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RESEARCH HIGHLIGHT

3D wakes on the femtometer scale by supersonic jets

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Concurrent simulations of partonic jets traveling through colored plasma show that the 3-dimensional structure of the diffusion wake induced by a supersonic jet provides an unambiguous signal of medium response to jet quenching. Future measurement of the diffusion wake combined with other observables may probe the equation of state and viscosity of quark–gluon plasma.

When an aircraft travels at a supersonic speed, it can trigger a sonic boom, namely the Mach cone. Such supersonic shock waves can be generated on the femtometer scale by high-energy partonic jets propagating through quark–gluon plasma (QGP) in relativistic heavy-ion collisions. Since the profile of the Mach cone is sensitive to the equation of state (EoS) and transport properties of the medium, it is of paramount significance and a long-standing hot topic to search for decisive signals of jet-induced shock waves in QGP. In a recent publication [1], the CCNU-LBL team (Yang et al.) performed a comprehensive study of such phenomena in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (see Fig. 1) and found that the three-dimensional (3D) structure of the diffusion wake behind the fast-moving jets and jet-induced wave front can serve as an unambiguous signature of medium response to jet quenching in QGP.

QGP is a novel state of matter consisting of deconfined quarks and gluons, as predicted by quantum chromodynamics (QCD), the fundamental theory of strong interaction. It is thought that a few microseconds after the Big Bang, the Universe was filled with hot and dense QGP. One of the central goals of relativistic heavy-ion collisions, such as those performed at the relativistic heavy-ion collider (RHIC) and the large hadron collider (LHC), is to create QGP in the laboratory and study its novel properties.

A wealth of evidence has shown that the QGP created in RHIC and LHC heavy-ion collisions is the hottest, most perfect, and extremely opaque fluid ever observed in the laboratory. The temperatures of QGP can reach up to approximately 350–480 MeV, which is much higher than the pseudo-critical temperature ($\sim$ 155 MeV) predicted by lattice QCD simulations [2]. The strong collective flow, which can be successfully explained by relativistic hydrodynamics [3], shows that the QGP droplet is a strongly coupled liquid with an extremely small specific shear viscosity (the ratio of shear viscosity to entropy density η/s). QGP also exhibits strong opaqueness to fast-moving partonic jets, as characterized by significant amount of parton energy loss in QGP owing to interaction with the colored medium; this phenomenon is known as jet quenching [4].

When high-energy jet partons traverse the opaque QGP, they not only lose energy but also induce medium excitation, which is usually referred to as medium response. Since jet partons travel much faster than the speed of sound of QGP, they should be able to trigger Mach-cone-like shockwaves. Earlier studies of medium responses have confirmed this expectation [5–7]. However, various complications have been reported in later studies. For example, a jet is a spray of partons, and every shower parton can serve as a source to deposit energy into the medium [8, 9]. It is therefore important to have a comprehensive understanding of the deposition profile in both momentum and coordinate spaces. The strong radial flow of the expanding QGP can significantly distort the Mach cone [10]. Furthermore, jet evolution and energy loss are event-by-event fluctuating; the final observable is the averaged result over many production points and propagation directions. In addition, the medium response is on top of a large and event-by-event fluctuating bulk-medium background.

To systematically study jet-induced medium response in QGP, two different types of dynamical approaches have been developed: the weakly coupled approach and the coupled jet transport and hydrodynamics approach [11]. In a series of publications [1, 12, 13], the CCNU-LBL team developed the

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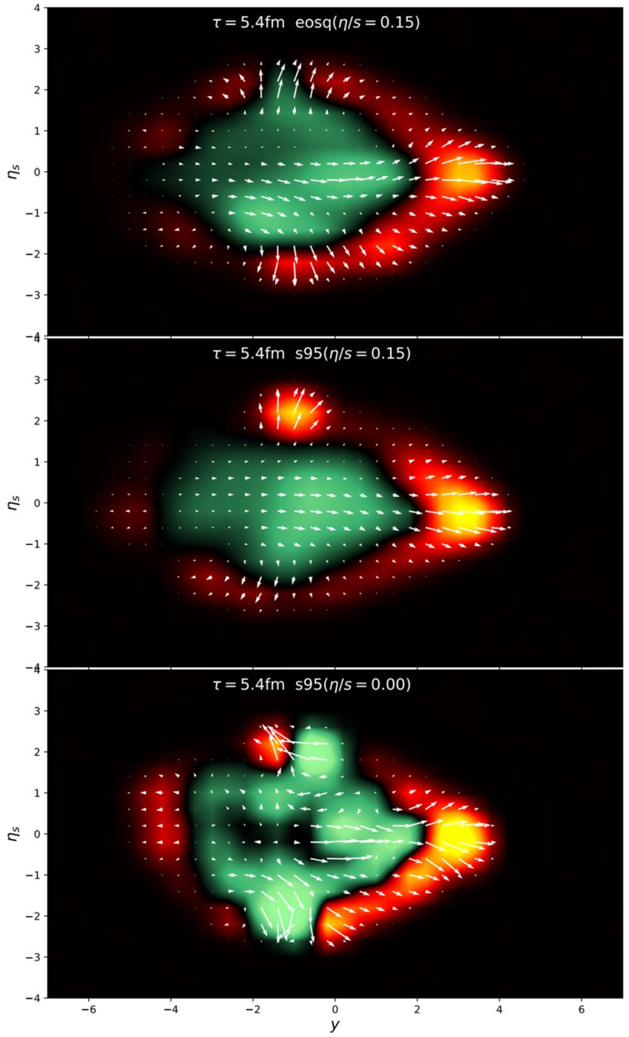

