Beam energy dependence of the linear and mode-coupled flow harmonics in Au+Au collisions

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Abstract

The linear and mode-coupled contributions to higher-order anisotropic flow are presented for Au+Au collisions at $\sqrt{s_{NN}} = 27, 39, 54.4,$ and $200$ GeV and compared to similar measurements for Pb+Pb collisions at the Large Hadron Collider (LHC). The coefficients and the flow harmonics’ correlations, which characterize the linear and mode-coupled response to the lower-order anisotropies, indicate a beam energy dependence consistent with an influence from the specific shear viscosity ($\eta/s$). In contrast, the dimensionless coefficients, mode-coupled response coefficients, and normalized symmetric cumulants are approximately beam-energy independent, consistent with a significant role from initial-state effects. These measurements could provide unique supplemental constraints to (i) distinguish between different initial-state models and (ii) delineate the temperature ($T$) and baryon chemical potential ($\mu_B$) dependence of the specific shear viscosity $\frac{\eta}{s}(T, \mu_B)$.

Keywords: Collectivity, correlation, shear viscosity

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Experimental studies of heavy-ion collisions at the LHC and the Relativistic Heavy Ion Collider (RHIC) indicate the creation of the Quark-Gluon Plasma (QGP) [1][2], a state of matter predicted by Quantum Chromodynamics (QCD). A central aim of prior and current experimental investigations of this plasma is to understand its transport properties such as its specific viscosity or ratio of shear viscosity to entropy density ($\eta/s$) [3][4]. Anisotropic flow measurements continue to be a valuable route to $\eta/s$ estimation because they reflect the viscous hydrodynamic response to the anisotropy of
the initial-state energy density \[^{[6][12][24]}\] which is characterized by the complex eccentricity vectors \(^{[25][29]}\):

\[
E_n \equiv e_n e^{i n \Phi_n} \equiv -\int \frac{dx \, dy \, r^n \rho_n(r, \phi)}{dx \, dy \, r^n \rho_n(r, \phi)}, \quad (n > 1),
\]

where \(e_n\) and \(\Phi_n\) are the magnitude and azimuthal direction of the \(n\)th eccentricity vector, \(x = r \cos \phi\), \(y = r \sin \phi\), \(r\) is the radial coordinate, \(\phi\) is the spatial azimuthal angle, and \(\rho_n(r, \phi)\) is the initial energy density profile \[^{[28][30][31]}\].

The azimuthal anisotropy of particles produced can be expressed as \[^{[32]}\]:

\[
E_p \frac{d^3N}{d^3p} = \frac{1}{2 \pi T_p} \frac{d^3N}{d^3p} \left(1 + \sum_{n=1}^{5} 2 v_n \cos (n(\phi - \psi_n))\right),
\]

where \(N\) is the number of the particles produced, \(E_p\) is the energy of the particle, \(p_T\) is transverse momentum, \(y\) is the rapidity, and \(\varphi\) is the azimuthal angle of the particle’s momentum; \(v_n\) and \(\psi_n\) represent the magnitude and the direction of the vector \(V_n = v_n e^{i n \Phi_n}\). The coefficients \(v_1\), \(v_2\), and \(v_3\) are commonly termed directed, elliptic and triangular flow, respectively.

Prior investigations of \(v_2\) and \(v_3\) and their fluctuations \[^{[29][33][44]}\] as well as higher-order flow harmonics \(v_n (n > 3)\) \[^{[20][33][35][45][50]}\] have provided invaluable initial insights into the properties of the QGP. Notably, the extensively studied \(v_2\) \[^{[39][51][53]}\] and \(v_3\) flow coefficients \[^{[46][54]}\] are linearly related to \(\varepsilon_2\) and \(\varepsilon_3\) \[^{[17][29][55][62]}\]:

\[
v_n = \kappa_n \varepsilon_n,
\]

where the parameter \(\kappa_n\) encodes the effects of viscous attenuation \[^{[46][61][62]}\] which depend on the particle \(p_T\), charged particle multiplicity and \(\eta/s\). The higher-order flow harmonics show a linear response to the same-order eccentricity but also include a mode-coupled response to the lower-order eccentricities \(\varepsilon_2\) and \(\varepsilon_3\) \[^{[22][30][51][64]}\]:

