Jet quenching in a strongly interacting plasma

A lattice approach

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Outline

Based on:

★ M. P., K. Rummukainen and A. Schäfer, *A lattice study of the jet quenching parameter*, arXiv:1307.xxxx

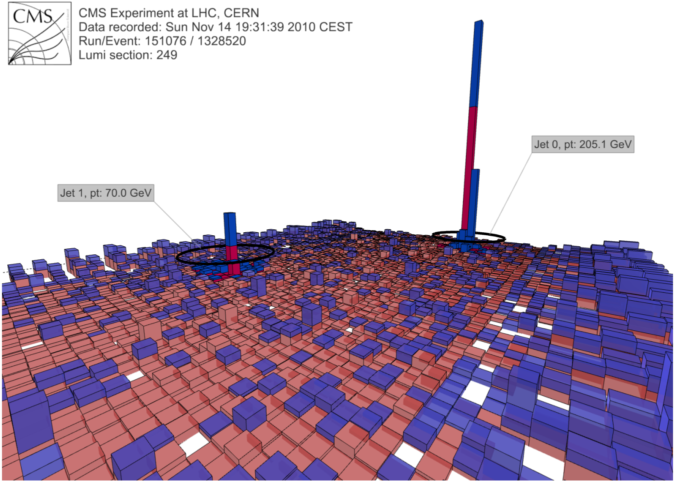
Related works:

- S. Caron-Huot, *$O(g)$ plasma effects in jet quenching*, arXiv:0811.1603
- M. Benzke, N. Brambilla, M. A. Escobedo and A. Vairo *Gauge invariant definition of the jet quenching parameter*, arXiv:1208.4253
- M. Laine, *A non-perturbative contribution to jet quenching*, arXiv:1208.5707
- J. Ghiglieri, J. Hong, A. Kurkela, E. Lu, G. D. Moore and D. Teaney, *Next-to-leading order thermal photon production in a weakly coupled quark-gluon plasma*, arXiv:1302.5970
- M. Laine and A. Rothkopf, *Light-cone Wilson loop in classical lattice gauge theory*, arXiv:1304.4443

Outline

Jet quenching

Jet quenching is the suppression of high-p_T particles and back-to-back correlations in nuclear collisions



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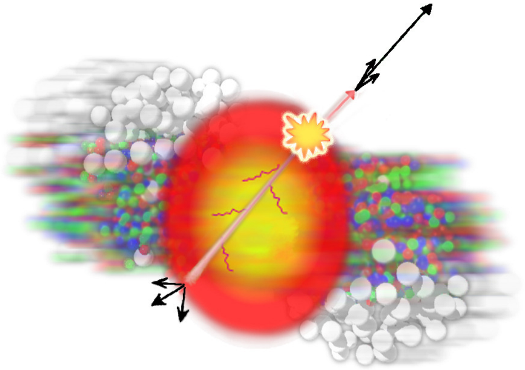
Provides important experimental evidence for the quark-gluon plasma (QGP) existence Bjorken, 1982



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Overview of the theoretical approach

Jet quenching belongs to the class of *hard probes* to heavy-ion collisions, involving a large energy scale Q (see Casalderrey-Solana and Salgado, 2007 and Apolinário's talk at EPS HEP 2013)

QCD factorization theorems:

$$\sigma_{(M+N\to\text{hadron})} = f_M(x_1, Q^2) \otimes f_N(x_2, Q^2) \otimes \sigma(x_1, x_2, Q^2) \otimes D_{\text{parton}\to\text{hadron}}(z, Q^2)$$

$f_A(x, Q^2)$: parton distribution functions

$\sigma(x, y, Q^2)$: short-distance cross-section

$D_{\text{parton}\to\text{hadron}}(z, Q^2)$: fragmentation function

Here: Focus on propagation of a high-energy parton in QGP medium

Hard parton propagation in QGP

Multiple soft-scattering description, in the *eikonal approximation*

Leading effect: *transverse momentum broadening*, described by the jet quenching parameter:

$$\hat{q} = \frac{\langle p_\perp^2 \rangle}{L}$$

Can be evaluated in terms of a *collision kernel* $C(p_\perp)$ (differential parton-plasma constituents collision rate)

$$\hat{q} = \int \frac{\mathrm{d}^2 p_\perp}{(2\pi)^2} p_\perp^2 C(p_\perp)$$

$C(p_\perp)$ can be related to a two-point correlator of *light-cone Wilson lines*

Computing the jet quenching parameter

What tools are available?

