Improvement of heavy flavor productions in a multi-phase transport model updated with modern nPDFs

L. Zheng, C. Zhang, S.S. Shi, and Z.W. Lin

1 School of Mathematics and Physics, China University of Geosciences (Wuhan), Wuhan 430074, China
2 Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China
3 Department of Physics, East Carolina University, Greenville, North Carolina 27858, USA

Recently we have updated a multi-phase transport (AMPT) model with modern parton distribution functions of nuclei (nPDFs). Here we study open charm productions in the updated AMPT model and compare to the experimental data from pp and AA collisions over a wide range of collision energies. Besides the update of nPDFs, we have removed the transverse momentum cutoff on initial heavy quark productions and also included the resultant heavy flavor cross section into the total minijet cross section in the initial condition as described by the HIJING model. We show that the AMPT model with these updates provides a much better description of the yields and transverse momentum spectra of various open charm hadrons in comparison with the experimental data. This lays the foundation for further heavy flavor studies within the transport model approach.

I. INTRODUCTION

In high energy hadronic collisions, heavy flavor production provides us a powerful tool to study quantum chromodynamics (QCD) [1]. The initial production of heavy flavor quarks is calculable with the perturbative QCD (pQCD) method due to the relatively large value of the heavy quark mass. In heavy ion physics, heavy quarks also play an important role because their masses are typically larger than the temperatures achieved in the produced quark-gluon plasma (QGP). Therefore, they are predominantly produced in the initial hard scatterings between the two nuclei on a time scale shorter than the formation time of the QGP. As a result, heavy quarks can experience almost the full evolution of the deconfined nuclear medium and are thus sensitive to early dynamics of the collision system [2, 3].

Recently, it has been realized that the strong electromagnetic fields in the initial state of heavy ion collisions may significantly affect the heavy quark directed flow $v_1$ and result in a larger charm $v_1$ than lighter particles [4, 5]. In addition, heavy quarks or hadrons are also expected to interact with the QGP or hadronic medium through elastic or inelastic processes during their propagation in the dense matter. This would lead to the suppression of heavy hadron yields at high transverse momentum often represented by the nuclear modification factor $R_{AA}$ and anisotropic flows of heavy hadrons such as elliptic flow $v_2$. These observables can be extracted to study the transport properties of the QGP matter such as the drag and diffusion coefficients [7, 9]. For example, a large suppression in $R_{AA}$ and/or a substantially non-zero $v_2$ for open heavy particles indicates that heavy quarks experience significant interactions with the bulk medium.

Multiple theoretical frameworks have been developed to describe heavy flavor productions in high energy collisions. For example, pQCD calculations for the initial charm productions in pp and pA collisions include the General-Mass variable flavor number scheme (VFNS) approach [10] and the Fixed-Order plus Next-to-Leading Logarithms (FONLL) formalism [11]. These theoretical calculations usually can reasonably describe open charm productions in pp collisions, although their central values are often below the experimental data. In addition, medium induced effects can be included with models based on the heavy quark transport or pQCD calculations of the parton energy loss. At the high transverse momentum ($p_T$) region, models [12, 13] that include both collisional and radiative energy loss of heavy quarks usually provide a fair description of the $R_{AA}$ from central to peripheral collisions. On the other hand, the evolution of low-$p_T$ heavy quarks in the bulk medium is similar to the Brownian motion and can thus be studied with transport approaches based on the Langevin or Boltzmann equation, which has been implemented in the models like POWLANG [14], TAMU [15], Duke [10], BAMPS [17], LBT [13], MC@HQ+EPOS [19], PHSD [20] and Cata
ing [21, 22].

A multi-phase transport (AMPT) model [23] is a useful tool to study the bulk medium through the microscopic dynamical processes of the evolving system. The ZPC component solves the Boltzmann equation for two-body scatterings via the parton cascade approach [24]. As a self-contained event generator, the AMPT model provides a unified framework to explore the medium evolution with different flavors including the event-by-event fluctuation and conservation of conserved charges. For example, the initial production of heavy quarks is modeled together with that of the light quarks and therefore the conservation of quantities such as energy, momentum, net baryon number, and net charm number is guaranteed in the AMPT initial condition of each event. Transport model studies of the dense matter, including
heavy flavor studies with the AMPT model [25–26], help
us to understand the QGP evolution and the transition
from the non-equilibration stage to the hydrodynamic
stage [27–30]. In particular, systematic comparisons of
model predictions with the measured heavy flavor ratio
and v2 [31–32] allow us to determine the relevant QGP
medium transport coefficients such as the spatial diffu-
sion constant Ds, the drag coefficient ηD, and the momen-
tum transport coefficients κs, κT, ˌq..

