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Jet quenching from the lattice

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Abstract

We present a lattice study of the momentum broadening experienced by a hard parton in the quark–gluon plasma. In particular, the contributions to this real-time phenomenon from soft modes are extracted from a set of gauge-invariant operators in a dimensionally-reduced effective theory (electrostatic QCD), which can be simulated on a Euclidean lattice. At the temperatures accessible to present experiments, the soft contributions to the jet quenching parameter are found to be quite large. We compare our results to phenomenological models and to holographic computations.

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

1. Introduction

Jet quenching, namely the suppression of particles with large transverse momenta and of correlations between back-to-back hadrons detected after a heavy-ion collision, is an effect directly related to the energy loss and momentum broadening experienced by a hard parton moving in the deconfined medium, due to its interactions with the quark–gluon plasma (QGP) constituents [1].

Under the assumption that the parton is much harder than the typical momenta of thermal excitations in the QGP, the standard formalism to describe jet quenching theoretically relies on a multiple soft-scattering picture, in the eikonal approximation [2–6]. The average increase in the

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(squared) transverse momentum component of the hard parton per unit length is constant, and defines the phenomenological jet quenching parameter $\hat{q}$,

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

expressed as the second moment of the differential collision rate between the parton and the QGP constituents, $C(p_\perp)$. In turn, the latter quantity is directly related to the two-point correlation function of Wilson lines on the light cone.

What tools can be used to calculate this two-point correlator of null Wilson lines? Analytical weak-coupling expansions are a well-defined first-principles approach; however, the infrared divergences characteristic of thermal QCD pose limitations on the order to which they can be pushed [7,8]—and the quantitative accuracy of perturbative computations truncated at the leading (LO) or next-to-leading order (NLO) is generally observable-dependent, and may be questionable at RHIC and LHC temperatures T, at which the QCD coupling g is not very small [9]. On the other hand, holographic computations based on the gauge/string correspondence are an ideal tool to investigate the strong-coupling limit of the plasma; however, they are not derived from the microscopic formulation of QCD, but rather from some models, like the $\mathcal{N} = 4$ supersymmetric Yang–Mills theory [10]. Finally, numerical lattice calculations (which do not rely on either strong- or weak-coupling assumptions) are based on a Euclidean formulation, hence they are generally unsuited for the whole class of phenomena involving real-time dynamics in the QGP [11].

2. Soft contributions from lattice EQCD

As pointed out in Ref. [12] (see also Ref. [13]), however, it is possible to show that the contribution to $C(p_\perp)$ from *soft* QGP modes (i.e., those at momentum scales up to gT) can be exactly evaluated in a dimensionally reduced, low-energy effective theory, namely electrostatic QCD (EQCD) [14–21], which is nothing but Yang–Mills theory in three spatial dimensions, coupled to an adjoint scalar field. The EQCD Lagrangian is

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

its parameters can be fixed by matching to high-temperature QCD. For example, at LO the gauge coupling, the squared mass and the quartic coupling of the scalar are related to the QCD parameters via

$$g_{\mathrm{E}}^2 = g^2 T + \ldots, \qquad m_{\mathrm{E}}^2 = \left(1 + \frac{n_f}{6}\right) g^2 T^2 + \ldots, \qquad \lambda_3 = \frac{9 - n_f}{24\pi^2} g^4 T + \ldots, \tag{3}$$

where n_f denotes the number of dynamical light quark flavors. This effective theory can be regularized on a lattice [22] and studied non-perturbatively by means of Monte Carlo simulation. The parameters of our study correspond to QCD with $n_f = 2$ light quarks at $T \simeq 398$ MeV and at $T \simeq 2$ GeV (roughly equal to twice and ten times the deconfinement temperature). To get sufficient accuracy at these “low” temperatures, we included subleading corrections in the EQCD parameter definitions.

Although this effective theory is purely spatial, the operator of interest for our computation of $\hat{q}$ must describe dynamical evolution *in real time* [23]. This operator can be interpreted as the dimensionally-reduced counterpart of (a gauge-invariant version of) the light-cone Wilson line correlator, and can be written as the trace of a “decorated Wilson loop”: