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Energy dependence of event-by-event kaon fluctuation in Au + Au collisions at $\sqrt{s_{NN}} = 19.6-200$ GeV – a simulated study

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A detailed study of energy dependence of event-by-event pseudo-rapidity fluctuations of the produced kaons in Au + Au collisions at $\sqrt{s_{NN}} = 19.6-200$ GeV in terms of the Φ measure has been carried out in the framework of UrQMD model. The study of event-by-event kaon fluctuation in pseudo-rapidity space reveals energy dependence. It has been seen that as energy increases event-by-event fluctuation increases for both positive and negative kaons. Moreover, the positive kaons show larger event-by-event fluctuations than the negative kaons.

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1. Introduction. Relativistic heavy ion collisions [1] allow us to study the extended state of matter under extremes of density and temperature reachable otherwise in hot early universe. Lattice quantum chromodynamics (QCD) calculations indicate [2] that at zero net baryon density at a critical temperature of $\varepsilon_c \sim 1\,\mathrm{GeV/fm^3}$ a color deconfined and chirally restored Quark-Gluon Plasma (QGP) phase is formed [3]. These energy densities may be attained in relativistic heavy ion collision where a dense system of quarks and gluons is created. The system undergoes rapid collective expansion before the patrons hadronize and eventually decouple. The systematic study on correlation and fluctuations may provide direct information about the internal degrees of freedom of the QGP state and its evolution. Fluctuations in the multiplicities and momentum distributions of particles emitted in relativistic heavy-ion collisions have been widely considered as probes of thermalization and the multiparticle production [4–10]. The characteristic behavior of pion multiplicity fluctuations in the final state has been proposed as a tool for the measurement of the specific heat [11] and, specifically, for the detection of a critical point in the nuclear matter phase diagram [12, 13]. Although the hot and dense matter created in heavy-ion collisions is not directly observed at the critical point but rather at the point of kinetic freeze-out where the particles decouple from the system, certain features of the critical fluctuations were shown to survive [14].

When any system undergoes phase transition, there is an abrupt change in the specific heat whereas energy density remains a smooth function of temperature. However, large fluctuations in energy density are expected in both first order and second order phase transitions. In the context of locating the critical point of QGP phase transition, where the fluctuations are predicted to be large [12, 13], such study is interesting and challenging.

2. Event-by event fluctuations–current status. The heavy ion programmes using Relativistic Heavy ion Collider (RHIC) and more recently by Large Hadron Collider (LHC) have furnished an unprecedented amount and quality of information about the ultra-relativistic nucleus–nucleus collisions. The main motivation of these programmes is that they provide unique experimental access to the matter under conditions of extreme temperature and density resulting a huge amount of produced particles. This opens up an opportunity to study the particle fluctuations in event-by-event basis. Analysis of single event with large statistics can reveal very different physics than studying averages over a large statistical sample of events. Event-by-event analysis is potentially a powerful technique to study relativistic heavy-ion collisions, as the magnitude of fluctuations of various quantities around their mean values is controlled by the dynamics of the system. It has been predicted that critical density fluctuation in the vicinity of phase transition leads to the event-by-event fluctuation of different physical observables. Where the particle source is a hadrochemical composition, event-by-event study offers the possibility to detect the ef-

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fects of phase transition directly. NA49 collaboration presented [15] first data on event-by-event fluctuations in the average transverse momentum of charged particles produced in central Pb + Pb collision at 158 GeV per nucleon at the CERN SPS. They found that the observed variance of the event-by-event average transverse momentum is consistent with independent particle production modified by the known two-particle correlations due to quantum statistics and final state interactions and folded with the resolution of the NA49 apparatus. S. Bhattacharyya et al. [16] presented a detailed study of event-by-event pseudo-rapidity fluctuations of pions in high energy nucleus-nucleus interactions at (4.1–4.5) AGeV/c using nuclear emulsion track detector.

Belkacem et al. [17] investigated event-by-event fluctuations for ensembles with non-fixed multiplicity. In their analysis moments of event observable distributions, like total energy distribution, total transverse momentum distribution, etc., were shown to be related to the multi-body correlations present in the system. For classical systems these moments are reduced in the absence of any correlations to the moments of inclusive particle momentum distribution. As a consequence, a zero value for the Φ variable which measures the event-by-event fluctuations has been shown to indicate the vanishing of two-body correlations from one part, and of correlations between multiplicity and momentum distributions from the other part.

