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Event-plane decorrelation over pseudorapidity and its effect on azimuthal anisotropy measurements in relativistic heavy-ion collisions

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Within a multiphase transport model, we investigate decorrelation of event planes over pseudorapidity and its effect on azimuthal anisotropy measurements in relativistic heavy-ion collisions. The decorrelation increases with increasing η gap between particles used to reconstruct the event planes. The third harmonic event planes are found even anticorrelated between forward and backward rapidities, the source of which may root in the opposite orientation of the collision geometry triangularities. The decorrelation may call into question the anisotropic flow measurements with pseudorapidity gap designed to reduce nonflow contributions, hence the hydrodynamic properties of the quark-gluon plasma extracted from those measurements.

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I. INTRODUCTION

Relativistic heavy-ion collision data indicate that a strongly interacting quark-gluon plasma (QGP) is formed where the relevant degrees of freedom are quarks and gluons [1]. In a non-head-on heavy-ion collision, the geometrical overlap region—where interactions take place between the participant nucleons—is elliptic on the transverse plane perpendicular to the collision axis. Due to interactions, the high energy density and pressure built up in the center of the collision region power an anisotropic expansion and collective motion of the QGP. This results in an elliptical distribution in the final-state particle azimuthal distribution, called elliptic flow [2]. The measured elliptic flow is so large that hydrodynamical descriptions are applicable and the shear viscosity to entropy density ratio (η/s) cannot be much larger than the conjectured quantum low limit of $1/4\pi$ [3]. A similar phenomenon was also observed in a gas of cold Fermionic lithium-6 atoms, a system very different from the QGP, where a magnetic field is used to induce strong, resonant interactions [4].

It was not realized until recently [5] that there can be a triangular shape component in the transverse overlap region in the configuration space because of fluctuations in the nucleon distributions inside nuclei. This triangularity can result in a third harmonic in the azimuthal distribution of final particles, called triangular flow. Hydrodynamical calculations indicate that triangular flow is more sensitive to the η/s [6]. Although the initial configuration space information of the overlap region is not directly observable, their footprint is contained in the final-state particle correlations [2]. This is analogous to the nonuniform cosmological microwave background as a result of the primordial density fluctuation of the universe by gravitational interactions [7].

Hydrodynamic flow manifests itself in the anisotropic azimuthal distribution of final-state particles relative to the harmonic plane of the overlap geometry in initial configuration space in the limit of infinite participants [8]. However, the configuration space harmonic planes are not experimentally accessible. Heavy-ion experiments measure anisotropic flow via final-state particle correlations [1]. For example, one constructs an event plane (EP) to be the maximum particle emission direction, as a proxy for the participant plane—the minor symmetry axis of the nuclear overlap region in the configuration space. One then correlates a test particle with the event plane to measure anisotropic flow [9]. As such, the measured anisotropy is contaminated by other particle correlations unrelated to the symmetry harmonic plane, generally referred to as nonflow [10].

Many nonflow correlations are short ranged, such as resonance decays and jet correlations. Thus, to reduce nonflow contributions, one often applies a pseudorapidity (η) gap between the particles used for EP construction and those used for anisotropy measurements [9]. The basic assumption is that the participant plane is the same for all pseudorapidities. This may not be true, because unlike the reaction plane which is unique in a given event, participant planes can be different in different phase-space regions of the same event. In this study, we investigate the event-plane correlations in pseudorapidity in a theoretical model and find they are indeed different. In other words, it may not be reliable to measure anisotropic flow using the nonflow-reducing η-gap method. This finding, if also true in real data, would have important implications in terms of the QGP properties one extracts by comparing data to hydrodynamic calculations.

II. ANALYSIS METHOD

The "a multiphase transport" (AMPT) model describes many experimental data reasonably well, particularly the anisotropic flow measurements [11]. We thus use the AMPT model with string melting for our study. There are four main components in AMPT: the initial conditions, parton interactions, hadronization, and hadron interactions. The initial

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conditions are obtained from the HIJING model [12], which includes the spatial and momentum information of minijet partons from hard processes and strings from soft processes. The time evolution of partons is then treated according to the ZPC parton cascade model [13]. After parton interactions cease, a combined coalescence and string fragmentation model is used for the hadronization of partons. The scattering among the resulting hadrons is described by a relativistic transport (ART) model [14] which includes baryon-baryon, baryon-meson and meson-meson elastic, and inelastic scatterings.

