Study of first-order event plane correlated anisotropic flow in heavy-ion collisions at high baryon density region

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Abstract

Directed flow (v_1) describes the collective sideward motion of particles in heavy-ion collisions and serves as a key probe of in-medium dynamics, sensitive to the equation of state (EoS). A minimum in its slope (dv_1/dy) with collision energy has been proposed as a signature of a first-order phase transition between hadronic matter and Quark-Gluon Plasma (QGP), which can arise from the softening of the equation of state near the transition. Triangular flow (v_3) typically originates from initial state fluctuations and is uncorrelated with the reaction plane. However, recent measurements at lower collision energies ($\sqrt{s_{NN}}$ = 2.4 and 3 GeV) suggest a correlation between v_3 and the first-order event plane angle (Ψ_1). These proceedings present a study of the dependencies of $v_1\{\Psi_1\}$ and $v_3\{\Psi_1\}$ on rapidity, transverse momentum (p_T), centrality, and collision energy in Au+Au collisions at $\sqrt{s_{NN}}$ = 3.2, 3.5, 3.9, and 4.5 GeV. The results are compared with JAM model calculations to gain insights into the physics of high baryon density regions.

Keywords:
STAR, heavy-ion collisions, anisotropic flow, azimuthal, reaction plane, mid-rapidity, potential

1. Introduction

The relativistic heavy-ion collisions aims to explore the properties and evolution of strongly interacting matter, known as the Quark-Gluon Plasma (QGP) [1]. To investigate the transition from hadronic matter to QGP and map the Quantum Chromodynamics (QCD) phase diagram, the Relativistic Heavy Ion Collider (RHIC) initiated the Beam Energy Scan (BES) program [2]. One of the key observables in this study is the anisotropic flow, which characterizes the shape and direction of expansion of the medium formed in heavy-ion collisions. The flow is reflected in the azimuthal distribution of particles relative to the event plane (Ψ_r) and can be described mathematically using a Fourier series expansion of the following triple differential distribution

$$E\frac{\mathrm{d}^3N}{\mathrm{d}p^3} = \frac{\mathrm{d}^2N}{2\pi p_T \mathrm{d}p_T \mathrm{d}y}\left\{1 + \sum_{n\geq 1} 2\, v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right\}, \tag{1}$$

where p_T, y, ϕ and Ψ_n are particle transverse momentum, rapidity, azimuthal angle of the particle and the n^{th} order event plane angle, respectively [3]. The coefficients in the expansion, v_1 (directed flow), v_2 (elliptic flow), and v_3 (triangular flow) , etc., describe the collective response of the medium to the initial collision geometry. They are sensitive to medium properties such as the viscosity and mean-fields that determine the equation of state (EOS).

2. Analysis Details

In these proceedings, we report the measurement of $v_1\{\Psi_1\}$ and $v_3\{\Psi_1\}$ for identified hadrons ($\pi^{\pm}$, $K^{\pm}$, and p), net-particle (net-K, net-p), and light nuclei (d and t) in Au+Au collisions at $\sqrt{s_{NN}}$ = 3.2, 3.5, 3.9, and 4.5 GeV using the data from fixed target (FXT) collisions at the Solenoidal Tracker at RHIC (STAR) experiment. The FXT setup was implemented at STAR to explore the region of high baryon chemical potential (μ_B) on the QCD phase diagram. This data was collected during the second phase of the Beam Energy Scan program (BES-II) after the detector upgrades for it were incorporated.
The identification of charged particles in STAR is done by the combination of Time Projection Chamber (TPC) and Time of Flight (TOF) detectors. The TPC uses the information of the ionization energy loss (dE / dx), whereas the TOF uses m^2 information for particle identification [4].
The anisotropic flow coefficients are determined by the azimuthal angle of a particle relative to the azimuth of the event plane (EP). In experiments, the event plane is determined by measuring the azimuthal distribution of produced particles and calculating the flow vector ($\vec{Q}_n$) for a given harmonic n [3]. The event plane angle Ψ_n is then estimated using:

$$\Psi_n = \frac{1}{n} \tan^{-1}\left(\frac{Q_{n,y}}{Q_{n,x}}\right) \tag{2}$$

The first order EP is correlated with the reaction plane, which is spanned by the direction of the beam and the impact parameter. We used the first-order event plane angle Ψ_1 for the calculations v_1 and v_3. The Ψ_1 is measured using the event plane detector (EPD). The v_1 and v_3 are computed via $v_n = \langle\cos[\mathrm{n}(\phi - \Psi_1)]\rangle/R_n$, where R_n being the resolution of the n^{th} order event plane, determined using a three sub-event plane correlation method [3].

