First Search for FCNC Decay of $D^0 \rightarrow \gamma \gamma$

Abstract

Using the full CLEO II and II.V data set of 13.76 fb$^{-1}$, we search for Flavor-Changing-Neutral-Current (FCNC) process of $D^0 \rightarrow \gamma \gamma$. We observe no significant signals for this decay mode and set 90% C.L. upper limits on the following branching ratios:

$$\frac{Br(D^0 \rightarrow \gamma \gamma)}{Br(D^0 \rightarrow \pi^0 \pi^0)} < 0.034$$

$$Br(D^0 \rightarrow \gamma \gamma) < 3.0 \times 10^{-5}$$

1 Introduction

In the Standard Model (SM), Flavor-Changing-Neutral-Current (FCNC) processes are forbidden at the tree level but can occur at higher loop level. SM loops are largest for $K$ and $B$ transitions due to the large t-quark mass and favorable CKM dependence. The experimental studies of FCNC processes for charm have lagged behind those of the other flavors. Eugene Golowich pointed out this irony in his recent paper [1]: it is precisely because SM signals are expected to be so small for charm FCNC that the opportunities for evidence of New Physics to emerge become enhanced relative to the other flavors. The current situation begs for experimental input.

Table 1 [1, 2] lists 4 types of FCNC charm decays, together with their current experimental bounds and SM calculations. While all existing experimental bounds lie below the SM predictions, for some decays, the gap between SM and experiment is enormous, leaving ample opportunity for signals from New Physics beyond the SM to appear. Supersymmetry (SUSY), Extra Degrees of Freedom: Higgs bosons, Gauge bosons, Fermions including Extra dimensions etc are all candidates of New Physics, if these FCNC charm decays can be observed at levels much higher than SM calculations. $D^0 \rightarrow \gamma \gamma$ is one of these FCNC rare charm decay process which is highly suppressed in the SM. This process has never been measured so far.

2 Analysis Strategy

Figure 1 shows the momentum spectrum of $D^0$ production in inclusive $B\overline{B}$ and continuum Monte Carlo. As expected, the average $D^0$ momentum from inclusive continuum MC events is much harder than those from $B\overline{B}$ MC events. Figure 2 shows the momentum spectrum of the two $\gamma$’s in the $D^0 \rightarrow \gamma \gamma$ decays. Because there are only two quite energetic photons in the
Table 1: Summary of current experimental and theoretical FCNC processes of rare charm decays.

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Experimental Limit</th>
<th>Standard Model Predictions</th>
</tr>
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<tbody>
<tr>
<td>$D^+ \to \pi^+ e^+ e^-$</td>
<td>$&lt; 4.5 \times 10^{-9}$</td>
<td>$2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$D^+ \to \pi^+ \mu^+ \mu^-$</td>
<td>$&lt; 1.5 \times 10^{-5}$</td>
<td>$1.9 \times 10^{-6}$</td>
</tr>
<tr>
<td>$D^+ \to \rho^+ e^+ e^-$</td>
<td>$&lt; 1.0 \times 10^{-4}$</td>
<td>$4.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>$D^0 \to \pi^0 e^+ e^-$</td>
<td>$&lt; 6.6 \times 10^{-5}$</td>
<td>$0.8 \times 10^{-6}$</td>
</tr>
<tr>
<td>$D^0 \to \rho^0 e^+ e^-$</td>
<td>$&lt; 5.8 \times 10^{-4}$</td>
<td>$1.8 \times 10^{-6}$</td>
</tr>
<tr>
<td>$D^0 \to \rho^0 \mu^+ \mu^-$</td>
<td>$&lt; 2.3 \times 10^{-4}$</td>
<td>$1.8 \times 10^{-6}$</td>
</tr>
<tr>
<td>$D^0 \to e^+ e^-$</td>
<td>$&lt; 1.3 \times 10^{-5}$</td>
<td>$10^{-24}$</td>
</tr>
<tr>
<td>$D^0 \to \mu^+ \mu^-$</td>
<td>$&lt; 3.3 \times 10^{-6}$</td>
<td>$10^{-13} - 10^{-19}$</td>
</tr>
<tr>
<td>$D^0 \to \gamma \gamma$</td>
<td>No Data</td>
<td>$10^{-8} - 10^{-10}$</td>
</tr>
<tr>
<td>$D \to \pi(K)\nu\bar{\nu}$</td>
<td>No Data</td>
<td>$10^{-15} - 10^{-16}$</td>
</tr>
</tbody>
</table>

