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Disentangling shadowing from coherent energy loss using the Drell-Yan process

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We propose the measurement of Drell-Yan (DY) lepton pairs in p-Pb collisions at the LHC in order to disentangle the relative contributions of leading-twist shadowing and coherent energy loss in quarkonium production off nuclei. The nuclear modification of low-mass DY production is computed at next-to-leading order using various sets of nuclear parton densities. It is then observed that shadowing effects strongly cancel out in the J/ψ over DY suppression ratio $R_{p\mathrm{A}}^{\psi}(y)/R_{p\mathrm{A}}^{\mathrm{DY}}(y)$, unlike the effect of coherent energy loss. Such a measurement can be performed at forward rapidity by the ALICE and LHCb Collaborations at the LHC.

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I. INTRODUCTION

Measurements of J/ψ production in p-Pb collisions at the LHC ($\sqrt{s} = 5.02$ TeV) by ALICE [1,2] and LHCb [3], and the observation of a strong attenuation at large rapidity with respect to the p–p data interpolation at the same collision energy, have triggered an intense debate on the origin of such a nuclear suppression [4]. Several groups have attributed the suppression to the depletion of the gluon distribution in the target nucleus expected at small $x_2 \lesssim 10^{-2}$, commonly named "shadowing." Within the collinear factorization approach, "shadowing" is understood as the *leading-twist* shadowing affecting the nuclear parton distribution functions (nPDFs) obtained from global fits based on Dokshitzer-Gribov-Lipatov-Altarelli-Parisi evolution. Within the saturation formalism (see [5,6] for reviews), "shadowing" is determined from nonlinear QCD evolution and incorporates additional, *higher-twist* effects.

However, another fundamental phenomenon, namely fully coherent energy loss in cold nuclear matter [7–16], could also affect the rate of hard forward processes in nuclear collisions. Fully coherent energy loss arises from the induced radiation of gluons with formation time t_{f} much larger than the medium length, $t_{\mathrm{f}} \gg L$. In this regime, the average energy loss becomes proportional to the parton energy E, $\Delta E_{\mathrm{coh}} \propto E$, thus overwhelming (at large E) the Landau-Pomeranchuk-Migdal energy loss $\Delta E_{\mathrm{LPM}} \propto \alpha_s \hat{q} L^2$, where $\hat{q}$ is the transport coefficient in cold nuclear matter. Phenomenology indicates that fully coherent energy loss could explain the present J/ψ nuclear suppression LHC data [8,9,11].

Leading-twist shadowing and (fully) coherent energy loss are two distinct effects, and should in principle be both taken into account in nuclear suppression models. However, as discussed in [9,11] coherent energy loss *alone* allows one to describe J/ψ nuclear suppression observed at large x_{F} ($x_{\mathrm{F}} \gtrsim 0.1$) [17] at fixed-target collision energies $\sqrt{s} \lesssim 40$ GeV [18], with a value of the cold nuclear matter transport coefficient $\hat{q}_0 = 0.07$–0.09 GeV^2/fm. This is consistent with the fact that shadowing is expected to be small at those energies and those values of x_{F}. Taking nevertheless into account nPDF effects given by either EPS09 [19] or DSSZ [20] next-to-leading-order (NLO) nPDF sets leads to a slightly smaller value of $\hat{q}_0$, but energy loss remains the dominant effect at fixed-target energies [9]. Extrapolating coherent energy loss to collider energies leads to a central prediction [9] (with a rather narrow theoretical uncertainty band [4]) which agrees well with the J/ψ suppression data measured in d–Au collisions at the RHIC [21,22] and p-Pb collisions at the LHC [1,3]. Although experimental uncertainties still leave room for shadowing in J/ψ suppression at collider energies, the results of the pure energy loss scenario tend to favor nPDF sets with a moderate shadowing.

Regarding calculations of J/ψ nuclear suppression including only leading-twist shadowing, a prediction at NLO within the color evaporation model (CEM) for quarkonium production using EPS09 NLO is in reasonable agreement with the LHC data, except in the most forward bins where the measured suppression is stronger than predicted [23] (these calculations were updated in [24]). After the data came, a leading-order (LO) color singlet model (CSM) calculation [25] using EPS09 LO proved to be in apparent agreement with data; however in this case the theoretical uncertainty associated with the use of EPS09 LO appears very large. The only prediction in the saturation formalism [26] turns out to largely overestimate J/ψ nuclear suppression. Using the same model but with an improved treatment of the nonlinear QCD evolution, a more recent calculation [27] led to less J/ψ suppression at forward rapidity, hence to lesser disagreement with experimental results. Finally, saturation effects have also been investigated within the nonrelativistic QCD (NRQCD) formalism, in which the resulting theoretical uncertainty band is large and encompasses the data [28]. Clearly, the large theoretical uncertainties of nPDF and saturation calculations do not yet allow for a clear interpretation of J/ψ suppression at the LHC.

