Scaling of collective flow of charged and identified hadrons in Au+Au collisions at $\sqrt{s_{NN}} = 11.5 - 62.4$ GeV from the STAR experiment

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Heavy-ion collisions create a hot and dense matter called Quark-Gluon Plasma (QGP). Azimuthal anisotropy of produced particles is sensitive to the transport properties of QGP (the equation of state, speed of sound and specific shear viscosity) and may provide information about initial state of the collision. In this work, we report results for elliptic (v_2) and triangular (v_3) flow of charged and identified hadrons ($\pi^{\pm}, K^{\pm}, p, \bar{p}$) in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 11.5, 14.5, 19.6, 27, 39 and 62.4 GeV from the STAR experiment at RHIC. Measurements of the collective flow coefficients v_2 and v_3 are presented as a function of particle transverse momentum ($\rm p_T$) and collision centrality. In addition the number of constituent quark scaling will be presented for these energies.

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Introduction

One of the main goals of relativistic nuclear collision experiments is to study the properties of nuclear matter produced in heavy-ion collisions. In such collisions, extreme temperatures and energy densities are reached, which allows the creation of Quark-Gluon Plasma (QGP) where quarks and gluons are not anymore confined inside hadrons [1, 2]. First calculations of Lattice QCD indicated the transition from quark-gluon plasma to hadron gas [3]. One of the main tasks of Beam Energy Scan program [4] at RHIC is the study of the QCD diagram in wide ranges of temperature T and baryon chemical potential $\mu_{\rm B}$.

The azimuthal anisotropy of produced particles is one of the most widely studied observables. Azimuthal asymmetry in coordinate space in the collision of nuclei is created at the initial stages prior to the QGP evolution. Through the interaction of quarks and gluons, the azimuthal asymmetry in the coordinate space transforms into the anisotropy of the momentum space of the final products. It can be presented by the Fourier expansion of the produced particles azimuthal distribution relative to the reaction plane: $\mathrm{dN/d}\phi \approx 1 + \sum_{\rm n=1} 2v_n \cos(\mathrm{n}(\phi - \Psi_{\rm n}))$, where n - order of harmonic flow, ϕ - azimuthal angle of particle and $\Psi_{\rm n}$ is the azimuthal angle of the $\rm n^{th}$-order event plane [5,6]. The coefficients v_n are called coefficients of the anisotropic

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flow and can be used to quantitatively describe the azimuthal anisotropy. The n$^{\text{th}}$-order flow coefficients can be calculated as $v_n = \langle \cos[\text{n}(\phi - \Psi_\text{n})] \rangle$, where averaging is performed over all particles and events. Measurement of the anisotropic flow allows to get information about the equation of state (EOS) and transport propeties of the strongly interacting matter [7, 8]. Elliptic (v_2) and triangular (v_3) flow coefficients are the dominant signals and have been studied at top RHIC and LHC energies [9, 10]. For the low p_T region (< 2 GeV/c) v_2 and v_3 as a function of transverse momentum are well described by viscous hydrodynamic models with small values of specific shear viscosity η/s [11].

In this work we present new results of triangular flow for charged and identified hadrons ($\pi^{\pm}$, $\text{K}^{\pm}$, p, $\bar{\text{p}}$) at midrapidity in Au+Au collisions at $\sqrt{s_{NN}} = 11.5$, 14.5, 19.6, 27, 39 and 62.4 GeV from the STAR experiment at RHIC and compare them to elliptic flow v_2.

Data Analysis

The results presented in this work are obtained from the data by the STAR experiment at RHIC. The data of Au+Au collisions at $\sqrt{\text{s}_\text{NN}}$ =11.5, 14.5, 19.6, 39, 62.4 GeV used in this analysis are from the beam energy scan program phase I and 27 GeV dataset is from the year 2018.