3. Results and Discussions

Net particle refers to the excess yield of particle over its antiparticle. To highlight the contribution of transported quarks over those produced in collisions, $v_{1,net}$ is calculated and is defined as $v_{1,net} = v_{1,p} - rv_{1,\bar{p}}/(1 - r)$, where $v_{1,p}$, $v_{1,\bar{p}}$ are the v_1 of the particle and antiparticle, and r is the ratio of antiparticles to particles. Based on the hydrodynamic calculations, a minimum in slope of v_1 has been proposed as a signature of a first-order phase transition between hadronic matter and QGP [5]. The p_T-integrated $v_1(y)$ slope at mid-rapidity, $dv_1/dy|_{y=0}$, is obtained by fitting the data (v_1 vs. y) with a third-order polynomial. Figure 1 shows the collision energy dependence of $dv_1/dy|_{y=0}$ for identified hadrons (left panel), net particles (middle panel) and light nuclei (right panel) in mid-central (10 - 40%) collisions. The extracted slope parameters, $dv_1/dy|_{y=0}$, are scaled by mass number (A) for light nuclei to compare with protons. The magnitude of slope decreases with increasing collision energy for all particles, including light nuclei. The net-kaon $dv_1/dy|_{y=0}$ shows a minimum between $\sqrt{s_{\mathrm{NN}}}$ = 4.5 and 7.7 GeV, at lower collision energies than for net-protons, where the minimum is found between $\sqrt{s_{\mathrm{NN}}}$ = 11.5 and 19.6 GeV [6]. The light nuclei v_1 slope exhibits an approximate mass number scaling, consistent with the nucleon coalescence mechanism for the production of light nuclei.

Figure 2 shows the p_T dependence of dv_1/dy for mesons ($\pi^{\pm}$ and $K^{\pm}$). A strong p_T dependence is observed for all the studied mesons, showing negative slopes, or anti-flow, at $p_T \leq 0.6$ GeV/c across all collision energies. The E895 experiment also observed kaon anti-flow in this region, attributing it to kaon potential [7]. However, JAM (Jet AA Microscopic Transport Model) calculations, with and without spectator effects, reveal that spectators alone shift $dv_1/dy|_{y=0}$ for mesons in the negative direction, suggesting kaon anti-flow may result from spectator shadowing rather than exclusively from kaon potential [8].

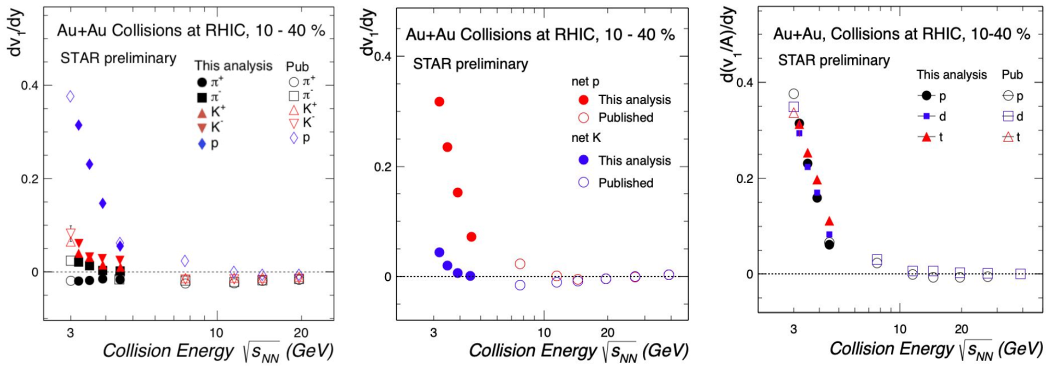

Figure 1: Collision energy dependence of $\mathrm{d}v_1/\mathrm{d}y|_{y=0}$ for identified hadrons (left panel), net particles (middle panel) and light nuclei (right panel) in Au+Au collisions at RHIC for 10-40% centrality. The published data are shown in open markers [4].

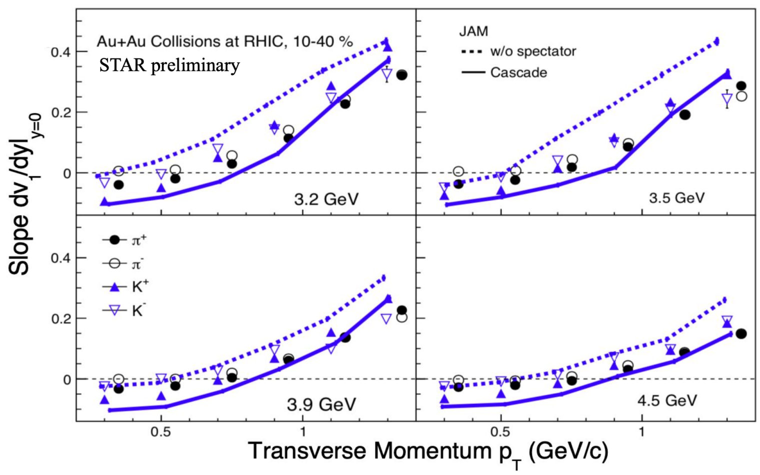

Figure 2: p_T dependence of $\mathrm{d}v_1/\mathrm{d}y$ of mesons in $10-40\%$ centrality in Au+Au collisions at $\sqrt{s_{NN}} = 3.2 - 4.5$ GeV. The markers represent the experimental data whereas lines represents JAM model prediction for K^+.

