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Nuclear modification of high transverse momentum particle production in p + A collisions at RHIC and LHC

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ABSTRACT

We present results and predictions for the nuclear modification of the differential cross sections for inclusive light hadron and prompt photon production in minimum bias d + Au collisions at $\sqrt{s} = 200$ GeV and minimum bias p + Pb collisions at $\sqrt{s} = 5$ TeV at RHIC and LHC, respectively. Our calculations combine the leading order perturbative QCD formalism with cold nuclear matter effects that arise from the elastic, inelastic and coherent multiple scattering of partons in large nuclei. We find that a theoretical approach that includes the isospin effect, Cronin effect, cold nuclear matter energy loss and dynamical shadowing can describe the RHIC d + Au data rather well. The LHC p + Pb predictions will soon be confronted by new experimental results to help clarify the magnitude and origin of cold nuclear matter effects and facilitate precision dense QCD matter tomography.

1. Introduction

Medium-induced modification of high transverse momentum (p_T) particle production in nucleus collisions (p + A, A + A) relative to the naive binary collision-scaled proton–proton (p + p) baseline expectation is a powerful probe of the properties of dense QCD matter. In particular, the nuclear modification in d + Au collisions at RHIC and the forthcoming p + Pb results at the LHC can provide valuable information on the elastic, inelastic and coherent multiple parton scattering processes inside a large nucleus and are vital testing grounds for novel nontrivial QCD dynamics [1]. The manifestation of such nontrivial QCD dynamics in p + A reactions is usually referred to as cold nuclear matter (CNM) effects, as opposed to the effects of parton and particle formation and propagation in the ambiance of the quark-gluon plasma created in high energy A + A collisions [2].

There have been several different approaches to studying CNM effects. One of them is based on the leading-twist perturbative QCD factorization and attributes all these effects to universal nuclear parton distribution functions (nPDFs), which are the only ingredients different from the case of p + p collisions [3–5]. Through a global fitting procedure to fix the parametrization of nPDFs, this approach can describe part of the RHIC d + Au data reasonably well and has made predictions for p + Pb collisions [6–8]. Another approach is the so-called Color Glass Condensate (CGC) approach [9–14]. It focuses on non-linear corrections to QCD evolution equations in very dense gluonic systems and is only applicable in the very small-x region – the so-called classical gluon saturation regime. Various predictions for the p + Pb run have also been made based on CGC approach, see Refs. [12–14]. There are also calculations and predictions for the nuclear modification factor in Monte Carlo models such as HIJING [15].

In this manuscript we follow an approach different from the above mentioned. It is based on perturbative QCD factorization and CNM effects are implemented separately within the formalism. The advantage of this approach is that all CNM effects have clear physical origin, mostly centered around the idea of multiple parton scattering [16]. Thus, they can be calculated and their implementations is well documented in the literature. They are also process-dependent. In this manuscript we discuss the isospin effect, Cronin effect, cold nuclear matter energy loss, and dynamical shadowing. The isospin effect is easily incorporated by replacing the nPDFs by the Z, $A - Z$-weighted average of proton and neutron PDFs [17,18]. Theoretical interpretations of the Cronin effect are reviewed in [19] and our implementation is via initial-state parton transverse momentum broadening. Initial-state cold nuclear matter parton energy loss was calculated in [20,21]. Nuclear shadowing can be implemented as coherent power corrections to the differential particle production cross section [22,23]. A perturbative QCD formalism with these effects incorporated can be used to

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understand the qualitative and in most cases quantitative features of the nuclear modification in p + A (or d + A) collisions observed at CERN SPS and RHIC experiments [23–26]. In anticipation of the new LHC p + Pb results we present predictions in the framework of this approach to incorporating CNM effects. Specifically, we focus on inclusive particle production in d + Au and p + Pb collisions and show results for the nuclear modification factor of neutral pions, charged hadrons and prompt photons.

This Letter is organized as follows. In Section 2, we present our approach to studying CNM effects. We first review the basic perturbative QCD formalism for single inclusive particle production in p + p collisions. We then discuss how various CNM effects are incorporated in this formalism. In Section 3, we implement these CNM effects and show that the formalism can describe particle production in d + Au collisions at RHIC energies. We then present our theoretical model predictions for the upcoming p + Pb collision results at the LHC. We summarize our Letter in Section 4.

2. Single inclusive particle production

In this section we review the basic perturbative QCD formalism for single inclusive particle production in p + p collisions. In particular, we focus on light hadron and prompt photon production. We then discuss the incorporation of various cold nuclear matter effects within this formalism. Specifically, we comment on the isospin effect, Cronin effect, cold nuclear matter energy loss and dynamical shadowing.