It is therefore crucial to discriminate between shadowing and coherent energy loss, and Drell-Yan forward production offers a unique opportunity to achieve this goal. In this article, we show that the measurement of Drell-Yan (DY) lepton pairs of relatively low mass ($10 \lesssim M_{\mathrm{DY}} \lesssim 20$ GeV) in p-Pb collisions at the LHC could be decisive to discriminate between J/ψ nuclear suppression models based on coherent energy loss and those based on shadowing within collinear factorization. Discriminating between coherent energy loss and saturation-based models of J/ψ suppression will not be addressed here. In the following, the term "shadowing" thus refers to the (leading-twist) shadowing of nPDFs.

Shadowing effects on both J/ψ and DY are expected to be of similar magnitude, since small-x_2 gluons and sea antiquarks in nuclei—contributing respectively to J/ψ and DY production at large enough rapidity—have a similar depletion in most nPDF global fits, $R_g^{\mathrm{A}} \simeq R_{\bar{q}}^{\mathrm{A}}$ [with $R_i^{\mathrm{A}}(x,Q) \equiv f_i^{p/\mathrm{A}}(x,Q)/f_i^p(x,Q)$, where f^{p} and $f^{\mathrm{p/A}}$ are respectively the PDF in a free proton and in a proton bound in nucleus A]. Consequently, comparing the J/ψ and DY nuclear modification factor in p-A collisions,

$$R_{p\mathrm{A}}(y) \equiv \frac{1}{A}\frac{\mathrm{d}\sigma_{p\mathrm{A}}}{\mathrm{d}y} \bigg/ \frac{\mathrm{d}\sigma_{pp}}{\mathrm{d}y}, \tag{1}$$

for instance through the measurement of the double ratio,

$$\mathcal{R}_{p\mathrm{A}}^{\psi/\mathrm{DY}}(y) \equiv R_{p\mathrm{A}}^{\psi}(y)/R_{p\mathrm{A}}^{\mathrm{DY}}(y), \tag{2}$$

allows for an important "cancellation" of nPDF effects. Remarkably, when it comes to coherent energy loss effects, no such cancellation is expected.

Indeed, coherent energy loss arises from the interference between initial and final state gluon radiation and therefore affects, in p-A collisions, only those partonic subprocesses with a *colorful* final state [13]. Moreover, since soft coherent radiation does not probe the final parton system, only the *global* color charge of the latter matters [15]. Coherent energy loss is thus present in J/ψ production, where the $c\bar{c}$ pair is produced either as a color octet or as part of an octet system (like $c\bar{c}+g$ in the CSM), but absent in the DY subprocess at leading order, $q\bar{q} \to \gamma^\star$. At NLO, the virtual photon is produced together with an additional parton, mainly through $qg \to q\gamma^\star$ at large y, making DY production potentially sensitive to coherent energy loss. However, the medium-induced coherent radiation spectrum associated with $qg \to q\gamma^\star$ is small ($\propto 1/N_c$) and moreover *negative* [13], leading to a slight DY *enhancement*, at variance with J/ψ suppression. Thus, quite independent of the relative weights of the $q\bar{q} \to \gamma^\star$ and $qg \to q\gamma^\star$ processes in the total DY cross section, we expect the DY nuclear modification factor R^{DY} to be unity or slightly larger in the pure energy loss scenario.

In summary, the qualitative expectations for the J/ψ over DY suppression at large rapidity are as follows:

$$\begin{aligned} &\textbf{nPDF} \quad R^{\psi} \simeq R^{\mathrm{DY}} \to \mathcal{R}^{\psi/\mathrm{DY}} \simeq 1, \\ &\textbf{E. loss} \quad R^{\psi} < 1; \quad R^{\mathrm{DY}} \gtrsim 1 \to \mathcal{R}^{\psi/\mathrm{DY}} < 1. \end{aligned}$$

This is supported by the quantitative study below.

