Anisotropy fluctuation and correlation in central α -clustered $^{12}\text{C} + ^{197}\text{Au}$ collisions

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In the framework of a multiphase transport model, fluctuation and correlation of the azimuthal anisotropies in $^{12}\text{C} + ^{197}\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV are explored. Properties of the initial eccentricity and final harmonic flow fluctuation resulted from $^{12}\text{C} + ^{197}\text{Au}$ collisions with Woods-Saxon configuration and triangular α -clustering configurations of ^{12}C are investigated via scaled variance, skewness, and kurtosis. Comparisons are made between results from α -clustered configurations and Woods-Saxon configuration. The triangular flow fluctuation is found to have particular sensitivity in distinguishing triangular α -clustering structure of ^{12}C . Furthermore, correlations between initial eccentricities and final flow harmonics are studied with strong multiplicity dependence observed for the correlation functions.

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I. INTRODUCTION

Anisotropic flow as a typical collective behavior of particles emitted was proved to be a good observable to study the equation of state of the hot and dense matter created in the early stage of ultrarelativistic heavy-ion collisions [1–7]. The flow harmonics defined as v_n ($n = 2, 3, \dots$) which are the Fourier expansion coefficients of the azimuthal anisotropy of the final-state particles are suggested to be sensitive to not only the early partonic dynamics but also the transportation properties of the source evolution [8–10]. Theoretically, the hydrodynamic model and the multiphase transport model have been widely used to make predictions and were successful in giving comparable descriptions on experimental measurements [11–17].

The essential role of the initial collision geometry was realized when looking into the flow harmonics of different collision systems scaled by initial eccentricities [18,19]. Important information about the fluctuating initial conditions is believed to be transferred to the final flow anisotropy during source expansion. In the past two decades, significant efforts have been made on the studies of initial geometry fluctuation effect on the final flow observables [20–28]. In addition, experimental measurements of the event-by-event anisotropic flow fluctuation suggest the close correlation between flow fluctuation and the fluctuations of the initial

geometry [29–32]. It was realized that the flow fluctuation on the event-by-event basis provides good access to the initial eccentricity fluctuation, elucidating both source evolution and initial fluctuation properties [33–35].

The nuclear cluster is one of the essential features of a nuclear system. Systematic studies on the α cluster in light nuclei have been performed for more than 40 years [36–44]. Recent studies suggest that the intrinsic structure of light nuclei can be captured by the “snapshots” made in relativistic nuclear collisions by colliding light nucleus on the heavy nuclei target [45]. As the final-state anisotropy inherits geometric information from the initial state, it was proposed that the nuclear clustering configurations can be explored by harmonic flow in the final stage of the nuclear collisions. Extensive theoretical studies have been performed on harmonic flow as a probe for the α -clustering structure of light nuclei in nuclear collisions involving ^{12}C or ^{16}O as the projectile and it is found that the intrinsic nuclear structure, predetermined by the arrangement of the α clusters, leads to quantitative difference of the flow measurements [46–50]. In addition, flow fluctuation characterized by the ratio of the cumulant flow is also proposed to be an approach for investigating clustering in light nuclei [51,52]. Studying the effects of initial α clustering on flow fluctuation offers valuable information about the sensitivity of experimental measurement of flow fluctuation in probing the signatures of α -clustering configurations in light nuclei.

In this paper, we present systematic simulation study of the fluctuation and correlation properties of initial eccentricity and final flow harmonics for $^{12}\text{C} + ^{197}\text{Au}$ collision at 200 GeV with a multiphase transport model. Influence of α clustering on flow fluctuation and initial-final anisotropy correlation is investigated in particular. This paper is organized as follows: In Sec. II, model and research methods are described. In Sec. III, results and discussion are presented. In Sec. IV, a brief summary is given.

