Constraining Particle Production Mechanism in Au + Au Collisions at RHIC Energies Using A Multi Phase Transport Model

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We study the production of pions, kaons, and (anti-) protons in A Multi Phase Transport (AMPT) Model in Au + Au collisions at \( \sqrt{s_{NN}} = 7.7, 27, \) and 200 GeV. We present the centrality and energy dependence of various bulk observables such as invariant yields as a function of transverse momentum \( p_T \), particle yields \( dN/dy \), average transverse momentum \( \langle p_T \rangle \) and various particle ratios, and compare them with experimental data. Both default and string melting (SM) versions of the AMPT model are used with three different sets of initial conditions. We observe that neither the default nor the SM model could consistently describe the centrality dependence of all observables at the above energies with any one set of initial conditions. The energy dependence behavior of the experimental observables for 0–5% central collisions is in general better described by the default AMPT model using the default HIJING parameters for Lund string fragmentation and 3mb parton scattering cross-section.

I. INTRODUCTION

Relativistic collisions of heavy ions make it possible to subject nuclear matter to the extreme energy densities required for a possible deconfinement of quarks and gluons. A dense matter with partonic degrees of freedom, often called the quark-gluon plasma (QGP), is expected to form in the initial moments after the collision [1–4]. Exploring the quantum chromodynamics (QCD) phase diagram to understand the properties of quark matter is one of the most important goals of high-energy heavy ion experiments [5–7]. Comparing the results obtained from theoretical models with the experimental data helps in understanding the space-time evolution of QGP and many of its other properties. The QCD phase diagram is usually plotted as temperature (T) versus baryon chemical potential (\( \mu_B \)). Assuming a thermalized system is reached in heavy-ion collisions, both T and \( \mu_B \) can be varied by changing the collision energy [8–10]. To this end, the Beam Energy Scan program at the Relativistic Heavy Ion Collider (RHIC), completed its first phase of operation in 2010 and 2011 [11–13]. The measurements of the bulk properties of identified hadrons using the BES data were recently published [13]. The measurements from STAR cover the \( \mu_B \) interval from 20 to 450 MeV. This is also believed to be the region in which the transition from hadronic matter to QGP takes place [12–23].

In this paper, we have studied Au + Au collisions at \( \sqrt{s_{NN}} = 7.7, 27 \) and 200 GeV using a multi-phase transport (AMPT) model and compared bulk properties such as transverse momentum \( p_T \) spectra, multiplicity densities \( dN/dy \), average transverse momentum \( \langle p_T \rangle \) and particle ratios with the experimental data. For this study we have used three different sets of parameters for both the default and string melting (SM) versions of the AMPT model.

The paper is organized as follows. In Section II we give a brief description of the AMPT model and its parameters. In Section III A we present the comparison of transverse momentum spectra between models and experimental data. In Section III B and Section III C we study the centrality dependence of particle yields and average transverse momenta respectively and compare the results with experimental data. The centrality and energy dependence of various particle ratios are discussed in Section III D and Section III E respectively. We summarize in Section IV.

II. THE AMPT MODEL

In this section, we give a short description of the AMPT model and its parameters. The AMPT model was developed to give a coherent description of the dynamics of relativistic heavy-ion collisions [26] and has been used extensively to study them at various energies and environments. It is a hybrid transport model and has four main components: the initial conditions, partonic interactions, hadronization and hadronic interactions [26]. Initial conditions are obtained from the Heavy Ion Jet Interaction Generator (HIJING) model [27]. Hard minijet partons are produced perturbatively if the momentum transfer is more than a threshold \( (p_0 = 2 \text{ GeV/c}) \) and soft strings are produced otherwise. Depending on the version of AMPT model used, default or string melting, the soft strings are either retained or are completely converted to partons.

Zhang’s Parton Cascade (ZPC) [28] is used for partonic interactions. The differential scattering cross section is given by

\[
\frac{d\sigma}{dt} \approx \frac{9\pi\alpha_s^2}{2(t - \mu^2)^2} \tag{1}
\]

Where \( \sigma \) is the parton-parton scattering cross section, \( t \) is the standard Mandelstam variable for four-momentum transfer, \( \alpha_s \) is the strong coupling constant and \( \mu \) is the Debye screening mass in partonic matter.
In the default model, only the minijet partons take part in the ZPC and the energy stored in the excited strings is only released after hadrons are formed. For the default model, after the partons stop interacting, they combine with their parent strings. Hadronization of these strings take place using the Lund string fragmentation model \cite{29,30}. The longitudinal momentum of the hadrons generated is given by the Lund string fragmentation function \( f(z) \propto z^{-1}(1 - z)^\alpha \exp(-bmz^2/z) \), \( z \) being the light-cone momentum fraction of the hadron of transverse mass \( m_T \) with respect to the fragmenting string. The average squared transverse momentum \( \langle p_T^2 \rangle \) of the produced particles is proportional to the string tension \( \kappa \), i.e. the energy stored per unit length of a string, and depends on the Lund string fragmentation parameters as

\[
\kappa \propto \langle p_T^2 \rangle = \frac{1}{b(2 + a)} \tag{2}
\]

In the string melting version, hadronization takes place via a quark coalescence model in which the nearest partons are combined to form mesons and baryons. The dynamics of the hadronic matter is described by a Relativistic Transport (ART) model which includes meson-meson, meson-baryon, baryon-baryon, elastic and inelastic scatterings \cite{31}. The parton density in ZPC for the SM version is quite dense as all HIJING strings are converted to partons. As a result the SM version was found to reasonably fit the elliptic flow at RHIC \cite{20}.

