Baseline study for net-proton number fluctuations at top RHIC and LHC energies with Angantyr model

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The multiplicity percentile dependence of cumulants, of net-proton multiplicity distribution in Au−Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV have been investigated using the Angantyr model (the heavy-ion extension of Pythia 8 model). The effects of the finite transverse momentum ($p_T$) and pseudorapidity ($\eta$) ranges on the net-proton cumulants have also been studied. Furthermore, the effect of hydrodynamic expansion and feed down from resonance decays were explored. It was found that radial flow has substantial impact on the cumulants and their ratios, while resonance decays have finite but relatively smaller effect. The obtained values of cumulants and their ratios with Angantyr model, where the formation of thermalised medium is not assumed can serve as a baseline for future measurements.

I. INTRODUCTION

Understanding the phase transition of strongly interacting matter at extreme conditions and mapping its phase diagram has always been a matter of great interest in fundamental physics. The Quantum Chromodynamics (QCD) phase diagram is studied with respect to temperature ($T$) and baryo-chemical potential ($\mu_B$). In recent years, considerable progress has been made both in the theoretical and experimental areas to gain further insights. The nature of deconfinement phase transition on the QCD phase diagram can be comprehended at two limits of $\mu_B$. For $\mu_B = 0$, Pisarski and Wilczek demonstrated that at vanishing quark masses, the phase transition is of second order belonging to the $O(4)$ universality class of 3-dimensional symmetric spin model [1]. Further, lattice QCD calculations showed evidence of a smooth crossover transition along the temperature axis [2]. At $\mu_B \neq 0$, the phase transition was shown to be of first order [3,4]. Therefore, the presence of critical point (CP) at the end of second order phase transition line and the beginning of the first order phase transition line is anticipated by various theoretical models [5,6]. Due to fermion sign problem at this limit, the presence or absence of CP cannot be established by lattice QCD. Recently, many progresses have been made in lattice QCD to circumvent the sign problem and study the QCD matter beyond the continuum limit.

The presence of CP is characterised by the divergence of correlation lengths. The higher-order cumulants of the conserved-charges, like net-charge, net-baryon and net-strangeness multiplicity distributions are related to the correlation lengths of the system [10, 11]. Many theoretical works suggest that the CP can be searched in heavy-ion collision experiments and the measurement of event-by-event fluctuations of conserved-charge distributions can be an excellent tool to probe the CP in heavy-ion collisions [12]. The $T$–$\mu_B$ plane can be scanned by varying the collision energy and the observation of non-monotonic behavior of measured observables can be regarded as a signature of CP. The Beam -Energy Scan (BES) program at Relativistic Heavy-ion Collision (RHIC) and Compress Baryonic Matter (CBM) experiment at FAIR facility aim to search the CP by studying the beam energy dependence of higher order cumulants of conserved-charge distributions [13–16].

At $\mu_B = 0$, lattice QCD calculations can estimate the chemical freeze-out parameters ($T, \mu_B$) from its first principle, where the order parameters are the quark number susceptibilities. These quark number susceptibilities are related to the cumulants of the conserved-charge distributions [17]. It has been demonstrated that the freeze-out parameters can be estimated from the ratio of cumulants of the conserved-charge distributions [17, 19]. Additionally, the freeze-out parameters are also estimated from statistical models using the particle yield ratios from experiments [20, 21]. The temperature estimated from lattice QCD and statistical models are compatible within the uncertainties, which implies that the chemical freeze-out line is close to the crossover line. Therefore, experimental

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measurement of ratios of cumulants at top RHIC and LHC energies can be used to constrain the lattice QCD predictions, as well as to map the phase diagram at vanishing $\mu_B$. Recently, ALICE experiment has reported the preliminary results of cumulants of net-proton number distributions up to 4th order in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV [22]. However, before comparing the experimental measurement with the lattice QCD predictions, it is imperative to understand and consider the effects of finite kinematic acceptance, radial flow and contributions from resonance decays on the measured cumulants.

In this work, an attempt has been made to investigate the effects of finite detector acceptance, radial flow and resonance decays on the cumulants of the net-proton multiplicity distributions, using Angantyr model. In section II, a brief introduction of Angantyr model and working methodology has been discussed. The baseline estimations for cumulants obtained for top RHIC and LHC energies are discussed in Section III. The study on the effect of limited acceptance has been presented in section IV, where the effects of different transverse momentum ($p_T$) and pseudorapidity ($\eta$) cutoffs are discussed. The contribution of radial flow and resonance decays are studied in section V and VI, respectively.

