Strangeness in STAR experiment at RHIC

Shusu Shi (for the STAR collaboration)

Key Laboratory of Quarks and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan, 430079, China

E-mail: shiss@mail.ccnu.edu.cn

Abstract. We present the recent results of strangeness production at the mid-rapidity in Au + Au collisions at RHIC, from $\sqrt{s_{\rm NN}}$ = 7.7 to 200 GeV. Elliptic asymmetry v_2 of multi-strange baryon Ω and ϕ mesons are similar to that of pions and protons in the intermediate p_T range (2 - 5 GeV/c) in $\sqrt{s_{\rm NN}}$ = 200 GeV Au + Au collisions, indicating that the major part of collective flow has been built up at partonic stage. The breaking of mass ordering between ϕ mesons and protons in the low p_T range (< 1 GeV/c) is consistent with a picture that ϕ mesons are less sensitive to later hadronic interaction. The nuclear modification factor $R_{\rm CP}$ and baryon to meson ratio change dramatically when the collision energy is lower than 19.6 GeV. It suggests a possible change of the created QCD medium properties at lower energies compared to those from high energies.

1. Introduction

The main motivations of the experiments of heavy-ion collision at RHIC are 1) generating the new form of matter Quark Gluon Plasma at high energy collisions and studying its properties, and 2) exploring the QCD phase structure by scanning the collision energy from 200 to 7.7 GeV. Strangeness production is regarded as a sensitive probe to the phase transition [1]. In addition, the hadronic interaction cross sections for strange hadrons, especially for multi-strange hadrons Ξ, Ω and ϕ mesons are expected to be small and their freeze-out temperatures are close to the quark-hadron transition temperature predicted by lattice QCD [2, 3, 4]. Hence, these hadrons are expected to provide information primarily from the partonic stage of the collision. They are good probes to study the QGP properties and explore the QCD phase structure. The STAR experiment has covered the beam energies of $\sqrt{s_{\rm NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 and 200 GeV. The extracted baryonic chemical potental (μ_B) range based on a statistical model [5] from the 0-5% central collisions is $20 \leq \mu_B \leq 420$ MeV which covers a wide region of the QCD phase diagram. In these proceedings, we will focus on the following observables for strange and multi-strange hadrons: elliptic flow v_2, nuclear modification factor $R_{\rm CP}$ and baryon to meson ratio.

2. Results and Discussions

In the RHIC runs of year 2010 and 2011, about 730 million minimum bias events of Au + Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV were recorded by STAR. Sufficient statistics of multi-strange hadrons and ϕ mesons allow for the precise measurements on v_2. Figure 1 shows the v_2 as a function of p_T for (a) pions, protons and (b) ϕ, Ω in Au + Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV for 0-80% centrality [6]. A comparison between v_2 of charged pions and protons, consisting of up

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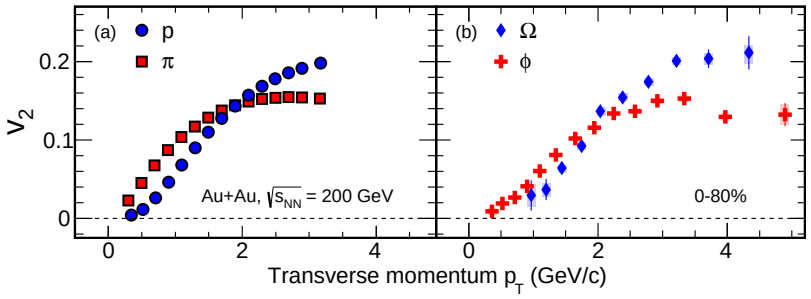


Figure 1. The v_2 as function of p_T for π ($\pi^+ + \pi^-$), p ($p + \bar{p}$) and ϕ, Ω ($\Omega^- + \bar{\Omega}^+$) in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV for 0-80% centrality [6].

