Using the $\phi$-meson elliptic flow to map the strength of partonic interaction

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A compilation of recently measured STAR data for elliptic flow ($v_2$) of $\phi$ mesons in RHIC Beam Energy Scan program and comparison with a multiphase transport model (AMPT) has been presented. The experimental data at $\sqrt{s_{NN}} \geq 19.6$ GeV agrees well with string melting version of the AMPT model. The model includes partonic interactions and quark coalescence as a mechanism of hadronization. This indicates that there is a substantial contribution to collectivity from partonic interactions at $\sqrt{s_{NN}} \geq 19.6$ GeV. The measured $\phi$-meson $v_2$ at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV are found to be smaller than those obtained from AMPT model without partonic interactions. This indicates negligible contribution of partonic collectivity to the observed $\phi$-meson $v_2$ at $\sqrt{s_{NN}} \leq 11.5$ GeV.

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I. INTRODUCTION

One of the main goals of the high energy heavy-ion collision experiments is to study the various aspects of the QCD phase diagram [1]. With this purpose the Relativistic Heavy Ion Collider (RHIC) has finished the first phase of the Beam Energy Scan (BES) program [2-4]. The aim of the BES program was to look for changes in observation of various measurements as a function of beam energy to establish transition region between the partonic and/or hadronic dominant interactions in the QCD phase diagram [5].

The elliptic flow parameter $v_2$ is a good tool for studying the system formed in the early stages of high energy collisions at RHIC [6-11]. It describes the azimuthal momentum anisotropy of particle emission in heavy-ion collisions. It is defined as the second harmonic coefficient of the azimuthal Fourier decomposition of the momentum distribution with respect to the reaction plane angle ($\Psi$) and can be written as

$$v_2 = \langle \cos(2(\phi - \Psi)) \rangle,$$

where $\phi$ is emission azimuthal angle [11]. According to hydrodynamical description $v_2$ is an early time phenomenon and sensitive to the equation of state of the system formed in the collision [6-10, 12]. The results from Relativistic Heavy Ion Collider (RHIC) on $v_2$ as a function of transverse momentum ($p_T$) shows that at low $p_T$ elliptic flow of identified hadrons follows mass ordering (lower $v_2$ for heavier hadrons than that of lighter hadrons) whereas at intermediate $p_T$ all mesons and all baryons form two different groups. When $v_2$ and $p_T$ are scaled by number of constituent quarks of the hadrons, the measured $v_2$ values are consistent with each other as the parton coalescence or recombination models predicted [13-17]. This observation, is known as number of constituents quark scaling (NCQ scaling). This effect has been interpreted as collectivity being developed at the partonic stage of the evolution of the system in heavy-ion collision [10].

Although the parton coalescence or recombination model can successfully explain the observed quark scaling in experimental data but one can not say that only NCQ scaling of identified hadrons [10] is sufficient signature for the formation of de-confined matter. The study of NCQ scaling of identified hadrons from UrQMD model shows that the pure hadronic medium can also reproduced such scaling in $v_2$ [15-19]. This is due to modification of initially developed $v_2$ by later stage hadronic interactions [18]. So the $v_2$ of those particles which do not interact with hadronic interaction will be the clean and good probe for early dynamics in heavy-ion collisions. The $\phi$ meson, which is the bound state of $s$ and $\bar{s}$ quark, has small interaction cross-section with other hadrons [20] and freezes out early [1]. Due to small hadronic interaction cross-section, $\phi$-mesons $v_2$ are almost unaffected by later stage interaction and it will have negligible value if $\phi$ mesons are not produced via $s$ and $\bar{s}$ quark coalescence [21, 22]. Therefore, it is very important to study the $\phi$-meson $v_2$ in BES program at RHIC.

The paper is organized in the following way. In the section II, AMPT model has been briefly discussed. Section III describe the comparison of experimentally measured $\phi$-meson $v_2$ with the corresponding results from the AMPT model (version 1.11). Finally the summary and conclusion has been discussed in section IV.

II. THE AMPT MODEL

The AMPT model, which is a hybrid transport model, has four main stages: the initial conditions, partonic interactions, the conversion from the partonic to the hadronic matter, and hadronic interactions [23]. It uses the same initial conditions from HIJING [24]. Scattering among partons are
FIG. 1: (Color online) The $\phi$-meson $v_2(p_T)$ for Au+Au minimum-bias collisions at mid-rapidity ($|y| < 1.0$) from the STAR experiment at RHIC compared to the corresponding AMPT model calculation at various beam energies [3]. The errors shown are statistical.

modelled by Zhangs parton cascade [25], which calculates two-body parton scatterings using cross sections from pQCD with screening masses. In the default AMPT model, partons are recombined with their parent strings and when they stop interacting, the resulting strings fragment into hadrons according to the Lund string fragmentation model [26]. However in the string melting scenario (labeled as AMPT-SM), these strings are converted to soft partons and 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. The interactions between the minijet partons in the AMPT Default model and those between partons in the AMPT-SM could give rise to substantial $v_2$. Therefore, agreement between the data and the results from AMPT-SM would indicate the contribution of partonic interactions to the measured $v_2$. The parton-parton interaction cross section in the string-melting version of the AMPT is taken to be 3mb and 10 mb. In this study, approximately 1.5 million events for each configuration were generated for minimum-bias Au+Au collisions.

