Collisional broadening of angular correlations in a multiphase transport model

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(Dated: September 21, 2016)

Systematic comparisons of jetlike correlation data to radiative and collisional energy loss model calculations are essential to extract transport properties of the quark-gluon medium created in relativistic heavy ion collisions. This paper presents a transport study of collisional broadening of jetlike correlations, by following parton-parton collision history in a multiphase transport (AMPT) model. The correlation shape is studied as a function of the number of parton-parton collisions suffered by a high transverse momentum probe parton ($N_{\text{coll}}$) and the azimuth of the probe relative to the reaction plane ($\phi_{\text{fin}}$). Correlation is found to broaden with increasing $N_{\text{coll}}$ and $\phi_{\text{fin}}$ from in- to out-of-plane direction. This study provides a transport model benchmark for future jet-medium interaction studies.

PACS numbers: 25.15.+j, 25.75.Gz

I. INTRODUCTION

Relativistic heavy ion collisions aim to create quark-gluon plasma (QGP) to allow study of quantum chromodynamics (QCD) at the extreme conditions of high temperature and energy density. The system created in these collisions is described well by hydrodynamics where the high pressure buildup drives the system to expand at relativistic speed. Hydrodynamics inspired model fit to experimental data at low transverse momentum. The high temperature buildup drives the system to expand at relativistic speed. The system created in these collisions is described well by hydrodynamics where the high pressure buildup drives the system to expand at relativistic speed. The system created in these collisions is described well by hydrodynamics where the high pressure buildup drives the system to expand at relativistic speed. They traverse and interact with the medium and lose energy. Due to the energy loss, the number of high-$p_T$ particles is suppressed by a factor of several in heavy ion collisions compared to properly normalized proton-proton collisions. How the parton showers (jet shape) change from proton-proton collisions to heavy ion collisions, due to parton-medium interactions, is a valuable tool to study jet-medium interactions.

Jets lose energy via gluon radiations and collisions of the parent parton and/or the daughter fragments with medium particles. Particle angular correlations with high-$p_T$ particles, originating from jets, imprint all those information, including the medium particles that are not originated from jets but now correlated with the jet due to interactions. Collisional energy loss has been studied by various models. The focus of those studies has been on the amount of the energy loss by energetic partons, not on the angular correlations induced by parton-parton collisions. In this paper, we study the effect of collisional energy loss on jetlike correlations. We use, for the first time, a multiphase transport (AMPT) model for our study. We trace the collision history of high-$p_T$ partons (referred to as probe partons), one by one, with partons from the medium (referred to as medium partons). We study the angular correlation width as a function of the medium parton $p_T$ and the number of parton-parton collisions suffered by each high-$p_T$ probe parton ($N_{\text{coll}}$). Of particular interest are non-central collisions where the overlap zone of the colliding nuclei is anisotropic in the transverse plane (perpendicular to beam). The interaction strength varies with the azimuthal angle of the probe parton relative to the reaction plane (RP), which is experimentally accessible.

We note, however, AMPT does not have jet production. The initial (di)jets produced in HIJING simulation, used as the initial condition to AMPT, are treated by AMPT as energies for parton liberation. The high-$p_T$ particles and the angular correlations of dijets are destroyed. In fact, the probe partons and medium partons are both from the medium in AMPT; there is no distinction between the two except that the probe partons are required to have an initial $p_T$ of at least 3 GeV/$c$. It is, however, still relevant to use a high-$p_T$ parton in AMPT as a probe and study the effect of its collisional energy loss as it propagates through the medium; it does not matter whether or not the probe parton is originated from a jet. The probe parton that has suffered relatively few collisions and emerges still as a high-$p_T$ parton can be viewed as the near-side particle in jet correlation terminology; likewise, the probe parton that has suffered many collisions and become a low-$p_T$ parton at freezeout can be viewed as emerging on the away side. To have focused discussion, we will use the jet terminology, namely jetlike correlations, to referred to the parton-parton correlations we study in this paper.

II. MODEL SETUP AND ANALYSIS TECHNIQUE

AMPT has been widely used to describe experimental data. The string melting version of AMPT reasonably reproduces particle yields, $p_T$ spectra, and elliptic flow of low-$p_T$ pions and kaons in central and
mid-central Au+Au collisions at nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 200$ GeV and Pb+Pb collisions at $\sqrt{s_{NN}} = 2760$ GeV \cite{24}. We employ the same string melting version of AMPT (v2.26t5) in this study. The model consists of fluctuating initial conditions inherited from Glauber nuclear geometry in HIJING \cite{35, 36}, $2 \rightarrow 2$ parton elastic scatterings \cite{37}, quark coalescence for hadronization \cite{29, 38}, and hadronic interactions \cite{29, 39}. Parton-parton interaction stops when no parton pairs can be found within their interaction range, given by parton-parton interaction cross section. We use Debye screened differential cross-section $d\sigma/dt \propto \alpha_s^2/(t - \mu_D^2)^2$ \cite{29}, with strong coupling constant $\alpha_s = 0.33$ and Debye screening mass $\mu_D = 2.265$/fm. The total parton scattering cross section is then $\sigma = 3$ mb.

