ENERGY DEPENDENCE OF ELLIPTIC FLOW OF ϕ-MESON IN STAR AT RHIC*

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We present the measurement of elliptic flow (v_2) as a function of transverse momentum ($p_{\rm T}$) for the ϕ-meson in Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5 and 39 GeV. At low $p_{\rm T}$ ϕ-meson v_2 decreases with decrease in beam energy. The number of constituent quark ($n_{\rm cq}$) scaled v_2 for ϕ-meson *versus* $(m_{\rm T} - m_0)/n_{\rm cq}$ follows similar trend as other hadrons for $\sqrt{s_{NN}} = 39$ GeV, whereas the $n_{\rm cq}$ scaled v_2 for ϕ-mesons follows a different trend compared to the other hadrons at $\sqrt{s_{NN}} = 11.5$ GeV.

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1. Introduction

The elliptic flow (v_2) measured in heavy-ion collision is believed to arise due to the pressure gradients developed in the overlap region of two nuclei colliding at nonzero impact parameters. According to hydrodynamical model v_2 is an early time phenomenon and sensitive to the equation of state of the system formed in the collision [1]. Thus v_2 can be used as a probe for early system although its magnitude may change due to later stage hadronic interactions. The ϕ-meson, which is the bound state of s and $\bar{s}$ quark, has small interaction cross-section with hadrons [2]. So for the ϕ-meson v_2, effect of later stage hadronic interaction is small. Therefore, elliptic flow of ϕ-mesons can be used as a clean probe to measure early time collectivity of the system created in heavy-ion collision. Recent results from Relativistic Heavy Ion Collider (RHIC) on v_2 as function of transverse momentum ($p_{\rm T}$) show that at low $p_{\rm T}$ elliptic flow of identified hadrons follows mass ordering (lower v_2 for heavier hadrons than that of lighter hadrons), whereas at intermediate $p_{\rm T}$ all mesons and all baryons form two different groups. When

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v_2 and p_{T} are scaled by number of constituent quarks of the hadrons, the measured v_2 values are consistent with each other as parton coalescence or recombination models predicted [3,4]. This observation is known as number of constituents quark scaling (NCQ scaling). This effect has been interpreted as collectivity being developed at the partonic stage of the evolution of the system in heavy-ion collision [5]. ϕ-meson has mass 1.02 GeV/c^2 comparable to mass of the lightest baryons (protons, Λs), and at the same time it is the meson, so the study of NCQ scaling of ϕ-meson v_2 would be more appropriate to understand the collectivity at partonic level and coalescence as mechanism of hadronization at intermediate p_{T}. One of the main goal of RHIC Beam Energy Scan (BES) program is to see NCQ scaling of v_2 for all hadrons as function of energy. In this program ϕ-mesons v_2 plays an important role. Because violation of NCQ scaling by ϕ-mesons could be considered as a signature of matter dominated by hadronic interactions.

2. Detectors and data sets

The results presented here are based on data collected in the BES program at $\sqrt{s_{NN}}$ = 7.7, 11.5 and 39 GeV in Au + Au collisions with the STAR detector with minimum bias trigger [6] in the year 2010. The Time Projection Chamber (TPC) and Time-of-Flight (TOF) detectors with full 2π coverage were used for particle identification in the central rapidity (y) region ($|y| < 1.0$). Particles are identified from information of specific energy loss as a function of momentum (using TPC) and square of mass as a function of momentum (using TOF). A cut on vertex radius (defined as $V_{\mathrm{R}} = \sqrt{V_x^2 + V_y^2}$, where V_x and V_y are the vertex positions along the x and y directions) smaller than 2 cm has been used to reject events from beam pipe interaction. The total number of minimum bias events analyzed are about 169 million for 39 GeV, 10.5 million for 11.5 GeV and 4 million for 7.7 GeV.

