

Elliptic flow of ϕ mesons and strange quark collectivity at RHIC

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Based on A Multi-Phase Transport (AMPT) model, we have studied the elliptic flow v_2 of ϕ mesons from reconstructed K^+K^- decay channel at the top Relativistic Heavy Ion Collider energy at Brookhaven National Laboratory. The dependences of v_2 on transverse momentum p_T and collision centrality are presented and the rescattering effect of ϕ mesons in the hadronic phase is also investigated. The results show that experimental measurement of v_2 for ϕ mesons can retain the early collision information before ϕ decays and that the ϕ v_2 value obeys the constituent quark number scaling which has been observed for other mesons and baryons. Our study indicates that the ϕ v_2 mostly reflects partonic level collectivity developed during the early stage of the nucleus-nucleus collision and the strange and light up/down quarks have developed similar angular anisotropy properties at the hadronization.

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I. INTRODUCTION

Elliptic flow in heavy ion collisions is a measure of the azimuthal angular anisotropy of particle distribution in momentum space with respect to the reaction plane [1]. The magnitude of the elliptic flow depends on both initial spatial asymmetry in non-central collisions and the subsequent collective interactions. The elliptic flow is thus sensitive to the properties of the dense matter formed during the initial stage of heavy ion collision [2, 3, 4, 5] and parton dynamics [6] at Relativistic Heavy Ion Collider (RHIC) energies. Experimentally, elliptic flow has been measured as functions of collision centrality, transverse momentum, (pseudo)rapidity and particle species [7, 8, 9, 10, 11] in $^{197}\text{Au} + ^{197}\text{Au}$ collisions from RHIC at Brookhaven National Laboratory (BNL). The experimental results of charged kaon, proton and pion [8] show that the elliptic flow first increases with particle transverse momentum following the hydrodynamic behavior and then reaches a saturation in intermediate transverse momentum region. More importantly, a Number-of-Constituent-Quark (NCQ) scaling has been discovered for identified particle elliptic flow in the intermediate p_T region for baryons and mesons. The data of pion elliptic flow v_2 are somewhat higher than the NCQ scaling, which can be attributed to the large contribution to the pion yield from secondary decays [12, 13]. The NCQ scaling at RHIC is an important indication for the effective constituent quark degree of freedom at hadronization and the formation of hadrons through parton coalescence mechanism [14, 15]. Similarly, a Number-of-Nucleon scaling for anisotropic flow of light nuclear clusters in nuclear collisions at Fermi energies was recently demonstrated by

Ma et al. [16], which is interpreted as a consequence of nucleon coalescence mechanism.

Strange quark dynamics is a useful probe of the dense matter created at RHIC. Enhanced strangeness production [17] has been proposed as an important signal for the formation of the Quark-Gluon Plasma (QGP) in nuclear collisions. The dominant production of $s\bar{s}$ pairs via gluon-gluon interaction may lead to a strangeness (chemical and flavor) equilibration time comparable to the lifetime of the QGP whereas the strangeness equilibration time in a hadronic fireball is much longer than the lifetime of the hadronic fireball. The subsequent hadronization of the QGP is then expected to result in an enhanced production of strange particles. In particular, it has been argued that with the formation of QGP the production of ϕ mesons is enhanced. Furthermore ϕ mesons could retain the information on the condition of the hot plasma at hadronization because ϕ mesons interact weakly in the hadronic matter [18]. The measurement of ϕ mesons has been of great interest in the study of collision dynamics and the properties of the dense matter created at RHIC [19, 20, 21].

We use A Multi-Phase Transport (AMPT) model to investigate effect of parton dynamics related to ϕ mesons. The AMPT consists of four main components [22]: initial conditions, partonic interactions, conversion from partonic matter into hadronic matter and hadronic interactions in collision evolution. The initial conditions, which include the spatial distribution of participant matter, minijet partons production and soft string excitations, are obtained from the HIJING model [23]. Scattering among partons are modelled by Zhang's parton cascade (ZPC) [24], which calculates two-body parton scatterings using cross sections from pQCD with screening masses. In the default AMPT model [25] partons are recombined with their parent strings when they stop interacting, and the resulting strings fragment into hadrons according to

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the Lund string fragmentation model [26]. In the AMPT model with string melting scenario [27], a quark coalescence model is used to combine parton into hadrons. The evolution dynamics of the hadronic matter is described by A Relativistic Transport (ART) model [28]. Details of the AMPT model can be found in [22].

