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Effects of elliptic flow and resonance decay process on the Kurtosis of net baryon distributions*

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Abstract: Kurtosis is regarded as a meaningful and promising observable in searching for the possible critical point predicted by QCD. In this paper, the effects of elliptic flow and resonance decay process on the Kurtosis have been studied with Monte Carlo event generators in Au + Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. The results show that the Kurtosis is not sensitive to elliptic flow and resonance decay process.

Key words: the critical point, the Kurtosis, elliptic flow, resonance decay process

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1 Introduction

In heavy-ion collision experiments, much attention has been drawn to mapping the QCD phase diagram. Searching for the critical point, which may occur at the end of the first-order phase transition, is one of the main driving forces to study the QCD medium [1–3]. In order to further characterize this transition, the NA49 collaboration has conducted analyses of the event-by-event fluctuations of various hadronic observables [4]. And we are looking forward to the forthcoming Relativistic Heavy Ion Collider (RHIC) with its Beam Energy Scan (BES) program for the critical point [5, 6].

Numerous probes based on fluctuations, which may imply the deconfinement phase transition, have been proposed. The baryon, charge and strangeness susceptibilities, which are a function of the temperature of the system, have large jumps at the critical temperature from lattice QCD calculations [7]. Also, these susceptibilities can be related to event-by-event moments of various observables in heavy-ion collisions [8]. Moreover, the fluctuations of event-by-event observable will diverge at the critical point [9]. Finding direct evidence of the divergence fluctuations is considered as one of the feasible methods to bracket the location of the critical point [6]. Theoretical calculations predict that $\xi \sim 2$–3 fm (ξ is correlation length) for heavy ion collisions [10]. However, it is extremely difficult to measure in experiments. Higher moments of the multiplicity distributions are sensitive to the correlation length. The fourth moment (Kurtosis) is expected to be proportional to the seventh power of the correlation length [3]. Therefore, the Kurtosis of multiplicity distributions would provide a more sensitive observable for the search for the critical point.

In the reference [11], it suggests that the acceptance, quark coalescence hadronization process and hadronic rescatterings do not affect the higher moments of net baryon distributions. However, it notes that other sources may make contributions to the Skewness and Kurtosis: remnants of initial fluctuations and flow. A quantitative study of these effects might be necessary to identify the critical point signal [3]. Moreover, it argues that the elliptic flow and resonance decay process may bring about uncertain-

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ties on the higher moments of net baryon distributions [12]. In this paper, with different Monte Carlo event generators, we study these effects on the Kurtosis in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}=200$ GeV.

2 Monte Carlo models

Monte Carlo event generators, AMPT, RQMD and UrQMD, have been used in this study. A Multi-Phase Transport (AMPT) model consists of four main parts: the initial conditions, partonic interactions, hadronization and hadronic rescatterings. The initial conditions, which include the spatial and momentum distributions of minijet partons and soft string excitations, are obtained from the Heavy Ion Jet Interaction Generator(HIJING) model [13]. Scatterings between partons are modeled by Zhang's Parton Cascade (ZPC) [14], which currently includes only two-body scatterings with cross sections obtained from the pQCD with screening masses. In the default AMPT model (abbr. "AMPT Default") [15], partons are recombined with their parent strings when they stop interacting and the resulting strings are converted to hadrons using the Lund string fragmentation model [16, 17]. In the AMPT model with string melting (abbr. "AMPT StringMelting") [18], the transition from the partonic matter to the hadronic matter is achieved by a simple coalescence model, which combines two quarks into mesons and three quarks into baryons [19]. The authors of AMPT model use a hadronic cascade, which is based on the A Relativistic Transport (ART) model [20], to describe the dynamics of the subsequent hadronic matter. In this paper, we will utilize the AMPT String Melting model instead.

Relativistic Quantum Molecular Dynamics (RQMD) [21] is a semiclassical microscopic model that combines classical propagation with stochastic interactions. Strings and resonances can be excited in elementary collisions. There, overlapping strings may fuse into color ropes. The fragmentation products from ropes, strings and resonances may then interact with each other and with the original nucleons. The nature of the active degrees of freedom in RQMD depends on the relevant length and time scales of the processes considered. A more detailed description of the model can be found in Ref. [21].

The Ultra Relativistic Quantum Molecular Dynamics (UrQMD) model [22] is also used in this paper. It is a microscopic many-body approach and can be applied to study hadron-hadron, hadron-nucleus and heavy ion reactions. This microscopic transport approach is based on the covariant propagation of color strings, constituent quarks and diquarks (as string ends) accompanied by meson and baryon degrees of freedom. It simulates multiple interactions of in-going and newly produced particles, the excitation and fragmentation of color strings and the formation and decay of hadronic resonances. In the input file, one can control unstable particles whether they decay after final time-step. More detailed descriptions can be found in Ref. [22].

