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Testing nuclear parton distributions with pA collisions at the TeV scale

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Global perturbative QCD analyses, based on large data sets from electron-proton and hadron collider experiments, provide tight constraints on the parton distribution function (PDF) in the proton. The extension of these analyses to nuclear parton distribution functions (nPDFs) has attracted much interest in recent years. nPDFs are needed as benchmarks for the characterization of hot QCD matter in nucleus-nucleus collisions, and attract further interest since they may show novel signatures of nonlinear density-dependent QCD evolution. However, it is not known from first principles whether the factorization of long-range phenomena into process-independent parton distribution, which underlies global PDF extractions for the proton, extends to nuclear effects. As a consequence, assessing the reliability of nPDFs for benchmark calculations goes beyond testing the numerical accuracy of their extraction and requires phenomenological tests of the factorization assumption. Here, we argue that a proton-nucleus collision program at the Large Hadron Collider would provide a set of measurements, which allow for unprecedented tests of the factorization assumption, underlying global nPDF fits.

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Parton distribution functions (PDFs) $f_{i/h}(x, Q^2)$ play a central role in the study of high-energy collisions, involving hadronic projectiles h. They define the flux of quarks and gluons ($i = q, g$) in hadrons as a function of the partonic resolution scale Q^2 and hadronic momentum fraction x. For protons, sets of collinearly factorized universal PDFs, obtained in global perturbative QCD analyses, have been available for a long time. These are based on data from deep-inelastic lepton-proton scattering (DIS) and Drell-Yan (DY) production, as well as W/Z and jet production at hadron colliders. These data provide tight constraints on PDFs over logarithmically wide ranges in Q^2 and x and have allowed precision testing of linear perturbative QCD evolution. In comparison to proton PDFs, our understanding of parton distribution functions $f_{i/A}(x, Q^2)$ in nuclei of nucleon number A is much less mature. Knowledge of nuclear parton distribution functions (nPDFs) is important in heavy-ion collisions at the BNL Relativistic Heavy-Ion collider (RHIC) and at the Large Hadron Collider (LHC) for a quantitative control of hard processes, which are employed as probes of dense QCD matter. Characterizing nuclear modifications of PDFs is also of great interest in its own right, since the nuclear environment is expected to enhance parton density-dependent effects, which can reveal qualitatively novel nonlinear features of QCD evolution.

Paralleling the determination of proton PDFs, several global QCD analyses of nPDFs have been made within the last decade [1–5]. Until recently, these analyses were based solely on fixed-target nuclear DIS and DY data. Compared to the data constraining proton PDFs, these are of lower precision and lie in a much more limited range of Q^2 and x. Constraints on nuclear gluon distribution functions are particularly poor, since they cannot be obtained from the absolute values of DIS structure functions, but only from their logarithmic Q^2 evolution, for which a wide Q^2 range is mandatory. To improve on this deficiency, for the first time, a recent global nPDF analysis [1,2] has included data from inclusive high-p_T hadron production in hadron-nucleus scattering measured at RHIC [6–8].

However, in contrast to the theoretical basis for global analyses of proton PDFs, the separability of nuclear effects into process-independent nPDFs and process-dependent but A-independent hard processes is not established within the framework of collinear factorized QCD. In particular, some of the characteristic nuclear dependencies in hadron-nucleus collisions, such as the Cronin effect [9], may have a dynamical origin that cannot, or can only partly, be absorbed in process-independent nPDFs. In view of the importance of nPDFs for characterizing benchmark processes in heavy-ion collisions, it is, thus, desirable to look for stringent phenomenological tests of the working assumption of global nPDF fits that the dominant nuclear effects can be factorized into the incoming PDFs. Here, we argue that a program of hadron-nucleus collisions at the LHC would provide for such tests with unprecedented quality.

