# Fluctuations of identified particle yields using the $\nu_{\rm dyn}$ variable at energies available at the BNL Relativistic Heavy Ion Collider

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We study the fluctuations of net charge, net pion, net kaon, and net proton using the $\nu_{\rm dyn}$ variable in the heavy-ion jet interaction generator (HIJING), ultrarelativistic quantum molecular dynamics (UrQMD), and hadron resonance gas (HRG) model at different collision energies $\sqrt{s_{NN}}$. It has been observed that the values of $\nu_{\rm dyn}$ strongly depend on $\Delta\eta$ in the HIJING and UrQMD models and are independent in the HRG model. The present work emphasizes the particle species dependence of net charge fluctuation strength and provides a baseline for comparison with the experimental data.

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## I. INTRODUCTION

One of the major goals of heavy-ion experiments is to study the phase transition from hadronic matter to quark-gluon plasma (QGP). Event-by-event fluctuation of conserved quantities such as net-baryon number, net-electric charge, and net strangeness were proposed as possible signals of the QCD phase transition [1]. Measurements of fluctuations can also help in understanding the nature of such a phase transition. One of the observables, net-charge fluctuation, has been considered as a signal for such studies. The reason behind net charge fluctuation study is similar to the original study of color charge in $e^+e^-$ experiment. There the color charge ratio was measured and depending upon the difference in fundamental degrees of freedom between quark-gluon state and hadronic state, the origin of the color charge was determined [2,3]. Several experiments have measured net-charge fluctuation at SPS, RHIC, and LHC energies [4–9].

Event-by-event fluctuations in high-energy heavy-ion collisions have been used to study the equilibrium of thermodynamical fluctuations at freeze-out. In the QGP phase, quarks are the charge carriers with a fractional charge of $\pm 1/3$ or $\pm 2/3$, while in the hadronic phase hadrons are the charge carriers each with an integer charge. Hence, net-charge fluctuations in the QGP phase are predicted to be a factor of 2 to 3 smaller as compared to that of the hadronic phase [1]. These differences may be considered as indicators of the formation of quark-gluon plasma in high-energy heavy-ion collisions. Thus, the net-charge fluctuations are strongly dependent on the phase of their origin. Due to the rapid expansion of the fireball created in the heavy-ion collisions, the fluctuations created in the initial state may survive during the hadronization process [2]. If the relaxation time happens to be shorter than the lifetime of the hadronic stage of the collisions, then the values of such fluctuations should deviate from their equilibrium hadron gas values towards their earlier, primordial values, typical for QGP [1,2]. The fluctuations of different lengths or ranges in rapidity space relax on different time scales. Since relaxation can only proceed via diffusion of the charge, the longer range of fluctuations relaxes gradually. The relaxation time is expected to grow as a square of the rapidity range [10]. It is evident that fluctuations of the total charge in a wider rapidity window relax slower. The minimal rapidity window that one can consider must be larger than the mean rapidity change of a charged particle in a collision, $\delta y_{\rm coll}$. It is observed that the typical $\delta y_{\rm coll}$ for the baryon and the electric charge is around 0.2 and 0.8, respectively [10].

The Beam Energy Scan (BES) program at RHIC has been initiated to explore the QCD phase diagram and study the transport properties of nuclear matter at finite temperature ($T$) and baryonic chemical potential ($\mu_B$). At lower collision energy, e.g., $\sqrt{s_{NN}} = 7.7$ GeV, the baryon chemical potential can reach up to $\mu_B \sim 400$ MeV, which is significant compared to the temperature of the fireball. At such energies, strong gradients in the chemical potential of conserved charges are expected. Hence, the lower beam energy scan program at RHIC will be useful to explore the properties of net-charge diffusion in nuclear matter. However, it is important to mention that the role of baryon stopping and long range correlations need to be explored extensively before making any conclusion on diffusion coefficients.

