Anisotropic flow of Pb+Pb $\sqrt{s_{\rm NN}}$ = 5.02 TeV from a multi-phase transport model*

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Abstract: Anisotropic flow is an important observable in the study of the quark-gluon plasma that is expected to be formed in heavy-ion collisions. With a multiphase transport (AMPT) model we investigate the elliptic (v_2), triangular (v_3), and quadrangular (v_4) flow of charged particles in Pb+Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. We then compare our flow results with the published ALICE flow results. We find our AMPT simulated results are consistent with ALICE experimental data.

Keywords: azimuthal anisotropy, anisotropic flow, ALICE Pb+Pb 5.02 TeV, AMPT

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1 Introduction

Ultrarelativistic heavy-ion collisions enable the study of matter at high temperature and pressure, where quantum chromodynamics predicts the existence of the quark-gluon plasma (QGP) [1]. Anisotropic flow, which is caused by initial asymmetries in the geometry of a system produced in a non-central collision, provides experimental information about the equation of state and the transport properties of the created QGP [2]. Since the transition from normal nuclear matter to the QGP state is expected to occur at extreme values of energy density, elliptic flow has been intensively investigated in some large heavy-ion experimental accelerators like the Alternating Gradient Synchrotron (AGS) [3], Relativistic Heavy-Ion Collider (RHIC) [4–6], and Large Hadron Collider (LHC) [7–10], which has recently injected Pb+Pb $\sqrt{s_{\rm NN}}$=5.02 TeV beam energy. From previous studies, azimuthal anisotropy of particle production have contributed significantly to the characterization of the system created in heavy-ion collisions because it is sensitive to the properties of the system at an early time of its evolution. We compare the AMPT model simulation results with string melting mechanism with the ALICE published data, and try to investigate the azimuthal distribution of particle production for different dependencies at LHC energy.

Anisotropic flow is characterized by coefficients in the Fourier expansion of the azimuthal dependence of the invariant yield of particles relative to the reaction plane [11, 12]:

$$E\frac{{\rm d}^3N}{{\rm d}^3p}=\frac{{\rm d}^2N}{2\pi p_{\rm T}{\rm d}p_{\rm T}{\rm d}y}\left\{1+\sum_{n=1}^{\infty}2v_n\cos\left[n(\phi-\Psi_{\rm R})\right]\right\}. \quad (1)$$

Here $v_n=\langle\cos\left[n\left(\phi-\Psi_{\rm R}\right)\right]\rangle$ are coefficients to quantify anisotropic flow. The first coefficient, v_1, is usually called directed flow, and the second coefficient, v_2, is called elliptic flow. In this analysis, we use the Q-cumulant method to obtain the anisotropic flow coefficients. Multi-particle correlations can be expressed in terms of the flow vector Q_n:

$$Q_n\equiv\sum_{i=1}^{M}{\rm e}^{{\rm i}n\phi_i}, \quad (2)$$

where M is the number of particles. Then 2-particle and 4-particle azimuthal correlations in one event can be expressed as [13, 14]:

$$\langle 2\rangle=\frac{|Q_n|^2-M}{M\left(M-1\right)}, \quad (3)$$

$$\langle 4\rangle=\frac{|Q_n|^4+|Q_{2n}|^2-2\cdot{\rm Re}\left[Q_{2n}Q_n^*Q_n^*\right]}{M\left(M-1\right)\left(M-2\right)\left(M-3\right)}$$
$$-2\frac{2\left(M-2\right)\cdot|Q_n|^2-M\left(M-3\right)}{M\left(M-1\right)\left(M-2\right)\left(M-3\right)}. \quad (4)$$

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For detectors with uniform acceptance, the 2nd order cumulant and 4th order cumulant are obtained with:

$$c_n\{2\}=\langle\langle 2\rangle\rangle, \tag{5}$$

$$c_n\{4\}=\langle\langle 4\rangle\rangle-2\cdot\langle\langle 2\rangle\rangle^2. \tag{6}$$

