Jet-medium interaction and conformal relativistic fluid dynamics

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(Received 17 August 2017; published 26 March 2018)

A formalism to study the mode-by-mode response to the energy deposition of external hard partons propagating in a relativistic fluid is developed, based on a semianalytical solution of conformal fluid dynamics. The soft-particle production resulting from the jet-medium interaction is calculated, and the recoil of the viscous medium is studied for different orientations of the relativistic jets and for different values of the specific shear viscosity η/s.

DOI: 10.1103/PhysRevC.97.034914

I. INTRODUCTION

One achievement of the Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) heavy-ion program has been the realization that the medium created at those facilities—the quark-gluon plasma (QGP)—could be successfully modeled theoretically using relativistic fluid dynamics. The development of hydrodynamical models that followed has further fueled the hopes of being able to extract transport coefficients of QCD from detailed measurements of the collective behavior of soft observables in relativistic nuclear collisions [1,2].

Another remarkable property of the new state of matter created during relativistic heavy-ion collisions, the energy loss of QCD jets, has been revealed by using "hard probes," i.e., probes well calibrated with a behavior in vacuum that can be calculated within perturbative QCD (pQCD). An early suggestion about using jets as a baseline in nuclear collisions was based on elastic interactions [3] and pictured the energy loss process as similar to the ionization loss experienced by charged particles in regular matter. It was later realized that medium-induced bremsstrahlung could be even more efficient in removing energy from the hard traveling parton ("quenching the jet") [4]. Thanks to decades of progress in theory and in experiments, it is now firmly established that jet quenching in high-energy heavy-ion collisions probes the energy loss mechanisms of a hard parton traversing a hot and dense quark-gluon plasma (QGP) [5,6]. The properties of the strongly interacting medium created by colliding heavy ions at high energies, as revealed by the analysis of jets, manifest themselves mainly through transport parameters such as the transverse momentum diffusion rate, $\hat{q}$, and the elastic energy loss rate $\hat{e}$ [4,7].

How do jets affect the medium? Only recently has the medium itself been included directly in jet observables. For instance, measurements at the LHC energy have extended the reconstructed jet substructures to large jet-cone radii [8], where contributions from soft particles were found to be essential. Also, the energy imbalance observed in the dihadron correlations is restored by the relatively low transverse momentum out-of-cone particles, which highlights the significance of jet-medium interaction in a theoretical description of jets [9]. Indeed, in a recent calculation of the complete jet and of its hydrodynamic medium response [10], the theoretical interpretation of the measured jet shape requires the jet-induced medium excitations to be included in the dynamical evolution of the fluid background. Even though a growing number of efforts have been devoted to simulating jet partons propagating through a QGP medium (cf. Refs. [11–22]), a wholistic treatment which includes also the medium recoil remains challenging. Some of the complications seeking resolution stem from the dynamically evolving medium. For example, the medium expansion will distort the generated conical flow structure expected in a static system [11].

In light of the complications involved in a complete and consistent theoretical treatment in 3D involving jets and fluid background, we turn to an approach with a simpler geometry but which has a formal solution. In this work, we use the flow solution put forward by Gubser *et al.* [23,24], to develop a semianalytical formalism for the treatment of the jet-medium interaction on a mode-by-mode basis. In this way, perturbation modes of small wave numbers are captured in the linearized hydrodynamic equation of motion, while modes associated with large wave numbers can be safely ignored since they are strongly suppressed by viscosity.

