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Predictions for $p + \mathrm{Pb}$ at 4.4A TeV to test initial-state nuclear shadowing at energies available at the CERN Large Hadron Collider

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Collinear factorized perturbative QCD model predictions are compared for $p + \mathrm{Pb}$ at 4.4A TeV to test nuclear shadowing of parton distribution at the CERN Large Hadron Collider (LHC). The nuclear modification factor (NMF), $R_{p\mathrm{Pb}}(y = 0,\ p_T < 20\ \mathrm{GeV}/c) = dn_{p\mathrm{Pb}}/[N_{\mathrm{coll}}(b)dn_{pp}]$, is computed with an electron-nucleus $(e + A)$ global fit with different nuclear shadow distributions and compared to the fixed Q^2 shadow ansatz used in Monte Carlo Heavy Ion Jet Interacting Generator (HIJING)–type models. Because of the rapid Dokshitzer Gribov Lipatov Altarelli Parisi (DGLAP) reduction of shadowing with increasing Q^2 used in the $e + A$ global fit, our results confirm that no significant initial state suppression is expected $[R_{p\mathrm{Pb}}(p_T) = 1 \pm 0.1]$ in the p_T range 5 to 20 GeV/c. In contrast, the fixed Q^2 shadowing models assumed in HIJING-type models predict in the range above p_T a sizable suppression, $R_{p\mathrm{Pb}}(p_T) = 0.6$–0.7, at midpseudorapidity that is similar to the color glass condensate (CGC) model predictions. For central $(N_{\mathrm{coll}} = 12)$ $p + \mathrm{Pb}$ collisions and at forward pseudorapidity $(\eta = 6)$, the HIJING-type models predict smaller values of nuclear modification factors $[R_{p\mathrm{Pb}}(p_T)]$ than in minimum-bias events at midpseudorapidity $(\eta = 0)$. Observation of $R_{p\mathrm{Pb}}(p_T = 5 - 20\ \mathrm{GeV}/c) \lesssim 0.6$ for minimum bias $p + A$ collisions would pose a serious difficulty for separating initial-state from final-state interactions in $\mathrm{Pb} + \mathrm{Pb}$ collisions at LHC energies.

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I. INTRODUCTION

In this paper we compare predictions for moderate $p_T < 20$ GeV/c observables in $p + \mathrm{Pb}$ reactions at 4.4A TeV at the CERN Large Hadron Collider (LHC), which should help to discriminate between models of initial conditions assumed in $\mathrm{Pb} + \mathrm{Pb}$ collisions at 2.76A TeV. The possibility that the first data on $p + \mathrm{Pb}$ may be taken soon, with a potential high physics payoff, motivates this paper. All model details are extensively discussed in the literature, and we focus only on the updated nuclear modification factor, $R_{p\mathrm{Pb}}(\eta, p_T, b) = dn_{p\mathrm{Pb}}/[N_{\mathrm{coll}}(b)dn_{pp}]$, predictions testable with a short 4.4A TeV run. In minimum bias (MB) and central (0–20%) $p + \mathrm{Pb}$ collisions, the average numbers of binary nucleon-nucleon (NN) interactions (with an inelastic cross section $\sigma^{\mathrm{in}}_{NN} \approx 65$ mb) are $N^{\mathrm{MB}}_{\mathrm{coll}} \approx 7$ and $N^{\mathrm{Cen}}_{\mathrm{coll}} \approx 12$ respectively.

This control experiment has long been anticipated to play a decisive role in helping to deconvolute initial-state and final-state interaction effects in $\mathrm{Pb} + \mathrm{Pb}$ reactions at the LHC. The $d + \mathrm{Au}$ control experiment at 0.2A TeV played a similar critical role for Au+Au at the Relativistic Heavy Ion Collider (RHIC) in 2004 [1,2]. The importance of $p + \mathrm{Pb}$ was also emphasized in the 2007 last call for LHC compilation of predictions [3] and many other works [4–10].

An open problem after the first very successful LHC heavy ion run in 2010 [11] remains: how to deconvolute nuclear modification effects due to initial-state and final-state effects. Without a clear calibration of the magnitude of initial-state suppression of the incident nuclear partonic flux, it is not possible to draw firm conclusions about the properties of the quark gluon plasma (QGP) phase of matter produced at the LHC. At RHIC, the same problem was resolved at midrapidity by the observation of no appreciable nuclear modification in $d + \mathrm{Au}$ control experiments in 2003 [1,2] (see also Fig. 3 below). Suppression of moderate p_T midrapidity pions by a factor of 4, observed in $\mathrm{Au} + \mathrm{Au}$ at RHIC, could be interpreted as due to final-state jet energy loss in a high-opacity QGP produced in central $\mathrm{Au} + \mathrm{Au}$ collisions at RHIC.

At LHC, the initial flux is much more uncertain than at RHIC because of the higher density of partons at fractional momenta $x = 2p_T/\sqrt{s} < 10^{-3}$, which is an order of magnitude smaller. At high initial densities, all models predict a breakdown of additivity of the nuclear parton distribution functions (nPDFs). However, the magnitude of the breakdown varies greatly in the literature in both collinear factorized approaches and k_T factorized parton saturation model approaches [3–5,7–10]. Therefore, even a rough first experimental constraint from $p + \mathrm{Pb}$ interactions would have high impact on the development of nuclear collision modeling.