Reference flows v_n estimated from the 2nd order cumulant and 4th order cumulant are:

$$v_n\{2\}=\sqrt{c_n\{2\}}, \tag{7}$$

$$v_n\{4\}=\sqrt[4]{-c_n\{4\}}. \tag{8}$$

For a differential cumulant, we use the p-vector and q-vector derived from Eq.(2):

$$p_n=\sum_{i=1}^{m_\mathrm{p}}\mathrm{e}^{\mathrm{i}n\phi_i} \tag{9}$$

$$q_n=\sum_{i=1}^{m_\mathrm{q}}\mathrm{e}^{\mathrm{i}n\phi_i} \tag{10}$$

Here m_p is the total number of particles labeled as POIs (Particle Of Interest), and m_q is the total number of particles tagged both as RFP (Reference Particle) and POI. The single-event average differential cumulant goes to:

$$\langle 2'\rangle=\frac{p_nQ_n^*-m_\mathrm{q}}{m_\mathrm{p}M-m_\mathrm{q}}, \tag{11}$$

$$\langle 4'\rangle=\begin{bmatrix} p_nQ_nQ_n^*Q_n^*-q_{2n}Q_n^*Q_n^*-p_nQ_nQ_{2n}^*-2\cdot Mp_nQ_n^* \\ -2\cdot m_\mathrm{q}|Q_n|^2+7\cdot q_nQ_n^*-Q_nq_n^*+q_{2n}Q_{2n}^* \\ +2\cdot p_nQ_n^*+2\cdot m_qM-6\cdot m_\mathrm{q} \end{bmatrix} \\ /\left[(m_\mathrm{p}M-3m_\mathrm{q})(M-1)(M-2)\right]. \tag{12}$$

For detectors with uniform azimuthal acceptance the differential 2nd order cumulant and 4th order cumulant are given by:

$$d_n\{2\}=\langle\langle 2'\rangle\rangle, \tag{13}$$

$$d_n\{4\}=\langle\langle 4'\rangle\rangle-2\langle\langle 2'\rangle\rangle\langle\langle 2\rangle\rangle. \tag{14}$$

Finally:

$$v_n'\{2\}=\frac{d_n\{2\}}{\sqrt{c_n\{2\}}}, \tag{15}$$

$$v_n'\{4\}=\frac{d_n\{4\}}{(-c_n\{4\})^{3/4}}. \tag{16}$$

However, non-flow effects which are produced from resonance decays and jets should be reduced in the correlation, so an η gap need to be applied for 2-particle correlation. Equation (7) and Eq. (15) are then changed to [15]:

$$\langle 2\rangle=\frac{Q_n^\mathrm{A}\cdot Q_n^{\mathrm{B}*}}{M_\mathrm{A}M_\mathrm{B}}, \tag{17}$$

$$\langle 2'\rangle=\frac{p_n^\mathrm{A}\cdot Q_n^{\mathrm{B}*}}{m_{\mathrm{p,A}}M_\mathrm{B}}, \tag{18}$$

where Q_n^A and Q_n^B mean the 2 Q-vectors of the left and right side of the gap respectively, and similarly for the p_n^A.

In this analysis, we use the events simulated from a multiphase transport (AMPT) model [16] to obtain anisotropic flow coefficient. The AMPT model is constructed to describe nuclear collisions ranging from p+A to A+A systems at center-of-mass energies from about $\sqrt{s_\mathrm{NN}}$ = 5 GeV up to 5500 GeV at LHC, where strings and minijets dominate the initial energy production and effects from final-state interactions are important. It consists of four main components: the initial conditions, partonic interactions, the conversion from the partonic to the hadronic matter, and hadronic interactions. The initial conditions are generated by the heavy-ion jet interaction generator (HIJING) model. The strings are converted into partons and the next stage, which models the interactions between all the partons, is based on ZPC (Zhang's parton cascade [17]). In ZPC, the default value of the cross section is 3 mb. The transition from partonic to hadronic matter is modeled by a simple coalescence model, which combines two quarks into mesons and three quarks into baryons. The dynamics of the subsequent hadronic matter is described by a hadronic cascade, which is based on the ART model. We used AMPT version v2.26t5 with Lund parameter $a=0.30$, $b=0.15/\mathrm{GeV}^2$ in this analysis. The anisotropic flow for Pb+Pb $\sqrt{s_\mathrm{NN}}$=5.02 TeV from AMPT model has been generally investigated [18], and in this anaysis we would like to apply the ALICE TPC cut specifically and compare the simulated results with ALICE's newly published results [10].

2 Results and discussions

In 2015, LHC launched Pb+Pb collisions at $\sqrt{s_\mathrm{NN}}$=5.02 TeV. In this analysis, we use the results obtained from AMPT simulated minimal bias events to compare with ALICE experimental data in Run 2. We use the transverse momentum range 0.2< p_T <5.0 GeV and pseudorapidity range $-0.8<\eta<0.8$, in order to keep the same η and p_T cuts as ALICE data. In this analysis, we use 150k AMPT simulated minimal-bias Pb+Pb $\sqrt{s_\mathrm{NN}}$=5.02 TeV events to extract flow coefficients, to make sure all simulated results have fairly low uncertainty.

