PHENIX Measurements of Higher-order Flow Harmonics for Identified Charged Hadrons in Au+Au collisions at $\sqrt{s_{NN}} = 39 - 200$ GeV

Yi Gu (for the PHENIX Collaboration)\(^1\)

Department of Chemistry, State University of New York, Stony Brook, NY 11794, U.S.A

Abstract

The azimuthal anisotropy coefficients $v_{2,3,4}$, characterizing collective flow in Au+Au collisions, are presented for identified particle species as a function of transverse momentum ($p_T$), centrality (cent) and beam collision energy ($\sqrt{s_{NN}}$). The $v_n$ values for each particle species, show little, if any, change over the measured beam energy range, and $v_n/(n_q)^{n/2}$ vs. $KE_T/n_q$ scales to a single curve (constituent quark number ($n_q$) scaling) for each $n$, over a broad range of transverse kinetic energies ($KE_T$). A comparison of $v_2(p_T)$ for individual particle species obtained in Au+Au collisions at $\sqrt{s_{NN}} = 0.20$ TeV (RHIC) and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV (LHC), indicate stronger collective flow at the LHC. These flow measurements and their scaling patterns, can provide important additional constraints for extraction of the specific viscosity $\eta/s$.

1. Introduction

Collective flow continues to play a central role in ongoing efforts to characterize the transport properties of the Quark Gluon Plasma (QGP) produced in heavy ion collisions at RHIC. An experimental manifestation of this flow is the anisotropic emission of particles in the plane transverse to the beam direction. This anisotropy can be characterized by the Fourier coefficients $v_n$ determined relative to the estimated participant event planes $\Psi_n$:

$$v_n = \frac{\langle \cos n(\phi - \Psi_n) \rangle}{Res\{\Psi_n\}}$$

(1)

where $\phi$ is the azimuthal angle of an emitted particle, $Res\{\Psi_n\}$ is a resolution factor which accounts for the dispersion of the azimuthal angle of $\Psi_n$, and brackets denote averaging over particles and events. The anisotropic emission of particles can also be characterized equivalently by the pair-wise distribution in the azimuthal angle difference ($\Delta\phi = \phi_a - \phi_b$) between particle pairs with transverse momenta $p_T^a$ and $p_T^b$ (respectively)

$$\frac{dN_{pairs}}{d\Delta\phi} \propto \left( 1 + \sum_{n=1}^{N} 2v_n^{p_T}v_n^{p_T} \cos(n\Delta\phi) \right),$$

(2)

\(^1\)A list of members of the PHENIX Collaboration and acknowledgements can be found at the end of this issue.

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Significant attention has been given to the use of $v_2$($p_T$) measurements for the extraction of the specific shear viscosity $\eta/s$, (i.e. the ratio of viscosity to entropy density) $[^1]$. However, the uncertainty for $\eta/s$ remains large, primarily because of an uncertainty in the initial state geometry used in model calculations. Recent developments suggest that the higher order flow harmonics $v_{n>2}$ for inclusive charged hadrons, provide tighter constraints for disentangling the respective role of initial state geometry and $\eta/s$ $[^2,^3]$. Consequently, systematic measurements of the flow coefficients $v_n$ for identified particle species might be expected to provide additional constraints.

2. Methods and Analysis

In PHENIX, flow coefficients are extracted via the event plane method (Eq. $[^1]$) and the long-range two particle correlation method (2PC) (Eq. $[^2]$). The results presented at QM (and in this proceeding) are for particles produced at mid-rapidity, and reconstructed in the PHENIX central arms.

For the event plane method (EP) (cf. Eq$[^1]$), several event plane detectors, with different pseudo-rapidity ($\eta_p$) coverages were employed: the Raction Plane detector (RxnP: $|\eta_p|$ = 1.0–2.8), the Muon Piston Calorimeter (MPC: $|\eta_p|$ = 3.1–3.7) and the Beam-Beam Counter (BBC: $|\eta_p|$ = 3.1–3.9). These event planes enabled robust consistency checks, as well as reliable systematic error estimates. The 2PC method (cf. Eq$[^2]$) was performed by correlating tracks in the central PHENIX arm ($|\eta_p|$ ≤ 0.35) with hits in RxnP ($|\eta_p|$ = 1.0–2.8) to produce correlation functions (the ratio of the distributions for correlated pairs and uncorrelated pairs from mixed events). The flow coefficients were extracted by Fourier analyzing these correlation functions.
The flow coefficients $v_{2,3,4}(p_T)$ obtained with both methods, for pions ($\pi^\pm$), kaons ($K^\pm$) and (anti)protons ($\bar{p}p$) in 0-50% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, are compared in Fig. 1. The open symbols (2PC method) and filled symbols (EP method) indicate good consistency, suggesting that “non-flow” correlation (primarily from jet fragmentation and resonance decays) might be small. The relatively large values of $\Delta n_{\eta}$ between the PHENIX central arms and the event plane detectors serve to reduce such correlations. Similarly good agreement were obtained for finer (10%) centrality cuts.

