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Jets, Mach cone, hot spots, ridges, harmonic flow, dihadron and γ-hadron correlation in high-energy heavy-ion collisions

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Within the AMPT Monte Carlo model, fluctuations in the initial transverse parton density are shown to lead to harmonic flows. The net back-to-back dihadron azimuthal correlation after subtraction of contributions from harmonic flows still has a double-peak that is independent of the initial geometric triangularity and unique to the jet-induced Mach cone and expanding hot spots distorted by radial flow. The longitudinal structure of hot spots also leads to a near-side ridge in dihadron correlation with a large rapidity gap. By successively randomizing the azimuthal angle of the transverse momenta and positions of initial partons, one can isolate the effects of jet-induced medium excitation and expanding hot spots on the dihadron azimuthal correlation. The double-peaks in the net dihadron and γ-hadron correlation are quantitatively different since the later is caused only by jet-induced Mach cone.

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Dihadron correlation in high-energy heavy-ion experiments provides a useful tool to study jet quenching [1] that suppresses not only single inclusive large p_T hadrons [2] but also large p_T back-to-back correlation [3]. By decreasing p_T of the away-side hadrons associated with a high p_T triggered hadron, one can further study the medium modification of hadron distribution from an energetic jet as well as the jet-induced medium excitations. Experimental data in $Au + Au$ collisions at the Relativistic Heavy-Ion Collider (RHIC) [4–6] show a double-peaked back-to-back azimuthal dihadron correlation with a maximum opening angle of $\Delta\phi \approx 1$ (rad) relative to the back-side of a high p_T trigger. Such a feature in dihadron correlation was suspected to be caused by Mach-cone excitation induced by jet-medium interaction [7, 8]. However, hydrodynamic study of jet-induced medium excitation with a realistic source term for energy-momentum deposition [9] and parton transport study of jet propagation [10] both show that it is the deflection of jet showers and medium excitation by radial flow that produces double-peaked back-to-back dihadron correlation. Moreover, recent studies also found that expanding hot spots in the initial parton transverse density distorted by radial flow [11, 12] and the triangular flow [13, 14] all contribute to a double-peaked back-to-back dihadron correlation. If these local fluctuations are extended in the longitudinal direction like a string model [15] or glasma [16, 17], they would also lead to a ridge structure in the near-side dihadron correlation with large rapidity gap [18, 19]. With these different mechanisms contributing to the dihadron correlation, it is important to explore ways to separate different contributions and study the characteristics of the dihadron correlation from each of them.

In this Letter, we will use a multiphase transport (AMPT) model [20] to study dihadron correlation as a result of harmonic flows, expanding hot spots, jets and jet-induced medium excitation. We first study harmonic flows of hadron spectra due to fluctuations in initial parton density, which all contribute to dihadron azimuthal correlation. The dihadron correlation after subtraction of contributions from harmonic flows should provide information on the unique structures of hadron correlation from medium modified jets, jet-induced medium excitation and expanding hot spots distorted by radial flow in high-energy heavy-ion collisions. We will also investigate the longitudinal structures of hot spots and the resulting dihadron azimuthal correlation with large rapidity gap. By successively randomizing the azimuthal angles of transverse momenta and coordinates of initial jet shower partons, we can isolate the effects of medium modified dijets, jet-induced medium excitation and expanding hot spots. We will also compare dihadron correlation after subtraction of the contributions from harmonic flow with γ-hadron correlation which is only affected by jet-induced medium excitation. The AMPT results shown in this paper are central $Au + Au$ collisions with fixed impact-parameter $b = 0$ at the RHIC energy $\sqrt{s} = 200$ GeV.

