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Elliptic and Hexadecapole Flow of Charged Hadrons in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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Differential measurements of the elliptic (v_2) and hexadecapole (v_4) Fourier flow coefficients are reported for charged hadrons as a function of transverse momentum (p_T) and collision centrality or number of participant nucleons ($N_{\rm part}$) for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The $v_{2,4}$ measurements at pseudorapidity $|\eta| \leq 0.35$, obtained with four separate reaction-plane detectors positioned in the range $1.0 < |\eta| < 3.9$, show good agreement, indicating the absence of significant $\Delta\eta$-dependent nonflow correlations. Sizable values for $v_4(p_T)$ are observed with a ratio $v_4(p_T, N_{\rm part})/v_2^2(p_T, N_{\rm part}) \approx 0.8$ for $50 \lesssim N_{\rm part} \lesssim 200$, which is compatible with the combined effects of a finite viscosity and initial eccentricity fluctuations. For $N_{\rm part} \gtrsim 200$ this ratio increases up to 1.7 in the most central collisions.

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The discovery of large azimuthal anisotropy at the Relativistic Heavy Ion Collider (RHIC) is a key piece of evidence for the creation of dense partonic matter in ultrarelativistic nucleus-nucleus collisions [1,2]. With sufficiently strong interactions, the medium in the collision zone can be expected to locally equilibrate and exhibit hydrodynamically driven flow [3–5]. The momentum anisotropy results from an initial "almond-shaped" collision zone produced in noncentral collisions [3,4]. It is now routinely characterized, at midrapidity, by the even order Fourier coefficients $v_n = \langle e^{i\,n(\phi_p - \Phi_{\rm RP})} \rangle$, $n = 2, 4, \ldots$, where ϕ_p is the azimuthal angle of an emitted particle, $\Phi_{\rm RP}$ is the azimuth of the reaction plane and the brackets denote averaging over particles and events.

At the highest RHIC collision energy of $\sqrt{s_{NN}} = 200$ GeV, differential elliptic flow measurements $v_2(p_T)$ (for transverse momentum $p_T \lesssim 2.5$ GeV$/c$) and $v_2(N_{\rm part})$ have been measured for a broad range of centralities or number of participants $N_{\rm part}$. These data are found to be in accord with calculations that model an essentially locally equilibrated quark gluon plasma (QGP) having little or no viscosity [4,6–8]. Quark number scaling of elliptic flow data (suggestive of partonic degrees of freedom in the collision zone) is observed for a broad range of particle species, collision centralities, and transverse kinetic energy [9,10]. Small violations of the scaling of $v_2(N_{\rm part})$ with the initial eccentricity of the collision zone ε, suggest a strongly-coupled low-viscosity plasma ($4\pi\frac{\eta}{s} \sim 1 - 2$ for the ratio of viscosity η to entropy density s) in energetic Au + Au collisions [11–13]. Nonetheless, the degree to which the QGP is thermalized [14], and whether it is strongly or weakly coupled [5,15], is still being debated.

Recent theoretical studies indicate that the hexadecapole flow harmonic v_4 is a more sensitive constraint on the magnitude of $\frac{\eta}{s}$ and the freeze-out dynamics [16], and the ratio $v_4/(v_2)^2$ can indicate whether full local equilibrium is achieved in the QGP [17]. The role of fluctuations and so-called "nonflow" correlations is important for such measurements. It is well established that initial eccentricity fluctuations significantly influence the magnitudes of $v_{2,4}$ [18–22]. However, the precise role of nonflow, which leads to a systematic error in the determination of $v_{2,4}$ is less clear. Nonflow correlations among produced particles may arise from jets, whose influence is found to vary with pseudorapidity η and p_T [23]. This provides a tool to evaluate how jets influence the measurements presented here.

We report precise measurements of charged hadron v_2 and v_4 in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The measurements were performed in the two PHENIX central arms ($|\eta| \leq 0.35$) with respect to event planes obtained from four separate reaction-plane detectors in the range $1.0 < |\eta| < 3.9$. Multiple event planes allow a search for possible $\Delta\eta$-dependent nonflow contributions that would influence the magnitude of $v_{2,4}$, which may be crucial for reliable extraction of transport coefficients.

