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Beam-energy and collision-system dependence of the linear and mode-coupled flow harmonics from STAR

Niseem Magdy for the STAR Collaboration[1]

Department of Physics, University of Illinois at Chicago, Chicago, Illinois 60607, USA

Abstract

Recent measurements and hydrodynamic model calculations suggest that the higher-order flow coefficients, v_4 and v_5, have two contributions: a linear contribution driven by the initial-state eccentricities, ε_n, and a mode-coupled contribution derived from the lower-order eccentricity coefficients ε_2 and ε_3. Measurements of these two contributions to v_4 and v_5 provide crucial insights to discern initial-state models and to constrain the temperature-dependent specific shear viscosity, η/s, of the plasma produced in heavy-ion collisions. In this work, we have employed the two-subevents cumulant technique to provide the first beam-energy and collision-system dependence of the linear and mode-coupled contributions to the higher-order flow harmonics. Our results are shown and discussed for several centrality intervals for U+U collisions at $\sqrt{s_{NN}}$= 193 GeV, Au+Au collisions at $\sqrt{s_{NN}}$=200, and 54 GeV and Cu+Au collisions at $\sqrt{s_{NN}}$=200 GeV. The results are compared with similar studies performed by ALICE experiments at LHC.

Keywords:

1. Introduction

Ongoing investigations of the matter produced in heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) indicate that an exotic state of matter called Quark-Gluon Plasma (QGP) is produced in these collisions. Many of these studies are aimed at understanding the dynamical evolution and the transport properties of the QGP [1, 2, 3].

The measurements of the azimuthal anisotropy of the particle production called anisotropic flow have been used in various studies to explain the viscous hydrodynamic response to the initial spatial distribution in energy density, created in the early stages of the collision [1, 2, 6].

The anisotropic flow can be described via the Fourier expansion [8] of the azimuthal angle distribution of the particle production,

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + 2\sum_{n=1} V_n e^{-in\phi}\right), \tag{1}$$

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[1] niseemm@gmail.com

where $V_n = v_n \exp(in\Psi_n)$ are the n$^{\text{th}}$ complex flow vectors, Ψ_n represent the flow vector direction, and v_n is the flow vector magnitude. The azimuthal anisotropic flow harmonic v_1 is known as directed flow, v_2 is the elliptic flow, and v_3 is the triangular flow, etc.

To a good degree, the lower order flow harmonics v_2 and v_3 are linearly related to the initial-state anisotropies, ε_2 and ε_3, respectively [9]. However, the higher-order flow harmonics $v_{n>3}$ are arising from linear response to the same-order initial-state anisotropies along with nonlinear response to the lower-order eccentricities ε_2 and/or ε_3 [5]. Consequently, the full benefit of the higher-order flow harmonics for η/s extraction [12] benefits form a robust separation of their linear and nonlinear contributions.

The higher-order flow harmonic V_4 can be expressed as,

$$\begin{aligned} V_4 &= V_4^{\text{Linear}} + V_4^{\text{Nonlinear}}, && (2)\\ V_4^{\text{Nonlinear}} &= \chi_{4,22} V_2 V_2, && (3) \end{aligned}$$

where $\chi_{4,22}$ is the nonlinear response coefficients. The value of $\chi_{4,22}$ constrains the magnitude of $V_4^{\text{Nonlinear}}$, also the magnitude of $V_4^{\text{Nonlinear}}$ encodes the correlations between the flow symmetry planes Ψ_2 and Ψ_4.

In this work, we employ the multiparticle cumulant method [14] to measure the p_T-integrated inclusive, nonlinear and linear higher-order flow harmonic v_4, in collisions of U+U at $\sqrt{s_{NN}}$ = 193 GeV, Cu+Au at $\sqrt{s_{NN}}$ = 200 GeV and Au+Au at at several beam energies.

