

Using local nuclear scaling of initial condition parameters to improve the system size dependence of transport model descriptions of nuclear collisions

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We extensively study the system size dependence of nuclear collisions with a multiphase transport model. Previously, certain key parameters for the initial condition needed significantly different values for pp and central AA collisions for the model to reasonably describe the yields and transverse momentum spectra of the bulk matter in those collision systems. Here we scale two key parameters, the Lund string fragmentation parameter b_L and the minijet transverse momentum cutoff p_0 , with local nuclear thickness functions from the two colliding nuclei. This allows the model to use the parameter values for pp collisions with the local nuclear scaling to describe the system size and centrality dependences of nuclear collisions self-consistently. In addition to providing good descriptions of pp collisions from 23.6 GeV to 13 TeV and reasonable descriptions of the centrality dependence of charged particle yields for Au+Au collisions from 7.7A GeV to 200A GeV and Pb+Pb collisions at Large Hadron Collider energies, the improved model can now well describe the centrality dependence of the mean transverse momentum of charged particles below $p_T \lesssim 2$ GeV. It works similarly well for smaller systems including p Pb, Cu+Cu and Xe+Xe collisions.

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I. INTRODUCTION

A main purpose of the field of high-energy heavy ion collisions is to explore the properties of the produced hot and dense matter, the quark-gluon plasma (QGP). Many theoretical models including transport models [1–4], hydrodynamic models [5–8], and hybrid models [9–11] are constructed to simulate and study the phase space evolution of the QGP. Comprehensive comparisons between such models and the experimental data can provide key information about the high-density matter.

In particular, the dependences of various observables on the size of the collision system or the centrality of a given collision system are useful as they may exhibit the onset or transition of certain phenomena such as the momentum anisotropy from initial-state correlations [12,13] or from final-state interactions [14–18]. For large systems, it is commonly believed that viscous hydrodynamics applies well to the bulk of the matter, while transport models essentially approach the hydrodynamical limit since the average number of collisions per particle is large. For small colliding systems, however, hydrodynamic models and transport models may be quite different due to nonequilibrium dynamics. Recently, it has been found that parton transport can convert the initial spatial anisotropy into significant anisotropic flows in the momentum space through the parton escape mechanism [14,15],

especially in small systems where the average number of collisions per particle is relatively small. Studies [17] also show that transport theory with a single scattering is very efficient in changing the particle distribution. Therefore, the system size dependence of anisotropic flows could provide key information on the origin of collectivity and the region of applicability of hydrodynamics in nuclear collisions.

A multiphase transport (AMPT) model, which we improve in this study, contains four main parts: the fluctuating initial condition from the Heavy Ion Jet INteraction Generator (HIJING) model [19], partonic interactions, hadronization, and hadronic interactions. The string melting version of the AMPT model can reasonably describe many experimental data at low transverse momentum (p_T) in central and semicentral Au+Au collisions at 200A GeV and Pb+Pb collisions at the Large Hadron Collider (LHC) [20,21] including the pion, kaon, proton yields, p_T spectra, and elliptic flow. Recently, we updated the AMPT model with an improved quark coalescence model [21] and modern nuclear parton distribution functions (nPDFs) [22], where the string melting version can also reasonably describe the charged particle rapidity distributions and p_T spectra in pp collisions at different energies. On the other hand, from the comparison to experimental data, we have found that certain key parameters in the AMPT model need to have very different values for pp and central AA collisions. First, the b parameter in the Lund symmetric fragmentation function [23,24] (denoted as b_L in this study) needs to be $\approx 0.15/\text{GeV}^{-2}$ for central Au+Au or Pb+Pb collisions, which is a few times smaller than its value for pp

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collisions. Second, the minijet transverse momentum cutoff p_0 for central Pb+Pb collisions at the LHC energies needs to be significantly bigger than its value for pp collisions at the same energy in the AMPT model updated with modern nPDFs [22]. These observations clearly indicate that these two parameters should depend on the size of the colliding system.

From the theoretical point of view, we also expect these two parameters to depend on the system size (as detailed in Sec. II). First, the mean transverse momentum of the initially produced partons, which is negatively correlated with the b_L parameter, should be higher for larger systems due to the higher initial temperature; as a result, b_L is expected to be smaller for larger systems. Second, the introduction of the p_0 cutoff is partially motivated by the physics of color glass condensate, where p_0 in the saturation regime is presumably proportional to the saturation momentum Q_s and thus should increase with the system size.

Therefore, in this study we improve the system size and centrality dependences of the AMPT model [3] by treating the two parameters in its initial condition, the Lund b_L parameter and the minijet cutoff p_0 , as local variables that depend on the local nuclear thickness functions from the two colliding nuclei in each event. The rest of the paper is organized as follows. In Sec. II, we discuss the local nuclear scaling of the Lund b_L and momentum cutoff p_0 parameters. We then systematically compare results from the improved AMPT model with the experimental data for pp , pA , and AA collisions at RHIC and LHC energies in Sec. III, including the charged particle yields and p_T spectrum or mean p_T and their centrality dependences in nuclear collisions. After more discussions in Sec. IV, we then summarize in Sec. V.

II. IMPROVEMENT OF THE INITIAL CONDITION OF THE AMPT MODEL

The initial condition component of the AMPT model is based on the HIJING two-component model [19]. The primary interactions between the two incoming nuclei are divided into two components: the soft component described by the Lund string fragmentation model [23–25] that includes the parameter b_L , and the hard component with a minijet transverse momentum cutoff p_0 that is described by perturbative QCD through the PYTHIA program [25]. Rather than treating p_0 and b_L as constant parameters (at least for a given collision system at a given energy), as done in almost all previous studies with the AMPT model, here we model them as local variables that depend on the nuclear thickness functions, $T_A(s_A)$ and $T_B(s_B)$, of the two nuclei.

