Photoproduction of $J/\psi$ mesons in peripheral and semi-central heavy ion collisions

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Abstract

We calculate total and differential cross sections for $J/\psi$ photoproduction in ultrarelativistic lead-lead collisions at the LHC energy $\sqrt{s_{NN}} = 2.76$ TeV. In the present approach we use a simple model based on vector dominance picture and multiple scattering of the hadronic ($c\bar{c}$) state in a cold nucleus as an example. In our analysis we use both the classical mechanics and quantum (Glauber) formulae for calculating $\sigma_{\text{tot}}(J/\psi\text{Pb})$ which is a building block of our model. We compare our UPC results with ALICE and CMS data. For semi-central collisions ($b < R_A + R_B$) a modification of the photon flux seems necessary. We discuss different physics motivated approximations. We try to estimate the cross sections for different centrality bins and for $J/\psi$ mesons emitted in forward rapidity range ($2.5 < y < 4$) corresponding to recent ALICE experimental results. Reasonable results are obtained but open questions are discussed.

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I. INTRODUCTION

Last years the ALICE Collaboration studied production of $J/\psi$ mesons mostly in central $^{208}\text{Pb}^{208}\text{Pb}$ collisions (see e.g. [1]) at $\sqrt{s_{NN}} = 2.76$ TeV i.e. at the highest available nucleus-nucleus center-of-mass energies. At these high energies different theoretical mechanisms come into game (see e.g. [2–6] and references therein). For instance in Ref. [3] the authors emphasized thermal aspect of charmonia production. In order to describe detailed distributions in transverse momentum, rapidity or multiplicity several dynamical mechanisms have to be taken into account. In contrast to early expectations [7] there are mechanisms which lead to both suppression and regeneration of $J/\psi$ quarkonia in cold and hot medium. Experimental studies discuss usually so-called nuclear modification factor as a function of multiplicity, transverse momentum and rapidity of $J/\psi$ and smooth dependences have been observed (a nice summary was presented e.g. in [8]).

In last years there was also an interest in calculating cross sections for exclusive production of $J/\psi$ mesons in ultrarelativistic heavy ion collisions [9–14]. The main reason for these investigations was a better understanding of interaction of a small size ($c\bar{c}$) perturbative dipole with a nucleus or more explicitly with the nuclear gluons incorporated in different ways in different models. In general, this may be related to gluon saturation phenomenon which in the case of nucleus may be more efficient than for the case of nucleon due to a coherent action of many nucleons (larger gluon occupation). All the previous investigations were related to purely ultraperipheral collisions (UPC), i.e. when the nuclei stay intact 1. In theoretical calculations UPC means in practice $b > R_{A} + R_{B}$ (sum of nuclear radii). All the calculations must be therefore performed in the impact parameter space to include this condition.

Can the photoproduction process (photon emission, its fluctuation into $c\bar{c}$ and subsequent rescattering of the dipole (or hadron) in the nucleus) be active also for less peripheral collisions i.e. when nuclei collide and break apart producing, at these high energies, quark-gluon plasma? A recent analysis of the ALICE Collaboration [15] presents differential studies of inclusive production of $J/\psi$ in Pb-Pb collisions exclusively at forward rapidities. At low transverse momenta and small multiplicity they observe an enhancement of $R_{AA} > 1$. According to our knowledge this enhancement was not explained so far in the literature.

We wish to address this issue in the following paper. We will try to discuss the issue in the equivalent photon approximation (EPA). In the present first estimate of the cross section we will discuss several approximations how to calculate relevant photon fluxes to include approximately the physical conditions relevant in the photoproduction of $J/\psi$. This is very important for the peripheral and semi-central collisions. For simplicity in the following we will use a simple vector dominance model (VDM) combined with multiple scattering of the hadronic photon fluctuation for calculating the $\gamma A$ cross section which, as will be shown in this paper, describes relatively well the cross section for production of $J/\psi$ mesons in UPCs.

A very recent analysis of the ALICE Collaboration [16] confirms the presence of the enhancement at very small $J/\psi$ transverse momentum and tries to extract the new not fully understood contribution for different centrality bins. We shall try to describe the ALICE preliminary data [16] assuming the mentioned above photoproduction mechanism.

1 An emission of extra neutrons caused by additional purely electromagnetic interactions could be included too.
II. DESCRIPTION OF OUR SIMPLE MODEL

Nuclear photoproduction of a single vector meson $V$ can be understood as a photon fluctuation into hadronic (virtual $V$ meson or quark-antiquark pair) component and its subsequent propagation through the second (cold) nucleus and a transformation (fragmentation) into the on-shell $V$ meson.