II. RESULTS

Before moving to the actual results on DY and J/ψ nuclear suppression, we first illustrate in Fig. 1 the gluon (top) and $\bar{u}$ (bottom) nPDF ratios (for a lead target) and their uncertainties given by the three most recent NLO

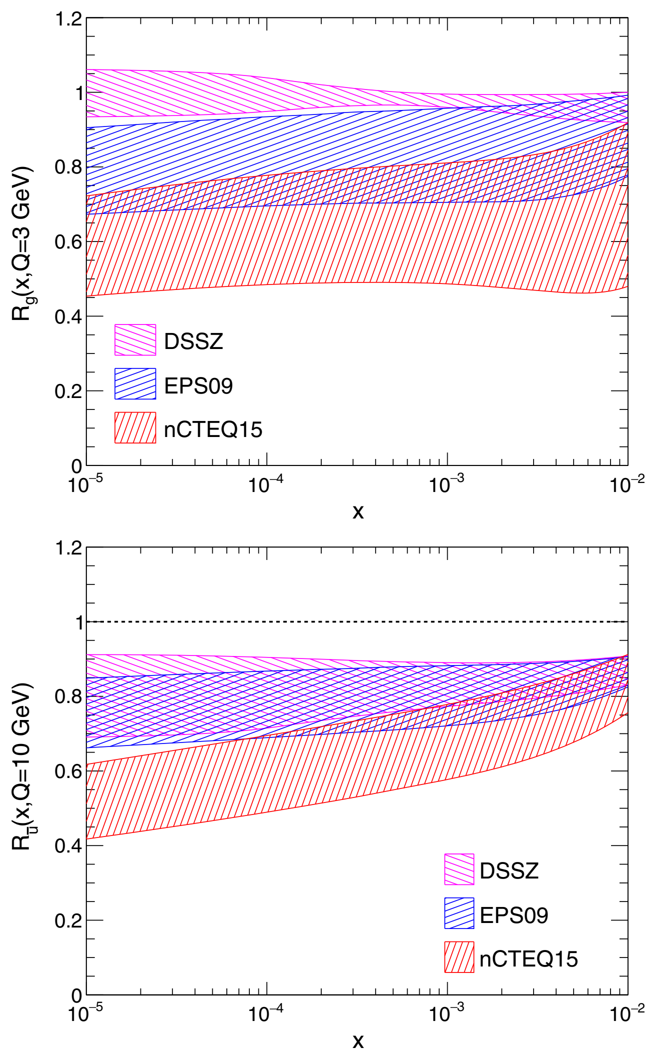

FIG. 1. $R_g^{Pb}(x, Q = 3\ \mathrm{GeV})$ (top) and $R_{\bar{u}}^{Pb}(x, Q = 10\ \mathrm{GeV})$ (bottom) for various nPDF sets.

nPDF sets from global fits: EPS09 [19], DSSZ [20], nCTEQ15 [29]. (Results using the earlier HKN07 set [30] are very similar to those obtained with the central set of EPS09 and are therefore not reproduced here.) The choice $Q = 3$ GeV (resp. $Q = 10$ GeV) for the factorization scale in R_g (resp. $R_{\bar{u}}$) and the small-x range $10^{-5} < x < 10^{-2}$ reflect our proposal to compare J/ψ to DY pairs of mass above that of the Υ states, in the rapidity range $0 < y < 5$ in p-Pb collisions at the LHC. The bands are determined from the spread of 30, 50, and 32 uncertainty sets around the central prediction of EPS09, DSSZ, and nCTEQ15, respectively. Although useful for clarity purposes, it should be kept in mind that bands obscure many correlated uncertainties, for instance that between different parton flavors (e.g. when comparing R_g and $R_{\bar{u}}$ in the present context) or the x dependence (and thus the rapidity dependence of particle production) of the individual member sets. Moreover, the probability density is also not uniform within the uncertainty bands. In fact, for systematic uncertainties such as the ones we discuss here (and unlike uncorrelated errors of statistical nature), showing individual member sets provides more information than showing bands only.

The current uncertainty on the small-x gluon shadowing is striking (Fig. 1, top). Depending on which set is used, the nPDF ratio at $x = 10^{-5}$ varies from $R_g \simeq 0.95$–1.05 in DSSZ to $R_g \simeq 0.45$–0.7 in nCTEQ15. Moreover the uncertainty bands are rather broad and almost do not overlap in the entire x domain, reflecting the fact that these should be seen as *lower* estimates for the theoretical uncertainty, as discussed in [19,29]. We also note that for EPS09 and nCTEQ15, the shadowing of sea antiquarks is of the same magnitude as that of gluons. Although not directly apparent in the uncertainty bands of Fig. 1, the latter statement holds separately for *each* uncertainty set of EPS09 and nCTEQ15. As a consequence, the double ratio $R_g/R_{\bar{u}}$ is close to unity, with an uncertainty band much smaller than that of the single nPDF ratios R_g and $R_{\bar{u}}$. This will translate into rather precise nPDF predictions for the double ratio $\mathcal{R}^{\psi/\mathrm{DY}}$ using EPS09 and nCTEQ15 sets. In the particular case of DSSZ, gluon and sea antiquark shadowing do not have similar magnitudes ($R_g \simeq 0.95$–1.05 whereas $R_{\bar{u}} \simeq 0.7$–0.9) and the uncertainty band for $\mathcal{R}^{\psi/\mathrm{DY}}$ will remain large but above unity, hence even further away from the prediction of the coherent energy loss model (see Fig. 3).

