Analysis of the $\gamma\gamma \rightarrow D\bar{D}$ reaction and the $D\bar{D}$ bound state

En Wang, 1, 2, * Hong-Shen Li, 1 Wei-Hong Liang, 2, 3, † and Eulogio Oset 2, 4, ‡

1 School of Physics and Microelectronics, Zhengzhou University, Zhengzhou, Henan 450001, China
2 Department of Physics, Guangxi Normal University, Guilin 541004, China
3 Guangxi Key Laboratory of Nuclear Physics and Technology, Guangxi Normal University, Guilin 541004, China
4 Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia - CSIC, Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain

In this work, we investigate the reaction of $\gamma\gamma \rightarrow D\bar{D}$, taking into account the s-wave $D\bar{D}$ final state interaction. By fitting to the $D\bar{D}$ invariant mass distributions measured by the Belle and BaBar Collaborations, we obtain a good reproduction of the data by means of a $D\bar{D}$ amplitude that produces a bound $D\bar{D}$ state with $I = 0$ close to threshold. The error bands of the fits indicate, however, that more precise data on this reaction are needed to be more assertive about the position and width of such state.

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I. INTRODUCTION

The $\chi_{c0}(2P)$ state was introduced in the PDG [1] ($\chi_{c0}(3860)$) with $J^{PC} = 0^{++}$, $M = 3862^{+26+40}_{-32-13}$ MeV, and $\Gamma = 201^{+154+88}_{-67-82}$ MeV] 1 based on the single experimental measurement on the $e^+e^- \rightarrow J/\psi D\bar{D}$ reaction reported by the Belle Collaboration [2], by looking into the $D\bar{D}$ invariant mass distribution close to threshold. These experimental data have only four points below 3900 MeV, with very large errors [2], and it was shown in Ref. [3] that this information was not sufficient to draw any conclusion about the existence of this state. Three important facts were stressed in Ref. [3]: 1) The data divided by phase space did not show any peak that would justify a claim of a state at 3860 MeV. 2) A fit of the data with a bound state of $D\bar{D}$, which has been found in Refs. [4–6], was possible, but again the uncertainties were too large to make any conclusive claims. 3) A fit of the data close to threshold using a Breit-Wigner, as discussed in Ref. [3], should be avoided. This last point has been often recalled concerning fits to data [7, 8].

The question remains whether there are other data which can provide good information on the possible $D\bar{D}$ bound state. One attempt was done in Ref. [9] using early data of the $e^+e^- \rightarrow J/\psi D\bar{D}$ reaction from the Belle Collaboration [10]. Although a $D\bar{D}$ bound state was found consistent with the data, the quality of these data did not allow one to be too strong on the claim of this bound state. Several reactions have been suggested, measuring $D\bar{D}$ mass distributions close to threshold, which can help, with good statistics, to bring an answer to this question. In Ref. [11] three methods were devised to find an answer to this problem: the first one is the radiative decay of the $\psi(3770), \psi(3770) \rightarrow \gamma X(3700) \rightarrow \gamma\eta\eta$. The second one proposes the analogous reaction $\psi(4040) \rightarrow \gamma X(3700) \rightarrow \gamma\eta\eta$, and the third reaction is the $e^+e^- \rightarrow J/\psi X(3700) \rightarrow J/\psi\eta\eta$. In Ref. [12] the $B^0$ decay to $D^0\bar{D}^0 K^0$ reaction was suggested. The $B^+ \rightarrow D^0\bar{D}^0 K^+$ reaction has been measured by the BaBar Collaboration [13] and is well reproduced in Ref. [12], but the unmeasured $B^0 \rightarrow D^0\bar{D}^0 K^0$ reaction was found to be more useful because it does not have the tree level contribution for $D^0\bar{D}^0$ production and is proportional to the $D^+D^- \rightarrow D^0\bar{D}^0$ transition amplitude which contains the bound state. In Ref. [14] the $\psi(3770) \rightarrow \gamma D^0\bar{D}^0$ decay was retaken, separating the $D^+D^-$ production from the $D^0\bar{D}^0$ one and showing that the latter has a much bigger potential to provide valuable information concerning the existence of the $D\bar{D}$ bound state.

