Nuclear modification of high-p_T hadron spectra in high-energy $p + A$ collisions

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Multiple parton scatterings in high-energy $p + A$ collisions involve multiparton correlation inside the projectile and color coherence of multiple jets, which will lead to nuclear modification of final hadron spectra relative to that in $p + p$ collisions. Such modifications of final hadron spectra in $p + A$ collisions are studied within the HIJING 2.1 model. Besides parton shadowing and transverse momentum broadening, which influence final hadron spectra at intermediate p_T, modification of parton flavor composition due to multiple scattering and hadronization of many-parton jets system are shown to lead to suppression of final hadrons at large p_T in $p + A$ collisions at the CERN Large Hadron Collider.

In the search for the formation of quark-gluon plasma (QGP) in high-energy heavy-ion collisions, jet quenching or suppression of high-p_T hadrons [1] can be used for tomographic study of medium properties [2,3]. However, initial multiple-parton scatterings in cold nuclei before the formation of QGP can also lead to nuclear modification of final high-p_T hadron spectra that needs to be understood for a quantitative study of QGP properties through jet quenching.

Parton shadowing or nuclear modification of parton distributions inside large nuclei is one of the most-studied cold nuclear effects. The QCD evolution, however, dramatically reduces the effect on final high-p_T hadron spectra in $p + A$ collisions [4–7]. Modification of parton distributions in the projectile nucleon through parton energy loss [8,9] is estimated to have a small effect on hadron spectra in the central rapidity region of high-energy $p + A$ collisions. These cold nuclear effects have also been studied within the color glass condensate (CGC) model [10–12]. However, multiple-parton correlations inside the projectile nucleon should also be considered. Energy momentum and valence quark number conservation alone could modify the momentum and flavor dependence of final-state parton and hadron spectra at large p_T. Hadronization of multiple-jet systems from multiple scattering in $p + A$ collisions could also affect final hadron spectra at intermediate and large p_T.

In this Rapid Communication, we study the nuclear modification of parton and hadron spectra due to parton shadowing, initial- and final-state transverse momentum broadening, final-state parton flavor composition, and hadronization of multiple jets within the HIJING [13] Monte Carlo model. It is based on a two-component model for hadron production in high-energy nucleon and nuclear collisions. The soft and hard components are separated by a cutoff p_0 in the transverse momentum exchange. Hard parton scatterings with $p_T > p_0$ are assumed to be described by the perturbative QCD (pQCD) and soft interactions are approximated by string excitations with an effective cross section σ_{soft}. In HIJING 2.0 [14], parton distribution functions (PDFs) are given by the Gluck-Reya-Vogt (GRV) parametrization [15]. An energy-dependent cutoff

$p_0(\sqrt{s})$ and soft cross section $\sigma_{\text{soft}}(\sqrt{s})$ are assumed in order to fit experimental values of the total and inelastic cross sections of $p + p/(\bar{p})$ collisions and the energy dependence of the central rapidity density of charged hadron multiplicities. HIJING 2.0 can describe most features of hadron production in $p + p$ collisions at colliding energies up to 7 TeV at the CERN Large Hadron Collider (LHC) [14].

Hard processes for parton scattering with $p_T > p_0$ in HIJING are based on the lowest order pQCD in which the single-jet inclusive cross section,

$$\frac{d\sigma_{pA}^{\text{jet}}}{dy_1 d^2 p_T} = K \int dy_2 d^2 b t_A(b) \sum_{a,b,c} x_1 f_{a/p}\left(x_1, p_T^2\right)$$
$$\times x_2 f_{a/A}\left(x_2, p_T^2, b\right) \frac{d\sigma_{ab \to cb}}{dt}, \quad (1)$$

in $p + A$ collisions is directly proportional to nuclear parton distributions $f_{a/A}(x_2, Q^2, b)$. Here $x_{1,2} = p_T(e^{\pm y_1} + e^{\pm y_2})/\sqrt{s}$ are fractional momenta of the initial partons, $y_{1,2}$ are rapidities of the final-state parton jets, and $K \approx 2$ accounts for higher-order corrections. The nuclear thickness function is normalized to $\int d^2 b t_A(b) = 1$.