![Fig. 1: Schematic diagrams for the single vector meson production by photoproduction photon-Pomeron (left) or Pomeron-photon (right) fusion. Here the word Pomeron and its symbol is an abbreviation for multiple diffractive scattering of the hadronic system in the nuclear medium.](image)

Fig. 1 illustrates a mechanism of a single vector meson production in ultraperipheral ultrarelativistic heavy-ion collisions. The cross section for this mechanism is usually written differentially in the impact parameter $b$ and in the vector meson rapidity $y$

$$\frac{d\sigma_{A_1A_2 \rightarrow A_1A_2V}}{d^2bdy} = \frac{dP_{\gamma IP}(b,y)}{dy} + \frac{dP_{\gamma IP}(b,y)}{dy}. \quad (2.1)$$

Above $P_{\gamma IP}(y,b)$ or $P_{\gamma IP}(y,b)$ is the probability density for producing a vector meson $V$ at rapidity $y$ for fixed impact parameter $b$ of the heavy-ion collision. Probability density expresses two-different possibilities of the production of vector meson shown in Fig. 1. Each of the probabilities is the convolution of the cross section for $\gamma_1A_2 \rightarrow J/\psi A_2$ or $\gamma_2A_1 \rightarrow J/\psi A_1$ (the photon emitted from first or second nucleus ($\omega_1/2 = m_V/2 \exp(\pm y)$)) and a corresponding flux of equivalent photons:

$$\frac{dP_{1/2}(y,b)}{dy} = \omega_{1/2} N(\omega_{1/2},b) \sigma_{\gamma A_2/J\psi A_2} (W_{\gamma A_2/J\psi A_2}) S(b), \quad (2.2)$$

where $N(\omega_{1/2},b)$ is usually a function of impact parameter between heavy ions ($b$) and not of photon-nucleus impact parameter. Finally $S(b)$ is an impact parameter dependent survival factor which with good precision can be approximated as $S(b) \approx \theta(b - R_A - R_B)$.

Now we wish to proceed to semi-central collisions i.e. to the case of $b < R_A + R_B$. Then the survival factor has to be omitted as we are interested also in situations when colliding nuclei break apart. In the present approach we will modify only photon fluxes and leave the coherent $\gamma A \rightarrow J/\psi A$ cross section unmodified. This seems a crude approximation which should be reasonable only for rather peripheral collisions $b \approx R_A + R_B$. We shall try to see how far this approximation can be extrapolated down to smaller $b$. The effective photon flux which includes the geometrical aspects can be formally expressed through the real photon flux of one of the nuclei and effective strength for the interaction of the photon with the second nucleus

$$N^{(1)}(\omega_1,b) = \int N(\omega_1,b_1) \frac{\theta(R_A - b_2)}{\pi R_A^2} d^2b_1, \quad (2.3)$$
where $b_1 = b + b_2$. The extra $\theta(R_A - b_2)$ factor ensures collision when the photon hits the nucleus-medium. For the photon flux in the second nucleus one needs to replace $1 \rightarrow 2$ (and $2 \rightarrow 1$). For large $b \gg R_A + R_B$: $N^{(1)}(\omega_1, b) \approx N(\omega_1, b)$. For small impact parameters this approximation is, however, not sufficient. This has some consequences also for ultraperipheral collisions, which will be discussed somewhat later in this section.

Since it is not completely clear what happens in the region of overlapping nuclear densities we suggest another approximation which may be considered rather as lower limit. In this approximation we integrate the photon flux of the first (emitter) nucleus only over this part of the second (medium) nucleus which does not collide with the nucleus-emitter (some extra absorption may be expected in the tube of overlapping nuclei). This may decrease the cross section for more central collisions. In particular, for the impact parameter $b = 0$ the resulting vector meson production cross section will fully disappear by the construction. In the above approximation the photon flux can be written as:

$$N^{(2)}(\omega_1, b) = \int N(\omega_1, b_1) \frac{\theta(R_A - b_2) \times \theta(b_1 - R_A)}{\pi R_A^2} d^2 b_1 . \quad (2.4)$$

