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IMPACT OF LHC HEAVY-FLAVOUR DATA ON NUCLEAR GLUON PDF*

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We use for the first time experimental data for the inclusive heavy-quark production in proton–lead collisions at the LHC in order to improve our knowledge of the gluon distribution in nuclei. We first check that the two most recent global nuclear parton distribution analyses (nCTEQ15 and EPPS16) provide a good overall description of the data, and then use these data in a PDF reweighing analysis. We find a first clear confirmation of gluon shadowing at small x. Additionally, it demonstrates that the inclusion of such heavy-flavour data in a global fit would significantly reduce the uncertainty on the gluon density down to $x \simeq 7 \times 10^{-6}$ while keeping an agreement with the other data of the global fits. Our study accounts for the factorisation scale uncertainties which become the largest for the charm(onium) sector.

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1. Introduction

Nuclear parton distribution functions (nPDFs) are important quantities necessary to describe high-energy collisions including heavy ions, as well as to give insight into the structure of nuclei. nPDFs are non-perturbative objects that cannot be calculated by the known methods[1]. Instead, similarly to what is done in the case of proton PDFs, nPDFs are extracted from experimental data in the process of global analysis. However, in the nPDF case not only the x-dependence is modeled, but also the A-dependence (where A is the atomic number of the nucleus). This is partly by design to have a general parametrization of different nuclei, and partly by necessity as there is typically not a sufficient amount of experimental data to separately constrain distributions for individual nuclei. The lack of kinematical data is actually one of the main practical differences between the proton and nuclear PDF fits. This is illustrated in Fig. 1, where we compare the kinematical range of data in both cases.

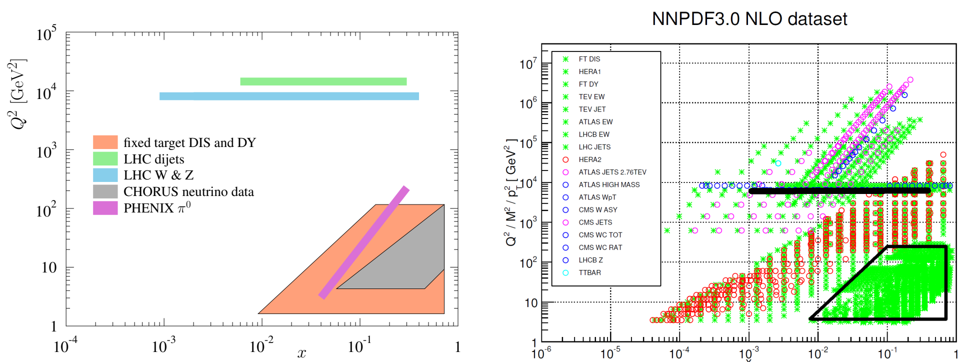


Fig. 1: Left: Kinematical range of data used in the most recent EPPS16 nPDF global analysis [3]. Right: Example kinematical range of data used in free-proton PDF global analysis NNPDF3.0 [4] (black lines correspond to nuclear data).

The lack of data is also the reason why in many cases additional assumptions need to be introduced in the nPDF analyses in order to obtain stable fits. This necessity, however, can lead to sizable systematic differences (much bigger than for proton PDFs) between various nPDFs. In particular, the nuclear gluon distribution is one of the least know flavours. This is caused by the fact that most of the data used in global nPDF analyses is from deep inelastic scattering (DIS) process which is not directly sensitive

[1] Recently, there is substantial progress in obtaining proton PDFs using Lattice QCD methods, see *e.g.* [1]. However, there is still a long way to be competitive with global fits, especially in the case of nuclei, for a recent review, see [2].

to the gluon distribution. The only data used in the current analyses with direct sensitivity to the gluon is pion production from RHIC [5] and dijet data from CMS [6] (the later is currently included only in the EPPS16 fit). This leads to large uncertainties which are, however, still underestimated especially in the small-x region (the dijet data reach down to $\sim 5 \times 10^{-3}$). The current errors of the gluon distribution are displayed in Fig. 2.

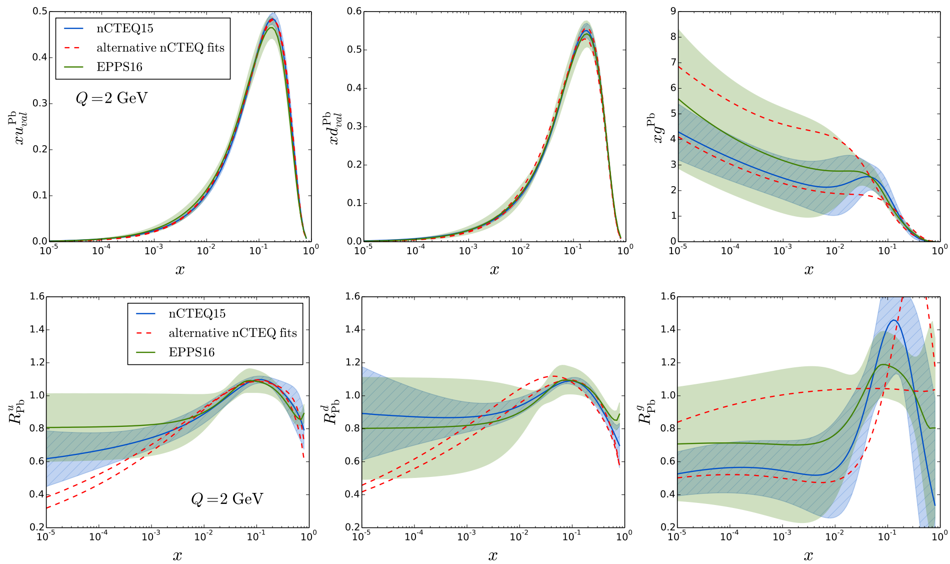


Fig. 2: (Color online) Comparison of lead nuclear nPDFs (upper plot) and a corresponding nuclear ratio, $R_i^{\mathrm{Pb}} = f^{\mathrm{Pb}}/f^{\mathrm{Pb}}_{\text{free-proton}}$ (lower plot), from nCTEQ15 [7] and EPPS16 [3] nPDF global analyses. The dashed/red curves represent alternative nCTEQ fits aiming at a more realistic representation of the gluon uncertainty [8].

