# ENERGY DEPENDENCE OF TRIANGULAR FLOW OF IDENTIFIED HADRONS IN AU+AU COLLISIONS AT $\sqrt{s_{NN}} = 14.5 - 62.4$ GEV FROM THE STAR EXPERIMENT

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Heavy-ion collisions create matter which is characterized by high temperature and energy density, called Quark-Gluon Plasma (QGP). One of the methods to study of the transport properties and equation of state of the created matter is the measurement of azimuthal anisotropy of particles using the Fourier expansion of the azimuthal angle with respect to the event plane.

This work is devoted to the study of triangular flow in a wide energy range of Au+Au collisions from the STAR experiment at RHIC ($\sqrt{s_{NN}}$ = 11.5, 14.5, 19.6, 27, 39, 62.4 GeV). Measurements of triangular flow will be presented as a function of particle transverse momentum ($p_T$) and collision energy. Physics implications will be discussed.

## I. INTRODUCTION

The relativistic nuclear collision experiments allow to study properties of strongly interacting matter in laboratory. At high temperature and energy density quarks and gluons are in a deconfinement state. This stage of matter is called Quark-Gluon Plasma (QGP). The study of the properties of QGP is important for understanding strong interactions. One of the main tasks of Beam Energy Scan program [1] at RHIC is the study of the QCD phase diagram in wide ranges of temperature (T) and baryon chemical potential ($\mu_B$).

Azimuthal anisotropy is one of the variables that can directly provide information about the initial stages of heavy-ion collisions. This anisotropy can be presented by the Fourier expansion of the produced particles of azimuthal distribution of produced particles relative to the reaction plane: $dN/d\phi \approx 1 + \sum_{n=1} 2v_n \cos(n(\phi - \Psi_n))$, where n - order of harmonic

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flow, $\phi$ - azimuthal angle of particle and $\Psi_{\rm n}$ is the azimuthal angle of the $\rm n^{th}$-order event plane [2, 3]. Anisotropic flow coefficient $\upsilon_n$ can be used to quantitatively describe the azimuthal anisotropy. The $\rm n^{th}$-order flow coefficients can be calculated as $\upsilon_n = \langle \cos[{\rm n}(\phi - \Psi_{\rm n})]\rangle / {\rm Res}\{\Psi_{\rm n}\}$, where averaging is performed over all particles and events and ${\rm Res}\{\Psi_{\rm n}\}$ is resolution of the $\rm n^{th}$-order event plane. Elliptic ($\upsilon_2$) and triangular ($\upsilon_3$) flow coefficients are the dominant signals and have been studied at top RHIC and LHC energies [4, 5].

In these proceedings, we present measurements of triangular flow of identified particles ($\pi^{\pm}$, $\rm K^{\pm}$, p, $\bar{\rm p}$) in 0%-60% central 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.

## II. DATA ANALYSIS

In this work, the data of Au+Au collisions collected from the beam energy scan (BES) program at RHIC were used. Data set with collision energy of 27 GeV was taken from the BES-II program (2018) and other energies ($\sqrt{\rm s_{NN}}$ =11.5, 14.5, 19.6, 39, 62.4 GeV) from BES-I program. Events with minimum bias trigger were selected. Vertex position from the center of Time Projection Chamber (TPC) along the beam direction ($\rm V_Z$) was required to be within ±40 cm for $\sqrt{\rm s_{NN}}$ = 39, 62.4 GeV, ±50 cm for $\sqrt{\rm s_{NN}}$ = 11.5 GeV and ±70 cm for other energies. Primary vertex radial position in the transverse direction ($\rm V_r = \sqrt{X^2 + Y^2}$) was required to be within 2 cm (1 cm for 14.5 GeV). In addition due to shift of the beam along Y direction in 2014 for 14.5 GeV the $\rm V_r$ cut was applied relative to the beam center (0.0 cm, -0.89 cm).

Only primary tracks were used for event plane reconstruction and collective flow calculation. It was required that all tracks have number of fit points in TPC larger than 14, and ratio number of hit points to maximum possible number of hits ($\rm N_{hits}/N_{poss}$) is larger than 0.5. The distance of closest approach (DCA) of track to the event vertex was required to be less than 1 cm for identified particles. All tracks are required to be within a pseudorapidity range $|\eta| < 1$. Particle identification was carried out using the information about ionization energy losses (dE/dx) in TPC and $\rm m^2$ from time-of-flight system (TOF).