The conservation laws limit the dissipation of the fluctuations after the hadronization has occurred. It is observed

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that, due to the diffusion of particles in rapidity space, these fluctuations may also get diluted in the expanding medium [10,11]. The hadronic diffusion from the time of hadronization $\tau_0$ to a freeze-out time $\tau_f$ can dissipate these fluctuations. It is argued that the reduction of the fluctuations in the QGP phase might be observed only if the fluctuations are measured over a large rapidity range [10]. The work also quantifies the reduction of fluctuations with the increase of accepted rapidity interval. The suppression of charge fluctuations observed in the experimental data is consistent with the diffusion estimates [12]. Earlier efforts were made to estimate the fluctuation strength using a transport model for all inclusive charged particles [13]. However, the contribution of different identified particles towards dilution of the measured fluctuation strength may be different.

One cannot measure the volume formed in heavy-ion collisions directly in the experiments. To avoid volume fluctuations, the ratio of positive (+) to negative (−) charged particles normalized by the total number of charged particles under consideration for a fixed centrality class of events is used to measure the fluctuation strength, usually known as $D$ measure [14]. This is defined as

$$D = \langle N_{\rm ch}\rangle\langle \delta R^2\rangle = \frac{4}{\langle N_{\rm ch}\rangle}\langle \delta N_+^2 + \delta N_-^2 - 2\delta N_+\delta N_-\rangle \approx \frac{4\langle \delta Q^2\rangle}{\langle N_{\rm ch}\rangle}, \quad (1)$$

where $R(=N_+/N_-)$ is the ratio of number of positive particles to the number of negative particles, $Q = N_+ - N_-$ is the difference between the number of positive and negative particles (net charge), and $\langle N_{\rm ch}\rangle = \langle N_+ + N_-\rangle$ is the average number of charged particles measured within the experimental acceptance. The $\langle \delta Q^2\rangle$ is the variance of the net charge $Q$, which is proportional to the net-charge fluctuation in the system. The value of $D$ is predicted to be approximately four times smaller in the QGP phase as compared to the hadron gas phase [14]. However, the $D$ measure has been found to be dependent on detection efficiency [4].

Another variable, $\nu_{(\pm,{\rm dyn})}$, is used to measure the fluctuation strength, which is robust and independent of detection efficiency. It is defined as

$$\nu_{(\pm,{\rm dyn})} = \frac{\langle N_+(N_+-1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_--1)\rangle}{\langle N_-\rangle^2} - 2\frac{\langle N_-N_+\rangle}{\langle N_-\rangle\langle N_+\rangle}. \quad (2)$$

The value of $\nu_{(\pm,{\rm dyn})}$ gives the measure of the relative correlation strength of ("++," "−−," and "+−") charged particle pairs. The relation between $D$ and $\nu_{(\pm,{\rm dyn})}$ is given as [14]

$$\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})} \approx D - 4. \quad (3)$$

It is found that global charge conservation has a finite effect on the fluctuation variable $\nu_{(\pm,{\rm dyn})}$ [15,16]. However, we have refrained from applying these corrections to our estimated values. One of the important aspects of this measured fluctuation strength is its survival probability. At high energy, i.e., in the limit $\langle N_+\rangle = \langle N_-\rangle$, the magnitude of $\nu_{(\pm,{\rm dyn})}$ is determined by the integral of the balance function in the acceptance of the measurement [15]. This integral depends on the relative width of the acceptance as well as the width of the balance function. The diffusion can further affect the value, but the magnitudes of $\nu_{(\pm,{\rm dyn})}$ are mainly determined by the $1/N_{\rm ch}$ effect and charge conservation. Thus it is suggested to measure the fluctuation strength over large rapidity space which allows us to see deeper back into the history of the collision [10].

In the present study, we have calculated the fluctuation strength of identified charged particles, mainly for net pion, net kaon, and net proton using the hadron resonance gas model (HRG), the heavy-ion jet interaction generator (HIJING) model, and the transport model ultrarelativistic quantum molecular dynamics (UrQMD), which will provide the reference for the behavior of fluctuations measured in the experiments.

