Jet-flow coupling in heavy-ion collisions and the jet-induced diffusion wake

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Abstract. The diffusion wake accompanying the jet-induced Mach cone serves as a distinctive tool for investigating the characteristics of quark-gluon plasma(QGP) in high-energy heavy-ion collisions. This phenomenon results in a reduction of soft hadrons opposite to the direction of the propagating jet. Our study explores the 3D structure of the diffusion wake induced by γ-triggered jets in Pb+Pb collisions at the LHC energy, utilizing the coupled linear Boltzmann transport and hydro model. We identify a valley structure caused by the diffusion wake, superimposed on the initial multiple parton interaction (MPI) ridge in both rapidity and azimuthal angle. This leads to a double-peak pattern in the rapidity distribution of soft hadrons opposite to the jets. In addition, when jet goes through the QGP medium, it will be affected by the flow velocity. So we take a new method to detect the effect of jet-flow coupling in heavy-ion collisions.

1 Introduction

Jets generated in the initial hard scattering traverse the quark-gluon plasma(QGP) medium, interacting with it and inducing a medium response in the form of Mach-cone-like excitation[1, 2]. The study of this jet-induced medium response is crucial for extracting properties of the QGP, such as bulk transport properties and the equation of state (EoS).

The diffusion wake as negative part of the Mach cone is an ambiguous part of medium response, and has the potential to result in the reduction of soft hadrons in the final hadron spectra, specifically in the direction opposite to the propagating jet. Given that jets are three-dimensional observables, the jet-induced diffusion wake is expected to possess a three-dimensional structure. We conduct jet-hadron correlations in both azimuthal angle and rapidity direction within γ-jet events in Pb+Pb collisions using the CoLBT-hydro model to explore

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this structure. Our findings indicate that the diffusion wake results in a pronounced valley in the γ direction, giving rise to a distinctive double-peak pattern in the rapidity distribution of soft hadrons, positioned opposite to the jets. We refer this structure as a unique sign of jet-induced diffusion wake.

Finally, when the jet goes through the QGP medium, it will also be affected by the flow velocity. We explore a new observable called intra-jet asymmetry to detect the effect of this jet-flow coupling.

2 The model setup

We use the CoLBT-hydro model[2] to simulate γ-jet propagation and jet-induced medium response in Pb+Pb collisions at the LHC. CoLBT-hydro combines the linear Boltzmann transport (LBT) model[4, 5] with the event-by-event (3+1)D CCNU-LBNL viscous (CLVisc) hydrodynamic model[6, 7]. PYTHIA8 model is used to generate the initial configurations of γ-jet . The Trento model is used to get the initial transverse position of γ-jet and the initial energy density of CLVisc model. In CoLBT-hydro model, The propagation of jet parton and recoil parton in QGP is simulated by the LBT model. Meanwhile, the CLVisc model is responsible for the evolution of the bulk medium and soft partons.

A combination of a freeze-out temperature T_f=137 MeV and specific shear viscosity η/s=0.15, along with the s95p parameterization of lattice QCD EoS with a rapid crossover and the initial condition with a longitudinal envelope at an initial time τ_0=0.6fm/c, is employed in the CLVisc to reproduce experimental data on bulk hadron spectra and anisotropic flows at the LHC.

The final hadron spectra of CoLBT-hydro model have two parts. One is the hadronization of hard partons from LBT model within a parton recombination model, the other is hydro response via Cooper-Frye freeze-out.

3 Results

3.1 3D structure of diffusion wake

We use the γ-jet to investigate the 3D structure of diffusion wake with the following cuts: $p_T^{\mathrm{jet}} > 30$ GeV/c, $\left|\eta^{\mathrm{jet}}\right| < 1.6$, $p_T^{\gamma} > 60$ GeV/c, $|\eta^{\gamma}| < 1.44$, $\left|\Delta\phi_{\gamma\mathrm{jet}}\right| > 7/8\pi$, and R=0.3. In Fig. 1, we present jet-hadron correlations for soft hadrons with $p_{\mathrm{T}} \in (0, 2)$ GeV/c in (a) p+p and (b) 0-10% central Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV.

In p+p collisions, a peak along the jet direction is observed, originating from hadrons in the jet and multiple parton interactions (MPI). In Pb+Pb collisions, this peak is significantly enhanced due to the jet-induced medium response and medium-induced gluon radiation. Conversely, on the side opposite to the jet axis where $|\Delta\phi| > \pi/2$, a valley emerges atop the MPI ridge. This valley, known as the diffusion wake (DF-wake) valley, results from the depletion of soft hadrons by the jet-induced diffusion wake. We identify this valley in rapidity $\Delta\eta$ as a distinctive signal of the diffusion wake.

To gain a thorough understanding of this DF-wake valle, we plot in Fig. 2(a) the jet-hadron correlation as a function of rapidity $\Delta\eta$ in the region $|\Delta\phi| > \pi/2$. This is done to minimize the interference of jet partons on the observed valley. We also plot jet-hadron correlation as a function of $\Delta\phi$ in the region $|\Delta\eta| < 2.2$ in Fig. 2(b). In p+p collisions, the Gaussian-like MPI ridge in the rapidity distribution of the jet-hadron correlation comes from independent mini-jets in MPI. In Pb+Pb collisions, these mini-jets are also quenched, resulting in an increase in soft hadrons and a suppression of high p_T hadrons. The DF-wake valley on top of the MPI ridge gives rise to a double peak feature in the rapidity distribution in

