RECENT ELLIPTIC FLOW MEASUREMENTS AT RHIC

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We present recent STAR measurements of elliptic flow v_2 in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$ - 39 GeV from Bean Energy Scan at RHIC. We observe that the relative difference of v_2 between baryons and anti-baryons significantly increases with decreasing the beam energy, and the v_2 for ϕ mesons is deviated from other hadrons at $\sqrt{s_{NN}} = 11.5$ GeV. These results are the possible implication where hadronic phase is dominated at lower energies.

1 Introduction

Elliptic flow is one of the key observables to study the properties of the Quark Gluon Plasma (QGP) created in heavy ion collisions [1]. It is characterized by the second harmonic coefficient of azimuthal particle distribution

$$v_2 = \langle \cos\left(2[\phi - \Psi_{\mathrm{RP}}]\right) \rangle \,, \tag{1}$$

where ϕ denotes the azimuth of produced particles, Ψ_{RP} is the azimuth of reaction plane made by the beam direction and the impact parameter vector, and brackets denote the average over particles of interest and over events.

The Beam Energy Scan (BES) program at Relativistic Heavy Ion Collider (RHIC) has begun since 2010 in order to search for the phase boundary as well as for the critical point by exploring the QCD phase diagram [2]. There are two main groups of signatures proposed to achieve these goals; (1) disappearance of QGP signatures and (2) critical point induced fluctuations. One of the main signatures is the number of constituent quark (NCQ) scaling of elliptic flow (v_2) observed at top RHIC energies [3,4], where the measured v_2 for identified particles shows the scaling behavior by number of constituent quarks at $p_T > 2$ GeV/c. The results indicate that the large amount of elliptic flow is developed at partonic phase prior to the hadronization. It is also important to point out that the ϕ mesons show the same magnitude of v_2 and also follow the NCQ scaling [5]. If the hadron phase is dominated in heavy ion collisions, their v_2 is expected to be small due to the small hadronic cross section of ϕ meson with other hadrons and hence the NCQ scaling for ϕ is broken [6]. Therefore, the measurements of elliptic flow are critical to study the structures of QCD phase diagram and to search for the possible phase boundary at low beam energies.

In this article, we present the recent STAR measurements of v_2 for unidentified charged particles as well as identified π, K, p, ϕ and Λ in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$ - 39 GeV from RHIC BES, and discuss the implications of dominance of hadronic phase at low energies.

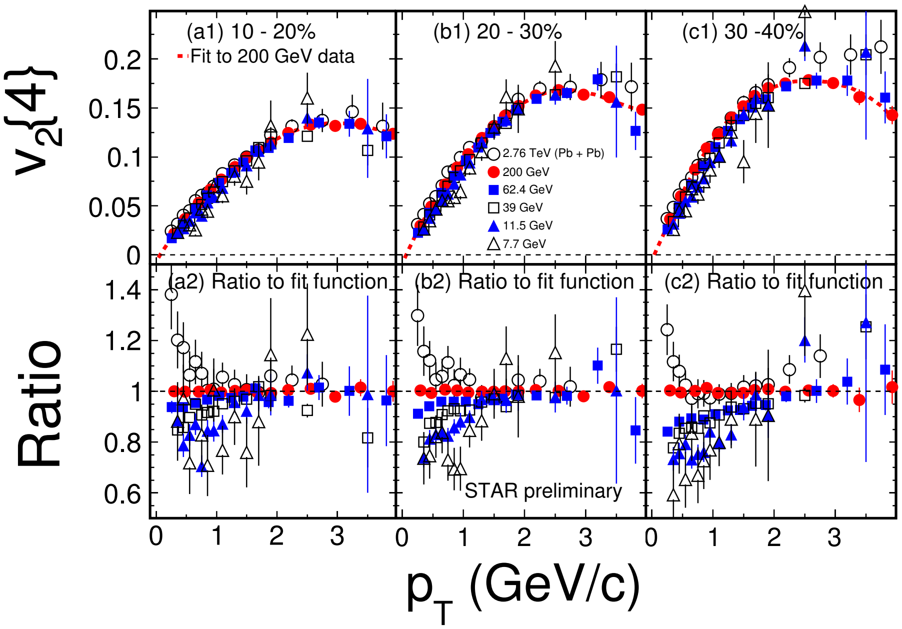


Figure 1: Top three panels show p_T dependence of v_2 for unidentified charged particles at $\sqrt{s_{NN}}$ = 7.7 - 200 GeV from STAR, and 2.76 TeV from ALICE in 10-20%, 20-30% and 30-40% centrality classes. Bottom panels show the ratio of v_2 to the polynomial fit of that at $\sqrt{s_{NN}}$ = 200 GeV. The error bars are statistical errors only.

