Initial fluctuation effects on harmonic flows in high-energy heavy-ion collisions

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Within the framework of a multi-phase transport model, harmonic flows $v_n$ ($n = 2, 3$ and 4) are investigated for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The event-by-event geometry fluctuations significantly contribute to harmonic flows. Triangular flow ($v_3$) originates from initial triangularity ($\varepsilon_3$) and is developed by partonic interactions. The conversion efficiency ($v_{n}/\varepsilon_n$) decreases with harmonic order and increases with partonic interaction cross section. A mass ordering in the low $p_T$ region and number of constituent quark scaling in the middle $p_T$ region seem to work roughly for $n$-th harmonic flows at both energies. All features of harmonic flows show similar qualitative behaviors at RHIC and LHC energies, which implies that the formed partonic matters are similar at the two energies.

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I. INTRODUCTION

Results from the Brookhaven Relativistic Heavy-Ion Collider (RHIC) indicate that a strongly-interacting partonic matter has been created in relativistic nucleus-nucleus collisions [1]. A powerful probe exposing the characteristics of new matter, elliptic flow, has been measured via the second Fourier coefficient ($v_2$) in the azimuthal distribution of final particles. It is translated from an early stage coordinate space asymmetry, which can reflect how the hot matter evolves hydrodynamically [1, 3]. The $v_2$ data show remarkable hydrodynamical behaviors, which implies the formed matter is thermalized in a very short time and expands collectively as a perfect-like liquid with a very small shear viscosity over entropy density ratio ($\eta/s$) [4, 5]. Elliptic flow ($v_2$) has been studied widely as functions of centrality, transverse momentum ($p_T$) and pseudorapidity ($\eta$) etc. A mass-ordering at low $p_T$ and a Number of Constituent Quark (NCQ) scaling at intermediate $p_T$ for $v_2$ have been observed, which suggests that a thermalized partonic matter is formed and a collective motion is developed prior to hadronization [8, 12]. On the other hand, a geometry (participant eccentricity) scaling was observed for $v_2$ fluctuations, which implies not only participant eccentricity is responsible for elliptic flow, but also the event-by-event initial state geometry fluctuations contribute to harmonic flow [13, 13].

It has been recently found that the triangular flow ($v_3$) is not zero in the azimuthal distribution of final particles. In fact, because of the non-smooth profile, coming from the event-by-event fluctuations of participant nucleons, it shows a triangular initial geometry shape can be transferred into momentum space by hydrodynamical evolution. In recent studies, it has been demonstrated that triangular flow significantly contributes on the near-side ridge and away-side double bumps in two-particle azimuthal correlations [16, 17]. As a new probe, triangular flow is believed to provide more information about the formed hot and dense matter. It has been studied as functions of centrality, transverse momentum, pseudorapidity ($\eta$), as well as the relations with the initial triangularity ($\varepsilon_3$) and shear viscosity over entropy density ratio [16, 20]. However, the dependence of triangular flow on the elastic two-body partonic scattering cross section is absent. In addition, a possible NCQ-scaling, which has been found held by the elliptic flow [21], have not been studied in details for other $v_n$ ($n=3,4...$) when the initial fluctuations are taken into account.

This work presents the initial deformation scaling of elliptic ($v_2$), triangular ($v_3$) and quadrangular flows ($v_4$) for different cross sections within the framework of the AMPT model [22, 23]. The mass ordering at low $p_T$ and constituent quark number scaling at higher $p_T$ for the $v_n$ are investigated after considering the event-by-event initial state geometry fluctuations at RHIC and LHC energies. Meanwhile, a special care is discussed for s-quark and $\phi$ meson for $v_n$-scaling.

The paper is organized in the following way. A brief description of the AMPT model is introduced in Sec. II. The results and discussions are presented in Sec. III. Finally, a summary is given in Sec. IV.

