Elliptic ($v_2$) and triangular ($v_3$) anisotropic flow of identified hadrons from the STAR Beam Energy Scan program

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Abstract.
Elliptic ($v_2$) and triangular ($v_3$) anisotropic flow coefficients for inclusive and identified charged hadrons ($\pi^{\pm}$, $K^{\pm}$, $p$, $\bar{p}$) at midrapidity in Au+Au collisions, measured by the STAR experiment in the Beam Energy Scan (BES) at the Relativistic Heavy Ion Collider at $\sqrt{s_{NN}} = 11.5 - 62.4$ GeV, are presented. We observe that the triangular flow signal ($v_3$) of identified hadrons exhibits similar trends as first observed for $v_2$ in Au+Au collisions, i.e. (i) mass ordering at low transverse momenta, $p_T < 2$ GeV/c, (ii) meson/baryon splitting at intermediate $p_T$, $2 < p_T < 4$ GeV/c, and (iii) difference in flow signal of protons and antiprotons. New measurements of $v_3$ excitation function could serve as constraints to test different models and to aid new information about the temperature dependence of the transport properties of the strongly interacting matter.

1. Introduction
The heavy-ion experiments at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) have established the existence of a strongly coupled Quark Gluon Plasma [1, 2], a new state of QCD matter with partonic degrees of freedom and with low specific shear viscosity $\eta/s$ [3]. Lattice QCD calculations [4] indicate that the quark-hadron transition is a smooth crossover at top RHIC energy and above (at high temperatures $T$ and small values of baryonic chemical potential $\mu_B$). A Beam Energy Scan (BES) program at RHIC plays a central role in the experimental study of the QCD phase diagram over a wide range in $T$ and $\mu_B$ [5, 6]. The anisotropic flow is one of the important observables sensitive to the equation of state (EOS) and transport properties of the strongly interacting matter such as the shear viscosity over entropy ratio $\eta/s$ [3, 7, 8]. The azimuthal anisotropy of produced particles can be quantified by the Fourier coefficients $v_n$ in the expansion of the particles azimuthal distribution as: $dN/d\phi \propto 1 + \sum_{n=1}^{2} 2v_n \cos(n(\phi - \Psi_n))$ [7, 9], where $n$ is the order of the harmonic, $\phi$ is the azimuthal angle of particles for a given type, and $\Psi_n$ is the azimuthal angle of the $n$th-order event plane. The $n$th-order flow coefficients $v_n$ can be calculated as $v_n = \langle \cos[n(\phi - \Psi_n)] \rangle$, where the brackets denote an average over particles and events. Elliptic ($v_2$) and triangular ($v_3$) flows are the dominant flow signals and have been studied very extensively both at top RHIC and LHC energies [10, 11, 12]. For low transverse momentum ($p_T < 2-3$ GeV/c), the $p_T$ dependence of $v_2$ and $v_3$ for produced particles is well described by viscous hydrodynamic models and a good
agreement between data and model calculations can be reached for the small values of $\eta/s$ close to the lower conjectured bound of $1/4\pi$ [3]. The shear viscosity suppresses triangular flow signal $v_3$ more strongly than elliptic flow signal $v_2$ [13, 14]. The data for top RHIC energy show that, for a given collision centrality, the measured values of $v_n$ ($n = 2, 3$) for all hadrons scale to a single curve when plotted as $v_n/n_q^{n/2}$ versus scaled transverse kinetic energy, $(m_T-m_0)/n_q$, where $n_q$ is the number of constituent quarks in the hadron and $m_0$ is mass [10, 11]. The observed empirical Number-of-Constituent Quark (NCQ) scaling with transverse kinetic energy may indicate that the bulk of the anisotropic flow at top RHIC energies is partonic, rather than hadronic [15]. The collision energy dependence of elliptic flow ($v_2$) for inclusive and identified hadrons at mid-rapidity in Au+Au collisions, has been studied very extensively by STAR experiment at $\sqrt{s_{NN}} = 7.7 - 62.4$ GeV [16, 17, 18, 19]. The elliptic flow signal $v_2(p_T)$ for inclusive charged hadrons shows a very small change over such a wide range of collision energies [16]. Hybrid model calculations show that the weak dependence of $v_2(p_T)$ on the beam energy may result from the interplay of the hydrodynamic and hadron transport phase [14]. The triangular flow $v_3$ is expected to be more sensitive to the viscous damping and might be an ideal observable to probe the formation of a QGP at different collision energies [20]. However, a significant difference in the $v_2$ values between particles and the corresponding anti-particles was observed [18, 19]. This difference increases with decreasing collision energy and is larger for baryons than mesons. Several different theoretical models have been proposed for the possible physical reason for this effect and new measurements of $v_3$ for particles and anti-particles might be important for distinguishing between them [18, 19]. In this work, we report new measurements of triangular ($v_3$) anisotropic flow coefficients for inclusive and identified charged hadrons ($\pi^\pm$, $K^\pm$, $p$, $\bar{p}$) at midrapidity in Au+Au collisions at $\sqrt{s_{NN}} = 11.5 - 62.4$ GeV and compare them to $v_2$ results.