2.1. Basic pQCD formalism

To leading order in the framework of factorized perturbative QCD, single inclusive hadron production in p+p collisions, $p(p_1) + p(p_2) \to h(p_h) + X$, can be written as follows [27]:

$$\frac{d\sigma}{dy\, d^2p_T} = K\frac{\alpha_s^2}{s}\sum_{a,b,c}\int\frac{dx_a}{x_a}\,d^2k_{aT}\, f_{a/N}\big(x_a, k_{aT}^2\big) \times \int\frac{dx_b}{x_b}\,d^2k_{bT}\, f_{b/N}\big(x_b, k_{bT}^2\big) \times \int\frac{dz_c}{z_c^2}D_{h/c}(z_c)H_{ab\to c}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u}), \tag{1}$$

where y and p_T are the rapidity and transverse momentum of the produced hadron and $\sum_{a,b,c}$ runs over all parton flavors. In Eq. (1) $s = (p_1 + p_2)^2$, $D_{h/c}(z_c)$ is the fragmentation function (FF) of parton c into hadron h, $H_{ab\to c}(\hat{s},\hat{t},\hat{u})$ are the hard-scattering coefficient functions with $\hat{s},\hat{t},\hat{u}$ being the usual partonic Mandelstam variables [27,28]. We also include a phenomenological K-factor to account for higher order QCD contributions [17,29]. $f_{a,b/N}(x, k_T^2)$ are the parton distribution functions with longitudinal momentum fraction x and transverse momentum component k_T. We have included this k_T-dependence in order to incorporate the Cronin effect in p + A collisions. We assume a Gaussian form in this variable [17,27],

$$f_{a/N}\big(x_a, k_{aT}^2\big) = f_{a/N}(x_a)\frac{1}{\pi\langle k_T^2\rangle}e^{-k_{aT}^2/\langle k_T^2\rangle}, \tag{2}$$

where $f_{a/N}(x_a)$ are the usual collinear PDFs in a nucleon.

On the other hand, prompt photon production in p+p collisions has two components – the so-called direct and fragmentation contributions [27,30]:

$$\frac{d\sigma}{dy\, d^2p_T} = \frac{d\sigma^{\text{dir.}}}{dy\, d^2p_T} + \frac{d\sigma^{\text{frag.}}}{dy\, d^2p_T}. \tag{3}$$

The fragmentation contribution is given by

$$\frac{d\sigma^{\text{frag.}}}{dy\, d^2p_T} = K\frac{\alpha_s^2}{s}\sum_{a,b,c}\int\frac{dx_a}{x_a}\,d^2k_{aT}\, f_{a/N}\big(x_a, k_{aT}^2\big) \times \int\frac{dx_b}{x_b}\,d^2k_{bT}\, f_{b/N}\big(x_b, k_{bT}^2\big) \times \int\frac{dz_c}{z_c^2}D_{\gamma/c}(z_c)H_{ab\to c}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u}). \tag{4}$$

In other words, it is exactly the same as Eq. (1) if one replaces the parton-to-hadron FF $D_{h/c}(z_c)$ by the parton-to-photon FF $D_{\gamma/c}(z_c)$. On the other hand, the direct contribution can be written as

$$\frac{d\sigma^{\text{dir.}}}{dy\, d^2p_T} = K\frac{\alpha_{\text{em}}\alpha_s}{s}\sum_{a,b}\int\frac{dx_a}{x_a}\,d^2k_{aT}\, f_{a/N}\big(x_a, k_{aT}^2\big) \times \int\frac{dx_b}{x_b}\,d^2k_{bT}\, f_{b/N}\big(x_b, k_{bT}^2\big)H_{ab\to\gamma}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u}), \tag{5}$$

where $H_{ab\to\gamma}$ are the well-known partonic hard-scattering functions for direct photon production [27,31,32].

In the numerical calculations we choose $\langle k_T^2\rangle_{pp} = 1.8\ \text{GeV}^2$ in p + p collisions [24,25]. We use CTEQ6L1 PDFs [33], fDSS parametrization for parton-to-hadron FFs [34] and GRV parametrization for parton-to-photon FFs [35]. We fix the factorization and renormalization scales to the transverse momentum of the produced particle, $\mu_f = \mu_r = p_T$. We find that an $\mathcal{O}(1)$ K-factor can give a good description of hadron production in both RHIC and LHC energies, see Fig. 1. For prompt photons the K-factor values are slightly larger and also $\sqrt{s}$-dependent but, importantly, the shape is well-described. In the left panel of Fig. 1, we compare our calculation to RHIC photon and π^0 data at $\sqrt{s} = 200$ GeV [36,37]. We also consider LHC photon data at $\sqrt{s} = 7$ TeV [38] and charged hadron data at $\sqrt{s} = 2.76$ TeV [39], shown in the right panel. The leading order pQCD formalism provides a reasonable baseline description of particle production in p + p collisions. The precise value of the K-factor is not important for the study of the nuclear modification of inclusive particle cross sections in p + A collisions (it cancels in ratios). We will incorporate nuclear effects relevant to p+A reactions in this formalism in the next subsection.