$D^0 \to \gamma \gamma$ final states and due to the lack of constraints of any kind (vertex, $\pi^0$ constraint), the mass resolution for $D^0 \to \gamma \gamma$ is much worse than decay modes with only charged tracks ($D^0 \to K^- \pi^+$, for example). Figure 3 shows the invariant mass of the reconstructed $D^0 \to \gamma \gamma$ Monte Carlo signal events from inclusive continuum production. Due to the poor mass resolution and huge combinatoric background from random photons, it is hopeless to look for a $D^0$ mass peak in searching for FCNC $D^0 \to \gamma \gamma$ decays.

However, if we search for $D^{*+} \to D^{0} \pi^+$ where $D^0 \to \gamma \gamma$, things will be very different. The $(D^{*+} - D^0 - \pi^+)$ mass resolution is less than 1MeV which does not depend much on the $D^0$ decay mode. Furthermore, we have an excellent calibration mode of $D^{*+} \to D^{0} \pi^+$ where $D^0 \to \pi^0 \pi^0$.

The branching fraction of $D^0 \to \pi^0 \pi^0$ was measured to be: $Br(D^0 \to \pi^0 \pi^0) = (8.4 \pm 2.2) \times 10^{-4}$ [3, 4]. In the recent CLEO paper searching for CP violation in $D^0$ decays [5], $810 \pm 89$ signal events were observed in $D^{*+} \to D^{0} \pi^+$ where $D^0 \to \pi^0 \pi^0$.

### 2.1 Comparison of $D^{*+} \to D^{0} \pi^+$ where $D^0 \to \pi^0 \pi^0$ and $\gamma \gamma$

Figure 4 compares the momentum spectra of $\gamma$ in $D^0 \to \gamma \gamma$ decays and $\pi^0$ in $D^0 \to \pi^0 \pi^0$ decays. They are almost identical, as we can expect. It is the softer particle’s momentum that is more relevant to the signal selection efficiency. Figure 5 shows the momentum spectra of the less energetic $\gamma$ in $D^0 \to \gamma \gamma$ decays and the less energetic $\pi^0$ in $D^0 \to \pi^0 \pi^0$ decays. They are very similar as expected. The $D^0$ momentum and the momentum of its decay product is certainly correlated. Figure 6 shows the momentum of $D^0$ vs momentum of the less energetic $\gamma$ in $D^0 \to \gamma \gamma$ decays and the less energetic $\pi^0$ in $D^0 \to \pi^0 \pi^0$ decays. Figure 7 compares the mass resolutions for $D^0 \to \pi^0 \pi^0$ and $D^0 \to \gamma \gamma$. The mass resolution for $D^0 \to \pi^0 \pi^0$ is better than $D^0 \to \gamma \gamma$, thanks to the $\pi^0$ mass constraint.

Each $\pi^0$ in $D^0 \to \pi^0 \pi^0$ decay further decays into two photons. Figure 8 shows the momentum
spectra of \( \gamma \)'s in \( D^0 \rightarrow \pi^0 \pi^0 \) decays where \( \pi^0 \rightarrow \gamma \gamma \). Figure 9 shows the momentum spectrum of the least energetic \( \gamma \) in \( D^0 \rightarrow \pi^0 \pi^0 \) decays where \( \pi^0 \rightarrow \gamma \gamma \). Though the \( \pi^0 \) in \( D^0 \rightarrow \pi^0 \pi^0 \) decay is quite energetic, the final state \( \gamma \)'s are quite soft, which hurts the signal selection efficiency for \( D^0 \rightarrow \pi^0 \pi^0 \).

