A multi-phase transport (AMPT) model has been successful in explaining a wide range of observables in relativistic heavy ion collisions. In this work, we implement a modern set of free proton parton distribution functions and an impact parameter-dependent nuclear shadowing in the AMPT model. After refitting the parameters of the two-component initial condition model to the experimental data on pp and p\bar{p} total and inelastic cross sections from √s ~ 4 GeV to 13 TeV, we study particle productions in pp and AA collisions. We show that the updated AMPT model with string melting can reasonably describe the overall particle yields and transverse momentum spectra for both pp and AA collisions at RHIC and LHC energies after we introduce a nuclear scaling of the minijet transverse momentum cutoff for AA collisions at LHC energies that is motivated by the color glass condensate. Since heavy flavor and high-p_T particles are produced by perturbative-QCD processes and thus directly depend on parton distribution functions of nuclei, the updated AMPT model is expected to provide a more reliable description of these observables.

I. INTRODUCTION

Experimental results from the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) [1–3] indicate that a hot and dense medium with partonic degrees of freedom, namely the Quark-Gluon Plasma (QGP), is created in heavy ion collisions at high energies. To study the properties of QGP, various theoretical methods and models are being developed including a multi-phase transport (AMPT) model [4]. The AMPT model aims to describe the whole phase space evolution of heavy-ion collisions as it contains four main components: the fluctuating initial condition, partonic interactions, hadronization, and hadronic interactions. The AMPT model has been widely used to simulate the evolution of the dense matter created in high energy heavy ion collisions. In particular, the string melting version of the AMPT model [4, 5], which converts the created matter in the overlap volume into parton degrees of freedom, can well describe the anisotropic flows and particle correlations in collisions of small or large systems at both RHIC and LHC energies [4–8].

However, the current public AMPT model (up to version v1.26/v2.26 [9]) uses the old Duke-Owens parton distribution functions for the free proton and a schematic nuclear shadowing parameterization from the HIJING 1.0 model [10, 11]. Therefore, it significantly underestimates the gluon and quark distributions at small x. This would lead to significant uncertainties in its predictions on heavy flavor and/or high-p_T observables, because those particles are initially produced by perturbative-QCD processes and thus directly depend on the parton distribution functions (PDFs) of nuclei. To improve the AMPT model for high energy nuclear collisions, especially on heavy flavor and high-p_T observables, we incorporate in this study a modern set of free proton parton distribution functions (the CTEQ6.1M set [12]) and an impact parameter-dependent EPS09sNLO nuclear shadowing [13] in an updated AMPT model.

The paper is organized as follows. After the introduction, we describe the initial condition of the AMPT model in section II, including the HIJING two-component model, the CTEQ6.1M parton distribution functions for the free proton, the impact parameter-dependent EPS09s nuclear shadowing functions, and our determination of the energy dependence of two key parameters (p_0 and σ_{sat}) in the two-component model. We then investigate particle rapidity distributions and transverse momentum spectra from the string melting version of the updated AMPT model in Sec. III, including our results for both pp collisions and AA collisions at RHIC and LHC energies in comparison with the experimental data. More discussions can be found in section IV including the effects of nuclear shadowing and the nuclear scaling of the minijet transverse momentum cutoff p_0 on particle productions in AA collisions. Finally, a summary is given in section V.

II. THE INITIAL CONDITION OF THE AMPT MODEL

The string melting version of a multi-phase transport model [4, 5] contains four main parts: the fluctuating initial conditions based on the HIJING two-component model [10, 11], elastic parton scatterings modeled by the ZPC parton cascade [14], a spatial quark coalescence model to describe the hadronization of the parton matter [5, 7], and a hadron cascade based on the ART
model [4, 15]. When we incorporate new parton distribution functions of nuclei in the AMPT model, two key parameters in the HIJING two-component model, $p_0$ and $\sigma_{\text{soft}}$, need to be re-tuned in order to describe the cross sections of $pp$ and $p\bar{p}$ collisions.

