Understanding pseudorapidity dependence of elliptic flow in heavy-ion collisions using a transport model

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A systematic study of the pseudorapidity dependence of elliptic flow parameter using transport models (e.g., a multiphase transport model, AMPT, and ultrarelativistic quantum molecular dynamics, UrQMD) has been presented. We have observed that while at mid-pseudorapidity the elliptic flow measured using the event-plane method differs significantly from that measured by actual reaction plane method, both the event-plane and reaction-plane methods give the same elliptic flow for far forward and backward pseudorapidity. This indicates that the magnitude of measured v_2 around midrapidity strongly depends on the analysis method. Therefore, one should use the same procedure (as used in data analysis) in model calculations while comparing model results and experimental data. We find the shape of $v_2(\eta)$ measured by the PHOBOS experiment is not reproduced by using actual v_2 (i.e., measured with respect to the reaction plane) from AMPT and UrQMD models. The shape and magnitude of measured $v_2(\eta)$ can be explained by the AMPT model with string-melting mode only if one uses the same procedure as used in data analysis. Magnitude of elliptic flow can be reproduced for all pseudorapidity range by taking the parton-parton interaction cross section to be 3 mb at $\sqrt{s_{NN}} = 62.4$ and 200 GeV. This implies that the partonic interactions are necessary to reproduce data at $\sqrt{s_{NN}} = 62.4$ and 200 GeV and the strength of partonic interactions at far forward and backward rapidity is as strong as at midrapidity. Both UrQMD and AMPT with default mode fail to explain the data.

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I. INTRODUCTION

One of the fundamental questions is what happens when two heavy nuclei collide with each other at extremely high temperatures and densities. The Relativistic Heavy-Ion Collider (RHIC) at the Brookhaven National Laboratory started colliding heavy ions in 2000, when two oppositely moving Au nuclei were allowed to collide at maximum center-of-mass energy $\sqrt{s_{NN}} = 200$ GeV. The elliptic flow parameter v_2 has been considered as a good tool for studying the system formed in the early stages of high-energy collisions at RHIC. Elliptic flow is believed to arise out of the pressure gradient developed when two nuclei collide at nonzero impact parameter followed by subsequent interactions among the constituents [1–5]. Within a hydrodynamical framework, v_2 has been shown to be sensitive to the equation of state of the system formed in these collisions. It describes the azimuthal momentum anisotropy of produced particles 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 (Ψ_r) and can be written as

$$v_2 = \langle \cos[2(\phi - \Psi_r)] \rangle, \tag{1}$$

where ϕ is emission azimuthal angle [6]. The reaction plane angle Ψ_r is the angle subtended by the plane formed by impact parameter and beam (z) axis with respect to the x axis. True orientation of the reaction plane angle is unknown in an experiment, as one cannot measure the impact parameter between two colliding nuclei. However, one can estimate the reaction plane by measuring the positions of the spectator nucleons in noncentral collisions. The most commonly used method to estimate the reaction plane is the use of anisotropic flow itself [6]. The estimated reaction-plane angle is known as event-plane angle (Ψ). The nth harmonic event plane angle can be calculated as

$$\Psi_n = \frac{1}{n} \tan^{-1} \frac{\sum_i^N w_i \sin(n\phi_i)}{\sum_i^N w_i \cos(n\phi_i)}, \tag{2}$$

where N is the total number of particles in an event used for the event-plane calculation. The weights (w_i) are chosen so as to maximize event-plane resolution. After measuring v_2 with respect to the event plane, one needs to correct for event-plane resolution.

