Probe the partonic/hadronic matter with elliptic flow in STAR Beam Energy Scan

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Abstract. One of the goal of RHIC Beam Energy Scan program is to search for the phase transition boundary between partonic and hadronic matters. Azimuthal anisotropy is expected to be sensitive to the degree of freedom of the produced matter in the early stage of high energy nuclear collisions, which makes it an important probe to QCD phase transition. In this paper, we present the results of mid-rapidity elliptic flow measurements in Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5$ and 39 GeV from the STAR experiment at RHIC. The energy evolution of Number-of-Constituent-Quark (NCQ) scaling will be tested with the $v_2$ of identified hadrons ($\pi^{\pm}, K^{\pm}, K_0^0, p, \phi, \Lambda, \Xi^-, \Xi^+$). A significant difference in $v_2$ is observed between particles and corresponding anti-particles at the lowest energies of the beam energy scan. The implications on partonic-hadronic phase transition are discussed.

1. Introduction
One of the goal of RHIC Beam Energy Scan program is to search for the phase transition boundary between partonic and hadronic matters [1]. By systematic study of Au+Au collisions at $\sqrt{s_{NN}} = 5 - 200$ GeV, one could access a wide region of temperature $T$ and baryon chemical potential $\mu_B$ in the QCD phase diagram [1]. The elliptic flow ($v_2$) is a good probe to characterize the partonic or hadronic properties in the early stage of high energy nuclear collisions [2–4]. $v_2$ describes the azimuthal momentum space anisotropy of particle emission from non-central heavy-ion collisions in the plane transverse to the beam direction. It can be characterized by the second harmonic coefficient ($v_2$) of a Fourier decomposition of azimuthal momentum distribution of final state hadrons with respect to the reaction plane [5, 6], that is, $v_2 = \langle \cos 2(\varphi - \psi_R) \rangle$, where $\varphi$ is the azimuthal angle of a produced particle in the laboratory frame, $\psi_R$ is the reaction plane angle (for the details of $\psi_R$ estimation from experimental data, see Ref. [6]), and the brackets denote the arithmetic average over all interested particles in corresponding events.

$v_2$ originates in the spatial anisotropy of the system when it is created in a non-central collision and in interactions in the evolving system which convert the spatial anisotropy to momentum anisotropy. This anisotropy is driven by the azimuthal dependent pressure gradient developed from the rescatterings. The frequency and intensity of such rescatterings depends on the partonic or hadronic properties of the system, which makes $v_2$ especially sensitive to the degrees of freedom of the system in the early time. From transport model calculations, $v_2$ in the partonic dominated system is expected to be significantly larger than that in hadronic case [2–4]. In Au+Au $\sqrt{s_{NN}} = 200$ GeV collisions, RHIC has discovered the Number-of-Constituent-Quark
(NCQ) scaling of $v_2$ for identified light and strange hadrons, which is an important evidence for the discovery of a new kind of deconfined matter with partonic collectivity [7]. Because of the possible transition from partonic dominated phase to hadronic dominated phase, it is expected that the established paradigm for partonic degrees of freedom at top RHIC energy may break at given low collision energy. Especially, the absence or reduction of collective flow and the breaking of NCQ scaling could indicate the system in hadronic phase [2–4]. In this paper, we study the energy dependence of $v_2$ in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5 and 39 GeV, based on data taken from STAR experiment at RHIC in the year 2010.