**TABLE I:** Used values of parameters in Lund string fragmentation and parton scattering cross-sections for the three sets of AMPT data.

| Set   | Cross-section (\( \sigma \)) | \( a \) (GeV\(^{-2} \)) | \( b \) (GeV\(^{-2} \)) | \( \alpha_s \) | \( \mu \) (fm\(^{-1} \)) |
|-------|-----------------------------|----------------|----------------|--------------|--------------|
| Set A | 3 mb                        | 0.55           | 0.15           | 0.33         | 2.265        |
| Set B | 1.5 mb                      | 0.5            | 0.9            | 0.33         | 3.2          |
| Set C | 10 mb                       | 2.2            | 0.5            | 0.47         | 1.8          |

We have chosen the three parameter sets as given in Table I by taking guidance from earlier studies as detailed below. The parton scattering cross-section is given as \( \sigma \approx 9\pi\alpha_s^2/(2\mu^2) \). Thus, the value of \( \sigma \) depends on a given combination of \( \alpha_s \) and \( \mu \). It has been observed that the multiplicity is not much sensitive to the parton scattering cross-section \( \sigma \) but \( \sigma \) seems to affect the elliptic flow such that larger parton scattering cross-section leads to large elliptic flows \cite{32}.

It has been observed that the default HIJING values for the Lund string fragmentation parameters \( a = 0.5 \) and \( b = 0.9 \) GeV\(^{-2} \) in set B were able to describe the pp data when used in the AMPT default model but underestimated the charged particle yield in central Pb + Pb collisions at the top SPS energy \cite{33,34}. For Pb+Pb collisions at LHC energies, the AMPT SM model with default HIJING values for the Lund string fragmentation parameters \( a = 0.5 \) and \( b = 0.9 \) GeV\(^{-2} \) in set B was able to reproduce the yield and elliptic flow of charged particles but underestimated the \( p_T \) spectrum except at low \( p_T \) \cite{32,33}.

From Eq. \( \ref{2} \) it is clear that parameters \( a \) and \( b \) determine the \( p_T \) distribution of the particles. For larger \( a \) and \( b \) there will be a smaller average square transverse momentum that will produce a steeper \( p_T \) spectra (with large slope), while their smaller values will lead to a flatter distribution. It has been reported that the values of \( a = 2.2 \) and \( b = 0.5 \) GeV\(^{-2} \) produce larger multiplicity density as compared to other values of \( a \) and \( b \) \cite{32}. Thus, the modified values of \( a = 2.2 \) and \( b = 0.5 \) GeV\(^{-2} \) (Set C) were used to fit the charged particle yield in Pb+Pb collisions at SPS \cite{33,34}. For heavy-ion collisions at RHIC energies, the default AMPT model with these parameters was found to reasonable fit the rapidity and pseudo-rapidity density and the \( p_T \) spectra but underestimate the elliptic flow \cite{33,35}. On using the AMPT SM with same parameters, the elliptic flow and two-pion HBT were reproduced but the charged particle yield was overestimated while the slopes of the \( p_T \) spectra were underestimated \cite{33,33}.

In order to simultaneously fit the rapidity density, \( p_T \) spectrum and elliptic flow of pions and kaons at low \( p_T \) in Au+Au collisions at RHIC energies, the AMPT SM model was used with modified Lund string fragmentation parameters \( a = 0.55 \) and \( b = 0.15 \) GeV\(^{-2} \) in Set A \cite{33}.

Thus we observe that each of these sets satisfactorily describe the heavy-ion data at different energies from various experiments. The availability of centrality dependent results at the RHIC for a vast range of energies allows us to test the validity of the said parameters at these conditions. We generated AMPT events for Au+Au collisions at three energies viz., the lowest RHIC energy (7.7 GeV), an intermediate energy (27 GeV) and the top RHIC energy of 200 GeV. The events are generated using both string melting and default versions of the AMPT. In each of these versions, we use the three sets of parameters as listed in table I to generate the events. About 20k events are used for the analysis at each energy, for each set and for each of the two versions of the model. The centrality selection is done in the same way as in the experimental data \cite{18}. Thus, the AMPT data are divided into nine centrality classes 0–5\%, 5–10\%, 10–20\%, 20–30\%, 30–40\%, 40–50\%, 50–60\%, 60–70\%, and 70–80\%.

**III. RESULTS**

We present the mid-rapidity (|\( y \)| < 0.1) transverse momentum \( p_T \) spectra, particle yields \( dN/dy \), average transverse momentum \( \langle p_T \rangle \) and ratios of identified particles \( \pi^\pm \), \( K^\pm \), \( p \) and \( \bar{p} \) at \( \sqrt{s_{NN}} = 7.7, 27 \) and 200 GeV. The results are obtained for both AMPT SM and default versions at each energy and using three different sets of parameters listed in table I. The simulated results are compared with corresponding results from the STAR experiment.
A. Transverse Momentum Spectra

Figure 1 shows the invariant yield versus $p_T$ in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV for positively charged particles ($\pi^+$, $K^+$, $p$). The results are shown using the set B parameters just for representation. The top three panels represent the results for default AMPT version while the AMPT string melting results are shown in the bottom three panels. Results from the nine collision centralities 0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 60-70% and 70-80% are shown. The invariant yield decreases with increasing $p_T$ and also while going from central to peripheral collisions. On comparing the inverse slopes of the spectra for three particles, we observe that they follow the order $p > K > \pi$. The same behavior is observed at 7.7 and 200 GeV and for all parameter sets. The negatively charged particles (not presented here) also show similar behavior.