The pseudorapidity (η) dependence of v_2, v_3, v_4 for the 30%–40% most central collisions are presented in Fig. 1. We obtained this result using the same Q-cumulant method as the ALICE Pb+Pb $\sqrt{s_\mathrm{NN}}$=2.76 TeV experimental result [19]. We can see that v_2 is obviously larger than v_3 and v_4. The results show the distribution for all of these 3 harmonics are flat in the middle rapidity region($-0.8<\eta<0.8$). So we could integrate this dimension to obtain the anisotropic flow of other physical quantities.

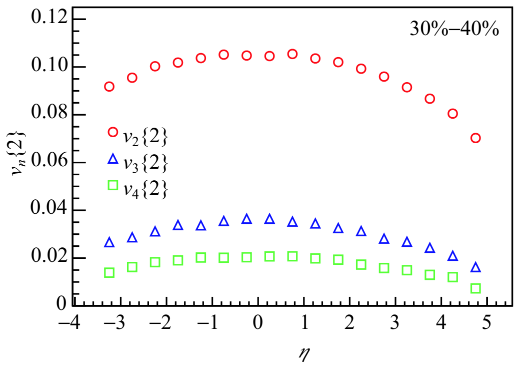

Fig. 1. (color online) $v_n\{2\}$ as a function of pseudorapidity in the $-3.5<\eta<5$ range for centrality 30%–40%.

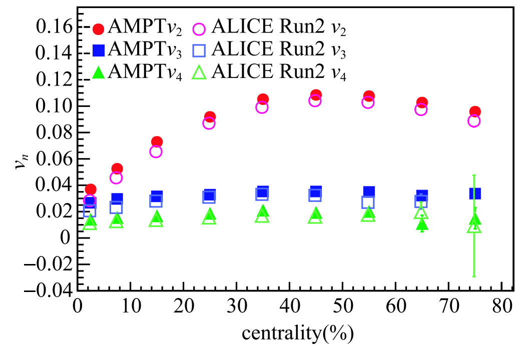

Fig. 2. (color online) Anisotropy flow v_n as a function of event centrality, using the two-particle cumulant method with $|\Delta\eta|>1$. Solid markers are for AMPT simulated results while open markers are for ALICE Pb+Pb 5.02 TeV experimental data.

