Probing the QCD phase diagram with measurements of ϕ-meson production and elliptic flow in heavy-ion collisions at STAR

Md. Nasim (for the STAR Collaboration)

National Institute of Science Education and Research (NISER),
Bhubaneswar-751005, India.

E-mail: nasim@rcf.rhic.bnl.gov/mnasim2008@gmail.com

Abstract. We present measurements of ϕ-meson production and elliptic flow (v_2) at mid-rapidity in Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7 - 200 GeV. Energy dependence of nuclear modification factor ($R_{\rm CP}$) of ϕ meson is presented. The ϕ-meson $R_{\rm CP}$ has a value $\geq$ 1.0 for $\sqrt{s_{NN}}$ $\leq$ 39 GeV. The Ω/ϕ ratios are also presented and show a different trend at the intermediate transverse momentum (p_T) for $\sqrt{s_{NN}}$ = 11.5 GeV compared to higher beam energies. The number-of-constituent quark (NCQ) scaling of v_2 has been studied at various beam energies. The NCQ scaling holds for particles and anti-particles separately including the ϕ meson for $\sqrt{s_{NN}} \geq$ 19.6 GeV, which can be considered as an evidence of partonic collectivity. We observe that ϕ-meson v_2 falls off the trend from the other hadrons at highest measured p_T values by 1.8σ and 2.3σ at $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV, respectively.

1. Introduction

The ϕ vector meson is the lightest bound state of a strange (s) quark and a anti strange ($\bar{s}$) quark. It has a mass of 1.01945 $\pm$ 0.00002 GeV/c^2 which is comparable to the mass of lightest baryons p (0.938 GeV/c^2) and Λ (1.115 GeV/c^2) [1]. The life time of ϕ meson is $\sim$ 42 fm/c. ϕ meson mostly decay outside the fireball because of its longer life time, therefore its daughters do not have much time to re-scatter in the hadronic phase. The hadronic interaction cross-section of ϕ meson is expected to have a small value and hence seems to freeze out early compared to other lighter hadrons (π, K and p) [2]. 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 elliptic flow parameter v_2 is a good tool for studying the system formed in the early stages of high energy collisions at RHIC [3]. It describes the momentum anisotropy of particle emission from non-central heavy-ion collisions. It is defined as the second harmonic coefficient of the Fourier decomposition of azimuthal distribution with respect to the reaction plane angle (Ψ) and can be written as

$$v_2 = \langle \cos(2(\phi - \Psi)) \rangle, \quad (1)$$

where ϕ is emission azimuthal angle [4]. Although elliptic flow is an early time phenomenon, its magnitude might still be affected by the later stage hadronic interaction. Since the hadronic interaction cross section of ϕ meson is smaller than the other hadrons, its v_2 remain almost unaffected by the later stage interaction [5, 6]. Therefore ϕ-meson v_2 reflect the collective motion of the partonic phase. This makes ϕ meson a clean probe for the study of the QCD phase diagram in the Beam Energy Scan (BES) program at the Relativistic Heavy Ion Collider (RHIC) [7].

2. Data Sets and Analysis Details

The results presented here are based on data collected from Au+Au collisions at $\sqrt{s_{NN}}$= 7.7, 11.5, 19.6, 27, 39, 62.4 and 200 GeV with the STAR detector for minimum bias trigger in 2010 and 2011. The cuts on primary vertex position along the longitudinal beam direction (V_z) is 30 cm for 200 GeV; 40 cm for 39 and 62.4 GeV; 50 cm for 11.5 GeV; 70 cm for 7.7, 19.6 and 27 GeV data set. An additional cut on vertex radius (< 2 cm) has been used to reject contamination from beam pipe interaction. The Time Projection Chamber (TPC) and Time Of Flight (TOF) detectors with full azimuthal coverage were used for particle identification in the central pseudo-rapidity (η) region ($|\eta| < 1.0$). For spectra analysis we have used only the TPC whereas for elliptic flow analysis both TPC and TOF detectors have been used. ϕ mesons are identified using the invariant mass technique from their decay to $K^+ + K^-$ (branching ratio $\sim$ 49.04 $\pm$ 0.6 %). The mixed event technique has been used for combinatorial background estimation [8]. The η-sub event plane method with a η gap of $|\Delta\eta| < 0.05$ has been used for elliptic flow measurements [4].