II. THE ANGANTYR MODEL

The Angantyr model, which is an augmentation of p–p collisions to nucleon-nucleus (p–A) and nucleus-nucleus (A–A) collisions by Pythia 8 MC event generator has been used for this study [23–25]. In this model, for each heavy-ion event, the nucleons are distributed randomly in the impact parameter space based on Glauber model. The number of wounded or spectator nucleons are estimated from Glauber formalism with Gribov corrections, to the diffractive excitation of the individual nucleon. The model considers the improvised version of Fritiof model used for p–A system, where the wounded nucleons contribute to the final state [24]. It considers two interaction scenarios (sub-events) for the projectile and target nucleons. In the first scenario, some of the interactions between the projectile and the target nucleons are treated as p–p-like non-diffractive (ND) collisions, which are labeled as primary ND interactions. The parton-level event generation for these primary ND interactions (as well as diffractive interactions) are done using the full Pythia 8 machinery. In the second scenario, a projectile nucleon, which has already been wounded is allowed to have ND interactions with multiple target nucleons. These type of interactions are labeled as secondary ND collisions. Later on, secondary ND (sub-)collisions are treated as modified single diffractive (SD) process, and standard Pythia 8 diffractive machinery is used for the sub-event generation. The interactions between wounded nucleons in projectile and target are labeled as elastic, ND, secondary ND, SD and double-diffractive depending upon their interaction probability, and considered in the model with appropriate modifications as given in Ref. [25]. Finally, all the sub-events are stacked together to represent a fully exclusive final state heavy-ion collision.

One of the novel features of Angantyr model is that it considers the fluctuations of nucleons both in the projectile and target nucleons in the Glauber calculation [26]. Furthermore, the sub-events are treated independently where hadrons are produced using the string fragmentation model. Therefore, it does not have any collective effects and does not assume formation of a hot thermalised medium unlike AMPT and EPOS [27, 28]. Hence, it can be used as a baseline model to understand the non-collective backgrounds for various observables which are affected by collectivity in data.

Angantyr model has provided a very good description of some final state observables, like rapidity distribution, centrality dependent charged particle multiplicity and $p_T$ distributions in p–A and A–A collisions at top RHIC and LHC energies [25]. Therefore, the model predictions can be used as a baseline study for the cumulants of net-proton multiplicity distributions in Au–Au and Pb–Pb collisions at $\sqrt{s_{NN}} = 200$ GeV and 2.76 TeV, respectively.

III. BASELINE RESULTS

The analysis is carried out using $50 \times 10^6$ events for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV, and $30 \times 10^6$ events for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the default setting of Angantyr model. Each event is classified into different centrality percentile classes using the total charged particle multiplicity recorded in the range of $3 \leq |\eta| \leq 4$ to avoid auto-correlation. For a given centrality percentile, the number of protons ($p$), anti-protons ($\bar{p}$) and net-proton ($\Delta N_p = p - \bar{p}$) are counted on an event-by-event basis within $0.4 < p_T < 2.0$ GeV/$c$ and pseudorapidity ($\eta$) range,
$|\eta| < 0.8$. The standard expressions used for the estimation of cumulants of net-proton multiplicity distributions are the following:

\[
\begin{align*}
C_1 &= m_1, \\
C_2 &= m_2 - m_1^2, \\
C_3 &= m_3 - 3m_1m_2 + 2m_1^3, \\
C_4 &= m_4 - 4m_1m_3 - 3m_2^2 + 12m_1^2m_2 - 6m_1^4. \\
\end{align*}
\]

Here $m_n = \langle (\Delta N_p)^n \rangle$ is the $n^{th}$ order moments of net-proton multiplicity distribution for $n = 1, 2, 3, 4$. Unless otherwise mentioned, the $p, \bar{p}$ and $\Delta N_p$ refer to inclusive numbers, which have contributions from resonance decays. In this work, the cumulants of net-proton multiplicity distribution are estimated for each unit centrality percentile bin. The final results are presented for the wider bin of 10% bin-width after doing centrality bin-width correction (CBWC) \[29\]. CBWC is used for eliminating the volume fluctuations originating from the initial participant fluctuations and finite centrality bin size \[3\]. The statistical uncertainties are estimated using Delta theorem method \[31\].