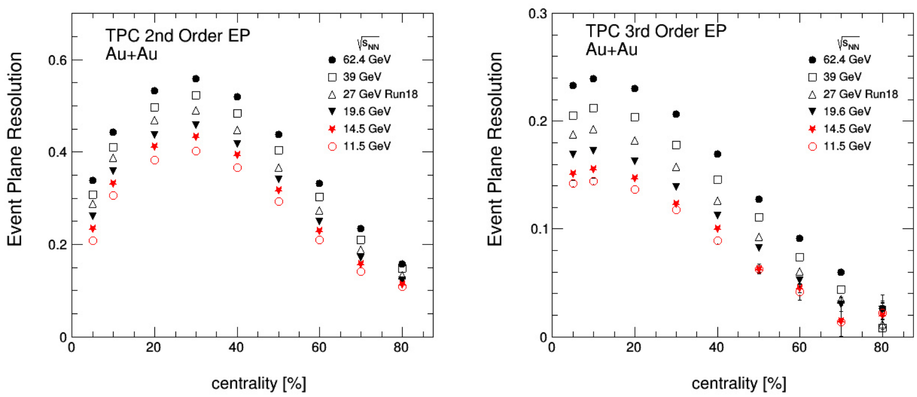

Fig. 1. The centrality dependence of the event plane resolution for v_2 (left panel) and v_3 (right panel) for six energies of collisions.

The selection of events was carried out using minimum bias trigger. Events were selected with vertex position from the center of the detector along the beam direction (V_Z) of ±40 cm for $\sqrt{\text{s}_\text{NN}} = 39$, 62.4 GeV, ±50 cm for $\sqrt{\text{s}_\text{NN}} =$ 11.5 GeV and ±70 cm for other energies. In addition the event vertex coordinates in transverse plane ($\text{V}_\text{r} = \sqrt{\text{V}_\text{X}^2 + \text{V}_\text{Y}^2}$) from the center of the beam position were required to be less than 1 cm for 14.5 GeV and 2 cm for other energies. Center of the beam position for 14.5 GeV was taken as (0.0, -0.89 cm) due to shift in the beam along Y direction. In addition the number of reconstructed tracks matching to the hits in TOF detector was required to be more than 4 each events.

In this analysis primary tracks were used [12]. All tracks to have a minimum number of 15 fit points and the number of fit points is required to be more than half (0.52) of the number of total possible points for track. For charged hadrons, tracks were used with the distance of closest approach (DCA) to the event vertex less than 2 cm and for identified particles less than 1 cm [12, 13]. All tracks are required to be within a pseudorapidity range $|\eta| < 1$. Information about charged particle ionization losses dE/dx in TPC and m^2 from TOF were used for the identification of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$.

In this work we used the event plane method for for flow measurement [6]. Due to limited detector acceptance, recentering and flattening corrections were applied to event plane angle [14]. Resolution of event plane was calculated by two sub-event method [15]. TPC tracks were divided into two part (east $\eta < 0$ and west $\eta > 0$) and event planes were calculated in each sub-event. We used η-gap ($\Delta\eta$) between sub-events to reduce "nonflow" effect such as decay of resonances, HBT correlation and jets. For charged hadrons $\Delta\eta = 0.15$ and for identified particles 0.1. In Figure 1 resolutions of event plane for v_2 and v_3 are presented as a function of collision centrality for six energies.

Results

Results of v_2 and v_3 of charged hadrons as a function transverse momentum p_T are shown on the left panel of Figure 2 for 5 bins of collision centrality: 0-10%, 10-20%, 20-30%, 30-40% and 40-60%. Values of triangular flow are