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II. MODEL AND METHOD

A multiphase transport model (AMPT) is employed for studying $^{12}\text{C} + ^{197}\text{Au}$ collisions. The model consists of four main components: the initial condition, partonic interactions, hadronization, and hadronic interactions [53,54]. Starting from Monte Carlo Glauber initial conditions, phase space distributions of minijet partons and soft string excitations are generated from the Heavy Ion Jet Interaction Generator (HIJING) model [55]. In the string melting scenario, both excited strings and minijet partons are decomposed into partons followed by elastic partonic scatterings. Scatterings among partons are treated according to a parton cascade model—Zhang’s parton cascade (ZPC) model which includes parton-parton elastic scattering with cross sections obtained from the theoretical calculations [56]. After partons stop interacting with each other, a simple quark coalescence model is used to combine partons into hadrons. Partonic matter is then turned into hadronic matter and the subsequent hadronic interactions are simulated using a relativistic transport model (ART) including both elastic and inelastic scattering descriptions for baryon-baryon, baryon-meson, and meson-meson interactions [57]. With properly choosing partonic scattering cross section, the AMPT model was successful in describing many experimental observations in heavy-ion collisions at RHIC and LHC energies [58–61].

Simulation events are generated for $^{12}\text{C} + ^{197}\text{Au}$ collisions at center-of-mass energy of 200 GeV. By default, the initial nucleon distribution in ^{12}C and ^{197}Au are initialized event-by-event according to Woods-Saxon distribution from the HIJING model. For studying the α -clustering effect, ^{12}C is configured with three α clusters in triangular structure based on the information given by an extended quantum molecular dynamics model (EQMD) [62]. The distribution of the radial centers of the α clusters are assumed to be Gaussian and initialized according to $e^{-0.5(\frac{r_c(\alpha)}{\sigma_{r_c(\alpha)}})^2}$, where $r_c(\alpha)$ is the averaged radial center coordinate of an α cluster and $\sigma_{r_c(\alpha)}$ is the width of the distribution. Nucleons inside each α cluster are initialized according to Woods-Saxon distribution. In our simulation study, the parameters for configuring the ^{12}C are taken from the EQMD calculation with $r_c(\alpha) = 1.8$ fm and $\sigma_{r_c(\alpha)} = 0.1$ fm for the triangular α -clustering configuration. Details about the methodology applied for the initialization of the collision system can be found in Refs. [39,40]. Figure 1 shows the comparison of the normalized nucleon radial density distributions initialized with Woods-Saxon and triangular α -clustering configurations of ^{12}C in this study. One can find that though the root mean square radius of the two configurations are comparable, the difference in the shape of the density distribution can be clearly seen.

III. RESULTS AND DISCUSSION

A. Eccentricity fluctuation in $^{12}\text{C} + ^{197}\text{Au}$ collisions

For nuclear-nuclear collision, the initial geometric anisotropy of the collision zone in the transverse plane (perpendicular to the beam direction) can be characterized with eccentricity. It was argued that the magnitude and trend of the eccentricity and its fluctuation imply specifically

FIG. 1. Nucleon radial density distributions of ^{12}C for the Woods-Saxon (W-S) and Triangle α -clustering configurations. Results are normalized to the number of nucleons of ^{12}C .

testable predictions for final stage harmonic flow [21,63,64]. Definition of the eccentricity for the n th-order harmonic in the coordinate space of the participant nucleons or partons for a single collision event is in the form,

$$\varepsilon_n\{P\} = \frac{\sqrt{\langle r^n \cos(n\varphi) \rangle^2 + \langle r^n \sin(n\varphi) \rangle^2}}{\langle r^n \rangle}, \quad (1)$$

where r and φ are position and azimuthal angles of each nucleon or parton in the transverse plane. $\varepsilon_n\{P\}$ characterizes the eccentricity through the distribution of participant nucleons or partons which naturally contains event-by-event fluctuation. $\varepsilon_n\{P\}$ defined in this way is usually named as a “participant eccentricity.”