The azimuthal anisotropy is usually characterized by the Fourier coefficients [9]:

$$v_n^{\rm obs} = \langle \cos[n(\phi - \Psi_n)] \rangle, \quad (1)$$

where ϕ is the particle azimuthal angle and Ψ_n is the nth harmonic plane angle. In the AMPT model Ψ_n can be calculated in coordinate space by [5]

$$\Psi_n^r = \frac{1}{n}{\rm atan2}(\langle r^2 \sin(n\phi_{\rm part})\rangle, \langle r^2 \cos(n\phi_{\rm part})\rangle) + \frac{\pi}{n}, \quad (2)$$

where r and $\phi_{\rm part}$ are the polar coordinate positions of each parton. The Ψ_n^r is generally called the participant plane. Note Ψ_2^r is not necessarily the reaction plane (the plane defined by beam direction and impact parameter) due to event-by-event fluctuations. However, the coordinate space information is not accessible by experiment. The event plane is instead constructed from measured particle momenta by

$$\Psi_n^p = \frac{1}{n}{\rm atan2}(\langle \sin(n\phi)\rangle, \langle \cos(n\phi)\rangle), \quad (3)$$

where ϕ is the azimuthal angle of the particle momentum. In the limit of infinite multiplicity and absent nonflow, Ψ_n^p should coincide with Ψ_n^r. We study both the configuration space Ψ_n^r and the momentum space Ψ_n^p in narrow η windows of 0.5 unit wide.

Due to the finite multiplicity of constituents, the constructed harmonic plane is smeared from the true one (i.e., the geometry harmonic plane of the participant partons in configuration space in the limit of infinity parton multiplicity) by a resolution factor. We calculate the resolution factor by the subevent method with an iterative procedure [9], dividing the constituents in each η window randomly into two subevents. Because of the large initial parton multiplicity, our calculated $\mathscr{R}_2^r$ and $\mathscr{R}_3^r$ are nearly unity, even in the most forward or backward η range ($3.5 < |\eta| < 4$). However, the resolution on the final-state momentum space event planes deviate significantly from 1. For 20%–50% centrality Au + Au collisions, $\mathscr{R}_2^p$ ($\mathscr{R}_3^p$) decreases from 0.302 (0.053) at $\eta = 0$–0.5 to 0.072 (0.008) at $\eta = 3.5$–4. Experimentally, the observed anisotropy parameter is corrected by the corresponding event-plane resolution as

$$v_n = v_n^{\rm obs} / \mathscr{R}_n^p. \quad (4)$$

III. RESULTS AND DISCUSSIONS

Figure 1(a) shows the event probability distribution in the difference of the configuration space event-plane angles (Ψ_2^r and Ψ_3^r) constructed from initial parton transverse coordinates in the forward and backward η ranges. Sharp peaks are

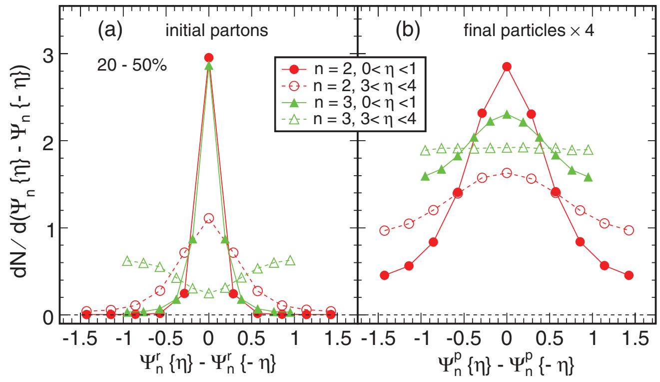

FIG. 1. (Color online) Event probability distribution in the difference of event planes constructed by (a) initial parton coordinates and (b) final-particle momenta in the forward and backward η ranges for 20%–50% centrality in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the AMPT model.

observed when Ψ^r are constructed not far from midrapidity for both the elliptic and triangular harmonic planes. This indicates a strong correlation between $\Psi\{\eta\}$ and $\Psi\{-\eta\}$. With increased η gap between the forward and backward regions, the probability distribution broadens for Ψ_2^r. Interestingly, the Ψ_3^r from forward and background η with large η gap are anticorrelated on average.

The probability distribution in event-plane angle difference constructed from final-state charged particle momenta is shown in Fig. 1(b). Similar to the results in panel (a), the event-plane angle correlations are relatively stronger close to midrapidity and become weaker when the η gap increases. Especially, the triangular harmonic plane at very forward and backward η are random with respect to each other. The event-plane correlations from final-state particle momenta are weaker than those from the initial-state parton configurations. This is due to the worse resolution of the momentum space event plane, a direct result of much fewer final-state particles than the initial partons.