Figure 2 compares the $p_T$ spectra of $\pi^+$, $K^+$, and $p$ for both the versions of the AMPT model and using the three different parameter sets with experimental data in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$ and 200 GeV for 0–5% collision centrality. The top six panels represent the comparison of default model with the experimental data, while the six panels at the bottom represent the same for the string melting version. The data to model ratios are shown at the bottom of each plot. For the default version, at 7.7 GeV, set B parameters describe the $\pi^+$ spectra better. Both the $K^+$ and $p$ spectra are described better by the set A parameters at this energy. At 27 GeV (plots not presented here), the $\pi^+$ spectra is described well by set C parameters. The $K^+$ and $p$ spectra are explained better by set A parameters. At 200 GeV, the set A and B parameters describe the $\pi^+$ and $K^+$ while set A describes the $p$ spectra better as compared to the other sets.

For string melting, at 7.7, 27 (plots not presented here) and 200 GeV, set A parameters describe the $\pi^+$ and $p$ spectra well for 0–5% centrality. The $K^+$ spectra at 7.7 GeV are under-predicted by all sets by about a factor of 2 with set A parameters showing a better $p_T$ dependence. At 27 GeV, the data over model ratio comes closer to unity for set A parameters but is still under-predicted. At 200 GeV, the ratio of data to model for $K^+$ becomes less than unity. Thus, the ratio of data to model for $K^+$ decreases with increasing energy from about 2 at 7.7 GeV to just less than unity at 200 GeV using set A parameters. This suggests that the string melting version is important for description of kaons towards higher center-of-mass collision energies but does not characterize lower energy collisions well.

To summarize the observations from Fig. 1.

![Graph](image-url)
FIG. 2: Mid-rapidity (|y| < 0.1) transverse momentum spectra of π⁺, K⁺, p at √s_{NN} = 7.7 and 200 GeV for 0-5% central Au + Au collisions from default (top two rows) and string melting (bottom two rows) versions of the AMPT model using parameter sets A, B and C. Experimental data from the STAR collaboration [18, 36] are shown by solid circles. The data/model ratios are presented at the bottom of each panel.
The pion spectra at 7.7 GeV is described well by SM model set A parameters. At 27 GeV, it is described better by default set A parameters. At 200 GeV, it is described by both default and SM set A parameters.

The kaon spectra at 7.7 and 27 GeV is described better by default set A parameters. At 200 GeV, it is described OK by default set A parameters but is slightly overestimated.

The proton spectra at 7.7 and 27 GeV is described well by SM set A parameters at low $p_T$ and by default set A parameters at high $p_T$. At 200 GeV, the spectra is described OK by both default and SM set A parameters.

The spectra comparison are quantized by comparing particle yields, average transverse momenta, and particle ratios.

B. Particle Yields ($dN/dy$)

Figure 3 shows the centrality dependence of yield $dN/dy$ normalized by half the number of participants $\langle N_{\text{part}}\rangle/2$ for $\pi^+$, $K^+$ and protons in Au+Au collisions at 7.7, 27 and 200 GeV. The results from the default version are shown in the top three rows, while those using the string melting version are shown in the bottom three rows. The results using the three sets of parameters in both the model versions are compared with the experimental data. The experimental data show an increase of yield from peripheral to central collisions suggesting particle production by both soft and hard processes.

In default version, the $dN/dy/(0.5\langle N_{\text{part}}\rangle)$ of $\pi^+$ at 7.7 GeV is described by set B parameters at all $\langle N_{\text{part}}\rangle$ values. At 27 GeV, set C parameters agree with data at all $\langle N_{\text{part}}\rangle$ values, but $\langle N_{\text{part}}\rangle$ dependence is flat as opposed to the data in which it increases from peripheral to central collisions. At 200 GeV, none of the sets could explain the behavior observed in data for all $\langle N_{\text{part}}\rangle$ values. The set A parameters could only describe the data for $\langle N_{\text{part}}\rangle > 100$ while set C parameters agree with data for $\langle N_{\text{part}}\rangle < 40$. The $K^+$ yields at 7.7 GeV are not explained by any of the parameter sets for all $\langle N_{\text{part}}\rangle$. The set A parameters can only describe the data for $\langle N_{\text{part}}\rangle < 120$. At 27 GeV, $K^+$ yields are better described by set C parameters for all $\langle N_{\text{part}}\rangle$, while at 200 GeV, the set A parameters describe the $K^+$ yields for all $\langle N_{\text{part}}\rangle$. The proton yields are described by all parameter sets at all $\langle N_{\text{part}}\rangle$ for 7.7 GeV, but none of them work for 27 GeV other than set A and C at $\langle N_{\text{part}}\rangle < 30$. Whereas at 200 GeV, none of the parameters could explain the $p$ yields at any centrality.

For the AMPT model with string melting, the $dN/dy/(0.5\langle N_{\text{part}}\rangle)$ of $\pi^+$ at 7.7 GeV is described by all the parameters at all $N_{\text{part}}$ values. However, the set C parameters show a rather flat behavior as opposed to the slight increase from peripheral to central collisions. At 27 GeV, the set C parameters describe the $\pi^+$ yields at all $\langle N_{\text{part}}\rangle$ values but set A and B parameters are closer in agreement with the data in peripheral collisions. At 200 GeV, in central collisions ($\langle N_{\text{part}}\rangle > 100$), pion yields are well described by set B parameters while those in peripheral collisions ($\langle N_{\text{part}}\rangle < 130$) are described by set C parameters. The $K^+$ yields are only described by set A parameters below $\langle N_{\text{part}}\rangle$ 50 at 7.7 GeV, below $\langle N_{\text{part}}\rangle$ 130 by set C parameters at 27 GeV and for all $\langle N_{\text{part}}\rangle$ by set C parameters at 200 GeV. The proton yields at 7.7 GeV are described by all parameter sets at all $\langle N_{\text{part}}\rangle$, at 27 GeV by set A parameters at all $\langle N_{\text{part}}\rangle$, and at 200 GeV by set B parameters for $\langle N_{\text{part}}\rangle > 220$ and by set C parameters for $\langle N_{\text{part}}\rangle < 90$ but not by any parameter set at the most peripheral point.

