# Effects of triangular flow on di-hadron azimuthal correlations in relativistic heavy ion collisions

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Using the AMPT model for relativistic heavy ion collisions, we have studied the di-hadron azimuthal angular correlations triggered by emitted jets in Au + Au collisions at center-of-mass energy $\sqrt{s_{NN}} = 200$ GeV and impact parameter $b = 8$ fm. A double-peak structure for the associated particles at the away side of trigger particles is obtained after subtracting background correlations due to the elliptic flow. Both the near-side peak and the away-side double peaks in the azimuthal angular correlations are, however, significantly suppressed (enhanced) in events of small (large) triangular flow or triangularity in the initial collision geometry as a result of fluctuations. After subtraction of background correlations due to the triangular flow, the away-side double peaks change into a single peak with broad shoulders on both sides. The away side of the di-hadron correlations becomes essentially a single peak after further subtraction of higher-order flows.

Collisions of heavy nuclei at the Relativistic Heavy-Ion Collider (RHIC) have created a hot and dense matter that is believed to consist of deconfined quarks and gluons, as the inferred energy density is much greater than the critical value of $\sim 1$ GeV/fm$^3$ for the formation of a quark-gluon plasma (QGP) [1–4]. This matter was found to have a very small viscosity and thus behaves like a nearly perfect fluid [5,6]. Among the signatures for the formation of the QGP is the large quenching of energetic jets produced from initial hard collisions, leading to the suppressed production of hadrons with large transverse momenta [7,8]. Further studies of the di-hadron azimuthal angular correlations triggered by emitted jets have provided the possibility of investigating the response of the QGP to the quenched away-side jets [9–11]. It was found in these studies that for central and mid-central collisions of heavy nuclei, there existed not only a pronounced peak at the near side of trigger jets but also a broad double-peak structure at their away side [12,13]. Different mechanisms have been proposed to explain this interesting phenomenon, including medium-induced gluon radiation [14,15], a Mach cone from the shock wave generated by the traversing jet in the produced QGP [16,17], a path-length-dependent jet energy loss [18,19], Cerenkov radiation from the jet [20], a strong parton cascade [21], and the deflection of jets by partons in the QGP [22–24]. Also, it was recently pointed out that the so-far overlooked large triangular flow, resulting from the nonvanishing triangularity in the initial collision geometry as a result of the spatial fluctuation of participating nucleons [25–27], could be responsible for the double-peak structure at the away side of di-hadron correlations [28,29]. This stems from the observation that the azimuthal angular correlations of hadrons resulting from their triangular flow have peaks at 0, $2\pi/3$, and $4\pi/3$, which are similar to the peaks observed in the experimentally measured di-hadron azimuthal angular correlations. It was shown that the away-side double peaks could indeed appear in the hydrodynamic model if the initial density fluctuations are included [30]. However, a recent paper by the STAR Collaboration [31] shows that the away-side double-peak structure is not much affected after subtracting

the background correlations that include the effect based on an estimated triangular flow. It is therefore of great interest to use a dynamical model to study consistently the effect of triangular flow on di-hadron azimuthal angular correlations triggered by emitted jets in relativistic heavy ion collisions. In this paper, we carry out such a study within the framework of the AMPT model [32,33].

The AMPT model is a hybrid model with the initial particle distributions generated by the HIJING model [34]. In the version of string melting, which has been shown to better describe the experimental observations at RHIC [35–37], hadrons produced from the HIJING model are converted to their valence quarks and antiquarks, and their evolution in time and space is then modeled by the ZPC parton cascade model [38]. After stopping scattering, quarks and antiquarks are converted via a spatial coalescence model to hadrons, which are followed by hadronic scattering via the ART model [39]. As in previous studies [35–37], the elastic two-body scattering cross section used in the parton cascade is set to be 10 mb, which is larger than the value expected from leading-order perturbative QCD, to compensate for the neglected higher-order inelastic processes.

