Impact of the nuclear modification of the gluon densities on J/ψ production in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV

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Based on our previous studies, we predict the nuclear-matter effects on J/ψ production in proton-nucleus collisions for the recent Large Hadron Collider pPb runs at $\sqrt{s_{NN}} = 5$ TeV. We have analyzed the effects of the modification of the gluon parton distribution functions in the nucleus, using an exact kinematics for a $2 \rightarrow 2$ process, namely, $g + g \rightarrow J/\psi + g$ as expected from leading-order perturbative QCD. 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 the nuclear modification factor $R_{p\text{Pb}}$, we have derived forward-to-backward and central-to-peripheral yield ratios in which the unknown proton-proton yield cancels. 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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Introduction. In this Brief Report, we predict nuclear-matter effects on the production of J/ψ in proton-nucleus collisions for the Large Hadron Collider (LHC) experimental conditions based on our eartier studies [1] at the Relativistic Heavy Ion Collider (RHIC). In these previous studies, we have indeed shown that the way to accurately evaluate the parton kinematics—and thus nuclear shadowing—depends on the J/ψ partonic-production mechanism. Doing so, we could go beyond other J/ψ-production studies in pA collisions [2] in which it was assumed that the $c\bar{c}$ pair was produced by a $2 \rightarrow 1$ partonic process where the colliding gluons necessarily carried intrinsic transverse momentum k_T, entirely transferred to the quarkonium final state.

Our earlier works, as well as the present one, account for a kinematics corresponding to a $2 \rightarrow 2$ partonic process for J/ψ production at α_s^3, as in the color-singlet model (CSM) or the color-octet mechanism (COM). In both cases, the partonic process is similar, i.e., $gg \rightarrow J/\psi + g$.

Our initial motivation stemmed from the recent findings that J/ψ production at low P_T—where most of the J/ψ's are—likely proceeds via color singlet transitions [3]. Recent studies of QCD corrections have confirmed this by showing, on one hand, that the too soft P_T dependence of the leading order (LO) CSM [4] was significantly improved when incorporating α_S^4 and α_S^5 [5] topologies and, on the other, that the yield predicted by the next-to-leading-order (NLO) CSM for $e^+e^- \rightarrow J/\psi + X_{\text{non } c\bar{c}}$ [6,7] saturates Belle experimental values [8]. The COM component [9], which happens to be precisely the one appearing in the low-P_T description of hadroproduction via a $2 \rightarrow 1$ process [10], is therefore likely not significant. This confirms the results of a global survey of low-energy data by Maltoni *et al.* [11] and the recent one by Feng *et al.* [12]. Yet, as we mentioned in the previous paragraph, a $2 \rightarrow 2$ kinematics is also the relevant one in the COM for finite P_T (see, e.g., [13]).

To follow the lines of our earlier works, we have used a generic $2 \rightarrow 2$ matrix element which matches the P_T dependence of the LHC data (dubbed an *extrinsic* scheme in [1]) such as $g + g \rightarrow J/\psi + g$, as opposed to a $2 \rightarrow 1$ process as can be in the color evaporation model and color octet mechanism at low P_T (for recent reviews see [14,15]).

We therefore present here our results for proton-lead collisions at 5 TeV. We have studied the effect of the nuclear modification of the gluon parton distribution functions (PDFs) on the J/ψ yield. We have also looked at the impact of an effective nuclear absorption as an illustration of possible additional effects.

Other phenomena as such the Cronin effect, coherent power corrections, and nuclear-matter-induced energy loss may also be at work. The latter effect is the subject of recent activities [16,17] whose conclusions may seem contradictory. As such and since this work has only as ambition to provide predictions at LHC energies based on [1], we have not considered these effects.

Theoretical framework. We have thus used our probabilistic Glauber Monte Carlo framework, JIN [18], which allows us to encode $2 \rightarrow 2$ partonic mechanisms for J/ψ production. As far as the nuclear modification of the gluon PDF is concerned, we have employed the parametrizations EPS09 [19] and nDSg [20]. The former comes with several sets to be used to map out the nuclear PDF (nPDF) fit uncertainties. The spatial dependence of the nPDF has been included in our approach, by assuming an inhomogeneous shadowing proportional to the local density [21,22]. The behavior of the different sets we have used is depicted in Fig. 1. We note that, for instance, the range spanned by the nCTEQ [23] and DSSZ [24] parametrizations can even be wider. See also [25] for a recent review.