Initial eccentricity can also be quantified by cumulants of $\varepsilon_n\{P\}$ following the same way as in Ref. [65]. The definitions in terms of two-particle and four-particle cumulant moments of the eccentricities are in the form,

$$\begin{aligned} \varepsilon_n\{2\} &= \sqrt{\langle \varepsilon_n^2\{P\} \rangle}, \\ \varepsilon_n\{4\} &= (2\langle \varepsilon_n^2\{P\} \rangle^2 - \langle \varepsilon_n^4\{P\} \rangle)^{1/4}. \end{aligned} \quad (2)$$

In central nuclear collision involving clustered light nuclei colliding on a heavy-ion target, the profile of the initial collision zone inherits intrinsic geometry of the nucleon distribution of the light nuclei. The clustering configuration of nuclei is expected to be reflected by the eccentricity coefficients. In Fig. 2, simulation results of ε_n are shown up to fourth order of the harmonic as a function of N_{track} for central $^{12}\text{C} + ^{197}\text{Au}$ collisions with different α -clustering configurations of ^{12}C . N_{track} is defined to be the number of charged particles within the rapidity window $-1.0 < y < 1.0$ and transverse momentum window $0.2 < p_T < 6.0$ GeV/c in the collision event. ε_n results from two- and four-particle cumulant definitions by Eq. (2) are compared with participant definition by Eq. (1). It is found $\varepsilon_n\{P\}$ ($n=2,3,4$) for all the configurations are quantitatively between $\varepsilon_n\{2\}$ and $\varepsilon_n\{4\}$ over the whole N_{track} range. Nonmonotonous dependence on N_{track} can be seen for ε_n resulted from the triangle and unclustered Woods-Saxon (W-S) configurations. In comparison, triangle and W-S configurations exhibit a clear decreasing trend for $N_{\text{track}} < 100$. ε_3 and ε_4 are similar in trend as a function

FIG. 2. Initial eccentricity ε_n ($n=2,3,4$) as a function of N_{track} for $^{12}\text{C} + ^{197}\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV in the AMPT model. Results from the triangle α -clustering configuration are compared with the Woods-Saxon (W-S) configuration without α clusterization.

of N_{track} but show different magnitude orderings for different α -clustered cases.

Event-by-event fluctuation of the eccentricity is studied by first looking into the scaled standard deviations (scaled variance) of eccentricity distribution defined as

$$R_{\varepsilon_n} = \sigma_{\varepsilon_n} / \langle \varepsilon_n \rangle = \sqrt{\frac{\langle \varepsilon_n^2 \rangle - \langle \varepsilon_n \rangle^2}{\langle \varepsilon_n \rangle^2}}, \quad (3)$$

where σ_{ε_n} is the variance which quantifies the absolute fluctuation. The brackets denote event averaging. Figure 3 comparatively shows the scaled standard deviation of eccentricity fluctuation R_{ε_n} ($n=2,3,4$) for W-S and α -clustering configurations of ^{12}C . In comparison, R_{ε_2} and R_{ε_4} show a similar decreasing trend as a function of N_{track} . This is consistent with the expectation that quadrangularity ε_4 is strongly correlated with ellipticity ε_2 and their fluctuations should behave similarly [66]. It is interesting to see the difference between W-S and triangle configurations that R_{ε_3} shows different ordering compared with R_{ε_2} and R_{ε_4} . It could be understood in view of the geometrical origin that the triangular structure from the intrinsic geometric bias contributes more to the ellipticity or quadrangularity fluctuation but less triangularity fluctuation. It is also found that for both ε_n and R_{ε_n} the discrepancy between different configurations tend to converge when approaching low N_{track} and diverge at higher N_{track} .

