CLEO-c Measurements of Purely Leptonic Decays of Charmed Mesons & other Wonders

Sheldon Stone, Syracuse University
Leptonic Decays: $D \to \ell^+ \nu$

Introduction: Pseudoscalar decay constants $c$ and $\bar{q}$ can annihilate, probability is $\propto$ to wave function overlap.

Example:

In general for all pseudoscalars:

$$\Gamma(P^+ \to \ell^+ \nu) = \frac{1}{8\pi} G_F^2 f_P^2 m_\ell M_P \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2 |V_{Qq}|^2$$

Calculate, or measure if $V_{Qq}$ is known.
New Physics Possibilities

- Besides the obvious interest in comparing with Lattice & other calculations of $f_P$ there are NP possibilities
- Another Gauge Boson could mediate decay
- Or leptoquarks (see Kronfeld’s talk)
- Ratio of leptonic decays could be modified e.g. in Standard Model

$$\frac{\Gamma(P^+ \rightarrow \tau^+ \nu)}{\Gamma(P^+ \rightarrow \mu^+ \nu)} = m^2_\tau \left(1 - \frac{m^2_\tau}{M^2_P}\right)^2 / m^2_\mu \left(1 - \frac{m^2_\mu}{M^2_P}\right)^2$$

- If $H^\pm$ couples to $M^2 \Rightarrow$ no effect

New Physics Possibilities II

- Leptonic decay rate is modified by $H^\pm$
- Can calculate in SUSY as function of $m_q/m_c$,
- In 2HDM predicted decay width is $x$ by

$$r_q = \left[ 1 - M_D^2 \left( \frac{\tan \beta}{M_{H^\pm}} \right)^2 \left( \frac{m_q}{m_c + m_q} \right) \right]^2$$

- Since $m_d$ is $\sim 0$, effect can be seen only in $D_S$

See Akeryod [hep-ph/0308260]
Experimental methods

- $D\bar{D}$ production at threshold: used by Mark III, and more recently by CLEO-c and BES-II.
  - Unique event properties
    - Only $\bar{D}D$ not $\bar{D}Dx$ produced
  - Large cross sections:
    - $\sigma(D^0\bar{D}^0) = 3.72\pm0.09$ nb
    - $\sigma(D^+D^-) = 2.82\pm0.09$ nb
    - $\sigma(D_sD_s^*) = \sim0.9$ nb
    - Continuum $\sim$12 nb
  - Ease of $B$ measurements using "double tags"
    - $B_A = \# \text{ of } A/\# \text{ of } D's$
Technique for $D^+ \to \mu^+\nu$

- Fully reconstruct a $D^-$, and count total # of tags
- Seek events with only one additional oppositely charged track and no additional photons > 250 MeV (to veto $D^+ \to \pi^+\pi^0$)
- Charged track must deposit only minimum ionization in calorimeter (< 300 MeV case 1)
- Compute $MM^2$. If close to zero then almost certainly we have a $\mu^+\nu$ decay.

$$MM^2 = (E_{D^+} - E_{\ell^+})^2 - (\vec{p}_{D^+} - \vec{p}_{\ell^+})^2$$

We know $E_{D^+} = E_{beam}$, $\vec{p}_{D^+} = - \vec{p}_{D^-}$.
D\textsuperscript{-} Candidates (in 281 pb\(^{-1}\))

# of tags = 158,354±496, includes charge-conjugate modes
The Missing Mass Squared

To find signal events, we compute

$$MM^2 = (E_{CM} - E_D - E_\mu)^2 - (\vec{p}_D - \vec{p}_\mu)^2$$

Monte Carlo Signal $\mu\nu$

Monte Carlo Signal $\tau\nu$, $\tau \rightarrow \pi\nu$
Measurement of $f_{D^+}$

### Backgrounds

<table>
<thead>
<tr>
<th>Mode</th>
<th># Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^0$</td>
<td>$1.40\pm0.18\pm0.22$</td>
</tr>
<tr>
<td>$K^0\pi^+$</td>
<td>$0.33\pm0.19\pm0.02$</td>
</tr>
<tr>
<td>$\tau^+\nu$ ($\tau\to\pi^+\nu$)</td>
<td>$1.08\pm0.15\pm0.16$</td>
</tr>
<tr>
<td>Other $D^+$, $D^0$</td>
<td>&lt;0.4, &lt;0.4 @ 90% c.l.</td>
</tr>
<tr>
<td>Continuum</td>
<td>&lt;1.2 @ 90% c.l.</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$2.81\pm0.30^{+0.84}_{-0.27}$</td>
</tr>
</tbody>
</table>

- $\mathcal{B}(D^+ \rightarrow \mu^+\nu) = (4.40\pm0.66^{+0.09}_{-0.12}) \times 10^{-4}$
- $f_{D^+} = (222.6\pm16.7^{+2.3}_{-3.4})$ MeV
  \[|V_{cd}| = 0.2238\]
- $\mathcal{B}(D^+ \rightarrow e^+\nu) < 2.4 \times 10^{-5}$
  @ 90% c.l.