Because of the much larger Lorentz boost between the lead rest frame compared to RHIC energies, the heavy-quark pair propagating in nuclear matter will nearly always be in a

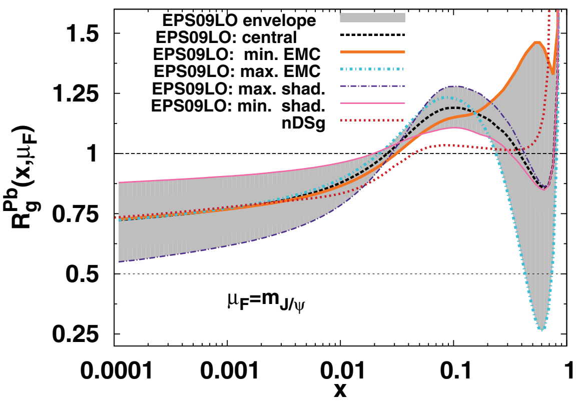


FIG. 1. (Color online) The nuclear modification of the gluon density in a lead nucleus at a scale taken to be the J/ψ mass as obtained with the nDSg set, the envelope of the 30 EPS09 LO sets, as well as its central set and four specific sets reproducing its envelope for the gluon.

pre-resonant state, i.e., smaller than the physical J/ψ size. Indeed, the relevant time scale for analyzing the pair evolution is its formation time, which, following the uncertainty principle, is related to the time needed (in their rest frame) to distinguish the energy levels of the $1S$ and $2S$ states, $t_f = \frac{2M_{c\bar{c}}}{(M_{2S}^2 - M_{1S}^2)} = (2 \times 3.3\ \text{GeV})/(4\ \text{GeV}^2) = 0.35$ fm for the ψ. t_f has to be considered in the rest frame of the target nucleus. Table I summarizes the various formation times in the lead rest frame. Only in the most backward region does t_f get to the order of the lead radius, r_{Pb}.

The probability for the heavy-quark pair to be broken up during its propagation through the nuclear medium is commonly known as the nuclear absorption, usually parametrized by an effective breakup cross section σ_{eff}. Since the pair is smaller $[O(1/(2m_c)]$ instead of $O\{1/[\alpha_s(2m_c)2m_c]\}$, we have considered smaller (1.5 and 2.8 mb) values for the effective breakup cross section. Note that a pre-resonant pair along its way off the lead nucleus can still be broken up if, for instance, the scatterings increase its invariant mass until it is above the open-charm threshold (see, e.g., [26]). That being said, our results with nonzero breakup cross section are primarily shown for illustrative purposes. Only qualitative statements should be drawn from them.

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

$$R_{pA} = \frac{dN_{pA}^{J/\psi}}{\langle N_{\text{coll}} \rangle dN_{pp}^{J/\psi}}. \tag{1}$$

Any nuclear effect affecting J/ψ 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 normalization 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 emphasizing the rapidity or the centrality dependence of the nuclear effects. Forward-to-backward ratios such as

$$R_{\text{FB}}(|y_{\text{c.m.}}|) \equiv \frac{dN_{pA}^{J/\psi}(y_{\text{c.m.}})}{dN_{pA}^{J/\psi}(-y_{\text{c.m.}})} = \frac{R_{p\text{Pb}}(y_{\text{c.m.}})}{R_{p\text{Pb}}(-y_{\text{c.m.}})} \tag{2}$$

can then be formed in given rapidity and/or P_T bins. Since the yield in pp collisions is symmetric in $y_{\text{c.m.}}$, it cancels out in the double ratio in the left-hand side of Eq. (2). Central-to-peripheral ratios, for instance,

$$R_{\text{CP}} = \frac{\left(\frac{dN_{J/\psi}}{dy} / \langle N_{\text{coll}} \rangle\right)}{\left(\frac{dN_{J/\psi}^{60\%-80\%}}{dy} \Big/ \left\langle N_{\text{coll}}^{60\%-80\%} \right\rangle\right)}, \tag{3}$$

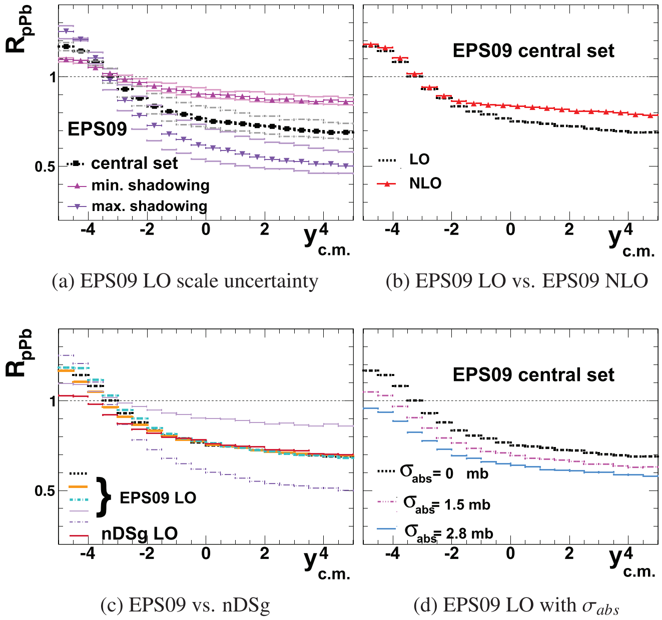
or conversely peripheral-to-central ratios, are more common and they are recognized to reduce experimental systematical uncertainties, e.g. those related to the luminosity or to the corrections in acceptance and efficiency. A value close to unity at least indicates the absence of a centrality dependence of the nuclear effects.

