1. Introduction

The study of the behavior of the matter under extreme conditions of temperature and energy density is important to understand the processes involved in the phase transition of the matter in Quantum Chromodynamics (QCD). Experiments at Relativistic Heavy Ion Collider (RHIC) at BNL, USA and Large Hadron Collider (LHC) at CERN, Geneva, Switzerland are specially designed to study the matter under these extreme conditions. In these experiments, the results have suggested that a strongly interacting de-confined state of quarks and gluons, also called Quark-Gluon Plasma (QGP), is formed in ultra-relativistic heavy-ion collisions. This plasma is a very hot and dense state and exists for a very short duration of time. The relevant degrees of freedom in the QGP phase are quarks and gluons instead of mesons and baryons (which are color neutral confined state). After the formation, this QGP cools, expands hydrodynamically, and reaches firstly the chemical freeze-out (the hadron abundances are fixed) phase and then reaches the kinetic freeze-out (the hadron momenta are fixed) phase.

The observable which is important to characterize the properties of the created matter in these collisions is the multiplicity of the charged particles. This is due to the fact that the particle production is affected by the initial energy density reached in the collision. The colliding nuclei are extended objects. Therefore, in a collision, the region of overlap between the two colliding nuclei varies from collision to collision. This degree of overlap is expressed by the impact parameter (denoted as “b”). The impact parameter cannot be measured directly. To overcome
this difficulty, a different parameter called central- ity is used. The centrality characterizes the initial overlapping region geometry, which corresponds to the number of participating nucleons $N_{\text{part}}$ and binary collisions $N_{\text{coll}}$. $N_{\text{part}}$ and $N_{\text{coll}}$ will be different for similar overlaps in collisions of nuclei of different sizes.

Transverse spherocity is an event shape variable which has been introduced recently. The recent development in event shape variables provides an alternate way to characterize the high multiplicity events in small systems considering particle production, event multiplicity, and event shape variable together. Event shape observables provide information about the energy distribution in an event. The event shape observables calculated event-by-event allows one to isolate jet-like $(p_T > 10 \text{ GeV/c})$ and isotropic (partonic scattering with low $Q^2$) events [1]. The ALICE, CMS, and ATLAS experiments have done the studies based on transverse spherocity [2,3]. These studies involved the understanding of event shape as a function of the charged particle multiplicity of the event. The results from these studies show that, for a high multiplicity, the events are more isotropic. After studying extensively small systems [4], the use of the transverse spherocity parameter in heavy-ion collisions may reveal new and unique results from heavy-ion collisions, where the production of a QGP is well established fact.

Transverse momentum ($p_T$) spectra of the charged particles produced in the heavy-ion collisions carry the essential information about the thermal nature of the interacting system [5–11]. The Maxwell–Boltzmann distribution law tells us that the $p_T$ spectra are related to the temperature of the system formed in these collisions. At low to intermediate $p_T$ (up to $10 \text{ GeV/c}$), the collective expansion of the system governs the charged particle production, which is observed in the shapes of single-particle transverse-momentum spectra [12, 13] and multiparticle correlations [14]. At high $p_T$ (typically above $10 \text{ GeV/c}$), the parton fragmentation governs the particle production. This production is affected by the amount of energy loss that the partons suffer, when propagating in the medium. Moreover, the numbers of charged particles ($N_{\text{ch}}$) produced in these ultra-relativistic collisions are also related to the temperature and energy density of the system created. The ratios of the yields of identified hadrons are also important to understand the processes involved in the production of hadron. The ratios of protons to pions ($p/\pi$) and kaons to pions ($K/\pi$) characterize the relative baryon and meson productions, respectively.

In this work, we have explored all the above-mentioned aspects related to the particle production. We have also used the transverse spherocity for the first time in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44 \text{ TeV}$ using A Multi-Phase Transport Model (AMPT) [15] and the Angantyr model [16] which is incorporated in PYTHIA8. The purpose of the present analysis is to study the dynamics of heavy-ion collisions using transverse spherocity and collision centrality in Xe–Xe collisions. Thus, we have used the PYTHIA8 and the string melting parametrization available in the AMPT model. We hope for that this would drive experimentalists to pursue such study in experiments at RHIC and LHC. The work is arranged as follows. We begin with a brief introduction and the motivation for the study in Section 1. In Section 2, the detailed analysis methodology along with a brief description of AMPT and PYTHIA8 (Angantyr) is given. Section 3 discusses the results for the charged-particle pseudorapidity density, $p_T$ spectra of $\pi^\pm$, $K^\pm$, and $p^\pm$ in different centrality and transverse spherocity ranges. Finally, the results are summarized in Section 4.