Let us now discuss shadowing effects on J/ψ suppression. Unlike DY production, quarkonium production in hadronic collisions is not yet fully understood. As a consequence, *absolute* quarkonium production cross sections may strongly depend on the assumed quarkonium production model (CEM, CSM, NRQCD). On the contrary, we expect the J/ψ nuclear modification factor (1) to depend negligibly on the production model, for the following reasons. In the domain $x_2 \lesssim 10^{-2}$ probed at the LHC, J/ψ production is dominated by partonic subprocesses involving the *gluon* distribution in the target, for any production model and at any order (LO or NLO) in perturbative QCD (pQCD). If the gluon nPDF ratio $R_g^{\mathrm{A}}(x_2, Q)$ were a constant, then we would have exactly $R_{\mathrm{pA}}^{\psi} = R_g^{\mathrm{A}}$. In practice R_g^{A} depends on x_2, whose typical value may depend on the specific J/ψ production mechanism and on the order of the pQCD calculation. However, as can be seen in Fig. 1 (top), R_g^{Pb} is extremely flat at small values of x (note the logarithmic scale), for all nPDF sets. Due to this fact, we can easily verify that $R_{p\mathrm{Pb}}^{\psi}(y) \simeq R_g^{\mathrm{Pb}}(\langle x_2 \rangle)$ (with $\langle x_2 \rangle$ given e.g. by the LO expression $x_2 = M_\psi e^{-y}/\sqrt{s}$), up to a relative systematic uncertainty $\delta R_{p\mathrm{A}}^{\psi}/R_{p\mathrm{A}}^{\psi}$ not exceeding 1% even when the uncertainty on x_2 is large, $\delta x_2/x_2 \sim 25\%$. Within this accuracy, any J/ψ production model should yield the prediction

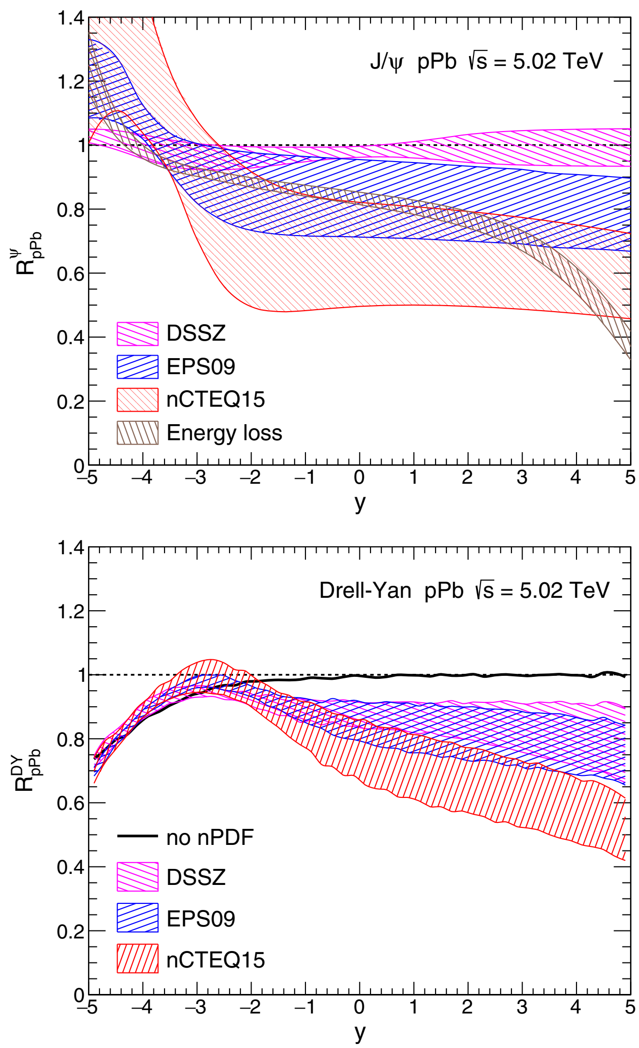

FIG. 2. J/ψ (top) and DY (bottom) suppression in p-Pb collisions at $\sqrt{s} = 5.02$ TeV for the various nPDF sets used in this study. The prediction for J/ψ suppression from the effect of coherent energy loss alone is also shown (top).

