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PROBE OF THE QCD PHASE DIAGRAM WITH ϕ-MESON PRODUCTION IN RELATIVISTIC NUCLEAR COLLISIONS AT STAR*

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We present ϕ-meson transverse momentum distribution as well as its elliptic flow (v_2) measurements in Au + Au collisions at center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 7.7$, 11.5 and 39 GeV with the data taken from STAR experiment at RHIC in the year 2010. We discuss the energy dependence of ϕ-meson elliptic flow (v_2) and central-to-peripheral nuclear modification factors ($R_{\rm CP}$). The v_2 of ϕ-mesons are compared to those from other hadron species. The implications on partonic-hadronic phase transition are discussed.

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1. Introduction

The goals of the Beam Energy Scan program at BNL Relativistic Heavy Ion Collider (RHIC) are to search for the Quantum Chromodynamics (QCD) critical point as well as the phase transition boundary between partonic and hadronic phases [1]. By systematic study of Au + Au collisions at $\sqrt{s_{NN}} = 5$–200 GeV, one could access a wide region of temperature T and baryon chemical potential μ_B in the QCD phase diagram. Due to its small hadronic cross section, the ϕ-meson may decouple early from the system, which makes it an important probe to study early partonic evolution in high energy nuclear collisions [2, 3, 4]. In Au + Au collisions at RHIC with $\sqrt{s_{NN}} = 200$ GeV, the baryon–meson separation of ϕ-mesons $R_{\rm CP}$ and Number-of-Constituent-Quark (NCQ) scaling for ϕ-meson v_2 at intermediate transverse momentum ($p_{\rm T}$) have provided evidence for the formation of a new kind of deconfined matter with partonic collectivity [3,5]. Because of the

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possible transition from partonic dominated phase to hadronic dominated phase, it is expected that the established paradigm for partonic degrees of freedom at top RHIC energy may break at a given low collision energy. Especially, the absence or reduction of collective flow and the breaking of NCQ scaling for ϕ-mesons could indicate the system in hadronic dominated phase [6]. With the fully installed Barrel Time-of-Flight detector (TOF) [7] in the year 2010, the signal-to-background ratio of reconstructed ϕ-mesons is greatly enhanced, which improves the measurement of ϕ-meson v_2 significantly at lower energies. Here, we discuss the energy dependence of ϕ-meson v_2 and $R_{\rm CP}$ in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5, and 39 GeV, based on data taken from STAR experiment at RHIC in the year 2010.

2. Experimental data analysis

The Au + Au collision events collected by the minimum bias trigger are used in this analysis. STAR's Time Projection Chamber (TPC) [8] and TOF [7] are used for tracking, particle identification and event plane determination. The events are required to have a primary Z vertex (along beam direction) within 40, 50, and 50 cm of the center of the TPC for Au + Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5, and 39 GeV, respectively, to ensure nearly uniform detector acceptance. After the event selection, we obtain about 4 million, 12 million, and 130 million Au + Au minimum bias triggered events at $\sqrt{s_{NN}} = 7.7$, 11.5, and 39 GeV, respectively. For the ϕ-meson v_2 analysis at 39 GeV, we use the full statistics (130 million), while part of the statistics (16 million) is used for spectra analysis at present. The collision centrality is determined by the measured raw charged hadron multiplicity from the TPC within a pseudorapidity window $|\eta| < 0.5$ [9].

In ϕ-meson spectra analysis, identified charged kaons, from the TPC [8], are used to reconstruct the invariant mass distributions of ϕ-mesons at each well defined $p_{\rm T}$ bin. For ϕ-meson v_2 analysis, additional kaon identification from TOF [7] is used to get a clean kaon identification up to $p_{\rm T} = 1.6$ GeV/c and hence increase the signal-to-background ratio of reconstructed ϕ-mesons. The background is reconstructed by a mixed event method. Raw yields of the ϕ-mesons are determined by fitting the background subtracted invariant mass distribution with a Breit–Wigner function superimposed on a linear residual background function [5]. After taking into account the detector resolution, the reconstructed ϕ-meson masses and widths are consistent with the PDG values [10]. Next, the corrections for reconstruction efficiency and geometrical acceptance are applied to get the corrected ϕ-meson yields. For the ϕ-meson v_2 analysis, we use the TPC η-sub event plane method [11]. With an η-gap between the charged particles used in the event plane reconstruction and the measured ϕ-mesons, the non-flow effects related to the short range η-correlation are expected to be reduced. This is especially important when the expected v_2 value is small. More details of STAR ϕ-meson analysis can be found in Refs. [5, 12].

