System-size scan of dihadron azimuthal correlations in ultra-relativistic heavy ion collisions

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Abstract

System-size dependence of dihadron azimuthal correlations in ultra-relativistic heavy ion collision is simulated by a multi-phase transport model. The structure of correlation functions and yields of associated particles show clear participant path-length dependences in collision systems with a partonic phase. The splitting parameter and root-mean-square width of away-side correlation functions increase with collision system size from ^{14}N+^{14}N to ^{197}Au+^{197}Au collisions. The double-peak structure of away-side correlation functions can only be formed in sufficient "large" collision systems under partonic phase. The contrast between the results with partonic phase and with hadron gas could suggest some hints to study onset of deconfinment.

Key words: Di-hadron azimuthal correlation, Splitting parameter, Partonic transport

1. Introduction

Quantum Chromodynamics (QCD) calculation predicted an exotic quark-gluon matter in QCD phase diagram [1] may be created in the early stage of heavy ion collisions at ultra-relativistic energy [2]. For mapping the QCD phase diagram and locating QCD phase boundary and critical point [3], one needs to find a way to vary temperature (T) as well as chemical potential (μ_B). The NA61 collaboration and NA49-future collaboration [4] suggested that it can be achieved via a systematic energy (E) and system-size (A) ($E-A$) scan.

Jet quenching phenomenon has been theoretically predicted [5] and experimentally observed [6]. So far, dihadron azimuthal correlations have been demonstrated as a good method to reconstruct particle and energy distribution induced by the quenched jet. In experiment, a double-peak structure was found on the away side of dihadron azimuthal correlation functions [7, 8, 9] and the indication of conical emission of charged hadrons was reported by the STAR collaboration [10]. The centrality and transverse momentum dependences of double-peak structure of away-side correlation functions were experimentally investigated by RHIC-BNL [9, 11] and theoretically simulated in Ref. [12].

These interesting phenomena have attracted some theorists to explain the physical mechanisms for the origin of the double-peak structure. These mechanisms include a Cherenkov-like

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gluon radiation model [13], medium-induced gluon bremsstrahlung radiation [14, 15], shock wave model in hydrodynamic equations [16], waking the colored plasma and sonic Mach cones [17], sonic booms and diffusion wakes in thermal gauge-string duality [18], jet deflection [19] and strong parton cascade mechanism and so on [12, 20, 21, 22, 23]. Recently, Gyulassy and his collaborators suggest that the conical emission can stem from universal flow-driven mechanism [24]. In Ref. [25], the shock wave phenomena are discussed in viscous fluid dynamics and kinetic theory. Renk and Neufeld [26] presented their systematic study of dependence of the Mach cone signal on the energy deposition into the medium in linearized hydrodynamics. The path-length effect on the correlations relative to the reaction plane are studied, respectively, by Jia et al. in a simple model [27] and by Ma et al. in AMPT model [28]. In the shock wave model [16], the emission angle relative to jet is calculated to be about 1.23 rad for QGP, 1.11 rad for hadronic gas and zero for mixed phase. The gluon radiation mechanism for the double-peak structure [13] suggests that the more energetic the jet, the smaller the emission angle. In Ref. [29], it is suggested that the suppression or even disappearance of Mach cone at the QCD critical point due to the attenuation of the sound mode. While it remains unclear what the main mechanism for the emergence of the double peak structure is, all the experimental and theoretical works suggest that it should depend on the nature of the hot and dense matter created in the collisions [30, 31]. In this paper, we study the properties of hot-dense matter produced by different system size by investigating the system-size dependence of dihadron azimuthal correlations.

In this paper, we present participant path-length, defined as $\nu = 2N_{bin}/N_{part}$ [32] (N_{bin} and N_{part} are the number of binary collision and participants, respectively), dependence of the double-peak structure of away-side correlation function in the most central collisions (0-10%). The structure of away-side correlation function changes near ^{40}Ca + ^{40}Ca collisions at $\sqrt{s_{NN}} = 200$ GeV in central collisions (0-10%). The results show obvious degree of freedom dependence in the system with a partonic phase or with a pure hadron gas [33], which implies information of the onset of deconfinement.

