Experimental status of rare $D$ decays

Vindhyawasini Prasad
(On behalf of the BESIII experiment)

Email: vindy@ustc.edu.cn

Department of Modern Physics
University of Science & Technology of China
Hefei City, Anhui Province, 23006, China
Introduction

- **Flavor-changing neutral currents (FCNC)** are forbidden at tree level in the Standard Model (SM), only possible via loops, such as:
  - Measured in K and B meson systems.
  - Highly suppressed in charm sector by the Glashow-Iliopoulos-Maiani (GIM) mechanism due to the absence of high mass down-type quark. [PRD 2, 1285 (1970)]
  - Rare decays are highly sensitive to the searches of new physics effects.
  - Charm is complementary to the B and K sectors, and a unique window on the new physics affecting the up-type quark dynamics.
Experimental status up to June 2016

D^0 decays

D^+ decays

D_s^+ decays

http://www.slac.stanford.edu/xorg/hfag/charm/
In rare decays of $D^+ \to D^0 e^+ \nu_e$, the heavy-quark (c) remains unchanged, and the weak decays are managed by the light-quark sectors.

In the limit of the flavour SU(3) symmetry of the light quark, the branching fraction of this decay mode is predicted to be about $2.78 \times 10^{-13}$. [EPJC 59, 841-845(2009)]

Measuring this decay can shed light on testing the SM predictions for the rare semi-leptonic decays.

Use 2.92 fb$^{-1}$ $\psi(3770)$ data collected by BESIII experiment to perform this search.
The search uses a double tag technique pioneered by MARKIII collaboration. [PRL 56, 2140 (1986)]

$M_{BC}$ and $\Delta E$ are used to identify $D^-$:

$$M_{BC} = \sqrt{E_{\text{beam}}^2 / c^4 - |\vec{p}_{D^-}|^2 / c^2}, \Delta E = E_{D^-} - E_{\text{beam}}$$

**Momentum**  **Energy**  **Beam energy**

Reconstructed with three signal modes: $K\pi, K\pi\pi^0$ & $K\pi\pi\pi$

Modeling of MC shape $\otimes$ Gaussian function + ARGUS function.

Total single tag yield: $N_{ST}^{tot} = 1508368 \pm 1421$
$D^+ \rightarrow D^0 e^+ \nu_e$

Results

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

|$N^\text{obs}_{\text{data}} = 0.3 \pm 3.6$
$N^\text{peak}_{\text{bkg}} = 3.0 \pm 0.6$

|$N^\text{obs}_{\text{data}} = 5.6 \pm 2.9$
$N^\text{peak}_{\text{bkg}} = 6.4 \pm 0.9$

|$N^\text{obs}_{\text{data}} = 6.4 \pm 3.5$
$N^\text{peak}_{\text{bkg}} = 10.3 \pm 1.2$

$N^\text{obs}_{\text{data}}$ is computed while performing the 2D fit to the $m^D_{BC}$ and invariant mass distribution of the $D^0$ meson of the data.

$N^\text{peak}_{\text{bkg}}$ is evaluated using inclusive MC sample.

$N^\text{sig} = N^\text{obs}_{\text{data}} - N^\text{peak}_{\text{bkg}}$

- No significant events are found in any decay modes.

- $B(D^+ \rightarrow D^0 e^+ \nu_e) < 8.7 \times 10^{-5}$ @ 90% C.L. upper limit
The FCNC decays of $D^+ \to h^\pm e^+ e^- \mp$ are expected to be very rare due to not occur at tree level in the SM.

- Branching fraction (BF) values due to short distance effect ($c \to u \ell^+ \ell^-$): $\sim 10^{-6}$-$10^{-5}$ [MPLA 8, 967 (1993)]

- BF values due to long distance effect ($D^+ \to h^+ V, V \to \ell^+ \ell^-$): $10^{-6}$-$10^{-5}$ [PRD 76, 074010 (2007)]

- Lepton flavour process (LNV) of $D^+ \to h e^+ e^+$ can only be explained by new physics models beyond the SM.