2 STAR detector at RHIC

The first phase of Beam Energy Scan was accomplished in the year 2010 and 2011 at RHIC by varying the beam energies from 7.7 to 62.4 GeV in $\sqrt{s_{NN}}$. The main tracking detector at the STAR, Solenoid Tracker At RHIC, is the Time Projection Chamber (TPC) [7], which covers the full azimuth and pseudorapidity $|\eta| < 1.8$. The measurements of v_2 are carried out in $|\eta| < 1$ to ensure the uniform acceptance across the different beam energies. The TPC is also used to determine the collisions centrality by measuring the charged particle multiplicity distribution in $|\eta| < 0.5$. The event plane method is used to estimate the reaction plane using the TPC. A minimum $|\eta|$ gap 0.05 is used between particle of interest and event plane to avoid self-correlation of particles, and to reduce the non-flow effects. The π, K and p are identified by using the specific energy loss in the TPC together with the mass square from the Time-Of-Flight detector [8]. Other hadrons are measured through their hadronic decay channel; $K^0_S \to \pi^+ + \pi^-$, $\phi \to K^+ + K^-$ and $\Lambda \to p + \pi^-$ ($\bar{\Lambda} \to \bar{p} + \pi^+$) with additional topological cuts to improve the signal to background ratio for weak decays.

3 Unidentified charged particles

Figure 1 shows the comparison of v_2 for unidentified charged particles at $\sqrt{s_{NN}}$ = 7.7 - 2760 GeV as a function of transverse momentum p_T in three different centrality classes, 10-20%, 20-30% and 30-40% [9]. The results from $\sqrt{s_{NN}}$ = 7.7 - 39 GeV are compared to the previously published STAR measurements at $\sqrt{s_{NN}}$ = 62.4 [10] and 200 GeV [11], and also to the results at $\sqrt{s_{NN}}$ = 2.76 TeV from ALICE [12]. The $v_2\{4\}$ in the y-axis title indicates that the results are obtained by using the four particle cumulant method [13,14] in order to reduce the background contributions from direct two particle correlations, such as di-jets, resonance decays and so on. Bottom panels show the ratio of $v_2\{4\}$ to the polynomial fit of that at 200 GeV. In $p_T > 2$ GeV/c, the $v_2\{4\}$ are consistent within statistical errors from 7.7 to 2.76 TeV, whereas the

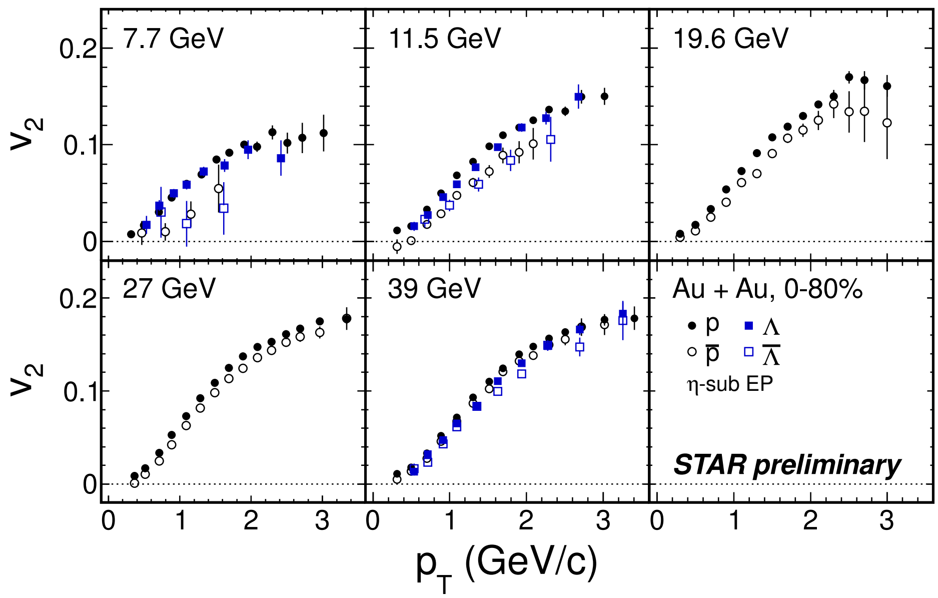


Figure 2: The v_2 for protons (circles) and Λ's (squares) as a function of p_T in 0-80% Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7 - 39 GeV. The error bars are statistical errors only.