In addition to the standard deviation, skewness and kurtosis which characterize the non-Gaussian fluctuation

properties have been used to study flow fluctuation and explain possible contributions to the splitting of higher-order flow cumulants [67,68]. The standardized skewness and kurtosis of ε fluctuations are defined as

$$S_{\varepsilon_n} = \frac{\langle (\varepsilon_n - \langle \varepsilon_n \rangle)^3 \rangle}{\langle (\varepsilon_n - \langle \varepsilon_n \rangle)^2 \rangle^{3/2}}, \quad (4)$$

$$K_{\varepsilon_n} = \frac{\langle (\varepsilon_n - \langle \varepsilon_n \rangle)^4 \rangle}{\langle (\varepsilon_n - \langle \varepsilon_n \rangle)^2 \rangle^2} - 3,$$

where angular brackets denote an average over events. Both skewness and kurtosis vanish if the distribution is Gaussian.

In addition to the scaled variance, we further studied skewness and kurtosis of the eccentricity fluctuation. Figure 4 displays skewness and kurtosis of ε_n for W-S and triangle α -clustering configurations of ^{12}C . The skewness of eccentricity fluctuation S_{ε_n} defined by Eq. (4) takes a similar trend as R_{ε_n} for a different order of harmonics. In comparison, $S_{\varepsilon_{2,4}}$ and $K_{\varepsilon_{2,4}}$ for triangle and W-S configurations show tiny multiplicity dependence. In addition, a significant difference in both magnitude and trend can be seen for S_{ε_3} and K_{ε_3} as a function of N_{track} in the cases of different initial configurations. The pronounced dependencies of N_{track} of skewness and kurtosis of ε_2 and ε_3 fluctuations imply possible approaches for studying α clusterization of the collision system by looking into the high-order fluctuation properties.

FIG. 3. Eccentricity fluctuation R_{ε_n} as a function of N_{track} for $^{12}\text{C} + ^{197}\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV in the AMPT model. Results from the triangle clustering configuration are compared with the Woods-Saxon (W-S) configuration without α clusterization. (a)–(c) Scaled standard deviations R_{ε_n} for a different order of harmonics.

FIG. 4. The AMPT results on skewness and kurtosis of ε_n ($n = 2, 3, 4$) fluctuation for $^{12}\text{C} + ^{197}\text{Au}$ collisions at 200 GeV with α clustering and W-S configurations of ^{12}C , as a function of N_{track} . (Upper panels) Skewness of ε_n fluctuation. (Lower panels) Kurtosis of ε_n fluctuation.

B. Flow fluctuation in $^{12}\text{C} + ^{197}\text{Au}$ collisions

It is predicted that the azimuthal anisotropy characterized by anisotropic flow coefficients v_n ($n = 2, 3, \dots$) of final-state particle distribution is correlated in magnitude and phase with initial eccentricity. Considering the event-by-event fluctuation, calculation of v_n can be referred to the participant plane angle [20] defined with the coordinate information of initial participant partons,

$$\psi_n\{PP\} = \frac{1}{n} \left[\arctan \frac{\langle r^2 \sin(n\phi_{PP}) \rangle}{\langle r^2 \cos(n\phi_{PP}) \rangle} + \pi \right], \quad (5)$$

where n denotes the n th-order participant plane, r and ϕ_{PP} are the position and azimuthal angle of each parton in the AMPT initial stage, and the bracket denotes the density weighted average. Flow coefficients v_n calculated with respect to the participant plane ψ_n are defined as

$$v_n\{PP\} = \langle \cos[n(\phi - \psi_n\{PP\})] \rangle, \quad (6)$$

where ϕ is the azimuthal angle of final-state charged hadrons in the momentum space, and the average $\langle \dots \rangle$ denotes event average. Similar to the definition of the eccentricity, this method for calculation of v_n is referred to as participant plane v_n which was widely used for flow calculations in different models.

FIG. 5. The AMPT results on elliptic and triangular flow fluctuation as a function of N_{track} for W-S and triangle α -clustering configurations of ^{12}C in $^{12}\text{C} + ^{197}\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Results are shown from both the event plane method and the participant plane method. (Left panel) v_2 fluctuation; (right panel) v_3 fluctuation.