III. RESULTS AND DISCUSSION

In this section, the $\phi$-meson $v_2$ measured by STAR experiment at mid-rapidity ($|y| < 1.0$) for $\sqrt{s_{NN}} = 7.7 - 200$ GeV [3, 4] has been compared with AMPT model. $\phi$ mesons are identified from the $K^+$ and $K^-$ decay channel, the same method as used in experimental analysis.

A. Differential $v_2$

Figure 1 shows the comparison of elliptic flow of $\phi$ mesons in 0-80% minimum-bias Au+Au collisions at mid-rapidity ($|y| < 1.0$) for $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39$ and 62.4 GeV with the corresponding results from the AMPT model [2, 4]. The measured data points are compared with both AMPT String Melting (3 mb and 10 mb parton-parton cross-section) and AMPT Default version. At $\sqrt{s_{NN}} = 62.4$ GeV experimental data are in a good agreement with AMPT String Melting model with 10 mb parton-parton cross-section. This is also true for $\sqrt{s_{NN}} = 200$ GeV as reported in Ref. [21]. The measured $\phi$ $v_2$, for $p_T < 1.5$ GeV/c, lie between 3 mb and 10 mb for the energy range $19.6 \leq \sqrt{s_{NN}} \leq 39$ GeV, but in order to explain the measurements for $p_T > 1.5$ GeV/c, a parton-parton cross-section of the order of 10 mb is required. None of the above model can explain the trend of $\phi$-mesons $v_2$ at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV where the event statistics for data is also small. As we expect that the $\phi$-meson $v_2$ mostly reflect the collectivity from the partonic phase, therefore from the comparison of experimental data with AMPT model one can conclude that the partonic collectivity has been developed for $\sqrt{s_{NN}} \geq 19.6$ GeV at RHIC. Whereas the contribution from the partonic collectivity to the final collectivity seems negligible at $\sqrt{s_{NN}} \leq 11.5$ GeV.
B. $p_T$ Integrated Elliptic Flow ($\langle v_2 \rangle$)

The $p_T$ integrated elliptic flow $\langle v_2 \rangle$, which is also an interesting observable, can be defined as:

$$\langle v_2 \rangle = \frac{\int v_2(p_T) dN/dp_T dp_T}{\int dN/dp_T dp_T}.$$

(2)

i.e. the $\langle v_2 \rangle$ folds the measured $v_2$ versus $p_T$ with the $p_T$ distribution ($dN/dp_T$) of that particle. The $p_T$-averaged $v_2$ may have a better statistical precision than the $p_T$ differential measurements. To calculate the $\langle v_2 \rangle$ of $\phi$ mesons, each $v_2(p_T)$ distribution was fitted with function (shown in Fig. 2): a $3^{rd}$ order polynomial function and a function of the form

$$f_{\nu_2}(n) = \frac{an}{1 + \exp[-(p_T/n - b)/c]} - dn,$$

(3)

where $a$, $b$, $c$ and $d$ are free parameters and $n$ is the number of constituent quarks. This function was inspired by parameterizations of quark number scaling [27]. The $p_T$ distribution of $\phi$ mesons has been fitted with Levy function as shown in panel (b) of Fig. 2. The functional form of Levy function is given by

$$f_{Levy}(p_T) = \frac{dN}{dp_T} \times \frac{(n-1)(n-2)}{(nT + m_0(n-2))} \times (1 + \frac{\sqrt{p_T^2 + m_0^2} - m_0}{nT})^{-n},$$

(4)

where $T$ is known as the inverse slope parameter, $dN/dy$ is the $\phi$-meson yield per unit rapidity, $m_0$ is the rest mass of $\phi$ meson and $n$ is the Levy function parameter. The $\langle v_2 \rangle$ for each choice of $v_2(p_T)$ parameterization is given by the integral of the corresponding distributions normalized by integral of the $p_T$ distribution. In addition, the $\langle v_2 \rangle$ has been calculated directly from measured data points of $v_2(p_T)$ with corresponding yield obtained from the fit function to the $p_T$ distribution. The final $\langle v_2 \rangle$ was obtained by calculating the mean of the three $\langle v_2 \rangle$ results and the systematic error was estimated from maximum deviation from the mean value. There are two sources for the statistical error, one is error on $p_T$ distribution and other is error on $v_2(p_T)$. Since the error on $dN/dp_T$ is very small compared to that on $v_2(p_T)$, one can simply neglect the error of $dN/dp_T$. Hence, only errors on $v_2(p_T)$ are taken care for calculation of final statistical error on $\langle v_2 \rangle$.