Over the past decades, v_2 has been measured widely in heavy-ion experiments. Many interesting phenomena have been observed by looking at measured v_2 as a function of transverse momentum (p_T), pseudorapidity (η), and centrality. The PHOBOS experiment at RHIC has studied η dependence of v_2 [7], directed flow (v_1) [7], multiplicity ($dN/d\eta$) [8], etc., extensively. The shape of η dependence of v_1 and ($dN/d\eta$) has been well explained and understood by theoretical studies [9–15]. However, the η dependence of v_2 has not been completely understood [9–11,14,16]. In this paper, we have systematically studied the η dependence of v_2 using transport models, namely a multiphase transport model (AMPT) and ultrarelativistic quantum molecular dynamics (UrQMD).

The paper is organized in the following way. In Sec. II, transport models used are briefly discussed. Section III describes our model calculation using reaction-plane and event-plane methods. Comparisons between model and data at $\sqrt{s_{NN}} = 62.4$ and 200 GeV are also presented in Sec. III. Finally, we summarize in Sec. IV.

II. MODEL DESCRIPTION

Various observables are compared to theoretical calculations to understand the physical mechanism behind the measurements. Some of the frequently used models in heavy-ion collisions are the UrQMD model [17] and AMPT [18]. The UrQMD model is based on a microscopic transport theory where the phase space description of the reactions and hadron-hadron interactions are important. It includes all hadrons with masses up to 2.2 GeV. In this model, hadron-hadron collisions are performed stochastically, in a way similar to the original cascade model. Particle production in UrQMD model either takes place via the decay of a resonance or via string excitation and fragmentation. It incorporates baryon-baryon, meson-baryon, and meson-meson interactions. The collisional term includes more than 50 baryon species and 45 meson species.

The AMPT model is a hybrid transport model [18]. It uses the initial conditions from Heavy Ion Jet INteraction Generator [19]. The AMPT model can be studied in two configurations, in the AMPT default version (labeled as AMPT-Def) in which the minijet partons are made to undergo scattering before they are allowed to fragment into hadrons [20], and in the AMPT string melting scenario (labeled as AMPT-SM) where additional scattering occurs among the quarks and hadronization occurs through the mechanism of parton coalescence. Scattering among partons are modeled by Zhang's parton cascade [21], which calculates two-body parton scattering using cross sections from pQCD with screening masses. The parton-parton interaction cross sections (σ_{PP}) in the string-melting version of the AMPT are taken to be 3 and 10 mb. In this study, approximately 100 000 events are generated for minimum-bias Au+Au collisions.

III. RESULTS AND DISCUSSION

The measurement of elliptic flow over a full-rapidity region is considered to be interesting as it gives information of early dynamics over full rapidity region. Figure 1 shows p_T integrated charged hadrons v_2 ($\langle v_2 \rangle$) as function of η measured by PHOBOS experiment in Au+Au collision at $\sqrt{s_{NN}} = 19.6$, 62.4, and 200 GeV. The measurements are for 0-40% collisions centrality. The magnitude of v_2 falls very quickly from mid-pseudorapidity to forward and backward pseudorapidity. This is quite unlike the distribution of $dN/d\eta$ [8]. The shape of

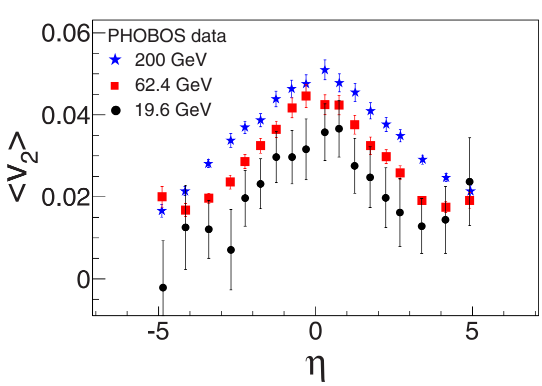

FIG. 1. v_2 of charged hadrons as a function of η in 0-40% Au+Au collisions at $\sqrt{s_{NN}} = 19.6$, 62.4, and 200 GeV measured by PHOBOS experiment [7]. Only statistical errors are shown.