2. Experimental data analysis

The Au+Au collision events collected by the minimum bias trigger are used in this analysis. STAR’s Time Projection Chamber (TPC) [8] and Time-of-Flight (TOF) detector [9, 10] are used for tracking, particle identification and event plane determination. The events are required to have a primary Z vertex (along beam direction) within 70, 50, and 40 cm of the center of the TPC for Au+Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5, and 39 GeV, respectively, to ensure nearly uniform detector acceptance. After the event selection, we obtain about 4, 12, and 130 million Au+Au minimum bias triggered events at $\sqrt{s_{NN}} = 7.7$, 11.5, and 39 GeV, respectively. The collision centrality is determined by the measured raw charged hadron multiplicity from the TPC within a pseudorapidity window $|\eta| < 0.5$ [11]. The $v_2$ measurement is based on the $\eta$-sub event plane method to reduce the non-flow effect from short range $\eta$-correlations. The $\eta$-sub event plane method is similar to the event plane method, except one defines the flow vector for each particle based on the particles measured in the opposite hemisphere in pseudorapidity [12]. An $\eta$ gap of $|\Delta \eta| > 0.05$ is guaranteed between the measured particle and the particles used for event plane reconstruction.

The TPC can identify particles by the specific energy loss ($dE/dx$) of charged particles traversing the TPC gas at low momentum. In the momentum range about 1–3 GeV/c, the pions, kaons and protons could not be identified by TPC $dE/dx$ only. With the fully installed TOF detector [9, 10] in the year 2010, one can identify event-by-event the $\pi^{\pm}$, $K^{\pm}$, proton, and anti-proton with the momentum above 0.2 GeV/c. The multi-strange hadron signals are obtained from the invariant mass distribution reconstructed by their hadronic decay channels: $\phi \rightarrow K^{+}\!\!\!\!+K^{-}$, $\Xi^{-}(\Xi^{+}) \rightarrow \Lambda(\bar{\Lambda}) + \pi^{+}(\pi^{-})$. The decay daughters $\Lambda(\bar{\Lambda})$ are reconstructed through $\Lambda(\bar{\Lambda}) \rightarrow p(\bar{p}) + \pi^{+}(\pi^{-})$. $K_{S}^{0}$ is reconstructed through its decay channel $K_{S}^{0} \rightarrow \pi^{+} + \pi^{-}$. Detailed descriptions on analysis cuts about geometry, kinematics as well as particle identification can be found in Refs. [12–15].

3. Results and discussions

In figure 1 we show the $v_2$ of $\Lambda$ and $\bar{\Lambda}$ as a function of transverse momentum ($p_T$) in minimum bias (0-80%) Au+Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5 and 39 GeV. The $v_2$ gradually increases with the collision energy. One can see from figure 1 that $\Lambda$ $v_2$ is systematically larger than $\bar{\Lambda}$ $v_2$. This difference increases with decreasing beam energy as shown for the data at 7.7 and 11.5 GeV.

Figure 2 shows the integrated $v_2$ difference between particles ($P$) and their corresponding anti-particles ($\bar{P}$) relative to the particle $v_2$. The difference is less than 5% between $K^{+}(\pi^{+})$ and $K^{-}(\pi^{-})$ at 39 GeV. For baryons such as protons($\Lambda$) and anti-protons($\bar{\Lambda}$), the differences are a little bit larger than those of pions and kaons, about 10% at 39 GeV. At 7.7 and 11.5 GeV, a significant $v_2$ difference (up to 60%) between protons($\Lambda$) and anti-protons($\bar{\Lambda}$) is observed. For mesons, the $v_2$ difference between $K^{+}(\pi^{+})$ and $K^{-}(\pi^{-})$ is up to 15%, much smaller compared to the baryons. Color bands in figure 2 are calculations from a multi-phase transport model (AMPT) [16]. The mean-field potentials in the hadronic phase are included in the AMPT model, which lead to the splittings of the elliptic flows of particles and their anti-particles. In this way, it
Figure 1. $v_2$ of $\Lambda$ and $\bar{\Lambda}$ as a function of $p_T$ in minimum bias (0−80%) Au+Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5 and 39 GeV.