II. BRIEF DESCRIPTION OF AMPT MODEL

A multi-phase transport (AMPT) model consists of four main components: the initial condition, partonic interactions, conversion from partonic to hadronic matter, and hadronic interactions. The initial condition, which includes the spatial and momentum distributions of minijet partons and soft string excitations, is obtained from the Heavy Ion Jet Interaction Generator (HIJING) model. Scatterings among partons are modeled by Zhang’s Parton Cascade (ZPC) model, which includes...
III. RESULTS AND DISCUSSIONS

A. Brief definition of $v_n$ with initial fluctuations

We know harmonic flows are defined as the $n$-th Fourier coefficient $v_n$ of the particle distribution with respect to the reaction plane. However, after considering event-by-event fluctuations in the initial density distribution \cite{10}, the particle distribution should be written as

$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)],$$

(1)

where $\phi$ is the momentum azimuthal angle of each hadron, $\psi_n$ is the $n$-th event plane which varies due to event-by-event fluctuations and can be calculated by

$$\psi_n = \frac{1}{n} \left[ \arctan \left( \frac{\langle p_T \sin(n\phi) \rangle}{\langle p_T \cos(n\phi) \rangle} \right) + \pi \right],$$

(2)

where $r$ and $\varphi$ are the coordinate position and azimuthal angle of each parton and the average $\langle \cdots \rangle$ is density weighted in the initial state, and the superscript $r$ denotes initial coordinate space. The $n$-th order eccentricity $\varepsilon_n$ for initial geometric distribution is defined as

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

(3)

There is some arbitrariness in the definition of $\psi_n(r)$ and $\varepsilon_n$ \cite{29}, because one could, for instance, replace $r^2$ with $s^n$ in Eq. (2) and (3) \cite{30}. With this replacement, however, $v_3$ and $v_4$ only change little in our calculations (less than 3% for $v_3$ and 12% for $v_4$, respectively, for 0-80% centrality). In the following calculations, we will use Eq. (2) and Eq. (3) to decide $\psi_n$ and $\varepsilon_n$.

After $\psi_n$ is determined, the $n$-th harmonic flow $v_n$ can be obtained by

$$v_n = \langle \cos[n(\phi - \psi_n)] \rangle.$$

(4)

In alternative way, $\psi_n$ and $v_n$ can also be calculated in momentum space as,

$$\psi_n^p = \frac{1}{n} \left[ \arctan \left( \frac{\langle p_T \sin(n\phi) \rangle}{\langle p_T \cos(n\phi) \rangle} \right) \right],$$

(5)

and

$$v_n^p = \langle \cos[n(\phi - \psi_n^p)] \rangle,$$

(6)

where $p_T$ and $\phi$ are the transverse momentum and azimuthal angle of each hadron, respectively, which is selected from pseudorapidity $|\eta| > 1$ in the final state to avoid autocorrelation, and the superscript $p$ denotes final momentum space.

For $v_n^p$ determined by the final momentum phase space, we can even-by-event correct $v_n^p$ into $v_n^r$ by

$$v_n^r = \left( \frac{v_n^p - s_n^r \sin[n(\psi_n^p - \psi_n^r)]}{R_n^r} \right),$$

(7)

where the superscript $p$ denotes "event-wise", $R_n^r$ is event-wise event plane resolution, and $s_n^r = \sin[n(\phi - \psi_n^r)]$ is event-wise sine term harmonic coefficient. We found that the contribution from sine-term is only approximately 10% , therefore we neglect the sine-term and correct $v_n^p$ into $v_n^r$ by

$$v_n^r = \left( \frac{v_n^p}{R_n^r} \right),$$

which is more operable experimentally.