A. Local Lund string fragmentation parameter b_L

In the Lund string model [23,24], the symmetric fragmentation function is given by

$$f(z) \propto z^{-1}(1-z)^{a_L} e^{-b_L m_T^2/z}, \quad (1)$$

where z is the light-cone momentum fraction of the produced hadron with respect to the fragmenting string, and m_T is the hadron transverse mass. The average squared transverse momentum of massless hadrons from fragmentation is then

related to the Lund fragmentation parameters a_L and b_L as [3]

$$\langle p_T^2 \rangle = \frac{1}{b_L(2+a_L)}. \quad (2)$$

As a result, the average p_T of partons after string melting and consequently the final hadron p_T spectrum from the string melting version of the AMPT model strongly depend on b_L . In the AMPT model updated with modern nPDFs [22], we have found that a constant values of $a_L = 0.8$ and $b_L = 0.4 \text{ GeV}^{-2}$ can reasonably describe the p_T spectra of pp and $p\bar{p}$ collisions over a wide energy range. However, a much smaller value of $b_L \approx 0.15 \text{ GeV}^{-2}$ is needed to describe the p_T spectra in central Au+Au collisions at RHIC and central Pb+Pb collisions at LHC [20–22]. It was also realized that the centrality dependence of the charged particle mean transverse momentum $\langle p_T \rangle$ in heavy ion collisions has the opposite trend in comparison to the experimental data [26], where the system size dependence of the Lund fragmentation parameters was proposed as a possible solution. Since we expect the mean transverse momentum of initial partons to be higher in larger systems due to the higher initial temperature and Eq. (2) relates the mean squared transverse momentum after string melting to the Lund b_L parameter, it is natural that b_L should depend on the system size.

We now make b_L a local variable that depends on the transverse position of the corresponding excited string in each event. Note that its value has been found to be smaller for a larger collision system, which is consistent with the expectation of a stronger color field and thus a higher string tension κ since $\kappa \propto 1/b_L$ [3]. Therefore, we scale b_L with the local nuclear thickness functions in a general AB collision as

$$b_L(s_A, s_B, s) = \frac{b_L^{pp}}{[\sqrt{T_A(s_A)T_B(s_B)}/T_p]^{\beta(s)}}. \quad (3)$$

In the above, b_L^{pp} is the value for pp collisions (to be discussed further in Sec. III A), s represents the square of the center-of-mass collision energy per nucleon pair (often written as s_{NN} for nuclear collisions), $T_A(s_A) = \int \rho_A(s_A, z) dz$ is the nuclear thickness function at the transverse distance s_A from the center of nucleus A from Woods-Saxon nuclear density profiles [27], and T_p (taking the value of 0.22 fm^{-2} in this study) can be considered as the average value of the effective thickness function of the proton. Note that in Eq. (3) [and Eqs. (7), (9) and (10)] T_p is used instead of $T_A(s_A)$ or $T_B(s_B)$ when the projectile or the target is proton or when $T_A(s_A)$ or $T_B(s_B)$ from the nucleus is smaller than the T_p value. Also note that there are two types of strings in the fragmentation process. The first type is a wounded nucleon from the projectile (or target) nucleus that has interacted with one or more nucleons in the target (or projectile); we take the nucleon position in the nucleus s_A (or s_B) in Eq. (3) and then for simplicity take the other position s_B (or s_A) via the relation $\vec{s}_B = \vec{s}_A + \vec{b}$. Here \vec{b} is the impact parameter vector that points from the center of the target nucleus to that of the projectile nucleus. The other type is an independent string from the primary nucleon-nucleon interaction through the hard process, where the values of both s_A and s_B are unique and thus directly used in Eq. (3).

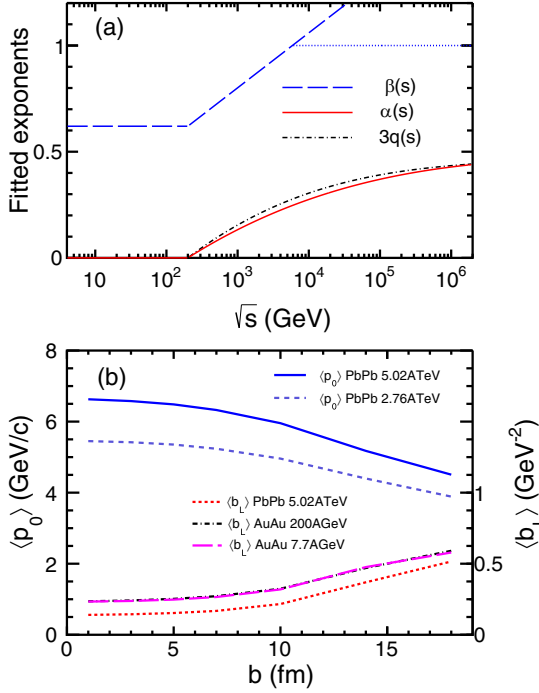


FIG. 1. (a) Fitted exponent functions $\beta(s)$ and $\alpha(s)$ vs the center-of-mass energy per nucleon pair \sqrt{s} , where the function $3q(s)$ is also shown for comparison. (b) Average p_0 and b_L values vs the impact parameter in Pb+Pb and Au+Au collisions at several energies.

First we have determined that a constant value $b_L^{pp} = 0.7 \text{ GeV}^{-2}$ provides a reasonably good description of the charged particle $\langle p_T \rangle$ in pp collisions (details in Sec. III A). Next we fit the charged particle $\langle p_T \rangle$ in the most central Au+Au collisions at RHIC energies and most central Pb+Pb collisions at LHC energies to obtain the preferred $\beta(s)$ value at each of those energies. The results show that the preferred $\beta(s)$ is almost a constant at and below the top RHIC energy but needs to be significantly bigger at LHC energies. We thus parametrize the $\beta(s)$ function as

$$\beta(s) = 0.620 + 0.112 \ln \left(\frac{\sqrt{s}}{E_0} \right) \Theta(\sqrt{s} - E_0), \quad (4)$$

where $E_0 = 200 \text{ GeV}$ throughout this study, \sqrt{s} is the center-of-mass collision energy per nucleon pair, and $\Theta(x)$ is the unit step function. The fitted $\beta(s)$ function is shown in Fig. 1(a) (dashed line). Note that the fit is not constrained or tested by data between the energy of 200A GeV and 2.76A TeV or above 5.44A TeV due to the lack of heavy ion data. On the other hand, the value of $\beta = 1$ (dotted line) may be a “natural” limit for Eq. (3) at high energies if all local strings would fully overlap so that the string tension would add up, since it corresponds to $b_L \propto 1/T_A(s_A)$ for central AA collisions where $T_A(s_A)$ is proportional to the local number of participant nucleons or excited strings integrated over the longitudinal length.

