# Exclusive $D\bar{D}$ meson pair production in peripheral ultrarelativistic heavy ion collisions

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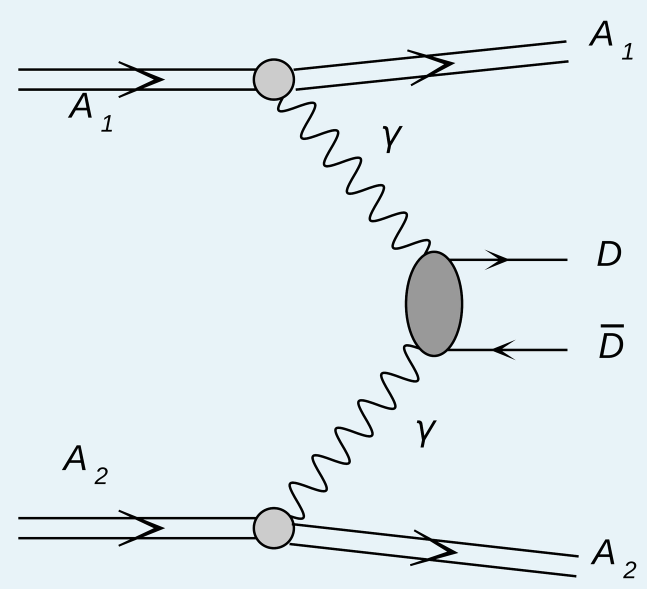
## Abstract

The cross sections for exclusive $D^+D^-$ and $D^0\bar{D}^0$ meson pair production in peripheral nucleus - nucleus collisions are calculated and several differential distributions are presented. The calculation of the elementary $\gamma\gamma \to D\bar{D}$ cross section is done within the heavy-quark approximation and in the Brodsky- Lapage formalism with distribution amplitudes describing recent CLEO data on leptonic $D^+$ decay. Realistic (Fourier transform of charge density) charge form factors of nuclei are used to generate photon flux factors. Absorption effects are discussed and quantified. The cross sections of a few nb are predicted for RHIC and of a few hundreds of nb for LHC with details depending on the approximation made in calculating elementary $\gamma\gamma \to D\bar{D}$ cross sections.

## Introduction

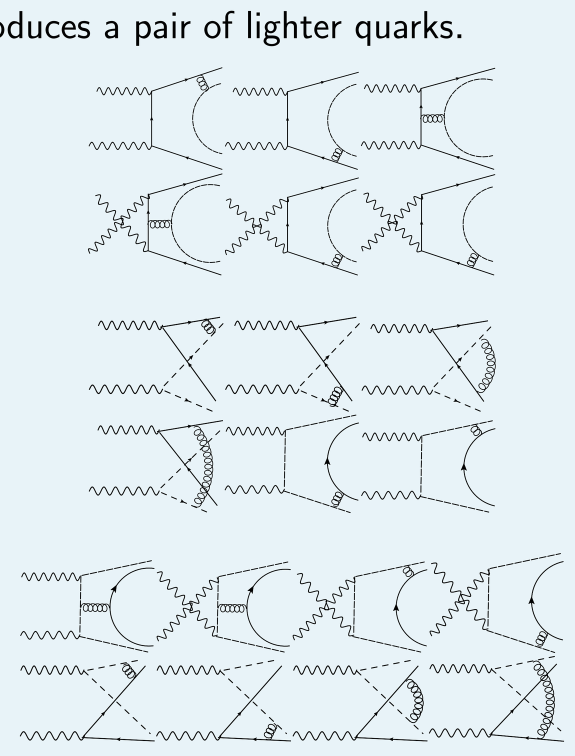
Heavy quark meson pair production was studied theoretically only in Ref.[2] where formulas have been derived in the heavy quark approximation with Dirac delta-like distribution amplitudes. On the other hand both lattice QCD and the CLEO collaboration extracted the D-meson distribution amplitude which turned out to differ considerably from the delta-like distribution amplitude assumed in heavy quark approximation. In the present studies we will use also the more realistic distribution amplitudes.

