Rare D Decays
(dirty and clean)

Pono: 5.75
Katie: 3.1

Brendan Casey, FNAL
CHARM 2007
Outline

• **Focus on annihilation and radiative decays**
  – Highlight sensitivity to new physics
  – Point out strengths and weaknesses of different channels

• **Compare to similar topologies in beauty and strange system**
  – Better, worse, just different

• **Contrast different techniques used in different environments**

• **Motivate future studies**

• **Try to cover almost everything in last 5 years but will put most focus on \(h\ell^+\ell^-\)**
Charged Annihilation

Sensitive to tree level charged current phenomena
SM rate calculable and experimentally accessible

If you know the decay constant and CKM element you can limit new phenomena
If you don’t find any, you can make precise measurements of SM parameters
BeautY:

3rd generation so very sensitive to high $\tan \beta$ SUSY/2HDM...

Sensitivity limited by errors in $V_{ub}, f_B + \text{stats}$

CHARM:

In some cases, not even a rare decay

Not as sensitive to ‘favored’ new phenomena models

$\tau \nu$ and $\mu \nu$ accessible

Ratios provide clean test of models that don’t preserve lepton universality
Radiative (and neutral annihilation)

Sensitive to tree level neutral current phenomena or anything that fits in a loop or box

SM rate suppressed in all cases

SM calculations range from simple to impossible.

Completely different for different flavors
Rad and Neutral A: B, D, K

Radiative:

• Beauty
  – Precision: theory and exp.
• Strange
  – Precision theory, exp in reach
  – Lower SN rate = greater sensitivity
• Charm
  – Theory = long distance
  – Existing measurements beautiful but...

Neutral Annihilation:

Almost all NP param space limited by exp measurements
Better limit = better physics (!)
What is the SM telling us?

SM cares about flavor and charge. How can BSM not?

$$V_{CKM} = \begin{pmatrix} 0.97383^{+0.00024}_{-0.00023} & 0.2272^{+0.0010}_{-0.0010} & (3.96^{+0.09}_{-0.09}) \times 10^{-3} \\ 0.2271^{+0.0010}_{-0.0010} & 0.97296^{+0.00024}_{-0.00024} & (42.21^{+0.10}_{-0.80}) \times 10^{-3} \\ (8.14^{+0.32}_{-0.64}) \times 10^{-3} & (41.61^{+0.12}_{-0.78}) \times 10^{-3} & 0.999100^{+0.000034}_{-0.000004} \end{pmatrix}$$

$$V_{up quarks} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$V_{down quarks}$$

Neutral leptons

Up quarks

Down quarks

Mass (MeV/c^2)

Generation

SM cares about flavor and charge. How can BSM not?
**Different Environments**

- $e^+e^-$ at threshold
  - Average
  - $\sim 5$ tracks / evt

- $e^+e^-$ above threshold
  - Average
  - $\sim 10$ tracks / evt

- Tevatron
  - Average
  - $\sim 50$ tracks / int.
  - Up to 10 int/evt
Threshold: CLEO-c

- Very clean
- Beam constraints
- Double tags
- Now enough data for competitive rare decay studies
4S: Belle & BaBar

- Still pretty clean
- Excellent PID
- All charmed hadron species accessible
- Enormous data sets and still growing
Fixed Target: FOCUS

- Large boost, all species available. Dedicated experiment.
Energy Frontier: DØ & CDF

- Enormous cross-sections
- Large boost
- All species available
- Good dimuon triggers
- Lots of data and collecting much more
Some comparisons

\[ m(K\pi\mu) - m(K\pi) \]

\[ \sim 10^5 D^* \text{ semi/100fb}^{-1} \]

\[ \sim 10^6 D^* \text{ semi/fb}^{-1} \]

A ton of data at the Tevatron waiting for you!

\[ m(K\pi\pi) - m(K\pi) \]

\[ \sim 7k \text{ WS/fb}^{-1} \]

\[ \sim 1k \text{ WS/100fb}^{-1} \]
Charged Leptonic Decays

- **New this summer:** Belle $D_s \rightarrow \mu \nu$
  
  Covered in detail tomorrow by Laurenz Widhalm

$$B(D_s \rightarrow \mu \nu) = (6.44 \pm 0.76 \pm 0.52) \times 10^{-3}$$

- **My combination:** PDG’06, Belle, BaBar 07, Cleo-c 07:

$$B(D_s \rightarrow \mu \nu) = (6.25 \pm 0.49) \times 10^{-3}$$

- **Now measured to ~8%**
  
  ~37% error in $B \rightarrow \tau \nu$
NP LIMITS?