ATLAS Collaboration evaluated [18] the distributions of event-by-event harmonic flow coefficients v_n for $n = 2{-}4$ for Pb + Pb interactions at energy $\sqrt{s_{NN}} = 2.76$ TeV at LHC using the ATLAS detector. S.A. Voloshin et al. [19] have presented an event-by-event fluctuation analysis of particle production in heavy ion collisions. They compared different approaches to the evaluation of event-by-event dynamical fluctuations of mean transverse momentum; slope of transverse momentum spectrum and strength of anisotropic flow etc. They showed that fluctuation of different quantities can be related to each other.

3. Kaon production in nuclear collisions. Multiparticle production in high-energy nuclear collisions is still a mystery, as far as the understanding of the dynamics of the production of secondaries, especially of the soft varieties, is concerned. Of the various types of particles produced, mesons, especially the π-mesons, constitute, in practical terms, the near totality of the secondaries. Kaons are also important because of their strangeness content and because they are supposedly related with the physics of the QGP signatures [20]. Secondly, kaons are the lightest variety of the measurable strange particles. Lastly, kaon production is considered to have a bearing on the nuclear equation of state [21]. In fact, our interest to take up these problems was further arisen and intensified by a study of inclusive production of particles in nucleus-nucleus collisions by Kahana and Kahana [22].

Microscopic transport calculations indicate that the yield of kaons created in collisions between heavy nuclei at sub-threshold beam energies is sensitive to the compressibility of nuclear matter at high baryon densities [23, 24]. This sensitivity is due to the production mechanism of K^+ mesons. At sub-threshold beam energies, the production of kaons requires multiple nucleon-nucleon collisions or secondary collisions. These processes are expected to occur predominantly at high baryon densities, and the densities reached in the fireball depend on the nuclear equation-of-state [25]. K^+ mesons are well suited to probe the properties of the dense nuclear medium because of their long mean free path. The propagation of K^+ mesons in nuclear matter is characterized by the absence of absorption (as they contain an anti-strange quark) and hence kaons emerge as messengers from the dense phase of the collision. In contrast, the pions created in the high-density phase of the collision are likely to be reabsorbed and most of them will leave the reaction zone in the late phase [26, 27]. The influence of the medium on the K^+ yield is amplified by the steep excitation function of kaon production near threshold energies. Early transport calculations find that the K^+ yield from Au + Au collisions at sub-threshold energies will be enhanced by a factor of about two if a soft rather than a hard equation-of-state is assumed [23, 24].

The K^- and K^+ yields together provide a sensitive probe of the space-time evolution of heavy-ion reactions. Since K^-'s have a large annihilation cross section with neutrons, their yield is sensitive to the baryon density. The K^- and K^+ distributions may also hint at the degree of thermalization achieved, and their transverse mass spectra allow detailed study of rescattering and collective expansion effects. The pions are less sensitive to collective expansion because of their small mass. However, because they are the most numerous of the produced particles, they give information on the total entropy produced in the collision. Different studies of kaon production take into account the modification of the kaon properties in the dense nuclear medium [28, 29]. When assuming a repulsive K^+ N potential as proposed by various theoretical models (see [30] and references therein) the energy needed to create a K^+ meson in the nuclear medium is increased and hence the K^+ yield will be reduced. Therefore, the yield of K^+ mesons produced in heavy ion collisions is affected by both the nuclear compressibility and the in-medium kaon potential.

4. Goal of the present study and the method of analysis. We have discussed earlier that event-by-event pseudo-rapidity and transverse momentum fluctuations have been studied for the pions. No attempt has been made so far to study the event-by-event kaon fluctuations either in transverse momenta or in pseudo-rapidity space. In this paper we have presented a detailed analysis of event-by-event pseudo-rapidity fluctuations of the produced positive and negative kaons in Au + Au collisions at $\sqrt{s_{NN}} = 19.6$, 62.4, and 200 GeV in the framework of Ultra Relativistic Quantum Molecular Dynamics (UrQMD) model. The UrQMD model is a microscopic transport model which does not explicitly incorporate phase transition and critical point. The study with UrQMD may provide a baseline for the experimental results and deviation seen in the data from this model might be an indication of interesting physics outcome.