Figure \[1\] illustrates the centrality percentile dependence of $C_1$, $C_2$, $C_3$, and $C_4$, and their ratios $C_2/C_1$, $C_3/C_2$, and $C_4/C_2$. The baseline results for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are represented by open circles and triangles, respectively. A strong collision centrality dependence for the individual cumulants is observed for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV. A similar behavior is also observed for Pb–Pb system with an exception of $C_3$ which shows no significant centrality dependence. Furthermore, at a given centrality, the value of $C_2$ and $C_4$ increases while going from RHIC to LHC. However, $C_1$ and $C_3$ show the opposite trend. $C_1$ is the mean, and $C_3$ is the alternative representation of the skewness of a distribution. At LHC energies ($\mu_B \approx 0$), equal number of protons (and anti-protons) are expected to be produced at mid-rapidity. Consequently, the net-proton multiplicity distribution will be symmetric around zero. Therefore, small values of mean and skewness (close to zero) of net-proton distributions in Pb–Pb collisions are observed from this model. The $C_2/C_1$ ratio does not show any centrality dependence for Au–Au collisions, whereas Pb–Pb results show an increasing trend from central to peripheral. The ratio of cumulants, $C_3/C_2$ and $C_4/C_2$ do not show any collision centrality dependence for both the energies within the statistical uncertainties. Additionally, it is observed that $C_3/C_2$ moves closer to zero and $C_4/C_2$ to unit value while going from top RHIC to LHC energies. A similar observation is also made by recent ALICE measurement \[22\]. It is to be noted that ALICE preliminary results are obtained in a small kinematic window of $0.4 < p_T < 1.0$ GeV/c. A study on the effect of kinematic acceptance used in experiments is discussed in the following section.

IV. EFFECT OF LIMITED ACCEPTANCE

The experimental results of the ratios of cumulants of conserved charge fluctuations are compared with lattice QCD calculations for estimation of freeze-out parameters. However, experimental measurements are carried out in finite phase space due to limited detector acceptance, while lattice QCD calculations are done in full phase space. It has already been demonstrated that there is a strong influence of various kinematic cuts, such as $p_T$ and $\eta$ on the measured cumulant results \[32,33\]. Therefore, their effects are required to be understood before comparing the experimental results with the theoretical calculations. In this section, the effects of various $p_T$ and $\eta$ cutoffs on the net-proton cumulants for top RHIC and LHC energies are investigated.

A. Transverse momentum cutoff

In experiments, the identified particles such as $p(\bar{p})$ can only be recorded within a specific $p_T$ range due to the detector limits and inefficiencies, and hence the cumulants of net-proton multiplicity distributions are reported in a specific $p_T$ window \[14,22\]. Both STAR and ALICE experiments use a lower $p_T$ cutoff at 0.4 GeV/c. This non-zero lower $p_T$ cutoff ($p_{T,\text{min}}$) and different upper bounds of $p_T$ ($p_{T,\text{max}}$) can influence the net-proton multiplicity distribution and the higher order cumulants \[34\]. Therefore, the effect of $p_T$ acceptance is studied by varying the upper $p_T$ cutoff while keeping the lower value fixed at $p_T = 0.4$ GeV/c for $|\eta| < 0.8$.

The $p_{T,\text{max}}$ dependence of $C_1$, $C_2$, $C_3$, $C_4$ and their ratios, $C_2/C_1$, $C_3/C_2$, $C_4/C_2$ of net-proton...
multiplicity distributions in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are shown in Figure 2. The results are shown for the most central (0-10%) and semi-central (30-40%) collisions, which are represented by circles and triangles, respectively. The open markers represent the Au–Au collisions while the filled ones represent the Pb–Pb results. It is observed that the value of cumulants, $C_1$, $C_2$, and $C_4$ show an increasing trend with an increase of the $p_{T,max}$ cutoff till 2.0 GeV/c. The cumulant values seem to saturate thereafter. The saturation for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV is faster than Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. This implies that the cumulants at LHC energy are more sensitive to the $p_{T,max}$ cutoff below 2.0 GeV/c. However, the values of $C_3$ show no such dependence for mid-central collisions in both the systems. In central collisions, $C_3$ shows a similar trend as others for Au–Au system while it is almost flat for Pb–Pb collisions. For Au–Au collisions, $C_2/C_1$ values do not show $p_{T,max}$ cutoff dependence for both the centrality percentile classes. But Pb–Pb results show an initial increase which saturate after $p_{T,max} = 2.0$ GeV/c. The $C_3/C_2$ values show an increasing trend for Au–Au collision, whereas the trend is reversed for Pb–Pb collisions. But for both the collision energies, they seem to saturate after $p_{T,max} = 2.0$ GeV/c. The $C_4/C_2$ values do not show such strong $p_{T,max}$ cutoff dependence, admittedly, within the large statistical uncertainties. The $C_3/C_2$ and $C_4/C_2$ of net-proton reported by STAR experiment for different $p_{T,max}$ also show similar weak dependence for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