To be more specific, we consider the energy-momentum conservation of the jet parton and fluid system,

$$\partial_\mu T^{\mu\nu} = \partial_\mu\left(T^{\mu\nu}_{\rm hydro} + T^{\mu\nu}_{\rm jet} + \delta T^{\mu\nu}\right) = 0, \tag{1}$$

where $T^{\mu\nu}_{\rm hydro}$ and $T^{\mu\nu}_{\rm jet}$ are energy-momentum tensors for the background fluid and the jet parton, respectively. The effect of jet-medium interaction is described by $\delta T^{\mu\nu}$. For the perturbations induced by the jet parton, the energy-momentum conservation of the whole system can be separated into the equation of motion of the background fluid $\partial_\mu T^{\mu\nu}_{\rm hydro} = 0$, and a linearized equation of motion for the jet-medium interaction [11],

$$\partial_\mu \delta T^{\mu\nu} = -\partial_\mu T^{\mu\nu}_{\rm jet} = J^\nu, \tag{2}$$

where we have written effectively the loss of energy momentum from the parton as a source current. To solve Eq. (2) with respect to the source current for jet-medium interaction, one needs the explicit form of $\delta T^{\mu\nu}$, which, however, is not given *a priori*. It is only for the long-wavelength modes (with wave number k satisfying $k\lambda_{\mathrm{mfp}} \ll 1$) that one can identify $\delta\tilde{T}^{\mu\nu}(k) = \delta\tilde{T}^{\mu\nu}_{\mathrm{hydro}}(k)$ [25] in terms of perturbations in the energy density, pressure, and flow velocity. In a mode-by-mode analysis, as in this work, this is realized naturally by focusing on long-wavelength modes [11,12,19].

Inspired by Ref. [10], by applying the Landau matching condition to the evolution of jet parton distribution function, we find the following source current in Eq. (2) for a light-like parton ($|\mathbf{v}_{\mathrm{jet}}| = c$) [26],

$$J^\mu(t,\mathbf{x}) = \hat{e}\, v^\mu_{\mathrm{jet}} n_{\mathrm{jet}}(t,\mathbf{x}), \tag{3}$$

where $\hat{e} = \langle \Delta E\rangle/dt$ is the average rate of energy loss of the jet parton and $v^\mu_{\mathrm{jet}} = (1,\mathbf{v}_{\mathrm{jet}})$ is the parton four-velocity. The density of jet partons n_{jet} contains information on the source shape. We consider a boost-invariant configuration in this work. In particular, the jet parton passing through the transverse plane presents a knife-like shape, which spans the whole rapidity range and is captured by the density as $n_{\mathrm{jet}}(t,\mathbf{x}_\perp) = \delta^{(2)}(\mathbf{x}_\perp - \mathbf{v}_{\mathrm{jet}\perp}\Delta\tau)/\tau$, where τ is the longitudinal proper time. The boost-invariant assumption of a jet parton is an idealization, but it captures qualitatively the main effect of an energetic parton going through the QGP medium. In the context of this work, a boost-invariant structure corresponds quantitatively to the mode with the longest wavelength along the space-time rapidity, whose dynamical evolution is more sensitive in the jet-medium interaction. In obtaining the source, Eq. (3), we have also assumed that the jet parton is of sufficiently high energy, $E_{\mathrm{jet}} \gg T$, so that contribution from parton transverse momentum broadening is negligible.

II. MODE-BY-MODE HYDRODYNAMICS

Solutions to fluid-dynamical equations are few and far in between, and therefore one may gain considerable insight from cases that are exactly solvable. The method developed by Gubser and Yarom for solving the equations of viscous hydrodynamics *analytically* characterizes the longitudinal and radial expansions of a conformal fluid system ($e = 3\mathcal{P}$) and incorporates rotational symmetry in azimuth and Bjorken boosts in the longitudinal direction [23,24]. Importantly, those solutions are regularly used to test modern hydrodynamics codes for accuracy [27–30].

The solution technique consists of making a coordinate transformation from Milne space-time (τ,r,ϕ,ξ), where τ is proper time and ξ is the space-time rapidity, to a $dS_3 \times R$ coordinate system (ρ,θ,ϕ,ξ), through

$$\sinh\rho = -\frac{1 - q^2\tau^2 + q^2r^2}{2q\tau}, \tag{4a}$$

$$\tan\theta = \frac{2qr}{1 + q^2\tau^2 - q^2r^2}, \tag{4b}$$

so that a SO(3) rotational symmetry becomes manifest in the subspace (θ,ϕ), for the transformed metric tensor. The parameter q in Eq. (4) specifies the inverse length scale of the system.

