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Collision system and beam energy dependence of anisotropic flow fluctuations

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Abstract

New measurements of elliptic flow from two- and four-particle correlations are used to investigate flow fluctuations in collisions of U+U at $\sqrt{s_{NN}}$ = 193 GeV, Cu+Au at $\sqrt{s_{NN}}$ = 200 GeV and Au+Au at several beam energies. These measurements highlight the dependence of these fluctuations on the event shape, system size and beam energy and indicate a dominant role for initial-state-driven fluctuations. These measurements could provide further constraints for initial-state models, as well as for precision extraction of the temperature-dependent specific shear viscosity $\eta/s(T)$.

Keywords: heavy-ion collision, anisotropic flow, beam energy scan, flow fluctuations

1. Introduction

Ongoing studies at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) are aimed at characterizing the properties of the Quark-Gluon Plasma (QGP) created in ion-ion collisions. Anisotropic flow measurements have played, and continue to play, a central role in studies aiming to extract the specific shear viscosity (i.e., the ratio of shear viscosity to entropy density η/s) of the QGP [1, 2]. Anisotropic flow is often characterized by the Fourier coefficients, v_n, obtained from a Fourier expansion of the azimuthal angle, ϕ, distribution of the emitted hadrons [3]:

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n \cos(n(\phi - \Psi_n)), \quad (1)$$

where Ψ_n represents the n^{th}-order event plane; the flow coefficients v_1, v_2 and v_3 are called directed, elliptic and triangular flow, respectively. Initial-state fluctuations influence the magnitude of the flow coefficients. Consequently, precision extraction of the specific shear viscosity of QGP requires reliable constraints for the initial-state models employed in such extractions. Such constraints can be obtained via measurements of

[1] A list of members of the STAR Collaboration and acknowledgements can be found at the end of this issue.

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flow harmonics from two- and four-particle correlations utilizing a multiparticle correlation method involving the use of cumulants [5]. The two- and four-particle cumulants allow direct access to the event-by-event flow fluctuations [6].

In this work, we employ the multiparticle cumulant method [5] to measure the p_T-integrated (for $0.2 < p_T < 4$ GeV/c) two- and four-particle flow harmonics $v_2\{2\}$ and $v_2\{4\}$, in collisions of U+U at center-of-mass energy per nucleon-nucleon collision, $\sqrt{s_{NN}}$ = 193 GeV, Cu+Au at $\sqrt{s_{NN}}$ = 200 GeV and Au+Au at at several beam energies. These measurements are used to gain insight on the origin of the fluctuations, as well as their dependence on event shape, system size and beam energy.

2. Measurements

The cumulant method is extensively discussed in Ref. [7]; its recent extension to incorporate sub-events is discussed in Ref. [5]. In this method, a $2m$-particle azimuthal correlator is constructed by averaging over all tracks in one event then over all events [7]:

$$\langle\langle 2m \rangle\rangle \quad = \quad \langle\langle e^{in\sum_{j=1}^{m}(\phi_{2j-1}-\phi_{2j})} \rangle\rangle. \tag{2}$$

The four-particle cumulants presented in this work, were obtained with the standard cumulant method with particle weights. All quadruplets and pairs from the full acceptance of the detector, $|\eta| < 1$, are combined as:

$$c_n\{4\} \quad = \quad \langle\langle 4 \rangle\rangle - 2\,\langle\langle 2 \rangle\rangle^2 \tag{3}$$

To suppress non-flow contributions in the two-particle cumulants, particles were grouped into two sub-events (a and b) with $\eta^a < -0.35$ and $\eta^b > 0.35$:

$$\langle\langle 2 \rangle\rangle_{a|b} \quad = \quad \langle\langle e^{in(\phi_1^a-\phi_2^b)} \rangle\rangle, \quad c_n\{2\} = \langle\langle 2 \rangle\rangle_{a|b}\,. \tag{4}$$

The flow coefficients were obtained via Eqs. 3 and 4 as:

$$v_n\{2\} \quad = \quad \sqrt{c_n\{2\}}, \quad v_n\{4\} = \sqrt[4]{-c_n\{4\}}. \tag{5}$$

The ratio $v_n\{4\}/v_n\{2\}$ is used to estimate the strength of the flow fluctuations as a fraction of the measured $v_n\{2\}$ harmonic. That is a large contribution from flow fluctuations result in the ratio $v_n\{4\}/v_n\{2\} \ll 1.0$, while a weak influence from flow fluctuations leads to $v_n\{4\}/v_n\{2\} \sim 1$.