We shall use the three different approximations how to calculate photon fluxes and three different form factors which are main ingredients of the photon flux. We shall start with

$$F_{pl}(q) = 1 \quad (2.5)$$

corresponding to point-like charge. In this approximation the flux of the photons is given by the simple formula

$$\frac{d^3N(\omega, r)}{d\omega dr} = \frac{Z^2 \alpha_{em} X^2}{\pi^2 \omega r^2} k_1^2(X) , \quad (2.6)$$

where $Z$ is the nuclear charge, $\omega$ is energy of the photon, $r$ is a distance in the impact parameter space between the photon and the emitting nucleus, $K_1$ is a modified Bessel function and $X = r \omega / \gamma$. The photon flux integrated over all $r$ is approximately equal to the photon flux in the region of $r > R_A + R_B$. This can be calculated analytically:

$$\frac{dN(\omega)}{d\omega} = \frac{2Z^2 \alpha_{em}}{\pi \omega} \left( \chi K_0(\chi) K_1(\chi) - \frac{X^2}{2} \left[ K_1^2(\chi) - K_0^2(\chi) \right] \right) , \quad (2.7)$$

where $\chi = 2R_A \omega / \gamma$.

In our calculations we use also a form factor which is Fourier transform of the charge distribution in nucleus. Two-parameter Fermi distribution (called equivalently Woods-Saxon distribution)

$$\rho(r) = \frac{\rho_0}{1 + \exp \left( \frac{r - c}{a} \right) } , \quad (2.8)$$

where the normalization constant $\rho_0$ for the lead nuclei equals to $0.1572 \text{ fm}^{-3}$ and $c = 6.62 \text{ fm}$, $a = 0.546 \text{ fm}$ is used in the calculation. The form factor (called here realistic form factor for brevity) is calculated then as

$$F_{real}(q^2) = \frac{4\pi}{q^2} \int \rho(r) \sin(qr) r dr . \quad (2.9)$$

In the literature often a monopole form factor is used

$$F_{mon}(q^2) = \frac{\Lambda^2}{\Lambda^2 + q^2} \quad (2.10)$$
which simplifies the calculations. The value of $\Lambda$ can be expressed through the root mean square electric radius

$$\sqrt{\langle r^2 \rangle} = \sqrt{\frac{6}{\Lambda^2}}$$

(2.11)

giving $\Lambda = 88$ MeV for $\sqrt{\langle r^2 \rangle} = 5.5$ fm for $^{208}$Pb. In our calculation we use the following generic formula for calculating the photon flux (see e.g. Ref. [17]) for any nuclear form factor

$$N(\omega, b) = \frac{Z^2\alpha_{em}}{\pi^2} \left| \int u^2 J_1(u) \frac{F_{\gamma} \left( \frac{(\frac{\omega}{\gamma})^2 + u^2}{b^2} \right)}{\left( \frac{\omega b}{\gamma} \right)^2 + u^2} \right|^2.$$ 

(2.12)

We shall compare the cross sections for the $J/\psi$ photoproduction using the point-like, monopole and realistic form factors (see Table I). But let us have first a closer look at the photon fluxes. The general situation in the impact parameter space is shown in Fig. 2. The two-dimensional vectors $\vec{b}$, $\vec{b}_1$ and $\vec{b}_2$ are distances between colliding nuclei, between the photon position and the middle of the first (emitter) nucleus and between the photon position and the middle of the second (medium) nucleus, respectively. The production of the $J/\psi$ mesons may occur provided the photon (hadronic fluctuation) hits the second nucleus, otherwise the (photo)production is not possible. The hatched area of overlapping nuclei in the right panel (semi-central collision) of the figure represents the area in the impact parameter space for which the situation is not so clear. As will be discussed below we shall exclude this region to get lower limit for the cross section for the $AA \rightarrow J/\psi$ reaction. In this region of the impact parameter space the quark-gluon plasma is created and its role in damping the $J/\psi$ production is not clear. The lower limit is obtained by assuming the full damping.

![FIG. 2: Impact parameter picture of the collision and the production of the $J/\psi$ meson for ultraperipheral (left panel) and for semi-central (right panel) collisions. It is assumed here that the first nucleus is the emitter of the photon which rescatters then in the second nucleus being a rescattering medium.](image)

Let us start our discussion by showing standard fluxes used routinely in ultraperipheral collisions. Fig. 3 presents the two-dimensional photon fluxes (see Eq. (2.12)) as a function of the distance between two colliding nuclei ($b$) and the energy of the photon ($\omega$). One can observe that the difference between photon fluxes obtained with realistic (left panel) (or monopole (middle panel)) form factors and the result for point-like photon source (right panel) is huge for $b < R_A$ (especially for $b \approx 0$).

Fig. 4 presents the realistic photon flux which is calculated including extra absorption effects in three different ways. The left panel shows the result which is obtained from
FIG. 3: Standard photon fluxes calculated for realistic (left panel) monopole (middle panel) and point-like (right panel) form factors.