It is essential to check if the $v_n(p_T)$ calculated by different $\psi_n$ defined in coordinate space and momentum space is similar or not, because the determination of $\psi_n^r$ in coordinate space by the Eq. (2) is not accessible in experiment. The $p_T$ dependences of $v_2$ and $v_3$ with respect to $\psi_n$ determined by initial coordinate and final momentum spaces are shown in Figure 1 together with the PHENIX $v_2$ data \cite{31}. We observed that $v_2$ and $v_3$ determined by the final momentum space is very close to the ones with respect to initial coordinate space. (Note: we check that the differences are due to sin-term contributions in event-by-event resolution corrections.) Also, the values can basically fit the PHENIX data, especially at low $p_T$.

Based upon the above observations on $v_2$ and $v_3$ with different phase space methods, we conclude that they basically can present the same results. Therefore in our following calculations, we apply the initial coordinate space to calculate $\psi_n^r$ and then obtain the corresponding $v_n^r$. 

the equation of state (EOS) and viscosity, however, has been found to be sensitive to the freeze-out dynamics, and the event plane resolution. The PHENIX data are shown by solid stars [31]. The ratio of elliptic flow to eccentricity ($v_2/\epsilon_2$) has a larger magnitude for lower harmonic than higher harmonic. As presented in Figure 2, the $n$-th order eccentricity $\epsilon_n$ and final harmonic flow $v_n$ ($n = 2, 3$ and $4$) increases with impact parameter. Also, $v_n$ has a larger magnitude for lower harmonic than higher harmonic. Similarly, Figure 4 shows impact parameter and partonic cross section dependences of $v_n/\epsilon_n$ for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The value of ratios decreases with impact parameter, which implies that the conversion from the initial geometry asymmetry to final momentum anisotropy is less efficient for peripheral collisions than for central collisions. And for higher harmonics, there is also less conversion efficiency. The trend for $v_n/\epsilon_n$ as a function of impact parameter looks similar for the different partonic interaction cross sections of $3, 6$ and $10$ mb. However, the magnitude of $v_n/\epsilon_n$ decreases with the cross section, which reveals that the conversion from the initial geometry asymmetry to the final momentum anisotropy becomes weaker for a smaller cross section. This indicates that frequent parton-parton collisions help the system to develop the harmonic collectivity.

From Figure 3 we also saw that the $v_n/\epsilon_n$ becomes smaller for higher harmonic order, this may reflect the viscous damping. Recently, it was claimed that the relative magnitude of the higher-order harmonics ($v_n/n \geq 3$) can provide additional constraints on both the magnitude of $\eta/s$ and the determination of initial condition [33-35]. Fig. 5 shows the $n$-dependence of $v_n/\epsilon_n$ for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for 0-20 % centrality and low $p_T$ region ($p_T < 0.55$ GeV/$c$) (3 mb) with corresponding exponential fitting functions. Compared with PHENIX data, only the trend can be reproduced.
C. $p_T$ dependence of $v_n$ with different partonic cross sections and comparisons with the data

Figure 3 presents our simulations of $v_2$, $v_3$ and $v_4$ as a function of $p_T$ with different parton interaction cross sections together with the PHENIX data $[40]$. For triangular flow, it totally arises from the event-by-event fluctuations of the initial collision geometry, because it persists zero if without considering the fluctuations. $v_n$ ($n = 2, 3$ and $4$) decreases when parton-parton cross section decreases. Experimental data of $v_2$ can be described by the large cross sections (from 3 mb to 10 mb), after one considers of the initial fluctuations. However, the AMPT model underestimates the data if without taking the initial fluctuations into account. Recently, Xu and Ko adjusted more parameters in the AMPT model, which include not only parton interaction cross section but also the parametrization of the Lund string fragmentation, and found that a smaller cross section of 1.5 mb is good to describe both the charged particle multiplicity and elliptic flow $[40]$. In our work, we will not focus on how to further improve parameters, but we do find that initial geometry fluctuations significantly affect harmonic flows and should not be ignored.

