System size, energy and centrality dependence of strange hadron elliptic flow at STAR

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Abstract. The elliptic flow ($v_2$) pattern in terms of hadron mass and transverse momentum $p_T$ is qualitatively described for $p_T < 2$ GeV/c by ideal hydrodynamics in Au + Au collisions at RHIC. In addition, for $p_T = 2 - 6$ GeV/c the measured $v_2$ follow a universal scaling by the number of quarks explained by quark coalescence/recombination models. These observations suggest that a partonic collectivity develops in the matter in early stage of heavy ion collisions. Centrality as well as system size and energy dependence of the $v_2$ is important to shed light on the underlying collision dynamics in heavy ion collisions. We present the measurements of centrality dependence of $v_2$ at $\sqrt{s_{NN}} = 200$ and 62.4 GeV in Au + Au and Cu + Cu collisions for $K^0_S$, $\phi$, $\Lambda$, $\Xi$ and $\Omega$ at STAR experiment. We focus on the recent Cu + Cu results and discuss the centrality dependence of $v_2$ as well as the number of quark scaling as a function of transverse kinetic energy at different system size and energies. We also discuss the eccentricity scaled $v_2$ for identified hadrons and implications that ideal hydrodynamical limit has not been reached at RHIC.

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1. Introduction

Elliptic flow is expected to be one of the most sensitive observable to study early stage of heavy ion collisions at Relativistic Heavy Ion Collider (RHIC), see recent review in [1]. The elliptic flow is defined by the second harmonic Fourier coefficient of azimuthal distribution of produced particles with respect to the reaction plane

\[ v_2 = \langle \cos (2\phi - 2\Psi_{RP}) \rangle, \]

where \( \phi \) is the azimuth of particles in the laboratory frame, \( \Psi_{RP} \) is the azimuthal angle of reaction plane which is determined by the direction of impact parameter and beam axis [2]. Brackets denote the average over all particles and events. In Au + Au collisions at RHIC, it has been found that heavier hadrons has smaller \( v_2 \) than lighter hadrons for transverse momentum \( p_T < 2 \text{ GeV/c} \), which is qualitatively explained by hydrodynamical models [3]. Above \( p_T = 2 \text{ GeV/c} \), the \( v_2 \) had a reversed trend where protons and \( \Lambda \)'s have larger \( v_2 \) than the charged mesons [4, 5]. The reversed trend can be well described by quark recombination/coalescence models [6, 7, 8] that indicate the \( v_2 \) has already developed during the early partonic stage prior to the hadronization. It is important to study the systematics of \( v_2 \), such as system size, beam energy as well as centrality dependence, in order to understand the underlying collision dynamics in heavy ion collisions.

2. Data Analysis

In this analysis, we used minimum bias 24 M events in Cu + Cu collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) taken at STAR experiment. The event centrality was determined by the uncorrected charged particle multiplicity measured by the main TPC within pseudorapidity \( |\eta| < 0.5 \). Particle identifications were performed by the energy loss in the main TPC that enable us to separate \( K_S^0 \), \( \Lambda \) and \( \Xi \) in \( 0.2 < p_T < 4 \text{ GeV/c} \). Event plane method [2] was used to measure \( v_2 \) at midrapidity. The \( v_2 \) can be expressed as

\[ v_2 = \frac{\langle \cos (2\phi - 2\Psi_{EP}^2) \rangle}{\langle \cos (2\Psi_{EP}^2 - \Psi_{RP}) \rangle}, \]

where \( \Psi_{EP}^2 \) denote the second harmonic event plane determined from elliptic flow, and brackets represent the average over detected particles and events. Event plane was determined by using the forward time projection chamber (FTPC) covered at \( 2.5 < |\eta| < 4 \). Since the FTPC has a rapidity gap from the main TPC region, it can reduce the non-flow contributions that are not correlated with the reaction plane, such as di-jets and resonance decays etc. The denominator in (2) is defined as an event plane resolution that is about 0.18 in midcentral Cu + Cu collisions. We also analyzed the data in Cu + Cu collisions at \( \sqrt{s_{NN}} = 62.4 \text{ GeV} \), which has 12.5 M minimum bias events. The event plane resolution was by a factor of 2 smaller than that at 200 GeV due to lower multiplicity.
3. Results

![Diagram](image)

Figure 1. (a) The $v_2$ as a function of $p_T$ for $K^0_S$, $\Lambda + \bar{\Lambda}$, $\Xi + \bar{\Xi}$ in 0 - 60 % (top), 0 - 20 % and 20 - 60 % centralities (bottom). Dashed lines represent ideal hydrodynamical calculation [9]. Only statistical errors are shown. (b) Number of quark scaling of $v_2$ as a function of $m_T - \text{mass}$ in 0 - 60 % (top), 0 - 20 % and 20 - 60 % (bottom). Data symbols are the same as those in (a).

Figure 1 (a) shows the $v_2$ for $K^0_S$, $\Lambda + \bar{\Lambda}$ and $\Xi + \bar{\Xi}$ as a function of $p_T$ in different centrality selections. We have observed that $\Lambda$ has smaller $v_2$ than $K^0_S$ below $p_T = 2$ GeV/c in Cu + Cu collisions. For $p_T > 2$ GeV/c, however, $\Lambda$ $v_2$ become larger than that of $K^0_S$. We have also found $\Xi$ has sizable $v_2$ in minimum bias 0 - 60 % centrality. Results were compared to an ideal hydrodynamical calculation with the first order phase transition from the QGP to the hadron phase. The ideal hydrodynamical model does not describe the centrality dependence of our data. For 0 - 20 %, the model under-predicts our data and for 20 - 60 %, it over-predicts the $v_2$. Effects not included in the model which may be relevant are geometric fluctuations in the initial conditions (particularly important in central collisions) and finite viscosity effects. It remains to be seen if these effects can account for the difference between the models and data. Figure 1 (b) shows the number of quark (NQ) scaling of $v_2$ as a function of transverse mass minus particle mass $m_T - \text{mass}$, namely both vertical and horizontal axes are divided by the number of valence quarks for each hadron. One can see that all measured hadrons lie on the universal curve up to $p_T = 4$ GeV/c in all centrality bins. This results indicate that the $v_2$ has already established in the partonic stage in Cu + Cu collisions.

