Evidence of subnucleonic degrees of freedom in J/ψ photoproduction in ultraperipheral collisions at energies available at the CERN Large Hadron Collider

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We present calculations for the incoherent photoproduction of J/ψ vector mesons in ultraperipheral heavy ion collisions (UPCs) in terms of hadronic interactions. This study was carried out using the recently developed Monte Carlo model CRISP extended to include UPCs at energies available at the CERN Large Hadron Collider. A careful study of rescattering and destruction of the J/ψ particles is presented for Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. We have also compared our method to Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured at the BNL Relativistic Heavy Ion Collider.

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I. INTRODUCTION

Photoproduction of vector mesons is important in many aspects because it provides insight into basic QCD dynamics not only in the perturbative but also in the nonperturbative region. The associated form factors and intermediate isobar states should test quark models. At the Large Hadron Collider (LHC) at CERN recent experiments in $p + p$ and p + Pb collisions led to ions zipping past each other at relativistic energies. They are excellent supplies of Fermi's almost real photons due to intense electromagnetic fields [1], leading to numerous possibilities for studying photonuclear and photon-photon collisions not always available with real photons [2–4].

Recent experiments at the LHC have reported J/ψ production in Pb + Pb and p + Pb collisions in ultraperipheral collisions (UPCs) [5–7]. Previous theoretical works have predicted the magnitude of the cross sections based on subnucleonic degrees of freedom [8–11]. One major conclusion of these efforts is that UPCs are an excellent probe of parton distribution functions (PDFs) and the evolution of gluon distributions in nuclei [12,13]. It is the goal of this work to show how a purely hadronic model could describe the incoherent photoproduction of J/ψ at energies as high as $\sqrt{s_{NN}} = 200$ GeV and how the need for nuclear gluon dynamics at higher energies can be inferred in a more reliable manner through the aid of an intranuclear cascade model based on hadronic consideration.

II. MODEL

Our tool for investigating J/ψ production in UPCs is the CRISP model (acronym for Collaboration Rio–Ilhéus–São Paulo), which is implemented through a cascade of hadronic collisions using Monte Carlo techniques [14,15]. The CRISP model describes the nuclear reaction as a two-step process, namely, the intranuclear cascade and the evaporation/fission competition. For the present work the first one is the most important.

The intranuclear cascade encompasses all the processes from the first interaction of an incident particle with the nucleus, which is called primary interaction, up to the final thermalization of the nucleus [16]. The evaporation/fission stage describes all processes that occur after thermalization, including all possible decay channels through strong interactions, which are the successive evaporation of nucleons or cluster of nucleons and fission [17,18]. Intranuclear cascade and evaporation/fission competition are also called fast and slow processes, respectively.

A particular feature of the CRISP model is that the intranuclear cascade is described as a multicollisional process involving all nucleons in the nuclei. This aspect allows a more realistic description of reaction mechanisms such as Pauli blocking, nuclear density fluctuations, propagation of resonances in the nuclear medium, final state interactions (FSI), and pre-equilibrium emissions. As a result, many different observables are properly calculated with a small number of parameters for several nuclear masses and different collision energies.

In the evaporation/fission stage, the Weisskopf mechanism for evaporation is used [19], with the nuclear masses being calculated by the Pearson nuclear mass formula [20]. The input parameters, such as the neutron, proton, and α-particle level densities, are calculated according to the Dostrovsky empirical formulas [21].

Both intranuclear cascade and evaporation/fission calculations with the CRISP model have been extensively investigated yielding good results for reactions induced by photons, electrons, and protons and observables such as neutron or proton multiplicity, fission and spallation cross sections, and fragment mass distributions [14,16,17,22–27].

Recently the CRISP model was extended to higher energies (up to the TeV region) with the inclusion of vector meson photoproduction [28]. Some aspects of vector meson production by real photons have already been analyzed, such as subthreshold production, nuclear transparency, and FSI. In this work we apply for the first time this new tool for the study of UPC production of J/ψ.

