THE SIGNALS OF JET-INDUCED DIFFUSION WAKE ON Z/γ-HADRON CORRELATIONS IN HIGH-ENERGY HEAVY-ION COLLISIONS*

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Diffusion wake is an unambiguous part of the jet-induced medium response in high-energy heavy-ion collisions that leads to a depletion of soft hadrons in the opposite direction of the jet propagation. Using a coupled linear Boltzmann transport and hydro model, we identify a valley structure caused by the diffusion wake on top of a ridge from the initial multiple parton interaction (MPI) in the jet–hadron correlation as a function of azimuthal angle and rapidity. This gives rise to the unambiguous signals of the diffusion wake on soft hadrons in the opposite direction of the jets, which are reflected in the depletion in azimuthal angle distribution after subtraction of the contributions from MPI with a mixed-event procedure, and the double-peak structure in the rapidity distribution. We further employ the longitudinal and transverse gradient jet tomography for the first time to localize the initial jet production positions in Z/γ-jet events in which the effect of the diffusion wake is apparent in Z/γ-hadron correlation even without the subtraction of MPI.

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1. Introduction

Strong jet–medium interaction should lead to the jet-induced medium response in the form of Mach-cone-like excitations [1], which consists of the wake front and the diffusion wake. The wake front is known to contribute to an enhancement of soft hadrons with an energy scale of the medium temperature $\omega \sim T$ within the jet cone [2]. However, it is difficult to separate this contribution from medium-induced soft gluon radiations. The diffusion wake, on the other hand, leads to a depletion of soft hadrons in the back direction of the jet and, therefore, is an unambiguous signal of the jet-induced medium excitation without any similar competing effect.

In this paper, we will present our study of Z/γ-hadron correlation in Pb+Pb collisions at the LHC within the CoLBT-hydro model, and explore the inner structure of the diffusion wake in both rapidity and azimuthal angle direction.

2. Jet quenching within the CoLBT-hydro model

The jet-induced Mach cone and diffusion wake arise from the propagation of recoil partons and the diffusion of particle–holes in a microscopic transport picture. Macroscopically, they can also be described by the collective response from the energy momentum deposited into the QGP by the propagating jet in a hydrodynamic approach. In this study, we use the CoLBT-hydro model [3, 4] to simulate Z/γ-jet propagation and the jet-induced medium response in Pb+Pb collisions at the LHC. The CoLBT-hydro combines the microscopic linear Boltzmann transport (LBT) model [6] for the propagation of energetic jets and recoil partons with the event-by-event (3+1)D CCNU-LBNL viscous (CLVisc) hydrodynamic model [7] for the evolution of the bulk medium and soft modes of the jet-induced medium response. The LBT and CLVisc are coupled in real-time through a source term from the energy-momentum lost to the medium by the jet shower and recoil partons as well as the particle–holes or "negative partons" from the back-reaction. The LBT model [6] is based on the Boltzmann equation for both the jet shower and recoil partons with perturbative QCD (pQCD) leading-order elastic scattering and induced gluon radiation according to the high-twist approach. The CLVisc [7] parallelizes the Kurganov–Tadmor algorithm to solve the hydrodynamic equation for the bulk medium including medium response and Cooper–Frye particlization on GPU. The parameters for CLVisc together with the s95p parameterization of the equation of state [8] and AMPT or TRENTo initial conditions are used in CLVisc which can reproduce experimental data on bulk hadron spectra and anisotropic flows at both RHIC and LHC energies [7]. For more detailed descriptions of the LBT and CoLBT-hydro model we refer readers to Refs. [6] and [3, 4].

3. The signals of the diffusion wake

To find out the signals of the jet-induced medium response in the momentum space, we plot in Fig. 1 the jet–hadron correlations in $\Delta\eta = \eta_h - \eta_{\rm jet}$ and $\Delta\phi = \phi_h - \phi_{\rm jet}$ for soft hadrons in $p_{\rm T} \in (0, 2)$ GeV/c in (a) $p+p$ and (b) 0–10% central Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The correlation in $p+p$ collisions has a peak around the jet axis for hadrons from the jet on top of a ridge along the azimuthal angle from MPI. In Pb+Pb collisions, the jet peak is clearly enhanced by both the recoil and radiated partons as a result of the jet modification. This is consistent with soft-hadron enhancement in the modified jet fragmentation functions [3–5]. In the azimuthal angle region $|\Delta\phi| > \pi/2$ opposite to the jet axis around $|\Delta\phi| = \pi$, however, a valley is formed on top of the MPI ridge due to the depletion of soft hadrons by the jet-induced diffusion wake. We refer to this as the diffusion wake (DF-wake) valley.

