
  - 71 pb\(^{-1}\)

**CLEO-c:** 60 pb\(^{-1}\)

- Energy scan
- Now: ~ 200 pb\(^{-1}\) at or near 4170 MeV
+ More this summer

<table>
<thead>
<tr>
<th>Mode</th>
<th>( \mathcal{B} ) (%) (CLEO-c)</th>
<th>( \mathcal{B} ) (%) PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_SK^+ )</td>
<td>1.28 ±0.13 ( \pm 0.07 )</td>
<td>1.80±0.55</td>
</tr>
<tr>
<td>( K^+K^-\pi^+ )</td>
<td>4.54 ±0.44 ( \pm 0.25 )</td>
<td>4.3±1.2</td>
</tr>
<tr>
<td>( K^+K^-\pi^+\pi^0 )</td>
<td>4.83 ±0.49 ( \pm 0.46 )</td>
<td>-</td>
</tr>
<tr>
<td>( \pi^+\pi^+\pi^- )</td>
<td>1.02 ±0.11 ( \pm 0.05 )</td>
<td>1.00±0.28</td>
</tr>
</tbody>
</table>

**Errors:** 11\% now; more data & more tag modes will improve
**ψ(3770): Mixing, non-DD decays, ...**

Naively, \( \psi(2S) \): S-wave, \( \psi(3770) \): D-wave

But \( \psi(3770) \) must have some S-wave to couple as much as it does to \( e^+e^- \)

*BES has made many studies related to mixing of these states...*

Older experiments: some indication that total resonant cross section
exceeds the rate to make D pairs...
*But not clear, and large errors.*

Newer results:

<table>
<thead>
<tr>
<th>( \sigma(D^+D^-) ) (nb)</th>
<th>( \sigma(D^0\bar{D}^0) ) (nb)</th>
<th>( CLEO-c )</th>
<th>( BES )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.60 ± 0.07 ( ^{+0.07}_{-0.05} )</td>
<td>2.79 ± 0.07 ( ^{+0.10}_{-0.04} )</td>
<td>3.58 ± 0.09 ± 0.31</td>
<td></td>
</tr>
</tbody>
</table>

Tiny rates found for some particular non-DD modes...

But, need total cross-section to check for inclusive excess:

CLEO-c measures: \( \sigma_{\text{tot}} = (6.38 ± 0.08 \ ^{+0.41}_{-0.30}) \) nb

This gives non-DD as: \( (−0.01 ± 0.08 \ ^{+0.41}_{-0.30}) \) nb

No need for non-DD excess? Limit at \(~10\%\) level...

---

*BES*

PLB 603, 130 (2004)

PRL 95, 121801 (2005) 56 pb\(^{-1}\)

*CESR CLEO*

PRL 96, 092002 (2006) 281 pb\(^{-1}\)
\( \psi(3770) \rightarrow \text{non-DDbar decays} \)

**BES results:** maybe there is significant non-DD after all ?!?

Two different analyses;

\[
\mathcal{B}(\psi(3770) \rightarrow \text{non-DD}) = (16.1 \pm 1.6 \pm 5.7)\% \quad (\text{w/ } R_{\text{had}})
\]

\[
\mathcal{B}(\psi(3770) \rightarrow \text{non-DD}) = (16.4 \pm 7.3 \pm 4.2)\% \quad (\text{w/ resonance fits})
\]

**Very detailed papers posted exactly one week ago to hep-ex.**

Method of treatment of radiative corrections may be important ?

( Hard for me to digest papers with a beautiful beach so close by! My apologies… )
# The Future: BESIII & BEPCII

## BEPCII accelerator

Dec’07: test run for luminosity
Dec’08: achieve $3 \times 10^{32}$ cm$^{-2}$ s$^{-1}$

## BESIII detector: all new!

- **CsI calorimeter**
- **Precision tracking**
- **Time-of-flight + dE/dx PID**

### Yearly data possibilities:

( $10^7$ s at 1/2 peak lumi = 5 fb$^{-1}$)

<table>
<thead>
<tr>
<th>Data Sample</th>
<th>Central-of-Mass (MeV)</th>
<th>#Events per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$</td>
<td>3097</td>
<td>$10 \times 10^9$</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>3670</td>
<td>$12 \times 10^6$</td>
</tr>
<tr>
<td>$\psi(2S)$</td>
<td>3686</td>
<td>$3.0 \times 10^9$</td>
</tr>
<tr>
<td>$D^0\bar{D}^0$</td>
<td>3770</td>
<td>$18 \times 10^6$</td>
</tr>
<tr>
<td>$D^+D^-$</td>
<td>3770</td>
<td>$14 \times 10^6$</td>
</tr>
<tr>
<td>$D^+_SD^-$</td>
<td>4030</td>
<td>$1.0 \times 10^6$</td>
</tr>
<tr>
<td>$D^+_SD^-_S$</td>
<td>4170</td>
<td>$2.0 \times 10^6$</td>
</tr>
</tbody>
</table>

For more information, see Weiguo Li at FPCP06
**BESIII Physics Potential**

*Many exciting ways to use higher luminosity!*

**Charmonium states:** \( J/\psi, \psi(2S), \eta_c(1S), \eta_c(2S), \chi_{cJ}, \) and \( h_c \)

**Exotics:** hybrids, glueballs and other exotics in \( J/\psi \) and \( \psi(2S) \) radiative decays;

**Open charm physics:** \( D, D^+, D_s \) (like CLEO-c)
  - Improve statistics-hungry analyses
  - Improved reach for mixing, rare decays, CP violation
  - Quantum correlations, strong \( K\pi \) phase, ...
  - Spectroscopy via Dalitz plots

**Energy scans:** \( R_{had}, \) resonances, DD composition, ...

**Tau Physics**

**No doubt many more innovations...**

*Charm 2006 workshop next week in Beijing*
Conclusion & Outlook

We are in a Charm Physics Renaissance

BESII showed us the richness of charm factory datasets
CLEO-c now in its prime: precise results aid flavor physics
⇒ both have re-written parts of the PDG re: charm...

CLEO-c will also do $D_s$ decay constants, semilept., abs. Hadr. BF’s
& novel analyses at $\psi(3770)$ (quantum correl’s, CP tags, etc.)
Great promise of BESIII upgrade beginning next year!
... plus p-pbar for charmonia will return with PANDA.

Much untapped potential at B factories
-- Precise mixing analyses
-- Hadronic BR’s (esp. baryons), Dalitz plot analyses, Rare, ...

What else will CDF & DO learn to do with their large rates ???

Fixed target “done”, but analysis machine goes on...
A *big* lesson here:
  Let’s hope Charm & B factories can do as well after their runs!
Selected Topics That Didn’t Fit

Numerous $J/\psi$, $\psi(2S)$, $\chi$ decays (BES & CLEO-c)
Dalitz analyses of $D$ and $J/\psi$ (Many exp’ts)
Updates on $D_s(2317,2460)$ decays (BaBar)
Inclusive $D$ semileptonic (CLEO-c)
$D_s \Rightarrow \phi X$, $\eta X$, $\eta'X$ (CLEO-c)

etc...

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FOCUS: John Cumalat

Belle: Yoshi Sakai
CLEO: David Asner, Hanna Mahlke, Sheldon Stone
DO: Brendan Casey
SELEX: Jim Russ