\[
\frac{\Gamma(D_s \to \tau\nu)}{\Gamma(D_s \to \mu\nu)} = \frac{m_\tau^2}{m_\mu^2} \times \left(\frac{m_{D_s}^2 - m_\tau^2}{m_{D_s}^2 - m_\mu^2}\right)^2
\]

**My Comb:** \(B(D_s \to \tau\nu) = (7.28 \pm 1.00)\%\)

**Exp/theory \(\tau\nu/\mu\nu:**
\[
R\left(\frac{\tau\nu}{\mu\nu}\right) = 0.73 \pm 0.12
\]

**Exp/theory \(B \to \tau\nu:**
\[
R(B \to \tau\nu) = 0.9 \pm 0.4
\]

**Exp/theory \(B \to D^*\tau\nu:**
Order(30%)}

**Precision looking for a theory**
Neutral Leptonic Decays

Normalize to, then veto $D^*$ tagged $\pi \pi$.

Fakes measured with $D^*$ tagged $K\pi > 7 \text{ k } \pi \pi$

$B(D \rightarrow \mu^+ \mu^-) < 2.5 \times 10^{-6}$

$B(D^0 \rightarrow e^+ e^-) < 1.2 \times 10^{-6}$
Neutral Leptonic Decays

Normalize to, then veto $D^*$ tagged $\pi\pi$.

Fakes measured with $D^*$ tagged $K\pi$ >7 k $\pi\pi$

Not background limited and based on ~10% of the data on tape ($D\bar{0}$, CDF, Belle, BaBar)

$B(D \to \mu^+ \mu^-) < 2.5 \times 10^{-6}$

$B(D^0 \to e^+ e^-) < 1.2 \times 10^{-6}$
**2-BODY RADIATIVE**

**Short distance**

\[ D^0 \left( \begin{array}{c} c \\ \bar{u} \end{array} \right) \rightarrow \phi \left( \begin{array}{c} s \\ \bar{s} \end{array} \right) \]

**Long distance**

\[ D^0 \left( \begin{array}{c} c \\ \bar{u} \end{array} \right) \rightarrow \phi \left( \begin{array}{c} s \\ \bar{s} \end{array} \right) \]

**Peaking backgrounds not measured so measure them first**

\[ B(D^0 \rightarrow \phi \gamma) = (2.60^{+0.70+0.15}_{-0.61-0.17}) \times 10^{-5} \]

**First radiative charm decay**

\[ D^0 \rightarrow \phi \gamma \]

78 fb⁻¹
2 vs 3 body radiative

Two processes: Long distance (strong scale), short distance (weak scale)

Clear separation of long distance and short distance components

Burdman et al.
hep-ph/0112235
**Focus**

1996-1997 Fixed Target Run Data

**Double Boot Strap**

**Grid**

Expected Limit

**Background Reduction**
Takes Advantage of Very Large Boost

**Good PID System to Separate Modes**

Lots of Effort into Getting Very Best Limit Out
Focus results

\[ B(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 8.8 \times 10^{-6} \]

\[ B(D^+_s \rightarrow K^+ \mu^+ \mu^-) < 36 \times 10^{-6} \]

Also several forbidden decay channel results in backup

Number to beat for B factories and Tevatron
Cleo-c

281 pb\(^{-1}\) at \(\psi(3770)\)

1.6 million \(D^{\pm}\)

Use beam kinematics

Double semileptonics removed with missing energy type vetos

Focus on the di-electron mode

\(~0.1\%\) fakes from peaking backgrounds

Absolute BF measurement

\(D^+ \rightarrow K^- \pi^+ \pi^+\) or \(D^- \rightarrow K^+ \pi^- \pi^-\),

15,120 events

\((57 \text{ pb}^{-1})\)
Cleo-c results

\[ m(e^+e^-) \]

\[
B(D^+ \to \pi^+\phi \to \pi^+e^+e^-) = (2.7^{+3.6}_{-1.8} \pm 0.2) \times 10^{-6}
\]

\[ B(D^+ \to \pi^+e^+e^-) < 7.4 \times 10^{-6} \]
288 fb$^{-1}$

Very similar to CLEO approach

Select continuum D’s to be able to make missing energy vetos

Expanded to include all hadron species and both di-electrons and di-muons
BaBar results

\[ B(D^+ \rightarrow \pi^+ e^+ e^-) < 11.2 \times 10^{-6} \]
\[ B(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 24.4 \times 10^{-6} \]

\[ B(D_s^+ \rightarrow K^+ e^+ e^-) < 11.2 \times 10^{-6} \]
\[ B(D_s^+ \rightarrow K^+ \mu^+ \mu^-) < 6.6 \times 10^{-6} \]

\[ B(\Lambda_c \rightarrow p e^+ e^-) < 3.6 \times 10^{-6} \]
\[ B(\Lambda_c \rightarrow p \mu^+ \mu^-) < 40.4 \times 10^{-6} \]
1.3 fb⁻¹, very similar to FOCUS approach.
1.3 fb⁻¹, very similar to FOCUS approach