We have simulated 200,000 Au+Au collisions with fixed impact parameter $b = 8$ fm at 200 A GeV using AMPT. We trace the collision history of the initially produced high-$p_T$ probe partons. We know exactly which medium partons have interacted with the probe parton. We study the correlations of those medium partons with the probe partons. We focus only on the parton level angular correlations. All results shown in this study are for partons within pseudo-rapidity window $|\eta| < 2$; $\eta \equiv -\ln \theta/2$ where $\theta$ is the polar angle relative to the beam direction.

### III. RESULTS

#### A. Collisional broadening

Figure 1 shows the $p_T$ distributions of the probe partons. The black histogram shows the initial probe parton $p_T$ (which we require to be at least 3 GeV/c). The dark green histogram shows the final-state $p_T$ of those partons. Significant energy is lost on average by the high-$p_T$ probe partons and the final-state $p_T$ can be very small. The number of high-$p_T$ partons is reduced by a factor of 3-4, and the reduction factor is approximately $p_T$ independent. The red and blue histograms show the final-state $p_T$ of partons having suffered, respectively, no more than 2 and more than 2 collisions with other partons. The more the collisions, the more the energy loss on average. Due to energy loss (parton-parton interactions in general), partons emerging in one particular direction come preferentially from the region close to the surface in that direction. This surface bias is stronger for high-$p_T$ partons emerging in the final state.

Figure 2 shows the normalized azimuthal correlation functions of medium partons with the probe parton, initially at high $p_T$. There is no cut on the probe final-state $p_T$; all probe partons are included. Different $p_T$ ranges of the correlated medium partons are shown. The correlation function is broader for lower $p_T$ medium partons. This is because low-$p_T$ particles can be more easily scattered to large angles. Note that the medium partons included in the plot are only those that have interacted with the probe parton in the evolution history. We do not need to do any background subtraction in this study because we know exactly which partons from the medium have interacted with the probe parton.

Figure 3 shows the correlation functions of a particular medium parton $p_T$ range for different number of collisions ($N_{\text{coll}}$) suffered by the probe parton. The correlation broadens with increasing $N_{\text{coll}}$, as expected. We fit the correlations to the sum of a Gaussian plus a constant pedestal (referred to hereon as Gaussian+pedestal), $dN/d\Delta \phi = A \exp\left(-\frac{(\Delta \phi - \alpha)^2}{2 \sigma^2}\right) + C$ where $A$, $\alpha$, $\sigma$, and $C$ are fit parameters. The Gaussian $\sigma$ is shown in the inset of Fig. 3 quantitatively indicating the broadening of the correlations with increasing $N_{\text{coll}}$.

#### B. Pathlength dependence

In non-central collisions, the overlap collision zone between the two nuclei is almond shaped. One expects partons in the long-axis direction to suffer more collisions than those in the short-axis direction. This is indeed true in AMPT. As a consequence, the correlation function broadens as the probe parton varies from the short-axis direction to the long-axis direction. This is shown in Fig. 4 by the filled black circles where the Gaussian+pedestal fit $\sigma$ is plotted as a function of $p_T$. The other data points will be discussed later.

Because of parton-parton interactions, the parton’s final-state momentum is generally correlated with its
freeze-out position. This is referred to as radial flow and could be a consequence of hydrodynamic expansion of the collision system. The probe partons generally move along with the medium partons. For example, the majority of probe partons with positive $\phi_{\text{fin.}}$, i.e. counter-clockwise (c.c.w.) from the RP, comes from the first (and third) quadrant. However, there are probe partons with positive $\phi_{\text{probe}}$ that come from the fourth (and second) quadrant, although their population is relatively small. These partons move more or less orthogonally with respect to the medium flow. Similarly for probe partons with negative $\phi_{\text{fin.}}$, i.e. clockwise (c.w.) from the RP. One can imagine that the correlation functions of these two groups of probe partons with the medium partons would be very different. This is indeed true and shown in Fig. 5 left and middle panels: the direction of motion of the probe is indicated by the cartoon insert. For those probe partons moving along the medium flow (left panel), the fit Gaussian centroids are slightly offset from $\Delta \phi = 0$. For those probe partons that move orthogonally from the medium flow (middle panel), the angular correlation function is significantly offset from $\Delta \phi = 0$; which direction of the offset depends on whether the probe parton is c.w. or c.c.w. For probe partons moving in the direction c.c.w. away from the RP (red arrows in the insert cartoon in Fig. 5 middle panel), the correlation is strongly shifted toward negative $\Delta \phi$, because the medium partons mostly move in the direction toward the more negative azimuth from the probe parton direction. Likewise, for those moving in the direction c.w. away from the RP, the correlation is shifted to the positive side. Note the correlation functions for probes c.w. and c.c.w. away from the RP are, by definition, reflectively symmetric about $\Delta \phi = 0$, and this is apparent in Fig. 5. The correlation functions have been normalized by dividing by the number of probe partons ($N_{\text{probe}}$). There are relatively few probe partons that move against than along the medium flow, and this is reflected by the relative statistical precision between the left and middle panels of Fig. 5.