3. Flow analysis methods

The Event Plane method [7] (both full and η-sub event plane) has been used for the flow analysis. In this method, each particle correlates with event plane determined from all particles in a events except the particle of interest. The event plane angle ψ_2 is defined by the equation

$$\psi_2 = \tfrac{1}{2}\tan^{-1}\frac{\sum w_i \sin(2\phi_{\mathrm{i}})}{\sum w_i \cos(2\phi_{\mathrm{i}})}, \tag{1}$$

where sum goes over all the particles used in the event plane calculation. ϕ_i is the azimuthal angle of the i-th particle and $w_i (= w_\phi * w_{\mathrm{pt}})$ are weights. The weight w_ϕ, inverse of azimuthal distribution of particles, has been used to

make the distribution of event planes isotropic in the laboratory system [7]. In order to improve the event plane resolution, the weights $w_{\rm pt}$ are set equal to $p_{\rm T}$ up to 2 GeV/c and then constant at 2.0 above $p_{\rm T} > 2$ GeV/c.

The observed $v_2^{\rm obs}$ is the second harmonic of the azimuthal distribution of particles with respect to ψ_2

$$v_2^{\rm obs} = \langle \cos[2(\phi - \psi_2)] \rangle \,, \tag{2}$$

where angular brackets denote an average over all particles in all events. Since finite multiplicity limits the resolution in estimating the angle of the reaction plane, the observed $v_2^{\rm obs}$ has to be corrected for the event plane resolution as

$$v_2 = \frac{v_2^{\rm obs}}{\langle \cos[2(\psi_2 - \psi_{\rm r})] \rangle} \,, \tag{3}$$

where $\psi_{\rm r}$ is the reaction plane angle. The event plane resolution [7] is estimated by the correlation of the events planes of two sub-events A and B and is given by

$$\langle \cos[2(\psi_2 - \psi_{\rm r})] \rangle = C \langle \cos\left[2\left(\psi_2^{\rm A} - \psi_2^{\rm B}\right)\right] \rangle \,, \tag{4}$$

where C is a constant calculated from the known multiplicity dependence of the resolution.

In η-sub event plane method [7], one defines the event flow vector for each particle based on particles measured in the opposite hemisphere in pseudorapidity

$$v_2(\eta_\pm) = \frac{\left\langle \cos\left[2\left(\phi_{\eta_\pm} - \psi_{2,\eta_\mp}\right)\right]\right\rangle}{\sqrt{\langle \cos[2(\psi_{2,\eta_+} - \psi_{2,\eta_-})] \rangle}} \,. \tag{5}$$

Here $\psi_{2,\eta_+}(\psi_{2,\eta_-})$ is the second harmonic event plane angle defined for particles with positive (negative) pseudorapidity. An η gap of $|\eta| < 0.075$ between positive and negative pseudorapidity sub-events has been introduced to suppress non-flow effects. Event-by-event resolution correction has been done. Typical values of event plane resolution (in η-sub event plane method) for minimum bias collision are 0.43, 0.32 and 0.27 at $\sqrt{s_{NN}} = 39$, 11.5 and 7.7 GeV, respectively.

4. Results

ϕ-mesons are identified using the invariant mass technique from their decay to $K^+ + K^-$. Mixed event technique has been used for combinatorial background subtraction. Figure 1 (a) shows ϕ-mesons signal after combinatorial background subtraction in Au + Au collision at $\sqrt{s_{NN}} = 39$ GeV for

p_{T} window 1.1 to 1.3 GeV/c and for 0–80% centrality. The ϕ-mesons signal fitted with Briet–Wigner function and 1st order polynomial for residual background to extract ϕ-mesons yield. The yield distribution as a function of $\phi - \psi_2$ was fitted by the function

$$A\left(1 + 2v_2^{\mathrm{obs}}\cos[2(\phi - \psi_2)]\right) \tag{6}$$

to extract the v_2^{obs} value, where A is a constant. A typical result for p_{T} window 1.1 to 1.3 GeV/c at $\sqrt{s_{NN}} = 39$ GeV is shown in Fig. 1 (b).