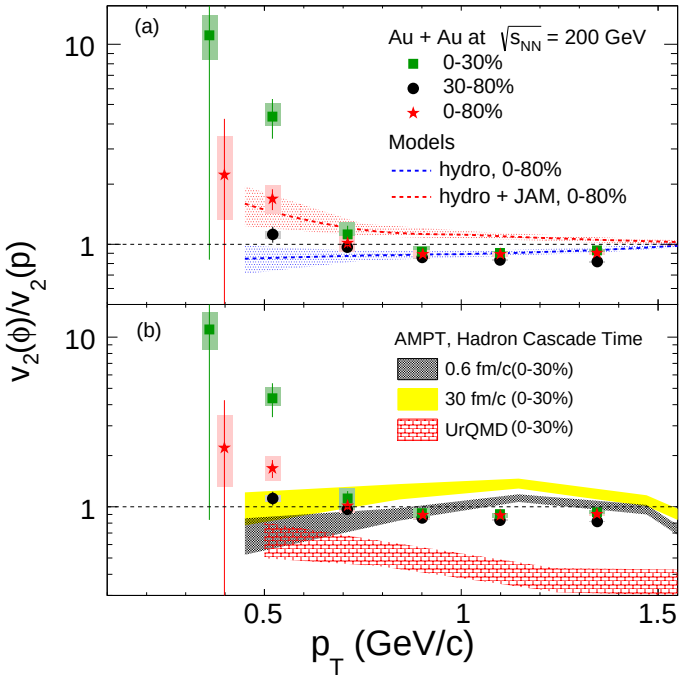


Figure 2. The ratio of $v_2(\phi)$ to $v_2(p)$ as function of p_T in Au + Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV for 0-30% and 30-80% centrality. The bands in panel (a) and (b) represent the hydro and transport model calculations for $v_2(\phi)/v_2(p)$, respectively [6].

($u(\bar{u})$) and down ($d(\bar{d})$) light constituent quarks is shown in panel (a). Correspondingly, panel (b) shows a comparison of v_2 of ϕ and $\Omega(\Omega^- + \bar{\Omega}^+)$ containing $s(\bar{s})$ constituent quarks. This is the first time that high precision measurement of Ω baryon v_2 up to 4.5 GeV/c is available in experiments of heavy-ion collisions. In the low p_T region ($p_T < 2.0$ GeV/c), the v_2 of ϕ and Ω follows mass ordering. At intermediate p_T ($2.0 < p_T < 5.0$ GeV/c), a baryon-meson separation is observed. It is evident that the $v_2(p_T)$ of hadrons consisting only of strange constituent quarks (ϕ and Ω) is similar to that of light hadrons, pions and protons. However the ϕ and Ω do not participate vigorously in the hadronic interactions, because of the smaller hadronic cross sections compared to pions and protons. This suggests the major part of the collectivity is developed

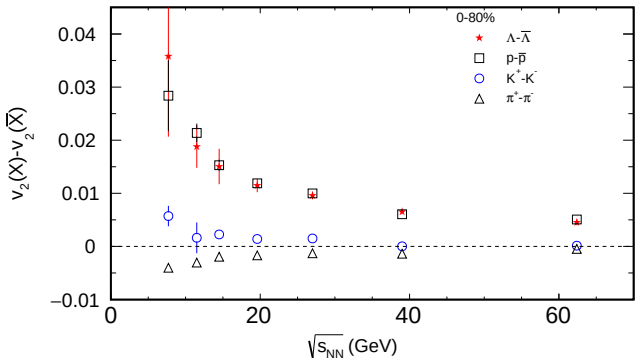


Figure 3. The difference in v_2 between particles (X) and their corresponding antiparticles ($\bar{X}$) as a function of beam energy for $0-80\%$ central Au + Au collisions [10, 11].