One of the nuclear effects in hard processes in $p + A$ collisions that one has to consider is nuclear modification of initial parton distributions due to multiple scatterings. HIJING 2.0 employs a factorized form of PDFs in nuclei,

$$f_{a/A}(x, Q^2, b) = A R_a^A(x, Q^2, b) f_{a/N}(x, Q^2), \quad (2)$$

where Q is the momentum scale, b the impact parameter, x the momentum fraction carried by the parton a, and $R_a^A(x, Q^2, b)$ is the impact-parameter-dependent nuclear modification factor as given by the new HIJING parametrization [16]. The form of the nuclear-PDF (nPDF) modification in Ref. [16] was guided by the experimental data from deeply inelastic scattering (DIS) of nuclei. There are two parameters, s_q and s_g, that describe the nuclear shadowing for quark and gluon distributions, respectively, at small $x \ll 1$. The value $s_q = 0.1$ is determined by the nuclear DIS data and $s_g = 0.17$–0.22 was used to fit to the centrality dependence of the pseudorapidity multiplicity

density per participant pair $2dN_{ch}/d\eta/N_{part}$ at the Relativistic Heavy-Ion Collider (RHIC) [14]. Since the multiplicity density in heavy-ion collisions at the LHC energy is more sensitive to the parton shadowing than at RHIC, data from the A Large Ion Collider Experiment (ALICE) experiment further constrained the gluon shadowing parameter to $s_g = 0.20$–0.23 [17].

In addition to modification of initial parton distributions, multiple scatterings inside a nucleus should also lead to transverse momentum (k_T) broadening of both initial- and final-state partons. The k_T broadening is responsible for the Cronin effect or enhancement of intermediate-p_T hadron spectra in $p + A$ collisions [18]. It is implemented in HIJING 2.1 as a k_T kick by each binary nucleon-nucleon scattering to the initial partons of a hard scattering as well as final-state partons produced prior to the current scattering. The k_T kick for each scattering follows a Gaussian distribution and an energy dependence of the width,

$$\langle k_T^2 \rangle = 0.14 \log(\sqrt{s}/\text{GeV}) - 0.43 \text{ GeV}^2, \qquad (3)$$

is assumed to describe the measured Cronin effect in $p + A$ collisions. After the k_T kick, longitudinal momenta of partons are reshuffled pairwise between projectile and target partons in order to ensure four-momentum conservation. Consequently, introduction of the k_T kick will also influence hadron rapidity distributions. The value $s_g = 0.20$–0.23 was obtained from comparison between HIJING without k_T kick and experimental data on charged multiplicity density at both RHIC and LHC [17]. With the k_T kick, we have to readjust the gluon shadowing parameter s_g again to describe experimental data on rapidity distributions.

Shown in Fig. 1 are HIJING 2.1 results on pseudorapidity distributions of charged hadrons in minimum-biased $d + Au$ (a) and $p + Pb$ (b) collisions (solid) at $\sqrt{s_{NN}} = 200$ GeV and 5.0 TeV, respectively, as compared to $d + Au$ data from the STAR experiment [19]. Here the gluon shadowing parameter

is set to $s_g = 0.28$. Also shown are HIJING2.1 results for $p + p$ collisions (dashed) as compared to the PHOBOS data [20] and $p(d) + A$ collisions without parton shadowing (dot-dashed). Gluon shadowing in HIJING 2.1 is seen to suppress the hadron yield in mid- and forward-rapidity regions, especially at the LHC energy. Measurement of the hadron rapidity distribution at LHC therefore would provide further constraints on the gluon shadowing.

