



Coherent J/ψ production—A novel feature at LHC?

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Abstract

Energy dependence of heavy quarkonia production in hadron–nucleus collisions is studied in the framework of the Glauber–Gribov theory. We emphasize a change in the space–time picture of heavy-quark state production on nuclei with energy. Longitudinally ordered scattering of a heavy-quark system takes place at low energies, while with increasing energy it transforms to a coherent scattering of projectile partons on the nuclear target. The characteristic energy scale for this transition depends on masses and rapidities of produced particles. For J/ψ , produced in the central rapidity region, the transition happens at RHIC energies. The parameter-free calculation of J/ψ in dAu collisions is in good agreement with recent RHIC data. We use distributions of gluons in nuclei to predict suppression of heavy quarkonia at LHC.

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1. Introduction

The heavy-ion programme at RHIC (BNL) and LHC (CERN) aims at discovering features of a possible new state of deconfined QCD matter anticipated to form in nucleus–nucleus collisions. An important signal of the quark–gluon plasma (QGP) formation would be a suppression of charmonium yield [1] produced in these collisions. A proper baseline for the discovery of this effect is charmonium production in hadron–nucleus collisions, where the QGP is absent and only cold nuclear matter effects are present [2,3].

Nuclear effects in hadron–nucleus collisions are usually discussed in terms of the power-law parameterization

$$\frac{d\sigma_{hA}^a}{d^3p} = \frac{d\sigma_{hN}^a}{d^3p} A^{\alpha(x_F)}, \quad (1)$$

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where σ_{hA}^a (σ_{hN}^a) is the inclusive cross section of particle a off a nucleus (nucleon). The function $\alpha(x_F)$ characterizes nuclear effects at different longitudinal momentum fractions of the produced particle, x_F . For J/ψ production, measurements show a decrease of α from 0.95 at $x_F \approx 0$ to values ~ 0.75 at $x_F \simeq 0.8$ [4–6] thus indicating an increase of absorption as x_F increases. Also, data over a large range of energies show an approximate scaling of α with x_F [4–6] rather than a scaling with x_2 (fraction of the total momentum carried by a parton from a nucleus) expected from QCD factorization.

Recently, the substantial decrease of nuclear absorption in J/ψ production in deuteron–gold (dAu) collisions at RHIC energy, $\sqrt{s} = 200$ GeV, where $\sigma_{\text{abs}} \sim 1\text{--}2$ mb [7], compared to $\sigma_{\text{abs}} \sim 4$ mb [8] measured in proton–lead (pPb) collisions at SPS energy, $\sqrt{s} = 17.3$ GeV has attracted a lot of attention. This corresponds to a value of α consistent with 1 at $x_F = 0$. It was widely believed that absorptive effects would increase or, at least, remain constant with rising collision energy [9–11]. In the model of [11, Section 4.1], e.g., the postulated growth of σ_{abs} with energy is motivated by a growth of charmonium–nucleon center-of-mass energy, reflecting the

rapid growth of partons carrying small momentum fractions in the nucleon.

An equally important implication resides in the fact that the RHIC data does not scale in x_F : whereas the lower-energy data points display a flat behavior at small x_F , the new points delineate a steep tilt. This novel feature seems also to be hard to reproduce in models describing the energy dependence of α [12,13].

Such a behavior of $\alpha(x_F)$ allows for a natural explanation in the Glauber–Gribov theory of multi-particle production on nuclei [14]. At very high energies Abramovsky–Gribov–Kancheli (AGK) cutting rules [15] lead to a cancellation of the Glauber-type diagrams in the central rapidity region, i.e., for $x_F \approx 0$, and only so-called “enhanced” diagrams [16,17], corresponding to multi-pomeron interactions, contribute to a difference of α from unity. For light quarks, this coherent hadroproduction sets in at a typical energy scale $E_0 \sim m_N \mu R_A$, where R_A is the radius of the nucleus, m_N is the mass of a nucleon and μ is a typical hadronic scale of the order of ~ 1 GeV. For heavy quark states, the mass $M_{Q\bar{Q}}$ of the heavy system introduces a new scale

$$s_M = \frac{M_{Q\bar{Q}}^2 R_A m_N}{x_+ \sqrt{3}}, \quad (2)$$

where $x_+ = \frac{1}{2}(\sqrt{x_F^2 + 4M_{Q\bar{Q}}^2/s} + x_F)$ is the longitudinal momentum fraction of the heavy system.

