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Medium excitation by jet shower propagation inside a quark-gluon plasma is studied within a linear Boltzmann transport and the AMPT model. Contrary to the naive expectation, it is the deflection of both the jet shower and the Mach-cone-like excitation in an expanding medium that is found to gives rise to a double-peak azimuthal particle distribution with respect to the initial jet direction. Such deflection is the strongest for hadron-triggered jets which are often produced close to the surface of dense medium due to trigger-bias and travel against or tangential to the radial flow. Without such trigger bias, the effect of deflection on γ-jet showers and their medium excitation is weaker. Comparative study of hadron and γ-triggered particle correlations can therefore reveal the dynamics of jet-induced medium excitation in high-energy heavy-ion collisions.

Strong jet quenching has been observed in experiments [1–4] at the Relativistic Heavy-ion Collider (RHIC) as a consequence of jet quenching or parton energy loss in high-energy heavy-ion collisions [5]. The energy and momentum lost by a propagating parton will be carried by radiated gluons and recoiled medium partons which in turn will go through further interaction and eventually lead to collective medium excitation such as supersonic waves or Mach cones [6, 7]. Indeed, Mach cones have been found in the solutions of both hydrodynamic response [8–12] and linearized Einstein equations in string theory [13, 14] excited by a propagating jet. Such collective excitation by a propagating jet is expected to be responsible for the observed conic back-to-back (b2b) azimuthal dihadron [15, 16] and trihadron correlations [17] with a maximum opening angle of $\Delta\phi \approx 1$ (rad) relative to the back-side of a triggered high-p_T hadron. However, hadron spectra from the freeze-out of the Mach cone in both hydrodynamics with realistic energy-momentum deposition by jets [6, 9, 10] and string calculations in the hydrodynamic regime [14] fail to reproduce the observed conic azimuthal correlations. Such correlations on the other hand are observed in the AMPT Monte Carlo simulations [18] which could come from jet induced wakes that are deflected by a radially expanding medium [10].

Dihadrons with a high-p_T trigger are mostly dominated by b2b jets that are produced close to the surface of the dense matter [19] with the away-side jets often traveling against or tangential to the radial flow. Deflection of these jet showers and associated Mach cones by the radial flow can lead to double-peaked hadron azimuthal correlations. On the other hand, high-p_T γ's are produced throughout the volume of the dense matter [20]. The effect of deflection should be reduced for γ-triggered jet showers after averaging over all possible production position and propagation direction, leading to a weaker double-hump γ-hadron correlation as compared to dihadron correlation.

In this Letter, we will study medium excitation by a propagating jet shower using both a linear Boltzmann transport and AMPT model [21]. We will illustrate that while a Mach-cone-like excitation by a propagating jet in a uniform medium cannot give rise to a conic distribution of the final partons, deflection of the jet shower and the Mach-cone-like excitation in an expanding medium will result in a double-peaked azimuthal distribution as observed in dihadron measurements [15, 16]. Because of the different geometric distributions and propagation direction of the initial produced jets, we will illustrate that γ-hadron and dihadron azimuthal correlation will be quantitatively different, depending on the value of jet-medium cross section. We therefore propose to use comparative study of γ-hadron and dihadron azimuthal correlations to shed light on the dynamics of jet-induced Mach-cone-like excitation in high-energy heavy-ion collisions. It can also disentangle other mechanisms such as triangular flow [22] and hot spots [23] that contribute to dihadron but not γ-hadron azimuthal correlation, though they in general enhance jet-medium interaction and the resulting medium modification of γ-hadron and dihadron azimuthal correlations.

We first study the jet shower propagation and medium excitation through a linearized Monte Carlo simulation of the Boltzmann transport equation

$$
\begin{aligned}
p_1 \cdot \partial f_1(p_1) &= -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) |M_{12\to34}|^2 \\
&\times (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4),
\end{aligned} \tag{1}
$$

including only elastic $1 + 2 \to 3 + 4$ processes as given by the matrix elements $M_{12\to34}$, where $dp_i \equiv d^3p_i/[2E_i(2\pi)^3]$, $f_i = 1/(e^{p_i \cdot u/T} \pm 1)$ $(i = 2, 4)$ are thermal parton phase-space densities in a medium with local temperature T and flow velocity $u = (1, \vec{v})/\sqrt{1-v^2}$, $f_i = (2\pi)^3 \delta^3(\vec{p} - \vec{p}_i)\delta^3(\vec{x} - \vec{x}_i)$ $(i = 1, 3)$ are the jet shower parton phase-space densities before and after scattering, and we neglect the quantum statistics in the final state of the scattering. We will consider quark propagation in a thermal medium and assume small angle approximation of the elastic scattering amplitude $|M_{12\to34}|^2 = Cg^4(s^2 +$

$u^2)/(t+\mu^2)^2$ with a screened gluon propagator, where s, t and u are Mandelstam variables, $C=1$ (9/4) is the color factor for quark-gluon (gluon-gluon) scattering and μ is the screening mass which we consider here as a constant cut-off of small angle scattering. The corresponding elastic cross section is $d\sigma/dt = |M_{12\to34}|^2 /16\pi s^2$.