According to the Leading Order (LO) pQCD jet production cross section in Eq. (1), transverse momenta of final-state jets in the central-rapidity region ($y_{1,2} = 0$) determine the momentum fractions $x_{1,2} = 2p_T/\sqrt{s}$ of the initial colliding partons. Therefore, p_T spectra of produced partons via hard scatterings in $p + A$ collisions should depend directly on the nuclear modification of parton distributions in nuclei. To study parton shadowing and other cold nuclear effects, we calculate the nuclear modification factor for final-state parton and hadron p_T spectra,

$$R_{pA}(p_T) = \frac{dN_{pA}/dy d^2 p_T}{\langle N_{\text{bin}} \rangle dN_{pp}/dy d^2 p_T}, \qquad (4)$$

where $\langle N_{\text{bin}} \rangle$ is the average number of binary nucleon-nucleon interactions in $p + A$ collisions.

Shown in Fig. 2 are parton modification factors from the HIJING 2.1 for minimum-biased $d + Au$ and $p + Pb$ collisions at $\sqrt{s_{NN}} = 200$ GeV and 5.0 TeV, respectively. The enhancement of parton spectra at intermediate p_T is the signature effect of k_T broadening, which should disappear at large p_T. In the HIJING model, hard scatterings are simulated each time the projectile parton interact with a target parton
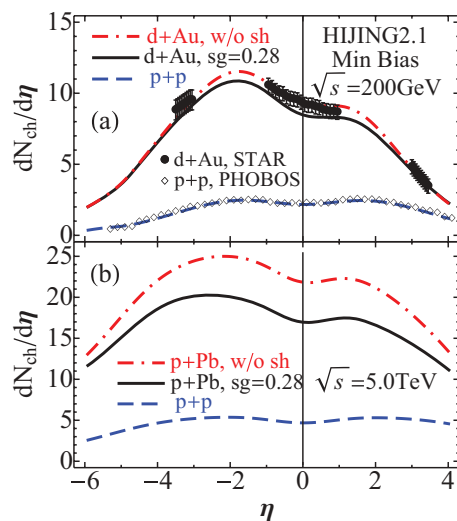

FIG. 1. (Color online) (a) Charged hadron rapidity distribution from HIJING 2.1 with (solid) and without (dot-dashed) parton shadowing in $p(d) + A$ and $p + p$ (dashed) collisions at $\sqrt{s_{NN}} = 200$ GeV and (b) 5.0 TeV as compared to data from the STAR [19] and PHOBOS [20] experiments.
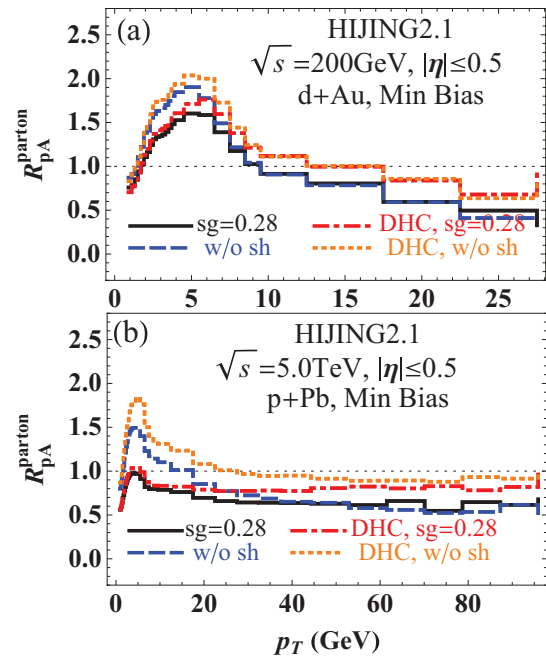

FIG. 2. (Color online) (a) Nuclear modification factor for parton p_T spectra in $p(d) + A$ collisions at $\sqrt{s_{NN}} = 200$ GeV and (b) 5.0 TeV from HIJING 2.1 with (solid) and without (dashed) parton shadowing and with decoherent hard scatterings (DHC) (dot-dashed and dotted).

alongside soft interactions with the remnants of colliding nucleons. HIJING ensures energy-momentum conservation by subtracting energy-momentum transfers in the previous hard and soft interactions from the projectile and thus restricting energy available for subsequent hard collisions. Since the time scale of hard scatterings is much shorter than soft interactions, such a coupling between hard and soft interactions might not be physical. As an option in our study, we turn off such a coupling and do not restrict energy available for hard scatterings. We denote the results as DHC (decoherent hard scattering). As one can see from Fig. 2, both parton shadowing and soft-hard coupling suppress high-p_T parton production. These features of parton spectra will be reflected in the final hadron spectra after hadronization.