2.2. Cold nuclear matter effects

The p + A (e.g. d + Au or p + Pb) nuclear modification factor R_{pA} is usually defined as

$$R_{pA} = \frac{1}{\langle N_{\text{coll}}\rangle}\frac{d\sigma_{pA}}{dy\, d^2p_T}\Big/\frac{d\sigma_{pp}}{dy\, d^2p_T}, \tag{6}$$

where $\langle N_{\text{coll}}\rangle$ is the average number of binary collisions. The deviation of R_{pA} from unity reveals the presence of CNM effects in p + A collisions. A variety of CNM effects can affect particle production. In this manuscript we discuss the ones that have been theoretically evaluated as arising from the elastic, inelastic and coherent scattering of partons in large nuclei [16]. We also account for the proton and neutron composition of the interacting nucleus. In particular, we implement the isospin effect, Cronin effect, cold nuclear matter energy loss and dynamical shadowing. These effects have been well documented in the literature. We give a brief overview of their implementation in preparation for LHC predictions.

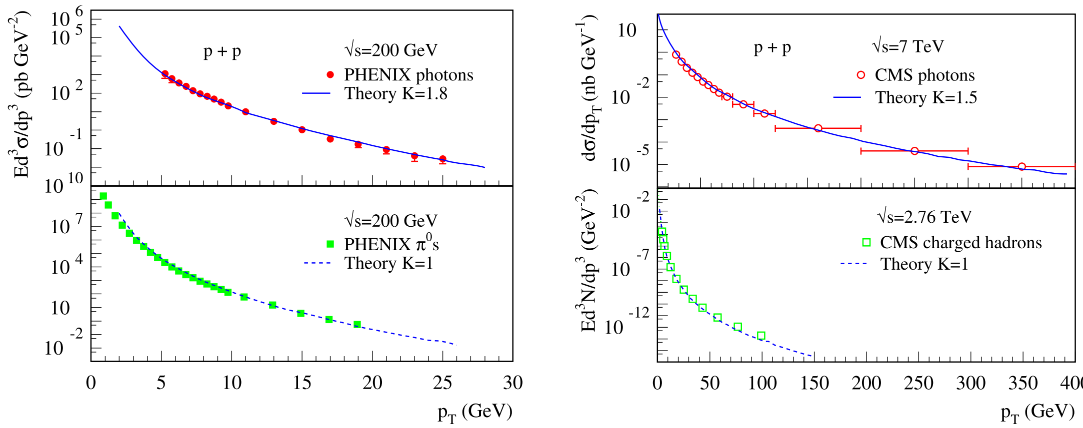

Fig. 1. Left panel: our calculation at $\sqrt{s} = 200$ GeV and rapidity $y = 0$ is compared to RHIC photon data (top) [36] and π^0 data (bottom) [37]. We choose $K = 1$ for π^0 and $K = 1.8$ for photon production. Right panel: comparison to LHC photon data at $\sqrt{s} = 7$ TeV and $|y| < 0.9$ [38] and charged hadron data at $\sqrt{s} = 2.76$ TeV and $|y| < 1$ [39]. We choose $K = 1.5$ for photon and $K = 1$ for charged hadron production.

Isospin effect. Isospin effect can be easily accounted for on average in the nPDFs for a nucleus with atomic mass A and Z protons via [17,18]:

$$f_{a/A}(x) = \frac{Z}{A} f_{a/p}(x) + \left(1 - \frac{Z}{A}\right) f_{a/n}(x). \tag{7}$$

In Eq. (7), $f_{a/p}(x)$ and $f_{a/n}(x)$ are the PDFs inside a proton and neutron, respectively. The PDFs in the neutron are related to the PDFs in the proton via isospin symmetry.

Cronin effect. Theoretical approaches to understanding the Cronin effect are well documented in [19]. It can be modeled via multiple initial-state scatterings of the partons in cold nuclei and the corresponding induced parton transverse momentum broadening [40,41]. In particular, if the parton distribution function $f_{b/A}(x_b, k_{b,T}^2)$ has a normalized Gaussian form, the random elastic scattering induces further k_T-broadening in the nucleus [17,29]:

$$\langle k_{b,T}^2 \rangle_{pA} = \langle k_{b,T}^2 \rangle_{pp} + \left\langle \frac{2\mu^2 L}{\lambda_{q,g}} \right\rangle \zeta. \tag{8}$$

Here $k_{b,T}$ is the transverse momentum component for the parton prior to the hard scattering, $\zeta = \ln(1 + \delta p_T^2)$ [24,25], and we choose $\delta = 0.14$ GeV^{-2}, $\mu^2 = 0.12$ GeV^2, $\lambda_g = C_F/C_A \lambda_q = 1$ fm. These parameters can describe reasonably well RHIC data.