In this paper, we present a detailed study of the elliptic flow of ϕ mesons at the top RHIC energy based on the AMPT model with the string melting scenario [22]. The string melting scenario is believed to be much more appropriate than the default AMPT scenario since the energy density in these collisions is much higher than the critical density for the QCD phase transition. The AMPT model with string melting scenario has successfully described the elliptic flow of stable baryons and mesons [22, 27]. It can also describe higher-order anisotropic flow parameters v_n including the odd- n ones [29]. In this work, we focus on the ϕ mesons. We follow the method used in experimental analysis by reconstructing ϕ mesons in the final state from fitting the invariance mass distribution of all K^+ and K^- pairs with a Breit-Wigner function including the intrinsic decay width of ϕ mesons [30]. The parton scattering cross section is chosen as 10 mb. The transverse momentum and collision centrality dependences of ϕ meson v_2 have been studied and the NCQ-scaling has also been observed in the AMPT model. In addition, the rescattering effect on ϕ meson v_2 has been investigated in the hadronic phase using the ART model where rescattering processes of ϕ mesons and their decay daughters are included [31]. We note that our study based on the AMPT model for ϕ meson elliptic flow is different from that of Ref. [32], where dynamical quark coalescence model has been used for studies of ϕ meson production and elliptic flow.

II. ANALYSIS METHOD

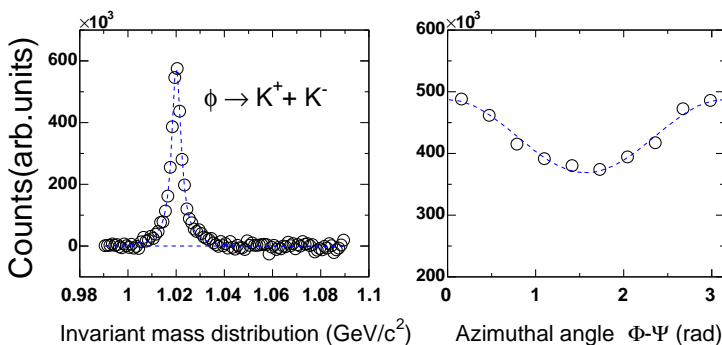


FIG. 1: (Color online) Left panel: m_{inv} distribution from minimum bias (0-80%) Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Dashed line is a fit of Breit-Wigner function plus a linear background. Right panel: azimuthal angular distributions of raw ϕ yields with respect to the event plane. Dashed line represents the fit result. The transverse momentum range of the figure is $0.4 < p_T < 3.0$ GeV/c.

The reconstruction of ϕ mesons was accomplished by calculating the invariant mass (m_{inv}), transverse momen-

tum (p_T), azimuthal angle (Φ) of pairs that formed from all permutations of candidate K^+ with K^- at a given ϕ rapidity range ($|y| < 1.0$). The resulting m_{inv} distributions consist of the ϕ signal superimposed on a large background that is predominantly combinatorial. The shape of the combinatorial background was calculated using the mixed-event method [33]. A Breit-Wigner function plus a linear function can describe the m_{inv} distribution well. The left panel of Fig.1 shows the m_{inv} distribution for ϕ mesons from minimum bias collisions using ~ 1.8 M Au+Au Monte Carlo AMPT events.