- Majorana neutrino: $\sim 10^{-30}$-$10^{-23}$ [PRD 64, 114009 (2001)]

- may be greatly enhanced: $\sim 10^{-6}$-$10^{-5}$ [EPJC 71, 1715 (2011)]

- Thus, the process of $D^+ \to h^\pm e^+ e^- \mp$ is an ideal framework for investigating the new physics beyond the SM.

- The large data set collected by BESIII experiment collected at $\psi(3770)$ resonance can provide a better sensitivity on this decay process.
$D^+ \rightarrow h^\pm e^+ e^\mp$ (h=K, π)

Use single tag method to perform the search using 2.92 fb$^{-1}$ of $\psi(3770)$ data

$\Delta E = E_{\text{beam}} - E_{h^\pm e^\mp e^\mp}$

$M_{BC} \equiv \sqrt{E_b^2/c^4 - p_{h^\pm e^\mp e^\mp}^2/c^2}$

Scatter plots for $M_{BC}$ versus $\Delta E$, where the signal boxes are shown as blue rectangle. The contours are determined from MC simulation to enclose 84% of signal events for each channel.
\[ \text{Results} \]

<table>
<thead>
<tr>
<th>( \text{Process} )</th>
<th>( N_{\text{inside}}^{\text{data}} )</th>
<th>( N_{\text{outside}}^{\text{data}} )</th>
<th>( f_{\text{scale}} )</th>
<th>( \epsilon ) [%]</th>
<th>( \Delta_{\text{sys}} ) [%]</th>
<th>( s_{90} )</th>
<th>( \mathcal{B} [\times 10^{-6}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D^+ \rightarrow K^+ e^+ e^- )</td>
<td>5</td>
<td>69</td>
<td>0.08 ± 0.01</td>
<td>22.53</td>
<td>5.4</td>
<td>19.4</td>
<td>&lt; 1.2</td>
</tr>
<tr>
<td>( D^+ \rightarrow K^- e^+ e^+ )</td>
<td>3</td>
<td>55</td>
<td>0.08 ± 0.01</td>
<td>24.08</td>
<td>6.1</td>
<td>10.2</td>
<td>&lt; 0.6</td>
</tr>
<tr>
<td>( D^+ \rightarrow \pi^+ e^+ e^- )</td>
<td>3</td>
<td>65</td>
<td>0.09 ± 0.02</td>
<td>25.72</td>
<td>5.9</td>
<td>4.2</td>
<td>&lt; 0.3</td>
</tr>
<tr>
<td>( D^+ \rightarrow \pi^- e^+ e^+ )</td>
<td>5</td>
<td>68</td>
<td>0.06 ± 0.02</td>
<td>28.08</td>
<td>6.8</td>
<td>20.5</td>
<td>&lt; 1.2</td>
</tr>
</tbody>
</table>

Where \( s_{90} \) is estimated with a profile likelihood method, TROLKE program, incorporating the systematic uncertainties and detection efficiencies. [NIM A551, 493 (2005)]

\[
\mathcal{B} < \frac{s_{90}}{N_{D^+}^{\text{tot}}} ,
\]

where \( N_{D^+}^{\text{tot}} = 2 \cdot \mathcal{L} \cdot \sigma_{D^+ D^-}^{\text{obs}} = (1.681 \pm 0.032) \times 10^7 \)

<table>
<thead>
<tr>
<th>( \mathcal{B}(D^+ \rightarrow) ) ( [\times 10^{-6}] )</th>
<th>( K^+ e^+ e^- )</th>
<th>( K^- e^+ e^+ )</th>
<th>( \pi^+ e^+ e^- )</th>
<th>( \pi^- e^+ e^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>3.0</td>
<td>3.5</td>
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<tr>
<td>Babar</td>
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<td>0.9</td>
<td>1.1</td>
<td>1.9</td>
</tr>
<tr>
<td>PDG</td>
<td>1.0</td>
<td>0.9</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>This work</td>
<td>1.2</td>
<td>0.6</td>
<td>0.3</td>
<td>1.2</td>
</tr>
</tbody>
</table>

[PRD 82, 092007 (2010)]

[PRD 84, 072006 (2011)]
The FCNC decay of $D^0 \rightarrow \gamma \gamma$ is strongly suppressed by GIM mechanism. 