To improve the precision of the nuclear gluon (and more generally nPDFs), we need to include new data into the current analyses. Recently, using heavy-flavour production at the LHC was proposed for an improved determination of the small-x gluons in the *proton* [9–13]. Motivated by the results of these studies, we had performed the first analysis of the impact of heavy-quark and heavy-quarkonium data in LHC proton–lead (pPb) collisions on the determination of the nuclear gluon PDF [14]. In the following part of this contribution, we summarise this study where the reweighting method has been employed to analyse data for D^0, J/ψ, $B \to J/\psi$ and $\Upsilon(1S)$ meson production.

The interpretation of our results depends on the reliability of nPDF factorisation in the nuclear environment, which is a question of considerable theoretical and practical importance. In this context, we note that other

Cold-Nuclear Matter (CNM) effects [15–30] could become relevant in some specific conditions, in particular for the quarkonium case. In our study, they can be seen as Higher-Twist (HT) contributions and the use of Leading-Twist (LT) factorization thus becomes a working assumption to be tested. Once validated by data, as we will show, this assumption of LT factorization can then be employed to learn about the internal structure of the nucleus.

2. Data selection

Just like for all global PDF fits, a data selection is in order to avoid HT corrections. In our case, it is also important to select a kinematical region where gluon fusion dominates and other effects are negligible. As such, we considered the open- and hidden-heavy-flavor production in pA collisions at LHC energies. In the quarkonium case, due to the large Lorentz boost at these energies, the heavy-quark pair remains almost point-like all along its way through the nuclear matter. Therefore, break-up [31, 32], thought to be important at lower energies, is negligible at the LHC. We also focused on J/ψ and $\Upsilon(1S)$ data to limit the contamination by possible comover effects [17–20, 33] on the more fragile excited states ($\psi(2S)$, $\Upsilon(2S)$, $\Upsilon(3S)$).

Overall, this reduces the data set to that of the D^0, J/ψ, $B \to J/\psi$ and $\Upsilon(1S)$. The particular data sets included in the analysis are summarized in Table I. We could also add the forward dAu J/ψ RHIC data. Instead, we preferred to focus on the LHC data and to use the RHIC [34, 35] ones as a cross check.

TABLE I

Summary of the input data and the choice of the central factorization scales for the meson production.

	$p+p$ data	$R_{p\mathrm{Pb}}$ data	μ_0 scale
D^0	LHCb [36]	ALICE [37], LHCb [38]	$\sqrt{4M_{D^0}^2 + P_{\mathrm{T},D^0}^2}$
J/ψ	LHCb [39, 40]	ALICE [41, 42], LHCb [43, 44]	$\sqrt{M_{J/\psi}^2 + P_{\mathrm{T},J/\psi}^2}$
$B \to J/\psi$	LHCb [39, 40]	LHCb [44]	$\sqrt{4M_B^2 + \left(\frac{M_B}{M_{J/\psi}} P_{\mathrm{T},J/\psi}\right)^2}$
$\Upsilon(1S)$	ALICE [45], ATLAS [46], CMS [47], LHCb [48, 49]	ALICE [50], ATLAS [51], LHCb [52]	$\sqrt{M_{\Upsilon(1S)}^2 + P_{\mathrm{T},\Upsilon(1S)}^2}$

3. Methodology

In this work, we concentrate on pA (with A being lead nucleus) data normalized to the corresponding pp measurements, and given in terms of nuclear modification factors (NMF) $R_{pA} \equiv \mathrm{d}\sigma_{pA}/(A \times \mathrm{d}\sigma_{pp})$. Similarly, it is convenient to define parton level counterparts of the NMF for quarks, R_q^A, and gluons, R_g^A, as a ratio of nuclear and proton PDFs. In the absence of nuclear effects, $R^A_{g(q)} = 1$ and one should observe $R_{pA}(O_{\mathcal{H}}) \simeq 1$.

The focus on R_{pA} has several advantages. It allows us to leave aside, in the theory evaluation, the *proton* PDF uncertainty at very small x which may not always be negligible. Second, R_{pA} is in general less sensitive to QCD corrections (to the parton scattering) which may affect the normalization of the cross-section predictions. Third, some experimental uncertainties cancel in R_{pA} and, at the LHC, $R_{p\mathrm{Pb}}$ is usually more precise than the corresponding pPb cross sections.