Cold nuclear matter energy loss. As the parton from the proton undergoes multiple scattering in the nucleus before the hard collisions, it can lose energy due to medium-induced gluon bremsstrahlung. This effect can be easily implemented as a momentum fraction shift in the PDFs

$$f_{q/p}(x_a) \rightarrow f_{q/p}\left(\frac{x_a}{1 - \epsilon_{\text{eff.}}}\right),$$
$$f_{g/p}(x_a) \rightarrow f_{g/p}\left(\frac{x_a}{1 - \epsilon_{\text{eff.}}}\right). \tag{9}$$

Ideally, Eq. (9) should include a convolution over the probability distribution of cold nuclear matter energy loss [43]. However, concurrent implementation of such distribution together with the Cronin effect and coherent power corrections is computationally very demanding. The main effect of the fluctuations due to multiple gluon emission is an effective reduced fractional energy loss $\epsilon_{\text{eff.}}$ relative to the mean value $\langle \epsilon \rangle = \langle \sum_i \frac{\Delta E_i}{E} \rangle$. Here, the sum runs over all medium-induced gluons. In this work we follow Ref. [42] and use $\epsilon_{\text{eff.}} = 0.7\langle \epsilon \rangle$. The average cold nuclear matter energy loss is obtained by integrating the initial-state medium-induced bremsstrahlung spectrum, first derived in [20]. It also depends on the typical transverse momentum transfer squared μ^2 per interaction between the parton and the medium and the gluon mean free path λ_g. For this reason, the parameters are constrained to be the same as in the implementation of the Cronin effect, $\mu^2 = 0.12$ GeV^2 and $\lambda_g = 1$ fm in our comparison to RHIC data in the next section. This calculation of initial-state cold nuclear matter energy loss has been shown to give a good description of the nuclear modification of Drell–Yan production in fixed target experiments [43].

Dynamical shadowing. Power-suppressed resummed coherent final-sate scattering of the struck partons leads to shadowing effects (suppression of the cross section in the small-x region) [23]. The effect can be interpreted as a generation of dynamical parton mass in the background gluon field of the nucleus [44]. It is included via:

$$x_b \rightarrow x_b\left(1 + C_d \frac{\xi^2 (A^{1/3} - 1)}{-\hat{t}}\right), \tag{10}$$

where x_b is the parton momentum fraction inside the target nucleus, $C_d = C_F(C_A)$ if the parton $d = q(g)$ in the partonic scattering $ab \rightarrow cd$. ξ^2 represents a characteristic scale of the multiple scattering per nucleon. In the RHIC energy range $\sqrt{s} = 200$ GeV, $\xi_q^2 = C_F/C_A \xi_g^2 = 0.12$ GeV^2 [22,23] can give a good description for nuclear modification in d + Au collisions for both single hadron and di-hadron production [23,26].

3. Theoretical model predictions in p + A collisions

In this section we compare our theoretical model predictions to existing light hadron and direct photon data in minimum bias d + Au reactions at RHIC at $\sqrt{s} = 200$ GeV. We also present predictions for these inclusive final states in minimum bias p + Pb collisions at the LHC at $\sqrt{s} = 5$ TeV. It should be understood that in nucleus collisions we quote the center-of-mass energy per nucleon pair.

3.1. Nuclear modification factor in d + Au reactions at RHIC

We have incorporated the cold nuclear matter effects discussed in the previous section into the leading order pQCD photon and hadron production formalism, Eqs. (1) and (4), (5). Such theoretical approach is able to give a good description of single