A. The HIJING two-component model

The HIJING model [10, 11], which combines jet production that scales with the number of binary collisions with string fragmentation, provides the initial condition of heavy ion collisions in the AMPT model. In the HIJING model, the primary interactions between the projectile and target are divided into soft and hard components with a transverse momentum scale $p_0$. An interaction with a momentum transfer larger than $p_0$ is considered to be a hard process and its production is calculated with perturbative QCD. On the other hand, the soft component with a momentum transfer below $p_0$ is considered to be non-perturbative and characterized by the cross section $\sigma_{\text{soft}}$.

The inclusive jet differential cross section [16] in HIJING is determined by

$$\frac{d\sigma_{\text{jet}}}{dp_T^2 dy_1 dy_2} = K \sum_{a,b} x_1 f_a(x_1, Q^2) x_2 f_b(x_2, Q^2) \frac{d\sigma_{ab}}{dt},$$

where $p_T$ is the transverse momentum transfer, $y_1$ and $y_2$ are respectively the rapidity of the two produced partons, and the $K$ factor aims to account for higher-order corrections, $x_1$ and $x_2$ are respectively the fraction of the momentum carried by the two initial partons, $f_a(x_1, Q^2)$ is the parton distribution function of parton type $a$ at the $x$-value of $x_1$ and factorization scale $Q^2$, and $\sigma_{ab}$ is the cross section between parton types $a$ and $b$. The total inclusive jet cross section is then obtained by integrating the above with a transverse momentum cutoff $p_0$:

$$\sigma_{\text{jet}}(s) = \frac{1}{2} \int_{p_0^2}^{s^4} dp_T^2 dy_1 dy_2 \frac{d\sigma_{\text{jet}}}{dp_T^2 dy_1 dy_2}.$$  \hfill (2)

By introducing a soft interaction cross section $\sigma_{\text{soft}}$, one can write an eikonal function [17, 18] as

$$\chi(b, s) = \frac{1}{2} \sigma_{\text{soft}}(s) T_N(b, s) + \frac{1}{2} \sigma_{\text{jet}}(s) T_N(b, s),$$

where $T_N(b, s)$ is the partonic overlap function between two nucleons at impact parameter $b$ [10, 11]. Then in the eikonal formalism, the total, elastic and inelastic cross section of the nucleon-nucleon collisions can be written respectively as

$$\sigma_{\text{tot}} = 2\pi \int_0^{\infty} db^2 \left[ 1 - e^{-\chi(b, s)} \right],$$

$$\sigma_{el} = \pi \int_0^{\infty} db^2 \left[ 1 - e^{-\chi(b, s)} \right]^2,$$

$$\sigma_{in} = \pi \int_0^{\infty} db^2 \left[ 1 - e^{-2\chi(b, s)} \right],$$

and they depend on both $p_0$ and $\sigma_{\text{soft}}$.

B. Parton distribution functions of the free proton

![Figure 1](image_url)

Figure 1 compares the parton density distributions of the free proton from the CTEQ6.1M set (solid curves) in comparison with the Duke-Owens (dot-dashed) and CJ15 (dashed) sets.

The HIJING 1.0 model in the current AMPT model uses the Duke-Owens parton distribution function set 1 [19] for the free proton. However, it is well known that the Duke-Owens PDFs are outdated, especially when the minijet productions reach the small-$x$ region of the parton distributions at high energies [20]. So in this work we implement the modern CTEQ6.1M set [12] for the parton PDFs of free proton (and free neutron). A similar update of parton PDFs has been done for the HIJING model, where the GRV PDFs [21] were used in the updated HIJING 2.0 model [22] to replace the Duke-Owens PDFs.

