Strange-quark collectivity of the ϕ-meson at RHIC

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Abstract. Based on A Multi-Phase Transport (AMPT) model, the elliptic flow v_2 of ϕ-mesons which is reconstructed from K^+K^- at the Relativistic Heavy-Ion Collider (RHIC) energy has been studied. The results show that the reconstructed v_2 of the ϕ-meson can keep the earlier information before ϕ decays and it seems to obey the number of constituent-quark scaling as other mesons and baryons. This result indicates that the ϕ v_2 mostly reflects the parton level collectivity developed during the early stage of the collisions and the strange and light up/down quarks have similar collectivity properties before the hadronization.

1 Introduction

Elliptic flow in heavy-ion collisions is a measure of the azimuthal anisotropy of particle momentum distribution in the plane perpendicular to the beam direction [1]. It results from the initial spatial asymmetry in noncentral collision and the subsequent collective interaction is thus sensitive to the properties of the dense matter formed during the initial stage of heavy-ion collisions [2–4] and parton dynamics [5] at RHIC energies. The experimental results of charged kaons, protons and pions [6,7] show that the elliptic flow first increases with particle transverse momentum following the hydrodynamic behavior and then tends to saturation in the intermediate transverse-momentum region. More importantly, a Number of Constituent-Quark (NCQ) scaling phenomenon of the elliptic flow has been discovered from this saturation region for baryons and mesons.

Strange-quark dynamics is believed to be a useful probe of the QCD matter created at RHIC. Enhanced strangeness production [8] has been proposed as an important signal for the QGP phase transition. The dominant production of $s\bar{s}$ pairs via gluon-gluon interaction may lead to strangeness (chemical and flavor) equilibration times comparable to the lifetime of the plasma and much shorter than that of a thermally equilibrated hadronic fireball. The subsequent hadronization is then expected to re-

sult in an enhanced production of strangeness particles. In particular, it has been argued that with the formation of QGP not only the production of ϕ-mesons, which consists of $s\bar{s}$, is enhanced but they also retain the information on the condition of the hot plasma. It is believed that the ϕ-meson interacts weakly in the hadronic matter and therefore freezes out quite early from the system [9]. Therefore the ϕ-meson in RHIC has been of great interest [10,11].

We use A Multi-Phase Transport (AMPT) model to investigate the effect of parton dynamics on the ϕ-meson. The AMPT model is a hybrid model which consists of four main components: the initial condition, partonic interactions, the conversion from partonic matter into hadronic matter and hadronic interactions. Details of the AMPT model can be found in [12]. In the default AMPT model [13] partons are recombined with their parent strings when they stop the interaction, and the resulting strings are converted to hadrons using a Lund string fragmentation model [14]. In the AMPT model with string melting [15], a simple quark coalescence model is used to combine partons into hadrons.

In this work, we present a study for the elliptic flow of the ϕ-meson at the RHIC energy based on the AMPT model with string melting scenario. We illustrate that the partonic effect could not be neglected for ϕ-mesons as demonstrated for other hadrons in [15] and a string melting AMPT version is much more appropriate than the default AMPT version when the energy density is much higher than the critical density for the pQCD phase tran-

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sition. So far, the AMPT model with string melting scenario has been successful in describing the elliptic flow of stable baryons and mesons [12,15]. In this work, we try to investigate an unstable particle: the ϕ-meson. In order to compare with the experimental data, we adopt the value of the particle mass with the mass width according to the Breit-Wigner shape and then a broadening width of the Breit-Wigner shape has been obtained when we reconstruct ϕ [16]. The value of the parton scattering cross-section is chosen as 10 mb. The transverse-momentum dependence and the collision centrality dependence have been studied and the NCQ-scaling phenomenon has been observed for ϕ-mesons. In addition, the rescattering effect of ϕ flow has been investigated in the hadronic scattering model, namely the ART model, which has been modified to include ϕ-meson scattering processes [17].

2 Analysis method

The azimuthal distribution with respect to the reaction plane at rapidity y can be written in the form of a Fourier series as follows:

$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_T\mathrm{d}p_T\mathrm{d}y}\left(1 + \sum_{n=1}^{\infty}2v_n\cos[n(\Phi - \Psi)]\right), \quad (1)$$

where p_T is the transverse momentum, Φ is the azimuthal angle and Ψ is the reaction plane angle. The first and second Fourier coefficients, v_1 and v_2, are called directed and elliptic flow, respectively.

