Recent Results in Charm Physics

Topics

• Rare Charm Processes as probes of New Physics

• Spectroscopy of New States

John Yelton (University of Florida)
CLEO, CMS and BES III Collaborations

Thanks to ICHEP reviews of David Asner and Galina Pakhlova

SPLIT 2008
The Experiments

THREE DIFFERENT ENVIRONMENTS STILL OPERATING

1. $e^+e^-$ colliders in the charmonium region

Very clean! Can only run at one energy at a time.

BES II 1996-2004

CLEO-c 2003-2008

The Future –

BES III (running on the $\Psi(2S)$ as we speak)
2. $e^+e^-$ in the bottomium energy range

BELLE 1998-date

BaBar 1998-2008

Clean environment – several different ways of studying charm
a) Continuum
b) B-decays to charm
c) ISR to scan the charmonium resonances
3. Hadron colliders

Huge cross section for charm – but complicated environment. Physics can be done because of the kinematically clean decays of $D^{*+}$ and $J/\psi$.

The Future: LHC-b, and maybe CMS and ATLAS. Huge production rates, but only LHC-b designed with a view specifically B and thus c physics.
Search for New Physics (NP) in Charm Sector

Very low SM rates \( \text{BF}(c \rightarrow u \ell l) \sim 10^{-8} \) for loop processes provide unique window to observe NP in rare charm processes.

**Rare Decays, \( D^0 - \bar{D}^0 \) oscillations & CP Violation**

**NP can introduce new particles into loop**

Particles and couplings in rare charm processes are NOT the same as in rare B and K processes.
Rare Charm Decay Rates Modified by NP

- **Radiative** - $D \rightarrow (\gamma, \phi, K^*)\gamma$ SM $10^{-4}$ - $10^{-6}$
  - CLEO $D \rightarrow \gamma \gamma < 2.6 \times 10^{-5}$ @90% C.L.
  - BABAR $D \rightarrow \phi\gamma (2.73 \pm 0.30 \pm 0.36) \times 10^{-5}$ (new)
  - BABAR $D \rightarrow K^*\gamma (3.22 \pm 0.20 \pm 0.27) \times 10^{-4}$ (new)

- **Leptonic** $D \rightarrow \mu\mu$ SM $< 10^{-13}$ RPV SUSY $\sim 10^{-7}$
  - CDF $< 4.3 \times 10^{-7}$ @90% C.L. (new)

- **GIM Suppressed** $D \rightarrow \pi\pi$ SM $\sim 10^{-6}$
  - Distinguish NP from SM with dilepton invariant mass, FB asymmetries
    - $D_0 \rightarrow \pi\mu\mu < 3.9 \times 10^{-6}$
    - CLEO-c $D \rightarrow \pi\mu\mu < 3.9 \times 10^{-6}$

- **Lepton Flavor Violation** - BABAR @90% C.L.
  - $D \rightarrow e^+\mu^- < 8.1 \times 10^{-7}$
  - $D^+ \rightarrow K^+ e^-\mu^+ < 3.7 \times 10^{-6}$
  - $D_s^+ \rightarrow K^+ e^-\mu^+ < 3.6 \times 10^{-6}$
  - $\Lambda_c^+ \rightarrow p e^-\mu^+ < 7.5 \times 10^{-6}$

- **Lepton Number Violation** $D^+ \rightarrow \pi^- e^+ e^+$
  - CLEO-c $< 3.6 \times 10^{-6}$ @90% C.L
Radiative D decays

- Radiative - $D \rightarrow (\phi, K^*)\gamma$ SM $10^{-4}$-$10^{-6}$
  - BABAR $D \rightarrow \phi\gamma (2.73 \pm 0.30 \pm 0.36) \times 10^{-5}$ (new at ICHEP)
  - BABAR $D \rightarrow K^*\gamma (3.22 \pm 0.20 \pm 0.27) \times 10^{-4}$ (new at ICHEP)

Though interesting, these observations do not indicate new physics, they indicate final state interactions.
Purely Leptonic Decay $D \to \mu\mu$

No evidence of a signal $D \to \mu\mu < 4.3 \times 10^{-7}$ @90% C.L.

