J/ψ Production in the Saturation Regime

F. O. Durães[1,2]

[1]*Departamento de Física, Centro de Ciências e Humanidades,*
Universidade Presbiteriana Mackenzie, C.P. 01302-907 São Paulo, SP, Brazil
[2]*Instituto de Física, Universidade de São Paulo, C.P. 66318, 05389-970 São Paulo, SP, Brazil*

In this work we calculate the *J/ψ* production in the initial stage of proton-proton, proton-nucleus and nucleus-nucleus collisions at RHIC and LHC energies, taking into account the high parton density regime of QCD, where the physics of parton saturation is expected to be dominant. We perform a quantitative analysis of the x_F distributions in these collisions with the Color Glass Condensate (CGC) approach. The ratio between distributions with or without saturated gluons shows that this mechanism produces a suppression on the *J/ψ* yield in the forward region and presents a dip in intermediate values of x_F, which is visible only at LHC energies.

Keywords: *J/ψ* production; Nucleus-nucleus collisions; Color Glass Condensate

I. INTRODUCTION

Heavy quark production in hard collisions of hadrons has been considered [1] as a clean test in order to provide some of the most important backgrounds to new physics processes, which have been studied at DESY-HERA, Tevatron and LHC. The main motivation of these studies is the strong dependence of the total cross section on the behavior of the gluon distribution, which determines the QCD dynamics at high energies.

At small Bjorken-*x* and/or large *A* (in nuclei collisions) one expects the transition of the regime described by the linear dynamics (DGLAP, BFKL), where only the parton emissions are considered, to a new regime where the physical process of recombination of partons becomes important in the parton cascade and the evolution is given by a nonlinear evolution equation [2, 3].

In a scattering at high energies, the wave function of a hadron (or nucleus), boosted to large rapidity, exhibits a large number of gluons at small Bjorken-*x* and the density of gluons, per unit of transverse area and of rapidity, provides an intrinsic momentum scale which grows with atomic number (for nuclei) and with rapidity, due to continued gluon radiation as phase space grows. It is denoted by Q_s, the so-called saturation momentum scale, which marks the onset of gluon recombination.

The large values of the gluon distribution at saturation (large occupation number of the soft gluon modes) suggests the use of semi-classical methods, which allow to describe the small-*x* gluons inside a fast moving nucleus by a classical color field. This color field is driven by a classical Yang-Mills equation whose source term is provided by faster partons. In this regime a Color Glass Condensate is expected to be formed [4–7], being characterized by a new type of high density matter, where the transition amplitudes are dominated not by quantum fluctuations, but by the configurations of classical field containing large ($\approx 1/\alpha_s$) numbers of gluons. Even though the coupling α_s becomes small due to the high density of partons, the fields interact strongly due to the classical coherence.

The CGC framework is an effective theory describing high energy scattering in QCD and have been applied to study phenomena at a number of existing and upcoming high energy collider facilities, in particular related to the initial conditions and equilibration in heavy ion collisions and to describe heavy ion phenomenology.

Recently, the *J/ψ* production in proton (deuteron)-nucleus collisions at high energies was considered in the CGC framework [8]. The main conclusion of that work was that, at high energies (LHC energies), the saturation of gluons in the proton will result in the exact x_1 scaling and therefore, because $x_F = x_1$ when $x_2 \ll 1$, an exact x_F scaling can be considered as a signature of the saturation in the proton. Apart from this interesting effect, other previous investigations concluded that charm production will not be very much affected by nonlinear effects because, in most of the interesting cases, the saturation scale is never much larger than the charm quark mass [9]. However, even if the overall effect is small, saturation may affect strongly a certain small region of the phase space, or in this particular case the x_F space. We found this situation before, studying the x_F distribution of *J/ψ*'s produced in the quark gluon plasma [10]. Motivated by this suspicion and by our previous experience with x_F spectra, in this work we calculate the x_F distributions of *J/ψ*, produced in proton-proton and proton-nucleus collisions at RHIC and LHC energies. We shall use the Color Evaporation Model (CEM) [11] in two different regimes for the gluon densities: the regime described by the linear dynamics (DGLAP evolution) and the regime where gluon recombination is governed by nonlinear dynamics and leads to the saturation effect. Although our approach is phenomenological, as it will be seen, our results show a clear signal of saturation in the x_F spectrum of *J/ψ*'s produced in proton - nucleus collisions.