\[
V_4 = v_4 e^{i4\Phi_4} = k_4 e^{i4\Phi_4} + k_4' e^{i2\Phi_2} = V_4^{\text{Linear}} + \chi_4,22 V_2^{\text{MC}},
\]

\[
V_5 = v_5 e^{i5\Phi_5} = k_5 e^{i5\Phi_5} + k_5' e^{i2\Phi_2} e^{i2\Phi_2} = V_5^{\text{Linear}} + \chi_5,23 V_3^{\text{MC}}.
\]

where \(k_n (k = 4, 5)\) reflects the combined influence of the medium properties and the coupling between the lower- and higher-order eccentricity harmonics. In Eqs. \(^{[4]}\) and \(^{[5]}\) the terms \(V_k^{\text{Linear}}\) and \(V_k^{\text{MC}}\) are the linear and the mode-coupled contributions and \(\chi_{k,n,m}\) represents the mode-coupled response coefficients.

The mode-coupled contributions to \(V_k\) and the normalized symmetric cumulants \(\text{NSC}(n,m)\) can provide further constraints for \(\eta/s\) and the initial-stage dynamics \[^{[30][33][34][38][65][70]}\]. Consequently, ongoing efforts seek to leverage extensive measurements of the linear and mode-coupled contributions to \(V_k\) and \(\text{NSC}(n,m)\) to develop unique supplemental constraints that can (i) distinguish between different initial-state models and (ii) pin down the temperature \((T)\) and baryon chemical potential \((\mu_B)\) dependence of the specific shear viscosity \(\eta/\sigma(T,\mu_B)\); note that \(T\) and \(\mu_B\) vary with beam energy. Prior measurements have been reported for charged hadrons in \(\text{Pb+Pb}\) collisions at \(\sqrt{s_{NN}} = 2.76\) and \(5.02\ \text{TeV}\) \[^{[71][73]}\] and \(\text{Au+Au}\) collisions at \(\sqrt{s_{NN}} = 200\ \text{GeV}\) \[^{[11][33]}\]. Here, we report the \(V_n^{\text{Linear}}, V_n^{\text{MC}}, \chi_{k,n,m}\) and \(\text{NSC}(n,m)\) measurements for \(\text{Au+Au}\) collisions at \(\sqrt{s_{NN}} = 27, 39, 54.4, \) and \(200\ \text{GeV}\) to extend the data set that can provide simultaneous constraints for \(\frac{1}{2}(T,\mu_B)\) and the initial-state. The initial-state effects which influence the dimensionless mode-coupled coefficients and the normalized symmetric cumulants could be insensitive to the beam energy, while \(\frac{1}{2}(T,\mu_B)\) is not \[^{[74][76]}\].

The data for the present analysis were collected with the STAR detector at RHIC using a minimum-bias trigger \[^{[77]}\] in 2017, 2010 and 2018 at \(\sqrt{s_{NN}} = 54.4, 39\) and \(27\ \text{GeV}\) respectively. Charged particle tracks with full azimuthal angle and pseudorapidity \(|\eta| < 1.0\) coverage were used to reconstruct the collision vertices of tracks measured in the Time Projection Chamber (TPC) \[^{[78]}\]. A Monte Carlo Glauber simulation has been used to determine the collision centrality from the measured event-by-event charged particle multiplicity in \(|\eta| < 0.5\) with at least \(10\) hits \[^{[79][80]}\]. In this analysis, tracks with at least \(15\) TPC space points and Distance of Closest Approach (DCA) to the primary vertex of less than \(3\) cm were used. We accept tracks with transverse momentum \(0.2 < p_T < 4\ \text{GeV}/c\). Events are chosen with vertex positions within \(\pm 40\ \text{cm}\) from the TPC center (along the beam direction), and within \(\pm 2\ \text{cm}\) in the radial direction relative to the center of the TPC.
The two- and multi-particle cumulant methods are employed for our correlation analysis. The framework for the cumulant method is described in Refs. [65, 81]; its extension to the case of subevents is also described in Refs. [82, 83]. Here, the two- and multi-particle correlations were formed using the two-subevents cumulant technique [83], with \( \Delta \eta = \eta_1 - \eta_2 > 0.7 \) between the subevents A and B (i.e., \( \eta_A > 0.35 \) and \( \eta_B < -0.35 \)). The use of the two-subevents technique serves to reduce the nonflow correlations [84]. The two- and multi-particle correlations are given as:

\[
\chi_{k,nm}^{\text{MC}} = \frac{C_{k,nm}}{\sqrt{\langle v_k^2 \rangle_{\text{inclusive}}^n}} \approx \langle \cos(k\Psi_k - n\Psi_n - m\Psi_m) \rangle \tag{11}
\]

The mode-coupled response coefficients, \( \chi_{k,nm} \), which quantify the contributions of the coupling to the higher-order anisotropic flow harmonics, are defined as:

\[
\chi_{k,nm} = \frac{\chi_{k,nm}^{\text{MC}}}{\sqrt{\langle v_k^2 \rangle_{\text{inclusive}}^n}} \tag{12}
\]

The normalized symmetric cumulants, \( \text{NSC}(n,m) \), from the standard cumulants method [65, 81] are given as:

\[
\text{SC}(n,m) = \langle \cos(n\varphi_1 + m\varphi_2 - n\varphi_3 - m\varphi_4) \rangle - \langle \cos(n\varphi_1 - \varphi_2) \rangle - \langle \cos(m\varphi_1 - \varphi_2) \rangle \tag{13}
\]

\[
\text{NSC}(n,m) = \frac{\text{SC}(n,m)}{(\langle v_{\text{inclusive}}^n \rangle)^2 (\langle v_{\text{inclusive}}^m \rangle)^2} \tag{14}
\]

with the condition that \( m \neq n \) and \( n \) and \( m \) are positive integers. The \( \rho_T \)-integrated measurements for \( k = n + m, n = 2, m = 2 \) and 3 were performed as a function of centrality for each beam energy.

The systematic uncertainties of the presented measurements are obtained from variations in the analysis cuts for event selection, track selection and non-flow suppression; (I) event selection was varied via cuts on the vertex positions determined in the TPC along the beam direction, -40 to 0 cm or 0 to 40 cm instead of the nominal value of ±40 cm. (II) Track selection was varied by (a) reducing the DCA from its nominal value of 3 cm to 2 cm, and (b) increasing the number of TPC space points from greater than 15 points to more than 20 points. (III) The pseudorapidity gap, \( \Delta \eta \) for the track pairs, used to mitigate the non-flow effects due to resonance decays, Bose-Einstein correlations, and the fragments of individual jets, was varied from \( \Delta \eta = 0.6 \) to \( \Delta \eta = 0.8 \).

![Figure 1](image_url): Comparison of the \( \rho_T \) integrated three-particle correlators, \( C_{4,22} \) (a) and \( C_{5,23} \) (b), for Au+Au collisions at \( \sqrt{s_{NN}} = 54.4, 39 \) and 27 GeV, obtained with the two-subevents cumulant method. The \( C_{4,22} \) and \( C_{5,23} \) measurements for Au+Au at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) are taken from Ref. [11].

Table 1 gives a summary of these systematic uncertainty estimates. The overall systematic uncer-
Figure 2: Comparison of the centrality dependence of the $C_{4,22}$ and $C_{5,23}$ coefficients for 0.2 < $p_T$ < 4.0 GeV/c in Au+Au collisions at $\sqrt{s_{NN}} = 54.4, 39$ and 27 GeV. The $v_4$ and $v_5$ measurements at $\sqrt{s_{NN}} = 200$ GeV are taken from Ref. [12]. The solid points indicate LHC measurements at $\sqrt{s_{NN}} = 5.0$ GeV/c from the ALICE experiment [7] and for 0.5 < $p_T$ < 2.0 GeV/c from the ATLAS experiment (set-2) [38] for Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

Quantities | Minimum value | Maximum value
---|---|---
Event | 2% | 5%
Track | 3% | 7%
$\Delta \eta$ | 2% | 7%

Table 1: Summary of the estimated systematic uncertainty contributions (see text).