Results. Before showing the results for R_{FB} and R_{CP} which can directly be compared to data, we have found it important to emphasize three features of our theoretical predictions—likely also pertaining to other works—which may be overlooked along the way of making 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.

First, nuclear-effect predictions based on nPDFs parametrizations significantly depend on the factorization

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

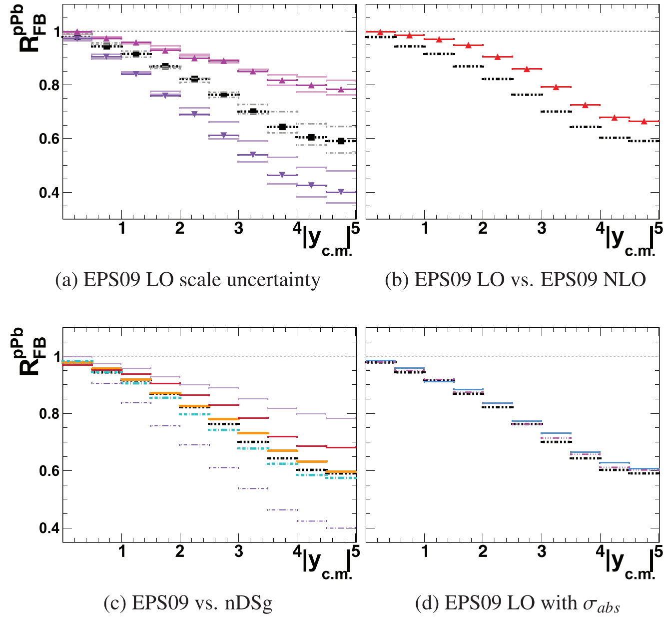
y	$\gamma(y)$	$t_f(y)$	y	$\gamma(y)$	$t_f(y)$	y	$\gamma(y)$	$t_f(y)$
−4.0	20	6 fm	−0.5	10^3	3.0×10^2 fm	1.5	6×10^3	2.3×10^3 fm
−3.5	50	15 fm	0.0	1.7×10^3	5.3×10^2 fm	2.5	1.5×10^4	6.0×10^3 fm
−2.5	140	45 fm	0.5	2.7×10^3	8×10^2 fm	3.5	4.2×10^4	1.7×10^4 fm
−1.5	370	110 fm				4.5	1.2×10^5	6.0×10^4 fm



(a) EPS09 LO scale uncertainty (b) EPS09 LO vs. EPS09 NLO

(c) EPS09 vs. nDSg (d) EPS09 LO with σ_{abs}

FIG. 2. (Color online) Illustration of the uncertainties in the prediction of the J/ψ nuclear modification factor in pPb collisions, $R_{p\text{Pb}}$, at $\sqrt{s_{NN}} = 5$ TeV vs y. (a) Effect of the unknown factorization 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 (with the same color code as in Fig. 1). (d) Effect of the unknown effective $c\bar{c}$ breakup cross section for $t_f \gg R_{\text{Pb}}$.



(a) EPS09 LO scale uncertainty (b) EPS09 LO vs. EPS09 NLO

(c) EPS09 vs. nDSg (d) EPS09 LO with σ_{abs}

FIG. 3. (Color online) Same as Fig. 2 for R_{FB}.

scale (also referred to as Q), μ_F, at which they are evaluated. This 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 $R_{p\text{Pb}}$ obtained with three sets of EPS09LO with three choices of μ_F, namely, $0.75 m_T$, m_T and $2 m_T$. As 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 μ_F.

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 in 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 antishadowing one, as can be seen in Fig. 2(c). Yet, to be rigorous, we should have derived an error band from the EPS09 eigensets. The error band may have then been closer to the nDSg for instance.