Data: 50 events in the signal region in 281 pb$^{-1}$
## Systematic Errors

<table>
<thead>
<tr>
<th>Source of Error</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finding the $\mu^+$ track</td>
<td>0.7</td>
</tr>
<tr>
<td>Minimum ionization of $\mu^+$ in EM cal</td>
<td>1.0</td>
</tr>
<tr>
<td>Particle identification of $\mu^+$</td>
<td>1.0</td>
</tr>
<tr>
<td>MM$^2$ width</td>
<td>1.0</td>
</tr>
<tr>
<td>Extra showers in event &gt; 250 MeV</td>
<td>0.5</td>
</tr>
<tr>
<td>Background</td>
<td>0.6</td>
</tr>
<tr>
<td>Number of single tag $D^+$</td>
<td>0.6</td>
</tr>
<tr>
<td>Monte Carlo statistics</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.1</strong></td>
</tr>
</tbody>
</table>
Upper limit on $D^+ \rightarrow \tau^+ \nu$

- By using intermediate MM$^2$ region
- $\mathcal{B}(D^+ \rightarrow \tau^+ \nu) < 2.1 \times 10^{-3}$
- $\frac{\Gamma(D^+ \rightarrow \tau^+ \nu)}{\Gamma(D^+ \rightarrow \mu^+ \nu)} < 1.8 \times (2.65)$
- where 2.65 is SM expectation
- both at 90% c.l

Ecal $< 300$ MeV

Ecal $> 300$ MeV
Measurements of $f_{D_s}$

- Two separate techniques. [Here expect in SM: $\Gamma(D_S \rightarrow \tau^+\nu)/\Gamma(D_S \rightarrow \mu^+\nu) = 9.72$]
  - (1) Measure $D_S^+ \rightarrow \mu^+\nu$ along with $D_S \rightarrow \tau^+\nu$, $\tau \rightarrow \pi^+\nu$. This requires finding a $D_S^-$ tag, a $\gamma$ from either $D_S^- \rightarrow \gamma D_S^-$ or $D_S^{*-} \rightarrow \gamma \mu^+\nu$. Then find the muon or pion & apply kinematical constraints (mass & energy) to resolve this ambiguity & improve resolution (use 314 pb$^{-1}$, results are published)
  - (2) Find $D_S^+ \rightarrow \tau^+\nu$, $\tau \rightarrow e^+\nu\nu$ opposite a $D_S^-$ tag (use 298 pb$^{-1}$, results are final arXiv:0712.1175)

OCD & High Energy Hadronic Interactions, Moriond, March 8 – 15, 2008
Invariant masses

- $D_s$ studies done at $E_{cm}=4170$ MeV
- To choose tag candidates:
  - Fit distributions & determine $\sigma$
  - Cut at $\pm2.5\sigma$
- Define sidebands to measure backgrounds 5-7.5 $\sigma$
- Total # of Tags
  \[ = 31,302\pm 472 \text{ (stat)} \]
Tag Sample using $\gamma$

- First we define the tag sample by computing the $\text{MM}^*^2$ off of the $\gamma$ & $D_S$ tag:
  $$\text{MM}^*^2 = (E_{CM} - E_{D_s} - E_{\gamma})^2 - \left(\vec{p}_{D_s} - \vec{p}_{\gamma}\right)^2$$

- Total of 11880±399±504 tags, after the selection on $\text{MM}^*^2$. 
The MM$^2$

To find the signal events, we compute

$$\text{MM}^2 = (E_{\text{CM}} - E_{D_S} - E_{\gamma} - E_{\mu})^2 - (\vec{p}_{D_S} - \vec{p}_{\gamma} - \vec{p}_{\mu})^2$$

Monte Carlo Signal $\mu\nu$

Monte Carlo Signal $\tau\nu$, $\tau \rightarrow \pi\nu$
**MM^2 In Data**

- Clear $D_s^+ \rightarrow \mu^+\nu$ signal for case (i)
- Most events $<0.2$ GeV^2 are $D_s \rightarrow \tau^+\nu$, $\tau \rightarrow \pi^+\nu$ in cases (i) & (ii)
- No $D_s \rightarrow e^+\nu$ seen, case (iii)