Figure 1 compares the centrality dependence of the $C_{4,22}$ and $C_{5,23}$ coefficients for 0.2 < $p_T$ < 4.0 GeV/c in Au+Au collisions at $\sqrt{s_{NN}} = 200, 54.4, 39$ and 27 GeV. The coefficients show similar centrality dependent patterns and magnitudes that decrease with beam energy. These dependencies suggest that $C_{4,22}$ and $C_{5,23}$ are sensitive to the initial-state eccentricity and the change in viscous attenuation with beam energy. The latter could result from both a change in the charge particle multiplicity and $\eta/s(\mu_B, T)$ [74, 75] with beam energy. Thus, detailed model comparisons to the centrality and beam energy dependence of $C_{4,22}$ and $C_{5,23}$ could serve as an additional constraint for precision extraction of $\eta/s$ [74].

The $v_k^{\text{Inclusive}}$, $C_{4,22}$ and $C_{5,23}$ coefficients were used to extract $\varepsilon_k^{\text{MC}}$, $v_k^{\text{Linear}}$, $\rho_k, \chi_k$, and NSC(n, n) (cf. Eqs. 9 - 12) to home in on further constraints for the initial- and final-states respectively. The centrality dependence of $v_k^{\text{Inclusive}}$ ((a) and (d)), $v_k^{\text{Linear}}$ ((b) and (e)), and $v_k^{\text{MC}}$ ((c) and (f)) $v_{4,5}$ coefficients are shown for several beam energies in Fig. 2. The mode-coupled coefficients ((b) and (e)) indicate a much stronger increase with centrality than that for the linear coefficients ((c) and (f)), suggesting that the $v_k^{\text{Linear}}$ coefficients are subject to much larger viscous attenuation than the $v_k^{\text{MC}}$ coefficients; note that $\varepsilon_k^{\text{MC}}$ and $\varepsilon_k^{\text{Linear}}$ increase with centrality. The $v_k^{\text{MC}}$ and $v_k^{\text{Linear}}$ coefficients for Au+Au collisions also indicate a relatively weak dependence on beam energy, suggesting that the viscous attenuation and the eccentricity are weak functions of the beam energy (cf. Eq. 3) especially for the energy span $\sqrt{s_{NN}} = 27 - 54.4$ GeV. The LHC measurements (set-1 [71], or ALICE measurements for 0.2 < $p_T$ < 5.0 GeV/c and $|\eta| < 0.8$, and set-2 [38], or ATLAS measurements for $p_T > 0.5$ GeV/c and $|\eta| < 2.5$) (panels (a)-(f)) show patterns that are similar to those for Au+Au collisions, albeit with magnitudes that are much larger, implying a more sizable dependence on beam energy from RHIC to LHC energies [74, 75]. The difference between the magnitudes for the set-1 and set-2 LHC measurements reflects the dependence of these coefficients on $p_T$. Note however, that the $p_T$ is a weak function of the RHIC beam energy range.
of interest in this work \[86\]. These beam energy and centrality dependencies can be used to further constrain theoretical models.

Figure 3: Comparison of the \(\chi_{n=m_{nm}}\) ((a) and (c)) and \(\rho_{n=m_{nm}}\) ((b) and (d)) obtained with the two-subevents cumulant method, as a function of centrality in the \(p_T\) range 0.2–4.0 GeV/c for \(\text{Au}+\text{Au}\) collisions at \(\sqrt{s_{NN}} = 54.4, 39\) and 27 GeV. The \(\chi_{n=m_{nm}}\) and \(\rho_{n=m_{nm}}\) at \(\sqrt{s_{NN}} = 200\) GeV are taken from Ref. \[34\]. The solid points are the LHC measurements for Pb+Pb collisions at \(\sqrt{s_{NN}} = 2.76\) TeV set-1 \[71\] and set-2 \[38\].

The centrality dependence of the mode-coupled response coefficients \(\chi_{k,nm}\) \((n = 2 \text{ and } m = 2 \text{ and } 3)\) for \(\text{Au}+\text{Au}\) \((\sqrt{s_{NN}} = 200, 54.4, 39\) and 27 GeV) and Pb+Pb collisions \((\sqrt{s_{NN}} = 2.76\) TeV\) \[71\] are compared in Figs. 3(a) and (b). Results demonstrate a weak dependence on centrality and beam energy, confirming that (I) the mode-coupled \(v_{3,5}\) coefficients are dominated by the correlations from the lower-order flow harmonics and (II) \(\chi_{k,nm}\) is weakly sensitive to the viscous effects \((\eta/s)\) \[71, 76\] and hence, more sensitive to the initial-state effects.

Figure 3(c) and (d) compares the centrality dependence of the \(\rho_{k,nm}\) coefficients for \(\text{Au}+\text{Au}\) collisions \((\sqrt{s_{NN}} = 200, 54.4, 39\) and 27 GeV) and Pb+Pb collisions \((\sqrt{s_{NN}} = 2.76\) TeV\) \[71\]. Within the indicated uncertainties, they indicate a strong centrality dependence and a relatively weak dependence on beam energy. These characteristic dependencies suggest that \(\rho_{k,nm}\) can provide an additional constraint for the beam energy dependence of the viscous effects \((\eta/s)\) \[71, 76\] and could be used to discern different initial-state models \[74\].

Figure 4 summarizes the results for the NSC(n,m) that reflect the strength of the correlation/anti-correlation between the \(v_2\) and \(v_n\) flow harmonics. Figs. 4(a) and (b) show the NSC(2,3) and NSC(2,4) respectively, for \(0.2 < p_T < 4.0\) GeV/c in \(\text{Au}+\text{Au}\) collisions at \(\sqrt{s_{NN}} = 200, 54.4\) and 27 GeV and the corresponding LHC measurements \[34\]. The NSC(2,3) coefficients indicate an anti-correlation (negative values) \[66, 87\] between \(v_2\) and \(v_3\), as expected from the known anti-correlation between \(\varepsilon_2\) and \(\varepsilon_3\). In contrast, the NSC(2,4) coefficients indicate a correlation between \(v_2\) and \(v_3\) consistent with the mode-coupled correlations between \(\varepsilon_2\) and \(\varepsilon_4\). Within the uncertainties, the weak beam energy dependence further indicates that NSC(2,3) and NSC(2,4) are less sensitive to the effects of viscous attenuation \[71\] and could set a constraint on the initial-state eccentricity correlations.

In summary, we have presented new \(p_T\)-integrated measurements of the charge-inclusive, linear and mode-coupled contributions to the higher-order anisotropic flow coefficients \(v_{4,5}\), mode-coupled response coefficients \(\chi_{k,nm}\), correlations of the event plane angles \(\rho_{k,nm}\) and normalized symmetric cumulant NSC(2,3) and NSC(2,4), for \(\text{Au}+\text{Au}\) collisions at \(\sqrt{s_{NN}} = 200, 54.4, 39\) and 27 GeV. Our measurements are compared with similar LHC measurements for Pb+Pb collisions at \(\sqrt{s_{NN}} = 2.76\) TeV. For all presented energies, the mode-coupled \(v_{4,5}\) measurements indicate a large centrality dependence. In contrast, the linear \(v_{4,5}\), which dominates the central collisions, displays a
weak centrality dependence. The $v_{4,5}$ measurements show a beam energy dependence which reflects the sensitivity to $\eta/s$. The dimensionless coefficients $\chi_{k,nm}$, $\rho_{k,nm}$, NSC(2,3) and NSC(2,4) show magnitudes and trends which are approximately beam energy independent, suggesting that the measured dimensionless quantities are dominated by initial-state effects. These results should prove invaluable to theoretical efforts which seek simultaneous constraints for $\frac{d}{dN}(T, \mu_B)$ and the initial-state.

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