Recently we have updated the AMPT model with an
improved quark coalescence process [33] and modern nu-
clear parton distribution functions (nPDFs) [34]. In this
work, we will use the improved AMPT model to address
open charm productions and then compare the model re-
sults with the experimental data. The rest of the paper
is organized as follows. In Sec. II we discuss the physics
changes we have made for open heavy flavor productions
in the AMPT model. Then we calculate the yield and
pT spectra of various open charm hadrons in comparison
with the experimental data in pp and AA collisions in
Sec. III and Sec. IV respectively. After discussions in
Sec. V, we summarize in Sec. VI.

II. DESCRIPTIONS OF HEAVY FLAVORS IN
THE UPDATED AMPT MODEL

In the AMPT model, the initial productions of heavy
quarks (Q) are modeled by the HIJING model [35]. They
include the pair production processes (q +  ¯q → Q +  ¯Q,
q + g → Q + Q) and gluon splitting process (g → Q + Q).
However, the flavor excitation processes (g + Q → q + Q,
y + Q → g + Q) are not included. This is partly because
the HIJING model only deals with closed string objects
created by minijet productions but a flavor excitation
process usually delivers a single heavy quark jet in the
final state. The pair production cross section for heavy
quarks in pQCD at leading order can be expressed as

\[
\frac{dσ^{QQ}}{dp_T^2dy_1dy_2} = K \sum_{a,b} x_1 f_a(x_1, μ_F^2) f_b(x_2, μ_F^2) \frac{dσ^{ab→QQ}}{dt}
\]  

(1)

In the above, y1 and y2 are respectively the rapidity of the
two produced partons, the K factor aims to account for
higher-order corrections of heavy quark productions, a
and b refer to the type of interacting partons in the initial
state, x denotes the nucleon momentum fraction taken by
the interacting parton, μF represents the factorization scale,
f_a represents the parton distribution function of parton
type a in a (free or bound) nucleon, and σ^{ab→QQ}
is the cross section for parton types a and b to produce
the heavy quark pair. The K-factor K = 2.5 is used for
both light and heavy flavor productions, as done in our
previous study of light flavor observables after the update
of nPDFs [34]. For charm quark productions we take
μ_F^2 = 2(p_T^2 + m_c^2), where p_T is the transverse momen-
tum transfer and we take the charm quark mass as m_c = 1.3
GeV/c^2 in this study.

The calculation of hard scatterings in AMPT is imple-
mented within the HIJING two-component model, where
each hard parton is generated with a minimum transverse
momentum cut, p_0, to regulate the total minijet produc-
tion cross section. The differential minijet cross section
at leading order has the same form as Eq. (1):

\[
\frac{dσ^{cd}}{dp_T^2dy_1dy_2} = K \sum_{a,b} x_1 f_a(x_1, μ_F^2) f_b(x_2, μ_F^2) \frac{dσ^{ab→cd}}{dt}
\]  

(2)

where σ^{ab→cd} is the cross section for parton types a and
b to produce a pair of minijets c and d. Then the total
minijet cross section can be written as

\[
\sigma_{jet}(s) = \sum_{c,d} \frac{1}{1 + δ_{cd}} \int_{p_0^2}^{s/4} dp_T^2dy_1dy_2 \frac{dσ^{cd}}{dp_T^2dy_1dy_2}.
\]  

(3)

This minijet transverse momentum cutoff p_0 and the
soft interaction cross section σ_{soft} are the two key pa-
rameters in the HIJING two-component model, which
control the elastic, inelastic and total cross sections of
pp and pp collisions [35–37]. Note that there is an extra
factor of 1/2 for final states with identical partons, such
as g + g → g + g for minijet gluon productions, in the
above equation. In contrast, the original HIJING model
applies the factor of 1/2 to all light flavor minijet produc-
tion processes [36], and that leads to a slightly smaller
total σ_{jet} than Eq. (3) (at the same p_0).

In the HIJING model as well as the previous AMPT
model (denoted as “old AMPT”) before our most recent
updates as done in Ref. [31] and this study, the minijet
cross sections of Eqs. (2) do not include the cross sec-
tion of heavy flavors such as charm and bottom quarks
as given by Eq. (1). As a result, σ_{soft}(s), which is used in
the eikonal formalism for the total, elastic and inelastic
cross sections [35–36], represents the cross section of light
flavor (u/d/s) minijets. Then in the actual generation of
minijets, heavy flavor minijets are still being generated
and their fraction is calculated by the ratio of the heavy
flavor cross section over the total minijet cross section,
i.e., σ^{QQ}/σ_{jet}, where the same minimum transverse
momentum cut p_0 is used in calculating σ^{QQ} as done in
Eq. (3) for σ_{jet}.