Figures 2(a) and 2(b) show the distributions of b_L values of Eq. (3) over the transverse plane of multiple central ($b = 0$) and peripheral ($b = 10 \text{ fm}$) 5.02A TeV Pb+Pb events,

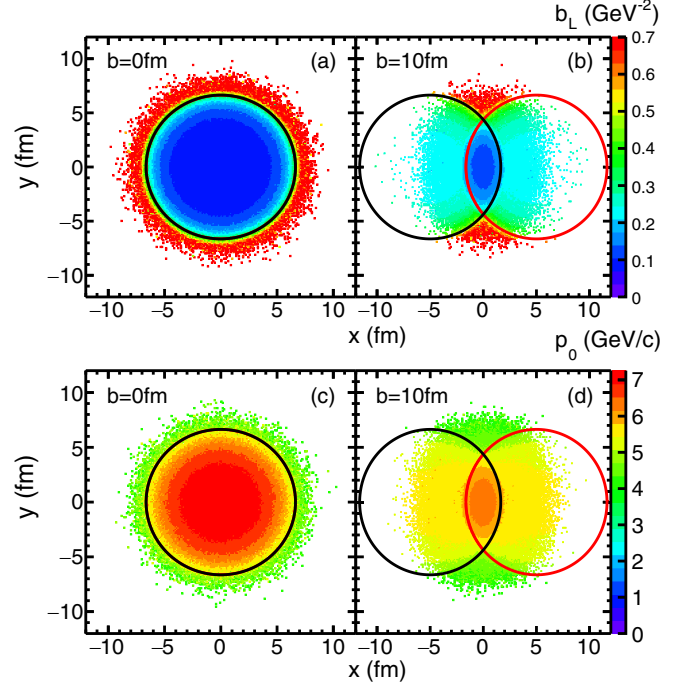


FIG. 2. Distributions of b_L values of Eq. (3) (upper panels) and p_0 values of Eq. (7) (lower panels) over the transverse plane from multiple central (left panels) and peripheral (right panels) Pb+Pb events at 5.02A TeV from the AMPT model.

respectively, from the AMPT model simulations. Specifically, each point represents the b_L value of a wounded nucleon or an independent string versus its transverse position in the collision. The red and black circles represent the hard-sphere boundaries of the projectile and target nuclei, respectively, to indicate the scale. We see that the b_L values in less overlapped regions are close to the value for pp collisions, while the b_L values in highly overlapped regions are much lower. Figure 1(b) shows the b_L value averaged over the overlap volume as a function of the impact parameter for Pb+Pb collisions at 5.02A TeV and Au+Au collisions at two RHIC energies. We see that as expected $\langle b_L \rangle$ at the LHC energy is lower mostly due to the larger value of the exponent $\beta(s)$, while the impact parameter dependences of $\langle b_L \rangle$ at different RHIC energies are essentially the same due to the constant value of $\beta(s)$ within that energy range.

B. Local minijet transverse momentum cutoff p_0

In the hard component of the HIJING model, the total jet cross section is given by

$$\sigma_{\text{jet}} = \sum_{c,d} \frac{1}{1 + \delta_{cd}} \int dy_1 dy_2 \int_{p_0^2}^{\hat{s}/4} dp_T^2 \frac{d\sigma^{cd}}{dp_T^2 dy_1 dy_2}. \quad (5)$$

In the above, p_0 is the cutoff of the minijet transverse momentum, \hat{s} is the Mandelstam variable for the minijet production subprocess, and $d\sigma^{cd}/(dp_T^2 dy_1 dy_2)$ is the differential cross section [28] for the two colliding nuclei to produce the pair of minijet partons of flavor c and d at rapidity y_1 and y_2 , respectively. The p_0 cutoff (relevant when $\sqrt{s} > 10 \text{ GeV}$)

together with the soft component cross section (σ_{soft}) are the two key parameters to determine the total, elastic, and inelastic cross sections of nuclear collisions in the HIJING model [19,22,29]. In our recent update of the AMPT model with modern nPDFs [22], using the pp cross-section data, we determined p_0 and σ_{soft} as functions of the colliding energy. Motivated by the physics of color glass condensate [30], we further introduced a nuclear scaling of the p_0 cutoff for central AA collisions above the top RHIC energy of 200A GeV to describe the experimental data on charged particle yields in central Pb+Pb collisions at LHC energies. That scaling [22] can be considered as a global nuclear scaling because, for a given collision system at a given energy, the scaled p_0 value is a constant for all events regardless of the impact parameter and the minijet position.

In a subsequent work that improved heavy flavor productions [31], we started to use the minijet cross section as shown in Eq. (5), which changed the factor of 1/2 in the original HIJING model [3,19,22] to $1/(1 + \delta_{cd})$ to differentiate minijet final states with or without identical partons. We also removed the momentum cutoff for heavy quark productions and then included heavy quark production cross sections in the total minijet cross section [31]. These modifications have little effect on σ_{soft} , but they lead to an increase of the total minijet cross section and consequently a small increase of the p_0 cutoff in pp collisions as given below (in the unit of GeV/ c):

$$p_0^{pp}(s) = 2.38 + 0.349 \ln\left(\frac{\sqrt{s}}{E_0}\right) + 0.00575 \ln^2\left(\frac{\sqrt{s}}{E_0}\right) + 0.0176 \ln^3\left(\frac{\sqrt{s}}{E_0}\right). \quad (6)$$

For the global nuclear scaling relation $p_0^{AA}(s) = p_0^{pp}(s)A^{q(s)}$ [31], the modifications also lead to a small change of the nuclear scaling exponent $q(s)$ for central AA collisions: $q(s) = 0.0369 \ln(\sqrt{s}/E_0) - 0.00318 \ln^2(\sqrt{s}/E_0) + 0.0000990 \ln^3(\sqrt{s}/E_0)$ for $\sqrt{s} \geq E_0$ while $q(s) = 0$ for $\sqrt{s} < E_0$. On the other hand, we do not expect the global nuclear scaling to hold for noncentral AA collisions; for example, we expect little nuclear scaling for very peripheral AA collisions since they should be similar to pp collisions. Indeed, we have shown [22] that the charged particle yield in peripheral Pb+Pb collisions at 5.02A TeV is better described without using the global nuclear scaling of p_0 , although the scaling is necessary for central Pb+Pb collisions.

We now go beyond the global nuclear scaling and instead make p_0 a local variable that depends on the transverse position of the corresponding hard process in each event. Since the p_0 cutoff has been found to increase with the system size, it is natural to relate it to the nuclear thickness functions in a general AB collision; thus we write

$$p_0(s_A, s_B, s) = p_0^{pp}(s) [\sqrt{T_A(s_A)T_B(s_B)}/T_p]^{q(s)}. \quad (7)$$

Since $T_A(s_A) \propto A^{1/3}$, Eq. (7) approximately gives $p_0 \propto A^{\alpha(s)/3}$ for central AA collisions and thus essentially recovers the previous global nuclear scaling relation if $\alpha(s) = 3q(s)$. On the other hand, for peripheral collisions $T_A(s_A)$ and $T_B(s_B)$ are expected to be small and close to the proton value (T_p),

and then Eq. (7) automatically gives the p_0 value for pp collisions. In this way, Eq. (7) captures the expected system size dependence as well the centrality dependence of the p_0 cutoff parameter.