We will focus mainly on single inclusive high-p_T hadron production. In the factorized QCD ansatz to hadron-nucleus collisions, the cross section for production of a hadron h takes the form

$$d^3\sigma^{pA\to hX} = A \sum_{ijk} f_{j/p} f_{i/A} \otimes d^3\sigma^{ij\to kX} \otimes D_{k\to h}, \qquad (1)$$

where the symbol $\otimes$ stands for the convolution of the incoming PDFs with the cross section of the hard partonic process and with the fragmentation function for a parton k into a hadron h. The sum goes over all parton species, which contribute to the production of h. By construction, the entire nuclear dependence of the cross section Eq. (1) resides in the nPDF

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$f_{i/A}(x, Q^2)$. It is customary to characterize nuclear effects by the ratios:

$$R_i^A(x, Q^2) \equiv f_{i/A}(x, Q^2)/f_{i/p}(x, Q^2). \quad (2)$$

In global nPDF analyses, characteristic deviations of $R_i^A(x, Q^2)$ from unity are found for all scales of Q^2 tested so far and for essentially all scales of the momentum fraction x. These effects are typically referred to as nuclear shadowing ($x \lesssim 0.01$), antishadowing ($0.01 \lesssim x \lesssim 0.2$), European Muon Collaboration (EMC) effect ($0.2 \lesssim x \lesssim 0.7$) and Fermi motion ($x \gtrsim 0.7$). A typical example for the nuclear x dependence of $R_i^A(x, Q^2)$ is shown in the upper left plot of Fig. 1. Nuclear effects on single inclusive hadron production are typically characterized by the nuclear modification factor R^h_{pA}, which depends on the transverse momentum p_T and the rapidity y of the hadron:

$$R^h_{pA}(p_T, y) = \frac{d\sigma^{p\mathrm{A}\to h+X}}{dp_T^2 dy} \bigg/ N^{p\mathrm{A}}_{\mathrm{coll}} \frac{d\sigma^{pp\to h+X}}{dp_T^2 dy}. \quad (3)$$

Here, $N^{p\mathrm{A}}_{\mathrm{coll}}$ denotes the average number of equivalent nucleon-nucleon collisions in a pA collision. It is determined by Glauber theory, which can be subjected to independent phenomenological tests. The lower left plot of Fig. 1 shows the nuclear modification factor $R^{\pi^0}_{d\mathrm{Au}}(p_T, y)$ for the production of neutral pions in $\sqrt{s_{NN}} = 200$ GeV deuteron-gold collisions at RHIC, calculated within the factorized ansatz Eq. (1) at leading order (LO). Results shown in Fig. 1 are also consistent with the next-to-leading order calculation of $R^{\pi^0}_{d\mathrm{Au}}(p_T, y)$ in Ref. [1]. All our calculations use LO PDFs from CTEQ6L [10] with nuclear modifications EPS09 LO [1] and the KKP fragmentation functions [11]. We have checked our conclusions for another set of fragmentation functions [12] (data not shown).

The p_T dependence of the nuclear modification factor traces the x dependence of nPDFs. The precise kinematic connection between the momentum fractions x_1, x_2 and the measured hadronic momentum p_T is complicated by the convolution of the distributions in Eq. (1). Qualitatively, at fixed rapidity y of the produced hadron, increasing p_T tests larger values of x_1, x_2. Inspection of the nuclear modification factor in the lower left panel of Fig. 1 reveals that the enhancement of $R^{\pi^0}_{d\mathrm{Au}}(p_T, y)$ in the region around $p_T \simeq 4$ GeV at midrapidity tests momentum fractions in the antishadowing region. The RHIC data [6] in Fig. 1 have been used in constraining the nPDF analysis EPS09 [1], but they were not employed in a closely related nPDF fit [3], which provides an equally satisfactory description of these RHIC data. Therefore, the agreement of data and calculation in Fig. 1 is in support of collinear factorization.

