Cold Nuclear Matter Effects on J/ψ Production with Extrinsic P_T at $\sqrt{s_{NN}} = 5.5$ TeV at the LHC

N. Matagne[a], E. G. Ferreiro[b], F. Fleuret[c], J. P. Lansberg[d], A. Rakotozafindrabe[e]

[a]*Université de Mons, Service de Physique Nucléaire et Subnucléaire, Place du Parc 20, B-7000 Mons, Belgium*
[b]*Departamento de Física de Partículas, Universidad de Santiago de Compostela, 15782 Santiago de Compostela, Spain*
[c]*Laboratoire Leprince Ringuet, École polytechnique, CNRS-IN2P3, 91128 Palaiseau, France*
[d]*IPNO, Université Paris-Sud 11, CNRS/IN2P3, 91406 Orsay, France*
[e]*IRFU/SPhN, CEA Saclay, 91191 Gif-sur-Yvette Cedex, France*

Abstract

Taking into account the gluon shadowing and the J/ψ nuclear absorption, we evaluate the Cold Nuclear Matter (CNM) effects on J/ψ production in pPb and PbPb collisions at the design LHC energy for PbPb collisions, $\sqrt{s_{NN}} = 5.5$ TeV. In view of the good agreement between the yield prediction using the LO CSM and the ALICE data at 7 TeV, we employ the latter model to use a complete description of the kinematics of the underlying $2 \to 2$ partonic process, namely $g + g \to J/\psi + g$. We observe a large J/ψ suppression in pPb and PbPb collisions due to the strong shadowing of the gluon distribution in the lead ion at the corresponding gluon momentum fractions. This suppression from CNM effects has a strong rapidity dependence which may compensate, partially or completely, that of of the predicted charm recombination in PbPb collisions.

Keywords: J/ψ production, heavy-ion collisions, cold nuclear matter effects

1. Introduction

Quark Gluon Plasma (QGP), a deconfined state of QCD matter, is expected to be produced by Relativistic nucleus-nucleus (AB) collisions at high enough densities or temperatures. The J/ψ meson should be [1] sensitive to Hot and Dense Matter (HDM) effects, through processes like the colour Debye screening of the $c\bar{c}$ pair. A significant suppression of the J/ψ yield was observed at SPS energy by the NA50 experiment [2], and at RHIC by the PHENIX experiment in CuCu [3] and AuAu [4] collisions at $\sqrt{s_{NN}} = 200$ GeV. In 2010, data have been taken at the LHC in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. After the long LHC shutdown planned in 2012, LHC will hopefully run at its design energy with PbPb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. These results will give the possibility to test the available models at a new energy scale. However, the interpretation of the results obtained in AB collisions relies on a good understanding and a proper subtraction of the Cold Nuclear Matter (CNM) effects which are known to already impact the J/ψ production in proton (deuteron)-nucleus (pA or dA) collisions, where the deconfinement cannot be reached. Two CNM effects are of particular importance [5]: (i) the shadowing of the initial parton distributions (PDFs) due to the nuclear environment, and (ii) the breakup of $c\bar{c}$ pairs after multiple scatterings with the remnants of the incident nuclei, referred to as the nuclear absorption. In our previous works [6–9], we developed an exhaustive study of these effects at $\sqrt{s_{NN}} = 200$ GeV and we confronted our results to the measurements from PHENIX [10]. It is our purpose here to extend our results to pPb and PbPb collisions at the energy $\sqrt{s_{NN}} = 5.5$ TeV.

We have shown in earlier studies [6–9] that J/ψ partonic production mechanism affects both the way to compute the nuclear shadowing and its expected impact on the J/ψ production. Most studies on the J/ψ production in hadronic