The above approach has two issues. First, for self-
consistency the heavy flavor cross sections need to be
included in the total minijet cross section in the two-
component model. Secondly, the heavy quark cross sec-
tions can be calculated with pQCD without any mini-
mum transverse momentum requirement and the large
heavy quark mass (compared to Λ_{QCD}) naturally regu-
lates the heavy quark total cross section. Therefore, we
make significant changes to the descriptions of heavy fla-
vers in the AMPT model by removing the p_0 cut for the
heavy quark production cross sections and then includ-
ing them in the total minijet cross section. These changes
can be illustrated by the following modified formula for
the new minijet cross section:

$$\sigma_{\text{jet}}(s) = \sum_{c,d} \frac{1}{1 + \delta_{cd}} \int_{p_0^2}^{s/4} dp_1^2 dy_1 dy_2 \frac{d\sigma_{\text{light}}^c_1}{dp_1^2 dy_1 dy_2} \int_{0}^{s/4} dp_1^2 dy_1 dy_2 \frac{d\sigma_{\text{heavy}}^c_1}{dp_1^2 dy_1 dy_2},$$

where the first term represents the total cross section of light flavor ($u/d/s/g$) minijets and the second term represents that of heavy flavor minijets including charm and bottom flavors.

Naively one may expect that including the heavy quark production cross sections in the total minijet cross section will have negligible effects because heavy quarks are very rare. However, in the two-component model such as HIJING the light flavor ($u/d/s/g$) minijets require a minimum $p_0$ while we think the heavy flavor minijets should not. Therefore when the $p_0$ value is high, which is especially the case for the new HIJING2.0 [37] and the updated AMPT model [34] that use newer PDFs, the charm production cross section may be a significant fraction of the total minijet cross section for $AA$ collisions at high energies. Note that in the AMPT model updated with new nPDFs we have related the $p_0$ value for central $AA$ collisions at high energies to that for $pp$ collisions with a nuclear scaling of $p_0$. That leads to a larger $p_0$ in $AA$ collisions and thus suppresses light flavor minijet productions at high energies, while the initial heavy flavor productions are not affected.

The event averaged $c\bar{c}$ yield as a function of the collision energy is shown in Fig. 1. Results without heavy quark channel in the total minijet cross section are presented by the dashed curves while the solid curves show the charm quark pair numbers after heavy flavor channels are included as done in Eq. 5. The inclusion of heavy quark cross section slightly increases the charm quark yield at high energies in $pp$ collisions. At low energies, the difference between these two curves become negligible as expected due to the decreasing of heavy flavor cross section. In $AA$ collisions, the impact of including heavy flavor sector becomes more significant, up to a factor of 2 at very high energies.

We expect the string melting version of the AMPT model [38] (instead of the default version of AMPT) to be applicable in describing the dense matter at high energies when a QGP is believed to be formed in the early stage of the collisions. Therefore we use the string melting version throughout this study. The hadronization of the partonic matter is accomplished by a spatial quark coalescence model [33] after partons stop interacting. The open heavy flavor hadron species formed by quark coalescence includes the following charm and bottom hadrons at all possible charge states (plus the corresponding anti-particles when applicable): $D$, $D^*$, $D_s$, $D_s^*$, $\Lambda_c$, $\Sigma_c$, $\Xi_c$, $\Xi_c'$, $\Xi_c''$, $\Omega_c$, $\Omega_c'$, $\Omega_c''$, as well as $B$, $B^*$, $B_s$, $B_s^*$, $B_c$, $B_c^*$, $\Lambda_b$, $\Sigma_b$, $\Xi_b$, $\Xi_b'$, $\Omega_b$, $\Omega_b'$, $\Omega_b''$, $\Omega_{bb}$, $\Omega_{bc}$, and $\Omega_{bb}$. The hadron species are determined by the flavor combination of the two or three coalescing (anti)quarks. In addition, for a pseudo-scalar meson and a vector meson with the same flavor combination, our previous approach is to form the meson to which the invariant mass of the coalescing quark and antiquark is closer [24]. However, we find that the resultant vector to pseudo-scalar meson ratios such as the $K^*/K$ ratio and the $D^*/D$ ratio are often far away from the experimental data [39]. Therefore, we change the previous approach and now set the ratio of each type of vector to pseudo-scalar meson in the quark coalescence model, 0.30 for primordial $\rho/\pi$, 0.50 for primordial $K^*/K$, and 1.0 for primordial $D^*/D$ or $B^*/B$. For example, for all the flavor combinations that could form either $D$ or $D^*$ mesons, we order them in terms of the excess mass (i.e. the difference between the two-quark invariant mass and the sum of two quarks’ masses) and assign the half with lower excess masses to form $D$ and the half with higher excess masses to form $D^*$. The above values are chosen to roughly reproduce the overall magnitudes of the final vector to pseudo-scalar meson ratios observed in $pp$ collisions of various energies. Note that the above values determine the ratios of the primordial (i.e. right after quark coalescence) meson multiplicities in each event, not the ratios in the final state that often include effects from resonance decays and hadronic rescatterings.