3. Results and discussions

3.1. ϕ-meson transverse momentum distribution and $R_{\rm CP}$

In Fig. 1, we show the STAR preliminary ϕ-meson $p_{\rm T}$ distribution in $\sqrt{s_{NN}} = 7.7$, 11.5, and 39 GeV Au + Au collisions at mid-rapidity ($|y| < 0.5$). The 0–10% in the plot corresponds to central collisions, while 40%–60% to peripheral collisions. The $p_{\rm T}$ spectra in the above collision centralities and energies are well described by a Levy function [5].

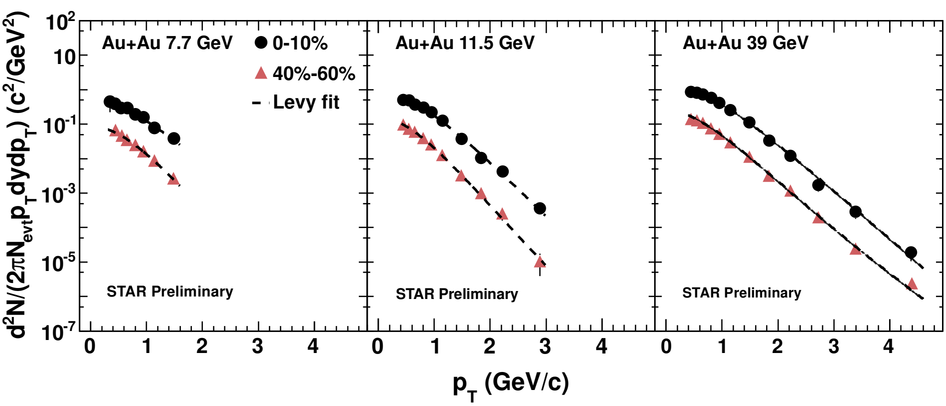

Fig. 1. Transverse momentum spectra of mid-rapidity ($|y| < 0.5$) ϕ-mesons produced in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5 and 39 GeV (statistical error only). The dashed curves are obtained from fits to the experimental data with a Levy function [5].

In Fig. 2, we present the $R_{\rm CP}$ of ϕ-mesons in Au + Au $\sqrt{s_{NN}} = 7.7$, 11.5, and 39 GeV collisions. The $R_{\rm CP}$ is defined as the ratio of particle yields in central collisions over those in peripheral ones scaled by the number of inelastic binary collisions $N_{\rm bin}$, that is,

$$R_{\rm CP} = \frac{[dN/(N_{\rm bin} p_{\rm T} dp_{\rm T})]_{\rm central}}{[dN/(N_{\rm bin} p_{\rm T} dp_{\rm T})]_{\rm peripheral}} . \quad (1)$$

Here, $N_{\rm bin}$ is determined from Monte Carlo Glauber model calculations [9]. The $N_{\rm bin}$ are 709.3 ± 26.8 (76.0 ± 17.0), 718.2 ± 26.3 (76.3 ± 16.3) and 781.8 ± 28.0 (80.3 ± 17.7) for 0–10% (40%–60%) Au + Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5, and 39 GeV, respectively. 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.

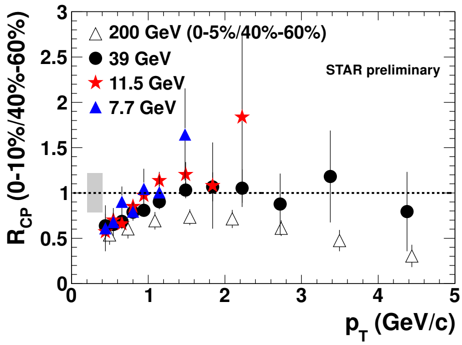

Fig. 2. ϕ-meson $R_{\rm CP}(0\text{–}10\%/40\%\text{–}60\%)$ at mid-rapidity ($|y| < 0.5$) in Au + Au $\sqrt{s_{NN}} = 7.7$, 11.5 and 39 GeV collisions. ϕ-meson $R_{\rm CP}(0\text{–}5\%/40\%\text{–}60\%)$ in Au + Au 200 GeV [5] is also plotted for comparison. Errors are statistical only. The left grey band is the normalization error from $N_{\rm bin}$.

At $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions, there is a large suppression of ϕ-meson yields in central collisions (0–5%) compared to peripheral collisions (40%–60%) [5]. This could be interpreted as final-state partonic energy loss in dense matter with a high gluon density [13]. At $\sqrt{s_{NN}} = 39$ GeV Au + Au collisions, the $R_{\rm CP}(0\text{–}10\%/40\%\text{–}60\%)$ is consistent with unity for $p_{\rm T} > 1$ GeV/c. This means no significant suppression in Au + Au 39 GeV, which is quite different from the Au + Au 200 GeV case. We note that it does not mean that there is no nuclear or medium effect, since there could be interplay between the Cronin effect (parton $p_{\rm T}$ broadening due to multiple scatterings) which enhances hadron yields at intermediate $p_{\rm T}$ [14, 15] and parton energy loss that suppresses the yields. However, the data may suggest a smaller parton energy loss in Au + Au 39 GeV than that in Au + Au 200 GeV. At 11.5 GeV, the ϕ-meson $R_{\rm CP}(0\text{–}10\%/40\%\text{–}60\%)$ seems to be larger than 1 for $p_{\rm T} > 1$ GeV/c. In other words, the ϕ-meson $R_{\rm CP}$ reflects the decreasing partonic effects with decreasing beam energies.