FIG. 4: Two-dimensional distributions of the photon flux in the impact parameter $b$ and in the energy of photon $\omega$ for three different conditions (more in the text).

Eq. (2.3). This limit allows a production of vector mesons only inside the second nucleus (the one which does not emit the photon). The second panel is obtained with a condition which follows from the definition of the absorption factor. $\theta(b_1 - R_A)$ in Eq. (2.4) allows a production of the meson everywhere except of the inside of the tube defined by the emitter. The last panel shows the result which is obtained from Eq. (2.4). Here we have included both conditions applied separately in the two previous panels of the figure. This condition can be understood as follows. For centrality smaller than 100% we consider only these cases when particle can be produced inside the medium excluding this part of the medium which coincides with the emitter in the impact parameter space.

We think that it is more pedagogical to inspect the ratio of the effective flux in the new approach $N^{(2)}(\omega, b)$ to the standard photon flux (called below $N^{(0)}(\omega, b)$). Fig. 5 presents the ratio of the “new” to the standard flux for three types of the nuclear form factor. More precisely, it is a ratio of the result presented in the last panel of Fig. 4 to the result shown in the first panel of Fig. 3. The three panels represent cases with realistic (left panel), monopole (middle panel) and point-like (right panel) form factors. Here we consider lead-lead collisions at the LHC energy $\sqrt{s_{NN}} = 2.76$ TeV ($\gamma = 1471$). It is shown that the ratio of $N^{(2)}(\omega, b)$ to $N^{(0)}(\omega, b)$ is almost 1 in the region of large $b$ for all form factors. However, it is not the case for the semi-central collisions. These differences very weakly depend on the energy of the emitted photon. Thus interesting seems to be the cross section for different
Centrality is a parameter which is often used to characterize the collision of nuclei at high energies. To efficiently compare our results with the preliminary ALICE data for semi-central collisions [16] we need a simple relation between impact parameter and the centrality. In Ref. [18] the authors gave an approximate and practical geometric relation between them. In general, centrality of collisions depends on the impact parameter \( b \) and a total inelastic nucleus-nucleus cross section

\[
c(N) \simeq \frac{\pi b^2(N)}{\sigma_{\text{inel}}}.
\]  

(2.13)

In this case the centrality corresponds to a multiplicity higher than \( N \). \( b(N) \) expresses the value of the impact parameter for which the average multiplicity fulfills the dependence \( \langle n(b) \rangle = N \). In a purely geometrical picture (\( \sigma_{\text{inel}} = \pi (2R_A)^2 \)) we get:

\[
c = \frac{b^2}{4R_A^2}.
\]  

(2.14)
Fig. 6 presents the centrality as a function of impact parameter. The large value of the centrality corresponds to the large value of the impact parameter. The larger value of $b$ the more peripheral collisions.

Let us concentrate now for a while on the second ingredient of the model (see Eq. (2.2)) - the $\sigma_{\gamma A \to J/\psi A}$ cross section. In our present calculations we use the following sequence of equations:

$$
\frac{\mathrm{d}\sigma(\gamma p \to J/\psi p; t = 0)}{\mathrm{d}t} = b_{J/\psi} X_{J/\psi} W_{\gamma p}^{J/\psi},
$$

$$
\frac{\mathrm{d}\sigma(J/\psi p \to J/\psi p; t = 0)}{\mathrm{d}t} = f_{J/\psi}^2 \frac{\mathrm{d}\sigma(\gamma p \to J/\psi p; t = 0)}{\mathrm{d}t},
$$

$$
\sigma_{\text{tot}}^2(J/\psi p) = 16\pi \frac{\mathrm{d}\sigma(J/\psi p \to J/\psi p; t = 0)}{\mathrm{d}t},
$$

$$
T_A(r) = \int \rho \left(\sqrt{r^2 + z^2}\right) \, \mathrm{d}z,
$$

$$
\frac{\mathrm{d}\sigma(\gamma A \to J/\psi A; t = 0)}{\mathrm{d}t} = \frac{\alpha_{\text{em}}\sigma_{\text{tot}}^2(J/\psi A)}{4f_{J/\psi}^2}.
$$

Constants for the $\gamma p \to J/\psi p$ production are obtained from a fit to HERA data (Ref. [19]): $b_{J/\psi} = 4$ GeV$^{-2}$, $X_{J/\psi} = 0.0015 \mu$b, $\epsilon_{J/\psi} = 0.8$ and vector-meson coupling square is $f_{J/\psi}^2 = 4\pi \cdot 10.4$.