The results reported here are derived from $\sim 3.6 \times 10^9$ minimum-bias Au + Au events obtained at $\sqrt{s_{NN}} = 200$ GeV with the PHENIX detector [24] during the 2007 running period. The event centrality was determined via cuts on the analog response of the Beam-Beam Counters (BBC). For each centrality selection, the number of participant nucleons $N_{\rm part}$, was estimated via a Glauber model Monte Carlo simulation [25]. The drift chambers and two layers of multiwire proportional chambers with pad readout (PC1 and PC3) were used for charged particle tracking and momentum reconstruction with azimuthal coverage $\Delta\varphi = \pi/2$ in the central region ($|\eta| \leq 0.35$). Tracks were required to have $E/p_T > 0.1$ and a confirmation hit within a 2σ matching window in PC3 and the electromagnetic calorimeters (E denotes the energy deposited in the electromagnetic calorimeters). This minimized albedo, conversions, and weak decay products.

The event-plane method [26] was used to correlate the azimuthal angles ϕ_p of the charged tracks in the PHENIX central arms ($|\eta| \leq 0.35$) with the azimuth of the estimated second order event plane Φ_2, determined via hits in the two BBCs and muon piston calorimeters (MPCs), and the two inner (i), outer (o) and combined (io) rings of newly installed reaction-plane detectors (RXN). The two RXNs are situated at $|z| = 38$–40 cm of the nominal crossing point and their inner and outer rings are comprised of 12 plastic scintillators ($\Delta\phi = \pi/6$ for each). The MPCs are $\mathrm{PbWO_4}$ based electromagnetic calorimeters with 2π azimuthal acceptance. The respective η coverage for these event-plane detector pairs are $3.1 < |\eta_{\mathrm{BBC}}| < 3.9$, $3.1 < |\eta_{\mathrm{MPC}}| \lesssim 3.7$, $1.5 < |\eta_{\mathrm{RXN}_i}| < 2.8$, and $1.0 < |\eta_{\mathrm{RXN}_o}| < 1.5$. For a given pair the detector, which is located at positive (negative) η, is designated North (N) [South (S)].

Charge-averaged values for the second and fourth flow harmonics were evaluated separately for each estimated event plane i as

$$v_{2k}^{i} = \frac{\langle\cos[2k(\phi_p - \Phi_2^i)]\rangle}{\mathrm{Res}(\Psi_{2k}^i)} \qquad k = 1, 2, \qquad (1)$$

where the denominator represents a resolution factor that corrects for the difference between the true azimuth Φ_{RP} and the 2nd order estimate Φ_2^i of the event plane. This estimate was obtained from the combined subevents (North and South) for each detector pair. Resolution factors were evaluated via the three-sub-events method [26,27]

$$\mathrm{Res}\,(\Psi_{2k}^i) = \sqrt{\frac{\langle\cos[2k(\Phi_2^i - \Phi_2^l)]\rangle\langle\cos[2k(\Phi_2^i - \Phi_2^m)]\rangle}{\langle\cos[2k(\Phi_2^l - \Phi_2^m)]\rangle}}, \qquad (2)$$

where i, l, and m indicate event and subevent planes with disparate η values (eg., $i = \mathrm{RXN}_{io}$, $l = \mathrm{MPC}_N$, and $m = \mathrm{BBC}_S$). An advantage of this procedure is that, for any given centrality, it allows several independent estimates of $\mathrm{Res}(\Psi_{2,4})$ for each event plane. In turn, such estimates allow an evaluation of the systematic errors for $\mathrm{Res}(\Psi_{2,4}^i)$. It is noteworthy that estimates for these correction factors were also obtained (for $k = 1$ and 2) via the two-sub-events method [26,27], which is regularly used for elliptic flow analysis. For RXN the difference between both methods is small for v_2, i.e., ~1% for midcentral collisions and ~5% for the most central and peripheral collisions. For v_4, it is ~2% for midcentral collisions and grows to ~7% and 20% in the most peripheral and central collisions, respectively.

Figure 1 shows the centrality dependence of $\langle\mathrm{Res}(\Psi_2)\rangle$ and $\langle\mathrm{Res}(\Psi_4)\rangle$ for several event planes. Similar maxima are observed for $N_{\mathrm{part}} \approx 200$ with a falloff at lower and higher N_{part}. Measurements with the RXN_{io} event plane benefit from about a factor of 2 (5) improvement in the resolution for v_2 (v_4) compared to prior PHENIX measurements with the BBC event plane [26].