The paper is organized as follows. In the following section, we discuss the HRG model used in this paper as well as the implementation of resonance decay. We also briefly discuss the HIJING and UrQMD models in the same section. In Sec. III, we discuss our estimated results on $\nu_{(\pm,{\rm dyn})}$ for identified particles at different $\Delta\eta$ and $\sqrt{s_{NN}}$. We finally summarize our findings in Sec. IV.

## II. ESTIMATION OF $\nu_{\rm dyn}$ IN DIFFERENT MODELS

In this section, we briefly describe the models used in the calculation of $\nu_{\rm dyn}$, which captures the strength of the correlations. These models are extensively used to explain the experimental data from heavy-ion collisions.

### A. Hadron resonance gas model

The partition function in the HRG model has all relevant degrees of freedom of the confined, strongly interacting matter and implicitly includes all the interactions that result in resonance formation [17,18]. In the ambit of the grand canonical ensemble, the logarithm of the partition function is given as

$$\ln Z_i(T,V,\mu_i) = \pm\frac{Vg_i}{(2\pi)^3}\int d^3p \ln\{1 \pm \exp[(\mu_i - E)/T]\}, \quad (4)$$

where $i$ is the particle number index, $V$ is the volume of the system, $g_i$ is the degeneracy factor for the $i$th particle, $\pm ve$ signs correspond to the baryon or meson, respectively. We have used the total chemical potential of individual particle $\mu_i$ in our calculations as given in Ref. [17]. Using the partition function, one can calculate various thermodynamical quantities of the system in heavy-ion collisions. The susceptibilities of different orders are related to the $\langle N_{\rm ch}\rangle$ and $\langle \delta Q^2\rangle$ representing mean and variance of individual particle, respectively. These quantities can be calculated by taking the first and second derivative of Eq. (4) with respect to $\mu$:

$$\langle N_{\rm ch}\rangle = \pm\frac{g_i}{2\pi^2}\int \frac{d^3p}{\{1 \pm \exp[(\mu_i - E)/T]\}}, \quad (5)$$

$$\langle \delta Q^2\rangle = -\frac{g_i}{2\pi^2}\int \frac{d^3p}{T}\frac{\pm\exp[(\mu_i - E)/T]}{\{1 \pm \exp[(\mu_i - E)/T]\}}. \quad (6)$$

Equations (5) and (6) are used to calculate $\nu_{\rm dyn}$ in HRG model.

Experimentally measured stable particles (pions, kaons, and protons along with their antiparticles) have contributions from the production of both primordial as well as from resonance decay. Further, neutral resonances introduce positive correlations between $N_+$ and $N_-$ and hence their decay daughters can affect the fluctuation of the final measured particles. The ensemble averaged stable particle yield will have contributions from both primordial production and the resonance decays [3,19],

$$\langle N_i\rangle = \langle N_i^*\rangle + \sum_R \langle N_R\rangle\langle n_i\rangle_R, \tag{7}$$

where $\langle N_i^*\rangle$ and $\langle N_R\rangle$ correspond to the average primordial yield of particle species $i$ and of the resonances $R$, respectively. The summation runs over all the resonances which decay to the final particle $i$ with $\langle n_i\rangle_R = \sum_r b_r^R n_{i,r}^R$ being the average number of particle type $i$ produced from the resonance $R$. Further, $b_r^R$ is the branching ratio of the $r$th decay channel of the resonance $R$ and $n_{i,r}^R$ is the number of particle $i$ produced in that decay branch. The generalized $n$th order susceptibility for stable particle $i$ can be written as [20]

$$\chi_i^{(n)} = \chi_i^{*(n)} + \sum_R \chi_R^{(n)}\langle n_i\rangle_R^n. \tag{8}$$

The first term in Eq. (8) corresponds to the contribution from primordial yield and the second term corresponds to the contribution from the fluctuation of primordial resonances and the average number of produced particle of type $i$, assuming the number of decay daughters is fixed.

### B. HIJING and UrQMD models

We have used HIJING (V.1.37) and UrQMD (V.1.30) to study the fluctuation variable $\nu_{\rm dyn}$. Both HIJING and UrQMD models are Monte Carlo event generators used for nucleon-nucleon and nucleus-nucleus collisions in high-energy physics simulations. These models provide a baseline to compare with the experimental data.

