Search for $D^0 \rightarrow \gamma \gamma$ at BESIII

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Based on the \( \sim 2.9 \text{ fb}^{-1} \) data set taken at the nominal mass of $\psi(3770)$, we report our preliminary result on a search for $D^0 \rightarrow \gamma \gamma$. We find no significant signal and set an upper limit on $\mathcal{B}(D^0 \rightarrow \gamma \gamma)/\mathcal{B}(D^0 \rightarrow \pi^0 \pi^0) < 5.8 \times 10^{-3}$ at 90% confidence level.

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1 Why $D^0 \to \gamma \gamma$?

In the Standard Model (SM), flavor-changing neutral currents (FCNC) occur only at the loop level, where they are highly suppressed by the GIM mechanism [1]. The decay of $D^0 \to \gamma \gamma$ must be produced by charm-changing neutral currents. From the short distance contributions, the decay rate for $D^0 \to \gamma \gamma$ is predicted to be $3 \times 10^{-11}$ [2, 3, 4]. However, the long distance contributions significantly enhance the decay rate which is estimated to be $(1 - 3) \times 10^{-8}$ [3, 4]. This FCNC decay could be enhanced by new physics (NP) effects which lead to contributions at loop level [5, 6]. For instance, in the framework of the Minimal Supersymmetric Standard Model (MSSM), the calculation shows that the decay rate for $c \to u \gamma$ transition could be $6 \times 10^{-6}$, which is one to two orders of magnitudes enhanced relative to the SM rate, by considering gluino exchange [5].

Experimental searches for $D^0 \to \gamma \gamma$ were performed by the CLEO [7] and BABAR [8] experiments based on data samples collected at the $\Upsilon(4S)$ peak. They found no significant signals. The latter experiment yields the most stringent experimental upper limit to date on the $B(D^0 \to \gamma \gamma)$, $2.4 \times 10^{-6}$ at 90\% confidence level (C.L.).

Here I report a preliminary result of our search for $D^0 \to \gamma \gamma$ based on a sample acquired at the BEPCII energy-symmetric $e^+e^-$ collider with the BESIII detector [9]. This sample was collected at $\sqrt{s} = 3.773$ GeV with an integrated luminosity of $\sim 2.9$ fb$^{-1}$ in which the background level at this open charm threshold is expected to be substantially lower than that at the $\Upsilon(4S)$ peak.

2 Analyses

One of the major backgrounds in the analysis of $D^0 \to \gamma \gamma$ comes from $D^0 \to \pi^0 \pi^0$. I first describe our study on the decay of $D^0 \to \pi^0 \pi^0$, then move on to discuss our search for $D^0 \to \gamma \gamma$. In the end, we give our result in terms of a ratio of branching fractions, $B(D^0 \to \gamma \gamma)/B(D^0 \to \pi^0 \pi^0)$.

2.1 $D^0 \to \pi^0 \pi^0$

Each $\pi^0$ candidate is constructed from a pair of good photons, each of which is defined as: it is based on a shower in the electromagnetic CsI crystal calorimeter (EMC) of the BESIII detector [9]; should not match with any charged tracks reconstructed by the main drift chamber; must be reconstructed within barrel ($|\cos \theta| < 0.80$) or endcap ($0.86 < |\cos \theta| < 0.93$) sections of the EMC where $\theta$ is a polar angle with respect to the positron beam direction; deposited energy of the shower must be at least 25 (50) MeV when it is reconstructed in the barrel (endcap) section. Once a pair is found to be a $\pi^0$ candidate ($110 < M_{\gamma \gamma} < 150$ MeV/$c^2$), it is kinematically
constrained to the known mass \([10]\) from which the resultant constrained momentum of \(\pi^0\) is used for the rest of the analysis. These \(\pi^0\) candidates are also tested for the possibility that one of their showers could form a \(\pi^0\) with some other shower, and are rejected if any other pairing were more consistent with a \(\pi^0\) mass. Then, we form \(\Delta E (\equiv E_{\pi^0\pi^0} - E_{\text{beam}})\) for every two \(\pi^0\) candidates and require \((-60 < \Delta E < 30)\) MeV. In the end, we extract our signal from a distribution of beam-constrained mass, \(M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - \mathbf{p}_D^2c^2}\) where \(E_{\text{beam}}\) is the beam energy and \(\mathbf{p}_D\) is the \(D^0(\rightarrow \pi^0\pi^0)\) candidate momentum.

We perform a maximum likelihood fit to the resultant \(M_{bc}\) distribution based on our data sample as shown in Figure 1. The signal shape is represented by a double Gaussian and its background is described by an ARGUS background function. In this figure, we also overlay the expected background component based on our Monte Carlo (MC) samples, represented by the blue-solid histogram, which apparently fails to describe the observed background level in data. We attribute this discrepancy to the incomplete simulation of continuum process under the \(\psi(3770)\) peak.