2. Model and analysis method

In this work, a multi-phase transport model (AMPT) [34], which is a hybrid dynamic model, is employed to study dihadron azimuthal correlations. It includes four main components to describe the physics in relativistic heavy ion collisions: 1) the initial conditions from HIJING model [35], 2) partonic interactions modeled by a Parton Cascade model (ZPC) [36], 3) hadronization (discussed later), 4) hadronic rescattering simulated by A Relativistic Transport (ART) model [37]. Excited strings from HIJING are melted into partons in the AMPT version with string melting mechanism [38] (abbr. '*the Melt AMPT version*') and a simple quark coalescence model is used to combine the partons into hadrons. In the default version of AMPT model [39] (abbr. '*the Default AMPT version*'), minijet partons are recombined with their parent strings when they stop interactions and the resulting strings are converted to hadrons via the Lund string fragmentation model [40]. The Melt AMPT version undergoes a partonic phase, while a pure hadron gas is in the Default AMPT version. Details of the AMPT model can be found in a review paper [34] and previous works [34, 38, 41].

The analysis method for dihadron azimuthal correlations is similar to that used in previous experiments [31, 8], which describes the azimuthal correlation between a high p_T particle (trigger particle) and low p_T particles (associated particles). The raw signal can be obtained by accumulating pairs of trigger and associated particles into $\Delta\phi = \phi_{assoc} - \phi_{trig}$ distributions in the same event. The background which is expected mainly from elliptic flow is simulated by mixing

event method [31, 8]. To reconstruct the background, we accumulate pairs of one fake trigger particle (high p_T) in one event and another fake associated particle (low p_T) in another event to obtain the $\Delta\phi$ distribution as the corresponding background, the centralities of the above two events are requested very closed. Then the background is subtracted from raw signal by using "A Zero Yield At Minimum" (ZYAM) assumption as that used in experimental analysis [8] (see our detailed analysis in Ref. [12]). Recently, Wang et al. [42] discussed the background in the correlations and presented an analytical form for flow background to jet-like azimuthal correlations in a cluster approach. And it is suggested that the collision geometry fluctuations and triangular flow should be taken into account in the correlation analysis [43, 44, 45]. But those go beyond our discussion in this paper.

3. Results and discussions

3.1. Structure of dihadron correlation function

The participant path-length, defined as $\nu = 2N_{bin}/N_{part}$ [32], can describe degree of multiple collisions between participants in the early stage of heavy ion collisions and characterize the size of the reaction zone. The n_{col}^{parton} represents average collision number of partons in the Melt AMPT version. The values of ν and n_{col}^{parton} significantly increase with varying collision system ($CSYS$) from "small" size to "large" size at $\sqrt{s_{NN}}$ = 200 GeV in the most central collisions (0-10%) as shown in Table 1. From this table, we can see the multiple collisions are more frequent in "large" size collision system than in "small" size one. The values of N_{part}, N_{bin} and ν are comparable to those from the Glauber Model [46] for both ^{64}Cu + ^{64}Cu and ^{197}Au + ^{197}Au collisions.

When the mixed background which mainly stems from elliptic flow is subtracted from the raw dihadron correlation signal taken in the same events, we can get the correlation function. Fig. 1 shows dihadron azimuthal correlation functions of different collision systems in the most central (0-10%) collisions at $\sqrt{s_{NN}}$ = 200 GeV. The correlation functions are calculated in the kinetic windows, $1 < p_T^{assoc} < 3$ GeV/c as well as $2.5 < p_T^{trig} < 6$ GeV/c and $|\eta| < 1$. It shows that the structure of away-side correlation function changes from the Gaussian-like distribution to double-peak structure near ^{40}Ca + ^{40}Ca collisions with varying collision system from ^{14}N + ^{14}N to ^{197}Au + ^{197}Au collisions in the Melt AMPT version. In this figure, the amplitude of the correlation function becomes higher with the increasing of collision system size. The associated particles in the Melt AMPT version are more abundant than those in the Default AMPT version.

Table 1: $N_{part}(CSYS)$, $N_{bin}(CSYS)$, $\nu(CSYS) = \frac{2N_{bin}(CSYS)}{N_{part}(CSYS)}$, n_{col}^{parton} in different collision system at $\sqrt{s_{NN}}$ = 200 GeV for centrality 0-10 %, the value in blanket is taken from Glauber Model [46].