To summarize the observations for all centralities:

- The pion yield is described by set C parameters for $\sqrt{s_{NN}} \leq 27$ GeV for SM model, but by none of the models at 200 GeV. However, the 200 GeV pion yield is constrained between Set A and C at all $\langle N_{\text{part}}\rangle$ for both versions of AMPT.
- The kaon yield at 7.7 GeV is not explained at all $\langle N_{\text{part}}\rangle$ by any set with either versions (the models underestimate the data), explained at 27 GeV by the default model with set C parameters and also at 200 GeV by the default model with set A parameters and by the SM model with set C parameters. Thus, at 7.7 GeV, the strange particle production is not explained by AMPT model.
- The proton yield at 7.7 GeV is explained by all parameter sets with both the models, at 27 GeV by set A parameters with SM model, but by none of the models at 200 GeV. However, the 200 GeV proton yield is constrained between Set B and C at all $\langle N_{\text{part}}\rangle$ for the AMPT SM version.
- In general, for most cases, it is observed that the Set C parameters corresponding to largest $s = 2.2$ give higher yields while Set B corresponding to smallest $s = 0.5$ give smaller yields as expected.

C. Average Transverse Momentum ($p_T$)

Figure 4 shows the centrality dependence of average transverse momentum ($p_T$) for $\pi^+$, $K^+$ and protons, in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$, 27 and 200 GeV. The results from the default version are shown in the top three rows while those from the string melting version are shown in the bottom three rows. The results using the three parameter sets A, B and C are compared with experimental data using both the default and string melting versions. The data shows increase of ($p_T$) from peripheral to central collisions suggesting increasing radial flow towards central collisions. The ($p_T$) reflects the shape (slope) of the spectra.
FIG. 3: Centrality dependence of $dN/dy$ normalized by half participant $\langle N_{\text{part}} \rangle/2$ for positive particles at mid-rapidity ($|y| < 0.1$) in Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 27, 200$ GeV from the AMPT default (top three rows) and string melting (bottom three rows) models. Results are presented using the parameter sets A, B and C. Experimental data from the STAR collaboration [18, 30] are shown by solid circles.
FIG. 4: Centrality dependence of $\langle p_T \rangle$ for positive particles at mid-rapidity ($|y| < 0.1$) in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$, 27 and 200 GeV from the AMPT default (top three rows) and string melting (bottom three rows) models. Results are presented using the parameter sets A, B and C. Experimental data from the STAR collaboration [18, 36] are shown by solid circles.
Using the default version, \( \langle p_T \rangle \) of \( \pi^+ \) at 7.7 GeV is described by set C parameters for all \( \langle N_{\text{part}} \rangle \). At 27 GeV, set A and set C parameters agree with data at \( \langle N_{\text{part}} \rangle > 220 \). While the set A parameters do not follow the behavior of data, set B and C reproduce the data qualitatively and tend to agree with it at the last two peripheral points. At 200 GeV, none of the sets could explain the behavior observed in data for all \( \langle N_{\text{part}} \rangle \) values. The set A parameters only describe the most peripheral data. The \( K^+ \) \( \langle p_T \rangle \) at 7.7 GeV can only be explained by set A parameters for \( \langle N_{\text{part}} \rangle > 220 \), and by sets B and C for \( \langle N_{\text{part}} \rangle < 170 \). At 27 GeV, \( K^+ \) \( \langle p_T \rangle \) are better described by set A parameters for \( \langle N_{\text{part}} \rangle > 150 \). Set A shows a flat behavior with \( \langle N_{\text{part}} \rangle \). However, sets B and C only qualitatively describe the experimental data. At 200 GeV, set A parameters describe the \( K^+ \) \( \langle p_T \rangle \) for \( \langle N_{\text{part}} \rangle > 150 \). Both set B and C parameters underestimate the data at all \( \langle N_{\text{part}} \rangle \). For protons at 7.7 GeV \( \langle p_T \rangle \) are described by set A parameters for \( \langle N_{\text{part}} \rangle > 50 \) and by both set B and C below \( \langle N_{\text{part}} \rangle \approx 80 \). At 27 GeV, set A parameters describe the proton \( \langle p_T \rangle \) for \( \langle N_{\text{part}} \rangle > 220 \). For peripheral collisions, set B and C parameters give closer values to experimental data but underestimate nevertheless. At 200 GeV, the set A parameters could explain the \( p \) \( \langle p_T \rangle \) for all \( \langle N_{\text{part}} \rangle \) values except the two peripheral bins. The other two parameter sets underestimated the data quite significantly.

For AMPT string melting, the \( \langle p_T \rangle \) of \( \pi^+ \) at 7.7 GeV is described by set A parameters at three mid-central collisions but under(over) estimated at central(peripheral) collisions. Sets B and C can only describe the data at the last three peripheral bins. At 27 GeV, the set A parameters could explain the data for \( \langle N_{\text{part}} \rangle \geq 70 \) while set B and C parameters could only agree with data at the most peripheral bin. Increasing the energy further to 200 GeV leads to the overestimation of data by set A parameters with only the most central point sufficiently close to the data. Set C can describe the data at three most peripheral and set B at the two most peripheral points. The \( K^+ \) \( \langle p_T \rangle \) at 7.7 GeV are described by set A parameters for four mid-central points but under(over) estimated at central(peripheral) collisions. The set C parameters tend to describe the data below \( \langle N_{\text{part}} \rangle \) 90. Increasing the energy to 27 GeV for \( K^+ \), leads to better agreement also in central collisions by set A parameters. These parameters describe the data for all but last two most peripheral \( \langle N_{\text{part}} \rangle \) values. Increasing the energy further to 200 GeV, for \( K^+ \), does not change the results much for set A parameters which still describe the data from mid-central to central collisions. Using set C parameters for \( K^+ \), the model agrees with data at the most peripheral point. The proton \( \langle p_T \rangle \) at 7.7 GeV are described by set A parameters at all \( \langle N_{\text{part}} \rangle \) except at the most peripheral bin. The set C parameters seem to describe the data at peripheral collisions below \( \langle N_{\text{part}} \rangle \approx 100 \). At 27 GeV, the set A parameters describe the proton data at all but the two most central and the most peripheral point. The other two parameter sets underestimate the data. At 200 GeV, the set A parameters only describe the proton data at most peripheral bin and underestimate the data for all other \( \langle N_{\text{part}} \rangle \) values. The sets B and C underestimate the data at all \( \langle N_{\text{part}} \rangle \) values.