For measurements of collective flow, the event plane method was used [3]. Tracks from TPC were divided in two pseudorapidity intervals: east and west (east $-1 < \eta < -0.05$ and west $0.05 < \eta < 1$). Event planes were estimated in each sub-events for each collision centrality. To reduce the impact of nonflow effect (decay of resonances, HBT correlation, and jets), $\eta$-gap ($\Delta\eta$) of 0.1 was required between sub-events. Recentering ant shifting corrections were applied for each event planes due to limited acceptance of the TPC [6]. Resolution of event plane was calculated using two sub-events method [7]. Event plane resolution for the second and third harmonics are shown on Figs. 1 and 2 as a function of collision centrality.

## III. RESULTS

Results of elliptic and triangular flow for 0%-60% central Au+Au collisions as a function of $p_T$ are presented in Figs. 3 and 4 for positively and negatively charged particles, respectively. Values of $v_3$ were multiplied by 2.5 for better visualisation. The mass ordering is observed at low $p_T$ range smaller than 1.5 GeV/$c$ and the meson-baryon splitting is seen for $p_T$ larger than 2 GeV/$c$. It is seen that triangular flow shows similar features to that of elliptic flow [8–11].

Figures 5 and 6 show $v_2$ and $v_3$ scaled with the number-of-constituent quarks (NCQ). This results are presented as a function of $(m_T - m_0)/n_q$ where $m_T$ is transverse mass, $m_0$ is particle mass and $n_q$ is the number of constituent quarks. Values of $v_3$ were multiplied by 2.5. Triangular flow values seem to follow the NCQ scaling. It is seen that (anti)protons, pions, and kaons follow the same curve for each energy.

The $\sqrt{s_{NN}}$-dependence of difference of triangular flow between positively and negatively charged particles is presented in Fig. 7 for 0%-60% centrality. The difference increases with decreasing collision energy. Absolute value of $v_3(X) - v_3(\bar{X})$ is larger for protons and antiprotons than for pions and kaons. The similar trends were observed for elliptic flow in Refs. [12, 13] for 0%-80% and 10%-40% central Au+Au collisions.

## IV. SUMMARY

We have presented measurements of triangular flow of identified particles ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$) in 0%-60% central 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. Triangular flow as a function of transverse momentum shows similar features to that of $v_2$, namely the mass ordering and the meson-baryon splitting. The number-of-constituent quark (NCQ) scaling was studied. The NCQ scaling holds better for higer energies. The $v_3$ difference of particles and antiparticles was presented as a function of $\sqrt{s_{NN}}$. The difference increases with decreasing collision energy.

## ACKNOWLEDGMENTS

The reported study was funded by the Ministry of Science and Higher Education of the Russian Federation, Project "Fundamental properties of elementary particles and cosmology" No. 0723-2020-0041., and by the MEPhI Program Priority 2030. The work was partially performed using resources of the heterogeneous computing platform HybriLIT of JINR (LIT) (http://hlit.jinr.ru) and NRNU MEPhI high-performance computing center.

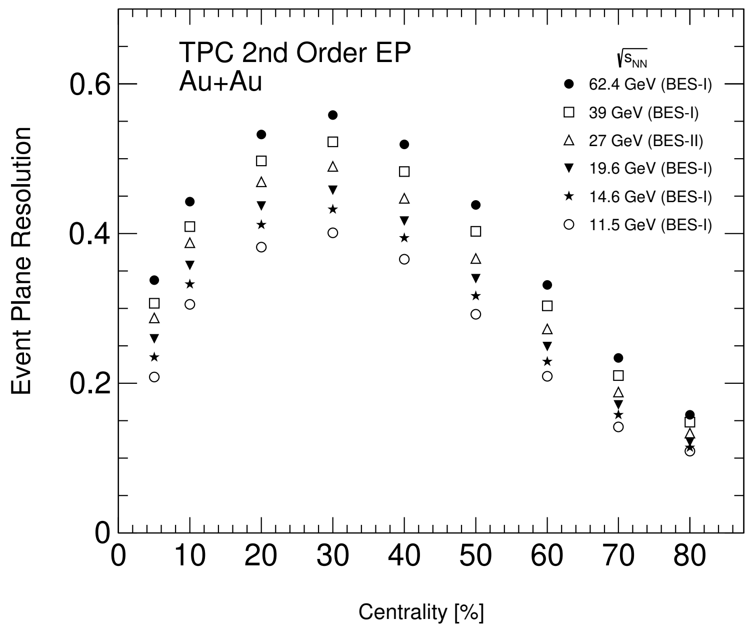


FIG. 1. Event plane resolution of the second harmonic as a function of collision centrality for different energies.