Since $p_0^{pp}(s)$ works for the charged particle yield in central Au+Au collisions at 200A GeV but not for central Pb+Pb collisions at LHC energies, we have assumed that the need to modify p_0 in nuclear collisions starts at the top RHIC energy [22]. This means that $\alpha(s) = 0$ at and below 200A GeV. From the comparison to charged particle yields in the most central Pb+Pb collisions at 2.76A and 5.02A TeV, we obtain the preferred $\alpha(s)$ values at those two energies. We then fit the $\alpha(s)$ function as

$$\alpha(s) = 0.0918 \ln\left(\frac{\sqrt{s}}{E_0}\right) - 0.00602 \ln^2\left(\frac{\sqrt{s}}{E_0}\right) + 0.000134 \ln^3\left(\frac{\sqrt{s}}{E_0}\right), \text{ for } \sqrt{s} \geq E_0 \quad (8)$$

with $\alpha(s) = 0$ for $\sqrt{s} < E_0 = 200$ GeV. As shown in Fig. 1(a), $\alpha(s) \approx 3q(s)$ as expected, and both have values close to 1/2 at very high energies. Note that the high energy $q(s)$ value of about 1/6 [22] is motivated by the color glass condensate [30], where the saturation momentum Q_s scales with the nuclear size as $Q_s \propto A^{1/6}$ in the saturation regime.

Figures 2(c) and 2(d) show the distributions of p_0 values of Eq. (7) over the transverse plane of multiple central ($b = 0$) and peripheral ($b = 10$ fm) simulated 5.02A-TeV Pb+Pb events, respectively. Each point represents the p_0 value of a wounded nucleon that is involved in hard processes versus its transverse position in the collision. We see that the p_0 value varies from p_0^{pp} (≈ 4.2 GeV at this energy) in less overlapped regions to bigger values in highly overlapped regions as expected, and the variation is larger for more central collisions. In addition, the relative variation of the p_0 values is much smaller than that of the b_L values because $\alpha(s) \ll \beta(s)$ for the exponents. The average p_0 value, i.e., averaged over the wounded nucleons in the overlap volume, is shown in Fig. 1(b) as a function of the impact parameter for Pb+Pb collisions at 2.76A and 5.02A TeV. We see that $\langle p_0 \rangle$ gradually decreases with the increase of impact parameter and that $\langle p_0 \rangle$ is smaller at the lower LHC energy due to the smaller $\alpha(s)$ value there.

III. RESULTS FOR VARIOUS COLLISION SYSTEMS

We apply the local Lund parameter b_L of Eq. (3) and local minijet cutoff p_0 of Eq. (7) to systematically study charged particle productions in different collision systems over a wide range of energies.

A. pp and $p\bar{p}$ collisions

For pp and $p\bar{p}$ collisions, we first determine the value of b_L^{pp} in Eq. (3), while the minijet cutoff $p_0^{pp}(s)$ has been specified in Eq. (6). We first obtain the preferred value of b_L at each energy (symbols in Fig. 3) by fitting the mean p_T data of charged particles in pp or $p\bar{p}$ collisions from 23.6 GeV to 13 TeV ($p\bar{p}$ at 546, 900, and 1800 GeV). The uncertainty of b_L at each energy is obtained by assuming a 3% uncertainty for

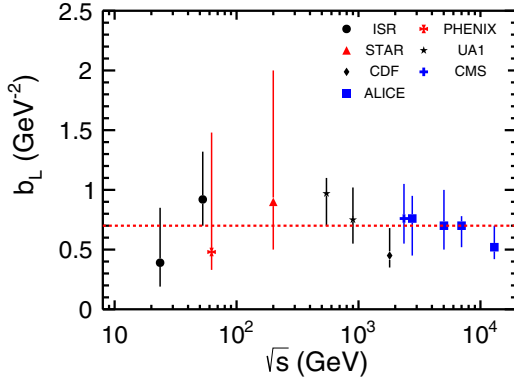


FIG. 3. The preferred individual b_L values from fitting the experimental $\langle p_T \rangle$ of charged particles in pp or $p\bar{p}$ collisions at different energies; the error bar corresponds to an assumed 3% uncertainty of the experimental $\langle p_T \rangle$ value, while the dashed line represents our choice of $b_L^{pp} = 0.7 \text{ GeV}^{-2}$ in this study.

the experimental $\langle p_T \rangle$ value. We see that the preferred central value of b_L fluctuates approximately within $0.4\text{--}1.0 \text{ GeV}^{-2}$ and a constant value of 0.7 GeV^{-2} (dashed line) describes the experimental $\langle p_T \rangle$ data within about 3%. Therefore, we take $b_L^{pp} = 0.7 \text{ GeV}^{-2}$ for pp and $p\bar{p}$ collisions at all energies. Note that a constant Lund parameter $a_L = 0.8$ is taken for all collision systems at all energies in the AMPT model improved with modern nPDFs [22,31].

The $\langle p_T \rangle$ in this study is calculated for charged hadrons up to $p_T \approx 2 \text{ GeV}/c$ for both the AMPT results and the experimental data, because the AMPT model cannot reliably be used for high- p_T hadrons due to its lack of the radiative energy loss and independent fragmentation of high- p_T partons. Note the different p_T ranges used for the $\langle p_T \rangle$ calculation in Fig. 3: $[0.90, 2.15] \text{ GeV}/c$ at 23.6 GeV [32], $[0.73, 2.10] \text{ GeV}/c$ at 53 GeV [32], $[0.6, 2] \text{ GeV}/c$ at 62.4 GeV [33], $[0.2, 2] \text{ GeV}/c$ at 200 GeV [34] and 546 and 900 GeV [35], $[0.1, 2] \text{ GeV}/c$ at 2.36 TeV [36], and $[0.15, 2] \text{ GeV}/c$ at 1.8 TeV [37], 2.76 TeV [38], 5.02 TeV [39], 7 TeV [40], and 13 TeV [41]. Also note that in this study we treat charged particles from the AMPT model more carefully in the comparisons with data. Specifically, we decay the Σ^+ , Σ^- hyperons including their antiparticles as well as all open charm hadrons (with PYTHIA [42]) before calculating charged particle observables. This treatment leads to a slight increase of the charged particle yield at low p_T but a slight decrease at high p_T (by several percent) compared to results using the previous analysis method [22].