In Fig.1 we show the basic QED mechanism of the exclusive production of $D\bar{D}$ pairs in the peripheral heavy-ion collisions. We consider both $D^+D^-$ and $D^0\bar{D}^0$ production.




## Heavy charmed meson pair production in photon- photon collisions

In the two- photon case, 20 Feynman diagrams are involved even in the leading order of $\alpha_s$. The diagrams can be classified into three parts. Six diagrams of first part in below Figure represent the heavier- quark pair production by two- photon collisions followed by one virtual gluon emission to allow the produced heavier quarks to hadronize into heavy mesons. The second part of that diagrams are obtained by exchanging heavier quark lines with lighter antiquark line. The last part consists of eight diagrams where one photon produces a pair of heavier quarks and the other photon produces a pair of lighter quarks.



- Heavy meson pair production in photon- photon collision. The wiggly (curly) line is for a photon (gluon), while the solid (dotted) one is for the heavier (lighter) (anti)quark.

In Ref.[2] the distribution amplitudes of the form:

$$\Phi_M(x,Q^2) = f(x,Q^2)\frac{1+V}{2}\gamma_5, \Phi_{\bar{M}}(x,Q^2) = f^*(x,Q^2)\frac{1-V}{2}\gamma_5 \quad (1)$$

have been assumed with the heavy-quark approximation

$$f(x,Q^2) = f^*(x,Q^2) = \delta(x - \Lambda/M)\ , \quad (2)$$

where $\Lambda = M - m_Q$.

The resulting pseudoscalar-pseudoscalar (PP) production amplitude $M^{\gamma\gamma}_{PP}(\lambda,\lambda')$ can be written as [2]

$$M^{\gamma\gamma}_{PP}(\lambda,\lambda') = 2\frac{F^{\gamma\gamma}}{(1-z^2)^2}(1+z^2)\Big[e_Q^2 F_{PP}(\lambda,\lambda') + e_q^2 F'_{PP}(\lambda,\lambda')\Big]$$

$$-2e_Q e_q G_{PP}(\lambda,\lambda')$$

$$-(1-z^2)\Big[\frac{1-x}{x}e_Q^2 H_{PP}(\lambda,\lambda') + \frac{x}{1-x}e_q^2 H'_{PP}(\lambda,\lambda')\Big], \quad (3)$$

where

$$F^{\gamma\gamma} = \frac{16\pi^2\alpha_e\alpha_s C_F}{\hat{s}x^2(1-x)^2}\left[\frac{f_M}{M}\right], \quad (4)$$

$$F_{PP}(\lambda,\lambda') = \Big[(1-x)[2-x(\hat{s}+2)] + \frac{\hat{s}}{2}\sigma_{\lambda,-\lambda'}\Big](\beta^2 - z^2), \quad (5)$$

$$F'_{PP}(\lambda,\lambda') = \Big[x - [2-(1-x)(\hat{s}+2)]\frac{\hat{s}}{2}\sigma_{\lambda,-\lambda'}\Big](\beta^2 - z^2), \quad (6)$$

$$G_{PP}(\lambda,\lambda') = \Big[\frac{\hat{s}}{2}[1+z^2+(1-z^2)\sigma_{\lambda,-\lambda'}] - 2x(1-x(2+\hat{s}))\Big]$$
$$(\beta^2 - z^2) - [\hat{s}(1-z^2) - 2(3-z^2)\sigma_{\lambda,-\lambda'}, \quad (7)$$

$$H_{PP}(\lambda,\lambda') = [2-x(\hat{s}+2)]\Big[(1-x)\beta^2 - z^2) + z^2\sigma_{\lambda,-\lambda'}\Big]$$
$$+x(\hat{s}+2)\sigma_{\lambda,-\lambda'}, \quad (8)$$

$$H'_{PP}(\lambda,\lambda') = \Big[2-(1-x)(\hat{s}+2)\Big]\Big[x(\beta^2-z^2) + z^2\sigma_{\lambda,-\lambda'}\Big]$$
$$+(1-x) + x(\hat{s}+2)\sigma_{\lambda,-\lambda'}. \quad (9)$$

In the formulas above: $\hat{s} = \frac{s}{M^2}$, $z = \beta cos\theta$, and $\beta = \sqrt{1-\frac{4}{\hat{s}}}$.