3 Analysis, results and discussion

For a given moment of net baryon distributions, the fourth moment could be expressed in terms of the Kurtosis as given by

$$\mathrm{Kurtosis}=\frac{\langle(\delta N)^4\rangle}{\sigma^4}-3$$

where $\delta N=N-\langle N\rangle$, N is the net baryon number in each event. $\sigma=\sqrt{\langle(\delta N)^2\rangle}$ is the standard deviation. For a Gaussian distribution, the magnitudes of the Kurtosis are zero. The Kurtosis is a measurement of the peakedness. The positive value of the Kurtosis means that there is a peak at the center, whereas a negative value shows that this distribution is flatter than a Gaussian distribution in the center [23].

Theoretical calculations suggest that the proton number is a meaningful observable for the purpose of detecting the critical point in heavy ion experiments [24], and its fluctuations completely reflect the singularity of the baryon number susceptibility. Thus, only if the measurements from net baryon and net proton distributions are similar can we search for the critical point by measuring the fluctuation of various moments of net proton distributions. As suggested in the Ref. [11], the Kurtosis has little dependence on the chosen transverse momentum region and is not sensitive to the system evolution time. However, the complexity of the collision system imposes restrictions on our study. Some backgrounds may bring about uncertainties on the chosen observables. Therefore, to understand the characteristics of the fluctuations and correlations, some backgrounds such as elliptic flow, resonance decays and other sources of correlations not related to the critical point should be excluded [12]. As elliptic flow is sensitive to the interactions of constituents in the early stage of collisions. The stronger partonic interactions generate a larger magnitude of elliptic flow [25]. At the same time, the additional amount of elliptic flow could be generated by the late hadronic rescatterings. The flow-like correlations may have an influence on the measurement of the Kurtosis [12], therefore, it is important to study whether the Kurtosis is sensitive to the collective flow.

Based on the AMPT and RQMD models, we study the elliptic flow effect on the Kurtosis of net baryon distribution. Fig. 1 shows the comparison of v_2 as a function of transverse momentum in Au + Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV with rescatterings and without rescatterings. As discussed in Ref. [26], the Kurtosis can be scaled by $\langle N_{\rm part}\rangle$. If the Kurtosis deviates from this $\langle N_{\rm part}\rangle$ scaling curve and exhibits a non-monotonic behavior, it would indicate the new physics, which is related to the critical point.

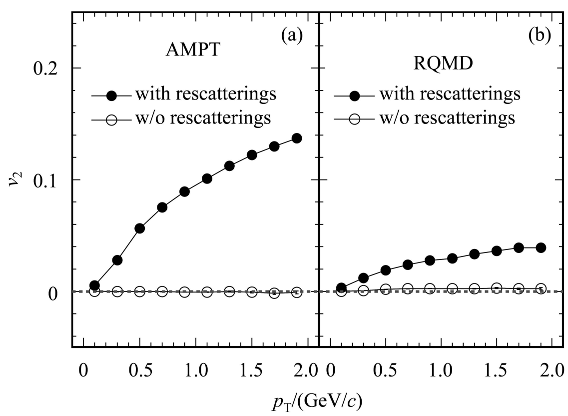

Fig. 1. A comparison of v_2 as a function of transverse momentum in Au + Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV with rescatterings and without rescatterings from (a) AMPT String Melting model and (b) RQMD model.

We measure the Kurtosis as a function of $\langle N_{\rm part}\rangle$ in two cases: 1) Monte Carlo events are generated by the model with default settings; 2) we turn off the rescatterings in the models, thus the elliptic flow is not built up in the whole collisions process. In the AMPT model, we set the partonic cross sections equal to 10 mb. As shown in Fig. 1(a), the significant elliptic flow can be observed in the final state. While in Fig. 1(b), as it only includes the hadronic rescatterings in the RQMD model, the signal of elliptic flow is much smaller than that in the AMPT model. After turning off the rescatterings, the elliptic flow is equal to 0. Thus, we can study the elliptic flow effect on the Kurtosis measurements.

As shown in Fig. 2, this describes the comparison of the Kurtosis as a function of centrality in Au + Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV with flow and without flow in the AMPT and RQMD models. In Fig. 2(a), comparing the results of the Kurtosis of net baryon distributions from these two cases, it shows that the magnitudes of the Kurtosis with flow and without flow are consistent with each other in the AMPT model. In the central collisions, the value of the Kurtosis approaches zero, which means that these distributions are more similar to Gaussian distribution. At the same time, from peripheral to central collision, the decreasing trends of the Kurtosis are similar in these two cases. This indicates that the Kurtosis of net baryon distribution is not sensitive to the elliptic flow within the AMPT model. The flow background has no influence on the Kurtosis. In Fig. 2(b), we compare the results with flow and without flow in the RQMD model. This shows that the magnitudes of the Kurtosis from these two cases accord with each other as well. In addition, the trends of fluctuations of net baryon are similar to those in the AMPT model.

