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Investigating jet quenching on the lattice

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Abstract

Due to the dynamical, real-time, nature of the phenomenon, the study of jet quenching via lattice QCD simulations is not straightforward. In this contribution, however, we show how one can extract information about the momentum broadening of a hard parton moving in the quark–gluon plasma, from lattice calculations. After discussing the basic idea (originally proposed by Caron-Huot), we present a recent study, in which we estimated the jet quenching parameter non-perturbatively, from the lattice evaluation of a particular set of gauge-invariant operators.

Keywords: Jet quenching; Quark–gluon plasma; Lattice QCD calculations

1. Introduction

Jet quenching is a very important experimental signature of the quark–gluon plasma (QGP): when a hard parton propagates in the deconfined medium, it undergoes multiple interactions with the QGP constituents, which decrease its energy and induce a transverse momentum component. Eventually, this leads to the suppression of yields at large transverse momenta and of correlations between back-to-back hadrons in particle spectra detected in heavy-ion collisions. The momentum broadening of a hard parton in the QGP can be described in terms of the phenomenological parameter $\hat{q}$: it represents the average increase of the squared transverse momentum component per unit length [1–3]. It can be computed as the second moment of the collision kernel $C(p_\perp)$ associated with the interactions between the parton and the plasma constituents:

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$$\hat{q} = \frac{\langle p_\perp^2 \rangle}{L} = \int \frac{\mathrm{d}^2 p_\perp}{(2\pi)^2} p_\perp^2 C(p_\perp). \tag{1}$$

A theoretical derivation of the jet quenching parameter $\hat{q}$ from first principles is very challenging, since it involves different energy scales and, consequently, non-trivial interplay of perturbative and non-perturbative dynamics.

In principle, Monte Carlo simulations on the lattice would be an ideal tool to compute $\hat{q}$ numerically—especially at temperatures close to deconfinement, in which the QGP is relatively strongly coupled. Unfortunately, due to the *real-time* nature of the phenomenon, a formulation of the problem on a *Euclidean* lattice is far from straightforward. In this contribution, however, following an idea originally proposed by Caron-Huot [4], we will discuss how it is possible to make progress in this direction, presenting the results of our recent work [5].

2. A dimensionally reduced effective theory for high-temperature QCD

Although asymptotic freedom implies that the QCD coupling is weak for processes involving sufficiently high energy scales (like the hard thermal scale πT characteristic of a system at high temperature T), a purely perturbative approach fails in thermal non-Abelian gauge theories. Even at arbitrarily high temperatures, the physics of long-wavelength modes—those at soft $O(gT)$ or ultrasoft $O(g^2T/\pi)$ scales—has non-perturbative features: this is due to the fact that infrared singularities lead to a non-trivial structure for perturbative expansions, and limit their validity to a finite order [6,7]. At temperatures attainable in present accelerators, the contributions from non-perturbative terms are generally non-negligible. This problem can be properly addressed by means of a dimensionally reduced effective theory [8–11], obtained from the formulation of equilibrium finite-temperature QCD as a four-dimensional theory (with a compact Euclidean time direction playing the rôle of the inverse temperature), by integrating out all non-static modes for the temporal component of the gauge field. This leads to an effective theory (electrostatic QCD, or EQCD) defined by the Lagrangian of three-dimensional SU(3) Yang–Mills theory coupled to an adjoint scalar field:

$$\mathcal{L} = \frac{1}{4} F_{ij}^a F_{ij}^a + \mathrm{Tr}\big((D_i A_0)^2\big) + m_{\mathrm{E}}^2 \,\mathrm{Tr}\big(A_0^2\big) + \lambda_3 \big(\mathrm{Tr}\big(A_0^2\big)\big)^2. \tag{2}$$

Fixing the dimensionful 3D gauge coupling g_{E}, the mass and quartic coupling via a *matching* procedure, this effective theory describes the physics of high-temperature QCD for all modes up to the soft scale gT.[1]

A key observation pointed out in Ref. [4] (see also Refs. [12–17] for work on related ideas) is that, for a hard massless parton moving through the QGP, the contributions to $\hat{q}$ from collinear components of the medium fields are suppressed, and the momentum broadening would be the same even if the parton velocity exceeded the speed of light, making its trajectory space-like. This suggests that the problem can be addressed in a Euclidean setup. In fact, one can rigorously prove that the soft contribution to jet quenching can be directly computed in EQCD. Such computation was carried out perturbatively in Refs. [4,14] and non-perturbatively (through lattice simulations) in our work [5].

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[1] Integrating out the scalar field, one can obtain a further effective theory (magnetostatic QCD, or MQCD), which is just three-dimensional SU(3) Yang–Mills theory and describes the ultrasoft modes $O(g^2T/\pi)$ of QCD.