II. *J/ψ* PRODUCTION IN PROTON-PROTON AND PROTON-NUCLEUS COLLISIONS

In the CEM, charmonium is defined kinematically as a $c\bar{c}$ state with mass below the $D\bar{D}$ threshold. In leading order (LO) the cross section is computed with the use of perturbative QCD for the diagrams of the elementary processes $q\bar{q} \to c\bar{c}$ and $gg \to c\bar{c}$ convoluted with the parton densities in the pro-

jectile (A) and in the target (B).

Calling x_F the fractional momentum of the produced pair (with respect to the momentum of a projectile nucleon in cm frame) and $\sqrt{s}$ the cm energy of a nucleon - nucleon collision, the cross section for production of a $c\bar{c}$ pair with mass m is just given by:

$$
\begin{aligned}
\frac{d\sigma^{AB\to c\bar{c}}}{dx_F dm^2} &= \int_0^1 dx_1\, dx_2\, \delta(x_1 x_2 s - m^2) \\
&\times\ \delta(x_F - x_1 + x_2)\, H(x_1, x_2; m^2) \\
&= \frac{1}{s\sqrt{x_F^2 + 4m^2/s}}\, H(x_{01}, x_{02}; m^2)\,; \\
x_{01,02} &= \frac{1}{2}\left(\pm x_F + \sqrt{x_F^2 + 4m^2/s}\right)
\end{aligned}
\tag{1}
$$

where x_1 and x_2 are the nucleon momentum fractions carried respectively by partons in the projectile and target. The function $H(x_1, x_2; m^2)$, which represents the convolution of the elementary cross sections and parton densities is given by:

$$
\begin{aligned}
H(x_1, x_2; m^2) &= AB\Big\{ f_g^A(x_1, m^2) f_g^B(x_2, m^2)\, \hat{\sigma}_{gg}(m^2) \\
&+ \sum_{q=u,d,s} [f_q^A(x_1, m^2) f_{\bar{q}}^B(x_2, m^2) \\
&+ f_{\bar{q}}^A(x_1, m^2) f_q^B(x_2, m^2)]\, \hat{\sigma}_{q\bar{q}}(m^2) \Big\}
\end{aligned}
\tag{2}
$$

with the parton densities $f_i(x, m^2)$ in the nucleon computed at the scale $m^2 = x_1 x_2 s$.

The LO elementary cross sections in terms of the pair invariant mass (m) are given by [12, 13]:

$$
\begin{aligned}
\hat{\sigma}_{gg}(m^2) &= \frac{\pi\alpha_s^2(m^2)}{3m^2}\Big\{ \left(1 + \frac{4m_c^2}{m^2} + \frac{m_c^4}{m^4}\right) ln\left[\frac{1+\lambda}{1-\lambda}\right] \\
&- \frac{1}{4}\left(7 + \frac{31m_c^2}{m^2}\right)\lambda \Big\}
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
\hat{\sigma}_{q\bar{q}}(m^2) &= \frac{8\pi\alpha_s^2(m^2)}{27m^2}\left(1 + \frac{2m_c^2}{m^2}\right)\lambda\,; \\
\lambda &= \left[1 - \frac{4m_c^2}{m^2}\right]^{1/2}
\end{aligned}
\tag{4}
$$

where m_c is the mass of the c quark. The production cross section of the charmed state $i\ (= J/\psi,\ \psi'$ or $\chi_{cJ})$, σ_i, is then finally obtained by integrating the free pair cross section $c\bar{c}$ over the invariant mass m starting from the production threshold $2m_c\,(= 2.4\,GeV)$ up to open charm production threshold $2m_D\,(= 3.74\,GeV)$. This model describes well the experimentally measured x_F distribution of hidden charm both with LO and NLO cross sections, provided that F_i^{LO} is defined as F_i^{NLO} multiplied by a theoretical factor κ, which is equal to the ratio of the NLO and LO cross sections ($F_{J/\psi}^{NLO} \simeq 2.54\%$) [13]. Therefore the J/ψ production cross section can be written as:

$$
\frac{d\sigma^{AB\to J/\psi X}}{dx_F} = \kappa F_{J/\psi}^{NLO} \int_{4m_c^2}^{4m_D^2} dm^2 \frac{d\sigma^{AB\to c\bar{c}}}{dx_F dm^2}
\tag{5}
$$

In the CEM non-perturbative effects are hidden in the factors κ, $F_{J/\psi}^{NLO}$ and in the choice of the integration domain in the expression above. There are other ways to deal with these effects, either employing the Color Octect Model [14] or using QCD sum rules, where cross sections become functions of the vacuum condensates [15].

