Identified particle production in Xe+Xe collisions at $\sqrt{\text{NN}} = 5.44$ TeV using a multiphase transport model

Rutuparna Rath, Sushanta Tripathy, Raghunath Sahoo*, and Sudipan De†

Discipline of Physics, School of Basic Sciences, Indian Institute of Technology Indore, Simrol, Indore 453552, India

Mohammed Younus
Department of Physics, Nelson Mandela University, Port Elizabeth, 6031, South Africa

(Dated: January 16, 2019)

Xe+Xe collisions at relativistic energies provide us with an opportunity to study a possible system with deconfined quarks and gluons, whose size is in between those produced by p+p and Pb+Pb collisions. In the present work, we have used AMPT transport model with nuclear deformation to study the identified particle production such as ($\pi^+ + \pi^-$), ($K^+ + K^-$), $K^0_s$, ($p+\bar{p}$), $\phi$ and ($\Lambda + \bar{\Lambda}$) in Xe+Xe collisions at $\sqrt{\text{NN}} = 5.44$ TeV. We study the $p_T$-spectra, integrated yield, $p_T$-differential and $p_T$-integrated particle ratios to ($\pi^+ + \pi^-$) and ($K^+ + K^-$) as a function of collision centrality. The particle ratios are focused on strange to non-strange ratios and baryon to meson ratios. The effect of deformations has also been highlighted by comparing our results to non-deformation case. We have also compared the results from AMPT string melting and AMPT default version to explore possible effects of coalescence mechanism. We observe that the differential particle ratios show strong dependence with centrality while the integrated particle ratios show no centrality dependence. We give thermal model estimation of chemical freeze-out temperature and the Boltzmann-Gibbs Blast Wave analysis of kinetic freeze-out temperature and collective radial flow in Xe+Xe collisions at $\sqrt{\text{NN}} = 5.44$ TeV.

PACS numbers: 12.38.Mh, 25.75.Ld, 25.75.Dw

I. INTRODUCTION

Ultra-relativistic heavy ion collisions experiments conducted at RHIC and LHC give us opportunities to peek into the past when Universe was a few microseconds old. The collisions result into a system of deconfined quarks and gluons at very high temperature and density or, quark-gluon-plasma (QGP) [1]. Till recent times, mainly symmetrical nuclei such as lead (Pb) ions or assuming spherical gold (Au) ions have been used to collide and form QGP. Recently, interests have come forth to conduct experiments with intrinsically deformed nuclei. Experiments have been conducted at RHIC, BNL with Uranium (U), which is heavier than gold and lead ions and is considered to be highly deformed (lead ion has zero deformity). A comparison of central collision of spherical nuclei with that of deformed nuclei helps in establishing if the elliptic flow observed in heavy-ion collisions, which is considered as a signature of QGP, is an initial state effect [2–4]. In case of a deformed nuclei collision, one expects the charged particle multiplicity density in the transverse phase space to be higher as compared to the collision of spherical nuclei [5–7]. Particle density per unit volume in ideal hydrodynamical models is independent of mass number of colliding species. A violation of scaling behavior is seen in the observables due to the deformed structures of the colliding nuclei [8].

*Corresponding author: Raghunath.Sahoo@cern.ch
†Presently at NISER, Bhubaneswar
In this paper, we have included deformation to the nucleus defined within AMPT model. We will discuss this briefly in one of the following sections. We have calculated particle ratios for the charged hadrons and have tried to find out the effects of the deformation on particle production. The present section of introduction is followed by sections on formalism and results and discussion respectively. These are followed by conclusion at the end.

FIG. 2: (Color online) $p_T$-spectra of identified particles in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV for 0-10% centrality using AMPT-SM. Different symbols show different particle species. The vertical lines in the results show the statistical uncertainties.