3.2. ϕ-meson elliptic flow v_2

In Figs. 3 (a)–(c), we compare the v_2 of ϕ-meson to those of proton and Λ in minimum bias Au + Au collisions at $\sqrt{s_{NN}} = 11.5$, 39, and 200 GeV. We use the TPC event plane for v_2 measurement at 200 GeV [16], and the TPC η-sub event plane at 11.5 and 39 GeV [11] for the above particles. One can see from Fig. 3 (a) that ϕ-meson v_2 is close to those of proton and Λ for $p_{\rm T}$ below 1.5 GeV/c in Au + Au 200 GeV collisions. This is expected from the hydrodynamic model since the mass of ϕ-meson is close to those of the

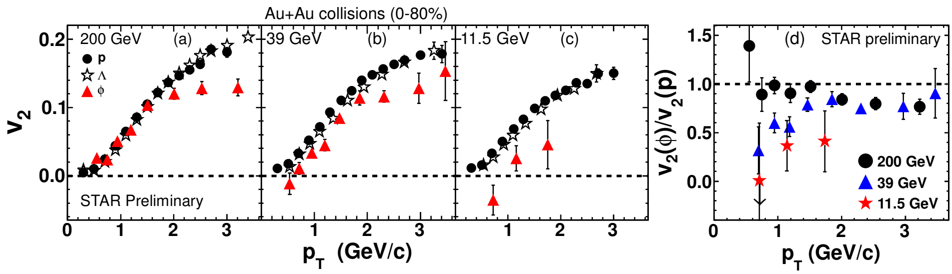

Fig. 3. (a)–(c): ϕ-meson v_2 *versus* $p_{\rm T}$ compared to proton and Λ in minimum bias Au + Au collisions at 11.5, 39 and 200 GeV, respectively. The proton and Λ v_2 are from Refs. [16, 17]. (d) The ratio between ϕ-meson v_2 and proton v_2 *versus* $p_{\rm T}$ in above energies. The central value of $v_2(\phi)/v_2(p)$ is far below 0 for the first low $p_{\rm T}$ point in Au + Au 11.5 GeV collisions. To suppress the y-axis scale, we place the central value of this point at $v_2(\phi)/v_2(p) = 0$ and use a down arrow to show that the real central value of this point is below 0. Errors are statistical only.

proton and Λ. For $p_{\rm T} > 2$ GeV/c, there is baryon–meson separation which could be understood by quark coalescence in deconfined matter [19]. In Au + Au 39 GeV collisions, we observe the similar baryon–meson separation for $p_{\rm T} > 2$ GeV/c, indicating that there is a partonic degree of freedom in the collision system. However, the ϕ-meson v_2 at low $p_{\rm T}$ is smaller than the proton and Λ v_2 at 11.5 and 39 GeV. One can see from Fig. 3 (d) that the ratios between ϕ-meson v_2 and proton v_2 show a decreasing trend with decreasing collision energy at low $p_{\rm T}$, indicating that relative to light quarks, the strange quark collectivity becomes weaker. Possible reasons could be that the strange quark are not fully thermalized in 11.5 and 39 GeV Au + Au collisions and/or the hadronic interactions start to play an important role in driving ϕ-meson elliptic flow.

4. Summary

In summary, we present STAR preliminary measurements on ϕ-meson central-to-peripheral nuclear modification factor ($R_{\rm CP}$) and elliptic flow (v_2) in $\sqrt{s_{NN}} = 7.7$, 11.5, and 39 GeV Au + Au collisions. The $R_{\rm CP}$ results show that there is no significant suppression of intermediate-$p_{\rm T}$ ϕ-meson yields in 0–10% central Au + Au collisions at 39 GeV compared to peripheral collisions (40%–60%), indicating a smaller partonic effect in Au + Au 39 GeV collisions than in Au + Au 200 GeV collisions. The lack of suppression in Au + Au 39 GeV collisions could be an interplay between Cronin effect and parton energy loss. The baryon–meson separation between ϕ-meson and proton (or Λ) v_2 at $p_{\rm T} > 2$ GeV/c supports the quark coalescence picture in Au + Au 39 GeV collisions. At low $p_{\rm T}$, the ϕ-meson v_2 is smaller than those of the proton and Λ, thus violates the mass ordering observed in Au + Au 200 GeV collisions. This might be related to the thermalization of s-quarks and/or the increasing contributions from hadronic interactions to the elliptic flow with decreasing collision energies.

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