CLEO Results on Charm Leptonic & Semileptonic Decays

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Why Study These Decays?

- They are the simplest decays, depend on $f \cdot V_{cq}$ in both cases; for leptonics $f$ is decay constant, for semileptonics $f(q^2)$, for charm $V_{cs}$ & $V_{cd}$ are “known”
- Can also learn about the final state hadron
**Toolkit**

- **Use e⁺e⁻→D̅D**
  - Fully reconstruct one D, the tag
  - For D→Xe⁺ν, positively id the e⁺
  - For D→μ⁺ν, make sure μ⁺ doesn’t interact in EM cal
  - For D→τ⁺ν, also use extra energy, E_{extra}, deposited in EM cal, that is not matched with the tag or final state decay products of the τ⁺, either e⁺νν, π⁺ν, or ρ⁺ν

Moriond QCD, 2010
**Toolkit: Missing Mass Squared**

\[ MM^2 = (E_{D^+} - E_{\ell^+} - E_{\text{hadron}})^2 - (\vec{p}_{D^+} - \vec{p}_{\ell^+} - \vec{p}_{\text{hadron}})^2 \]

- We know \( E_{D^+} = E_{\text{beam}} \), \( \vec{p}_{D^+} = -\vec{p}_{D^-} \)
- If close to zero then almost certainly we have a missing \( \nu \).

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**Monte Carlo Signal \( \mu \nu \)**

**Monte Carlo Signal \( \tau \nu, \tau \rightarrow \pi \nu \)**
Leptonic Decays

In general for all pseudoscalars:

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

Calculate, or measure if \( V_{Qq} \) is known, here take \( V_{cd} = V_{us} = 0.2256 \), 
\( V_{cs} = V_{ud} - V_{cb}/4 = 0.9734 \)
Reasons to Measure

- Lattice calculations needed for all sorts of heavy flavor parameters, e.g. $\xi=f_B/f_{Bs}$, $B \rightarrow \pi \ell \nu$ form-factors... $f_D$ & $f_{Ds}/f_D$ provide an experimental check.

- Possibilities to see effects of New Physics
  - Interference with $H^+$.
  - Rate ratio
    \[
    \frac{\Gamma(P^+ \rightarrow \tau^+ \nu)}{\Gamma(P^+ \rightarrow \mu^+ \nu)} = m_\tau^2 \left(1 - \frac{m_\tau^2}{M_P^2}\right)^2 / m_\mu^2 \left(1 - \frac{m_\mu^2}{M_P^2}\right)^2
    \]
    is sensitive to neutrino couplings, e.g. a sterile neutrino coupling differently to $\nu_\mu$ & $\nu_\tau$, or any model which doesn’t couple as $m_\ell^2$, e.g. Leptoquarks.
Experimental Considerations

- In principle have access to 6 decays:
  \[ D^+ \rightarrow e^+\nu, \mu^+\nu, \tau^+\nu \]
  \[ D_s^+ \rightarrow e^+\nu, \mu^+\nu, \tau^+\nu \]

- Helicity suppression causes \( e^+\nu \) mode to be highly suppressed.

- \( D \rightarrow \tau^+\nu \) has at 2 neutrinos missing, so is more difficult to detect.

- Only \( B^+ \) available, not \( B^0 \) or \( B_S \) & \( \mathcal{B} \) is low.

Moriond QCD, 2010
D- Tags

• Total of 460,000
• Background 89,400
$D^+ \rightarrow \mu^+ \nu$

- Require $E_{\text{cal}} < 300$ MeV for candidate; no extra $\gamma > 250$ MeV
- $\tau^+ \nu / \mu^+ \nu$ is **fixed** to SM ratio
  - $149.7 \pm 12.0$ $\mu\nu$
  - $28.5$ $\tau\nu$
- $\tau^+ \nu / \mu^+ \nu$ is allowed to float
  - $153.9 \pm 13.5$ $\mu\nu$
  - $13.5 \pm 15.3$ $\tau\nu$
Branching Fractions & $f_{D^+}$