In $p + A$ collisions, the projectile proton scatters with multiple nucleons inside the target, each with finite probability of hard parton scattering. The leading contribution comes from independent hard scatterings, each involving independent initial partons from projectile and target nucleons. In principle, a fast projectile parton can also suffer multiple hard scatterings which will affect the final-state parton spectra but do not increase the projectile's contribution to the final-state parton multiplicity. Momentum correlation of multiple partons inside the projectile is neglected beyond the conservation of the total momentum. Flavor conservation, however, will limit the availability of valence quarks from the projectile for each of these multiple independent hard scatterings as the projectile plunges through the target nucleus. Such limitation on the number of valence quarks available for each independent hard scattering will lead to a change in the flavor composition of produced partons per average binary nucleon-nucleon collision. Shown in Fig. 3 are the ratios of produced quark and gluon p_T spectra in the central rapidity region of $d +$ Au and $p +$ Pb collisions at $\sqrt{s_{NN}} = 200$ GeV and 5.0 TeV, respectively, as compared to that in $p + p$ collisions. The quark number conservation in multiple scatterings is seen to lead to smaller quark-gluon ratio in $p + A$ relative to $p + p$ collisions. The suppressed quark yield and high quark-gluon ratio, especially at RHIC, will lead to the modification of final-state parton spectra at large p_T as shown in Fig. 2. Because gluon fragmentation functions are softer than quarks, the increased fraction of gluon jets in $p + A$ collisions will lead to apparent suppression of high-p_T hadron spectra relative to $p + p$ collisions.

The modified flavor composition of the final parton due to multiple scattering in pA collisions could also change the flavor composition of final hadrons due to flavor dependence of the fragmentation functions. Gluon jets in general have higher proton-to-pion ratio than in quark jets. HIJING has a strong gluon shadowing which suppresses larger p_T gluon jets. This should reduce the proton-to-pion ratio in HIJING 2.1 results as compared to the results without gluon shadowing as shown in Fig. 4. This reduction of proton-to-pion ratio by gluon shadowing is much stronger at the LHC energy. Nevertheless, the proton-to-pion ratio in $d +$ Au collisions at RHIC and $p +$ Pb collisions at LHC will still be larger than that in $p + p$ collisions because of the enhanced gluon-to-quark ratio in $p + A$ collisions relative to that in $p + p$ as shown in Fig. 3. Such a trend is already seen in the STAR data [21] at RHIC.
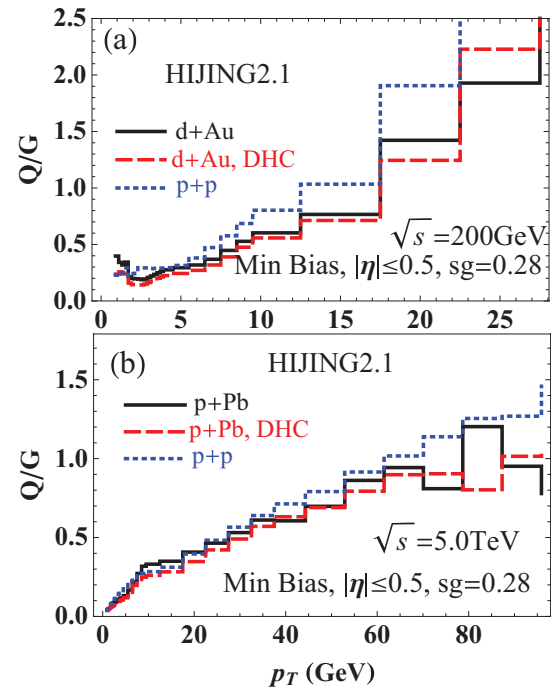

FIG. 3. (Color online) (a) Quark-to-gluon ratio as a function of p_T in $p + p$ (dotted) $p(d) + A$ collisions at the RHIC and (b) LHC energies from HIJING 2.1 without (solid) and with (dashed) decoherent hard scatterings (DHC).