AMPT [20] model combines initial conditions from HIJING model [22] with parton and hadron cascade for final state interaction. We will use a version of AMPT with string melting and parton recombination for hadronization which was shown to better describe the collective phenomenon in heavy-ion collisions at RHIC [21]. The parton cascade employed in AMPT includes only elastic parton collisions whose cross sections are controlled by the values of strong coupling constant and the Debye screening mass. Within HIJING, Glauber model for multiple nucleon scattering is used to describe the initial parton production in heavy-ion collisions. Nucleon-nucleon scatterings contain both independent hard parton scattering and coherent soft interaction that is modeled by string formation for each participant nucleon. Strings are then converted into soft partons via string melting scheme in AMPT. Such multiple scatterings lead to fluctuation in local parton number density or hot spots from both soft and hard interactions which are proportional

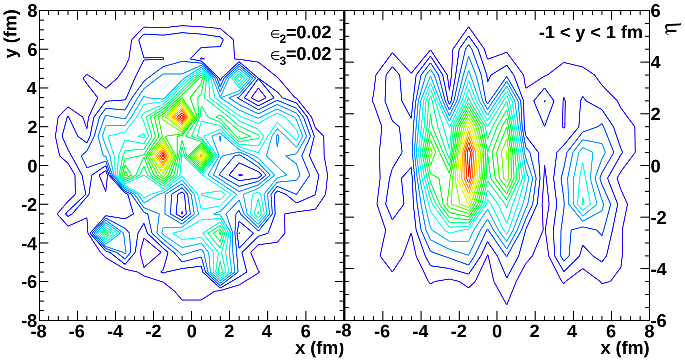

FIG. 1: (Color online) Contour plot of initial parton density (in arbitrary unit) $dN/dxdy$ in transverse plane (left panel) and $dN/dxd\eta$ (right panel) in x-η (pseudorapidity) plane in a typical AMPT central $Au + Au$ event ($b = 0$) at $\sqrt{s} = 200$ GeV, with ellipticity $\epsilon_2 = 0.02$ and triangularity $\epsilon_3 = 0.02$ of the transverse parton distribution.

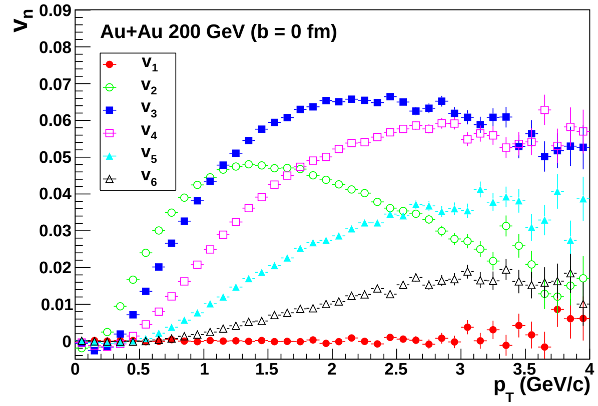

FIG. 2: (Color online) Azimuthal anisotropies of hadron spectra $v_n(p_T)$ ($n = 1 - 6$) in central ($b = 0$) $Au + Au$ collisions at $\sqrt{s} = 200$ GeV from AMPT model calculation.

to local transverse density of participant nucleons and binary collisions, respectively.

Shown in Fig. 1 are contour plots of initial parton density in the transverse plane $dN/dxdy$ (left panel) and in $x - \eta$(pseudorapidity) plane $dN/dxd\eta$ within a slice $|y| < 1$ fm (right panel) of a typical AMPT event. We assume the transverse position of both hard and soft partons are confined to the size of their parent nucleons $r_N \sim 1$ fm. Therefore, fluctuations in local density of participant nucleons and binary nucleon-nucleon collisions lead to fluctuations in parton transverse density or hot spots with the smallest transverse size of about 1 fm. These hot spots and valleys give rise to finite values of initial geometric irregularities ϵ_n defined as

$$\epsilon_n = \frac{\sqrt{\langle r^2 \cos(n\varphi)\rangle^2 + \langle r^2 \sin(n\varphi)\rangle^2}}{\langle r^2\rangle}, \qquad (1)$$

where (r, φ) are polar coordinates of each parton and the average $\langle \cdots \rangle$ is density weighted. Normally, ϵ_2 is referred to as eccentricity and ϵ_3 as triangularity.

