Elliptic flow of $\phi$ meson a sensitive probe for onset of de-confinement transition in high energy heavy-ion collisions

Md. Nasim$^1$, Bedangadas Mohanty$^2$ and Nu Xu$^{3,4}$

$^1$Variable Energy Cyclotron Centre, Kolkata 700064, India,
$^2$School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar 751005, India, $^3$College of Physical Science and Technology, Central China Normal University, Wuhan 430079, China, and $^4$Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

(Dated: December 11, 2013)

Elliptic flow ($v_2$) of $\phi$ meson is shown to be a sensitive probe of the partonic collectivity using a Multi Phase Transport (AMPT) model. Within the ambit of the AMPT model with partonic interactions (string melting version), the $\phi$ meson $v_2$ at midrapidity is found to have negligible contribution from hadronic interactions for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Changing the hadron cascade time in the model calculations does not change the $\phi$ meson $v_2$, while it reduces the $v_2$ of proton at low transverse momentum ($p_T$). These observations indicate that a substantial reduction in $\phi$ mesons $v_2$ as a function of colliding beam energy would suggest the dominance of hadronic interactions over partonic interactions.

PACS numbers: 25.75.Ld

I. INTRODUCTION

One of the current focus of the high energy heavy-ion collision experiments is to study the various aspects of the QCD phase diagram [1, 2]. After observing the clear signatures of the formation of strongly interacting quark-gluon plasma (QGP) at the top RHIC energies [3-8], attempts are being made to vary the colliding beam energy and search for the transition region between the partonic and/or hadronic dominant interactions in the phase diagram. This is one of the goals of the RHIC Beam Energy Scan (BES) program [7, 8].

In Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV the $\phi$ meson production has played a crucial role to establish the formation of the partonic matter [9]. Number of constituent quark scaling of the elliptic flow of $\phi$ meson [10], enhancement in yield of $\phi$ meson in Au + Au collisions relative to $p + p$ collisions [11] and the ratio of yield of the $\Omega$ baryon to the yield of $\phi$ meson as a function of $p_T$ [12] have been the key measurements. In general, multi-strange hadrons are understood [12] to have a smaller hadronic interaction cross sections. As a result, their momentum distributions, and particularly the momentum dependence of the azimuthal anisotropy [10], are expected to be primarily controlled by the early partonic interactions in high-energy nuclear collisions. In order to demonstrate that the multi-strange hadrons, are a clean tool for phase identification, we have performed model simulations to study the $\phi$ meson production. The paper focuses on using the AMPT model for the $\phi$ meson production, leading to the establishment of the $\phi$ $v_2$ as a key observable for studying the onset of the de-confinement transition.

Further, with high statistics data being collected in high energy heavy-ion collisions, it is now possible to have high precision measurements of $v_2$ for various produced hadrons. One possibility that opens up is to study the effect of the late stage hadronic re-scattering on $v_2$ at low $p_T$. Initial simulations using a hybrid model showed that the usual mass ordering trend of $v_2(\phi) < v_2(p)$ will get reversed due to the late stage hadronic re-scattering [13]. In this paper we also study this aspect using the AMPT model.

The paper is organized as follows. In the section II we will briefly introduce the AMPT model [14] used in this study. In the section III the results from the AMPT model calculations regarding $v_2$ of $\phi$ mesons and protons for various configurations (different parton-parton cross section and hadronic cascade time) are presented. Finally in section IV we summarize our findings and present a short discussion on the implications of this work to the current experimental measurements in high energy heavy-ion collisions.

II. MODEL CALCULATIONS

A. AMPT

The AMPT [14] model used for the calculations presented in this paper has four main stages: the initial conditions, partonic interactions, the conversion from the partonic to the hadronic matter, and hadronic interactions. The initial conditions are obtained from the HIJING model [15]. Scatterings among partons are modeled by Zhang’s parton cascade (ZPC) [16], it includes only two-body scatterings with cross sections obtained from the pQCD
with screening masses. Some of the results presented are by varying the parton-parton scattering cross sections within 3 mb to 14 mb. The AMPT model with string melting \cite{17} leads to hadron formation using a quark coalescence model. The subsequent hadronic matter interaction is described by a hadronic cascade, which is based on A Relativistic Transport (ART) model \cite{18}. The termination time of the hadronic cascade is varied in this paper from 0.6 fm/c to 30 fm/c to study the effect of the hadronic re-scattering on the observables presented. More detailed discussions regarding the AMPT model can be found in Ref. \cite{14}. In this study, approximately one million events for each configuration (different cross section and hadronic cascade time) were generated for Au + Au 0-80% minimum bias collisions at \( \sqrt{s_{NN}} = 200 \) GeV. All results presented are for the rapidity range ± 1.0 unit.

