Title	Measurement of the higher-order anisotropic flow coefficients for identified hadrons in Au + Au collisions at $\sqrt{s_{NN}}$= 200 GeV
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Citation	Physical Review C,93(5),p.051902_1-051902_8
Text Version	Publisher's Version
URL	https://jopss.jaea.go.jp/search/servlet/search?5057546
DOI	https://doi.org/10.1103/PhysRevC.93.051902
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PHYSICAL REVIEW C **93**, 051902(R) (2016)

Measurement of the higher-order anisotropic flow coefficients for identified hadrons in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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(Received 3 December 2014; revised manuscript received 13 July 2015; published 31 May 2016)

Measurements of the anisotropic flow coefficients $v_2\{\Psi_2\}$, $v_3\{\Psi_3\}$, $v_4\{\Psi_4\}$, and $v_4\{\Psi_2\}$ for identified particles ($\pi^{\pm}$, $K^{\pm}$, and $p+\bar{p}$) at midrapidity, obtained relative to the event planes Ψ_m at forward rapidities in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, are presented as a function of collision centrality and particle transverse momenta p_T. The v_n coefficients show characteristic patterns consistent with hydrodynamical expansion of the matter produced in the collisions. For each harmonic n, a modified valence quark-number N_q scaling [plotting $v_n\{\Psi_m\}/(N_q)^{n/2}$ versus transverse kinetic energies $(\mathrm{KE}_T)/N_q$] is observed to yield a single curve for all the measured particle species for a broad range of KE_T. A simultaneous blast-wave model fit to the observed $v_n\{\Psi_m\}(p_T)$ coefficients and published particle spectra identifies radial flow anisotropies $\rho_n\{\Psi_m\}$ and spatial eccentricities $s_n\{\Psi_m\}$ at freeze-out. These are generally smaller than the initial-state participant-plane geometric eccentricities $\varepsilon_n\{\Psi_m^{\mathrm{PP}}\}$ as also observed in the final eccentricity from quantum interferometry measurements with respect to the event plane.

DOI: 10.1103/PhysRevC.93.051902

Introduction. The quark-gluon plasma (QGP) is a novel phase of nuclear matter at high temperatures and energy density, whose existence is predicted by quantum chromodynamics [1]. A wide variety of experimental observations at the Relativistic Heavy Ion Collider (RHIC) [2–5] provides strong evidence for the formation of a QGP in ultrarelativistic heavy ion collisions, particularly (1) the magnitude of the observed suppression of high-p_T ($p_T \gtrsim 4$ GeV/c) particles, relative to the scaled yield from $p+p$ collisions and (2) the large azimuthal anisotropy or anisotropic flow of the low-p_T ($p_T \lesssim 3$ to 4 GeV/c) bulk of hadrons (HADs) in the final state. The flow of low-p_T particles has been attributed to anisotropic expansion of the QGP [6–8], and consequently the measured strength of anisotropic flow should be sensitive to the transport properties of the QGP and the mechanism for its space-time evolution.

The magnitude of anisotropic flow can be quantified by the Fourier coefficients $v_n\{\Psi_m\} = \langle\cos[n(\phi - \Psi_m)]\rangle$ of the azimuthal distribution of produced particles [9–12], where n and m are the order of the harmonics, ϕ is the azimuthal angle of the particles, and Ψ_m is the azimuthal angle of the mth-order event plane (EP). In early studies with symmetric systems, $v_n\{\Psi_m\}$ was presumed to be zero for odd n owing to the assumption that initial-state energy densities were smooth and symmetric across the transverse plane. The recent observations of sizable $v_n\{\Psi_n\}$ values for odd n [13–17] confirm the important role of fluctuations in the initial-state collision geometry [18].

Model-dependent analyses of higher-order harmonics for inclusive hadrons measured in Au + Au and Pb + Pb collisions at RHIC and the Large Hadron Collider have indicated that such measurements can provide simultaneous constraints for initial-state fluctuation models and the ratio of shear viscosity to entropy density of the QGP [8,13,19,20]. The new data on higher-order $v_n\{\Psi_m\}$ for identified particles presented here provide additional information about the initial conditions and hydrodynamic properties. Here, we show that our $v_n\{\Psi_m\}$ measurements for different particle species provide (1) further tests for the constituent quark-number scaling and quark coalescence models [21–23] by extending our previously observed scaling for $v_2\{\Psi_2\}$ [24,25] to higher harmonics [26] and (2) freeze-out parameters for hydrodynamic expansion with anisotropic blast-wave (BW) model fits [27–30].