Cant make missing energy veto like CLEO/BaBar
Don’t have particle ID like CLEO/BaBar/FOCUS
Outstanding muon system allows us to capitalize on enormous cross section with no punch through
$B(D^+ \to \pi^+ \phi \to \pi^+ \mu^+ \mu^-) = (1.8 \pm 0.5 \pm 0.6) \times 10^{-6}$

$B(D^+ \to \pi^+ \mu^+ \mu^-) < 3.9 \times 10^{-6}$

1.3 fb$^{-1}$ #s UPDATED FOR THIS CONFERENCE
Some comparisons: $\phi\pi$

Milestone I: All three have reached sensitivity to see $\phi\pi$ in the $ll\pi$ channel.
**Some Comparisons:** $ul^+l^-$

**Milestone II:** All three have set limits near $10^{-6}$ level using modes best suited for their experiment/environment.

$B(\Lambda_c \rightarrow pe^+e^-) < 3.6 \times 10^{-6}$

$B(D^+ \rightarrow \pi^+e^+e^-) < 7.4 \times 10^{-6}$

$B(D^+ \rightarrow \pi^+\mu^+\mu^-) < 3.9 \times 10^{-6}$
**Some Comparisons:** $u l^+ l^-$

**Milestone II:** All three have set limits near $10^{-6}$ level using modes best suited for their experiment/environment.

If we ever see something, diversity of channels will be crucial for interpretation.

- $B(\Lambda_c \rightarrow p e^+ e^-) < 3.6 \times 10^{-6}$
- $B(D^+ \rightarrow \pi^+ e^+ e^-) < 7.4 \times 10^{-6}$
- $B(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 3.9 \times 10^{-6}$
$10^{-6} \rightarrow 10^{-7}$ w/ $hl^+l^-$

- **BaBar**: fraction of data set, background limited
- **Belle**: whole data set
- **DØ**: fraction of data set but background limited
- **CDF**: whole data set
- **Enough data on tape to make significant progress and much more coming**
- **Knowing how to do things like combine $\Lambda_c$ and $D$ would be helpful**
- **Getting smarter about background suppression real key**
Conclusions

• **Not so rare**
  — Annihilation now at precision level

• **Rare charm from $10^{-5}$ to $10^{-6}$**
  — Very diverse set of results from 6 experiments at 4 energies
    • None specifically designed for rare charm
    • All basically done by one or two people

• **Rare charm at $10^{-7}$**
  — Data sets will exist
    • Large fraction already on tape
<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Sensitivity</th>
<th>F-C</th>
<th>R-L</th>
<th>R-L incl.</th>
<th>Single Cut incl. σᵣ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ \to K^+\mu^+\mu^-$</td>
<td>7.5</td>
<td>11</td>
<td>9.1</td>
<td>9.2</td>
<td>12</td>
</tr>
<tr>
<td>$D^+ \to K^-\mu^+\mu^+$</td>
<td>4.8</td>
<td>13</td>
<td>13</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>$D^+ \to \pi^+\mu^+\mu^-$</td>
<td>7.6</td>
<td>9.3</td>
<td>8.7</td>
<td>8.8</td>
<td>7.4</td>
</tr>
<tr>
<td>$D^+ \to \pi^-\mu^+\mu^+$</td>
<td>5.5</td>
<td>4.6</td>
<td>4.8</td>
<td>4.8</td>
<td>5.1</td>
</tr>
<tr>
<td>$D_s^+ \to K^+\mu^+\mu^-$</td>
<td>33</td>
<td>31</td>
<td>33</td>
<td>36</td>
<td>38</td>
</tr>
<tr>
<td>$D_s^+ \to K^-\mu^+\mu^+$</td>
<td>21</td>
<td>11</td>
<td>13</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>$D_s^+ \to \pi^+\mu^+\mu^-$</td>
<td>31</td>
<td>20</td>
<td>24</td>
<td>26</td>
<td>18</td>
</tr>
<tr>
<td>$D_s^+ \to \pi^-\mu^+\mu^+$</td>
<td>23</td>
<td>29</td>
<td>26</td>
<td>29</td>
<td>22</td>
</tr>
</tbody>
</table>
### BaBar full results