However, qualitatively different explanations of the $R^{\pi^0}_{d\mathrm{Au}}(p_T, y)$ measured at RHIC are conceivable. The preceding calculation accounted for $R^{\pi^0}_{d\mathrm{Au}}(p_T, y = 0)$ in terms of a nuclear modification of the *longitudinal* parton momentum distribution, only. Alternatively, it has been suggested (see, e.g., Ref. [13]) that the characteristic enhancement of $R^h_{pA}(p_T, y)$ in the p_T range of a few GeV (typically referred to as the Cronin effect [9]) can be understood in terms of *transverse* parton momentum broadening induced by multiple scattering. Transverse nuclear broadening is the prototype of a generic nuclear modification, for which we do not know whether and how it could be absorbed in collinear process-independent nPDFs. How can one test whether the physics, underlying $R^h_{pA}(p_T, y)$, can be attributed to a nuclear modification of longitudinal parton momentum distributions and, thus, can indeed provide reliable quantitative constraints on nPDFs? To address this question, we have calculated $R^{\pi^0}_{p\mathrm{Pb}}(p_T, y)$ for the

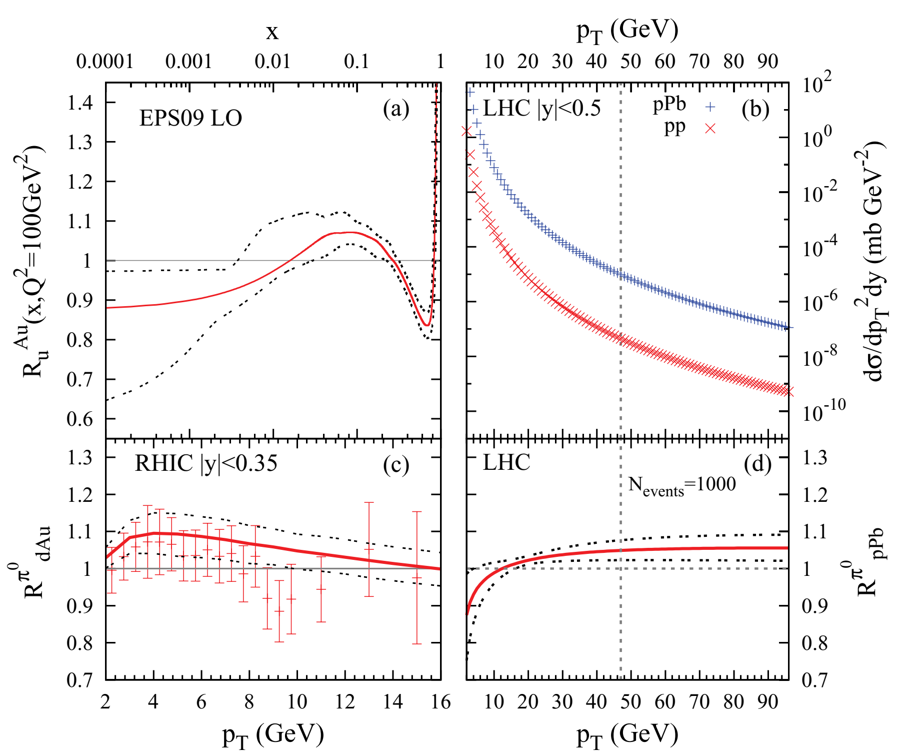

FIG. 1. (Color online) (a) The ratio Eq. (2) of nuclear to nucleon PDFs for valence up-quarks at $Q^2 = (10\ \mathrm{GeV})^2$ obtained in the EPS09 LO analysis. Dashed lines characterize the range of uncertainties. (c) The nuclear modification factor Eq. (3) for neutral pion production in $\sqrt{s_{NN}} = 200$ GeV dAu (RHIC). Data from PHENIX [6] are compared to an EPS09 LO calculation. Hereafter, uncertainty bands are from EPS09 LO only (uncertainties from proton PDFs and FF are neglected). (d) As in (c) for $\sqrt{s_{NN}} =$ 8.8 TeV pPb (LHC). (b) The corresponding single inclusive pion spectra. The thin vertical line denotes the kinematic range with statistics of more than 1000 events per GeV bin after one month of LHC operation with pPb.

production of neutral pions in proton-lead collisions at the LHC, see the right-hand side of Fig. 1.