$\text{SM} < 10^{-13}$

$\text{RPV SUSY} \sim 10^{-7}$

This gives constraints on R-parity violating SUSY models
D⁰-\overline{D}⁰ Mixing

Two state system: \( |D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \)

Mass Eigenstates\(\neq\)Flavor Eigenstates

D⁰–\overline{D}⁰ transitions observables

\[
x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta \Gamma}{2\Gamma} \quad R_M = \frac{1}{2}(x^2 + y^2)
\]

\[
x' = x \cos\delta_{K\pi} + y \sin\delta_{K\pi}
\]

\[
y' = y \cos\delta_{K\pi} - x \sin\delta_{K\pi}
\]

\[
A\arg\left(\frac{q}{p}\right)
\]

SM calculations based on box diagrams alone gives \( x \sim 10^{-5}, y \sim 10^{-7} \) [Falk et al. PRD 65 (2002) 054034]

Long-distance effects dominate \( x, y \)

Any CPV in this system would be clear evidence for New Physics

New-physics

Supersymmetry:  

Extended Higgs:
D⁰-\bar{D}⁰ Mixing:

- ‘Wrong sign’ K(⁎)ev (R₉)
  BELLE PRD 77 (2008) 112003
  BaBar PRD 76 (2007) 014018
- ‘Wrong sign’ Kπ (x', y')
  BELLE PRL 96 (2006) 151801
  BaBar PRL 98 (2007) 211802
  CDF PRL 100 (2008) 121802
- Eigenstate lifetime analyses:
  y₉
  BaBar PRD 78 (2008) 011105
  BELLE PRL 98 (2007) 211803
- K_Sπ⁺π⁻ Dalitz analyses: x, y
  BELLE PRL 99 (2007) 131803
- Quantum Correlation: δ_Kπ
  CLEO-c PRL 100 (2008) 221801

New 2008 (unpublished)

BABAR: ‘wrong-sign’ D⁰→K⁺π⁻π⁰
arXiV:0807.4544
Finds:
  x' = 2.61±0.57±0.39

Belle: y₉ D⁰→K_SK⁺K⁻
(Preiminary ICHEP. No significant mixing found in this CP- mode.)
**D⁰-D⁰ Mixing:**

No mixing \((x,y) \neq (0,0)\) excluded at 9.8\(\sigma\)

**No evidence for CP violation**

\[ x = 1.00^{+0.24}_{-0.25} \, \% \quad 3.4\sigma \]

\[ y = 0.76^{+0.17}_{-0.18} \, \% \quad 4.1\sigma \]

**MIXING HAPPENS! Why?** Could be long range interactions, but could be NP
(Extra fermions, gauge bosons, scalars, dimensions, symmetries etc.)

HFAG Average for ICHEP08
Direct CPV

In Singly Cabibbo Suppressed decays, interference between penguin & tree can generate direct CP asymmetries which:

- Could reach $\sim 10^{-3}$ in SM - may be observable!

- In NP models effects of $\sim 10^{-2}$ possible
**CPV searches in $D^0\rightarrow KK$ (or $\pi\pi$)**

Measure asymmetry in time integrated rates:

$$A_{CP} = \frac{\Gamma(D^0 \rightarrow KK) - \Gamma(\bar{D}^0 \rightarrow KK)}{\Gamma(D^0 \rightarrow KK) + \Gamma(\bar{D}^0 \rightarrow KK)}$$

Distinguish $D$ flavor from ‘slow pion’ charge in $D^*\rightarrow D^0\pi$

BaBar, PRD 100 (2008) 061803, 386 fb$^{-1}$, ~130k KK events

Also, limits in multi-hadron decays from BaBar and CLEO-c!

BaBar $A(KK)_{CP} = [0.00 \pm 0.34 \text{ (stat)} \pm 0.13 \text{ (syst)}]$

Belle $A(KK)_{CP} = [-0.43 \pm 0.30 \text{ (stat)} \pm 0.11 \text{ (syst)}]$

Entering interesting territory!

