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Jet quenching in a strongly interacting plasma – A lattice approach

Marco Panero*
Department of Physics and Helsinki Institute of Physics, University of Helsinki, P.O. Box 64, FI-00014 Helsinki, Finland
E-mail: marco.panero@helsinki.fi

Kari Rummukainen
Department of Physics and Helsinki Institute of Physics, University of Helsinki, P.O. Box 64, FI-00014 Helsinki, Finland
E-mail: kari.rummukainen@helsinki.fi

Andreas Schäfer
Institute for Theoretical Physics, University of Regensburg, D-93040 Regensburg, Germany
E-mail: andreas.schaefer@physik.uni-regensburg.de

The phenomenon of jet quenching, related to the momentum broadening of a high-energy parton, provides important experimental evidence for the production of a strongly coupled, deconfined medium in heavy-ion collisions. Its theoretical description has been addressed in a number of works, both perturbatively and non-perturbatively (using the gauge-gravity duality). In this contribution, following a proposal by Caron-Huot, we discuss a novel approach to this problem, enabling one to extract non-perturbative information on this real-time phenomenon from simulations on a Euclidean lattice.

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1. Introduction

More than thirty years ago, Bjorken suggested a possible way to detect the creation of deconfined QCD matter in collisions of ultrarelativistic nuclei: due to interactions with the medium constituents, a hard parton propagating through the quark-gluon plasma (QGP) at a given temperature T would experience energy loss and momentum broadening, and this would result in the suppression of final-state hadrons with large transverse momentum and of back-to-back correlations [1]. This prediction was eventually confirmed by experiments [2].

Providing a firm theoretical description for this beautiful physical idea is, however, challenging, as it involves an interplay of both perturbative and non-perturbative physics effects [3]. Even if one focuses only on the short-distance interactions between the hard parton and QGP constituents [4], the problem is still complicated by the fact that, for temperatures within the reach of present experiments, the QCD coupling g is not very small, so perturbative computations may not be reliable. On the other hand, strong-coupling approaches based on the gauge/string duality, like the ones carried out for a massless hard parton [5] or for the drag force experienced by a heavy quark [6], are not based on the QCD Lagrangian. Finally, non-perturbative lattice QCD computations are not straightforward for this real-time problem.

In this contribution, however, we would like to discuss some recent progress in the latter direction [7], based on an idea proposed in ref. [8]. Related studies include refs. [9 – 11], whereas a different way to study the jet quenching phenomenon on the lattice was proposed in ref. [12].

2. Soft contribution to jet quenching from a Euclidean lattice

Jet quenching can be described in terms of a phenomenological parameter $\hat{q}$, defined as the average increase in the squared transverse momentum component $p_\perp$ of the hard parton per unit length. This quantity can be expressed in terms of a differential collisional rate between the parton and plasma constituents $C(p_\perp)$:

$$\hat{q} = \frac{\langle p_\perp^2 \rangle}{L} = \int \frac{\mathrm{d}^2 p_\perp}{(2\pi)^2} p_\perp^2 C(p_\perp). \tag{2.1}$$

In turn, $C(p_\perp)$ is related to the two-point correlation function of light-cone Wilson lines. Although the full computation of this correlator cannot be carried out on a Euclidean lattice, it is possible to extract the non-perturbative contributions to it from the soft sector, i.e. from physics at momentum scales up to gT, which can be proven to be time-independent [8, 9]. Evaluating the non-perturbative contribution from soft (and ultrasoft, of order g^2T/π) modes is important, since they are responsible for the peculiar analytical structure of weak-coupling computations in thermal QCD and for the large corrections affecting the corresponding perturbative series. A proper systematic framework to deal with these problems can be formulated in terms of dimensionally reduced effective theories [13]. In particular, the soft-scale dynamics can be described by electrostatic QCD (EQCD): an effective theory for the static QGP modes, given by three-dimensional Yang-Mills theory coupled to an adjoint scalar field,

$$\mathscr{L} = \frac{1}{4} F_{ij}^a F_{ij}^a + \mathrm{Tr}\left((D_i A_0)^2 \right) + m_{\mathrm{E}}^2 \mathrm{Tr}\left(A_0^2 \right) + \lambda_3 \left(\mathrm{Tr}\left(A_0^2 \right) \right)^2. \tag{2.2}$$

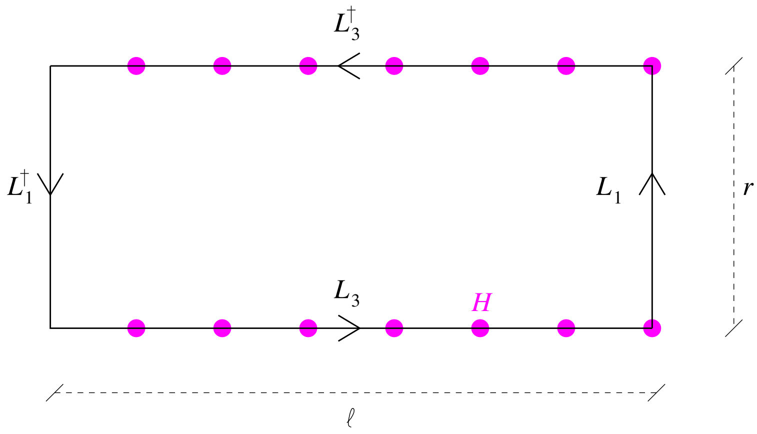

Figure 1: The "decorated" Wilson loop $W(\ell,r)$ describing a two-point correlation function of light-cone Wilson lines involves Hermitian parallel transporters $H(x)$ along the real-time direction.