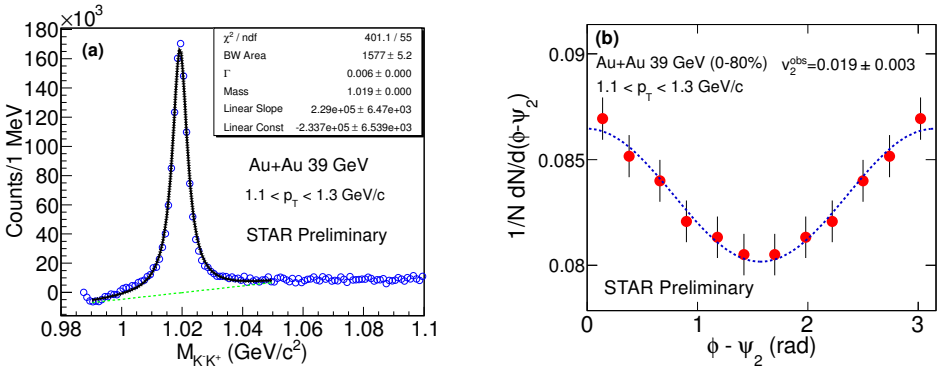

Fig. 1. (a) ϕ-mesons signal after combinatorial background subtraction in Au + Au collision (0–80%) at $\sqrt{s_{NN}} = 39$ GeV from a selected p_{T} bin (1.1 to 1.3 GeV/c). (b) $\phi - \psi_2$ distribution for ϕ-meson at $1.1 < p_{\mathrm{T}} < 1.3$ GeV/c in Au + Au collision at $\sqrt{s_{NN}} = 39$ GeV.

The measurements of ϕ-meson v_2 as function of transverse momentum at $\sqrt{s_{NN}} = 39$, 11.5 and 7.7 GeV is shown in Fig. 2. These results are from η-sub event plane method. The published results [5] at $\sqrt{s_{NN}} = 200$ GeV in Au + Au collision is also shown in figure 2 (a) for comparison. At $\sqrt{s_{NN}}$= 11.5 GeV, ϕ-meson v_2 is observed to be significantly smaller than at 39 and 200 GeV. Due to limited statistics, there are only two data points with large statistical error for ϕ-meson v_2 at $\sqrt{s_{NN}}$= 7.7 GeV. To understand these results we will discuss effect of partonic and hadronic interaction on ϕ-mesons v_2. The two main possibility of ϕ-meson production are (a) kaon coalescence and (b) coalescence of s and $\bar{s}$ quarks in the medium. The recent results [8] from RHIC and NA49 Collaboration [9] to ϕ-meson production shows that the contribution from kaon coalescence should be small in this energy range and the ϕ-mesons production is dominated by partonic interaction. So the contribution to ϕ-meson v_2 is mostly from partonic phase.

Now we will discuss the effect of system evolution on v_2 of ϕ mesons. Phenomenological analysis [2] and experimental result on coherent ϕ photoproduction [10] suggest that interaction cross-section of ϕ-mesons with other

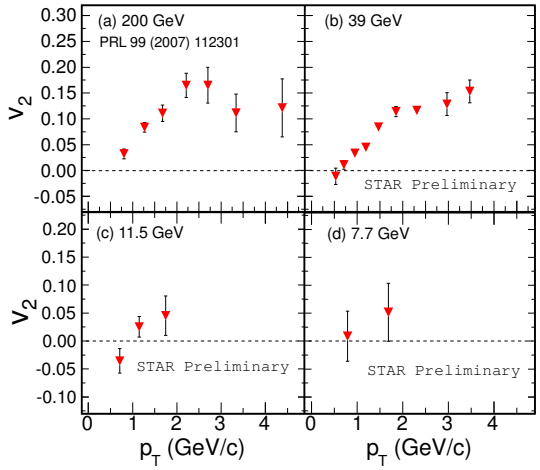

Fig. 2. v_2 *versus* p_{T} of ϕ-meson for Au + Au collision (0–80%) at $\sqrt{s_{NN}}$ = 7.7, 11.5, 39 and 200 GeV with $|y| < 1.0$.