The decorrelation between the forward and backward event planes are, in part, due to finite event-plane resolutions. We therefore show in Fig. 2 the correlation strength $\langle \cos[n(\Psi_n\{\eta\} - \Psi_n\{-\eta\})]\rangle$ divided by the corresponding event-plane resolutions $\mathscr{R}_n\{\eta\} \times \mathscr{R}_n\{-\eta\}$. The correlation is plotted as a function of the η gap ($\Delta\eta$, defined as the difference between the centers of the η regions used for event-plane calculation); $\Delta\eta \equiv 2\eta$ for our choice of the symmetric η ranges. Ideally, when $\Delta\eta$ is small close to zero, $\Psi\{\eta\}$ should be the same as $\Psi\{-\eta\}$. Indeed Fig. 2 shows the event-plane correlation approaches unity at small $\Delta\eta$. However, we find that the correlation decreases with increasing $\Delta\eta$, falling significantly below unity. This indicates that the event-plane decorrelation is not simply due to the degrading event-plane resolution, but physics—the event planes from forward and backward pseudorapidities are indeed different. The decorrelation of Ψ_2^r and Ψ_2^p are similar as a function of $\Delta\eta$. The decorrelations in the triangular event planes are much stronger than those in the elliptic ones. They also have different $\Delta\eta$ dependencies; the decorrelation magnitudes differ between

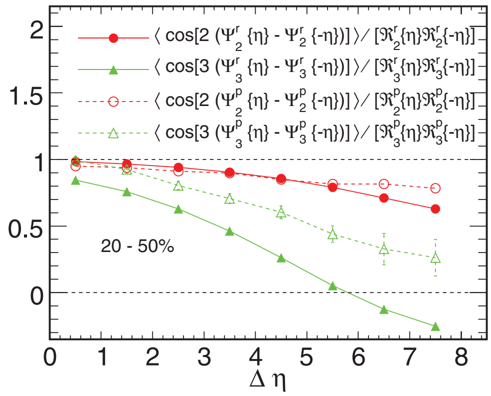

FIG. 2. (Color online) Pseudorapidity gap dependence of the correlation strength $\langle\cos[n(\Psi_n\{\eta\} - \Psi_n\{-\eta\})]\rangle$ corrected by the corresponding event-plane resolutions for 20%–50% centrality in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the AMPT model.

Ψ_3^r and Ψ_3^p. With large enough η gap, the triangular event planes from configuration space are anticorrelated.

To illustrate the physics further, we show in Fig. 3(a) the event probability distribution in Ψ_2, constructed from both the initial parton coordinates and the final-particle momenta in different η ranges, relative to the reaction plane angle (fixed at zero). The forward and backward Ψ_2 distributions are consistent with each other. The Ψ_2 distribution is wider than the $\Delta\Psi_2$ distribution in Fig. 1, even though there is decorrelation beyond event-plane resolution in $\Delta\Psi_2$. This suggests that the reconstructed event plane does not reflect the reaction plane but the participant plane [8]; there exists an additional fluctuation in the participant plane about the reaction plane. In other words, the two nonidentical participant planes (one at forward and the other at backward pseudorapidity) are closely correlated, but both deviate significantly from the reaction plane.

The Ψ_3 distributions are displayed in Fig. 3(b). Unlike Ψ_2, the forward and backward Ψ_3 are anticorrelated, especially between those with a large $\Delta\eta$ gap. As the system expands, the property of this anticorrelation in the initial geometry is transferred to the final-state particles in the momentum space, although at a much reduced magnitude. This is shown in Fig. 3(c). The reductions at forward and backward rapidities appear significantly stronger than at midrapidity, likely due to a much weaker conversion power from initial spatial anisotropy to final momentum anisotropy at large rapidities.

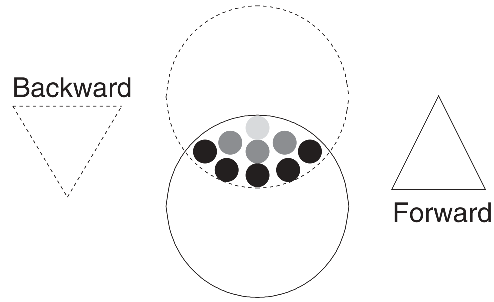

FIG. 4. The panel is a cartoon of interacting nucleons from the two nuclei.

