Flow in the RHIC Beam Energy Scan from STAR

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Abstract.

The first phase of the beam energy scan (BES) program at RHIC was successfully taken in the years 2010 and 2011. Data were collected at $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39$ and $62.4$ GeV, covering a wide range of baryon chemical potentials from $\mu_B$ 420 to 40 MeV. The main goals are the search for the QCD critical point and to find signatures for a phase transition between the hadron gas and the QGP. Directed ($v_1$), elliptic ($v_2$) and triangular ($v_3$) flow are important observables to study the early evolution of the created matter in relativistic heavy-ion collision experiments. In particular, it is expected that flow is sensitive to the phase transition from a quark gluon plasma to a hadron gas.

We will present measurements of identified hadrons for $v_1$ ($\pi^\pm, p, \bar{p}$), $v_2$ ($\pi^\pm, K^\pm, K^0, p, \bar{p}, \phi, \Lambda, \bar{\Lambda}, \Xi^+, \Xi^0, \Omega^+$) for all BES energies, and $v_3$ ($\pi^\pm, K^\pm, p, \bar{p}$) for $\sqrt{s_{NN}} = 39$ GeV. We will discuss the beam-energy dependent difference of $v_2$ between particles and anti-particles. Furthermore, we will address mass ordering at low $p_T$ and number-of-constituent-quark scaling at intermediate $p_T$ of $v_2$ and $v_3$ for identified hadrons.

1. Introduction

One of the main goals of heavy ion collision experiments at RHIC is to study the properties of the Quark-Gluon Plasma (QGP). To understand the formation of QGP and the structure of the phase diagram, the Beam Energy Scan (BES) phase one was started in the years 2010/2011 at RHIC [1], and recorded Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39$ and $62.4$ GeV. This paper reports the azimuthal anisotropy of identified particles of BES experiments by using the STAR detector at RHIC.

The azimuthal anisotropy is one of the most important observables for relativistic nuclear collisions. In the non-central Au+Au collision, the overlap region is an almond shape with the major axis perpendicular to the reaction plane which is defined by the impact parameter and the beam direction. Due to initial state fluctuations, the participant plane [2] in each event is not necessarily the same as the reaction plane. As the system evolves, the pressure gradient pushes the anisotropy from coordinate space to momentum space. The produced particle distribution [3, 4] can be written as:

$$E \frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{d\phi d\ln y} \left(1 + \sum_{n=1}^{\infty} 2n \cos[n(\phi - \Psi_n)]\right)$$  (1)
where $\phi$ is the azimuthal angle of a particle, and $\Psi_n$ is the n-th order event plane angle reconstructed by the final produced particles, which is an estimation of the participant plane. The first harmonic coefficient of the Fourier expansion $v_1$ is called directed flow, the second harmonic coefficient $v_2$ is called elliptic flow and the third harmonic coefficient $v_3$ is called triangular flow. In this paper, we will discuss the recent experimental results for $v_1$, $v_2$ and $v_3$ of identified particles from the BES.

This paper is organized as follows. In Sec. 2, the recently published results from BES I of $v_1$, $v_2$ [5, 6], and the new results for $v_3$ are discussed. Then the summary is presented in Sec. 3.

2. Recent Flow Results

Collective flow is one of the most widely studied observables in relativistic heavy ion experiments. Different harmonic coefficient reflects different dynamic properties of the fireball. For instance, $v_1$ reflects the compressibility of the created dense matter, $v_2$ is dominated by the initial geometry and $v_3$ is generated by the initial state fluctuations. A systematic study of flow coefficients as a function of beam energy, particle ID, and centrality, may reveal important properties of the QGP and the phase diagram.

2.1. Directed Flow

The STAR collaboration recently published directed flow results for protons, anti-protons, and pions for BES I in Au+Au collisions. In Ref. [5], the directed flow of protons, anti-protons and pions for 0%-10%, 10%-40% and 40%-80% central Au+Au collisions are shown, and the slopes ($dv_1/dy$) at 10%-40% central Au+Au collisions are calculated. Since a three-fluid hydrodynamic model with a first order phase transition from a QGP phase to a hadronic phase predicted a minimum in $dv_1/dy$ of net baryons, which is considered a "softest point collapse" [7], the STAR collaboration also analyzed the beam-energy dependent slopes of protons, anti-protons and net protons which are shown in Figure 1.