during the partonic phase in high energy heavy-ion collisions. Experimental results indicate that partonic collectivity has been built up in top energy heavy-ion collisions at RHIC. The ϕ mesons and protons show different sensitivity to the hadronic rescatterings. The ϕ mesons are less sensitive to the late hadron hadron interactions than light hadrons due to the smaller hadronic cross section. Hydrodynamical model calculations [7] predict that v_2 as a function of p_T for different particle species follows mass ordering, where the v_2 of heavier hadrons is lower than that of lighter hadrons. Hirano *et al.* predict the mass ordering of v_2 could be broken between ϕ mesons and protons at low p_T ($p_T <$ 1.5 GeV/c) based on a model with ideal hydrodynamics with hadron cascade process [7]. As the model calculations assign a smaller hadronic cross section for ϕ mesons compared to protons, the broken mass ordering is regarded as the different hadronic rescattering contributions on the ϕ meson and proton v_2. Figure 2 shows the ratios of ϕ v_2 to proton v_2 from model calculations and experimental data [6]. This ratio is larger than unity at $p_T \sim 0.5$ GeV/c for 0-30% centrality. It indicates breakdown of the expected mass ordering in that momentum range. This could be due to a large effect of hadronic rescatterings on the proton v_2. The data of 0-80% centrality around 0.5 GeV/c quantitatively agrees with hydro + hadron cascade calculations indicated by the shaded red band in panel (a) of Fig. 2, even though there is a deviation in higher p_T bins. A centrality dependence of $v_2(\phi)$ to $v_2(p)$ ratio is observed in the experimental data. The breakdown of mass ordering of v_2 is more pronounced in 0-30% central collisions than in 30-80% non-central collisions. This observation indirectly supports the idea that the ϕ meson has a smaller hadronic interaction cross section. The ratio of ϕ v_2 to proton v_2 was also studied by using the transport models AMPT [8] and UrQMD [9]. The panel (b) of Fig. 2 shows the $v_2(\phi)$ to $v_2(p)$ ratio for 0-30% centrality from AMPT and UrQMD models. The black shaded band is from AMPT with a hadronic cascade time of 0.6 fm/c while the yellow band is for a hadronic cascade time of 30 fm/c. Larger hadronic cascade time is equivalent to stronger hadronic interactions. It is clear that the $v_2(\phi)/v_2(p)$ ratio increases with increasing hadronic cascade time. This is attributed to a decrease in the proton v_2 due to an increase in hadronic rescattering while the ϕ meson v_2 is less affected. The ratios from the UrQMD model are much smaller than unity (shown as a brown shaded band in the panel (b) of Fig. 2). The UrQMD model lacks partonic collectivity, thus the ϕ meson v_2 is not fully developed. None of these models could describe the detailed shape of the p_T dependence.

A very interesting feature of the v_2 measurements from RHIC Beam Energy Scan program is the observation of an energy dependent difference in v_2 between particles and their corresponding antiparticles [10]. Figure 3 shows the difference in v_2 between particles and their corresponding

antiparticles as a function of beam energy. The difference between baryon and anti-baryon is much more pronounced than difference between mesons. Proton versus anti-proton and Λ versus $\bar{\Lambda}$ show the same magnitude of difference. This difference naturally breaks the number of constituent quark scaling (NCQ) in v_2 which is regarded as an evidence of partonic collectivity in the top energy heavy-ion collisions at RHIC. It indicates the hadronic degrees of freedom play a more important role at lower collision energies.