collisions assume that the $c\bar{c}$ pair is produced by a $2 \rightarrow 1$ partonic process where both initial particles are two gluons carrying some intrinsic transverse momentum k_T. The sum of the gluon intrinsic k_T is transferred to the $c\bar{c}$ pair, thus to the J/ψ since the soft hadronisation process does not significantly alter the kinematics. This is supported by the picture of the Colour Evaporation Model (CEM) at LO (see [11] and references therein) or of the Colour-Octet (CO) mechanism at α_s^2 [12]. Thus, in such approaches, the transverse momentum P_T of the J/ψ comes *entirely* from the intrinsic k_T of the initial gluons. This is not sufficient to describe the P_T spectrum of quarkonia in hadron collisions [1] [11]. As a consequence, J/ψ production at low and mid P_T likely proceeds via a $2 \rightarrow 2$ process, such as $g + g \rightarrow J/\psi + g$, instead of a $2 \rightarrow 1$ process[2]. This amounts to the bulk of the J/ψ production cross section. For instance, as illustrated by Fig 1a, the yield predicted by the LO CSM [18] reproduces correctly the PHENIX, CDF and ALICE measurements without resorting to any colour-octet mechanism nor parameter twisting. Consequently, one is entitled to consider that the former $2 \rightarrow 2$ kinematics is the most appropriate to derive CNM effects at RHIC, and to provide predictions at LHC energy. In this work, we shall focus on the CNM effects expected at the energy $\sqrt{s_{NN}} = 5.5$ TeV in the extrinsic scheme. The article is organized as follows: in section 2, we will describe our model and in section 3, we will present and discuss our results.

2. Our approach

To describe the J/ψ production in nuclear collisions, our Monte Carlo framework [6, 19] is based on the probabilistic Glauber model. The nucleon-nucleon inelastic cross section at $\sqrt{s_{NN}} = 5.5$ TeV is taken to be $\sigma_{NN} = 70$ mb [20] and the maximum nucleon density to be $\rho_0 = 0.17$ nucleons/fm^3. We also need to implement the partonic process for the $c\bar{c}$ production model that allows us to describe the pp data and the CNM effects.

For $P_T \gtrsim 2 - 3$ GeV, most of the transverse momentum of the quarkonia should have an extrinsic origin, *i.e.* the J/ψ's P_T would be balanced by the emission of a recoiling particle – a hard gluon – in the final state. The J/ψ would then be produced by gluon fusion in a $2 \rightarrow 2$ process. This emission, which is anyhow mandatory to conserve C-parity, has a definite influence on the kinematics of the J/ψ production. Indeed, for a given J/ψ momentum (thus for fixed rapidity y and P_T), the processes discussed above, *i.e.* the intrinsic $g + g \rightarrow c\bar{c} \rightarrow J/\psi$ $(+X)$ and the extrinsic $g + g \rightarrow J/\psi + g$, will proceed from initial gluons with different Bjorken-x on the average. Therefore, they will be affected by different shadowing corrections.

In the intrinsic scheme, the measurement of the J/ψ momentum in pp collisions completely fixes the longitudinal momentum fraction of the initial partons: $x_{1,2} = \frac{m_T}{\sqrt{s_{NN}}} \exp{(\pm y)} \equiv x_{1,2}^0(y, P_T)$ with $m_T = \sqrt{M^2 + P_T^2}$, M being the J/ψ mass. On the contrary, in the extrinsic scheme, the knowledge of the y and P_T spectra is not sufficient to determine x_1 and x_2. Actually, the presence of a final-state gluon introduces further degrees of freedom, allowing several (x_1, x_2) for a given set (y, P_T). The four-momentum conservation results in a complex expression of x_2 as a function of (x_1, y, P_T): $x_2 = \frac{x_1 m_T \sqrt{s_{NN}} e^{-y} - M^2}{\sqrt{s_{NN}}(\sqrt{s_{NN}} x_1 - m_T e^y)}$. Equivalently, a similar expression can be written for x_1 as a function of (x_2, y, P_T). Even if the kinematics determines the physical phase space, models are anyhow *mandatory* to compute the proper weighting of each kinematically allowed (x_1, x_2). This weight is simply the differential cross section at the partonic level times the gluon PDFs, *i.e.* $g(x_1, \mu_F)g(x_2, \mu_F) \, d\sigma_{gg \rightarrow J/\psi + g}/dy \, dP_T \, dx_1 dx_2$. In the present implementation of our code, we are able to use the partonic differential cross section computed from *any* theoretical approach. In this work, we shall use the Colour-Singlet Model (CSM) at LO at LHC energy, shown to be compatible (see Fig. 1a) [14, 18] with the magnitude of the P_T-integrated cross-section as given by the PHENIX pp data [21], the CDF $p\bar{p}$ data [22] and the LHC pp data at $\sqrt{s_{NN}} = 7$ TeV.