We assume partons follow classical trajectories between scatterings and keep track of the propagation of both jet shower partons and the recoiled medium parton after each scattering. Both the jet and recoiled medium parton are allowed to scatter again with other medium partons as they further propagate. We determine the probability of jet-medium scattering in each time step Δt_j according to an exponential distribution

$$P_i = 1 - \exp[-\sum_j \Delta x_j \cdot u \, \sigma_i \rho(\vec{x}_j, t_j)], \qquad (2)$$

where σ_i is the scattering cross section between jet and medium partons, the sum is over the time steps along the classical trajectory since the last scattering and ρ is the local medium parton density. For each scattering, we keep record of both the leading jet parton (p_3) and the recoil medium parton (p_4). Thermal partons with the initial momentum (p_2) will be subtracted from final parton phase-space density to account for the back-reaction in the Boltzmann transport equation. The net parton phase-space density $\delta f(p)$ averaged over many events will be the medium excitation by the propagating jet. We call such Monte Carlo simulation a linearized Boltzmann jet transport since we neglect scatterings between recoiled medium partons. This is a good approximation to the full Boltzmann jet transport as long as the medium excitation remains relatively small $\delta f(p) \ll f(p)$.

Within such a linearized Boltzmann jet transport one can study not only parton energy loss but also the evolution of the medium excitation induced by the propagating jet. Shown in the upper panel of Fig. 1 are the contour plots of the energy density $rdE/drdz$ of the medium excitation induced by a quark with initial energy $E = 20$ GeV at different times since the start of the propagation along z direction in a uniform medium with temperature $T = 300$ MeV. We used $\alpha_s = 0.5$ and $\mu = 1.0$ GeV. One can clearly see the formation of Mach-cone-like medium excitation at later times and a diffusion wake behind the jet which has negative energy density due to depletion of partons in this region by the propagating jet, similar to results of the linearized hydrodynamic response [6, 8, 11, 12] and string theory [13, 14] calculations.

We can also calculate parton spectra at different times, corresponding to equal-time freeze-out in hydrodynamic studies. Shown in the lower panel of Fig. 1 are the azimuthal distributions of partons from the medium excitation at different times. At early times, the azimuthal distribution is dominated by recoil thermal partons from the primary jet-medium scattering, which is given by the collision kernel in the Boltzmann equation. It has a double-hump feature in the azimuthal distribution for low energy partons with opening angles determined by the
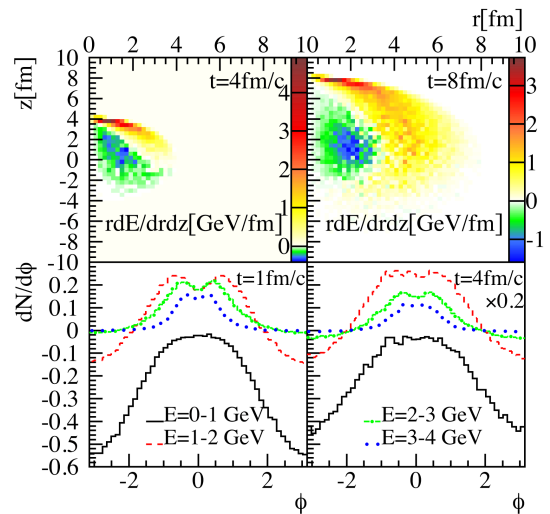

FIG. 1: (Color online) Contour plot of energy density $rdE/drdz$ of medium excitation induced by a quark with initial energy $E = 20$ GeV that propagates in the z direction in a uniform gluonic medium (upper panel) and the corresponding azimuthal parton distributions (lower panel).

value of temperature and screening mass μ in the scattering matrix element. As a parton propagates through the medium, such recoil thermal partons alway accompany it as the neck of the Mach-cone-like excitation. This is very similar to the non-equilibrium part of jet-induced medium excitation in the AdS/CFT study [25].

At later times, the recoil medium partons from the primary jet-medium interaction will scatter with other thermal partons as they further propagate through the medium, causing diffusion of the wake front. As a consequence, low energy partons from the body of the Mach-cone-like excitation overwhelm that from the neck and the final azimuthal distribution has only a broad single peak along the direction of the propagating jet.