Awaiting future results from some of the suggested reactions, there are interesting data that we wish to investigate here concerning that point, and these are the $\gamma\gamma \rightarrow D\bar{D}$ data measured by the Belle [15] and BaBar Collaborations [16]. In Ref. [15], the Belle Collaboration has reported the charmonium state $X(3930)$ in the reaction of $\gamma\gamma \rightarrow D\bar{D}$, with mass $3929 \pm 5 \pm 2$ MeV and width $29 \pm 10 \pm 2$ MeV, which are consistent with expectations for the $\chi_{c2}(2P)$ charmonium state. Later the BaBar collaboration has also performed the $\gamma\gamma$ production of the $D\bar{D}$ system, and the

*Electronic address: wangen@zzu.edu.cn
†Electronic address: liangwh@gxnu.edu.cn
‡Electronic address: eulogio.ose@ific.uv.es

1 It should be stressed that the hypothesis of the quantum numbers $J^{PC} = 0^{++}$ is favored over the $2^{++}$ hypothesis at the level of 2.5σ [2].
$D\bar{D}$ invariant mass distribution shows clear evidence for the $X(3930)$ state, its mass and width determined to be $M = 3926.7 \pm 2.7 \pm 1.1$ MeV, and $\Gamma = 21.3 \pm 6.8 \pm 3.6$ MeV [16].

On the other hand the Belle and BaBar data of Refs. [15, 16] were also used in Ref. [17], making fits with Breit-Wigner structures, to suggest that there could be an indication of a $\chi_{c0}(2P)$ state around 3840 MeV and a width about 200 MeV, with the warning that "More refined analysis of the data with higher statistics is definitely necessary to confirm our assertion". Actually we will show that the data divided by phase space does not show any peak around 3840 MeV, thus weakening the guess of Ref. [17], and then provide an alternative explanation of the combined data of Belle and BaBar [15, 16] based on the explicit consideration of the $D\bar{D}$ final state interaction, which can shed some light on the possible $D\bar{D}$ bound state.

II. FORMALISM

A. $D\bar{D}$ interaction in $I = 0$

In Ref. [4], the $s$-wave meson-meson scattering in the charm sector was studied and a prediction for a $D\bar{D}$ bound state with isospin $I = 0$ was made. In Ref [9], it was found that the state with mass $M_{D\bar{D}} = 3730$ MeV, and width $\Gamma_{D\bar{D}} = 30$ MeV was compatible with the data of the process $e^+e^- \rightarrow J/\psi D\bar{D}$ reported by the Belle Collaboration [10].

In Ref. [11], where three methods to detect this state were suggested, a state with $M_{D\bar{D}} = 3720$ MeV and $\Gamma_{D\bar{D}} = 36$ MeV was found including decays to all possible pairs of light pseudoscalar.

In this paper, we use only one channel, apart from the three channels $D^+D^-, D^0\bar{D}^0$, and $D_s\bar{D}_s$, which is $\eta\eta$ to account for the width of the $D\bar{D}$ bound state, as used in Refs. [3, 11, 12]. The transition potentials $V_{i,j}$ ($i,j = D^+D^-, D^0\bar{D}^0$, and $D_s\bar{D}_s$) are tabulated in Table 9 of Appendix A of Ref. [4], and we introduce the potentials of $\eta\eta \rightarrow D^0\bar{D}^0$ with a dimensionless strength $a_{\eta\eta}$ to give the width of the $D\bar{D}$ bound state. The transition potentials of $\eta\eta$ to $\eta\eta$ and $D_s\bar{D}_s$ are not relevant and are taken as zero. As done in Ref. [3], we will multiply the potentials $V_{D^+D^-D_s\bar{D}_s}$ and $V_{D^0\bar{D}^0D_s\bar{D}_s}$ by a factor $f_{D_s\bar{D}_s}$ to stress more the cusp effect.

Then the amplitude $t_{i,j}$ for the $i$ channel to $j$ channel can be obtained from the Bethe-Salpeter equation,

$$T = [1 - VG]^{-1}V,$$

where the matrix $G$ is diagonal with each of its elements given by the loop function for the two particles, and we take the expression of the dimensional regularization as shown in Eq. (31) of Ref. [4], where the $\mu = 1500$ MeV, and the subtraction constant $\alpha$ will be taken as a free parameter.