The $\theta$ is the scattering angle between the photon and a heavy meson, the color factor $C_F = \frac{4}{3}$.

## Nuclear collisions, Equivalent Photon Approximation

To calculate the cross section of the nuclear process it is convenient to introduce a new kinematic variable: $x = \frac{\omega}{E_A}$, where $\omega$ is the energy of the photon and the energy of the nucleus $E_A = \gamma A m_{proton} = \gamma M_A$, where $M_A$ is the mass of the nucleus and $\gamma$ is the Lorentz factor.

The total cross section can be calculated by the convolution [1]:

$$\sigma\left(AA \to AAD\bar{D}; s_{AA}\right) = \int \hat{\sigma}\left(\gamma\gamma \to D\bar{D}; W_{\gamma\gamma} = \sqrt{x_1 x_2 s_{AA}}\right) \quad (10)$$
$$\mathrm{d}n_{\gamma\gamma}\left(x_1, x_2, \mathbf{b}\right).$$

The effective photon fluxes can be expressed through the electric fields generated by the nuclei:

$$\mathrm{d}n_{\gamma\gamma}\left(x_1,x_2,\mathbf{b}\right) = \frac{1}{\pi}\mathrm{d}^2\mathbf{b}_1|\mathbf{E}\left(x_1,\mathbf{b}_1\right)|^2\frac{1}{\pi}\mathrm{d}^2\mathbf{b}_2|\mathbf{E}\left(x_2,\mathbf{b}_2\right)|^2$$
$$\times\ S^2_{abs}\left(\mathbf{b}\right)\delta^{(2)}\left(\mathbf{b} - \mathbf{b}_1 + \mathbf{b}_2\right)\frac{\mathrm{d}x_1}{x_1}\frac{\mathrm{d}x_2}{x_2}. \quad (11)$$

The total cross section for the $AA \to AAD\bar{D}$ process can be factorized into the equivalent photons spectra ( $n(\omega)$ ) and the $\gamma\gamma \to D\bar{D}$ subprocess cross section as:

$$\sigma\left(AA \to AAD\bar{D}; s_{AA}\right) = \int \hat{\sigma}\left(\gamma\gamma \to D\bar{D}; W_{\gamma\gamma}\right)\theta\left(|\mathbf{b}_1 - \mathbf{b}_2| - 2R_A\right)$$
$$\times\ N\left(\omega_1,\mathbf{b}_1\right)N\left(\omega_2,\mathbf{b}_2\right)\mathrm{d}^2\mathbf{b}_1\mathrm{d}^2\mathbf{b}_2\frac{\mathrm{d}\omega_1}{\omega_1}\frac{\mathrm{d}\omega_2}{\omega_2}, \quad (12)$$

where $W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}$ is energy in the $\gamma\gamma$ subsystem.

Additionally, we define $Y = \frac{1}{2}\left(y_D + y_{\bar{D}}\right)$, rapidity of the outgoing meson system which is produced in the photon–photon collision. Performing the following transformations:

$$\omega_1 = \frac{W_{\gamma\gamma}}{2}e^Y, \qquad \omega_2 = \frac{W_{\gamma\gamma}}{2}e^{-Y}, \quad (13)$$