FIG. 6. Ratio of the relative flow fluctuation R_{v_3}/R_{v_2} as a function of N_{track} for $^{12}\text{C} + ^{197}\text{Au}$ collisions with α -clustered ^{12}C in different structures. Flow fluctuations are calculated based on the event-plane method.

One can also characterize the different orders of azimuthal anisotropies with the event plane (EP) method [2,69]. Unlike the participant plane which is not accessible experimentally, the event plane can be reconstructed using final-state charged particles. Definition of the n th-order event plane angle is in the form,

$$\psi_n\{\text{EP}\} = \frac{1}{n} \arctan \frac{\langle \omega \sin(n\phi) \rangle}{\langle \omega \cos(n\phi) \rangle}, \quad (7)$$

where ϕ and ω are the azimuthal angle and weight for the final particle, respectively. Flow coefficients v_n with respect to the n th-order event plane $\psi_n\{\text{EP}\}$ is defined as

$$v_n\{\text{EP}\} = \frac{\langle \cos(n[\phi - \psi_n\{\text{EP}\}]) \rangle}{\text{Res}\{\psi_n\{\text{EP}\}\}}, \quad (8)$$

where $\text{Res}\{\psi_n\{\text{EP}\}\}$ is the resolution of the event plane angle and the brackets indicate the average over particles.

Ideal hydrodynamics predicts linear response to the initial eccentricities of the final flow harmonics [66]. Approximate proportionality of the flow coefficients v_n to the eccentricities ε_n is suggested to hold for $n=2$ and 3, $v_n = \kappa \varepsilon_n$ ($n=2,3$), where κ is the linear response coefficient. Assuming linear flow response, flow fluctuation quantified with scaled standard deviation should be approximately equal to the eccentricity fluctuation quantified in the same way,

$$\frac{\sigma_{v_n}}{\langle v_n \rangle} \approx \frac{\sigma_{\varepsilon_n}}{\langle \varepsilon_n \rangle}. \quad (9)$$

This relation can be applied only on the premise that the initial-final correlation is dominated by linear response. Though fluctuations of v_n mainly stem from the fluctuations of ε_n , during the source evolution, nonlinear responses may play an important role in the development of final flow fluctuation with the presence of nonzero higher order effects [70–74]. Nevertheless, we can still examine the flow fluctuation to see how sensitive it is in distinguishing initial nuclear clustering structure.

FIG. 7. Skewness and kurtosis of v_2 and v_3 fluctuations as a function of N_{track} for α -clustered $^{12}\text{C} + ^{197}\text{Au}$ collisions at 200 GeV. Comparisons are made between results from the event plane method and the participant plane method. (Upper panels) Skewness of v_2 and v_3 fluctuations. (Lower panels) Kurtosis of v_2 and v_3 fluctuations.

FIG. 8. 2D plots illustrating the event-by-event correlation of v_n and ε_n for $^{12}\text{C} + ^{197}\text{Au}$ collisions with W-S and triangle α -clustering configuration of ^{12}C . The values of the correlation coefficients $C_{v,\varepsilon}$ are shown in the plots. (Upper panels) v_2 vs ε_2 for $80 < N_{\text{track}} < 100$. (Lower panels) v_3 vs ε_3 for $80 < N_{\text{track}} < 100$. Red and blue data points present the ε_n -bin averaged profile.

Defined in the same way as Eq. (3), Fig. 5 shows the simulation results of the scaled variance of the elliptic and triangular flow fluctuation of the charged hadrons at midrapidity ($-1.0 < y < 1.0$) for $^{12}\text{C} + ^{197}\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Comparisons are made between the α -clustered case and the Woods-Saxon case where the nucleons are distributed without clusterization. $R_{v_n}\{\text{EP}\}$ which quantifies $v_n\{\text{EP}\}$ fluctuation are shown in addition to $v_n\{\text{PP}\}$ fluctuation $R_{v_n}\{\text{PP}\}$ based on the participant plane method. $R_{v_n}\{\text{EP}\}$ ($n=2,3$) show similar behavior as $R_{v_n}\{\text{PP}\}$ but comparably much higher for low-multiplicity collisions owing to the smearing effect brought by the source evolution.