The hot matter created in high-energy heavy-ion collisions has a finite initial transverse size as given by that of two colliding nuclei. Because of the tremendous initial pressure, the hot matter will experience rapid transverse expansion and develop strong radial flow. The non-uniformity over a finite transverse size and strong radial flow of the hot medium should influence the propagation of jet showers and their medium excitation.

To take into account of the dynamical evolution of the hot matter in our linearized Boltzmann jet transport model, we will use the numerical results from a (3+1)D ideal hydrodynamical calculation [26] for local temperature and flow velocities, from which we generate thermal momentum p_2 and p_4 for each jet shower and medium parton interaction in Eq. (1). We also use HIJING Monte Carlo model [27] to provide the initial jet shower parton distribution which consists of multiple partons from the final-state radiation in γ-jet events. Shown in the upper panel of Fig. 2 are the contour plots of the energy density in both transverse (x-y) and the beam (x-z) plane

excited by a γ-triggered jet shower with initial position $(x, y, z) = (-4, 0, 0)$ fm and energy $E_T^\gamma = 20$ GeV in central $Au+Au$ collisions at $\sqrt{s} = 200$ GeV/n. As compared to the case of a uniform medium, the shape of the medium excitation is distorted considerably by the transverse and longitudinal flow of the expanding medium. The distortion depends on the direction of the jet propagation relative to the flow.
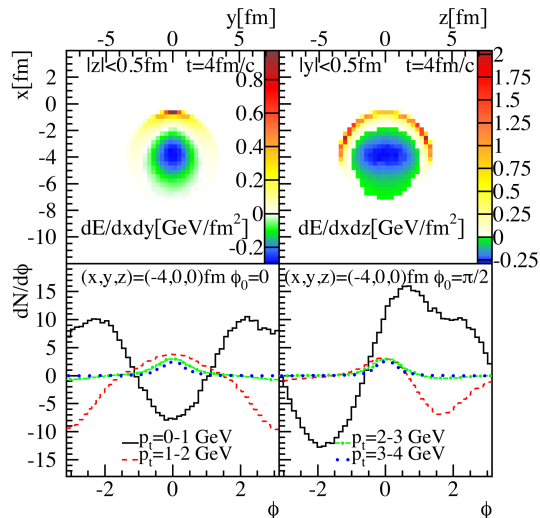

FIG. 2: (Color online) (upper panel) Contour plot in the transverse (x-y) and beam (x-z) plane of energy density excited by a quark jet shower with $E_T = 20$ GeV and initial position at $(x, y, z) = (-4, 0, 0)$ fm and travels toward the center of the expanding medium as given by ideal hydrodynamics [26] for central $Au+Au$ collisions at the RHIC energy. The azimuthal distribution of medium and jet shower partons when the jet shower travels against (lower left) and perpendicular (lower right) to the transverse flow.

The azimuthal distribution of partons from both the jet shower and jet-induced medium excitation is also distorted by the transverse flow and the non-uniformity of the dense medium. To illustrate the influence of transverse flow and the density gradience, we show in the lower panel of Fig. 2 the azimuthal distribution of jet shower and medium partons from a γ-triggered jet that is produced at an initial position $(x, y, z) = (-4, 0, 0)$ fm away from the center of the dense medium and propagating against (lower left) and perpendicular (lower right) to the radial flow, respectively. For a tangentially propagating jet shower (lower right), low p_T partons from the jet shower and Mach-cone-like excitation are clearly deflected by both the density gradience (we verify this by setting the transverse flow velocity to zero) and the radial flow, giving rise to the azimuthal distributions that peak at an angle away from the initial jet direction. For jet showers that travel against the radial flow (lower left), the same deflection essentially splits the azimuthal distribution of low p_T partons to become a double-peaked one. Such deflection in an expanding system is also observed in an ideal hydrodynamical study of Mach cone

propagation [10] and it will give rise to both the diagonal (tangential jet showers) and off-diagonal (split jet shower) part of the 3 particle correlation if analyzed as in the experimental study [17]. The magnitude of the conic correlations depends on the parton cross section while the opening (deflection) angle also depends on the radial flow velocity.