The background medium evolution has an analytical solution in this new coordinate system. In what follows, we shall indicate hydro variables in this new system with an overbar. While the flow four-velocity is explicitly determined as $\bar{u}^\mu = (1,0,0,0)$, with first-order viscous corrections (Navier-Stokes hydro) the energy density is solved as [23] $\bar{\epsilon}(\rho) = (\cosh\rho)^{-8/3}[\bar{T}_0 + H_0F_d(\rho)/3]^4$, where $F_d(\rho)$ is an analytical function whose form is given in Ref. [23]. In the expression of energy density, $\bar{T}_0$ and H_0 are constant parameters to be fixed by the system multiplicity and shear viscosity over entropy ratio, respectively. Owing to symmetry constraints, the energy density depends only on the de Sitter time ρ. Solutions with respect to second-order viscous corrections of a conformal fluid [31] can be achieved by solving an ordinary differential equation. Hydro variables in the original Milne space-time and in the $dS_3 \times R$ frame are related to each other through mappings associated with Eq. (4). In particular, the source term in Eq. (3) in the $dS_3 \times R$ frame becomes $\bar{J}_\mu = \hat{e}\,\bar{n}_{\mathrm{jet}}\,\bar{v}^{\mathrm{jet}}_\mu$ with, $\bar{n}_{\mathrm{jet}} = \delta(\theta - \theta(\rho))\delta(\phi - \phi(\rho))/\cosh^2\rho\sin\theta$.

Since transverse coordinates of the Milne space-time possess apparent rotational symmetry in terms of (θ,ϕ), the mode decomposition of Eq. (2) can be achieved using spherical harmonics, resulting in perturbations of temperature and flow velocity:

$$\delta\bar{T} = \bar{T}\sum_{lm}\int\frac{dk_\xi}{2\pi}t^{lm}(\rho)Y_{lm}(\theta,\phi)e^{ik_\xi\xi}, \tag{5a}$$

$$\delta\bar{u}_i = \sum_{lm}\int\frac{dk_\xi}{2\pi}\left[v_s^{lm}(\rho)\Psi_i^{lm}(\theta,\phi) + v_v^{lm}(\rho)\Phi_i^{lm}(\theta,\phi)\right]e^{ik_\xi\xi}, \tag{5b}$$

$$\delta\bar{u}_\xi = \sum_{lm}\int\frac{dk_\xi}{2\pi}v_\xi^{lm}(\rho)Y_{lm}(\theta,\phi)e^{ik_\xi\xi}. \tag{5c}$$

Here, Y_{lm} is the scalar spherical harmonics, while Ψ_i^{lm} and Φ_i^{lm} are vector spherical harmonics which have a vanishing curl and divergence in the subspace (θ,ϕ), respectively [32]. The quantity k_ξ is the conjugate coordinate of the space-time rapidity ξ. Mode decomposition in Eqs. (5) results in three scalar modes (t,v_s,v_ξ) and one vector mode v_v. Similarly, one also has the mode decomposition of the source current $\bar{J}_\mu$, which leads to a set of

$$\bar{J}_\rho = \sum_{lm}\int\frac{dk_\xi}{2\pi}c_\rho^{lm}Y_{lm}(\theta,\phi)e^{ik_\xi\xi}, \tag{6a}$$

$$\bar{J}_i = \sum_{lm}\int\frac{dk_\xi}{2\pi}\left[c_s^{lm}\Psi_i^{lm}(\theta,\phi) + c_v^{lm}\Phi_i^{lm}(\theta,\phi)\right]e^{ik_\xi\xi}, \tag{6b}$$

$$\bar{J}_\xi = \sum_{lm}\int\frac{dk_\xi}{2\pi}c_\xi^{lm}Y_{lm}(\theta,\phi)e^{ik_\xi\xi}. \tag{6c}$$

The typical length scale of each mode in the decomposition is determined by index (l,m) and k_ξ. In particular, in this boost-invariant case, in which only the modes associated with $k_\xi = 0$ contribute, we found it mostly dependent on l and it behaves like $\sim 1/(\sqrt{l}q/3)$.[1] From this, one can deduce that for a mode to be considered hydrodynamic, it must satisfy $\lambda_{\rm mfp}\sqrt{l}q/3 \sim \eta\sqrt{l}q/3sT \ll 1$. For the fluid medium created in high-energy heavy-ion collisions, this inequality is usually satisfied up to a typical value of $l \ll 10^2$.