ArXiV:0807.0148 submitted to PLB
Leptonic D Decays and Decay Constants

In $D^+$ and $D_s$, the $c$ and spectator quark can annihilate to produce leptonic final state:

In general, for all pseudoscalars:

$$\Gamma(P^+ \rightarrow l^- \nu) = \frac{1}{8\pi} G_F^2 f_P^2 m_l^2 M_P \left(1 - \frac{m_l^2}{M_P^2}\right)^2 |V_{Ql}|^2$$

Since $V_{cd}$ and $V_{cs}$ are well known, we can extract $f_D$ and $f_{D_s}$ and compare with lattice!
Measurements of $D_{(s)} \rightarrow l\nu$ Branching Fractions

Precise measurements now exist for:

- $\mu^+\nu, \tau^+ (\rightarrow \pi^+\nu)\nu$ CLEO-c (PRL 99 (2007) 071802; arXiv:0704.0437 + FPCP08)
- $\tau^+ (\rightarrow e^+\nu\nu)\nu$ CLEO-c (PRL 100 (2008) 161801)
- $D^+ \mu^+\nu$ CLEO-c (Phys. Rev. D 78, 052003 , 2008)

Basic methods for $\mu\nu$ measurement:

- CLEO-c: for $f_D$ reconstruct one $D^+$, look for MIP ($\mu$), and then compute missing mass squared (similar for $f_{Ds}$, but here exploit $D_sD_s^*$ production in 4170 MeV dataset)
- Belle: infer presence of $D_s$ from recoiling mass against reconstructed $D$ & fragmentation. Add candidate $\mu$ and compute missing mass
- BaBar: Select $e^+e^- \rightarrow cc$ events with high momentum $D^0, D^+, D_s, D^{**}$ close to $B$ kinematic end-point. Search for $D_s^* \rightarrow \gamma, D_s \rightarrow \gamma\mu\nu$ in the recoil
CLEO-c \( D^+ \rightarrow \mu^+ \nu \)

Missing mass squared distribution (including log zoom with fit):

\[
\begin{align*}
\text{BR}(D^+ \rightarrow \mu^+ \nu) &= (3.82 \pm 0.32 \pm 0.09) \times 10^{-4} \\
f_D &= (205.8 \pm 8.5 \pm 2.5) \text{ MeV}
\end{align*}
\]

(result with \( \tau \nu/\mu \nu \) fixed at SM expectation)
$D_s \rightarrow \mu^+ \nu$ & $D_s \rightarrow \tau^+ \nu$

548 fb$^{-1}$

CLEO-c prelim: 424 pb$^{-1}$

$D_s \rightarrow \mu \nu + D_s \rightarrow \tau \nu$, $\tau \rightarrow \pi \nu \nu$

Background

$D_s \rightarrow \tau \nu$, $\tau \rightarrow e \nu \nu$

298 pb$^{-1}$
**D\(^+\) and D\(_s\) Decay Constants**

Final D\(_s\) results from CLEO-c expected soon with full data sample.

Current CLEO results use 70% of data for D\(_s\)→μν + D\(_s\)→τν, τ→πνν and use 50% of data for D\(_s\)→τν, τ→eνν.

---

Bar graph showing decay constants for D\(_s\) with data from various experiments.
$D_s \rightarrow p\bar{n}$: First Observation

PRL 100, 181802 (2008)

- Same analysis technique as $D \rightarrow \mu\nu$

- Only kinematically allowed $D$ meson baryonic decay

- Consequence for understanding $W$ annihilation dynamics

Chen, Cheng, Hsiao 0803.2910v3 [hep-ph]

$\mathcal{B}(D_s^+ \rightarrow p\bar{n}) = (1.30 \pm 0.36^{+0.12}_{-0.10}) \times 10^{-3}$
Spectroscopy of the **XYZ** charmonium-like states

It all started with BELLE 5 years ago, finding the X(3872) resonance in $B\rightarrow XK\rightarrow(J/\Psi\pi\pi)K$. This particle since confirmed by BaBar, D0, and CDF.

<table>
<thead>
<tr>
<th></th>
<th>$M(X(3872))$, MeV/c²</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B\rightarrow XK$</td>
<td>3871.46±0.37±0.07</td>
</tr>
<tr>
<td>$X\rightarrow J/\psi\pi^+\pi^-$</td>
<td>3871.61±0.16±0.19</td>
</tr>
<tr>
<td>PDG07</td>
<td>3871.4±0.6</td>
</tr>
<tr>
<td>$M(D^0)+M(D^{*0})$</td>
<td>3871.81±0.35</td>
</tr>
</tbody>
</table>

**Possible explanations:**
- Unlikely to be conventional charmonium
- Tetraquark
- Hybrid
- Threshold Cusp
- $D^0D^{*0}$ molecular state?