Data taking and particle identification. The results presented here for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV are obtained with the PHENIX Collaboration's experiment from an analysis of 4.14×10^9 minimum-bias events taken during the 2007 running period. Collision centrality is determined with the beam-beam counters [31]. Charged hadrons are reconstructed in a pseudorapidity (η) range of $|\eta| < 0.35$ using the drift-chamber and pad-chamber subsystems [32], which achieve the momentum resolution $\delta p/p \approx 1.3\% \oplus 1.2\% \times p$ (GeV/c) [33]. The ring imaging Čerenkov counter is employed to veto conversion electrons. Time-of-flight detectors in both the east [(TOFE), $\Delta\varphi = \pi/4$ rad] and the west [(TOFW), $\Delta\varphi = 0.342$ rad] arms are used for $\pi^{\pm}$, $K^{\pm}$, and $p+\bar{p}$ identification after the conversion electron veto [33]. The timing resolution of TOFE (TOFW) is 133 (84 ± 1) ps. For $p_T < 3$ GeV/c, both TOFE and TOFW detectors were used. For $p_T > 3$ GeV/c particle identification utilizes the TOFW in conjunction with the aerogel Čerenkov counter. The two detectors have a common azimuthal acceptance of

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$\Delta\varphi = 0.171$ rad. With these detectors, a $p + \bar{p}$ purity of greater than 97% was achieved for $p_T < 4$ GeV/c; and purities for $\pi^{\pm}$ and $K^{\pm}$ greater than 98% for $p_T < 3$ GeV/c and 90% for $3 < p_T < 4$ GeV/c were also achieved as detailed in Ref. [33]. The purity and efficiency of particle identification (PID) are independent of the relative azimuthal angle between the particles and the event plane $\phi - \Psi_m$.

Experimental technique. Measurements of the flow coefficients $v_2\{\Psi_2\}$, $v_3\{\Psi_3\}$, $v_4\{\Psi_4\}$, and $v_4\{\Psi_2\}$ as a function of centrality and p_T for $\pi^{\pm}$, $K^{\pm}$, and $p + \bar{p}$ (i.e., with charge signs combined) are obtained with both the EP and the long-range two-particle correlation (2PC) methods. In the EP method, a measured event-plane direction Ψ_m^{obs} is determined for every event and for each order m using the south and north reaction-plane detectors (RXN), covering $\Delta\varphi = 2\pi$ and $1 < |\eta| < 2.8$ [34]. Each is made of plastic scintillator paddles with lead converters in front and with optical fibers guided to photomultiplier tubes. Each RXN detector is segmented into 12 sections in φ and two rings in η. The Ψ_m^{obs}'s are determined via a sum over the azimuthal angle ϕ_i of each RXN element in both the arms with its charge w_i deposited by particles for that event as $\tan(m\Psi_m^{\text{obs}}) = \sum_i w_i \sin(m\phi_i)/\sum_i w_i \cos(m\phi_i)$. The flow magnitudes $v_n\{\Psi_m\} = \langle \cos n(\phi - \Psi_m^{\text{obs}})\rangle/\text{Res}\{n,\Psi_m\}$ are then measured with respect to each harmonic event plane, where ϕ is the azimuthal angle of the hadron and $\text{Res}\{n,\Psi_m\} = \langle \cos n(\Psi_m - \Psi_m^{\text{obs}})\rangle$ is the event plane resolution, which is estimated for each centrality by the standard subevent method as described in Refs. [10,35,36]. The best resolution of each harmonic is measured to be $\text{Res}\{2,\Psi_2\} \sim 0.75$ and $\text{Res}\{4,\Psi_2\} \sim 0.5$ ($\text{Res}\{3,\Psi_3\} \sim 0.3$ and $\text{Res}\{4,\Psi_4\} \sim 0.15$) in 20%–30% (0%–10%) central collisions.