B. Model for the reaction $\gamma\gamma \rightarrow D\bar{D}$

In this section, we present the model for the reaction,

$$\gamma(p, \epsilon_1) + \gamma(k, \epsilon_2) \rightarrow D^+(p') + D^-(k'),$$

where $p, k, p',$ and $k'$ are the four-momenta of the two incoming photons, $D^+$, and $D^-$, respectively, and $\epsilon_{1,2}$ are the polarizations of the two incoming photons. We can get the mechanism for this process inspired by the work of Ref. [18], where the reactions $\gamma\gamma \rightarrow \pi^+\pi^-$, $\pi^0\pi^0$ were studied. In Ref. [18], the whole range of $\pi\pi$ invariant mass from 280 MeV ($2m_{\pi}$) till 1400 MeV was studied. The model used was good up to about 1000 MeV with no free parameters, and for higher energies the $f_2(1270)$ excitation was introduced by hand. In the present case, we only need the model for about a range of 144 MeV, from the $D\bar{D}$ threshold to 3880 MeV. The model for the process $\gamma\gamma \rightarrow D\bar{D}$ combines the Born terms: the contact term, the $D$ meson exchange in the $t$ and $u$ channels, as shown in Fig. 1.

Contrary to the $\gamma\gamma \rightarrow \pi^+\pi^-$, the $D$ exchange terms are now here much smaller than those of $\pi$ exchange of Ref. [18], because we have the denominator in the $D$ meson propagator at threshold,

$$\frac{1}{(q'^0)^2 - (q')^2 - m_D^2},$$

where $q = (q^0, \vec{q})$ is the four-momentum of the exchanged $D$ meson, and we have $q^0 = p^0 - p'^0 = 0$ and $|\vec{q}| = |\vec{p}| = p^0 \approx m_D$ at the $D\bar{D}$ threshold. So we have,

$$\frac{1}{0 - m_D^2} \approx \frac{1}{-2m_D^2},$$

...
which is much smaller than $1/(−2m^2)$ in absolute value.

These terms have also energy dependence, because we have the vertex with the term $\epsilon \cdot (p' - q)$, which in the Coulomb gauge $\epsilon^0 = 0$ and $\vec{\epsilon} \cdot \vec{p} = 0$ for the photon, which we use to evaluate, is given by,

$$\vec{\epsilon} \cdot (\vec{q} - \vec{p}') = \vec{\epsilon} \cdot (\vec{q} + \vec{p}' - 2\vec{p}') = -2\vec{\epsilon} \cdot \vec{p}'.$$  \hfill (5)

In the limited range of the $D\bar{D}$ invariant masses that we consider $\vec{p}'$ is small and one can easily see that the contribution of the $D$-exchange terms are smaller than 3% of the contact term of Fig. 1(a), $2e^2\vec{\epsilon}_1 \cdot \vec{\epsilon}_2$. Hence we neglect these exchange terms and take the amplitude as,

$$M_{\gamma\gamma \rightarrow D^+D^-} = 2e^2\vec{\epsilon}_1 \cdot \vec{\epsilon}_2.$$  \hfill (6)

Thus, we will neglect the contributions of Figs. 1(b) and (c) in this work.

In addition, there are also other possible exchanges of $D^*$ resonances with anomalous terms but again, the denominator of the propagators are large and the terms are small close to the threshold.

We have the differential cross section for the reaction $\gamma\gamma \rightarrow D\bar{D}$,

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2} \frac{1}{s} \frac{|\vec{p}'|}{|\vec{p}|} \sum |M|^2 = \frac{1}{64\pi^2} \frac{1}{s} \frac{|\vec{p}'|}{|\vec{p}|} \sum |2e^2\vec{\epsilon}_1 \cdot \vec{\epsilon}_2|^2,$$  \hfill (7)

where we average the polarization vectors of the transverse photons,

$$\sum (\vec{\epsilon}_1 \cdot \vec{\epsilon}_2)^2 = \frac{1}{4} \sum_{i,j} \epsilon_{1i}\epsilon_{2i}\epsilon_{1j}\epsilon_{2j}$$

$$= \frac{1}{4} \sum_{i,j} \left( \delta_{ij} - \frac{p_{1i}p_{1j}}{p^2_1} \right) \left( \delta_{ij} - \frac{p_{2i}p_{2j}}{p^2_2} \right) = \frac{1}{2}$$  \hfill (8)

with no angular dependence. Thus, we have the cross section,

$$\sigma = \frac{1}{8\pi} \frac{1}{s} \frac{|\vec{p}'|}{|\vec{p}|} e^4,$$  \hfill (9)

where $s = (p + k)^2$, $\vec{p}$ and $\vec{p}'$ are the three-momenta of the incoming photon and the $D^+$ in the center-mass frame, respectively,

$$|\vec{p}| = \frac{\sqrt{s}}{2}, \quad |\vec{p}'| = \frac{\lambda^{1/2}(s,m^2_D,m^2_{\bar{D}})}{2\sqrt{s}}.$$  \hfill (10)