2. Method

The STAR data were analyzed with the multi-particle cumulant technique [13, 14]. The framework for the standard cumulant method is discussed in Ref. [13]; its extension to the subevents method is reported in Refs. [14]. In the two-subevent method and to minimize the non-flow correlations, the cumulants are constructed from two-subevents which are separated in η. Thus, the constructed two- and multi-particle correlations can be written as:

$$\begin{aligned} v_n &= \langle\langle \cos(n(\varphi_1^A - \varphi_2^B))\rangle\rangle^{1/2}, && (4)\\ C_{n+m,n,m} &= \langle\langle \cos((n+m)\varphi_1^A - n\varphi_2^B - m\varphi_3^B)\rangle\rangle, \\ \langle v_n^2 v_m^2\rangle &= \langle\langle \cos(n\varphi_1^A + m\varphi_2^A - n\varphi_3^B - m\varphi_4^B)\rangle\rangle, \end{aligned}$$

where,$\langle\langle\ \rangle\rangle$ represents the average over all particles then average over events, k, n and m are harmonic numbers and φ_i are the ith particles azimuthal angle. For the two-subevent method, subevent A and subevent B are required to have a minimum $\Delta\eta > 0.6$ separation, i.e. $\eta_A > 0.3$ and $\eta_B < -0.3$.

Using Eq.(4) the linear and nonlinear modes in the higher order anisotropic flow harmonic, v_4, can be expressed as,

$$\begin{aligned} v_4^{\text{Nonlinear}} &= C_{4,22} / \sqrt{\langle \mathrm{v}_2^2 \mathrm{v}_2^2 \rangle}, && (5)\\ v_4^{\text{Linear}} &= \sqrt{(v_4^{\text{Inclusive}})^2 - (v_4^{\text{Nonlinear}})^2}. \end{aligned}$$

Equation (5) assumes that the linear and nonlinear contributions in v_4 are independent, which is a correct approach if the correlation between the lower v_n $(n = 2, 3)$ and higher order flow coefficients $(n > 3)$ is weak.

3. Results

The centrality dependencies of the inclusive, linear and nonlinear v_4 in the p_T range from 0.2 to 4.0 GeV/c for Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV are shown in Fig. 1. Our study indicates that the v_4^{Linear} depends weakly on the collision centrality and it dominates over the nonlinear contribution to the inclusive v_4 in central collisions.

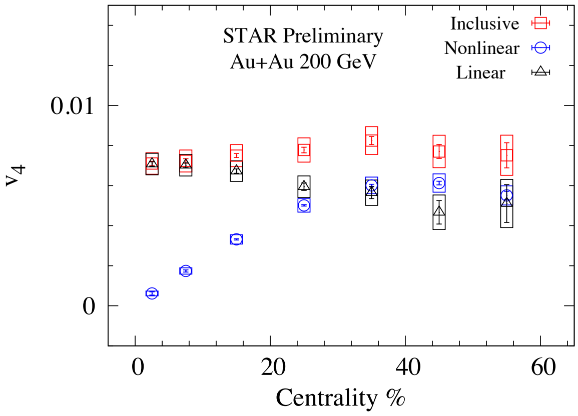

Fig. 1. The inclusive, nonlinear and linear higher-order flow harmonic v_4 using the two subevent cumulant method as a function of centrality in the p_T range from 0.2 to 4.0 GeV/$c$are shown. The respective systematic uncertainties are shown as open boxes.