Figure 10 shows the momentum spectrum of the soft charged \( \pi^+ \) in \( D^{++} \rightarrow D^0 \pi^+ \) which is strongly correlated to the \( D^0 \) momentum. Figure 11 shows the momentum of the soft charged \( \pi^+ \) vs the momentum of the \( D^0 \) in \( D^{++} \rightarrow D^0 \pi^+ \). The common requirement of \( D^0 \) momentum to be greater than 2.0 GeV/c in CLEO charm analyses corresponds to a momentum cut of the soft charge \( \pi^+ \) around 100 MeV/c.

Figure 12 shows the reconstructed \( (D^{++} - D^0 - \pi^-) \) mass from same amount of signal MC \( D^{++} \rightarrow D^0 \pi^+ \) where \( D^0 \rightarrow \pi^0 \pi^0 \) and \( \gamma \gamma \) after very similar selection cuts. From the shapes and relative sizes of the peaks we can see the \( (D^{++} - D^0 - \pi^-) \) mass resolution are very similar for \( D^{++} \rightarrow D^0 \pi^+ \) where \( D^0 \rightarrow \pi^0 \pi^0 \) and \( \gamma \gamma \), while the selection efficiency for \( D^0 \rightarrow \gamma \gamma \) is higher than \( D^0 \rightarrow \pi^0 \pi^0 \).

2.2 Analysis Strategy to Search for \( D^0 \rightarrow \gamma \gamma \)

Using \( D^{++} \rightarrow D^0 \pi^+ \) and comparing \( D^0 \rightarrow \pi^0 \pi^0 \) with \( D^0 \rightarrow \gamma \gamma \) is a good analysis strategy to search for \( D^0 \rightarrow \gamma \gamma \). Giving \( Br(D^0 \rightarrow \pi^0 \pi^0) = (8.4 \pm 2.2) \times 10^{-4} \) [3, 4], and the observation of \( 810 \pm 89 \) signal events in \( D^{++} \rightarrow D^0 \pi^+ \) where \( D^0 \rightarrow \pi^0 \pi^0 \) [5], we should be able to achieve a sensitivity of around \( 10^{-5} \) for \( Br(D^0 \rightarrow \gamma \gamma) \) with full CLEO II+II-V data.

3 Event Selection

Hadronic event with KLASGL = 10 are selected. Monte Carlo study shows that this requirement only results in a \( \sim 2\% \) loss in signal MC event selection efficiency.

3.1 \( D^0 \rightarrow \gamma \gamma \) selection

Photon candidates are required to satisfy the Rare B Group photon quality cuts [6]. To select good isolated photon candidates and reject background from \( \pi^0 \) decays, photon candidates that forms \( \pi^0 \) candidates (3\( \sigma \)) are rejected (see section 3.7 for the determination of this cut). The momentum of each photon candidate is required to be greater than 0.55 GeV/c (see section 3.6 for the determination of this cut). The mass of \( D^0 \rightarrow \gamma \gamma \) candidates are required to satisfy: \(-100 \text{MeV} < \gamma \gamma - D^0 < 75 \text{MeV} \) (2.5\( \sigma \)). To further suppress huge combinatoric background, the momentum of each \( D^0 \) candidate is required to be great than 2.2 GeV/c. (see section 3.6 for the determination of this cut).

3.2 \( D^0 \rightarrow \pi^0 \pi^0 \) selection

\( \pi^0 \) candidates are required to satisfy the Rare B Group \( \pi^0 \) quality cuts [6]. The momentum of each \( \pi^0 \) candidate is required to be greater than 0.55 GeV (see section 3.6 for the determination
of this cut. The mass of $D^0 \rightarrow \pi^0 \pi^0$ candidates are required to satisfy: $-70 \text{MeV} < \gamma \gamma - D^0 < 50 \text{MeV}$ (2.5$\sigma$). To further suppress huge combinatoric background, the momentum of each $D^0$ candidate is required to be great than 2.2GeV/c. (see section 3.6 for the determination of this cut).