### II. FORMALISM

A Mutli-Phase Transport (AMPT) model

AMPT is a hybrid transport model which contains four components namely, initialization of collisions, parton transport after initialization, hadronization mechanism and hadron transport [21]. The initialization of the model follows HIJING model [22] and calculates the differential cross-section of the produced minijet particles in $p+p$ collisions which is given by,

$$\frac{d\sigma}{dp_T^2 dy_1 dy_2} = K \sum_{a,b} x_1 f_a(x_1, \hat{p}^2_T) x_2 f_b(x_2, \hat{p}^2_T) \times \frac{d\tilde{\sigma}_{ab}}{dt},$$

where $\sigma$ is the produced particle cross-section and $i$ is the momentum transfer during partonic interactions in $p+p$ collisions. $x_i$'s are the momentum fraction of the mother protons which are carried by interacting partons and $f(x, \hat{p}^2_T)$'s are the parton density functions (PDF). The produced partons calculated in $p+p$ collisions is then converted into $A+A$ and $p+A$ collisions by incorporating parametrized shadowing function and nuclear overlap function using in-built Glauber model within HIJING. In case of Pb nucleus, we use Woods-Saxon (WS) [23] distribution to define the distribution of nucleons (HIJING). For the deformed nucleus such as Xenon, we may include deformation parameter, $\beta_n$, along with spherical harmonics, $Y_{n}(\theta)$, in the WS function [6, 24–27]. This is known as modified Woods-Saxon (MWS) density distribution.
We have used MWS within the HIJING model to calculate initial distributions of partons etc., for tip, body or random configuration collisions of Xenon nuclei. Let us now describe briefly MWS. Nucleon density in HIJING is usually written as a three parameter Fermi distribution [28].

\[ \rho(r) = \rho_0 \left[ \frac{1 + w(r/R)^2}{1 + \exp[(r - R)/a]} \right]. \]  

(2)

Here \( \rho_0 \) is the nuclear matter density in the centre of the nucleus, \( R \) is the radius of the nucleus from its centre. The parameter, \( a \), is the skin depth or surface thickness, \( w \) is the deviation from a smooth spherical surface. \( \text{Au}^{197} \) or \( \text{Pb}^{208} \) nucleus is assumed here to have uniform distribution of nucleons in its approximately spherical volume and smooth surface, so that \( w \) can be taken to be zero. This reduces eqn.2 to Woods-Saxon [29] distribution, which has been used in HIJING in most cases. This may be written as:

\[ \rho(r) = \frac{\rho_0}{1 + \exp[(r - R)/a]}. \]  

(3)

When we use an axially symmetric or prolate deformed nucleus (viz. \( \text{U}^{238}, \text{Xe}^{136} \) etc.), nuclear radius \( R \), has been modified to include spherical harmonics. The modified Woods-Saxon nuclear radius \([30]\) may be written as:

\[ R_{A\Theta} = R[1 + \beta_2 Y_{20}(\Theta) + \beta_4 Y_{40}(\Theta)], \]

(4)

where the symbols \( \beta_i \) are deformation parameters, \( Y_{20} \), and \( Y_{40} \) are given by [31],

\[ Y_{20}(\Theta) = \frac{1}{4} \sqrt{\frac{5}{\pi}} (3 \cos^2 \Theta - 1) \]

\[ Y_{40}(\Theta) = \frac{3}{16\sqrt{\pi}} (35 \cos^4 \Theta - 30 \cos^2 \Theta + 3). \]

(5)

We have used deformation parameters from the Ref. [32]. The positions of nucleons within the distribution, \( \rho(r) \), are sampled using the volume element \( r^2 \sin \Theta \, dr \, d\Theta \, d\phi \) [33, 34]. For random orientation of nuclei, position configurations are sampled with both polar angle, \( \Theta \) in \([0, \pi]\) and azimuthal angle, \( \phi \) within limits \([0, 2\pi]\). Both target and projectile nuclei are rotated event-by-event in azimuth and polar space. In this paper, calculations have been done only with random orientation which means, unpolarized and averaged value over random \( \Theta \) and \( \Phi \) [35]. In Fig. 1, we show normalized nuclear density profile of Xenon with and without deformations. The lower panel shows the ratio of the density profile with nuclear deformation, with respect to the case of no-deformation.

