PHENIX Measurements of collectivity in Au plus Au collisions at $\sqrt{s_{NN}}$=200 GeV from higher order cumulants and flow unfolding

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journal or publication title	Nuclear physics. A
volume	982
page range	331-334
year	2019-02
権利	(C) 2018 Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
URL	http://hdl.handle.net/2241/00157773

Available online at www.sciencedirect.com

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Nuclear Physics A 982 (2019) 331–334

NUCLEAR PHYSICS A

www.elsevier.com/locate/nuclphysa

XXVIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
(Quark Matter 2018)

PHENIX Measurements of collectivity in $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV from higher order cumulants and flow unfolding

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Abstract

Detailed measurements of collectivity in Au+Au collisions at RHIC provide a key connection between the initial geometry of the deposited energy and the hydrodynamic evolution of the medium created in heavy-ion collisions. Utilizing the highly segmented PHENIX inner trackers, we present new measurements of flow coefficients extending over a wide range in pseudorapidity $1 < |\eta| < 3$ and p_T. Over a centrality range of 0-90%, we present cumulant results $v_2\{2\} - v_2\{8\}$ and $v_3\{2\}$ as well as quantifying the event-by-event flow fluctuations. Complementing these results, we measure event-by-event v_2 and v_3 distributions using an unfolding procedure.

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1. Introduction

Measurements of the azimuthal anisotropy of particle production has been a staple of heavy ion physics for much of the past twenty years. This observable has been interpreted as the result of a collective expansion, or flow, of the nuclear medium, translating the initial spatial anisotropy of the overlapping nuclei into the final state azimuthal particle distribution. Almost ten years ago, it was proposed that fluctuations in the initial state can account for a sizable portion of the flow signal, which is typically quantified by the coefficients of the Fourier decomposition of the azimuthal particle distribution. Furthermore, different analysis methods are sensitive to these fluctuations in different ways [1].

Cumulants constructed from multi-particle correlations can be used to quantify the anisotropy of particle distributions and, as a whole, have a number of convenient features. Higher order cumulants, constructed from a larger number of particles, are thought to be less sensitive to local correlations, or non-flow, that tend to involve fewer particles. Additionally, different order cumulants have different sensitivities to event-by-event flow fluctuations. Thus, by comparing flow measured through different order cumulants, information about both non-flow and flow fluctuations can be obtained [2, 1].

Alternatively, one can examine the event-by-event flow distributions. This method poses a challenge because the underlying distributions are convolved with the detector response, however, once unfolded, any observable of interest may be determined directly.

Here we present measurements of v_2 and v_3 and their fluctuations from multi-particle cumulants as well as via event-by-event distributions measured in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with the PHENIX detector.

https://doi.org/10.1016/j.nuclphysa.2018.09.035

2. Methods

2.1. Experiment

This analysis uses tracks measured in the PHENIX silicon forward vertex tracker with pseudorapidity coverage of $1 < |\eta| < 3$ and with efficiency $> 60\%$ for tracks with momentum larger than 0.3 GeV/c. Event centrality is inferred by measuring charged particle multiplicity in the PHENIX beam-beam counters (BBC) which have pseudorapidity coverage of $3.1 < |\eta| < 3.9$. The BBCs are also used for minimum bias triggering, requiring a minimum signal in each side.

2.2. Cumulant analysis

Two- and four-particle correlation functions ,$\langle 2\rangle$ and $\langle 4\rangle$, can be constructed as in reference [2]. From these, one can define multi-particle cumulants as $c_n\{2\} = \langle 2\rangle$ and $c_n\{4\} = \langle 4\rangle - 2\langle 2\rangle^2$ from which Fourier coefficients $v_n\{k\}$ are computed as $v_n\{2\} = (c_n\{2\})^{1/2}$ and $v_n\{4\} = (-c_n\{4\})^{1/4}$. Analogous expressions can be derived for higher number of particle correlations. Additionally it can be shown that, in the small variance limit [1],

$$v_n\{2\} = \sqrt{v_n^2 + \sigma_{v_n}^2} \text{ and } v_n\{4\} \approx \sqrt{v_n^2 - \sigma_{v_n}^2}. \tag{1}$$

Therefore, in this limit, one can extract the fluctuations on v_n, σ_{v_n}, from the 2 and 4 particle cumulants.

