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Nuclear Physics A 932 (2014) 387–391

NUCLEAR PHYSICS A

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Di-jet asymmetric momentum transported by QGP fluid

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Received 7 April 2014; received in revised form 24 September 2014; accepted 25 September 2014

Available online 1 October 2014

Abstract

We study the collective flow of the QGP-fluid which transports the energy and momentum deposited from jets. Simulations of the propagation of jets together with expansion of the QGP-fluid are performed by solving relativistic hydrodynamic equations numerically in the fully $(3 + 1)$-dimensional space. Mach cones are induced by the energy–momentum deposition from jets and extended by the expansion of the QGP. As a result, low-p_T particles are enhanced at large angles from the jet axis. This provedes an intimate link between the observables in di-jet asymmetric events in heavy-ion collisions and theoretical pictures of the medium excitation by jet-energy deposition.

Keywords: QGP; Jet quenching; Relativistic hydrodynamics; Mach cone

1. Introduction

In heavy-ion collisions at Relativistic Heavy-Ion Collider (RHIC) in BNL and Large Hadron Collider (LHC) in CERN, the deconfined phase of quarks and gluons, namely the quark–gluon plasma (QGP) is supposed to be realized experimentally. The expansion of the QGP is well described by relativistic hydrodynamics [1–5]. At the same time as the QGP, large-p_T partons, so-called jets, are produced through the initial hard scattering between the partons inside colliding nuclei and penetrate the QGP. Due to the strong coupling with the QGP-medium, these jet

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http://dx.doi.org/10.1016/j.nuclphysa.2014.09.095
0375-9474/

particles travel losing their energy. At the leading order, the jet particles are created as a back-to-back pair with the same energy owing to the energy–momentum conservation law. Depending on the relation between the geometry of the medium and the position of the pair creation, the amount of the energy loss differs between the jet partons. At the LHC, events such that the transverse momentum of jets are highly-asymmetric are observed and these experimental facts are consistent with jet quenching picture [6,7]. Furthermore, according to the data from the CMS Collaboration, this imbalance of di-jet-p_T is compensated by low-p_T particles at large angles from the jet axis and the total-p_T of the entire system is well balanced [7]. It can be supposed that these low-p_T particles are originating from a medium wake induced by the energy and momentum deposited from jets.

Here, we perform simulations of di-jet asymmetric events to study the transport process of energy and momentum deposited from jet particles in the expanding QGP medium. To describe the medium response to the energy–momentum deposition, we solve relativistic hydrodynamic equations with source terms in the fully $(3+1)$-dimensional coordinate system numerically. Then, we investigate the transverse-momentum balance in di-jet events and show that low-p_T particles at large angles from the jet axis play a crucial role in the transverse-momentum balance.

2. Model and simulations

Assuming local thermal equilibrium of the QGP, we solve relativistic hydrodynamic equations to describe the space–time evolution of the QGP. Here, source terms, which are the 4-momentum density deposited from the traversing jet partons, are introduced in the hydrodynamic equations.

$$\partial_\mu T^{\mu\nu}(x) = J^\nu(x), \tag{1}$$

where $T^{\mu\nu}$ and J^ν are the energy–momentum tensor of the QGP-fluid and the source terms, respectively. The energy–momentum tensor for perfect fluids can be decomposed using the 4-flow velocity $u^\mu = \gamma(1, \boldsymbol{v})$ as

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}. \tag{2}$$

Here ϵ is the energy density, P is the pressure and $g^{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$ is the Minkowski metric. As an equation of state, the ideal gas equation of state for massless partons is employed here: $P(\epsilon) = \epsilon/3$. We assume that the deposited energy and momentum are immediately equilibrated. The source terms for a massless particle traveling through the fluid are given by

$$J^\mu = -\frac{dp^0_{\mathrm{jet}}}{dt}\frac{p^\mu_{\mathrm{jet}}}{p^0_{\mathrm{jet}}}\delta^{(3)}\big(\boldsymbol{x} - \boldsymbol{x}_{\mathrm{jet}}(t)\big). \tag{3}$$

For dp^0_{jet}/dt, the collisional energy loss is used [8]. Here we multiply the energy loss by a constant, whose value is fixed throughout all simulations, to simulate large asymmetric di-jet events such as observed at the LHC. We solve Eqs. (1) numerically without linearization in the $(3+1)$-dimensional Milne coordinates (τ, x, y, η_s). This framework enables us to simulate the collective flow induced by jet particles on an expanding medium. Through the Cooper–Frye formula, we calculate the momentum distribution of particles from hydrodynamic outputs $T(x)$, $u^\mu(x)$ [9].

We set up the initial profile of the QGP-fluid at $\tau_0 = 0.6$ fm/c. The initial energy density in the η_s-direction is flat like the Bjorken scaling solution in the mid-rapidity region $|\eta_s| < 10$. The flat region is smoothly connected to the vacuum at both ends by a half Gaussian with the width