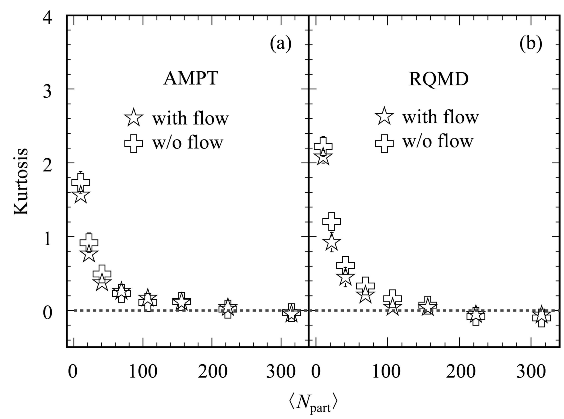

Fig. 2. A comparison of the Kurtosis as a function of the number of participants($\langle N_{\rm part}\rangle$) in Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV with flow and without flow from (a) the AMPT String Melting model and (b) the RQMD model.

Resonance decay has a probabilistic character. This itself causes the particle number fluctuations in the final state [27]. The final state multiplicity fluctuations may be enlarged due to the existence of resonances decaying into at least two hadrons [28]. In the Ref. [11], it suggests that the resonance decay process does not affect the Kurtosis within the AMPT StringbMelting model. However, we argue whether the effect of the resonance decay process on the Kurtosis would have model dependence, in particular to the RQMD and UrQMD models. The difference between the RQMD and UrQMD models is that the latter includes more high mass resonance states and more string excitation and fragmentation. A large fraction of the final state particles comes from the decays of various hadron resonances in these two models. Therefore, we study the resonance decay process, which may have some influence on the observable in the RQMD and UrQMD models. Fig. 3 shows a comparison of the Kurtosis as a function of centrality in Au+Au collisions at $\sqrt{s_{\rm NN}}=200$ GeV with decay and without decay from the RQMD and UrQMD models. By utilizing these two models, we measure the Kurtosis as a function of centrality, which belongs to two cases: 1) Monte Carlo events are generated by the model with default settings; and 2) we keep unstable particles not to decay at the end of the collisions, thus we measure more resonances.

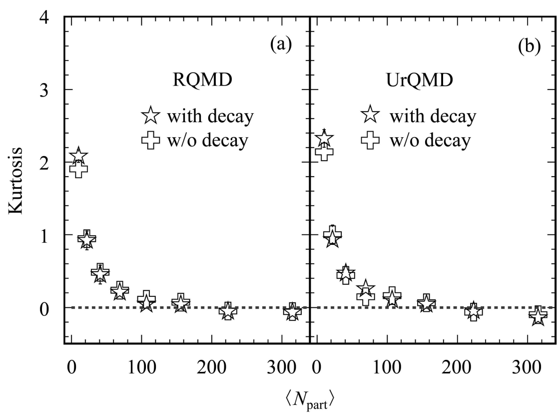

Fig. 3. A comparison of the Kurtosis as a function of the number of participants($\langle N_{\rm part}\rangle$) in Au + Au collisions at $\sqrt{s_{\rm NN}}=200$ GeV with decay and without decay from (a) the RQMD model and (b) the UrQMD model.

Comparing the results with decay and without decay, we find that the magnitudes of the Kurtosis are in agreement with each other in these two models. It seems that the resonance decay process doesn't affect the Kurtosis either. Moreover, the values of the Kurtosis nearly keep the same trends within the RQMD and UrQMD models.

4 Summary and outlook

In this paper, by utilizing the AMPT, RQMD and UrQMD models, we study the effects of backgrounds from the elliptic flow and resonance decay process, which may have influence on the Kurtosis. Comparing the results with flow and without flow, it shows that the values of the Kurtosis are consistent with each other. In addition, the results with decay and without decay are almost in agreement with each other. This indicates that the Kurtosis of net baryon distributions is not sensitive to the elliptic flow and resonance decay process. Together with the study done in Ref. [11], we argue that the Kurtosis should be a good observable in searching for the possible critical point predicted by QCD. Any non-monotonic behaviors of the Kurtosis as a function of beam energy or centrality will demonstrate the existence of the critical point [26]. One may consider the Monte Carlo model results on the Kurtosis of net baryon distributions as a baseline prediction for the currently ongoing low energy heavy ion runs at RHIC.

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