The transverse momentum dependences of $v_2$ and $v_3$ with different cross sections in four different centrality bins are shown in Figure 7 and 8. The PHENIX data is also accompanied $[41]$. For each centrality bin, $v_2$ and $v_3$ increase with the cross section. For elliptic flow (Fig. 7), data seem to prefer a bigger cross section in higher transverse momentum range. In the case of triangular flow similar trend is present in Fig. 8, though $v_3$ shows a less centrality dependence than $v_2$, which is consistent with the trends shown in Figure 2.

The transverse momentum dependences of $v_2$ and $v_3$ are also calculated for four different centrality bins in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for LHC energy, which are shown in Figure 9 and 10 together with the ATLAS data $[42]$. Similarly, $v_2$ and $v_3$ increase with the cross section from 3 mb to 10 mb, which can basically describe the ATLAS data.

Even though a general behavior of $p_T$-dependent $v_n$ can be nicely demonstrated by the comparison of our calculations with the data, we found that the AMPT simula-
(v_2/n_q vs K_{ET}/n_q) reveals a universal scaling of v_2 for all identified particles over the full transverse kinetic energy (K_{ET}) range, which is more pronounced rather than p_T. Such scaling indicates that the collective elliptic flow has been developed during the partonic stage and the effective constituent quark degree of freedom plays an important role in hadronization process.

For higher even-order harmonics, v_4 and v_6 etc, appear to be scaled as v_n \propto v_2^{n/2} [47], and their NCQ-scaling has also been suggested in Ref. [48]. Even in very low energy heavy ion collisions, the v_2-scaling and the v_4/v_2-scaling have been suggested for light nuclear clusters in nucleonic level interaction [47]. Instead scaling by the number of constituent quarks (n_q) for v_2, the measured data v_4, however, seems to be scaled by n_q^2 [21]. It is interesting
FIG. 9: (Color online) $v_2$ as a function of $p_T$ in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from the AMPT simulations (3 mb and 10 mb) for different centrality bins (0-5%, 10-20%, 30-40%, and 40-50%) at midrapidity. Circles and triangles represent the calculations with 10 mb and 3 mb, respectively. The ATLAS data shown by solid triangles [42].

FIG. 10: (Color online) Same as Fig. 9 but for $v_3$.

To check if these scaling relations are still valid for the $v_n$ calculations in which the initial fluctuations are taken into account, including the odd harmonics, such as $v_3$.

Figure 11 presents $v_2$, $v_3$ and $v_4$ of different types of hadrons in mid-rapidity for Au + Au collisions (0-80% centrality) at $\sqrt{s_{NN}} = 200$ GeV. Figure 11 (a) shows that $v_2$ preserves an obvious mass ordering in relatively low $p_T$ region, and hadron type grouping in intermediate $p_T$ region, even after considering event-by-event fluctuations. Similarly, $v_3$ and $v_4$, [Figure 11 (b) and (c)] also present a mass ordering in the low $p_T$ region. The study on $v_n$ of different hadron species will give more information about the initial geometry and the viscosity of hot and dense matter [34].

As shown in Figure 12(a), $v_2$ scaled by the number of constituent quarks ($v_2/n_q$) as a function of the transverse kinetic energy ($KE_T = \sqrt{p_T^2 + m^2} - m$) scaled by the number of constituent quarks ($KE_T/n_q$) shows a universal scaling regardless of the initial geometry fluctuations are taken into consideration or not. The only difference is that the initial fluctuations enhance the value of $v_2/n_q$. Therefore, the initial fluctuations have little effect on the breaking of the NCQ-scaling for elliptic flow. Figure 12 (b) and (c) display $v_3/n_3^{3/2}$ and $v_4/n_4^{2}$ for all hadrons as a function of $KE_T/n_q$, respectively, when the initial fluctuations are considered. From the above results, it seems that $v_n$ can still be roughly scaled by $n_q^{n/2}$ for all hadrons as a function of $KE_T/n_q$. Of course, the scaling behavior is not perfect within the present statistics. For example, the amount of spread between different particle species is less than 10% for the $v_2$-scaling, it is less than 20% for the $v_3$-scaling, but it can reach 20-30% for the $v_4$-scaling.