Since the ϕ-meson is unstable, it can only be reconstructed in final state from its decay products of either the K^+K^- pair or the lepton (e^+e^- or $\mu^+\mu^-$) pair. The present simulation results are reconstructed from the former decay products among ~ 100000 events. All identified K^+ and K^- particles in a given event within the rapidity range $(-1, 1)$ are combined to form the invariant-mass distribution. There are a large number of combinatorial backgrounds when the invariant-mass distribution is reconstructed by the K^+K^- pair. The combinatorial backgrounds are estimated by an event mixing method [18] in which all K^+ particles from one event are combined with K^- particles of ten other events within the same centrality. Then, the number of the combinational backgrounds is obtained after the normalized factor of the mixed event number (ten in our analysis). Finally, the yield in each bin is determined by fitting the background-subtracted invariant-mass distribution to a Breit-Wigner function plus a linear background in a limited mass range. Figure 1 shows some examples in certain transverse-momentum ranges for the reconstructed invariant-mass spectra of ϕ-mesons.

The magnitude of the anisotropy and the finite number of particles available to determine the reaction plane leads to a finite resolution. Therefore, the reconstructed v_n^{rec} coefficients with respect to the reaction plane have to be corrected for the reaction plane resolution [19]:

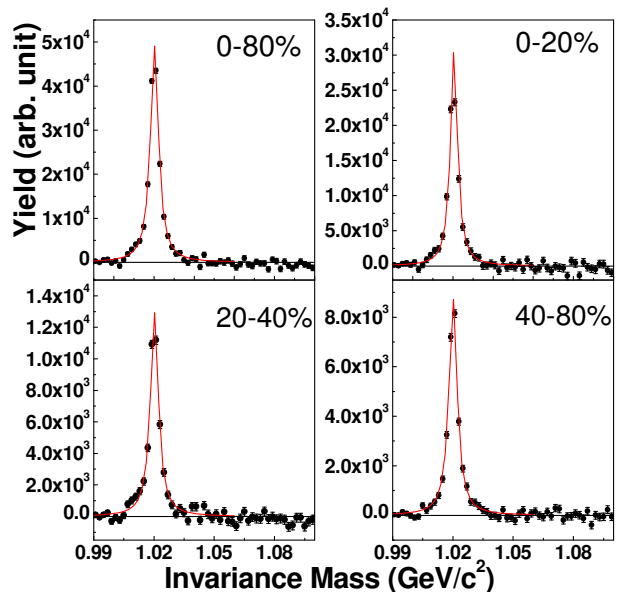$$v_n = \frac{v_n^{res}}{\langle\cos(n(\Psi_n - \Psi_R))\rangle}, \quad (2)$$

Fig. 1. The reconstructed invariant-mass distribution (dots with statistical error bar) with the fits of the Breit-Wigner function plus a linear background in the mass (GeV/c^2) range (0.98, 1.06) of ϕ-mesons from K^+K^- pairs. From top left to bottom right it corresponds to the centrality of 0–80%, 0–20%, 20–40% and 40–80%, respectively. The azimuth angle range is 0–π and the p_T (GeV/c) range is 0.4–2.4 GeV/c. The FWHM from fitted function is 5.003, 5.073, 5.004 and 4.869 MeV, respectively, while the default value in the AMPT model is 4.43 MeV.

where Ψ_n is the reconstructed event plane angle. The mean cosine values are less than unity, thus this correction always increases the flow coefficients. After such correction, the flow should tend to the "true" flow which is supposed to be determined in the true reaction plane.

3 Results

The upper panel of fig. 2 shows the elliptic flow v_2 of the ϕ-meson from minimum-bias ^{197}Au + ^{197}Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Experimental data [7] of $K^+ + K^-$ and $p + \overline{p}$ are also presented for comparison. First, we observe that v_2 of the ϕ-meson seems to follow the same behavior of $K^+ + K^-$: it is higher than the baryon at low-p_T region and then saturates in the intermediate-p_T region. The ϕ-meson v_2 is in agreement with the hydrodynamic model calculation [20] which predicts its mass ordering at low-p_T region —perhaps implying that an early thermalized system has been created in collisions at the RHIC energy. Compared with experimental data of $K^+ + K^-$ and $p + \overline{p}$, the reconstructed result can give a good description of the ϕ-meson v_2 within error bars.