B. Pseudorapidity cutoff

Usually, the experimental data is compared with lattice QCD or statistical models where the predictions are made in the Grand Canonical Ensemble formulation of thermodynamics. To meet these thermodynamical conditions in experiments, the rapidity window ($\Delta y$) or $\Delta \eta$ dependence of the cumulants needs to be studied. In grand canonical ensemble system, the average number of net-baryon number is conserved and there can be significant effects of global baryon number conservation in the experimental measurements. This effect grows with an increase in the $\Delta \eta$ range. Hence, to minimize the effect due to global baryon

FIG. 1. Centrality percentile dependence of cumulants ($C_1$, $C_2$, $C_3$, and $C_4$) and their ratios ($C_2/C_1$, $C_3/C_2$, and $C_4/C_2$) of net-proton distributions for Au–Au and Pb–Pb collisions at $\sqrt{s_{NN}} = 200$ GeV and 2.76 TeV, respectively. The results are obtained from the default setting of Angantyr model for 0.4 < $p_T$ < 2.0 GeV/c and $|\eta| < 0.8$. The Au–Au and Pb–Pb results are shown for the most central (0-10%) and semicentral (30-40%) collisions, which are represented by circles and triangles, respectively. The open markers represent the Au–Au collisions while the filled ones represent the Pb–Pb results. It is observed that the value of cumulants, $C_1$, $C_2$, and $C_4$ show an increasing trend with an increase of the $p_{T,max}$ cutoff till 2.0 GeV/c. The cumulant values seem to saturate thereafter. The saturation for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV is faster than Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. This implies that the cumulants at LHC energy are more sensitive to the $p_{T,max}$ cutoff below 2.0 GeV/c. However, the values of $C_3$ show no such dependence for mid-central collisions in both the systems. In central collisions, $C_3$ shows a similar trend as others for Au–Au system while it is almost flat for Pb–Pb collisions. For Au–Au collisions, $C_2/C_1$ values do not show $p_{T,max}$ cutoff dependence for both the centrality percentile classes. But Pb–Pb results show an initial increase which saturate after $p_{T,max} = 2.0$ GeV/c. The $C_3/C_2$ values show an increasing trend for Au–Au collision, whereas the trend is reversed for Pb–Pb collisions. But for both the collision energies, they seem to saturate after $p_{T,max} = 2.0$ GeV/c. The $C_4/C_2$ values do not show such strong $p_{T,max}$ cutoff dependence, admittedly, within the large statistical uncertainties. The $C_3/C_2$ and $C_4/C_2$ of net-proton reported by STAR experiment for different $p_{T,max}$ also show similar weak dependence for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV.
number conservation, the size of $\Delta\eta$ window can be reduced. This might hinder the observation of genuine correlations (A similar study on the effect of global and local baryon number conservation is done in [36, 37]). Moreover, the transverse expansion of the medium also largely affects the rapidity distributions and $p_T$ spectra of protons. The cumulants measured in an expanding medium can have different values than those measured in a static medium [34]. Furthermore, $\Delta\eta$ study also helps to explore the time evolution and hadronization mechanism of the medium [38]. The effects of different $\Delta\eta$ cutoff will be discussed in the following section where the effects of transverse expansion have been taken into account.

V. EFFECT OF TRANSVERSE EXPANSION

In heavy-ion collisions, the created fireball experiences a hydrodynamical expansion both in transverse and longitudinal direction. During this expansion, it encounters two freeze-out boundaries: chemical and kinetic. After the chemical freeze-out, the inelastic scattering stops and the particle composition of the system is fixed. But the elastic scattering continues which change the momenta of particles. After the kinetic freeze-out, the elastic scattering stops and the particles move freely. A blue-shift is observed in the particle spectra as a consequence of this hydrodynamic expansion and one can use the Blast Wave model to extract the transverse velocity profile (also known as radial flow velocity $\langle \beta \rangle$), from the $p_T$ spectra. Although the particle yields are not affected after the chemical freeze-out, the presence of radial flow in transverse direction can still affect the $p_T$ spectra and hence their correlations. This in turn can influence the cumulants of the net-proton multiplicity distributions.