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Yield (events)</th>
<th>Efficiency (90% CL)</th>
<th>BR (10^{-4}) (90% CL)</th>
<th>BF (10^{-6}) (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^{+} \to \pi^{+}e^{+}e^{-}$</td>
<td>24.0^{+25.0}<em>{-24.1}^{+13.4}</em>{-5.1}</td>
<td>3.93%</td>
<td>&lt; 17.7</td>
<td>&lt; 11.2</td>
</tr>
<tr>
<td>$D^{+} \to \pi^{+}\mu^{+}\mu^{-}$</td>
<td>1.5^{+20.1}<em>{-19.3}^{+3.4}</em>{-2.6}</td>
<td>1.09%</td>
<td>&lt; 38.7</td>
<td>&lt; 24.4</td>
</tr>
<tr>
<td>$D^{+} \to \pi^{+}e^{+}\mu^{-}$</td>
<td>4.1^{+17.8}<em>{-16.3}^{+3.1}</em>{-2.1}</td>
<td>2.27%</td>
<td>&lt; 17.1</td>
<td>&lt; 10.8</td>
</tr>
<tr>
<td>$D^{+} \to \pi^{+}e^{+}e^{-}$</td>
<td>-12.1^{+15.5}<em>{-14.8}^{+3.2}</em>{-0.0}</td>
<td>2.29%</td>
<td>&lt; 9.3</td>
<td>&lt; 5.9</td>
</tr>
<tr>
<td>$D_{s}^{+} \to \pi^{+}e^{+}e^{-}$</td>
<td>-1.7^{+5.3}_{-1.6}^{+0.2}</td>
<td>1.14%</td>
<td>&lt; 2.1</td>
<td>&lt; 7.6</td>
</tr>
<tr>
<td>$D_{s}^{+} \to \pi^{+}\mu^{+}\mu^{-}$</td>
<td>-9.4^{+5.0}<em>{-4.4}^{+10.2}</em>{-1.4}</td>
<td>0.31%</td>
<td>&lt; 5.1</td>
<td>&lt; 18.5</td>
</tr>
<tr>
<td>$D_{s}^{+} \to \pi^{+}e^{+}\mu^{-}$</td>
<td>4.8^{+4.7}<em>{-3.9}^{+10.8}</em>{-0.3}</td>
<td>0.66%</td>
<td>&lt; 6.2</td>
<td>&lt; 22.3</td>
</tr>
<tr>
<td>$D_{s}^{+} \to \pi^{+}\mu^{+}\mu^{-}$</td>
<td>0.5^{+4.0}<em>{-3.3}^{+11.0}</em>{-0.1}</td>
<td>0.65%</td>
<td>&lt; 3.8</td>
<td>&lt; 13.9</td>
</tr>
<tr>
<td>$D^{+} \to K^{+}e^{+}e^{-}$</td>
<td>5.9^{+8.9}<em>{-7.8}^{+13.8}</em>{-0.3}</td>
<td>3.21%</td>
<td>&lt; 8.2</td>
<td>&lt; 5.2</td>
</tr>
<tr>
<td>$D^{+} \to K^{+}\mu^{+}\mu^{-}$</td>
<td>2.9^{+8.0}<em>{-7.0}^{+10.2}</em>{-3.7}</td>
<td>0.75%</td>
<td>&lt; 22.2</td>
<td>&lt; 14.0</td>
</tr>
<tr>
<td>$D^{+} \to K^{+}e^{+}\mu^{-}$</td>
<td>-3.4^{+6.5}<em>{-5.6}^{+11.0}</em>{-0.1}</td>
<td>1.64%</td>
<td>&lt; 5.7</td>
<td>&lt; 3.6</td>
</tr>
<tr>
<td>$D^{+} \to K^{+}\mu^{+}\mu^{-}$</td>
<td>-4.4^{+7.1}<em>{-6.1}^{+11.4}</em>{-3.0}</td>
<td>1.64%</td>
<td>&lt; 5.9</td>
<td>&lt; 3.7</td>
</tr>
<tr>
<td>$D_{s}^{+} \to K^{+}e^{+}e^{-}$</td>
<td>-3.8^{+6.2}<em>{-5.3}^{+11.5}</em>{-1.3}</td>
<td>2.81%</td>
<td>&lt; 1.8</td>
<td>&lt; 6.6</td>
</tr>
<tr>
<td>$D_{s}^{+} \to K^{+}\mu^{+}\mu^{-}$</td>
<td>5.0^{+6.5}<em>{-6.1}^{+10.1}</em>{-0.3}</td>
<td>0.68%</td>
<td>&lt; 7.1</td>
<td>&lt; 25.4</td>
</tr>
<tr>
<td>$D_{s}^{+} \to K^{+}e^{+}\mu^{-}$</td>
<td>-3.7^{+5.1}<em>{-4.4}^{+11.4}</em>{-1.4}</td>
<td>1.40%</td>
<td>&lt; 1.5</td>
<td>&lt; 5.6</td>
</tr>
<tr>
<td>$D_{s}^{+} \to K^{+}\mu^{+}\mu^{-}$</td>
<td>-6.5^{+4.9}<em>{-4.3}^{+10.2}</em>{-1.1}</td>
<td>1.40%</td>
<td>&lt; 1.0</td>
<td>&lt; 3.6</td>
</tr>
<tr>
<td>$A_{e}^{+} \to pe^{+}e^{-}$</td>
<td>0.9^{+4.1}<em>{-3.4}^{+10.4}</em>{-0.1}</td>
<td>4.11%</td>
<td>&lt; 0.7</td>
<td>&lt; 3.6</td>
</tr>
<tr>
<td>$A_{e}^{+} \to pu^{+}\mu^{-}$</td>
<td>6.9^{+4.7}<em>{-3.7}^{+10.3}</em>{-0.6}</td>
<td>0.67%</td>
<td>&lt; 8.1</td>
<td>&lt; 40.4</td>
</tr>
<tr>
<td>$A_{e}^{+} \to pe^{+}\mu^{-}$</td>
<td>0.2^{+2.9}<em>{-2.0}^{+5.0}</em>{-0.5}</td>
<td>1.19%</td>
<td>&lt; 1.8</td>
<td>&lt; 8.9</td>
</tr>
<tr>
<td>$A_{e}^{+} \to pu^{+}\mu^{-}$</td>
<td>-0.2^{+2.5}<em>{-1.7}^{+5.0}</em>{-0.6}</td>
<td>1.18%</td>
<td>&lt; 1.5</td>
<td>&lt; 7.5</td>
</tr>
</tbody>
</table>