C. Parton distribution functions in a nucleus

Nuclear shadowing functions describe the modifications of parton distribution functions in a nucleus relative to a simple superposition of parton distribution functions in the nucleon. Since we will be interested in describing nucleus-nucleus collisions at various impact pa-
rameters, we implement the impact parameter-dependent EPS09sNLO nuclear shadowing functions [24]. They describe the spatial dependence of nuclear PDFs (nPDFs) and are based on data from deep inelastic lepton-nucleus scatterings, Drell-Yan dilepton productions, and specifically pion productions measured at RHIC [24] which improve the determination of the gluon densities. Note that the EPS09sNLO set was calculated with the CTEQ6M set as the free proton PDFs, which is almost equivalent in every respect to the CTEQ6.1M set [25].

For an average bound proton in a nucleus, the distribution function of parton flavor $i$ can be written as

$$f_i^A(x, Q^2) = R_i^A(x, Q^2) f_i^p(x, Q^2),$$  \hspace{1cm} (5)

where $f_i^p(x, Q^2)$ is the corresponding PDF in the free proton. Here $R_i^A(x, Q^2)$ represents the spatially-averaged nuclear modification or shadowing function, which mainly contains three effects depending on the $x$ range: the shadowing effect, anti-shadowing effect, and the EMC effect. It is an integral of the spatially-dependent nuclear shadowing function as given by

$$R_i^A(x, Q^2) = \frac{1}{A} \int d^2 s \ T_A(s) \ r_i^A(x, Q^2, s).$$  \hspace{1cm} (6)

In the above, $T_A(s)$ is the nuclear thickness function at transverse position $s$, and $r_i^A(x, Q^2, s)$ is the spatially-dependent nuclear shadowing.

Figure 2 shows the gluon shadowing functions at the center of a lead nucleus from the EPS09s NLO set at two different $Q^2$ values and from the HIJING 2.0 model at two different $s_g$ values suggested for LHC energies [22]. We see that the EPS09sNLO gluon shadowing at small $x$ is much weaker than the HIJING shadowing. Note that the current AMPT model uses the HIJING 1.0 nuclear shadowing parametrization, which is spatially dependent but independent of $Q^2$ or the parton flavor [4, 10] and similar to the HIJING 2.0 nuclear shadowing.

D. Fitting the two-component model to $pp$ and $p\bar{p}$ cross section data

The two parameters, $p_0$ and $\sigma_{\text{soft}}$, in the HIJING 1.0 model directly affect the total and inelastic cross sections of $pp$ and $p\bar{p}$ collisions, as shown in Sec. II A. In the current AMPT model that uses the Duke-Owens PDFs, constant values of $p_0 = 2.0$ GeV/c and $\sigma_{\text{soft}} = 57$ mb (at high energies [26]) are found to be able to describe the experimental cross sections of $pp$ and $p\bar{p}$ collisions [10, 11]. This is no longer the case after we use the CTEQ PDFs here, or when the GRV PDFs were used for the HIJING 2.0 model [22]. Instead, energy-dependent $p_0(s)$ and $\sigma_{\text{soft}}(s)$ values are needed.

Again we use the experimental total and inelastic cross sections of $pp$ and $p\bar{p}$ collisions within the energy range $4 < \sqrt{s} < 10^2$ GeV, as shown in Fig. 3, to determine these two parameters at a given energy. To fit the experimental cross sections, we minimize the sum of squared relative difference between the model results and the cross section data points. We then determine the following fit
functions of \(p_0(s)\) and \(\sigma_{\text{soft}}(s)\):

\[
p_0^{pp}(s) = -1.71 + 1.63 \ln(\sqrt{s}) - 0.256 \ln^2(\sqrt{s}) + 0.0167 \ln^3(\sqrt{s}),
\]

\[
\sigma_{\text{soft}}(s) = 45.1 + 0.718 \ln(\sqrt{s}) + 0.144 \ln^2(\sqrt{s}) + 0.0185 \ln^3(\sqrt{s}).
\]