3. Results

3.1. Transverse momentum spectra

We present $R_{\rm CP}(0-10\%/40-60\%)$ measurement of ϕ mesons at mid-rapidity ($|y| < 0.5$) in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 - 39 GeV. The $R_{\rm CP}$ is defined as the ratio of the particles yield in the central to peripheral collisions normalized by number of inelastic binary collisions (N_{bin}). The value of N_{bin} is calculated from the Monte Carlo Glauber simulation [9]. The $R_{\rm CP}$ will be equal to one if the nucleus-nucleus collision is simply a superposition of nucleon-nucleon collision. Deviation of $R_{\rm CP}$ from the unity would imply the 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 meson goes below unity at 200 GeV [2]. One can see from Fig. 1, at the intermediate p_T (> 1.5 GeV/c) $R_{\rm CP} \geq 1.0$ for $\sqrt{s_{NN}} \leq 39$ GeV. This indicates that, at low energy the parton energy loss effect is less important.

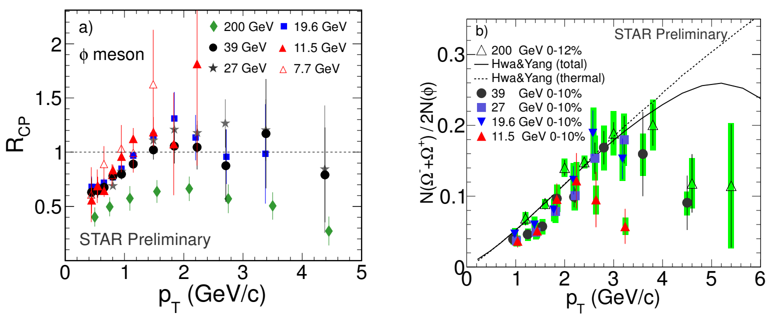

Figure 1. (Color online) Left panel : $R_{\rm CP}$ as function of p_T in Au+Au collisions at various beam energies. The $R_{\rm CP}(0-05\%/40-60\%)$ at $\sqrt{s_{NN}}$ = 200 GeV are taken from previous STAR measurement [10]. Error bars are only statistical uncertainties. Right panel : $(\Omega^- + \overline{\Omega}^+)/2\phi$ as a function of p_T. Green bands are the systematic error and vertical lines are statistical error.

The panel (b) of Fig. 1 shows the baryon-to-meson ratio, $N(\Omega^- + \overline{\Omega}^+)/2N(\phi)$, as a function of p_T in Au + Au collisions from $\sqrt{s_{NN}}$ = 11.5 GeV to 200 GeV. The data points for 200 GeV are taken from Ref. [10]. The dashed lines are the results from the recombination model calculations with thermal strange quarks [11]. In Au+Au central collisions at $\sqrt{s_{NN}}$ = 200 GeV, the ratios of $N(\Omega^- + \overline{\Omega}^+)/2N(\phi)$ in the intermediate p_T range are explained by the recombination model with thermal strange quarks. The ratios $N(\Omega^- + \overline{\Omega}^+)/2N(\phi)$ 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. The value of χ^2/ndf for deviation between 11.5 and 19.6 GeV is $\sim$ 8.3/2 for $p_T > 2.4$ GeV/c. This may suggest a change in Ω and/or ϕ production mechanism at $\sqrt{s_{NN}}$ = 11.5 GeV.

3.2. Elliptic flow

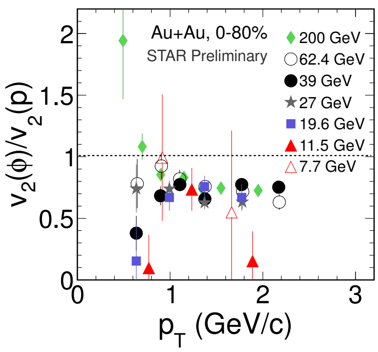

Figure 2. (Color online) $v_2(\phi)/v_2(p)$ ratio as function of p_T in the Au+Au collision at various beam energies for 0-80% centrality [13, 14]. Error bars are only statistical uncertainties.

Figure 2 shows $v_2(\phi)/v_2(p)$ ratios as function of p_T for all beam energies from $\sqrt{s_{NN}}$ = 7.7 GeV to 200 GeV. We observe that at low p_T the $v_2(\phi)/v_2(p)$ ratio decreases with decrease in beam energy. This could be due to less partonic collectivity at low energy, as the ϕ v_2 mostly reflect collectivity from the partonic phase. On the other hand, if we look at 200 GeV, the situation is different. One can see that at top RHIC energy $v_2(\phi)/v_2(p) > 1.0$ at low p_T (< 0.7 GeV/c). This can be explained due to later stage hadronic interaction effect on proton v_2 as predicted in the theoretical (hydro + hadron cascade) model [12].