Finally, the nuclear cross section can be expressed as the five-fold integral:

$$\sigma\left(AA \to AAD\bar{D}; s_{AA}\right) = \int \hat{\sigma}\left(\gamma\gamma \to D\bar{D}; W_{\gamma\gamma}\right)\theta\left(|\mathbf{b}_1 - \mathbf{b}_2| - 2R_A\right)$$
$$\times N\left(\omega_1,\mathbf{b}_1\right)N\left(\omega_2,\mathbf{b}_2\right)2\pi b_m\,\mathrm{d}b_m\,\mathrm{d}\bar{b}_x\,\mathrm{d}\bar{b}_y\frac{W_{\gamma\gamma}}{2}\mathrm{d}W_{\gamma\gamma}\mathrm{d}Y \quad (14)$$

where $\bar{b}_x \equiv (b_{1x} + b_{2x})/2$, $\bar{b}_y \equiv (b_{1y} + b_{2y})/2$ and $\vec{b}_m = \vec{b}_1 - \vec{b}_2$ have been introduced. This formula is used to calculate the total cross section for the $AA \to AAD\bar{D}$ reaction as well as the distributions in the impact parameter $b = b_m$, the meson invariant mass $W_{\gamma\gamma} = M_{D\bar{D}}$ and the meson pair rapidity $Y(D\bar{D})$.

## Results for the nuclear collisions

Table: Total cross section for the exclusive $D\bar{D}$ production for RHIC ($s_{NN}^{1/2} = 200$ GeV) and LHC ($s_{NN}^{1/2} = 5500$ GeV) calculated with distribution amplitudes from [2] and [3].

| Process | $\sigma_{tot}$ | |
|---|---|---|
| | BCS94 DA | ZH2007 DA |
| $AuAu \to AuAu\, D^+D^-$ | 12.44 $nb$ | 0.08 $\mu b$ |
| $AuAu \to AuAu\, D^0\bar{D}^0$ | 21.2 $nb$ | 5.06 $nb$ |
| $PbPb \to PbPb\, D^+D^-$ | 1.68 $\mu b$ | 1.92 $\mu b$ |
| $PbPb \to PbPb\, D^0\bar{D}^0$ | 4.09 $\mu b$ | 0.28 $\mu b$ |

- The maximum of the cross section is for the impact parameter $b$ when colliding nuclei almost touch each other and the cross section decrease for larger $b$. The decrease is much sharper for RHIC than for LHC.

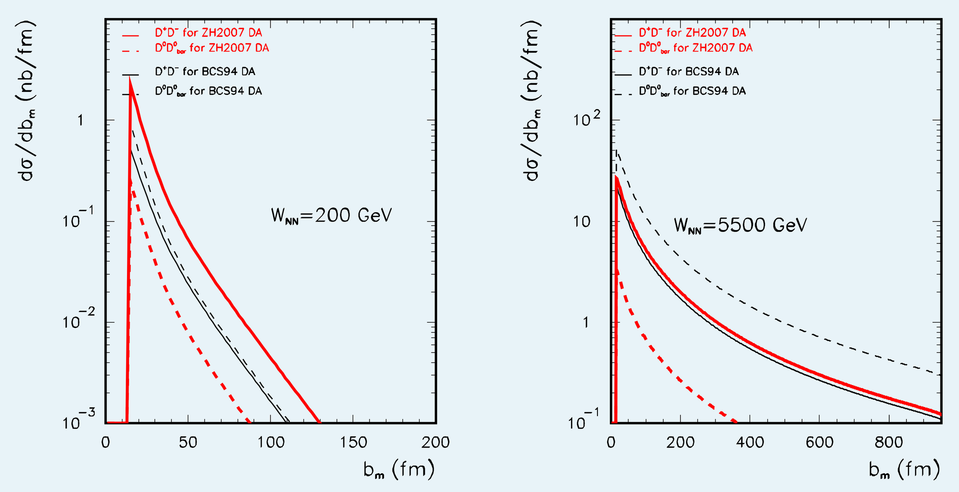


Figure: Distribution in impact parameter for $D^+D^-$ and $D^0\bar{D}^0$ for the BCS94 DA [2] (black) and for the ZH2007 DA [3] (red) for RHIC and LHC energies.