3.1. Data driven method

To connect R_{pA} and R_g^A, we will use the data-driven approach of [53–55], where the parton-scattering-matrix elements squared $|A|^2$ are determined from pp data assuming a $2 \to 2$ kinematics. It was first motivated to bypass the complications inherent to our lack of understanding of the quarkonium-production mechanisms (see *e.g.* [56, 57]), whereas it suffices to evaluate the nPDF effects in R_{pA} with the requested accuracy. Such an approach also applies to open heavy-flavored (HF) hadrons [53]. In the latter cases, full-fledged perturbative QCD computations exist: GM-VFNS [58–62], MG5aMC [63] and FONLL [64–66] which we have used to further validate the method. As in [53], we use a specific empirical functional form for $|A|^2$

$$\overline{|\mathcal{A}|^2} = \frac{\lambda^2 \kappa s x_1 x_2}{M^2_{\mathcal{H}}} \exp\left(-\kappa \frac{\min\left(P^2_{\mathrm{T},\mathcal{H}}, \langle P_{\mathrm{T}}\rangle^2\right)}{M^2_{\mathcal{H}}}\right) \times \left[1 + \theta\left(P^2_{\mathrm{T},\mathcal{H}} - \langle P_{\mathrm{T}}\rangle^2\right) \frac{\kappa}{n} \frac{P^2_{\mathrm{T},\mathcal{H}} - \langle P_{\mathrm{T}}\rangle^2}{M^2_{\mathcal{H}}}\right]^{-n}, \tag{1}$$

which was initially proposed in [67] to model single-quarkonium hadroproduction for double-parton scattering studies [67–71] and which is sufficiently flexible to give a good description of single-inclusive-particle-production data. In the above equation, the four parameters $\kappa, \lambda, \langle P_{\mathrm{T}}\rangle$ and n are, in general, free parameters to be determined by the experimental data. Here, k_i denotes the partons involved in the hard scattering, $x_{1,2}$ are the longitudinal momentum fractions carried by the initial partons, and s is the square of the center-of-mass energy of the nucleon–nucleon collisions. The transverse momentum and the mass of the produced particle $\mathcal{H}$ are labeled $P_{\mathrm{T},\mathcal{H}}$ and $M_{\mathcal{H}}$. After convolving with the nucleon PDF, one gets the physical cross section. There are several advantages in using this approach: *(i)* the uncertainty in the pp cross section is controlled by the measured data, which also enters R_{pA}, *(ii)* it can be applied to any single-inclusive-particle spectrum as long as the relative weights of the different channels (parton luminosities times $|A|^2$) are known, *(iii)* the event generation is much faster than with QCD-based codes, which allowed us to study several nPDFs (2 in our case) with several scale choices in an acceptable amount of computing time. Indeed, to fully quantify the intrinsic theoretical uncertainty from the factorization scale μ_{F}, we have varied it about a default scale μ_0 as $\mu_{\mathrm{F}} = \xi\mu_0$ with $\xi = 1, 2, 0.5$. The choice of the μ_0 scale for different types of data is provided in Table I. We have also checked that, for the cases of D^0 meson and $B \to J/\psi$ production, the scale uncertainty is nearly identical to that obtained with FONLL. As expected, FONLL gives much larger scale uncertainties on the *yields*.

3.2. Reweighting method

As announced, to study the impact of HF experimental data on the gluon nPDF determination without performing a full fit, we employed the Bayesian-reweighting method [72–77]. Since both nCTEQ15 and EPPS16 are Hessian nPDFs, we first converted the 32 and 40 Hessian error PDFs into 10^4 Monte Carlo PDF replicas[2]; then we prescribe weights to individual replicas (which results in a change of the underlying probability distribution). Different versions of the reweighting method use different weight definitions. In the present study, we followed the same approach as in the recent nCTEQ paper [77], which features the following weight definition:

$$w_k = \frac{e^{-\frac{1}{2}\chi_k^2/T}}{\frac{1}{N_{\mathrm{rep}}}\sum_i^{N_{\mathrm{rep}}} e^{-\frac{1}{2}\chi_i^2/T}}\,, \quad \text{with } \chi_i^2(f_{\mathrm{N}}) = \left(\frac{1-f_{\mathrm{N}}}{\delta^{\mathrm{global}}}\right)^2 + \Sigma_j \left(\frac{T_j - f_{\mathrm{N}} D_j}{\delta_j^{\mathrm{uncorr}}}\right)^2, \tag{2}$$

where T is a tolerance factor used in the initial fit, f_{N} is a global normalization factor for each data set, δ^{global} is the global relative error, T_i is the theoretical prediction, D_i is the central value of the experimental data and $\delta_i^{\mathrm{uncorr}}$ is the uncorrelated error. The expectation value and variance of any PDF-dependent observable can be then computed as

[2] The nCTEQ15 and EPPS16 Hessian nPDFs provide a 90% confidence level (C.L.) uncertainty. However, in what follows, our results will be displayed at 68% C.L., *i.e.* 1σ. This simply amounts to reduce the uncertainties by $\sqrt{2}\mathrm{erf}^{-1}(0.90) \simeq 1.645$.

$$\langle\mathcal{O}\rangle_{\rm new}=\frac{1}{N_{\rm rep}}\sum_{k=1}^{N_{\rm rep}}w_k\mathcal{O}(f_k)\,,\;\;\delta\,\langle\mathcal{O}\rangle_{\rm new}=\sqrt{\frac{1}{N_{\rm rep}}\sum_{k=1}^{N_{\rm rep}}w_k\big(\mathcal{O}(f_k)-\langle\mathcal{O}\rangle_{\rm new}\big)^2}\,. \tag{3}$$