$CSYS$	^{14}N + ^{14}N	^{16}O + ^{16}O	^{23}Na + ^{23}Na	^{27}Al + ^{27}Al	^{40}Ca + ^{40}Ca	^{64}Cu + ^{64}Cu	^{197}Au + ^{197}Au
$N_{part}(CSYS)$	20.78	24.25	35.92	43.61	65.97	107.04 (99.0)	343.32 (325.9)
$N_{bin}(CSYS)$	19.63	23.69	41.01	54.34	91.15	179.98 (188.8)	914.71 (939.4)
$\nu(CSYS)$	1.89	1.95	2.28	2.49	2.76	3.36 (3.8)	5.33 (5.7)
n_{col}^{parton}	1.31	1.44	1.93	2.23	2.79	3.80	7.24

The Default AMPT version is used to compare the properties of the double-peak structure in partonic phase and in hadron gas. For investigating the properties of collision system-size

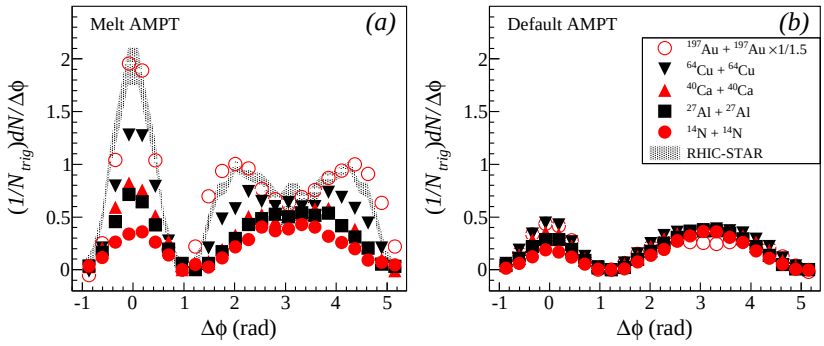

Figure 1: Dihadron azimuthal correlation functions for different collision systems in centrality 0-10% at $\sqrt{s_{NN}}$ = 200 GeV; Kinetic windows: 1 < p_T^{asso} < 3 GeV/c, 2.5 < p_T^{trig} < 6 GeV/c, $|\eta|$ <1; the shadowing area from the STAR data [7].

dependences of away-side dihadron azimuthal correlations, we extract the associated particle yield N_{away}^{assoc}, splitting parameter (D) (half distance between double peaks on the away side) and Root Mean Square Width ($\Delta\phi_{rms}$) of away-side associated particles, which will be discussed in the following sections, respectively.

3.2. Yield of associated particles

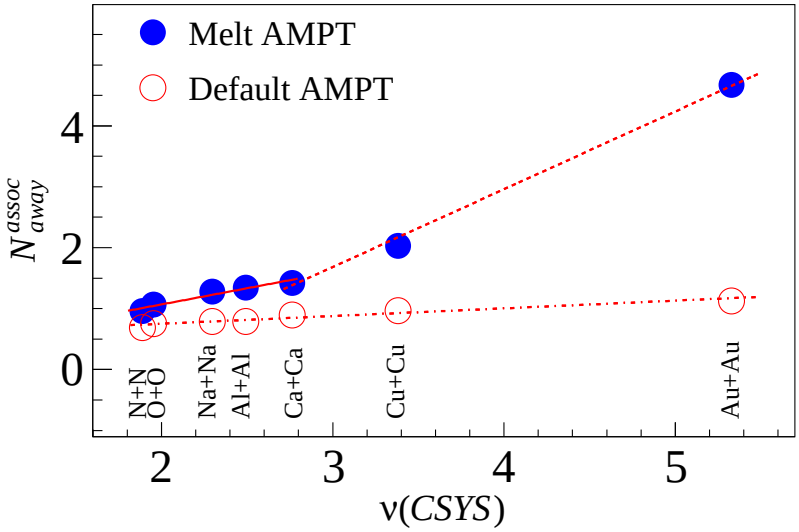

Figure 2: Yield of associated particles on away-side correlation functions, N_{away}^{assoc}, as a function of $\nu(CSYS)$ by the Melt/Default AMPT version in the centrality of 0-10% at $\sqrt{s_{NN}}$ = 200 GeV.