In terms of these scalar and vector modes $\bar{\mathcal{V}}^{lm} = (t^{lm}, v_s^{lm}, v_\xi^{lm}, v_v^{lm})$, the linearized hydrodynamics Eq. (2) reduces to a set of coupled differential equations

$$\partial_\rho \bar{\mathcal{V}}^{lm}(\rho,k_\xi) = -\Gamma(\rho,l,k_\xi)\bar{\mathcal{V}}^{lm}(\rho,k_\xi) + \bar{\mathcal{S}}^{lm}(\rho,k_\xi), \qquad (7)$$

where Γ, whose explicitly expression can be found in Eq. (109) of Ref. [23], is a matrix determined by the background medium expansion. The source term $\bar{\mathcal{S}}^{lm}$ is

$$\bar{\mathcal{S}}^{lm} = \begin{pmatrix} -\frac{1}{3\bar{w}}c_\rho^{lm} \\ -\frac{2\bar{T}\tanh\rho}{3\bar{w}\bar{T}'}c_s^{lm} \\ \frac{\bar{T}}{\bar{w}(\bar{T}+H_0\tanh\rho)}c_\xi^{lm} \\ -\frac{2\bar{T}\tanh\rho}{3\bar{w}\bar{T}'}c_v^{lm} \end{pmatrix}, \qquad (8)$$

where $\bar{w} = \bar{e} + \bar{\mathcal{P}}$ is the enthalpy density.

The matrix $\Gamma(\rho,l,k_\xi)$ is block-diagonalized in such a way that the scalar modes and the vector modes decouple. Furthermore, v_ξ is also decoupled from the rest of the scalar modes when $k_\xi = 0$, corresponding to a system including also boost-invariant hydro perturbations. Thus we shall ignore the contribution of v_ξ mode in what follows. In the case of an ideal fluid with $H_0 = 0$, Γ has two scalar eigenmodes with eigenvalues

$$\lambda_\pm = -\tfrac{1}{3}\tanh\rho \pm \tfrac{1}{3}\mathrm{sech}\rho\sqrt{\sinh^2\rho - 3l(l+1)}. \qquad (9)$$

When $\sinh^2\rho < 3l(l+1)$, $\lambda_\pm$ becomes complex, indicating sound wave propagation of the scalar modes. In the original Milne space-time, complex eigenvalues of scalar modes appear mostly at late τ, while at very early τ, scalar modes are still diffusive. For the vector mode, however, $\Gamma_v = -\frac{2}{3}\tanh\rho$ is always real, which is purely diffusive. The viscous corrections damp mode evolution and the damping is systematically stronger for higher order modes (larger l) [24].

III. JET-MEDIUM INTERACTION IN HEAVY-ION COLLISIONS

We solve Eq. (7) for ultracentral Pb+Pb collisions at the LHC energy $\sqrt{s_{NN}} = 2.76$ TeV. This is done in the semi-analytical solution of conformal viscous hydrodynamics by specifying $\bar{T}_0 = 7.3$ and $1/q = 4.3$ fm [33,34]. To stress both the effects of medium expansion and dissipation, we consider three representative events with one pair of boost-invariant back-to-back jet partons ($k_\xi = 0$). These events are illustrated in Fig. 1, corresponding respectively to back-to-back partons oriented along the x axis (case I), at an angle of $\pi/3$ (case II), and at an angle of $\pi/2$ (case III), all starting from $\vec{x}_\perp^{\rm jet} = (1.0,0)$ at $\tau_0 = 0.5$ fm/c. For each of these cases, we calculate separately the medium response to the near-side and away-side jet partons, whose superposition results in the medium response to a dijet in linearized hydrodynamics. It is worth mentioning that each individual jet parton may as well be recognized as a parton in a γ jet, for which the QGP medium is transparent to the photon recoiling against a parton.