In the above, \(p_0^{pp}\) and \(\sigma_{\text{soft}}\) are in the unit of GeV/c and mb, respectively; while the center-of-mass colliding energy \(\sqrt{s}\) is in the unit of GeV. Note that we have denoted the above minijet transverse momentum cutoff as \(p_0^{pp}\) because it represents the \(p_0\) fit function for \(pp\) collisions, while we shall see in Sec. III B that \(p_0\) needs to be \(A\)-dependent in order to reproduce the particle yields in \(AA\) collisions at very high energies such as LHC energies. Also, \(p_0\) values are only relevant when the center-of-mass energy per nucleon-pair is higher than 10 GeV, because the jet production in the HIJING model is switched off at \(\sqrt{s} < 10\) GeV.

Figure 4 shows these two fit functions versus the colliding energy. We see that both show a strong energy dependence, especially the minijet cutoff scale \(p_0\). Because the CTEQ parametrization has much higher gluon densities at small \(x\) than the Duke-Owens PDFs, it has a larger jet cross section at high colliding energies, therefore a higher \(p_0\) value than the previous value of 2 GeV/c is needed in order to reproduce the total and elastic cross section data at high energies. As shown in Fig. 3, the above fit functions of \(p_0(s)\) and \(\sigma_{\text{soft}}(s)\) allow the updated AMPT model to describe the experimental data on the total and elastic cross sections of \(pp\) collisions within a wide energy range \(4 < \sqrt{s} < 10^5\) GeV.

III. RESULTS ON PARTICLE PRODUCTIONS

We now study particle productions in \(pp\) and \(AA\) collisions with the string melting version of the updated AMPT model and compare with the experimental data. In the string melting AMPT model \([4, 5]\), the initial partons are produced through the intermediate step of Lund string fragmentation, where hadrons and resonances from the fragmentation process are decomposed into (anti)quarks according to the quark model. Therefore the initial phase-space distribution of the produced partons depends on the string fragmentation parameters, particularly the \(a\) and \(b\) parameters in the Lund symmetric fragmentation function:

\[
f(z) \propto z^{-1}(1-z)^a \exp(-bm_T^2/z).
\]

In the above, \(z\) is the light-cone momentum fraction of the produced hadron with respect to the fragmenting string, and \(m_T\) is the hadron transverse mass. As a result, the final spectrum of produced particles in the AMPT model depends on the Lund \(a\) and \(b\) parameters \([4, 27]\). In particular, a smaller Lund \(b\) value leads to a harder \(p_T\) spectrum \([27]\). Note that the updated AMPT model used for this study also includes the new quark coalescence \([7]\), which respects the net-baryon conservation in each event but does not force the numbers of mesons, baryons, and antibaryons in an event to be separately conserved through the quark coalescence process.

In this section, we first investigate particle productions in \(pp\) collisions at RHIC and LHC energies to determine the values of the Lund \(a\) and \(b\) parameters. We then apply the same Lund \(a\) and \(b\) values as well as the same minijet cutoff value \(p_0\) to \(AA\) collisions, and we shall see that they fail to describe the experimental data of central \(AA\) collisions. We then keep the same Lund \(a\) value but determine the Lund \(b\) value and the \(A\)-scaled \(p_0\) value that are needed for the string melting AMPT model to reproduce the overall particle productions in central \(AA\) collisions at RHIC and LHC energies.