It is found that the scaled variances of both v_2 and v_3 present a monotonous decreasing trend at low N_{track} ($N_{\text{track}} < 100$) and change slowly towards higher N_{track} . R_{v_2} is insensitive for distinguishing triangle and W-S configurations as they are close in magnitude. A magnitude ordering can be seen for R_{v_3} resulted from W-S and clustering configurations. It is observed that R_{v_3} for triangle configuration is lower than W-S configuration similar to the behavior of $R\varepsilon_3$ which is consistent with the picture of the flow response.

Experimentally, one could take $R_{v_n}\{\text{EP}\}$ as a probe of α -clustering structure in ^{12}C . Similar to probing nuclear clustering structure with the ratio of flow harmonics, by choosing an isobar nucleus close to ^{12}C with nonexotic structure

colliding against ^{197}Au as a reference, quantitative difference of $R_{v_n}\{\text{EP}\}$ between the α -clustering collision system and the unclustered reference system can serve as a good probe to distinguish the clustering nuclear structure.

We further study the ratio of flow fluctuations. Figure 6 displays the ratio of the relative fluctuation of v_3 and v_2 . Significant difference in magnitude can be seen for the N_{track} dependence of R_{v_3}/R_{v_2} for W-S and triangle α -clustering configurations. It is found that both triangle and W-S configurations show monotonic N_{track} dependence. The ratio is more sensitive for distinguishing triangle and W-S configurations of ^{12}C at large N_{track} .

Assuming linear flow response, the approximation relation shown by Eq. (9) also applies to the kurtosis and skewness of flow fluctuations. We study the skewness (S_{v_n}) and kurtosis (K_{v_n}) of v_n ($n=2,3$) fluctuation in a similar way as corresponding ε_n fluctuation as approaches for investigating the initial α -clustering effect. Results from both the participant plane method and the event plane method are shown in comparison in Fig. 7. Different from the eccentricity fluctuation, one can find that both skewness and kurtosis of the flow harmonic are insensitive for distinguishing the unclustered W-S configuration and the triangular α -clustering configuration. It could be from the source evolution that in the final state of AMPT the v_n ($n=2,3$) distributions are nearly Gaussian,

FIG. 9. Correlation coefficients C_{v_n, ϵ_n} ($n=2,3$) as a function of N_{track} for $^{12}\text{C} + ^{197}\text{Au}$ collisions with different ^{12}C α -clustering configurations.

thus the skewness and kurtosis of elliptic and triangular flow fluctuations especially at large N_{track} are almost consistent with zero within statistical uncertainties.

C. Correlation of the initial eccentricity with final flow harmonic

Impressive progresses have been made in studying the sensitivity of flow response to the initial geometry in relativistic heavy-ion collisions [75,76]. We understand that elliptic flow v_2 and triangular flow v_3 are driven mainly by the linear response to the initially produced ellipticity and triangularity of the source geometry. For asymmetric colliding systems involving the α -clustered nucleus, the conversion of the initial geometry to the final flow could become more complicated. Quantitative study of the initial-final correlation on an event-by-event basis in model simulation is important for understanding the sensitivity of flow and flow fluctuation in probing clustering configurations.