The elliptic flow v_2 is calculated by the STAR standard method [11] based on the distribution of particle raw yields as a function of azimuthal angle Φ with respect to the event plane angle Ψ . The raw yields of ϕ mesons are extracted from fits to m_{inv} distribution in each p_T and $\Phi - \Psi$ bin. The event plane angle Ψ is determined from the azimuthal distribution of charged tracks within a window of $0.2 < p_T < 2.0$ GeV/c and pseudo-rapidity $|\eta| < 1.0$, which is used as an estimate of the reaction plane angle [34, 35]. To avoid autocorrelations, tracks associated with a ϕ candidate are explicitly excluded from the event plane calculation. The right panel of Fig.1 shows the azimuthal angular distribution of raw ϕ yields with respect to the event plane from the minimum bias collisions in the $0.4 < p_T < 3.0$ GeV/c range. Dashed line is the fitting result with a function $\frac{dN}{d(\Phi-\Psi)} = A[1 + 2v_2 \cos 2(\Phi - \Psi)]$, where A is a normalization constant. The finite resolution in the approximation of event plane as reaction plane smears out the azimuthal angular distribution and leads to a lower value in the apparent anisotropy parameters [35]. This event plane resolution is determined by dividing each event into random sub-events and calculating the difference in event plane angles between sub-events. We obtained an event plane resolution of 0.91, which is 20% larger than the experimental resolution reported by STAR [11]. This is due to the fact that the number of tracks per event used in our simulation is larger than that from the data. In order to verify our resolution correction, we have also calculated the v_2 with respect to the real reaction plane ($\Psi = 0$) which is known a priori in our model calculation. From Fig. 2, the v_2 extracted from the true reaction plane is in good agreement with the one extracted from the event plane corrected for resolution effect. Our result also illustrates that the experimental elliptic flow analysis method can faithfully describe the magnitude of the elliptic flow for ϕ mesons.

III. RESULTS

The upper panel of Fig.3 shows the elliptic flow v_2 of ϕ mesons from minimum-bias AMPT $^{197}\text{Au} + ^{197}\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Experimental data [8] of $K^+ + K^-$ and $p + \bar{p}$ are also presented for comparison. We note that the ϕ meson v_2 , in comparison with v_2 of charged kaons and protons all from the AMPT model,

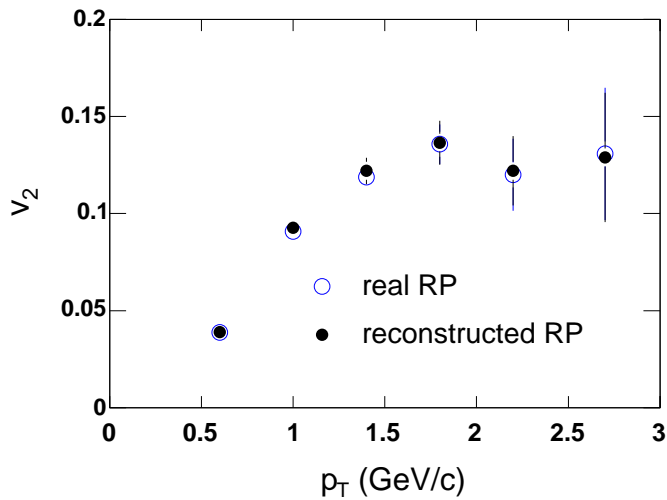


FIG. 2: (Color online) Comparison of elliptic flow values obtained from using real reaction plane (RP) and event plane angle corrected for resolution effect.

satisfies the mass ordering behavior of v_2 predicted by the hydrodynamic model calculation [36] in the low p_T region. However, the AMPT calculation results of v_2 for charged kaons and protons are about 25% larger than the experimental data in the $p_T < 1.5 \text{ GeV}/c$ region. This may result from the large parton scattering cross section (10 mb) used in this Monte Carlo AMPT calculation. In order to explore the intermediate p_T ($1.5 < p_T < 4.0 \text{ GeV}/c$) phenomenon, where the so-called NCQ-scaling in elliptic flow for identified particles has been observed at RHIC [7] and the quark coalescence or recombination mechanism has been used to explain the scaling [14, 15], the large parton scattering cross section is needed in order to produce the magnitude of the elliptic flow in the intermediate p_T region matching the experimental measurement [27].