2.3. Event-by-event analysis

To extract flow on an event-by-event basis, the Q-vector formalism is employed. The Q-vector (or flow vector), $\vec{Q}_n$, has x and y components defined by $\sum_{i=1}^{N} \cos n\phi_i$ and $\sum_{i=1}^{N} \sin n\phi_i$ respectively. Here N is the total number of particles, calculated on a per-event basis. If the measured flow vector fluctuates about some underlying flow vector, $\vec{v_n}^{\mathrm{RP}}$, one expects the probability density function for the measured flow vector to be approximately Gaussian distributed about $\vec{v_n}^{\mathrm{RP}}$. Integrating over the azimuthal angle in the $x-y$ plane returns a Bessel-Gaussian function in the magnitude of the flow vector, v_n, with width δ_{v_n} and mean $\vec{v_n}^{\mathrm{RP}}$ [1]. However, the measured distribution is a convolution with the detector response. If the response is Gaussian in the two transverse coordinates, the conditional probability distribution to measure the magnitude of the flow vector, v_n^{obs}, given a true value v_n is also Bessel-Gaussian with width parameter δ quantifying the response. To extract the underlying distribution, an unfolding procedure must be used to deconvolve the two distributions.

To measure the detector response, the flow vector is measured independently in both the negative and positive η regions of the detector. The distribution of the event-by-event difference is fit with a Gaussian in each coordinate. The Gaussians describes the data over four orders of magnitude, with a χ^2/ndf of 1.02 and 1.18 for the x and y coordinates.

To obtain the underlying flow distribution, the observed data was unfolded using both singular value decomposition and Bayesian techniques [3], however, both of the processes failed to converge. Therefore, justified by previous ATLAS publications [4], we use the assumption that the flow fluctuations are exactly Gaussian making the underlying flow distribution Bessel-Gaussian. Given this assumption, a fit is performed by scanning over the two parameters δ_{v_n} and $\vec{v_n}^{\mathrm{RP}}$, folding it through the detector response, and calculating a χ^2 against the observed distribution. The parameters that minimize the χ^2 distribution are chosen as the best fit.

3. Results

3.1. Cumulant results

Figure 1 shows v_2 (left) and its relative fluctuations (right), calculated via multi-particle correlations, and plotted as a function of event centrality. $v_2\{2\}$ is calculated using particle pairs with $|\Delta\eta| > 2$ to reduce the contribution from non-flow correlations. The figure shows that $v_2\{4\}$, $v_2\{6\}$, and $v_2\{8\}$ in agreement, while the $v_2\{2\}$ points are slightly higher. This behavior is consistent with Gaussian fluctuations in the small variance limit as defined in Eq. 1. Assuming this limit, the relative fluctuation σ_{v_n}/v_2 is obtained as a function of event centrality as shown in the right panel of Figure 1. The relative fluctuations are consistent with that calculated, using the same cumulant method, from nucleons participating in the collisions obtained from MC Glauber simulations [5] except in the very peripheral events. In this case, non-linearities in the translation of the initial geometry to final state particles are expected to arise [6]. In central events, the relative fluctuations from MC Glauber found via the cumulant method differ from those determined by a direct calculation using the Q-vector formalism, indicating a breakdown in the small variance approximation 1. It is interesting to note here that AMPT [7] using Glauber initial conditions can also describe the data.