The AGK cutting rules are violated at larger values of x_F and at low energies; the first effect is interpreted as conservation of energy–momentum [18]. The latter effect is in turn related to a change of the space–time picture of the interaction [19]. At energies below s_M longitudinally ordered rescatterings of the heavy system take place. In this situation we can unambiguously define the production point of the heavy system and, in turn, the distance it has to travel through the surrounding nuclear matter. This leads naturally to the notion of an absorptive cross section. At $s > s_M$ the heavy state in the projectile, which also includes light degrees of freedom, scatters coherently off the nucleons of a nucleus, and the conventional treatment of nuclear absorption is not adequate.

In the central rapidity region, the values of s_M for J/ψ are within the RHIC energy range. Accordingly, the effects of shadowing of nuclear partons become important and can be calculated using the Glauber–Gribov theory of nuclear structure functions in the region of $x_2 < (m_N R_A)^{-1}$.

2. Model description and comparison to data

Consider first production of heavy onia in the “low” energy regime, $s < s_M$. It was shown in [19] that the contribution of all diagrams with intermediate heavy-quark state to the total cross section is canceled in this energy region. However, the different s-channel discontinuities (cuttings) of these diagrams are different from zero. Consider, as an example, the cuttings shown in Fig. 1. Their contributions to the total cross section are equal in magnitude and have opposite signs. Their contributions to the inclusive cross section would also cancel each other if the $Q\bar{Q}$ final states in Figs. 1(a) and 1(b) would have the same dis-

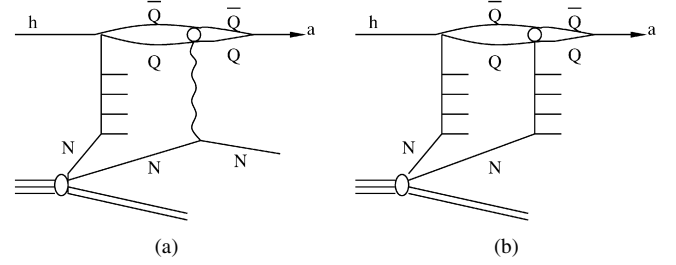


Fig. 1. (a) Elastic and (b) inelastic scattering of a $Q\bar{Q}$ system. The former does not have to be the leading one.

tribution in x_F . However, the elastic rescattering in Fig. 1(a) does not change the momentum, while in the case of inelastic interaction of the $Q\bar{Q}$ system, Fig. 1(b), it can lose some of its momentum and (or) transform into another state which is weakly coupled to the observed particle a (absorption). We parameterize the probability to produce these states in a single rescattering by a parameter $(1 - \epsilon)$.

Thus at energies $s < s_M$ the absorption is determined by

$$f_{hA}^a(x_+) = f_{hN}^a \int d^2b \frac{1 - e^{-\xi(x_+) \sigma_{Q\bar{Q}} T_A(b)}}{\xi(x_+) \sigma_{Q\bar{Q}} T_A(b)}. \quad (3)$$