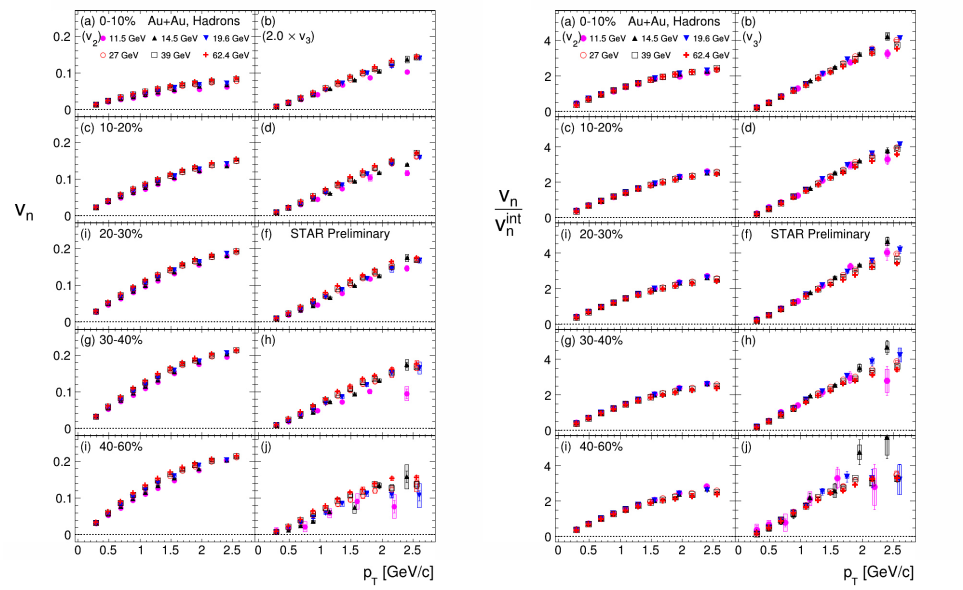

Fig. 2. Left: v_2 and v_3 of charged hadrons as a function of p_T for different collision energies and centrality. Right: p_T-dependence of v_2/v_2^{int} and v_3/v_3^{int} where v^{int} – p_T-integrated flow values.

multiplied by 2.0 for better comparison with elliptic flow. We see that

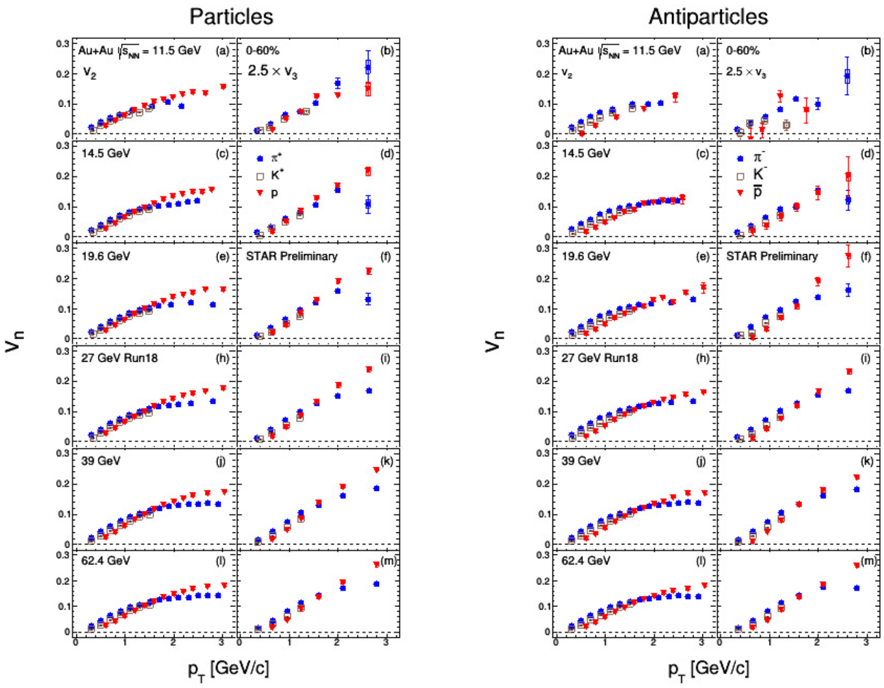

Fig. 3. Elliptic and triangular flow of $\pi^+, \mathrm{K}^+, \mathrm{p}$ (left) and $\pi^-, \mathrm{K}^-, \bar{p}$ (right) for 0%-60% collisions centrality and six energies.