Fig. 1 The energy density and flow velocity distributions of the medium response in y-η_s plane induced by a γ-triggered jet initially produced at $(x, y) = (0, -1)$ fm traveling in the y direction in central 0–10% Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Different EoS and specific viscosity are used in different panels. The figure is taken from the supplemental materials of Ref. [1]

CoLBT-hydro model, which combines the linear Boltzmann transport (LBT) model [14] and CLVisc hydrodynamics [15] into a consistent framework by rewriting LBT in the Milne coordinates. This was the first concurrent simulation of jet propagation, QGP medium evolution, and jet-medium interaction. In the CoLBT-hydro model, jet partons at hard scales evolve in the LBT model, whereas the colored medium at the thermal scale evolves in the CLVisc model. The energy-momentum deposited by jets into QGP is described by the hydrodynamic source term, which can be constructed from the jet evolution. Jet partons and medium-recoil partons inside LBT with energies below a cutoff scale (~ 1–4 GeV) in the local rest frame of the fluid contribute to the source term.

In the first CoLBT-hydro paper [12], the CCNU-LBL team studied the effect of jet-induced medium excitation in γ-hadron correlations in Au+Au collisions at RHIC top energy. By studying the nuclear modification of the γ-triggered fragmentation function, they found that while the yield of associated hadrons at high transverse momentum (p_T) is suppressed owing to the energy loss of leading jet partons, the yield of associated hadrons at low p_T is significantly enhanced owing to the contribution from jet-induced medium excitations. Another interesting result is the diffusion wake: as the jet-induced wave front carries away energy from the medium, there is a depletion of energy in the region behind the jet and wave front. Contrary to the wave front, which enhances soft-hadron yield on the near side of the jet direction, the diffusion wake instead leads to a depletion of soft hadrons on the opposite side of the jet. This unique feature of the diffusion wake provides an unambiguous signature of the medium response to jet quenching.

While the above prediction of the diffusion wake is very exciting, CMS data [16] on Z-hadron correlations in Pb+Pb collisions at the LHC instead demonstrated an enhancement of soft hadrons in both Z and jet directions. To investigate this puzzling result, the CCNU-LBL team published another paper [13] and showed that hadrons in the Z direction (opposite to the jet direction) mainly arise from the multi-parton interaction (MPI) effect, such as the independent production of mini-jets associated with the triggered hadron processes in initial nuclear collisions. After subtracting the MPI contribution via a mixed-event procedure, the signal of the jet-induced diffusion wake became visible. To enhance the diffusion wake signal, they further proposed the use of longitudinal and transverse jet tomography techniques [17, 18] to localize the initial positions of the Z/γ-jet events by controlling the amount of Z/γ-jet asymmetry and/or the transverse asymmetry of emitted particles with respect to the jet-beam plane.

To obtain more decisive signals of the diffusion wake, the CCNU-LBL team recently performed a detailed analysis of the 3D structure of the diffusion wake induced by γ-jet events in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [1]. An extremely interesting finding of this study is the double-peak structure in the γ-hadron correlations as a function of rapidity and azimuthal angle. This double-peak structure is the combined effect of a valley structure caused by the diffusion wake and a ridge resulting from the MPI effect. The depth of the diffusion-wake valley was found to increase with increasing jet energy loss, as characterized by γ-jet asymmetry. The sensitivity of the diffusion wake to the EoS and viscosity of QGP was also explored (see Fig. 1). Future experimental data on the diffusion wake together with other observables will provide combined constraints on the EoS and transport properties of QGP.

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