2. Data Analysis

The data reported in this analysis are from Au+Au collisions at $\sqrt{s_{NN}} = 11.5, 14.5, 19.6, 27, 39$ and 62.4 GeV, collected during the beam energy scan phase-I and II (BES-I & BES-II) programs by the STAR detector using a minimum bias trigger. The collision vertices were reconstructed using charged-particle tracks measured in the Time Projection Chamber (TPC). The TPC covers the full azimuth and has a pseudorapidity range of $|\eta| < 1.0$.

Figure 1. The centrality dependence of the event plane resolution for $v_2$ (left panel) and $v_3$ (right panel) for all six collision energies.

Events were selected to have a vertex position about the nominal center of the TPC in the beam direction of $\pm 40$ cm at $\sqrt{s_{NN}} = 62, 39, 27, 19.6$ and 14.5 GeV, $\pm 50$ cm at $\sqrt{s_{NN}} = 11.5$ GeV, and to be within a radius of $1 - 2$ cm with respect to the beam axis. The centrality of each collisions was determined by measuring event-by-event multiplicity and interpreting the measurement with a tuned Monte Carlo Glauber calculation [16, 18]. Analyzed
tracks were required to have a distance of closest approach to the primary vertex to be less than 3 cm, and to have at least 15 TPC space points used in their reconstruction [16, 17]. The particle identification for charged hadrons (\(\pi^{\pm}, K^{\pm}, p, \bar{p}\)) was based on a combination of the ionization energy loss, \(dE/dx\), in the TPC, and the squared mass, \(m^2\), from the TOF detector [17, 18, 19].

In this study, the event plane method with \(\eta\)-sub-events, separated by an additional \(\eta\)-gap of \(\Delta \eta > 0.1\), was used to measure elliptic \(v_2\) and triangular \(v_3\) flow [16]. The \(\eta\) gap is introduced to suppress the non-flow correlations between the two sub-events. The \(\eta\) sub-event method was implemented using the procedure in Ref [16] [17] [18]. The centrality dependence of event plane resolution for \(v_2\) and \(v_3\) for the six collision energies is shown in the Fig. [1]. The systematic uncertainty associated with the non-flow effects is estimated for each collision energy by comparing \(v_2\) and \(v_3\) results obtained with different \(\Delta \eta\) gaps. Studies were performed for \(\Delta \eta\) values of 0.1, 0.3, 0.5, 0.7.

3. Results

**Figure 2.** Left: \(p_T\)-integrated \(v_2^{\text{int}}\) and \(v_3^{\text{int}}\) of inclusive charged hadrons as a function of \(\sqrt{s_{NN}}\) for different bins in collision centrality. Right: \(p_T\)-dependence of \(v_2(p_T)/v_2^{\text{int}}\) and \(v_3(p_T)/v_3^{\text{int}}\) of charged hadrons for different bins in collision centrality. The measured \(v_n(p_T)\) values were divided by the corresponding \(v_n^{\text{int}}\) values from the left part of the figure. The results are presented for all 6 collision energies: \(\sqrt{s_{NN}} = 11.5, 14.5, 19.6, 27, 39\) and 62.4 GeV.