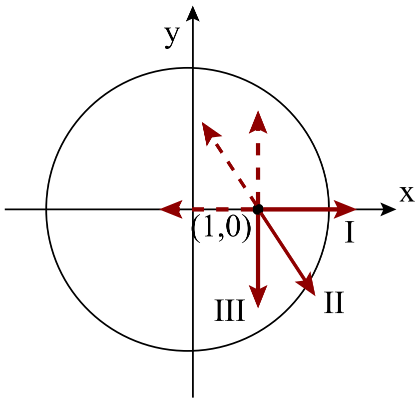

FIG. 1. Three events with dijets considered in this work. Solid arrows indicate jet partons generating the near-side (leading) peak of the observed spectrum, while dashed arrows are those generating the away-side (subleading) peak.

We adopt in this work a T^2-dependent jet energy loss rate: $\hat{e} = \kappa T^2$ [35–37], while generalization to other parametrizations is straightforward. We can determine the coefficient κ via the dissipative properties of the QGP medium. In a weakly coupled system, where medium dynamical properties can be estimated perturbatively based on a quasiparticle assumption, the coefficient is inversely proportional to the specific viscosity as $\kappa \approx s/3\eta$, from the proposed relation $1.25\,T^3/\hat{q} \approx \eta/s$ [38] and the fluctuation-dissipation relation $\hat{q} = 4\hat{e}T$ [39,40]. As a consequence, for a weakly coupled system, a jet parton loses less energy to a more viscous medium and one expects correspondingly a suppression of the jet-medium interaction inversely proportional to η/s, an effect we refer to as *dynamical* viscous suppression. Whereas for a strongly coupled system, there is no obvious relation between the coefficient κ and η/s, except a lower bound to the rate of jet energy loss, $\kappa \gg s/3\eta$, according to $1.25\,T^3/\hat{q} \ll \eta/s$ [38], and the effect of *dynamical* viscous suppression is less clear. Nevertheless, considering some extreme case of strongly coupled QCD medium where jet energy loss has very little dependence on the medium dissipative properties, *dynamical* viscous suppression may be negligible. We shall return to this point later.

One may now proceed to study the medium response to a jet parton and to also explore the effect of shear viscosity on that system. Let us first start with the weakly coupled system paradigm (which relates $\hat{q}$ with η/s), with the values of the specific shear viscosity being considered as $\eta/s = 1/4\pi$ and $2/4\pi$.[2] We have verified that, with these values, the mode summation always converged up to mode $l < 35$, so that a

[1]This is inferred empirically from the width at half maximum of the basis function of the mode decomposition.

[2]In this work, we shall take $\eta/s = 1/4\pi$ as the specific shear viscosity in a "weakly coupled" system, even though it is known

