Rare and Forbidden Charm Meson Decays in FOCUS

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Three Categories of Decays

**FCNC**
- $D^+ \rightarrow K^+ l^+ l^-$
- $D^+ \rightarrow \pi^+ l^+ l^-$
- $D_s^+ \rightarrow K^+ l^+ l^-$
- $D_s^+ \rightarrow \pi^+ l^+ l^-$
- $D^0 \rightarrow l^+ l^-$

**LFNV**
- $D^+ \rightarrow K^+ \mu^\pm e^{\mp}$
- $D^+ \rightarrow \pi^+ \mu^\pm e^{\mp}$
- $D_s^+ \rightarrow K^+ \mu^\pm e^{\mp}$
- $D_s^+ \rightarrow \pi^+ \mu^\pm e^{\mp}$
- $D^0 \rightarrow \mu^\pm e^{\mp}$

**LNV**
- $D^+ \rightarrow K^- l^+ l^+$
- $D^+ \rightarrow \pi^- l^+ l^+$
- $D_s^+ \rightarrow K^- l^+ l^+$
- $D_s^+ \rightarrow \pi^- l^+ l^+$

Talk will present $D^0 \rightarrow \mu^+\mu^-$ analysis of complete FOCUS data set as an example of our rare decay reach. Will show preliminary evaluations of sensitivity for these decays.
FOCUS has reconstructed over one million charm decays from the Fermilab 1997 fixed target run.

An excellent vertex detector but also great particle id including full muon detection and E&M calorimetry.
Event Selection Criteria

• Vertexing (Candidate driven)
  – Secondary vertex
    • Confidence Level
    • Isolation - No other tracks come from that vertex.
  – Primary vertex
    • Require consistent with D track from secondary
    • Confidence Level
    • Require a minimum multiplicity
    • Isolation - No tracks from secondary are consistent with coming from the primary.
    • In target (z position)
  – Detachment (L/σ)
More Event Selection Criteria

- **Muon Identification**
  - Number of Muon Planes with Hits (Mupl)
  - Confidence Level
  - Not consistent with being a kaon.

- **Hadron identification – Triple Cerenkov System**
  - Log likelihood for consistency between Cerenkov hits and a particular particle id hypothesis
  - Compare log likelihoods for different species (Kaonicity)
Fixed (loose) Cuts

• Vertexing
  – CLP and CLS > 1%
  – Primary Multiplicity > 2
  – $L/\sigma > 3$

• Muon Identification
  – $\text{Mupl} \geq 4$
  – Confidence Level > 1%
Mass Distributions with Fixed Cuts

Fairly clean even with loose cuts but can be improved. Signal area ($\pm 2\sigma$) has been masked in data (blind analysis).
Optimization of Cuts – Blind Analysis

- Only sidebands are used to study background.
- First determine cut ranges by looking at individual variable histograms.
- Vertexing
  - \(L/\sigma > 5, 7, 9\)
  - CLS > 1\%, 5\%, 10\%
  - ISOS < 10^{-4}, 10^{-3}, 10^{-2}
  - ISOP < 10^{-4}, 10^{-3}, 10^{-2}
  - Distance of primary outside target edge < 0, 2
- Muon Identification
  - \(M_{\mu} \geq 4, 5, 6\)
  - Confidence Level > 1\%, 3\%, 5\%
  - Kaonicity < 2, 5, 8
More Blind Analysis

• Determine a baseline set of cuts with the best (lowest) “sensitivity”.

\[ BR_{\text{rare}} = \frac{N_{\text{rare}} / \varepsilon_{\text{rare}}}{N_{\text{norm}} / \varepsilon_{\text{norm}}} \times BR_{\text{norm}} \quad (\text{Branching Ratio}) \]

\[ S = \frac{N_L / \varepsilon_{\text{are}}}{N_{\text{norm}} / \varepsilon_{\text{norm}}} \times BR_{\text{norm}} \quad (\text{Sensitivity}) \]

\( N_L \) is the average of the 90\% upper limit for an ensemble of experiments with zero signal and the background rate estimated from the sidebands.
90\% Confidence Intervals Table
Including Uncertainty in Background Estimate

From hep-ph/0005187. The number of events in the signal region is \( x \). The background is estimated as \( y / \tau \) from an observation of \( y \) sideband events. This table is for the case \( \tau = 2 \).