Using the AMPT model, we have studied Au + Au collisions at center-of-mass energy $\sqrt{s_{NN}} = 200$ GeV and impact parameter $b = 8$ fm. The latter is similar to the average value in minimum-bias collisions that have been studied in experiments. The azimuthal angle $\phi$ distribution of the $N(p_T)$ final hadrons with transverse momentum $p_T$ in the transverse plane of a single AMPT event can be written as [29]

$$f(p_T, \phi) = \frac{N(p_T)}{2\pi}\left\{1 + 2\sum_{n=1}^{+\infty} v_n(p_T)\cos[n(\phi - \psi_n)]\right\}, \quad (1)$$

where the $n$th-order event plane angle $\psi_n$ and the anisotropic flow $v_n(p_T)$ of hadrons with transverse momentum $p_T$ in this event can be calculated, respectively, from

$$\psi_n = \frac{1}{n}\arctan\frac{\langle \sin(n\phi) \rangle}{\langle \cos(n\phi) \rangle}, \quad (2)$$

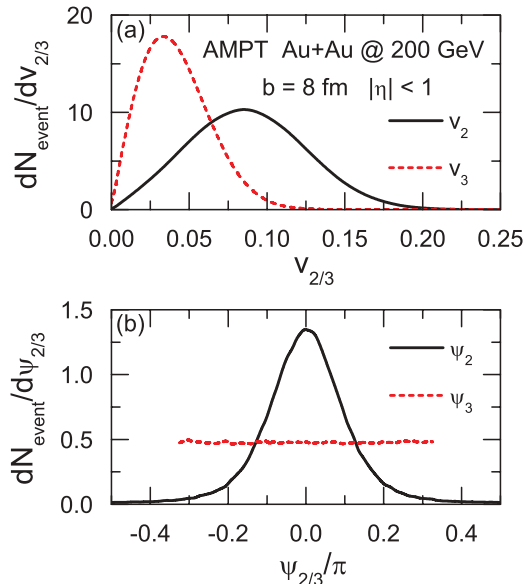$$v_n(p_T) = \langle \cos[n(\phi - \psi_n)] \rangle_{p_T}, \quad (3)$$

FIG. 1. (Color online) Event distributions of elliptic flow $v_2$ and triangular flow $v_3$ (a) and corresponding event plane angles $\psi_2$ and $\psi_3$ (b) in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and $b = 8$ fm from the AMPT model.

with $\langle \cdots \rangle$ and $\langle \cdots \rangle_{p_T}$ denoting, respectively, averages over all hadrons in the event and over those of transverse momentum $p_T$. The total $n$th-order anisotropic flow $v_n$ in this event is then obtained by integrating $v_n(p_T)$ over transverse momentum.

In Fig. 1(a), we show the event distributions of the dominant elliptic flow $v_2$ and triangular flow $v_3$ of hadrons in the mid-pseudorapidities $|\eta| < 1$. It is seen that both elliptic and triangular flows are large, although their values change from event to event. The event distributions of the event plane angles $\psi_2$ and $\psi_3$ of mid-pseudorapidity hadrons are displayed in Fig. 1(b). Similar to the results from the ideal hydrodynamic model using initial fluctuating collision geometry from the UrQMD model [25], the event plane angle $\psi_2$ for the elliptic flow peaks at 0 while the event plane angle $\psi_3$ for the triangular flow is uniformly distributed between $-\pi/3$ and $\pi/3$, as the former is mainly due to the collision geometry while the latter is solely due to fluctuations in the initial collision geometry. We have further found that the distribution of $\psi_3$ remains similar for events of fixed $\psi_2$, which shows that $\psi_3$ and $\psi_2$ are essentially independent of each other.

In Fig. 2, we show the transverse momentum dependence of the event-averaged elliptic and triangular flows of mid-pseudorapidity hadrons, i.e., $\langle N(p_T) v_n(p_T) \rangle_e / \langle N(p_T) \rangle_e$ with $\langle \cdots \rangle_e$ denoting the average over all events, which are the ones usually shown in the experimental results. It is seen that both elliptic and triangular flows are appreciable at high transverse momenta.