The 2PC method pairs the HADs with deposited charges in the RXN segments. The distribution of the relative azimuthal angles of particle hits in separate η ranges A and $B, \Delta\phi \equiv \phi^A - \phi^B$ reflects the product of the v_n's via $dN/d\,\Delta\phi \propto 1 + \sum_{n=1} 2 v_n^A v_n^B \cos(n\,\Delta\phi)$ [10,37,38]. We analyze the $\Delta\phi$ correlations using the mixed-event technique for two pair combinations $(A,B) = (\text{HAD},\text{RXN})$ and $(A,B) = (\text{RXN-N},\text{RXN-S})$. These correlations then fix the event-averaged products $\langle v_n^{\text{HAD}} v_n^{\text{RXN}}\rangle$ and $\langle v_n^{\text{RXN}} v_n^{\text{RXN}}\rangle$ and allow us to obtain $v_n^{\text{HAD}} = \langle v_n^{\text{HAD}} v_n^{\text{RXN}}\rangle/\sqrt{\langle v_n^{\text{RXN}} v_n^{\text{RXN}}\rangle}$. Note that flow harmonics extracted with the 2PC method are not measured with respect to event planes. Thus, from this point forward we refer to flow harmonics in the 2PC methods as $v_n\{\text{2PC}\}$. We use v_n in cases when the discussion is generically about either method. In both of the analysis methods used, the results for wider centrality ranges are obtained by averaging across several smaller ranges, weighted by the multiplicity of the selected particle [39].

The systematic uncertainties in the v_n measurements were estimated for: (1) η acceptance variation of the RXNs in the EP and 2PC methods; this is correlated among $v_n(p_T)$'s for each hadron species with the same fractional v_n amount in the entire p_T range, except for $v_4\{\Psi_4\}$ where it tends to decrease as p_T increases; (2) detector acceptance effects of TOFE and TOFW, including occupancy; these are correlated among $v_n(p_T)$'s for each hadron species with the same v_n constant in the entire p_T range; (3) hadron track-hit matching cut; and (4) particle identification purity. The systematic uncertainties (1) and (2) are p_T correlated, whereas (3) and (4) are p_T uncorrelated. These uncertainties are similar between the EP and the 2PC methods. Table I summarizes typical systematic uncertainties on the different $v_n\{\Psi_m\}$ measures in the EP method for $\pi^{\pm}$ at $p_T = 2$ GeV/c.

TABLE I. Systematic uncertainties on the measured $v_n\{\Psi_m\}$ by the EP method for $\pi^{\pm}$ at $p_T = 2$ GeV/c in 0%–10% (30%–50%) central collisions. Uncertainties of type (2) are absolute in the $v_n\{\Psi_m\}$ value with the multiplication factor 10^{-3}; the others are relative fractions of $v_n\{\Psi_m\}$ expressed in percentages.

Type	Source	$v_2\{\Psi_2\}$	$v_3\{\Psi_3\}$	$v_4\{\Psi_4\}$	$v_4\{\Psi_2\}$
(1)	RXN η (%)	4.3(3.0)	4.7(12.5)	16(31)	34(7.0)
(2)	Acceptance [10^{-3}]	5.0(1.0)	0.5(2.0)	0.7(2.5)	0.1(0.2)
(3)	Matching (%)	1.4(0.3)	0.7(1.0)	2.6(2.8)	7.7(1.7)
(4)	PID (%)	0.3(0.1)	0.3(0.3)	0.8(1.0)	2.7(0.4)

Results for the 0%–50% centrality bin. Figures 1(a)–1(c) show a comparison of $v_2(p_T)$, $v_3(p_T)$, and $v_4(p_T)$ for $\pi^{\pm}$, $K^{\pm}$, and $p + \bar{p}$ for the EP (solid points) and 2PC (open points) methods in a 0%–50% centrality sample; they indicate very good agreement between the two methods. Shown in Fig. 1(d) is $v_4\{\Psi_2\}$, i.e., the fourth harmonic coefficient with respect to the second-order harmonic event plane. It can be seen that $v_4\{\Psi_2\}$ is smaller than $v_4\{\Psi_4\}$ but still sizable, indicating significant correlations between Ψ_2 and Ψ_4 [40], which can be ascertained through the trigonometric identity $v_4\{\Psi_2\}/v_4\{\Psi_4\} = \langle \cos 4(\Psi_2 - \Psi_4)\rangle$ [41]. There are two trends common to all n's in Fig. 1: (1) in the low-p_T region the anisotropy appears largest for the lightest hadron and