CDF most accurate mass measurement

Observation of radiative decays $X \rightarrow J/\psi \gamma$ and $X \rightarrow \psi(2S) \gamma$ at these levels disfavor a $D^0 D^*0$ molecular state identification.

**Question:** is the peak in $D^0 D^*$ and $D^0 D^0 \pi^0$ the same particle?

**Answer:** probably yes.

<table>
<thead>
<tr>
<th>State</th>
<th>$M$, MeV/$c^2$</th>
<th>$\Gamma_{tot}$, MeV</th>
<th>Decay Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(3875)$</td>
<td>3875.2$^{+0.7}_{-0.3}$</td>
<td>1.22 $^{+0.23}_{-0.30}$</td>
<td>$D^0 D^0 \pi^0$</td>
</tr>
<tr>
<td>$X(3872)$</td>
<td>3872.6$^{+0.5}_{-0.4}$</td>
<td>3.9$^{+2.5}_{-1.8}$</td>
<td>$D^0 D^0$</td>
</tr>
<tr>
<td>$X(3875)$</td>
<td>3875.1$^{+0.7}_{-0.5}$</td>
<td>3.0$^{+1.9}_{-1.4}$</td>
<td>$D^0 D^*0$</td>
</tr>
<tr>
<td>$X(3872)$</td>
<td>3871.81$^{+0.22}_{-0.0}$</td>
<td>&lt; 2.3</td>
<td>$\pi^+ \pi^- J/\psi$</td>
</tr>
</tbody>
</table>

CDF etc.
New peak found in $e^+e^- \rightarrow \Lambda_c^+\Lambda_c^- \gamma_{ISR}$

Named the $X(4630)$. Interpretation?

Is it the same as the $Y(4660)$ found by BELLE in $e^+e^- \rightarrow \psi(2S) \pi^+\pi^- \gamma_{ISR}$?

<table>
<thead>
<tr>
<th>State</th>
<th>$M$, MeV/c$^2$</th>
<th>$\Gamma_{tot}$, MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(4630)$</td>
<td>$4634^{+8}_{-7-8}$</td>
<td>$92^{+40}_{-24-21}$</td>
</tr>
<tr>
<td>$Y(4660)$</td>
<td>$4664 \pm 11 \pm 5$</td>
<td>$48 \pm 15 \pm 3$</td>
</tr>
</tbody>
</table>
Z(4430)$^+$ first report of a charged charmonium like state

$B \rightarrow KZ$, $Z(4430)^+ \rightarrow \pi^+ \psi(2S)$

$K = K^-, K^0_s$; $\psi(2S) \rightarrow \ell^+ \ell^-, \pi^+ \pi^- J/\psi$

Interpretations:
- S-wave $D^*D_1$ threshold effect
- $D^*D_1$ molecular state
- Radially excited tetraquark
- Baryonium state
- Hadro-charmonium

$M = (4433\pm4\pm2)$ MeV
$\Gamma = (45^{+18}_{-13}^{+30}_{-13})$ MeV

$BF(B \rightarrow KZ) x BF(Z \rightarrow \psi(2S) \pi) = (4.1\pm1.0\pm1.3) \times 10^{-5}$

BUT…
Results are not confirmed by BaBar. Extensive study $B^{-0}\rightarrow\psi\pi^-K^0+(*)$ making sure to include all reflections. Find no significant peaks and place limits on the “BELLE” peak.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$Z(4430)^-$ signal</th>
<th>Branching fraction ($x10^{-5}$)</th>
<th>Upper limit ($x10^{-5}$ (@95% C.L.))</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^-\rightarrow ZK^0, Z^-\rightarrow J/\psi\pi^-$</td>
<td>$-16 \pm 140$</td>
<td>$-0.1 \pm 0.8$</td>
<td>$&lt;1.5$</td>
</tr>
<tr>
<td>$B^0\rightarrow ZK^+, Z^-\rightarrow J/\psi\pi^-$</td>
<td>$-666 \pm 203$</td>
<td>$-1.2 \pm 0.4$</td>
<td>$&lt;0.4$</td>
</tr>
<tr>
<td>$B^-\rightarrow ZK^0, Z^-\rightarrow (2S)\pi^-$</td>
<td>$110 \pm 118$</td>
<td>$1.3 \pm 1.4$</td>
<td>$&lt;3.8$</td>
</tr>
<tr>
<td>$B^0\rightarrow ZK^+, Z^-\rightarrow (2S)\pi^-$</td>
<td>$327 \pm 170$</td>
<td>$1.4 \pm 0.7$</td>
<td>$&lt;2.6$</td>
</tr>
</tbody>
</table>