- **Fix $\tau \nu/\mu \nu$ at SM ratio of 2.65**
  - $\mathcal{B}(D^+\rightarrow\mu^+\nu)= (3.82\pm0.32\pm0.09)x10^{-4}$
  - $f_{D^+}=(205.8\pm8.5\pm2.5) \text{ MeV}$
  - This is best number in context of SM

- **Float $\tau \nu/\mu \nu$**
  - $\mathcal{B}(D^+\rightarrow\mu^+\nu)= (3.93\pm0.35\pm0.10)x10^{-4}$
  - $f_{D^+}=(207.6\pm9.3\pm2.5) \text{ MeV}$
  - This is best number for use with Non-SM models

- These are final numbers with 818 pb$^{-1}$
- This is the only measurement
$D_S^-$ Tags: Invariant Mass

- $K^+K^ {-}\pi^-$
- $K_SK^-$
- $\eta'\pi^-$
- $\eta'\rightarrow\pi^-\pi^+\eta$
- $K^+K^-\pi^-\pi^0$
- $\eta'\rho^-$
- $\eta'\pi^-$
- $\eta'\rightarrow\rho\gamma$

Events / (0.002 GeV)

$M(D_S)$ (GeV)
MM*2 Distributions From $D_s^{-} + \gamma$

e$^+e^-\rightarrow D_s D_s^{*}$

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

$K_S K^-$

$\eta\pi^-$

$\eta'\pi^-$

$\eta'\rightarrow\pi^-\pi^+\eta$

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

$\pi^-\pi^-\pi^+$

$K^{*0}K^*$

$\eta'\rho^-$

$\eta'\rightarrow\rho\gamma$
$D_s \rightarrow \mu^+\nu$ Fit to signal & background

$\frac{\text{Events}}{0.02 \text{ GeV}^2}$

$\mu^+\nu$

$\tau\nu, \tau \rightarrow \pi\nu$

Background

$D_s$ sidebands

Extra $\gamma$

background

$f_{D_s} = (257.6 \pm 10.3 \pm 4.3) \text{ MeV}$
Because of the two neutrinos, the signal does not peak in MM$^2$, but the most important backgrounds do.

Use $E_{\text{extra}}$ as an important discriminant.
Analysis Strategy

- Signal and MC predicted backgrounds

- Measure the $\mathcal{B}$ of the 3 indicated peaking modes. Use same set of $D_S^-$ tags. Find:

$$\mathcal{B}(D_s^+ \rightarrow K^0\pi^+\pi^0) = (1.00 \pm 0.18 \pm 0.04)\%,$$

$$\mathcal{B}(D_s^+ \rightarrow \pi^+\pi^0\pi^0) = (0.65 \pm 0.13 \pm 0.03)\%,$$

$$\mathcal{B}(D_s^+ \rightarrow \eta\rho^+) = (8.9 \pm 0.6 \pm 0.5)\%.$$
Analysis Strategy Continued

- We will fit simultaneously the invariant tag mass & the MM² distributions, separately in three $E_{\text{extra}}$ intervals, $<0.1$ GeV where signal dominates, $(0.1, 0.2)$ GeV where S & B are equivalent, and $>0.8$ GeV for checking of understanding background, where signal is absent.

- In the fits, we put Gaussian constraints on the bkgrnd yields using known branching fractions and their errors. For the remaining sum of small modes we use the MC estimated rate with a rather large error. Thus the uncertainties in the background will be taken care of in the statistical error.
Fit to $E_{\text{extra}} > 0.8$ GeV

- No signal, fit consistent with background expectations

![Graph showing data points and fit curves for various particles, including $\eta\rho^+$ and $K^0\pi\pi^0$.](image)

- Points are data
- Blue curve is overall fit
- Red dashed curve is sideband background
- Green dotted curve is other background with shape fixed to MC
Signal Region I: $E_{\text{extra}} < 0.1$ GeV

- $\eta \rho^+$
- $\Sigma^0 \pi^0$, $\eta \pi$, $\phi \pi$, $\tau(3\pi \nu)\nu$, $\mu \nu$, $X \mu \nu$
Signal Region II: $0.1 < E_{\text{extra}} < 0.2$ GeV