To summarize the above observations:

- The \( \langle p_T \rangle \) of pion at 7.7 GeV is described at all \( \langle N_{\text{part}} \rangle \) by default AMPT set C parameters. At 27 GeV, it is described by AMPT SM set A parameters for only \( \langle N_{\text{part}} \rangle > 50 \) and is constrained between sets A and C below that. At 200 GeV, it is explained by none of the models but constrained between sets A and B for both the default and SM versions.

- The kaon \( \langle p_T \rangle \) at 7.7 GeV is described partially by default AMPT set A parameters for \( \langle N_{\text{part}} \rangle > 220 \), and by default AMPT set B and C parameters for \( \langle N_{\text{part}} \rangle < 170 \). At 27 GeV, it is explained by SM set A parameters for all \( \langle N_{\text{part}} \rangle \) except at the two most peripheral points. For the two most peripheral bins, it is constrained between SM sets A and C. At 200 GeV, it is explained by default and SM set A parameters for \( \langle N_{\text{part}} \rangle > 100 \). Below that, it is constrained better between SM sets A and C.

- The proton \( \langle p_T \rangle \) at 7.7 GeV is described by SM set A parameters at all \( \langle N_{\text{part}} \rangle \) except the most peripheral bin. The SM sets B and C describe the peripheral bin. At 27 GeV, again, SM set A parameters work better for all but the most peripheral bin and two most central bins. At 200 GeV, the proton \( \langle p_T \rangle \) is explained at all but last two peripheral bins by default set A parameters. The last two bins are constrained between default sets A and B.

### D. Particle Ratios

In Fig. 6 we show the centrality dependence of various antiparticle to particle \( \pi^-/\pi^+ \), \( K^-/K^+ \), \( \bar{p}/p \) ratios at mid-rapidity \( (|y| < 0.1) \) in Au + Au collisions at \( \sqrt{s_{NN}} = 7.7, 27 \) and 200 GeV obtained from the default (top three rows) and SM (bottom three rows) AMPT model using the three parameter sets A, B and C. The results are again compared with the corresponding experimental data.

The default AMPT model could reasonably predict the \( \pi^-/\pi^+ \) ratio at the three energies with all the parameter cases. The \( K^-/K^+ \) ratio at 7.7 GeV is mostly underestimated by set A parameters while the set B and set C parameters give closer values to data in general. At 27 GeV, the results with the three parameter sets are close to each other and the data agreeing marginally with the data. At 200 GeV, the \( K^-/K^+ \) ratio is mostly underestimated by three parameter sets but matches with the data in peripheral collisions. The \( \bar{p}/p \) ratio at 7.7 GeV is mostly overestimated by all the three parameter sets. For \( \langle N_{\text{part}} \rangle < 90 \) (except the most peripheral bin), set B
FIG. 5: Centrality dependence of antiparticle to particle \( \left( \pi^-/\pi^+, K^-/K^+, \bar{p}/p \right) \) ratios at mid-rapidity \((|y| < 0.1)\) in \( \text{Au + Au} \) collisions at \( \sqrt{s_{\text{NN}}} = 7.7, 27, \) and 200 GeV from the AMPT default and SM models. Results are presented using the parameter sets A, B and C. Experimental data from the STAR collaboration\cite{18,36} are shown by solid circles.
FIG. 6: Centrality dependence of mixed particle (\(K^+/\pi^+, K^-/\pi^-, p/\pi^+, \bar{p}/\pi^-\)) ratios at mid-rapidity (\(|y| < 0.1\)) in Au + Au collisions at \(\sqrt{s_{NN}} = 7.7, 27, \) and 200 GeV from the default and AMPT SM models. Results are presented using the parameter sets A,B and C. Experimental data from the STAR collaboration\[18, 36\] are shown by solid circles.
parameters explain the data. At 27 GeV, the \( \bar{p}/p \) ratio is explained by set B parameters for \( \langle N_{\text{part}} \rangle > 100 \). At 200 GeV, all the three parameter sets seem to describe the \( \bar{p}/p \) ratio, only with the exception of the most peripheral point by set A parameters.

Similar to the default model, the AMPT model with string melting could reasonably predict the \( \pi^-/\pi^+ \) ratio at the three energies with all the three parameter cases. The \( K^-/K^+ \) ratio at 7.7 GeV is generally described by set C parameters for central collisions \( \langle N_{\text{part}} \rangle > 150 \). Set B parameters could only explain the ratio at three points before the most peripheral bin. At 27 and 200 GeV, set A parameters describe the data at all centralities. The set B parameters could also explain the data at all but two centralities. The \( \bar{p}/p \) ratio at 7.7 GeV is described by the set C parameters for all centralities except at the two most peripheral bins. At 27 GeV, the ratio is described by the set C parameters at all centralities. At 200 GeV, all three sets give similar values and close to the experimental \( \bar{p}/p \) ratio.