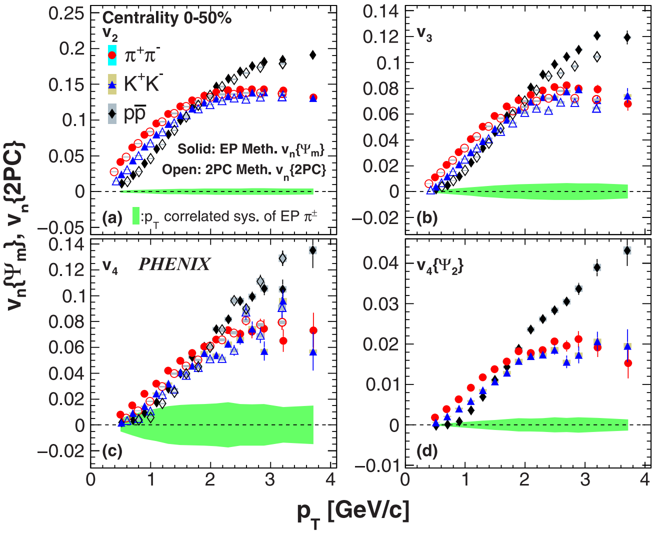

FIG. 1. Fourier coefficients for charge-combined $\pi^{\pm}$, $K^{\pm}$, and $p + \bar{p}$ at midrapidity for 0%–50% central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Different p_T bins were used for the EP and 2PC methods. The green bands indicate the p_T -correlated systematic uncertainties of the $\pi^{\pm}$ results from the EP method. The shaded boxes around the data points are p_T -uncorrelated systematic uncertainties, which are smaller than the symbols in many cases.

smallest for the heaviest hadron, and (2) in the intermediate-p_T ($3 \lesssim p_T \lesssim 4$-GeV/$c$) region this mass dependence partly reverses such that the anisotropy is greater for the baryons ($N_q = 3$) than for the mesons ($N_q = 2$) at the same p_T. These trends remain significant after taking into account the p_T-correlated systematic uncertainties. These patterns have been observed previously in $v_2\{\Psi_2\}$ measurements for identified particles in Au + Au collisions at RHIC [29,33] and are seen here to hold for the higher moments $v_3\{\Psi_3\}$, $v_4\{\Psi_4\}$, and $v_4\{\Psi_2\}$. The mass dependence in the low-p_T range is a generic feature of hydrodynamical models, reflecting the mass ordering from the common velocity field (i.e., radial flow), and the dependence on valence quark number in the intermediate-p_T region has been associated with the development of flow in the partonic phase [24].

Results for finer centrality bins. The $v_n\{\Psi_m\}$ of $\pi^\pm$, $K^\pm$, and $p + \bar{p}$ measured with the event-plane method are shown in Fig. 2 for the centrality selections 0%–10% and 30%–50%. The same mass dependence of $v_n\{\Psi_m\}$ is seen in the low-p_T region for all harmonics and centralities. The evolution of baryon-meson splitting at intermediate p_T is also observed for all centralities in $v_2\{\Psi_2\}$ and $v_3\{\Psi_3\}$ but could not be confirmed for $v_4\{\Psi_4\}$ in the most-central and more peripheral events or for $v_4\{\Psi_2\}$ in the most-central events owing to the lower statistical significance of the measurements in those bins.