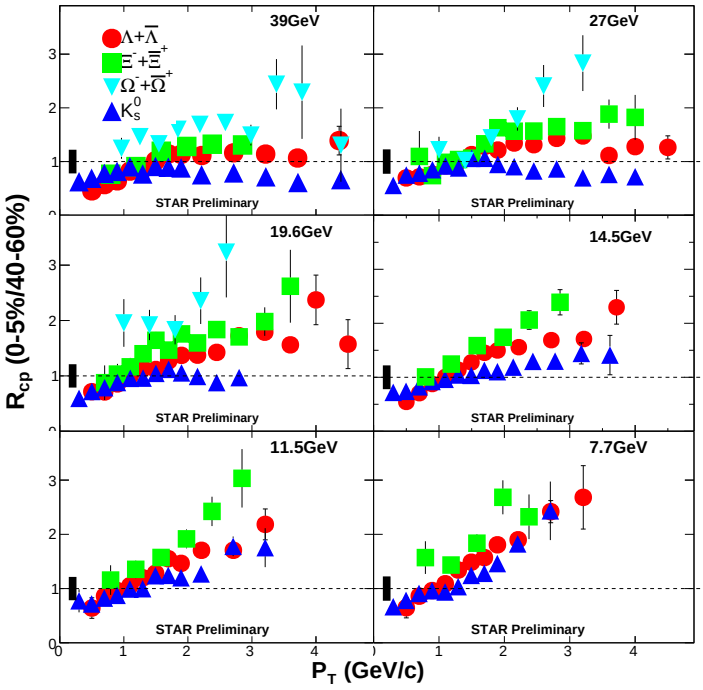


Figure 4. The nuclear modification factor $R_{\rm CP}$ as a function of p_T in Au + Au collisions at $\sqrt{s_{\rm NN}}$ = 7.7 - 39 GeV for K^0_S, Λ, Ξ and Ω at mid-rapidity $|y| < 0.5$ [12].

The $R_{\rm CP}$ ratio is defined as the ratio of particle yields in central collisions over those in peripheral ones scaled by number ($N_{\rm bin}$) of inelastic binary collisions. Here, $N_{\rm bin}$ is determined from Monte Carlo Glauber model calculations. The $R_{\rm CP}$ of K^0_S, Λ, Ξ and Ω in Au+Au 7.7 - 39 GeV collisions are presented in Fig. 4 [12]. The $R_{\rm CP}$ will be unity if nucleus-nucleus collisions are just simple superpositions of nucleon-nucleon collisions. Deviation of these ratios from unity would imply contributions from nuclear or medium effects. At collision energy $\geq$ 19.6 GeV, the $R_{\rm CP}$ of $K^0_S \leq 1$ at $p_T > 1.5$ GeV/c and stays below $R_{\rm CP}$ of baryons. The high p_T suppression of K^0_S and baryon/meson separation is qualitatively consistent with the behavior observed at higher RHIC energies [13]. However, for collisions at 14.5 GeV and below, the data seem to be qualitatively different from those from higher energies. There is no suppression for K^0_S at $p_T > 1.5$ GeV/c, and at intermediate p_T the baryon/meson separation becomes less significant. It suggests that different properties of the system have been created in collisions at 14.5 GeV and below compared to those from high energies.

The enhancement of baryon to meson ratios at intermediate p_T compared to elementary collisions is interpreted as a consequence of hadron formation from parton recombination and parton collectivity [13]. Therefore, the baryon to meson ratios are expected to be sensitive to parton dynamics of the collision system. Figure 5 shows the ratio of $\bar{\Lambda}/K^0_S$ as a function of p_T in Au + Au collisions at 7.7 - 39 GeV at mid-rapidity $|y| < 0.5$ [12]. The ratios of $\bar{\Lambda}$ to K^0_S at intermediate p_T are close to each other at 27 and 39 GeV, and show a slight decrease at 19.6