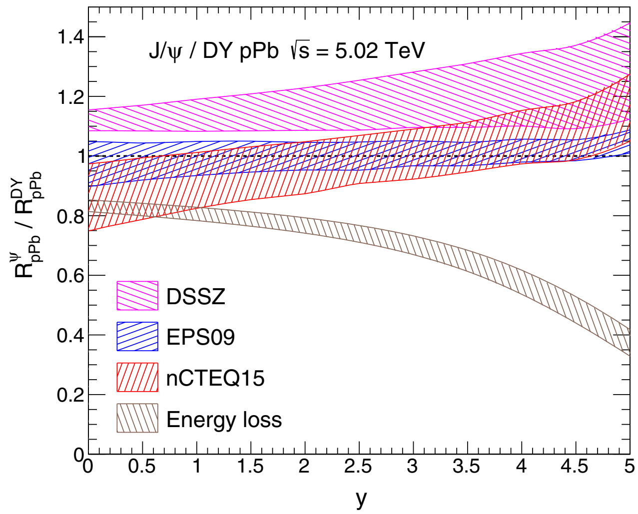

FIG. 3. Double ratio $\mathcal{R}^{\psi/\mathrm{DY}}_{\mathrm{pPb}}$ in p-Pb collisions at $\sqrt{s} =$ 5.02 TeV for the various nPDF sets and in the coherent energy loss model.

$R^{\psi}_{p\mathrm{Pb}}(y) \simeq R^{\mathrm{Pb}}_{g}(\langle x_2 \rangle)$ displayed in Fig. 2 (top) [31]. Thus, as far as the nuclear production *ratio* R^{ψ}_{pA} is concerned, the choice of a specific quarkonium production model is irrelevant given the present nPDF uncertainties. The predictions for J/ψ suppression from coherent energy loss *alone* are also shown in Fig. 2 (top), which illustrates the difficulty to trace the physical origin of J/ψ suppression seen in the LHC data [32].

We now come to the main point of this article, namely, how the study of the DY nuclear modification factor can help clarify this situation. In the following, we first determine the nPDF effects on the DY nuclear modification factor defined in (1), and then discuss the double ratio (2).

Contrary to J/ψ production, the basic pQCD process for DY production is known, and the absolute cross section under control. In the following we determine the DY nuclear modification factor $R^{\mathrm{DY}}_{\mathrm{pPb}}(y)$ at NLO, using the DYNNLO [33,34] Monte Carlo program. The single differential cross section $\mathrm{d}\sigma/\mathrm{d}y$ is computed in p–p and p-Pb collisions at $\sqrt{s} = 5.02$ TeV (similar results are obtained at $\sqrt{s} = 8$ TeV), from which $R^{\mathrm{DY}}_{p\mathrm{Pb}}(y)$ is determined. We use the MSTW NLO [35] proton PDF [36] and factorization and renormalization scales equal to the DY mass M_{DY}. The p-Pb calculations were carried out using the NLO nPDF sets already discussed. For completeness, the DY cross section has also been computed in p-Pb collisions assuming no nPDF corrections $[R^{\mathrm{Pb}}_{i}(x, Q) = 1]$. The mass range considered in this calculation, $10.5 < M_{\mathrm{DY}} < 20$ GeV, appears as an interesting compromise. On the one hand, M_{DY} should not be too large, both to guarantee a good cancellation of nPDF effects between J/ψ and DY suppression, and moreover to ensure a reasonable statistics at the LHC. On the other hand, for $M_{\mathrm{DY}} < 10.5$ GeV the extraction of the DY signal is extremely delicate, due to the large background of lepton pairs coming from heavy-flavor hadron decays [adding to those from quarkonia up to the $\Upsilon(3S)$ of mass 10.35 GeV] [37]. Note that this mass range has also been considered in saturation studies [38–40] although no DY nuclear modification factor was determined.