Our AMPT calculation indicates that the v_2 of ϕ mesons at the intermediate p_T seems to saturate and to follow the same behavior as that of $K^+ + K^-$. The lower panel of Fig. 3 shows elliptic flow v_2 normalized by the number of constituent quarks for charged kaons, protons and ϕ mesons. In the intermediate p_T region of $p_T/n_q > 0.6 \text{ GeV}/c$ the elliptic flow of charged kaons, protons and ϕ mesons from the AMPT calculation seems to satisfy the NCQ scaling. This result implies that u, d and s quarks in the initial partonic matter formed in relativistic heavy ion collisions develop significant collectivity with strength characterized by v_2/n_q .

We have also studied the collision centrality dependence of ϕ meson v_2 at several centrality intervals: 0-20%, 20-40% and 40-80% as well as 0-80%. Fig. 4 shows that for each centrality bin, $v_2(p_T)$ of ϕ mesons increases with their p_T . Among different centrality bins, the values of $v_2(p_T)$ increase from central to semi-peripheral collisions, which can be understood as a result of increasing initial spatial eccentricity.

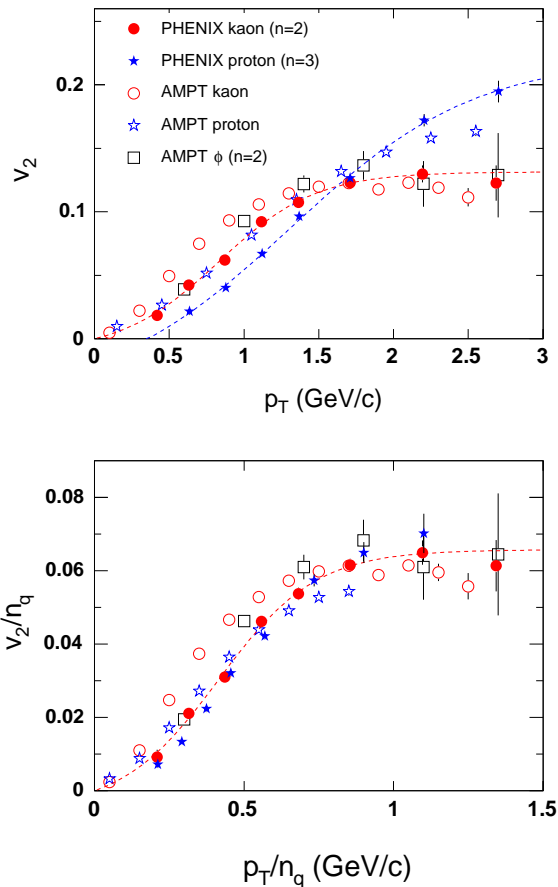


FIG. 3: (Color online) Top panel: p_T dependence of the v_2 for ϕ mesons compared with $K^+ + K^-$ and $p + \bar{p}$. Data are taken from Ref. [8]. Dot-dashed lines are the fitted results with function ($f_{v_2}(n) = \frac{an}{1 + \exp(-(p_T/n - b)/c)} - dn$, where a, b, c and d are the fit parameters, n is the constituent-quark number). Bottom panel: NCQ scaled v_2 as a function of NCQ scaled transverse momentum. The error bars represent statistical errors only.

As the $K^+ + K^-$ pair from the decay of a ϕ meson is likely to undergo rescatterings in the medium during the hadronic evolution, this might lead to a reconstructed K^+K^- invariant mass situated outside the original ϕ meson mass peak. It is thus of interest to study the in-medium rescattering effect in details. This is carried out by turning on and off the ART process during the hadronic evolution in the AMPT model. The elliptic flow v_2 of ϕ mesons without ART indicates the elliptic flow developed before the hadronic rescattering stage. In contrast, the v_2 of ϕ mesons after ART includes all contributions from both partonic and hadronic stages. In Fig. 5, the v_2 for ϕ mesons before ART are directly extracted from the AMPT model without the ART processes. In that case, ϕ mesons are explicitly present and do not need to be reconstructed from $K^+ + K^-$ decay channels. The v_2 after the ART processes is reconstructed from