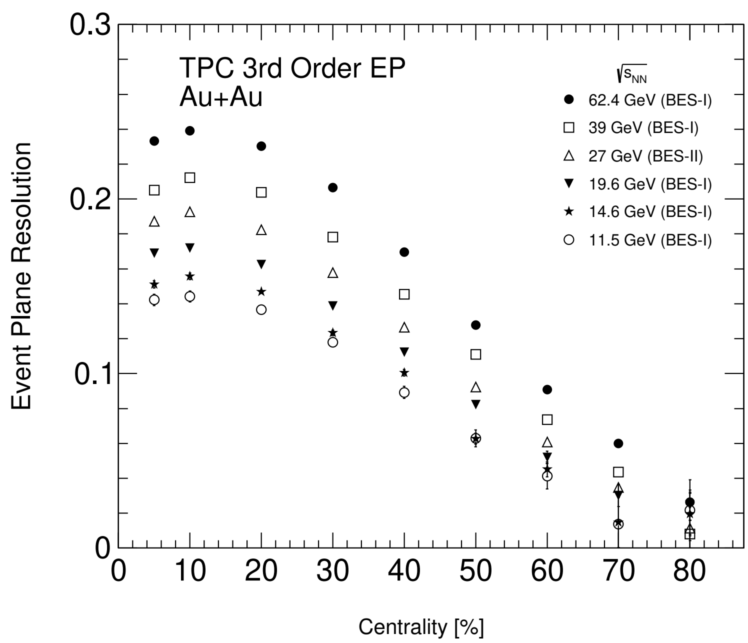


FIG. 2. Event plane resolution of the third harmonic as a function of collision centrality for different energies.

