Azimuthal anisotropy: the higher harmonics

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Abstract. We report the first observations of the fourth harmonic (v_4) in the azimuthal distribution of particles at RHIC. The measurement was done taking advantage of the large elliptic flow generated at RHIC. The integrated v_4 is about a factor of 10 smaller than v_2. For the sixth (v_6) and eighth (v_8) harmonics upper limits on the magnitudes are reported.

Anisotropic flow, an anisotropy of the particle azimuthal distribution in momentum space with respect to the reaction plane, is a sensitive tool in the quest for the quark-gluon plasma and the understanding of bulk properties of the system created in ultrarelativistic nuclear collisions. It is commonly studied by measuring the Fourier harmonics (v_n) of this distribution [1]. Elliptic flow, v_2, is well studied at RHIC and is thought to reflect conditions from the early time of the collision. Recently, Kolb [2] reported that the magnitude and even the sign of v_4 are more sensitive than v_2 to initial conditions in the hydrodynamic calculations. Besides one early measurement at the AGS [3], reports of higher harmonics have not previously been published. Some of the present work has already appeared [4].

Experiment— The data come from the reaction Au + Au at $\sqrt{s_{\rm NN}}$ = 200 GeV. The STAR detector main time projection chamber (TPC) was used in the analysis of two million events. The main TPC covered pseudorapidity (η) from –1.2 to 1.2 and the low transverse momentum (p_t) cutoff was 0.15 GeV/c. In the present work all charged particles were analyzed, regardless of their particle type. The errors presented in the figures are statistical.

Analysis— The difficulty is that the signal is small and the non-flow contribution to the two-particle azimuthal correlations can be larger than the correlations due to flow. To suppress the non-flow effects the current analysis uses the knowledge about the reaction plane derived from the large elliptic flow. One method for eliminating the non-flow contribution in a case when the reaction plane is known was proposed in [1]. Results obtained with this method we designate by $v_4\{EP_2\}$. The analysis for v_4 was also done with three-particle cumulants [5] by measuring $\langle\cos(2\phi_a + 2\phi_b - 4\phi_c)\rangle$.

P_t-dependence— The results as a function of p_t are shown in Fig. 1 (left) for minimum bias collisions ($0-80\%$ centrality). Shown for v_4 are both the analysis relative to the second harmonic event plane, $v_4\{EP_2\}$, and the three-particle cumulant, $v_4\{3\}$.

§ For the full author list and acknowledgments see Appendix "Collaborations" in this volume.

Both methods determine the sign of v_4 to be positive. As a function of p_t, v_4 rises more slowly from the origin than v_2, but does flatten out at high p_t like v_2. The $v_6(p_t)$ values are consistent with zero. Ollitrault has proposed [6] for the higher harmonics that v_n might be proportional to $v_2^{n/2}$ if the ϕ distribution is a smooth, slowly varying function of $\cos(2\phi)$. In order to test the applicability of this v_2 scaling we have also plotted v_2^2 and v_2^3 in the figure as dashed lines. The proportionality constant has been taken to be 1.2 in order to fit the v_4 data. The ratio, v_4/v_2^2, is shown in Fig. 1 (right) as a function of p_t.

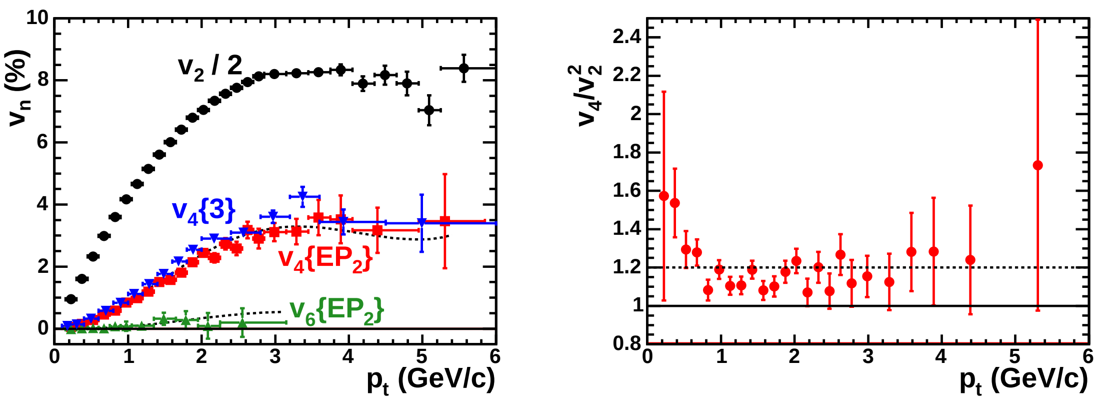

Figure 1. (left) The minimum bias values of v_2, v_4, and v_6 with respect to the second harmonic event plane as a function of p_t for $|\eta|<1.2$. The v_2 values have been divided by a factor of two to fit on scale. Also shown are the three particle cumulant values (triangles) for v_4 ($v_4\{3\}$). The dashed curves are $1.2 \cdot v_2^2$ and $1.2 \cdot v_2^3$. (right) The ratio v_4/v_2^2 is plotted against p_t. The dashed line is at the value of 1.2.