In what follows we shall use the CEM to study perturbative J/ψ production in proton-proton ($A = B = 1$), proton-nucleus ($A = 1$) and nucleus-nucleus collisions at RHIC and LHC. As it is well known, in nuclear collisions and in processes involving small values of x, shadowing plays an important role (see, for example, [16]). However, for simplicity we will, in a first moment, neglect nuclear effects and will make use of parton distribution functions (PDF) in the proton taken from [17] (GRV98 LO).

We shall also use this approach to study the J/ψ production in the CGC framework. In the quark/antiquark sectors we will employ the same PDF's above to explicitly investigate the effects of saturation of gluons on the J/ψ production. For the gluon densities in this regime we will adopt the *Ansatz* of Ref. [18, 19]:

$$
xG^{KLN}(x, Q^2) = \begin{cases} \frac{C_1}{\alpha_s(Q^2)} Q^2 (1-x)^{C_2} & ;\ Q^2 < Q_s^2 \\ \frac{C_1}{\alpha_s(Q^2)} Q_s^2 (1-x)^{C_2} & ;\ Q^2 > Q_s^2 \end{cases}
\tag{6}
$$

where the saturation scale is given by:

$$
Q_s^2(x) = A^{1/3} Q_0^2 \left(\frac{x_0}{x}\right)^\lambda
\tag{7}
$$

with $Q_0^2 = 0.34\,GeV^2$, $x_0 = 3.10^{-4}$ and $\lambda = 0.29$.

The factor $(1-x)^{C_2}$ is introduced to account for the fact that the gluon density is small at $x \to 1$, according to the quark counting rules. We will make use of the dependence of the parameter C_2 on Q^2, which is typically parameterized in terms of the $ln\,[ln\,(Q^2/\Lambda^2)/ln\,(Q^2/\mu^2)]$ ($C_2 \simeq 4$ at small Q^2), taken from the Ref. [17].

The comparison between the two scenarios for J/ψ production, namely with and without gluon saturation, only makes sense if both gluon distributions in these regimes obey the same energy-momentum conservation relation in the proton. We will thus fix the normalization constant C_1 in our modified gluon density in the saturation regime, at given Q^2, requiring that:

$$
\int_0^1 xG^{KLN}(x, Q^2) = \int_0^1 xG^{GRV98L0}(x, Q^2)
\tag{8}
$$

Before presenting results a remark is in order. Expressions (1) and (2) imply the validity of collinear factorization, which is violated in many cases in the context of saturation physics. In many cases of interest, expressions analogous to (1) and (2) are valid, in which we have to replace $G(x)$ by the unintegrated (in the gluon transverse momentum) gluon distribution $\phi(x, k_T^2)$. This is called k_T factorization and was proven to hold in many cases. As shown in [20], k_T factorization is valid for gluon production but is violated in quark production, especially in p-A and A-A collisions. However, from the quantitative point of view, this violation is not very large.

FIG. 1: Ratios of J/ψ momentum distributions
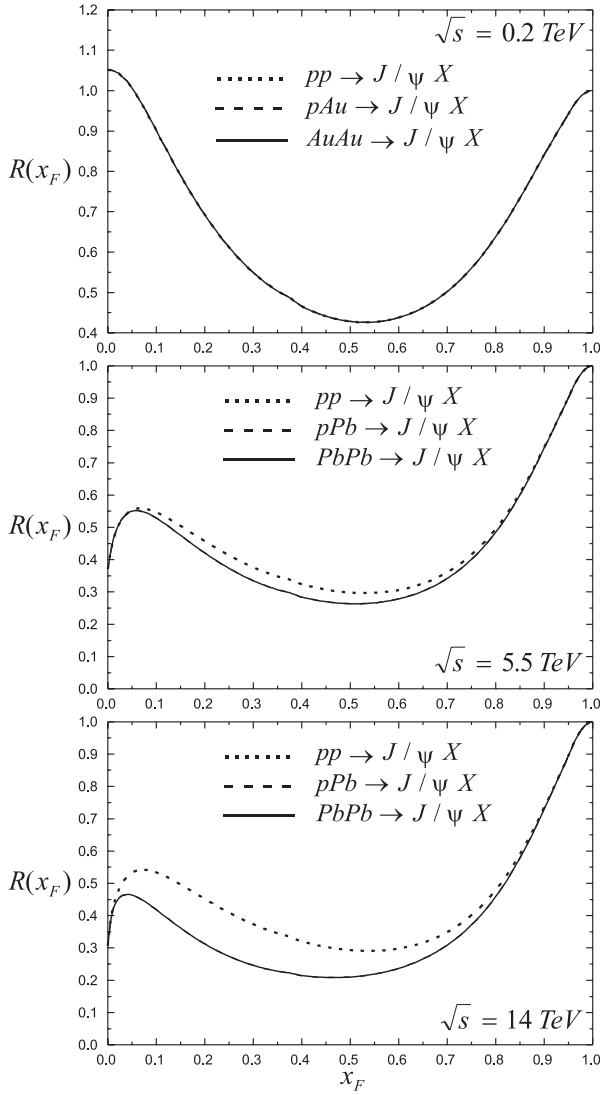
FIG. 2: Ratios of "full to linear" momentum distributions