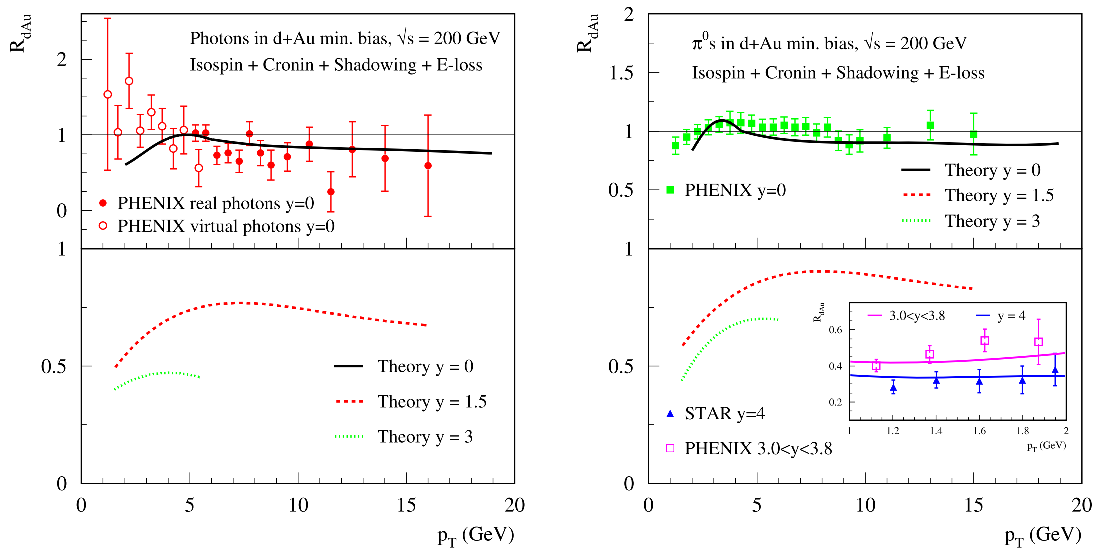

Fig. 2. The nuclear modification factor R_{dAu} is plotted as a function of transverse momentum p_T for photons (left panel) and π^0s (right panel) at RHIC energy of $\sqrt{s} =$ 200 GeV. Empty and filled circles are low-mss virtual photon and real photon experimental data at mid-rapidity from PHENIX [36]. Filled squares are the minimum bias mid-rapidity π^0 data [45], filled triangles are the forward rapidity $y = 4$ STAR π^0 data [47], and empty squares are the forward rapidity $3 < y < 3.8$ PHENIX π^0s [46]. We have also presented predictions for rapidity $y = 1.5$ (dashed curves) and $y = 3$ (dotted curves) for both photon and hadron production.

inclusive particle production in d + Au collisions at RHIC energies. While such calculations have been presented in the past, in this manuscript we extend our results to direct photons at forward rapidity. In Fig. 2 we plot the minimum bias nuclear modification factor R_{dAu} as a function of transverse momentum for both photon (left panel) and π^0 (right panel) production at $\sqrt{s} = 200$ GeV. The photon data is from the PHENIX collaboration at rapidity $y = 0$ [36]. For π^0s we have included both mid-rapidity $y = 0$ [45] and forward rapidity $3 < y < 3.8$ [46] PHENIX data, and forward rapidity $y = 4$ STAR data [47]. We conclude that implementation of cold nuclear matter effects based on the physics of multiple parton scattering in dense QCD matter can describe both photon and hadron data quite well at mid and forward rapidities. With the future RHIC upgrade program in mind, we also show predictions for the nuclear modification factor R_{dAu} for photon and π^0 production in different kinematic regions: the dashed curves are for $y = 1.5$ and the dotted curves are for $y = 3$.

3.2. Predictions for the p + Pb run at the LHC

We are now in good position to present predictions for minimum bias p + Pb reactions at the LHC energy of $\sqrt{s} = 5$ TeV. These results will soon be confronted by new experimental data. The main parameters in our approach include: the Cronin momentum broadening parameters $\mu^2, \lambda_{q,g}$, which also determine the cold nuclear matter energy loss, and the dynamical shadowing parameter ξ^2. As emphasized in [31], $\mu^2/\lambda_{q,g}$ and ξ^2 represent the strength of the multiple scattering between the incoming and outgoing partons and the target nucleus, thus proportional to the number of the soft gluons in the nuclear medium. Following [31], beyond the possibility of fixed ξ^2, which we take as the lower limit for this parameter, we study a scenario where $\xi^2 \propto \sigma_{in}$, the inelastic nucleon–nucleon scattering cross section. Taking into account that $\sigma_{in} = 42$ mb [48] at RHIC energy of $\sqrt{s} = 200$ GeV and $\sigma_{in} = 70$ mb [49] at the LHC energy $\sqrt{s} = 5$ TeV, we consider a potential increase in the ξ^2 parameter by 67%. Specifically, for the upper limit of this parameter we take $\xi^2 = 0.20$ GeV^2 in our prediction for the LHC p+Pb run at $\sqrt{s} = 5$ TeV. We will also consider a correlated enhancement in μ^2/λ_g.

In Fig. 3 we present our theoretical model predictions for the nuclear modification factor R_{pPb} as a function of p_T for neutral pion (left panel) and charged hadron (right panel) production in minimum bias p + Pb collisions at the LHC energy of $\sqrt{s} = 5$ TeV. Rapidities $y = 0$ (top), $y = 2$ (middle), and $y = 4$ (bottom) were considered. The upper edge of the bands corresponds to the RHIC parameters $(\mu^2, \xi^2) = (0.12, 0.12)$ GeV^2. The lower edge corresponds to a potential enhancement of these parameters as discussed above, $(\mu^2, \xi^2) = (0.2, 0.2)$ GeV^2, to be tested against the experimental data. In Fig. 4 we present similar results for prompt photon production.