Parton coalescence— Assuming a simple parton coalescence model, for mesons one gets [7]

$$v_4/v_2^2 \approx 1/4 + 1/2(v_4^q/(v_2^q)^2). \tag{1}$$

Since experimentally this ratio is 1.2, v_4^q must be greater than zero. If one assumes that the hadronic v_2^2 scaling results from partonic v_2^2 scaling [8], then

$$v_4^q = (v_2^q)^2 \tag{2}$$

and

$$v_4/v_2^2 = 1/4 + 1/2 = 3/4. \tag{3}$$

But this is still less than 1.2. Therefore either v_4^q is even greater than simple parton v_2^2 scaling would indicate, or the simple parton coalescence model is inadequate.

Waist— Kolb [2] points out that for $v_2 > 10\%$, which occurs at high p_t, and no other harmonics, the azimuthal distribution is not elliptic, but becomes “peanut” shaped. He calculates the amount of v_4 (which looks like a four-leaf clover) needed to eliminate this waist. Our values of v_4 as a function of p_t are about a factor of two larger than needed to just eliminate the waist.

Centrality-dependence— The values of $v_4(p_t)$ for eight centrality bins are shown in Fig. 2 (left). Integrating these values weighted with the yield gives Fig. 2 (right) which shows the centrality dependence of v_2, v_4, and v_6 with respect to the second harmonic event plane and also v_4 from three-particle cumulants ($v_4\{3\}$). The v_6 values are close to zero for all centralities. To again test the applicability of $v_2^{n/2}$ scaling we have also plotted v_2^2 and v_2^3 in the figure as dotted histograms. The proportionality constant has been taken to be 1.4 to approximately fit the v_4 data. The larger constant here compared to that used in Fig. 1 is understood as coming from the use of the square of the average instead of the average of the square, and because the integrated values weighted by yield emphasize low p_t, where the best factor is slightly larger.

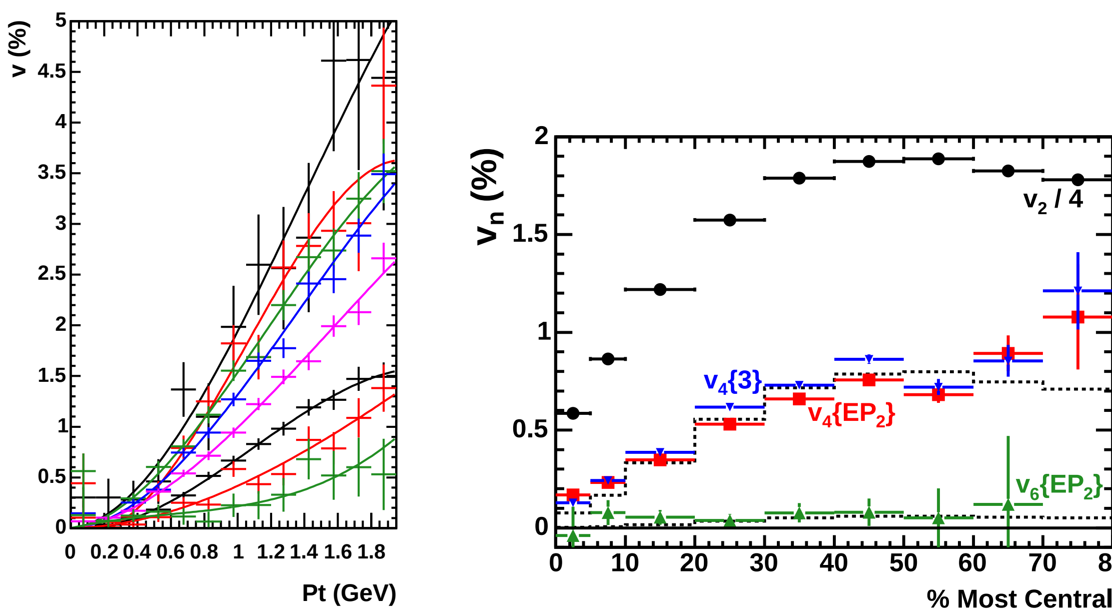

Figure 2. (left) $v(p_t)$ for the centrality bins (bottom to top) 5 to 10 % and 10, 20, 30, 40, 50, 60, and 70 up to 80 %. (right) The p_t- and η- integrated values of v_2, v_4, and v_6 as a function of centrality. The v_2 values have been divided by a factor of four to fit on scale. Also shown are the three particle cumulant values for v_4 ($v_4\{3\}$). The dotted histograms are $1.4 \cdot v_2^2$ and $1.4 \cdot v_2^3$.