The LHC can collide protons and Pb ions with a maximum center-of-mass energy of $\sqrt{s_{NN}} = 8.8$ TeV. While pPb is not yet part of the initial LHC program, there are estimates [14] that without major upgrades, a luminosity of $\mathcal{L}_{p\mathrm{Pb}} = 10^{29}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ could be achieved. With these assumptions, we find that running the LHC for one month would allow one to map out the single inclusive π^0 spectrum up to transverse momenta well above $p_T \simeq 50$ GeV (see Fig. 1).

Remarkably, if the entire nuclear effect in pPb collisions can be factorized into nPDFs, then the shape of the nuclear modification factor measured at the LHC will be qualitatively different from that observed at RHIC. This is so because at more than 40 times higher center-of-mass energy, final-state hadrons at the same transverse momentum test $O(40)$ times smaller momentum fractions x_i. As a consequence, $R^{\pi^0}_{p\mathrm{Pb}}(p_T, y = 0)$ at the LHC will be dominated by the shadowing regime, and, thus, will show a suppression for $p_T \lesssim 10 \div 20$ GeV, whereas RHIC data show a clear enhancement in this region. Furthermore, LHC data will show a nuclear enhancement in the antishadowing dominated range of $p_T \gtrsim 10 \div 20$ GeV, whereas the RHIC nuclear modification factor starts being dominated by x values in the EMC regime.

A shift of the maximum of $R^{\pi^0}_{p\mathrm{Pb}}(p_T, y = 0)$ to values of $p_T > 50$ GeV at the LHC is a natural consequence of nuclear modifications in *longitudinal* parton momentum distributions, as encoded, for example, in EPS09. In contrast, no mechanism is known that could account for such a large p_T shift in terms of *transverse* parton momentum broadening; the $\sqrt{s}$ dependence of transverse momentum broadening is much milder. The inverse is equally true: A mild shift of the maximum of $R^{\pi^0}_{p\mathrm{Pb}}(p_T, y = 0)|_{\sqrt{s_{NN}}=8.8\ \mathrm{TeV}}$ to values of $p_T \leqslant 10$ GeV could not be accommodated naturally in a collinear factorized approach, since it would imply a nuclear enhancement of some PDFs below $x \simeq 0.01$, which is inconsistent with the position of the antishadowing region. However, such a mild shift would be a natural consequence of transverse momentum broadening.

Moreover, at the LHC, a collinearly factorized approach typically results in a mild enhancement of $R^{\pi^0}_{p\mathrm{Pb}}(p_T, y = 0)$ above unity for a wide transverse momentum range $p_T > 10$. In this kinematic range, suppression factors of order 2 are inconsistent with all existing nPDFs. In contrast, models based on nonlinear small-x evolution (see, e.g., Ref. [15]) naturally arrive at such large suppression factors.

In the present paper, we use the notion collinearly factorized approach exclusively to refer to the technical framework in which global nPDF fits are performed. This framework attributes the entire nuclear dependence of $R_{p\mathrm{Pb}}$ to nuclear parton distribution functions. The main point to be made by the present work is that given the much wider kinematic range