| $N_{bg}$  | 0.02 | 3.34 ± 0.31 | 0.21 |
| $N_{comb}$ | 2.21 ± 0.38 | 1.28 ± 0.32 | 1.93 ± 0.36 |
| $N_{bg}$  | 2.23 ± 0.38 | 4.63 ± 0.45 | 2.14 ± 0.36 |
| $S$ [10^{-7}] | 2.25 ± 0.12 | 4.53 ± 0.30 | 3.27 ± 0.20 |
| $N_{obs}$ | 3    | 1           | 0   |
| UL obtained | $1.2 \times 10^{-6}$ | $1.3 \times 10^{-6}$ | $8.1 \times 10^{-7}$ |
### CLEO Full Results

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\epsilon$ (%)</th>
<th>$N$</th>
<th>$n$</th>
<th>$\sigma_{syst}$ (%)</th>
<th>$B$ ($10^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+e^+e^-$</td>
<td>36.41</td>
<td>1.99</td>
<td>2</td>
<td>8.7</td>
<td>$&lt; 7.4$</td>
</tr>
<tr>
<td>$\pi^-e^+e^+$</td>
<td>43.85</td>
<td>0.48</td>
<td>0</td>
<td>7.1</td>
<td>$&lt; 3.6$</td>
</tr>
<tr>
<td>$K^+e^+e^-$</td>
<td>26.18</td>
<td>1.47</td>
<td>0</td>
<td>10.0</td>
<td>$&lt; 6.2$</td>
</tr>
<tr>
<td>$K^-e^+e^+$</td>
<td>35.44</td>
<td>0.50</td>
<td>0</td>
<td>7.2</td>
<td>$&lt; 4.5$</td>
</tr>
<tr>
<td>$\pi^+\phi(e^+e^-)$</td>
<td>46.22</td>
<td>0.04</td>
<td>2</td>
<td>7.4</td>
<td>$2.7^{+3.6}_{-1.8} \pm 0.2$</td>
</tr>
</tbody>
</table>