Figure 3 shows v_2 divided by number-of-constituent quark (n_q) 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 rest mass of hadron, at $\sqrt{s_{NN}}$ = 7.7, 11.5 and 19.6 GeV [13, 14]. The NCQ scaling holds fairly well for $\sqrt{s_{NN}} \geq 19.6$ GeV for particles and anti-particles separately including ϕ meson (results for $\sqrt{s_{NN}} > 19.6$ GeV are not shown here). This could be considered as a signature of partonic collectivity [15]. However, we observe that ϕ-meson v_2 falls off the trend from the other hadrons at highest measured p_T values by 1.8σ and 2.3σ at $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV, respectively. Due to the small hadronic interaction cross-section, v_2 of ϕ meson mostly reflect collectivity from the partonic phase [5, 6]. So the small magnitude of ϕ-meson v_2 at $\sqrt{s_{NN}} \leq 11.5$ GeV could reflect that hadronic interaction are more important, however we need more statistics to make a strong conclusion.

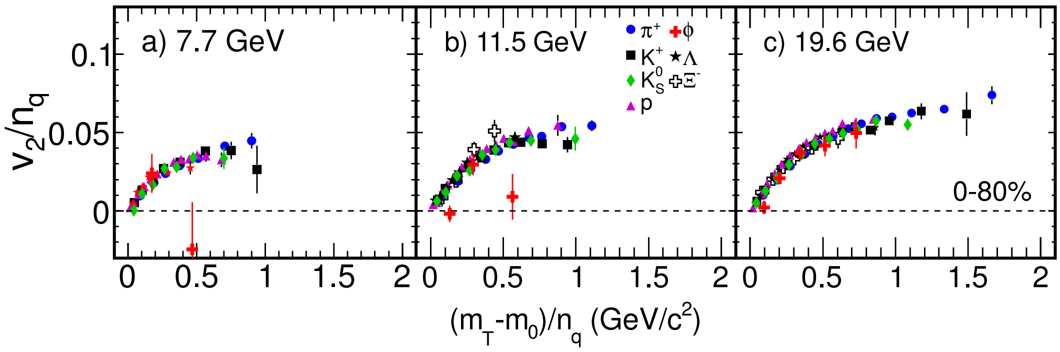

Figure 3. (Color online) The elliptic flow (v_2) scaled by number-of-constituent quark (n_q) as a function of $(m_T - m_0)/n_q$ for selected particles in the Au+Au collision at various beam energies for 0-80% centrality [13, 14]. Error bars are only statistical uncertainties.

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 for particle and anti-particle separately. We observe that ϕ-meson v_2 show deviation ($\sim 2\sigma$) from the other hadrons at highest measured p_T values at $\sqrt{s_{NN}} \leq$11.5 GeV and also the $v_2(\phi)/v_2(p)$ ratios at low p_T decreases with decrease in beam energy. This may indicate the contribution to the collectivity from partonic phases decreases at lower beam energies.

5. Acknowledgements

Financial assistance from DST International Travel Support and DST SwarnaJayanti project, Government of India is gratefully acknowledged.

References

[1] Beringer J *et al* 2012 *Phys. Rev.* D **86** 010001
[2] Adams J *et al* (STAR Collaboration) 2005 *Nucl. Phys.* A **757** 102
[3] Kolb P F *et al* 2003 *Nucl. Phys.* A **715** 653c
[4] Poskanzer A M and Voloshin S A 1998 *Phys. Rev.* C **58** 1671
[5] Mohanty B and Xu N 2009 *J. Phys.* G **36** 064022
[6] Nasim M, Mohanty B, and Xu N 2013 *Phys. Rev.* C **87**, 014903
[7] Aggarwal M M *et al* (STAR Collaboration) *Preprint* nucl-ex/10072613
[8] Abelev B I *et al* (STAR Collaboration) 2009 *Phys. Lett.* B **673** 183
[9] Abelev B I *et al* (STAR Collaboration) 2009 *Phys. Rev.* C **79** 034909
[10] Abelev B I *et al* (STAR Collaboration) 2009 *Phys. Rev.* C **49** 064903
[11] Hwa R C and Yang C B 2007 *Phys. Rev.* C **75** 054904
[12] Hirano T *et al* 2008 *Phys. Rev.* C **77** 044909
[13] Adamczyk L *et al* (STAR Collaboration) 2013 *Phys. Rev.* C **88** 014902
[14] Adamczyk L *et al* (STAR Collaboration) 2013 *Phys. Rev. Lett.* **110** 142301
[15] Molnar D and Voloshin S A 2003 *Phys. Rev. Lett.* **91** 092301