The di-hadron azimuthal angular correlations between trigger particles and associated particles are calculated from all such pairs within the same event and then averaged over all events. With trigger particles of transverse momenta in the window $2.5 < p_T^{\text{trig}} < 6$ GeV/$c$ and associated particles of transverse momenta in the window $0.15 < p_T^{\text{assoc}} < 2.5$ GeV/$c$, which are similar to the "soft" case in Ref. [21], the
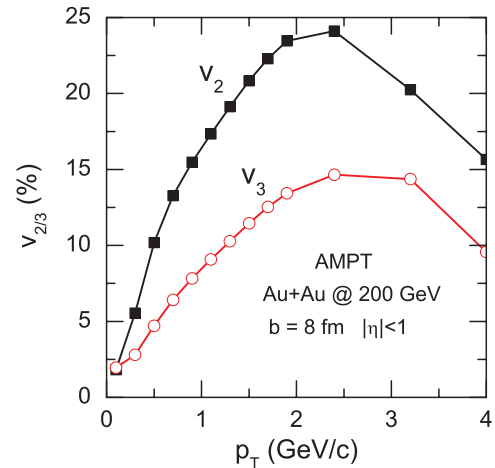
result for the total di-hadron correlations per trigger particle in the mid-pseudorapidity is shown by solid squares in Fig. 3(a). It is seen that the associated particles have not only a near-side peak at $\Delta\phi = 0$ but also a broad away-side peak at $\Delta\phi = \pi$.

The di-hadron correlations include contributions from both the back-to-back jet pairs and background anisotropic flows [40]. The latter can be obtained from the di-hadron azimuthal angular correlations calculated from Eq. (1), i.e.,

$$
\left\langle \frac{dN_{\text{pair}}}{d\Delta\phi} \right\rangle_e = \frac{1}{2\pi} \left[ \langle N^{\text{trig}} N^{\text{assoc}} \rangle_e \right.
$$
$$
\left. + 2 \sum_{n=1}^{+\infty} \langle N^{\text{trig}} N^{\text{assoc}} v_n^{\text{trig}} v_n^{\text{assoc}} \rangle_e \cos(n\Delta\phi) \right] \quad (4)
$$

by replacing $\langle N^{\text{trig}} N^{\text{assoc}} \rangle_e$ with $\langle N^{\text{trig}} \rangle_e \langle N^{\text{assoc}} \rangle_e$ and replacing $\langle N^{\text{trig}} v_n^{\text{trig}} N^{\text{assoc}} v_n^{\text{assoc}} \rangle_e$ with $\langle N^{\text{trig}} v_n^{\text{trig}} \rangle_e \langle N^{\text{assoc}} v_n^{\text{assoc}} \rangle_e \equiv \langle N^{\text{trig}} \rangle_e v_n^{\text{trig}} \langle N^{\text{assoc}} \rangle_e v_n^{\text{assoc}}$, where $N^{\text{trig}}$ and $N^{\text{assoc}}$ are the



FIG. 2. (Color online) Transverse momentum dependence of the hadron elliptic ($v_2$) and triangular ($v_3$) flows.
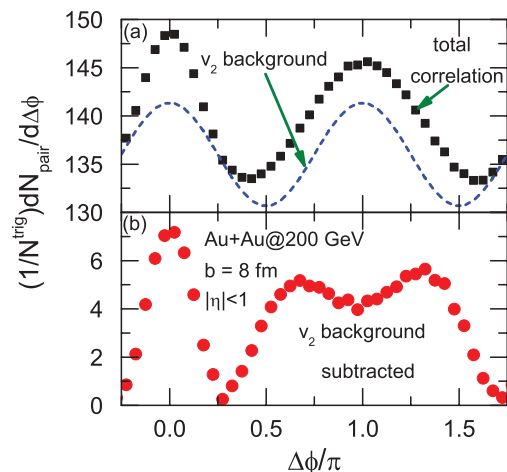


FIG. 3. (Color online) Di-hadron azimuthal angular correlations per trigger particle before (a) and after (b) subtracting background correlations due to the hadron elliptic flow shown by the dashed line in panel (a).

number of trigger and associated hadrons, respectively, and $v_n^{\text{trig}}$ and $v_n^{\text{assoc}}$ are their $n$th-order anisotropic flows averaged over all events, i.e.,

$$\frac{dN_{\text{pair}}^{\text{back}}}{d\Delta\phi} = \frac{\langle N^{\text{trig}}\rangle_e \langle N^{\text{assoc}}\rangle_e}{2\pi}\left[1 + 2\sum_{n=1}^{+\infty} v_n^{\text{trig}} v_n^{\text{assoc}} \cos(n\Delta\phi)\right]. \tag{5}$$

We note that the di-hadron azimuthal correlations calculated from Eq. (4) up to $n = 5$ are already very close to the ones calculated from hadron pairs shown in Fig. 3(a).