The function $f_{hN}^a(x_+) = \sigma_{hN}^a F_1^a(x_+)$, where F_1^a denotes the unmodified distribution of produced particles, and $\xi(x_+) = (1 - \epsilon) + \epsilon x_+^\gamma$ determines the x_+ dependence of the strength of the shadowing. Finally, $T_A(b) = \int_{-\infty}^{\infty} dz \rho_A(b, z)$ is the nuclear thickness function normalized to A . With $\xi(x_F = 0) = (1 - \epsilon)$ one recovers the well-known Glauber formula [20,21] with $\sigma_{\text{abs}} = (1 - \epsilon) \sigma_{Q\bar{Q}}$. As shown in Ref. [19], Eq. (3), with the inclusion of shadowing effects (see below), gives a good description of experimental data on charmonium production in pA collisions at $E_{\text{LAB}} \lesssim 800$ GeV/c with $\sigma_{Q\bar{Q}} = 20$ mb and $\epsilon = 0.75$. This corresponds to an absorption cross section of $\sigma_{\text{abs}} = 5$ mb. Note, that $\sigma_{Q\bar{Q}}$ is rather large, indicating that the $c\bar{c}$ pair is produced in the color octet state rather than in the colorless state. It can also be viewed as a $D\bar{D}$ ($D^* \bar{D}^*$) system.

Eq. (3) is not applicable at asymptotic energies as the assumption of longitudinal ordering is only valid at $s < s_M$. For energies higher than s_M the expression will change due to the correct treatment of coherence effects according to [9]

$$\frac{1 - e^{-\xi(x_+) \sigma_{Q\bar{Q}} T_A(b)}}{\xi(x_+) \sigma_{Q\bar{Q}}} \rightarrow T_A(b) e^{-\tilde{\sigma}_{Q\bar{Q}}(x_+) T_A(b)/2}, \quad (4)$$

which is similar to the energy–momentum conservation effect for light quarks [19]. In the model proposed in [9], $\tilde{\sigma}_{Q\bar{Q}}$ is equal to the total cross section of the $Q\bar{Q} - N$ process, and is not proportional to x_+^γ .

We would like to point out that this leads to an unnatural behavior at high energies due to the smallness of the pomeron vertex and to an effective double-counting of nuclear effects, and propose an alternative procedure. If one considers non-enhanced Glauber-type diagrams, then the effective cross section varies as $\tilde{\sigma}_{Q\bar{Q}} \sim x_+^\gamma$, thus satisfying the AGK cancellation. The suppression is concentrated at much higher x_F for $Q\bar{Q}$ production than for the light hadrons because of the large

mass of the $Q\bar{Q}$ system. It was shown in Ref. [19] that at $x_F \sim 1$ the second rescatterings in the low- and high-energy limits should coincide. This means that $\tilde{\sigma}_{Q\bar{Q}} \approx \epsilon x_+^{\gamma} \sigma_{Q\bar{Q}}$. Experiment on J/ψ production in dAu collisions at RHIC [7] was performed in the central rapidity region, where x_+ varies from 0.025 to 0.05 and $\tilde{\sigma}_{Q\bar{Q}}$ is, therefore, very small. This suggests an analysis of J/ψ suppression in dAu collisions at RHIC energies taking into account enhanced diagrams only. A similar approach, albeit with a simpler parameterization of nuclear shadowing, has been considered in [22].

We have studied gluon shadowing in Refs. [23–25], where a model for γ^*A collisions was considered within the Glauber–Gribov theory [14] including enhanced diagrams or, in other words, interactions among pomerons. Summing up an arbitrary number of pomeron tree diagrams as in the generalized Schwimmer model [26] one obtains the following expression for the total cross section of a γ^*A collision

$$\sigma_{\gamma^*A}^{\text{Sch}}(x, Q^2, b) = \frac{A\sigma_{\gamma^*N}}{1 + f(x, Q^2)T_A(b)}, \quad (5)$$

where

$$f(x, Q^2) = 4\pi \int_x^{\tilde{x}_{\mathbb{P}}} dx_{\mathbb{P}} B(x_{\mathbb{P}}) \frac{F_{2D}^{(3)}(x_{\mathbb{P}}, Q^2, \beta)}{F_2(x, Q^2)} F_A^2(t'),$$