![Graph showing signal and background events](image_url)

- $K^0 \pi \pi^0$
- $\pi \pi^0 \pi^0, \eta \pi, \phi \pi, \tau(3\pi\nu)\nu, \mu \nu, X\mu\nu$
- Other background
- Sideband background
## Branching Fraction

<table>
<thead>
<tr>
<th>$E_{\text{extra}} \in$</th>
<th>Signal yields</th>
<th>Efficiency</th>
<th>$\mathcal{B}(D_s^+ \rightarrow \tau^+\nu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0,100] MeV</td>
<td>155.2 ± 16.5</td>
<td>25.3%</td>
<td>$(5.48 \pm 0.59)%$</td>
</tr>
<tr>
<td>[100,200] MeV</td>
<td>43.7 ± 11.3</td>
<td>6.9%</td>
<td>$(5.65 \pm 1.47)%$</td>
</tr>
<tr>
<td>[0,200] MeV</td>
<td>198.8 ± 20.0*</td>
<td>32.2%</td>
<td>$(5.52 \pm 0.57 \pm 0.21)%$</td>
</tr>
</tbody>
</table>

- Sum of the above two

- $f_{D_s} = (257.8 \pm 13.3 \pm 5.2)$ MeV
**CLEO: $D_S^+ \rightarrow \tau^+ \nu, \tau^+ \rightarrow e^+ \nu \nu$**

- $\mathcal{B}(D_S^+ \rightarrow \tau^+ \nu) \cdot \mathcal{B}(\tau^+ \rightarrow e^+ \nu \nu) \sim 1.3\%$ is “large” compared with expected $\mathcal{B}(D_S^+ \rightarrow X e^+ \nu) \sim 8\%$

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

- Opt to use only a subset of the cleanest tags
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 $D_S^*$
- $\mathcal{B}(D_S^+ \rightarrow \tau^+ \nu) = (5.30 \pm 0.47 \pm 0.22)\%$
- $f_{Ds} = 252.5 \pm 11.1 \pm 5.2$ MeV

Largest source of systematic error
Results

\[ \mathcal{B}(D_s^+ \rightarrow \tau^+ \nu) \text{ from CLEO} \]

<table>
<thead>
<tr>
<th>Mode</th>
<th>Branching Fraction (%)</th>
<th>( f_{D_s} ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau^+ \rightarrow \rho^+ \nu )</td>
<td>5.52 ± 0.57 ± 0.21</td>
<td>257.8 ± 13.3 ± 4.9</td>
</tr>
<tr>
<td>( \tau^+ \rightarrow e^+ \nu\nu )</td>
<td>5.30 ± 0.47 ± 0.22</td>
<td>252.6 ± 11.1 ± 5.2</td>
</tr>
<tr>
<td>( \tau^+ \rightarrow \pi^+ \nu )</td>
<td>6.42 ± 0.81 ± 0.18</td>
<td>278.0 ± 17.5 ± 4.4</td>
</tr>
<tr>
<td>Average</td>
<td>5.54 ± 0.32 ± 0.15</td>
<td>259.2 ± 7.8 ± 3.4</td>
</tr>
</tbody>
</table>

- For New Physics searches important to separate \( \tau^+ \nu \) and \( \mu^+ \nu \) [See A.G. Akeroyd and F. Mahmoudi, JHEP 0904, 121(2009)]
- Recall for \( \mu^+ \nu \) \( f_{D_s} = (257.6 \pm 10.3 \pm 4.3) \) MeV
- Ratio \( f_{D_s} (\tau^+ \nu)/f_{D_s} (\mu^+ \nu) = (1.01 \pm 0.05) \) consistent with unity
Belle: $D_S^+ \rightarrow \mu^+ \nu$