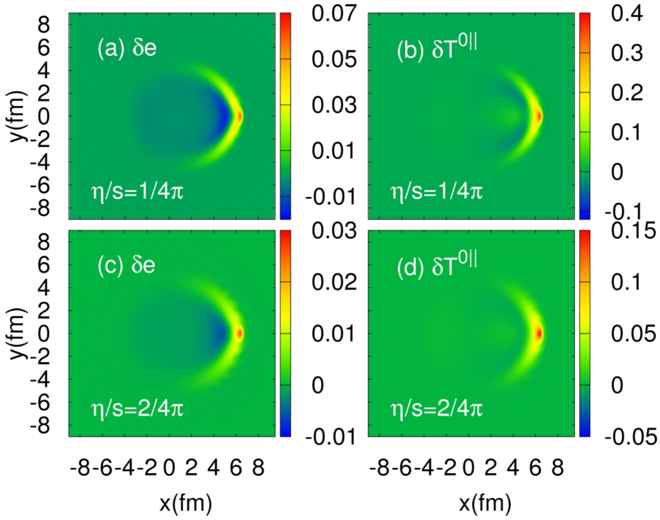

FIG. 2. Medium excitations on top of expanding viscous systems with $\eta/s = 1/4\pi$ (upper rows) and $\eta/s = 2/4\pi$ (lower rows) with respect to the near-side jet parton of event I, plotted in terms of energy density δe (left panels) and energy flux $\delta T^{0\parallel}$ (right panels), at $\tau = 6.0$ fm/c. The color coding reflects units of GeV/fm^3.

reliable solution of the jet-medium interaction was achieved for the viscous fluid. For instance, the additional contribution to the energy deposited from the jet parton becomes negligible for $l \geqslant 35$. A detailed comparison of the present result with complete numerical hydro simulations of the jet-medium interaction in Milne space-time will be given in Ref. [26].

As a supersonic object, a lightlike jet parton going through QGP creates a conical flow [11]. For a static medium, the conical flow has been found as a consequence of coherent superposition of sound wave propagation, with the cone angle θ_0^M related to the speed of sound c_s: $\theta_0^M = 2\sin^{-1}(c_s/c) \approx 70^\circ$ [11,12]. When the system expands, sound propagation gets Lorentz boosted by the radial flow, which effectively distorts the cone structure. For instance, when a jet parton goes with the medium expansion, as the trigger parton considered in our event I, the medium expansion "pushes" the sound waves outward, leading to a cone angle larger than θ_0^M. This is seen in Figs. 2(a) and 2(c), where the induced medium response on top of an expanding medium is presented in terms of perturbations of energy density δe at $\tau = 6$ fm/c.[3] Despite a larger cone angle, the formed Mach cone exhibits features very similar to those observed in a static medium [12,14]. In particular, the depletion behind the cone structure responsible for the sonic boom is observed. Sound modes also contribute to energy flux of the excited medium, which explains a similar Mach cone structure in $\delta T^{0\parallel}$ in Figs. 2(b) and 2(d). Note that in $\delta T^{0\parallel}$, a diffusive wake is generated behind the shock, which contains excited kinetic energy flowing along the jet parton. However, this diffusive wake is *not* visible in δe [12].

For a weakly coupled system, one observes that the viscous effects on the jet-medium interaction are many. First, an overall reduction of the hydro excitations in the medium response is expected due to the *dynamical* viscous suppression, which is inversely proportional to η/s. In addition, evolution of hydro modes is further damped by shear viscosity. Higher order modes get stronger relative viscous corrections [42], which is roughly proportional to $\exp(-\Delta t k^2 \eta/sT)$, with k being the wave number. (In the Gubser solution, this factor corresponds to $\exp(-l^2 H_0 \Delta\rho)$. Therefore, for each mode there is a suppression factor $\exp(-\Delta t k^2 \eta/sT)/(\eta/s)$. As a consequence, when comparing Figs. 2(c) and 2(d) to Figs. 2(a) and 2(b), although a Mach cone is formed with its angle barely affected,[4] the shock wave is smeared with its amplitude reduced. Apart from the reduction due to *dynamical* viscous suppression (by exactly a factor of 2 when increasing η/s from $1/4\pi$ to $2/4\pi$), additional reduction and smearing of the cone structure is entirely a fluidity effect reflected as the shock waves decaying and spreading some distance from the vertex, which we may refer to as the *hydro* viscous suppression. One should note that increasing specific viscosity from $1/4\pi$ to $2/4\pi$, the induced reduction of conical flow is dominated by the *dynamical* viscous suppression. In a similar way, in Figs. 2(b) and 2(d), the diffusive wake in $\delta T^{0\parallel}$ gets broadened due to medium viscous corrections.