with $\tilde{x}_{\mathbb{P}} = 0.1$, where shadowing is expected to disappear. Here $F_2(x, Q^2)$ is the structure function for a nucleon, $F_{2D}^{(3)}(x_{\mathbb{P}}, Q^2, \beta)$ is the t -integrated diffractive structure function of the nucleon, $B(x_{\mathbb{P}})$ is the t -slope of the diffractive distribution, and $F_A(t')$ is the nuclear form factor where $t' \approx -m_N^2 x_{\mathbb{P}}^2$. Eq. (5) determines shadowing for quarks (anti-quarks) in nuclei. For gluons the same expressions were used with substitutions $F_{2D}^{(3)}(x_{\mathbb{P}}, Q^2, \beta) \rightarrow F_{\mathbb{P}}^g(x_{\mathbb{P}}, Q^2, \beta)$, $F_2(x, Q^2) \rightarrow xg(x, Q^2)$, indicating gluon distributions in the pomeron, measured in diffractive deep inelastic scattering (DDIS), and in the proton, respectively. Gluon distribution of the nucleon is taken from CTEQ6M parameterization [27]. We take information on the diffractive gluon distribution and pomeron parameters from recent HERA measurements [28], where two independent fits of the gluon diffractive distribution function, called FIT A and FIT B, represent the overall uncertainty of extracting this information from the measurements. We will show results only from the latter fit, denoted as GGB, as it is closer to, as yet, preliminary combined fits where di-jet production has been included [29]. This model has previously been used to calculate quark shadowing in nucleus–nucleus interactions in Ref. [30].

PHENIX Collaboration has measured the nuclear modification factor (NMF) of J/ψ production in dAu collisions at RHIC as a function of centrality and rapidity in [7] and most recently in [31] (with a more up-to-date pp reference). We define the centrality dependent NMF as

$$R_{\text{dAu}}(\langle N_{\text{coll}} \rangle) = \frac{N_{\text{inv}}^{\text{dAu}}(\langle N_{\text{coll}} \rangle)}{\langle N_{\text{coll}} \rangle \times N_{pp}^{\text{inv}}}, \quad (6)$$

where the average number of nucleon–nucleon collisions $\langle N_{\text{coll}} \rangle$ is obtained from the Glauber model for a given centrality. The

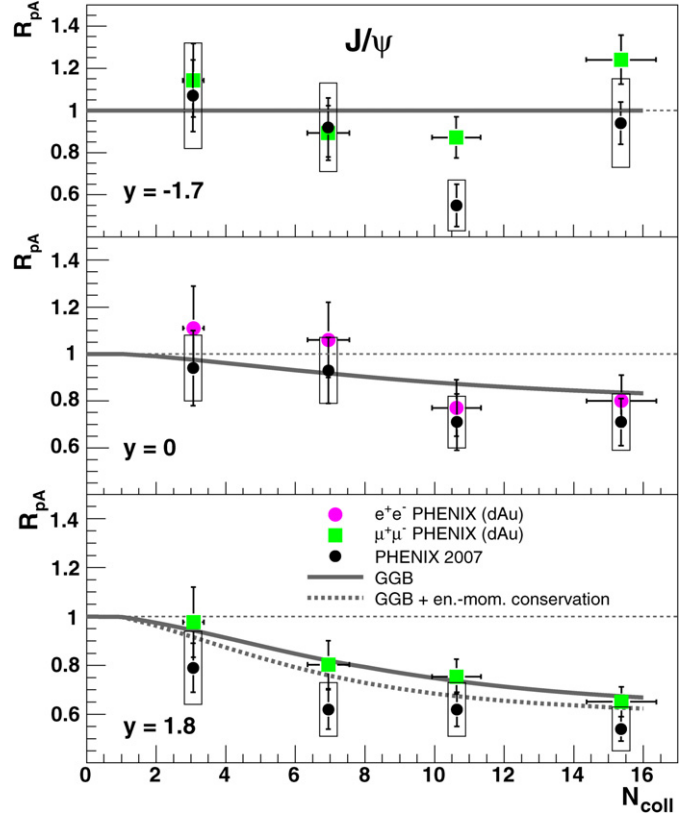


Fig. 2. J/ψ suppression as a function of centrality at different rapidities at RHIC. Data are taken from [7,31].