![Graph showing MM^2 distribution with 92 events < 0.3 GeV in CC, 31 events > 0.3 GeV in CC, and 25 events in Electron Sample.](image)

Electron Sample
Branching Ratio & Decay Constant

- $D_S^+ \rightarrow \mu^+ \nu$
  - 92 signal events, 3.5 background, use SM to calculate $\tau \nu$ yield near 0 MM$^2$ based on known $\tau \nu/\mu \nu$ ratio
  - $B(D_S^+ \rightarrow \mu^+ \nu) = (0.597 \pm 0.067 \pm 0.039)\%$

- $D_S^+ \rightarrow \tau^+ \nu$, $\tau^+ \rightarrow \pi^+ \nu$
  - Sum case (i) $0.2 > \text{MM}^2 > 0.05 \text{GeV}^2$ & case (ii) $\text{MM}^2 < 0.2 \text{GeV}^2$. Total of 56 signal and 8.6 bkgrnd
  - $B(D_S^+ \rightarrow \tau^+ \nu) = (8.0 \pm 1.3 \pm 0.4)\%$

- By summing both cases above, find $B_{\text{eff}}(D_S^+ \rightarrow \mu^+ \nu) = (0.638 \pm 0.059 \pm 0.033)\%$
  - $f_{D_S} = 274 \pm 13 \pm 7 \text{ MeV}$, for $|V_{cs}| = 0.9737$
  - $B(D_S^+ \rightarrow e^+ \nu) < 1.3 \times 10^{-4}$
\[ \mathcal{B}(D_{S}^{+} \rightarrow \mu^{+}\nu) \] Systematic errors

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Size (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track finding</td>
<td>0.7</td>
</tr>
<tr>
<td>Photon veto</td>
<td>1</td>
</tr>
<tr>
<td>Minimum ionization</td>
<td>1</td>
</tr>
<tr>
<td>Number of tags</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>5.2</td>
</tr>
</tbody>
</table>
Measuring $D_s^+ \rightarrow \tau^+ \nu$, $\tau^+ \rightarrow e^+ \nu \nu$

- $B(D_s^+ \rightarrow \tau^+ \nu) \cdot B(\tau^+ \rightarrow e^+ \nu \nu) \sim 1.3\%$ is "large" compared with expected $B(D_s^+ \rightarrow X e^+ \nu) \sim 8\%$

- We will be searching for events opposite a tag with one electron and not much other energy

![Graphs showing $D_s^- \rightarrow \phi \pi^-$, $D_s^- \rightarrow K^- K^{*0}$, and $D_s^- \rightarrow K^- K_S^0$.](image-url)
Measuring $D_S^+ \rightarrow \tau^+ \nu$, $\tau^+ \rightarrow e^+ \nu \nu$

- Technique is to find events with an $e^+$ opposite $D_S^-$ tags & no other tracks, with $\Sigma$ calorimeter energy $< 400$ MeV
- No need to find $\gamma$ from $D_S^*$
- $B(D_S^+ \rightarrow \tau^+ \nu) = (6.17 \pm 0.71 \pm 0.36)\%$
- $f_{Ds} = 273 \pm 16 \pm 8$ MeV
\[ f_{D_s} & \quad f_{D_s}/f_{D^+} \]

- **Weighted Average**: \( f_{D_s} = 274 \pm 10 \pm 5 \) MeV, the systematic error is mostly uncorrelated between the measurements

- **Using**
  \[ f_{D^+} = (222.6 \pm 16.7^{+2.3}_{-3.4}) \text{ MeV} \]


- \( f_{D_s}/f_{D^+} = 1.23 \pm 0.10 \pm 0.03 \)

- \( \Gamma(D_S^+ \rightarrow \tau^+ \nu)/\Gamma(D_S^+ \rightarrow \mu^+ \nu) = 11.0 \pm 1.4 \pm 0.6 \), SM = 9.72, consistent with lepton universality

- Radiative corrections i.e. \( D_S^+ \rightarrow \mu^+ \nu \gamma \) not included, estimated to be \( \sim 1\% \) (see Burdman et al., PRD 51, 11 (1995))
### Comparison with Other Experiments