The DY suppression in p-Pb collisions is shown in Fig. 2 (bottom) as a function of the lepton pair rapidity. In the most forward bins, $3 \lesssim y \lesssim 5$ (corresponding to $10^{-5} \lesssim x_2 \lesssim 10^{-4}$ using $x_2 = M_{\mathrm{DY}} e^{-y}/\sqrt{s}$), the similarity with the sea antiquark nPDF ratios shown in Fig. 1 (bottom) is clear: DY suppression is quite strong ($R_{\mathrm{pPb}} \simeq 0.4$–$0.6$) using nCTEQ15, and less pronounced using DSSZ or EPS09 ($R^{\mathrm{DY}}_{\mathrm{pPb}} \simeq 0.7$–$0.9$). Since no coherent energy loss (but a slight energy *gain*, as mentioned previously) is expected in DY production, these calculations already demonstrate the discriminating power of low-mass DY pair production in p-Pb collisions at the LHC, allowing for setting tight constraints on antiquark shadowing at very small x. Such measurement could be performed by either ALICE or LHCb (as demonstrated by the early results in p–p collisions [37]), whose dimuon rapidity acceptance extends up to $y_{\mathrm{lab}} = 4.5$ (this corresponds to $y = y_{\mathrm{lab}} - \Delta y \simeq 4$, where $\Delta y \simeq 0.465$ is the boost of the lab frame with respect to the center-of-mass frame). Moreover, counting rates are expected to be large. The p-Pb cross section is $\mathrm{d}\sigma^{\mathrm{DY}}_{p\mathrm{Pb}}/\mathrm{d}y \simeq$ 40 nb in the rapidity bin $3.5 < y < 4$. Using an integrated luminosity of $\mathcal{L}^{\mathrm{int}}_{p\mathrm{Pb}} = 100\ \mathrm{nb}^{-1}$ at the LHC run 2 (typically a few times larger than at run 1), approximately $\mathcal{N}_{3.5<y<4} =$ 2000 pairs are expected to be produced in that rapidity bin. This ensures the statistical uncertainties on the ratio $R^{\mathrm{DY}}_{p\mathrm{Pb}}$ to remain under control, at a few percent level, even at large rapidity. The backward region ($y < 0$), where the depletion of DY production in p-Pb with respect to p–p collisions is due to isospin effects [41], would also be interesting in itself.

Finally, in the forward rapidity domain the DY nuclear suppression factor, Fig. 2 (bottom), compared to that of J/ψ, Fig. 2 (top), can be used to disentangle coherent energy loss from leading-twist shadowing effects, taking advantage of the similarity between gluon and sea antiquark shadowing as well as of the absence (or smallness) of coherent energy loss effects in DY production. Shadowing effects on the *double ratio* $\mathcal{R}^{\psi/\mathrm{DY}}_{p\mathrm{A}}$ defined in (2) are shown in Fig. 3. The contrast with the single ratio $R^{\psi}_{p\mathrm{A}}$ is striking. Indeed, quite independent of the nPDF set, shadowing leads to a double ratio close to unity at forward rapidity (and slightly above in DSSZ, $\mathcal{R}^{\psi/\mathrm{DY}}_{p\mathrm{A}} \simeq 1.1$–$1.3$ at $y = 4$). Moreover, there is a rather small associated uncertainty resulting from using the *same* nPDF uncertainty set for both J/ψ and DY production. Assuming no coherent energy loss in DY production, the predictions of the sole effect of coherent energy loss on the double ratio are also shown in

Fig. 3, and differ significantly from the calculations based on shadowing effects only. For illustration one expects, at $y = 4$, $\mathcal{R}_{p\mathrm{A}}^{\psi/\mathrm{DY}} \lesssim 0.6$ for coherent energy loss effects while $\mathcal{R}_{p\mathrm{A}}^{\psi/\mathrm{DY}} \simeq 1$–1.3 for nPDF effects. Comparing Fig. 3 to Fig. 2 (top) emphasizes the discriminating power of the double ratio $\mathcal{R}_{p\mathrm{A}}^{\psi/\mathrm{DY}}$ in p-A collisions at the LHC. Finally we stress that the prediction for the double ratio arising from the *combined* effects of coherent energy loss and shadowing is roughly given by the product of the two [9]. Compared to the prediction assuming coherent energy loss only, it is thus either almost identical (when using EPS09 or nCTEQ15) or at most enhanced by 20%–30% (when using DSSZ).

III. SUMMARY

In summary, we propose to use the Drell-Yan process in p-Pb collisions at the LHC (i) to constrain nuclear PDFs through the nuclear modification factor $R_{p\mathrm{Pb}}^{\mathrm{DY}}$, and (ii) to discriminate between J/ψ suppression models based on coherent energy loss from those based on (leading-twist) shadowing by measuring the double ratio $\mathcal{R}_{p\mathrm{Pb}}^{\psi/\mathrm{DY}}$. Such measurements could be performed by ALICE and LHCb and would shed light on the physical origin of the current data, therefore entailing significant consequences for the interpretation of J/ψ suppression also in Pb–Pb collisions. Using the Drell-Yan process should more generally clarify the origin of *hadron* suppression in p-A collisions expected to be sensitive to coherent energy loss [7] on top of possible shadowing effects.

Finally, we stress that we consider two *extreme* scenarii ("energy loss *only*" vs "nPDF shadowing *only*") leading to opposite trends for the double ratio $\mathcal{R}_{p\mathrm{Pb}}^{\psi/\mathrm{DY}}$. It would be valuable to predict the latter double ratio in the saturation formalism, and see how it compares to the predictions based on coherent energy loss and on shadowing of nPDFs presented here.