The mixed particle ratio results could help in better differentiating among the three parameter sets. In Fig. 6 we show the centrality dependence of various mixed \( (K^+/\pi^+, K^-/\pi^-, p/\pi^+, \bar{p}/\pi^-) \) particle ratios at mid-rapidity \((|y| < 0.1)\) in Au+Au collisions at \( \sqrt{s_{NN}} = 7.7, 27 \) and 200 GeV obtained from the default (top three rows) and SM (bottom three rows) AMPT model using the three parameter sets A, B and C. The results are compared with the corresponding experimental data.

For default AMPT model, the \( K^+/\pi^+ \) ratio at 7.7 GeV is not explained by any of the parameter sets except at very peripheral collisions. At 27 GeV, the \( K^+/\pi^+ \) ratio is described by set C parameters at all \( \langle N_{\text{part}} \rangle \). The set A parameters describe the data at all centralities except at the most peripheral one, while set B parameters describe the ratio at almost all \( \langle N_{\text{part}} \rangle \) values except in mid-central collisions. Similar conclusions could be drawn for 200 GeV except that the set A parameters now miss the data at more \( \langle N_{\text{part}} \rangle \) values. Same as the \( K^+/\pi^+ \) ratio, the \( K^-/\pi^- \) ratio at 7.7 GeV is also not described by any of the three parameter sets except at the very peripheral points. At 27 GeV, the ratio is well explained by set C parameters for all \( \langle N_{\text{part}} \rangle \). The set A parameters also describe the data at all \( \langle N_{\text{part}} \rangle \) except at the most peripheral bin, while set C parameters work well at peripheral collisions. Similar conclusions could be drawn at 200 GeV except that the set C parameters also miss a few points towards the peripheral collisions. Thus, in this case, set A describes the data better at all \( \langle N_{\text{part}} \rangle \) except the peripheral point. The \( p/\pi^+ \) ratio at 7.7 GeV is described by all parameter sets at all \( \langle N_{\text{part}} \rangle \). At 27 GeV, the ratio is described by set A parameters at all \( \langle N_{\text{part}} \rangle \). At 200 GeV, the \( p/\pi^+ \) ratio predicted by set A parameters is closer to data but does not agree exactly with it. The \( \bar{p}/\pi^- \) ratio at 7.7 GeV is described by set B and C parameters at all \( \langle N_{\text{part}} \rangle \) except at one bin towards peripheral collisions. At 27 GeV, it is described well by set C parameters at all \( \langle N_{\text{part}} \rangle \) values. Set B also describes this ratio at almost all the centralities. At 200 GeV, the ratio is explained by set A parameters for all \( \langle N_{\text{part}} \rangle \).

For AMPT SM model, the \( K^+/\pi^+ \) ratio at 7.7 GeV is not explained by any parameter set except at the most peripheral collision. It is interesting to note that no set shows even the qualitative behavior of centrality dependence observed in experimental data. At 27 GeV, the \( K^+/\pi^+ \) ratio is marginally described by set A parameters for most centralities except the peripheral. However, the \( \langle N_{\text{part}} \rangle \) dependence is well predicted by set C parameters though they consistently underestimate the data. At 200 GeV, the set C parameters describe the data at all centralities. The set A parameters also describe the \( K^+/\pi^+ \) ratio for all centralities except at the most peripheral collisions. The \( K^-/\pi^- \) ratio at 7.7 GeV is also not described by any of the three parameter sets except at the most peripheral point by set C. At 27 GeV, the ratio is well explained by set C parameters for all \( \langle N_{\text{part}} \rangle \). The set A parameters also result in closer values to the data at most centralities. At 200 GeV, set C parameters describe the data at all centralities. Set A also describes the data at all centralities except at the most peripheral bin. The \( p/\pi^+ \) ratio at 7.7 GeV is described by all parameter sets at all \( \langle N_{\text{part}} \rangle \). At 27 GeV, the ratio is described by set A parameters at all \( \langle N_{\text{part}} \rangle \). The set B parameters describe the data for central collisions but fail at peripheral collisions while the set C parameters describe the data at peripheral collisions failing at central collisions. At 200 GeV, the \( p/\pi^+ \) ratio is described by set A and B parameters towards the central collisions \( \langle N_{\text{part}} \rangle > 200 \) and by set C parameters towards peripheral collisions \( \langle N_{\text{part}} \rangle < 150 \). The \( \bar{p}/\pi^- \) ratio at 7.7 GeV is described by both set B and C parameters at almost all \( \langle N_{\text{part}} \rangle \). At 27 GeV, the ratio is described by set C parameters from mid-central \( \langle N_{\text{part}} \rangle < 200 \) to peripheral collisions. At 200 GeV, the ratio is described by set C parameters for most \( \langle N_{\text{part}} \rangle \) except at a few centrality bins. To summarize the observations from the two models (Figs. 2 and 3):

- The \( \pi^-/\pi^+ \) ratio is described by both default and SM models using the sets A, B and C at the three energies \( \sqrt{s_{NN}} = 7.7, 27, \) and 200 GeV.
- The \( K^-/K^+ \) ratio at 7.7 GeV is better described by SM set C parameters for \( \langle N_{\text{part}} \rangle > 150 \). At 27 and 200 GeV, it is described at all \( \langle N_{\text{part}} \rangle \) by SM set A parameters.
- The \( p/\pi^+ \) ratio at 7.7 GeV is described better by SM set C parameters for all centralities except at the very peripheral bins. At 27 GeV, the ratio is described well by SM set C parameters and at 200 GeV, by default set B parameters at all centralities.
- The \( K^+/\pi^+ \) ratio at 7.7 GeV is not described well by any of the models at all centralities, except the peripheral bins. The default model gives similar
centrality dependence but underpredicts the data. At 27 GeV, this ratio is described better by default set C parameters at all \( \langle N_{\text{part}} \rangle \). At 200 GeV, it is explained by both default and SM set C parameters at all centralities. Thus, at 7.7 GeV, the strange particle production is not well explained by the AMPT model.