The dynamics of hydrodynamical expansion is not present in the event generation scheme of the Angantyr model. This makes the model apt for baseline studies related to static non-equilibrated system. To understand the possible changes in the cumulants of net-proton multiplicity distribution due to transverse expansion, the radial flow has been introduced as an afterburner as demonstrated in Ref. [39]. The numerical values of radial flow velocity, $\langle \beta \rangle$, for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are taken from Ref. [40] and Ref. [41], respectively.

The implementation of the radial flow after-
burner was verified by comparing the $p_T$ spectra of protons (and anti-protons) obtained from the default setting of Angantyr and the one obtained after introducing the radial boost with the measured spectra from STAR experiment. This is illustrated in Figure 3 for most central Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV within the rapidity window $|y| < 0.1$. The spectra with default settings are represented by the open squares while those with radial flow are represented by the open circles. The data is depicted by filled circles. It can be observed that the $p_T$ spectra of protons and anti-protons obtained from Angantyr model with radial flow are closer to the measured data than the default one.

Furthermore, the cumulants of net-proton multiplicity distribution is calculated with default settings and with radial flow in the range of $0.4 < p_T < 2.0$ GeV/$c$ and $|y| < 0.5$. A comparison between the measured data of STAR experiment and the model is done by obtaining their ratios. The ratios of data to model predictions for different cumulants are shown as a function of collision centrality in Figure 4. The left panel shows the ratios for default setting while the right panel shows the same with radial boost. It is observed that the default setting of Angantyr overestimates the $C_1$ values and underestimates $C_4$. The $C_2$ and $C_3$ values differ from the measured values within 10%-20%. The results obtained with the radial flow has the mean of net-proton distributions much closer to the data but it overestimates other cumulants, and is almost twice the value of the data. The observed discrepancy between data and the model for higher order cumulants can be attributed to the genuine correlations present among the particles in the data.

The effect of radial flow on the cumulants of net-proton multiplicity distributions in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with Angantyr model in the kinematic range $0.4 < p_T < 2.0$ GeV/$c$ and $|\eta| < 0.8$ has also been studied. The cumulants and their ratios for different centrality percentiles are illustrated in Figure 5. The mean ($C_1$) and variance ($C_2$) of the distributions are observed to increase for all centrality classes after applying the
radial boost in the model. The change in values are much larger in central events than the peripheral events. Consequently the value of $C_2/C_1$ also decreases due to radial flow. Except for the two most central bins, $C_3$, $C_4$ and their ratios, $C_3/C_2$, and $C_4/C_2$, do not show significant radial flow dependence. Additionally, $C_3/C_2$, and $C_4/C_2$ do not show any collision centrality dependence within the uncertainties.

The $\Delta \eta$ dependence of the cumulants of net-proton multiplicity distributions as a function of different $\Delta \eta$ windows for most central (0-10%) Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV within the $p_T$ range $0.4 < p_T < 2.0$ GeV/c have been performed with (and without) the radial flow.

Figure 6 shows a clear $\Delta \eta$ dependence of cumulants of net-proton multiplicity distributions. Except for $C_3$, the values of $C_1$, $C_2$, and $C_4$ increase linearly with an increase of the $\eta$ window in both the collision system. The model with radial flow shows a linear increasing trend for all the cumulants with increasing $\eta$ window. For Au–Au collisions, the $C_2/C_1$ ratios do not show any strong $\Delta \eta$ dependence for both the settings. However, it shows a decreasing trend with $\Delta \eta$ which further decreases with radial flow for Pb–Pb collisions. The $C_3/C_2$ and $C_4/C_2$ for Au–Au collisions with default settings do not show any variation up to $\Delta \eta < 2$, but sharply increase after this. The $C_3/C_2$ and $C_4/C_2$ show a gradual increase with respect to $\Delta \eta$ after the radial boost. A similar conclusion at LHC energies, is hindered due to large uncertainties in the present analysis.

VI. RESONANCE CONTRIBUTION

In heavy-ion collisions, the feed down from resonance decays have large contributions to the final state particle multiplicities and thus can influence the particle distributions. This may further introduce short-range correlations. In experiments, the measured number of protons contain the primordial as well as the contributions from weak decays (also known as secondaries). To minimize the contribution of secondaries, the protons (and anti-protons) are identified after imposing certain cuts related to interaction vertex and distance of closest approach (DCA) etc. At top RHIC energy, the secondary contribution is negligible. However, at LHC energies, in most central
FIG. 5. Centrality dependence of cumulants ($C_1$, $C_2$, $C_3$, and $C_4$) and its ratios ($C_2/C_1$, $C_3/C_2$, and $C_4/C_2$) of net-proton multiplicity distributions from Angantyr model without and with radial flow in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV obtained in the kinematic range of $0.4 < p_T < 2.0$ GeV/$c$ and $|\eta| < 0.8$. The open circles represent the results from default setting while the open triangles represent the ones with radial flow.