Although the background correlations contain contributions from anisotropic flows of all orders, only those due to the elliptic flow have been considered in the experimental analysis. As shown by the dashed line in Fig. 3(a), the di-hadron correlations due to the hadron elliptic flow show a peak structure similar to that of the total di-hadron correlations. The di-hadron correlations after subtracting the background correlations due to the elliptic flow are shown by solid circles in Fig. 3(b), and, as in the experimental data, they show a double-peak structure at the away side of trigger particles.

Before subtracting the background correlations due to the hadron triangular flow, we consider separately events of small ($v_3 < 0.03$) and large ($v_3 > 0.05$) triangular flows. Figure 4(a) shows the transverse momentum dependence of triangular flows in these two cases, indicated, respectively, by open triangles and inverted triangles, and these are compared with that for all events (solid circles). The di-hadron azimuthal angular correlations after subtracting background correlations due to the elliptic flow are shown in Fig. 4(b) for these

two cases. Compared with the result from all events, both the near-side peak and the away-side double peaks in the di-hadron correlations are significantly enhanced (suppressed) in events of large (small) triangular flow, which shows that the triangular flow has a large effect on the di-hadron correlations, as suggested in Refs. [28,29].

We have also studied how the initial triangularity in the collision geometry, which is defined as $\epsilon_3 = \sqrt{\langle r_{\text{init}}^3 \cos(3\phi_{\text{init}})\rangle^2 + \langle r_{\text{init}}^3 \sin(3\phi_{\text{init}})\rangle^2}/\langle r_{\text{init}}^3\rangle$ [25] with $r_{\text{init}}$ and $\phi_{\text{init}}$ being the polar coordinates of initial partons, affects the di-hadron azimuthal correlations. As in the above consideration of the effect of the triangular flow, we find that both the near-side peak and the away-side double peaks are appreciably enhanced (suppressed) in events of large (small) initial triangularity. This result thus indicates that in our model the initial triangularity has a stronger effect on the di-hadron azimuthal correlations than other physical mechanisms that can also generate triangular flow.

The background correlations due to both hadron elliptic and triangular flows are shown by the dashed line in Fig. 5(a). Subtracting these background correlations from the total correlations results in the di-hadron correlations shown in Fig. 5(b). It is seen that the away-side double peaks change into a single peak with broad shoulders on both sides, and the near-side peak is also suppressed. The residual correlations are similar to those from events of small triangular flow as shown in Fig. 4(b). After further subtracting background correlations due to anisotropic flows up to $n = 5$ shown by the dotted line in Fig. 5(a), the away side of the di-hadron correlations becomes essentially a single peak as shown in Fig. 5(c). The remaining near-side peak and the away-side broad peak in the di-hadron azimuthal correlations are then
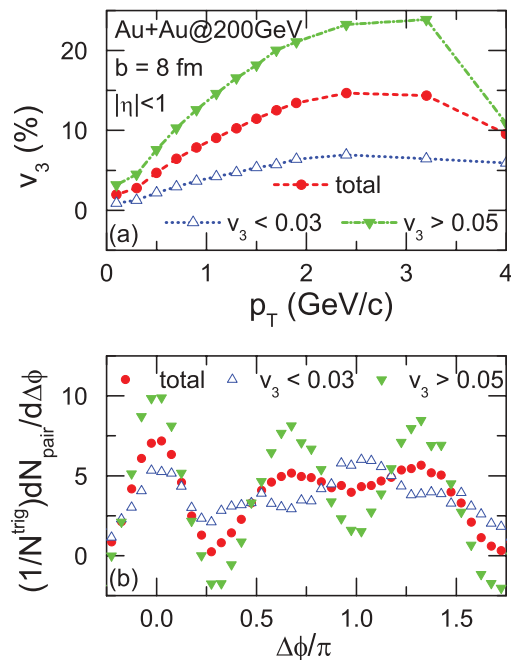