II. NUCLEAR SHADOWING AND JET QUENCHING AT LHC ENERGIES

Nuclear shadowing of quark and gluon nPDFs at large $x > 0.01$ and moderate Q^2 is well constrained from $e + A$ and lower energy $p + A$ data. Global fit parametrizations of the nPDFs are available [5,8,9]. DGLAP evolution [12] to higher Q^2 predicts a rapid reduction of shadowing effects, and therefore only modest modifications of $R_{p\mathrm{Pb}}(p_T) = 1 \pm 0.1$ for $p_T > 5$ GeV/c have been predicted [9,10,13]. As emphasized in Ref. [10], any observed significant modification from unity would be inconsistent with most current nPDFs and therefore pose a severe challenge to conventional collinear factorized QCD approximation to high-p_T processes not only in $p+\mathrm{Pb}$ but even more so in $\mathrm{Pb}+\mathrm{Pb}$ collisions. We continue here to investigate this central thesis.

At RHIC, there is clear evidence at high rapidities, where small fractional parton momenta $x \sim 10^{-3}$ similar to central $p+\mathrm{Pb}$ are probed, that binary collision scaling of collinear factorization breaks down. Color glass condensate (CGC) k_T factorization models have been developed to explain these deviations [14,15] and nearly identical $R_{pA} \approx 0.7 \pm 0.1$ nuclear modifications factors were predicted in Ref. [14] (KKT04) for forward rapidities at RHIC and midrapidity at the LHC.

However, collinear factorized approaches with DGLAP-evolved nPDF appear to provide an alternate explanation of forward single inclusive yields at RHIC [5,8]. At LHC energies, we can differentiate between these explanations because the collinear factorized approach predicts only small nuclear modification for midrapidity pions (see Fig. 3 below), while at RHIC energies it predicts large modifications, as CGC does, for forward produced pions. The much higher energy range at the LHC also opens the kinematic window on small x physics that can be explored in $p+A$ collisions at midrapidity. Some CGC models [16,17] predict a suppression with $R_{p\mathrm{Pb}}(\eta=0,\, p_T \approx 10\ \mathrm{GeV}/c) \approx 0.5$ with strong dependence on the initial evolution conditions. Such small values of $R_{p\mathrm{Pb}}$ would imply that nearly all nuclear suppression observed in NMF R_{PbPb} in $\mathrm{Pb}+\mathrm{Pb}$ collisions, previously attributed to jet quenching in the final state, could instead be due to nonlinear initial-state parton flux suppression.

Because of an increase by a factor of 2 in the final parton densities at the LHC, jet quenching is expected to produce higher suppression than at RHIC energies. Actually, the observed $\mathrm{Pb}+\mathrm{Pb}$ suppression of pions at the LHC energy was surprisingly weaker than expected from RHIC constrained analysis extrapolated to the LHC [18]. Thus, from the perturbative final-state interaction point of view, there appears to be no room for initial-state suppression. Therefore, a measurement of $R_{p\mathrm{Pb}}$ at midrapidity significantly less than unity would contradict not only perturbative QCD (pQCD) models of the initial state nPDF evolution but also theory of the final-state perturbative opacity series of jet energy loss. Since anti de Sitter/conformal field theory correspondence (AdS/CFT) of strong coupling [19] predicts even stronger final-state suppression effects, an observation in $p+\mathrm{Pb}$ of significant deviations from unity would then call into question the validity of holographic interpretations of RHIC and LHC $A+A$ results, including the applicability of minimal viscous hydrodynamics to apparent perfect fluidity.

At sufficiently high energies and virtualities, QCD factorization theorems guarantee that jet observables can be calculated in perturbation theory. The open question is at what scale does factorization break down for nuclear processes. CGC theory [14–17,20–28] has a saturation natural scale $Q_s(x,A)$ that in principle provides the answer when $Q_s \gg \Lambda_{\mathrm{QCD}}$. However, nuclear jet observables up to LHC energies are sensitive to details of large $x > 0.01$ as well as small $A=1$ "corona" nucleon distributions for which $Q_s \lesssim 1$ GeV.

Monte Carlo models as HINJING1.0 [29], HIJING2.0 [30], and HIJING/B$\bar{\mathrm{B}}$2.0 [31] have been developed to study hadron productions in $p+p$, $p+A$ and $A+A$ collisions. They are essentially two-component models, which describe the production of hard parton jets and the soft interaction between nucleon remnants. The hard jets production is calculated by employing collinear factorized multiple minijet within pQCD. A cutoff scale p_0 in the transverse momentum of the final jet production has to be introduced below in which ($p_T < p_0$) the interaction is considered nonperturbative and is characterized by a finite soft parton cross section σ_{soft}. Jet cross sections depend on the parton distribution functions (PDFs) that are parametrized from a global fit to data [30].

Nucleon remnants interact via soft gluon exchanges described by the string models [32,33] and constrained from lower energy $e+e$, $e+p$, $p+p$ data. The produced hard jet pairs and the two excited remnants are treated as independent strings, which fragment to resonances that decay to final hadrons. Longitudinal beam jet string fragmentations strongly depend on the values used for string tensions that control quark-antiquark ($q\bar{q}$) and diquark-antidiquark ($qq\overline{qq}$) pair creation rates and strangeness suppression factors (γ_s). In the HIJING1.0 and HIJING2.0 models, a constant (vacuum value) for the effective value of string tension is used, $\kappa_0 = 1.0$ GeV/fm. At high initial energy density, the novel nuclear physics is due to the possibility of multiple longitudinal flux tube overlapping, leading to strong longitudinal color field effects. Strong color field (SCF) effects are modeled in HIJING/B$\bar{\mathrm{B}}$2.0 by varying the effective string tension values. SCF also modifies the fragmentation processes, resulting in an increase of (strange) baryons, which play an important role in the description of the baryon-meson anomaly. In order to describe $p+p$ and central $\mathrm{Pb}+\mathrm{Pb}$ collision data at the LHC, we have shown that energy and mass dependence of the mean value of the string tension should be taken into account [31]. Moreover, to better describe the baryon-meson anomaly seen in data, a specific implementation of J$\bar{\mathrm{J}}$ loops has to be introduced. For a detailed discussion, see Ref. [31]. A similar result can be obtained by including extra diquark-antidiquark pair production channels from strong coherent fields formed in heavy ion collisions [34].