The initial low-momentum partons which are separated from high momenta partons by a momentum cut-off, are produced from parametrized coloured string fragmentation mechanisms. The produced particles are initiated into parton transport part, ZPC (Zhang’s Parton Cascade Model) [36], which transports the quarks and gluons using Boltzmann transport equation which is given by,

\[ p^\mu \partial_p f(x, p_t) = C[f] \]  

(6)

The leading order equation showing interactions among partons is approximately given by,

\[ \frac{d\hat{\sigma}}{dt} \approx \frac{9\alpha_s^2}{2(t - \mu^2)^2}. \]

(7)

Here \( \sigma_{gg} \) is the gluon scattering cross-section, \( \alpha_s \) is the strong coupling constant used in above equation, and \( \mu^2 \) is the cutoff used to avoid infrared divergences which can occur if the momentum transfer, \( t \), goes to zero during scattering. In the String Melting version of AMPT (AMPT-SM), melting of coloured strings into low momentum partons also take place at the start of the ZPC and are calculated using Lund FRITIOF model of HIJING. This melting phenomenon depends upon spin and flavour of the excited strings. The resulting partons undergo multiple scatterings which take place when any two partons are within distance of minimum approach which is given by \( d \leq \sqrt{\sigma/\pi} \), where \( \sigma \) is the scattering cross-section of the partons. In AMPT-SM, the transported partons are finally hadronized using coalescence mechanism [37], when two (or three) quarks sharing a close phase-space combine to form a meson (or a baryon). The coalescence in AMPT can be shown by the following equation (for e.g. meson),

\[ \frac{d^3N}{d^3p_M} = g_M \int d^3x_1 d^3x_2 d^3p_1 d^3p_2 f_q(\vec{x}_1, \vec{p}_1) f_{\bar{q}}(\vec{x}_2, \vec{p}_2) \]

\[ \delta^3(\vec{p}_M - \vec{p}_1 - \vec{p}_2) f_M(\vec{x}_1 - \vec{x}_2, \vec{p}_1 - \vec{p}_2). \]

(8)

Here \( g_M \) is the meson degeneracy factor, \( f_q, f_{\bar{q}}, f_{\bar{q}} \) is the quark distributions after the evolution, and \( f_M \) is the coalescing function commonly called Wigner functions [37]. The produced hadrons further undergo evolution in ART mechanism [38, 39] via meson-meson, meson-baryon and baryon-baryon interactions, before final spectra can be observed. The default version of AMPT known as AMPT-Def, where instead of coalescing the partons, we have fragmentation mechanism using Lund fragmentation parameters \( a \) and \( b \) used for hadronizing the transported partons. However, it can be shown that particle flow and spectra at the mid-p_{T} regions are well explained by quark coalescence mechanism for hadronization [40–42]. We have used AMPT-SM mode for our calculations. We will return to the discussion of our choice in results and discussion section. We have used the AMPT version 2.26t7 (released: 28/10/2016) in our current work. It is worthwhile to mention that earlier
allowed the dN/dy for all the identified particles seems to follow a monotonically decrease with an increase of N part (centrality). The N part-normalized integrated yield (dN/dy) as a function of N part (centrality) seems to follow a monotonic decrease with an increase of N part for pions, kaons and protons. However, this seems to be almost independent of centrality for φ and Λ. Furthermore, we have checked explicitly that when the decay of φ and K₀ is allowed the dN/dy for all the identified particles seems to show a monotonic rise with collision centrality.