The errors on $v_2$ are parameterized as a function of $p_T$ and extrapolated to low and high $p_T$ as shown in panel (c) of Fig. 2. Figure 2 is repeated for all the energies studied. For $\langle v_2 \rangle$ calculation in data, the final $\phi$ mesons spectra and $v_2(p_T)$ at 62.4 and 200 GeV published by STAR has been used [28]. For the other energies, the STAR preliminary spectra [29] and final $v_2(p_T)$ [3] has been used.

![Fig. 2](image_url)

**Fig. 2:** (Color online) Panel (a): The $\phi$-meson $v_2(p_T)$ at $\sqrt{s_{NN}}=39$ GeV for 0-80% centrality bin is fitted with $3^{rd}$ order polynomial (Poly. 3) and with function described in Eq. 3. Panel (b): The preliminary $\phi$-meson $dN/dp_T$ vs $p_T$ at $\sqrt{s_{NN}}=39$ GeV for 0-80% centrality bin is fitted with levy function. Panel (c): Statistical error on $v_2(p_T)$ at $\sqrt{s_{NN}}=39$ GeV for 0-80% centrality bin is fitted with $3^{rd}$ order polynomial.
The $p_T$ integrated $\phi$-meson $v_2$ for Au+Au minimum-bias collisions at mid-rapidity ($|y|<1.0$) are compared to the corresponding AMPT model calculation at various beam energies in Fig. 3. In contrast to observations from the data, the $\langle v_2 \rangle$ values from model remain constant for all the energies for a given parton-parton interaction cross-section. The $\langle v_2 \rangle$ of $\phi$ mesons for $\sqrt{s_{NN}} \geq 19.6$ can be explained by the AMPT with string melting depending on parton-parton cross-section. The AMPT-SM model with 10mb parton-parton cross-section explain the data very well at $\sqrt{s_{NN}} = 62.4$ and 200 GeV, where as 3mb parton-parton cross-section is sufficient to describe the data at $\sqrt{s_{NN}} = 19.6$, 27 and 39 GeV. On the other hand, both the AMPT-SM and AMPT Default model over predict data at $\sqrt{s_{NN}} = 11.5$ GeV, indicating negligible contribution of the partonic collectivity to the final collectivity. Due to very small statistics at $\sqrt{s_{NN}} = 7.7$ GeV, $\langle v_2 \rangle$ are not shown here. The observation that different parton-parton cross sections are needed to explain the data within the transport model framework indicates that the $\eta/s$ changes with beam energy. Higher the cross section, smaller is the $\eta/s$ expected for the system. This qualitative observation in variation of the value of $\eta/s$ with beam energy is consistent with the expectations from various calculations as reported in [30].

From the Fig. 3, one can conclude that as the energy decrease contribution to the collectivity from the partonic phase also decreases and for $\sqrt{s_{NN}} \leq 11.5$ GeV, the hadronic interaction plays a dominant role in experimentally observed data.

**IV. SUMMARY AND CONCLUSION**

In summary, a compilation of the available data for elliptic flow of $\phi$ mesons has been presented. The implications of these results on the quark-hadron phase transition has been discussed by comparing experimental data with AMPT model. The AMPT model with string melting scenario quantitively explain the data at $\sqrt{s_{NN}} \geq 19.6$ GeV by varying parton-parton interaction cross-section from 3mb to 10mb. The AMPT Default model under predict that experimental data for $\sqrt{s_{NN}} \geq 19.6$ GeV. This tells that there is a substantial contribution of partonic collectivity to the final collectivity for $\sqrt{s_{NN}} \geq 19.6$ GeV. However, both the AMPT-SM and AMPT Default can not explain the trend of $\phi$-meson $v_2$ as function of $p_T$ at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV. Also the $\langle v_2 \rangle$ from AMPT default over-predicts the data at $\sqrt{s_{NN}} = 11.5$ GeV. This indicates that possible turn off of partonic interaction starts at $\sqrt{s_{NN}} \leq 11.5$ GeV. Due to large statistical error on $\phi$ $v_2$ at $\sqrt{s_{NN}} = 7.7$ GeV, it is not possible to make any conclusions. The comparison of the experimental data on the beam energy dependence of the average elliptic flow of $\phi$ meson with the corresponding results from a transport model calculation with varying parton-parton cross section suggests that the partonic contribution to the collectivity decreases and possibly the value of the $\eta/s$ of the system increases as the beam energy decreases. The $\phi$-meson $v_2$ measurement should be one of the main focuses in the proposed BES phase II program and also in FAIR experiment at GSI to explore the phase diagram further.

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