- Look for $e^+e^- \rightarrow DKX\gamma(D_S)$, where $X=n\pi$ & the $D_S$ is not observed but inferred from calculating the MM
- Then add a candidate $\mu^+$ and compute $\text{MM}^2$
- $\mathcal{B}(D_S^+ \rightarrow \mu^+ \nu) = (0.644 \pm 0.076 \pm 0.057)\%$
- $f_{Ds} = (275 \pm 16 \pm 12) \text{ MeV}$

arXiv:0709.1340v2 [hep-ex]
Result Summary

- Average of All CLEO measurements:
  \( f_{Ds} = (259.0 \pm 6.2 \pm 3.0) \text{ MeV} \)

- Plus Belle (275 \( \pm 16 \pm 12 \) MeV gives
  \( f_{Ds} = (260.7 \pm 6.5) \text{ MeV} \)

- Follana et. al (241 \( \pm 3 \) MeV, difference 2.4\( \sigma \))

- A. Bazavov et al. [Fermilab Lattice and MILC Collaborations], PoS LATTICE 2009 (2009) 249 now claim \( f_{Ds} = (260 \pm 10) \text{ MeV} \)
Conclusions: Leptonic Decays

We are in close agreement with the Follana et al calculation for $f_{D^+}$. This gives credence to their methods, but here is a disagreement with $f_{D_S}$ at the $2.4\sigma$ level.

- CLEO $D_s^+ \rightarrow \mu^+\nu$
- CLEO $D_s^+ \rightarrow \tau^+\nu$
- CLEO $D_s^+ \rightarrow \mu^+\nu + \tau^+\nu$
- BELLE $D_s^+ \rightarrow \mu^+\nu$
- CLEO $D^+ \rightarrow \mu^+\nu$
- $D_s^+$ Average
- Unquenched Lattice QCD (Follana et al)
- Unquenched Lattice QCD (Fermilab Milc)

Absolute $\mathcal{B}$ measurements only
Conclusions Continued

- Although the calculations are somewhat different for $f_{B_s}/f_B$, if theoretical predictions of $f_{D_s}/f_{D^+}$ do not agree with the data, why should we believe $f_{B_s}/f_B$ from theory? What does this do to the CKM fits? (This statement assumes that NP is not present!)

- Perhaps new lattice calculations using somewhat different methods will help resolve this situation, along with new data from BES III
Some Topics in Semileptonic Decays

Much left out due to lack of time
$D_s \rightarrow f_0(980)e^+\nu$

- These $D_s$ semileptonic decays have been postulated (SS & L. Zhang) to be similar to $B_s \rightarrow J/\psi \phi (f_0)$ since $M(B_s) - M(J/\psi) \approx M(D_s)$

- Hadronic mass distributions

\[
\begin{align*}
M_{f_0} &= (977^{+11}_{-9} \pm 1) \text{ MeV} \\
\Gamma_0 &= (91^{+30}_{-22} \pm 3) \text{ MeV}
\end{align*}
\]
$\mathcal{B}(D_s^+ \rightarrow f_0(980)e^+\nu, \ f_0 \rightarrow \pi^+\pi^-) = (0.20 \pm 0.03 \pm 0.01)\%,$

$\mathcal{B}(D_s^+ \rightarrow \phi e^+\nu, \ \phi \rightarrow K^+K^-) = (1.16 \pm 0.11 \pm 0.06)\%$

**Ratio of Rates at $q^2=0$ is $(42 \pm 11)\%$**
D to Pseudoscalar

\[ B(D^0 \to \pi^- e^+ \nu_e) = (0.288 \pm 0.008 \pm 0.003)\% \]
\[ B(D^0 \to K^- e^+ \nu_e) = (3.50 \pm 0.03 \pm 0.04)\% , \]
\[ B(D^+ \to \pi^0 e^+ \nu_e) = (0.405 \pm 0.016 \pm 0.009)\% \]
\[ B(D^+ \to K^0 e^+ \nu_e) = (8.83 \pm 0.10 \pm 0.20)\% . \]

