Exclusive Photoproduction J/Ψ in Peripheral Pb-Pb

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Introduction

The ALICE collaboration measured the J/ψ hadroproduction in peripheral collisions Pb-Pb, with $\sqrt{s} = 2.76$ TeV, revealing an excess in the production of the meson in very small transverse momentum ($p_T < 0.3$ GeV/c) in the range rapidity $2.5 < y < 4.0$ [1]. Considering the J/ψ excess could be generated from exclusive photo-production, we calculated the J/ψ nuclear photo-production in peripheral collisions from the formalism adopted in the ultraperipheral collisions (UPC), which cross section can be separated in two components: the equivalent photon flux, $N(\omega, b)$, and the photonuclear cross section, $\sigma_{\gamma A \to VA}$. In our approach, the transition from ultraperipheral to peripheral regime is analised considering three scenarios: (1) direct application of the usual photon flux and of the photonuclear cross section without any change in relation to UPC's, (2) change only in the photon flux and (3) change in the photon flux and in the photonuclear cross section.

Theoretical Framework

In the ultrarelativistic limit, the exclusive nuclear photoproduction of a vector meson V can be written as the convolution between a photon flux, created from one of the nuclei, and the photonuclear cross section, which characterizes the photon-target interaction $\gamma A \to VA$. Assuming a photon flux with b dependence impact parameter, the differential cross section in the rapidity y and impact parameter b, is given by [2]

$$\frac{d^3\sigma_{AA \to AAV}}{d^2 b dy} = \omega N(\omega, b) \sigma_{\gamma A \to VA} + (y \to -y)\,. \tag{1}$$

where $\omega = \frac{1}{2} M_V \exp(y)$ is the photon energy and M_V is the meson mass. In the peripheral collisions the eletromagnetic form factor, $F(k^2)$, becomes relevant and, therefore, was adopted the following generic formula for the photon flux [3]

$$N(\omega, b) = \frac{Z^2 \alpha_{QED}}{\pi^2 \omega} \left| \int_0^\infty dk_\perp k_\perp^2 \frac{F(k^2)}{k^2} J_1(bk_\perp) \right|^2, \tag{2}$$

where Z is the nuclear charge, $\gamma = \sqrt{s_{NN}}/(2m_{\text{proton}})$ is the Lorentz factor, $k_\perp$ is the transverse momentum of the photon and $k^2 = (\omega/\gamma)^2 + k_\perp^2$. For the lead nucleus, it was used the form factor $F(k) = 4\pi\rho_0 \left[\sin(kR_A) - kR_A \cos(kR_A)\right] / \left[Ak^3(1 + a^2k^2)\right]$, where A is the mass number, $a = 0.7$ fm and $\rho_0 = 0.1385\ \text{fm}^{-3}$. The second component in (1), $\sigma_{\gamma A \to VA}$, is described in the light cone colour dipole formalism, which includes the partonic saturation phenomenum and the nuclear shadowing effects [4]. The formalism has already been explored in the last works [5] and, here, we showed only its mean equation,

$$\sigma_{(\gamma A \to VA)} = \frac{|\text{Im}\, A(x, t=0)|^2}{16\pi} \left(1 + \beta^2\right) R_g^2 \int_{t_{min}}^\infty |F(t)|^2 dt, \tag{3}$$

The photon-nuclei forward scattering amplitude, $|\text{Im}\, A(x, t=0)|$, carries most of the phenomenological models, such as, the meson wave function and the photonuclear cross section, being this last defined by

$$\sigma_{\gamma A \to VA}^{nuc} = 2 \int d^2 b \left(1 - e^{-\frac{1}{2}\sigma_{dip} T_A(b)}\right) \tag{4}$$

where $T_A(b)$ is the nuclear overlap function and σ_{dip} is the dipole cross section. In our calculations, were considered the GBW and CGC dipole models, since they presented a good agreement with the data in the ultraperipheral regime [5]. The form factor is integrated from $t_{min} = \left(M_V^2/2\omega\gamma\right)^2$ to infinity, with $F(k^2)$ as previously defined. The other parameters are detailed in [6]. The application of the equations (2) and (3) inside of (1) constitutes what we named the **scenario 1**, which produces the results showed in the second row of Table 1.

The Effective Photon Flux

In order to refine our calculation, it was modified the photon flux following the similar procedure suggested in [2], which an *effective* photon flux built in terms of the usual photon flux (eq. 2) with two restrictions: (1) only the photons that reach the geometrical region of the nuclear target will be considered and (2) the photons that reach the overlap region will be neglected. Then, the new photon flux can be expressed as [7]

$$N^{eff}(\omega, b) = \frac{1}{A_{eff}(b)} \int d^2 b_1 N(\omega, b_1)\, \theta(R_A - b_2) \theta(b_1 - R_A) \tag{5}$$

where, unlike [2], it was divide it by effective area $A_{eff}(b) = R_A^2 \left[\pi - 2\cos^{-1}\left(\frac{b}{2R_A}\right)\right] + \frac{b}{2}\sqrt{4R_A^2 - b^2}$, instead of the fixed value πR_A^2. In the Figure 1, was compared the usual photon flux with the effective photon flux to the energy of the photon $\omega = 0.01$ GeV and $\omega = 1$. For $b \lesssim 4$, the usual photon flux diverges considerably from the effective photon flux going to 0 as $b \to 0$. In the range 4 fm $\lesssim b \lesssim 11$ fm, the usual photon flux is bigger than the effective photon flux, mainly on the threshold $b \sim R_A \sim 7$. In the last, as $b \to \infty$, both models become similar as expected.

