A Study of the Impact of the Nuclear Modification of the Gluon Densities on $J/\psi$ production in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV

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We update our previous studies of nuclear-matter effects on $J/\psi$ production in proton-nucleus for the recent LHC pPb runs at $\sqrt{s_{NN}} = 5$ TeV. We have analysed the effects of the modification of the gluon PDFs in nucleus, using an exact kinematics for a $2 \to 2$ process, namely $g + g \to J/\psi + g$ as expected from LO pQCD. This allows us to constrain the transverse-momentum while computing the nuclear modification factor for different rapidities, unlike with the usual simplified kinematics. Owing to the absence of measurement in pp collisions at the same $\sqrt{s_{NN}}$ and owing to the expected significant uncertainties in yield interpolations which would hinder definite interpretations of nuclear modification factor –$R_{pp}$–, we have derived forward-to-backward yield ratios in which the unknown proton-proton yield cancel. These have been computed without and with a transverse-momentum cut, e.g. to comply with the ATLAS and CMS constraints in the central-rapidity region.

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| $y$ | $\gamma(y)$ | $t_{f}(y)$ | $y$ | $\gamma(y)$ | $t_{f}(y)$ |
|-----|-------------|-------------|-----|-------------|-------------|
| -4.0 | 20 6 fm | -0.5 | $10^{3}$ | 3.0 $10^{2}$ fm | 1.5 | $610^{3}$ |
| -3.5 | 50 15 fm | 0.0 | $1.710^{3}$ | 5.3 $10^{2}$ fm | 2.5 | $1.510^{4}$ |
| -2.5 | 140 45 fm | 0.5 | $2.710^{3}$ | 8 $10^{2}$ fm | 3.5 | $4.210^{4}$ |
| -1.5 | 370 110 fm | 4.5 | $1.210^{5}$ | 6 $10^{4}$ fm |

TABLE I: Boost and formation time in the Pb rest frame of the $J/\psi$ at $\sqrt{s_{NN}} = 5$ TeV in pPb collisions ($E_{CM}^{p} = 1.57$ TeV and the Pb has a negative rapidity).

Introduction.— In this brief report, we proceed to an update for the LHC experimental conditions of our earlier studies [1] of the nuclear-matter effects on the production of $J/\psi$ in proton-nucleus at RHIC. In these previous studies, we have indeed shown that the way to accurately evaluate the parton kinematics – and thus the nuclear shadowing – depends on the $J/\psi$ partonic-production mechanism. Doing so, we could go beyond other $J/\psi$-production studies in $pA$ collisions [2] in which it was assumed that the $c\bar{c}$ pair was produced by a $2 \to 1$ partonic process where the colliding gluons necessarily carried intrinsic transverse momentum $k_{T}$, entirely transferred to the quarkonium final state. Our works were based on the recent findings that $J/\psi$ production at low $P_{T}$ – where most of the $J/\psi$’s are – likely proceeds via colour singlet transitions [3] via a $2 \to 2$ process, which we referred to as the extrinsic scheme, such as $g + g \to J/\psi + g$, instead of a $2 \to 1$ process as it can be in the colour evaporation model and colour octet mechanism at low $P_{T}$ (for recent reviews see [4, 5]). We present here our results for proton-lead collisions at 5 TeV.

Theoretical framework.— We have thus used our probabilistic Glauber Monte-Carlo framework, JIN [17], which allows us to encode $2 \to 2$ partonic mechanisms for $J/\psi$ production. Because of the much larger Lorentz boost between the lead rest frame compared to RHIC energies, we have considered smaller $-1.5$ and $2.8$ mb$^{-}$ values for the effective