In the new quark coalescence model for AMPT [33], the overall relative probability of a quark to form a baryon instead of a meson is determined by the $r_{BM}$ parameter. Generally, there would be no antibaryon formation if this parameter is 0 but almost no meson formation if it goes to infinity. In the updated AMPT model [34] used for this work, the $r_{BM}$ value for light flavor ($u/d/s$) hadrons is set to 0.53. On the other hand, the $r_{BM}$ value for

![Fig. 1. (Color online) Effect of including heavy flavor cross sections into the minijet cross section on the yield of charm-anticharm quark pairs from the AMPT model for $pp$ and central $AA$ collisions ($Au+Au$ at or below 200 GeV and $Pb+Pb$ above 200 GeV).](image-url)
heavy flavor hadrons is set to 1.00, because the light flavor value of 0.53 would lead to too few charm baryons (by a factor of ~ 4) compared to the experimental data in pp or AA collisions. In principle, the $r_{BM}$ value for charm hadrons is related to the properties such as the number and masses of available charm baryon states versus charm meson states, and the higher $r_{BM}$ value for charm is consistent with the assumption that relative to light flavors there are more charm baryon states than charm meson states [10].

Heavy quark productions directly depend on the PDFs as shown in Eq. (1). In addition, for AA collisions $f$ in Eqs. (1-2) represents the parton PDFs in the nucleus instead of those in a free nucleon and thus contains the nuclear shadowing functions. Therefore we expect that our recent updates to the AMPT model [34] by including the newer parton distribution functions CTEQ6.1M [41] of free nucleon and the modern impact parameter-dependent EPS09s [42] nuclear shadowing functions should improve its descriptions of heavy flavor productions.

III. OPEN CHARM RESULTS FOR pp COLLISIONS

We now use the string melting version of the updated AMPT model [34], which already includes the heavy flavor improvements as detailed in the previous section, to study open charm productions in pp collisions in this section as well as AA collisions in the next section. Like the study on light flavors [33], we set the Lund string fragmentation parameters to $a = 0.8, b = 0.4 \text{ GeV}^{-2}$ for pp collisions and $a = 0.8, b = 0.15 \text{ GeV}^{-2}$ for the central Au+Au collisions at RHIC energies and Pb+Pb collisions at LHC energies. In addition, we set the parton elastic scattering cross section to $\sigma_p = 3 \text{ mb}$ and the hadron cascade cutoff time to 30 fm/c. The old AMPT results are often provided for comparisons, and there we use the AMPT version v2.26t9 with the same parameters as in an earlier study [43]. Unless otherwise specified, the yield of each charm meson species represents the average of the particles and the corresponding anti-particles.

The total $c\bar{c}$ pair cross section varying with $\sqrt{s}$ for pp collisions from the AMPT model is shown in Fig. 2 compared with the available world data. The data points from PHENIX, ATLAS and LHCb collaborations are slightly shifted on horizontally. We see that the updated AMPT model with our recent modifications (solid line) can provide a good description of the charm quark cross section in pp collisions on a wide energy range. On the other hand, the old AMPT model significantly underestimates the charm cross section, especially at low energies. The dashed line shows the results when charm quark productions are subject to the minimum $p_T$ requirement, where we see much lower charm quark cross sections.