Hot spots in the fluctuating initial parton density distribution are also extended in the longitudinal direction as shown in the right panel of Fig. 1. Such extended longitudinal distribution in pseudorapidity η is partially from soft partons via the materialization of strings. Partons from initial state radiation associated with hard scatterings have a distribution $dN/dy = dN/d\log(1/x) \sim 1$ which is also extended in rapidity.

Collective expansion due to parton rescattering will translate the initial geometric irregularities into harmonic flows in momentum space [23]. Shown in Fig. 2 are the harmonic flows of final hadron spectra $v_n = \langle \cos n(\phi - \psi_n)\rangle$ from AMPT calculations, where the event plane angle for each harmonics is given by

$$\psi_n = \frac{1}{n}\left[\arctan\frac{\langle r^2 \sin(n\varphi)\rangle}{\langle r^2 \cos(n\varphi)\rangle} + \pi\right]. \qquad (2)$$

Even in central collisions at fixed impact-parameter $b = 0$, the geometrical fluctuation of initial parton density leads to anisotropic collective expansion which translates the initial geometric irregularities into significant values of harmonic flows in momentum space in the central rapidity region. It is interesting to observe that all $v_n(p_T)$ decrease at high p_T but the turning points shift to higher p_T for higher harmonics. The higher harmonic flows v_n for $n > 6$ are insignificant due to viscous diffusion.

In the study of dihadron correlation to search for effects of medium modification of jet structure and jet-induced medium excitations, it is important to isolate and subtract contributions from harmonic flows, especially the triangular flow which contributes the most to the double-peak structure of back-to-back dihadron correlation. We will use the ZYAM (zero yield at minimum) scheme [4] to subtract contributions to dihadron correlation,

$$f(\Delta\phi) = B\left(1 + \sum_{n=1}^{\infty} 2\langle v_n^{\rm trig} v_n^{\rm asso}\rangle \cos n\Delta\phi\right), \qquad (3)$$

from harmonic flows, where B is a normalization factor determined by the ZYAM scheme, v_n^{trig} and v_n^{asso} are harmonic flow coefficients for trigger and associated hadrons. Shown in Fig. 3 are dihadron correlations before (dot-dashed) and after (solid) the removal of contributions from harmonic flows for $p_T^{\rm trig} > 2.5$ GeV/c and $1 < p_T^{\rm asso} < 2$ GeV/c. Also shown are contributions from each harmonic flow n = 2-6 (dashed). These contributions are significant for up to $n = 5$ harmonics.

After subtraction of contributions from harmonic flows, the dihadron correlation still has a double-peak feature on the away-side of the trigger which should reflect the azimuthal structure from deflection of medium

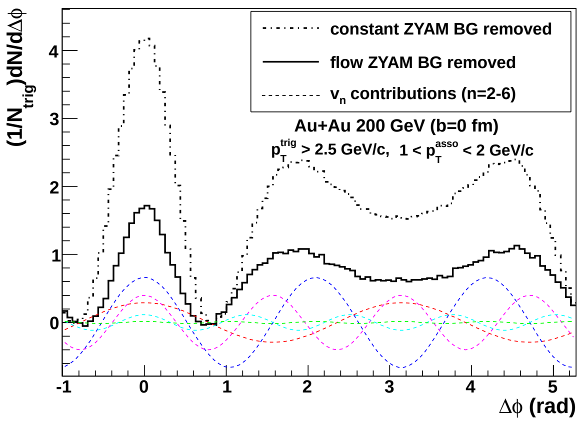

FIG. 3: (Color online) AMPT results on dihadron azimuthal correlation before (dot-dashed) and after (solid) subtraction of contribution from harmonic flow $v_n(n = 2-6)$ for $p_T^{\rm trig} >$ 2.5 GeV/c and $1 < p_T^{\rm asso} < 2$ GeV/c.