3. Results

Representative preliminary results for the dependence of $v_2\{2\}$, $v_2\{4\}$ and their ratio, $v_2\{4\}/v_2\{2\}$, on the multiplicity of charged particles produced in the collision, $\langle N_{ch}\rangle$, are shown in Fig. 1 for Au+Au collisions at several center-of-mass energies. Figures 1 (a) and (b) show the characteristic increase of both $v_2\{2\}$ and $v_2\{4\}$ with beam energy. The ratios $v_2\{4\}/v_2\{2\}$, which are sensitive to the magnitude and trend of the fluctuations,

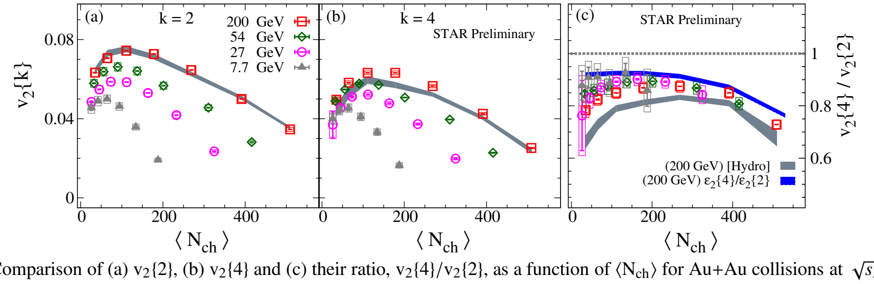

Fig. 1. Comparison of (a) $v_2\{2\}$, (b) $v_2\{4\}$ and (c) their ratio, $v_2\{4\}/v_2\{2\}$, as a function of $\langle N_{ch}\rangle$ for Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 27, 54 and 200 GeV. The bands represent model calculations for Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [4] (see text).

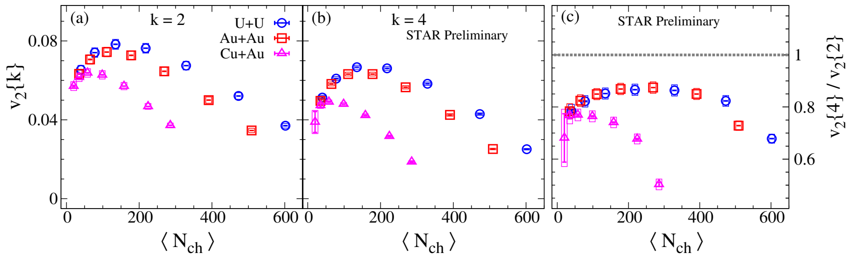

Fig. 2. Comparison of (a) $v_2\{2\}$, (b) $v_2\{4\}$ and (c) their ratio, $v_2\{4\}/v_2\{2\}$, as a function of $\langle N_{ch} \rangle$ for U+U, Au+Au and Cu+Au collisions at $\sqrt{s_{NN}}$ = 193 GeV and $\sqrt{s_{NN}}$ = 200 GeV respectively.

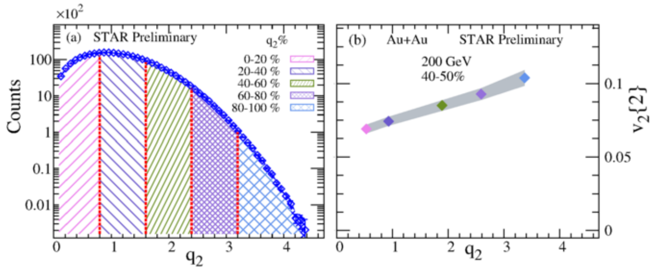

Fig. 3. (a) The q_2 distribution for Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV in the centrality class 40 – 50%, for the sub-event sample with $|\eta| < 0.35$. The indicated bands represent different q_2% selections. An illustrative plot of $v_2\{2\}$ as a function of the q_2 percentile selections are shown in (b).

are displayed in Fig. 1 (c). They show little, if any, dependence on the beam energy. However, they show a decrease in the magnitude of the fluctuations from central to peripheral collisions, consistent with the pattern expected when initial-state eccentricity fluctuations dominate. Recall that a small value for the $v_2\{4\}/v_2\{2\}$ ratio corresponds to large fluctuations. The ratios obtained from hydrodynamic calculations [4] (grey band) overpredict the measured magnitude of the fluctuations, while the eccentricity ratios, $\epsilon_2\{4\}/\epsilon_2\{2\}$ (blue band), obtained from a Monte Carlo based Glauber Model (MCGlauber), appear to underpredict the measured $v_2\{4\}/v_2\{2\}$ ratio; the latter is expected if eccentricity fluctuations are not the only source of the flow fluctuations.