Figures 4(a) and 4(b) show respectively the $dN_{ch}/d\eta$ distributions and the p_T spectra around midpseudorapidity of charged particles from the string melting AMPT model (curves) in comparison with the experimental data (symbols) in pp or $p\bar{p}$ collisions over a wide energy range. We see that using the constant Lund fragmentation parameters $a_L = 0.8$ and $b_L^{pp} = 0.7 \text{ GeV}^{-2}$ allows us to reasonably describe these data.

For the $dN_{ch}/d\eta$ distribution, we use the same procedure to select the events from the AMPT model calculations as the experimental data. The CERN intersecting storage rings

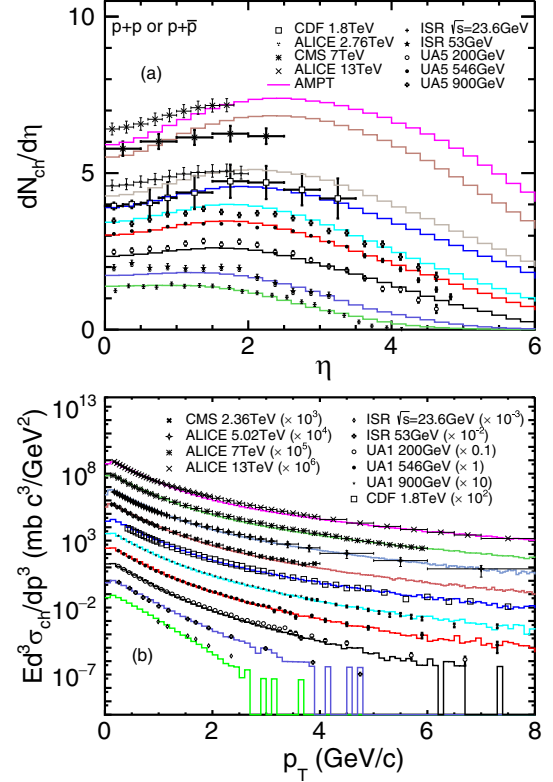


FIG. 4. (a) Pseudorapidity distributions of charged particles in inelastic pp collisions at 23.6 and 53 GeV, NSD $p\bar{p}$ collisions at 200, 546, 900, and 1800 GeV, and NSD pp collisions at 2.76, 7, and 13 TeV from the AMPT model in comparison with the experimental data. (b) Invariant transverse momentum cross sections around midpseudorapidity from the AMPT model in comparison with the experimental data that also include pp collisions at 2.36 TeV.

(ISR) data are for inelastic pp collisions [32]. The ALICE non-single-diffractive (NSD) data [41,43] refer to events that have at least one charged particle on each side of the V0 detectors which cover the η range of $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, while for the UA5 [44], CDF [37], and CMS [40] data the detectors cover the ranges of $2 < |\eta| < 5.6$, $3.2 < |\eta| < 5.9$, and $2.9 < |\eta| < 5.2$, respectively. For the transverse momentum spectra, we use the same η cut as the experimental data: $|\eta| < 0.35$ for pp collisions at 23.6 and 53 GeV [32,45], $|\eta| < 2.5$ for $p\bar{p}$ collisions at 200, 546, and 900 GeV [35], $|\eta| < 1$ for $p\bar{p}$ collisions at 1.8 TeV [46], $0 < \eta < 0.2$ for pp collisions at 2.36 TeV [36], and $|\eta| < 0.8$ for pp collisions at 5.02 TeV [39] and 7 and 13 TeV [41]. Also, the event selection procedure is the same as that used for Fig. 4(a), while the UA1 [35] selection criterion is the same as UA5. For the experimental data at LHC energies shown in Fig. 4(b), we have converted the Ed^3N/dp^3 data and AMPT Ed^3N/dp^3 results to $Ed^3\sigma/dp^3$ with the multiplication factor σ_{inel} . Note that the b_L^{pp} value of 0.7 GeV^{-2} here is different than the earlier value of 0.4 GeV^{-2} [22] mostly because we now determine its value from a systematic fit to the $\langle p_T \rangle$ data. We also need to point out that in the earlier study [22] the AMPT results on the invariant transverse momentum cross

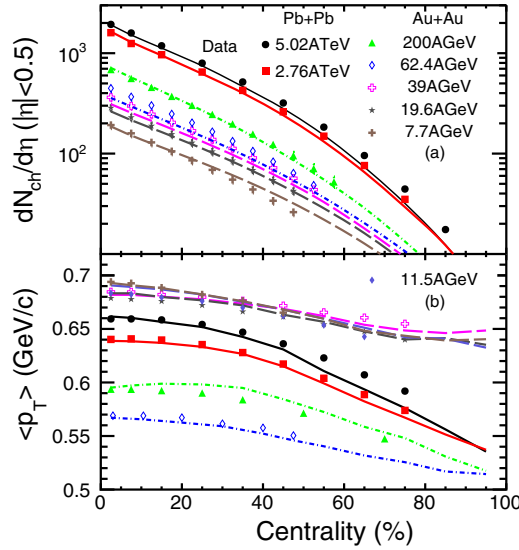


FIG. 5. $dN_{ch}/d\eta$ within $|\eta| < 0.5$ (a) and the mean transverse momentum $\langle p_T \rangle$ around midrapidity (b) vs centrality in Au+Au collisions at RHIC energies and Pb+Pb collisions at LHC energies from the AMPT model (curves) in comparison with the experimental data (symbols). Note the different p_T range used for the $\langle p_T \rangle$ calculation: [0.15, 2] GeV/c (solid), [0.2, 2] GeV/c (dot-dashed), and [0.4, 1.3] GeV/c (dashed).

sections for the lowest two energies (23.6 and 53 GeV) were mistakenly divided by a factor of 2.

B. Au+Au and Pb+Pb collisions

We now apply the improved AMPT model to Au+Au and Pb+Pb collisions. Figures 5(a) and 5(b) show respectively the $dN_{ch}/d\eta$ yield at midpseudorapidity and mean transverse momentum $\langle p_T \rangle$ around midrapidity of charged particles from the AMPT model versus centrality in comparison with experimental data for Au+Au collisions at RHIC energies and Pb+Pb collisions at LHC energies. We use the same method to determine centrality as the experiments. For example, the centrality for the LHC results (from the ALICE Collaboration) is based on the multiplicity of charged particles within $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, while for the PHENIX, PHOBOS, and STAR experiments at RHIC energies the centrality is based on the charged particle multiplicity within $3.0 < |\eta| < 3.9$, $|\eta| < 3.2$, and $|\eta| < 0.5$, respectively. Note that the $\langle p_T \rangle$ values from both the AMPT model and experimental data correspond to charged particles within the p_T range of [0.4, 1.3] GeV/c for collision energies from 7.7A to 39A GeV [47], [0.2, 2] GeV/c at 62.4A [48] and 200A GeV [34], and [0.15, 2] GeV/c at 2.76A [49] and 5.02A TeV [39]. Also, results in Fig. 5(b) correspond to the (pseudo)rapidity range of $|\eta| \leq 0.1$ at energies from 7.7A to 39A GeV, $0.2 < \eta < 1.4$ at 62.4A GeV, $|\eta| \leq 0.5$ at 200A GeV, and $|\eta| \leq 0.8$ at 2.76A and 5.02A TeV.