The calculation of $\sigma_{\text{tot}}(J/\psi A)$ requires incorporating multiple scattering of $J/\psi$ in the nuclear medium. In the present paper, the calculations are done using both classical mechanics (CM) and quantum mechanical (QM) Glauber formula for $\sigma_{\text{tot}}(J/\psi A)$ cross section. A quantitative and spectacular difference between these approaches can be shortly summarized as follows. In the black disk limit the classical mechanics approach leads to the total cross section equal to $\pi R_A^2$ and the quantum mechanical approach implies $\sigma_{\text{tot}}(J/\psi A) = 2\pi R_A^2$ [20]. The classical and quantum mechanics expressions for the $\sigma_{\text{tot}}(J/\psi A)$ cross section read:

$$
\sigma_{\text{tot}}^{\text{CM}}(J/\psi A) = \int \mathrm{d}^2r \left(1 - \exp\left(-\sigma_{\text{tot}}(J/\psi p) T_A(r)\right)\right),
$$

$$
\sigma_{\text{tot}}^{\text{QM}}(J/\psi A) = 2\int \mathrm{d}^2r \left(1 - \exp\left(-\frac{1}{2}\sigma_{\text{tot}}(J/\psi p) T_A(r)\right)\right),
$$

respectively, where $r$ is the distance in the impact parameter space of the photon (or $c\bar{c}$ fluctuation) from the middle of the nucleus-medium. These formulae are used to calculate the $\gamma A \to J/\psi A$ cross section, the main ingredient of our whole approach.

Finally, the total cross section for $\gamma A \to J/\psi A$ reaction can be written as

$$
\sigma_{\gamma A \to J/\psi A} = \int_{-\infty}^{t_{\text{max}}} \frac{\mathrm{d}\sigma_{\gamma A \to J/\psi A}(t = 0)}{\mathrm{d}t} \, |F_A(t)|^2.
$$

This cross section is actually a function of energy in the $\gamma A$ system. The factor $|F_A(t)|$ appears here due to assumed coherent rescattering of the $q\bar{q}$ dipole off a nucleus. A very good approximation is to use the realistic nuclear charge form factor which is defined in Eq. (2.9). The squared four-momentum transfer: $t = -q^2 = -(m_{J/\psi}/(2\omega_{\text{lab}}))^2$. 

8
We start verification of our model for purely ultraperipheral collisions. Fig. 7 presents results for coherent $J/\psi$ photoproduction in the $^{208}\text{Pb}+^{208}\text{Pb}$ UPC at $\sqrt{s_{NN}} = 2.76$ TeV. We show our results for classical and quantal rescattering in the nucleus-medium and for different nuclear form factors. The result with the monopole form factor strongly overestimates the ALICE and CMS data. The result with the quantal rescattering is about 15% larger than that for the classical rescattering. The difference is much smaller here than for the photoproduction of $\rho^0$ meson [21]. The CMS ”data point” was obtained by correcting a real data point with at least one neutron in zero-degree calorimeter (ZDC) using the Monte Carlo program STARLIGHT [22]. The ALICE data points are taken from Refs. [24, 25] and the CMS data point is from Ref. [23]. Relatively good agreement is obtained for the forward rapidity region provided the realistic nuclear form factor is used which supports application of the model also for more central ($b < R_A + R_B$) collisions especially in the considered rapidity range.

In Fig. 8 we show the nuclear cross section as a function of the impact parameter also for its small values ($b < R_A + R_B$) i.e. for the semi-central collisions. The different lines correspond to different approximations of photon fluxes within our approach as described in the figure caption. The dashed and solid lines represent upper and lower limit for the cross section. At larger values of impact parameter $b$ the cross sections obtained with the different fluxes practically coincide. At $b < R_A + R_B$ the different approximations give quite different results. The standard approach used in the literature for UPC (Eq. (2.12)) when naively applied to the semi-central collisions overestimates the cross section. We will return to this issue in the following.

In Tab. II we have collected the cross sections for six ranges of collision centrality used in
FIG. 8: Differential cross section for photoproduction of $J/\psi$ meson as a function of impact parameter for $\sqrt{s_{NN}} = 2.76$ TeV. Different lines correspond to different approximations: dotted - standard UPC approach, dashed - first approximation/correction (upper limit), solid - second approximation/correction (lower limit). Here realistic (charge) nuclear form factor was used.