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1 Recent studies of higher-order QCD corrections have also confirmed this by showing, on one hand, that the too soft $P_{T}$ dependence of the LO CSM [7] was significantly improved when incorporating $a_{2}^{2}$ and $a_{2}^{7}$ [8] topologies and, on the other, that the yield predicted by the NLO CSM for $e^{+}e^{-} \to J/\psi + X_{n\sigma}$ et al [9, 10] saturates the the Belle experimental values [11]. The Colour-Octet (CO) component [12], which happens to be precisely the one appearing in the low-$P_{T}$ description of hadroproduction via a $2 \to 1$ process [13], is therefore likely not significant. By the way, this confirms the results global survey of low energy data by Maltoni et al. [14] and the recent one by F. Yu et al. [15]. Along these lines, we shall assume that the bulk of the $J/\psi$ yield will not be affected by the fractional energy loss revived in [16].
and nDSg [19]. The former comes with several sets to be used to map out the nPDF fit uncertainties. The spatial dependence of the nPDFs has been included in our approach, assuming an inhomogeneous shadowing proportional to the local density [20, 21]. The behaviour of the different sets we have used is depicted on Fig. 1. We note that, for instance, the range spanned by the nCTEQ [22] and DSSZ [23] parametrisations can even be wider. See also [24] for a recent review.

Relevant observables for the 2013 LHC proton-lead run.— One usually characterises the suppression of the $J/\psi$ by the nuclear modification factor, $R_{pA}$, the ratio of the $J/\psi$ yield in $pA$ collisions to the $J/\psi$ yield in $pp$ collisions at the same energy multiplied by the average number of binary collisions in the proton-nucleus, $\langle N_{\text{coll}} \rangle$:

$$R_{pA} = \frac{dN_{J/\psi}}{\langle N_{\text{coll}} \rangle dN_{pp}^{J/\psi}}.$$

(1)

Any nuclear effect affecting $J/\psi$ production leads to a deviation of $R_{pA}$ from unity.

Yet, in the absence of a yield measurement at the same energy, $N_{pp}^{J/\psi}$, the normalisation of such a factor depends on an interpolation which brings in additional systematical uncertainties. If the nuclear modifications are of the order 10% in a given kinematical region, it is therefore likely that the measured nuclear modification factor will not be precise enough to call for a yield suppression or a yield enhancement. The same applies for comparison with theoretical calculations.

In such a case, to keep a specific character of an experimental measurement showing unity, one can resort to two additional ratios emphasising the rapidity or the centrality dependence of the nuclear effects. Forward-to-backward ratios can then be formed such

$$R_{FB}(y_{CM}) = \frac{dN_{J/\psi}}{dN_{pA}^{J/\psi}(-y_{CM})} = \frac{R_{pA}(y_{CM})}{R_{pA}(-y_{CM})},$$

(2)

in given rapidity and/or $p_T$ bins. Since the yield in $pp$ is symmetric in $y_{CM}$, it cancels out in the double ratio in the l.h.s. of Eq. (2). Central-to-peripheral ratios, for instance

$$R_{CP} = \frac{\langle dN_{J/\psi}/(N_{\text{coll}}) \rangle}{\langle dN_{J/psi}/(N_{60-80\%}) \rangle},$$

(3)

or conversely peripheral-to-central ratios, are more common and they are recognised to reduce experimental systematic uncertainties, such as the luminosity as well as acceptance and efficiency corrections. A value close to unity at least indicates the absence of a centrality dependence of the nuclear effects. In $pA$ collisions, where the number of participants is rather low, the definition of the centrality classes introduces significant systematical uncertainties which should be considered with care. We postpone the study of the centrality dependence to a future work.

Results.— Before showing the results for $R_{pA}$, which can directly be compared to data, we have found it important to emphasise three features of our theoretical predictions –likely also pertaining to other works— which may be overlooked along the way of the comparisons between experimental and theoretical results. Indeed, we currently have at our disposal improved nPDF fits with error analysis, but there are drawbacks to be kept in mind in the interpretation of the theoretical uncertainties obtained using them.

![Image](image-url)

FIG. 2: (Colour online) Illustration of the uncertainties in the prediction of the $J/\psi$ nuclear modification factor in $pPb$ collisions, $R_{pPb}$, at $\sqrt{s_{NN}} = 5$ TeV vs. $y$. (a) effect of the unknown factorisation scale taken to be $(0.75, 1, 2) \times m_T$, (b) central curves from EPS09 at LO and NLO, (c) extremal curves from EPS09 compared to nDSg, (d) effect of the unknown effective $c\bar{c}$ break up cross section for $t_f > R_{pPb}$.