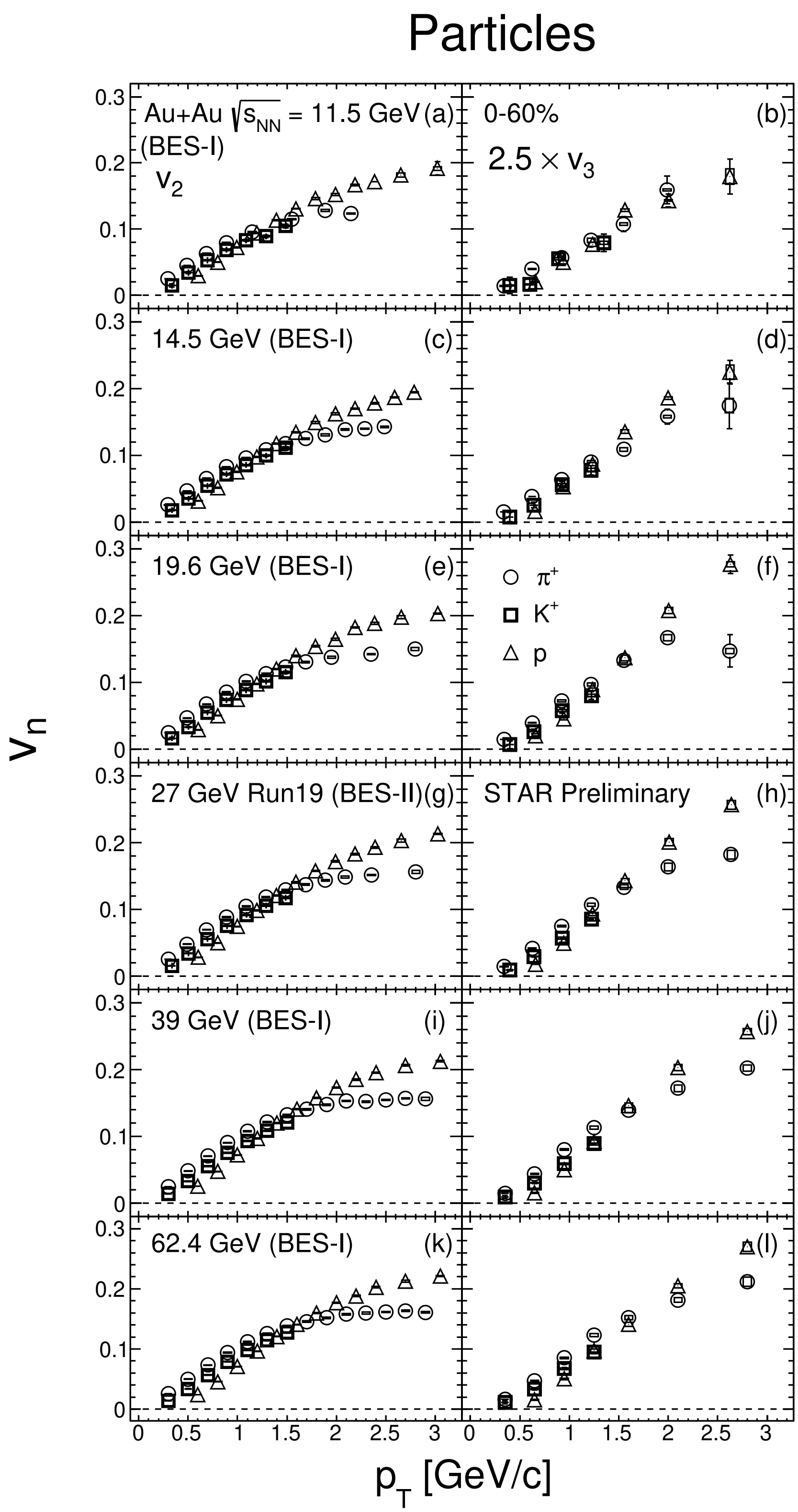


FIG. 3. $p_T$ dependence of elliptic (left) and triangular (right) flow of positively charged particles for 0%-60% central Au+Au collisions for different energies.