All HIJING-type models implement nuclear effects such as nuclear modification of the parton distribution functions (i.e., *shadowing* and *jet quenching*) via a medium-induced parton splitting process (collisional energy loss is neglected) [29]. In the HIJING1.0 and HIJING/B$\bar{\mathrm{B}}$2.0 models, Duke-Owen (DO) parametrization of PDFs [35] is used to calculate the jet production cross section with $p_T > p_0$. In both models, using a constant cutoff $p_0 = 2\ \mathrm{GeV}/c$ and a soft parton cross section $\sigma_{\mathrm{soft}} = 54$ mb fit the experimental $p+p$ data. However, for $A+A$ collisions in HIJING/B$\bar{\mathrm{B}}$ model, we introduced an energy and mass dependence of the cutoff parameter, $p_0(s,A)$ [31] at RHIC and at the LHC energies, in order to not violate the geometrical limit for the total number of minijets per unit transverse area. In the HIJING2.0 [30] model, which is also a modified version of HIJING1.0 [29], the Gluck-Reya-Vogt (GRV) parametrization of PDFs [36] is implemented. The gluon distributions in this different parametrization are much higher than the DO parametrization at small x. In addition, energy-dependent cutoffs $p_0(s)$ and $\sigma_{\mathrm{soft}}(s)$ are also assumed in order to better describe the $\mathrm{Pb}+\mathrm{Pb}$ collisions data at the LHC.

One of the main uncertainties in calculating charged particle multiplicity density in $\mathrm{Pb}+\mathrm{Pb}$ collisions is the nuclear modification of parton distribution functions, especially gluon distributions at small x. In HIJING-type models, one assumes that the parton distributions per nucleon in a nucleus (with atomic number A and charge number Z), $f_{a/A}(x, Q^2)$, are factorizable into parton distributions in a nucleon($f_{a/N}$) and the parton (a) shadowing factor ($S_{a/A}$),

$$f_{a/A}(x, Q^2) = S_{a/A}(x, Q^2) f_{a/N}(x, Q^2). \tag{1}$$

The impact parameter dependence is implemented through the parameter s_a,

$$s_a(b) = s_a \frac{5}{3}\left(1 - \frac{b^2}{R_A^2}\right), \tag{2}$$

where $R_A = 1.12A^{1/3}$ is the nuclear radius.

In HIJING/B$\bar{\text{B}}$2.0, the shadowing factors for gluon and quark are assumed to be equal [$S_{g/A}(x, Q^2) = S_{q/A}(x, Q^2)$] and are similar with those used in HIJING1.0 [29]. They were selected in order to fit the centrality dependence of the central charged particle multiplicity density at the LHC. In contrast, in HIJING2.0 a much stronger impact parameter dependence of the gluon ($s_g = 0.22$–0.23) and quark ($s_q = 0.1$) shadowing factor is used in order to fit the LHC data. Because of this stronger gluon shadowing, the jet quenching effect has to be neglected [30]. Note, all HIJING-type models assume a scale-independent form of shadowing parametrization (fixed Q^2). This approximation could break down at a very large scale because of the dominance of gluon emission dictated by the DGLAP [12] evolution equation. At $Q = 2.0$ and 4.3 GeV/c, which are typical scales for minijet production at RHIC and LHC, respectively, it was shown that the gluon shadowing varies by approximately13% in EPS09 parametrizations [6].

III. COMPARATIVE STUDY OF MODEL PREDICTIONS

Figure 1 shows HIJING/B$\bar{\text{B}}$2.0 predictions of the global observables $dN_{\text{ch}}/d\eta$ and $R_{p\text{Pb}}(\eta) = [(dN^{\text{ch}}_{p\text{Pb}}/d\eta)/(N_{\text{coll}} dN^{\text{ch}}_{pp}/d\eta)]$ characteristics of minimum bias $p + \text{Pb}$ collisions at 4.4A TeV. The predictions for $p + p$ are also shown. Minijet cutoff and string tension parameters $p_0 = 3.1$ GeV/c and $\kappa = 2.9$ GeV/fm for $p + \text{Pb}$ are determined from fits to $p + p$ and $A + A$ systematics from RHIC to the LHC (see Ref. [31] for details). Note, these calculations assume no *jet quenching*.

However, the absolute normalization of $dN_{\text{ch}}/d\eta$ is sensitive to the low $p_T < 2$ GeV/c nonperturbative hadronization dynamics that is performed via LUND [32] string JETSET [33] fragmentation as constrained from lower energy $e + e$, $e + p$, $p + p$ data. The default HIJING1.0 parametrization of the fixed $Q_0^2 = 2$ GeV^2 shadow function leads to substantial reduction (solid histograms) of the global multiplicity at the LHC. It is important to emphasize that the no shadowing results (dashed curves) are substantially reduced in HIJING/B$\bar{\text{B}}$2.0 relative to no shadowing predictions with default HIJING1.0 from Ref. [29], because both the default minijet cutoff $p_0 = 2$ GeV/c and the default vacuum string tension $\kappa_0 = 1$ GeV/fm (used in HIJING1.0) are generalized to vary monotonically with center of mass (c.m.) energy per nucleon $\sqrt{s}$ and atomic number, A. As discussed in Ref. [31], systematics of $p + p$ and Pb + Pb multiparticle production from RHIC to the LHC are used to fix the energy ($\sqrt{s}$) and the A dependence. Thus, the cutoff parameter $p_0(s, A) = 0.416\,\sqrt{s}^{0.191}\,A^{0.128}$ GeV/c and the mean value of the string tension $\kappa(s, A) = \kappa_0\,(s/s0)^{0.06}\,A^{0.167}$ GeV/fm. The above formulas lead to $p_0 = 3.1$ GeV/c and $\kappa = 2.9$ GeV/fm at 4.4A TeV for $p + \text{Pb}$ collisions. For $p + p$ collisions at 4.4 TeV, we use a constant cutoff parameter $p_{0pp} = 2$ GeV/c and a string tension value of $\kappa_{pp} = 2.7$ GeV/fm.