- Short-distance (an EM penguin transitions): $3 \times 10^{-11}$ 
  
- Long-distance (vector meson dominance model (VDM)): $(1-3) \times 10^{-8}$ 
  
- Minimal Supersymmetric Standard Model (due to gluino exchange via $c \rightarrow u \gamma$ transitions): $6 \times 10^{-6}$ 

$\mathcal{B}(D^0 \rightarrow \gamma \gamma) < 2.9 \times 10^{-5}$ CLEO collab. 

- $470.5 \text{ fb}^{-1}$ of data used by BaBar experiment to perform the search for $D^0 \rightarrow \gamma \gamma$ decay.

- Select the $D^0$ meson candidate from $D^{*+} \rightarrow D^0 (\rightarrow \gamma \gamma) \pi^+$

- Peaking background from $D^0 \rightarrow \pi^0 \pi^0$

\[
\mathcal{B}(D^0 \rightarrow \gamma \gamma) = \frac{N(D^0 \rightarrow \gamma \gamma)}{N(D^0 \rightarrow K_S^0 \pi^0)} \times \frac{\varepsilon_{K_S^0 \pi^0}}{\varepsilon_{\gamma \gamma}} \times \mathcal{B}(D^0 \rightarrow K_S^0 \pi^0)
\]

\[
\mathcal{B}(D^0 \rightarrow \gamma \gamma) < 2.2 \times 10^{-6} \text{ @ 90% C.L. upper limit}
\]
Double tag method

$D^0 \rightarrow \gamma \gamma$ [PRD 91, 112015 (2015)]

Use 2.92 fb$^{-1}$ of $\psi$(3770) data

Simultaneously fit to $\Delta E$ in both tag side and $\gamma \gamma$ sides to determine $D^0 \rightarrow \gamma \gamma$ yield.

$B(D^0 \rightarrow \gamma \gamma) < 3.8 \times 10^{-6}$ at 90% C.L. upper limit consistent with BaBar result [PRD 91, 112015 (2015)]
Select the $D^0$ meson candidate from $D^{*+} \rightarrow D^0 (\rightarrow \gamma \gamma) \pi^+$

- Peaking background from $D^0 \rightarrow \pi^0 \pi^0$, $\eta \pi^0$, $\eta$ etc.
- $\pi^0$ veto: reject all the photons which can be used for a good $\pi^0$
- Normalization to $D^0 \rightarrow K^0_S \pi^0$

Use 832 fb$^{-1}$ of data

$B(D^0 \rightarrow \gamma \gamma) < 8.5 \times 10^{-7}$ @ 90% C.L. upper limit

- Most stringent exclusion limit to date
- Large date samples may further improve the measurements

[PRD 93, 051102(R) (2016)]
The $D^0 \rightarrow \nu \bar{\nu}$ decay is helicity suppressed with the branching fraction of $1.1 \times 10^{-30}$. \[PRD 82, 034005 (2010)]

New physics models may enhance the branching fraction up to the level of $10^{-15}$.

\[PLB651, 374(2007); Phys.Rept.117,75(1985)]

Use a charm tagger method to select the $D^0$ candidate.

$X_{\text{frag}}$: a few unflavored mesons

\[\pi \pi \ldots\]

\[D^0 \rightarrow \nu \bar{\nu}\]

$D_{\text{tag}}^{(*)}, D_{\text{sig}}^{(*)}, D_{s}^{(*)}, \Lambda_{c}^{+}$

Four types of $D_{\text{tag}}$ are reconstructed using 23 decay modes

An illustration of the charm tagger method.

