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Energy dependence of ϕ-meson production and elliptic flow in Au+Au collisions at STAR

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We present, the measurements of the ϕ-meson production and elliptic flow (v_2) at mid-rapidity in Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7 - 200 GeV using the STAR detector in the years 2010 and 2011. The energy dependence of nuclear modification factors ($R_{\rm CP}$) is presented. At the intermediate transverse momentum (p_T) the Ω/ϕ ratio shows a different trend for $\sqrt{s_{NN}}$ = 11.5 GeV compared to higher beam energies. This may suggest change of particle production mechanism at $\sqrt{s_{NN}}$ = 11.5 GeV. The number-of-constituent quark (NCQ) scaling of v_2 has been studied at various beam energies. The NCQ scaling holds for all identified particles for $\sqrt{s_{NN}} \geq$ 19.6 GeV, which can be considered as an evidence of partonic collectivity. We observe at $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV, the ϕ-meson v_2 falls off the trend from the other hadrons at highest measured p_T values by 1.8σ and 2.3σ, respectively. This may indicate that the hadronic interaction plays an important role at lower beam energies.

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1. Introduction

The ϕ vector meson is the lightest bound state of s and $\bar{s}$ quarks. The interaction cross-section of the ϕ meson with non-strange hadrons is expected to have a small value [1] and therefore its production should be less affected by the later stage hadronic interactions in the evolution of the system formed in heavy-ion collisions. The ϕ meson seems to freeze out early compared to other light hadrons (π, K and p) [1]. The life time of the ϕ meson is $\sim$ 42 fm/c. Because of longer life time the ϕ meson will mostly decay outside the fireball and therefore its daughters will not have much time to re-scatter in the hadronic phase. The elliptic flow (v_2), a measure of the anisotropy in momentum space, for ϕ meson can be used to probe the dynamics of the early stage of heavy-ion collisions [2]. For the ϕ-meson v_2, effect of later stage hadronic interaction is small [3, 4]. Therefore, the ϕ meson can be considered as a clean probe to study the QCD phase diagram in the Beam Energy Scan (BES) program at the Relativistic Heavy Ion Collider (RHIC) [5].

2. Data sets and methods

The results presented here are based on data collected at $\sqrt{s_{NN}}$= 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV in Au+Au collisions by the STAR detector for a minimum bias trigger in the years of 2010 and 2011. The Time Projection Chamber (TPC) and Time of Flight (TOF) detectors with full 2π coverage were used for particle identification in the central pseudo-rapidity (η) region ($|\eta| < 1.0$). ϕ mesons are identified using the invariant mass technique from their decay to $K^+ + K^-$ (branching ratio is 49.04 $\pm$ 0.6 %). Mixed event technique has been used for combinatorial background estimation [6]. The η-sub event plane method [7] using TPC tracks has been applied to measure the elliptic flow. In this method, one defines the event flow vector for each particle based on particles measured in the opposite hemisphere in pseudo-rapidity (η). An η gap of $|\eta| < 0.05$ between positive and negative pseudo-rapidity sub-events has been introduced to suppress non-flow effects.

3. Results

The $R_{\rm CP}$(0-10%/40-60%) of ϕ mesons at mid-rapidity ($|y| < 0.5$) in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 - 39 GeV are presented in the panel (a) of Fig. 1. The $R_{\rm CP}$(0-05%/40-60%) at $\sqrt{s_{NN}}$ = 200 GeV are taken from previous STAR measurements [8]. The $R_{\rm CP}$ is defined as the ratio of the particles yield in the central to peripheral collisions normalized by number of binary collisions ($N_{\rm bin}$). The value of $N_{\rm bin}$ is calculated from the Monte Carlo Glauber simulation [9]. If $R_{\rm CP}$ is equal to one, then the nucleus nucleus collision is simply superposition of nucleon nucleon collisions. Deviation of $R_{\rm CP}$ from the unity would imply contribution from the nuclear medium effects. Because of the energy loss of the partons traversing the high density QCD medium the $R_{\rm CP}$ of ϕ mesons goes below unity at 200 GeV [1]. From the Fig. 1 one can see at the intermediate p_T, $R_{\rm CP}$ goes above unity with decrease in beam energy. This indicates that at lower beam energy the parton energy loss effect could be less important.

The panel (b) of Fig. 1 shows the baryon-to-meson ratio, $(\Omega^- + \overline{\Omega}^+)/2\phi$, as a function of p_T in Au + Au collisions at $\sqrt{s_{NN}}$ = 11.5 GeV to 200 GeV. The data points for 200 GeV are taken from

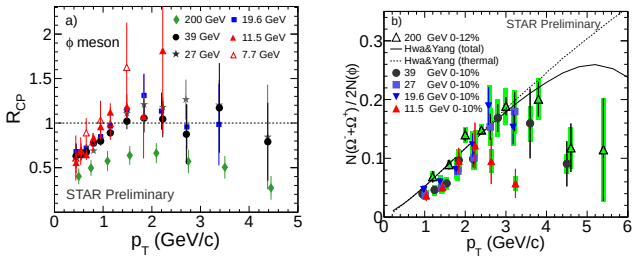

Figure 1: (Color online) Panel (a) : The $R_{\rm CP}$ as function of p_T at mid-rapidity ($|y| < 0.5$) in the Au+Au collision at various beam energy. Error bars are only statistical uncertainties. Panel (b): The baryon-to-meson ratio, $(\Omega^- + \overline{\Omega}^+)/2\phi$, as a function of p_T at mid-rapidity ($|y| < 0.5$). Green bands are the systematic errors and vertical lines are statistical errors.