**FIG. 8:** $f_+(q^2)$ comparison between isospin conjugate modes and with LQCD calculations [21]. The solid lines represent LQCD fits to the modified pole model [15]. The inner bands show LQCD statistical uncertainties, and the outer bands the sum in quadrature of LQCD statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th></th>
<th>$K f_+(0)$</th>
<th>$\pi f_+(0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO-C</td>
<td>0.739(7)(5)(0)</td>
<td>0.666(19)(4)(3)</td>
</tr>
<tr>
<td>Belle</td>
<td>0.695(7)(22)</td>
<td>0.624(20)(30)</td>
</tr>
<tr>
<td>BaBar</td>
<td>0.727(7)(5)(7)</td>
<td></td>
</tr>
<tr>
<td>LQCD [21] (Abada)</td>
<td>0.66(4)(1)</td>
<td>0.57(6)(2)</td>
</tr>
<tr>
<td>LQCD (Aubin)</td>
<td>0.73(3)(7)</td>
<td>0.64(3)(6)</td>
</tr>
</tbody>
</table>

**Extract**

\[ |V_{cd}| = 0.234 \pm 0.007 \pm 0.002 \pm 0.025 \]
\[ |V_{cs}| = 0.985 \pm 0.009 \pm 0.006 \pm 0.103 \]
### Various $D_s$ semileptonic rates

<table>
<thead>
<tr>
<th>$D_s$ Decay Mode</th>
<th>$\mathcal{B}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi e^+\nu$</td>
<td>$2.36\pm0.23\pm0.13$</td>
</tr>
<tr>
<td>(BaBar)</td>
<td>$2.61\pm0.03\pm0.08\pm0.15$</td>
</tr>
<tr>
<td>$\eta e^+\nu$</td>
<td>$2.48\pm0.29\pm0.13$</td>
</tr>
<tr>
<td>$\eta' e^+\nu$</td>
<td>$0.91\pm0.33\pm0.05$</td>
</tr>
<tr>
<td>$K^0 e^+\nu$</td>
<td>$0.37\pm0.10\pm0.02$</td>
</tr>
<tr>
<td>$K^* e^+\nu$</td>
<td>$0.18\pm0.07\pm0.01$</td>
</tr>
<tr>
<td>$f_0 e^+\nu, f_0 \rightarrow \pi^+\pi^-$</td>
<td>$0.20\pm0.03\pm0.01$</td>
</tr>
</tbody>
</table>
Conclusions - Semileptonics

- Lots of interesting measurements to compare with QCD
- More statistics would be wonderful
- Also

\[ \mathcal{B}(D^0 \rightarrow X e^+ \nu_e) = (6.46 \pm 0.09 \pm 0.11)\%, \]
\[ \mathcal{B}(D^+ \rightarrow X e^+ \nu_e) = (16.13 \pm 0.10 \pm 0.29)\%, \]
\[ \mathcal{B}(D_s^+ \rightarrow X e^+ \nu_e) = (6.52 \pm 0.39 \pm 0.15)\%. \]
The End
### Other Non-absolute Measurements

<table>
<thead>
<tr>
<th>Exp.</th>
<th>mode</th>
<th>$\mathcal{E}$</th>
<th>$\mathcal{E}(D_S \rightarrow \phi\pi)$ (%)</th>
<th>$f_{D_S}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO [11]</td>
<td>$\mu^+\nu$</td>
<td>$(6.2 \pm 0.8 \pm 1.3 \pm 1.6) \cdot 10^{-3}$</td>
<td>3.6$\pm$0.9</td>
<td>273 $\pm$ 19 $\pm$ 27 $\pm$ 33</td>
</tr>
<tr>
<td>BEATRICE [12]</td>
<td>$\mu^+\nu$</td>
<td>$(8.3 \pm 2.3 \pm 0.6 \pm 2.1) \cdot 10^{-3}$</td>
<td>3.6$\pm$0.9</td>
<td>312 $\pm$ 43 $\pm$ 12 $\pm$ 39</td>
</tr>
<tr>
<td>ALEPH [13]</td>
<td>$\mu^+\nu$</td>
<td>$(6.8 \pm 1.1 \pm 1.8) \cdot 10^{-3}$</td>
<td>3.6$\pm$0.9</td>
<td>282 $\pm$ 19 $\pm$ 40</td>
</tr>
<tr>
<td>ALEPH [13]</td>
<td>$\tau^+\nu$</td>
<td>$(5.8 \pm 0.8 \pm 1.8) \cdot 10^{-2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L3 [14]</td>
<td>$\tau^+\nu$</td>
<td>$(7.4 \pm 2.8 \pm 1.6 \pm 1.8) \cdot 10^{-2}$</td>
<td></td>
<td>299 $\pm$ 57 $\pm$ 32 $\pm$ 37</td>
</tr>
<tr>
<td>OPAL [15]</td>
<td>$\tau^+\nu$</td>
<td>$(7.0 \pm 2.1 \pm 2.0) \cdot 10^{-2}$</td>
<td></td>
<td>283 $\pm$ 44 $\pm$ 41</td>
</tr>
<tr>
<td>BaBar [16]</td>
<td>$\mu^+\nu$</td>
<td>$(6.74 \pm 0.83 \pm 0.26 \pm 0.66) \cdot 10^{-3}$</td>
<td>4.71$\pm$0.46</td>
<td>283 $\pm$ 17 $\pm$ 7 $\pm$ 14</td>
</tr>
</tbody>
</table>