FIG. 4. (Color online) (a) The triangular flow $v_3$ as a function of transverse momentum and (b) di-hadron azimuthal angular correlations per trigger particle from all events and from events of small or large triangular flow.
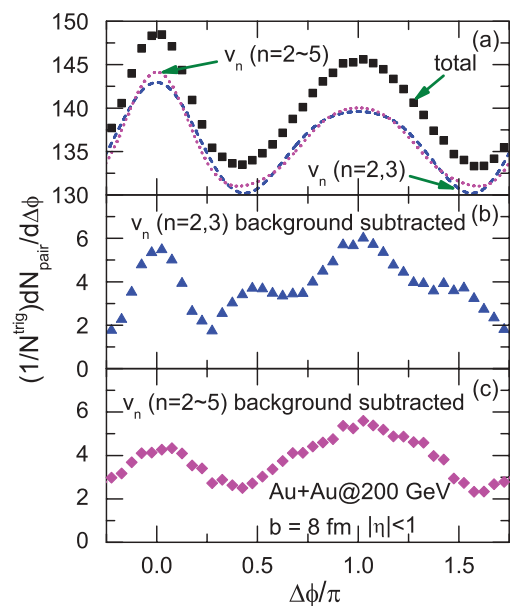


FIG. 5. (Color online) Di-hadron azimuthal angular correlations per trigger particle before (a) and after subtracting background correlations due to both hadron elliptic and triangular flows (b) shown by the dashed line in panel (a) and due to anisotropic flows up to the fifth order (c) shown by the dotted line in panel (a).

due to the effect of the back-to-back jet pairs produced in initial hard scattering. Our results thus indicate that the effects of elliptic and triangular flows on the di-hadron azimuthal correlations are very important, while those of higher-order anisotropic flows are also not negligible.

Although the away-side double-peak structure in di-hadron azimuthal correlations is dominated by the triangular flow in heavy ion collisions at $b = 8$ fm, it was shown, however, in Ref. [41] that the double-peak structure remains appreciable in central heavy ion collisions at $b = 0$ fm after subtracting background correlations due to anisotropic flows even up to the fifth order. This is likely because the anisotropic flows from initial density fluctuations are much weaker in central collisions as a result of the larger particle multiplicity and other effects such as those from jet deflections or Mach cone shock waves are stronger.

In conclusion, we have investigated the di-hadron azimuthal angular correlations triggered by emitted jets in the AMPT model with string melting for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV with $b = 8$ fm. Although the total

di-hadron correlations show only a single away-side peak besides a near-side peak, a double-peak structure appears in the away side after subtracting the background correlations due to the hadron elliptic flow. Both the near-side peak and away-side double peaks in the di-hadron correlations are found to be sensitive to the hadron triangular flow or initial triangularity as they are enhanced (suppressed) when events of large (small) hadron triangular flow or initial triangularity are considered. Moreover, the away-side double peaks change into a single peak after the subtraction of background correlations due to both hadron elliptic and triangular flows. Although other effects [14–24] on di-hadron correlations are appreciable in central collisions, the away-side double peaks seem to be dominated by the triangular flow in mid-central collisions.

[1] I. Arsene *et al.* (PHOBOS Collaboration), Nucl. Phys. A **757**, 1 (2005).

[2] B. B. Back *et al.* (BRAHMS Collaboration), Nucl. Phys. A **757**, 28 (2005).

[3] J. Adams *et al.* (STAR Collaboration), Nucl. Phys. A **757**, 102 (2005).

[4] K. Adcox *et al.* (PHENIX Collaboration), Nucl. Phys. A **757**, 184 (2005).

[5] M. Gyulassy and L. McLerran, Nucl. Phys. A **757**, 30 (2005).

[6] E. Shuryak, Nucl. Phys. A **757**, 64 (2005).

[7] K. Adcox *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **88**, 022301 (2002).

[8] C. Adler *et al.* (STAR Collaboration), Phys. Rev. Lett. **89**, 202301 (2002).