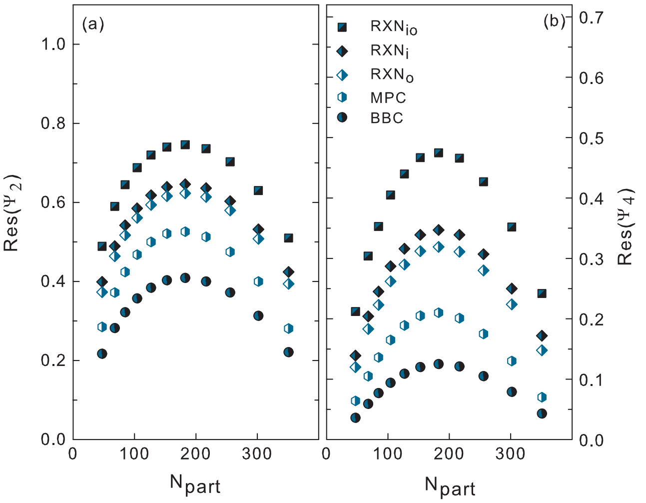

FIG. 1 (color online). Event-plane resolution factors vs N_{part} for v_2 (a) and v_4 (b) measurements for the indicated event planes.

The systematic errors associated with the RXN_{io} resolution factors for v_2 (v_4) are estimated to be less than 2% (6%) for midcentral collisions but increase to about 3% (10%) in the most central and peripheral collisions. Similar estimates were obtained for the RXN_i and RXN_o event planes. On average, those for the BBC and the MPC event planes are about a factor of 2 larger. Other sources, such as

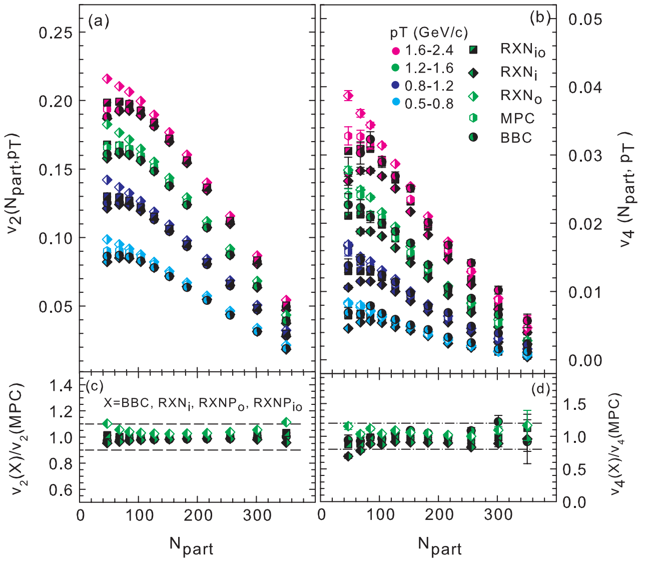

FIG. 2 (color online). Comparison of v_2 vs N_{part} (a) and v_4 vs N_{part} (b) for charged hadrons obtained with several reaction-plane detectors for the p_T selections indicated. Ratios for the p_T range 1.2–1.6 GeV/c are shown in (c) and (d); the curves indicate ±10% and ±20% systematic error bands.

track cuts, are estimated to range from ~1–2% (3–4%) for $p_T \gtrsim 0.5$ GeV/c to ~5% (10%) for the lowest p_T values.

Figures 2(a) and 2(b) compare the double differential flow coefficients $v_{2,4}(p_T, N_{\rm part})$ for event-plane detectors spanning the range $1.0 < |\eta| < 3.9$. Within systematic errors, they agree to better than ~5% (10%) for v_2 (v_4) in midcentral collisions and approximately 10% (20%) in central and peripheral events [c.f., ratios in Figs. 2(c) and 2(d)] independent of p_T. This agreement indicates a reliable measurement free of significant $\Delta\eta$- and p_T-dependent nonflow contributions (for $p_T \lesssim 3$ GeV/c), which would affect v_2 and v_4 (very little influence is expected from a possible $\Delta\eta$-independent long-range correlation [28]). Nonflow correlations, such as from dijets, would lead to a difference in the v_2 (v_4) values obtained with event planes determined at different rapidity gaps ($\Delta\eta$) with respect to the central arms [23]. In the following we utilize the RXN$_{io}$ event plane due to its good resolution. The associated systematic error for v_2 (v_4) is estimated to be ≈ 3% (8%) for midcentral collisions and increase to about 7% (15%) in the most peripheral and central collisions.