| Centrality range [%] | 0-10 | 10-30 | 30-50 | 50-70 | 70-90 | 0-100 | UPC |
|----------------------|------|-------|-------|-------|-------|-------|-----|
| $\sigma_{tot}^{REAL}$ [mb] | 1.19 | 3.36 | 2.58 | 1.57 | 0.97 | 10.08 | 16.32 |
| $\sigma_{tot}^{MONOP}$ [mb] | 3.64 | 3.99 | 2.16 | 1.36 | 0.99 | 12.58 | 16.26 |
| $\sigma_{tot}^{PL}$ [mb] | 211.00 | 6.11 | 2.46 | 1.50 | 1.06 | 222.68 | 16.43 |

TABLE I: Integrated and differential cross section for the photoproduction of $J/\psi$ in $Pb + Pb$ collisions for $\sqrt{s_{NN}} = 2.76$ TeV calculated with a simple flux factor according to Eq. (2.12) for the case when realistic (REAL), monopole (MONOP) and point-like (PL) form factors are used. We show results for different ranges of centrality as well as for ultraperipheral events. The differential cross section is compared with the ALICE experimental data [16]. $\Delta y = 1.5$ means $\gamma \in (2.5,4.0)$ for brevity.

[16] as well as for UPC. We show total (full range of rapidity) and differential ($d\sigma/dy_{J/\psi}$) cross section for rapidity range of the ALICE experimental studies ($y_{J/\psi} = (2.5−4)$). Here we take the photon flux given by Eq. (2.12). For each case, the largest cross section appears for centrality range 10−30% which corresponds to $b \approx (4.4−7.6)$ fm according to formula (2.14). One should be aware that the results for the point-like form factor ($F(q) = 1$) at very small centrality are not physical. Here there is a very strong dependence on impact parameter $b$. The photon flux for very small value of $b$ tends to infinity. Looking at the agreement
of our results with the experimental ALICE data, one can observe that calculations with realistic form factor are in fairly good agreement with the experimental data. For centrality larger than 30% the cross section obtained with the monopole form factor is closer to the experimental value. However, for each form factor the cross section is larger than that given by the ALICE Collaboration. Only for centrality range 70 − 90% we get a good agreement with the experimental result.

It is worth to note here that the nuclear form factor actually appears in two formulas in the calculation of the cross section for the $AA \rightarrow AA J/\psi$ reaction. A first one is for the flux of photons (see Eq. (2.12)) and the second one is for the cross section for the $\gamma A \rightarrow J/\psi A$ reaction (see Eq. (2.22)) which is integrated over squared four-momentum transfer. Only hard sphere form factor was used so far in the literature in the context of the $J/\psi$ photoproduction [9]. The results presented in Table II are calculated for the case when realistic charge distribution is included both in Eq. (2.12) and in (2.22), and for the case when the monopole or point-like form factors are used only in calculating the photon flux and realistic form factor is used in Eq. (2.22). We suppose that a consistent calculation should use the same form factor in both places (Eqs. (2.12) (or (2.4)/(2.3)) and (2.22)).

The results presented in Table II are calculated for the case when realistic charge distribution is included both in Eq. (2.12) and in (2.22), and for the case when the monopole or point-like form factors are used only in calculating the photon flux and realistic form factor is used in Eq. (2.22). We suppose that a consistent calculation should use the same form factor in both places (Eqs. (2.12) (or (2.4)/(2.3)) and (2.22)).

| Centrality range [%] | 0-10 | 10-30 | 30-50 | 50-70 | 70-90 | 0-100 | UPC |
|----------------------|------|-------|-------|-------|-------|-------|-----|
| $\sigma_{tot}^{MONOP}$ [mb] | 8.23 | 9.03 | 4.89 | 3.08 | 2.45 | 28.50 | 38.42 |
| $\sigma_{tot}^{PL}$ [mb] | 17 037.50 | 926.26 | 379.30 | 223.40 | 158.50 | 18795.50 | 2838.30 |
| $d\sigma/dy_{J/\psi}[\mu b]$ ($\Delta y = 1.5$) | <318 | <290 | 73 | ±44±26 | ±16±10 | ±11±10 | 58 | 59 |
| $d\sigma_{tot}^{MONOP}/dy_{J/\psi}[\mu b]$ ($\Delta y = 1.5$) | 892 | 817 | 365 | 201 | 132 |
| $d\sigma_{tot}^{PL}/dy_{J/\psi}[\mu b]$ ($\Delta y = 1.5$) | 1 488 700 | 88 230 | 28 800 | 14 660 | 9 370 |

TABLE II: Integrated and differential cross section for the production of $J/\psi$ in $Pb+Pb$ collisions for $\sqrt{s_{NN}} = 2.76$ TeV for the case when monopole (MONOP) and point-like (PL) form factor is included in photon fluxes and in the total cross section for the $\gamma A \rightarrow J/\psi A$ reaction. We show results for different ranges of centrality as well as for ultraperipheral case. The differential cross section is compared with the ALICE experimental data [16]. $\Delta y = 1.5$ means $y \in (2.5,4.0)$ for brevity.