To obtain the final jet-induced medium parton distribution in γ-jet events in heavy-ion collisions, one should average over the propagation direction and the initial production positions that are distributed in the transverse plane according to the binary collisions with the nuclear geometry. The averaged azimuthal distribution is found to have a broadened single peak in the jet direction for small values of the parton cross section. The deflection is expected to give a double-peak azimuthal parton distribution for sufficiently large values of the parton cross section. However, within the linearized Boltzmann jet transport model, larger parton cross sections will lead to larger amplitudes of the medium excitation and eventually the linear Boltzmann transport breaks down which neglects interaction among jet-excited medium partons.
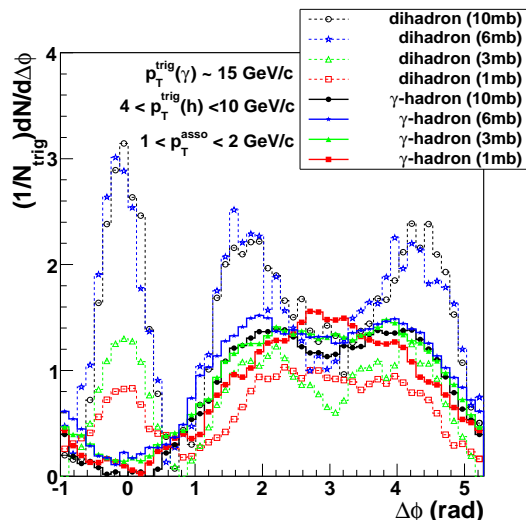

FIG. 3: (Color online) Dihadron (open symbol) and γ-hadron (filled symbol) azimuthal correlation from AMPT [21] model calculation with different values of parton cross section.

To go beyond the linear Boltzmann transport, we use the AMPT Monte Carlo model to simulate hadron and γ-triggered jet events and study jet-induced medium excitation. AMPT [21] is essentially a full Boltzmann parton and hadron transport model with only elastic parton collisions and initial conditions given by HIJING model [27]. Shown in Fig. 3 are azimuthal distributions of hadrons (with $p_T^{asso} = 1 - 2$ GeV/c) associated with both a high-p_T trigger γ (closed symbols with solid lines) and hadron (open symbols with dashed lines) in central $Au+Au$ collisions at the RHIC energy with different values of the parton cross section. The hadron correlations develop a double-peak feature in the opposite direction of the trig-
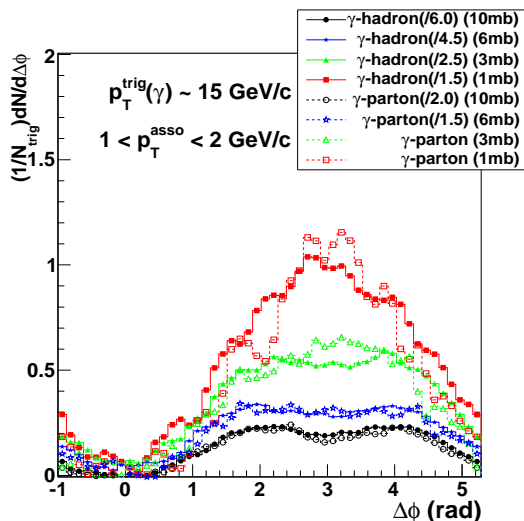
FIG. 4: (Color online) γ-hadron (filled symbol) and γ-parton (open symbol) azimuthal correlation from AMPT [21] model calculation with different values of parton cross section. Results are scaled with different factors for clear presentation

ment that the deflection of jet shower and Mach-cone-like excitation by the radial flow has a stronger effect on the azimuthal dihadron correlation than γ-hadron correlation because of the difference in the trigger bias on the initial jet production position and propagation direction. Therefore comparative study of dihadron and γ-hadron azimuthal correlations can shed light on the dynamics of jet propagation, medium excitation, the strength of medium parton interaction and other effects such as hot spots [23] and triangle flow [22] in high-energy heavy-ion collisions.

Hadronization mechanism such as parton coalescence employed in AMPT model can quantitatively influence the final hadron correlation [24] as compared to the parton correlation before hadronization. As shown in Fig. 4 such an effect, as manifested in the differences between γ-hadron and γ-parton correlation before hadronization, is rather small in AMPT. We have not included inelastic parton interaction in this study but expect the results remain qualitatively the same. However, for quantitative theoretical predictions and comparison to experimental data, one should include inelastic parton interaction and hadronic interaction in the future study. In addition, the finite formation time for the jet parton shower, which is neglected in this study, will delay the jet shower and medium parton interaction and quantitatively influence the final jet-induced γ-hadron and dihadron correlations.

ger due to the deflection of jet shower and Mach-cone-like excitation by the transverse flow and density gradience as one increases the value of parton cross section. The opening angle between two peaks increases with the value of parton cross section. At very large values of the parton cross section, one should approach the hydrodynamic limit with an opening $\Delta\phi \approx 1$ (rad) for the double-peak structure. Most importantly, one can observe that the amplitudes of the double-peaks in dihadron correlations are much bigger than that of γ-hadron correlations for a given value of parton cross section, verifying our argu-

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