A. Particle productions in \(pp\) collisions

With the \(p_0^{pp}(s)\) minijet cutoff function, using constant Lund fragmentation parameters of \(a = 0.8\) and \(b = 0.4\) GeV\(^{-2}\) allows the string melting AMPT model to reasonably describe the \(pp\) and \(pp\) data in both the \(dN_{ch}/d\eta\) distributions and the \(p_T\) spectra. Figure 5 shows charged particle pseudo-rapidity distributions from the updated AMPT model in comparison with the experimental data of \(pp\) and \(pp\) collisions from \(\sim 20\) GeV to 13 TeV. Note that we use the same procedure to select events for the AMPT analysis as that used for the experimental data. For example, NSD events in the UA5 data refer to events that contains at least one hit simultaneously on both sides of the chambers covering \(2 < |\eta| < 5.6\), while for the CDF and CMS data they refer to the ranges of \(3.2 < |\eta| < 5.9\) and \(2.9 < |\eta| < 5.2\), respectively.
We have used the same $\eta$ we have converted the data on $E_d$ to $E_d \sigma/d^3$. We have used the same $\eta$ range in calculating the AMPT results as that in the experimental data: $|\eta| < 0.35$ for $\sqrt{s} = 23.6$ and $53$ GeV, $|\eta| < 2.5$ for $200, 546$, and $900$ GeV, $|\eta| < 1$ for $1.8$ TeV, $|\eta| < 0.8$ for $7$ TeV, and $|\eta| < 2.4$ for $13$ TeV.

Figure 6 shows the transverse momentum spectra of charged particles in $pp$ and $\bar{p}p$ collisions from the string melting AMPT model at different colliding energies in comparison with data. Note that for $\sqrt{s} = 7$ and $13$ TeV, we have converted the data on $E_d N/d\eta$ to $E_d \sigma/d^3$. We also see from Fig. 7 that charged pion and kaon productions from the updated AMPT model show good consistency with the $pp$ experimental data at different colliding energies, including the $K^+ / \pi^+$ and $K^- / K^+$ ratios as functions of the colliding energy as shown in the lower panel of Fig. 7. However, the AMPT model here underestimates the antiproton yield and overestimates the proton yield at lower colliding energies. As a result, the $\bar{p}/p$ ratios from the AMPT model are lower than the data at the lower RHIC energies. Note that in Fig. 7 the PHENIX proton and antiproton data [38] shown at $62.4$ GeV are corrected for feed-down effects, but the STAR proton and antiproton data [39] shown at $200$ GeV are not.

**FIG. 7. Identified particle $dN/d\eta$ and particle ratios at mid-rapidity in $pp$ collisions versus the colliding energy; curves represent the AMPT results with $a = 0.8$ and $b = 0.4$ GeV$^{-2}$, while symbols represent the experimental data from NA61SHINE [37], PHENIX [38], STAR [39] and ALICE [40–42].**

**FIG. 6. Invariant cross sections of charged particles versus $p_T$ in $pp$ collisions at $\sqrt{s} = 23.6$ and $53$ GeV [31], $\bar{p}p$ collisions at $200, 546, 900$ [33] and $1800$ GeV [34], and $pp$ collisions at $7$ [35] and $13$ TeV [36] from the AMPT model in comparison with the experimental data.**

For identified particles, we compare in the upper panel of Fig. 7 the string melting AMPT results on $dN/d\eta$ at mid-rapidity for pions, kaons, protons and anti-protons in $pp$ collisions as functions of the colliding energy from $6$ GeV to $13$ TeV. The experimental data are shown by symbols for comparison. We see that the string melting AMPT model can reasonably describe the energy dependence of most of these hadrons, including the fast increase of the antiproton yields with the colliding energy and the non-monotonous energy dependence of the proton $dN/d\eta$.

**B. Particle productions in AA collisions**

Now we investigate results from the updated AMPT model on particles productions in nucleus-nucleus collisions. First we take the same parameters as for $pp$ collisions, i.e., Lund fragmentation parameters $a = 0.8$, $b = 0.4$ GeV$^{-2}$, and the $p^0_{T}(s)$ minijet cutoff function.
Figure 8 shows the $dN/dy$ (left panels) and $p_T$ spectra (right panels) of $\pi^+, K^+, p$ and $\bar{p}$ for 0–5% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and 0–5% central Pb+Pb collisions at 2.76 TeV, where results from the updated AMPT model are being compared to the experimental data [43–45]. Note that we show the PHENIX proton and antiproton data because they have been corrected for feed-down effects. Also, the kaon and (anti)proton $dN/dy$ values from both the model and the experimental data have been multiplied by a constant factor for easier identification.