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Mode</th>
<th>$B_{\phi \pi}$ (%)</th>
<th>$f_{D^+_s}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO-c [8]</td>
<td>$\mu^+\nu$</td>
<td></td>
<td>264 ± 15 ± 7</td>
</tr>
<tr>
<td>CLEO-c [8]</td>
<td>$\tau^+\nu$</td>
<td></td>
<td>310 ± 25 ± 8</td>
</tr>
<tr>
<td>CLEO-c [9]</td>
<td>$\tau^+\nu$</td>
<td></td>
<td>273 ± 16 ± 8</td>
</tr>
<tr>
<td>CLEO-c</td>
<td>combi</td>
<td></td>
<td>274 ± 10 ± 5</td>
</tr>
<tr>
<td>Belle [10]</td>
<td>$\mu^+\nu$</td>
<td>preliminary Manchester EPS</td>
<td>275 ± 16 ± 12</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td><strong>274 ± 10</strong></td>
</tr>
<tr>
<td>CLEO [11]</td>
<td>$\mu^+\nu$</td>
<td>3.6±0.9</td>
<td>273 ± 19 ± 27 ± 33</td>
</tr>
<tr>
<td>BEATRICE [12]</td>
<td>$\mu^+\nu$</td>
<td>3.6±0.9</td>
<td>312 ± 43 ± 12 ± 39</td>
</tr>
<tr>
<td>ALEPH [13]</td>
<td>$\mu^+\nu$</td>
<td>3.6±0.9</td>
<td>282 ± 19 ± 40</td>
</tr>
<tr>
<td>ALEPH [13]</td>
<td>$\tau^+\nu$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L3 [14]</td>
<td>$\tau^+\nu$</td>
<td></td>
<td>299 ± 57 ± 32 ± 37</td>
</tr>
<tr>
<td>OPAL [15]</td>
<td>$\tau^+\nu$</td>
<td></td>
<td>283 ± 44 ± 41</td>
</tr>
<tr>
<td>BaBar [16]</td>
<td>$\mu^+\nu$</td>
<td>4.71±0.46</td>
<td>283 ± 17 ± 7 ± 14</td>
</tr>
</tbody>
</table>

- CLEO-c is most precise result to date for both $f_{D_s}$ & $f_{D^+}$
Comparisons with Theory

- We are ~3σ above Follana et al. Either:
  - Calculation is wrong
  - There is new physics that interferes constructively with SM
  - Note: No value of $M_H$ is allowed in 2HDM at 99.5% c.l.

- Comparing measured $f_{D_S}/f_{D^+}$ with Follana prediction we find $m_H>2.2\text{ GeV}\tan\beta$

- Using Follana ratio find $|V_{cd}/V_{cs}|=0.217\pm0.019$(exp) ±0.002(theory)
Projections

- We will almost triple the $D^+$ sample, including some improvements in technique, error in $f_{D^+}$ should decrease to ~9 MeV
- We doubled the $D_s$ sample, improved the technique, expect error in $f_{D_s}$ to decrease to ~7 MeV
Discover of $D_s^+ \rightarrow p\bar{n}$

- Use same technique as for $\mu^+\nu$, but plot MM from a detected proton
- No background
- First example of a charm meson decaying into baryons

$$B(D_s^+ \rightarrow p\bar{n}) = (1.30 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$$
Semileptonic Decays

- Precise $\mathcal{B}(D^0 \rightarrow K^- e^+ \nu)$ & $\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu)$

![Graphs showing $\mathcal{B}(D^0 \rightarrow K^- e^+ \nu)$ and $\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu)$]
Form Factors: $D^0 \rightarrow K^- e^+ \nu$

$$f_+(q^2) = \frac{f_+(0)}{(1-q^2/m_{pole}^2)(1-\alpha q^2/m_{pole}^2)}$$

Assuming $V_{cs} = 0.9745$
$D^0 \rightarrow \pi^- e^+ \nu$
SYMPOSIUM
CELEBRATING
CLEO & CESR

GREETINGS FROM CESR

For information and to register, visit: www.lepp.cornell.edu/Events/CLEOCESRSym/

Friday, May 30, 2008
Reception, Clark Hall

Saturday, May 31, 2008
Symposium, Cornell University
Ithaca, New York, USA

Invited Talks, Clark Hall
Dinner, Statler Hotel

MILESTONES

CESR

1975 CESR proposal
1977 RF funding approved
1979 First circulating beam
1981 First muon collision
1981-83 Early beam-focusing at interaction region
1984 Multiple beams in booster rings
1989 Development of 10" Booster rings
1994 Cycling upgrade and luminosity increase
1999 Supercollider gift certificate
2003-04 CESR upgrades, improvements