Its parameters (the 3D gauge coupling g_{E} and the mass- and quartic-term coefficients) can be fixed by *matching* to the physics of high-temperature QCD, and the theory can be regularized on a lattice. We chose a setup corresponding to the dimensional reduction of QCD with $n_f = 2$ light dynamical quark flavors, at two temperatures ($T \simeq 398$ MeV and 2 GeV) approximately twice and ten times larger than the deconfinement temperature [14].

We simulate this theory and study (a gauge-invariant generalization of) the two-point correlator of light-cone Wilson lines, defined in terms of a lattice operator which involves parallel transporters $H(x) = \exp[-ag_{\mathrm{E}}^2 A_0(x)]$ along *real time*, which are Hermitian—rather than unitary—operators. This results in a "decorated" Wilson loop $W(\ell,r)$ (see fig. 1) with well-defined renormalization properties [15]. From its expectation values (computed with the multilevel algorithm [16]) we extract a "potential"

$$V(r) = -\frac{1}{\ell}\ln\langle W(\ell,r)\rangle, \tag{2.3}$$

which is equal to the transverse Fourier transform of $C(p_\perp)$.

At short distances our results for $V(r)$ (shown in fig. 2) are compatible with perturbative expectations, which involve, in particular, a delicate cancellation between gluon and scalar propagators [8, 9]. The non-perturbative contributions to $V(r)$ can be related to $\hat{q}$: the latter is given by the second moment of the distribution associated with $C(p_\perp)$, which corresponds to curvature terms in $V(r)$. Following an approach similar to ref. [10], we arrive at quite large values for the soft NLO contribution to the jet quenching parameter: $0.55(5)g_{\mathrm{E}}^6$ for $T \simeq 398$ MeV, and $0.45(5)g_{\mathrm{E}}^6$ for $T \simeq 2$ GeV. In turn, these numbers lead to a final estimate for $\hat{q}$ around 6 GeV^2/fm for RHIC temperatures, comparable with those from holographic estimates [5] and from computations with phenomenological input [17].

3. Conclusions and outlook

We have shown that, contrary to naïve intuition, the lattice study of certain real-time phenomena involving physics on the light cone is possible. Here we have discussed the phenomenon of jet

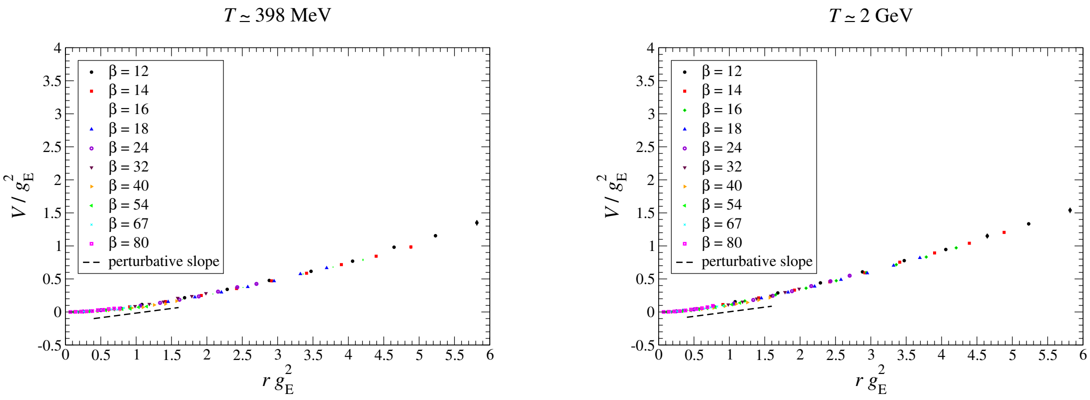

Figure 2: The "potential" $V(r)$ extracted from the expectation values of $W(\ell, r)$, at $T \simeq 398$ MeV (left-hand-side panel) and at $T \simeq 2$ GeV (right-hand-side panel). Both V and r are shown in the appropriate units of the dimensionful 3D gauge coupling g_{E}. The slope predicted perturbatively for the potential at values $rg_{\mathrm{E}}^2 \gtrsim 1$ is also displayed.

quenching in thermal QCD, but related ideas have also been proposed for QCD at zero temperature [18].

By construction, the bosonic effective theory that we simulated in our approach allows one to separate the soft contributions to $\hat{q}$ from those due to hard thermal modes, with momenta of order πT. It does so in a controlled, systematic way, consistent with the modern theoretical framework to study finite-temperature QCD [13, 19].

In the near future, we plan to improve our extrapolation of the potential $V(r)$ to the continuum limit at short r by carrying out further simulations on finer lattices, and/or using improved actions [20]. It would also be interesting to study the dependence of $\hat{q}$ on T, and on the number of color charges N. As it is well-known, the large-N limit is characterized by a rich and interesting phenomenology [21], and lattice studies have shown that the static equilibrium properties of the QGP have very little dependence on N, both in four [22] and in three [23] spacetime dimensions.

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