To obtain the J/ψ yield in pA and AA collisions, a shadowing-correction factor has to be applied to the J/ψ yield obtained from the simple superposition of the equivalent number of pp collisions. This shadowing factor can be

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[1] In addition, recent theoretical works incorporating QCD corrections or s-channel cut contributions have emphasized [13–15] that the Colour-Singlet (CS) mediated contributions are sufficient to describe the experimental data for hadroproduction of both charmonium and bottomonium systems without the need of CO contributions. Furthermore, recent works [16] focusing on production at e^+e^- colliders have posed stringent constraints on the size of CO contributions, which are the precise ones supporting a $2 \rightarrow 1$ hadroproduction mechanism [11].

[2] One may also go further and consider more than two particles in the final state, as expected from the real-emission contributions at NLO and NNLO [13]. It is clear from the yield polarisation [17] that these contributions start to dominate for P_T above $1 - 2m_c$. The effect of more partons in the final state is to increase the difference between the results obtained in both schemes. However the implementation of NLO and NNLO codes in a Glauber model with an inhomogeneous shadowing is not yet available.

expressed in terms of the ratios R_i^A of the nuclear Parton Distribution Functions (nPDF) in a nucleon belonging to a nucleus A to the PDF in the free nucleon: $R_i^A(x, Q^2) = \frac{f_i^A(x, Q^2)}{A f_i^{nucleon}(x, Q^2)}$, $i = q, \bar{q}, g$. The numerical parameterisation of $R_i^A(x, Q^2)$ is given for all parton flavours. Here, we restrict our study to gluons since, at high energy, the J/ψ is essentially produced through gluon fusion [11]. Several shadowing parametrisations are available [23, 24]. In the following, we shall restrict ourselves to EKS98 [23], which is very close to the mean in the current evaluation of the uncertainty [24] on the gluon nPDF and exhibits a moderate antishadowing. We postpone the propagation of the uncertainty on the gluon nPDF to the CNM effects evaluated at LHC energy for future studies.

The second CNM effect that we are going to take into account concerns the nuclear absorption. In the framework of the probabilistic Glauber model, this effect is usually parametrised by introducing an effective absorption cross section σ_{abs}. It reflects the break-up of correlated $c\bar{c}$ pairs due to inelastic scattering with the remaining nucleons from the incident cold nuclei. The value of σ_{abs} is unknown at LHC. At high energy, the heavy state in the projectile should undergo a coherent scattering off the nucleons of the target nucleus [25], in contrast with the incoherent, longitudinally ordered scattering that takes place at low energies. As argued in [26, 27], this should lead to a decrease of σ_{abs} with increasing $\sqrt{s_{NN}}$. The systematic study of many experimental data indicate that σ_{abs} appears either constant [28] or decreasing [29] with energy. Hence, we can consider our estimates [8, 9] of σ_{abs} at RHIC energy as upper bounds for the value of σ_{abs} at LHC. We choose three values of σ_{abs} that should span that interval ($\sigma_{abs} = 0, 1.5, 2.8$ mb).

3. Results and discussion

(a) *pp* collisions [18]   (b) *p*Pb collisions   (c) PbPb collisions
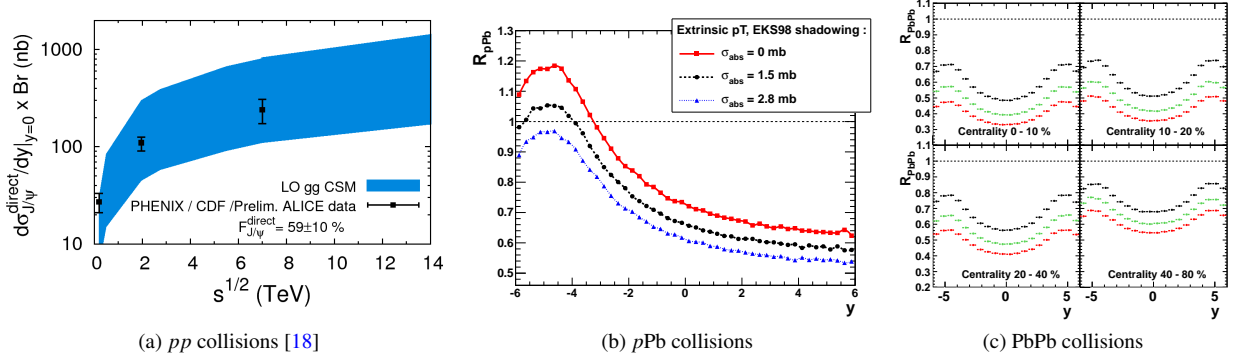
Figure 1: (a) $d\sigma_{J/\psi}^{direct}/dy|_{y=0} \times$ Br from gg fusion in pp collisions for $\sqrt{s}$ from 200 GeV up to 14 TeV compared to the PHENIX [21], CDF [22] and ALICE data. (b)-(c) J/ψ nuclear modification factor versus y in pPb and PbPb collisions at $\sqrt{s_{NN}} = 5.5$ TeV, using EKS98 [23] gluon shadowing parametrisation and three values of σ_{abs} (from top to bottom: $0, 1.5, 2.8$ mb) in the extrinsic scheme. For PbPb collisions, the y-dependence is shown for various centrality selections.