III. RESULTS AND DISCUSSIONS

As described in the previous section, we have generated events using AMPT model in different centralities for Xe+Xe collisions at the mid-rapidity for √sNN = 5.44 TeV, so that the results could be compared with the corresponding ALICE/CMS experimental data, when become available. We study the pT-spectra and integrated yield of identified particle production such as (π⁺ + π⁻), (K⁺ + K⁻), K₀ (p+̅p), φ and (Λ + ¯Λ). We also study the pT-differential and pT-integrated particle ratios to pions (π), kaons (K), protons (p) and Λ, respectively. As the particle production mechanisms are highly dependent on the transverse momentum range, e.g., when at intermediate pT, coalescence becomes the major mechanism, at high pT, the fragmentation takes over, it is worth studying pT-differential particle ratios. This is the prime focus of the present work.

In Fig.2, we have shown pT-spectra of identified hadrons for 0-10% central collisions of Xe+Xe at mid-rapidity (|η|<0.8). Different symbols represent the pT spectra for various particle species. Pions, being the lightest hadron, the production is maximum. At low-pT, we observe a mass-dependent behavior of the produced hadrons.
particles. The global mass ordering is violated as the production of $\phi$ is lesser compared to $\Lambda$. This behavior is similar to the experimental data from ALICE at the LHC [45]. While pions show almost an exponentially decreasing behavior, other particles’ spectra show dip at $p_T < 0.5 \text{ GeV/c}$ and they approach the pion spectra at intermediate $p_T$. This behavior could be due to the radial flow effects in a medium as the radial flow pushes the particles from low-$p_T$ to intermediate-$p_T$ [46]. Also, these shapes of the $p_T$-spectra may be due to the coalescence mechanism [47] at the low and intermediate momenta and/or the reason might also be the production of high-$p_T$ jets [40, 48] caused by fragmentation mechanism but it’s effects are mostly found beyond intermediate momentum region. It would be interesting to study the kinetic freeze-out properties in Xe+Xe collisions. Taking $(0-10)\%$ centrality class and pion $p_T$-spectra, we observe the average radial flow velocity to be $<\beta_r> = 0.45 \pm 0.04$ and the $T_{\text{kin}} = 109 \pm 12 \text{ MeV}$. This estimation is done by fitting Boltzmann-Gibbs Blast Wave model (BGBW) [49] to the $p_T$-spectra up to $p_T \sim 3 \text{ GeV/c}$. We have assumed a linear velocity profile in BGBW, which considers the produced fireball as a hard sphere uniform-density particle source. A centrality dependent study shows that both $T_{\text{kin}}$ and $<\beta_r>$ are centrality dependent- higher radial flow in central collisions resulting in drop in $T_{\text{kin}}$, as was earlier observed in heavy-ion collisions [50].

Figure 3 shows $p_T$-differential particle ratios of kaons, protons, $\phi$ and $\Lambda$ to pions at different centralities. All the particle ratios with respect to $\pi$ increases as a function of $p_T$. Considering K to $\pi$ ratio as a measure of strangeness, we observe enhancement of strangeness production as a function of $p_T$. This enhancement has a weak-dependence on centrality at low-$p_T$, while it strongly depends on centrality at intermediate-$p_T$ region. At intermediate-$p_T$, the strangeness production is maximum for the central collisions and it decreases with the centrality. A similar behavior is observed for the case of $\Lambda$ to $\pi$ ratio, where $\Lambda$ has the same strangeness content as of K. However, K to $\pi$ ratio rises more rapidly than $\phi$ to $\pi$ ratio which is more gradual. The reason may be due to the higher probability for a strange quark to find a up or a down quark to form kaons rather than find its anti-strange quark to form $\phi$ meson at low momentum region. As we move from low particle momenta to intermediate momentum region when particle moment is comparable to or more than the mass of strange ($s$) quark, the probability of $s\bar{s}$ production increases considerably so that $\phi$ to $\pi$ ratio is found to increase. However at higher momentum, more number of $u$ and $d$ quarks are also produced as compared to $s$ quark so that both ratios also start to drop beyond $p_T \approx 2 \text{ GeV}$. Similar trend of particle ratios are also observed in p-Pb and Pb-Pb collisions [51, 52].