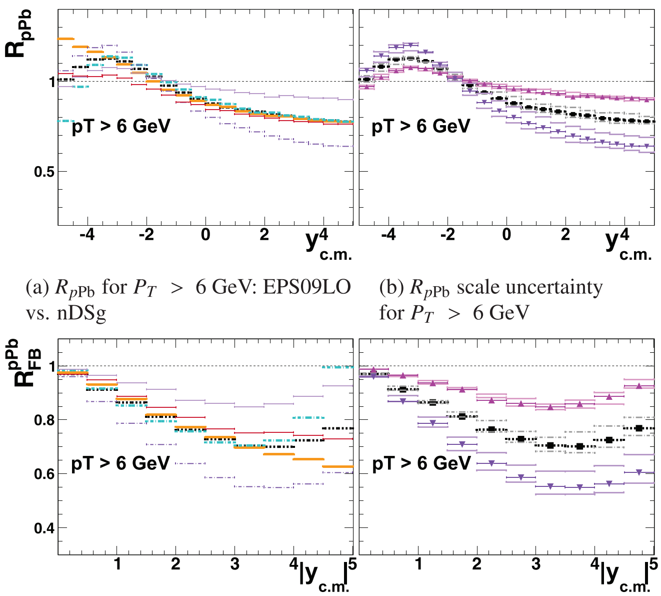
In addition to the uncertainties from the nPDF and their implementation, we also have to consider the effect of a breakup probability on the nuclear-modification factor as in Fig. 2(d).

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 breakup probability. Its effect on R_{FB} [see Fig. 3(d)] is much smaller than on $R_{p\text{Pb}}$ and can in practice be disregarded.

These values can be compared to the preliminary measurements by the LHCb and ALICE Collaborations. LHCb has reported [27] for the prompt J/ψ yield a preliminary value of $R_{\text{FB}} = 0.66 \pm 0.08$ for $2.5 < |y_{\text{c.m.}}| < 4$, whereas ALICE has reported [28] a preliminary value of $R_{\text{FB}} = 0.60 \pm 0.07$ for $3 < |y_{\text{c.m.}}| < 3.5$ for the inclusive one. These values are compatible with a strong shadowing.

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 a computation can also be done by including the impact-parameter dependence along with involved production mechanisms containing a nontrivial P_T dependence.

The effect of imposing a P_T cut is shown in Fig. 4. We emphasize that it 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 antishadowing peak is shifted to less negative rapidities, which modifies R_{FB} at large $|y_{\text{c.m.}}|$ [Fig. 4(c)]. The uncertainty coming from the choice of the factorization scale is not much reduced [Figs. 4(b) and 4(d)], despite the larger value of m_T.



(a) $R_{p\mathrm{Pb}}$ for $P_T > 6$ GeV: EPS09LO vs. nDSg

(b) $R_{p\mathrm{Pb}}$ scale uncertainty for $P_T > 6$ GeV

(c) R_{FB} for $P_T > 6$ GeV: EPS09LO vs. nDSg

(d) R_{FB} scale uncertainty for $P_T > 6$ GeV

FIG. 4. (Color online) Effect of the cut $P_T > 6$ GeV on the J/ψ nuclear modification factor (a and b) and its forward-to-backward ratio (c and d) in pPb collisions at $\sqrt{s_{NN}} = 5$ TeV vs y.

Finally, we show on Fig. 5 our predictions for R_{CP} for the five sets of EPS09 which we used and nDSg with and without a P_T cut. We see that the trend of R_{CP} is similar to that of $R_{p\mathrm{Pb}}$, with a larger magnitude. $R_{p\mathrm{Pb}}$ curves in four centrality classes are provided as Supplemental Material [29]. Since part of the experimental uncertainties and that related to the unknown pp reference cancel in R_{CP}, we are hopeful that forthcoming data will tell us more about the magnitude of the gluon shadowing despite the theoretical complications which we enumerated before.

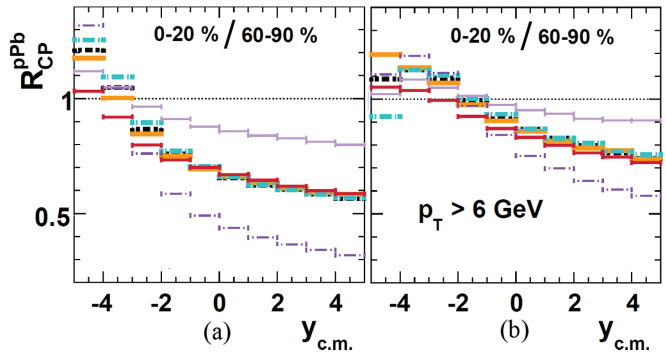


FIG. 5. (Color online) Central-over-peripheral ratio for five sets of EPS09 and nDSg as functions of y without (a) and with (b) a P_T cut.

Conclusions. We have provided predictions for the J/ψ nuclear modification factors in pPb collisions, its forward-to-backward ratio, R_{FB}, and its central-over-peripheral ratio, R_{CP}, 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 data taken during the 2013 LHC pPb run.

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

Note added: During the publication process of this report, the LHCb and ALICE Collaborations have released [30,31] their final results; these are in very good agreement with their preliminary values quoted above [27,28].

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