Figure 3 represents the y (left panel), p_T (middle panel), and centrality (right panel) dependence of v_3 for proton in Au+Au collisions at $\sqrt{s_{NN}}$ = 3.2, 3.5, 3.9, and 4.5 GeV. The magnitude of v_3 increases with increasing y, p_T, and centrality whereas it decreases with increasing collision energy. The left panel of Figure 4 presents the energy dependence of the v_3 slope, dv_3/dy, which decreases with increasing energy and approaches zero around 4.5 GeV. The right panel compares experimental data with JAM model predictions, demonstrating that the inclusion of momentum-dependent potential (MD2) enhances agreement, highlighting the significance of mean-field effects alongside collision geometry for developement of v_3 signal at these energies [10].

4. Summary

In summary, we studied $v_1\{\Psi_1\}$ and $v_3\{\Psi_1\}$ of identified hadrons, net-particles, and light nuclei in Au+Au collisions at $\sqrt{s_{NN}}$ = 3.2 - 4.5 GeV. The $dv_1/dy|_{y=0}$ of identified hadrons, net-particles, and light nuclei decreases with increasing energy, with net-kaons showing a minimum at lower energies (4.5 – 7.7 GeV) than net-protons (11.5 – 19.6 GeV). Light nuclei exhibit approximate mass number scaling,

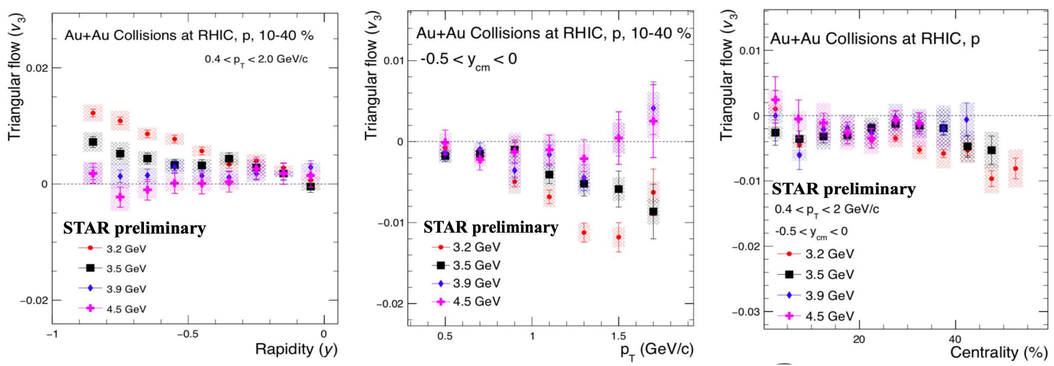

Figure 3: v_3 as a function of y (left panel), p_T (middle panel), and centrality (right panel) in Au+Au collisions at $\sqrt{s_{NN}}$ = 3.2 – 4.5 GeV.

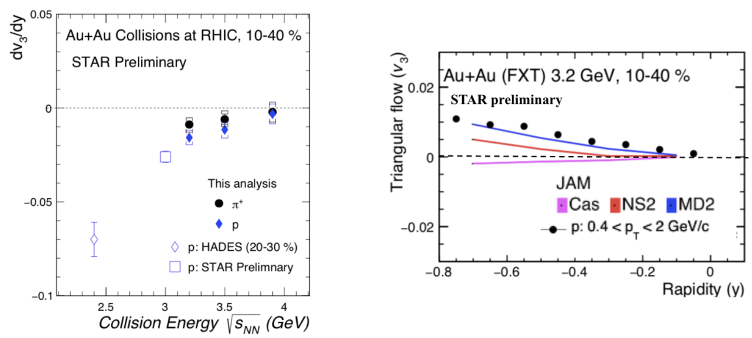

Figure 4: (Left panel) Collision energy dependence of dv_3/dy for identified hadrons. The published data are shown in open markers [9, 10]. (Right panel) JAM model comparison of v_3 as a function of rapidity(y). The solid markers represents experimental data whereas line represents JAM model calculations.

consistent with nucleon coalescence. The anti-flow of mesons at low p_T can be attributed to spectator effects, indicating a kaon potential is not necessary. The observed $v_3\{\Psi_1\}$ signal at low energies is driven by collision geometry and medium potential. It decreases with increasing collision energy and approaches zero around 4.5 GeV.

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