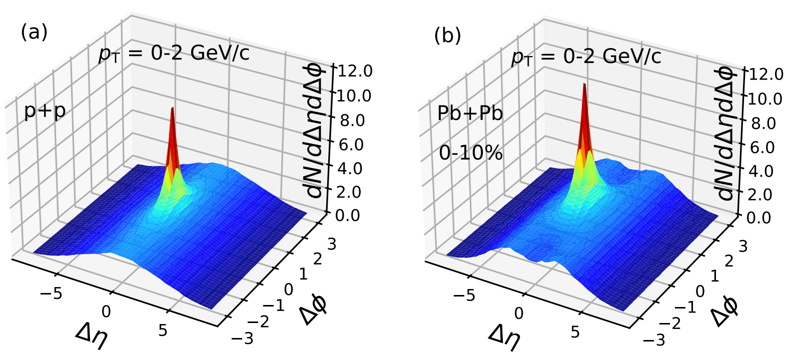

Fig. 1. CoLBT-hydro results on γ-triggered jet–hadron correlation for soft hadrons ($p_{\rm T} = 0$–2 GeV/c) in $\Delta\eta = \eta_h - \eta_{\rm jet}$ and $\Delta\phi = \phi_h - \phi_{\rm jet}$ in (a) $p+p$ and (b) 0–10% Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

To examine the structure of the DF-wake valley in detail, we plot in Fig. 2 the jet–hadron correlation (a) as a function of rapidity $\Delta\eta$ in the region $|\Delta\phi| > \pi/2$ and (b) as a function of $\Delta\phi$ in the region $|\Delta\eta| < 1.8$ for soft hadrons in $p+p$ (dashed) and 0–10% central Pb+Pb (solid) collisions. The Gaussian-like MPI ridge of the correlation in $p+p$ collisions comes from independent mini-jets in MPI. In Pb+Pb collisions, these mini-jets are also quenched, leading to the enhancement of soft hadrons and suppression of high-$p_{\rm T}$ hadrons. Their rapidity-azimuthal distributions, however, remain a Gaussian-like ridge plus a valley due to the diffusion wake. The DF-wake valley on top of the MPI ridge gives rise to a double-peak feature in the rapidity distribution of the jet–hadron correlation in Fig. 2 (a). The DF-wake valley is the deepest in the direction opposite to the jet-axis ($|\Delta\phi| = \pi$).

As one moves toward the jet-axis in azimuthal angle, the valley gradually gives away to the jet peak starting at around $|\Delta\phi| \leq \pi/2$ as seen in Figs. 1 (b) and 2 (b).

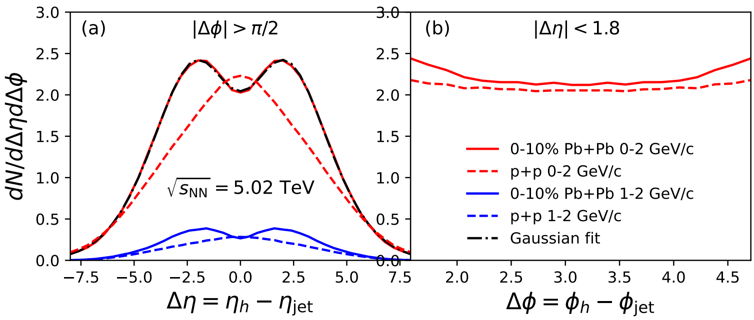

Fig. 2. (Color online) CoLBT-hydro results on γ-triggered jet–hadron correlation (a) in $\Delta\eta$ within $|\Delta\phi| > \pi/2$ and (b) in $\Delta\phi$ within $|\Delta\eta| < 1.8$ for soft hadrons within $p_T = 0$–2 GeV/c (red/dark gray) and $p_T = 1$–2 GeV/c range (blue/light gray) in p+p (dashed) and 0–10% central Pb+Pb (solid) collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The black dot-dashed line is the 2-Gaussian fit using Eq. (1).

In order to disentangle the DF-wake valley and MPI ridge in the jet–hadron correlation, we assume that the DF-wake valley and MPI ridge are both Gaussian-like and expressed by $F_1(\Delta\eta) = A_1\, \mathrm{e}^{-\Delta\eta^2/\sigma_1^2}$ and $F_2(\Delta\eta, \eta_j) = A_2\, \mathrm{e}^{-(\Delta\eta+\eta_j)^2/\sigma_2^2}$. We use a 2-Gaussian

$$F(\Delta\eta) = \int_{\eta_{j1}}^{\eta_{j2}} \mathrm{d}\eta_j F_3(\eta_j)(F_2(\Delta\eta, \eta_j) + F_1(\Delta\eta)) \tag{1}$$

to fit the rapidity distribution of the correlation. $F_3(\eta_j)$ is the self-normalized Gaussian-like rapidity distribution of γ-triggered jets from the CoLBT-hydro simulations, and $\eta_{j1,j2}$ define the jet rapidity range in the analysis. The dot-dashed line in Fig. 2 (a) demonstrates the robustness of the 2-Gaussian fit to the double-peak structure.