In our process, we have to take into account the final state interaction of the mesons $D$ and $\bar{D}$. We will differentiate between $D^+D^-$ or $D^0\bar{D}^0$, since in the experiments there is information about both.

### C. Final state interaction

So far we have evaluated the amplitude and cross section of the $\gamma\gamma \rightarrow D^+D^-$ at the tree level without considering the final state interaction of $D^+D^-$. We address here this problem. In addition, the $\gamma\gamma \rightarrow D^0\bar{D}^0$ is null at this level.
and it can only proceed via rescattering of $D^+D^- \rightarrow D^0\bar{D}^0$. This makes this reaction more favorable to learn about a possible $D\bar{D}$ bound state since the $\gamma\gamma \rightarrow D^0\bar{D}^0$ amplitude is then proportional to the $D^+D^- \rightarrow D^0\bar{D}^0$ amplitude which contains information on this possible state. The final state interaction proceeds as depicted in Fig. 2(b). The amplitude in Eq. (6) is now replaced by,

$$\mathcal{M} = 2e^2\bar{c}_1 \cdot \bar{c}_2 \times t$$

where,

$$t_{D^+D^-} = 1 + G_{DD}(M_{inv})t_{D^+D^-D^+D^-}(M_{inv}),$$ \hspace{1cm} (12)

$$t_{D^0\bar{D}^0} = G_{D\bar{D}}(M_{inv})t_{D^0\bar{D}^0D^0\bar{D}^0}(M_{inv}),$$ \hspace{1cm} (13)

with $G_{DD}$ the $D\bar{D}$ loop function and $t_{D^+D^-D^+D^-}$ the $D\bar{D}$ scattering amplitudes, as functions of the $D\bar{D}$ invariant mass $M_{inv}$. The strength of the $D\bar{D} \rightarrow D\bar{D}$ scattering matrix close to threshold is driven by the $D\bar{D}$ bound state in $I = 0$ [4–6] and we write the $D^+D^- \rightarrow D^+D^-$ and $D^+D^- \rightarrow D^0\bar{D}^0$ scattering matrices in terms of the $D\bar{D} \rightarrow D\bar{D}$ ($I = 0$) one. With the isospin doublets ($D^+, -D^0$, $(D^0, D^-)$, we have,

$$|D^+D^-\rangle = \frac{1}{\sqrt{2}}|D\bar{D}, I = 0, I_3 = 0\rangle + \frac{1}{\sqrt{2}}|D\bar{D}, I = 1, I_3 = 0\rangle,$$

$$|D^0\bar{D}^0\rangle = \frac{1}{\sqrt{2}}|D\bar{D}, I = 0, I_3 = 0\rangle - \frac{1}{\sqrt{2}}|D\bar{D}, I = 1, I_3 = 0\rangle,$$

and hence,

$$t_{D^+D^-, D^+D^-} = \frac{1}{2}t_{DD, D\bar{D}}^{I=0},$$

$$t_{D^+D^-, D^0\bar{D}^0} = \frac{1}{2}t_{DD, D\bar{D}}^{I=0}.$$ \hspace{1cm} (16)

Equations (12) and (13) can be rewritten as,

$$t_{D^+D^-} = \left(1 + \frac{1}{2}G_{D^+D^-}t_{DD, D\bar{D}}^{I=0}\right),$$ \hspace{1cm} (17)

$$t_{D^0\bar{D}^0} = \frac{1}{2}G_{D^+D^-}t_{DD, D\bar{D}}^{I=0}.\hspace{1cm} (18)$$

The cross section is now given by Eq. (9) multiplying it by $|t_{D^+D^-}|^2$ or $|t_{D^0\bar{D}^0}|^2$ for $D^+D^-$ or $D^0\bar{D}^0$ production, respectively.