Figure 1 shows that for intermediate-centrality collisions, the slope of anti-protons increases with increasing beam energy and remain negative, but protons and net protons show a non-monotonic behavior. Proton $dv_1/dy$ decreases from 7.7 to 11.5 GeV and changes sign from positive to negative, increases from 19.6 to 200 GeV but remains negative and shows a minimum between 11.5 and 19.6 GeV. Net protons $dv_1/dy$ shows a similar trend but crosses zero between 27 and 39 GeV, and also shows a minimum between 11.5 and 19.6 GeV. For both protons and net protons, UrQMD model cannot reproduce this non-monotonic behavior. This observed minimum for protons and net protons is a possible signature for the softest point of the EoS and the first order phase transition.

2.2. Elliptic Flow

One of the most important observations from BES I is the difference in $v_2$ between particles and anti-particles [6]. Figure 2 shows the $p_T$-independent difference in $v_2$ between particles and anti-particles of different particle species (see legend in Figure 2) as a function of $\sqrt{s_{NN}}$ for 0%-80% central Au+Au collisions (please check Ref. [6] for details). Larger $v_2(X)$ values are found at lower beam energies for all particle species except pions which is the opposite. The magnitude of the difference between particles and anti-particles ($\Delta v_2 = v_2(X) - v_2(\bar{X})$) increases with decreasing beam energy. There are several theoretical calculations which try to explain this difference such as hybrid model [8] and the Nambu-Jona-Lasinio (NJL) model [9], but they can only qualitatively describe the experimental data so far.

Since the $v_2$ of particles and anti-particles are different, we cannot expect a single number-of constituent-quark (NCQ) scaling for both particles and anti-particles, therefore, we test the NCQ scaling for particles and anti-particles separately. The upper panels of Figure 3 shows the $v_2(m_T - m_0)$ scaled with number of constituent quarks on both axes for 11.5 and 62.4 GeV
Figure 1. Directed flow slope \( (dv_1/dy) \) near midrapidity versus beam energy for 10%-40% central Au+Au collisions. The dashed curves are smooth fits to guide the eye. Figure 1 is taken from Ref. [5].

Figure 2. The difference in \( v_2 \) between particles \( (X) \) and their anti-particles \( (\bar{X}) \) as a function of beam energy for 0%-80% central Au+Au collisions. Figure 2 is taken from Ref. [6].

(for more energies, please see Ref. [10]). The ratios of data to fit are shown in the lower panels of Figure 3. Most of the ratio values are within \( \pm 10\% \) of unity, which shows that the NCQ scaling holds for particles and anti-particles separately. The \( \phi \) meson is an exception, since the
Figure 3. The NCQ scaling of particles (frame a and b) and corresponding anti-particles (frame c and d) for 11.5 GeV and 62.4 GeV. Figure 3 is taken from Ref. [6]

$v_2$ value of $\phi$ mesons are lower by $2.5 \sigma$ at 11.5 GeV ($p_T = 1.9 \text{ GeV/c}$). The smaller $v_2$ value of $\phi(s\bar{s})$ meson, which has a smaller hadronic interaction cross section[11], may indicate that the hadronic interactions become more important than partonic interactions at lower energies ($\sqrt{s_{NN}} \leq 11.5 \text{ GeV}$).

2.3. Triangular Flow

A surprising result was observed for inclusive charged hadron $v_3$ results recently published by the the STAR collaboration [12]. “A good agreement is found not only between RHIC experiments but also between RHIC and LHC experiments. This is surprising because of the somewhat different $\Delta \eta$ ranges.” [12] In order to investigate detailed properties of $v_3$, the $v_3$ of identified particles needs to be studied.