We also compute the Z/γ-hadron correlation in azimuthal angle. Shown in Fig. 3 is the difference of charged hadron yields per Z-trigger as a function of $|\Delta\phi^{hZ}|$ between p+p and 0–30% Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as compared to the CMS data [10] for $p_T^Z > 30$ GeV/c and $p_T^h > 1$ GeV/c. One can see there are both an enhancement and a broadening of the peak in the jet direction in Pb+Pb as compared to p+p collisions. The hadron yield in the Z direction is also sizable and is further enhanced in Pb+Pb collisions. This is contrary to the expectation of a depletion due to the jet-induced diffusion wake. This is because medium modification of partons

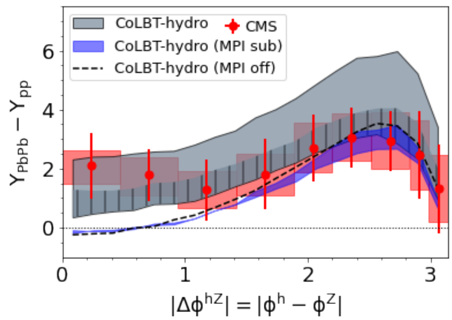

Fig. 3. Difference in charged hadron yields per Z-trigger as a function of $|\Delta\phi^{hZ}|$ between p+p and 0–30% Pb+Pb collisions at $\sqrt{s}_{NN} = 5.02$ TeV as compared to CMS data [10].

from the initial multiple parton interaction (MPI) gives rise to a uniform (in azimuthal angle) soft-hadron enhancement that can overwhelm the depletion of soft hadrons due to the diffusion wake. After subtracting the above MPI contributions with a mixed-event procedure, the Z-hadron correlation in the Z direction indeed becomes slightly negative after the subtraction of the MPI contribution, a signal of the jet-induced diffusion wake similar to the γ-hadron correlation at RHIC.

To enhance the signal of the jet-induced diffusion wake in the azimuthal angle direction, we use a 2D jet tomography to select events with longer jet propagation lengths. Shown in Fig. 4 (dashed lines) are medium modifica-

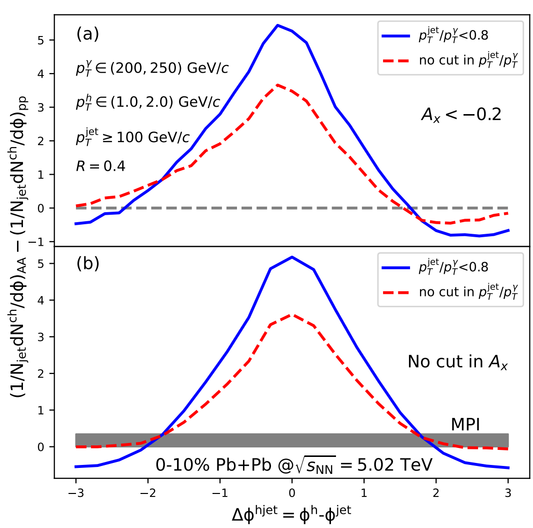

Fig. 4. Difference in γ-hadron yields as a function of $\Delta\phi^{h\text{jet}}$ between 0–10% Pb+Pb and p+p collisions at $\sqrt{s}_{NN} = 5.02$ TeV.

tions of soft-hadron yields in 0–10% Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in γ-jet events (a) with and (b) without the transverse asymmetry $A_x < -0.2$. The initial transverse positions of γ-jets in events with the transverse asymmetry $A_x < -0.2$ are biased toward the upper half of the transverse plane and propagate tangentially. In addition, the events with the value of the γ-jet momentum asymmetry $p_{\mathrm{T}}^{\mathrm{jet}}/p_{\mathrm{T}}^{\gamma} < 0.8$ bias toward longer jet propagation length. This asymmetry will further enhance soft hadrons from the Mach-cone-like excitation in the jet direction as well as the soft-hadron depletion in the γ direction due to the diffusion wake.

4. Summary

We have investigated Z/γ-hadron correlation in high-energy heavy-ion collisions within the CoLBT-hydro model in search for the signal of jet-induced diffusion wake. We found that the jet–hadron correlation in azimuthal angle and rapidity has a valley structure in the opposite direction of the jet on top of a ridge along the azimuthal angle. The valley is unambiguously caused by the diffusion wake, while the ridge is mostly due to soft hadrons from MPI. We further apply the 2D jet tomography technique to select events, which can enhance the signals of jet-induced diffusion wake along azimuthal angle direction.

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