In Table II we have collected the nuclear cross section for the $PbPb \rightarrow PbPbJ/\psi$ reaction. This table is very similar to the previous one, but now we use the monopole and point-like form factor also in the formula which describes the total cross section for the $\gamma A \rightarrow J/\psi A$ reaction (2.22). These numbers are much larger than in the previous approach. We conclude that the point-like approximation cannot be used to calculate the $\gamma Pb \rightarrow J/\psi Pb$ cross section because it leads to unphysical behaviour for $b < R_A + R_B$.

Table III and Table IV collect the cross sections for different centrality bins for the first (Eq. (2.3)) and second (Eq. (2.4)) approximation of the photon flux, respectively. A fairly good agreement with the ALICE data is obtained with the second approximation for all measured centrality bins.

We summarize the numbers from the tables in Fig. 9. We present both statistical and systematic error bars (shaded area). The ALICE Collaboration could not extract actual values of the cross section for the two lowest centrality bins. The results for standard photon flux exceed the ALICE data. Rather good agreement with the data is achieved for the $N^{(2)}$ photon flux obtained with the realistic nucleus form factor. The fact that this
TABLE III: Integrated and differential cross section for the production of $J/\psi$ in $Pb+Pb$ collisions for $\sqrt{s_{NN}} = 2.76$ TeV calculated with the help of the first approximation of the photon flux $N^{(1)}(\omega, b)$ (Eq. (2.3)) for the realistic form factor. The differential cross section is compared with the ALICE experimental data \cite{16}. $\Delta y = 1.5$ means $y \in (2.5, 4.0)$ for brevity.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Centrality range [%] & 0-10 & 10-30 & 30-50 & 50-70 & 70-90 & 0-100 \\
\hline
$\sigma_{\text{tot}}^{\text{REAL}}$ [mb] & 1.42 & 2.47 & 2.08 & 1.60 & 1.24 & 9.37 \\
\hline
$\frac{d\sigma}{dy_{J/\psi}}$ [$\mu b$] ($\Delta y = 1.5$) & <318 & <290 & 73 & $\pm 44^{+26}_{-27}$ & $\pm 16^{+8}_{-10}$ & $\pm 11^{+7}_{-10}$ \\
ALICE data & & & & & & \\
$\frac{d\sigma^{\text{REAL}}}{dy_{J/\psi}}$ [$\mu b$] ($\Delta y = 1.5$) & 123 & 201 & 160 & 116 & 84 & \\
\hline
\end{tabular}
\end{table}

TABLE IV: Integrated and differential cross section for the production of $J/\psi$ in $Pb+Pb$ collisions for $\sqrt{s_{NN}} = 2.76$ TeV calculated with the help of the second approximation of the photon flux $N^{(2)}(\omega, b)$ (Eq. (2.4)) for the realistic form factor. The differential cross section is compared with the ALICE experimental data \cite{16}. $\Delta y = 1.5$ means $y \in (2.5, 4.0)$ for brevity.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Centrality range [%] & 0-10 & 10-30 & 30-50 & 50-70 & 70-90 & 0-100 \\
\hline
$\sigma_{\text{tot}}^{\text{REAL}}$ [mb] & 0.38 & 1.19 & 1.29 & 1.21 & 1.11 & 5.47 \\
\hline
$\frac{d\sigma}{dy_{J/\psi}}$ [$\mu b$] ($\Delta y = 1.5$) & <318 & <290 & 73 & $\pm 44^{+26}_{-27}$ & $\pm 16^{+8}_{-10}$ & $\pm 11^{+7}_{-10}$ \\
ALICE data & & & & & & \\
$\frac{d\sigma^{\text{REAL}}}{dy_{J/\psi}}$ [$\mu b$] ($\Delta y = 1.5$) & 30 & 88 & 91 & 82 & 72 & \\
\hline
\end{tabular}
\end{table}

FIG. 9: $d\sigma/dy$ cross sections for different centrality bins. Theoretical results for different models of the photon flux are compared with the preliminary ALICE data \cite{16}. The shaded area represents the experimental uncertainties.

lower limit exceeds somewhat the ALICE data may be due to the fact that the coherent $\gamma A \rightarrow J/\psi A$ cross section was used in our EPA calculation whereas only spectators may be active in the production of $J/\Psi$. 