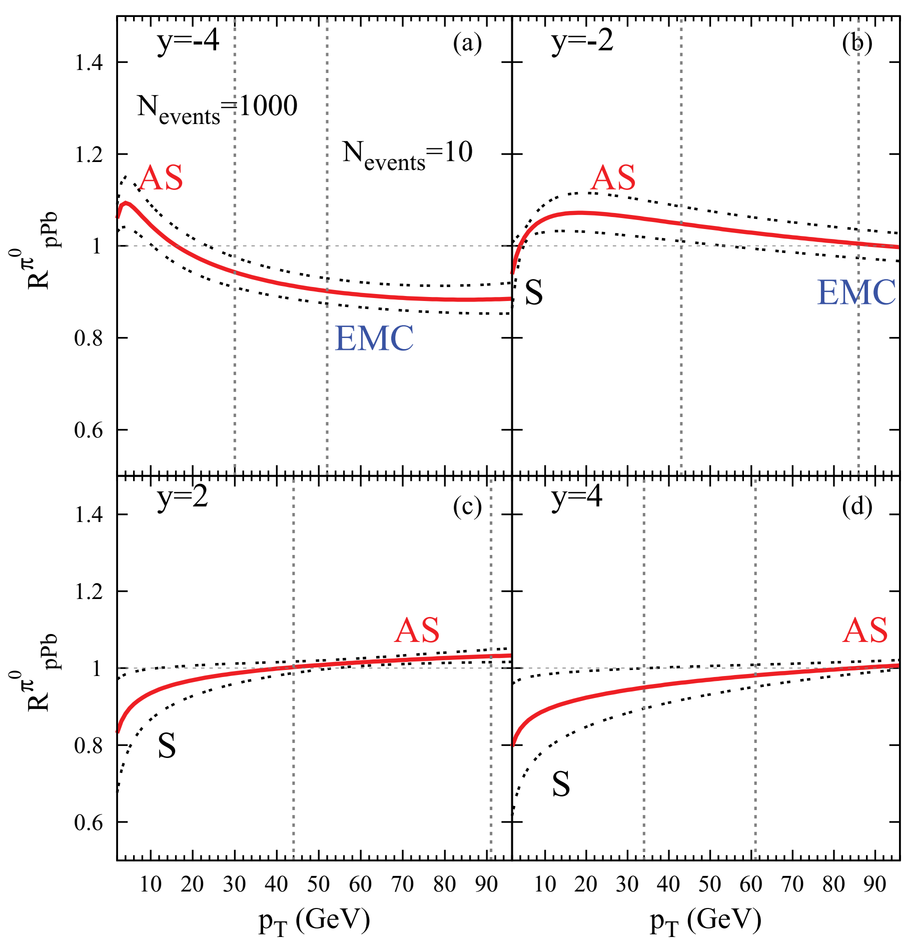

FIG. 2. (Color online) Rapidity dependence of $R^{\pi^0}_{p\mathrm{Pb}}$ Eq. (3) for $\sqrt{s_{NN}} = 8.8$ TeV pPb (LHC). The different plots scan the dependence from $y = -4$ (close to Pb projectile rapidity) up to $y = 4$ (close to proton projectile rapidity). Labels indicate whether the nuclear modification originates mainly from the shadowing (S), the antishadowing (AS), or the EMC regime. Vertical lines illustrate the rapidity-dependent p_T range, which can be accessed experimentally with more than $N_{\mathrm{events}} = 1000$ (=10) per GeV bin within one month of running at nominal luminosity.

available at the LHC, this assumption, which underlies global nPDF fits, can be tested decisively for the first time. We note that models, which include other nuclear effects, such as *pt* broadening, nonlinear small-*x* evolution, or medium-modified fragmentation functions, may also be written as a convolution of factorized expressions. As a tool to discriminate them from the collinearly factorized underlying nPDF fits, we now further discuss the characteristic energy dependence and rapidity dependence of the latter.

The dynamical explanation of the nuclear modification factor $R^h_{p\mathrm{Pb}}$ in terms of process-independent collinearly factorized nPDFs implies that, as a function of $\sqrt{s_{NN}}$ and rapidity y, the same nuclear effect manifests itself in very different kinematic ranges of pA collision data. As seen in Fig. 2, the rapidity dependence of $R^h_{p\mathrm{Pb}}$ allows one to scan the main qualitatively different ranges of standard nPDFs in an unprecedented way.At backward proton projectile rapidity ($y = -4$), where relatively large nuclear momentum fractions x are required for hadron production, the nuclear effects in Fig. 2 are seen to be dominated by the antishadowing regime at low transverse momentum $p_T < 20$ GeV and by the EMC suppression at higher p_T. As one moves to larger rapidity, where smaller nuclear momentum fractions dominate hadron production, the antishadowing regime contributes up to increasingly high p_T, and opens up a wide window of transverse momentum, in which the shadowing region of nPDFs can be tested experimentally.