From Fig. 5(a), we see that the improved AMPT model can reasonably reproduce the midpseudorapidity $dN_{ch}/d\eta$ data for the most central (0–5% centrality) collisions at all these energies except for 39A and 62.4A GeV, where it underestimates

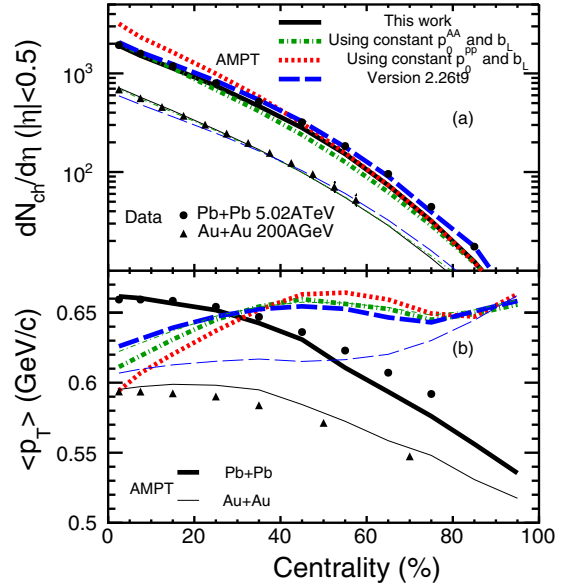


FIG. 6. $dN_{ch}/d\eta$ within $|\eta| < 0.5$ (a) and $\langle p_T \rangle$ around midpseudorapidity (b) vs centrality in 5.02A TeV Pb+Pb collisions (thick curves) and 200A GeV Au+Au collisions (thin curves) from this work (solid curves) and earlier versions of the AMPT model in comparison with the experimental data (symbols); the p_T range used for the $\langle p_T \rangle$ calculation is [0.15, 2] GeV/c at 5.02A TeV and [0.2, 2] GeV/c at 200A GeV.

the data. We also see that the model can reasonably describe the centrality dependence of $dN_{ch}/d\eta$ in Au+Au collisions at RHIC energies [50], while for Pb+Pb collisions at 2.76A TeV [49] and 5.02A TeV [51] it underestimates the $dN_{ch}/d\eta$ for peripheral collisions. Figure 5(b) shows that the string melting version of the AMPT model describes the energy dependence of $\langle p_T \rangle$ reasonably well for Au+Au and Pb+Pb collisions over the colliding energies from 7.7A GeV to 5.02A TeV. The model underestimates the $\langle p_T \rangle$ for peripheral collisions at the LHC energies while overestimates the $\langle p_T \rangle$ for semiperipheral and peripheral collisions at the top RHIC energy of 200A GeV; however, the difference from the data is no more than $\approx 3\%$.

We now compare this work with two earlier versions of the string melting AMPT model in Fig. 6(a) for $dN_{ch}/d\eta$ within $|\eta| < 0.5$ and in Fig. 6(b) for the $\langle p_T \rangle$ around midrapidity versus centrality in Pb+Pb collisions at 5.02A TeV and Au+Au collisions at 200A GeV. When we do not use the local nuclear scaling of p_0 and b_L but instead use constant $b_L = 0.15 \text{ GeV}^{-2}$ and a constant $p_0(s)$ at a given energy for the AMPT model of this work, the model is the same as the one developed in Ref. [31], and we obtain the dot-dashed curves when using $p_0(s) = p_0^{AA}(s)$ and the dotted curves when using $p_0(s) = p_0^{PP}(s)$ (note, however, that $p_0^{AA}(s) = p_0^{PP}(s)$ at 200A GeV). Results from the public AMPT version 2.26t9 [52] are also shown (dashed curves) for comparison, where the Lund parameters are taken as $a_L = 0.55$ at 200A GeV and 0.30 at 5.02A TeV with $b_L = 0.15 \text{ GeV}^{-2}$ [20].

In Fig. 6(a), we see that the charged particle yield in central Pb+Pb collisions at 5.02A TeV from using $p_0(s) = p_0^{PP}(s)$ is much higher than the experimental data, and it is necessary

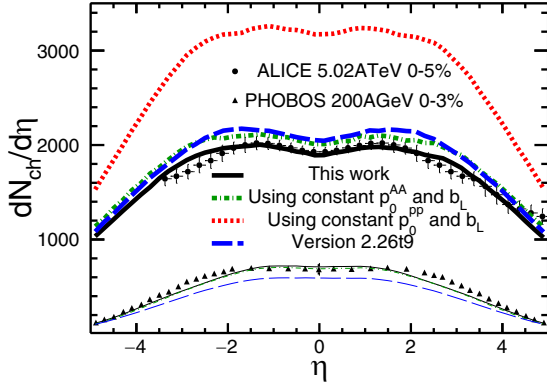


FIG. 7. $dN_{ch}/d\eta$ distributions from this work (solid curves) and earlier versions of the AMPT model for central 5.02A TeV Pb+Pb collisions (thick curves) and 200A GeV Au+Au collisions (thin curves) vs the experimental data (symbols).

to use the global nuclear scaling [31], i.e., $p_0(s) = p_0^{AA}(s)$, to reduce the total minijet cross section and consequently the particle yield. For peripheral collisions, however, the effect from the global nuclear scaling of p_0 is much smaller because the binary scaling of minijet productions makes p_0 less important than for central collisions. These features are essentially the same as our earlier results (Fig. 11 of Ref. [22]). We also see as expected that the $dN_{ch}/d\eta$ results from this work are close to the AMPT results using the constant p_0^{AA} for central collisions but close to the AMPT results using the constant p_0^{pp} for peripheral collisions. In addition, we see that, compared to the $dN_{ch}/d\eta$ results from the AMPT version 2.26t9, the centrality dependence results from this work are slightly worse at 5.02A TeV but slightly better at 200A GeV.