Figure 4 shows $v_3(p_T)$ of $\pi^\pm, K^\pm, p$ and $\bar{p}$ for 0%-80% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ and 39 GeV. Since we already observed the difference of $v_2$ values between particles and anti-particles, it is natural to separate particles and anti-particles for $v_3$. For both 200 and 39 GeV, we see a mass ordering at low $p_T$ range which means the particle with a lower mass has a higher $v_2$. The region of mass ordering is $p_T < 1.6 \text{ GeV/c}$ for 200 GeV and $p_T < 1.2 \text{ GeV/c}$ for 39 GeV. The difference of mass ordering regions indicates different magnitudes of radial flow at different beam energies, which means the radial flow at 200 GeV is larger than that at 39 GeV. We also observe a baryon-meson splitting at the intermediate $p_T$ region of 200 GeV. The baryons ($p$ and $\bar{p}$) and mesons ($\pi^\pm$ and $K^\pm$) follow different trends. There are some hints that baryon-meson splitting also exist at 39 GeV but the uncertainties are too large. Therefore more particle species are needed to investigate the baryon-meson splitting ($\Lambda$ and $\bar{\Lambda}$).

To understand the partonic behavior of $v_3$, we check the NCQ scaling, which is observed for $v_2$ for particles and anti-particles separately as mentioned above, for $v_3$. As shown in Figure 5, we show $v_3(m_T - m_0)$ scaled with number of constituent quarks on both axes for 200 and 39 GeV. No NCQ scaling is observed with the same scaling factor $n_q$ used for $v_2$; we can see clearly the baryon band deviates from the meson band for both 200 and 39 GeV. This indicates that partonic interactions might have different influences on $v_3$ compared to $v_2$.

On the other hand, theoretical calculations suggest that we should use a new scaling factor which is $n_q^{n/2}$, where n is the n-th harmonic [13]. And an AMPT calculation also indicates that
**Figure 4.** Triangular flow of $\pi^\pm$, $K^\pm$, $p$ and $\bar{p}$ for 0%-80% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ and 39 GeV. Statistical uncertainties only.

**Figure 5.** $v_3(m_T - m_0)$ scaled with number of constituent quark ($n_q$) of $\pi^\pm$, $K^\pm$, $p$ and $\bar{p}$ for 0%-80% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ and 39 GeV. Statistical uncertainties only.
NCQ scaling works for $v_3$ within 20% by using a $n^{3/2}_q$ scaling factor [14]. We did the same thing to the experimental data. Figure 6 shows $v_3 (m_T - m_0)$ scaled with $n^{3/2}_q$ on the y-axis and $n_q$ on the x-axis for 200 and 39 GeV. We do observe the NCQ scaling at 200 GeV by using this $n^{3/2}_q$ factor; the baryon band and meson band come together. For 39 GeV we see some hint for NCQ scaling. With the future BES II program we will collect enough data to cover the important $m_T - m_0$ region above 1 GeV/$c^2$ where is the region we expect NCQ scaling and analyze more particle species.

![Figure 6. $v_3 (m_T - m_0)$ scaled with the new scaling factor $(n^{3/2}_q)$ for $\pi^\pm$, $K^\pm$, $p$ and $\bar{p}$ for 0%-80% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ and 39 GeV. Statistical uncertainties only.](image)

3. Summary
We present the recent flow results from BES I at RHIC from the STAR collaboration.

For directed flow ($v_1$), we show the slope $(dv_1/dy)$ as a function of beam energy, and a minimum between 11.5 and 19.6 GeV for protons and net protons is observed, which is a possible signature for the softest point of the EoS.

For elliptic flow ($v_2$), we show the difference of $v_2$ values for particles and anti-particles. As the $v_2$ value of particles and anti-particles is different, we expect a break-down of the NCQ scaling between particles and anti-particles. But the NCQ scaling holds for particles and anti-particles separately.

For triangular flow ($v_3$), the mass ordering at the low $p_T$ region is observed, where the larger mass ordering region at 200 GeV indicates larger radial flow. We also observe that the NCQ scaling breaks by using the same scaling factor as what we used for $v_2$ ($n_q$). But the NCQ scaling seems to hold at 200 GeV by using a $n^{3/2}_q$ factor. We also see some hints that NCQ scaling holds at lower energy by using this $n^{3/2}_q$ factor but we need more particle species and more beam energies.
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