The fit yields \(4081 \pm 117\) signal events with \(52\sigma\) statistical significance. The significance is obtained by \(\sqrt{-2 \times \ln (\mathcal{L}_w/\mathcal{L}_{wo})}\) where \(\mathcal{L}_w\) and \(\mathcal{L}_{wo}\) are the likelihood values obtained from a fit without and with the signal shapes. The \(\chi^2\) for the fit is \(42.0\) for 56 data points (minus the 5 floated parameters).

We estimate possible systematic uncertainties on the extracted yields that include fit range, background shape, the requirement on \(\Delta E\), and reconstruction of \(\pi^0\). The single largest source of systematic uncertainty is due to the assumed signal shape. While we use a double Gaussian to represent the signal shape, the shape of a double Gaussian was fixed based on our MC simulation which cannot describe the data well. This is currently under the investigation as of this writing. Table 1 shows a summary of dominant sources of the estimated systematic uncertainties.

### Table 1: Systematic uncertainties on the extracted yields of \(D^0 \rightarrow \pi^0\pi^0\).

| Sources          | Rel. error (%) |
|------------------|----------------|
| Signal shape     | ±8.7           |
| \(\pi^0\) recon. | ±2.0           |
| MC stat.         | ±0.3           |
| **Total**        | ±8.9           |

With the total reconstruction efficiency of \((23.3 \pm 0.1)\%\), the preliminary efficiency-corrected yield of \(D^0 \rightarrow \pi^0\pi^0\) based on our \(\psi(3770)\) data set is \(17521 \pm 500(\text{stat.}) \pm 1559(\text{syst.})\) events.
Figure 1: A fit to the $D^{0} \rightarrow \pi^{0}\pi^{0}$ candidate $M_{bc}$ distribution based on the $\psi(3770)$ data sample. The black points are data, the black-smooth curve represents the overall fit (signal plus background), and the red-dashed curve corresponds to the fitted background shape. The blue-solid histogram represents the expected background shape and size based on our MC samples while the blue-dotted histogram is a fit to the data based on this expected MC-based background shape.
2.2 $D^0 \to \gamma\gamma$

The analysis of $D^0 \to \gamma\gamma$ starts by taking the most and the $2^{nd}$ most energetic photon candidates in a given event, where the photon selection criteria are the same as the ones for the good photons previously described except we restrict these two photons to be reconstructed only within the barrel section of the EMC in order to suppress contaminations from continuum (i.e., $e^+e^- \to \gamma^* \to q\bar{q} \to$ light hadrons, where $q = u,d,s$), including doubly radiative Bhabha events. Even though these photons are Doppler broadened in the lab frame, the reconstructed photon energies, thus including the detector resolutions, are mostly found to be at least 700 MeV.

There are two major backgrounds in this analysis, one from the continuum processes as mentioned above and the other from $D^0 \to \pi^0\pi^0$. The latter poses an irreducible background when the two $\pi^0$s decay into four photons in which two of them carry away most of the initial $D^0$ momentum. Figure 2 shows the $\Delta E$ distribution based on our MC sample in which only generic decays of $D\bar{D}$ are present, and $D^0 \to \gamma\gamma$ is set to zero. It can be seen that the background in the signal region ($|\Delta E| < 150$ MeV which corresponds to $\sim \pm 3\sigma$) is dominated by the events from $D^0 \to \pi^0\pi^0$, represented by the blue-dotted histogram in the figure.

Figure 2: $D^0 \to \gamma\gamma$ candidate $\Delta E$ distribution based on MC sample in which only generic decays of $D\bar{D}$ are present, and $D^0 \to \gamma\gamma$ is set to zero. Notice that almost the entire background comes from two-body decays, $D^0 \to X + \pi^0$, denoted by the red-dashed histogram. In the signal region ($|\Delta E| < 150$ MeV corresponds to $\sim \pm 3\sigma$), the background is dominated by events from $D^0 \to \pi^0\pi^0$, represented by the blue-dotted histogram.
To further suppress these backgrounds, our signal selection criteria are optimized based on MC samples to maximize the signal sensitivity. Each of the signal photon candidates must have a lateral shower profile that is consistent with that of an isolated electromagnetic shower. We suppress photons that look like coming from \( \pi^0 \rightarrow \gamma\gamma \) by rejecting a candidate that forms \( \cos \theta_{\gamma\gamma} \geq 0.6 \) where \( \theta_{\gamma\gamma} \) is an opening angle between a signal photon candidate and any other photon when the given pair form \( 110 < M_{\gamma\gamma} < 150 \text{ MeV}/c^2 \). Requiring each of the signal photon candidates to be at least 20° away from any reconstructed charged track effectively suppresses the doubly radiative Bhabha events. In addition, we demand all selected events to satisfy \( E_{EMC}/p < 0.8 \) or \( E_{EMC}/p > 1.05 \), where \( p \) is the momentum of the fastest reconstructed charged track in a given event and \( E_{EMC} \) is the corresponding deposited energy in the EMC. Electrons and positons tend to give \( E_{EMC}/p \sim 1 \). To suppress contaminations from the rest of the continuum processes, we require there be at least one charged kaon reconstructed in a given event. In the end, we extract our signals from a \( \Delta E \) distribution while requiring \( 1860 < M_{bc} < 1870 \text{ MeV}/c^2 \) which gives an overall reconstruction efficiency of \( (12.02 \pm 0.1)\% \).