Note, even in the case of no shadowing shown in Fig. 1, the increase to $p_0 = 3.1$ GeV/c from $p_0 = 2$ GeV/c (value used in $p + p$ at 4.4 TeV) causes a significant reduction by a factor of roughly 2 of the minijet cross section and hence final

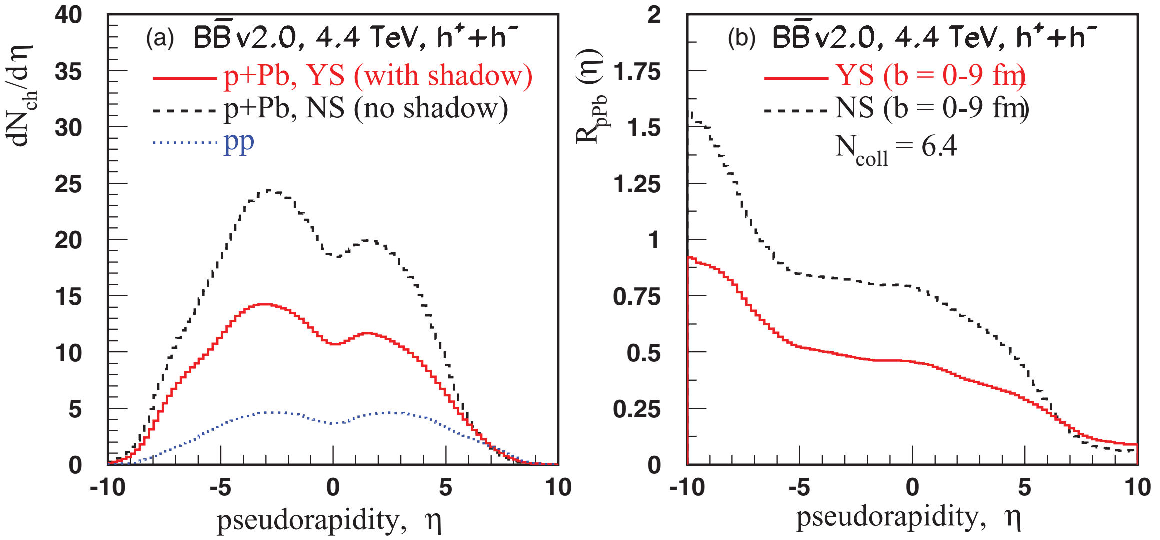

FIG. 1. (Color online) (a) HIJING/B$\bar{\text{B}}$2.0 predictions of charged particles' pseudorapidity distribution ($dN_{\text{ch}}/d\eta$) for minimum bias (MB) $p + \text{Pb}$ collisions at 4.4A TeV. Solid YS curve includes fixed Q^2 shadowing functions from HIJING1.0 [29], while the dashed NS curve has no shadowing. (b) Ratio $R_{pPb}(\eta)$ calculated assuming $N_{\text{coll}}(\text{MB}) = 6.4$.

pion multiplicity. This reduction of minijet production also is required to fit the low charged-particle multiplicity growth in $A + A$ collisions from RHIC to LHC (a factor of 2.2) [37].

We interpret this as additional phenomenological evidence for gluon saturation physics not encoded in leading twist shadow functions. The $p_T > 5$ GeV/c minijets tails are unaffected but the bulk low $p_T < 5$ GeV/c multiplicity distribution is sensitive to this extra energy ($\sqrt{s}$) and A dependence of the minijet shower suppression effect. It is difficult to relate p_0 to saturation scale Q_{sat} directly, because in HIJING hadronization proceeds through longitudinal field string fragmentation. The energy ($\sqrt{s}$) and A dependence of the string tension value arises from strong color field (color rope) effects not considered in CGC phenomenology that assumes k_T factorized gluon fusion hadronization. HIJING hadronization of minijets is not via independent fragmentation functions as in PYTHIA [33], but via string fragmentation with gluon minijets represented as kinks in the strings. The interplay between longitudinal string fragmentation dynamics and minijets is a nonperturbative feature of HIJING-type models. The approximate triangular (or trapezoidal) rapidity asymmetry seen in the ratio $R_{p\mathrm{Pb}}(\eta)$ sloping downward from the nuclear beam fragmentation region at negative pseudorapidity $\eta < -5$ toward $1/N_{\mathrm{coll}}$ in the proton fragmentation region ($\eta > 5$) is a basic Glauber geometric effect first explained in Refs. [38,39] and realized via string fragmentation in HIJING.

Figure 2 displays the predicted transverse spectra and nuclear modification factor for charged hadrons at midpseudorapidity, $|\eta| < 0.8$. Including shadowing reduces $R_{p\mathrm{Pb}}$ from unity to about 0.7 in the interesting 5 to 10 GeV/c region close to the prediction of the CGC model [14] (KKT04). A similar nuclear modification factor is found [13] using LO pQCD collinear factorization with HIJING2.0 parametrization of shadowing functions [40], GRV parton distribution functions (nPDF) from Ref. [36], and hadron fragmentation functions from Ref. [41].