results of calculations based on Eq. (5) are shown in Fig. 2 for the NMF, given by Eq. (6), at backward, mid- and forward rapidity. Since the model of gluon shadowing does not include anti-shadowing effects, the result is quite trivial in the backward hemisphere, although not inconsistent with the data. Anti-shadowing is assumed to be a 10% effect. At rapidity $y = 0$ and $y = 1.8$ the consistency with experimental data is quite good. The rapidity dependence of nuclear modification factor R_{dAu} for minimum bias dAu collisions at RHIC [7,31] and predictions for pPb collisions at LHC, $\sqrt{s} = 5.5$ TeV, are presented in Fig. 3. At mid-rapidity, gluon shadowing at LHC is a 40% effect, being barely significant, $\sim 10\%$, at RHIC. This fact is important for the calculation of charmonium yield in nucleus–nucleus collisions at these energies.

The current PHENIX data [31] indicate that at forward rapidity shadowing alone cannot be accounted for the full drop of the NMF of J/ψ . Therefore, the dash-dotted curves in Figs. 2 and 3 depict calculations including both gluon shadowing and a model for energy–momentum conservation to be presented in the next section. The latter effect is shown to be relevant already at $y = 1.8$ at RHIC.

3. Energy dependence of $\alpha(x_F)$

Based on the previous discussion we will now formulate a model for J/ψ production in hadron–nucleus collisions at all energies. Fig. 4 shows experimental points for α in Eq. (1) as a function of both x_F and x_2 [4,5,7]. In order to calculate J/ψ

suppression at different energies and for all values of x_F it is necessary to make a modification of Eqs. (3)–(4) to describe a transition from low-energy to high-energy regime, which happens at $x_2^c \approx (m_N R_A)^{-1}$. The term ϵx_+^c in the expression for $\xi(x_+)$ (or $\tilde{\sigma}_{Q\bar{Q}}(x_+)$) provides a smooth transition between the two regions. On the other hand, the term $\sigma_{Q\bar{Q}}(1 - \epsilon)$ describing the absorption should be modified in such a way that it should tend to zero in the high-energy region, being substituted in this region by gluon shadowing. To fulfill these requirements we introduce an extra multiplier

$$f(x_2, x_2^c) = \exp\left\{-\left(x_2^c/x_2\right)^2\right\}, \quad (7)$$

for this term. This procedure corresponds to a suppression of Glauber-type, non-enhanced diagrams at high-energies, and has

the correct high-energy behavior, i.e., it satisfies the AGK cutting rules.

The dashed curve in Fig. 4 at $\sqrt{s} = 39$ GeV has been calculated this way with $\epsilon = 0.93$ and $\sigma_{Q\bar{Q}} = 45$ mb. Following the prescription of Eq. (4) for the high-energy regime, solid and dotted curves are calculations of gluon shadowing and energy conservation effect for RHIC and LHC energies, respectively. The calculations for RHIC have been performed for all $0 < x_F < 0.8$, while for LHC we have, for illustrative purposes, only made calculations for the central rapidity region, $|y| < 4$. Although the coverage in x_F is small at this energy, the structure function of the nucleus is probed down to $x_2 \approx 10^{-5}$.

The model perfectly reproduces x_F , x_2 and energy dependence of all the experimental data. Going from low to high energies we observe a breaking of x_F scaling in the central rapidity region. The origin of this is that absorption effects, related to longitudinally ordered rescatterings, die out while shadowing slowly appears. This is most clearly seen in the α vs. x_2 plot. The form of the curve for $\alpha(x_F)$ is reinstated at $x_F > 0.25$, although shadowing leads to a stronger overall suppression. Additionally, scaling in x_2 is predicted to appear for J/ψ in the common kinematical window of RHIC and LHC, i.e., for $10^{-3} < x_2 < 0.05$. This is a novel feature in heavy-ion experiments and would imply the validity of the factorization theorem in hadronic processes at ultra-relativistic energies.