<table>
<thead>
<tr>
<th>( x )</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>0.221</td>
<td>0.227</td>
<td>0.158</td>
<td>0.128</td>
<td>0.09</td>
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<tr>
<td>1</td>
<td>0.365</td>
<td>0.322</td>
<td>0.344</td>
<td>0.306</td>
<td>0.287</td>
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<tr>
<td>2</td>
<td>0.42</td>
<td>0.487</td>
<td>0.443</td>
<td>0.4</td>
<td>0.441</td>
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<tr>
<td>3</td>
<td>0.97</td>
<td>0.86</td>
<td>0.593</td>
<td>0.549</td>
<td>0.505</td>
</tr>
<tr>
<td>4</td>
<td>1.54</td>
<td>0.74</td>
<td>0.36</td>
<td>0.691</td>
<td>0.647</td>
</tr>
<tr>
<td>5</td>
<td>2.16</td>
<td>1.42</td>
<td>0.748</td>
<td>0.783</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2.82</td>
<td>2.12</td>
<td>1.45</td>
<td>0.8962</td>
<td>0.17917</td>
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<tr>
<td>7</td>
<td>3.51</td>
<td>2.83</td>
<td>2.18</td>
<td>1.54</td>
<td>0.91</td>
</tr>
<tr>
<td>8</td>
<td>4.2</td>
<td>3.55</td>
<td>2.91</td>
<td>2.29</td>
<td>1.67</td>
</tr>
<tr>
<td>9</td>
<td>4.92</td>
<td>4.29</td>
<td>3.66</td>
<td>3.04</td>
<td>2.43</td>
</tr>
<tr>
<td>10</td>
<td>5.66</td>
<td>5.03</td>
<td>4.42</td>
<td>3.81</td>
<td>3.21</td>
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</table>
## Optimum Set of Cuts and Sensitivity

<table>
<thead>
<tr>
<th>Cut Combination</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>— Cuts —</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L/\sigma (&gt;)$</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Primary isolation ($&lt;$)</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Secondary isolation ($&lt;$)</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Secondary CL ($&gt;$)</td>
<td>0.01</td>
<td>0.05</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$</td>
<td>z_{\text{prim.}} - z_{\text{target edge}}</td>
<td>(&gt;)$</td>
<td>0.0</td>
<td>2.0 $\sigma$</td>
</tr>
<tr>
<td>Number of Muon Hit Planes ($&gt;$)</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Inner Muon CL ($&gt;$)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Outer Muon CL ($&gt;$)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Kaonicity ($&lt;$)</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>— Results —</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Background Rate in Sidebands</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Sensitivity Number ($N_L$)</td>
<td>3.17</td>
<td>3.17</td>
<td>3.17</td>
<td>3.17</td>
</tr>
<tr>
<td>$D^0 \rightarrow \mu^+\mu^-$ efficiency (%)</td>
<td>2.271</td>
<td>2.256</td>
<td>2.255</td>
<td>2.243</td>
</tr>
<tr>
<td>Sensitivity ($10^{-6}$)</td>
<td>1.493</td>
<td>1.502</td>
<td>1.503</td>
<td>1.512</td>
</tr>
</tbody>
</table>

The sensitivity is almost a factor of 3 lower than the existing limit.
Mass Distributions for Optimized Cuts

There are two events in the sidebands.
Background from $D^0 \rightarrow \pi^- \pi^+$ is negligible.

Doubly misid-ed $D^0 \rightarrow \pi^- \pi^+$ is a worry because it peaks in the signal! A Monte Carlo study with statistics equal to ten times FOCUS finds no events that survive all the baseline cuts.

No event survives all cuts.
Studies of $D^+$ or $D_s^+ \rightarrow h \mu \mu$

For now, preliminary estimates.

- **Vertex cuts** (*not optimized*)
  - $L / \sigma > 20$
  - CLS > 1%
  - CLP > 1%
  - ISOP < 1%

- **Efficiencies** (*conservative estimates*)
  - Assume efficiencies cancel except particle id.
  - Cerenkov cut on kaon ~ 80%
  - Muon Id ~ 95%
  - Relative trigger efficiency ~ 80%
Studies of $D^+$ or $D_s^+ \rightarrow h \mu \mu$, cont.

$D^+ \rightarrow$ Rare Mode

(D$^+$, $D_s$ signal masked)
Rare Decay Summary

- Another Factor of 10 soon!