The flux of virtual photons of a relativistic nucleus (projectile) is given by

$$n(E_\gamma,b) = \frac{Z^2\alpha}{\pi^2}\frac{x^2}{\beta^2 b^2}\left[K_1^2(x) + \frac{1}{\gamma^2}K_0^2(x)\right]e^{-2\chi(b)}, \quad (1)$$

with $x = E_\gamma b/\hbar\gamma\beta c$, where E_γ is the photon energy at the other colliding nucleus (target) frame of reference, b is the impact parameter, Z is the charge of the projectile nucleus, α is the fine structure constant, $\beta = v/c$, γ is the Lorentz factor, and K_0 and K_1 are the modified Bessel functions of the second type. The factor $e^{-2\chi(b)}$ is the survival probability of both ions at impact parameter b, with $\chi(b)$ given by

$$\chi(b) = \frac{\sigma_{NN}}{4\pi}\int_0^\infty dq\, q\, \tilde{\rho}_t(q)\tilde{\rho}_p(q)J_0(qb), \quad (2)$$

where σ_{NN} is the nucleon-nucleon total cross section, $\tilde{\rho}_{t(p)}(q)$ is the Fourier transform of the nuclear density of target (projectile), and J_0 is the cylindrical Bessel function of order zero. We use $\sigma_{NN} = 80$ mb for Pb + Pb collisions and $\sigma_{NN} = 53$ mb for Au + Au. We assume Fermi functions for the nuclear densities with radius $R = 6.62$ fm and diffuseness $a = 0.546$ fm for Pb, and $R = 6.43$ fm and $a = 0.541$ fm for Au.

The cross section of a process X in ultraperipheral collisions can then be calculated as [2]

$$\sigma_X = \int \frac{dE_\gamma}{E_\gamma} N(E_\gamma)\sigma_{\gamma A\to X}(E_\gamma), \quad (3)$$

where $\sigma_{\gamma A\to X}$ is the cross section due to a real photon and $N(E_\gamma)$ is the integral of $n(E_\gamma,b)$ over impact parameters.

We represent our results in terms of the rapidity y through the relation $d\sigma/dy = E_\gamma d\sigma/dE_\gamma$, where E_γ and the rapidity of the produced particle are related by

$$y = \ln\left[\frac{W_{\gamma p}^2}{2\gamma m_p M_P}\right] = \ln\left[\frac{E_\gamma}{\gamma M_P}\right], \quad (4)$$

where $W_{\gamma p} = \sqrt{2E_\gamma m_p}$ is the γp center-of-mass energy, m_p is the proton mass, M_P is the mass of the particle of interest, and $\gamma = 2\gamma_L^2 - 1$ with γ_L being the Lorentz factor of the beam in the laboratory. In terms of the rapidity of the particle X for AA collisions

$$\frac{d\sigma_{AA\to AAX}(y)}{dy} = \frac{d\sigma_{\gamma A\to AX}(y)}{dy} + \frac{d\sigma_{\gamma A\to AX}(-y)}{dy}. \quad (5)$$

III. RESULTS AND DISCUSSION

The CRISP model uses the universal model of a soft dipole Pomeron proposed by Martynov, Predazzi, and Prokudin [29,30] to calculate the photoproduction of vector mesons. The consistency of the model can be attested by Fig. 1 where

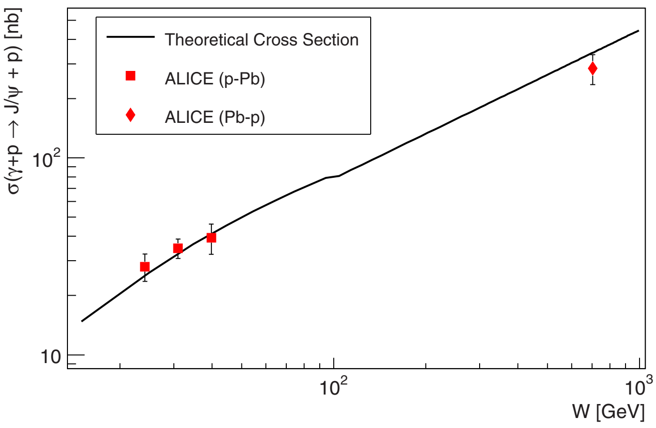

FIG. 1. (Color online) J/ψ photoproduction cross section off the proton. Experimental points are from the ALICE Collaboration measurements in p + Pb UPC at $\sqrt{s_{NN}} = 5.02$ TeV [31].

the cross section for J/ψ photoproduction off the proton is compared with measurements of the ALICE Collaboration for p + Pb ultraperipheral collisions at $\sqrt{s_{NN}} = 5.02$ TeV [31]. The connection between vector meson photoproduction off protons and UPCs was described in a recent work [32] where also several theoretical models were compared in the study of $p + p$ ultraperipheral collisions at 7 TeV.