The anticorrelation in Ψ_3 may root in the collision geometry. This is illustrated in the cartoon of Fig. 4. The nucleons in the overlap region of the forward-going projectile nucleus (indicated by the solid sphere) see various thicknesses of the backward-going target nucleus (indicated by the dashed sphere). The projectile nucleons indicated by the dark dots suffer fewer collisions than those indicated by the lighter ones, thus have a relatively larger probability to end up in the forward direction. In addition there are more of the "dark" nucleons than the light ones in the projectile nucleus. Therefore, at forward rapidity, the distribution of the struck nucleons is more likely to have an upward triangular shape (indicated by the solid triangle). Conversely, that at backward rapidity is more likely shaped by the oppositely oriented dashed triangle. Thus, triangularities of the forward and backward interaction zones are more likely anticorrelated.

Our pictorial explanation in Fig. 4, where the second harmonic plane points also upward (or downward), seems in contradiction to the common perception that the third harmonic plane is mostly uncorrelated to the second one. However, we found in AMPT, at a given forward η, that $\Psi_2\{\eta\}$ and $\Psi_3\{\eta\}$ are correlated and, due to symmetry, they are anticorrelated at backward η. Only after averaging over forward and backward η, do the two planes Ψ_2 and Ψ_3 appear uncorrelated, as observed in [5].

Bozek *et al.* [15] have studied the similar issue of event-plane decorrelation using the wounded nucleons model as the initial state. They found the effects for v_2 and v_3 are similar, and

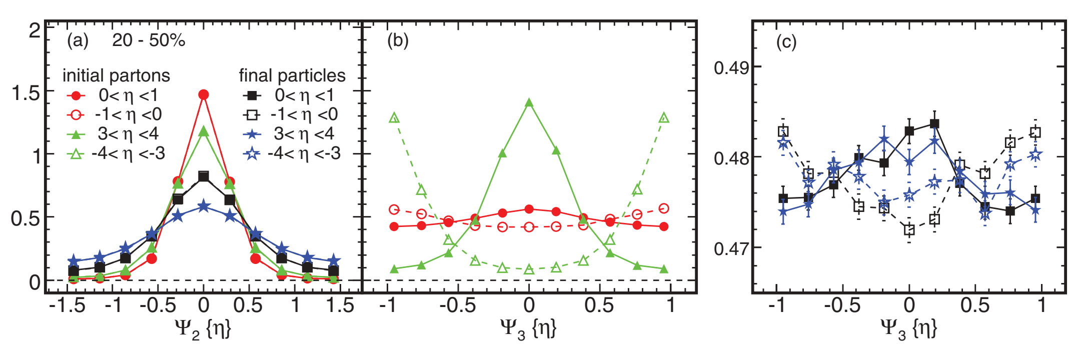

FIG. 3. (Color online) Event probability distribution in Ψ_2 (a) and Ψ_3 constructed by initial parton coordinates (b) and final-particle momenta (c) in different η ranges for 20%–50% centrality in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the AMPT model.

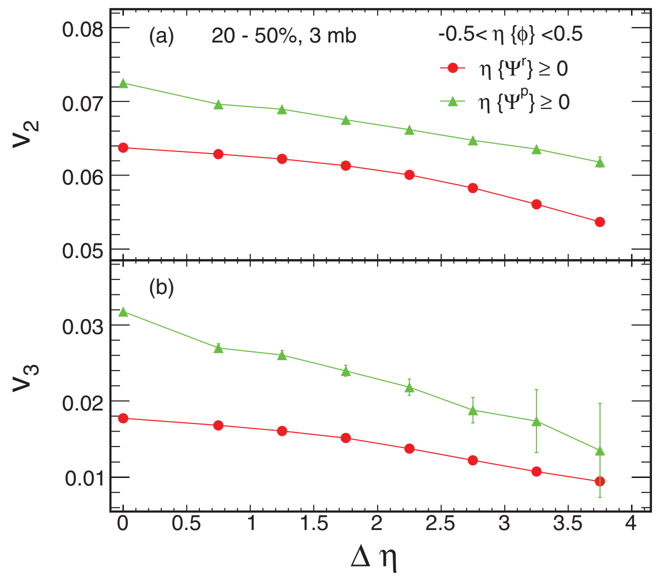

FIG. 5. (Color online) Pseudorapidity gap dependence of (a) v_2 and (b) v_3 with respect to Ψ^r and Ψ^p from different η ranges with 3-mb parton cross section for 20%–50% centrality in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the AMPT model.

significantly smaller than our finding. The preliminary STAR result of significantly smaller v_3 measured by forward than midrapidity event plane [16] may be in line with our finding.