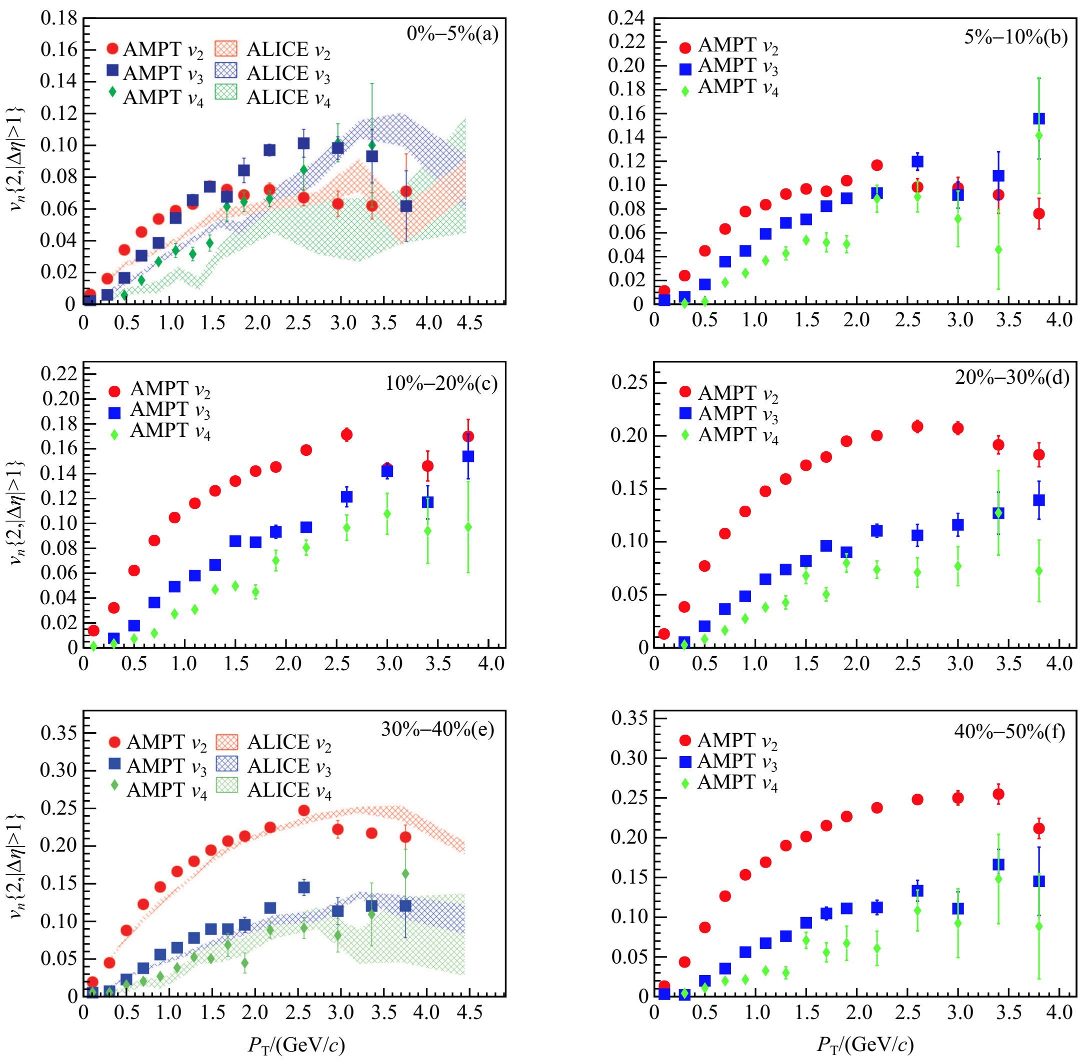

Fig. 3. (color online) Anisotropy flow v_n as a function of transverse momentum from 0%–5% to 40%–50%, using the two-particle cumulant method with $|\Delta\eta|>1$, compared with ALICE published 0%–5% and 30%–40% experimental results. Solid dots are for AMPT results and shadow grids are for ALICE Pb+Pb 5.02 TeV data, with grid height corresponding to uncertainties.

In Fig. 2 a clear centrality dependence of v_2 is observed, increasing from central to middle-central collisions, saturating in the 40%–50% centrality class, and then decreasing as the interactions during the system evolution become diluted. For v_3 and v_4, the centrality dependence is relatively weaker compared to v_2. It is also seen in Fig. 2 that the AMPT calculations successfully reproduce the centrality dependence of v_n but slightly overestimate the data.

Figure 3 shows the transverse momentum dependence of $v_2\{2,\Delta\eta>1\}$. We can see that from 0%–5% to 40%–50%, the anisotropic flow signals are increasing as centrality increases, while the difference between v_2 and v_3, v_4 is getting bigger too. For the 0%–5% most central collisions (see Fig. 3(a)), AMPT qualitatively reproduces the pt-differential anisotropic flow, but it works better in more peripheral collisions. For 30%–40% (see Fig. 3(e)), the situation seems better. The two results are consistent except for a few high momentum points (>3.5 GeV/c).

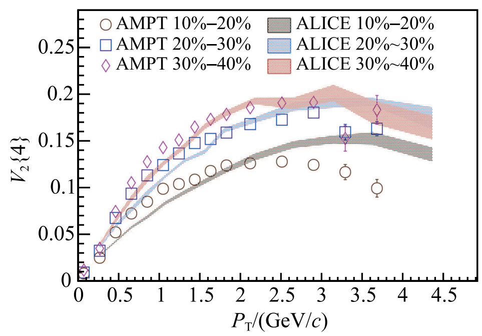

Fig. 4. (color online) Elliptic flow $v_2\{4\}$ as a function of transverse momentum for 10%–20%, 20%–30%, 30%–40%, no η gap applied.

Figure 4 represents v_2 as a function of transverse momentum using the 4-particle cumulant method. We can see AMPT calculations correctly reproduce the pt-dependence of anisotropic flow. The agreement between data and AMPT calculations seems better in more peripheral collisions, as we also observed in Fig. 3.

3 Conclusions

We have done a systematic study of the harmonic flow in Pb+Pb collisions at center of mass energy of 5.02 TeV with a multi-phase transport model. The centrality dependence of anisotropic flow has been presented, as well as the comparisons to the published measurements from ALICE. For different centrality classes, the dependence of anisotropy flow on transverse momentum has also been compared. For centrality dependence our AMPT results are consistent with the experimental data, and the higher harmonics v_3 and v_4 which come from the flow fluctuation show the same flattened distribution as the ALICE result. For p_T dependence the AMPT model can reproduce the v_2 of experimental data quite well. We can see from the comparisons that the string melting version of the AMPT model can describe the qualitative features of flow distribution, and it can reproduce the experimental data quantitatively.

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