The $\nu(CSYS)$ dependence of N_{away}^{assoc} is shown in Fig. 2 from the Melt/ Default AMPT version, respectively. It presents a significant increasing trend of N_{away}^{assoc} with varying the collision system from ^{14}N + ^{14}N to ^{197}Au + ^{197}Au collisions in the most central collisions (0-10%) at $\sqrt{s_{NN}}$ =

200 GeV in the Melt AMPT version. The Default AMPT version, with a hadronic gas, does not result in a rapid increasing dependence trend. In the Melt AMPT version, the dependence trend indicates the jet correlation information can be inherited by and transmitted to more particles in a partonic phase than in a hadronic gas, especially in "large" size collision system. Furthermore it implies that the interaction strength in "large" size collision system is more significant than that in "small" size collision system, and while strong parton cascade plays a dominant role to push more away-side associated particles in the Melt AMPT version. It is interesting that the increasing slope of N_{away}^{assoc} vs $\nu(CSYS)$ from the linear fitting in the Melt AMPT version is quicker above ^{40}Ca + ^{40}Ca collision system, where clear double-peak structure emerges, than that in small systems. This property indicates the double-peak (Mach-like) structure can enhance associated particles yields of jet correlations partially.

3.3. $\Delta\phi_{rms}$ and splitting parameter on the away side

Root Mean Square Width ($\Delta\phi_{rms}$) of away-side correlation function is defined as

$$\Delta\phi_{rms} = \sqrt{\frac{\sum\limits_{away}(\Delta\phi - \Delta\phi_m)^2(1/N_{trig})(dN/d\Delta\phi)}{\sum\limits_{away}(1/N_{trig})(dN/d\Delta\phi)}},$$

where $\Delta\phi_m$ is the mean $\Delta\phi$ of away-side correlation function and it approximates to π. $\Delta\phi_{rms}$ can describe the diffusion degree of the associated particles relative to the direction of back jet. The $\nu(CSYS)$ dependences of $\Delta\phi_{rms}$ in the Melt/ Default AMPT version are shown in Fig. 3, respectively. $\Delta\phi_{rms}$ from the Melt AMPT version are consistent with PHENIX data [8, 47] for Cu + Cu and Au + Au collisions. $\Delta\phi_{rms}$ increases from ^{14}N + ^{14}N collisions to ^{197}Au + ^{197}Au collisions in the Melt AMPT version as well as the Default AMPT version, but the increasing trend is not so quick in the later, especially for systems larger than ^{40}Ca + ^{40}Ca. The increasing trend of $\Delta\phi_{rms}$ shows broadening of away-side correlation functions with increasing size of collision system. It indicates that the jet correlation information can reach faraway relative to direction of jet with changing the collision system from "small" size one to "large" size in a partonic phase. It is remarkable that the increasing trend of $\Delta\phi_{rms}$ from the linear fitting in the Melt AMPT version shows two different slope after and before ^{40}Ca + ^{40}Ca collision system, where clear double-peak structure emerges. The double peak (Mach-like) phenomenon from quenched jet can enhance the diffusion degree of the associated particles relative to back jet in the "large" size collision system. This suggests that the back jet modification in the medium created in heavy ion collisions with a partonic phase is more distinct in the "large" size collision system than in "small" size one.

The splitting parameter (D) is another useful observable to characterize the structure of the double-peak of away-side correlation function, and further discloses essential of jet modification. The $\nu(CSYS)$ dependence of splitting parameters (D) in the Melt/Default AMPT version are shown in Fig. 4 for the most central collisions at $\sqrt{s_{NN}}$ = 200 GeV. For lighter systems from ^{14}N + ^{14}N to ^{27}Al + ^{27}Al collisions, the splitting parameter is not extracted since there is no observable double-peak structure of away-side correlation functions. In both simulation cases, the splitting parameter (D) increases from "small" size collision system to "large" size one, which indicates that there exists stronger jet-medium interaction in "large" system. It is also remarkable that the splitting parameter (D) is larger in the Melt AMPT version than that in the Default AMPT version. The Melt AMPT results are comparable to PHENIX data [9] for Cu + Cu and Au + Au collisions due to effect of parton cascade in the Melt AMPT version [12]. The parton interaction