2. Event Generation and Analysis Methodology

This section is devoted to discussions related to the event generators, AMPT, and PYTHIA8 (Angantyr). Around 0.5 Million Xe–Xe events have been generated for both event generators at $\sqrt{s_{NN}} = 5.44 \text{ TeV}$. A discussion will also be presented for the transverse spherocity.

2.1. PYTHIA8 (Angantyr)

PYTHIA8 is a general-purpose Monte Carlo event generator that has been quite successful in the study of elementary particle collisions. It has been extensively used to simulate proton-proton and proton-lepton collisions to understand the dynamics of strong and electroweak processes extending from high momentum transfer regions (perturbative scales) to the scales around $A_{QCD}$ (Lattice QCD scales). Recently, efforts have been made to modify PYTHIA8 that
made it possible to simulate ultra-relativistic heavy-ion collisions like proton-nuclei (pA) and nuclei-nuclei (AA) ones. PYTHIA8 incorporates what is called “Angantyr” which basically superpose many pp collisions to make a single heavy-ion collision. In this way, a bridge is formed between heavy ion and high energy hadron phenomenologies. An important point is to note that the assumption of the formation of a hot thermalized medium is not included in the Angantyr model, since the production mechanisms is the same as in small collision systems. Thus, it can be used to differentiate the effects of collective and non-collective behaviors in heavy-ion collisions.

The Angantyr model is basically inspired by the old Fritiof model and the notion of wounded nucleons, but with the inclusion of effects of hard partonic interactions. To calculate the number of wounded nucleons, the use of the Glauber model is made, with the consideration of fluctuations in the nucleon-nucleon (NN) interactions to differentiate non-diffractively and diffractively wounded nucleons. In the model, the fluctuations of the nucleonic wavefunction are accommodated as fluctuations in the nuclei radius. Nucleons inside nuclei are distributed randomly according to a Glauber formalism. Every nucleon is then identified as either wounded or a spectator. The interactions between wounded nucleons in the projectile and target are classified as elastic, non-diffractive (ND), secondary non-diffractive (SND), single-diffractive (SD), and double-diffractive (DD) which basically depends on the interaction probability. All the subevents generated at the parton level are stacked together to represent one pA or AA collision event.

In PYTHIA8, the hadronization is done via the Lund string fragmentation model. In this model, the Lund area law [17] provides the probability of creating hadrons from the initial state of partons. The produced partons are connected to the beam remnants through color fluxtubes or strings which store the potential energy. As the partons move away from each other, the string breaks causing the formation of new quark-antiquark pairs. This process continues until the string pieces reduce to very small pieces, which are recognized as shell hadrons. In this scheme, the reconnection of strings between the partons happens in such a way that the string length decreases; resulting in a decrease in the particle production and, hence, the multiplicity.

### 2.2. A multiphase transport (AMPT) model

The AMPT model has four main components: the initial conditions, partonic interactions, conversion from the partonic to the hadronic matter, and hadronic interactions. In the case of default AMPT model, initial conditions for heavy ion collisions at RHIC are carried from the HIJING model [18–20]. The production of particles is described either as hard or soft components. The hard components are the ones that involve a momentum transfer larger than a cutoff momentum $p_0$, while the soft components are the ones having a momentum transfer below the cutoff value. The hard component is evaluated in the perturbative Quantum Chromodynamics domain (pQCD) using parton distribution functions in a nucleus. These processes contribute to the production of the minijets of partons. The soft component is discussed in non-perturbative region and is modeled by the formation of strings. The excited strings then decay independently following the Lund JETSET fragmentation model. The energy density in the default AMPT model can be very high in heavy ion collisions. To incorporate this effect, the AMPT model is extended to include the string melting mechanism. The interactions between partons are described using equations of motion which can be approximately written as the Boltzmann ones. The Boltzmann equations are then solved by using Zhang’s parton cascade (ZPC) [21], in which two partons undergo the scattering, whenever they are within the minimum closest distance. In the String Melting version of AMPT (AMPT-SM), colored strings are melted to form low-momentum partons, which takes place at the start of the ZPC. Corresponding to two different initial conditions, the hadronization is also done via two different mechanisms. In the case of default AMPT model, the minijets and their remaining parent nucleons coexist, and, after partonic interactions, they together form new excited strings. The Lund string fragmentation model describes the hadronization of these strings. In the case of the AMPT model with string melting, the conversion of strings into soft partons takes place. Then the hadronization happens via the simple quark coalescence model. In the coalescence model, the hadronization is done by combining three closest quarks (antiquarks) into a baryon (antibaryon) and two closest partons into a meson. The
hadrons thus produced undergo the final evolution via the meson-meson, meson-baryon, and baryon-baryon interactions described by the relativistic transport mechanism. The quark coalescence mechanism for the hadronization well explains the spectra at the mid-$p_T$ regions and the particle flow [22–24]. Thus, for our work, we have used the AMPT-SM mode (AMPT version 2.26i7) with the default settings.