[9] C. Adler *et al.* (STAR Collaboration), Phys. Rev. Lett. **90**, 082302 (2003).

[10] C. Adler *et al.* (STAR Collaboration), Phys. Rev. Lett. **90**, 032301 (2003).

[11] J. Adams *et al.* (STAR Collaboration), Phys. Rev. Lett. **93**, 252301 (2004).

[12] J. Adams *et al.* (STAR Collaboration), Phys. Rev. Lett. **95**, 152301 (2005).

[13] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **97**, 052301 (2006).

[14] I. Vitev, Phys. Lett. B **630**, 78 (2005).

[15] A. D. Polosa and C. A. Salgado, Phys. Rev. C **75**, 041901(R) (2007).

[16] J. Casalderrey-Solanaa, E. V. Shuryaka, and D. Teaney, Nucl. Phys. A **774**, 577 (2006).

[17] T. Renk and J. Ruppert, Phys. Rev. C **73**, 011901 (2006).

[18] C. B. Chiu and R. C. Hwa, Phys. Rev. C **74**, 064909 (2006).

[19] W. Li, S. Zhang, Y. G. Ma, X. Z. Cai, J. H. Chen, H. Z. Huang, G. L. Ma, and C. Zhong, Phys. Rev. C **80**, 064913 (2009).

[20] V. Koch, A. Majumder, and X. N. Wang, Phys. Rev. Lett. **96**, 172302 (2006).

[21] G. L. Ma *et al.*, Phys. Lett. B **641**, 362 (2006).

[22] B. Betz, J. Noronha, G. Torrieri, M. Gyulassy, and D. Rischke, Nucl. Phys. A **830**, 777c (2009).

[23] B. Betz, J. Noronha, G. Torrieri, M. Gyulassy, and D. H. Rischke, Phys. Rev. Lett. **105**, 222301 (2010).

[24] H. Li, F. Liu, G. L. Ma, X. N. Wang, and Y. Zhu, Phys. Rev. Lett. **106**, 012301 (2011).

[25] H. Petersen, G. Y. Qin, S. A. Bass, and B. Müller, Phys. Rev. C **82**, 041901(R) (2010).

[26] B. Schenke, S. Jeon, and C. Gale, arXiv:1009.3244 [hep-ph].

[27] G. Y. Qin, H. Petersen, S. A. Bass, and B. Müller, Phys. Rev. C **82**, 064903 (2010).

[28] B. Alver and G. Roland, Phys. Rev. C **81**, 054905 (2010).

[29] B. H. Alver, C. Gombeaud, M. Luzum, and J. Y. Ollitrault, Phys. Rev. C **82**, 034913 (2010).

[30] J. Takahashi, B. M. Tavares, W. L. Qian, R. Andrade, F. Grassi, Y. Hama, T. Kodama, and N. Xu, Phys. Rev. Lett. **103**, 242301 (2009).

[31] H. Agakishiev *et al.* (STAR Collaboration), arXiv:1010.0690 [nucl-ex].

[32] B. Zhang, C. M. Ko, B. A. Li, and Z. W. Lin, Phys. Rev. C **61**, 067901 (2000).

[33] Z. W. Lin, C. M. Ko, B. A. Li, B. Zhang, and S. Pal, Phys. Rev. C **72**, 064901 (2005).

[34] X. N. Wang and M. Gyulassy, Phys. Rev. D **44**, 3501 (1991).

[35] Z. W. Lin and C. M. Ko, Phys. Rev. C **65**, 034904 (2002).

[36] Z. W. Lin, C. M. Ko, and S. Pal, Phys. Rev. Lett. **89**, 152301 (2002).

[37] L. W. Chen, C. M. Ko, and Z. W. Lin, Phys. Rev. C **69**, 031901(R) (2004).

[38] B. Zhang, Comput. Phys. Commun. **109**, 193 (1998).

[39] B. A. Li and C. M. Ko, Phys. Rev. C **52**, 2037 (1995).

[40] A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C **58**, 1671 (1998).

[41] G. L. Ma and X. N. Wang, arXiv:1011.5249 [nucl-th].