Unfortunately, because the parton configuration space positions are not experimental accessible, one cannot select probes according to the directions in Fig. 5 left and middle panels. One can only select particles according to their momentum direction, either c.w. or c.c.w. away from the RP. The correlation functions for such selections are shown in the right panel of Fig. 5. The offsets appear to be averaged out (note the average is weighted by the number of probe partons), and the correlation functions do not seem to be asymmetric any more, according to AMPT. This result is surprising as the sum correlation function does not have to be symmetric a priori; there is no physics requirement for a symmetry in the correlation function. The shape is determined by the relative abundance of the probe parton populations and the shapes of the individual correlation functions of the two sources. The fact that it is symmetric from AMPT must be accidental. Experimentally, it is still interesting to look for this possible asymmetry as it would provide sensitive information to the medium dynamics.

Since AMPT does not show significant difference be-
reaction-plane dependent correlation studies with the
ity (i.e. amount of jet-medium interactions) [44]. The
jetlike correlation width increases with collision central-
with a novel, robust flow subtraction method, show that
background subtraction [32, 33, 40–43]. Recent studies,
intermediate
pathlength dependent effect of parton-parton inter-
tegrated together, but also physics dynamics, namely
not simply due to the asymmetric correlation functions
for all selections. This indicates that the broadening is
increasing trend from in-plane to out-of-plane is observed
in Fig. 4. The Gaussian+pedestal fit $\sigma$ as a function of the
probe parton $\phi_{\text{fin.}}^\text{probe}$ (filled black circles). The other, colored data points show the corresponding fit $\sigma$ for the different configurations studied in Fig. 3; some of the data points are shifted horizontally for clarity.

tween c.w. and c.c.w. probe partons, we have combined them in Figs. 2, 3 and 4. The Gaussian centroid is treated as a free parameter for all fits in this paper, but the combined correlation function is by definition symmetric and we could simply fix the Gaussian centroid to zero and obtain the same results. However, since the correlation function is the sum of various sources, it is important to ask whether the broadening from in- to out-of-plane observed in Fig. 4 is due to real dynamics or simply different weightings of the various sources for in- and out-of-plane probe partons. To check this, we show in Fig. 4 also the Gaussian fit $\sigma$ for the various selections of the probe direction, together with that of the overall correlation function without distinguishing between c.w. or c.c.w. directions in the filled black circles. The general increasing trend from in-plane to out-of-plane is observed for all selections. This indicates that the broadening is not simply due to the asymmetric correlation functions integrated together, but also physics dynamics, namely the pathlength dependent effect of parton-parton interactions.

Experimental studies of jetlike correlations at low-to-
in- and out-of-plane probe partons. To check this, we show in
Intermediate
Jetlike correlation shape modification in heavy ion medium contains valuable information about the medium properties and partonic energy loss mechanisms, including both radiative and collisional energy losses. In order to learn about the medium properties, comparisons of jetlike correlation data to combinations of various radiative and collisional energy loss models are essential. Our transport model study of collisional energy loss effect on jetlike correlations should, therefore, provide useful benchmark in the study of jet-medium interactions.

As mentioned in the introduction, there is no dijet production in AMPT. We have only studied the correlations with respect to a single, initially energetic parton produced in AMPT. In the future, we plan to study collisional energy loss and jet broadening by embedding Pythia dijets into AMPT and follow the collision history of both the jet partners.

V. ACKNOWLEDGMENTS

This work was supported in part by the National Natural Science Foundation of China (Grant Nos. 11375062, 11547312) and the U.S. Department of Energy (Grant No. DE-FG02-88ER40412).
FIG. 5: Per probe normalized azimuthal correlation functions for probe partons within $68 < \phi_{\text{probe}} < \pi/3$ (red histograms) and $-\pi/3 < \phi_{\text{probe}} < -6$ blue points), separately. (a) The probe parton moves “along” the medium flow; (b) The probe parton moves “against” the medium flow; (c) The sum of the two cases. See the insert cartoon in panels (a), (b).

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