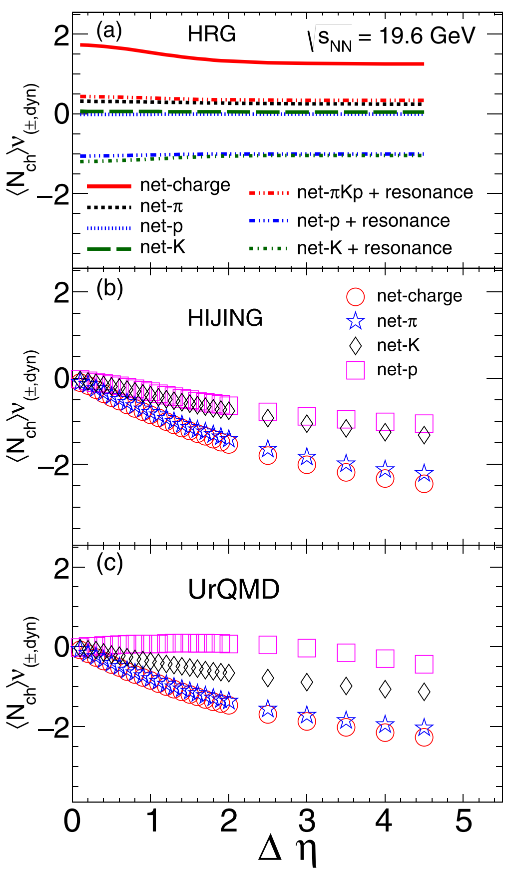


FIG. 1. Fluctuation parameter $\langle N_{\rm ch}\rangle\nu_{(\pm,{\rm dyn})}$ as a function of $\Delta\eta$ for net-charge, net-pion, net-kaon, and net-proton fluctuations for (0–5%) centrality in Au + Au collisions at $\sqrt{s_{NN}}$ = 19.6 GeV with HRG (upper panel), HIJING (middle panel), and UrQMD (lower panel) models. The $\langle N_{\rm ch}\rangle\nu_{(\pm,{\rm dyn})}$ from HRG model calculations for net-charge (solid line), net-$\pi$ and net-$p$ (dotted lines), net-$K$ (dashed line) without and with resonance (dashed dotted lines) decay. The statistical errors are within symbol size.