Figure 3 shows the result of a maximum-likelihood fit to the \( \Delta E \) distribution based on the \( \psi(3770) \) data set. In the fit, the signal shape is fixed by the corresponding MC shape. The background shape consists of three parts: MC-based shape to represent the contamination from \( D^0 \rightarrow \pi^0\pi^0 \) whose size is also fixed based on our own observation; a 1\textsuperscript{st} order polynomial that covers the contamination from Bhabha events which appear smoothly over the entire \( \Delta E \) spectrum; a 1\textsuperscript{st} order exponential polynomial, corresponding to the rest of the backgrounds. Black points are data, the black-solid curve is the overall fitted curve (signal plus backgrounds), the red-dashed curve is the fitted total backgrounds, the green curve is a sum of the exponential and linear polynomials. The fit gives \( \chi^2 \) of 63.7 for 80 data points (minus the 4 floated parameters) which yields \( -2.9 \pm 7.1 \) signal events. This translates into an upper limit of 11 events at 90% confidence level (C.L.) based on the Bayesian method.

Table 2 shows a summary of our estimation of the systematic uncertainties on the ratio, \( \mathcal{B}(D^0 \rightarrow \gamma\gamma)/\mathcal{B}(D^0 \rightarrow \pi^0\pi^0) \). The uncertainties we consider include: photon reconstruction efficiencies; the event-wise selections that require there be at least one charged Kaon reconstructed and the cut on \( E_{EMC}/p \); the requirement on \( M_{bc} \); the detector resolution of the signal shape; the assumed background shape, fit range. In this table, sources of uncertainties, that are estimated based on the data and that are determined to be no more than half of the measured statistical uncertainty, are listed as “negligible”.

Including the estimated total systematic uncertainty, we arrive at \( \mathcal{B}(D^0 \rightarrow \gamma\gamma)/\mathcal{B}(D^0 \rightarrow \pi^0\pi^0) < 5.8 \times 10^{-3} \) at 90% C.L.
Figure 3: A fit to the $D^0 \rightarrow \gamma\gamma$ candidate $\Delta E$ distribution based on the $\psi(3770)$ data sample. Black points are data, solid black curve is the overall fitted curve (signal plus backgrounds), the red-dashed curve is the fitted total background, and the green curve is the exponential and linear polynomials.

Table 2: Summary of the estimated systematic uncertainties on $\mathcal{B}(D^0 \rightarrow \gamma\gamma)/\mathcal{B}(D^0 \rightarrow \pi^0\pi^0)$.

| Sources                | rel. errors (%) |
|------------------------|-----------------|
| Photon recon.          | 5.0             |
| Event-wise cut         | 4.9             |
| Cut on $M_{bc}$        | 2.5             |
| Signal resolution      | negligible      |
| Background shape       | negligible      |
| Fit range              | negligible      |
| MC stat.               | 0.4             |
| Stat. from $D^0 \rightarrow \pi^0\pi^0$ | 2.9  |
| Syst. from $D^0 \rightarrow \pi^0\pi^0$ | 8.9  |
| Total                  | 12.0            |
3 Conclusions and a future prospect

Based on the $\sim 2.9 \text{ fb}^{-1}$ data set taken at $\sqrt{s} = 3.773$ GeV, we search for $D^0 \to \gamma\gamma$. We find no significant signal and set our preliminary upper limit on $\mathcal{B}(D^0 \to \gamma\gamma)/\mathcal{B}(D^0 \to \pi^0\pi^0) < 5.8 \times 10^{-3}$ at 90% C.L. With the known value of $\mathcal{B}(D^0 \to \pi^0\pi^0)$ [10], this corresponds to $\mathcal{B}(D^0 \to \gamma\gamma) < 4.7 \times 10^{-6}$.

While we are waiting for BESIII to take more data at $\sqrt{s} = 3.773$ GeV, there is an alternate analysis approach that is unique to our data sample. The produced $\psi(3770)$ in our sample decays into a pair of $D^0\overline{D^0}$. Reconstructing one of the $D^0$ mesons with known exclusive modes while searching for $D^0 \to \gamma\gamma$ in the other $D^0$ decay would yield an almost background-free environment, except for the irreducible contamination from $D^0 \to \pi^0\pi^0$ for which we have control. Such a study is also currently under way.

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