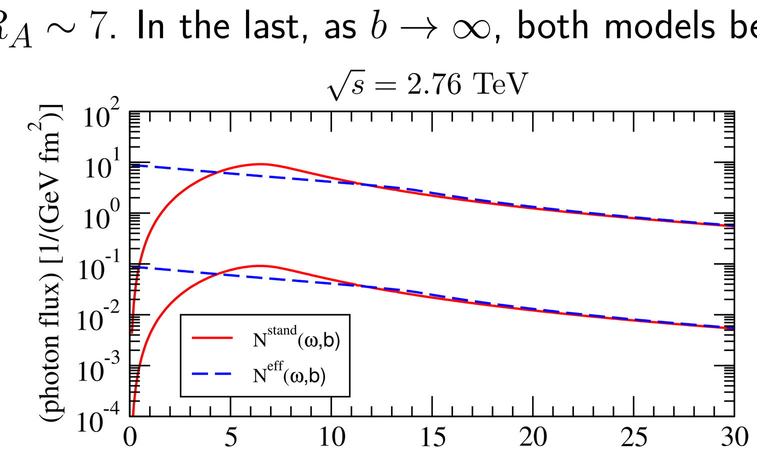

Figure: Comparison between the usual and effective photon flux for the $\omega = 0.01$ GeV and $\omega = 1$ GeV at $\sqrt{s} = 2.76$ TeV.

Rapidity Distribution

Considering the effective photon flux without changing the photonuclear cross section (**scenario 2**), was calculated the rapidity distribution for the J/ψ photoproduction in Pb-Pb collisions in the following centrality classes: 30%-50%, 50%-70% and 70%-90%. Adopting the GBW and CGC dipole models, we performed our analysis at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 5.02$ TeV as it can be seen in the Figure 2. For $\sqrt{s} = 2.76$ (left), it was observed an increase of the $\sim 12\%$ from 70%-90% to 50%-70% and of the $\sim 13.7\%$ from 50%-70% to 30%-50%, for the both models, at $y = 0$. Similarly, it was observed an increase of the $\sim 12\%$ from 70%-90% to 50%-70% and $\sim 13.3\%$ from 50%-70% to 30%-50% at $y = 0$. Therefore, the relative variation between the different centrality classes does not present sensitivity as the increase of the energy.

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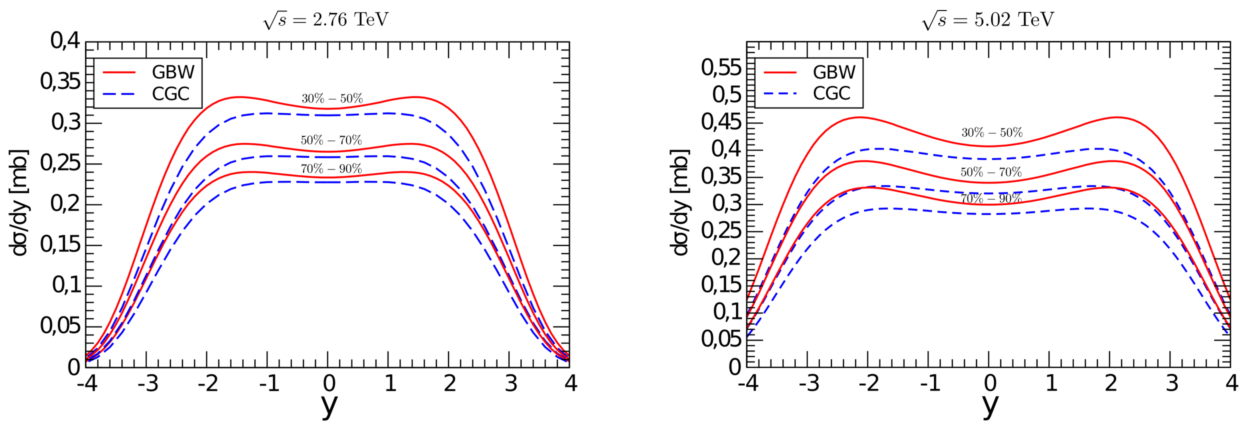

Figure: Rapidity distribution for J/ψ nuclear photoproduction at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 5.02$ TeV for different centrality classes using the GBW and CGC dipole models.