4. Results

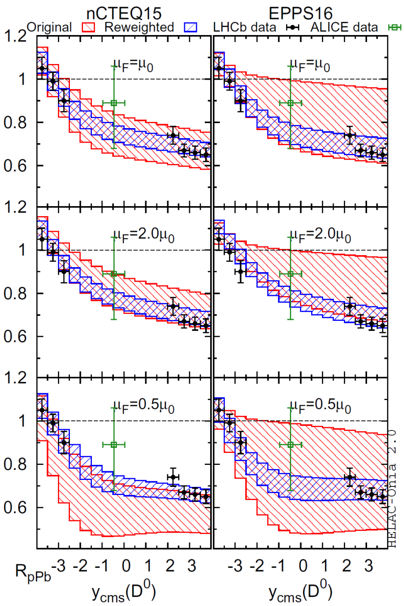
Figures 3 (a)–(d) show a representative comparison of our theoretical calculations with the data for D^0, J/ψ, $B\to J/\psi$ and $\varUpsilon(1S)$. The NMF obtained with nCTEQ15 and EPPS16 have significantly different central values and uncertainties but both agree with the data giving χ^2/N of 0.90 and 2.24 respectively. This observation is striking as the used gluon nPDFs were derived from totally different observables like DIS and Drell–Yan, and yet they allow one to reproduce the most important feature of the data [53] which makes our reweighting analysis meaningful. We see this as a confirmation of the LT factorization (see also [78–81]).

As for the reweighting results (black/blue hatched bands in Figs. 3 (a)–(b)), if we could simply fix the scale to a single value for each particle, the LHC $R_{p\rm Pb}$ data for prompt D^0 and J/ψ would reduce the uncertainties of the gluon density by a factor as large as 3 for EPPS16 and 2 for nCTEQ15 down to $x\simeq 7\times10^{-6}$ (compare the relative size of the black/blue and red/hatched bands in Figs. 3 (a) and (d)). The current $B\to J/\psi$ and $\varUpsilon(1S)$ data do not constrain the gluon nPDFs due to their very large uncertainties and relatively large scales. Yet, the larger samples collected at 8 TeV should improve the situation.

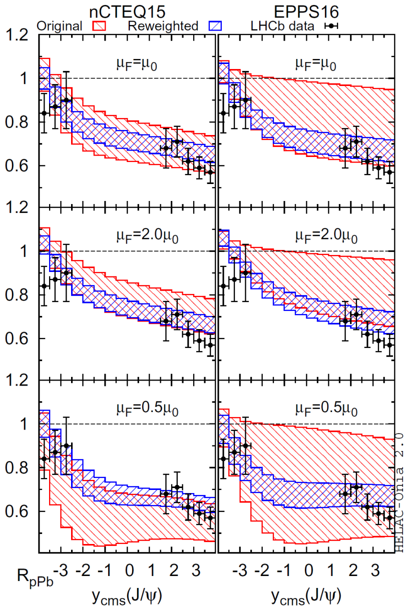
We now discuss the scale uncertainties and first recall that $d\sigma_{p\rm Pb}\sim f_g^p(f_g^pR_g^{\rm Pb})\otimes|A|^2$. Due to QCD evolution, a larger $\mu_{\rm F}$ implies a $R_g^{\rm Pb}$ closer to unity together with a smaller PDF uncertainty. These general features are clearly visible in Figs. 3 (a)–(d); the bands are closer to unity and shrink from $\mu_{\rm F}=0.5\mu_0$ to $\mu_{\rm F}=2\mu_0$. In the nCTEQ15 case, such variations for the D^0 and J/ψ cases are even similar to the nPDF uncertainty itself.

Clearly, such a scale ambiguity should impact the reweighting results even though the (black/blue) reweighted bands seems not to show such a sensitivity. It is perfectly normal since the replicas are to match the data. The key point is that they match it at different scales. Consequently, when the reweighted bands are evolved to a common scale (here $\mu_{\rm F}=2$ GeV), the reweighted nPDF uncertainties obtained with different scales do not superimpose (compare the black, blue and green bands in Figs. 4 (a)–(b)).

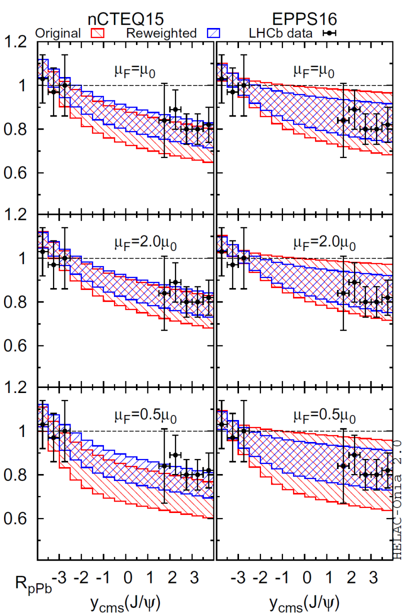
The envelope of these scale-induced variations is about twice as large as their width for the D^0 and J/ψ cases, confirming that the scale uncertainty must be accounted for to obtain reliable uncertainties from these rather