Figure 3(b) shows the ratio of p to $\pi$, which is a ratio between lightest baryons to lightest mesons, which serves as a proxy of baryon to meson ratio. We have found that the trend is similar as other ratios but the values are quite different for p to $\pi$ ratios. For most central Xe+Xe collisions, the p to $\pi$ and $\Lambda$ to $\pi$ ratios are more than 1 in the intermediate-$p_T$ region, which indicates that the baryon production is more compared to lightest meson in the intermediate-$p_T$ region. We will revisit about this behavior at the end of this section.

FIG. 4: (Color online) $p_T$-differential p to K (a) and $\Lambda$ to K (b) ratio for various centrality bins in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44 \text{ TeV}$. The vertical lines in the data points are the statistical uncertainties.

Figure 4 represents the ratios of baryons over lightestStrange meson, K. The upper panel of the figure shows p to K and the lower panel of the figure shows $\Lambda$ to K ratios as a function of $p_T$ for collisions at different centralities. Both the ratios are independent of centrality at low-$p_T$ while they depend on centrality in the intermediate-$p_T$ ranges. For a given $p_T$-bin, after $p_T > 1 \text{ GeV/c}$, the ratios decrease with centrality. This trend is similar to the particle ratios with respect to $\pi$ in Fig. 3.

Figure 5 shows the $p_T$-integrated ratios of identified hadrons over pions and kaons as a function of centrality. It is very interesting to see that while differential particle ratios show strong dependence with centrality (for $p_T > 1 \text{ GeV/c}$), the integrated particle ratios show no centrality dependence. This indicates that the relative particle production with respect to pion does not depend on the centrality. This is due to the fact that the integrated yield is dominated by low-$p_T$ ($p_T < 1 \text{ GeV/c}$) particles. Assuming both centrality and charged-particle...
multiplicities are used as a proxy for the system size, the centrality-dependent particle ratios of p to π and φ to π as a function of centrality in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV reproduces qualitatively (within uncertainties) the preliminary results as a function of charged-particle multiplicity of ALICE at the LHC [9, 53]. Also, the trend of these ratios are similar to the experimental data in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV reported by ALICE [9, 53–56].

Figure 6 shows the $p_T$-integrated Kaon to pion ratio as a function of charged-particle multiplicity for $p+p$ collisions at $\sqrt{s} = 7$ TeV, Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV. The ratios for $p+p$ and Pb+Pb collisions are from experimental data [54, 57]. The ratio for Xe+Xe collisions are from AMPT-SM. The experimental data from $p+p$ collisions are for $K^0_s/\pi$ while for others, the ratio is $(K^+ + K^-)/(\pi^+ + \pi^-)$.

Figure 7 shows the comparison of $p_T$-differential p to π, λ to $K^0_S$ and p to φ ratios for most central (0-10%) Xe+Xe collisions from AMPT-SM with the AMPT-Default version. Also, they are compared with the preliminary experimental data [53]. For p to π and λ to $K^0_S$ ratios, it is observed that the AMPT-Default version is more closer to the experimental data than that of AMPT-SM specially for $p_T > 1$ GeV/c. It seems that although AMPT-SM describes the elliptic-flow of the charged particles of experimental data [58] better than the AMPT-Default but in case of stable particle ratios, AMPT-Default does a better job than the AMPT-SM. This may be due to the coalescence mechanism involved in AMPT-SM, which affects the particle production at intermediate-$p_T$. However, in the case of p to φ ratio both the versions of AMPT fails to explain the experimental data at low-$p_T$. At intermediate and high-$p_T$, AMPT-SM prediction is closer to the experimental data. According to hydrodynamics-inspired models, particles with similar masses should have similar particle spectra at low-$p_T$. It is found that the ratio is flat for experimental data over all the $p_T$ region, whereas for AMPT it decreases upto $p_T \sim 1$ GeV/c and then remain flat over higher $p_T$ region.