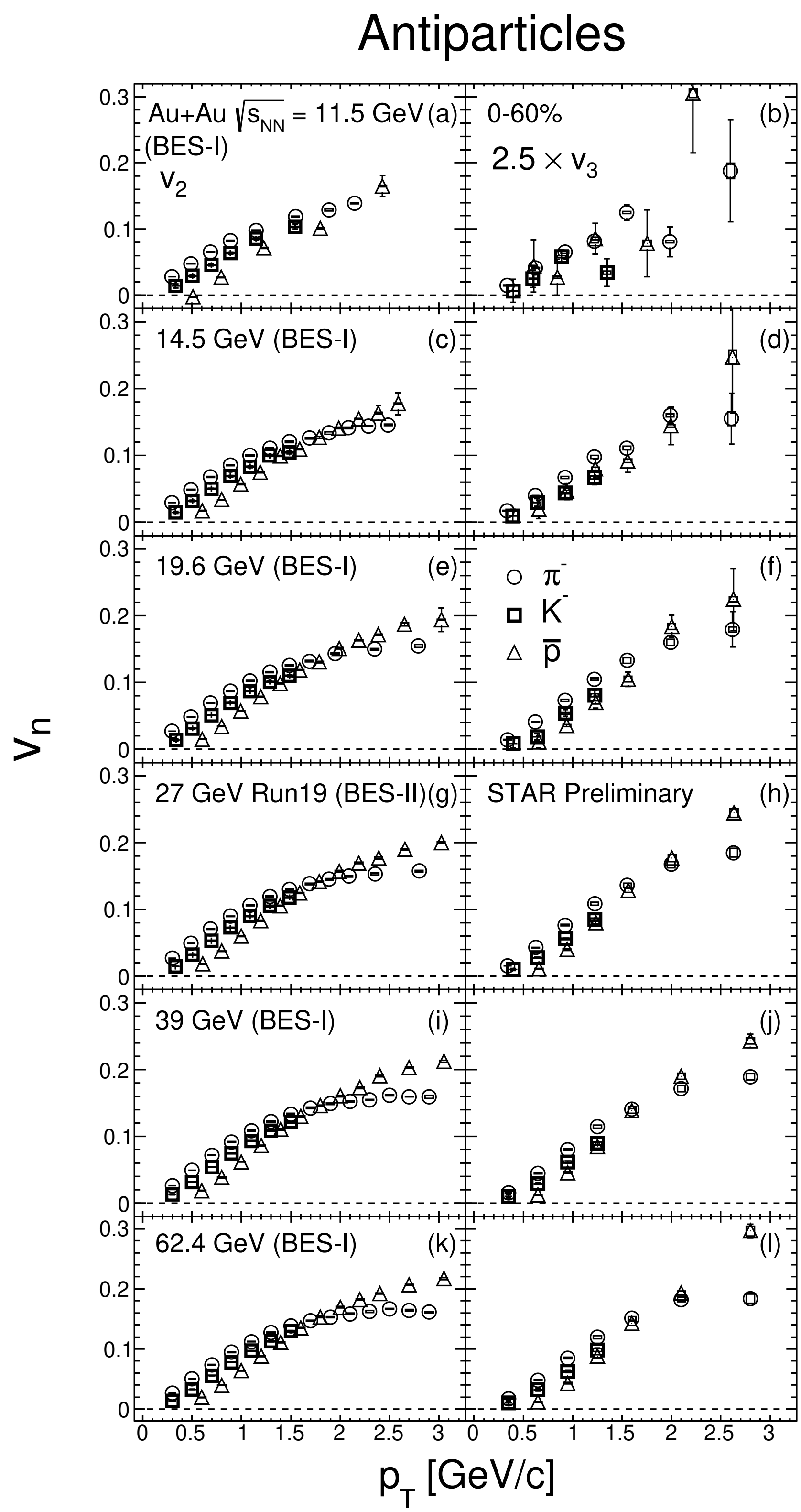


FIG. 4. $p_T$ dependence of elliptic (left) and triangular (right) flow of negatively charged particles for 0%-60% central Au+Au collisions for different energies.