We show the rapidity and transverse momentum distributions of charm quarks from the AMPT model at $\sqrt{s} = 200 \text{ GeV}$ and $\sqrt{s} = 7 \text{ TeV}$ in Fig. 3. We see that the enhancement of the charm quark yield is stronger in the mid-rapidity region. The charm quark transverse momentum spectra at mid-rapidity are shown in Fig. 3(b), where the statistical errors of the AMPT results are represented with a shaded band. We also see that the removal of the transverse momentum cutoff $p_T$ for charm quarks mostly enhances the charm quark production in the low $p_T$ region. It is interesting to observe in Fig. 3(a) that the old AMPT result (dotted line) is rather similar to the result from the updated AMPT model with the $p_T$ cut for charm quarks (dashed curve); this is also seen in Fig. 2 until 1 TeV. Note that the old AMPT model also has a $p_T$ cut (2 GeV/c) on charm quark productions.

Open charm hadron productions in pp collisions at $\sqrt{s} = 200 \text{ GeV}$ are shown in Fig. 4 for $D^0$, $D^*$, $D^{*+}$ and $\Lambda_c^+$. Note that the charm quark or hadron yields and spectra in this study have been averaged over those for particles and their corresponding anti-particles, e.g., the $\Lambda_c^+$ results in Fig. 4 represent the average results for $\Lambda_c$ and $\bar{\Lambda}_c$. In addition, results of $D^0$ include both primordial $D^0$ mesons and $D^0$ mesons from $D^*$ decays. We see that the shape and magnitude of the charm hadron distributions shown in Fig. 4 reflect those of the charm quarks in Fig. 3. For example, the $p_T$ spectra of charm hadrons from the updated AMPT model are much harder than those in the old AMPT model, as also seen for the charm quarks. The $D^*$ to $D^0$ ratio is rather flat across the shown $p_T$ region. We also see that results from the updated AMPT model are slightly lower than the STAR $D^0$ data but still within the uncertainties.

In Fig. 5(a) we confront the model results for $D^0$, $D^+$, $D^{*+}$, $D^{*+}$ and $\Lambda_c^+$ with the experimental data for pp collisions at $\sqrt{s} = 7 \text{ TeV}$. Fig. 5(a) shows that the re-
FIG. 3. (Color online) (a) Rapidity distributions and (b) transverse momentum spectra of charm quarks in pp collisions at $\sqrt{s} = 200$ GeV (thick) and $\sqrt{s} = 7$ TeV (thin) from the AMPT model. The shaded band represents statistical errors.

FIG. 4. (Color online) (a) Rapidity distributions and (b) transverse momentum spectra of open charm hadrons in pp collisions at $\sqrt{s} = 200$ GeV from AMPT in comparison with the experimental data.

IV. OPEN CHARM RESULTS FOR AA COLLISIONS

In AA collisions, charm productions are subject to additional initial state and final state effects. Initial state effects include the nuclear modification to the parton distribution functions, while final state effects include parton rescattering in ZPC parton cascade.

In Fig. 6, we show the charm quark yield at mid-rapidity for 0-10% central AA collisions at different colliding energies. We see that the EPS09s nuclear shadowing slightly enhances the charm yield at low energies but significantly suppresses the charm yield at high energies (above 1 TeV). This results from the anti-shadowing effect at large $x$ and the shadowing effect at small $x$. We also see that the AMPT result agrees with the charm quark pair yield for 0-10% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV extracted from the STAR $D^0$ data. The $D^0$ fragmentation fraction 0.27 is esti-
the current AMPT results (solid line) for the charm quark yield at mid-rapidity are significantly higher (by a factor of 2) compared to the old AMPT results (dotted line), the current AMPT result is significantly higher. Also, the AMPT result is significantly higher in comparison with the extracted STAR data ([51]).

Compared to the mid-rapidity STAR data ([51]), the updated AMPT model (solid line) gives significantly more charm quarks compared to the old AMPT model (dotted line) at both energies, which is already shown in Fig. 6. On the other hand, nuclear shadowing leads to a <50% suppression of the rapidity density of charm quarks for central Pb+Pb collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \). We can find in Fig. 7(b) that nuclear shadowing mainly suppresses the charm quark yield in the low \( p_T \) region. This is consistent with the fact that nuclear shadowing is stronger at low \( \mu_F^2 \) that is associated with low \( p_T \) charm quarks. Note that the EPS09s nuclear shadowing functions in the updated AMPT model include the QCD evolution with the \( \mu_F \), unlike the shadowing parameterization implemented in HIJING1.0.

FIG. 7. (Color online) (a) Rapidity distributions and (b) transverse momentum spectra of open charm hadrons in \( pp \) collisions at \( \sqrt{s} = 7 \text{ TeV} \) from AMPT in comparison with the ALICE \( D \) meson data ([50] and \( \Lambda_c \) data ([52]).