The general features of these nuclear modification factors are very similar to the ones observed at RHIC energies. At mid-rapidity $y = 0$, there is a very small "Cronin peak" in the low p_T region. The peak is very close to unity and not as pronounced as the one observed in low energy fixed target experiments. This is because the dynamical shadowing becomes important and strongly suppress the particle production in this region. Furthermore, initial-state energy loss is larger due to the bigger contribution of diagrams with incoming gluons to the cross section. At high p_T we still have ∼15% suppression, which is also due to the cold nuclear matter energy loss. In general, at forward rapidity all CNM effects are amplified due to the larger values of the momentum fraction x_a from the incoming proton (relevant to cold nuclear matter energy loss), the smaller values of the momentum fraction x_b of the incoming nucleus (relevant to dynamical shadowing) and the steeper falling spectra (relevant to the Cronin effect). As a result, at forward rapidity and at low p_T the dynamic shadowing effect can be most important and lead to stronger suppression of inclusive particle production while at high p_T the suppression is a combined effect of cold nuclear matter energy loss and the Cronin effect. Finally, the behavior of the R_{pPb} for π^0s, charged hadrons and direct photons is qualitatively the same and the quantitative differences are minor.

It is interesting to point out that our predictions for inclusive particle suppression at forward rapidities are for observable effects that are stronger than the effects found in calculations using EPS09

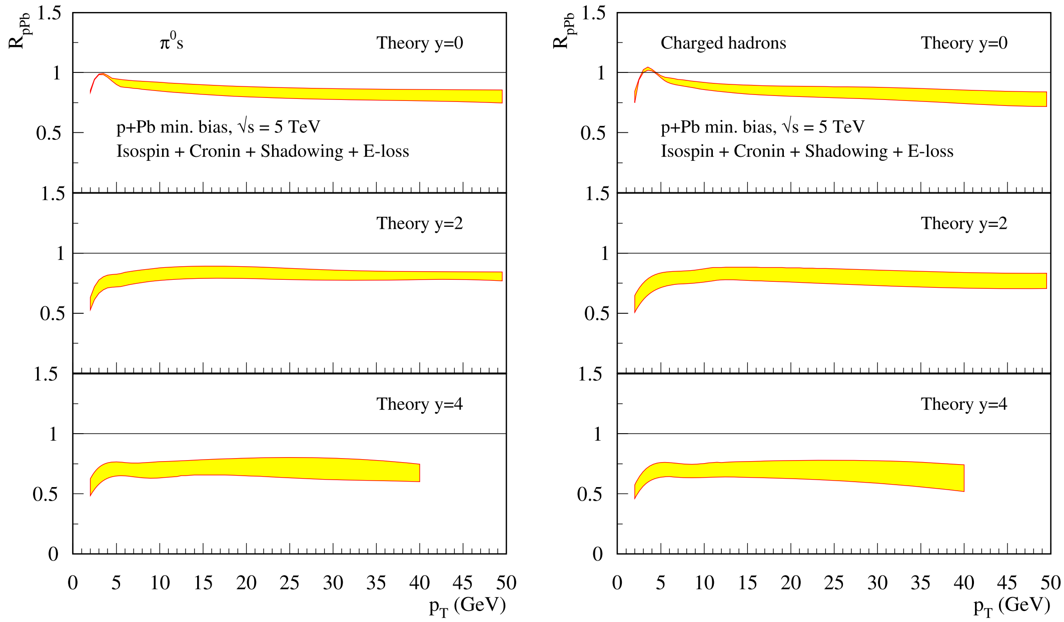

Fig. 3. Predictions for the nuclear modification factor R_{pPb} as a function of transverse momentum p_T for π^0 (left panel) and charged hadron (right panel) production in minimum bias $\mathrm{p}+\mathrm{Pb}$ collisions at the LHC energy of $\sqrt{s}=5$ TeV. Results for three rapidities $y=0$, $y=2$, and $y=4$ are shown.

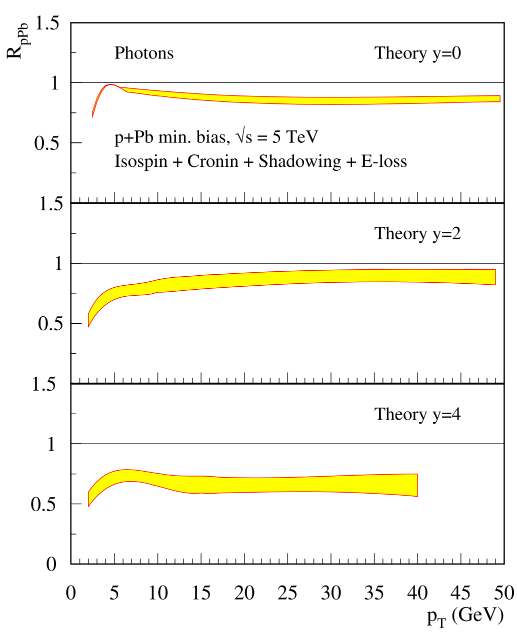

Fig. 4. Predictions for the nuclear modification factor R_{pPb} as a function of transverse momentum p_T for photon production in minimum bias $\mathrm{p}+\mathrm{Pb}$ collisions at the LHC energy of $\sqrt{s}=5$ TeV for rapidities $y=0$, $y=2$, and $y=4$.

nuclear PDFs. On the other hand, they lead to weaker suppression than the CGC predictions from a hybrid formalism in rc-BK-MC approach [8,14]. In other words, our predictions fall between EPS09 and CGC based approaches.