The flavor composition of final hadrons in $p + A$ collisions could also be influenced by other nonperturbative mechanisms such as parton recombination during hadronization [22] and hadronic final-state rescattering [23].

Another process that can also modify final hadron spectra in $p + A$ collisions is jet hadronization or fragmentation. HIJING follows the same routine as in PYTHIA that groups jet partons together with project and target remnants to form color-singlet string systems. In HIJING, jet parton showers from all hard scatterings, including initial- and final-state radiations, are ordered in rapidity and gluons are then connected to the valence quark and diquark of the associated projectile or target nucleons as kinks to form string systems. These string systems are hadronized according to the Lund string model [24]. The projectile can undergo multiple scatterings in $p + A$ collisions. Its string system therefore has more gluons attached as compared to that in $p + p$ collisions. Hadrons from such a string system are expected to be softer than independent fragmentation of individual gluons. To test the sensitivity of nuclear modification of final hadron spectra to jet hadronization, we also consider the independent fragmentation mechanism in HIJING for both $p + p$ and $p + A$ collisions.

Shown in Fig. 5 are nuclear modification factors for charged hadrons in $d +$ Au and $p +$ Pb collisions at $\sqrt{s_{NN}} = 200$ GeV and 5.0 TeV, respectively, as compared to existing data from both the PHENIX and STAR experiments at RHIC [25,26]. At low p_T, hadron production is dominated by hadronization of soft strings, which is proportional to the number of participant nucleons $N_{\text{part}} = 1 + N_{\text{bin}}$. The nuclear modification factor should approach $R_{pA} \approx (1 + 1/N_{\text{bin}})/2 \approx 1/2$ in the limit

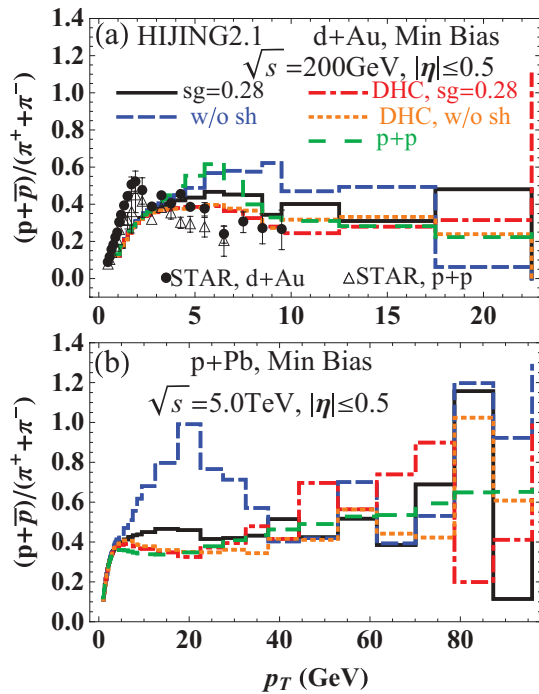RONG XU, WEI-TIAN DENG, AND XIN-NIAN WANG