Preliminary results for the excitation functions of \(p_T\)-integrated (0.2 < \(p_T\) < 3.2 GeV/c) values of \(v_2^{\text{int}}\) and \(v_3^{\text{int}}\) of inclusive charged hadrons are presented in the left part of Fig. [2]. The \(v_2^{\text{int}}\) results were not corrected for \(p_T\) dependent tracking efficiency, which will be explored in future analysis. Although the efficiency is \(p_T\) dependent but is similar between different collision energy, so it is not expected to influence the \(\sqrt{s_{NN}}\) trend. The results are presented for 6 bins in collision centrality: 0 – 5%, 5 – 10%, 10 – 20%, 20 – 30%, 30 – 40% and 40 – 60%. The results indicate an essentially monotonically increase for \(p_T\)-integrated \(v_2\) and \(v_3\) with \(\sqrt{s_{NN}}\), as expected from increase of the radial flow with collision energy which pushes the hadrons to larger \(p_T\).
and renders the momentum spectra less anisotropic at low $p_T$ \cite{20}. The $p_T$ dependence of $v_2(p_T)/v_{n}^{\text{int}}$ and $v_3(p_T)/v_{n}^{\text{int}}$ for inclusive charged hadrons is presented in the right part of the Fig. 2 for different bins in collision centrality. The measured $v_n(p_T)$ values were divided by the corresponding $p_T$-integrated $v_{n}^{\text{int}}$ values from the left part of the Fig. 2. The results in the figure are presented for all 6 collision energies: $\sqrt{s_{NN}} = 11.5, 14.5, 19.6, 27, 39$ and 62.4 GeV and they show that $v_n(p_T)/v_{n}^{\text{int}}$ has a very week dependence on $\sqrt{s_{NN}}$. This is in agreement with predictions from \cite{21}.  

Figure 3 shows the collision energy dependence in $v_2(p_T)$ and $v_3(p_T)$ for identified hadrons ( $\pi^{\pm}$, $K^{\pm}$, $p$, $\bar{p}$ ) for 0-60% central Au+Au collisions. The results for particles (left panel) and antiparticles (right panel) are presented separately. We observe that the $v_3(p_T)$ signal of identified charged hadrons exhibits similar trends as first observed for $v_2$ in Au+Au collisions: mass ordering at low transverse momenta, $p_T < 2$ GeV/c, and meson/baryon splitting at intermediate $p_T$, $2 < p_T < 4$ GeV/c \cite{17, 18, 19}.

![Figure 3](image)

**Figure 3.** $p_T$ dependence of $v_2$ and $v_3$ signals of $\pi^{\pm}$, $K^{\pm}$, $p$ (left) and $\pi^{-}$, $K^{-}$, $\bar{p}$ (right) for 0-60% central Au+Au collisions.

Figure 4 shows that the measured $v_3$ values of identified charged hadrons seems to follow the NCQ scaling, $v_3/n_q^{1/2}$ versus $(m_T - m_0)/n_q$, if we plot the results for particles (left part) and anti-particles (right part) separately. 

The analysis of the new dataset of Au+Au collisions at $\sqrt{s_{NN}} = 27$ GeV, collected by STAR experiment in 2018, allows us to observe the difference in the triangular $v_3$ flow between protons and anti-protons, see Fig. 5. It shows that, similar to elliptic flow $v_2$, the $v_3$ flow signal of protons is larger than $v_3$ of antiprotons and the difference has $p_T$ dependence. 

For other collision energies we can estimate the difference in $v_3$ values between particles and corresponding anti-particles for $p_T$-integrated $v_3$ values. The right part of Fig. 6 shows the difference in $v_3$ between particles (X) and their corresponding anti-particles ($\bar{X}$) as a function
In summary, we have employed the event plane method with \( \eta \) sub-events to carry out new measurements of the triangular \( (v_3) \) anisotropic flow coefficients for inclusive and identified charged hadrons \( (\pi^\pm, K^\pm, p, \bar{p}) \) at midrapidity in Au+Au collisions, spanning the collision energy range of 39 GeV to 62.4 GeV. These measurements allow us to study the anisotropic flow dynamics in heavy-ion collisions and provide insights into the collective flow properties of the collision system.
Figure 6. (left) The difference in $v_2$ between particles ($X$) and their corresponding anti-particles ($\bar{X}$) (see legend) as a function of $\sqrt{s_{NN}}$ for 0–80\% central Au+Au collisions. The figure is taken from [18]. (right) The preliminary results for the difference in the $v_3$ values between particles ($X$) and its corresponding anti-particles ($\bar{X}$) as a function of $\sqrt{s_{NN}}$ for 0-60\% central Au+Au collisions.

energy range $\sqrt{s_{NN}} = 11.5 - 62.4$ GeV. We observe that the triangular flow signal ($v_3$) of identified hadrons exhibits similar trends as first observed for $v_2$ [16] [17] [18]. New measurements of $v_3$ excitation function could serve as constraints to test different models and to aid new information about the temperature dependence of the transport properties of the strongly interacting matter.

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