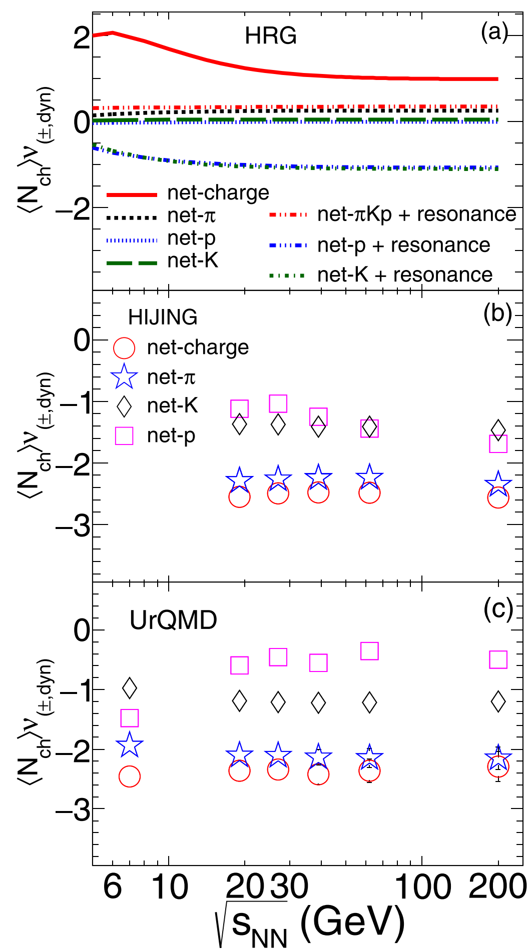


FIG. 2. Collision energy dependence of $\langle N_{\rm ch}\rangle\nu_{(\pm,{\rm dyn})}$ for net-charge, net-pion, net-kaon, and net-proton are calculated using HRG (upper panel), HIJING (middle panel), and UrQMD (lower panel) models for (0–5%) centrality in Au + Au collisions. The $\langle N_{\rm ch}\rangle\nu_{(\pm,{\rm dyn})}$ from HRG model calculations for net-charge (solid line), net-$\pi$ and net-$p$ (dotted lines), net-$K$ (dashed line) without and with resonance (dashed dotted lines) decay. The statistical errors are within symbol size.

The HIJING model is based on perturbative QCD (pQCD) considering that the multiple minijet partons produced in collisions are transformed into string fragments and later, fragments into hadrons. It uses the PYTHIA model to generate kinetic variables for each hard scattering and the JETSET model for jet fragmentation. In pQCD, the cross section for hard parton scattering is determined using the leading order to account for the higher-order corrections. The soft contributions are determined using the diquark-quark strings with gluon kinks induced by soft gluon radiation. The HIJING model considers the nucleus-nucleus collisions as a superposition of nucleon-nucleon collisions; it also takes into account other physics processes like multiple scattering, jet quenching, and nuclear shadowing to study the nuclear effects [21].

The UrQMD model considers the microscopic transport of quarks and diquarks with mesonic and baryonic degrees of freedom. The model preserves the conservation of baryon number, electric charge, and strangeness number. In this model, the space-time evolution of the fireball is studied in terms of excitation and fragmentation of color strings, and the formation and decay of hadronic resonances [16]. Interaction of the produced particles, which may influence the acceptance of certain windows, is included in the model. The formation of hadrons is explained by color string fragmentation, it also considers the resonance decays, multiple scattering between hadrons during the evolution including baryon stopping phenomena, which is one of the features of heavy-ion collisions especially at lower collision energies [22]. The UrQMD model has been applied successfully to study the thermalization [23], particle yields [24,25], leptonic and photonic probes [26], and event-by-event fluctuations [27–32].

It is noteworthy to mention that the measured values of fluctuation strength ($\nu_{\rm dyn}$) shall depend on the width of the acceptance, on the primordial mechanisms leading to $+ve$ and $-ve$ particle production, radial transport (flow), diffusion, etc. HIJING and UrQMD models do not account for such effects explicitly.

## III. RESULTS AND DISCUSSION

Due to the diffusion of charged particles in the hadronic phase, the measured fluctuation may get diluted during the evolution of the system and approaches the equilibrated values in the hadronic medium until their kinetic freeze-out. Hence, the experimental measurements of the magnitudes of fluctuation strength at a fixed $\Delta\eta$ and their dependence on $\Delta\eta$ enable us to explore various aspects of the time evolution of the hot medium and the hadronization mechanism. It is proposed to study the fluctuations of identified particle species in different rapidity intervals.

Figure 1 shows the estimated value of $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ for net charge, net pion, net kaon, and net proton as a function of $\Delta\eta$ interval with HRG, HIJING, and UrQMD models at $\sqrt{s_{NN}} = 19.6$ GeV. For the present study, we have used 0.2 million central (0–5%) Au + Au events at each energy in HIJING and UrQMD models. The particles having transverse momentum $0.2 \leqslant p_T$ (GeV/$c$) $\leqslant 5.0$ are considered for the present study. The lower $p_T$ selection threshold is motivated by the existence of the experimental measurements performed at RHIC. The $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values estimated from HRG (upper panel), HIJING (middle panel), and UrQMD (lower panel) models are shown as a function of $\Delta\eta$. The HRG calculations for net-charge, net-pion, net-kaon, and net-proton fluctuations are performed within the same kinematic acceptance as those used with HIJING and UrQMD models. Charged hadrons of masses up to 2.5 GeV as listed in the particle data book are considered in the HRG model. The HRG model calculations are performed for different cases by considering all the charged hadrons, individual identified stable particles ($\pi$, $K$, $p$), and contribution of resonance decays to the stable particles. The estimated values of $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ are found to be independent of $\Delta\eta$ in the case of the HRG model. However, there is a strong dependence of resonance decay effects observed for the identified particles. The calculation of $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ from the HRG model will provide a pure thermal baseline contribution as a function of $\Delta\eta$. In the case of