- The \( K^+ / \pi^+ \) ratio results at 7.7 GeV are similar to \( K^+ / \pi^+ \) ratio. It is also not explained by any model at all centralities except at the peripheral bins. At 27 GeV, this ratio is described by both default and SM set C parameters. At 200 GeV, it is explained by SM set C parameters.

- The \( p/\pi^+ \) ratio at 7.7 GeV is explained by both default and SM models with all parameter sets. At 27 GeV, the ratio is described by both default and SM Set A parameters at all centralities. However, at 200 GeV, it is not explained by a single parameter set in either models at all the centralities. For central collisions, SM set A and B parameters describe the data while for peripheral collisions SM set C parameters work better.

- The \( \bar{p}/\pi^- \) ratio at 7.7 GeV is described at most \( \langle N_{\text{part}} \rangle \) by both default and SM set B and C parameters. At 27 GeV, it is described by default set C parameters and is well explained at 200 GeV by default set A parameters at all \( \langle N_{\text{part}} \rangle \).

E. Energy Dependence of Particle Ratios

The particle yields and ratios are used in statistical thermal models to determine the freeze-out conditions in heavy-ion collisions \[8,10,18\]. We present the energy dependence of mixed particle ratios for 0–5% central collisions that play an important role in determining the freeze-out conditions.

Figure 7 presents the comparison of \( K^+ / \pi^+ \) ratios at mid-rapidity (\( |y| < 0.1 \)) for 0–5% centrality in Au + Au collisions at \( \sqrt{s_{NN}} = 7.7 \), 27 and 200 GeV from the AMPT default (left panels) and SM (right panels) models with experimental data \[13,18,36\]. The results from AMPT are presented with the parameters sets A, B and C. The default model is in closer agreement with the data at lower energies. Thus, it can be concluded that strangeness (kaon) production at \( \sqrt{s_{NN}} = 7.7 \) GeV is not explained by the AMPT model.

Figure 8 shows the comparison of \( p/\pi^+ \) and \( \bar{p}/\pi^- \) ratios at mid-rapidity (\( |y| < 0.1 \)) for 0–5% centrality in Au + Au collisions at \( \sqrt{s_{NN}} = 7.7, 27 \) and 200 GeV from the AMPT default (left panels) and SM (right panels) models with experimental data \[13,26\]. The results for AMPT are presented for the parameters sets A, B and C. In the default model, the set A parameters seem to describe the \( p/\pi^+ \) ratio better at the three energies. With the SM model, both sets A and B describe the data at the three energies. The \( \bar{p}/\pi^- \) ratio from default AMPT set A parameters describe the ratio at 7.7 and 200 GeV, while set B and C parameters describe it at 7.7 and 27 GeV. Overall, the set A parameters are closest to the data. For SM model, the set C parameters describe the ratio at 7.7 and 200 GeV, while set B and C only describe the data at 7.7 GeV. Again, we observe that the default AMPT model with set A parameters works better than SM model.

In general, considering the energy dependence behaviour in 0–5% central Au + Au collisions, we observe that for all observables including yields, \( \langle p_T \rangle \) and ratios, the AMPT default model with set A parameters explain the data better than the other sets and also better than AMPT SM with all the sets. The AMPT default explaining particle yields or ratios better than SM version is consistent with the earlier studies where it is mentioned that SM version is better suited to describe the elliptic flow \[20\].

IV. SUMMARY

This study is an attempt to the first detailed comparison of the AMPT model with experimental data of three extreme energy regions at RHIC, different centralities and various identified particles. The default and SM AMPT models were initiated with different sets of parameters (as given in Table 1) and the results obtained were compared with the data from the STAR experiment. For this study, we have looked at bulk properties like transverse momentum spectra, yields, average transverse momentum and various ratios corresponding to \( \pi^\pm, K^\pm, p \), and \( \bar{p} \).

The pion spectra in 0–5% central collisions is described better by SM Set A at 7.7 GeV, by default Set A at 27
FIG. 7: Comparison of $K^+/\pi^+$ ratios at mid-rapidity ($|y| < 0.1$) for 0–5% centrality in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$, 27, and 200 GeV from the AMPT default (left panels) and SM (right panels) models with experimental data [13, 18, 36–43]. The results from the AMPT model with parameter sets A, B and C are presented.

FIG. 8: Comparison of $p/\pi^+ \text{ and } \bar{p}/\pi^-$ ratios at mid-rapidity ($|y| < 0.1$) for 0–5% centrality in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$, 27, and 200 GeV from the AMPT default (left panels) and SM (right panels) models with experimental data [13, 36]. The results from the AMPT model with parameter sets A, B and C are presented.
GeV, and by both default and SM Set A at 200 GeV. For the kaon spectra, default Set A works better at three energies. For proton spectra, both default and SM Set A work fine at three energies.

It is observed that for all centralities, pion yield is described by set C parameters at √sNN ≤ 27 GeV with both default and SM models but by none of the models at 200 GeV. However, the 200 GeV pion yield is constrained between sets A and C at all \( \langle N_{\text{part}} \rangle \) for both versions of AMPT. The kaon yield at 7.7 GeV is not explained at all \( \langle N_{\text{part}} \rangle \) by any one set with either versions (the models underestimate the data), explained at 27 GeV by the default model with set C parameters, and also at 200 GeV by the default model with set A parameters and by the SM model with set C parameters. Thus, at 7.7 GeV, the strange particle production is not explained by AMPT model. The proton yield is explained at 7.7 GeV by all parameter sets with both models, at 27 GeV by set A parameters of SM model but by none of the models at 200 GeV. However, the 200 GeV proton yield is constrained between sets B and C at all \( \langle N_{\text{part}} \rangle \) for the SM version of AMPT. In general, for most cases, it is observed that the set C parameters corresponding to largest \( a = 2.2 \) give higher yields while set B corresponding to smallest \( a = 0.5 \) give smaller yields as expected.