$M_{D^0} \equiv M_{\text{miss}}(D_{\text{tag}}^{(*)} X_{\text{frag}} \pi_{-}^{s})$

https://indico.cern.ch/event/559999/contributions/2262553/attachments/1343046/2023381/shen_chengping.pdf
D$^0 \rightarrow$ invisible

- D$^0 \rightarrow$ invisible decays are selected by requiring no remaining final states associated with $\bar{D}_{\text{tag}}^0$.
- The residual energy in the ECL, $E_{\text{ECL}}$, is used for signal extraction.
- 2D fit: M(D0), $E_{\text{ECL}}$.

924 fb$^{-1}$

$-10.2^{+22.1}_{-20.8}$

- No significant signal yield is found.
- $\mathcal{B}(D^0 \rightarrow \text{invisible}) < 8.8 \times 10^{-5}$ at 90% C.L. upper limit

First exclusion limit on D$^0 \rightarrow$ invisible decay

https://indico.cern.ch/event/559999/contributions/2262553/attachments/1343046/2023381/shen_chengping.pdf
By using 2.92 fb\(^{-1}\) of \(\psi(3770)\) data, BESIII has set one of the most stringent exclusive limits on the decay processes of \(D^+\rightarrow D^0 e^+\nu_e\) and \(D^+\rightarrow h^\pm e^+e^\mp\) (\(h=K,\pi\)).

Large data samples collected by Belle experiment improve further the upper limit of \(D^0\rightarrow\gamma\gamma\) decay.

Belle experiment has also reported recently the first experimental exclusion limit on \(D^0\rightarrow\text{invisible decay}\).

Present upper limits are still above the SM predictions, no any signature of the new physics is found.

Large data samples to be collected by current and future flavor physics collider experiments may further improve the results and provide the hint of new physics.
Thank you!
Back up Slide
\[ D^+ \rightarrow D^0 e^+ \nu_e \]

\[ B_{D^+} = \frac{N_{sig}}{N_{ST}^{tot} \times \epsilon^i \times B^i} \]

Where \( i = 0, 1, 2 \) represent the signal modes \( D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^+\pi^- \) and \( K^-\pi^+\pi^0 \), respectively; \( N_{ST}^{tot} \) the total ST yield in data; \( \epsilon^i \) the efficiency of reconstructing \( D^+ \rightarrow D^0 e^+ \nu_e \) with the signal mode \( i \), which is weighted by the ST yield; \( B^i \) the branching fraction of \( D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^+\pi^- \) or \( K^-\pi^+\pi^0 \) from the PDG and \( B_{D^+} \) the branching fraction of \( D^+ \rightarrow D^0 e^+ \nu_e \)

### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>( D^0 \rightarrow K^-\pi^+ )</th>
<th>( D^0 \rightarrow K^-\pi^+\pi^+\pi^- )</th>
<th>( D^0 \rightarrow K^-\pi^+\pi^0 )</th>
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</thead>
<tbody>
<tr>
<td>Tracking</td>
<td>2.0</td>
<td>4.0</td>
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<tr>
<td>PID</td>
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<tr>
<td>Quoted branching fraction</td>
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<td>3.6</td>
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<tr>
<td>( \pi^0 ) reconstruction</td>
<td>-</td>
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<tr>
<td>Total</td>
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<td>12.7</td>
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</table>

BESIII Preliminary
$D^+ \rightarrow h^\pm e^+ e^\mp$ ($h=K, \pi$)

### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$D^+ \rightarrow K^+ e^+ e^-$</th>
<th>$D^+ \rightarrow K^- e^+ e^+$</th>
<th>$D^+ \rightarrow \pi^+ e^+ e^-$</th>
<th>$D^+ \rightarrow \pi^- e^+ e^+$</th>
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<tr>
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