First, nuclear-effect predictions based on nPDFs parametrisations significantly depend on the factorisation scale –also referred to as $Q^*$, $\mu_F$, at which they are evaluated. It introduces an additional –significant– uncertainty which is often overlooked, whereas it is known to be already large in the description of $pp$ collisions for which the PDFs are better known. In Fig. 2(a), we compare the $R_{pPb}$ obtained with 3 sets of EPS09LO with 3 choices of $\mu_R$, namely $(0.75, 1, 2) \times m_T$. As it can be seen, the effect is significant. It is essential to recall that no choice can be privileged. Therefore, drawing any conclusion on the strength of the nuclear modification of PDFs should be done with care when experimental data are only compared to a theoretical evaluation without uncertainty on $\mu_R$.

Second, while maybe anecdotal of EPS09, fits performed at different orders may show differences which may not be reflecting any specific physical phenomenon but a particular sensitivity to QCD corrections of some observables used in the fit at scales different than the ones used here. In our case, we are using a partonic cross section evaluated at Born (LO) order. The common practice is thus to employ a LO (n)PDF set. Yet, nothing forbids us to use a NLO one as a default choice. In a sense, any difference observed, as for instance the
one between EPS09 LO and NLO on Fig. 2(b), is an indication of the uncertainty attributable to the neglect of unknown higher QCD corrections.

Finally, the uncertainty spanned by a given nPDF set with error may not encompass curves which can be obtained by fits from different groups. This is, for instance, the case of nDSg and EPS09 LO, whose shadowing magnitudes are roughly the same unlike the anti-shadowing one as it can be seen on Fig. 2(c). Yet, to be rigorous, we should have derived an error band from the EPS09 eigen sets. The error band may have then been closer to the nDSg for instance.

In addition to the uncertainties from the nPDF and their implementation, we also have to consider the effect of a break-up probability on the nuclear-modification factor as in Fig. 2(d).

We would like to recall that in order to take into account the transverse-momentum dependence of the shadowing effects one needs to resort to a model which contains an explicit dependence on $P_T$ and $y$. Thanks to the versatility of our Glauber code, such computation can also be done including the impact-parameter dependence along with involved production mechanisms containing a non-trivial $P_T$-dependence.

We emphasise that the effect of the $P_T$ cut shown on Fig. 4 is not related to any Cronin effect which is not taken into account here. It simply comes from the increase of $x_2$ and $m_T(P_T)$ for increasing $P_T$. In particular, the anti-shadowing peak is shifted to less negative rapidities which modifies $R_{FB}$ at large $|y_{CM}|$.

All these effects also impact the forward-to-backward ratio $R_{FB}$ as can be seen on Fig. 3. Their impact remains significant, except for the break-up probability. Its effect on $R_{FB}$ (see Fig. 3(d)) is much smaller than on $R_{p\bar{p}}$ and can in practice be disregarded.

These values can be compared to the preliminary measurements by the LHCb and ALICE collaborations. LHCb has reported [25] for the prompt $J/\psi$ yield a preliminary value of $R_{FB} = 0.66 \pm 0.08$ for $2.5 < |y_{CM}| < 4$, whereas ALICE has reported [26] a preliminary value of $R_{FB} = 0.60 \pm 0.07$ for $3 < |y_{CM}| < 3.5$ for the inclusive one. These values are compatible with a strong shadowing.

We have provided predictions for the $J/\psi$ nuclear modification factors in $p\bar{p}$ collisions and its forward-to-backward ratio, $R_{FB}$, at $\sqrt{s_{NN}} = 5$ TeV as functions of $y$ for low and mid $P_T$, which can be compared to the ALICE and LHCb preliminary data and the forthcoming ATLAS and CMS one taken during the 2013 LHC $p\bar{p}$ run.

Unless there is an unexpectedly large anti-shadowing, the measured values of $R_{FB}$ support the presence of a significant shadowing of a magnitude stronger than the central value of EPS09LO. This should be taken into account in the interpretation the PbPb data.

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