Ref. [8]. The dashed lines are the results from the recombination model calculations with thermal strange quarks [10]. In Au+Au central collisions at $\sqrt{s_{NN}}$ = 200 GeV, the ratios of $(\Omega^- + \overline{\Omega}^+)/2\phi$ in the intermediate p_T range are explained by the recombination model with thermal strange quarks. The ratios $(\Omega^- + \overline{\Omega}^+)/2\phi$ for $\sqrt{s_{NN}} \geq$ 19.6 GeV show similar trend. But at $\sqrt{s_{NN}}$ = 11.5 GeV, the ratio at the highest measured p_T shows a deviation from the trend of other energies. This may suggest a change in Ω and/or ϕ production mechanism at $\sqrt{s_{NN}}$ = 11.5 GeV.

It has been observed from RHIC measurements that when v_2 and corresponding p_T are scaled by number of constituent quarks of the hadrons, the measured v_2 values at the intermediate p_T are consistent with expectations from parton coalescence or recombination models [14, 15]. This is known as NCQ scaling and considered as a signature of partonic collectivity. Figure 2 shows v_2

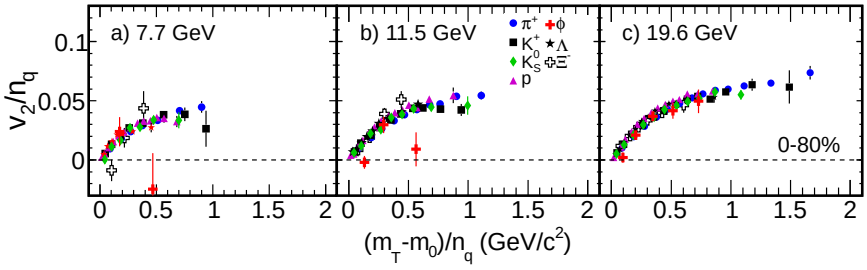

Figure 2: (Color online) The elliptic flow scaled by number-of-constituent quark (n_q) as a function of $(m_T - m_0)/n_q$ for selected particles in the Au+Au collision at $\sqrt{s_{NN}}$ = 7.7, 11.5 and 19.6 GeV for 0-80% centrality [12, 13]. Error bars are only statistical uncertainties.

divided by number of constituent quark as function of $(m_T - m_0)/n_q$, where $m_T = \sqrt{(p_T^2 + m_0^2)}$ is the transverse mass and m_0 is the mass of the hadron, at $\sqrt{s_{NN}}$ = 7.7, 11.5 and 19.6 GeV. The NCQ scaling holds fairly well at $\sqrt{s_{NN}} \geq$ 19.6 GeV (results for $\sqrt{s_{NN}} >$ 19.6 GeV are not shown here). This could be considered as a signature of partonic collectivity. However, we observe at $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV that the ϕ-meson v_2 deviates from the trend of the other hadrons at highest measured

p_T values by 1.8σ and 2.3σ, respectively. Due to the small hadronic interaction cross-section, v_2 of ϕ meson mostly reflect collectivity from the partonic phase [3, 4]. So the small magnitude of the ϕ-meson v_2 at $\sqrt{s_{NN}} \leq 11.5$ GeV could be the effect for a system, where hadronic interactions are more important. But more statistics are needed at $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV for ϕ-meson v_2 measurement to draw a clear conclusion and therefore ϕ measurement would be one of the focuses in the proposed BES phase II program.

4. Summary

We report the study of ϕ-meson production and elliptic flow at mid-rapidity in Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7 - 200 GeV recorded by the STAR detector. At the intermediate p_T, the nuclear modification factor $R_{\rm CP}$ of ϕ increases with decreasing beam energies, indicating that the partonic energy loss effect becomes less important at lower beam energies. The ratios of $(\Omega^- + \overline{\Omega}^+)/2\phi$ in the intermediate p_T range show a different trend at 11.5 GeV compared to those for the higher beam energies. This may suggest a change of particle production mechanism at lower beam energy. The NCQ scaling holds for $\sqrt{s_{NN}} \geq 19.6$ GeV. We observe at $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV the ϕ-meson v_2 show deviation from the other hadrons at highest measured p_T values by 1.8σ and 2.3σ, respectively. This may indicate that the contribution to the collectivity from partonic phases decreases at lower beam energies.

5. Acknowledgements

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