In order to understand possible origin of the NCQ-scaling of $v_n$ for different mesons and baryons, we also check $v_n$ of $u$, $d$ and $s$-quarks as a function of $p_T$ or $KE_T$. As expected, there exists similar NCQ-scaling of...
\(v_n\) \((n=2-4)\) for all those constituent quarks. Furthermore, we find that the values of \(v_n/n_q^{n/2}\) of different hadrons are similar to the values of \(v_n\) of \(u,d,s\)-quarks, which reflects that the NCQ-scaling of \(v_n\) for different hadrons stems from partonic level.

Furthermore, the ratios of \(v_3/v_3^{3/2}\) and \(v_4/v_4^{2}\) as functions of \(p_T\) for three different centrality bins (10-20%, 20-30%, and 30-40%) in Au + Au collisions at \(\sqrt{s_{NN}} = 200\) GeV are shown in Figure 13. It shows that the mass ordering is satisfied, i.e. \(v_n\) decreases from \(\pi, K, p, \phi\) to \(\Lambda\) in the lower \(p_T\) region (note that \(\phi\) is very close to \(p\) in the figure. However, the strict mass-ordering needs \(\phi\)'s \(v_n\) is little than \(p\)'s \(v_n\)). The baryon-meson typing is also evident above \(p_T \sim 1.2\) GeV. By transformation of \(p_T\) to \(K_{ET}/n_q\) as well as \(v_n\) to \(v_n/n_q^{n/2}\), the results of \(v_2/n_q\), \(v_3/n_q^{3/2}\) and \(v_4/n_q^{2}\) as a function of \(K_{ET}/n_q\) are shown in Figure 13. Again, the NCQ-scaling of \(v_n\) is roughly kept except for \(\phi\) meson whose \(v_3\) is a little larger. Of course, the amount of spread between different particle species for \(v_n\)-scaling keeps similar as RHIC energy. Comparing with the above \(v_n\) results at RHIC, LHC results are very similar but they reveal larger \(v_n\) values than RHIC's due to stronger partonic interactions at higher energy. But in general, the partonic matter formed at LHC energy is very similar to that created at RHIC energy.

At the same time, the mass ordering in the low \(p_T\) region and the NCQ-scaling in intermediate \(p_T\) region of \(v_n\) are also investigated at LHC energy in AMPT simulations. Fig. 13 presents the results of \(v_2, v_3, \) and \(v_4\) for different hadron species in Pb + Pb collisions \((0-80\%\) centrality) at \(\sqrt{s_{NN}} = 2.76\) TeV in mid-rapidity from the AMPT calculations \((3\) mb), with considering initial fluctuations. It displays that the mass ordering is satisfied, i.e. \(v_n\) decreases from \(\pi, K, p, \phi\) to \(\Lambda\) in the lower \(p_T\) region (note that \(\phi\) is very close to \(p\) in the figure. However, the strict mass-ordering needs \(\phi\)'s \(v_n\) is little than \(p\)'s \(v_n\)).

FIG. 12: (Color online) (a)-(c): \(v_2/n_q, v_3/n_q^{3/2}\) and \(v_4/n_q^{2}\) as a function of \(K_{ET}/n_q\) in Au + Au collisions \((0-80\%\) centrality) at \(\sqrt{s_{NN}} = 200\) GeV from the AMPT simulations \((3\) mb), where the solid symbols are the results for considering initial fluctuations \((w/\rangle\), while the open ones are for without considering initial fluctuations \((w/o)\).

FIG. 13: (Color online) The ratios of \(v_3/v_3^{3/2}\) (a) and \(v_4/v_4^{2}\) (b) as a function of \(p_T\) for three different centrality bins \((10-20\%, 20-30\%, \) and \(30-40\%)\) in Au + Au collisions at \(\sqrt{s_{NN}} = 200\) GeV from the AMPT simulations \((3\) mb).