### 3.3 $D^{*+} \rightarrow D^0 \pi^+$ selection

A charged track with $|\text{DBCD}| < 3 \text{ mm}$ and $|Z0\text{CD}| < 5 \text{ cm}$ is combined with the $D^0$ candidate to form $D^{*+} \rightarrow D^0 \pi^+$ [5]. The dE/dx information of this charged track, if exist, is required to be consistent with pion within 3$\sigma$. The $(D^{*+} - D^0 - \pi^+)$ mass is required to be between 0 and 0.025GeV.

### 3.4 Data and Monte Carlo Sample

Full CLEO II+II.V data which consists of 13.76fb$^{-1}$ integrated luminosity is used for this analysis. 40 million continuum Monte Carlo and 9.2 million $B\bar{B}$ Monte Carlo events are also used for event selection optimization and the study of the background.

### 3.5 Reproduce of $D^{*+} \rightarrow D^0 \pi^+$ where $D^0 \rightarrow \pi^0 \pi^0$ result

Very similar selection cuts (momentum of $D^0 > 2.0\text{GeV}$ and momentum of $\pi^0 > 0.4\text{GeV/c}$) are used to reproduce the CLEO published results [5] on $D^{*+} \rightarrow D^0 \pi^+$ where $D^0 \rightarrow \pi^0 \pi^0$ result. The comparison is shown in Figure 13. The plot on the left comes from CLEO published paper [5] and the plot on the right is produced with very similar selection cuts. The two results are consistent with each other. The differences between the CLEO published paper [5] and this analysis are:

- XBALL $\pi^0$ (published CLEO paper) vs CCFC $\pi^0$ (this analysis)
- Cut on $D^0$ decay angle (published CLEO paper) vs cut on $\pi^0$ momentum (this analysis)

Figure 14 shows the comparison of the full CLEO II+II.V data with normalized $B\bar{B}$ plus continuum MC for $D^{*+} \rightarrow D^0 \pi^+$ where $D^0 \rightarrow \pi^0 \pi^0$. Data and Monte Carlo are in very good agreement, both the $D^{*+} \rightarrow D^0(\pi^0 \pi^0) \pi^+$ signal and the background level.

### 3.6 Optimization of $D^{*+} \rightarrow D^0 \pi^+$ where $D^0 \rightarrow \pi^0 \pi^0$ Event Selection

Selection cuts are optimized to make full use of our date set. To achieve the best $Br(D^{*+} \rightarrow D^0(\pi^0 \pi^0) \pi^+)$ measurement (i.e. $\frac{Br(D^{*+} \rightarrow D^0(\gamma\gamma) \pi^+)}{Br(D^{*+} \rightarrow D^0(\pi^0 \pi^0) \pi^+)}$), we vary momentum requirements on the $D^0$ and $\pi^0$ to achieve the minimum (Yield Error)/(Signal Yield) for $D^{*+} \rightarrow D^0 \pi^+$ where $D^0 \rightarrow \pi^0 \pi^0$.

We vary the momentum requirement on $D^0$ from 1.0 GeV/c to 2.8 GeV/c at step of 0.2 GeV/c. At each step, we vary the momentum requirement on the $\pi^0$ from 0.4 GeV/c (pre-selection cut) to 0.8 GeV/c at step of 0.05 GeV/c. For each $D^0$ and $\pi^0$ cut, we plot the $(D^{*+} - D^0 - \pi^+)$
mass using normalized $B\overline{B}$ plus continuum MC. The signal yield and yield error come from
mn-fit using Threshold + Gaussian functions to the histogram.

Figure 15 shows the result of optimization. The $(\text{Yield Error})/(\text{Signal Yield})$ are plotted as
a function of various $D^0$ and $\pi^0$ momentum cuts. The minimum $(\text{Yield Error})/(\text{Signal Yield})$
is achieved at momentum of $D^0 > 2.2$GeV/c and momentum of $\pi^0 > 5.5$GeV/c. Figure 16 shows the comparison of full CLEO II+II.V data with normalized $B\overline{B}$ plus continuum MC for
$D^{*+} \rightarrow D^0\pi^+$ where $D^0 \rightarrow \pi^0\pi^0$ after the optimized selection cuts. Data and Monte Carlo are
in very good agreement, both the $D^{*+} \rightarrow D^0(\pi^0\pi^0)\pi^+$ signal and the background level. Figure 17 shows the mn-fit result of the full CLEO II+II.V data with the optimized selection cuts.
$628.0\pm31.8 \ D^{*+} \rightarrow D^0(\pi^0\pi^0)\pi^+$ signal events are observed.