2.3. Transverse spherocity

Transverse spherocity ($S_0$) is the property of an event and is defined using a unit vector $\hat{n}(\eta_T, 0)$ which minimizes the ratio [26] and chosen from all possible unit transverse vectors:

$$S_0 = \frac{\pi^2}{4} \min \left\{ \frac{\sum_i |p_T_i \times \hat{n}|}{\sum_i p_T_i} \right\}^2$$

The factor, $\pi^2/4$ normalizes the minimized value to 1 for the isotropic case. As a result, the value of transverse spherocity runs from 0 to 1, as the distribution of particles deviates from the jet-like to an isotropic structure, respectively, i.e.,

$$S_0 = \begin{cases} 0 & \text{pencil-like limit (hard events)}, \\ 1 & \text{isotropic limit (soft events)}. \end{cases}$$

Figure 1 shows the distribution of particles in both the scenarios.

3. Results

In Fig. 2, the charged-particle multiplicity density $dN/ch/\eta$ as a function of the pseudorapidity for different centrality classes is presented for AMPT and PYTHIA8. The centrality intervals for AMPT are defined using the charged-particle multiplicity distribution as can be seen in Table 1, whereas, for PYTHIA8, we define the centrality intervals which are based on the summed transverse energy ($\sum E_T$) in the pseudorapidity interval $[-0.8, 0.8]$. The motivation behind the use of the summed transverse energy distribution to define the centrality intervals has been studied in [16]. Figure 3 shows the distribution of events as a function of the charged-particle multiplicity for the AMPT generator, while Fig. 4 shows the event distribution for the PYTHIA8 event generator as a function of the summed transverse energy ($\sum E_T$). The $dN/ch/\eta$ values are also compared with the results...
from the experimental study with the ALICE Detector at the LHC at CERN [27]. In ALICE, the centrality classes are defined by using the sum of the amplitudes of the signals in the V0-A and V0-C detectors. The V0 system provides a charged particle multiplicity measurement based on the energy deposited in the scintillators. As mentioned above, Ref. [16] compares the measured V0 amplitude in ALICE with the $\sum E_T$ variable. The shape of the distribution is described quite well and, hence, $\Sigma E_T$ can be used as a centrality observable.

From Fig. 2, it can be seen that the AMPT describes the data fairly well at low centralities and slightly overestimates at high centralities. On the other hand, PYTHIA8 produces the shape pretty well, but slightly overestimates the data in the small centrality bins. For the Angantyr model, we find that the fluctuations, as well as the distinction between primary and secondary absorption-damaged nucleons, have a fairly significant impact on the final-state multiplicity. It is to be noted that AMPT presumes that a hot dense thermalized medium is formed in which a collective expansion occurs, whereas PYTHIA lacks a mechanism to reproduce the collective effects seen in pp collisions. Therefore, the Angantyr model lacks the assumption of production of a medium as well. Figure 5 shows the transverse spherocity distribution of the events in the 0–100% centrality interval for AMPT (black markers) and PYTHIA8 (red markers). The figure indicates that the more events produced by the PYTHIA8 are isotropic in nature as compared to AMPT. Figures 6 and 7 present the transverse spherocity distribution of events in different centrality classes for AMPT and PYTHIA8, respectively. It can be seen from the figures that small-centrality (high-multiplicity) events are more toward isotropic in nature, whereas high-centrality (low-multiplicity) events are toward the jetty side. This means that the peak of the transverse spherocity distribution shifts toward jetty events with the centrality, which shows that more central events contribute to the softer events and vice versa. The process of isotropization in a many-particle final state occurs through multiple interactions between the quanta of the system. If the final-state multiplicity in

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**Fig. 3.** Event distribution as a function of the charged-particle multiplicity for the AMPT model.

**Fig. 4.** Event distribution as a function of the summed transverse energy ($\sum E_T$) for the PYTHIA8 Angantyr model.