### B. \( \phi \) mesons production

The string melting version of the AMPT used in this paper, produces \( \phi \) meson using a quark coalescence model in the partonic stage \cite{14}. In the hadronic stage, the AMPT model includes the following reactions associated with the \( \phi \) meson. Inelastic scatterings in baryon-baryon channels includes \((N\Delta N^*)(N\Delta N^*) \rightarrow \phi NN\), those in the meson-baryon channel includes \((\pi\rho)(N\Delta N^*) \leftrightarrow \phi(N\Delta N^*)\) and \(K(\Lambda\Sigma) \leftrightarrow \phi N\). The \( \phi \) meson scatterings with other hadrons included in the model are \(\phi(\pi\rho\omega) \leftrightarrow (KK^*)(KK^*)\), and \(\phi(KK^*) \leftrightarrow (\pi\rho\omega)(KK^*)\). The cross section for the elastic scattering of the \( \phi \) meson with a nucleon is set to 8 mb while the \( \phi \) meson elastic cross section with a meson is set to 5 mb. For other details and specifically those related to inelastic scattering cross section can be found in \cite{14}.

For comparison with another transport based calculation, we also present \( v_2 \) for \( \phi \) meson from UrQMD (Ultra relativistic Quantum Molecular Dynamics) model \cite{19} for Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV. It is based on a microscopic transport theory where the phase space description of the reactions are important. It allows for the propagation of all hadrons on classical trajectories in combination with stochastic binary scattering, color string formation and resonance decay. It incorporates baryon-baryon, meson-baryon and meson-meson interactions, the collisional term includes more than 50 baryon species and 45 meson species.

### C. Elliptic flow

The anisotropic elliptic flow parameter presented in this paper is defined as the 2\(^{\text{nd}}\) Fourier coefficient \( v_2 \) of the particle distributions in emission azimuthal angle \(\phi\) with respect to the reaction plane angle \(\Psi\) \cite{20}, and can be written as

\[
\frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2(\phi - \Psi)).
\]

For a given rapidity window the second coefficient is

\[
v_2 = \langle \cos(2(\phi - \Psi)) \rangle = \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2},
\]

where \(p_x\) and \(p_y\) are the \(x\) and \(y\) component of the particle momenta. In the AMPT model the \(\Psi\) is along the \(x\)-axis.

### III. RESULTS

![Figure 1](image)

**FIG. 1**: (Color online) \( \phi \) meson \( v_2 \) for Au + Au minimum bias (0-80\%) collisions at midrapidity (± 1.0) at \( \sqrt{s_{NN}} = 200 \) GeV from STAR experiment at RHIC \cite{10} compared to the corresponding AMPT and UrQMD model calculations. The AMPT model calculations are shown for three different parton-parton interaction cross sections of 3, 10 and 14 mb. The errors shown are statistical.

Figure 1 shows the comparison of elliptic flow of \( \phi \) meson in 0-80\% minimum bias Au + Au collisions at midrapidity for \( \sqrt{s_{NN}} = 200 \) GeV measured by STAR experiment at RHIC \cite{10} with the corresponding results from the AMPT model for three different values of parton-parton cross sections of 3 (magenta solid circle), 10 (black open square), and 14 mb (red open cross). Although it is generally believed that perturbative QCD cross section is about 3 mb \cite{21},
in order to explain the measurements for $p_T > 1$ GeV/c a parton-parton cross section between 10-14 mb is found to be required. Thus the generation of this substantial $v_2$ for $\phi$ mesons as observed in the experiments requires a significantly large parton interaction cross section than obtained from pQCD calculations ($\sim 3$ mb) \cite{14, 21, 22}. Also shown in the figure is the corresponding $v_2$ results from the UrQMD model \cite{19}. The UrQMD model results (which does not include any partonic interactions) gives substantially smaller value of $v_2$ compared to the experimental data.

Within the framework of hydrodynamics, the collectivity reflected through the $v_2$ distributions are caused by the pressure gradients. Due to the effect of self quenching, one expects that the development of $v_2$ is dominantly from the early stages of the collision \cite{22, 23}. From the comparison shown in Fig. 1, we conclude that collectivity in the multi-strange hadron $\phi$ meson has been developed in the early partonic interactions in high-energy nuclear collisions at RHIC \cite{3}. We now proceed to investigate the contributions to $\phi$ meson $v_2$ in AMPT separately from partonic and hadronic interactions.

A. $\phi$ meson $v_2$ from partonic interactions

![Graph showing the relationship between $v_2$ and transverse momentum for proton and $\phi$ mesons](image)

**FIG. 2:** (Color online) $\phi$ meson $v_2$ for Au + Au minimum bias (0-80%) collisions at midrapidity ($\pm 1.0$) at $\sqrt{s_{NN}} = 200$ GeV from the AMPT model. Panels (a) and (b) shows the results as a function of $p_T$ for parton-parton interaction cross section of 0 and 10 mb and calculations before and after relativistic transport calculations for hadrons, respectively. The lower panels (c) and (d) shows the difference in $v_2$ shown in panels (a) and (b), respectively. The errors shown are statistical.

Figure 2 (a) shows the $\phi$ meson $v_2$ for minimum bias Au + Au collisions at midrapidity versus $p_T$ from AMPT model for parton-parton cross section of 10 mb (red solid circles) and results without any parton-parton interaction (blue solid square, obtained by setting the parton-parton cross section value to 0 mb). The hadronic cascade time is 30 fm/c for both the cases. The $\phi$ meson $v_2$ is consistent with zero in absence of parton-parton interactions. The panel (c) shows the difference between the two results, indicating that almost all the $\phi$ meson $v_2$ is generated via the partonic interactions.

B. Effect of hadronic re-scattering

![Graph comparing $v_2$ with hadron cascade time](image)

**FIG. 3:** (Color online) (a) $v_2$ of protons as a function of $p_T$ for Au + Au 0-80% collisions at $\sqrt{s_{NN}} = 200$ GeV from AMPT model at midrapidity. The results are shown for a parton-parton cross section of 10 mb and three different values of hadronic cascade time periods. (b) The same plot as (a) for the $\phi$ mesons. (c) Ratio of $v_2$ of protons for hadron cascade time of 0.6 fm/c to corresponding $v_2$ for time periods of 15 and 30 fm/c, and (d) same as in (c) for the $\phi$ mesons. The error bars shown are statistical.

To further study the effect of hadronic interactions, the model simulations were carried out for the Au + Au minimum bias collisions with parton-
parton interaction cross section fixed to be 10 mb and varying the hadronic cascade time from 0.6 fm/c to 30 fm/c. Higher value of hadronic cascade time reflects larger hadronic re-scatterings. We have checked that for RHIC energies going to even longer time duration does not contribute any further to the results presented. The $v_2$ calculations are carried out for both φ meson and proton. We chose protons mainly for two reasons: (a) as a hadron, it has a mass similar to that of the φ meson and (b) contrary to that of the φ meson, it has larger hadronic interaction cross sections.

Figure 3 (a) shows the $v_2$ of protons versus $p_T$ for 0-80% Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the AMPT model with parton-parton interaction cross section of 10 mb and three different values of hadronic cascade time of 0.6 fm/c (red solid circle), 15 fm/c (black open cross) and 30 fm/c (blue solid square). With increase in hadron cascade time, which reflects increasing contributions from hadronic interactions, the proton $v_2$ decreases at lower $p_T$. Implied is the development of the collective expansion in the hadronic period. This is more clearly illustrated in the panel (c) of the figure, which shows the ratio of the proton $v_2$ for the hadron cascade time of 0.6 fm/c to the corresponding $v_2$ values for time periods of 15 (open crosses) and 30 fm/c (solid squares) fm/c. Figure 3 (b) and (d) shows the corresponding results for φ mesons. In marked contrast to the case for protons, the φ meson $v_2$ remains unaffected by the hadronic interactions, indicating that $v_2$ is solely generated due to the partonic interactions in these model calculations.

Figure 4 shows the effect of hadron re-scattering on the mean values of the transverse momentum distributions for proton and φ meson. The average transverse momentum $<p_T>$ for protons increases as the hadronic cascade time increases, whereas as for φ mesons this change is much smaller. The results are shown for two different values of parton-parton cross section values of 3 and 10 mb. For both cases, the trends are identical, suggesting that the increase in value of $<p_T>$ with hadron cascade time is dominantly due to hadronic interactions. The magnitude of $<p_T>$ though is decided by both partonic and hadronic interactions taken together. Hence the $<p_T>$ for calculations with parton-parton cross section of 3 mb is lower compared to those with parton-parton cross section of 10 mb.

**IV. SUMMARY**

In summary, we have studied the generation of elliptic flow in AMPT model for φ mesons at midrapidity for 0-80% centrality Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The large value of $v_2$ for φ meson from the model which is comparable to the corresponding measurements at RHIC is due to the partonic interactions. Hadronic interactions as modelled in AMPT are unable to generate any $v_2$ for φ meson. Increasing the hadronic re-scattering by increasing the hadron cascade time period does not change the conclusions. In contrast to φ meson, the $v_2$ of protons decreases with increase in hadronic re-scattering effects at low transverse momentum. This effect is also seen in the average transverse momentum of protons which increases with increase in the time duration of the hadron cascade.

We have identified the multi-strange hadron φ meson as a clean tool for studying partonic interactions in high-energy nuclear collisions. Any significant change in φ meson collectivity will signal the possible change of in the nature of the medium formed in high energy heavy-ion collisions. Zero value of the $v_2$ for the φ meson would clearly indicate that the system formed in heavy-ion collisions did not make the de-confinement transition. Hence φ meson $v_2$ is an ideal probe for the search of the phase boundary in the QCD phase diagram.