Experimental data on J/ψ photoproduction in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV were published by the ALICE Collaboration [33] where an experimental definition of coherent and incoherent production was established, according to the transverse momentum being $p_T < 200$ MeV/c ($p_T > 200$ MeV/c) in the di-muon decay channel and $p_T < 300$ MeV/c ($p_T > 300$ MeV/c) in the di-electron decay channel in coherent (incoherent) events. The CRISP model yields the results displayed in Fig. 2.

We have also calculated J/ψ production for several values of rapidity in the interval $-3 < y < 3$, corresponding to the range 219 GeV $< E_\gamma <$ 89 TeV for the photon energy and 20 GeV $< W_{\gamma p} <$ 409 GeV for the γp center-of-mass frame. This is shown by the dashed curve in Fig. 2, whereas the dotted curve is obtained by the inversion symmetry $y \to -y$.

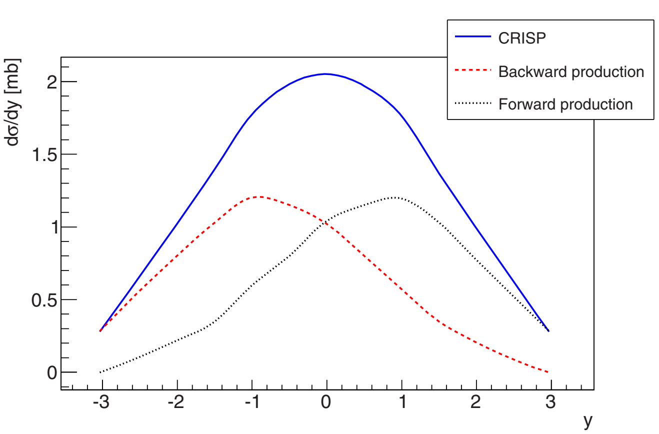

FIG. 2. (Color online) Incoherent cross section for J/ψ photoproduction showing contributions from both colliding ions of Pb at $\sqrt{s_{NN}} = 2.76$ TeV.

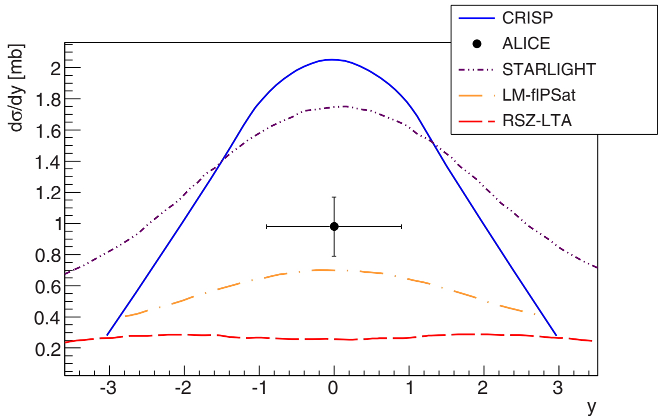

FIG. 3. (Color online) Incoherent J/ψ photoproduction cross section from Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Comparison with different models and experimental data, all extracted from Ref. [33].

It is readily noticed that J/ψ photoproduction is dominant at lower energies because the virtual photon flux falls rapidly with energy.

Figure 3 compares our results with the experimental data together with results from other models, all extracted from Ref. [33]. STARLIGHT is based on a Glauber model for participating nucleons folded with the J/ψ-nucleon cross section and accounting for the nuclear collision geometry [34]. LM-fiPsat adopts an impact parameter saturated dipole model with an eikonalized DGLAP-evolved gluon distribution [35]. RSZ-LTA is a partonic model in which the cross section depends on the square of the nuclear gluon distribution.

From Fig. 3 we notice that CRISP overestimates the experimental value by nearly 100%. Because we use a consistent γp cross section, a realistic intranuclear cascade model, and proper in-medium final state interactions, such a discrepancy could be evidence of the limitation of a purely hadronic model, at least for this particular system. It is worthwhile mentioning that other models are not successful either: a possible conclusion is that incoherent processes in the TeV range are not very well understood.