Previously, we found that the centrality dependence of charged particle $\langle p_T \rangle$ from the AMPT model is inconsistent with the experimental data at RHIC and LHC [26]. This is the case in Fig. 6(b) for the results from the AMPT version 2.26t9 (dashed curves). Similarly, the AMPT model when using constant $b_L = 0.15 \text{ GeV}^{-2}$ and $p_0^{pp}(s)$ or $p_0^{AA}(s)$ (constant at a given energy) [31] gives the wrong centrality dependence of $\langle p_T \rangle$ around midpseudorapidity, where the model results (dot-dashed or dotted) show a mostly increasing trend with the increase of centrality while the data show a mostly decreasing trend. We also find that the decrease of $\langle p_T \rangle$ toward the most central events from both earlier AMPT versions (dotted, dashed, and dot-dashed curves) is mainly a result of the stronger parton rescatterings in more central collisions. This is consistent with hydrodynamical results for the case of partial chemical equilibrium [53] (i.e., fixed number of particles, which is the case for the parton cascade of AMPT), where the decrease of the transverse energy per rapidity with time [54] leads to a corresponding decrease of particle $\langle p_T \rangle$. On the other hand, the local nuclear scaling of this work enables the string melting AMPT model (solid curves) to reasonably reproduce the centrality dependence of charged particle $\langle p_T \rangle$.

In Fig. 7, we compare the $dN_{ch}/d\eta$ distributions from this work and two earlier versions of the string melting AMPT model with the experimental data for central Au+Au collisions at 200A GeV [55] and Pb+Pb collisions at 5.02A TeV

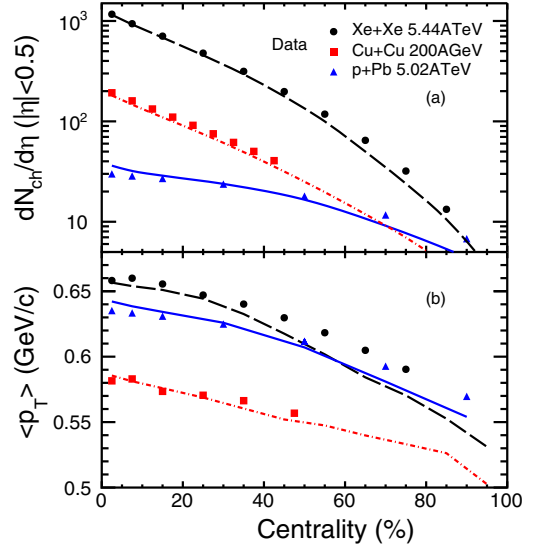


FIG. 8. $dN_{ch}/d\eta$ within $|\eta| < 0.5$ (a) and $\langle p_T \rangle$ around midpseudorapidity (b) vs centrality in Xe+Xe collisions at 5.44A TeV, Cu+Cu collisions at 200A GeV, and $p + \text{Pb}$ collisions at 5.02A TeV from the AMPT model (curves) in comparison with the experimental data (symbols). The p_T range used for the $\langle p_T \rangle$ calculation is $[0.2, 2] \text{ GeV}/c$ at 200A GeV and $[0.15, 2] \text{ GeV}/c$ at the other two LHC energies.

[51]. Note that we use the same method as the experiments to determine the centrality, which is based on the energy deposition of charged particles within $3 < |\eta| < 4.5$ for 200A GeV and the multiplicity of charged particles within $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$ for 5.02A TeV. Results from the AMPT version 2.26t9 [52] roughly describe the data as expected [20]. In addition, the charged particle yield at 5.02A TeV when using the minijet cutoff p_0^{pp} is much higher than the experimental data, while using the minijet cutoff p_0^{AA} (i.e., the global nuclear scaling of p_0) enables the model to reasonably reproduce the 5.02A-TeV data. Furthermore, the results from the local nuclear scaling of this work (solid curves) well describe the data at both energies, and they are also close to the results from the global nuclear scaling (dot-dashed curves) in both magnitude and shape.

C. Smaller systems including $p\text{Pb}$ collisions

For the system size dependence, it is of particular interest to study the same observables in smaller systems like pA and other AA collisions. Figure 8 shows the results for three smaller collision systems: Xe+Xe collisions at 5.44A TeV [56,57], Cu+Cu collisions at 200A GeV [50,58], and $p\text{Pb}$ collisions at 5.02A TeV [59]. We use the same centrality estimator as the experiments, which is the charged particle multiplicity within $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$ for Xe+Xe collisions [57] and within $|\eta| < 3.2$ for Cu+Cu collisions [50]. For $p\text{Pb}$ collisions at 5.02A TeV, the experiment used the energy deposit in the zero degree calorimeter detector coupled with a heuristic model related to the number of binary collisions (N_{coll}) to determine the centrality; due to the lack of slow nucleon physics in the AMPT model we use the

model N_{coll} as the centrality estimator in the AMPT model calculations.

Figures 8(a) and 8(b) show respectively the midpseudorapidity $dN_{\text{ch}}/d\eta$ and $\langle p_T \rangle$ of charged particles from the AMPT model versus centrality in comparison with the experimental data for the three collision systems. The $\langle p_T \rangle$ values are calculated for hadrons around midpseudorapidity: $|\eta| < 0.8$ for Xe+Xe collisions, $0.2 < \eta < 1.4$ for Cu+Cu collisions, and $|\eta| < 0.3$ for $p + \text{Pb}$ collisions. We see that the improved AMPT model describes these data rather well, confirming the validity of our method of using local nuclear scaling for the p_0 and b_L parameters. This is noteworthy because the data of these smaller systems are not considered in the fitting of the parameter functions such as $\alpha(s)$ and $\beta(s)$ in this study, although the midpseudorapidity $dN_{\text{ch}}/d\eta$ and $\langle p_T \rangle$ data for the most central Au+Au/Pb+Pb collisions have been used. Also note that the AMPT results in Fig. 8 underestimate both the midpseudorapidity $dN_{\text{ch}}/d\eta$ and $\langle p_T \rangle$ for peripheral Xe+Xe collisions; however, in this study we have not included the nonspherical deformation of the Xe nucleus [60].