The event-by-event fluctuations of observables can be defined as a sum of particle kinematical variables, such as transverse momentum or rapidity, where the summation runs over all particles produced in a given event. It was shown that by studying the second moment of the distribution of the sum-variable in different classes of events, it may be possible to evaluate the degree of randomization or thermalization characteristic of high-energy nucleus–nucleus collisions. M. Gazdzicki and S. Mrowczynski [4] defined a measure of fluctuations, which vanishes in the case of independent particle emission from a single source.

Let us define a single particle variable such that $z \equiv x - \bar{x}$ with the overline denoting the average over a single particle inclusive distribution, which is carried out as

$$\bar{x} = \frac{1}{N_{\text{total}}} \sum_{k=1}^{N} \sum_{i=1}^{N_k} x_i, \tag{1}$$

where N_k is the particle multiplicity of the k^{th} event; N is the total number of events and N_{total} is the total number of particles produced in all the events. We define average multiplicity $\langle N_{\text{total}} \rangle$ as $\langle N_{\text{total}} \rangle = \frac{N_{\text{total}}}{N}$. Thus, in Eq. (1) we sum over events and over particles from every event. The variable Z_k, which is a multiparticle analog of z is defined as

$$Z_k = \sum_{i=1}^{N_k} (x_i - \bar{x}). \tag{2}$$

We define a quantity $\langle Z \rangle$ averaging over event so that

$$\langle Z \rangle = \frac{1}{N} \sum_{k=1}^{N} Z_k. \tag{3}$$

The quantity Φ, which measures the event-by-event fluctuations, can be defined in the following way

$$\Phi = \sqrt{\frac{\langle Z^2 \rangle}{\langle N_{\text{total}} \rangle}} - \sqrt{\overline{z^2}}, \tag{4}$$

where the $\langle Z^2 \rangle$ represents the event average of the concerned variables and the term $\sqrt{\overline{z^2}}$ is the square root value of the second moment of inclusive z distribution. In case of pseudo-rapidity, for every particle in a given event we can define $z = \eta_i - \bar{\eta}$. It has been pointed out that [4], when the particles are emitted independently, there exists no correlation among the particles and this leads to Φ values to vanish. Thus the non-zero values of Φ may be attributed to the measure of correlations among the produced particles. M. Gazdzicki and S. Mrowczynski [4] demonstrated that under specific choice of the Z-distribution, the second moment of the Z-distribution is sensitive to the correlation present between single sourced particle multiplicity and momenta, provided that nucleus-nucleus collision consists of independent particle sources.

5. Analysis and results. In this paper, we have simulated the Au + Au collisions at $\sqrt{s_{NN}} = 19.6$, 62.4 and 200 GeV using UrQMD model. It is a microscopic transport theory, based on the covariant propagation of all the hadrons on the classical trajectories in combination with stochastic binary scattering, color string formation and resonance decay. It represents a Monte-Carlo solution of a large set of coupled partial integro-differential equations for the time evolution of various phase space densities. The main ingredients of the model are the cross sections of binary reactions, the two-body potentials and decay widths of resonances. The UrQMD collision term contains 55 different baryon species (including nucleon, delta and hyperon resonances with masses up to 2.25 GeV/c^2) and 32 different meson species (including strange meson resonances), which are supplemented by their corresponding anti-particle and all isospin-projected states. The states can either be produced in string decays, s-channel collisions or resonance decays. This model can be used in the entire available range of energies from the Bevalac region to RHIC. For more details about this model, readers are requested to consult [31, 32]. In order to study the event-by-event kaon fluctuations in Au + Au collisions at $\sqrt{s_{NN}} = 19.6{-}200$ GeV, we have generated a large