Transverse momentum distributions are another tool of relevance. A particular aspect of p_T distribution is its sensitivity to different models for the elastic channel of the final state interaction. Although the distributions of incoherent and coherent processes are not experimentally accessible, a comparison between different models is nonetheless useful. Figure 4 shows a comparison between CRISP and STARLIGHT incoherent calculations along with the corresponding rapidity distribution. Two elastic FSI channels are provided with CRISP.

CRISP uses the Martynov, Predazzi, and Prokudin soft dipole Pomeron model to evaluate the elastic FSI channel, identified as the solid line in Fig. 4(a). Another alternative [36] is a fit to the experimental photoproduction data as

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = 23.15s^{0.16} + 0.034s^{0.88} + 1.49s^{0.52}, \qquad (6)$$

where s is the γp center-of-mass energy. The first term accounts for the soft Pomeron contribution, the second one for

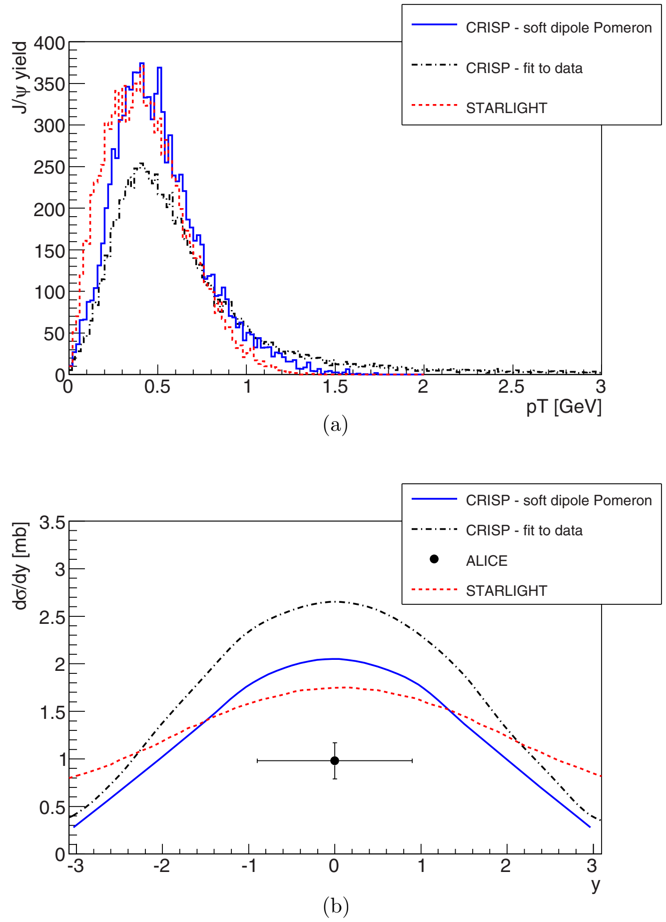

FIG. 4. (Color online) (a) Transverse momentum distributions of J/ψ calculated with the CRISP model compared with STARLIGHT. (b) Incoherent cross section of J/ψ production. Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

the hard Pomeron, and the third one is the interference between the two. Equation (6) yields higher values for the transverse momenta and considerably higher cross sections, shown in Fig. 4 by the dot-dashed line. The soft dipole Pomeron model, on the other hand, is effective in describing photoproduction off protons from threshold to several hundreds of GeV [29]. When applied to elastic FSI, it provides a lower average transverse momentum and the photoproduction cross section is closer to the experimental value.

Figure 4 also shows that the p_T distributions obtained with CRISP (soft dipole Pomeron) and STARLIGHT are compatible except for two aspects. The first one is the little shift to higher momenta given by CRISP model. The second is the narrowing of the CRISP distribution compared to STARLIGHT. This is the immediate reason why the CRISP incoherent cross section is higher at $y = 0$ and narrower. The differences are considerable in terms of the physics in the models but small in terms of p_T distribution. Both models agree that the mechanism called incoherent is not sufficient to explain the data and that a different process, namely, the coherent interaction, is necessary to explain the low transverse momentum observed experimentally [33].