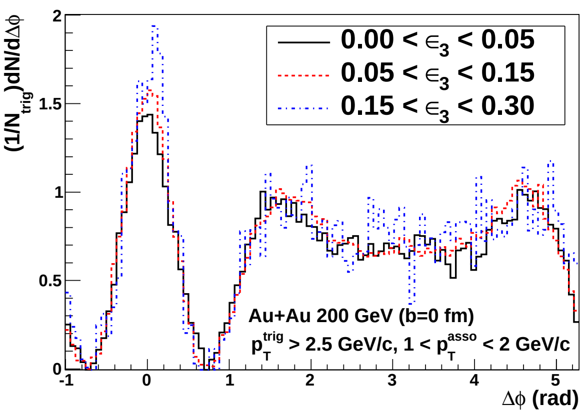

FIG. 4: (Color online) Dihadron correlations after subtraction of harmonic flow with different values of geometric triangularity ϵ_3 for $p_T^{\rm trig} > 2.5$ GeV/c and $1 < p_T^{\rm asso} < 2$ GeV/c .

modified dijets and jet-induced medium excitations and hadrons from expanding hot spots under strong radial flow. The structure therefore should be unique and insensitive to the fluctuation of the initial geometry of dense matter at a fixed impact-parameter. As shown in Fig. 4, the dihadron correlations after subtraction of contributions from harmonic flows become independent on the initial geometric triangularity ϵ_3.

In order to study the structure of dihadron azimuthal correlation from jets (including jet-induced medium excitation) and hot spots separately, we successively switch off each mechanism and calculate the dihadron correlation within AMPT model. We first randomize the azimuthal angle of each jet shower parton in the initial condition from HIJING simulations. This effectively switches off the initial back-to-back correlation of di-

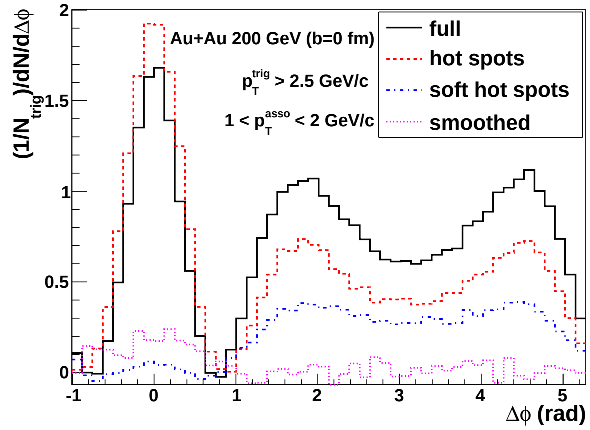

FIG. 5: (Color online) Dihadron correlation (with harmonic flow subtracted) from AMPT with different initial conditions for $p_T^{\rm trig} > 2.5$ GeV/c and $1 < p_T^{\rm asso} < 2$ GeV/c. See text for details on the different initial conditions.

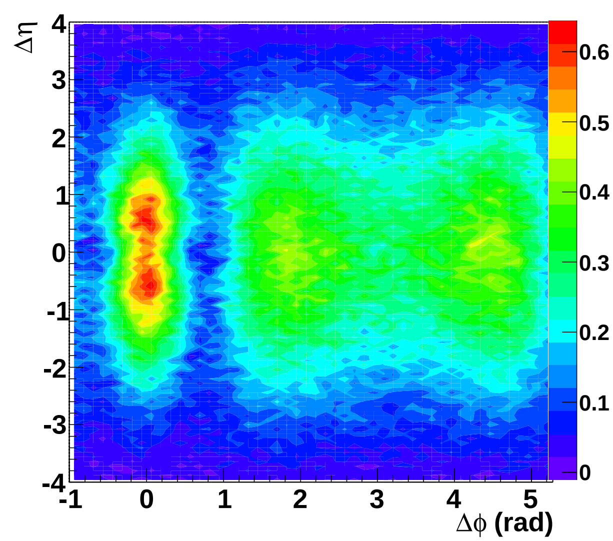

FIG. 6: (Color online) The contour plot of dihadron correlation (with harmonic flow subtracted) from AMPT in azimuthal and pseudorapidity for $p_T^{\rm trig} > 2.5$ GeV/c and $1 < p_T^{\rm asso} < 2$ GeV/c.