In stark contrast to the three curves near 0.7 ± 0.1 from completely different dynamical modeling, the standard DGLAP evolved global $e + A$ fit nPDF (dotted curve labeled EKS99 [4]) predicts near unity for transverse momenta above 5 GeV/c. The no shadowing HIJING/BB̄2.0 values (NS, thin dashed histogram) goes to unity above 5 GeV/c, but the nonperturbative string hadronization pulls the intercept at $p_T = 0$ near to $\frac{1}{2}$ as constrained by the global triangular enhanced form of $dN_{p\mathrm{Pb}}/d\eta$ relative to $dN_{pp}/d\eta$ shown in Fig. 1(b). Note that the model BGK77 from Refs. [38,39] also predicts $R_{pA}(y, p_T = 0) = 1$ at the nuclear target rapidity and $1/N_{\mathrm{coll}}(b)$ at the proton projectile rapidity.

However, a recent new version of the CGC-rcBK model [27] predicts essentially no shadowing or saturation effects at $\eta = 0$ in contrast to both CGC type models, i.e., KKT04 (Kharzeev, Kovchegov, Tuchin, 2004) from Ref. [14] and those using running-coupling Balitsky-Kovchegov equations (rcBK) from Ref. [16]. The absence of shadowing at midrapidity in the CGC-rcBK [27] model is due to a phenomenological extra anomalous dimension γ, introduced to modify color dipole cross section $\sigma_{\mathrm{dipole}}(r) \propto (r^2)^\gamma$. This significantly steepens the pp transverse momentum distribution relative to the quadratic form $\sigma_{\mathrm{dipole}}(r) \propto r^2$ used in CGC model (MV) [42] as required to reproduce LHC pp data. Recently, possible extra A dependence of this extra anomalous dimension has been proposed [28]. It would be very surprising indeed if future $p + Pb$ data would show no evidence of shadowing with a $R_{pPb} \approx 1.0$ at $\eta = 0$ midpseudorapidity, which could then be ascribed either to (i) rapid DGLAP Q^2 evolution of shadowing in EKS09 [6] parametrization or (ii) accidental cancellation of

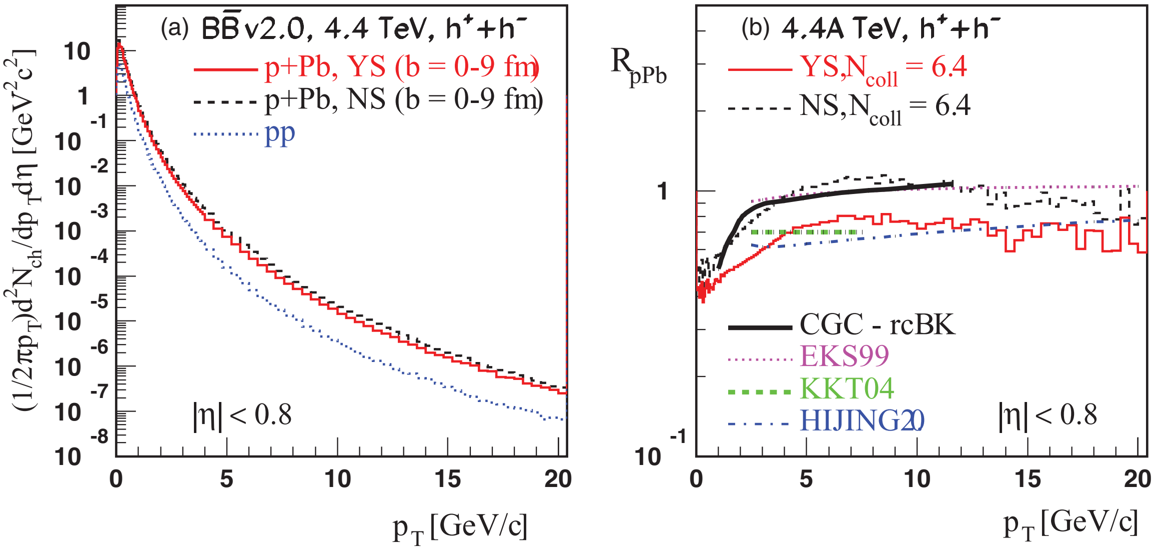

FIG. 2. (Color online) (a) Minimum bias transverse momentum distributions at midpseudorapidity $|\eta| < 0.8$ predicted by HIJING/BB̄2.0 with (solid histogram) and without (dashed histogram) HIJING1.0 shadowing functions [29]. The results for $p + p$ collisions at 4.4 TeV (dotted histogram) are also included. (b) The midpseudorapidity nuclear modification factor of charged hadrons $R_{p\mathrm{Pb}}$ from the HIJING/BB̄2.0 model. The solid and thin dashed histograms have the same meaning as in part (a). They are compared to pQCD leading order (LO) predictions (dash dotted line) [13] using HIJING2.0 shadowing functions [30] and to DGLAP Q^2 evolved nPDF, EKS99 (dotted line) [4]. Predictions of the CGC model (thick dashed line) [14] (KKT04) and CGC-rcBK model (thick solid line) from Ref. [27] are also included.

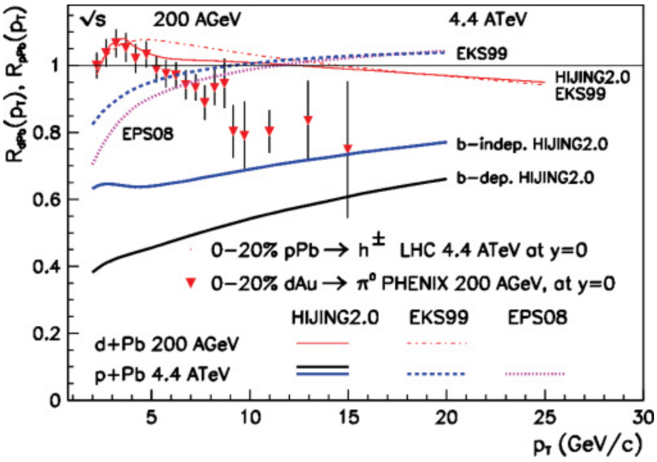

FIG. 3. (Color online) Predictions updated at 4.4A TeV of Ref. [13] results for central 0–20% ($b < 3.5$ fm) $p + Pb$ at midrapidity. The original predictions at 0.2A TeV for $d+\mathrm{Au}$ are also included. Compared are the results obtained with fixed Q^2 shadowing functions HIJING2.0 [30] with (b-dep) and without (b-indep) impact parameter dependence. Predictions with DGLAP Q^2 evolved shadowing functions from Ref. [4] (EKS99) and Ref. [5] (EPS08) are also shown. The data are from PHENIX Collaboration [43].

deep saturation effects due to an anomalous short distance behavior of the dipole cross section in CGC modeling.

What is significant about higher p_T deviations from unity is that the nuclear modification factor in central $A+A$ collisions is related to the minimum bias $p+A$ by simple Glauber geometric considerations, which can be expressed as

$$R_{AA}(y=0,\, p_T,\, b=0) \approx \langle [R_{pA}(y=0,\, p_T,\, \mathrm{min.bias})] \rangle^2, \quad (3)$$

where the average is calculated over all impact parameters. Thus, $R_{p\mathrm{Pb}} \approx 0.7$ for minimum-bias collisions implies a NMF $R_{\mathrm{PbPb}} \approx 0.5$ in central Pb + Pb collisions before any final-state interactions take place. The result for $R_{p\mathrm{Pb}}(p_T) \approx 0.7$ is similar to those reported recently with CGC-type models [16,17] (rcBK), albeit with huge error bars at midrapidity because of poorly known initial saturation conditions for $p+p$ and near the surface of heavy nuclei. However, if the prediction of $R_{p\mathrm{Pb}} \approx 0.5$ [17] turned out to be confirmed by the upcoming $p+\mathrm{Pb}$ measurements, then in central Pb + Pb collisions we expect a suppression of roughly a factor of 4 (≈0.25) in pions at transverse momenta of roughly 10 GeV/c. This fact would leave no room for final-state interactions in matter 100 times denser than ground-state nuclei. Needless to say, this point alone underlines more the importance of measuring the p_T dependence of NMF [$R_{p\mathrm{Pb}}(p_T)$] at the LHC.

In Fig. 3, the updated predictions at 4.4A TeV [13] of $R_{p\mathrm{Pb}}(p_T)$ in central (0–20%; $b < 3.3$ fm) $p+\mathrm{Pb}$ collisions at midrapidity are shown. The message is similar to that obtained from Fig. 2. The standard collinear Q^2 evolved nPDF models from Ref. [4] (EKS99) and from Ref. [5] (EPS08) predict only a slight deviation (≈10%) from unity, as discussed in detail in Refs. [9,10]. Fixed Q^2 shadowing functions used in HIJING1.0 or HIJING2.0 models predict $R_{p\mathrm{Pb}}(p_T) = 0.6 \pm 0.1$ in the p_T range 5 to 15 GeV/c, well below unity. Previous results at the RHIC energy [13] for central (0–20%) $d+\mathrm{Au}$ collisions at 0.2A TeV are also presented in comparison with PHENIX data [43]. At RHIC energy (0.2A TeV), all models predict approximately $R_{d\mathrm{Pb}}(p_T) = 1 \pm 0.1$. At this energy in HIJING2.0, the shadowing is much weaker for the $p_T > 5$ GeV/c domain because this corresponds to $x > 0.05$,

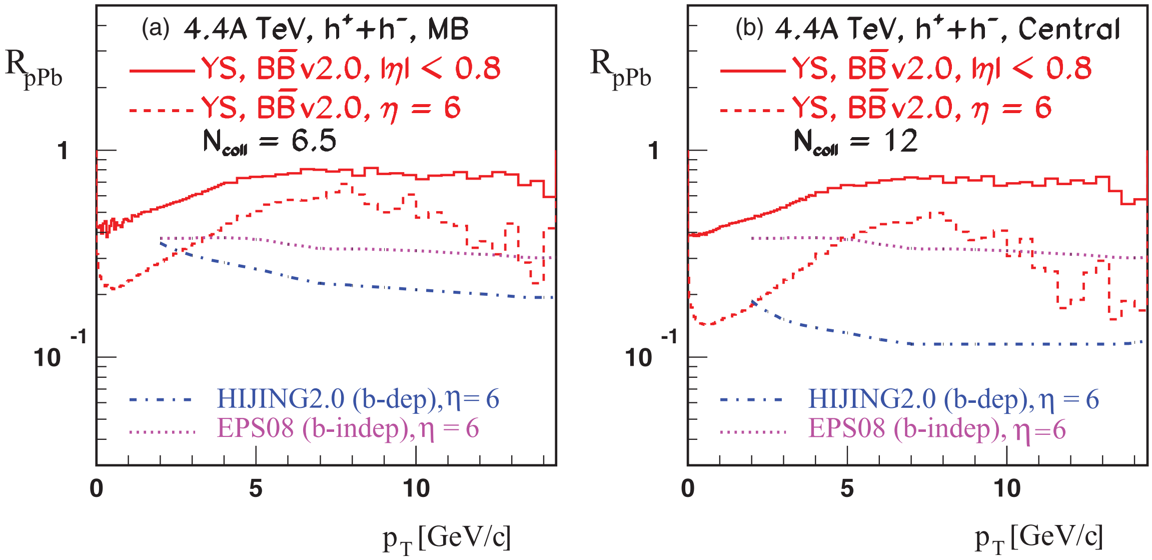

FIG. 4. (Color online) (a) The MB NMF of charged particles at forward pseudorapidity $\eta = 6$, from the HIJING/B$\bar{\mathrm{B}}$2.0 model (dashed histogram). The results are obtained with shadowing functions from the HIJING1.0 model [29]. They are compared to pQCD LO results at $\eta = 6$ (dash-dotted line) [13] using impact-parameter-dependent (b-dep) HIJING2.0 shadowing functions [30] and to predictions obtained with DGLAP Q^2 evolved shadowing functions (dotted line) with no impact parameter dependence (b-indep) from Ref. [5]. For reference, the results at midpseudorapidity $|\eta| < 0.8$ (solid histogram) are also included. (b) The results obtained for NMF of charged particles in central ($N_{\mathrm{coll}} = 12$) $p+\mathrm{Pb}$ collisions at 4.4A TeV. The histograms and the lines have the same meaning as in part (a).

which is more than an order of magnitude larger than at the LHC energy. Taking an impact parameter dependence of shadowing function in HIJING2.0 [30] for central $p+\mathrm{Pb}$ collisions results in a further decrease of the NMF $R_{p\mathrm{Pb}}(p_T)$ by 15–20%.