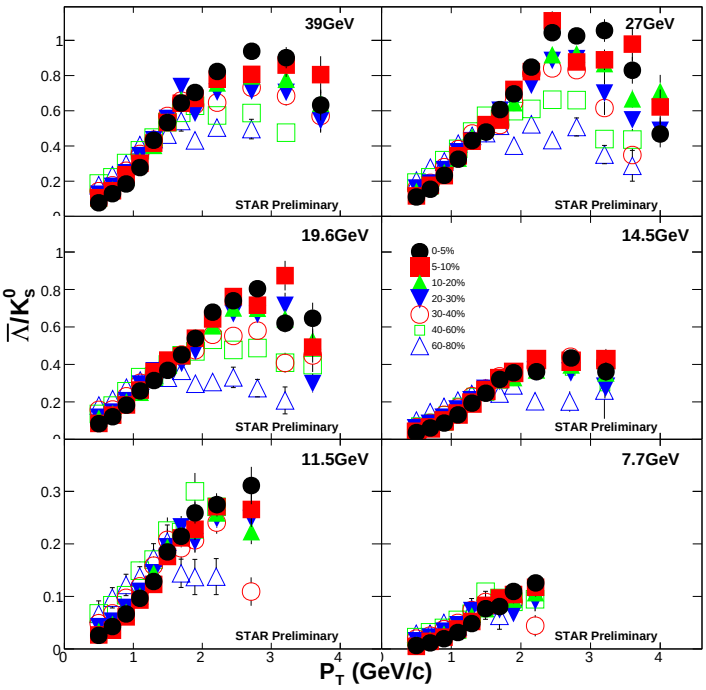


Figure 5. The ratio of $\bar{\Lambda}/K^0_S$ as a function of p_T in Au + Au collisions at $\sqrt{s_{\rm NN}}$ = 7.7 - 39 GeV at mid-rapidity $|y| < 0.5$ [12].

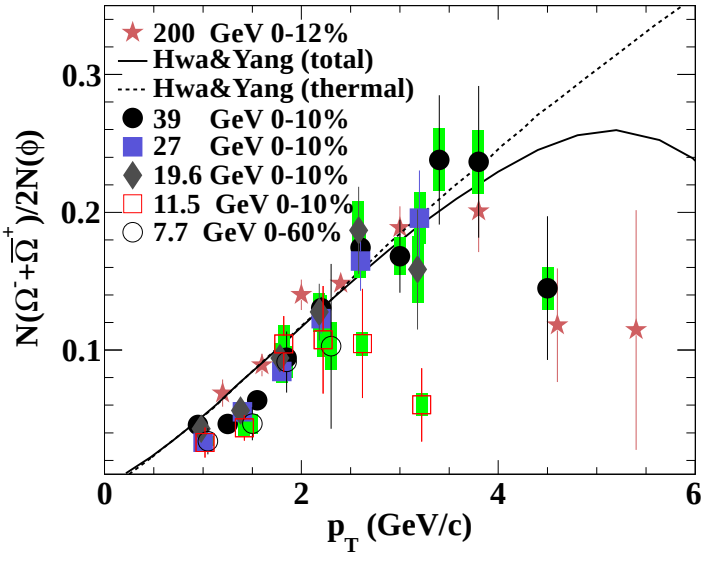


Figure 6. The ratio of $N(\Omega^- + \overline{\Omega}^+)$ to $(2N(\phi))$ as a function of p_T in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 7.7 to 200 GeV at mid-rapidity ($|y| < 0.5$) [14, 15]. The solid and dashed lines represent recombination model calculations for central collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV with total and thermal strange quark contributions respectively [16].

GeV. There is a sudden decrease of intermediate p_T ratios between 19.6 and 14.5 GeV. Besides, the separation of central (0-5%) and peripheral (40-60%) collisions in the ratio becomes less obvious in collisions at 14.5 GeV and below. It suggests a possible change of underlying hadron formation mechanism and/or parton dynamics between these two energies. We use multi-strange hadrons, Ω to ϕ ratios, to further study the energy dependence of baryon to meson ratios.