In the following, we present our results for the J/ψ nuclear modification factor due to CNM effects in the extrinsic sheme in pPb and PbPb collisions at $\sqrt{s_{NN}} = 5.5$ TeV: $R_{AB} = dN_{AB}^{J/\psi}/\langle N_{coll} \rangle dN_{pp}^{J/\psi}$, where $dN_{AB}^{J/\psi}(dN_{pp}^{J/\psi})$ is the observed J/ψ yield in $AB = p$Pb, PbPb (pp) collisions and $\langle N_{coll} \rangle$ is the average number of nucleon-nucleon collisions occurring in one pPb or PbPb collision. Without nuclear effects, R_{AB} should equal unity.

In Fig. 1b, we show $R_{p\text{Pb}}$ versus y. The curve with no absorption allows us to highlight the strong rapidity dependence of the shadowing. We can also notice that the shadowing alone should already be responsible for a quite large amount of J/ψ suppression, up to 36 % at $y = 6$. This is expected due to the very small x-region in the gluon nPDF that becomes accessible at LHC energy (down to 10^{-5}). At backward rapidity, we are in the antishadowing region, with the antishadowing peak at $y \simeq -5$. Fig. 1c shows that the y-dependence of R_{PbPb} for the centrality bins used by the ATLAS Collaboration [30] is similar for all the bins, with a dip at mid-y. This shape is the opposite of the one obtained at RHIC energy [6, 8], with a peak at mid-y. One can also notice that R_{PbPb} decreases at very large rapidity showing that one has gone beyond the antishadowing peak. Here, R_{PbPb} is systematically smaller at mid-y than at forward-y. This is also illustrated on Fig. 2, with the centrality dependence of R_{PbPb} for two regions in y.
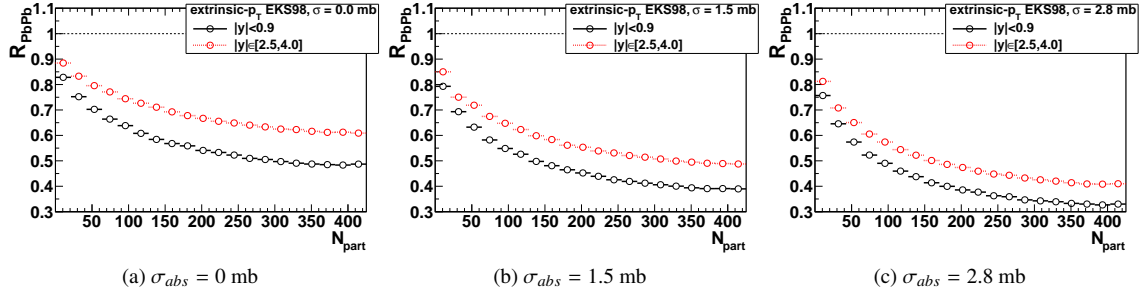
(a) $\sigma_{abs} = 0$ mb   (b) $\sigma_{abs} = 1.5$ mb   (c) $\sigma_{abs} = 2.8$ mb

Figure 2: (Color online) J/ψ nuclear modification factor, R_{PbPb}, in PbPb collisions at $\sqrt{s_{NN}} = 5.5$ TeV versus N_{part}, using EKS98 [23] gluon shadowing parametrisation and three values of the nuclear absorption cross section in the extrinsic scheme. R_{PbPb} is shown for two different experimental acceptances in rapidity, $|y| < 0.9$ and $|y| \in [2.5, 4]$.

This behaviour of the CNM effects may partially – or completely – compensate the opposite effect expected from $c\bar{c}$ recombination, with a maximum enhancement at $y = 0$. Overall, one may observe a R_{PbPb} rather independent of y resulting of two y-dependent effects.

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