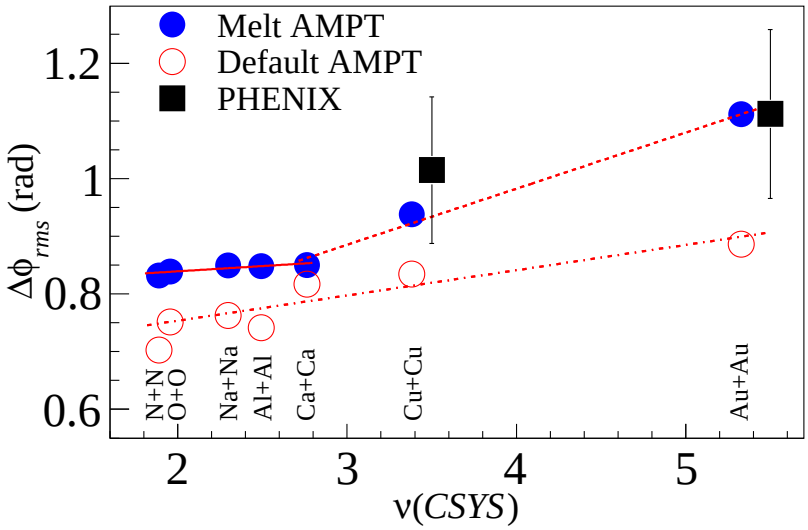

Figure 3: RMS-Width ($\Delta\phi_{rms}$) of the away-side correlation functions as a function of $\nu(CSYS)$ in the Melt/Defualt AMPT version for the centrality 0-10% at $\sqrt{s_{NN}}$ = 200 GeV; Square from PHENIX data [8, 47].

cross section is taken to be 10 mb in this work, which is also reasonable for reproducing elliptic flow as well as dihadron azimuthal correlations in the Melt AMPT version [34, 38, 41, 12]. This calculation reflects that it is necessary to pass a strong partonic stage to reproduce large enough double-peak structure as the experimental data demonstrate.

From these results, it can be concluded that a considerable "large" collision system is necessary and the strong parton cascade is essential for the formation of the double-peak structure of away-side correlation function. An onset of the observable double-peak structure occurs in the mass range of ^{40}Ca + ^{40}Ca collision. This phenomenon indicates that the correlation is sensitive to $\nu(CSYS)$ and n_{col}^{parton}, i.e. the correlation depends on the collision system size and the violent degree of the partonic interaction in a partonic phase. Different results obtained in a partonic phase and a pure hadron gas imply the double-peak structure and jet modification are sensitive to the effective degree of freedom of the dense medium created in relativistic heavy ion collisions, which can give us some hints of the onset of deconfinement in the system-size viewpoint.

4. Summary

In summary, the present work discusses the collision system-size dependence of dihadron azimuthal correlations at $\sqrt{s_{NN}}$ = 200 GeV by a multi-phase transport model. The yields of associated particles, width of away-side correlation functions and splitting parameter show significant system-size dependence. The away-side correlation function becomes more broadening with the increasing of collision system size and displays the onset of double-peak structure near ^{40}Ca + ^{40}Ca collisions after the system undergoes a strong partonic transport stage. These results also present the degree of freedom dependence, which might be related to onset of deconfinement. We would remark that these observations do not assume any dynamical mechanism for the

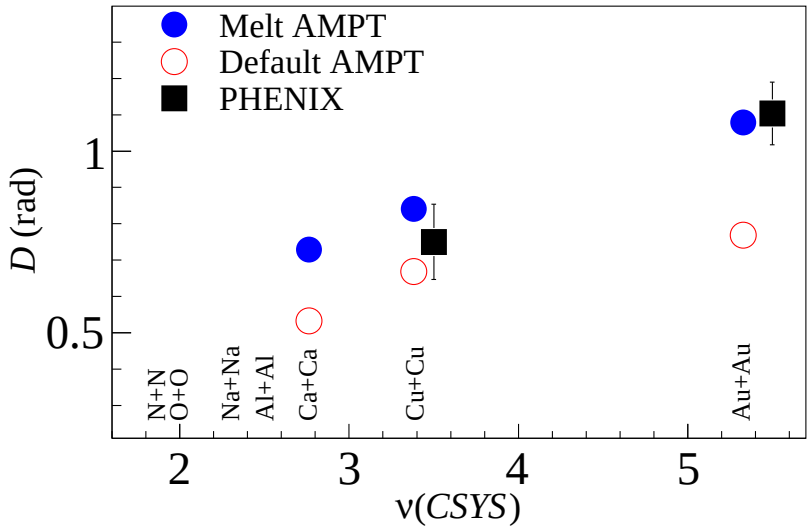

Figure 4: Splitting parameter (D) of the away-side correlation functions as a function of $\nu(CSYS)$ in the Melt/Defualt AMPT version for the centrality 0-10% at $\sqrt{s_{NN}}$ = 200 GeV; Square from PHENIX data [9].

formation of the double hump structure. The AMPT model would include collective Mach-like effects associated to the particles, but it would also include eccentricity fluctuating effects and triangle flow components. The result is, in this sense, robust.

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