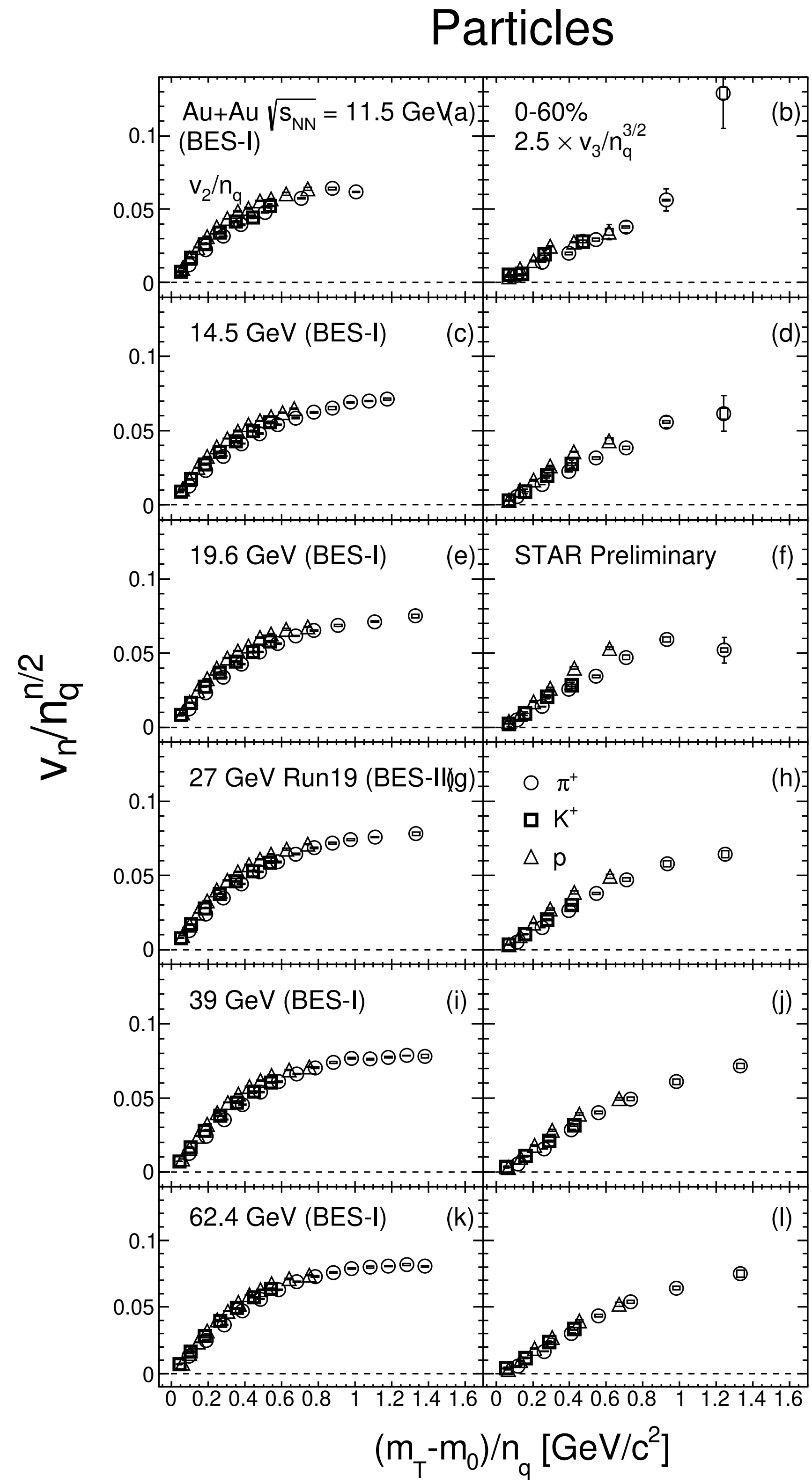


FIG. 5. The number-of-constituent quark (NCQ) scaled $v_2$ and $v_3$ of positively charged particles for 0%-60% central Au+Au collisions and six energies.