HFAG reinterpretation: 237 ± 13 ± 5

See Rosner & Stone, arXiv:0802.1043 for references
Beyond the SM Theories

- Leptoquark models & special Two-Higgs doublet model (Dobrescu & Kronfeld) [arXiv:0803.0512-hep-ph]
- R-parity violating Supersymmetry (Akeroyd & Recksiegel [hep-ph/0210376])
- A. Kundu & S. Nandi, “R-parity violating supersymmetry, $B_S$ mixing, & $D_S^+ \to \ell^+\nu$” [arXiv:0803.1898])
  - Dosner et al show that the above models should effect $\tau\nu$ and $\mu\nu$ differently [arXiv:0906.5585-hep/ph]
- Gninenko & Gorbunov argue that the neutrino in the $D_s$ decay mixes with a sterile neutrino, which enhances the rate, but should act the same in $D^+ & D_S$, & could be different for $\mu^+\nu & \tau^+\nu$ [arXiv:0907.4666-hep-ph]
Efficiencies

- Tracking, particle id, E<300 MeV (determined from $\mu$-pairs) = 85.3%
- Not having an unmatched shower > 250 MeV 95.9%, determined from double tag, tag samples
- Easier to find a $\mu\nu$ event in a tag then a generic decay (tag bias) (1.53%)
μν Signal Shape Checked

- Data $\sigma=0.0247\pm0.0012$ GeV$^2$
- MC $\sigma=0.0235\pm0.0007$ GeV$^2$
- Both average of double Gaussians
Case(i) With $\tau^+\nu/\mu^+\nu$ Floating

- **Fixed**
  - $149.7 \pm 12.0 \, \mu\nu$
  - $28.5 \, \tau\nu$

- **Floating**
  - $153.9 \pm 13.5 \, \mu\nu$
  - $13.5 \pm 15.3 \, \tau\nu$
New Physics Possibilities III

- 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

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

Corrected

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

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

See Akeroyd [hep-ph/0308260]

$\frac{r_s}{\text{meas rate/SM rate}}$

$m_s/m_c = 0.15$

From Akeroyd

Moriond QCD, 2010
Model of $K^0\pi^+$ Tail

- Use double tag $D^0\bar{D}^0$ events, where both $D^0\rightarrow K^{\mp}\pi^{\pm}$
- Make loose cuts on 2nd $D^0$ so as not to bias distribution: require only 4 charged tracks in the event

Computed ignoring charged kaon

Gives an excellent description of shape of low mass tail
“Extra” 1.3 event background in signal region

Expectation from residual $\pi^+\pi^-$ (1.1 events)
The MM$^2$ Distribution

- For $E < 300$ MeV in CsI

Moriond QCD, 2010
Residual Backgrounds for $\mu\nu$

- Monte Carlo of Continuum, $D^0$, radiative return and other $D^+$ modes, in $\mu\nu$ signal region