FIG. 4. (Color online) (a) Proton-to-pion ratio at RHIC and (b) LHC from HIJING 2.1 with different options: default (solid), without shadowing (dashed), DHC (dot-dashed), DHC without parton shadowing (dotted) in $d + Au$ collisions at RHIC and $p + Pb$ at LHC. The ratio in $p + p$ collisions is also shown (long dashed). The RHIC experimental data are from STAR [21].
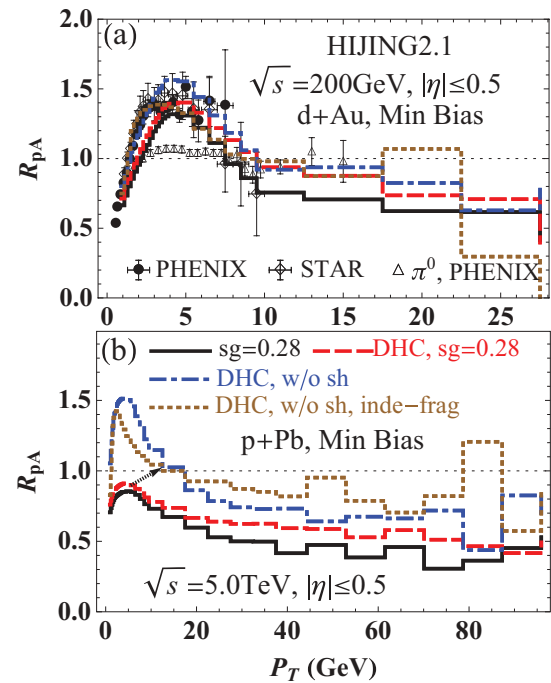

FIG. 5. (Color online) Nuclear modification factor for charged hadrons in $p + A$ collisions from HIJING 2.1 with different options: default (solid), DHC (dashed), DHC without parton shadowing (dot-dashed), and DHC without parton shadowing and independent fragmentation (dotted), as compared to data from the PHENIX and STAR experiments [25,26]. The arrowed lines indicate the most possible behavior of the nuclear modification factors at LHC between low- and high-p_T regions.

$N_{\rm bin} \gg 1$. At large p_T, incoherent hard parton scatterings dominate and $R_{pA} \approx 1$ without any nuclear modification. The peak in the nuclear modification factor is generally known as the Cronin enhancement of hadron spectra at intermediate p_T due to k_T broadening through multiple scatterings. Such a peak has been observed in pA collisions at the Fermilab energies ($E_{\rm lab} = 200$–800 GeV) [27] and the position of the peak at around 4 GeV/c has no apparent energy dependence and remains the same in HIJING results at both RHIC and LHC energies. Nuclear shadowing of parton distributions at LHC will only affect the overall value of R_{pA} at intermediate p_T, but the peak feature and its position remain the same. This is a unique prediction of the k_T broadening due to multiple scattering as implemented in HIJING 2.1. It is in sharp contrast to the prediction of disappearance of the peak in gluon saturation model or relocation to much higher p_T due to strong antishadowing in the collinear pQCD parton model. Experimental test of these features will shed light on the parton dynamics in high-energy nuclei.

At very large p_T, parton shadowing in nuclei, soft-hard coupling, and enhanced gluonic jets due to valence quark conservation all lead to suppression of charged hadron spectra. Fragmentation of the projectile string system with multiple gluon jets in $p + A$ collisions seems to further suppress high-p_T hadron spectra as compared to the independent fragmentation (dotted). These nuclear effects are consistent with existing $d + Au$ data at RHIC. However, $p + Pb$ collisions at LHC will be able to test these scenarios within the available p_T

range. Since parton shadowing will disappear at large p_T [4] due to QCD evolution and hard scatterings are decoherent from soft interactions, the nuclear modification factor at LHC will likely follow the default and DHC results at low p_T. It approachs DHC without shadowing at large p_T with possible further modifications due to hadronization of multiple jets. In Fig. 5, we indicate this trend by joining these two set of results with arrowed lines at intermediate p_T.