The excited medium response to the jet partons particlizes when it is decoupled from the fluid dynamical evolution. We follow the standard Cooper-Frye freeze-out prescription [43] at a constant proper time $\tau_f = 6$ fm/c,

$$E\frac{d\delta N}{d^3p} = \int d\Sigma_\mu p^\mu \delta f, \qquad (10)$$

to compute the contributions to the particle spectrum from jet-medium interaction. In Eq. (10), δf is obtained from the difference between a system with and without external jet source, and includes the appropriate viscous correction. For simplicity, we only consider pion production from the freeze-out surface and ignore further interactions of hadrons.

In Figs. 3(a), 3(b) and 3(c), the generated pion number density of the near-side (dashed lines) and away-side (dotted lines) from jet-medium interaction are plotted separately as a function of azimuthal angle ϕ_p, with medium specific viscosity $\eta/s = 1/4\pi$. The green arrows indicate the directions of external jet partons. Medium response to an individual parton leads to a peak of width of order $O(1)$ in the associated particle spectrum. Note that the width in azimuth identifies with jet cone size in the boost-invariant configuration. The overall height of the peak is related to the total energy loss of the parton, which is further determined by the jet parton's path. The shape of the peak reflects the structure of conical flow. Superposition of the near-side and away-side gives rise to a double-peak distribution (solid lines) of the produced pions from a dijet.

to be the default specific shear viscosity for systems analyzed with gauge and gravity duality [41].

[3]At $\tau = 6$ fm/c, the medium cools down to a temperature $T \lesssim 130$ MeV, at which fluid systems in heavy-ion collisions are commonly considered to freeze-out. See later discussions for more details.

[4]This can be understood since shear viscosity in the conformal fluid system significantly changes neither the speed of sound c_s nor the medium expansion.

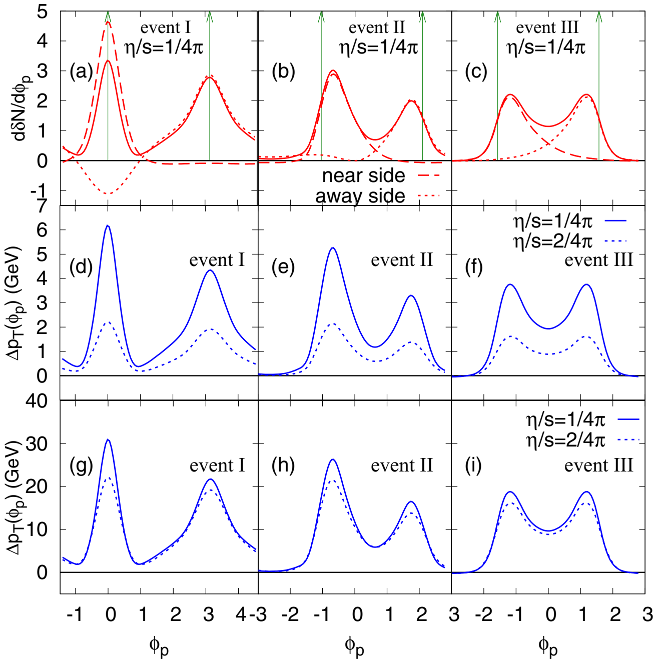

FIG. 3. First row: pion number density generated from the medium response to jet partons as a function of azimuthal angle. The near- and away-side number densities are shown separately, as well as their sum (solid line). Second row: transverse energy of the induced pions from the medium response to a dijet in a weakly coupled system. Third row: transverse energy of the induced pions from jet-medium interaction for a strongly coupled system. See the main text for more details. A lower cut of $p_T \geqslant 1$ GeV has been applied in these plots.

As a consequence of medium expansion, in events II and III, we notice that the two centers of the double peak are shifted from the original directions to back-to-back partons. It is also worth mentioning that the depletion in the Mach cone results in a depletion in the particle spectrum in the opposite direction of the jet parton, as is evident in Fig. 3(a).