Finally, in Fig. 4 we show the nuclear modification factor $R_{p\mathrm{Pb}}$ for inclusive charged hadrons $(h^+ + h^-)$ at $\sqrt{s} =$ 4.4 TeV obtained from different models for MB ($N_{\mathrm{coll}} = 6.4$) in Fig. 4(a) and central ($N_{\mathrm{coll}} = 12$) p + Pb collisions in Fig. 4(b) at forward pseudorapidity ($\eta = 6$). For reference, we include the NMF at midpseudorapidity $|\eta| < 0.8$ (solid histograms) predicted with HIJING/B$\bar{\mathrm{B}}$2.0. Smaller suppression in the region of interest ($5 < p_T < 10$ GeV/c) than obtained with the HIJING/B$\bar{\mathrm{B}}$2.0 model is predicted using EPS08 parametrization [5] with no impact parameter dependence (b-indep) of shadowing functions (dotted line) and with pQCD calculation using an impact parameter dependence (b-dep) from the HIJING2.0 model. In this range of transverse momenta, the HIJING/B$\bar{\mathrm{B}}$ v2.0 model predicts slightly higher values than those predicted (0.35–0.40) by the CGC model (rcBK) [16].

It is obvious that at forward pseudorapidity the suppression is higher for central than for MB $p+\mathrm{Pb}$ collisions. Moreover, for central $p+\mathrm{Pb}$ collisions, the sensitivity to parametrization of shadowing functions is amplified. The different shape predicted by HIJING/B$\bar{\mathrm{B}}$ v2.0 at forward pseudorapidity in both MB and central collisions could be explained as a specific interplay between J$\bar{\mathrm{J}}$ loops and SCF effects embedded in the model, which induce a baryon-meson anomaly. Note the same effect has been predicted in $p+p$ and Pb + Pb collisions at LHC energies [31]. To draw a definite conclusion, measurements of identified particle NMF $R^{\mathrm{ID}}_{p\mathrm{Pb}}(p_T)$ are needed. Such measurements will provide vital information on cold nuclear matter effects and will constrain the main parameters of shadowing functions used within different models.

IV. CONCLUSION

In conclusion, even with a small sample of 10^6 events, the study of $R_{p\mathrm{Pb}}(p_T)$ or central relative to peripheral NMF $[R_{\mathrm{CP}}(p_T)]$ could provide a definitive constraint on nuclear shadowing implemented within different pQCD-inspired models and CGC saturation models, with high impact on the interpretation or reinterpretation of the bulk and hard probes for nucleus-nucleus (Pb + Pb) collisions at LHC energies.

For central ($N_{\mathrm{coll}} = 12$) $p+\mathrm{Pb}$ collisions, HIJING-type models predict smaller values of nuclear modification factors $[R_{p\mathrm{Pb}}(p_T)]$ than in MB events. The possibility of triggering the highest multiplicity tails of transverse momentum spectra in $p+\mathrm{Pb}$ collisions will open the way to study collective phenomena in proton nucleus interactions with superdense nuclear cores, where the average number of binary collisions could increase to $N_{\mathrm{coll}} > 12$. These measurements will provide a stringent test of the phenomenological models discussed in this paper.

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[1] K. Adcox *et al.* (PHENIX Collaboration), Nucl. Phys. A **757**, 184 (2005); J. Adams *et al.* (STAR Collaboration), *ibid.* **757**, 102 (2005); B. B. Back *et al.* (PHOBOS Collaboration), *ibid.* **757**, 28 (2005); I. Arsene *et al.* (BRAHMS Collaboration), *ibid.* **757**, 1 (2005).

[2] M. Gyulassy and L. McLerran, Nucl. Phys. A **750**, 30 (2005).

[3] N. Armesto, N. Borghini, S. Jeon, U. A. Wiedemann (eds.), S. Abreu, V. Akkelin, J. Alam, J. L. Albacete *et al.*, J. Phys. G **35**, 054001 (2008); V. Topor Pop, J. Barrette, C. Gale, S. Jeon, and M. Gyulassy, *ibid.* p. 15, 57; H. Fujii, F. Gelis, A. Stasto, and R. Venugopolan, *ibid.* p. 34; K. L. Tuchin, *ibid.* p. 43; B. Z. Kopeliovich, I. K. Potaashnikova, and I. Schmidt, *ibid.* p. 103; I. Vitev, *ibid.* p. 154.

[4] K. J. Eskola, V. J. Kolhinen, and C. A. Salgado, Eur. Phys. J. C **9**, 61 (1999).

[5] K. J. Eskola, H. Paukkunen, and C. A. Salgado, J. High Energy Phys. 07 (2008) 102.

[6] K. J. Eskola, H. Paukkunen, and C. A. Salgado, J. High Energy Phys. 04 (2009) 065.