3.7 With or without $\pi^0$ veto for $D^{*+} \rightarrow D^0\pi^+$ where $D^0 \rightarrow \gamma\gamma$

Figure 18 shows the difference in signal efficiency and background level with or without the
$3\sigma \ \pi^0$ veto. The $3\sigma \ \pi^0$ veto requirement results in a signal efficiency loss of about 20% while
reduces the background level by almost a factor of 3. We therefore decide to use this selection
cut.

3.8 Sensitivity of searching for $D^{*+} \rightarrow D^0\pi^+$ where $D^0 \rightarrow \gamma\gamma$

Figure 19 shows the comparison of $D^{*+} \rightarrow D^0\pi^+$ where $D^0 \rightarrow \pi^0\pi^0$ and $\gamma\gamma$, both the signal
efficiency and background levels using the optimized event selection. The histograms in the
top plot comes from the same amount of $D^{*+} \rightarrow D^0\pi^+$ where $D^0 \rightarrow \pi^0\pi^0$ and $\gamma\gamma$ signal Monte Carlo. So the relative size of the two peaks represents the relative signal efficiencies for these
decay modes. The histograms in the bottom plot comes from normalized $B\overline{B}$ plus continuum
Monte Carlo after event selections for $D^{*+} \rightarrow D^0\pi^+$ where $D^0 \rightarrow \pi^0\pi^0$ and $\gamma\gamma$. The crossfeed
from $D^{*+} \rightarrow D^0\pi^+$ where $D^0 \rightarrow \pi^0\pi^0$ to $D^{*+} \rightarrow D^0\pi^+$ where $D^0 \rightarrow \gamma\gamma$ is negligible. The signal
efficiency for $D^{*+} \rightarrow D^0\pi^+$ where $D^0 \rightarrow \gamma\gamma$ is about 40% higher than that of $D^0 \rightarrow \pi^0\pi^0$, while
the background level is about factor of 3 lower.

Figure 20 shows the mn-fit fit result to the normalized background from $B\overline{B}$ plus continuum
Monte Carlo for $D^{*+} \rightarrow D^0\pi^+$ where $D^0 \rightarrow \gamma\gamma$. The $13.8\pm8.3$ yield from fit to background
gives us the sensitivity can be achieved. The sensitivity for searching for $D^0 \rightarrow \gamma\gamma$ is around
$10^{-5}$ for $Br(D^0 \rightarrow \gamma\gamma)$.

4 Results

Figure 20 shows the result of $D^{*+} \rightarrow D^0\pi^+$ where $D^0 \rightarrow \gamma\gamma$ with the full CLEO II+II.V data. Figure 21 shows the mn-fit fit to the full CLEO II+II.V data for $D^{*+} \rightarrow D^0\pi^+$ where $D^0 \rightarrow \gamma\gamma$
which gives a yield of $19.2\pm9.3$. No significant signal is observed for $D^{*+} \rightarrow D^0\pi^+$ where
$D^0 \rightarrow \gamma\gamma$. 

5
5 Systematic Errors

The systematic error sources and their contributions are summarized in Table 2. The photon, $\pi^0$ and soft $\pi^+$ finding efficiency systematic errors come from previous studies [7, 8, 9, 10]. We check the changes in signal yield using width of the Gaussian determined from Signal MC or background shape determined from normalized $B\bar{B}$ plus continuum MC. The maximum change in the signal yield is taken as the fit yield systematic error. The systematic errors in $D^{*+} \rightarrow D^0\pi^+$ where $D^0 \rightarrow \pi^0\pi^0$ and $\gamma\gamma$ are dominated by those due to $\pi^0$ and photon finding efficiencies.