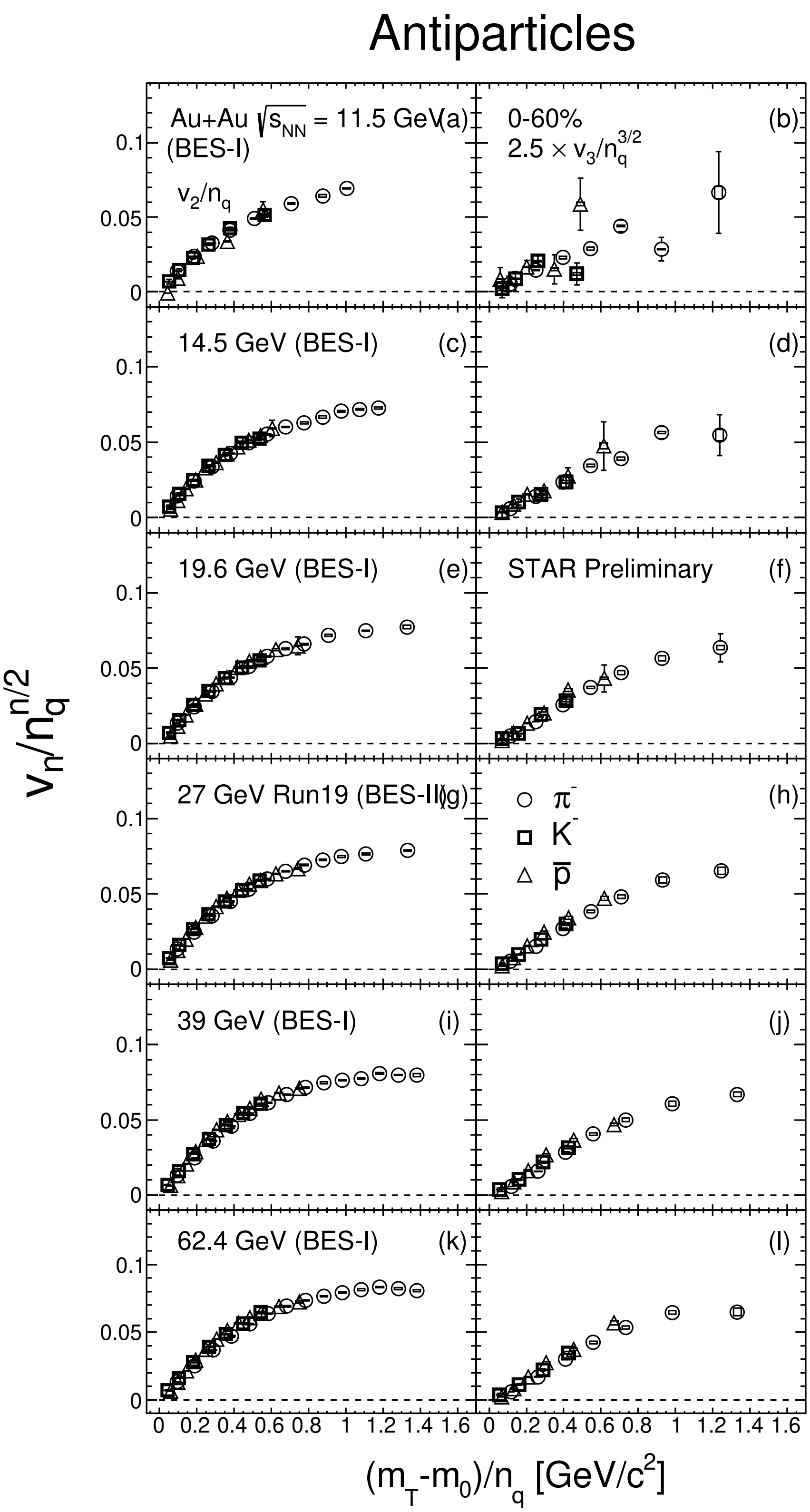


FIG. 6. The number-of-constituent quark (NCQ) scaled $v_2$ and $v_3$ of negatively charged particles for 0%-60% central Au+Au collisions and six energies.

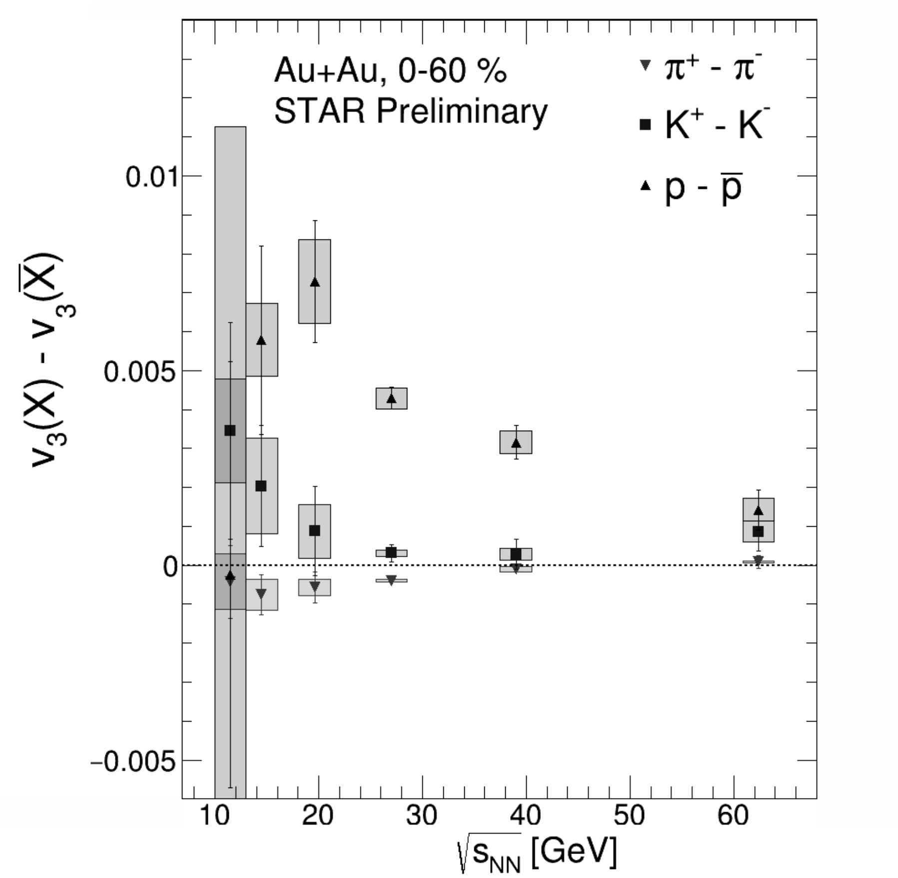


FIG. 7. Difference of triangular flow between positively and negatively charged particles as a function of collisions energy for centrality 0%-60%.

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