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THE ELLIPTIC FLOW IN Au + Au COLLISIONS AT $\sqrt{s_{NN}} = 7.7$, 11.5 AND 39 GeV AT STAR*

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We present elliptic flow, v_2, measurements for charged and identified particles at midrapidity in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5 and 39 GeV at STAR. We compare the inclusive charged hadron v_2 to those from high energies at RHIC ($\sqrt{s_{NN}} = 62.4$ and 200 GeV) and LHC ($\sqrt{s_{NN}} = 2.76$ TeV). A significant difference in v_2 between baryons and anti-baryons is observed and the difference increases with decreasing beam energy. The v_2 of ϕ meson is systematically lower than other particles in Au + Au collisions at $\sqrt{s_{NN}} = 11.5$ GeV.

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1. Introduction

The main physics motivation for the Beam Energy Scan at RHIC–STAR experiment is searching for the phase boundary and critical point predicted by QCD. The elliptic flow, v_2, which is generated by the initial anisotropy in the coordinate space, is defined by

$$v_2 = \langle \cos 2(\phi - \Psi_{\mathrm{R}}) \rangle \,, \tag{1}$$

where ϕ is the azimuthal angle of an outgoing particle, Ψ_R is the azimuthal angle of the impact parameter, and angular brackets denote an average over

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particles and events. Due to the self-quenching effect, it is sensitive to the early stage of heavy-ion collisions [1]. The number of constituent quark (NCQ) scaling, observed at the top energy of RHIC Au + Au and Cu + Cu collisions [2,3,5], reflects the fact that the collectivity has been built up at the partonic stage. Especially, the NCQ scaling for multi-strange hadrons, $\phi(s\overline{s})$ and $\Omega(sss)$ supports the deconfinement and partonic collectivity picture [4, 6]. A study based on a multi-phase transport model (AMPT) indicates the NCQ scaling is related to the degrees of freedom in the system [7]. The scaling and no scaling in v_2 reflects the partonic and hadronic degrees of freedom respectively. The importance of ϕ meson has been emphasized, where the ϕ-meson v_2 could be small or zero without partonic phase [8]. Thus, the measurements of elliptic flow with the Beam Energy Scan data offer us the opportunity to investigate the QCD phase boundary.

In this paper, we present the v_2 results of charged and identified hadrons from Au + Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5 and 39 GeV observed by the STAR experiment. STAR's Time Projection Chamber (TPC) [9] is used as the main detector for event plane determination. The centrality was determined by the number of tracks from the pseudorapidity region $|\eta| \leq 0.5$. The particle identification for $\pi^{\pm}$, $K^{\pm}$ and p ($\overline{p}$) is achieved via the energy loss in the TPC and the Time-of-Flight information from the multi-gap resistive plate chamber detector [10]. Strange hadrons are reconstructed with the decay channels: $K^0_{\mathrm{S}} \to \pi^+ + \pi^-$, $\phi \to K^+ + K^-$, $\Lambda \to p + \pi^-$ ($\overline{\Lambda} \to \overline{p} + \pi^+$), and $\Xi^- \to \Lambda + \pi^-$ ($\overline{\Xi}^+ \to \overline{\Lambda} + \pi^+$)). The detailed description of the procedure can be found in Refs. [2,3,11]. The event plane method [12] and cumulant method [13, 14] are used for the v_2 measurement.