Quark-number scaling. The baryon-meson splitting in the intermediate-p_T region can be taken as an indication that the number of constituent valence quarks N_q is an important determinant of final-state hadron flow in this range. Indeed, the $v_2\{\Psi_2\}$ data for identified hadrons had previously been seen to scale such that $v_2\{\Psi_2\}/N_q$ was the same for different particle species when evaluated at the same transverse kinetic energy (KE$_T$) per constituent quark number in the range of $\mathrm{KE}_T/N_q \lesssim 1$ GeV ($\mathrm{KE}_T \equiv m_T - m_0$ and $m_T \equiv \sqrt{{p_T}^2 + m_0^2}$, where m_0 is the hadron mass), i.e., "quark-number scaling" [24,33]. We have found that the present data obey a generalization of this scaling [26] where for each harmonic order n, the values of $v_n\{\Psi_m\}/(N_q)^{n/2}$ versus KE_T/N_q lie on a single curve for all the measured species within a ±15% range. Figure 3 shows the adherence of the data to this empirical scaling, which reflects the combination of quark-number scaling for $v_2\{\Psi_2\}$ by quark coalescence [42] and the empirical observation $v_n\{\Psi_n\}(p_T) \propto [v_2\{\Psi_2\}(p_T)]^{n/2}$ [15]. Any explanation of the underlying physics needs to match this scaling over this KE$_T$ range, and neither hydrodynamics [11,20,43,44] nor naive quark coalescence alone [45] predicts this scaling for the higher moments. It is notable that, for $v_2\{\Psi_2\}$, there are deviations from valence-quark scaling at higher p_T with mesons and baryons having comparable anisotropies [33]. Reconciling the different physics as a function of p_T remains an outstanding challenge.

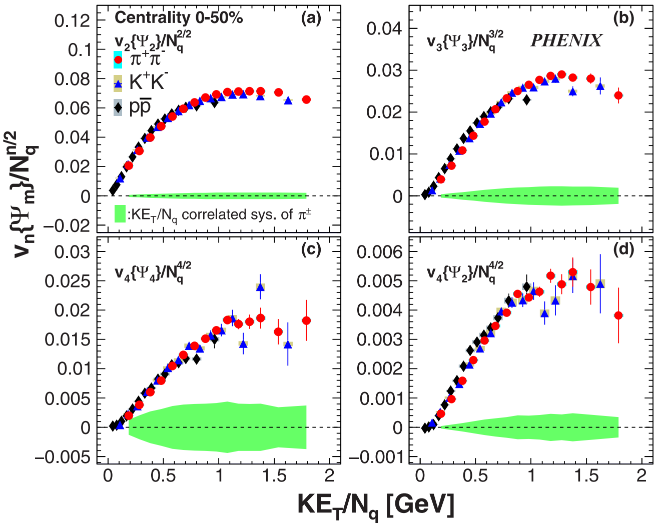

FIG. 3. Quark-number (N_q) scaling for 0%–50% central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, where N_q is the constituent valence quark number of each hadron. Systematic uncertainties are shown as in Fig. 1.