The productions of open charm hadrons including \( D^0, D^{*+}, D^+_s \) and \( \Lambda_c \) in 0-10% central Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) are shown in Fig. 8. As shown in Fig. 8(a), unlike the small \( D^{*+}/D^0 \) ratio in the old AMPT model, the \( D^0 \) yield from the updated AMPT model is about twice the \( D^{*+} \) yield, close to the ratio observed in Fig. 4(a) for \( pp \) collisions at the same energy. Compared to the mid-rapidity STAR \( D^0 \) data, however, the AMPT result is significantly higher. Also, the AMPT result on the \( D^0 \) \( p_T \) spectrum in Fig. 8(b) is too soft in comparison with the STAR data ([51] [53] and underpredicts the \( D^0 \) production at \( p_T > 4 \text{ GeV/c} \). Since the yield of midrapidity charm quarks from AMPT is consistent with the extracted STAR data as shown in Fig. 6, the overestimation of the \( D^0 \) yield in AMPT could be because the quark coalescence in AMPT gives fewer \( D_s \) and \( \Lambda_c \) than the data ([53]). It has been suggested that a sequential coalescence of different charm hadrons is important for the enhancement of \( \Lambda_c/D^0 \) and \( D_s/D^0 \) ratios in

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Including this sequential coalescence picture into AMPT could improve the descriptions of different charm hadron species in the future. In addition, the charm $p_T$ spectra depend on the scatterings cross section and its angular distribution between charm quarks and light flavors. The AMPT model currently uses the $g+g \rightarrow g+g$ cross section for scatterings between all parton flavors, and improvements should be made to treat parton scatterings between different flavors differently, where the comparison with the charm $p_T$ spectra data will enable us to extract the charm interaction strength with light flavors.

In Fig. 7 we show open charm hadron productions in 0-10% central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and compare with the ALICE data. We first see that the model results for all these open charm particles are lower than the experimental data, especially in the higher $p_T$ region. When we integrate the midrapidity $D^0$ yield at $p_T \geq 1.0$ GeV/c, the ALICE data give 6.0 while the AMPT result gives 3.3. This underestimation of the $D^0$ yield in AMPT is first related to the branching of charm quarks into different hadron species; e.g. the $\Lambda_c/D^0$ ratio from AMPT is higher than the LHC data as shown in Fig. 10(d). Secondly, the $D^0$ $p_T$ spectrum from the AMPT model is too soft, as also seen at RHIC energies in Fig. 8(b). Furthermore, the total charm quark yield in AMPT could be lower than that in the ALICE data, in part because of nuclear shadowing that has been shown in Fig. 6 to significantly suppresses the charm yield at LHC energies. Note that there is still a large uncertainty on the nuclear shadowing of gluons [42], which we have not explored in this study. We examine in Fig. 10 the ratios of open charm hadron yields in 7 TeV $pp$ collisions and 0-10% central Pb+Pb collisions at 5.02 TeV. Note that, although the AMPT results of the charm hadron yields are significantly lower than the experimental data for Pb+Pb collisions at LHC,
In the string melting AMPT model, the interactions between charm quarks and the QGP medium are modeled by parton elastic scatterings of ZPC. Thus our study includes the collisional energy loss of heavy quarks but neglects the radiative energy loss. Studies have suggested that the elastic collisional energy loss is dominant for heavy flavors below a moderately high $p_T$, e.g., for charm hadrons at $p_T < \sim 5 - 6$ GeV/c in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV or at $p_T < \sim 15$ GeV/c in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [20]. Therefore results in our study are applicable from low to moderately high $p_T$ but not at very high $p_T$.

In the ZPC parton cascade, the parton cross section and its angular distribution determine the interaction strength between heavy quarks and the medium. Note that any given scattering angular distribution can be exactly sampled with no need of the assumption of small-angle scatterings; and this is an advantage of the parton cascade approach. After the quark coalescence process, the formed hadrons go through hadron interactions as modeled by an extended ART model [23, 58]. Currently we have not implemented any hadron interactions for heavy hadrons except for decays of the heavy hadron resonances.

It is also interesting to note that, while we have removed the $p_0$ cut for initial heavy flavor productions, we need to use a $p_0$ cut, which grows with the collision energy and the system size, for the initial light flavor minijet productions to describe charged particle as well as light flavor multiplicities in heavy ion collisions at high energies [34]. This different treatment of the $p_0$ cut for different flavors seems to be inconsistent with initial state saturation models but consistent with final state saturation models such as the EKRT model [59].