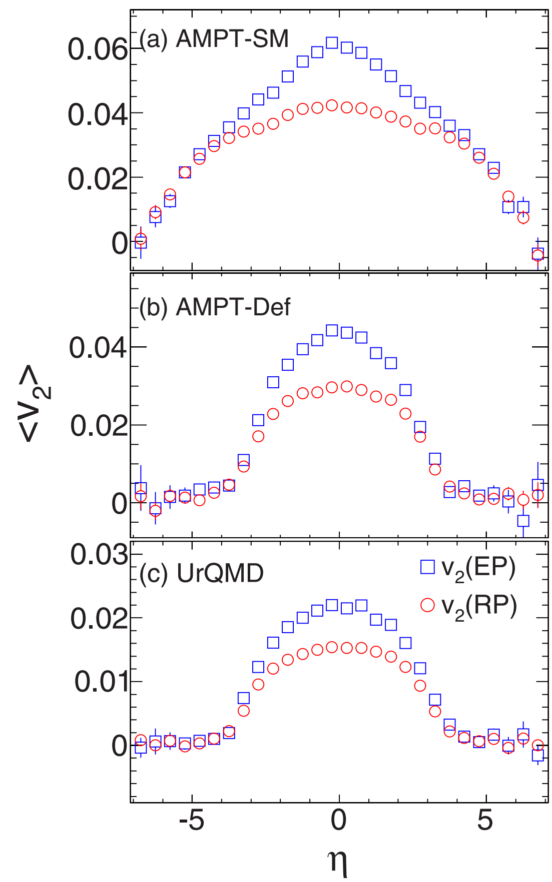

FIG. 2. p_T-integrated v_2 of charged hadrons as a function of η in 0-40% Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from (a) AMPT-SM, (b) AMPT-Def, and (c) UrQMD models.

$v_2(\eta)$ is not described by using a hydrodynamic model [9]. Also, a previous study [16] shows that the transport models (like AMPT and UrQMD) fail to explain the shape of $v_2(\eta)$ distribution. It is worth mentioning that the model results presented in Ref. [16] were calculated using the reaction-plane method, which gives the true average v_2. In this paper, we have calculated v_2 using both reaction-plane and event-plane methods.

Figure 2 shows $\langle v_2 \rangle$ as a function of η in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from AMPT and UrQMD models. Open red circles and open blue squares denote v_2 measurements using the reaction-plane (RP) method, which is known in model, and event-plane (EP) method, respectively. In the event-plane method, we have used the same procedure as used in data analysis [7]. Measured v_2 at mid-pseudorapidity differs significantly between reaction-plane and event-plane methods, whereas at very large pseudorapidity, both the methods give similar results for all the models. The observed difference at mid-pseudorapidity can be due to nonflow and flow fluctuations as the experimental data in Fig. 16 of Ref. [22] show that the 2-particle and 4-particle cumulant methods give the same v_2 at forward and backward pseudorapidity but differ at mid-pseudorapidity. We have also checked (not shown here) that AMPT-Def and UrQMD models cannot reproduce the shape and magnitude of data for both reaction-plane