The interpretation of the data in Refs. [15, 16] requires a prior discussion. The first surprise is that in both experiments there are more events of $D^0\bar{D}^0$ production than for $D^+D^-$ production. This is surprising since the strengths of $t_{D^+D^-\rightarrow D^+D^-}$ and $t_{D^+D^-\rightarrow D^0\bar{D}^0}$ are the same (see Eq. (16)), but in the case of $D^+D^-$ production we have the additional tree level mechanism (see Eq. (12)). The answer to this question has to be seen in Table II of Ref. [15] where the $D$ decay modes used in the detection are shown (the same detection method is used in Ref. [16]). For $D^0\bar{D}^0$ production, four decay modes are considered: 1) $D^0 \rightarrow K^-\pi^+$, $\bar{D}^0 \rightarrow K^+\pi^-$; 2) $D^0 \rightarrow K^-\pi^+$, $\bar{D}^0 \rightarrow K^+\pi^-\pi^0$; 3) $D^0 \rightarrow K^-\pi^+$, $\bar{D}^0 \rightarrow K^+\pi^-\pi^+$; 4) $D^0 \rightarrow K^-\pi^+\pi^+$, $\bar{D}^0 \rightarrow K^+\pi^-\pi^0$. However, for the $D^+D^-$ production only the $D^+ \rightarrow K^-\pi^+$, $D^- \rightarrow K^+\pi^-\pi^-$ decay mode is considered. It is thus not surprising that more $D^0\bar{D}^0$
TABLE I: The model parameters obtained by fitting to the experimental measurements.

| parameters | $a_{\eta_{0}}$ | $f_{D, D_{s}}$ | $\alpha$ | $C_{\text{Belle}}$ | $C_{\text{BaBar}}$ | $C$ | $\chi^{2}/\text{dof}$ |
|------------|---------------|---------------|----------|-----------------|-----------------|-----|-------------------|
| Fit A      | $1.00 \pm 0.38$ | $2.69 \pm 0.41$ | $-1.20 \pm 0.04$ | $7.39 \pm 0.37$ | -               | -   | $10.4/(17-4)$     |
| Fit B      | $41.0 \pm 5.4$  | $2.31 \pm 0.28$ | $-1.24 \pm 0.06$ | -               | -               | $8.86 \pm 0.61$ | $16.3/(14-4)$     |
| Fit C      | $39.1 \pm 7.7$  | $3.20 \pm 0.39$ | $-1.28 \pm 0.09$ | $7.85 \pm 0.39$ | $8.68 \pm 0.36$ | -   | $28.2/(31-5)$     |
| Fit D      | $42.1 \pm 11.0$ | $3.30 \pm 0.79$ | $-1.29 \pm 0.10$ | $7.90 \pm 0.41$ | $8.76 \pm 0.44$ | $3.57 \pm 0.067$ | $29.9/(34-6)$     |

production events than $D^{+}D^{-}$ ones are observed. Inspection of the data in Fig. 5 of Ref. [15] shows that the strength of the $D^{+}D^{-}$ production around 3850 MeV is about 1/3 of that of the $D^{0}\bar{D}^{0}$ production. We shall take this into account when comparing with the data. To increase the statistics, the sum of the two production modes is shown in Fig. 10 of Ref. [15], and we shall compare with those data taking into account the experimental weights for the $D^{+}D^{-}$ and $D^{0}\bar{D}^{0}$ production. On the other hand, the data of Ref. [16] for $D^{0}\bar{D}^{0}$ production have a good statistics to compare directly with them. In view of that, in order to compare with the BaBar [15] and Belle [16] data, we shall use Eq. (2) multiplied by $|t_{\text{Belle}}|^{2}$ and $|t_{\text{BaBar}}|^{2}$, where,

$$|t_{\text{Belle}}|^{2} = C_{\text{Belle}}|t_{D^{0}\bar{D}^{0}}|^{2},$$

$$|t_{\text{BaBar}}|^{2} = C_{\text{BaBar}}\left(|t_{D^{0}\bar{D}^{0}}|^{2} + B|t_{D^{+}D^{-}}|^{2}\right),$$

with a factor $B$ adjusted to get $\sigma_{D^{+}D^{-}}$ about 1/3 of $\sigma_{\eta\eta}^{D^{0}}$ around 3850 MeV. The normalization factors $C_{\text{Belle}}$ and $C_{\text{BaBar}}$ are introduced to compare with the number of events in Ref. [15] and Ref. [16] instead of cross sections.