We see from Fig. 8 that the updated AMPT model with $a = 0.8$, $b = 0.4$ GeV$^{-2}$ and the $p_{T}^{\text{AA}}(s)$ minijet cutoff significantly overestimates the yields of most of these particles for central heavy ion collisions at both RHIC and LHC energies. Also, the $p_T$ spectra of these particles from the AMPT model are mostly softer than the data for both collision systems. Moreover, with the $p_{T}^{\text{AA}}$ minijet cutoff and EPS09sNLO nuclear shadowing, we find it impossible to reproduce the overall particle yields of Pb+Pb collisions at LHC energies regardless of the Lund $a$ and $b$ values.

We thus introduce the following $A$-scaling of $p_0$, which increases the minijet cutoff $p_0$ for central AA collisions at high energies such as the LHC:

$$p_0^{\text{AA}} = p_0^{\text{pp}} A^q(s),$$

$$q(s) = 0.0334 \ln \left( \frac{\sqrt{s}}{200} \right) - 0.00232 \ln^2 \left( \frac{\sqrt{s}}{200} \right) + 0.0000541 \ln^3 \left( \frac{\sqrt{s}}{200} \right), \text{ for } \sqrt{s} \geq 200 \text{ GeV. (10)}$$

In the above, $\sqrt{s}$ refers to $\sqrt{s_{NN}}$ in AA collisions and is in the unit of GeV. This $q(s)$ fit function is shown in Fig. 4, where it is zero at $\sqrt{s_{NN}} \leq 200$ GeV, reaches a value of 0.13 at $\sqrt{s_{NN}} = 10^3$ GeV, and approaches 0.16 at $\sqrt{s_{NN}} \sim 10^7$ GeV. The above nuclear scaling of the minijet momentum cutoff scale $p_0$ is motivated by the physics of color glass condensate [46], where the saturation momentum scale $Q_s$ depends on the nuclear size as $Q_s \propto A^{1/6}$ in the saturation regime for small-$x$ gluons in AA collisions at high-enough energies.

We have decided to keep using the EPS09s nuclear shadowing, although it has significant uncertainties on its gluon shadowing function at small $x$ [13]. We also use the same Lund $a$ value of 0.8 for AA collisions as for $pp$ collisions, unlike in studies with the previous AMPT model [4, 7]. In addition, we find that a significantly smaller value for the Lund $b$ parameter, $b = 0.15$ GeV$^{-2}$, is needed to describe particle productions in AA collisions. This was also the case for the previous string melting version of the AMPT model [6, 27]. Note that throughout this study we use the default PYTHIA value of 0.30 for the relative production of strange to non-strange quarks, instead of imposing an upper limit of 0.40 as done for the string melting version of the previous AMPT model [27].

Figure 9 shows the $dN/dy$ distributions (left panels) and $p_T$ spectra (right panels) from the AMPT model using the new Lund $b$ parameter and $p_{T}^{\text{AA}}(s)$ cutoff in comparison with the experimental data. We see that most of the $dN/dy$ data of $\pi^+, K^+, p$ and $\bar{p}$ in these central heavy ion collisions can now be reasonably reproduced. The $p_T$ spectra are also much harder than those in Fig. 8 and mostly consistent with the corresponding heavy ion data, due to the smaller value of the Lund $b$ parameter [27].