- We show the distribution in the $D^+D^-$ and $D^0\bar{D}^0$ pair rapidity being $Y \approx \frac{1}{2}(y_D + y_{\bar{D}})$. The visible irregularities at larger $|Y|$ are caused by the oscillating nuclear form factor.

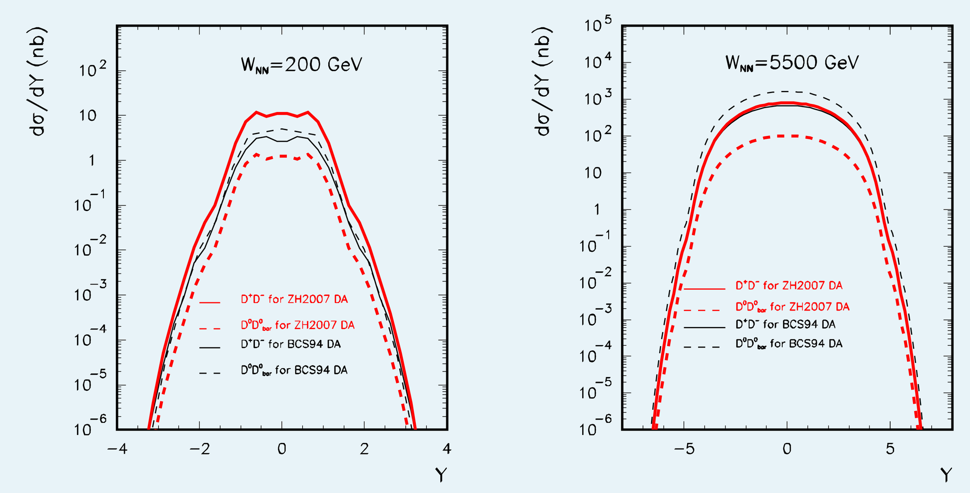


Figure: The cross section as a function of the meson pair rapidity for $D^+D^-$ and $D^0\bar{D}^0$ for the BCS94 DA [2] (black) and for the ZH2007 DA [3] (red) for RHIC and LHC energies.

- This figure shows that in experiments only a region of small invariant masses close to the threshold could be investigated.

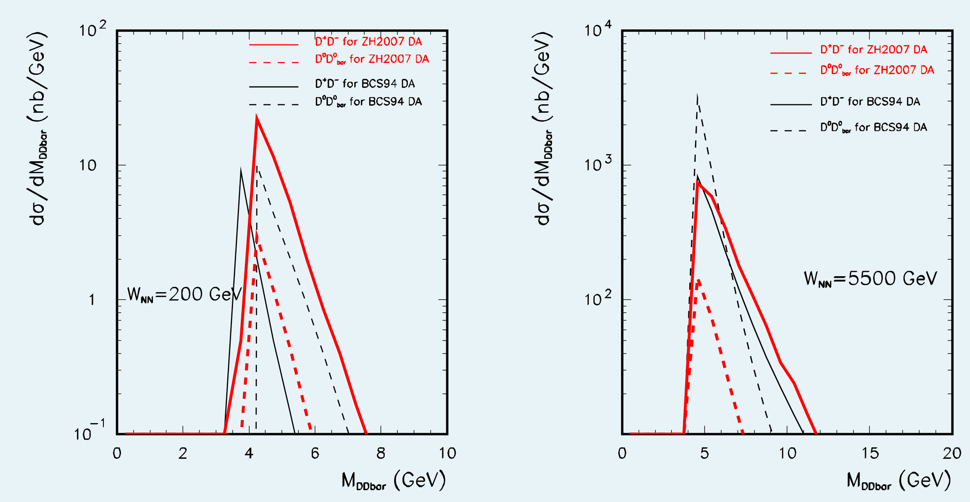


Figure: $D\bar{D}$ invariant mass distribution for RHIC and LHC.

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[2] M.S. Baek, S.Y. Choi and H.S. Song, Phys. Rev. **D50** (1994) 7.

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- Based on:
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