The anisotropic flow coefficients \( v_2 \) and \( v_4 \) in Au+Au collisions at RHIC

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Abstract. We present measurements by STAR of the anisotropic flow coefficients \( v_2 \) and \( v_4 \) as a function of particle-type, centrality, transverse momentum and pseudorapidity in Au+Au collisions at RHIC.

Anisotropic flow is an azimuthal correlation of the particle momenta with respect to the reaction plane. This flow is recognized as one of the main observables that provide information on the early stage of a heavy-ion collision [1].

In this study, we used \( 13 \times 10^6 \) minimum-bias Au+Au events taken at a center-of-mass energy of 200 GeV and \( 6 \times 10^6 \) events taken at 62.4 GeV. The particles were detected by the STAR main TPC [2] and by the forward TPCs [3] and cover a pseudorapidity of \( |\eta| < 1.3 \) and \( 2.5 < |\eta| < 4.0 \), respectively. From these data, \( v_2 \) is obtained by the 4-particle cumulant method [4] and is denoted by \( v_2\{4\} \). This method is less sensitive to non-flow effects compared to measurements based on two particle correlations like \( v_2\{2\} \) or \( v_2\{EP_2\} \). The \( v_4 \) coefficient is obtained with respect to the second harmonic event plane and is denoted by \( v_4\{EP_2\} \). The flow coefficients are studied for different particle species as function of transverse momentum \( (p_t) \), pseudorapidity \( (\eta) \) and centrality.

Only statistical errors are shown unless specified.

Transverse momentum dependence. The left panel of Fig. 1 shows the charged particle \( v_2 \) as a function of \( p_t \) for mid-central (20–60%) Au+Au collisions at 200 and 62.4 GeV. It is seen that the measured \( v_2 \) increases with \( p_t \), reaches its maximum around 3 GeV/c and then decreases again. At 200 GeV, \( v_2 \) is measured up to 10 GeV/c and is still sizable above 8 GeV/c. The behavior of \( v_2 \) at 62.4 GeV is similar to that observed at 200 GeV. It is argued in [5] that \( v_2 \) at large \( p_t \) might be related to the parton energy loss mechanism and may thus provide a constraint on the initial gluon density.

The \( p_t \) dependence of the charged particle \( v_4 \) is shown for both energies in the right panel of Fig. 1. It is seen that \( v_4 \) increases quadratically at low \( p_t \) and has, like \( v_2 \), its maximum around 3 GeV/c. At 200 GeV, \( v_4 \) is measured up to 7 GeV/c and is still sizable above 6 GeV/c. Similar values are obtained at 62.4 GeV.

\(^\ddagger\) For the full list of STAR authors and acknowledgements, see appendix ‘Collaborations’ in this volume.
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![Figure 1](image1.png)

**Figure 1.** Charged particle $v_2\{4\}$ (left-hand plot) and $v_4\{EP_2\}$ (right-hand plot) versus $p_t$ for 20–60% centrality at $|\eta| < 1.3$ in Au + Au collisions at 200 and 62.4 GeV.

![Figure 2](image2.png)

**Figure 2.** Charged particle $v_2\{4\}$ and $v_4\{EP_2\}$ versus $\eta - y_{beam}$ for different centrality bins at 200 (full circles) and 62.4 GeV (open circles). The flow coefficients are shown for particles in the forward hemisphere only.

**Rapidity dependence.** It has been shown that particle production in the fragmentation region exhibits longitudinal scaling when plotted as a function of $\eta - y_{beam}$ [6]. It is also known that the integrated elliptic flow for fixed centrality at mid-rapidity is proportional to the particle yield $dN/dy$ [7]. If this scaling with $dN/dy$ holds at all rapidities, then $v_2$ is also expected to show a longitudinal scaling behavior. Figure 2 (left) shows $v_2$ as a function of $\eta - y_{beam}$ for different centralities at 200 and 62.4 GeV. The $v_2$ values measured at both energies fall on a universal curve, indicating that the longitudinal scaling approximately holds. This scaling is also observed for $v_4$ as can be seen in the right panel of Fig. 2.

**Mass and particle type dependence.** It has been shown by STAR [8] that $v_2$ for identified particles at low $p_t$ exhibits a mass ordering. This ordering is well described by hydrodynamic calculations which indicates that all particles flow with a common
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velocity. At intermediate $p_t$, $v_2$ scales with the number of constituent quarks $n_q$ [9]. This scaling can be explained in the coalescence picture and is indicative of the partonic origin of flow [10]. The ratio $v_2/n_q$ is shown in Fig. 3 (left) for three different centralities at 200 GeV as a function of $p_t/n_q$ and as a function of the scaled transverse mass $(m_T - m_0)/n_q$. The scaled transverse mass, which takes into account relativistic effects, is sometimes considered to be a better scaling variable than $p_t/n_q$ [11].

An indication that $v_2$ follows constituent quark scaling independent of centrality is given by the fact that the $v_2/n_q$ falls onto a universal curve for each centrality bin. Figure 3 shows that the constituent quark scaling holds at both 200 GeV and 62.4 GeV.

The ratio $v_4/v_2^2$ In recent work [12], $v_4/v_2^2$ is proposed as a more sensitive probe of ideal hydrodynamic behavior. Furthermore, this ratio is directly related to the degree of thermalization of the medium, see also [13]. Under the assumption that $v_2\{4\}$ is a genuine measure of elliptic flow, the systematic error in the ratio $v_4/v_2^2$ is dominated by non-flow contributions to $v_4$. It can be shown that the non-flow contribution to $v_4$ is proportional to the difference $v_2\{2\}^2 - v_2\{4\}^2$. Obtaining this difference from the data allows us to estimate the systematic error on $v_4/v_2^2$. However, the difference can also originate from flow fluctuations [14]. In that case, the systematic error will be reduced. A detailed description of this systematic analysis is beyond the scope of these proceedings and will be described in a future publication.

Figure 4 shows the ratio $v_4/v_2^2$ measured at 200 GeV in the 20–30% centrality interval. The horizontal brackets in this figure show the lower limit of the systematic uncertainty as presently estimated. In this figure, the data are compared to two
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\[ \frac{v_4}{v_2} \]

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<td>2.0</td>
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</tbody>
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Figure 4. The ratio of $v_4/v_2^2$ versus $p_t$ for charged particles at $|\eta| < 1.3$ in Au+Au collisions at 200 GeV. The horizontal brackets indicate the systematic uncertainty. The curves correspond to two hydrodynamic calculations \cite{12,15}. The filled area shows the AMPT model calculations \cite{16}. It is seen that the data lie above the model predictions. However, the present systematic uncertainties do not allow us to either validate or exclude these two models.

References

11. PHENIX Collaboration, Adare A et al., nucl-ex/0608033.
13. Ko C M, in these proceedings;
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