The $v_n\{EP_2\}$ values averaged over p_t and η ($|\eta|$<1.2), and also centrality (minimum bias, $0 - 80\%$), are (in percent) $v_2 = 5.18 \pm 0.01$, $v_4 = 0.44 \pm 0.01$, $v_6 = 0.043 \pm 0.037$, and $v_8 = -0.06 \pm 0.14$. Since v_6 is essentially zero, we place a two sigma upper limit on v_6 of 0.1%. Also, v_8 is zero, but the error is larger because the sensitivity decreases as the harmonic order increases.

Blast Wave fits— We have fitted the data with a modified Blast Wave model [9]:

$$\rho(\phi) = \rho_0(1 + 2f_2\cos(2\phi) + 2f_4\cos(4\phi)) \tag{4}$$

$$v_n(p_t) = \frac{\int_{-\pi}^{\pi} d\phi \cos(n\phi) I_n(\alpha_t) K_1(\beta_t)(1 + 2s_2\cos(2\phi) + 2s_4\cos(4\phi))}{\int_{-\pi}^{\pi} d\phi I_0(\alpha_t) K_1(\beta_t)(1 + 2s_2\cos(2\phi) + 2s_4\cos(4\phi))}, \tag{5}$$

where I_n and K_1 are modified Bessel functions, and $\alpha_t(\phi) = (p_t/T)\sinh(\rho(\phi))$ and $\beta_t(\phi) = (m_t/T)\cosh(\rho(\phi))$. In these equations, ρ_0 is the transverse expansion rapidity ($v_0 = \tanh(\rho_0)$) of the cylindrical shell. The parameters f_2 and f_4 are the harmonic amplitudes of the azimuthal variation of ρ, and s_2 and s_4 describe the spatial anisotropy of the source.

The Blast Wave fits to v_2 and v_4 are shown in Fig. 3 (left) and expanded in Fig. 3 (right), showing the approximate agreement with the ratio. A temperature of 0.1 GeV was assumed giving the fit parameters $\rho_0 = 0.49$, $f_2 = 1.4\%$, $s_2 = 9.1\%$, $f_4 = 0.0\%$, and $s_4 = 4.4\%$. It is interesting that in this large p_t range the s values are considerably larger than the f values.

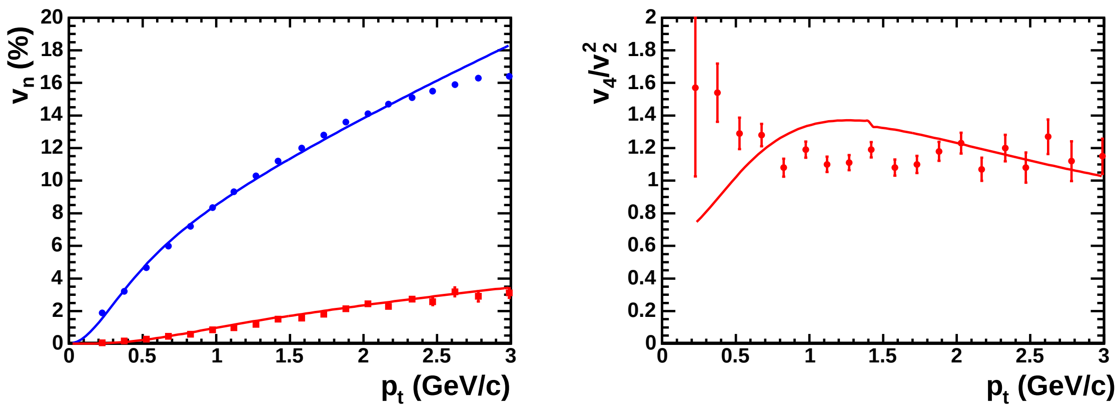

Figure 3. (left) v_2 and v_4 as a function of p_t with the lines showing the Blast Wave fits. (right) The ratio v_4/v_2^2 as a function of p_t with the line showing the ratio of the Blast Wave fits.

Conclusions— We have measured v_4 as a function of p_t, and centrality. This is the first measurement of higher harmonics at RHIC. It is expected that these higher harmonics will be a sensitive test of the initial configuration of the system, since they provide a Fourier analysis of the shape in momentum space which can be related back to the initial shape in configuration space.

References

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