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IV. CONCLUSIONS

So far photoproduction of vector mesons was considered only in the context of ultraperipheral collisions, i.e. in the case when nuclei survive the collision and appear in the final state, although the exclusivity is not checked in practice and experimentally a limited rapidity gap condition is imposed only. In this paper we have presented a first theoretical study of photoproduction mechanism also in the case when nuclei collide and produce quark-gluon plasma and as a consequence considerable number of hadrons, mostly pions is produced. On theoretical side, the nuclear photoproduction in UPC is treated in the equivalent photon approximation with photon fluxes and photon-nucleus cross section being the basic ingredients of the approach.

How to calculate contribution of the photoproduction mechanism for peripheral and semi-central collisions \((b < R_A + R_B)\) is not completely clear. We assume that the whole nucleus produces photons. The photon (or hadronic photon fluctuation) must hit the other nucleus to produce the \(J/\psi\) meson. The question arises how to treat the region of overlapping colliding nuclei in the impact parameter space where some absorption may be expected. We decided to include the effect of the "absorption" by modifying effective photon fluxes in the impact parameter space by imposing several additional geometrical conditions on impact parameters (between photon and nuclei and/or between colliding nuclei).

In the present paper, as an example, we have considered a vector-dominance based model which includes multiple scattering effects in addition. Any other model/approach can be applied in the future.

First we have compared results of our calculations with existing ALICE and CMS experimental data for UPC. We have obtained a reasonable agreement with the data especially in the forward rapidity region when realistic nuclear form factor is used. We have calculated the dependence of the total and differential cross section on the impact parameter (the distance between colliding nuclei in the plane perpendicular to the collision axis). By correcting standard photon fluxes valid only for UPC by collision geometry we have calculated cross section for different centrality bins adequately for the recent ALICE Collaboration analysis. Our results have been compared with their preliminary data. We have obtained a reasonable agreement for peripheral and semi-central collisions and set a lower and upper limits for the cross section for the semi-central collisions within our approach. Our lower limit is, however, model dependent. Since in our calculations we have used coherent \(\gamma A \rightarrow J/\psi A\) cross section our lower limit may be overestimated especially for small impact parameters where only so-called spectators are active for the \(J/\psi\) production. The time picture of the whole process is not clear to us in the moment. The rather reasonable agreement of our quite simplified approach with the preliminary ALICE data could suggest that the "coherent" (assumed by the formula used for the \(\gamma A \rightarrow J/\psi A\) process) scattering of the hadronic fluctuation happens before the nucleus undergoes the process of deterioration due to nucleus-nucleus collision and before the quark-gluon plasma is created. If this is not the case the "coherent" scattering must be replaced by incoherent one. Then the transition from UPC to semi-central collisions as a function of impact parameter would be more abrupt then in the present approach.

In the present paper we have performed analysis for a forward rapidity range. There the \(J/\psi\) quarkonia are emitted forward with large velocity therefore they could potentially escape from being melted by quark-gluon plasma. At midrapidities the situation can in principle be different. It would be therefore valuable if the ALICE Collaboration would
repeat their analysis also in the midrapidity range and verify the \( p_t \approx 0 \) enhancement.

The photoproduction of \( J/\psi \) seems rather special compared to photoproduction of other objects. Here the corresponding cross section \( \left( \frac{d\sigma^{UPC}_{PbPb \rightarrow PbPbJ/\psi}(y=0)}{dy} \right) \approx 2 \text{ mb} \), see Fig. 7, is of similar order of magnitude as the one for \( J/\psi \) produced in individual nucleon-nucleon collisions or produced in quark-gluon plasma (simple estimate including \( \frac{d\sigma_{pp \rightarrow J/\psi}(y=0)}{dy} \approx 4 \mu b \))

(Ref. [4]), estimated number of binary collisions and experimental nuclear modification factor (Ref. [1]) gives \( \frac{d\sigma_{ppPb \rightarrow J/\psi}(y=0)}{dy} \sim 1 \text{ mb} \) for minimum-bias collisions). In our simple estimate we get \( \frac{d\sigma^{photoprod.}_{PbPb \rightarrow J/\psi}(y=0; b<R_A+R_B)}{dy} \sim (0.91 - 1.42) \text{ mb} \), where the two numbers are obtained with \( N^{(2)} \) and \( N^{(1)} \) fluxes, respectively. These numbers are of similar size as the contribution of other mechanisms discussed above. For (photo)production of other objects the situation may be different. This was not discussed in the literature so far and requires dedicated studies.

\[ \text{Acknowledgments} \]

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