4. Summary

We studied the nuclear modification of high transverse momentum particle production in minimum bias $\mathrm{d}+\mathrm{Au}$ and $\mathrm{p}+\mathrm{Pb}$ collisions at RHIC and LHC, respectively. Such nuclear modification is manifestation of nontrivial and not yet fully understood QCD dynamics in large nuclei. It is, therefore, critical to further our understanding of high energy nuclear reactions through concurrent theoretical advances and comparison of model predictions to precise experimental data. With this motivation, we presented results from a theoretical approach that combines the leading order perturbative QCD baseline calculation of inclusive light hadron and photon production with cold nuclear matter effects that arise from the elastic, inelastic and coherent parton scattering in large nuclei. Our numerical simulations included the isospin effect, Cronin effect, cold nuclear matter energy loss and resummed QCD power corrections to the leading twist results. We found that this approach can describe quite well the nuclear modification factor in $\sqrt{s}=200$ GeV $\mathrm{d}+\mathrm{Au}$ collisions at the RHIC for both photon and light hadron production, including mid and forward rapidities. Detailed theoretical model predictions were then presented for inclusive particle production relevant to the recently completed $\mathrm{p}+\mathrm{Pb}$ run at $\sqrt{s}=5$ TeV at the LHC. Our results for the nuclear modification of light hadrons and photons at forward rapidities fall between the ones based on EPS09 shadowing parameterization and CGC approaches. These predictions will soon be confronted by new experimental data to help constrain the magnitude and clarify the origin of cold nuclear matter effects. Within the framework of our approach, such comparison will also shed light on the transport properties of cold nuclear matter.

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References

[1] C.A. Salgado, J. Alvarez-Muniz, F. Arleo, N. Armesto, M. Botje, M. Cacciari, J. Campbell, C. Carli, et al., J. Phys. G 39 (2012) 015010, arXiv:1105.3919 [hep-ph].
[2] M. Gyulassy, I. Vitev, X.-N. Wang, B.-W. Zhang, in: R.C. Hwa, et al. (Eds.), Quark Gluon Plasma, nucl-th/0302077.
[3] K.J. Eskola, H. Paukkunen, C.A. Salgado, JHEP 0904 (2009) 065, arXiv:0902.4154 [hep-ph].

