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

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Understanding pseudo-rapidity dependence of elliptic flow in heavy-ion collision using transport model

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A systematic study of the pseudo-rapidity dependence of elliptic flow parameter using transport model (e.g. AMPT and UrQMD) has been presented. We have observed that while at mid pseudo-rapidity, elliptic flow measured using event plane method differ significantly from that measured by actual reaction plane method, both the event plane and reaction plane method gives the same elliptic flow for far forward and backward pseudo-rapidity. This indicates that the magnitude of measured v_2 around mid-rapidity strongly depends on 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 PHOBOS experiment is not reproduced by using actual v_2 (i.e. measured with respect to reaction plane) from AMPT and UrQMD model. The shape and magnitude of measured $v_2(\eta)$ can be explained by AMPT model with string-melting mode only if one use same procedure as used in data analysis. Magnitude of elliptic flow can be reproduced for all pseudo-rapidity range by taking 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 mid-rapidity. 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) collider at the Brookhaven National Laboratory started colliding heavy ions in the years of 2000 where two oppositely moving Au nuclei are 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

$$v_2 = \langle \cos(2(\phi - \Psi_r)) \rangle, \qquad (1)$$

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 reaction plane angle is unknown in an experiment, as one cannot measure the impact parameter between two colliding nuclei. However one can estimate reaction plane by measuring the positions of the spectators nucleons in non-central collisions. 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 n^{th} harmonic event plane angle can be calculated as

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

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 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), pseudo-rapidity (η) and centrality. The PHOBOS experiment at RHIC has studied η dependence of v_2 [7], directed flow (v_1) [8], multiplicity ($dN/d\eta$) [9], etc. extensively. The shape of η dependence of v_1 and ($dN/d\eta$) has been well explained and understood by theoretical studies [10–12, 14–17]. However, the η dependence of v_2 has not been completely understood [10–13, 16]. In this paper, we have systematically studied the η dependence of v_2 using transport models, namely AMPT and UrQMD.

The paper is organized in the following way. In section II, transport models used have been briefly discussed. Section III describes our model calculation using reaction plane and event plane method. Comparisons between model and data at $\sqrt{s_{NN}}$ = 62.4 and 200 GeV is also presented in section III. Finally, we summarize in section 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 Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model [18] and A Multiphase Transport model (AMPT) [19]. 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 [19]. It uses the initial conditions from HIJING [20]. 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 [21], 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 [22], which calculates two-body parton scattering using cross sections from pQCD with screening masses. The parton-parton interaction cross section (σ_{PP}) in the string-melting version of the AMPT is taken to be 3 mb and 10 mb. In this study, approximately 100K 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. Fig. 1 shows p_T integrated charged hadrons v_2 ($< v_2 >$) 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 pseudo-rapidity to forward and backward pseudo-rapidity. This is quite unlike the distribution of $dN/d\eta$ [9]. The shape of $v_2(\eta)$ is not described by using a hydrodynamic model [10]. Also, previous study [13] shows that the transport models (like AMPT and UrQMD) fail to explain the shape of $v_2(\eta)$ distribution. It is worth to mention that the model results presented in Ref [13] were calculated using 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 method.

Fig. 2 shows $< v_2 >$ as a function of η in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV from AMPT and UrQMD model. Open red circle and open blue square denote v_2 measurements using reaction plane (RP), which is known in model, and event plane event (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 pseudo-rapidity differs significantly between reaction plane and event plane method, whereas at very large pseudo-rapidity, both the methods give similar results for all the models. The observed difference at mid pseudo-rapidity can be due to non-flow and flow fluctuations as the experimental data in Fig. 16 of ref [23] shows that the 2-particle and 4-particle cumulant method gives same v_2 at forward and backward pseudo-rapidity but differ at mid pseudo-rapidity. We have also checked (not shown here) that AMPT-Def and UrQMD cannot reproduce the shape and magnitude of data for both reaction plane and event plane method. Only AMPT-SM model can reproduce the shape of the $< v_2 >$ as a function of η if one uses the same measurement

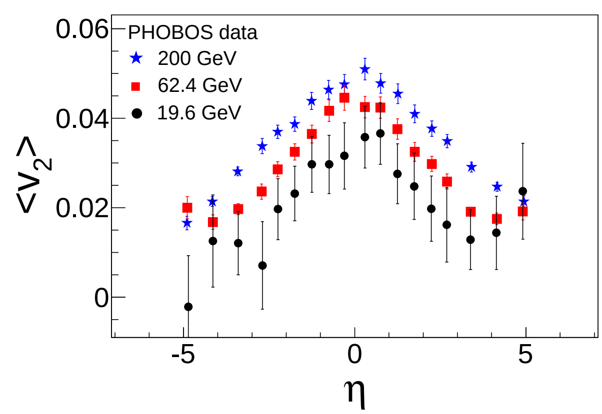

FIG. 1: (Color online) v_2 of charged hadrons as a function of η in 0-40% Au+Au collisions at $\sqrt{s_{NN}}$ = 19.6, 62.4 and 200 GeV measured by PHOBOS experiment [7]. Only statistical errors are shown.

method as used in experiment.