In AMPT partons are released from the overlap nucleons, similar to the physics of the gluon flux tube. Without the correlation between rapidity and the overlap geometry depicted in Fig. 4, the geometry in AMPT would be boost invariant and one would naively expect longitudinal correlation of the harmonic planes. Such correlation is indeed implicitly assumed in experiments where to reduce nonflow, one often measures particle anisotropy by applying an η gap between the particles of interest and those used for event-plane reconstruction. The event-plane decorrelation we have shown calls this η-gap method into question. Although warned previously by Petersen *et al.* [17], the apparent decorrelation observed in [17] could be due to the event-plane resolution smearing. Here we rigorously study the effect of event-plane decorrelation on anisotropy measurements. In Fig. 5, we show v_2 and v_3 of charged particles within $|\eta| < 0.5$ with respect to Ψ^r and Ψ^p from different η ranges as functions of the η gap. The v_n is already corrected by the corresponding event-plane resolutions. As the η gap increases, the magnitudes of v_2 and v_3 decrease. The decrease is, in part, due to the decorrelation between the event plane at forward η and the event plane at $|\eta| < 0.5$. The decorrelation increases with increasing $\Delta\eta$. This study suggests that one may be required to measure particle anisotropy using the event plane reconstructed from the same η region as the particles of interest.

The decreasing behavior of v_n with $\Delta\eta$ is found for both Ψ_n^r and Ψ_n^p. However, the interpretation is complicated for v_n using Ψ_n^p due to nonflow. Nonflow is generally also a decreasing function of $\Delta\eta$. The decreasing trends of v_n with respect to Ψ_n^p is therefore a result of combined effects from the reduced nonflow and decorrelation in the event-plane angles over η gap.

Is the difference in v_n from Ψ_n^r and Ψ_n^p entirely due to nonflow? The answer is no, because the event-plane decorrelations are different for Ψ_3^r and Ψ_3^p, which must result in a correlation $\langle\cos[3(\Psi_3^r\{\eta\} - \Psi_3^p\{\eta\})]\rangle$ varying with η. Even with the similar decorrelations for Ψ_2^r and Ψ_2^p, we found that $\langle\cos[2(\Psi_2^r\{\eta\} - \Psi_2^p\{\eta\})]\rangle$ varies with η. In other words, the difference in v_n between Ψ_n^r and Ψ_n^p is a combined effect of nonflow and $\langle\cos[n(\Psi_n^r\{\eta\} - \Psi_n^p\{\eta\})]\rangle$. The fact that $\Psi_n^r\{\eta\}$ and $\Psi_n^p\{\eta\}$, after resolution corrections, are not the same may suggest that the final-state particles in a given η region are not solely determined by the initial partons from the same η region. This is in fact not unexpected but the discussion of its physics is beyond the scope of this paper.

Luzum and Ollitrault argued that the event-plane method should be abandoned due to an uncontrolled bias and advocated the cumulant method [18]. The event-plane decorrelation also affects the cumulant method, because the event planes do not drop in two-particle azimuthal difference.

IV. CONCLUSIONS

By utilizing the AMPT model with string melting, we have studied the correlations between event-plane azimuthal angles reconstructed from particles in the forward and backward peudorapidity regions in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The event planes reconstructed from the initial parton coordinate space and the final-particle momentum space are both studied. The event plane correlations are corrected by the event-plane resolutions. The resolution corrected event-plane correlation is found to weaken as the forward-backward η gap increases. This indicates that the event planes from different η ranges differ. The decorrelation in the triangular event plane is significantly stronger than that in the elliptic one. Particularly, the initial parton coordinate Ψ_3 exhibits an anticorrelation between very forward and backward η. The anticorrelation may root in the collision geometry—the triangularity of the forward-going participants is opposite to that of the backward-going ones.

The event-plane decorrelation may call into question the anisotropic flow measurements with pseudorapidity gap designed to reduce nonflow contributions. The large η gap may result in an undermeasured anisotropic flow. If true in real data, it could have important implications to the QGP properties extracted by comparing data to hydrodynamic calculations. One may speculate that the extracted shear viscosity to entropy density ratio could be overestimated due to an undermeasured flow, which in turn could suggest that the QGP may be more perfect than we thought it was.

ACKNOWLEDGMENTS

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