Figure 2 show the comparison of $v_2$ for $K^0_S$ and $\Lambda + \bar{\Lambda}$ at $\sqrt{s_{NN}} = 200$ and 62.4 GeV in Cu + Cu collisions (left panel). For comparison, results in Au + Au collisions are presented in right panel [10, 11]. We found that the measured $v_2$ at $\sqrt{s_{NN}} = 200$ GeV are consistent with those at $\sqrt{s_{NN}} = 62.4$ GeV in both Cu + Cu and Au + Au
Figure 2. Comparison of \( v_2(p_T) \) for \( K^0_S \) and \( \Lambda + \bar{\Lambda} \) in 0 - 60 % centrality at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) with those at 62.4 GeV in Cu + Cu (left) and Au + Au collisions (right). The \( v_2 \) in Au + Au collisions are taken from [10, 11]. Only statistical errors are shown.

Figure 3. Number of quark scaling of \( v_2 \) divided by participant eccentricity \( \epsilon_{\text{part}} \) for \( K^0_S \) and \( \Lambda + \bar{\Lambda} \) as a function of \( m_T - \text{mass} \) in Cu + Cu collisions. For comparison, results in Au + Au collisions are also plotted.
collisions.

Figure 3 shows the eccentricity scaled $v_2$ for $K_S^0$ and $\Lambda + \bar{\Lambda}$ as a function of $m_T - \text{mass}$. In order to compare different particle species, NQ scaling was also applied. Since the event plane at the FTPC was determined by particles from participant nucleons, appropriate initial geometrical anisotropy should be participant eccentricity $\varepsilon_{\text{part}}$ that include event-by-event position fluctuation of participants [12]. The scaled $v_2$ in 0 - 20 % appeared to be larger than those in 20 - 60 %, which indicate that stronger collective flow has developed in more central collisions. In addition, scaled $v_2$ in Cu + Cu collisions are consistent with that in Au + Au collisions with similar number of participant $N_{\text{part}}$. This result suggest the observed $v_2$ is determined not only by initial geometry, but also by the $N_{\text{part}}$. Therefore, it is important to understand whether the $v_2$ in most central Au + Au collisions reach ideal hydrodynamical limit or not. Because ideal hydrodynamical models predict $v_2$ is only determined by the initial spatial anisotropy.

![Graph showing the comparison of $v_2/\varepsilon$ as a function of transverse number density $(1/S)dN/dy$ for different particle species in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV from PHENIX and STAR experiments. Published STAR and PHENIX results were taken from [4, 13, 14]. In order to extract the ideal hydrodynamical limit, we have used](image-url)
the formula based on a transport model with a finite Knudsen number [15]

\[ \frac{v_2}{\varepsilon} = \left( \frac{v_2}{\varepsilon} \right)_{\text{Hydro}} \left( \frac{1}{1 + K/K_0} \right), \quad \frac{1}{K} = \frac{\sigma c_s dN}{S dy}, \]

(3)

where \((v_2/\varepsilon)_{\text{Hydro}}\) is the ideal hydrodynamical limit of \(v_2\), \(K\) is the Knudsen number, \(c_s\) is the speed of sound, \(\sigma\) is the partonic cross section, \(S\) is the transverse area of collision zone and \(dN/dy\) is the total hadron multiplicity. We adopted \(K_0 = 0.7\) and \(c_s = 1/\sqrt{3}\) in order to reproduce the transport model calculation [16]. Hydrodynamical limits were extracted for different hadrons by fitting the available \(v_2\) simultaneously, where we assumed \(\sigma\) is the same for all hadrons. Right panel in Figure 4 shows the ratio of \(v_2\) to the resulting hydrodynamical limit from the fit as a function of \((1/S)dN/dy\). The ratio should be 1 when \(v_2\) reach hydrodynamical limit. We found that the ratio converge into a universal curve and ideal hydrodynamical limit has not been reached even at the most central collisions at RHIC.

4. Conclusions

In summary, we have measured \(v_2\) for \(K_0^0\), \(\Lambda + \bar{\Lambda}\) and \(\Xi + \bar{\Xi}\) at \(\sqrt{s_{NN}} = 200\) GeV in Cu + Cu collisions. We found that \(\Lambda\) has smaller \(v_2\) than \(K_0^0\) below \(p_T = 2\) GeV/c, whereas the trend was reversed above \(p_T = 2\) GeV/c. The measured hadrons follow the number of quark scaling as a function of \(m_T - \text{mass}\) in Cu + Cu collisions at \(\sqrt{s_{NN}} = 200\) GeV. This result is consistent with the idea that collective flow has been established in the partonic stage before the hadronization takes place. The \(v_2\) at \(\sqrt{s_{NN}} = 62.4\) GeV were consistent with those in \(\sqrt{s_{NN}} = 200\) GeV in Cu + Cu collisions. We observed that eccentricity scaled \(v_2\) was larger in more central events in Cu + Cu collisions, which indicate that stronger collective flow was developed in more central collisions. Finally, from the comparison of the data with a transport model approach, we found that ideal hydrodynamical limit has not been reached even at the most central collisions at RHIC.

[9] P. Huovinen, Private communication, \(T_c = 170\) MeV, \(T_f = 125\) MeV, first order phase transition, EOS Q.