**Fig. 5.** Event distribution as a function of transverse spherocity in different centrality intervals for the PYTHIA8 Angantyr model.
The probability of an event becoming isotropic is higher when the event is more central in both the AMPT and PYTHIA8 models. Therefore, the differential study of particle production as a function of centrality and transverse spherocity classes is important to understand the particle production mechanism. The distribution depends on the centrality and ultimately on the charged-particle multiplicity. Therefore, to define the jetty and isotropic limits of the transverse spherocity, the 20% events of the extremum of the spherocity distribution are considered. The cuts for jetty and isotropic events vary for different centrality classes which are shown in Table 2.

Table 2. Table showing the values of transverse spherocity for jetty and isotropic ranges for different centrality bins

| Centrality, % | AMPT       | PYTHIA8   |
|--------------|------------|-----------|
|              | Jetty      | Isotropic | Jetty      | Isotropic | |
| 0–10         | 0–0.87     | 0.95–1    | 0–0.93     | 0.97–1    | |
| 10–20        | 0–0.82     | 0.92–1    | 0–0.92     | 0.96–1    | |
| 20–30        | 0–0.78     | 0.90–1    | 0–0.91     | 0.96–1    | |
| 30–40        | 0–0.76     | 0.89–1    | 0–0.89     | 0.95–1    | |
| 40–50        | 0–0.75     | 0.89–1    | 0–0.87     | 0.94–1    | |
| 50–60        | 0–0.74     | 0.88–1    | 0–0.83     | 0.93–1    | |
| 60–70        | 0–0.72     | 0.87–1    | 0–0.77     | 0.93–1    | |
The $p_T$ spectra of particles ($\pi^\pm$, $K^\pm$ and $p^\pm$) have been studied in jetty and isotropic regions of the transverse spherocity for different centrality classes at the mid-rapidity $|\eta| < 0.8$. Figures 8 to 13 represent the transverse spherocity distribution for AMPT and PYTHIA8 generators in the centrality class 0–10%. Similarly, Figs. 14 to 19 represent the $p_T$ spectra in the centrality interval 60–70%. The jetty region of transverse spherocity corresponds to lower 20% of the events in the spherocity distribution, whereas the isotropic region corresponds to higher 20% of the events in the spherocity distribution, and the integrated region is defined over the complete transverse spherocity ($0 \leq S_0 \leq 1$) region. The ratio of the $p_T$-spectra for isotropic and jetty events with respect to the spherocity integrated events ($0 < S_0 < 1$) is shown in the lower panels. From the figures, we find that the low $p_T$ regions are dominated by isotropic events rather than jetty ones. However, this scenario is reversed, when moving to higher $p_T$. At certain points called crossing point, the jetty event dominates over the isotropic event. Therefore, the study of crossing points is of great interest with respect to feasible limits of event-type dominance and, hence, related particle generation mechanisms. As we pass from low to high multiplicities, it has been observed from prior
investigations of the light-flavor sector that the crossing point relies on the multiplicity greatly and that the isotropic events are populated over numerous events [25,30,31]. According to the observations, the QGP-like effects observed in high-multiplicity pp collisions may not be caused by jet-bias effects, but instead may be caused by a potential system development, which should be investigated. In the present work, similar studies of the identified particles ($\pi^\pm$, $K^\pm$, and $p^\pm$) in the central pseudorapidity region $|\eta| < 0.8$ in the heavy-ion collision system show that isotropic events are dominant at low centralities (high-multiplicities) and vice versa. Figure 20 shows the crossing point in different centrality ranges for PYTHIA8 and AMPT event generators. The values are also presented in Table 3. This illustrates how, for two event generators, the contribution of jets to the creation of charged particles varies with centrality conditions. From the Table 3 and Fig. 20, a comparison shows a shift of the crossing point toward lower-$p_T$ in the case of PYTHIA8 Angantyr model indicating the jet dominant contribution to the particle production for the AMPT model. This means that the contribution of jets is higher in AMPT as compared to PYTHIA8. The dominance of isotropy in low
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Fig. 18. $p_T$ spectra of $p^{\pm}$ in the centrality bin 60–70% bin for AMPT

Fig. 19. $p_T$ spectra of $p^{\pm}$ in the centrality bin 60–70% bin for PYTHIA

centrality (high-multiplicity) events and jettiness in high centrality (low-multiplicity) events in the charge particle production further suggests a reduction and the softening of the jet yields at high charged-particle multiplicities. Therefore, in the PYTHIA8 Angantyr model, where the high multiplicity events involve the large momentum transfer, the reduction in the jet contribution to the particle production may indicate a reduced production of back-to-back jets. However, we should keep in mind that the Angantyr does not include an assumption of a hot thermalized medium. Therefore, collective effects are absent in PYTHIA (Angantyr), whereas AMPT considers collective effects. From the Figs. 8 to 19, it is clearly visible that Pythia is clearly able to differentiate the ratio as compared to AMPT, where the ratio of jetty and isotropic $p_T$ spectra with respect to the integrated $S_0$ move along the unity in the large $p_T$ region. This indicates that the study of the jet production within PYTHIA8 Angantyr and AMPT will form an interesting subject.