In Fig. 10, the energy dependences of identified particle yields at mid-rapidity are shown in the upper panel for 0–5% central Au+Au collisions at RHIC energies and 0–5% central Pb+Pb collisions at LHC energies. The corresponding particle ratios are shown in the lower panel. Note that the rapidity range at 2.76 TeV is $|y| < 0.5$ while at other energies is $|y| < 0.1$, and that the PHENIX (anti)protons data at 62.4 and 130 GeV are not corrected for feed-down from weak decays. We see from Fig. 10 that the yields of charged pions and kaons as well as their ratios are well reproduced by the updated AMPT model. However, similar to the trend in $pp$ collisions, at lower energies the string melting AMPT model underestimates the anti-proton yield but tends to overestimates the proton yield at mid-rapidity. As a result, the mid-rapidity $\bar{p}/p$ ratios from the string melting AMPT model at the lower RHIC energies are significantly smaller than the experimental data. On the other hand, the AMPT model can reasonably reproduce the (anti)proton data for central Pb+Pb collisions at the LHC energy of 2.76 TeV. These features are similar to those in the earlier study that used the previous string melting AMPT model with the new quark coalescence [7].

IV. DISCUSSIONS

Since the EPS09s nuclear shadowing is impact parameter-dependent and diminishes for nucleons near the edge of the nucleus, we expect the effect of nuclear shadowing to depend on centrality and vanish for very peripheral AA collisions. This is shown in Fig. 11 by the centrality dependence of charged particle $dN/d\eta$ within $|\eta| < 0.5$ divided by $N_{\text{part}}/2$ for Au+Au collisions at 200 GeV and Pb+Pb collisions at 2.76 TeV and 5.02 TeV. Note that centrality is determined according to the number of charged particles detected by the Beam-Beam Counters that cover $3 < \eta < 5.1$ and $-3.7 < \eta < 1.7$ at 2.76 TeV or 5.02 TeV. The same centrality criterion is used in the analysis of our model results, and we take $N_{\text{part}}$ as the total number of nucleon participants from both the projectile and target nuclei due to inelastic collisions in the AMPT calculations.

As expected, we see in Fig. 11 that the shadowing effect is very small for peripheral collisions. Actually, the figure shows that nuclear shadowing has a small effect on charged particle yields at all centralities for AA collisions from the top RHIC energy to LHC energies. This is be-
because of the large $p_0$ value at high energies and the weak EPS09sNLO nuclear shadowing at large $Q^2$ values (that are at least $p_0^{AA^2}$) as shown in Fig. 2.

On the other hand, Fig. 11 shows that the $A$-scaling of $p_0$ has a large effect on charged particle yields in $AA$ collisions at LHC energies, especially for more central collisions. As mentioned earlier, the string melting AMPT model significantly overestimates the charged particle yields in central Pb+Pb collisions at LHC when it uses $p_0^{pp}$, the same minijet cutoff scale as for $pp$ collisions. After the $A$-scaling of $p_0$, however, the minijet cutoff scale in $AA$ collisions ($p_0^{AA}$) at LHC energies becomes significantly higher and thus $\sigma_{pi}$ becomes much smaller, as shown in Fig. 3 by the dashed line that is much lower than the dotted line at LHC energies. This leads to a significant decrease of the charge particle yields at LHC energies, especially for central $AA$ collisions where the binary scaling of minijet productions makes them more sensitive to the minijet cutoff $p_0$.

For peripheral $AA$ collisions however, we expect no need for the $A$-scaling of $p_0$, because participant nucleons there are near the edge of the nucleus and should be almost free of saturation effects. Since we have not implemented this impact parameter-dependent nuclear scaling of $p_0$ and the current $A$-scaling of Eq. (10) is only valid for central $AA$ collisions, we show in Fig. 11 the LHC Pb+Pb results without using the $A$-scaling of $p_0$ (dot-dashed lines), which are more suitable for peripheral collisions. Indeed, we see that the AMPT results without the $A$-scaling of $p_0$ give higher charged particle yields and are closer to the experimental data for peripheral collisions than the AMPT results with $A$-scaling of $p_0$. Also note that, since we have found that the Lund $b$ value is much smaller in central $AA$ collisions than in $pp$ collisions, the Lund $b$ value should depend on the system size or centrality, and increasing its value for peripheral $AA$ collisions (similar to $pp$ collisions) could further improve the description of charged particle yields there.