Within the collinearly factorized approach, one expects nonperturbative corrections to the ansatz Eq. (1). However, these corrections die out as inverse powers of the resolution scale. In contrast, while nuclear effects in nPDFs also depend on the resolution scale, their dependence is only logarithmic, so that sizable nuclear effects are expected to persist at perturbatively large p_T scales. Therefore, concise tests of the collinearly factorized approach require particle production processes at sufficiently large perturbative momentum transfers. In pPb collisions at the LHC, the experimental access to a wide nominally perturbative p_T range ($p_T > 10$ GeV, say) is, thus, a qualitative advantage. In particular, the forward rapidity dependence of RHIC data [8,16] on $R^h_{d\mathrm{Au}}$ does not yet provide a decisive test for the collinearly factorized approach, since they test relatively low-resolution scales, where large corrections to Eq. (1) could be expected even *within* the framework of a collinear factorized approach. For this reason, these data have not been included in recent nPDF analyses [1]. In contrast, *within* the framework of a collinearly factorized approach, one does not know of sizable corrections to Eq. (1) in the range $20 < p_T < 40$ GeV, which will be uniquely accessible at LHC and where characteristic rapidity-dependent features are seen in Fig. 2.

So far, we have emphasized that well beyond quantitative improvements, pPb collisions at the LHC have the potential to submit the very assumption of collinear factorization to decisive tests. In particular, a strong suppression of

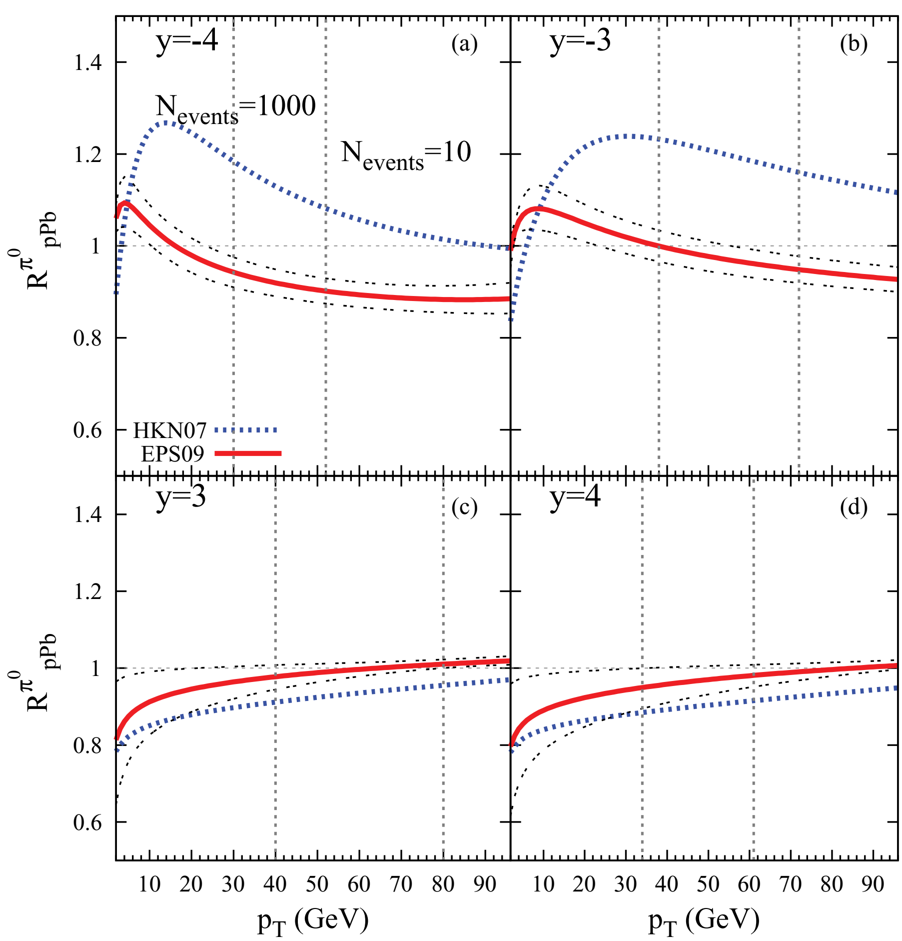

FIG. 3. (Color online) $R^{\pi^0}_{p\mathrm{Pb}}$ Eq. (3) for $\sqrt{s_{NN}} = 8.8$ TeV pPb (LHC), from two different sets of nPDFs.