Moreover, as shown in [21], k_T and collinear factorization are equivalent at the leading twist level. Given the exploratory nature of this study, we shall assume that (1) and (2) hold also for distributions like (6).

III.   RESULTS AND DISCUSSION

In order to investigate the differences between the two J/ψ production mechanisms we will first construct the ratio between their differential cross sections:

$$R(x_F) = \frac{d\sigma_{KLN}^{AB \to J/\psi X}/dx_F}{d\sigma_{GRV98}^{AB \to J/\psi X}/dx_F} \qquad (9)$$

In Figure 1 we show these ratios of J/ψ momentum distributions in collisions pp, pAu and $AuAu$ at $\sqrt{s} = 0.2\,TeV$ (RHIC) and pp, pPb and $PbPb$ at $\sqrt{s} = 5.5\,TeV$ and $\sqrt{s} = 14\,TeV$
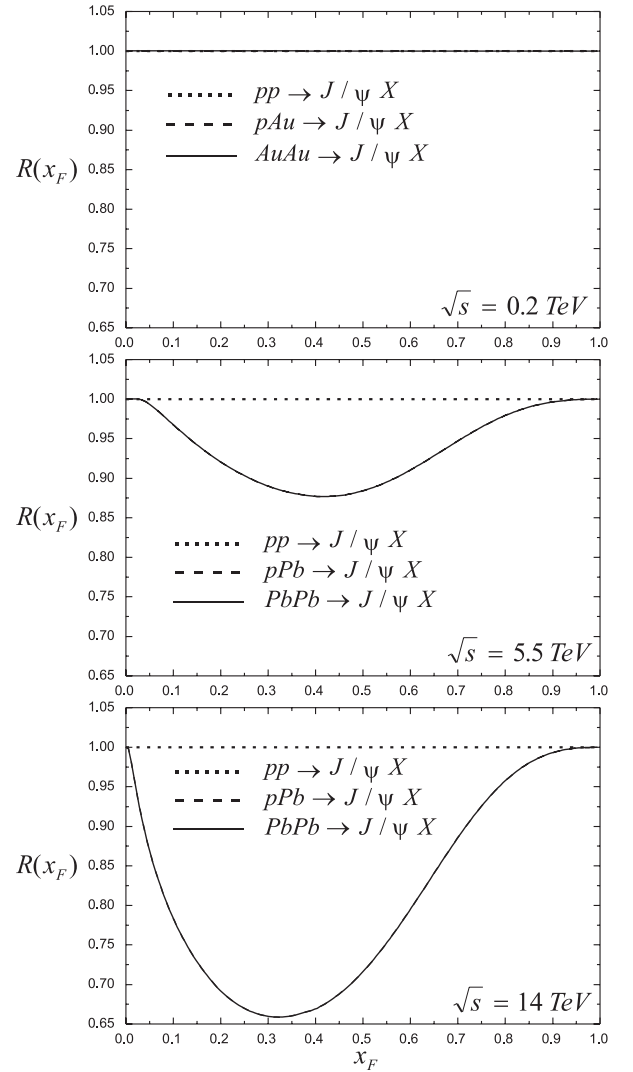
(LHC). It should be noted that the factors κ and $F_{J/\psi}^{NLO}$ in eq. (5) are cancelled out in the ratio (9). The same occurs, for proton-nucleus collisions, with the factors $A \equiv p(=1)$ and $B \equiv Au(Pb)(= 197(208))$ appearing in eq. (2) because we have neglected nuclear effects and assumed $f_i^A(x, Q^2) = A f_i^p(x, Q^2)$ in both mechanisms for J/ψ production. In spite of this cancellation there is a nontrivial dependence on the atomic number A coming from the saturation scale (7).