Figures 3 and 4 summarize the results for elliptic and hexadecapole flow. The magnitude and trends agree well with those reported earlier [1,2]. However they now benefit from a factor of 5 increase in statistics, as well as improved precision (~2) in the event plane. Figures 3(a) and 3(b) compare the measured charged hadron differential $v_2(p_T)$ and $v_4(p_T)$, as a function of centrality. In contrast to the approximately linear dependence observed in Fig. 3(a) for $p_T \lesssim 1.5$ GeV/c, the v_4 data exhibit a nonlinear dependence on p_T compatible with the prediction from hydrodynamics that $v_4 \propto v_2^2$ [29]. The large increase (~ ×6) from central to peripheral collisions reflects the expected increase due to the change in initial eccentricity from central to peripheral events [17,30].

Figure 4 compares the $v_2(N_{\rm part})$ (a) and $v_4(N_{\rm part})$ (b) for several p_T selections as indicated. The $N_{\rm part}$ values are mean values evaluated for the centrality selections indicated in Fig. 3. Here, the data trends in (a) and (b) are strikingly similar albeit with a much smaller magnitude in (b). The magnitude and trends with p_T and $N_{\rm part}$ in Figs. 4(a) and 4(b) follow expectations for a hydrodynamically expanding low-viscosity fluid [5,7,8,11–13].

The ratio $v_4/(v_2)^2$ is shown as a function of $N_{\rm part}$ in Fig. 4(c) for the same p_T selections used in (a) and (b); systematic errors are ≈4%–5% for midcentral collisions and increase to 8%–10% for central and peripheral collisions. Within errors, these data indicate that the magnitude of $v_4/(v_2)^2$ is essentially independent of p_T for the range 0.5–3.6 GeV/c, i.e., extending beyond the maxima in Fig. 3(a). An approximately constant ratio of value

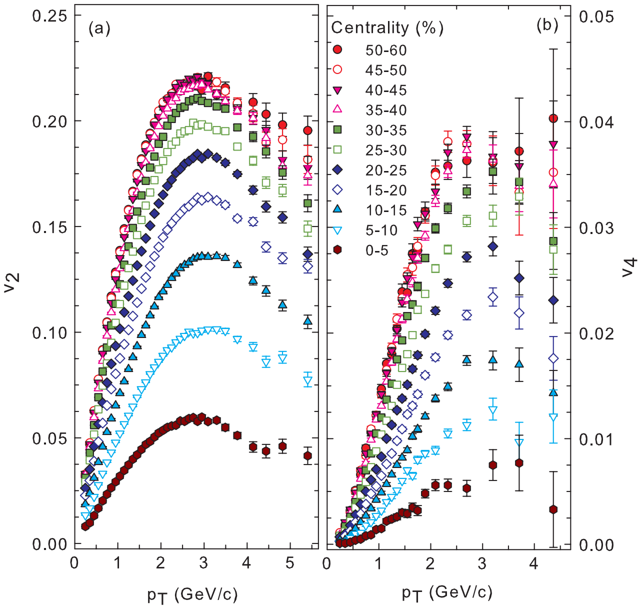

FIG. 3 (color online). p_T dependence of v_2 (a) and v_4 (b) for charged hadrons for several centrality selections as indicated. The error bars only indicate statistical errors.