FIG. 6. $\Delta\eta$ dependence of cumulants ($C_1$, $C_2$, $C_3$, and $C_4$) and their ratios ($C_2/C_1$, $C_3/C_2$, and $C_4/C_2$) of net-proton distributions with Angantyr model for 0-10% centrality class in Au–Au collisions (open markers) and Pb–Pb collisions (close markers) at $\sqrt{s_{NN}} = 200$ GeV and 2.76 TeV, respectively. The $\Delta\eta$ dependence is shown for default condition and with radial flow by circles and triangles, respectively.
events, even with stricter DCA cuts, the secondary fraction can reach up to 35% in the low $p_T$ region [41]. The main source of secondary contamination originates from $\Lambda$ decays. The contribution from other strange baryons like $\Sigma$ and $\Xi$ is relatively smaller. In event-by-event measurements, removing the secondaries is not a straightforward task. The protons (and anti-protons) coming from $\Lambda$ decays (weak decays) can have different thermodynamical properties due to the flavor hierarchy [42]. As their contribution is not negligible, they can affect the net-proton multiplicity distribution and hence the cumulants. The effect was studied by estimating the cumulants of net-proton multiplicity distributions for three cases. In the first case, the proton sample did not have any feed down from strange baryon decays while in the second case protons originating from $\Lambda$ decays only are also considered. In the third case, all the protons were considered.

The centrality percentile dependence of cumulants of net-proton multiplicity distributions for Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV for three different scenarios of proton selection are shown in Figure 7. It can be seen that the cumulant values increase while considering the protons coming from $\Lambda$ only. The values further increase when feed down from $\Sigma$ or $\Xi$ are considered. The increase is very negligible. A similar trend is observed for $C_2/C_1$ and $C_4/C_2$, with an exception for $C_3/C_2$, which does not show any effect.

A similar study performed for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, is shown in Figure 7. $C_1$, $C_2$, $C_4$ and their ratios are found to be less sensitive to the protons coming from strange baryons. The $C_3$ and $C_3/C_2$ are not affected by the resonance decays.

It is observed from the model studies done at RHIC and LHC energies that resonance decays have finite but very small contributions to the cumulants and their ratio. The contribution from $\Lambda$ decay is more compared to all other strange baryons. Therefore, these effects must be taken into consideration before comparing the experimental results with models.

VII. SUMMARY

The baseline study for the first four cumulants of the net-proton multiplicity distributions and their ratios in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV have been studied using Angantyr model. A strong centrality dependence of the cumulants was observed for both the collision systems. The values of $C_2/C_1$, $C_3/C_2$ and $C_4/C_2$ decrease while going from RHIC to LHC energies. The variation of the cumulants and their ratios were also studied for various kinematic acceptance of $p_T$ and $\eta$. It was observed that for both RHIC and LHC energies, the cumulant and their ratios saturate for a $p_T, max$ cutoff greater than 2.0 GeV/c. The effect of radial boost was studied by implementing the radial boost to the particles as an afterburner. The proton and anti-proton spectra are qualitatively described by the model simulation after the implementation of radial flow for RHIC top energy. The radial flow has a substantial effect on lower order cumulants for both the energies. The value of cumulants increase with an increase of $\Delta \eta$ window and the values are further increased with the radial boost. The effect of resonance decay contributions was found to be a relatively small effect in the measurement of higher order cumulants in heavy ion collisions. The obtained results can serve as a baseline for future experimental measurements.

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FIG. 7. Centrality dependence of cumulants \( C_1 \), \( C_2 \), \( C_3 \), and \( C_4 \) and its ratios \( C_2/C_1 \), \( C_3/C_2 \), and \( C_4/C_2 \) of net-\( p \) distributions obtained from Angantyr model without and with the resonance contribution in Au–Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \).

FIG. 8. Centrality dependence of cumulants \( C_1 \), \( C_2 \), \( C_3 \), and \( C_4 \) and its ratios \( C_2/C_1 \), \( C_3/C_2 \), and \( C_4/C_2 \) of net-\( p \) distributions obtained from Angantyr model without and with the resonance contribution in Pb–Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \).
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