hadrons is much smaller than that of other particles. Due to small hadronic interaction cross-section of ϕ-mesons, they freeze out very early and close to chemical freeze-out temperature. So the effect of hadronic interactions on ϕ-mesons v_2 is very small and most of the contribution on v_2 is from partonic phase. Therefore, large ϕ-meson v_2 indicates the formation partonic matter and small v_2 could indicate dominance of hadron interactions.

Figure 3 shows v_2 divided by number of constituent quark as a function of $(m_{\mathrm{T}} - m_0)/n_{\mathrm{cq}}$, where m_{T} $\left(= \sqrt{p_{\mathrm{T}}^2 + m_0^2}\right)$ is the transverse mass, p_{T} is the transverse momentum, and m_0 is the mass of the hadron, at $\sqrt{s_{NN}} = 39$ and 11.5 GeV. The ϕ-mesons v_2 shows similar v_2 values as other hadrons

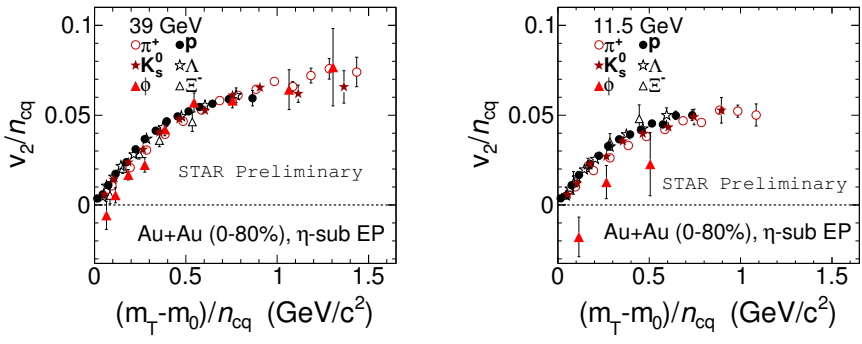

Fig. 3. v_2/n_{cq} *versus* $(m_{\mathrm{T}} - m_0)/n_{\mathrm{cq}}$ in Au + Au collisions at $\sqrt{s_{NN}}$ = 11.5 and 39 GeV.

at $\sqrt{s_{NN}}$ = 39 GeV, whereas for $\sqrt{s_{NN}}$ = 11.5 GeV ϕ-mesons falls off the trend from the other hadrons. The mean deviation of ϕ-mesons v_2 from the π-meson v_2 is 2.6 σ (σ is the error of ϕ-meson v_2). The NCQ scaling has been understood by considering quark coalescence as mechanism of hadronization and it is believed to be indication of deconfinement [11]. The study of ϕ-mesons v_2 using A Multi Phase Transport Model (AMPT) shows that partonic interaction are necessary for NCQ scaling of v_2 of hadrons [12]. So the small magnitude of ϕ-meson v_2 and its deviation from the values of other hadrons at $\sqrt{s_{NN}}$ = 11.5 GeV could be the effect of a matter, where hadronic interactions are dominant.

5. Summary

We have presented v_2 of ϕ-mesons in Au + Au collision at $\sqrt{s_{NN}}$= 7.7, 11.5 and 39 GeV obtained by the STAR experiment. Large ϕ-mesons v_2 at $\sqrt{s_{NN}}$=39 GeV indicates that partonic collectivity has been developed at $\sqrt{s_{NN}}$ = 39 GeV, as it has been seen before at top RHIC energies. Different trend has been observed for ϕ-mesons v_2 at $\sqrt{s_{NN}}$ = 11.5 GeV. The deviation of ϕ-meson v_2 from other hadrons could indicate the dominance of hadronic interactions with decreasing the beam energy.

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