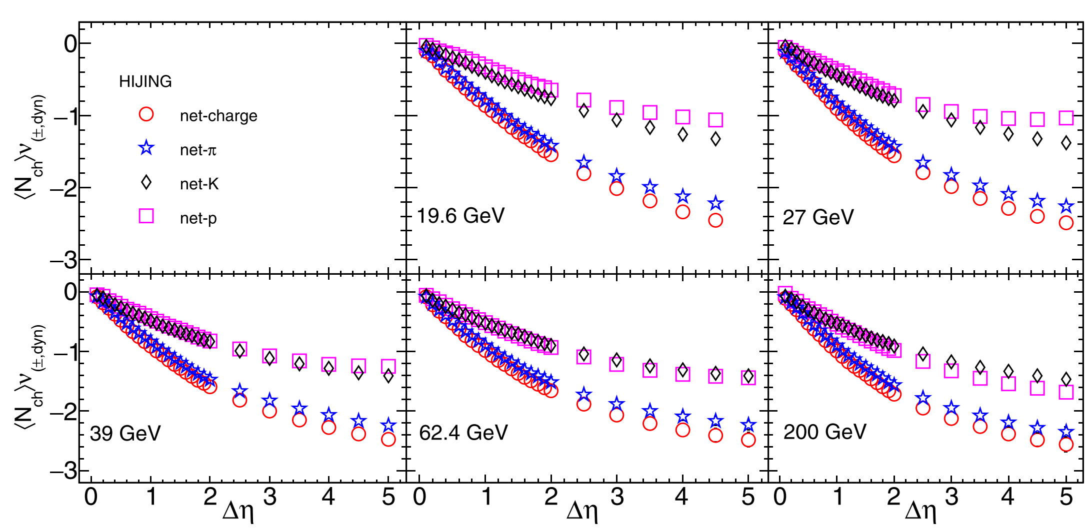


FIG. 3. The $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ for net-charge, net-pion, net-kaon, and net-proton as a function of $\Delta\eta$ window for (0–5%) centrality in Au + Au collisions at different $\sqrt{s_{NN}}$ in HIJING model. The statistical errors are within symbol size.