Figure 2. The relative difference of integrated $v_2$ between particles ($P$) and their corresponding anti-particles ($\bar{P}$) (see the legend) as a function of $\sqrt{s_{NN}}$ for 0−80% Au+Au collisions. Color bands are calculations from a multi-phase transport model (AMPT) [16].

could describe qualitatively the $v_2$ differences between particles and their anti-particles. Without including the hadronic mean-field potentials, the model fails to reproduce the $v_2$ differences. Even with the hadronic mean-field potentials included, the AMPT model still underestimates the $v_2$ difference between protons($\pi^+$) and anti-protons($\pi^-$), while overestimates that between $K^+$ and $K^-$. Another model considers the different $v_2$ between transported quarks ($u, d$) and produced quarks ($\bar{u}, \bar{d}$) due to baryon transportation to mid-rapidity [17]. It further assumes a smaller strange quark $v_2$ compared to produced light quarks. With above assumptions and a parton coalescence scenario, the model could qualitatively describe the $v_2$ difference between different hadrons. To distinguish different models, further quantitative comparisons with model calculations on $p_T$, centrality and rapidity dependent $v_2$ should be performed.

In figures 3(a)-(c), we compare the $v_2$ of $\phi$-meson to those of proton and $\Lambda$ in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 11.5$, 39, and 200 GeV. We use the TPC event plane for $v_2$ measurement at 200 GeV [18, 19], and the TPC $\eta$-sub event plane at 11.5 and 39 GeV. One can see from figure 3(a) that $\phi$-meson $v_2$ is close to those of proton and $\Lambda$ for $p_T$ below...
In summary, we present the results of mid-rapidity elliptic flow measurements in Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5$ and $39$ GeV from the STAR experiment at RHIC. A significant difference in $v_2$ is observed between particles and corresponding anti-particles in Au+Au 7.7, 11.5 and $39$ GeV collisions [17] and/or the hadronic interactions start to play an important role in driving $\phi$-meson elliptic flow [2–4]. Note that $\phi$-meson has small hadronic cross sections, a small $v_2$ is expected in hadronic dominated system [2–4], which is seen in the present experimental data.

In figure 4, we test the transverse kinetic energy ($m_T - m_0$) scaling of $v_2$ with various particles $\pi^\pm$, $K_S^0$, $\phi$, proton, $\Lambda$, and $\Xi^-$. Most of the particles follow one common curve except for the $\phi$ mesons at 11.5 GeV. The $\phi$ meson $v_2$ shows a different trend away from the scaling of other hadrons. The mean deviation of the $\phi$-meson $v_2$ from the $\pi^\pm$ $v_2$ is $0.02 \pm 0.008$ at 11.5 GeV. This observation shows that $\phi$ meson has a smaller $v_2$ than the expectation from $m_T - m_0$ scaling of other hadrons at 11.5 GeV.

4. Summary

In summary, we present the results of mid-rapidity elliptic flow measurements in Au + Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5$ and 39 GeV from the STAR experiment at RHIC. A significant difference in $v_2$ is observed between particles and corresponding anti-particles in Au+Au 7.7 and 11.5 GeV, suggesting that NCQ-scaling between particles and anti-particles is broken at low beam energies. In Au+Au collisions at $\sqrt{s_{NN}} = 39$ GeV, the baryon-meson separation between $\phi$-meson and proton (or $\Lambda$) $v_2$ at $p_T > 2$ GeV/c supports the quark coalescence picture. At low $p_T$, the $\phi$-meson $v_2$ is smaller than those of the proton and $\Lambda$, thus violates the mass ordering observed in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. This might be related to incomplete thermalization of strange quarks and/or the increasing contributions from hadronic interactions.
Figure 4. \( v_2 \) per number-of-constituent quarks (ncq) in 0–80% minimum bias Au+Au collisions for \( \pi^\pm, K_0^0, \phi, p, \Lambda \) and \( \Xi^- \) as a function of \( (m_T - m_0)/\text{ncq} \) for the three collision energies 7.7, 11.5 and 39 GeV. Errors are statistical only.

to the elliptic flow with decreasing collision energies. Coming results from Au+Au collisions at 19.6 and 27 GeV measured in year 2011 will provide further information.

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