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[1] B. B. Abelev *et al.* (ALICE Collaboration), J/ψ production and nuclear effects in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, J. High Energy Phys. 02 (2014) 073.

[2] J. Adam *et al.* (ALICE Collaboration), Rapidity and transverse-momentum dependence of the inclusive J/ψ nuclear modification factor in p-Pb collisions at $\sqrt{s_{NN}} =$ 5.02 TeV, J. High Energy Phys. 06 (2015) 055.

[3] R. Aaij *et al.* (LHCb Collaboration), Study of J/ψ production and cold nuclear matter effects in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV, J. High Energy Phys. 02 (2014) 072.

[4] A. Andronic *et al.*, Heavy-flavour and quarkonium production in the LHC era: from proton–proton to heavy-ion collisions, Eur. Phys. J. C **76**, 107 (2016).

[5] N. Armesto, Nuclear shadowing, J. Phys. G **32**, R367 (2006).

[6] F. Gelis, E. Iancu, J. Jalilian-Marian, and R. Venugopalan, The Color Glass Condensate, Annu. Rev. Nucl. Part. Sci. **60**, 463 (2010).

[7] F. Arleo, S. Peigné, and T. Sami, Revisiting scaling properties of medium-induced gluon radiation, Phys. Rev. D **83**, 114036 (2011).

[8] F. Arleo and S. Peigné, J/ψ suppression in p-A collisions from parton energy loss in cold QCD matter, Phys. Rev. Lett. **109**, 122301 (2012).

[9] F. Arleo and S. Peigné, Heavy-quarkonium suppression in p-A collisions from parton energy loss in cold QCD matter, J. High Energy Phys. 03 (2013) 122.

[10] N. Armesto, H. Ma, M. Martinez, Y. Mehtar-Tani, and C. A. Salgado, Interference between initial and final state radiation in a QCD medium, Phys. Lett. B **717**, 280 (2012).

[11] F. Arleo, R. Kolevatov, S. Peigné, and M. Rustamova, Centrality and pT dependence of J/psi suppression in proton-nucleus collisions from parton energy loss, J. High Energy Phys. 05 (2013) 155.

[12] N. Armesto, H. Ma, M. Martinez, Y. Mehtar-Tani, and C. A. Salgado, Coherence Phenomena between Initial and Final State Radiation in a Dense QCD Medium, J. High Energy Phys. 12 (2013) 052.

[13] F. Arleo, R. Kolevatov, and S. Peigné, Coherent medium-induced gluon radiation in hard forward $1 \to 1$ partonic processes, Phys. Rev. D **93**, 014006 (2016).

[14] T. Liou and A. H. Mueller, Parton energy loss in high energy hard forward processes in proton-nucleus collisions, Phys. Rev. D **89**, 074026 (2014).

[15] S. Peigné and R. Kolevatov, Medium-induced soft gluon radiation in forward dijet production in relativistic proton-nucleus collisions, J. High Energy Phys. 01 (2015) 141.

[16] S. Munier, S. Peigné, and E. Petreska, Medium-induced gluon radiation in hard forward parton scattering in the saturation formalism, arXiv:1603.01028.

[17] The variable x_{F} is defined as the longitudinal momentum fraction between the J/ψ and projectile proton in the c.m. frame of an elementary p–N collision (of energy $\sqrt{s}$). It is related to the J/ψ transverse mass $M_{\perp} \equiv (M^2 + p_{\perp}^2)^{1/2}$ and rapidity y in this frame as $x_{\mathrm{F}} = (2M_{\perp}/\sqrt{s}) \sinh y$.

[18] M. J. Leitch *et al.* (FNAL E866/NuSea Collaboration), Measurement of differences between J/ψ and ψ' suppression in p–A collisions, Phys. Rev. Lett. **84**, 3256 (2000).

[19] K. J. Eskola, H. Paukkunen, and C. A. Salgado, EPS09 - a New Generation of NLO and LO Nuclear Parton Distribution Functions, J. High Energy Phys. 04 (2009) 065.

[20] D. de Florian, R. Sassot, P. Zurita, and M. Stratmann, Global Analysis of Nuclear Parton Distributions, Phys. Rev. D **85**, 074028 (2012).

[21] A. Adare *et al.* (PHENIX Collaboration), Cold Nuclear Matter Effects on J/ψ Yields as a Function of Rapidity and Nuclear Geometry in Deuteron-Gold Collisions at $\sqrt{s_{\rm NN}} = 200$ GeV, Phys. Rev. Lett. **107**, 142301 (2011).