Concluding, we have argued that recent data on J/ψ production at RHIC imply a profound change of the space–time picture of charmonium production in hadron–nucleus collisions and described the experimental data at mid-, forward and backward rapidities in terms of nuclear shadowing. Already at $y > 1.7$ we obtain a quite strong influence of energy–momentum conservation, in accordance with most recent data from experiment. Furthermore, we presented a model to describe the energy dependence of these features at x_F larger or equal zero. The agreement with available data is very satisfactory. Nuclear effects at $x_F < 0$ are out of the scope of this Letter, and require a separate study [32]. These findings confirm the appearance of shadow-

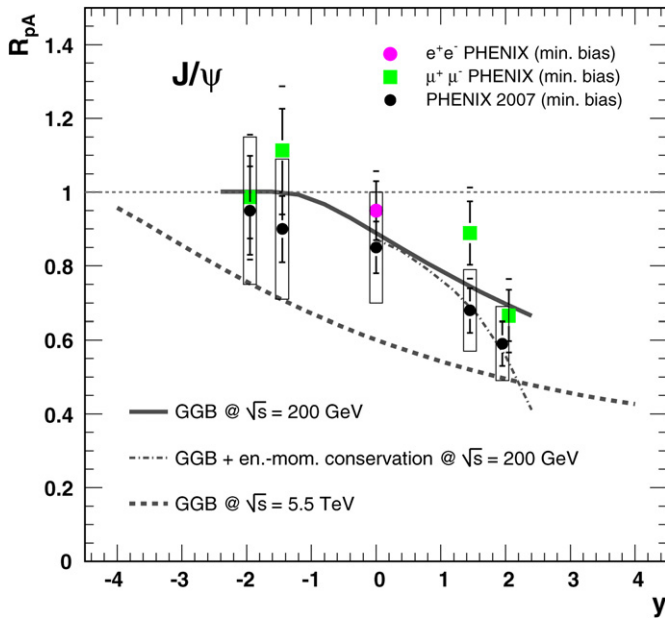


Fig. 3. Rapidity dependence of J/ψ suppression for minimum bias dAu collisions at RHIC and predictions for pPb collisions at LHC. Data are taken from [7,31].

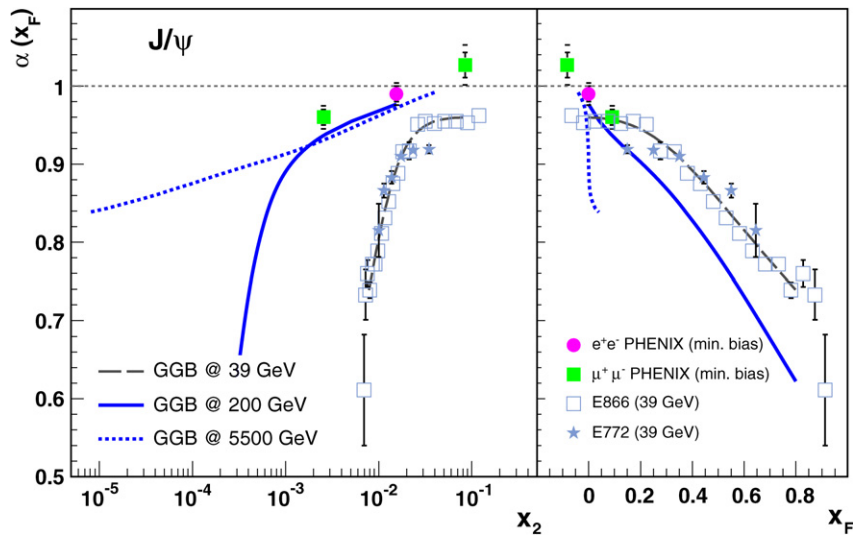


Fig. 4. α dependence in pA collisions vs. x_2 (left) and x_F (right) for $\sqrt{s} = 39$ –5500 GeV. Data are taken from [4,5,7].

ing effects in light particle production in dAu collisions, and will also have a great impact on models for nucleus–nucleus collisions both at RHIC and LHC.

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