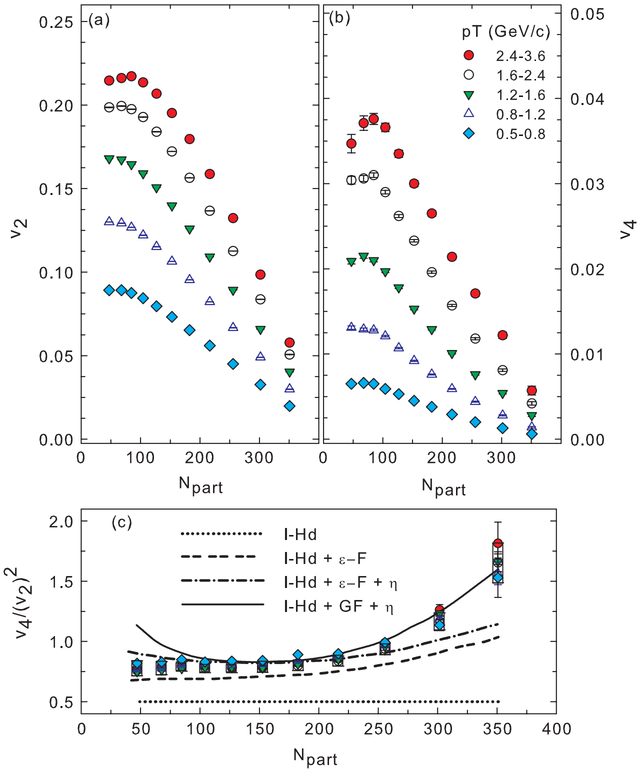

FIG. 4 (color online). v_2 vs $N_{\rm part}$ (a) and v_4 vs $N_{\rm part}$ (b) for charged hadrons for several p_T selections as indicated. Panel (c) shows the ratio $v_4/(v_2)^2$ vs $N_{\rm part}$ for the same p_T selections. The open boxes indicate systematic errors for the selection $1.6 < p_T < 2.4$ GeV/c. The curves show calculated results for ideal hydrodynamics (I-Hd), I-Hd + eccentricity fluctuations (ε-F), I-Hd + $\varepsilon - F$ + viscosity (η), and I-Hd + η + Gaussian Fluctuations (GF) (see [22]).

$v_4(p_T, N_{\text{part}})/v_2^2(p_T, N_{\text{part}}) \approx 0.8$ is observed for $50 \lesssim N_{\text{part}} \lesssim 200$, which is larger than the ratio ≈ 0.5 for ideal hydrodynamics in the model of [22]. The inclusion of eccentricity fluctuations in this model, cause this ratio to exceed 0.5 as shown by the dashed curve (from [22]) in Fig. 4(c). Viscosity from the hadron gas phase, in addition to a small value in the quark gluon plasma ($4\pi\frac{\eta}{s} \sim 2$) [12], results in a further increase of this ratio as indicated by the dash-dotted curve [22].

Our $v_4(p_T, N_{\text{part}})/v_2^2(p_T, N_{\text{part}})$ ratio is smaller than the centrality-averaged value of 1.2 reported by STAR [31]. Part of this difference can be understood by averaging over our measured centrality range (0%–60%) yielding the value $\approx$1.0. Comparison to STAR results [22] shows a 10% discrepancy for midcentral collisions, possibly reflecting differences in the methods used to estimate $\text{Res}(\Psi_4)$.

In more central collisions where $N_{\text{part}} \gtrsim 200$, v^4/v_2^2 increases rapidly. Adding eccentricity fluctuations to ideal hydrodynamics causes a similar trend, indicated by the dashed curve in Fig. 4(c). Central collisions are the most sensitive because the eccentricity decreases as the overlap region becomes more symmetric. In order to reproduce the central data, the authors of [22] introduced additional fluctuations shown as the solid line in Fig. 4(c), though the source of these fluctuations is as yet unspecified.

In summary, we have presented differential measurements of v_4 and v_2 for charged hadrons obtained with four reaction-plane detectors at different $\Delta\eta$ with respect to the PHENIX central arms. There are no significant $\Delta\eta$- and p_T-dependent nonflow contributions for $p_T \lesssim 3$ GeV/c in the centrality ranges of our study. Consequently there are no significant systematic errors from jets on the event-plane determinations or values of v_2 and v_4. The ratio $v_4(p_T, N_{\text{part}})/v_2^2(p_T, N_{\text{part}}) \approx 0.8$ for $50 \lesssim N_{\text{part}} \lesssim 200$ is essentially independent of p_T, consistent with the effects of finite viscosity and eccentricity fluctuations. For $N_{\text{part}} \gtrsim 200$ the ratio increases up to 1.7 in the most central collisions. The precision of these data provide stringent constraints for further theoretical modeling and more detailed extractions of the transport properties of hot and dense partonic matter.

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