<table>
<thead>
<tr>
<th>Mode</th>
<th># of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuum</td>
<td>0.8±0.4</td>
</tr>
<tr>
<td>$K^0\pi^+$</td>
<td>1.3±0.9</td>
</tr>
<tr>
<td>$D^0$ modes</td>
<td>0.3±0.3</td>
</tr>
<tr>
<td>Sum</td>
<td>2.4±1.0</td>
</tr>
</tbody>
</table>

- This we subtract off the fitted yields
CP Violation

- $D^+$ tags $228,945 \pm 551$
- $D^-$ tags $231,107 \pm 552$
- $\mu^- \nu$ events $64.8 \pm 8.1$
- $\mu^+ \nu$ events $76.0 \pm 8.6$

$$A_{CP} \equiv \frac{\Gamma(D^+ \rightarrow \mu^+ \nu) - \Gamma(D^- \rightarrow \mu^- \nu)}{\Gamma(D^+ \rightarrow \mu^+ \nu) + \Gamma(D^- \rightarrow \mu^- \nu)} = 0.08 \pm 0.08$$

- $-0.05 < A_{CP} < 0.21$ @ 90% c. l.
Leptonic Decays: $D \to \ell^+ \nu$

c and $\bar{q}$ can annihilate, probability is proportional to wave function overlap

Standard Model decay diagram:

In general for all pseudoscalars:

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

Calculate, or measure if $V_{Qq}$ is known, here take $V_{cd} = V_{us} = 0.2256$, $V_{cs} = V_{ud} - V_{cb}/4 = 0.9734$
CLEO’s Technique for $D^+ \rightarrow \mu^+ \nu$

- Exploit $e^+e^- \rightarrow D^-D^+$
- Fully reconstruct a $D^-$, and count total # of tags
- Seek events with only one additional oppositely charged track within $|\cos \theta| < 0.9$ & no additional photons $> 250$ MeV (to veto $D^+ \rightarrow \pi^+\pi^0$)
- Charged track must deposit only minimum ionization in calorimeter [$< 300$ MeV: case (i)]
- Compute $MM^2$. If close to zero then almost certainly we have a $\mu^+\nu$ decay.

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

We know $E_{D^+} = E_{\text{beam}}$, $\vec{p}_{D^+} = -\vec{p}_{D^-}$
Background Check

- Use case(ii) $E>300$ MeV in EM calorimeter
- Fix $\tau\nu$ from case(i) $\mu\nu$.
- Consider signal region $|MM^2|<0.05$ GeV$^2$. Expect $1.7 \mu\nu + 5.4 \pi^+\pi^0 + 4.0 \tau\nu = 11.1$
- Find 11 events
- Extra bkgrnd=-0.1±3.3 events
## 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>0.2</td>
</tr>
<tr>
<td>Extra showers in event &gt; 250 MeV</td>
<td>0.4</td>
</tr>
<tr>
<td>Background</td>
<td>0.7</td>
</tr>
<tr>
<td>Number of single tag $D^+$</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.2</strong></td>
</tr>
</tbody>
</table>
Upper limits on $\tau \nu$ & $e \nu$

- Here we fit both case(i) & case(ii) constraining the relative $\tau \nu$ yield to the pion acceptance, 55/45.

- Find
  - $\mathcal{B}(D^+ \rightarrow \tau^+ \nu) < 1.2 \times 10^{-3}$, @ 90% c.l.
  - $\mathcal{B}(D^+ \rightarrow \tau^+ \nu)/2.65 \mathcal{B}(D^+ \rightarrow \mu^+ \nu) < 1.2$ @ 90% c.l.
  - Also $\mathcal{B}(D^+ \rightarrow e^+ \nu) < 8.8 \times 10^{-6}$, @ 90% c.l.
## Systematic Errors $\mu^+\nu$