2σ peak! Not significant

$BF(B\rightarrow KZ)xBF(Z\rightarrow\psi(2S)\pi) = (4.1\pm1.0\pm1.3) \times 10^{-5}$
**$Z^+_{1,2} \rightarrow \chi_{c1}\pi^+$**

$B^0 \rightarrow \chi_{c1}\pi^+K^-; \quad \chi_{c1} \rightarrow J/\psi\gamma$

**Dalitz analysis**: fit $B^0 \rightarrow \chi_{c1}\pi^+K^-$ amplitude by coherent sum of contributions from:

- known $K\pi$ resonances
- $K^*$'s + one ($\chi_{c1}\pi$) resonance
- $K^*$'s + two ($\chi_{c1}\pi$) resonances

**PRELIMINARY and UNCONFIRMED**

Make projections onto $\chi_{c1}\pi^+$

- $M_1 = (4051 \pm 14^{+20}_{-41})$ MeV/$c^2$
- $\Gamma_1 = (82^{+21}_{-17} + 47^{+22}_{-12})$ MeV
- $M_2 = (4248^{+44}_{-29} + 180^{+18}_{-35})$ MeV/$c^2$
- $\Gamma_1 = (177^{+54}_{-39} + 316^{+316}_{-61})$ MeV

$B(B^0 \rightarrow K^-Z_1^+) \times B(Z_1^+ \rightarrow \pi^+\chi_{c1}) = (3.1^{+1.5+3.7}_{-0.9-1.7}) \times 10^{-5}$

$B(B^0 \rightarrow K^-Z_2^+) \times B(Z_2^+ \rightarrow \pi^+\chi_{c1}) = (4.0^{+2.3+10.7}_{-0.9-0.5}) \times 10^{-5}$. 

**Events / 0.024 GeV/$c^2**

- $J_1=0$, $J_2=0$
- two $Z$'s
- without $Z$'s
Summary & Outlook

Rare Charm Decays: Experiments entering interesting territory - expect more results soon from CLEO/BES, B-factories and Tevatron that provide constraints on New Physics.

Charm Mixing: Discovery of $D^0$-$\bar{D}^0$ oscillation points the way forward to searches for CPV and New Physics

CP Violation: None found, but experiments entering interesting territory

$f_{Ds}$ Growing disagreement between experiment and lattice calculations: sign of new physics?

XYZ More new questions than answers. Is our view of all hadrons being $q\bar{q}$ or $qqq$ incorrect?

Future: Tighter constraints on New Physics, more stringent tests of LQCD, more precise input to B-physics expected soon from CLEO, B-factories & Tevatron. In the near future charm results from BESIII & LHCb. Higher luminosity B factories (SuperB) will lead to better understanding NP observed at LHC.
• EXTRAS
D$^0$-D$^0$ Mixing:

New HFAG Average for ICHEP08

Previous measurements all from D$^0$→KK,ππ (CP+)

New Belle result uses Dalitz plot analysis of D$^0$→K$^0$K$^+K^-$, dominated by D$^0$→K$^0$φ (CP-)
arXiv:0808.0074
CPV Searches in Multibody \((n \geq 3)\) Decays

BaBar & Belle study of \(D^0 \rightarrow K^+K^0, \pi^+\pi^-\pi^0\)

CLEO study of \(D^+ \rightarrow K^+K^-\pi^+\)

Several complementary analyses:

- Look for phase space integrated asymmetry.
- Form residuals of \(D^0, \bar{D}^0\) w.r.t. mean in Dalitz space
- Look for difference in angular moments of \(D^0\) & \(\bar{D}^0\) distributions
- Compare amplitude fits of \(D^0\) & \(\bar{D}^0\) Dalitz plot (model dependent)

No CPV observed

BABAR 385 fb\(^{-1}\), arXiv:0802.4035

CLEO 818 pb\(^{-1}\), arXiv:0807.4545