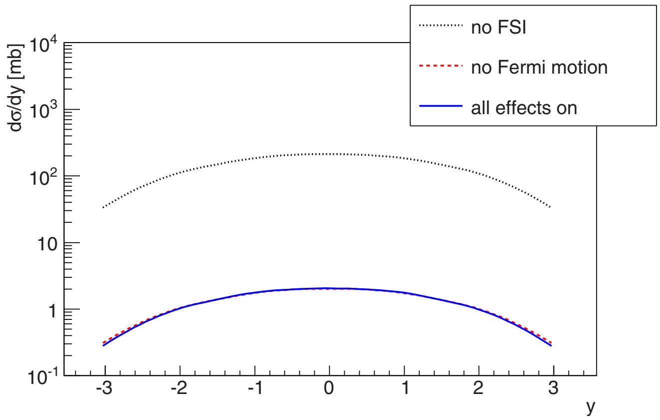

FIG. 5. (Color online) Incoherent J/ψ photoproduction cross section for different scenarios. Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

Our model also allows us to assess nuclear medium effects such as Fermi motion and final state interactions of J/ψ in the nuclear matter. The behavior of the cross section by switching off each of these effects can be seen in Fig. 5. The cross section increases by orders of magnitude in the absence of FSI, revealing the importance that this feature has over the results. In fact, Fig. 6 shows the position distribution of the created J/ψ according to subsequent emission or suppression by the nuclear matter, evidencing that the emitted particles are indeed those produced very close to the surface.

Two important features of the production process can be learned from Fig. 6. The large quenching of J/ψ production by FSI and the shadowing effects are noticeable due the small number of produced J/ψ close to the center of the nucleus. According to a previous work [28], the hadronization of the photon accounts for a dump in the photoproduction cross section in the internal region of the nucleus, resulting from the shadowing effect. As a consequence the cross section is not proportional to the number of nucleons, but to A^{α}, α being an exponent smaller than unity. For strongly interacting particles

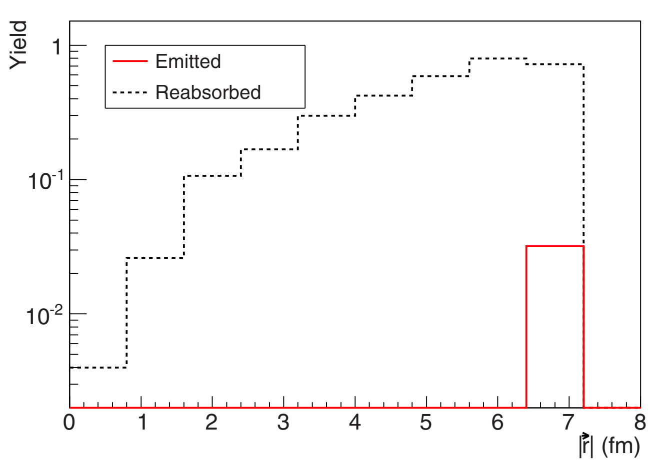

FIG. 6. (Color online) Distribution of the position of the created J/ψ according to its emission or suppression in the nuclear matter. Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

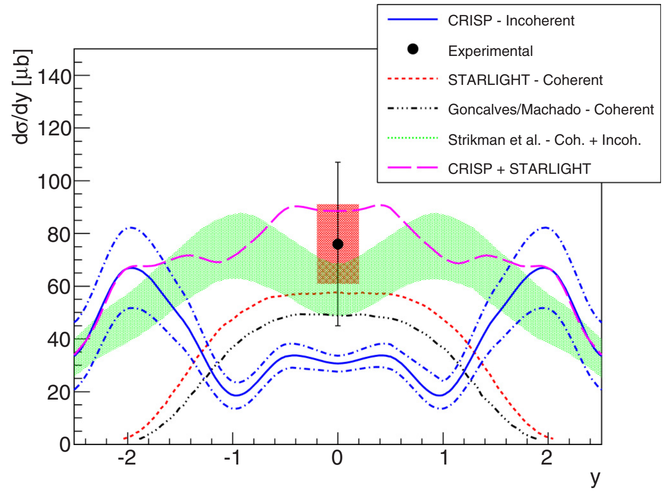

FIG. 7. (Color online) Total photoproduction cross section of J/ψ in Au + Au collision at $\sqrt{s_{NN}} = 200$ GeV. Comparison with STARLIGHT, Strikman *et al.,* and Gonçalves-Machado models, all extracted from [37] as well as the experimental data. The lines (–.) delimit the statistical uncertainties in the calculations.

$\alpha \approx 2/3$, meaning that the particles interact already at the nuclear surface. However, for J/ψ $\alpha \approx 0.94$, similar to values found for the photoproduction of other mesons, $\alpha \approx 0.9$ [28]. The fact that J/ψ is produced also for small values of r is in accordance with the shadowing effect predictions.