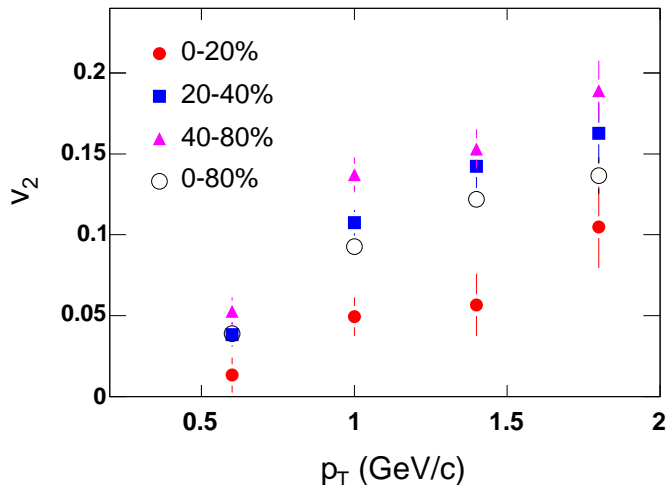


FIG. 4: (Color online) v_2 of ϕ meson as a function of p_T in the centralities of 0-20%, 20-40%, 40-80% and 0-80%. The error bars represent statistical errors only.

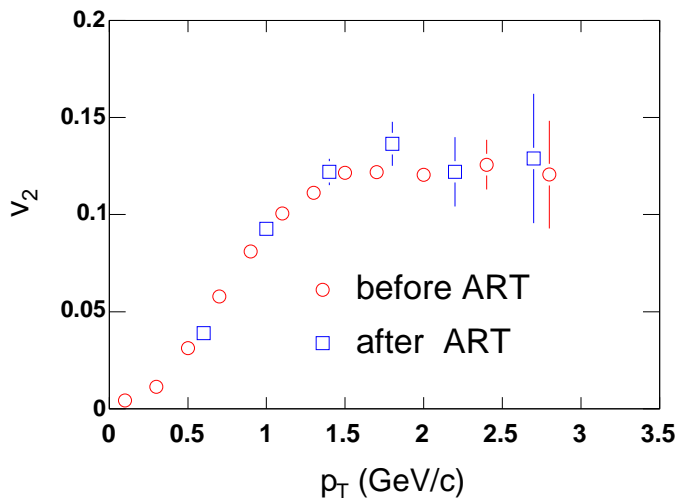


FIG. 5: (Color online) The hadronic rescattering effect on elliptic flow v_2 of ϕ -meson from AMPT model with string melting scenario.

$K^+ + K^-$ pairs and the hadronic rescatterings are mostly due to kaon rescatterings in the hadronic stage. Error bars are statistical errors only. An interesting feature in Fig. 5 is that the two scenarios are in good agreement with each other after $p_T > 0.4$ GeV/c. In this case, the final hadronic rescattering effect on the ϕ meson elliptic flow can be ignored within the errors. Our study of ϕ v_2 confirms that ϕ mesons can retain useful information from the early stage of the nuclear collisions.

IV. SUMMARY

In summary, we have presented a study of elliptic flow of ϕ mesons using reconstructed K^+K^- pairs from minimum-bias $^{197}\text{Au} + ^{197}\text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV in a multi-phase transport model with string melting scenario. The v_2 of ϕ mesons seems to exhibit a similar behavior as other mesons. A NCQ-scaling phenomenon of elliptic flow has been observed for ϕ mesons from the reconstruction of K^+K^- pairs. The coefficient $v_2(p_T/n_q)$ of ϕ mesons represents essentially the momentum space anisotropy of constituent strange quarks that have arisen from the partonic collectivity developed in the initial stage of heavy ion collisions. The collision centrality dependence of elliptic flow for ϕ mesons has also been studied. It is found that the ϕ meson elliptic flow increases from central to semi-peripheral collisions as a result of increasing initial spatial eccentricity. We have also studied the in-medium hadronic rescattering effect on elliptic flow of ϕ mesons. The results confirm that within error bars, our reconstructed ϕ meson v_2 can retain the early information before it decays. Comparing our predictions with the RHIC data for the elliptic flow of ϕ mesons is expected to shed light on these issues.

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