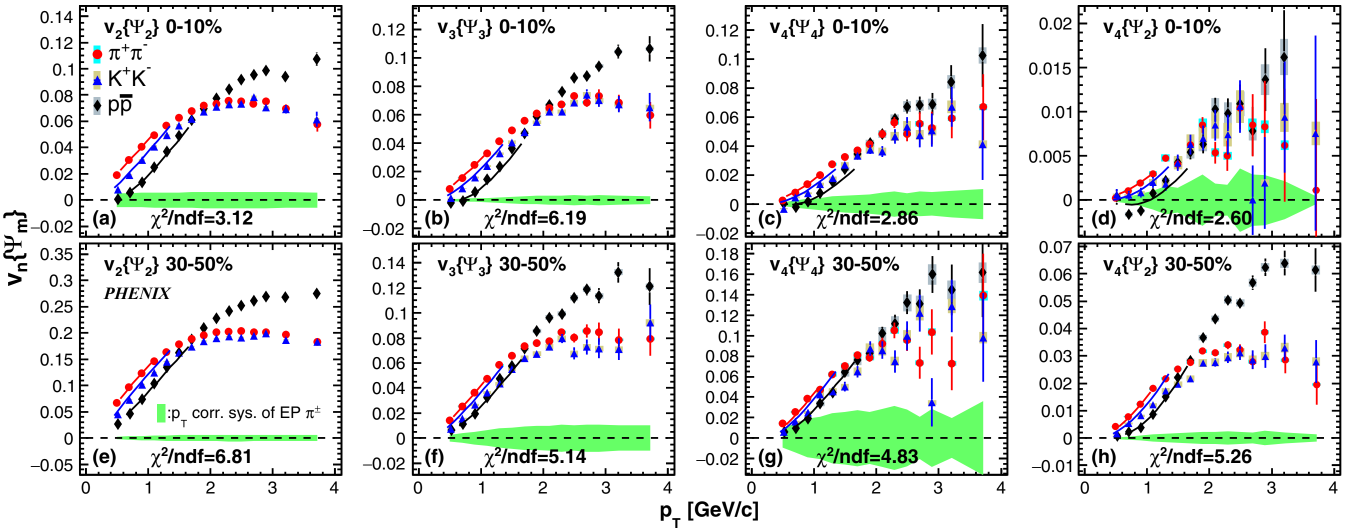

FIG. 2. Fourier coefficients for charge-combined $\pi^\pm$, $K^\pm$, and $p + \bar{p}$ at midrapidity in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Coefficients are determined using the event-plane method. The curves illustrate the fits from the BW model. Systematic uncertainties are shown as in Fig. 1.

Blast-wave fitting. The BW model [27–30] is a description of a fluid freeze-out state characterized by its temperature T_f and its ϕ-averaged maximal radial flow rapidity ρ_0. Here we extend the BW description to incorporate azimuthal anisotropies in both radial rapidities $\rho_n\{\Psi_m\}$ and spatial density $s_n\{\Psi_m\}$ for $n = 2$–4 using the empirically defined quantities $\rho(n,m,\phi,r) = \rho_0[1 + 2\rho_n\{\Psi_m\}\cos(n\phi)] \times r/R^{\max}$ and $S(n,m,\phi) = 1 + 2s_n\{\Psi_m\}\cos(n\phi)$. The spectra and anisotropies of all hadrons freezing out of the fluid can then be predicted via [28,29]

$$\frac{dN}{p_T dp_T} \propto \int^{R^{\max}} r\,dr \int d\phi\; m_T I_0(\alpha_t) K_1(\beta_t),$$

$$v_n\{\Psi_m\} = \frac{\int^{R^{\max}} r\,dr \int d\phi\, \cos(n\phi) I_n(\alpha_t) K_1(\beta_t) S(n,m,\phi)}{\int^{R^{\max}} r\,dr \int d\phi\, I_0(\alpha_t) K_1(\beta_t) S(n,m,\phi)}, \tag{1}$$

where I_n and K_1 are modified Bessel functions of the first and second kinds, $\alpha_t = (p_T/T_f)\sinh\rho(n,m,\phi,r)$, and $\beta_t = (m_T/T_f)\cosh\rho(n,m,\phi,r)$. Using single-particle spectra from Ref. [46] together with the present $v_n\{\Psi_m\}$ data, BW parameters $T_f, \rho_0, \rho_n\{\Psi_m\}$ and $s_n\{\Psi_m\}$ are extracted via simultaneous fitting of the $\pi^\pm$, $K^\pm$, and $p + \bar{p}$ data with a minimization of global χ^2, separately for each centrality selection and each $v_n\{\Psi_m\}$. The fit ranges used for the $\pi^\pm$, $K^\pm$, and $p + \bar{p}$ are $0.5 < p_T < 1.1$ GeV/c, $0.4 < p_T < 1.3$ GeV/c, and $0.6 < p_T < 1.7$ GeV/c, respectively. The BW fits to $v_n\{\Psi_m\}(p_T)$ + spectra are compared to the data in Fig. 2 for 0%–10% and 30%–50% central collisions, together with the global $\chi^2/n\,df$ of the fits determined using the quadrature sum of the statistical and systematic uncertainties of the data. The global $\chi^2/n\,df$ in 10%–20% and 20%–30% central collisions is similar to that in 0%–10% and 30%–50% central collisions.

The results for the BW parameters are shown in Fig. 4. The freeze-out temperatures T_f and radially averaged flow rapidities $\langle\rho\rangle = \int[\rho_0 \times r/R_{\max}] r\,dr / \int r\,dr$ are in good agreement for the fits at different n's as would be required for a model of freeze-out. T_f and $\langle\rho\rangle$ are primarily determined by the single-particle spectra [47], whereas $\rho_n\{\Psi_m\}$ and $s_n\{\Psi_m\}$ are determined by $v_n\{\Psi_m\}$ measurements including p_T and particle mass dependences.