- Perturbation theory (PT) expansions
  - ✓ Based on first principles
  - ✓ Well established technology
  - ✓ Problems with infrared divergences are well understood
  - ✗ May not be reliable at RHIC or LHC temperatures
- Holographic computations
  - ✓ Mathematically *beautiful*
  - ✓ Ideally suited for strong coupling
  - ✗ Not directly applicable to real-world QCD
- Lattice simulations
  - ✓ Based on first principles
  - ✓ Well established (computer) technology
  - ✓ Do not rely on weak- or strong-coupling assumptions
  - ✗ Euclidean setup, so *generally* unsuitable for real-time phenomena

Outline

Key idea

Energy scale hierarchy in high-temperature, perturbative QCD:

$$g^2 T/\pi \text{ (ultrasoft)} \ll gT \text{ (soft)} \ll \pi T \text{ (hard)}$$

IR divergences accounted for by 3D effective theories Braaten and Nieto, 1995:

- electrostatic QCD (3D Yang-Mills + adjoint scalar field) for soft scale
- magnetostatic QCD (3D pure Yang-Mills) for ultrasoft scale

Large NLO corrections hindering PT due to *soft*, essentially *classical* fields

Observation: Soft contributions to physics of light-cone partons *insensitive* to parton velocity $\longrightarrow$ Can turn the problem Euclidean!

Proof

Spatially separated ($|t| < |z|$) light-like Wilson lines:

$$G^<(t, x_\perp, z) = \int \mathrm{d}\omega \mathrm{d}^2 p_\perp \mathrm{d}p^z \, \tilde{G}^<(\omega, p_\perp, p^z) e^{-i(\omega t - x_\perp \cdot p_\perp - z p^z)}$$

$$= \int \mathrm{d}\omega \mathrm{d}^2 p_\perp \mathrm{d}p^z \left[\frac{1}{2} + n_\mathrm{B}(\omega) \right] \left[\tilde{G}_\mathrm{R}(\omega, p_\perp, p^z) - \tilde{G}_\mathrm{A}(\omega, p_\perp, p^z) \right] e^{-i(\omega t - x_\perp \cdot p_\perp - z p^z)}$$

Shift $p'^z = p^z - \omega t / z$, integrate over frequencies by analytical continuation into upper (lower) half-plane for retarded (advanced) contribution $\longrightarrow$ sum over Matsubara frequencies

$$G^<(t, x_\perp, z) = T \sum_{n \in \mathbb{Z}} \int \mathrm{d}^2 p_\perp \mathrm{d}p^z \, \tilde{G}_\mathrm{E}(2\pi n T, p_\perp, p^z) e^{i(x_\perp \cdot p_\perp + z p^z)}$$

- $n \neq 0$ contributions: exponentially suppressed at large separations
- Soft contribution: from $n = 0$ mode. Time-independent: evaluate in EQCD

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Electrostatic QCD on the lattice

Super-renormalizable EQCD Lagrangian

$$\mathcal{L} = \frac{1}{4} F^a_{ij} F^a_{ij} + \mathrm{Tr}\left((D_i A_0)^2 \right) + m_{\mathrm{E}}^2 \mathrm{Tr}\left(A_0^2 \right) + \lambda_3 \left(\mathrm{Tr}\left(A_0^2 \right) \right)^2$$

Parameters chosen (by matching) to reproduce soft physics of high-T QCD

- 3D gauge coupling: $g_{\mathrm{E}}^2 = g^2 T$
- Debye mass parameter: $m_{\mathrm{E}}^2 = \left(1 + \frac{n_f}{6}\right) g^2 T$
- 3D quartic coupling: $\lambda_3 = \frac{9-n_f}{24\pi^2} g^4 T$