It is observed that the \( \langle p_T \rangle \) of pion at 7.7 GeV is described at all \( \langle N_{\text{part}} \rangle \) by default AMPT set C parameters. At 27 GeV, it is described by AMPT SM set A parameters for only \( \langle N_{\text{part}} \rangle > 50 \) and is constrained between sets A and C below that. At 200 GeV, it is explained by none of the models but is constrained between sets A and B for both default and SM versions. The kaon \( \langle p_T \rangle \) at 7.7 GeV is described partially by default set A parameters for \( \langle N_{\text{part}} \rangle > 220 \), and by default set B and C parameters for \( \langle N_{\text{part}} \rangle < 170 \). At 27 GeV, it is explained by SM set A parameters for all \( \langle N_{\text{part}} \rangle \) except at the two most peripheral points. For the two most peripheral bins, it is constrained between SM sets A and C. At 200 GeV, it is explained by the default and SM set A parameters for \( \langle N_{\text{part}} \rangle > 100 \). Below that, it is constrained better between SM sets A and C. The proton \( \langle p_T \rangle \) at 7.7 GeV is described by SM set A parameters all \( \langle N_{\text{part}} \rangle \) except at the most peripheral bin. The SM sets B and C describe the peripheral bin. At 27 GeV, again, SM set A parameters work better for all but the most peripheral bin and two most central bins. At 200 GeV, the proton \( \langle p_T \rangle \) is explained at all but last two peripheral bins by default set A parameters. The last two bins are constrained between default set A and B.

It is observed that the \( \pi^-/\pi^+ \) ratio is described by both default and SM models using the sets A, B and C at the three energies \( \sqrt{s_{NN}} = 7.7, 27 \) and 200 GeV. The \( K^-/K^+ \) ratio at 7.7 GeV is better described by SM set C parameters for \( \langle N_{\text{part}} \rangle > 150 \). At 27 and 200 GeV, it is described for all \( \langle N_{\text{part}} \rangle \) by SM set A parameters. The \( p/p \) ratio at 7.7 GeV is described better by SM set C parameters for all centralities except at the last two peripheral bins. At 27 GeV, the ratio is described well by SM set C parameters and at 200 GeV, by default set B parameters at all centralities. The \( K^+/\pi^+ \) ratio at 7.7 GeV is not described well by any of the models at all centralities, except the peripheral bins. The default model gives similar centrality dependence but under predicts the data. At 27 GeV, this ratio is described better by default set C parameters at all \( \langle N_{\text{part}} \rangle \). At 200 GeV, it is explained by both default and SM set C parameters at all centralities. Thus, at 7.7 GeV, the strange particle production is not explained by AMPT model. The \( K^-/\pi^- \) ratio results at 7.7 GeV are similar to \( K^+/\pi^+ \) ratio. It is also not explained by any model at all centralities except the peripheral bins. At 27 GeV, this ratio is described by both default and SM set C parameters. At 200 GeV, it is explained by SM set C parameters. The \( p/\pi^+ \) ratio at 7.7 GeV is explained by both default and SM models with all parameter sets. At 27 GeV, the ratio is described by both default and SM set A parameters at all centralities. However, at 200 GeV, it is not explained by a single parameter set in either models at all the centralities. For central collisions, SM set A and B parameters describe the data while for peripheral collisions SM set C parameters work better. The \( p/\pi^- \) ratio at 7.7 GeV is described at most \( \langle N_{\text{part}} \rangle \) by both default and SM set B and C parameters. At 27 GeV, it is described by default set C parameters and is well explained at 200 GeV by default set A parameters at all \( \langle N_{\text{part}} \rangle \).

For the energy dependence of \( K^+/\pi^+ \) ratio in 0–5% Au + Au central collisions, we observe that in case of the default AMPT model, the three sets are consistent with data at 27 and 200 GeV. At 7.7 GeV, all the three sets under-predict the ratio significantly. However, among the three sets, the set A parameters are closest to the data. For SM, set A seems to be in better agreement with the data at 27 and 200 GeV but under-predicts the data at 7.7 GeV. Comparing between default and SM, the default set A parameters describe the energy dependence of \( K^+/\pi^+ \) ratio better. The \( K^-/\pi^- \) ratio at 200 GeV is described by all three sets of the default and SM model. At 27 GeV, the set A and C parameters are consistent with the data. At 7.7 GeV, the ratio is again under-predicted by both the versions. The default model is in relatively close agreement with data at lower energies. Thus, we again observe that the strangeness (kaon) production at \( \sqrt{s_{NN}} = 7.7 \) GeV is not explained by the AMPT model.

The energy dependence of \( p/\pi^+ \) and \( p/\pi^- \) ratios are also presented. In the default model, the set A parameters seem to describe the \( p/\pi^+ \) ratio better at the three energies. In the SM model, both sets A and B describe the data at the three energies. The \( p/\pi^- \) ratio from default AMPT set A parameters describe the ratio at 7.7 and 200 GeV, while set B and C parameters describe it at 7.7 and 27 GeV. Overall, the set A parameters are closest to the data. For SM model, the set C parameters describe the ratio at 7.7 and 200 GeV, while sets B and C only describe the data at 7.7 GeV. Again, we observe that the default AMPT model with set A parameters...
works better than SM model.

In general for the energy dependence behavior in 0–5% Au+Au central collisions we observe that for observables including yields, $\langle p_T \rangle$, and ratios, the default AMPT with set A parameters is generally better than the other sets and also better than AMPT SM with any set.

These comparisons of various bulk observables at three different energy regions and for different centralities provide help in constraining the models in a better way.

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