2. Results and discussions

The Beam Energy Scan data from RHIC–STAR experiment, offer an opportunity to study the beam energy dependence of v_2 in a wide range of beam energy. Figure 1 shows the results of transverse momentum (p_{T}) dependence of $v_2\{4\}$ for charged hadrons from $\sqrt{s_{NN}} = 7.7$ GeV to 2.76 TeV in 10–20% (a1), 20–30% (b1) and 30–40% (c1) centrality bins, where the ALICE results in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are taken from [15]. At low p_{T} ($p_{\mathrm{T}} < 2$ GeV/c), the v_2 values increase with increasing the beam energy. Beyond $p_{\mathrm{T}} = 2$ GeV/c the v_2 results show comparable values within the statistical errors. There is no saturation signal of v_2 up to collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Figure 2 shows excitation function for the relative difference of v_2 between particles and anti-particles. Here, to reduce the non-flow effect, the η-sub-event plane method is used to calculate v_2. The η-sub-event plane method is similar to the event plane method, except one defines the flow vector for each particle based on particles measured in the

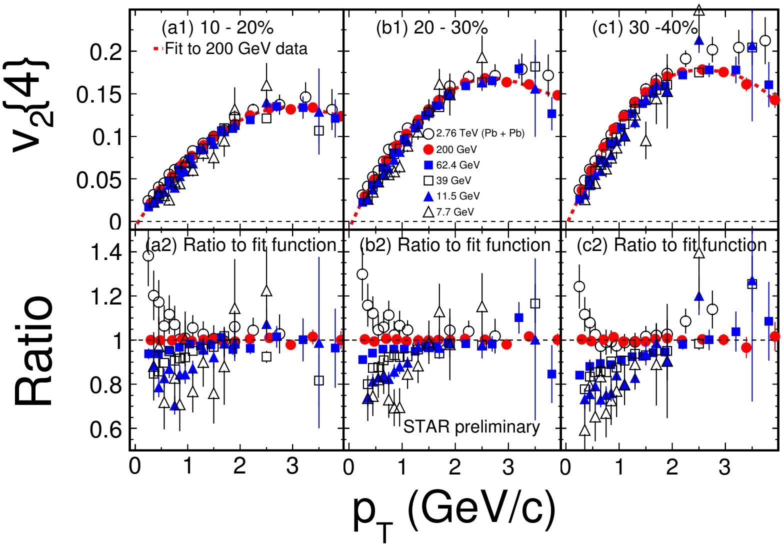

Fig. 1. (Color online) The top panels show the $v_2\{4\}$ *versus* $p_{\rm T}$ at midrapidity for various beam energies ($\sqrt{s_{NN}}$ = 7.7 GeV to 2.76 TeV). The results for $\sqrt{s_{NN}}$ = 7.7 to 200 GeV are for Au + Au collisions and those for 2.76 TeV are for Pb + Pb collisions. The line made of grey (red) circles shows the fit to the results from Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The bottom panels show the ratio of $v_2\{4\}$ *versus* $p_{\rm T}$ for all $\sqrt{s_{NN}}$ with respect to this fitted line. The results are shown for three collision centrality classes: 10–20% (a1), 20–30% (b1) and 30–40% (c1).

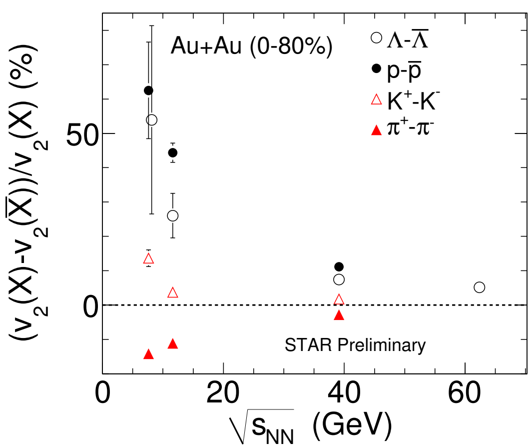

Fig. 2. (Color online) The difference of v_2 for particles and anti-particles ($v_2(X) - v_2(\overline{X})$) divided by particle v_2 ($v_2(X)$) as a function of beam energy in Au + Au collisions (0–80%).