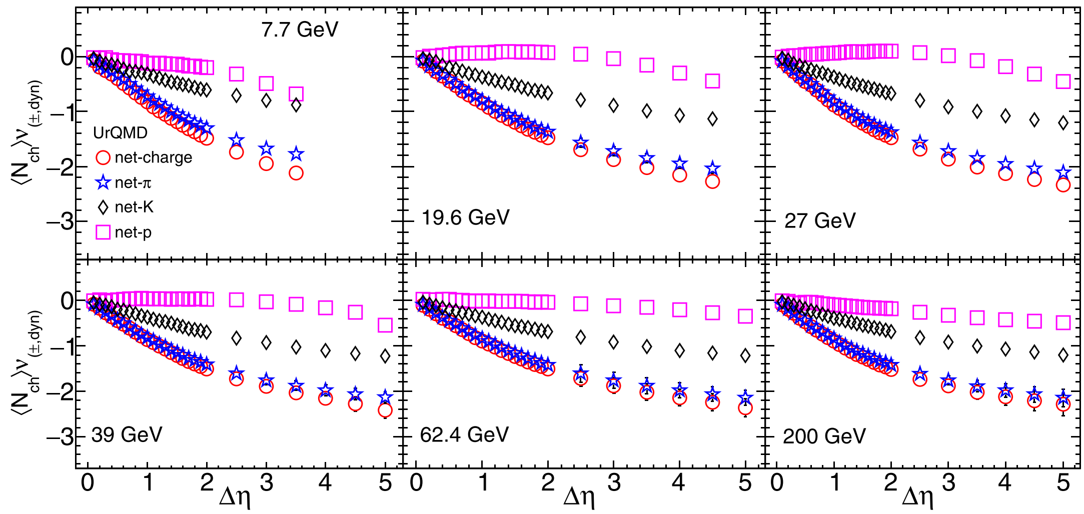


FIG. 4. The $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ for net-charge, net-pion, net-kaon, and net-proton as a function of $\Delta\eta$ window for (0–5%) centrality in Au + Au collisions at different $\sqrt{s_{NN}}$ in UrQMD model. The statistical errors are within symbol size.

HIJING and UrQMD models, there is a strong dependence of $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values on $\Delta\eta$ are observed for net charge as well as for identified particles. The higher $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ value at a lower $\Delta\eta$ interval suggests that the correlation is maximum for the smaller $\Delta\eta$ interval.

The curvature of $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ shows a decreasing slope up to higher $\Delta\eta$ intervals. This is in contrast to the observation made by the ALICE experiment at higher collision energy $\sqrt{s_{NN}} = 2.76$ TeV, which shows a flattening trend by extrapolating the fitted curve to higher $\Delta\eta$ range [9]. As can be seen, the $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values for net pion are closer to the results obtained for net-charge fluctuations. The net-charge fluctuation is dominated by the contribution from the pion fluctuation as the majority of the charged particles are pions. Similarly, the $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values for net kaon and net proton are closer to each other with a reduced slope as compared to net charge in the HIJING model. In the case of the UrQMD model, the slope of the $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values for net proton shows a flattening trend at a small $\Delta\eta$ and starts decreasing as a function of $\Delta\eta$ at a larger rapidity window.

Figure 2 shows the collision energy dependence of $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values for net charge and different identified net particles in most central Au + Au collisions using HRG (upper panel), HIJING (middle panel), and UrQMD (lower panel) models. The $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values for the net charge in the HRG model decrease with increasing collision energies. In the case of identified particles (net $\pi$, net $p$, and net $K$) and contributions of resonance decay to these stable particles, the $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values do not change as a function of $\sqrt{s_{NN}}$. The $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values for net charge, net pion, and net kaon are independent of $\sqrt{s_{NN}}$ in HIJING and UrQMD models. The $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values for the net-proton case show small energy dependence in both the models. There is a clear particle dependence of $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values for all collision energies in both the models.

Figures 3 and 4 show the $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ as a function of $\Delta\eta$ intervals for (0–5%) centrality in Au + Au collisions at different $\sqrt{s_{NN}}$ using HIJING and UrQMD models, respectively. The $\Delta\eta$ dependence of $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ for net proton is qualitatively different in both HIJING and UrQMD models, whereas net charge, net pion, and net kaon show similar behavior in both the models. In the case of the UrQMD model, the $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values are flattened at higher $\Delta\eta$ with increasing $\sqrt{s_{NN}}$. For all the $\sqrt{s_{NN}}$, it is observed that the $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values of net charge and net pion have larger suppression as compared to net proton and net kaon. The observed suppression of $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ for different particles may be due to the difference in the integral of the balance function of different identified particles [15].

## IV. SUMMARY

In summary, we have studied the fluctuations of net charge, net pion, net kaon, and net proton using the $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ observable within the ambit of HRG, HIJING, and UrQMD models at different collision energies. The $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values are estimated up to a higher $\Delta\eta$ window. A stronger dependence of the $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ value is observed for lower $\Delta\eta$ and the decreasing trend continues up to higher $\Delta\eta$ with the lower slope in both the models, except the net proton case in the UrQMD model. In the case of net proton in the UrQMD model, the curvature of $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values as a function of $\Delta\eta$ shows different behavior as observed in HIJING model. The $\langle N_{\rm ch}\rangle \nu_{(\pm,{\rm dyn})}$ values obtained from different model calculations are independent of collision energies but show particle species dependence. This study emphasizes the particle species dependence of fluctuation strength and provides a reference baseline for comparison with the experimental data.

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