[4] M. Hirai, S. Kumano, T.-H. Nagai, Phys. Rev. C 76 (2007) 065207, arXiv:0709.3038 [hep-ph].
[5] D. de Florian, R. Sassot, P. Zurita, M. Stratmann, Phys. Rev. D 85 (2012) 074028, arXiv:1112.6324 [hep-ph].
[6] P. Quiroga-Arias, J.G. Milhano, U.A. Wiedemann, Phys. Rev. C 82 (2010) 034903, arXiv:1002.2537 [hep-ph].
[7] G.G. Barnafoldi, J. Barrette, M. Gyulassy, P. Levai, V. Topor Pop, Phys. Rev. C 85 (2012) 024903, arXiv:1111.3646 [nucl-th].
[8] See also, F. Arleo, K.J. Eskola, H. Paukkunen, C.A. Salgado, JHEP 1104 (2011) 055, arXiv:1103.1471 [hep-ph].
[9] L.D. McLerran, R. Venugopalan, Phys. Rev. D 49 (1994) 2233, hep-ph/9309289.
[10] D. Kharzeev, Y.V. Kovchegov, K. Tuchin, Phys. Rev. D 68 (2003) 094013, hep-ph/0307037.
[11] J.L. Albacete, C. Marquet, Phys. Lett. B 687 (2010) 174, arXiv:1001.1378 [hep-ph].
[12] P. Tribedy, R. Venugopalan, Phys. Lett. B 710 (2012) 125, arXiv:1112.2445 [hep-ph].
[13] J. Jalilian-Marian, A.H. Rezaeian, Phys. Rev. D 85 (2012) 014017, arXiv:1110.2810 [hep-ph].
[14] J.L. Albacete, A. Dumitru, H. Fujii, Y. Nara, arXiv:1209.2001 [hep-ph].
[15] R. Xu, W.-T. Deng, X.-N. Wang, arXiv:1204.1998 [nucl-th].
[16] I. Vitev, J.T. Goldman, M.B. Johnson, J.W. Qiu, Phys. Rev. D 74 (2006) 054010, hep-ph/0605200.
[17] X.-N. Wang, Phys. Rev. C 61 (2000) 064910, nucl-th/9812021.
[18] See, for example: Z.-B. Kang, J.-W. Qiu, W. Vogelsang, Phys. Rev. D 79 (2009) 054007, arXiv:0811.3662 [hep-ph].
[19] A. Accardi, hep-ph/0212148.
[20] I. Vitev, Phys. Rev. C 75 (2007) 064906, hep-ph/0703002.
[21] H. Xing, Y. Guo, E. Wang, X.-N. Wang, Nucl. Phys. A 879 (2012) 77, arXiv:1110.1903 [hep-ph].
[22] J.-w. Qiu, I. Vitev, Phys. Rev. Lett. 93 (2004) 262301, hep-ph/0309094.
[23] J.-w. Qiu, I. Vitev, Phys. Lett. B 632 (2006) 507, hep-ph/0405068.
[24] I. Vitev, Phys. Lett. B 562 (2003) 36, nucl-th/0302002.
[25] I. Vitev, M. Gyulassy, Phys. Rev. Lett. 89 (2002) 252301, hep-ph/0209161.
[26] Z.-B. Kang, I. Vitev, H. Xing, Phys. Rev. D 85 (2012) 054024, arXiv:1112.6021 [hep-ph].
[27] J.F. Owens, Rev. Mod. Phys. 59 (1987) 465.
[28] Z.-B. Kang, F. Yuan, Phys. Rev. D 81 (2010) 054007, arXiv:1001.0247 [hep-ph].
[29] I. Vitev, B.-W. Zhang, Phys. Lett. B 669 (2008) 337, arXiv:0804.3805 [hep-ph].
[30] L.E. Gordon, W. Vogelsang, Phys. Rev. D 48 (1993) 3136;
L. Gamberg, Z.-B. Kang, arXiv:1208.1962 [hep-ph].
[31] H. Xing, Z.-B. Kang, I. Vitev, E. Wang, arXiv:1206.1826 [hep-ph].
[32] Z.-B. Kang, I. Vitev, Phys. Rev. D 84 (2011) 014034, arXiv:1106.1493 [hep-ph].
[33] J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P.M. Nadolsky, W.K. Tung, JHEP 0207 (2002) 012, hep-ph/0201195.
[34] D. de Florian, R. Sassot, M. Stratmann, Phys. Rev. D 75 (2007) 114010, hep-ph/0703242.
[35] M. Gluck, E. Reya, A. Vogt, Phys. Rev. D 48 (1993) 116;
M. Gluck, E. Reya, A. Vogt, Phys. Rev. D 51 (1995) 1427.
[36] A. Adare, et al., PHENIX Collaboration, arXiv:1205.5533 [hep-ex].
[37] A. Adare, et al., PHENIX Collaboration, Phys. Rev. D 76 (2007) 051106, arXiv:0704.3599 [hep-ex].
[38] S. Chatrchyan, et al., CMS Collaboration, Phys. Rev. D 84 (2011) 052011, arXiv:1108.2044 [hep-ex].
[39] S. Chatrchyan, et al., CMS Collaboration, Eur. Phys. J. C 72 (2012) 1945, arXiv:1202.2554 [nucl-ex].
[40] Y. Zhang, G.I. Fai, G. Papp, G.G. Barnafoldi, P. Levai, Phys. Rev. C 65 (2002) 034903, hep-ph/0109233.
[41] G. Ovanesyan, I. Vitev, JHEP 1106 (2011) 080, arXiv:1103.1074 [hep-ph].
[42] R. Sharma, I. Vitev, B.-W. Zhang, Phys. Rev. C 80 (2009) 054902, arXiv:0904.0032 [hep-ph].
[43] R.B. Neufeld, I. Vitev, B.-W. Zhang, Phys. Lett. B 704 (2011) 590, arXiv:1010.3708 [hep-ph].
[44] J.-W. Qiu, I. Vitev, Phys. Lett. B 587 (2004) 52, hep-ph/0401062.
[45] S.S. Adler, et al., PHENIX Collaboration, Phys. Rev. Lett. 98 (2007) 172302, nucl-ex/0610036.
[46] A. Adare, et al., PHENIX Collaboration, Phys. Rev. Lett. 107 (2011) 172301, arXiv:1105.5112 [nucl-ex];
M. Chiu, Talk at the 22nd International Conference on Ultra-Relativistic Nucleus–Nucleus Collisions (Quark Matter 2011).
[47] J. Adams, et al., STAR Collaboration, Phys. Rev. Lett. 97 (2006) 152302, nucl-ex/0602011.
[48] M.L. Miller, K. Reygers, S.J. Sanders, P. Steinberg, Ann. Rev. Nucl. Part. Sci. 57 (2007) 205, nucl-ex/0701025.
[49] D.G. d'Enterria, nucl-ex/0302016;
See also D.G. d'Enterria, http://dde.web.cern.ch/dde/glauber_lhc.htm.