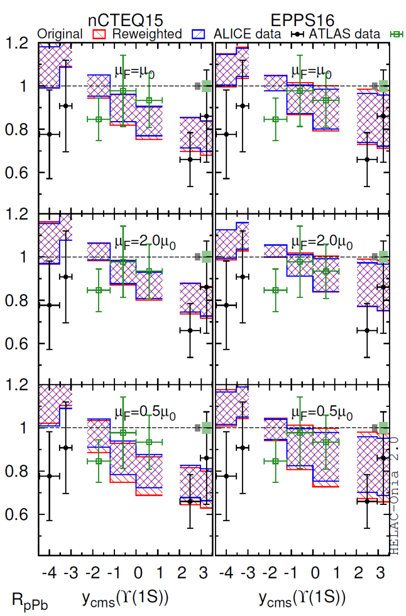
(a) Prompt D^0



(b) Prompt J/ψ



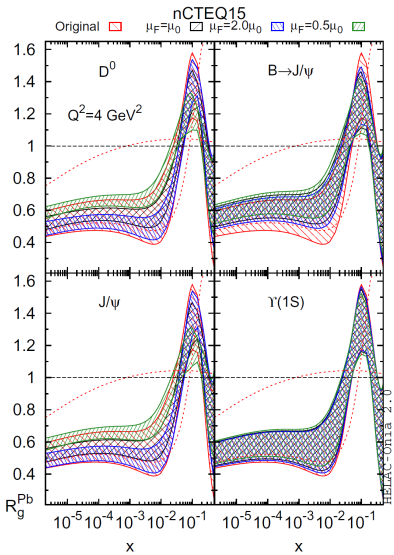
(c) $B \to J/\psi$



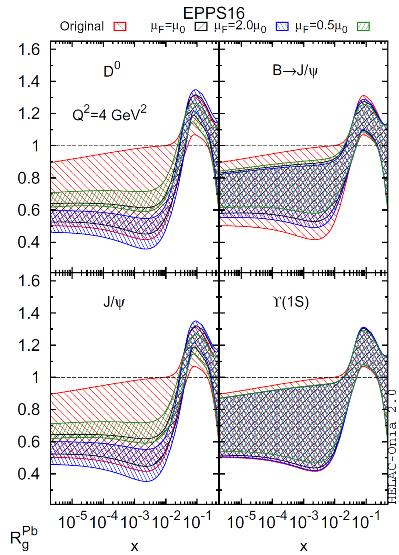
(d) $\Upsilon(1S)$

Fig. 3: (Color online) Selected $R_{p\mathrm{Pb}}$ results before and after reweighting for (a) prompt D^0, (b) prompt J/ψ, (c) $B \to J/\psi$, (d) $\Upsilon(1S)$. The experimental data are from [38, 44, 50, 82, 83].

precise data. For the heavier bottom(onium) states, the scale uncertainty is not only much smaller than the nPDF uncertainties but also very small in absolute value, which gives us confidence that more precise data could play a major role for a precision determination of the gluon nPDF at small x.



(a) nCTEQ15 nPDF



(b) EPPS16 nPDF

Fig. 4: (Color online) NPDF uncertainties for (a) nCTEQ15 and (b) EPPS16 after the reweighting.

Despite these uncertainties, our results are striking: the D^0 and J/ψ data point to the same magnitude of $R_g^{\rm Pb}$ and their inclusion in the EPPS16 fit would likely result in a considerable reduction of its gluon uncertainty by a factor as large as 1.7, see Fig. 4 (b). For nCTEQ15, the effect seems less spectacular but we should recall that the original nCTEQ15 values at x below 10^{-3} are pure extrapolation. The dashed/red lines in Fig. 4 (a) illustrate this by showing two equally good fits [8], which are, in fact, now excluded by the LHC HF pPb data. Overall, the extrapolation to small x of nCTEQ15 is unexpectedly well-confirmed by the charm(onium) data.

Beside the mere observations of the nPDF-uncertainty reduction, our results have two very important physics interpretations. First, the LHC pPb HF data give us the first real observation of gluon shadowing at small x with $R_g^{\rm Pb}$ smaller than unity — the no-shadowing null-hypothesis — by more than 11.7 (10.9) and 7.3 (7.1) σ at $x = 10^{-5}$ and $\mu_{\rm F} = 2$ GeV for nCTEQ15 and EPPS16 using D^0 (J/ψ) data (see Figs. 4 (a)–(b), left panels). Our results thus quantitatively confirm the qualitative observations of [80, 81, 84] indirectly made from J/ψ photoproduction on lead, which strictly speaking is sensitive on nuclear gluon generalized parton distributions — not nPDFs — and suffers from significant scale uncertainties [85, 86]. Second, our analysis corroborates the existence of a gluon anti-shadowing [87]: $R_g^{\mathrm{Pb}} > 1$ for $x \simeq 0.1$. We have explicitly checked these observations with FONLL calculations for D^0 production which returns very similar results. A comparative study paving the way to a first fit will be presented in a separate publication.

Last but not least, we consider the global coherence of the HF constraints with other data (to be) included in nPDF global fits. We do it with nCTEQ15 of which 2 of us are authors and for which we have all the data at hand. First, let us observe that the agreement with the DIS NMC data [88], the only DIS set with a mild sensitivity to the gluon distribution, is not degraded. The original χ^2/N, 0.58, becomes (with $\xi = (1, 2, 0.5)$) (0.58, 0.57, 0.81) for D^0, (0.58, 0.56, 0.85) for J/ψ, (0.68, 0.63, 0.75) for $B \to J/\psi$. Clearly, the inclusion of HF data does not create any tension with the DIS data. One can also make a similar comparison for the W/Z pPb LHC data whose impact on nCTEQ15 was recently studied [77] using the same reweighting technique. The χ^2/N of these data was found to be 2.43. It becomes, after our HF reweighting, (2.49, 3.11, 2.14) for D^0, (2.66, 3.25, 2.25) for J/ψ, (2.10, 2.15, 2.08) for $B \to J/\psi$. With the same caveats as above, they tend to be smaller for $\xi = 0.5$ and larger for $\xi = 2$ at variance with what one observes with the NMC data. Finally, let us look at the coherence with the J/ψ PHENIX forward $R_{d\mathrm{Au}}$ results [34, 35]. The χ^2/N of these data for nCTEQ15 is (1.99, 5.33, 2.33) (with $\xi = (1, 2, 0.5)$) and after our HF J/ψ LHC reweighting it becomes (1.93, 0.43, 3.35). This confirms the global coherence of the HF constraints.