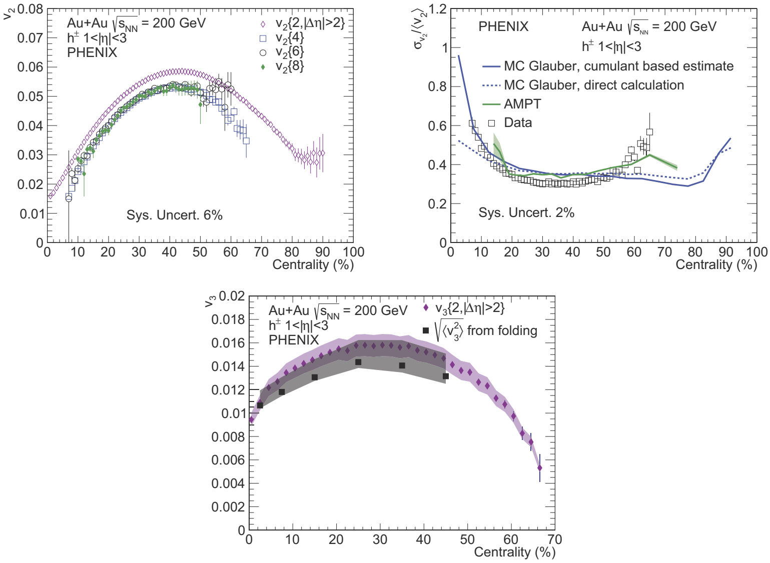

Fig. 1. v_2 (left) and its relative fluctuations (right) calculated via multi-particle correlations and plotted as a function of centrality in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. v_3 plotted as a function of centrality (bottom) calculated via two particle correlations with $|\Delta\eta| > 2$ gap in magenta diamonds and via event-by-event folding procedure.

The bottom panel of Figure 1 shows the results of v_3 as a function of event centrality calculated via two-particle correlations with $|\Delta\eta| > 2$ gap in magenta diamonds and via event-by-event folding procedure (discussed below), showing consistency.

3.2. *Event-by-event results*

When performing the event-by-event v_2 fitting procedure, both Bessel-Gaussian parameters were tightly constrained leading to well-determined $\langle v_2\rangle$ and σ_{v_2}. Figure 2 shows these results as a function of centrality. The mean values are in excellent agreement with those measured via multi-particle correlations, however the relative fluctuations differ in the most central category further suggesting the breakdown of the small variance approximation.

Interestingly, the fit to the event-by-event v_3 distributions yielded a band of reasonable best fit values while describing the observed v_3 distributions reasonably well, though the descriptions are not as good as the v_2 case which is reflected in the size of the uncertainties. Figure 2 (lower) shows these results as a function of centrality. It is interesting to note that the relative fluctuations in v_3 are constant around 0.52 which is the asymptotic value of the Bessel-Gaussian distribution in the large variance limit.

4. Conclusion

We have shown measurements of elliptic and triangular flow in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV using charged particles measured with the PHENIX detector at forward rapidity $1 < |\eta| < 3$. We presented

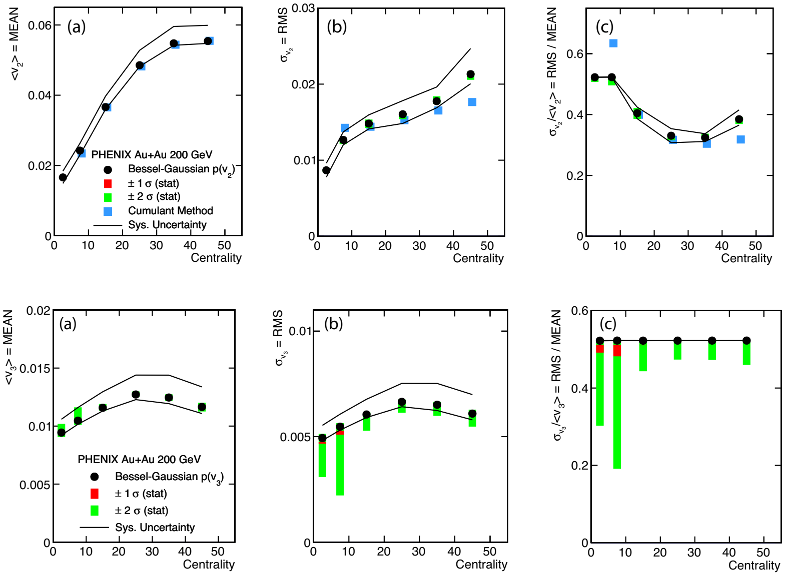

Fig. 2. (top-a) v_2, (top-b) σ, (top-c) relative fluctuations plotted as a function of centrality. It is calculated via the event-by-event flow fitting procedure using Bessel-Gaussian assumptions (black points) and overlayed with the results from multi-particle correlations assuming small variance (blue squares). The lower row shows the analogous results for v_3.

flow harmonics measured with the multi-particle cumulant method ($v_2\{2\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$ and $v_3\{2\}$) and the mean and variance of the v_2 and v_3 event-by-event distributions by assuming a Bessel-Gaussian form and performing a fit to data folded with the detector response. We find that both methods give consistent results for the mean v_2 and v_3, and both estimations of the fluctuations of v_2 are consistent except in the most central category, suggesting a breakdown in the small variance assumption. The relative fluctuations of v_3, extracted via the event-by-event method, are consistent with the large variance limit. All of these results are submitted for publication - see Ref. [8].

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