In Fig. 6 [15] we present the results on $\Omega^-+\bar{\Omega}^+$ and ϕ yields ratio as a function of p_T for Au+Au collisions at 7.7 to 200 GeV. A model calculation by Hwa and Yang for Au+Au collisions at 200 GeV predicted that most of the Ω and ϕ yields up to the intermediate p_T region are from coalescence of thermal strange quarks [16]. The straight dotted line assumes that these thermal strange quarks have exponential p_T distributions. Deviations from the straight line at high p_T are attributed [16] to recombination with strange quarks from high p_T showers. The measured ratios from central Au+Au collisions at 19.6, 27 and 39 GeV follow closely the ratio from 200 GeV and are consistent with a picture of coalescence dynamics over a broad p_T range of 1-4 GeV/c. The ratios at 11.5 GeV seem to deviate from the trend observed at higher beam energies. In particular, the ratios appear to turn down around p_T of 2 GeV/c. The decrease in the Ω to ϕ ratios from central collisions at 11.5 GeV compared to those at 19.6 GeV or above may indicate a significant change in the hadron formation and/or in strange quark p_T distributions at the lower energy. Such a change may arise from a transition from hadronic to partonic dynamics with increasing beam energy.

3. Summary

In summary, the high precision v_2 data of multi-strange hadrons, namely for Ω baryon and ϕ meson strongly suggest the partonic collectivity has been built-up at top energy heavy-ion collisions at RHIC. The violation of mass ordering between ϕ mesons and protons at low p_T agrees with the expectation that ϕ mesons are less sensitive to late hadronic interactions. $R_{\rm CP}$ ratio for K^0_S increases with decreasing beam energies indicating that partonic energy loss effect is less important at lower energy. The separation of central and peripheral $\bar{\Lambda}/K^0_S$ ratio is diminishing for Au+Au collisions at $\sqrt{s_{\rm NN}} = 14.5$, 11.5 and 7.7 GeV and the decrease of $(\Omega^-+\bar{\Omega}^+)/2\phi$ ratios from central collisions at 11.5 GeV suggest the change of medium property and phase transition possibly happen between 19.6 GeV and lower energies.

4. Acknowledgments

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[1] J. Rafelski and B. Muller, Phys. Rev. Lett. **48**, 1066 (1982).
[2] J. Adams *et al.*, Nucl. Phys. **A 757** 102 (2005).
[3] A. Shor, Phys. Rev. Lett. **54**, 1122 (1985).
[4] H. van Hecke, H. Sorge and N. Xu, Phys. Rev. Lett. **81**, 5764 (1998).
[5] A. Andronic, *et al.*, Nucl. Phys. **A834**, 237(2010); A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. **A772**, 167(2006).
[6] L. Adamczyk *et al.* (STAR Collaboration), Phys. Rev. Lett. **116**, 062301 (2016).
[7] T. Hirano *et al.*, Phys. Rev. **C 77**, 044909 (2008); S. Takeuchi *et al.*, Phys. Rev. **C 92**, 044907 (2015).
[8] Z.-W. Lin *et al.*, Phys. Rev. **C 72**, 064901 (2005).
[9] S. A. Bass *et al.*, Prog. Part. Nucl. Phys. **41**, 255 (1998).
[10] L. Adamczyk *et al.* (STAR Collaboration), Phys. Rev. C **86**, 054908 (2012); Phys. Rev. C **88**, 014902 (2013); Phys. Rev. C **93**, 014907 (2016).
[11] S.S. Shi, Adv. High Energy Phys. **2016**, 1987432 (2016).
[12] M. U. Ashraf (for the STAR Collaboration), J. Phys. Conf. Ser. **668** 012095 (2016).
[13] M. M.Aggarwal *et al.* (STAR Collaboration), arXiv:1007.2613.
[14] X. Zhang (for the STAR Collaboration), J. Phys. Conf. Ser. **668** 012033 (2016).
[15] L. Adamczyk *et al.* (STAR Collaboration), Phys. Rev. C **93**, 021903 (2016).
[16] R. C. Hwa and C. B. Yang, Phys. Rev. C **66**, 025205 (2002); Phys. Rev. C **75**, 054904 (2007).