III. RESULTS AND DISCUSSIONS

![Fig. 3: The $D\bar{D}$ invariant mass distributions of $\gamma\gamma \rightarrow D\bar{D}$ measured by Belle (a) and BaBar (b) divided by the phase space $|p^{i}/(s|p^{i})| of Eq. (9). The Belle data for $\gamma\gamma \rightarrow D^{0}\bar{D}^{0}$ are taken from Fig. 2(a) of Ref. [15], and the BaBar data for $\gamma\gamma \rightarrow D\bar{D}$ are taken from Fig. 10 of Ref. [16]. The units are in an arbitrary normalization.](image)

In this section, we will show our results. Firstly, we divide the $D\bar{D}$ invariant mass distributions of Belle and BaBar by the phase space factor $|p^{i}/(s|p^{i})|$ of Eq. (9), which, up to an arbitrary normalization, are shown in Fig. 3(a) and Fig. 3(b), respectively for the Belle and BaBar data. One can find that there are no peaks around 3860 MeV, and both distributions peak at the threshold, which implies that some possible states below the threshold may play an important role in the reaction of $\gamma\gamma \rightarrow D\bar{D}$, and the similar feature was found in the $\bar{p}A$ invariant mass distribution of $\chi_{c0} \rightarrow \bar{p}K\Lambda$ [19].

As discussed above, there are five parameters: 1), $a_{\eta_{0}}$ the dimensionless potential of $\eta_{0} \rightarrow D^{+}D^{-}$ and $\eta_{0} \rightarrow D^{0}\bar{D}^{0}$; 2), an extra factor $f_{D, D_{s}}$ of the potentials $V_{D^{+}D^{-}, D_{s}}$ and $V_{D^{0}\bar{D}^{0}, D_{s}}$; 3), the subtraction constant $\alpha$ in the loop function; 4), two normalization factors $C_{\text{Belle}}$ and $C_{\text{BaBar}}$. We will fit these parameters to the experimental data in following. It should be noted that the amplitudes produced by our model have a limited range of validity and
should not be used much above the $D_s \bar{D}_s$ threshold, thus we only consider the experimental data points from the $D\bar{D}$ threshold to 3860 MeV.

In the first step, we fit to the Belle data of $\gamma\gamma \rightarrow D^0\bar{D}^0$ alone (Fit A). The fitted parameters are tabulated in Table I, and the mass distribution is shown in Fig. 4(a). Our results are in good agreement with the Belle data of $\gamma\gamma \rightarrow D^0\bar{D}^0$. With the fitted parameters, the modulus squared of the amplitudes $|t_{D\bar{D}\rightarrow D\bar{D}}|^2$ is depicted in Fig. 4(b), where we can find that there is a peak around 3730 $\pm$ 3740 MeV, associated to a bound $D\bar{D}$ state.

Next we perform the fit to the BaBar data of $\gamma\gamma \rightarrow D\bar{D}$ alone (Fit B), and the fitted parameters are tabulated in Table I. With the fitted parameters, we show the $DD$ mass distribution and the modulus squared of the amplitude $|t_{D\bar{D}\rightarrow D\bar{D}}|^2$ in Fig. 5(a) and Fig. 5(b). We have adjusted the relative weight $B$ of Eq. (20) to get $\sigma_{D^+D^-}$ about $1/3$ of $\sigma_{D^0\bar{D}^0}$ around 3850 MeV in this case and also in the following fits. It is easy to see that there a peak around 3720 MeV, which can also be associated to the $D\bar{D}$ bound state.

Then we perform the fit to both the Belle and Babar data (Fit C), and the fitted parameters are tabulated in Table I. We present the $DD$ invariant mass distributions in Fig. 6(a) and Fig. 6(b), respectively for the Belle and Babar. With the fitted parameters, the modulus squared of the amplitude $|t_{D\bar{D}\rightarrow D\bar{D}}|^2$ is given in Fig. 6(c). Taking into account the uncertainties, our results are in reasonable agreement with the Belle and BaBar measurements, and the fit favors a narrow bound $D\bar{D}$ state, which can be seen from Fig. 6(c).
FIG. 6: The $D\bar{D}$ invariant mass distributions of $\gamma\gamma \rightarrow D\bar{D}$ with the parameters fitted to the Belle and BaBar data for (a) the $\gamma\gamma \rightarrow D^0\bar{D}^0$, and (b) the $\gamma\gamma \rightarrow D\bar{D}$. (c) The modulus squared of the amplitude $|t_{D\bar{D}\rightarrow D\bar{D}}|^2$ calculated with the fitted parameters. The explanations of the curves are the same as those of Fig. 4.