We have explicitly observed that the particle ratios are independent of nuclear deformation in Xe+Xe collisions. However, it should also be mentioned here that the identified particle $p_T$-spectra might be sensitive to nuclear deformation for central Xe+Xe collisions. For the case of deformation, the particle yield ratios are found to be comparable to the case of a spherical Xe nucleus. These findings indicate that nuclear deformation is insensitive to chemical freeze-out in Xe+Xe collisions. Similar re-
results are observed when particle ratios calculated from U+U collisions are compared to Au+Au collision systems [7].

We study chemical freeze-out temperature, $T_{ch}$ as a function of collision centrality measured through $<N_{part}>$ in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV. This is shown in Fig. 8 along with a comparison of kinetic freeze-out temperature, $T_{kin}$. The $T_{ch}$ for $(0-10\%)$ centrality is found to be around $154\pm8$ MeV, which is comparable with p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [59]. As expected, the present analysis of particle ratios reveal $T_{ch}$ to be independent of collision centrality in Xe+Xe collisions. Here we have taken the discussed particle ratios and have assumed a grand canonical ensemble in the thermal model [60] taking $\mu_B = 0$ and keeping $T_{ch}$, the strangeness saturation factor, $\gamma_s$ and the fireball radius as the free parameters. The kinetic freeze-out temperature is found to be highly dependent on collision centrality.

IV. SUMMARY

We have studied the $p_T$-spectra, integrated yield and particle ratios of identified particles for Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV using AMPT. Our findings are the following:

1. We have reported the simulation studies of identified particle production in Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV using AMPT model. This can be compared with experimental data, when become available. In particular, the effect of nuclear deformation warrants a simulation study, which through this work, would give a better understanding to experimental findings.

2. A BGBW analysis of pion $p_T$-spectra up to $p_T \sim 3$ GeV/c for $(0-10\%)$ centrality class shows the radial flow velocity, $<\beta_r> = 0.45 \pm 0.04$ and the kinetic freeze-out temperature, $T_{kin} = 109\pm12$ MeV. As observed earlier in heavy-ion collisions at RHIC, the radial flow velocity decreases and the kinetic freeze-out temperature increases towards peripheral collisions.

3. We observe enhancement of strangeness production as a function of $p_T$. This enhancement has a
We observe that the differential particle ratios show strong dependence with centrality (for $p_T > 1$ GeV/$c$) while the integrated particle ratios show no centrality dependence.

5. It is indeed interesting to note that the proxy of strangeness enhancement, $K/\pi$ ratio, when studied as a function of final state charged particle multiplicity for $p+p$, $\text{Xe}+\text{Xe}$ and $\text{Pb}+\text{Pb}$ collisions at different collision energies at the LHC, shows a scaling behavior indicating that the final state multiplicity drives the particle production. The availability of future experimental data at different energies for $p+p$, $p+\text{Pb}$ and $\text{Pb}+\text{Pb}$ collisions at the LHC would help in a better understanding of this observation.

6. We have found that for $p$ to $\pi$ and $\Lambda$ to $K^0_s$ ratios, the AMPT-Default version is more closer to the experimental data than that of AMPT-SM specially for $p_T > 1$ GeV/$c$. This may be due to the coalescence mechanism involved in AMPT-SM, which affects the particle production at intermediate-$p_T$.

7. For $p$ to $\phi$ ratio, the AMPT-SM does a better job compared to AMPT-Default version. The AMPT-SM seems to reproduce the experimental data after $p_T \sim 1$ GeV/$c$, which is expected by the hydrodynamics-inspired models.

8. It is explicitly observed from these extensive studies that the particle ratios are insensitive to nuclear deformation, at least in the case of $\text{Xe}+\text{Xe}$ collisions. However, it should also be noted here that the particle spectra are sensitive to nuclear deformation.