<table>
<thead>
<tr>
<th>Systematic Error Source</th>
<th>Systematic Error (in percent)</th>
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</thead>
<tbody>
<tr>
<td>$\pi^0$ finding Efficiency</td>
<td>5.0 per $\pi^0$</td>
</tr>
<tr>
<td>Photon finding Efficiency</td>
<td>3.0 per photon</td>
</tr>
<tr>
<td>Fit Yield</td>
<td>3.0</td>
</tr>
<tr>
<td>$D^0$ selection</td>
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<tr>
<td>MC Statistics</td>
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<tr>
<td>Hadronic Event Selection</td>
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</table>

6 Conclusion

The common systematic errors for $D^{*+} \rightarrow D^0\pi^+$ cancel out in measuring $\frac{Br(D^0\rightarrow\pi^0\pi^0)}{Br(D^0\rightarrow\pi^0\pi^0)}$. The relative efficiency for $D^0 \rightarrow \gamma\gamma$ and $D^0 \rightarrow \pi^0\pi^0$ is determined from signal MC to be: $\frac{Eff(D^0\rightarrow\gamma\gamma)}{Eff(D^0\rightarrow\pi^0\pi^0)} = 1.58 \pm 0.05$. With all the signal yields, relative selection efficiency and systematic errors, we set upper limit: $\frac{Br(D^0\rightarrow\pi^0\pi^0)}{Br(D^0\rightarrow\pi^0\pi^0)} < 0.034$ at 90% C.L.

Using CLEO’s branching fraction measurement of $Br(D^0 \rightarrow \pi^0\pi^0) = (8.4 \pm 2.2) \times 10^{-4}$ [3, 4], we set upper limit: $Br(D^0 \rightarrow \gamma\gamma) < 3.0 \times 10^{-5}$ at 90% C.L.

7 Acknowledgement

I would like to thank Feng Liu for the help with the signal Monte Carlo generation. I would also like to thank the other members of the SMU group for their encouragements.

References


Figure 1: Momentum spectrum of $D^0$ production in inclusive $\bar{B}B$ and continuum Monte Carlo.

Figure 2: Momentum spectrum of $\gamma$'s in $D^0 \to \gamma\gamma$ decay.
Figure 3: Invariant mass spectrum of the reconstructed $D^0 \rightarrow \gamma\gamma$ Monte Carlo signal from inclusive continuum production.

Figure 4: Momentum spectra of $\gamma$ in $D^0 \rightarrow \gamma\gamma$ and $\pi^0$ in $D^0 \rightarrow \pi^0\pi^0$. 
Figure 5: Momentum spectra of the less energetic $\gamma$ in $D^0 \rightarrow \gamma\gamma$ and the less energetic $\pi^0$ in $D^0 \rightarrow \pi^0\pi^0$.

Figure 6: Momentum of $D^0$ vs momentum of the less energetic $\gamma$ in $D^0 \rightarrow \gamma\gamma$ decays and the less energetic $\pi^0$ in $D^0 \rightarrow \pi^0\pi^0$ decays.
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Figure 9: Momentum spectra of the least energetic $\gamma$ in $D^0 \rightarrow \pi^0\pi^0$ where $\pi^0 \rightarrow \gamma\gamma$.

Figure 10: Momentum spectra of the soft $\pi^+$ in $D^{*+} \rightarrow D^0\pi^+$. 
Figure 11: Momentum of the soft $\pi^+$ vs the momentum of the $D^0$ in $D^{*+} \rightarrow D^0\pi^+$. 

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Figure 18: Normalized background from $B\bar{B}$ and continuum Monte Carlo for $D^{*+} \to D^0\pi^+$ where $D^0 \to \gamma\gamma$ with or without $\pi^0$ veto for $\gamma$ candidates.
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Figure 20: Fit to normalized background from $B\bar{B}$ and continuum Monte Carlo for $D^+ \rightarrow D^0\pi^+$ where $D^0 \rightarrow \gamma\gamma$. 
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Figure 22: Fit to full CLEO II+II.V data for $D^{*+} \rightarrow D^0\pi^+$ where $D^0 \rightarrow \gamma\gamma$. 