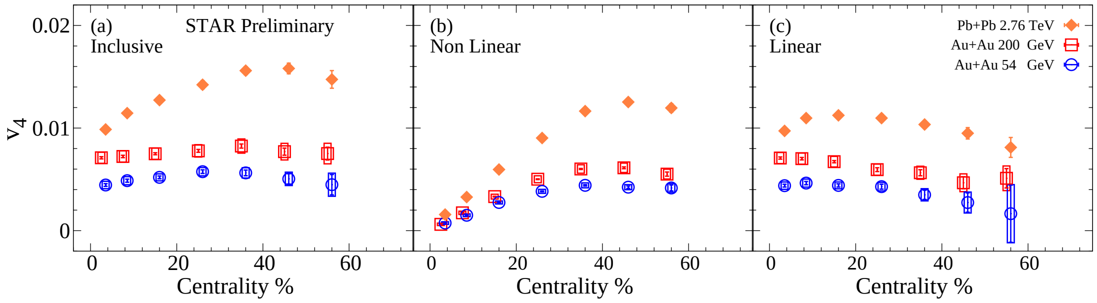

Fig. 2. The inclusive, nonlinear and linear higher-order flow harmonic v_4 using the two subevent cumulant method as a function of centrality in the p_T range from 0.2 to 4.0 GeV/c are shown. The respective systematic uncertainties are shown as open boxes. The results are compared with the LHC measurements in the p_T range from 0.2 to 5.0 GeV/c for Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV [17].

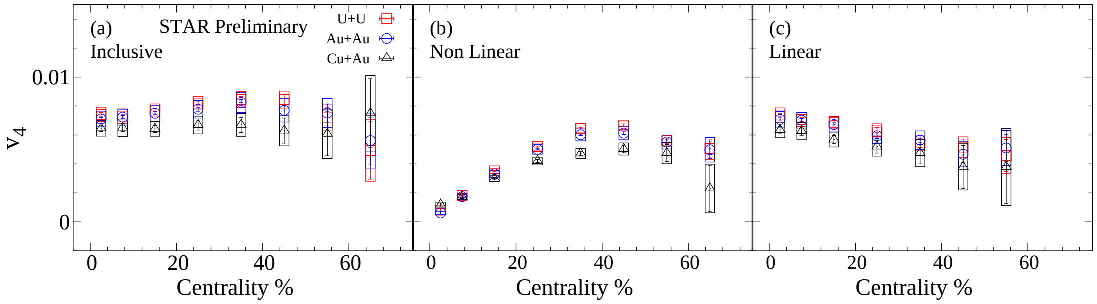

Fig. 3. The inclusive, nonlinear and linear higher-order flow harmonic v_4 for U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV, and Au+Au and Cu+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV are shown. The presented results are measured using the two subevent cumulant method as a function of centrality in the p_T range from 0.2 to 4.0 GeV/c. The respective systematic uncertainties are shown as open boxes.

Figure 2 compares the centrality dependence of the inclusive, linear and nonlinear v_4 in the p_T range from 0.2 to 4.0 GeV/c for Au+Au collisions at $\sqrt{s_{NN}}$ = 200 and 54 GeV. At both presented energies we observe that the linear mode of v_4 has a weak centrality dependence and it's the dominant contribution to the inclusive v_4 in central collisions. The preliminary results are compared with similar LHC measurements in the p_T range from 0.2 to 5.0 GeV/c for Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV [17]. The observed difference in the magnitude of v_4 between Au+Au collisions at $\sqrt{s_{NN}}$ = 200 and 45 GeV and Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV could be driven by the difference in the viscous effects between those energies.

The preliminary results for U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV, and Au+Au and Cu+Au collisions at

$\sqrt{s_{NN}}$ = 200 GeV are shown in Fig. 3. The magnitudes and trends for both inclusive and nonlinear v_4 show a weak system dependence, albeit with more visible differences between Cu+Au and Au+Au than between U+U and Au+Au.

4. Summary

In summary, we have used the cumulant method to measure the inclusive, linear and nonlinear v_4 as a function of collision centrality in U+U collisions at $\sqrt{s_{NN}}$ = 193 GeV, Cu+Au at $\sqrt{s_{NN}}$ = 200 GeV and Au+Au at several beam energies. The measurements show the expected characteristic dependencies of the inclusive, linear and nonlinear v_4 on centrality, system size and beam energy. Our study indicates that the linear contribution to the inclusive v_4 dominates over the nonlinear contribution in central collisions for all presented energies and systems. These newly presented measurements may give extra constraints to test different initial-state models and to assist an accurate extraction of the QGP specific shear viscosity.

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