[7] A. Accardi, F. Arleo, N. Armesto, R. Baier, D. G. d'Enterria, R. J. Fries, O. Kodolova, I. P. Lokhtin, A. Morsch, A. Nikitenko *et al.*, arXiv:hep-ph/0310274; A. Accardi, N. Armesto, M. Botje, S. J. Brodsky, B. Cole, K. J. Eskola, G. I. Fai, L. Frankfurt, R. J. Fries, W. M. Geist *et al.*, arXiv:hep-ph/0308248; N. Armesto, J. Phys. G **32**, R367 (2006).

[8] K. J. Eskola, H. Paukkunen, and C. A. Salgado, Nucl. Phys. A **855**, 150 (2011).

[9] C. A. Salgado, J. Alvarez-Muñiz, F. Arleo, N. Armesto, M. Botje, M. Cacciari, J. Campbell, C. Carli, B. Cole, D. D. Enteria *et al.*, J. Phys. G **39**, 015010 (2012).

[10] P. Quiroga-Arias, J. G. Milhano, and U. A. Wiedemann, Phys. Rev. C **82**, 034903 (2010).

[11] Y. Shutz and U. A. Wiedemann (eds.), *Proceedings of the 22nd International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions* (Annecy, France, 2011), J. Phys. G: Nucl. Part. Phys. **38**, 120301 (2011).

[12] G. Altarelli and G. Parisi, Nucl. Phys. B **126**, 298 (1977).

[13] P. Levai, Phys. Rev. C **84**, 044909 (2011); G. G. Barnafoldi, G. Fai, P. Levai, B. A. Cole, and G. Papp, Indian J. Phys. **84**, 1721 (2010); B. A. Cole, G. G. Barnafoldi, P. Levai, G. Papp, and G. Fai, arXiv:hep-ph/0702101.

[14] D. Kharzeev, Y. V. Kovchegov, and K. Tuchin, Phys. Rev. D **68**, 094013 (2003); Phys. Lett. B **599**, 23 (2004).

[15] D. Kharzeev, E. Levin, and M. Nardi, Nucl. Phys. A **747**, 609 (2005).
[16] J. Jalilian-Marian and A. H. Rezaeian, Phys. Rev. D **85**, 014017 (2012).
[17] J. L. Albacete and C. Marquet, Phys. Lett. B **687**, 174 (2010); J. Phys. Conf. Ser. **270**, 012052 (2011).
[18] W. A. Horowitz and M. Gyulassy, Nucl. Phys. A **872**, 265 (2011).
[19] W. A. Horowitz and M. Gyulassy, J. Phys. G **35**, 104152 (2008); Phys. Lett. B **666**, 320 (2008); J. Noronha, M. Gyulassy, and G. Torrieri, Phys. Rev. C **82**, 054903 (2010).
[20] Larry McLerran, Acta Phys. Polon. B **41**, 2799 (2010).
[21] F. Gelis, E. Iancu, J. Jalilian-Marian, and R. Venugopalan, Annu. Rev. Nucl. Part. Sci. **60**, 463 (2010).
[22] N. Armesto, C. A. Salgado, and U. A. Wiedemann, Phys. Rev. Lett. **94**, 022002 (2005).
[23] [http://physics.baruch.cuny.edu/node/people/adumitru/res_cgc].
[24] A. Kormilitzin, E. Levin, and A. H. Rezaeian, Nucl. Phys. A **860**, 84 (2011); A. H. Rezaeian and A. Schafer, Phys. Rev. D **81**, 114032 (2010).
[25] J. L. Albacete and A. Dumitru, arXiv:1011.5161 [hep-ph].
[26] E. Levin and A. H. Rezaeian, Phys. Rev. D **82**, 054003 (2010); **82**, 014022 (2010); **83**, 114001 (2011).
[27] P. Tribedy and R. Venugopalan, arXiv:1112.2445 [hep-ph].
[28] A. Dumitru and E. Petreska, arXiv:1112.4760 [hep-ph].
[29] X.-N. Wang and M. Gyulassy, Phys. Rev. Lett. **68**, 1480 (1992); Phys. Rev. D **44**, 3501 (1991).
[30] W.-T. Deng, X.-N. Wang, and R. Xu, Phys. Rev. C **83**, 014915 (2011); Phys. Lett. B **701**, 133 (2011).
[31] V. Topor Pop, M. Gyulassy, J. Barrette, and C. Gale, Phys. Rev. C **84**, 044909 (2011); V. Topor Pop, M. Gyulassy, J. Barrette, C. Gale, and A. Warburton, *ibid.* **83**, 024902 (2011).
[32] B. Andersson, G. Gustafson, and B. Nilsson-Almqvist, Nucl. Phys. B **281**, 289 (1987); B. Nilsson-Almqvist and E. Stenlund, Comput. Phys. Commun. **43**, 387 (1987).
[33] H.-U. Bengtsson and T. Sjostrand, Comput. Phys. Commun. **46**, 43 (1987).
[34] P. Levai, D. Berenyi, A. Pasztor, and V. V. Skokov, J. Phys. G **38**, 124155 (2011).
[35] D. W. Duke and J. F. Owens, Phys. Rev. D **30**, 49 (1984).
[36] M. Gluck, E. Reya, and A. Vogt, Z. Phys. C **67**, 433 (1995).
[37] J. W. Harris (ALICE Collaboration), arXiv:1111.4651 [nucl-ex].
[38] S. J. Brodsky, J. F. Gunion, and J. H. Kuhn, Phys. Rev. Lett. **39**, 1120 (1977).
[39] A. Adil and M. Gyulassy, Phys. Rev. C **72**, 034907 (2005).
[40] S.-Y. Li and X.-N. Wang, Phys. Lett. B **527**, 85 (2002).
[41] B. A. Kniehl, G. Kramer, and B. Potter, Nucl. Phys. B **582**, 514 (2000).
[42] L. McLerran and R. Venugopalan, Phys. Rev. D **49**, 2233 (1994).
[43] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **98**, 172302 (2007).