9. Thermal model analysis of the particle ratios in $\text{Xe}+\text{Xe}$ collisions at $\sqrt{s_{NN}} = 5.44$ TeV using AMPT gives the chemical freeze-out temperature for $(0 - 10\%)$ centrality, $T_{ch} = 154 \pm 8$ MeV. Further, we have found $T_{ch}$ to be independent of collision centrality, whereas the $T_{kin}$ is highly centrality dependent. This goes inline with the earlier findings at the RHIC [50] and LHC [59].

We believe the present exhaustive study of the particle spectra, ratios, and freeze-out criteria would be quite helpful in understanding the $\text{Xe}+\text{Xe}$ collisions at the LHC energies with nuclear deformation, when the corresponding experimental data will be available.

Acknowledgements

The authors acknowledge the financial supports from ALICE Project No. SR/MF/PS-01/2014-IITI(G) of Department of Science & Technology, Government of India. RR and ST acknowledge the financial support by DST-INSPIRE program of Government of India. The authors would like to acknowledge the usage of resources of the LHC grid computing facility at VECC, Kolkata. Dr. Swatantra K. Tiwari is acknowledged for initial discussions and Dr. Zi-Wei Lin for the necessary permission for implementing the nuclear deformation in AMPT. The authors are thankful to Arvind Khuntia for his helps in the thermal model analysis.

[1] S. A. Bass, M. Gyulassy, H. Stoecker and W. Greiner, J. Phys. G 25, R1 (1999).
[2] S. Voloshin and Y. Zhang, Z. Phys. C 70, 665 (1996).
[3] J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 92, 052302 (2004).
[4] L. Adamczyk et al. [STAR Collaboration], Phys. Rev. Lett. 115, 222301 (2015).
[5] C. Nepali, G. Fai and D. Keane, Phys. Rev. C 73, 034911 (2006).
[6] Md. Rihan Haque, Zi-Wei Lin and Bedangadas Mohanty, Phys. Rev. C 85, 034905 (2012).
[7] S. K. Tripathy, M. Younus, Z. Naik and P. K. Sahu, Nucl. Phys. A 980, 81 (2018).
[8] G. Giacalone, J. Noronha-Hostler, M. Luzum and J. Y. Ollitrault, Phys. Rev. C 97, 034904 (2018).
[9] S. Tripathy [ALICE Collaboration], arXiv:1807.11186 [hep-ex].
[10] B. I. Abelev et al. [STAR Collaboration], Phys. Rev. C 75, 054906 (2007).
[11] A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. 98, 162301 (2007).
[12] A. Adare et al. [PHENIX Collaboration], Phys. Rev. C 85, 064914 (2012).
[13] S. Singha and M. Nasim, Phys. Rev. C 93, 034908 (2016).
[14] Liang Zheng et al. Eur. Phys. J. A 53, 124 (2017).
[15] B. Kim [ALICE Collaboration], arXiv:1807.09061 [hep-ex].
[16] S. Acharya et al. [ALICE Collaboration], Phys. Lett. B 784, 82 (2018).
[17] B. B. Abelev et al. [ALICE Collaboration], Phys. Rev. C 91, 024609 (2015).
[18] Z. W. Lin and C. M. Ko, Phys. Rev. C 65, 034904 (2002).
[19] L. W. Chen, V. Greco, C. M. Ko and P. F. Kolb, Phys. Lett. B 605, 95 (2005).
[20] B. I. Abelev et al. [STAR Collaboration], Phys. Rev. Lett. 99, 112301 (2007).
[21] Z. W. Lin, C. M. Ko, B. A. Li, B. Zhang and S. Pal, Phys. Rev. C 72, 064901 (2005).
[22] X. N. Wang and M. Gyulassy, Phys. Rev. D 44, 3501 (1991).
[23] C. Loizides, J. Kamin and D. d’Enterria, Phys. Rev. C 97, 054910 (2018).
[24] Hiroshi Masui, Bedangadas Mohanty and Nu Xu, Phys. Letts. B 679 140 (2009).
Pingal Dasgupta, Rupa Chatterjee and Dinesh K. Srivastava Phys. Rev C 95, 064907 (2017).