5. Conclusions

We used for the first time experimental data for the inclusive HF (D^0, J/ψ, $B \to J/\psi$ and $\Upsilon(1S)$ mesons) production in pPb collisions at the LHC to improve our knowledge of the gluon density inside heavy nuclei. We compared the data with computations obtained in the standard LT factorization framework at NLO QCD endowed with the two most recent globally fit nPDFs (nCTEQ15, EPPS16). No other nuclear effects were included which are supposed to be of HT origin and hence suppressed as inverse powers of the hard scale. We found a good description of the LHC data with both nCTEQ15 and EPPS16 nPDFs validating our theoretical framework.

By performing a Bayesian-reweighting analysis and studying the scale uncertainties, we then demonstrated that the existing heavy quark(onium) data can significantly — and coherently — reduce the uncertainty of the gluon density down to momentum fractions $x \simeq 7\times10^{-6}$. For charm(onium), the gluons are shadowed with a statistical significance beyond 7σ at $\mu_{\mathrm{F}} =$

2 GeV and $x = 10^{-5}$. These data should thus be included in the next generation of global nPDF analyses. While our results cannot rule out that other HT CNM effects were effectively "absorbed" into seemingly universal LT nuclear PDFs, the observed consistent description of both the D^0 and J/ψ data is far non-trivial since they may interact differently with the nuclear matter.

REFERENCES

[1] C. Alexandrou *et al.*, `arXiv:1803.02685 [hep-lat]`.

[2] H.W. Lin *et al.*, *Prog. Part. Nucl. Phys.* **100**, 107 (2018) [`arXiv:1711.07916 [hep-ph]`].

[3] K.J. Eskola, P. Paakkinen, H. Paukkunen, C.A. Salgado, *Eur. Phys. J. C* **77**, 163 (2017) [`arXiv:1612.05741 [hep-ph]`].

[4] R.D. Ball *et al.* [NNPDF Collaboration], *J. High Energy Phys.* **1504**, 040 (2015) [`arXiv:1410.8849 [hep-ph]`].

[5] S.S. Adler *et al.* [PHENIX Collaboration], *Phys. Rev. Lett.* **98**, 172302 (2007) [`arXiv:nucl-ex/0610036`].

[6] S. Chatrchyan *et al.* [CMS Collaboration], *Eur. Phys. J. C* **74**, 2951 (2014) [`arXiv:1401.4433 [nucl-ex]`].

[7] K. Kovařik *et al.*, *Phys. Rev. D* **93**, 085037 (2016) [`arXiv:1509.00792 [hep-ph]`].

[8] T. Stavreva *et al.*, *J. High Energy Phys.* **1101**, 152 (2011) [`arXiv:1012.1178 [hep-ph]`].

[9] O. Zenaiev *et al.* [PROSA Collaboration], *Eur. Phys. J. C* **75**, 396 (2015) [`arXiv:1503.04581 [hep-ph]`].

[10] R. Gauld, J. Rojo, L. Rottoli, J. Talbert, *J. High Energy Phys.* **1511**, 009 (2015) [`arXiv:1506.08025 [hep-ph]`].

[11] M. Cacciari, M.L. Mangano, P. Nason, *Eur. Phys. J. C* **75**, 610 (2015) [`arXiv:1507.06197 [hep-ph]`].

[12] R. Gauld, J. Rojo, *Phys. Rev. Lett.* **118**, 072001 (2017) [`arXiv:1610.09373 [hep-ph]`].

[13] E.G. de Oliveira, A.D. Martin, M.G. Ryskin, *Phys. Rev. D* **97**, 074021 (2018) [`arXiv:1705.08845 [hep-ph]`].

[14] A. Kusina, J.-P. Lansberg, I. Schienbein, H.S. Shao, `arXiv:1712.07024 [hep-ph]`.

[15] C. Gerschel, J. Hufner, *Phys. Lett. B* **207**, 253 (1988).

[16] R. Vogt, *Phys. Rep.* **310**, 197 (1999).

[17] E.G. Ferreiro, *Phys. Lett. B* **749**, 98 (2015) [`arXiv:1411.0549 [hep-ph]`].

[18] A. Capella, E.G. Ferreiro, *Eur. Phys. J. C* **42**, 419 (2005) [`arXiv:hep-ph/0505032`].

[19] A. Capella, E.G. Ferreiro, A.B. Kaidalov, *Phys. Rev. Lett.* **85**, 2080 (2000) [`arXiv:hep-ph/0002300`].

[20] S. Gavin, R. Vogt, *Nucl. Phys. B* **345**, 104 (1990).