We have seen that the minijet cutoff scale $p_0$ becomes increasingly large with energy and can be more than 4 or even 6 GeV/c. However, it is questionable to treat transverse momentum exchanges below such a high value of $p_0$ as soft physics with the Lund string fragmentation, while the production of charm particles is usually viewed as a perturbative-QCD process where the FONNL approach has been very successful [52]. Therefore the two-
component model such as HIJING may be problematic for the initial condition at very high energies. For example, the need for us to introduce the nuclear scaling of $p_0$ for AA collisions at LHC energies and above may indicate the importance of saturation physics for large systems at very high energies. In addition, the current parton cascade in the AMPT model only includes elastic parton scatterings [14]. However, inelastic parton interactions [53] affect the parton abundance and momentum spectrum at high energies, and these effects are expected to be energy- and centrality-dependent. Therefore including inelastic parton scatterings should improve the physics of a multi-phase transport model [54].

The updated AMPT model has not shown obvious phenomenological improvements over the previous AMPT model when compared with the experimental data in this study, except that the updated model uses the same Lund $a$ value for $pp$ and AA collisions at all energies and thus removes the uncertainty of this parameter present in the previous AMPT model. However, the updated AMPT model should be more robust in its physics because of its inclusion of modern parton PDFs in the nuclei. Therefore we expect it to provide a better foundation for future model developments and also show improvements in certain observables such as heavy flavor productions [55].

V. SUMMARY

A multi-phase transport model has been using the old Duke-Owens parton distribution functions for the free proton and a schematic nuclear shadowing parameterization. This leads to significant uncertainties in its ability to address heavy flavor and/or high-$p_T$ particles, because they are produced by perturbative-QCD processes and thus directly depend on the parton distribution functions of nuclei. In this study, we have incorporated a modern set of free proton parton distribution functions, the CTEQ6.1M set, and the impact parameter-dependent EPS09sNLO nuclear shadowing in an updated AMPT model. We first determine the energy dependence of two key parameter functions, $p_0(a)$ and $\sigma_{soft}(s)$, in the HIJING two-component model by fitting the experimental data on total and inelastic cross sections of $pp$ and $p\bar{p}$ collisions from $\sqrt{s} \sim 4$ GeV to 13 TeV. We then compare particle productions from the string melting version of the updated AMPT model with the experimental data in both $pp$ and AA collisions at RHIC and LHC energies.
We find that the $p_0(s)$ function and the constant values for the Lund string fragmentation parameters that can reasonably describe the particle yields and $p_T$ spectra in $pp$ collisions fail to describe central $AA$ collisions at LHC energies. Therefore we introduce a nuclear scaling of the minijet transverse momentum cutoff $p_0$ for central $AA$ collisions at high energies that is motivated by the color glass condensate picture. Then the string melting AMPT model can also reasonably describe the overall particle yields and $p_T$ spectra of $AA$ collisions at both RHIC and LHC energies. We expect the updated AMPT model to provide more reliable descriptions of heavy flavor and high-$p_T$ observables in relativistic collisions of both small and large systems. It also serves as a good foundation for further improvements of the model.

![Graph 1](image1.png)  
**FIG. 10.** Identified particle $dN/dy$ and particle ratios at mid-rapidity in 0-5% central $AA$ collisions versus the colliding energy; curves represent AMPT results, while symbols represent experimental data at 62.4 GeV [44], 130 GeV [47], 200 GeV [43] and 2.76 TeV [45].

![Graph 2](image2.png)  
**FIG. 11.** Centrality dependence of charged particle $dN/d\eta$ at mid-rapidity divided by $N_{part}/2$ from the AMPT model for Au+Au collisions at 200 GeV and Pb+Pb collisions at 2.76 TeV and 5.02 TeV with (solid) and without (dashed) nuclear shadowing in comparison with the experimental data [48–51]. Dot-dashed curves represent AMPT results without using $A$-scaling of $p_0$ that are more applicable to peripheral $AA$ collisions.

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