After observing that AMPT-SM model can explain

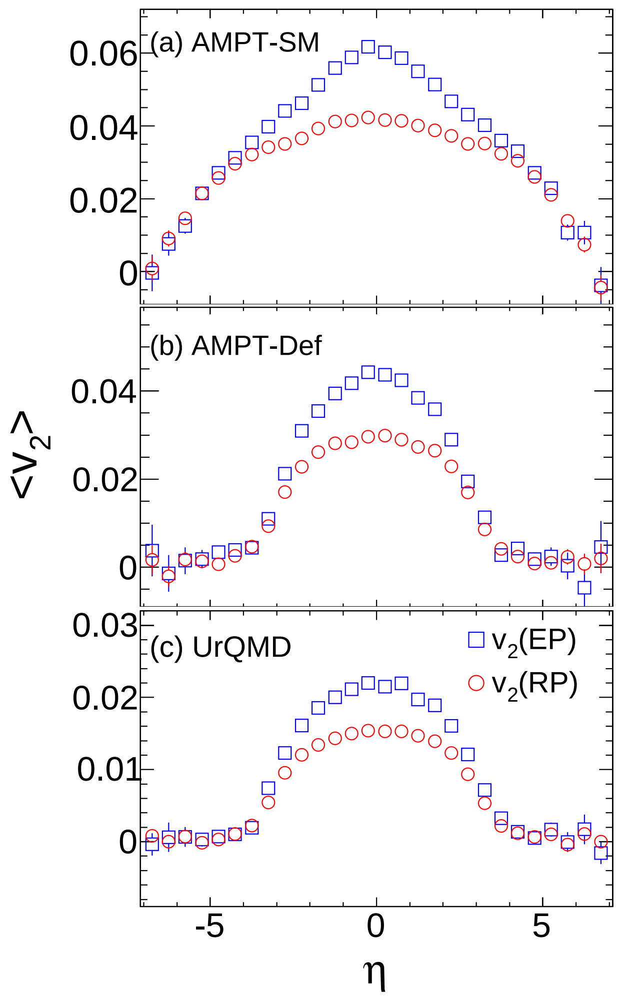

FIG. 2: (Color online) p_T-integrated v_2 of charged hadrons as a function of η in 0-40% Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV from (a) AMPT-SM, (b) AMPT-Def and (c) UrQMD model.

the shape of $< v_2 >$ as a function of η, we have compared the magnitude of $< v_2 >$ between experimental data [7] and AMPT-SM model. The comparison between data and AMPT-SM model for $\sqrt{s_{NN}}$ = 200 GeV and 62.4 GeV is shown in Fig. 3. Errors on data at $\sqrt{s_{NN}}$ =19.6 GeV are very large, hence not discussed in this section. The solid red star indicates data whereas open black star and open blue square denotes AMPT-SM model results using EP method with parton-parton interaction cross-section equal to 3 mb and 10 mb respectively. In AMPT-SM model, parton-parton interaction cross-section is responsible for generating finite v_2. Comparison

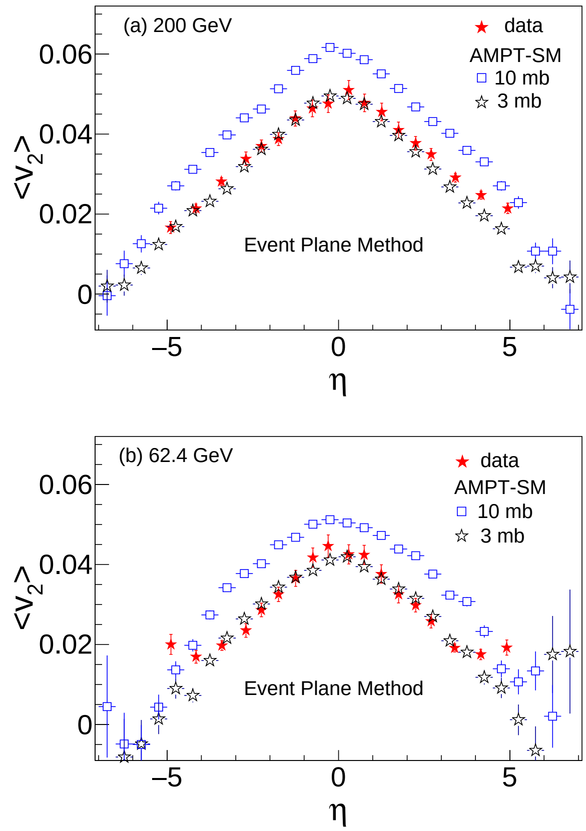

FIG. 3: (Color online) p_T-integrated v_2 of charged hadrons as a function of η in 0-40% Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV (a) and 62.4 GeV (b). Only statistical errors on data are shown [7].

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 explains the data very well for all rapidity region at $\sqrt{s_{NN}}$ = 200 GeV and 62.4 GeV. It is generally believed that perturbative QCD cross section is about 3 mb [24] and our result is consistent. Model calculations with 10 mb parton-parton interaction cross-section over-predict the data. If we use RP method, then AMPT-SM model with 10 mb parton-parton interaction cross-section describe data at mid-rapidity but fails to explain data at higher rapidity as reported in our earlier work [13]. 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, non-flow and flow fluctuation [37]. Therefore, the measured v_2 using EP method by PHOBOS experiment is not an average v_2. Hence one should use 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 pseudo-rapidity. There are significant differences in the magnitude of $< v_2 >$ at mid pseudo-rapidity when it is measured with respect to the known reaction plane and calculated event plane using produced particle. However, both reaction plane and event plane methods gives the same $< v_2 >$ for very large η. The observed difference is independent of model and can be due to non-flow effect and flow fluctuations. AMPT-SM model, which includes partonic effects and quark coalescence as a mechanism of hadronization, can explain data for full pseudo-rapidity range if we use the same method (EP) as used in data analysis in 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 pseudo-rapidity range for $\sqrt{s_{NN}} = 200$ GeV and 62.4 GeV. This indicates formation of partonic matter at $\sqrt{s_{NN}} = 200$ GeV and 62.4 GeV as claimed before and also shows that the interaction strength of partonic matter extends far away from mid-rapidity. The AMPT with default mode and UrQMD model can not explain the data. They can even not explain the shape of $< v_2 >$ as a function of η.

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