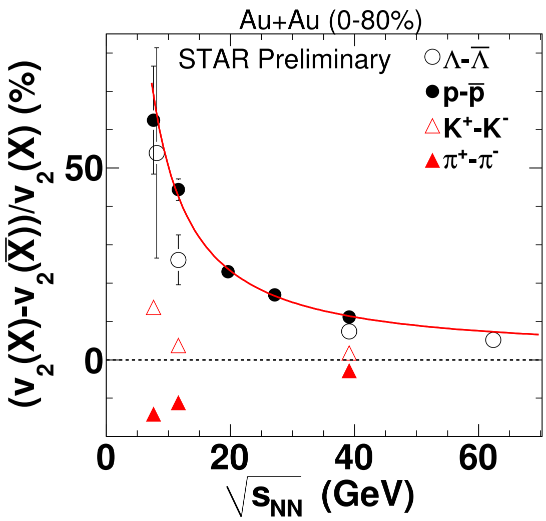
magnitude of $v_2\{4\}$ increase from 7.7 to 2.76 TeV in $p_T < 2$ GeV/c. The 20-40% decrease of $v_2\{4\}$ in low beam energies could be understood as different particle compositions, where the baryons (mesons) are dominated at low (high) energies with small (large) v_2 for a given p_T bin. In order to understand the systematics of v_2 in low beam energies, it is important to measure the v_2 for identified hadrons.

4 Identified hadrons

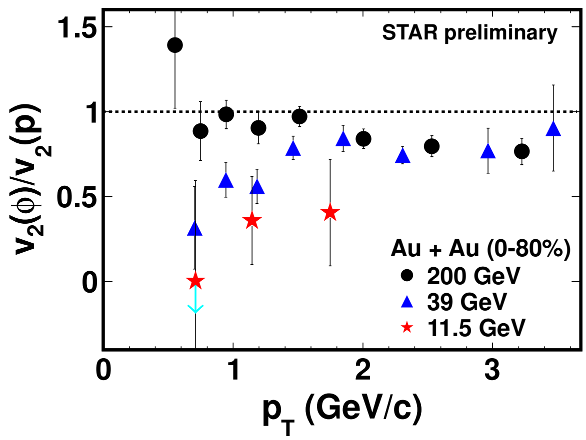
Figure 2 shows the v_2 for protons and Λ's as a function of p_T in 5 different collisions energies[9,15]. One can see that the magnitude of v_2 increases as a function of $\sqrt{s_{NN}}$, and the difference of v_2 between baryons and antibaryons increase with decreasing $\sqrt{s_{NN}}$. The measured v_2 for protons and Λ's are similar in terms of both magnitude and difference of v_2. One can argue that the NCQ scaling is broken between particles and antiparticles at $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV as a consequence of the significant difference of v_2. In order to quantify the difference of v_2 between particles and antiparticles, the relative difference of v_2 is calculated from the average v_2 in the measured p_T range. Figure 3 (a) shows the excitation function of the relative difference of v_2 for baryons and mesons. There are about 50-60% differences on v_2 for baryons at low beam energies, while the difference for mesons exhibit relatively smaller ($\sim$ 10%) than that for baryons. Several attempts to interpret the data have been made by baryon number transport[16], and by effects of hadronic potentials[17] but there are no quantitative conclusions to understand the difference of v_2 at low energies. Figure 3 (b) shows the ratio of v_2 for ϕ mesons to the protons as a function of p_T in 3 different $\sqrt{s_{NN}}$[18]. In $p_T < 2$ GeV/c, the ratio $v_2(\phi)/v_2(p)$ appears to decrease more than 50% at 11.5 GeV as compared to the results at 200 GeV. The decrease of v_2 for ϕ meson could be an indication that the hadronic phase is dominated at $\sqrt{s_{NN}} = 11.5$ GeV as predicted[6].

5 Conclusions

We present the STAR measurements of elliptic flow in Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7 - 39 GeV from Beam Energy Scan at RHIC. Relative difference of v_2 between particles and



(a)



(b)

Figure 3: (a) Relative difference of v_2 between particles and antiparticles as a function of $\sqrt{s_{NN}}$ in 0-80% Au + Au collisions for Λ's (open circles), protons (solid circles), kaons (open triangles) and pions (solid triangles). Solid line just guides your eyes for proton results. (b) Ratio of v_2 for ϕ mesons to the protons as a function of p_T in 0-80% Au + Au collisions at $\sqrt{s_{NN}} = 11.5$ (stars), 39 (triangles) and 200 GeV (circles). The error bars are statistical errors only for both figures.

antiparticles is found to increase with decreasing the beam energies. The number of constituent quark scaling of v_2 is broken between particles and antiparticles at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV as a consequence of the difference of v_2. The v_2 for ϕ mesons decreases with decreasing beam energies and is deviated from other hadrons at $\sqrt{s_{NN}} = 11.5$ GeV. These results might suggest that the hadronic phase is dominated at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV.

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