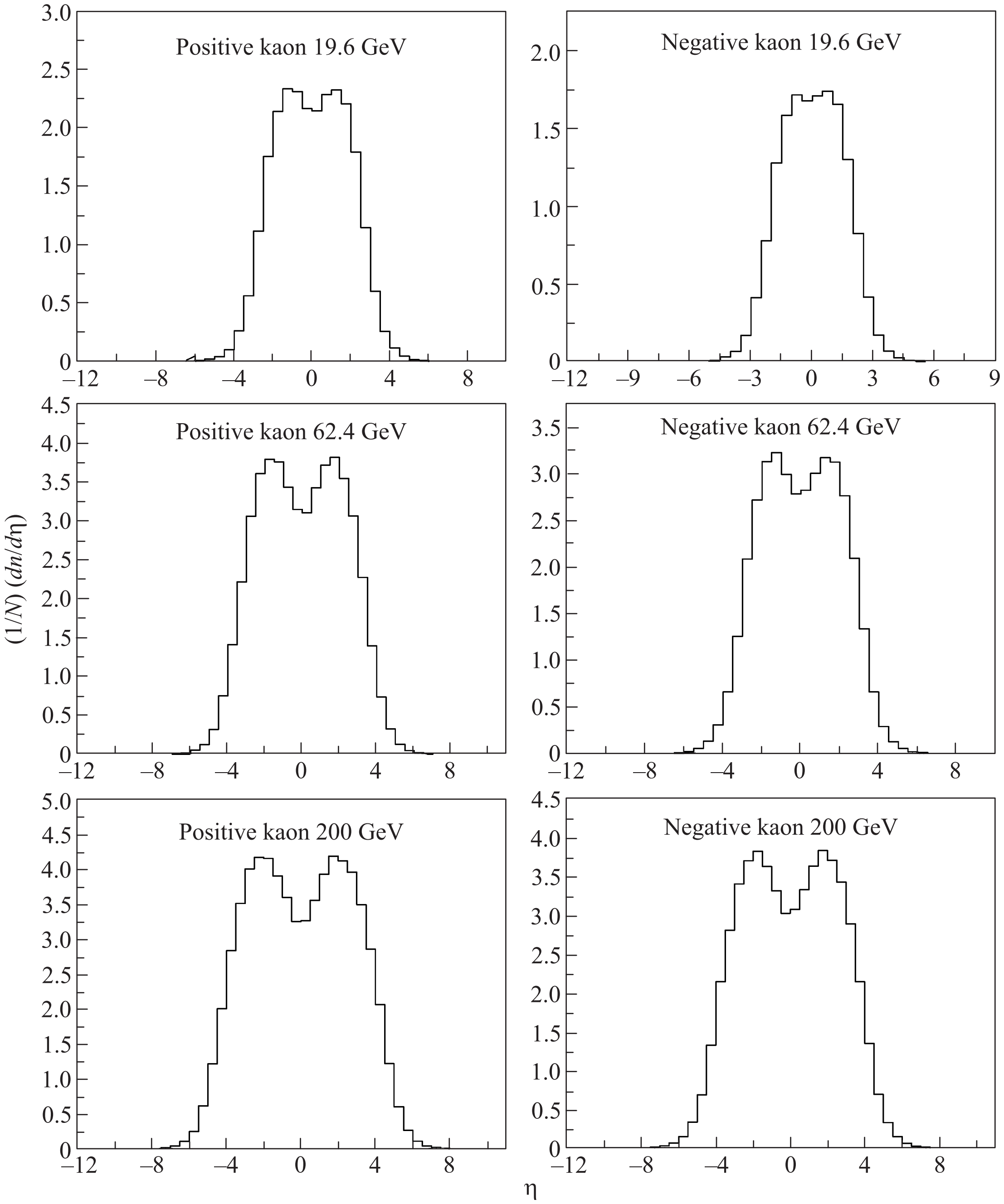

Fig. 1. Pseudo-rapidity distribution of positive and negative kaons in Au + Au collisions at $\sqrt{s_{NN}}$ = 19.6–200 GeV in the framework of UrQMD model

sample of events using the UrQMD model (UrQMD-3.3p1) in Au + Au collisions at $\sqrt{s_{NN}} = 19.6$, 62.4 and 200 GeV. The mass number and the charge of the target and projectile have been given as input along with the energy of collision. The maximum and the minimum values of the impact parameter were chosen as $b_{\max} = 10$ and $b_{\min} = 0$. In the input file one can control the time to propagate and the output time interval in fm/c. Both the time to propagate and the output time interval were set to 200 fm/c in the input file.