As we discussed in Ref. [3], the present quality of the $e^+e^- \rightarrow J/\psi D\bar{D}$ data from the Belle Collaboration [2] did not allow one to be too strong on the claim of a $D\bar{D}$ bound state around 3720 MeV, although this $D\bar{D}$ bound state was found to be compatible with the Belle measurements. Since the $D\bar{D}$ final state of the $e^+e^- \rightarrow J/\psi DD$ reaction is the same as the one of $\gamma\gamma \rightarrow D\bar{D}$, we make a global fit to the data of $\gamma\gamma \rightarrow D^0\bar{D}^0$ of Belle [15], $\gamma\gamma \rightarrow D\bar{D}$ of BaBar [16], and $e^+e^- \rightarrow J/\psi DD$ of Belle [2] (Fit D), and the fitted parameters are tabulated in Table I. The mass distributions of $\gamma\gamma \rightarrow D\bar{D}$ are shown in Fig. 7(a) and Fig. 7(b) for Belle and BaBar, respectively. The $D\bar{D}$ mass distribution of $e^+e^- \rightarrow J/\psi D\bar{D}$ is shown in Fig. 7(c). With the fitted parameters, the modulus squared of the amplitudes $|t_{D\bar{D}\rightarrow D\bar{D}}|^2$ is given in Fig. 7(d). The global fit also favors a $D\bar{D}$ bound state around 3720 MeV.

show that there are still large uncertainties to be assertive about the position and width of the state

IV. CONCLUSIONS

In this work, we have investigated the reaction of $\gamma\gamma \rightarrow D\bar{D}$ by taking into account the s-wave $D\bar{D}$ final state interactions. Since the present quality of the $e^+e^- \rightarrow J/\psi D\bar{D}$ data from the Belle Collaboration did not allow one to be too strong on the claim of the $D\bar{D}$ bound state, and the final states of $e^+e^- \rightarrow J/\psi D\bar{D}$ and $\gamma\gamma \rightarrow D\bar{D}$ are the same, we perform four kinds of fits to the data of $\gamma\gamma \rightarrow D^0\bar{D}^0$ from the Belle Collaboration, $\gamma\gamma \rightarrow D\bar{D}$ from the BaBar Collaboration, and $e^+e^- \rightarrow J/\psi DD$ from the Belle Collaboration. Considering the uncertainties from the fitted parameters, our results are consistent with the experimental data in the four fits, and the modulus squared of the amplitudes $|t_{D\bar{D}\rightarrow D\bar{D}}|^2$ show peaks around $3710 \sim 3740$, which can be associated to the $D\bar{D}$ bound state. Yet,

\footnote{The formalism for the $e^+e^- \rightarrow J/\psi DD$ can be found in Ref. [3]. In addition to the three parameters, $a_{\eta\eta}$, $\alpha$, $f_{D_sD_s}$, we have another parameter $C$ corresponding to the normalization factor in Eq. (1) of Ref. [3].}
FIG. 7: The $DD$ invariant mass distributions of $\gamma\gamma \rightarrow DD$ with the parameters fitted to the Belle and BaBar data for (a) the $\gamma\gamma \rightarrow D^0\bar{D}^0$, (b) the $\gamma\gamma \rightarrow D\bar{D}$, and (c) $e^+e^- \rightarrow J/\psi D\bar{D}$ . (d) The modulus squared of the amplitude $|t_{D\bar{D} \rightarrow D\bar{D}}|^2$ calculated with the fitted parameters. The explanations of the curves are the same as those of Fig. 4. The data labeled as ‘J/$\psi DD$’ are taken from Ref. [2].

the explicit evaluation of the errors done in each of the fit to the data, and particularly the last one including all the data, show that there are still large uncertainties to be assertive about the position and width of the state. Thus we encourage our experimental colleagues to measure both reactions with larger data samples, which can allow us to reduce the errors and be more precise concerning the $D\bar{D}$ bound state.

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