In addition our study shows that proton $v_2$ at low $p_T$ decreases with increase in hadron cascade time. This reflects the effect of late stage hadronic re-scattering. Whereas for the φ meson the $v_2$ remains unaffected by late stage hadronic re-scattering process. In experiments it has been observed that at low $p_T$ a distinct mass ordering of $v_2$ is followed. Heavier
particles have smaller $v_2^{2\phi}$. If re-scattering is sufficiently large the proton $v_2(p_T)$ could be smaller than the corresponding $v_2(\phi)$ for the $\phi$ meson. The key fact being that the $v_2(\phi)$ remains unchanged with increase in hadronic re-scattering, while the $v_2(p)$ decreases at low $p_T$. This can then be considered to be a signature of hadronic re-scattering and can be probed using high event statistics data sets in the high energy heavy-ion collision experiments.

Acknowledgments

We thank Dr. Zi-Wei Lin for useful discussions on AMPT model results. BM is supported by the DST SwarnaJayanti project fellowship.

[1] S. Gupta, X. Luo, B. Mohanty, H. G. Ritter and N. Xu, Science 332 (2011) 1525 [arXiv:1105.3934 [hep-ph]].
[2] B. Mohanty, New J. Phys. 13 (2011) 065031 [arXiv:1102.2396 [nucl-ex]].
[3] I. Arsene et al. [BRAHMS Collaboration], Nucl. Phys. A 757 (2005) 1 [nucl-ex/0410020].
[4] B. B. Back, M. D. Baker, M. Ballintijn, D. S. Barton, B. Becker, R. R. Betts, A. A. Bickley and R. Bindel et al., Nucl. Phys. A 757 (2005) 28 [nucl-ex/0410022].
[5] J. Adams et al. [STAR Collaboration], Nucl. Phys. A 757 (2005) 102 [nucl-ex/0501009].
[6] K. Adcox et al. [PHENIX Collaboration], Nucl. Phys. A 757 (2005) 184 [nucl-ex/0410003].
[7] B. I. Abelev et al. [STAR Collaboration], STAR Internal Note - SN0493, 2009.
[8] B. Mohanty [STAR Collaboration], J. Phys. G 38 (2011) 124023 [arXiv:1106.5902 [nucl-ex]] and references there in.
[9] B. Mohanty and N. Xu, J. Phys. G 36 (2009) 064022 [arXiv:0901.0313 [nucl-ex]].
[10] B. I. Abelev et al. [STAR Collaboration], Phys. Rev. Lett. 99 (2007) 112301 [nucl-ex/0703033 [nucl-ex]].
[11] B. I. Abelev et al. [STAR Collaboration], Phys. Lett. B 673 (2009) 183 [arXiv:0810.4979 [nucl-ex]].
[12] H. van Hecke, H. Sorge and N. Xu, Phys. Rev. Lett. 81 (1998) 5764 [nucl-th/9804035].
[13] T. Hirano, U. W. Heinz, D. Kharzeev, R. Lacey and Y. Nara, Phys. Rev. C 77 (2008) 044909 [arXiv:0710.5795 [nucl-th]].
[14] Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang and S. Pal, Phys. Rev. C 72 (2005) 064901 [nucl-th/0411110].
[15] M. Gyulassy and X.-N. Wang, Comput. Phys. Commun. 83 (1994) 307 [nucl-th/9502021].
[16] B. Zhang, Comput. Phys. Commun. 109 (1998) 193 [nucl-th/9709009].
[17] Z.-w. Lin and C. M. Ko, Phys. Rev. C 65 (2002) 034904 [nucl-th/0108039].
[18] B.-A. Li and C. M. Ko, Phys. Rev. C 52 (1995) 2037 [nucl-th/9505016].
[19] S. A. Bass et al., Prog. Part. Nucl. Phys. 41 (1998); M. Bleicher et al., J. Phys. G 25 (1999).
[20] S. Voloshin and Y. Zhang, Z. Phys. C 70 (1996) 665 [hep-ph/9407282].
[21] D. Molnar and M. Gyulassy, Nucl. Phys. A 697 (2002) 495 [Erratum-ibid. A 703 (2002) 893] [nucl-th/0104073].
[22] B. Zhang, M. Gyulassy and C. M. Ko, Phys. Lett. B 455 (1999) 45 [nucl-th/9902016].
[23] H. Sorge, Phys. Rev. Lett. 82 (1999) 2048 [nucl-th/9812057].
[24] B. I. Abelev et al. [STAR Collaboration], Phys. Rev. C 77 (2008) 054901 [arXiv:0801.3460 [nucl-ex]].