To compare with the ALICE data, the rapidity distribution was integrated in the rapidity region $2.5 < y < 4.0$, providing the results showed in the thirth row of the Table 1. In this case, it was observed a better aggrement with the data in the more central region in relation to scenario 1.

Effective Photonuclear Cross Section

For consistency, it was also modified the photonuclear cross section applying the restriction $\Theta(b1 - R_A)$ in Eq. (4) in order to consider only the interaction of the photon with non-overlap region (**scenario 3**). From this modification, were obtained the results showed in the fourth row of Table 1, which contain the results of the tree scenarios adopted. More details about each scenario can be found in [8].

Average Rapidity Distribution: $d\sigma/dy$

GBW/CGC	30%-50%	50%-70%	70%-90%
Scenario 1	200/170	100/84	60/51
Scenario 2	128/107	98/80	80/67
Scenario 3	73/61	78/66	75/63
ALICE data	$73 \pm 44^{+26}_{-27} \pm 10$	$58 \pm 16^{+8}_{-10} \pm 8$	$59 \pm 11^{+7}_{-10} \pm 8$

Table: Comparison between our results obtained from different approximations and the ALICE data [1].

R_{AA} Calculation

In the ALICE analysis, the excess of the J/ψ was quantified by nuclear modification factor, defined by [9],

$$R_{AA}^{hJ/\psi} = \frac{N_{AA}^{J/\psi}}{BR_{J/\psi \to l^+ l^-} \cdot N_{events} \cdot (A \times \varepsilon)_{AA}^{J/\psi} \cdot \langle T_{AA} \rangle \cdot \sigma_{pp}^{hJ/\psi}}\,, \tag{6}$$

where the measured number of J/ψ ($N_{AA}^{J/\psi}$) was corrected for acceptance and efficiency $(\mathcal{A} \times \varepsilon)_{AA}^{J/\psi}$ and branching ratio $\text{BR}_{J/\psi \to \mu^+\mu^-} = 5.96\%$. Then, the result is normalized to the equivalent number of MB events (N_{events}), defined in [9], average nuclear overlap function ($\langle T_{AA} \rangle$), calculated from [10], and proton-proton inclusive J/ψ production cross section ($\sigma_{pp}^{hJ/\psi}$), calculated from a parametrization detailed in [1]. In order to compare with ALICE measure, the results described in the Table 1 were used to calculate the values of the R_{AA} in the kinematic region $p_T < 0.3$ GeV/c and $2.5 < y < 4.0$, . Adopting the CGC dipole model, which provided the better results than GBW in the Table 1, we calculate R_{AA} for the three scenarios described in the text, Fig. 3.

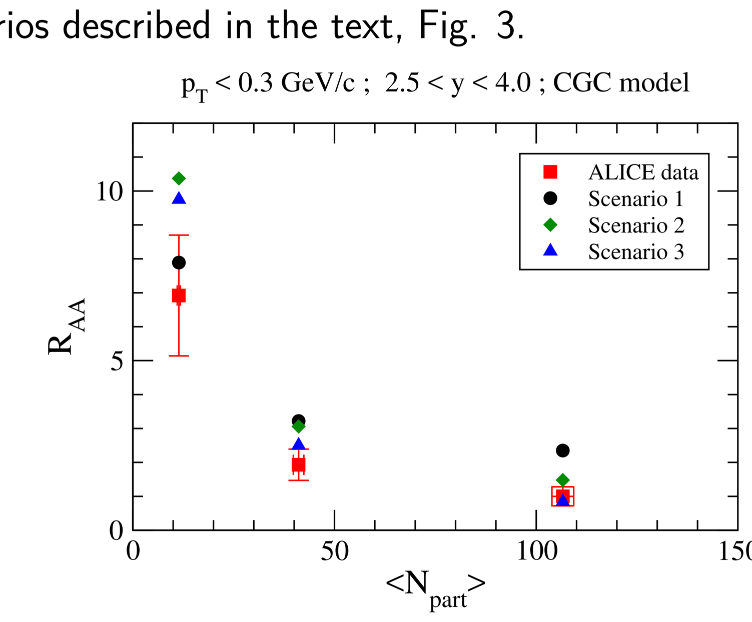

Figure: Comparison of the R_{AA} results with the ALICE data for the centrality classes 30%-50%, 50%-70% e 70%-90% [1].

Conclusion and Discussion

Our estimates for the rapidity distribution and nuclear modification factor were presented for the J/Ψ production in the centrality classes 30%-50%, 50%-70% and 70%-90%. In our calculation, were compared the ALICE data with our estimates, obtained from three different approaches. In the simplest approach (scenario 1), was obtained better aggrement with the data only in the more peripheral region, where there is a considerable uncertainty. On the other hand, for the more consistent approach (scenario 3), the result overestimate in the more peripheral region, however, it agrees better with the data in more central region where the incertainty is small. Although it is not yet possible to confirm that the exclusive photoproduction is solely responsible by J/ψ excess observed at ALICE, there are indications that it produces the most part of the effect.

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