We have calculated the number of positive and negative kaons from the generated output of the UrQMD model. The average multiplicities of positive and negative kaons have been calculated and presented in Table 1. From the table it can be seen that average multiplicity of both positive and negative kaons increase

Table 1. The average multiplicities of positive and negative kaons in Au + Au collisions at $\sqrt{s_{NN}} = 19.6-200$ GeV

Interaction	Energy	Average multiplicity	
	$\sqrt{s_{NN}}$, GeV	Positive kaon	Negative kaon
Au + Au	19.6	25.70 ± .17	15.63 ± .19
	62.4	51.27 ± .28	38.81 ± .33
	200	72.49 ± .40	61.36 ± .41

with the increase of energy. Average multiplicities of positive kaons are higher than those of the negative kaons indicating that the total yield of positive kaons is higher. We have calculated the pseudo-rapidity values of the positive and negative kaons separately for each collision energy. As we are studying the event-by-event pseudo-rapidity fluctuations, the presentation of pseudo-rapidity distribution (averaged over events) of the kaons may be pertinent. The pseudo-rapidity distributions of the kaons have been presented in Fig. 1. From the pseudo-rapidity distribution it can easily be seen that there is a double-peak structure in the distribution. The existence of the double-peak structure in the pseudo-rapidity distribution becomes more pronounced as energy increases.

To analyze particle fluctuations in pseudo-rapidity space, the Φ values as defined in Eq. (4), have been calculated for the positive and negative kaons in Au + Au collisions at $\sqrt{s_{NN}} = 19.6$, 62.4, and 200 GeV. Calculated values of the variable, which signifies the event-by-event fluctuations, have been tabulated in Table 2. From Table 2 it may be seen that the Φ values,

Table 2. The Φ values of positive and negative kaons in Au + Au collisions at $\sqrt{s_{NN}} = 19.6-200$ GeV

Interaction	Energy	Φ values	
	$\sqrt{s_{NN}}$, GeV	Positive kaon	Negative kaon
Au + Au	19.6	.310 ± .003	.190 ± .003
	62.4	.330 ± .007	.230 ± .006
	200	.470 ± .014	.250 ± .012

which quantifies the event-by-event fluctuations, are greater than zero indicating the presence of correlation in kaon production in Au + Au collisions at $\sqrt{s_{NN}} = 19.6-200$ GeV. From Table 2 it is also seen that for both positive and negative kaons as energy increase event-by-event fluctuations increases. Moreover, it may be pointed out from Table 2 that for positive kaons event-by-event fluctuations are significantly higher than for negative kaons. Positive and negative kaon has the same mass. Yet at the same collision energy, the event-by-event fluctuation is higher for the positive kaon. The difference in the values of event-by-event fluctuation between the positive and negative kaon may be attributed to the different production mechanism of K^+ and K^-. The variation of event-by-event fluctuations with the energy of collisions has been presented in Fig. 2.

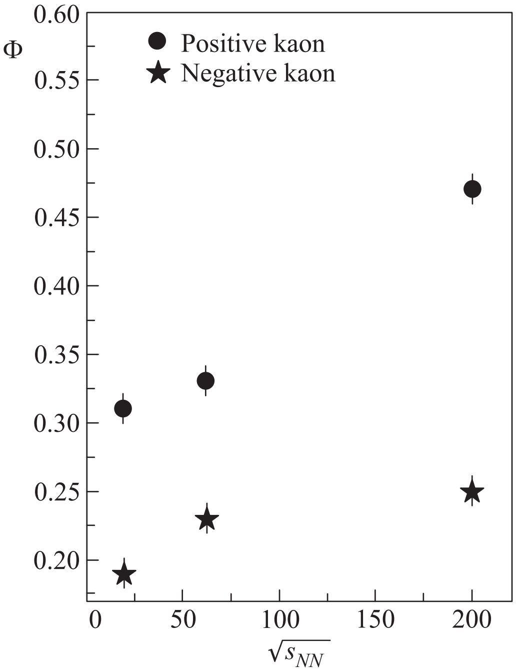

Fig. 2. The variation of the Φ values, the measure of event-by-event fluctuations with energy in case of Au + Au collisions at $\sqrt{s_{NN}} = 19.6-200$ GeV in the framework of UrQMD model

Fig. 2 also indicates that the event-by-event fluctuation increases with the collision energy more sharply for the positive kaons.

This is for the first time we have presented a simulated study of event-by-event kaon fluctuations in terms of measuring the Φ values. Results obtained from this analysis are modestly encouraging and may demand attention.

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