In particular, we study the correlations of the initial eccentricities with final flow harmonics for $^{12}\text{C} + ^{197}\text{Au}$ collisions with α -clustered ^{12}C configurations. The Pearson coefficient is used to quantify the strength of the correlation. We define the coefficient in the following form which takes into account both the magnitude and the angle:

$$C_{v_n, \epsilon_n} = \frac{\langle v_n \epsilon_n \cos(n[\psi - \psi_{\text{PP}}]) \rangle}{\sqrt{\langle |\epsilon_n|^2 \rangle \langle |v_n|^2 \rangle}}, \quad (10)$$

where ψ_{PP} is the participant plane angle, ψ is the phase of the flow coefficient v_n (e.g., ψ is the event-plane angle if v_n is calculated based on the event-plane method). As C_{v_n, ϵ_n} approaches one, good linear correlation can be expected, whereas when C_{v_n, ϵ_n} approaches zero other contributions beyond linear response could contribute. We remark here that the Pearson coefficient can be used to quantify correlations even when the nonlinear effect contributes.

The two-dimensional plots in Fig. 8 show the correlations between v_n and ϵ_n calculated using the participant plane method. As can be seen in the figures, for collision events with $80 < N_{\text{track}} < 100$, the v_2 and v_3 coefficients display a strong linear correlation to their corresponding initial-state coefficients for all the α -clustering cases considered.

Figure 9 compares the model predictions of the N_{track} dependence of the correlation function defined by Eq. (10) for $^{12}\text{C} + ^{197}\text{Au}$ collisions with W-S and α -clustered ^{12}C configurations. C_{v_n, ϵ_n} ($n=2,3$) are generally seen to follow a smooth increasing trend as a function of N_{track} indicating stronger linear v_n - ϵ_n correlation at larger N_{track} . In comparison, W-S results are comparable with triangle configuration for the correlation between v_2 and ϵ_2 whereas triangle configuration presents stronger v_3 - ϵ_3 correlation than W-S especially at large N_{track} .

IV. SUMMARY

In summary, we studied the α -clustering effects on the initial eccentricity and final flow fluctuations in α -clustered $^{12}\text{C} + ^{197}\text{Au}$ collisions at center-of-mass energy of 200 GeV using a multiphase transport model.

Event-by-event fluctuations of the initial eccentricity ϵ_n and final anisotropic flow v_n are characterized by scaled standard variance, skewness, and kurtosis. Differences in the multiplicity dependence of the flow fluctuation are observed for collision systems with W-S and triangle α -clustering configurations of ^{12}C . The triangular flow fluctuation is shown to have particular sensitivity in distinguishing the triangle α -clustering configuration which is consistent with the picture of the flow response to the initial geometry. The ratio of the triangular flow fluctuation over elliptic flow fluctuation decreases with increasing N_{track} for both W-S and triangle configurations but show difference in magnitude. We also note that the differences in flow fluctuation between clustered and unclustered W-S structures are more significant in high-multiplicity collisions. Furthermore, correlations between flow harmonic and initial eccentricity are investigated. The correlation functions for $^{12}\text{C} + ^{197}\text{Au}$ collisions generally show an increasing trend as a function of N_{track} , indicating stronger linear correlations at larger N_{track} . In the picture of the flow response to the initial geometry, it is expected that harmonic flow or flow fluctuation can better probe the α -clustering structure in higher multiplicity collision events.

Experimentally, as the ground state of ^{12}C could exist as a configuration mixing state in reality, the actual signifi-

cance of the fluctuation observable in distinguishing clustered configurations could be lower than we obtained in the ideal cases in our study. Nevertheless, because of the particular sensitivity of the flow fluctuation in reflecting the clustering structure, one could take flow fluctuation in addition to the flow measurement as an effective probe for the α -clustering structure.

As in high energy nuclear collisions, study of the event-by-event anisotropy fluctuation is crucial for understanding not only system initial conditions but also the afterburner evolution properties, future studies by looking into the flow fluctuation in other light-heavy collision systems (e.g., $^{16}\text{O} + ^{197}\text{Au}$, $^{16}\text{O} + ^{208}\text{Pb}$) with α -

clustering configurations will be promising for providing more important information about the nuclear clustering effect.

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