The radial rapidity and spatial density anisotropies $\rho_n\{\Psi_m\}$ and $s_n\{\Psi_m\}$ extracted from the fits are shown against the average initial-state spatial participant-plane (PP) anisotropy $\varepsilon_n\{\Psi_m^{\rm PP}\} = \langle\{r^2 \cos n(\phi^{\rm part} - \Psi_m^{\rm PP})\}/\{r^2\}\rangle$, where r and $\phi^{\rm part}$ are the polar coordinate positions of collision participant nucleons defined by Glauber models [18,48] and $\Psi_m^{\rm PP}$ is the angle determined as $\tan(m\Psi_m^{\rm PP}) = \{r^2 \sin m\phi^{\rm part}\}/\{r^2 \cos m\phi^{\rm part}\}$. Here, the brackets $\langle\,\rangle$ and $\{\,\}$ denote averages over events and participants, respectively. The amplitude of $\varepsilon_n\{\Psi_m^{\rm PP}\}$ is smallest for the most-central collisions and increases with centrality percentile.

Eccentricity of the medium at freeze-out. The $\rho_n\{\Psi_m\}$ and $s_n\{\Psi_m\}$ are generally smaller than the $\varepsilon_n\{\Psi_m^{\rm PP}\}$. The $\rho_n\{\Psi_m\}$ has a positive finite value and generally follows a common increasing curve as a function of $\varepsilon_n\{\Psi_m^{\rm PP}\}$ for $n = 2$–4. The $s_2\{\Psi_2\}$, $s_3\{\Psi_3\}$, and $s_4\{\Psi_4\}$ also show a common increasing trend in $\varepsilon_n\{\Psi_m^{\rm PP}\} \gtrsim 0.1$. We can interpret relative oscillations of event-plane-dependent Hanbury-Brown-Twiss (HBT) radii with respect to averaged radii as the eccentricity of the medium at freeze-out if the direction of the radii is selected perpendicular to beam and pair momentum ($R_{\rm side}$) where these radii are less influenced by the emission duration and position-momentum correlations [49].

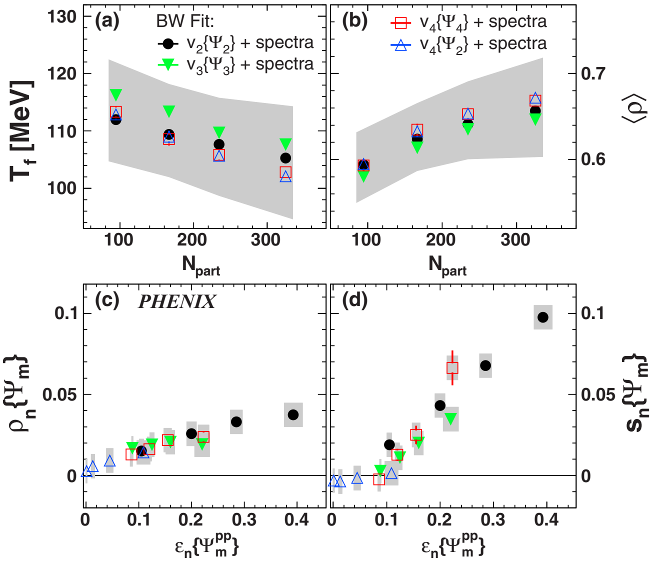

FIG. 4. BW model fit parameters extracted for each $v_n\{\Psi_m\}$ + spectrum across different centrality classes. The gray bands in (a) and (b) and shaded boxes in (c) and (d) indicate systematic uncertainties on the fitting p_T range and those propagated from the measurements. The width of the shaded boxes in the $\varepsilon_n\{\Psi_m^{\rm PP}\}$ direction in (c) and (d) indicates systematic uncertainties from Glauber models. Systematic uncertainties in (a) and (b) are similar among different fittings.