In Figure 1, we observe a suppression on J/ψ production, which becomes stronger for larger systems and for higher energies. In these situations we access more and more the saturated gluons with smaller x_1 and x_2 (remember that $4m_c^2 \leq m^2 = x_1 x_2 s \leq 4m_D^2$, see eq. (5)) which contribute with larger weight than at RHIC for J/ψ production. The results in Figure 1 might suggest that gluon saturation produces a significant suppression on J/ψ production. However this might be only an indication that the KLN and GRV98 PDF's are very different from each other. In order to see how much of this difference comes from the nonlinear regime we calculate the

ratios:

$$R(x_F) = \frac{d\sigma_{KLN}^{full}/dx_F}{d\sigma_{KLN}^{linear}/dx_F} \qquad (10)$$

where the cross section is always for the process $A\,B \rightarrow J/\psi\,X$ and "linear" means that the first line of (6) is switched off and we are considering only the case $Q^2 > Q_s^2$, where the evolution is in the linear regime. In this expression "full" means that the whole distribution (6) is active. If (10) is equal to one, then saturation plays no role. In Figure 2 we show the ratios (10) for *pp* (upper pannel) and *pA* collisions (lower pannel). We see that for *pp* reactions, even at higher energies the nonlinear effects are negligible. For *pA* and *AA* collisions they are negligible at RHIC but become rapidly very strong at LHC energies.

Although our calculation is admitedly crude, the results indicate very clearly that, at RHIC, saturation physics (the Color Glass Condensate) *plays no role in J/ψ suppression*. Therefore the *J/ψ* suppression at large rapidities measured by PHENIX [22] must come from some other mechanism. Of course, our conclusion has to be confirmed and the calculations redone with the more rigorous approach proposed in [20]. If this conclusion still holds, then understanding *J/ψ* production at RHIC will become a challenge for theorists.

Acknowledgements

[1] K.J. Eskola, V.J. Kolhine, and R. Vogt, Phys. Lett. B **582**, 157 (2004).

[2] For reviews on the subjects see: E. Iancu and R. Venugopalan, hep-ph/0303204; J. Jalilian-Marian and Y. V. Kovchegov, Prog. Part. Nucl. Phys. **56**, 104 (2006) and references therein.

[3] A.M. Stasto, Acta Phys. Polon. B **35**, 3069 (2004).

[4] L. McLerran and R. Venugopalan, Phys. Rev. D **49**, 2233 (1994).

[5] J. Jalilian-Marian, A. Kovner, L. McLerran, and H. Weigert, Phys. Rev. D **55**, 5414 (1997).

[6] Yu. V. Kovchegov, Phys. Rev. D **60**, 034008 (1999).

[7] E. Iancu, A. Leonidov, and L. McLerran, Nucl. Phys. A **692**, 583 (2001).

[8] D. Kharzeev and K. Tuchin, Nucl. Phys. A **770**, 40 (2006).

[9] V. P. Gonçalves and M. V. T. Machado, Eur. Phys. J. C **32**, 501 (2004).

[10] F. O. Durães, F. S. Navarra, and M. Nielsen, Phys. Rev. C **68**, 044904 (2003); J. Phys. G **31**, S1083 (2005); Braz. J. Phys. **34**, 290 (2004).

[11] V. Barger, W. Y. Keung, and R. N. Philips, Phys. Lett. B **91**, 253 (1980).

[12] M. Glück and E. Reya, Phys. Lett. B **79**, 453 (1978).

[13] R. V. Gavai *et al.*, Int. J. Mod. Phys. A **10**, 3043 (1995).

[14] C. Y. Wong, Phys. Rev. D **60**, 114025 (1999).

[15] F. O. Durães, S. H. Lee, F. S. Navarra, and M. Nielsen, Phys. Lett. B **564**, 97 (2003).

[16] N. Hammon, L. Gerland, H. Stocker, and W. Greiner, Phys. Rev. C **59**, 2744 (1999).

[17] M. Glück and E. Reya, and A. Vogt, Eur. Phys. J. C **5**, 461 (1998); M. Glück and E. Reya, and A. Vogt, Z. Phys. C **67**, 433 (1995).

[18] D. Kharzeev and E. Levin, Phys. Lett. B **523**, 79 (2001).

[19] D. Kharzeev, E. Levin, and M. Nardi, Nucl. Phys. A **730**, 448 (2004).

[20] H. Fujii, F. Gelis, and R. Venugopalan, Nucl. Phys. A **774**, 793 (2006); Phys. Rev. Lett. **95**, 162002 (2005).

[21] J. Kwiecinski and A.D. Martin, Phys. Lett. B **353**, 123 (1995).

[22] A. Adare (PHENIX Collaboration), arXiv:nucl-ex/0611020.