[21] S.J. Brodsky, P. Hoyer, *Phys. Rev. Lett.* **63**, 1566 (1989).
[22] B. Ducloue, T. Lappi, H. Mantysaari, *Phys. Rev. D* **91**, 115005 (2015) [arXiv:1503.02789 [hep-ph]].
[23] Y.-Q. Ma, R. Venugopalan, H.-F. Zhang, *Phys. Rev. D* **92**, 071901 (2015) [arXiv:1503.07772 [hep-ph]].
[24] H. Fujii, K. Watanabe, *Nucl. Phys. A* **915**, 1 (2013) [arXiv:1304.2221 [hep-ph]].
[25] J.-W. Qiu, P. Sun, B.-W. Xiao, F. Yuan, *Phys. Rev. D* **89**, 034007 (2014) [arXiv:1310.2230 [hep-ph]].
[26] B. Kopeliovich, A. Tarasov, J. Hufner, *Nucl. Phys. A* **696**, 669 (2001) [arXiv:hep-ph/0104256].
[27] E.G. Ferreiro, F. Fleuret, J.P. Lansberg, A. Rakotozafindrabe, *Phys. Lett. B* **680**, 50 (2009) [arXiv:0809.4684 [hep-ph]].
[28] E.G. Ferreiro *et al.*, *Eur. Phys. J. C* **73**, 2427 (2013) [arXiv:1110.5047 [hep-ph]].
[29] E.G. Ferreiro, F. Fleuret, J.P. Lansberg, A. Rakotozafindrabe, *Phys. Rev. C* **88**, 047901 (2013) [arXiv:1305.4569 [hep-ph]].
[30] R. Vogt, *Phys. Rev. C* **81**, 044903 (2010) [arXiv:1003.3497 [hep-ph]].
[31] R. Vogt, *Phys. Rev. C* **71**, 054902 (2005) [arXiv:hep-ph/0411378].
[32] C. Lourenco, R. Vogt, H.K. Woehri, *J. High Energy Phys.* **0902**, 014 (2009) [arXiv:0901.3054 [hep-ph]].
[33] E.G. Ferreiro, J.-P. Lansberg, arXiv:1804.04474 [hep-ph].
[34] A. Adare *et al.* [PHENIX Collaboration], *Phys. Rev. Lett.* **107**, 142301 (2011) [arXiv:1010.1246 [nucl-ex]].
[35] A. Adare *et al.* [PHENIX Collaboration], *Phys. Rev. C* **87**, 034904 (2013) [arXiv:1204.0777 [nucl-ex]].
[36] R. Aaij *et al.* [LHCb Collaboration], *J. High Energy Phys.* **1706**, 147 (2017) [arXiv:1610.02230 [hep-ex]].
[37] B.B. Abelev *et al.* [ALICE Collaboration], *Phys. Rev. Lett.* **113**, 232301 (2014) [arXiv:1405.3452 [nucl-ex]].
[38] R. Aaij *et al.* [LHCb Collaboration], arXiv:1707.02750 [hep-ex].
[39] R. Aaij *et al.* [LHCb Collaboration], *Eur. Phys. J. C* **71**, 1645 (2011) [arXiv:1103.0423 [hep-ex]].
[40] R. Aaij *et al.* [LHCb Collaboration], *J. High Energy Phys.* **1306**, 064 (2013) [arXiv:1304.6977 [hep-ex]].
[41] J. Adam *et al.* [ALICE Collaboration], *J. High Energy Phys.* **1506**, 055 (2015) [arXiv:1503.07179 [nucl-ex]].
[42] B.B. Abelev *et al.* [ALICE Collaboration], *J. High Energy Phys.* **1402**, 073 (2014) [arXiv:1308.6726 [nucl-ex]].
[43] R. Aaij *et al.* [LHCb Collaboration], *J. High Energy Phys.* **1402**, 072 (2014) [arXiv:1308.6729 [nucl-ex]].
[44] R. Aaij *et al.* [LHCb Collaboration], *Phys. Lett. B* **774**, 159 (2017) [arXiv:1706.07122 [hep-ex]].

[45] B.B. Abelev [ALICE Collaboration], *et al.*, *Eur. Phys. J. C* **74**, 2974 (2014) [arXiv:1403.3648 [nucl-ex]].
[46] G. Aad *et al.* [ATLAS Collaboration], *Phys. Rev. D* **87**, 052004 (2013) [arXiv:1211.7255 [hep-ex]].
[47] S. Chatrchyan *et al.* [CMS Collaboration], *Phys. Lett. B* **727**, 101 (2013) [arXiv:1303.5900 [hep-ex]].
[48] R. Aaij *et al.* [LHCb Collaboration], *Eur. Phys. J. C* **72**, 2025 (2012) [arXiv:1202.6579 [hep-ex]].
[49] R. Aaij *et al.* [LHCb Collaboration], *J. High Energy Phys.* **1511**, 103 (2015) [arXiv:1509.02372 [hep-ex]].
[50] B.B. Abelev *et al.* [ALICE Collaboration], *Phys. Lett. B* **740**, 105 (2015) [arXiv:1410.2234 [nucl-ex]].
[51] ATLAS Collaboration, *Eur. Phys. J. C* **78**, 171 (2018) [arXiv:1709.03089 [nucl-ex]].
[52] R. Aaij *et al.* [LHCb Collaboration], *J. High Energy Phys.* **1407**, 094 (2014) [arXiv:1405.5152 [nucl-ex]].
[53] J.-P. Lansberg, H.-S. Shao, *Eur. Phys. J. C* **77**, 1 (2017) [arXiv:1610.05382 [hep-ph]].
[54] H.-S. Shao, *Comput. Phys. Commun.* **184**, 2562 (2013) [arXiv:1212.5293 [hep-ph]].
[55] H.-S. Shao, *Comput. Phys. Commun.* **198**, 238 (2016) [arXiv:1507.03435 [hep-ph]].
[56] A. Andronic *et al.*, *Eur. Phys. J. C* **76**, 107 (2016) [arXiv:1506.03981 [nucl-ex]].
[57] N. Brambilla *et al.*, *Eur. Phys. J. C* **71**, 1534 (2011) [arXiv:1010.5827 [hep-ph]].
[58] B.A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, *Phys. Rev. D* **71**, 014018 (2005) [arXiv:hep-ph/0410289].
[59] B.A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, *Eur. Phys. J. C* **41**, 199 (2005) [arXiv:hep-ph/0502194].
[60] B.A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, *Eur. Phys. J. C* **72**, 2082 (2012) [arXiv:1202.0439 [hep-ph]].
[61] B.A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, *Phys. Rev. D* **84**, 094026 (2011) [arXiv:1109.2472 [hep-ph]].
[62] B.A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, *Eur. Phys. J. C* **75**, 140 (2015) [arXiv:1502.01001 [hep-ph]].
[63] J. Alwall *et al.*, *J. High Energy Phys.* **1407**, 079 (2014) [arXiv:1405.0301 [hep-ph]].
[64] M. Cacciari, M. Greco, P. Nason, *J. High Energy Phys.* **9805**, 007 (1998) [arXiv:hep-ph/9803400].
[65] M. Cacciari, S. Frixione, P. Nason, *J. High Energy Phys.* **0103**, 006 (2001) [arXiv:hep-ph/0102134].
[66] M. Cacciari *et al.*, *J. High Energy Phys.* **1210**, 137 (2012) [arXiv:1205.6344 [hep-ph]].