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. 2. The magnitudes and trends for both $v_2\{2\}$ and $v_2\{4\}$ show a clear system dependence, albeit with more pronounced differences between Cu+Au and Au+Au than between U+U and Au+Au. The magnitude and trend of the $v_2\{4\}/v_2\{2\}$ ratios for these collision systems are in line with those expected from initial-state eccentricity fluctuations.

Event shape selection gives access to more detailed differential measurements of the fluctuations because it allows more constraints to be placed on the initial-state fluctuations by partitioning the respective centrality classes into different shape selections. Such measurements can also help to disentangle the hydrodynamic response from the initial-state effects.

Event shape selections were made via selections on the magnitude of the second-order reduced flow vector q_2 [8], defined as:

$$q_2 = \frac{|Q_2|}{\sqrt{M}}, \tag{6}$$

where Q_2 is the magnitude of the second-order harmonic flow vector calculated from the azimuthal distribution of particles within $|\eta| < 0.35$, and M is the charged hadron multiplicity of the same sub-event. Note that the associated flow measurements are preformed within $|\eta| > 0.35$.

Figure 3 (a) shows that the q_2 distribution for Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV in the centrality class 40 – 50% is relatively broad and can accomodate several selections as indicated by the bands. Fig. (3) (b) illustrates the effectiveness of these selections. That is, it shows a clear increase of the extracted values

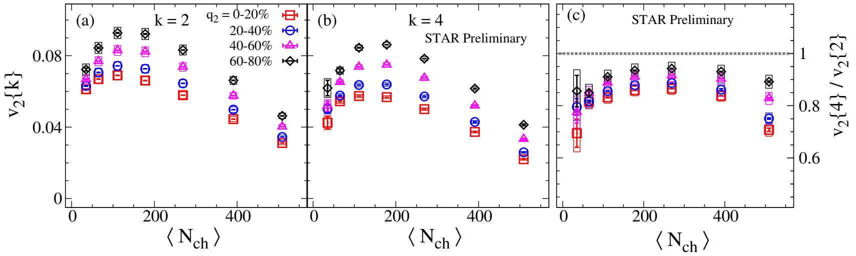

Fig. 4. Comparison of (a) $v_2\{2\}$, (b) $v_2\{4\}$ and (c) their ratio ,$v_2\{4\}/v_2\{2\}$, as a function of $\langle N_{ch} \rangle$ for several q_2 selections for Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

of $v_2\{2\}$ for $|\eta| > 0.35$ with q_2.

The preliminary results for $v_2\{2\}$, $v_2\{4\}$ and the ratio $v_2\{4\}/v_2\{2\}$ with shape selection in Au+Au collisions are shown in Fig. 4 as a function of $\langle N_{ch} \rangle$. Panels (a) and (b) indicate sizeable increases for both $v_2\{2\}$ and $v_2\{4\}$ with q_2 selection in all multiplicity (centrality) classes. However, panel (c) shows a more modest decreasing trend in the magnitude of the fluctuations with q_2 selection in all multiplicity/centrality classes. Nonetheless, the measurements indicate that the elliptic flow fluctuations are sensitive to the event shape selection and thus, provide an additional set of constraints for models.

4. Summary

In summary, we have used the cumulant method to carry out elliptic flow measurements from two- and four-particle correlations as a function of multiplicity and event shape 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 $v_2\{2\}$ and $v_2\{4\}$ on $\langle N_{ch} \rangle$, q_2 selection and beam energy. The elliptic flow fluctuations inferred from these measurements, indicate stronger fluctuations in more central collisions, a modest dependence on collision system and event shape, and a rather weak dependence on beam energy. Taken together, these observations are consistent with a dominant contribution of initial-state eccentricity fluctuations to the measured flow fluctuations.

Acknowledgments

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