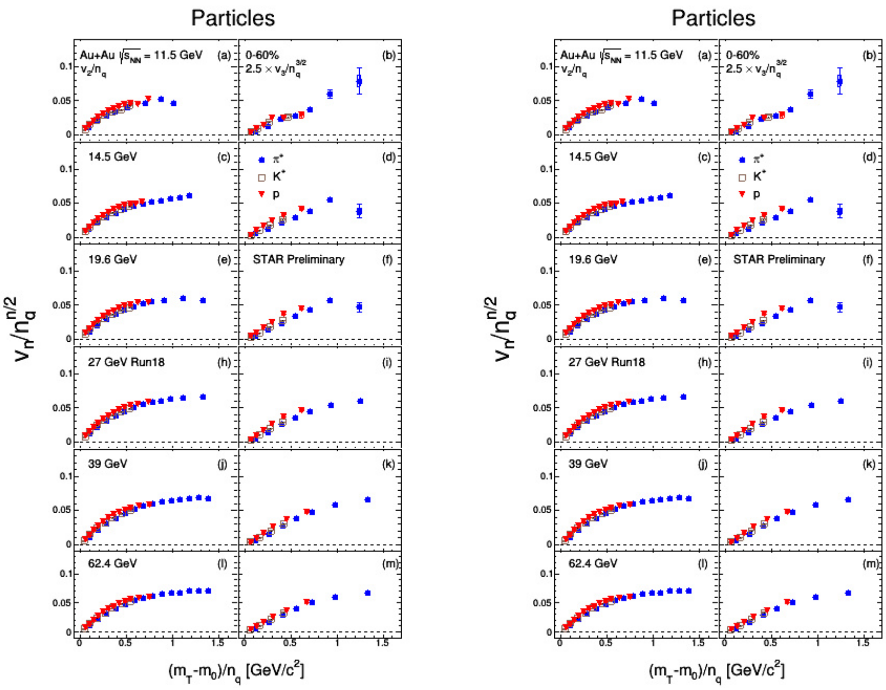

Fig. 4. The Number-of-Constituent Quark (NCQ) scaled v_2 and v_3 for 0%-60% central Au+Au collisions and six energies. Left panel - particles and right - corresponding antiparticles.

elliptic flow depends more on collision centrality than triangular flow. This can be explained by the fact that v_2 is more dependent on collision geometric overlap of two nuclei whereas v_3 is more dependent on initial density fluctuations [16]. In the right panel of Figure 2 p_T-dependence of $v_n(\mathrm{p_T})/v_n^{\mathrm{int}}$ is presented where v_n^{int} is p_T-integrated v_n over $\mathrm{p_T}$ 0.2 - 3.2 GeV/c. $v(\mathrm{p_T})_n/v_n^{\mathrm{int}}$ has a similar shapes for each collison centrality and energies, which is consistent with theoretical predictions [17].

The $\sqrt{\mathrm{s_{NN}}}$ dependence of $v_2(\mathrm{p_T})$ and $v_3(\mathrm{p_T})$ for identified particles ($\pi^{\pm}$, $\mathrm{K}^{\pm}$, p, $\bar{\mathrm{p}}$) for 0-60% collision centrality are presented in Figure 3. The left plot of this figure shows results for positive particles and the right shows the same for negative particles. Values of triangular flow v_3 are multiplied by 2.5 to improve visibility. We see that triangular flow values have mass ordering at low $\mathrm{p_T}$ range less than 1.5 GeV/c and meson/baryon splitting for transverse momentum greater than 2 GeV/c. These effects were observed for $v_2(\mathrm{p_T})$ in Au+Au collisions in previous measurements [18–21].

The number-of-constituent quark (NCQ) scaled v_2 and v_3 are presented in Figure 4 as a function of $(\mathrm{m_T} - \mathrm{m_0})/\mathrm{n_q}$ where $\mathrm{m_T}$ is transverse energy, $\mathrm{m_0}$ is particle mass and $\mathrm{n_q}$ is the number of constituent quarks. The left plot shows results for positive particles and the right shows the same for negative particles. Values of scaled v_3 are multiplied by 2.5 to improve visibility. Triangular flow of identified particles seems to follow the NCQ scaling. We observed that values of collective flow for baryons and mesons lie on one curve for each energy. This scaling holds better for higher energies. Values of v_3 for identified particles are new for this collision centrality and energies.

Summary

We have presented new measurements of triangular flow v_3 with comparisson to v_2 for charged and identified particles ($\pi^{\pm}$, $\mathrm{K}^{\pm}$, p, $\bar{\mathrm{p}}$) at midrapidity in Au+Au collisions at $\sqrt{s_{NN}}$ = 11.5, 14.5, 19.6, 27, 39 and 62.4 GeV from the STAR experiment at RHIC. Elliptic and triangular flow measurements are presented as a function of $\mathrm{p_T}$ for different collision centrality and energies. Also the number-of-constituent quark scaling of v_2 and v_3 was shown. We observed that v_3 exhibits similar trends as for v_2. New values of v_3 for identified particles can serve as constraints for ultrarelativistic hydrodynamic models.

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