O.S.K. Chaturvedi et al. Eur. Phys. J. Plus 132, 430 (2017).

Arpit Singh et al, Eur. Phys. J. C 78 419 (2018).

R. Hofstadter, Nobel Lecture, December 11, 1961.

Roger D. Woods and David S. Saxon, Phys. Rev. 95, 577 (1954).

D.L. Hendrie, N.K. Glendenning, B.G. Harvey, O.N. Jarvis, H.H. Duham, J. Saudinos, J. Mahoney, Phys. Letts B 26, 127 (1968).

C 5, Quantum Theory of Angular Momentum, By D A Varshalovich, A N Moskalev, V K Khersonskii, Singapore: World Scientific (1988).

PhD Thesis, Christopher Edward Flores, University of California, Davis http://nuclear.ucdavis.edu/thesis/CEF_Thesis_Final.pdf.

Schenke et al., Phys. Rev. C 89, 064908 (2014).

C. Nepali, G. Fai, and D. Keane, Phys. Rev. C 76, 051902(R) (2007).

B. Zhang, Comput. Phys. Commun. 109, 93 (1998).

V. Greco, C. M. Ko and P. Levai, Phys. Rev. Lett. 90, 202302 (2003).

B. Li, A. T. Sustich, B. Zhang and C. M. Ko, Int. J. Mod. Phys. E 10, 267 (2001).

B. A. Li and C. M. Ko, Phys. Rev. C 52, 2037 (1995).

V. Greco, C. M. Ko and P. Levai, Phys. Rev. C 68, 034904 (2003).

R. J. Fries, B. Muller, C. Nonaka and S. A. Bass, Phys. Rev. Lett. 90, 202303 (2003).

R. J. Fries, B. Muller, C. Nonaka and S. A. Bass, Phys. Rev. C 68, 044902 (2003).

Z. Feng, G. M. Huang and F. Liu, Chin. Phys. C 41, 024001 (2017).

S. Tripathy, S. De, M. Younus and R. Sahoo, Phys. Rev. C 98, 064904 (2018).

B. Abelev et al. [ALICE Collaboration], Phys. Rev. C 88, 044910 (2013).

S. Tripathy, S. K. Tiwari, M. Younus and R. Sahoo, Eur. Phys. J. A 54, 38 (2018).

L. Zhu, H. Zheng, R. Kong, arXiv:1811.09510 [hep-ph].

M. Younus, S. Tripathy, S. K. Tiwari and R. Sahoo, arXiv:1803.01578 [hep-ph].

E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. C 48, 2462 (1993).

B. I. Abelev et al. [STAR Collaboration], Phys. Rev. C 79, 034909 (2009).

J. Adam [ALICE Collaboration] Eur. Phys. J. C 75, 226 (2015).

B. Abelev [ALICE Collaboration], Phys. Lett. B 728, 25 (2014).

F. Bellini [ALICE Collaboration], arXiv:1808.05823 [nucl-ex].

B. Abelev et al. [ALICE Collaboration], Phys. Rev. C 88, 044910 (2013).

B. B. Abelev et al. [ALICE Collaboration], Phys. Lett. B 736, 196 (2014).

A. K. Dash [ALICE Collaboration], arXiv:1807.07469 [hep-ex].

J. Adam et al. [ALICE Collaboration], Nature Phys. 13, 535 (2017).

Z. W. Lin, Acta Phys. Polon. Supp. 7, 191 (2014).

N. Sharma, J. Cleymans, B. Hippolyte and M. Paradza, arXiv:1811.00399 [hep-ph].

S. Wheaton, J. Cleymans and M. Hauer, arXiv:1108.4588 [hep-ph].