<table>
<thead>
<tr>
<th>Source of Error</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Finding the $\mu^+$ track</td>
<td>0.7</td>
</tr>
<tr>
<td>Particle identification of $\mu^+$</td>
<td>1.0</td>
</tr>
<tr>
<td>MM$^2$ width</td>
<td>0.2</td>
</tr>
<tr>
<td>Extra showers in event $&gt; 300$ MeV</td>
<td>0.4</td>
</tr>
<tr>
<td>Background</td>
<td>1.0</td>
</tr>
<tr>
<td>Number of single tag $D_S^-$</td>
<td>2.0</td>
</tr>
<tr>
<td>Tag Bias</td>
<td>1.0</td>
</tr>
<tr>
<td>Radiative Correction</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.0</strong></td>
</tr>
</tbody>
</table>
Systematic Errors

- Measure efficiency of $E_{\text{extra}}$ cut. Use fully reconstructed $D_s D_s^*$ events.
- Value at 300 MeV is chosen, because it has the same efficiency as $\rho^+\nu$ for $E_{\text{extra}}$ 200 MeV.

<table>
<thead>
<tr>
<th>$E_{\text{extra}}$ (MeV)</th>
<th>$\epsilon_{\text{Data}}$ (%)</th>
<th>$\epsilon_{\text{MC}}$ (%)</th>
<th>$\frac{\epsilon_{\text{Data}}}{\epsilon_{\text{MC}}} - 1$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;100</td>
<td>40.24 ± 1.27</td>
<td>40.81 ± 0.31</td>
<td>-1.4 ± 3.2</td>
</tr>
<tr>
<td>&lt;200</td>
<td>57.75 ± 1.28</td>
<td>59.12 ± 0.31</td>
<td>-2.3 ± 2.2</td>
</tr>
<tr>
<td>&lt;300</td>
<td>72.35 ± 1.16</td>
<td>73.21 ± 0.28</td>
<td>-1.2 ± 1.6</td>
</tr>
<tr>
<td>&lt;400</td>
<td>83.27 ± 0.97</td>
<td>82.91 ± 0.24</td>
<td>0.4 ± 1.2</td>
</tr>
</tbody>
</table>

Set $\sqrt{1.2^2 + 1.6^2} = 2.0\%$ error.
<table>
<thead>
<tr>
<th>Source of Error</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finding the $\pi^+$ track</td>
<td>0.3</td>
</tr>
<tr>
<td>Particle identification of $\pi^+$</td>
<td>1.0</td>
</tr>
<tr>
<td>$\pi^0$ efficiency</td>
<td>1.3</td>
</tr>
<tr>
<td>$E_{\text{extra}} &lt; 200$ MeV signal efficiency</td>
<td>2.0</td>
</tr>
<tr>
<td>$E_{\text{extra}} &lt; 200$ MeV &amp; $\pi^0$ efficiencies on background</td>
<td>1.1</td>
</tr>
<tr>
<td>Background modeling</td>
<td>1.1</td>
</tr>
<tr>
<td>Number of single tag $D_s^-$</td>
<td>2.0</td>
</tr>
<tr>
<td>Tag Bias</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.8</strong></td>
</tr>
</tbody>
</table>
Use $e^+e^- \rightarrow D_S^0 D_S^*$ at 4170 MeV

- Reconstruct $D_S^-$
- Find the $\gamma$ from the $D_S^*$ & compute $MM^2$ from $D_S^-$ & $\gamma$
  \[ MM^{*2} = (E_{CM} - E_D - E_{\gamma})^2 - (\vec{p}_D - \vec{p}_{\gamma})^2 \]
- Select combinations consistent with a missing $D_S^+$ & count the number
- Find $MM^2$ from candidate muon for (i) $< 300$ MeV in Ecal, (ii) $E > 300$ MeV or (iii) $e^-$ cand.
  \[ MM^2 = (E_{CM} - E_D - E_{\gamma} - E_{\mu})^2 - (\vec{p}_D - \vec{p}_{\gamma} - \vec{p}_{\mu})^2 \]
MM$^2$ data for $D_S$

- Total of 30848±695 tags
- 99% of $\mu^+\nu$ in $E < 300$ MeV
- 55%/45% split of $\tau^+\nu$, $\tau^+\rightarrow\pi^+\nu$ in two cases
- Small $e^-$ background