### VI. SUMMARY

In this work, we use the recently updated AMPT model to study open heavy flavor productions. In addition to the incorporation of modern parton distribution functions in nuclei, we have removed the transverse momentum cutoff $p_0$ for the pQCD heavy flavor production channels. Systematic comparisons to the experimental data show that the updated AMPT model can well describe the yields and $p_T$ spectra of open charm hadrons including $D$, $D^*$, $D_s$, and $\Lambda_c$ in $pp$ collisions at different energies. The updated model also describes the charm data in central $AA$ collisions much better than the previous AMPT model, although it gives softer charm hadron spectra than the experimental data and also underestimates the open charm hadron yields in central Pb+Pb collisions at LHC energies. These improvements in the AMPT model lay a foundation for further studies of heavy flavor observables together with light flavor observables within the transport model framework.
FIG. 10. (Color online) Ratios of mid-rapidity open charm hadron yields as functions of $p_T$ in $pp$ collisions at $\sqrt{s} = 7$ TeV and 0-10% central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV from the AMPT model (curves) in comparison with the experimental data [50, 52, 56, 57]: (a) $D^+/D^0$, (b) $D^{*+}/D^0$, (c) $D_s^+/D^0$, and (d) $\Lambda_c^+/D^0$. Panel (d) also shows the AMPT result for 10-80% central Au+Au collisions at 200 GeV in comparison with the STAR data [53].

ACKNOWLEDGMENTS

We thank Xinye Peng for helpful discussions. This work is supported by National Natural Science Foundation of China under Grants No. 11890711, 11905188 and the Fundamental Research Funds for the Central Universities, China University of Geosciences (Wuhan) No. CUG180615.