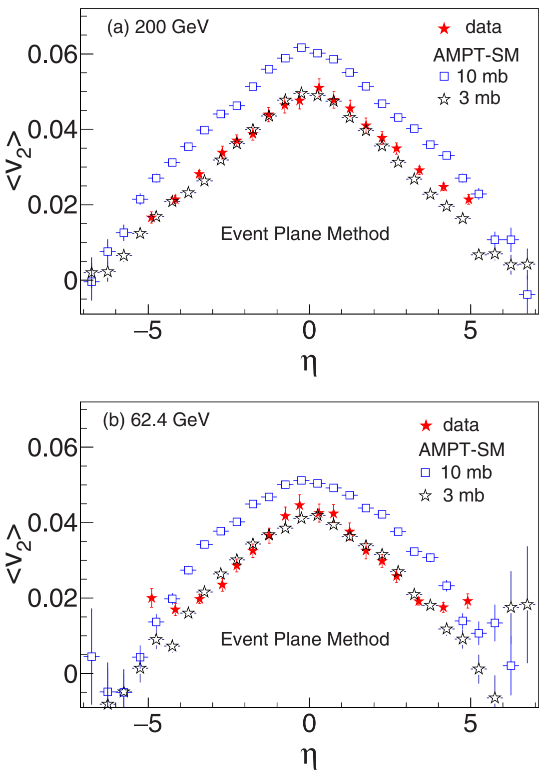

FIG. 3. p_T-integrated v_2 of charged hadrons as a function of η in 0-40% Au+Au collisions at $\sqrt{s_{NN}} = 200$ (a) and 62.4 GeV (b). Only statistical errors on data are shown [7].

and event-plane methods. Only the AMPT-SM model can reproduce the shape of the $\langle v_2 \rangle$ as a function of η if one uses the same measurement method as used in the experiment.

After observing that AMPT-SM model can explain the shape of $\langle v_2 \rangle$ as a function of η, we have compared the magnitude of $\langle v_2 \rangle$ between experimental data [7] and the AMPT-SM model. The comparison between data and AMPT-SM model for $\sqrt{s_{NN}} = 200$ and 62.4 GeV is shown in Fig. 3. Errors on data at $\sqrt{s_{NN}}$ =19.6 GeV are very large, and hence are not discussed in this section. The solid red stars indicates data whereas open black stars and open blue squares denote AMPT-SM model results using the EP method with parton-parton interaction cross sections equal to 3 and 10 mb respectively. In the AMPT-SM model, parton-parton interaction cross section is responsible for generating finite v_2. Comparison between data and AMPT-SM with various values of parton-parton interaction cross sections can give an estimate of the strength of partonic interaction in data. From Fig. 3, we can see that the model calculations with 3-mb parton-parton interaction cross section explain the data very well for all rapidity regions at $\sqrt{s_{NN}} = 200$ and 62.4 GeV. It is generally believed that perturbative QCD cross section is about 3 mb [23] and our result is consistent. Model calculations with 10-mb parton-parton interaction cross section overpredict the data. If we use the RP method, then AMPT-SM model with the 10-mb parton-parton interaction cross section describes data at midrapidity but fails to explain data at higher rapidity as reported in our earlier work [16]. The RP method gives true average v_2 from model, whereas the event-plane method gives v_2, which can be any value between average and root mean square of v_2 distribution depending on event-plane resolution, nonflow, and flow fluctuation. Therefore, the measured v_2 using the EP method by PHOBOS experiment is not an average v_2. Hence one should use the EP method while comparing data and model.

IV. SUMMARY AND CONCLUSION

In summary, we have presented a transport-model-based systematic study of elliptic flow as function of pseudorapidity. There are significant differences in the magnitude of $\langle v_2 \rangle$ at mid-pseudorapidity when it is measured with respect to the known reaction plane and calculated event plane using produced particles. However, both reaction-plane and event-plane methods give the same $\langle v_2 \rangle$ for very large η. The observed difference is independent of model and can be due to nonflow effect and flow fluctuations. The AMPT-SM model, which includes partonic effects and quark coalescence as a mechanism of hadronization, can explain data for the full pseudorapidity range if we use the same method (EP) as used in data analysis in the experiments. Therefore, one should always be careful while comparing experimental data with theoretical model calculation. We have observed that AMPT-SM with parton-parton interaction cross section of 3 mb can explain the magnitude of measured v_2 over all pseudorapidity range for $\sqrt{s_{NN}} = 200$ and 62.4 GeV. This indicates formation of partonic matter at $\sqrt{s_{NN}} = 200$ and 62.4 GeV as claimed before and also shows that the interaction strength of partonic matter extends far away from midrapidity. The AMPT with default mode and UrQMD model cannot explain the data. They cannot even explain the shape of $\langle v_2 \rangle$ as a function of η.

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