[22] A. Adare *et al.* (PHENIX Collaboration), Transverse-Momentum Dependence of the J/ψ Nuclear Modification in d+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. C **87**, 034904 (2013).

[23] J. Albacete, N. Armesto, R. Baier, G. Barnafoldi, J. Barrette *et al.*, Predictions for p–Pb Collisions at $\sqrt{s_N N} = 5$ TeV, Int. J. Mod. Phys. E **22**, 1330007 (2013).

[24] R. Vogt, Shadowing effects on J/ψ and Υ production at energies available at the CERN Large Hadron Collider, Phys. Rev. C **92**, 034909 (2015).

[25] E. Ferreiro, F. Fleuret, J. Lansberg, and A. Rakotozafindrabe, Impact of the Nuclear Modification of the Gluon Densities on J/ψ production in p–Pb collisions at $\sqrt{s_{NN}} = 5$ TeV, Phys. Rev. C **88**, 047901 (2013).

[26] H. Fujii and K. Watanabe, Heavy quark pair production in high energy pA collisions: Quarkonium, Nucl. Phys. **A915**, 1 (2013).

[27] B. Ducloué, T. Lappi, and H. Mäntysaari, Forward J/ψ production in proton-nucleus collisions at high energy, Phys. Rev. D **91**, 114005 (2015).

[28] Y.-Q. Ma, R. Venugopalan, and H.-F. Zhang, J/ψ production and suppression in high energy proton-nucleus collisions, Phys. Rev. D **92**, 071901 (2015).

[29] K. Kovarik *et al.*, nCTEQ15 - Global analysis of nuclear parton distributions with uncertainties in the CTEQ framework, Phys. Rev. D **93**, 085037 (2016).

[30] M. Hirai, S. Kumano, and T. H. Nagai, Determination of nuclear parton distribution functions and their uncertainties at next-to-leading order, Phys. Rev. C **76**, 065207 (2007).

[31] In particular, the uncertainty band of Fig. 2 (top) obtained for EPS09 is very similar to that found in [24] (see Fig. 8 therein) using explicit calculations within the CEM at NLO.

[32] Although the energy loss model predictions shown in Fig. 2 (top) do not include shadowing effects, note however that the transport coefficient is varied in a rather large interval, $\hat{q}_0 = 0.05$–0.09 GeV^2/fm, in order to encompass the smaller values of $\hat{q}_0$ extracted at fixed-target energies when attributing part of the J/ψ suppression to the (small) amount of shadowing expected at those energies [9].

[33] S. Catani and M. Grazzini, An NNLO subtraction formalism in hadron collisions and its application to Higgs boson production at the LHC, Phys. Rev. Lett. **98**, 222002 (2007).

[34] S. Catani, L. Cieri, G. Ferrera, D. de Florian, and M. Grazzini, Vector boson production at hadron colliders: a fully exclusive QCD calculation at NNLO, Phys. Rev. Lett. **103**, 082001 (2009).

[35] A. Martin, W. Stirling, R. Thorne, and G. Watt, Parton distributions for the LHC, Eur. Phys. J. C **63**, 189 (2009).

[36] The associated uncertainty coming from a specific choice of the *proton* PDF is of the order of a percent in the calculation of $R_{p\rm A}$; see Fig. 7 of [24].

[37] J. Anderson and K. Müller (LHCb Collaboration), Inclusive low mass Drell-Yan production in the forward region at $\sqrt{s} = 7$ TeV, Report No. LHCb-CONF-2012-013, 2012.

[38] F. Gelis and J. Jalilian-Marian, Drell-Yan production and Lam-Tung relation in the color glass condensate formalism, Phys. Rev. D **76**, 074015 (2007).

[39] K. Golec-Biernat, E. Lewandowska, and A. M. Stasto, Drell-Yan process at forward rapidity at the LHC, Phys. Rev. D **82**, 094010 (2010).

[40] M. B. G. Ducati, M. T. Griep, and M. V. T. Machado, Study on the low mass Drell-Yan production at the CERN LHC within the dipole formalism, Phys. Rev. D **89**, 034022 (2014).

[41] At large negative rapidity the neutrons present in the lead nucleus are less effective than protons in producing DY pairs, since $\bar{u}u \to \gamma^\star$ dominates over $\bar{d}d \to \gamma^\star$ (because of the respective electric charges, $e_u^2/e_d^2 = 4$). At positive rapidity, DY production is dominated by sea (anti)quarks in the nucleus, and isospin effects are negligible. Isospin effects were discussed previously in the case of photon production in p-A collisions; see e.g. [42].

[42] F. Arleo, Hard pion and prompt photon at RHIC, from single to double inclusive production, J. High Energy Phys. 09 (2006) 015.