[1] A. Andronic et al., Eur. Phys. J. C76, 107 (2016).
[2] B. Muller and X.-N. Wang, Phys. Rev. Lett. 68, 2437 (1992).
[3] Z.-W. Lin and M. Gyulassy, Phys. Rev. C51, 2177 (1995) [Erratum: Phys. Rev.C52,440(1995)].
[4] S. K. Das, S. Plumari, S. Chatterjee, J. Alam, F. Scar-dina, and V. Greco, Phys. Lett. B768, 260 (2017).
[5] S. Chatterjee and P. Böck, Phys. Rev. Lett. 120, 192301 (2018).
[6] M. Nasim and S. Singha, Phys. Rev. C97, 064917 (2018).
[7] M. He, R. J. Fries, and R. Rapp, Phys. Rev. Lett. 110, 112301 (2013).
[8] K. Huggins and R. Rapp, Nucl. Phys. A896, 24 (2012).
[9] T. Lang, H. van Hees, J. Steinheimer, G. Inghirami, and M. Bleicher, Phys. Rev. C93, 014901 (2016).
[10] B. A. Kniehl, G. Kramer, I. Schienbein, and H. Spies-berger, Phys. Rev. D71, 014018 (2005).
[11] M. Cacciari, P. Nason, and R. Vogt, Phys. Rev. Lett. 95, 122001 (2005).
[12] M. Djordjevic and M. Djordjevic, Phys. Rev. C92, 024918 (2015).
[13] J. Xu, J. Liao, and M. Gyulassy, JHEP 02, 169 (2016).
[14] A. Beraudo, A. De Pace, M. Monteno, M. Nardi, and F. Prino, Eur. Phys. J. C75, 121 (2015).
[15] M. He, R. J. Fries, and R. Rapp, Phys. Lett. B735, 445 (2014).
[16] S. Cao, G.-Y. Qin, and S. A. Bass, Phys. Rev. C92, 024907 (2015).
[17] J. Uphoff, O. Fochler, Z. Xu, and C. Greiner, J. Phys. G42, 115106 (2015).
[18] S. Cao, T. Luo, G.-Y. Qin, and X.-N. Wang, Phys. Lett. B777, 255 (2018).
[19] M. Nahrgang, J. Aichelin, P. B. Gossiaux, and K. Werner, Phys. Rev. C89, 014905 (2014)
[20] T. Song, H. Berrehrah, D. Cabrera, W. Cassing, and E. Bratkovskaya, Phys. Rev. C93, 034906 (2016).
[21] S. K. Das, F. Scardina, S. Plumari, and V. Greco, Phys. Lett. B747, 260 (2015).
[22] S. Plumari, V. Minissale, S. K. Das, G. Coci, and V. Greco, Eur. Phys. J. C78, 348 (2018).
[23] Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang, and S. Pal, Phys. Rev. C72, 064901 (2005).
[24] B. Zhang, Comput. Phys. Commun. 109, 193 (1998).
[25] B. Zhang, L.-W. Chen, and C.-M. Ko, Phys. Rev. C72, 024906 (2005).
[26] H. Li, Z.-W. Lin, and F. Wang, Phys. Rev. C99, 044911 (2019).
[27] L. He, T. Edmonds, Z.-W. Lin, F. Liu, D. Molnar, and F. Wang, Nucl. Phys. A956, 316 (2016).
[28] Z.-W. Lin, L. He, T. Edmonds, F. Liu, D. Molnar, and F. Wang, Phys. Lett. B753, 506 (2016).
[29] A. Kurkela, A. Mazeliauskas, J.-F. Paquet, S. Schlichting, and D. Teaney, Phys. Rev. Lett. 122, 122302 (2019).
[30] A. Kurkela, A. Mazeliauskas, J.-F. Paquet, S. Schlichting, and D. Teaney, Phys. Rev. C99, 034910 (2019).
[31] S. Cao et al., Phys. Rev. C99, 054907 (2019).
[32] Y. Xu et al., Phys. Rev. C99, 014902 (2019).
[33] Y. He and Z.-W. Lin, Phys. Rev. C96, 014910 (2017).
[34] C. Zhang, L. Zheng, F. Liu, S. Shi, and Z.-W. Lin, Phys. Rev. C99, 064906 (2019).
[35] M. Gyulassy and X.-N. Wang, Comput. Phys. Commun. 83, 307 (1994).
[36] X.-N. Wang and M. Gyulassy, Phys. Rev. D44, 3501 (1991).
[37] W.-T. Deng, X.-N. Wang, and R. Xu, Phys. Rev. C83, 014915 (2011).
[38] Z.-W. Lin and C. M. Ko, Phys. Rev. C65, 034904 (2002).
[39] S. Singha, B. Mohanty, and Z.-W. Lin, Int. J. Mod. Phys. E24, 1550041 (2015).
[40] M. He and R. Rapp, Phys. Lett. B795, 117 (2019).
[41] D. Stump, J. Huston, J. Pomplin, W.-K. Tung, H. L. Lai, S. Kuhlmann, and J. F. Owens, JHEP 10, 046 (2003).
[42] I. Helenius, K. J. Eskola, H. Honkanen, and C. A. Salgado, JHEP 07, 073 (2012).
[43] Z.-W. Lin, Phys. Rev. C90, 014904 (2014).
[44] C. Lourenco and H. K. Wohri, Phys. Rept. 433, 127 (2006).
[45] A. Adare et al. (PHENIX), Phys. Rev. C84, 044905 (2011).
[46] L. Adamczyk et al. (STAR), Phys. Rev. D86, 072013 (2012).
[47] R. Aaij et al. (LHCb), Nucl. Phys. B871, 1 (2013).
[48] G. Aad et al. (ATLAS), Nucl. Phys. B907, 717 (2016).
[49] B. Abelev et al. (ALICE), JHEP 07, 191 (2012).
[50] S. Acharya et al. (ALICE), Eur. Phys. J. C77, 550 (2017).
[51] J. Adam et al. (STAR), Phys. Rev. C99, 034908 (2019).
[52] S. Acharya et al. (ALICE), JHEP 04, 108 (2018).
[53] G. Xie (STAR), PoS Hard Probes 2018, 142 (2018).
[54] L. Adamczyk et al. (STAR), Phys. Rev. Lett. 113, 142301 (2014), Erratum: Phys. Rev. Lett. 121, no. 22, 229901 (2018).
[55] J. Zhao, S. Shi, N. Xu, and P. Zhuang, (2018), arXiv:1805.10858 [hep-ph].
[56] S. Acharya et al. (ALICE), JHEP 10, 174 (2018).
[57] C. Zampolli, “Latest results on \(D_s\) and \(\Lambda_c\) in Pb-Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV with ALICE at the LHC,” Strangeness in Quark Matter 2019 talk at https://indico.cern.ch/event/755366/contributions/3396487/attachments/1859933/3056377/CZampolli_v7.pdf.
[58] B.-A. Li and C. M. Ko, Phys. Rev. C52, 2037 (1995).
[59] K. J. Eskola, K. Kajantie, P. V. Ruuskanen, and K. Tuominen, Nucl. Phys. B570, 379 (2000).