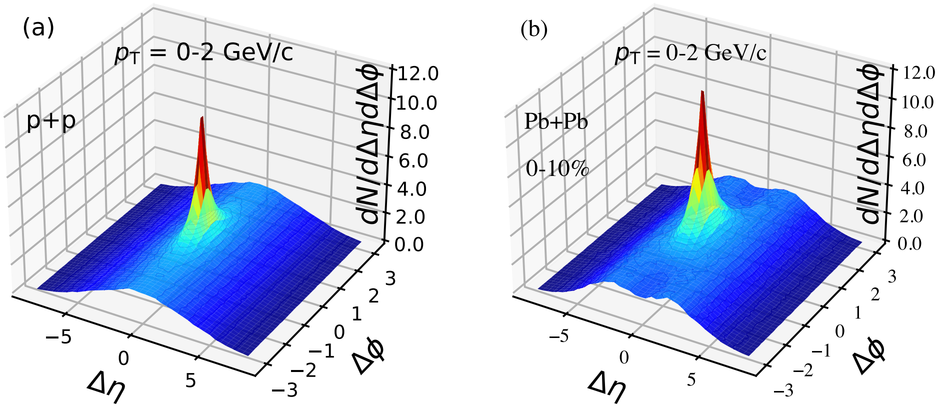

Figure 1. CoLBT-hydro results on γ-triggered jet-hadron correlation for soft hadrons (p_T = 0-2 GeV/c) in $\Delta\eta = \eta_h - \eta_{\rm jet}$ and $\Delta\phi = \phi_h - \phi_{\rm jet}$ in (a) p+p and (b) 0-10% Pb+Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV.

Fig. 2(a) The deepest DF-wake valley occurs 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).

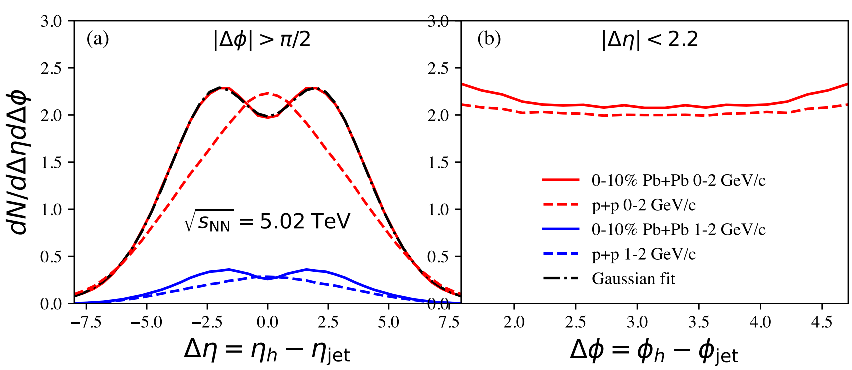

Figure 2. CoLBT-hydro results on γ-triggered jet-hadron correlation (a) in $\Delta\eta$ within $|\Delta\phi| > \pi/2$ and (b) in $\Delta\phi$ within $|\Delta\eta| < 2.2$ for soft hadrons within p_T = 0-2 GeV/c (red) and p_T = 1-2 GeV/c range (blue) in p+p (dashed) and 0-10% central Pb+Pb (solid) collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV.

3.2 Jet-flowing coupling

As the jet goes through the QGP medium, the presence of flow influences the jet and alters the distribution of particles within it. To investigate this phenomenon, we introduce a novel observable known as intra-jet asymmetry A_n.

$$A_n = \frac{Q_A - Q_B}{Q_A + Q_B}, \tag{1}$$

here Q means corresponding number, transverse momentum or $p_\perp$ of particles in region A and B. And region A and B are determined by the jet azimuthal angle and rapidity. For example, in the transverse plane, if $\phi_h - \phi_{\rm jet} > 0$, the particle belongs to region A, otherwise, it belongs to region B. In this work, we take $Q = p_\perp$ to study distributions of $A_{\Delta\phi}$ and $A_{\Delta\eta}$ in 0-10% and p+p collisions. Fig.3 is our final results. For the distribution of $A_{\Delta\phi}$, the outcomes in Pb+Pb

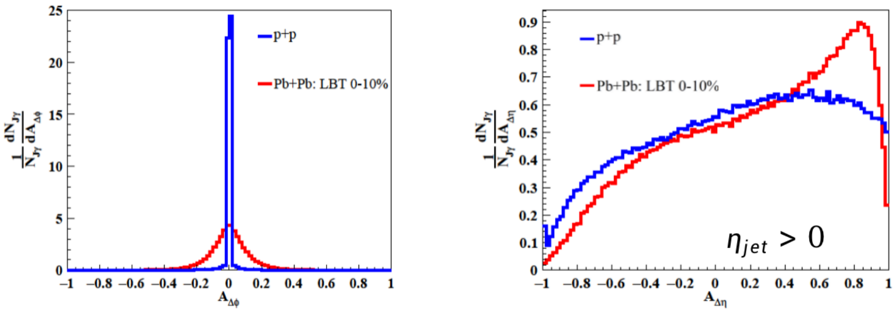

Figure 3. The distributions of $A_{\Delta\phi}$ and $A_{\Delta\eta}$ in 0-10% and p+p collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV

collisions display a wider distribution compared to that in p+p collisions, attributed to radial flow and transverse momentum broadening. Concerning the distribution of $A_{\Delta\eta}$, longitudinal flow propels particles towards higher rapidities, leading to an enhancement at large $A_{\Delta\eta}$ in Pb+Pb collisions as compared to p+p collisions.

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