[67] C.H. Kom, A. Kulesza, W.J. Stirling, *Phys. Rev. Lett.* **107**, 082002 (2011) [arXiv:1105.4186 [hep-ph]].
[68] J.-P. Lansberg, H.-S. Shao, *Phys. Lett. B* **751**, 479 (2015) [arXiv:1410.8822 [hep-ph]].
[69] J.-P. Lansberg, H.-S. Shao, *Nucl. Phys. B* **900**, 273 (2015) [arXiv:1504.06531 [hep-ph]].
[70] H.-S. Shao, Y.-J. Zhang, *Phys. Rev. Lett.* **117**, 062001 (2016) [arXiv:1605.03061 [hep-ph]].
[71] C. Borschensky, A. Kulesza, *Phys. Rev. D* **95**, 034029 (2017) [arXiv:1610.00666 [hep-ph]].
[72] W.T. Giele, S. Keller, *Phys. Rev. D* **58**, 094023 (1998) [arXiv:hep-ph/9803393].
[73] R.D. Ball *et al.* [NNPDF Collaboration], *Nucl. Phys. B* **849**, 112 (2011) [*Erratum ibid.* **855**, 927 (2012)] [arXiv:1012.0836 [hep-ph]].
[74] R.D. Ball *et al.*, *Nucl. Phys. B* **855**, 608 (2012) [arXiv:1108.1758 [hep-ph]].
[75] N. Sato, J.F. Owens, H. Prosper, *Phys. Rev. D* **89**, 114020 (2014) [arXiv:1310.1089 [hep-ph]].
[76] H. Paukkunen, P. Zurita, *J. High Energy Phys.* **1412**, 100 (2014) [arXiv:1402.6623 [hep-ph]].
[77] A. Kusina *et al.*, *Eur. Phys. J. C* **77**, 488 (2017) [arXiv:1610.02925 [nucl-th]].
[78] L. Frankfurt, V. Guzey, M. Strikman, *Phys. Rep.* **512**, 255 (2012) [arXiv:1106.2091 [hep-ph]].
[79] L. Frankfurt, V. Guzey, M. Strikman, *Phys. Rev. C* **95**, 055208 (2017) [arXiv:1612.08273 [hep-ph]].
[80] V. Guzey, E. Kryshen, M. Strikman, M. Zhalov, *Phys. Lett. B* **726**, 290 (2013) [arXiv:1305.1724 [hep-ph]].
[81] B. Abelev *et al.* [ALICE Collaboration], *Phys. Lett. B* **718**, 1273 (2013) [arXiv:1209.3715 [nucl-ex]].
[82] J. Adam *et al.* [ALICE Collaboration], *Phys. Rev. C* **94**, 054908 (2016) [arXiv:1605.07569 [nucl-ex]].
[83] M. Aaboud *et al.* [ATLAS Collaboration], *Eur. Phys. J. C* **78**, 171 (2018) [arXiv:1709.03089 [nucl-ex]].
[84] V. Khachatryan *et al.* [CMS Collaboration], *Phys. Lett. B* **772**, 489 (2017) [arXiv:1605.06966 [nucl-ex]].
[85] D.Yu. Ivanov, A. Schafer, L. Szymanowski, G. Krasnikov, *Eur. Phys. J. C* **34**, 297 (2004) [*Erratum ibid.* **75**, 75 (2015)] [arXiv:hep-ph/0401131].
[86] S.P. Jones, A.D. Martin, M.G. Ryskin, T. Teubner, *J. Phys. G* **43**, 035002 (2016) [arXiv:1507.06942 [hep-ph]].
[87] L.L. Frankfurt, M.I. Strikman, S. Liuti, *Phys. Rev. Lett.* **65**, 1725 (1990).
[88] M. Arneodo *et al.* [New Muon Collaboration], *Nucl. Phys. B* **481**, 23 (1996).