CLEO

1975 "South Area Experiment" group forms CLEO
1979 First data collected
1981 B meson discovered
1986 CESR electron vs. DC calorimeter installed
1989 K+ → φπ0 discovered
1991 K+ → γγγγ (four photons) discovered
1995 CLEO/C with silicon vertex detector installed
1999 CLEO II with liquid xenon detector
2003 CLEO III with detector upgrade
2004 K+ mesons
2005 D mesons
2007 D meson decay constant measured
2007 CLEO IV paper published
The End
Check: $\mathcal{B}(D_s^+ \rightarrow K^+ K^0)$

- Do almost the same analysis but consider $M M^2$ off of an identified $K^+$
- Allow extra charged tracks and showers so not to veto $K^0$ decays or interactions in EM
- Signal verifies expected $M M^2$ resolution
- Find $(2.90 \pm 0.19 \pm 0.18)\%$, compared with result from double tags $(3.00 \pm 0.19 \pm 0.10)\%$
Since $e^+e^- \rightarrow D_S^*D_S$, the $D_S$ from the $D_S^*$ will be smeared in beam-constrained mass.

\[ M_{BC}^2 = E_{\text{beam}}^2 - \sum_i \vec{p}_i^2 \]

\[ \therefore \text{cut on } M_{BC} \text{ & plot invariant mass (equivalent to a } p \text{ cut)} \]

We use 314 pb\(^{-1}\) of data
Measurement of $D_s^+ \rightarrow \mu^+ \nu$

- In this analysis we use $D_s^* D_s$ events where we detect the $\gamma$ from the $D_s^* \rightarrow \gamma D_s$ decay.
- We see all the particles from $e^+ e^- \rightarrow D_s^* D_s, \gamma, D_s$ (tag) $+ \mu^+$ except for the $\nu$.
- We use a kinematic fit to (a) improve the resolution & (b) remove ambiguities.
  - Constraints include: total $p$ & $E$, tag $D_s$ mass, $\Delta m = M(\gamma D_s) - M(D_s)$ (or $\Delta m = M(\gamma \mu \nu) - M(\mu \nu)$) = 143.6 MeV, $E$ of $D_s$ (or $D_s^*$) fixed.
  - Lowest $\chi^2$ solution in each event is kept.
  - No $\chi^2$ cut is applied.
Combining Semileptonics & Leptonics

Semileptonic decay rate into Pseudoscalar:

\[
\frac{d\Gamma(D \rightarrow Pe\nu)}{dq^2} = \frac{|V_{cq}|^2 P_P^3}{24\pi^3} \left| f_+(q^2) \right|^2
\]

Note that the ratio below depends only on QCD:

\[
\frac{1}{\Gamma(D^+ \rightarrow \ell\nu)} \frac{d\Gamma(D^+ \rightarrow \pi e\nu)}{dq^2} \propto \frac{P_P^3 \left| f_+(q^2) \right|^2}{f_{D^+}^2}
\]
Background Samples

- Two sources of background
  - A) Backgrounds under invariant mass peaks – Use sidebands to estimate
  - In $\mu^+\nu$ signal region $3.5$ background ($92$ total)
  - $bkgrnd \text{ MM}^2<0.20 \text{ GeV}^2=9.0\pm2.3$
  - B) Backgrounds from real $D_S$ decays, e.g. $\pi^+\pi^0\pi^0$, or $D_S \rightarrow \tau^+\nu$, $\tau \rightarrow \pi^+\pi^0\nu.... < 0.2 \text{ GeV}^2$, none in $\mu\nu$ signal region
  - $B(D_S \rightarrow \pi^+\pi^0) < 1.1\times10^{-3}$ & $\gamma$ energy cut yields $<0.2$ evts
As we will see, there is very little background present in any sub-sample for $MM^2 < 0.2$ GeV$^2$

Sum of $D_{s}^{+} \rightarrow \mu^{+}\nu + \tau^{+}\nu$, $\tau \rightarrow \pi^{+}\nu$

Sum of case (i) & case (ii)

$\mu\nu + \tau\nu$ signal line shape

148 events

$K^{0}\pi^{+}$
Radiative Corrections

- Not just final state radiation which is already corrected for.
- Includes $D \rightarrow D^* \rightarrow \gamma D \rightarrow \gamma \mu^+ \nu$. Based on calculations of Burdman et al.
- $\frac{\Gamma(D_{(S)}^+ \rightarrow \gamma \mu^+ \nu)}{\Gamma(D_{(S)}^+ \rightarrow \mu^+ \nu)} \sim 1/40 - 1/100$
  - Burdman et al. $\sim 1\%$
- Using narrow MM$^2$ region makes this much smaller