IV. DISCUSSION

The local nuclear scalings of the b_L parameter in Eq. (3) and p_0 parameter in Eq. (7) both depend on the geometric mean of the two nuclear thickness functions, $\sqrt{T_A(s_A)T_B(s_B)}$; therefore, this geometric form of scaling is similar to the binary scaling in heavy ion collisions. On the other hand, one could also scale the two parameters according to the arithmetic mean of the two thickness functions as the following:

$$b_L(s_A, s_B, s) = b_L^{pp} / \left[\frac{T_A(s_A) + T_B(s_B)}{2T_p} \right]^{\beta(s)}, \quad (9)$$

$$p_0(s_A, s_B, s) = p_0^{pp}(s) \left[\frac{T_A(s_A) + T_B(s_B)}{2T_p} \right]^{\alpha(s)}, \quad (10)$$

and this arithmetic form of local scaling is similar to the participant scaling. For symmetric (AA) collision systems at impact parameter $b = 0$ fm, the two different forms are almost identical, because $T_A(s_A) = T_B(s_B)$ is approximately true, which then reduces Eq. (9) to Eq. (3) and Eq. (10) to Eq. (7). Therefore, we expect that the different forms will not affect the model results for the most central AA collisions. On the other hand, the centrality dependence and the system size dependence of observables could be different for the two different forms. One can expect from Eqs. (3), (7), (9), and (10) that the difference between the two forms will be the biggest for the most asymmetric collisions, i.e., central pA collisions.

In Figs. 9(a) and 9(b), we compare the AMPT model results of $dN_{\text{ch}}/d\eta$ and $\langle p_T \rangle$ around midpseudorapidity versus centrality for both Pb+Pb and $p + \text{Pb}$ collisions at 5.02A TeV. Since one can choose separate forms for the local nuclear scaling of b_L and p_0 , the model results including four different combinations, e.g., the curves labeled as “ \times/\times ” represent our default results of using the geometric form for both b_L and p_0 , while the curves labeled as “ $\times/+$ ” represent the model results of using the geometric form of Eq. (3) for b_L but the arithmetic form of Eq. (10) for p_0 . We see that different forms have a relatively small effect on the $dN_{\text{ch}}/d\eta$ yield

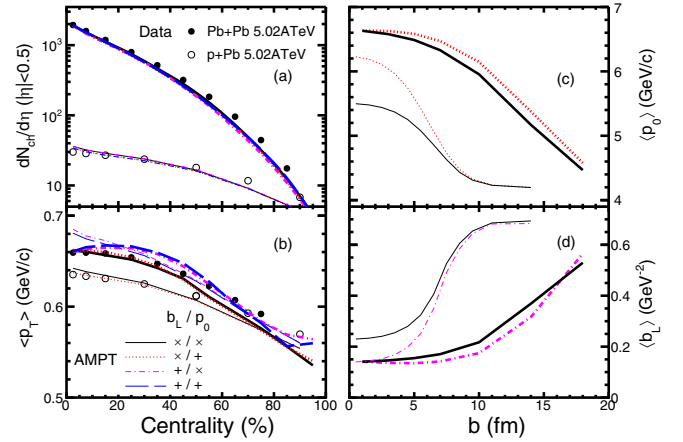


FIG. 9. $dN_{\text{ch}}/d\eta$ within $|\eta| < 0.5$ (a) and $\langle p_T \rangle$ around midpseudorapidity (b) vs centrality, as well as $\langle p_0 \rangle$ (c) and $\langle b_L \rangle$ (d) vs the impact parameter, for 5.02A TeV Pb+Pb (thick curves) and $p + \text{Pb}$ collisions (thin curves) from different forms of local nuclear scaling in the AMPT model (see text for details); symbols represent the experimental data.

and its centrality dependence. On the other hand, they have a significant effect on the mean transverse momentum, especially for $p + \text{Pb}$ collisions, where the arithmetic form for the b_L scaling significantly overpredicts the experimental data, regardless of the form used for the p_0 scaling. Therefore, we choose the geometric form for the local scalings of both b_L and p_0 as shown in Eqs. (3) and (7), while we note that the arithmetic form for the scaling of p_0 would work similarly well as indicated by the dotted curves in Fig. 9. We note that a Bayesian analysis of the TRENTo initial condition [61] with a hybrid model found that the geometric form for the initial state entropy deposition is preferred by the experimental data over several other forms including the arithmetic form [62].

We show in Figs. 9(c) and 9(d) the impact parameter dependence of $\langle p_0 \rangle$ and $\langle b_L \rangle$, respectively, from the two different forms of local nuclear scaling. Indeed, the difference between the geometric and arithmetic forms is the biggest for central $p + \text{Pb}$ collisions, where the arithmetic form gives a bigger variation of the $\langle p_0 \rangle$ and $\langle b_L \rangle$ values with the impact parameter. As a result, the higher p_0 value from the arithmetic form leads to a lower $dN_{\text{ch}}/d\eta$ while the lower b_L value from the arithmetic form gives a higher $\langle p_T \rangle$ for $p\text{Pb}$ collisions.

V. SUMMARY

A multiphase transport model can describe multiple observables in relativistic heavy ion collisions and can thus be very useful for the study of the dynamics and physical properties of the dense matter. However, certain key parameters need to have significantly different values for pp and central AA collisions for the model to well describe the yield and transverse momentum spectrum of the bulk matter. In this study, we use local nuclear scaling to relate two key parameters in the initial condition to the nuclear thickness functions of the two colliding nuclei so that the parameter values change with the system size self-consistently. Specifically, we let two

parameters in the string melting AMPT model with modern parton distribution functions of nuclei, the Lund string fragmentation parameter b_L and the minijet transverse momentum cutoff p_0 , to scale with powers of $\sqrt{T_A(s_A)T_B(s_B)}$ similar to the number of binary collisions. We then systematically study charged particle productions in different collision systems over a wide energy range.

We start from the parameter values for pp collisions that allow a good description of the charged particle yields and transverse momentum spectra in pp collisions from 23.6 GeV to 13 TeV. We then determine the two energy-dependent power functions in the local nuclear scaling of the p_0 and b_L parameters by comparing to data on the charged particle $dN_{ch}/d\eta$ and mean transverse momentum $\langle p_T \rangle$ (below $p_T \lesssim 2$ GeV) around midpseudorapidity in the most central Au+Au and Pb+Pb collisions. Then the centrality dependence and system size dependence are model predictions. We show that, for charged particles around midpseudorapidity in Au+Au collisions from 7.7A to 200A GeV and Pb+Pb collisions at LHC energies, the improved AMPT model not only pro-

vides reasonable descriptions of the centrality dependence of the $dN_{ch}/d\eta$ yield but also well describes the centrality dependence of $\langle p_T \rangle$. The model also provides reasonable descriptions of smaller systems including $p + \text{Pb}$, $\text{Cu} + \text{Cu}$, and $\text{Xe} + \text{Xe}$ collisions without any change of the parameter functions. This work allows a multiphase transport model to describe the system size and centrality dependences of nuclear collisions self-consistently, making the model more reliable for further studies of nuclear collisions from small to large systems.

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