$R^h_{p\text{Pb}}(p_T, y = 0)$ at high $p_T > 10$ GeV, or the persistence of the maximum of $R^h_{p\text{Pb}}(p_T, y = 0)$ at $p_T < 10$ GeV is inconsistent with *all* current nPDFs, and it tests an x range for which existing data provide constraints. Therefore, if observed, such features would shed significant doubt on the use of the factorized ansatz Eq. (1) for calculating nuclear effects, while they could be accounted for naturally in the context of qualitatively different dynamical explanations, mentioned earlier.

Despite these perspectives for qualitative tests of collinear factorization, we caution that current global analyses of nPDFs come with significant uncertainties. While not all conceivable data on $R^h_{p\text{Pb}}(p_T, y)$ at the LHC can be accommodated within a collinearly factorized approach, a significant spread could. To illustrate this, in Fig. 3, we have compared the nuclear modification factor for two nPDF sets, which are known to show marked differences. In particular, in contrast to EPS09, the gluon distribution of HKN07 [5] does not show an antishadowing peak but turns for $x > 0.2$ from suppression to strong enhancement at the initial scale $Q^2 = 1$ GeV^2. Inspection of Fig. 3 reveals that, for HKN07, the size and position of the maximum of $R^h_{p\text{Pb}}(p_T, y)$ at negative y arises from an interplay between the nuclear enhancement of the gluon PDF (which increases with x and, hence, with p_T) and the relative contribution of the gluon versus the quark distribution to $R^h_{p\text{Pb}}(p_T, y)$ (which decreases with p_T). Figure 3, thus, illustrates that within the validity of a collinearly factorized approach, LHC data can resolve the qualitative differences between existing nPDF analyses and can improve significantly and within a nominally perturbative regime on our knowledge of nuclear gluon distribution functions. Data on other single inclusive particle spectra and jets in pPb at the LHC can further constrain global nPDF analysis, thereby testing the concept of collinear factorization of nuclear effects and by improving our knowledge of nPDFs as long as this test is passed.

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[1] K. J. Eskola, H. Paukkunen, and C. A. Salgado, J. High Energy Phys. 04 (2009) 065.
[2] K. J. Eskola, H. Paukkunen, and C. A. Salgado, J. High Energy Phys. 07 (2008) 102.
[3] K. J. Eskola, V. J. Kolhinen, and C. A. Salgado, Eur. Phys. J. C **9**, 61 (1999).
[4] D. de Florian and R. Sassot, Phys. Rev. D **69**, 074028 (2004).
[5] M. Hirai, S. Kumano, and T. H. Nagai, Phys. Rev. C **76**, 065207 (2007).
[6] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **98**, 172302 (2007).
[7] J. Adams *et al.* (STAR Collaboration), Phys. Lett. B **637**, 161 (2006).
[8] I. Arsene *et al.* (BRAHMS Collaboration), Phys. Rev. Lett. **93**, 242303 (2004).
[9] J. W. Cronin *et al.*, Phys. Rev. D **11**, 3105 (1975).
[10] J. Pumplin, A. Belyaev, J. Huston, D. Stump, and W. K. Tung, J. High Energy Phys. 02 (2006) 032.
[11] B. A. Kniehl, G. Kramer, and B. Potter, Nucl. Phys. B **582**, 514 (2000).
[12] D. de Florian, R. Sassot, and M. Stratmann, Phys. Rev. D **75**, 114010 (2007).
[13] Y. Zhang, G. I. Fai, G. Papp, G. G. Barnafoldi, and P. Levai, Phys. Rev. C **65**, 034903 (2002).
[14] A. Accardi *et al.*, arXiv:hep-ph/0308248.
[15] J. L. Albacete and C. Marquet, Phys. Lett. B **687**, 174 (2010).
[16] B. B. Back *et al.* (PHOBOS Collaboration), Phys. Rev. C **70**, 061901 (2004).