opposite hemisphere in pseudorapidity. An η gap of $|\eta| < 0.05$ is used between negative/positive η sub-event to guarantee that non-flow effects are reduced by enlarging the separation between the correlated particles. The difference for baryon and anti-baryon (protons and Λs) could be observed from 7.7 to 62.4 GeV. The difference of v_2 for baryons is within 10% at $\sqrt{s_{NN}} = 39$ and 62.4 GeV, while a significant difference is observed below $\sqrt{s_{NN}} = 39$ GeV. For example, the difference of protons *versus* anti-protons is around 60%. There is no obvious difference for π^+ *versus* π^- (within 3%) and K^+ *versus* K^- (within 2%) when $\sqrt{s_{NN}} = 39$ GeV. As the beam energy decreases, π^+ *versus* π^- and K^+ *versus* K^- start to show the difference. The v_2 of π^- is larger than that of π^+ and the v_2 of K^+ is larger than that of K^-. This difference between particles and anti-particles might be due to the baryon transport effect to midrapidity [16] or absorption effect in the hadronic stage. The results could indicate the hadronic interaction become more dominant in lower beam energy. The immediate consequence of the significant difference between baryon and anti-baryon v_2 is that the NCQ scaling is broken between particles and anti-particles at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV. The transverse momentum dependence of v_2 for the selected identified particles is shown in Fig. 3. The v_2 and $m_{\mathrm{T}} - m_0$ has been divided by number of constituent quark in each hadron. In Au + Au collisions at $\sqrt{s_{NN}} = 39$ GeV, the similar scaling behavior at $\sqrt{s_{NN}} = 200$ GeV is observed. Especially, the ϕ mesons which are insensitive to the later hadronic rescatterings follows the same trend of other particles. It suggests that the partonic collectivity has been built up in collisions at $\sqrt{s_{NN}} = 39$ GeV. However, the v_2 for ϕ mesons falls off from other particles at $\sqrt{s_{NN}} = 11.5$ GeV. The mean deviation to the v_2 pions is 2.6 σ. It indicates that the hadronic interaction are dominant in collisions at $\sqrt{s_{NN}} = 11.5$ GeV.

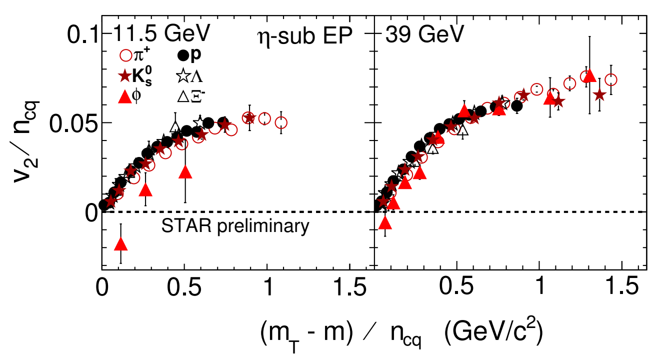

Fig. 3. (Color online) The number of constituent quark (n_{cq}) scaled v_2 as a function of transverse kinetic energy over n_{cq} ($(m_{\mathrm{T}} - m_0)/n_{\mathrm{cq}}$) for various identified particles in Au + Au (0–80%) collisions at $\sqrt{s_{NN}} = 11.5$ and 39 GeV.

3. Summary

In summary, we present the v_2 measurement for charged hadrons and identified hadrons in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5 and 39 GeV. The magnitude of v_2 increases as the beam energy increases from 7.7 GeV to 2.76 TeV. The difference between the v_2 of particles and anti-particles is observed. The baryons and anti-baryons show a significant difference at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV. The ongoing analysis with 19.6 and 27 GeV data collected in 2011 will fill the gap between 11.5 and 39 GeV. The pions and kaons are almost consistent at $\sqrt{s_{NN}} = 39$ GeV. The difference increases with decreasing of the beam energy. The v_2 of ϕ meson falls off from other particles in collisions at $\sqrt{s_{NN}} = 11.5$ GeV. Experimental data suggests the hadronic interactions are dominant when $\sqrt{s_{NN}} \leq 11.5$ GeV.

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