E. NCQ-scaling of \(v_n\) at LHC energy

It further gives more insights on the dynamics of strongly-interacting partonic matter and constituent quark degree of freedom in hadronization process.

FIG. 14: The ratios of \(v_3/v_3^{3/2}\) \((w/o)\) and \(v_4/v_4^{2}\) \((w/o)\) as a function of \(p_T\) for three different centrality bins \((10-20\%, 20-30\%, \) and \(30-40\%)\) in Au + Au collisions at \(\sqrt{s_{NN}} = 200\) GeV from the AMPT simulations \((3\) mb).
to proton but it is a multi-strange meson \([3, 50–54]\). This could be understood from the parton’s \(v_n\) in the same condition: \(v_n\) of \(s\)-quark displays a slight deviation from the \(u\) (\(d\))-quarks (not shown here). The reason could be that the \(v_n\) of heavier strange quarks has a smaller value at low \(p_T\) but a larger value at high \(p_T\), i.e. the mass ordering of partonic flow. However, a larger collective radial flow at LHC energy could push heavier \(s\)-quark to have stronger \(v_n\). The effect is of course more distinct at LHC energy because of larger initial partonic pressure. In contrast, in low energy RHIC run, such as 11.5 GeV/c \(Au + Au\) collision, \(s\)-quark may not reach full thermalization and therefore result in a smaller \(v_n\) compared to \(u(d)\)-quarks, which can lead to a smaller \(v_2\) of \(\phi\), i.e. the violation of the \(v_2\)-scaling for the \(\phi\)-mesons relative to other hadrons as observed in the STAR data \([54]\) as well as in a simulation \([12]\). Considering that the \(\phi\)-meson is coalesced by \(s\bar{\tau}\) in the present AMPT model calculation, it will certainly induce a larger \(v_n/\varepsilon_n^{1/2}\) for \(\phi\) in comparison with other hadrons, as shown in Fig. 14. Unfortunately, the data of \(\phi\)'s \(v_n\) is not available yet at LHC energy, which is worth waiting for checking.

Before closing the discussions on the NCQ-scaling of \(v_n\) in this subsection, we remind that the hadronic rescattering process is not yet taken into account in our calculation. Recently, the ALICE data shows that proton’s \(v_2\) and \(v_3\) seem to deviate from the NCQ-scaling of \(v_n\) of charged \(\pi\) and \(K\) \([55]\). The reason could be stronger final-state interaction for protons. Detailed model investigations are underway.

**IV. SUMMARY**

Within the framework of a multi-phase transport model, we investigated the different orders of harmonic flows, namely elliptic flow, triangular flow and quadrangular flow for \(Au + Au\) collisions at \(\sqrt{s_{NN}} = 200\) GeV as well as \(Pb + Pb\) collisions at \(\sqrt{s_{NN}} = 2.76\) TeV when the initial geometry fluctuations are taken into account. Basically, the harmonic flow is converted from initial geometry shape via parton cascade process, and its conversion efficiency \((v_n/\varepsilon_n)\) decreases with the increasing of harmonic order as well as the decreasing of the partonic cross section at both RHIC and LHC energies. Dependences of transverse momentum, centrality and partonic...
cross section of the $v_n$ ($n=2$, 3 and 4) have been studied and compared with data. For each centrality bin, $v_2$ and $v_3$ increases with cross section, especially at higher transverse momentum.

Triangular and quadrangular flows also roughly present a mass ordering in low $p_T$ region and the number of constituent quark scaling in intermediate $p_T$ region, similar to the behaviors of elliptic flow. From our results, a NCQ-scaling of $v_n/n_q$ for different hadrons holds for harmonic flow ($v_n$, $n=2$, 3 and 4), which can be related to $v_n$-scaling in partonic level. From all above results, it implies that the formed partonic matter should be very similar for RHIC and LHC energies.

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