The second aspect of J/ψ photonuclear production is the fact that the strong final state interactions inhibit the escape of J/ψ generated in the interior of the nucleus and only those produced near the nuclear surface will escape, the others being reabsorbed by the nucleus. In fact, as shown in Fig. 5, only ~1% of the produced J/ψ leave the nucleus. These results evidence the important role played by FSIs in the J/ψ production in UPCs. The effects of FSIs can be investigated in LHC energies using UPCs if collisions between nuclei of different sizes such as C + C and U + U (besides p+A collisions) can be performed.

With respect to Fermi motion, we observe that its effects are relatively small compared to the full calculation, of the order of the uncertainties in the Monte Carlo method.

J/ψ photoproduction in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV was also calculated in the $-2 < y < 2$ rapidity interval corresponding to the range 45 GeV $< E_{\gamma} <$ 2.44 TeV for the photon energy and 9 GeV $< W_{\gamma p} <$ 68 GeV. The calculation is shown in Fig. 7 compared with experimental data from the PHENIX Collaboration [37]. The data correspond to the total cross section measured without separation between coherent and incoherent events due to statistical limitations. In this case the PHENIX Collaboration estimated a dominant coherent contribution, which is the reason why comparisons with coherent calculations were provided in Ref. [37]. STARLIGHT calculations and the Gonçalves-Machado model were extracted from Ref. [37]. The calculations provided by Strikman *et al.* for the total cross section were also extracted from Ref. [37].

According to estimates by the PHENIX Collaboration, the incoherent contribution is approximately 40%, or $\sim$30 μb, in accordance with CRISP model calculations. Figure 7 also shows the summation of CRISP and STARLIGHT results. A fair agreement is found between the summation and both the Strikman model and the experimental data. The lack of more experimental data certainly reduces the extent of the analysis.

The slight disagreement between CRISP calculations and experimental results for Pb + Pb at $\sqrt{s_{NN}} = 2.76$ TeV cannot be attributed to FSIs. We have verified that the FSI effects saturate since the J/ψ effectively produced in UPCs are those generated exactly at the nuclear surface, so small modifications on J/ψ FSIs will not alter our results. We have also tested possible effects of a smooth surface by modifying the parameters of the survival probability inside a reasonable range. The decrease of the cross section for $y = 0$ is smaller than 6% and thus our conclusions are not modified.

The disagreement between calculation and experiment therefore can be attributed only to the primary interaction between the virtual photon and the nucleon. Since the model used is a nucleonic one, this can be an indication of the necessity of subnucleonic degrees of freedom in the description of J/ψ photoproduction. In this case the better agreement obtained with Au + Au collisions could be indicative of the fact that at lower energies the nucleon-based model is still satisfactory. In fact, considering again $y = 0$, the photon energy at target reference frame for Pb and Au are, respectively, $E_\gamma = 4.4$ and 0.3 TeV. The threshold for subnucleonic degrees of freedom would be inside this interval.

The work in Ref. [32], however, shows that models based on nucleonic degrees of freedom do describe rather well the cross section and rapidity distribution of J/ψ production in UPCs even at very high energies and a rapidity range between 2 and 4. It is worth noticing that in the above mentioned work the authors used a correction coefficient in the J/ψ photoproduction which was not used here. This would improve the comparison between our calculation and the experimental data, but not enough to allow a good agreement. This is a puzzling situation that can be solved only with more data from UPC production of vector mesons. It would be interesting to have information on J/ψ production in UPCs for both Pb and Au at different energies in the interval $\sqrt{s_{NN}} = 200$ GeV to 2.76 TeV.

IV. CONCLUSIONS

In summary, the J/ψ photoproduction for Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV was studied with the CRISP model and compared with the existing experimental data and models. The CRISP hadronic model describes reasonably well the photoproduction of J/ψ in UPCs at lower energies ($\leqslant$200 GeV) but with limitations at higher energies. An advantage and partial success of the model is that the use of the correct photoabsorption cross sections for the different channels of sequential hadronic collisions with the final state interactions of the J/ψ has proven to be of great relevance. Our findings lead to the reliable conclusion that the inclusion of subnucleonic degrees of freedom is needed to describe J/Ψ photoproduction in UPCs.

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