4. Summary

In conclusion, using A Multi-Phase Transport Model (AMPT) and PYTHIA8 Angantyr one, we present the first application of the transverse spherocity analysis for Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV. The findings demonstrate that the transverse spherocity

Table 3. Table showing the crossing point ($p_T$ in GeV/c) of jetty and isotropic events at mid-rapidity for Xe–Xe at $\sqrt{s_{NN}} = 5.44$ TeV collisions for PYTHIA8 and AMPT

| Centrality, % | $\pi^{\pm}$ | $K^{\pm}$ | $p^{\pm}$ |
|--------------|-------------|-----------|-----------|
|              | PYTHIA     | AMPT      | PYTHIA    | AMPT      | PYTHIA    | AMPT      |
| 0–10         | 2.61       | 5.83      | 3.56      | 5.97      | 3.63      | 6.09      |
| 10–20        | 2.59       | 5.2       | 2.82      | 5.41      | 2.93      | 5.53      |
| 20–30        | 2.32       | 5.02      | 2.41      | 5.18      | 2.65      | 5.31      |
| 30–40        | 2.16       | 4.79      | 2.31      | 4.91      | 2.63      | 4.99      |
| 40–50        | 2.02       | 4.63      | 2.04      | 4.83      | 2.35      | 4.90      |
| 50–60        | 1.89       | 4.21      | 1.90      | 4.43      | 2.24      | 4.57      |
| 60–70        | 1.73       | 3.9       | 1.83      | 3.99      | 1.88      | 4.1       |
successfully distinguishes between high-$S_0$ and low-$S_0$ heavy-ion collision event topologies. From the results, one can see that crossing points occur at relatively smaller $p_T$, as we go from low centrality to high centrality events. This means that, for low centrality events, the jetiness has a dominance over the isotropiness, whereas, for high centrality events, the isotropiness has dominance. For PYTHIA8 Angantyr, the crossing point occurs at much lower $p_T$ as compared to AMPT indicating that the jet production occurs at much lower $p_T$ for PYTHIA8 Angantyr as compared to AMPT. As we know, AMPT considers the formation of the medium and the collective effects, whereas PYTHIA8 Angantyr does not account for such happenings. Therefore, the jet production studies with both models will be of interest to do. The results, in our opinion, are extremely positive, and an experimental investigation in this direction would be very beneficial to comprehend the event topology dependence of the system dynamics in heavy-ion collisions.

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АНАЛІЗ ПРОСТОРОВОГО РОЗПОДIЛУ ЗАРЯДЖЕНИХ ЧАСТИНОК, НАРОДЖЕНИХ У Xe–Xe ЗIТКНЕННЯХ ПРИ $\sqrt{s_{NN}} = 5,44$ TeВ З ВИКОРИСТАННЯМ МОДЕЛI РYTHIA8 ANGANTYR I БАГАТОФАЗНОЇ ТРАНСПОРТНОЇ МОДЕЛI

Поперечна сферичнiсть є змiнною, яка дозволяє ефективно виокремлювати жорсткi та м’якi компоненти процесiв, що вiдповiдають подiям iз малою та великою кiлькiстю партонних взаємодiй, вiдповiдно. Експериментальнi данi, отриманi нещодавно на прискорювачi LHC для малих систем, свiдчать про важливiсть змiнної поперечної сферичностi для класифiкацiї подiй. В данiй роботi ми вивчаємо динамiку генерацiї частинок у Xe–Xe зiткненнях при $\sqrt{s_{NN}} = 5,44$ TeВ, використовуючи багатофазну транспортну модель i модель Angantyr, яка включена до РYTHIA8. Проаналiзовано спектри поперечного iмпульсу iдентифiкованих частинок для м’яких (iзотропних) та жорстких (струминоподiбних) подiй в рiзних iнтервалах центральностi.

Ключовi слова: кварк-глюонна плазма, псевдоподiбнiсть, зiткнення важких iонiв, багатофазна транспортна модель, РYTHIA8, модель Angantyr.