jets. The dihadron correlation (dashed) denoted as “hot spots” in Fig. 5 still exhibits a double-peak on the away-side that comes only from hot spots. It has roughly the same opening angle $\Delta\phi \sim 1$ (rad) as in the “full” simulation (solid). However, the magnitude of the double-peak in the away-side correlation is reduced by about 40%, which can be attributed to dihadrons from medium modified dijets and jet-induced medium excitation. Without knowing the relative yields of hadrons from jets and hot spots, it is difficult to extract dihadron correlation from dijets (and jet-induced medium excitation) alone. When

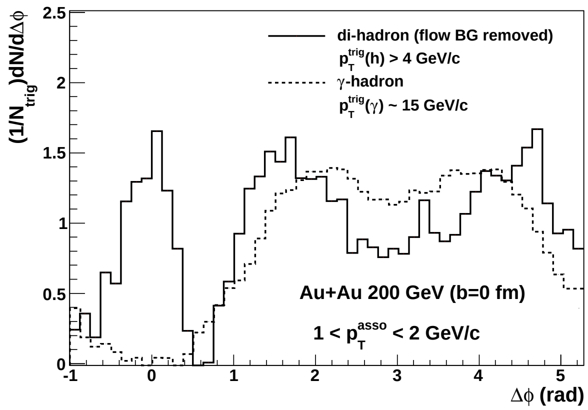

FIG. 7: Dihadron correlation (solid) compared with γ-hadron correlation (dashed) from AMPT for $p_T^{\rm trig}(h) > 4$ GeV/c, $p_T^{\rm trig}(\gamma) \geq 15$ GeV/c and $1 < p_T^{\rm asso} < 2$ GeV/c .

jet production is turned off in the HIJING initial condition, fluctuation in soft partons from strings can still form what we denote as "soft hot spots" that lead to a back-to-back dihadron correlation (dot-dashed) with a weak double-peak. It is clear that jet shower partons increase the local parton density in "hot spots" and lead to a stronger double-peaked dihadron correlation than that of "soft hot spots". Such "soft hot spots" are the likely candidate mechanism for the observed back-to-back dihadron correlation in heavy-ion collisions at the SPS energy [24] where jet production is insignificant. Without jets in AMPT, one can further randomize the polar angle of transverse coordinates of soft partons and therefore eliminate the "soft hot spots". The dihadron correlation from such "smoothed" initial condition becomes almost flat (dotted).

Because of the elongated shape of hot spots in the longitudinal direction as shown in Fig. 1 (left panel), the structure of dihadron azimuthal correlation should remain similar with a large range of rapidity gaps as shown in Fig. 6. Since dihadron correlation from a single jet is only restricted to small rapidity gap $\delta\eta \sim 1$, the near-side azimuthal correlation with a large rapidity gap, referred to as ridge, can only come from a hot spot. This is confirmed by our observation that dihadron correlation in AMPT with the "smoothed" initial conditions does not have any ridge structure. In addition, jet production is approximately proportional to binary nucleon-nucleon collisions and should also be correlated with hot spots. Therefore, the ridge in dihadron correlation can occur for both hard and soft trigger hadrons. In non-central collisions, the effects of jet-medium interaction and hot spots are shown to give only a broad single peak in dihadron correlation on the away-side [25]. With a large rapidity gap, it amounts to a dihadron correlation due to momentum conservation [26].

Since hard direct photons are produced uniformly in azimuthal angle, any structure in γ-hadron azimuthal correlation with large $p^{\gamma}_{\rm trig}$ can only come from γ-triggered jets and jet-induced medium excitation [10]. Shown in Fig. 7 are dihadron correlations (solid) after subtraction of harmonic flows as compared with γ-hadron correlation (dashed). The two correlations are comparable in magnitude but dihadron has a more pronounced double-peak which can be attributed to additional dihadrons from hot spots and the geometric bias toward surface and tangential emission that enhances deflection of jet showers and jet-induced medium excitation [10] by radial flow. Such difference is important to measure in experiments that will provide critical information on jet-induced medium excitation and hydrodynamic evolution of hot spots in high-energy heavy-ion collisions.

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