Spatial information. Finite final eccentricities for $n = 2$ and $n = 3$ are observed by both the BW fit to $v_n\{\Psi_m\}$ and the event-plane-dependent HBT radii measurements using positive and negative pion pairs [49]. The $s_n\{\Psi_m\}$ therefore could reflect physical effects at the freeze-out of the medium. The finite $s_n\{\Psi_m\}$ could be interpreted as a residual effect of initial-state anisotropy $\varepsilon_n\{\Psi_m^{\rm PP}\}$, especially the contribution of initial-state fluctuations for $n = 3,4$ after its dilution by the medium expansion. For $\varepsilon_n\{\Psi_m^{\rm PP}\} \lesssim 0.1$, $s_3\{\Psi_3\}$, $s_4\{\Psi_4\}$, and $s_4\{\Psi_2\}$ are consistent with zero within systematic uncertainties. Comparisons of these small $s_n\{\Psi_m\}$ to the finite $\rho_n\{\Psi_m\}$ and $v_n\{\Psi_m\}$ in this $\varepsilon_n\{\Psi_m^{\rm PP}\}$ range indicate that the anisotropic expansion velocity $\rho_n\{\Psi_m\}$ is a dominant source of the observed $v_n\{\Psi_m\}$ for higher harmonics. We expect this spatial information could provide new insights into freeze-out conditions in hydrodynamic calculations.

Summary and conclusions. To summarize, the anisotropy strengths $v_2\{\Psi_2\}$, $v_3\{\Psi_3\}$, $v_4\{\Psi_4\}$, and $v_4\{\Psi_2\}$ for $\pi^\pm$, $K^\pm$, and $p + \bar{p}$ produced at midrapidity in Au + Au collisions at RHIC have been presented. The higher-order harmonics $v_n\{\Psi_m\}$ show a particle mass splitting at low p_T and a baryon-meson difference at intermediate p_T, very similar to what has been seen already for $v_2\{\Psi_2\}$. The anisotropies obey a modified quark-number scaling, where $v_n\{\Psi_m\}/(N_q)^{n/2}$ falls on a common trend against KE$_T/N_q$ for each n. The data can be fit with a generalized BW model with empirically defined anisotropies in radial rapidity and spatial density at higher harmonic orders, which could provide a geometrical view of the hydrodynamical expansion at the end of freeze-out. Future analyses combining the results in this Rapid Communication with similar results from HBT and jetlike correlations with respect to higher-order event planes will further constrain the conditions and properties of the matter created at RHIC.

Acknowledgments. We thank the staff of the Collider-Accelerator and Physics Departments at Brookhaven National Laboratory and the staff of the other PHENIX Collaboration participating institutions for their vital contributions. We acknowledge support from the Office of Nuclear Physics in the Office of Science of the Department of Energy, the National Science Foundation, Abilene Christian University Research Council, Research Foundation of SUNY, and Dean of the College of Arts and Sciences, Vanderbilt University (USA), Ministry of Education, Culture, Sports, Science, and Technology and the Japan Society for the Promotion of Science (Japan), Conselho Nacional de Desenvolvimento Científico e Tecnológico and Fundação de Amparo à Pesquisa do Estado de São Paulo (Brazil), Natural Science Foundation of China (People's Republic of China), Ministry of Education, Youth and Sports (Czech Republic), Centre National de la Recherche Scientifique, Commissariat à l'Énergie Atomique, and Institut National de Physique Nucléaire et de Physique des Particules (France), Bundesministerium für Bildung und Forschung, Deutscher Akademischer Austausch Dienst, and Alexander von Humboldt Stiftung (Germany), National Science Fund, OTKA, Károly Róbert University College, the Ch. Simonyi Fund (Hungary), Department of Atomic Energy and Department of Science and Technology (India), Israel Science Foundation (Israel), Basic Science Research Program through NRF of the Ministry of Education (Korea), Physics Department, Lahore University of Management Sciences (Pakistan), Ministry of Education and Science, Russian Academy of Sciences, Federal Agency of Atomic Energy (Russia), VR and Wallenberg Foundation (Sweden), the U.S. Civilian Research and Development Foundation for the Independent States of the Former Soviet Union, the U.S.-Hungarian Fulbright Foundation for Educational Exchange, and the U.S.-Israel Binational Science Foundation.

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