One of the salient observations made at RHIC is a NCQ scaling of the hadronic elliptic flow at intermediate p_T ($1.2 < p_T < 4.0$ GeV/c) [6] and the quark coalescence or recombination mechanism has been used to explain the
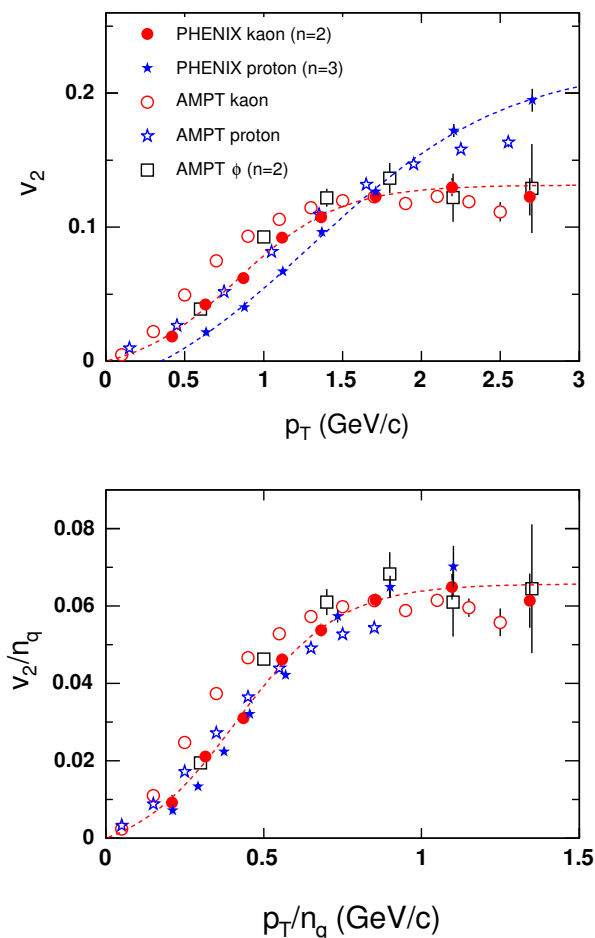
Fig. 2. Top panel: p_T-dependence of the v_2 of the ϕ-meson compared with $K^+ + K^-$ and $p + \overline{p}$. Data are taken from ref. [7]. The dashed lines are the fits results of the function $(f_{v_2}(n) = \frac{an}{1+\exp(-(p_T/n-b)/c)} - dn$, where a, b, c and d are the fit parameters, n is the constituent-quark number). Bottom panel: NCQ-scaled v_2. The error bars represent statistical errors only.

NCQ scaling [21,22] in that p_T region. In this coalescence or recombination mechanism, hadron is formed via quark coalescence. The lower panel of fig. 2 displays the angular anisotropy of the constituent quark based on the quark coalescence picture. The behavior is similar for all reference particles for $p_T/n_q > 0.6\,\text{GeV}/c$. The $v_2(p_T/n_q)$ represents a constituent-quark momentum space anisotropy v_2^q that may indicate a consequence of collectivity in a partonic stage which includes strange quarks. The reconstructed results imply that a new stage of partonic matter may be created with v_2^q characterizing the property of the matter.

As the $K^+ + K^-$ pair decaying from a ϕ-meson is likely to undergo appreciable rescattering in the medium, this might lead to a reconstructed invariant mass situated outside the original ϕ-meson peak. In this case, it is necessary to study the in-medium effect in detail. It is carried out through turning off or turning on the ART process [23] in the AMPT model. It was found that the in-medium

hadronic rescattering effect on the final ϕ elliptic flow can be ignored within the errors. The reason is that the spatial anisotropy during the hadronic phase is small as well as ϕ has smaller hadronic interaction cross-section. This may, however, depend on the hadronization scheme [15]. Our reconstructed result for ϕ v_2 confirms that it can keep useful information of the ϕ-meson which is produced during the earlier collision.

4 Summary

In summary, we have firstly presented the elliptic flow v_2 of the ϕ-meson from minimum-bias $^{197}\text{Au} + ^{197}\text{Au}$ collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$ in A Multi-Phase Transport model with string melting scenario. The v_2 of the ϕ-meson seems to demonstrate a similar behavior to other mesons. A NCQ-scaling phenomenon of elliptic flow reveals for ϕ from the reconstruction of $K^+ K^-$ pairs. The coefficient $v_2(p_T/n_q)$ of ϕ represents a constituent-strange-quark momentum space anisotropy v_2^q that may arise as a consequence of collectivity in a partonic degree of freedom. It may imply that a new state of partonic matter has been created with v_2^q characterizing the property of matter. The RHIC data for the elliptic flow of ϕ will shed light on these physics issues.

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