Figure 2 compares the respective $v_{2,3}(p_T)$ values obtained at $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV, for each particle species. Within systematic errors, the flow coefficients for $\pi^\pm$, $K^\pm$ and $\bar{p}p$ respectively, indicate very little, if any, change as the beam energy is increased. This points to a possible “saturation” of collective flow for the beam energy range $\sqrt{s_{NN}} = 39 - 200$ GeV. Here, it is important to emphasize that the saturation reflected in the comparison for each particle species cannot arise from the interplay between radial and elliptic flow which could result in a cancellation between the $v_n$ values for light and heavier particles to give a constant $v_n$ with beam collision energy. Such a saturation could however, result from a softening of the equation of state.

The number of constituent quark (NCQ) scaling properties of these flow measurements are shown in Fig. 3 and Fig. 4 for $\sqrt{s_{NN}} = 200$ GeV and 39, 62.4 GeV respectively. They indicate that $v_n/n_{\eta}^{1/2}$ vs. $KET/n_{\eta}$ (for $n=2,3,4$) scale to a single curve, confirming that NCQ scaling also holds for the lower beam energies of $\sqrt{s_{NN}} = 39$ and 62.4 GeV.

A comparison between RHIC and LHC $v_2(p_T)$ is shown for the 20-30% most central collisions in Fig. 5. It indicates a larger flow for pions and kaons at all $p_T$’s as might be expected from the significant energy density increase from RHIC to LHC. For (anti)protons, the LHC values are larger than the RHIC values for $p_T \gtrsim 2.5$ GeV/c, however this trend is inverted for lower $p_T$. The latter inversion can be attributed to a much larger radial flow [at the LHC] which
gives a larger blueshift to the $v_2(p_T)$ values for (anti)protons $^{[5]}$. Note that, in contrast to our measurements for identified particle species at RHIC, this interplay between radial and elliptic flow results in a subtle cancellation between increasing contributions from light, and decreasing contributions from heavier particles to make inclusive charged hadron $v_2$ similar at RHIC and the LHC. The reported $v_n$ measurements should provide important additional constraints for $\eta/s$ extraction via future model comparisons.

3. Summary

PHENIX has performed a new and comprehensive set of $v_n$ measurements for identified particle species at $\sqrt{s_{NN}} = 39, 62.4$ and 200 GeV. The new measurements show a “saturation” of flow, consistent with our previous inclusive charged hadron flow measurements. However, a comparison of $v_2(p_T)$ for individual particle species obtained in Au+Au collisions at RHIC and Pb+Pb collisions at the LHC, indicate stronger collective flow at the LHC. At the LHC, the interplay between radial and elliptic flow leads to a subtle cancellation between the $v_n$ values for light and heavier particles, to make the magnitude of inclusive charged hadron $v_2$ similar to those at RHIC. The RHIC $v_n$ measurements show that quark number scaling ($v_n/(n_q)^{n/2}$ vs. $KE_T/n_q$ for different particle species scale to a single curve) holds for each harmonic, for a broad range of transverse kinetic energies.

References

[1] H. Song, S. A. Bass, U. Heinz, T. Hirano, C. Shen, Phys.Rev. C83 (2011) 054910.
[2] R. A. Lacey, A. Taranenko, N. Ajitanand, J. Alexander, arXiv 1105.3782 (2011).
[3] Adare, A. and et al. (PHENIX Collaboration) Phys. Rev. Lett. 107 (2011) 252301.
[4] C. Shen, U. Heinz, Phys.Rev. C85 (2012) 054902.
[5] U. Heinz, C. Shen, H. Song, arXiv 1108.5323 (2012)
[6] R. Lacey, Y. Gu, X. Gong, D. Reynolds, N. N. Ajitanand, J. M. Alexander, A. Mwai and A. Taranenko, arXiv 1207.1886 (2012).
[7] R. Snellings, J.Phys. G38 (2011) 124013.