The initial-state interaction and fragmentation of multiple jet systems should also affect the final hadron spectra in high-energy heavy-ion collisions in addition to jet quenching due to final-state interaction. The existing experimental data on hadron spectra modification should provide some constraints on the initial-state parton interactions and the final hadronization mechanism. Shown in Fig. 6 are nuclear modification factors for final parton (a) and hadron spectra (b) in central Pb + Pb collisions at $\sqrt{s} = 2.76$ TeV. Note that there is no jet quenching effect in the calculation shown. On the parton level, the nuclear modification at large p_T mainly comes from parton shadowing, which should be small if the scale dependence of shadowing is taken into account. However, the final hadron spectra at large p_T are significantly suppressed due to the Lund string fragmentation of multiple parton systems [solid and dashed curves in Fig. 6(b)], leaving no room for additional suppression by jet quenching as compared to experimental data from ALICE [28] and CMS [29]. This is a strong indication that the Lund string fragmentation for hadronization is no longer
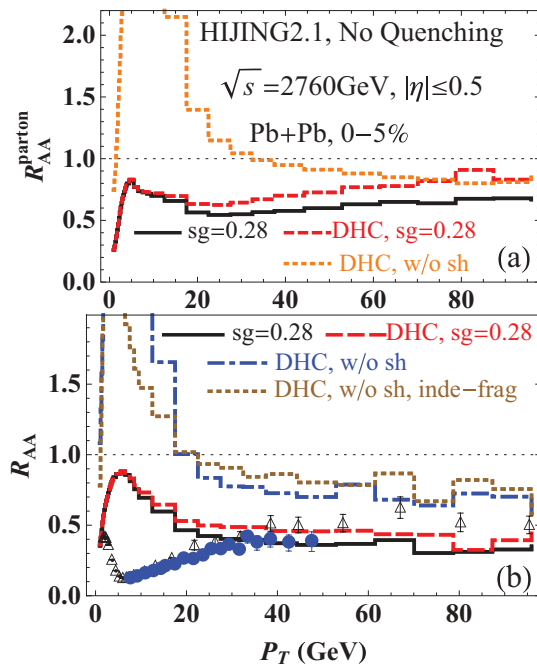
FIG. 6. (Color online) (a) Nuclear modification factors for final parton and (b) charged hadrons in central Pb + Pb collisions at $\sqrt{s} = 2.76$ TeV from HIJING 2.1 with different options: default (solid), DHC (dashed), DHC without parton shadowing (dot-dashed), and DHC without parton shadowing and independent fragmentation (dotted), as compared to data from the ALICE and Compact Muon Solenoid (CMS) experiment [28,29]. Jet quenching due to final-state interaction is not considered in the HIJING calculations.

a valid mode for multiple gluonic jet systems in heavy-ion collisions where a deconfined quark-gluon plasma is formed. Recent studies show that multiple parton scatterings inside a quark-gluon plasma can in fact change the the color flow of the jet parton shower from that in vacuum [30–33]. One therefore should expect the fragmentation processes in heavy-

ion collisions to be significantly modified from that in vacuum. An independent jet fragmentation mechanism such as parton recombination model might be a better alternative where local parton phase distributions determine the final hadron spectra and global color flow of the multiple jet system is no longer important. Since multiple gluonic jet systems in pA collisions can be considered as precursors of the quark-gluon plasma, investigation of the final hadron spectra at large p_T in $p + A$ collisions can shed light on the hadronization mechanism of energetic jets after they escape jet quenching and emerge from the quark-gluon plasma in high-energy heavy-ion collisions.

In summary, we have studied the nuclear modification of hadron spectra in $p + A$ collisions at both the RHIC and LHC energies within HIJING 2.1 Monte Carlo model and their sensitivities to cold nuclear effects. Multiple parton correlations in the projectile due to valence quark number conservation, string fragmentation of multiple gluon jets as well as parton shadowing can all lead to suppression of high-p_T hadron spectra in $p + A$ relative to $p + p$ collisions. Comparisons between HIJING 2.1 results without jet quenching and existing data on large p_T hadron suppression at LHC indicate an independence fragmentation mechanism for multiple jet systems such as in pA and AA collisions. Experimental test of these effects in $p + s$ collisions at LHC and their implications for hard scatterings in $A + A$ collisions are crucial for the study of jet quenching and extraction of jet transport properties in the hot quark-gluon plasma.

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