Viscous effect on the associated particle spectrum is revealed in Figs. 3(d), 3(e) and 3(f), where we present the total transverse energy induced from the medium response with respect to a dijet for $\eta/s = 1/4\pi$ and $2/4\pi$, respectively. Shear viscosity affects the calculated particle spectrum in two ways. First, it smears and suppresses the induced Mach cone structure, as a combined consequence of the *dynamical* and *hydro* viscous suppressions. Second, it modifies the phase space distribution in the Cooper-Frye freeze-out. By switching on and off the viscous corrections at freeze-out, we find the latter one is actually minor. Therefore, one observes in Figs. 3(d), 3(e) and 3(f) the strong suppression of the double-peak structure due to viscosity, which again is mostly due to the *dynamical* viscous suppression. We have verified that without introducing the dynamical viscous suppression, the change in the particle spectrum in the weakly coupled system is small.

At last, let us briefly discuss the jet-medium interaction in a strongly coupled system with a negligible *dynamical* viscous suppression, with an η/s-independent jet energy loss. As a crude estimate, we consider a value of $\kappa = 20\pi/3$, so that $\kappa \gg 3s/\eta$ is roughly satisfied with respect to $\eta/s = 1/4\pi$ and $2/4\pi$. Results are shown in Figs. 3(g), 3(h), and 3(i). Despite the fact our T^2-dependent jet energy loss rate does not rigorously implement a parametrization for the strongly coupled systems, the absence of *dynamical* viscous suppression is the key factor in the analysis. Since the only viscous effect is *hydro* viscous suppression, the changes in the spectrum are entirely from viscous damping of hydro modes. As anticipated, short-scale modes get stronger viscous damping, which explains the stronger suppression around the peaks. However, the overall viscous corrections to the double-peak structure are not large. Our analysis shows, however, that the details of the jet energy-loss mechanism do leave a potentially measurable imprint on the spectra of soft produced particles.

IV. SUMMARY AND CONCLUSIONS

We have developed a formalism of solving hydrodynamical response to an external source mode by mode, based on the Gubser's solution to conformal fluid systems. With respect to the ultracentral Pb + Pb collisions at the LHC energy, the medium response to a lightlike jet parton is analyzed, in which a conical flow structure is observed. The structure of the cone receives modifications from both the medium expansion and viscous damping, which then propagates to the generated particle spectrum. After Cooper-Frye freeze-out, we observe that a relatively wide peak structure in the associated particle spectrum is generated from the conical flow.

Viscous effect on the jet-medium interaction can be revealed in the suppressed peak structure of the particle spectrum. It is a result of the *dynamical* viscous suppression, which accounts for a reduced jet energy loss rate in a more dissipative fluid, and *hydro* viscous suppression, which accounts for medium viscous damping of hydro modes. With respect to the peak structure of the particle spectrum, we found that the dominant suppression is from the *dynamical* viscous suppression, while *hydro* viscous suppression is less important, which was clearly demonstrated in the extreme case of strongly coupled system. In a weakly coupled system, where *dynamical* viscous suppression is expected from the well-established relation between jet parton energy loss and η/s, viscous effect on the jet-medium interaction is strong. Since *dynamical* viscous suppression is inversely proportional to η/s, it implies a novel measure of medium transport coefficients in the observed jet substructures.

This present work concerns boost-invariant configuration of the background medium and the jet parton shape. Correspondingly, the resulting particle spectrum [as shown in Fig. (3)] is obtained under the condition $\Delta\eta = 0$. In terms of hydro modes, that case is associated with the mode with longest wavelength in the space-time rapidity, or $k_\xi = 0$. For more realistic situations, all higher order k_ξ modes should be taken into account in the mode summation. But for each of the k_ξ mode, we expect similarly that the effect from the *dynamical* viscous suppression will dominate over that from the *hydrodynamical* viscous suppression. Therefore, even after the summation over k_ξ modes, or to say, for a realistic jet parton localized in space-time rapidity, the conclusion that the dominant viscous effect to the induced jet-medium interaction is the *dynamical* viscous suppression is robust.

ACKNOWLEDGMENTS

We thank D. Pablos for helpful discussions. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada. C.G. gratefully acknowledges support from the Canada Council for the Arts through its Killam Research Fellowship program.

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