Standard Wilson lattice regularization

Our setup: QCD with $n_f = 2$ light flavors, two temperature ensembles:

- $T \simeq 398$ MeV
- $T \simeq 2$ GeV

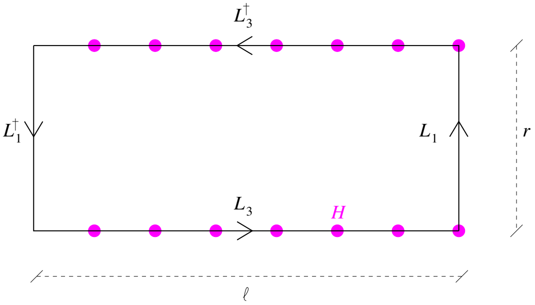
Operator implementation

Light-cone Wilson line correlator

$$\langle W(\ell, r)\rangle = \left\langle \mathrm{Tr}\left(L_3 L_1 L_3^\dagger L_1^\dagger\right)\right\rangle \sim \exp\left[-\ell V(r)\right]$$

with

$$L_3 = \prod U_3 H \qquad L_1 = \prod U_1 \qquad H = \exp(-a g_E^2 A_0)$$



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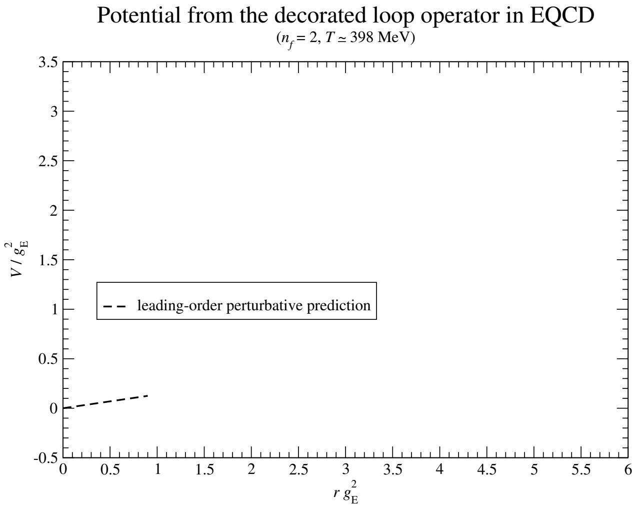
Light-cone Wilson line correlator: Lattice versus PT

Non-perturbative soft contribution to $\hat{q}$ from short-distance behavior of $V(r)$



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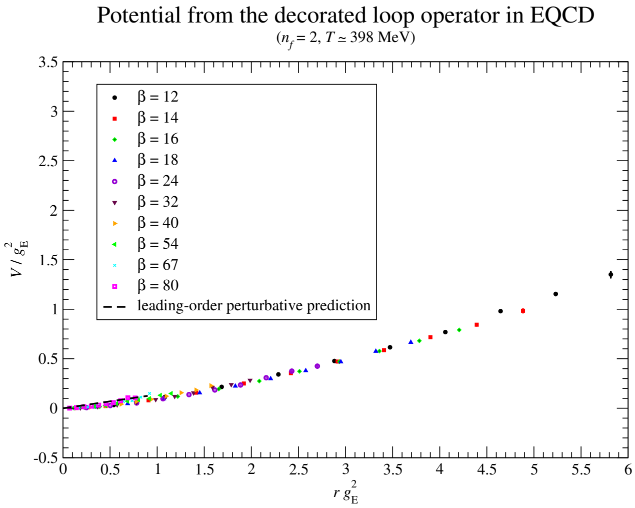

Soft NLO contribution to $\hat{q}$ is quite *large*:

$$\hat{q}_{\mathrm{EQCD}} \simeq \begin{cases} 0.55(5) g_{\mathrm{E}}^6 & \text{for } T \simeq 398 \text{ MeV} \\ 0.45(5) g_{\mathrm{E}}^6 & \text{for } T \simeq 2 \text{ GeV} \end{cases}$$

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These results lead to an *approximate* estimate $\hat{q} \sim 6$ GeV^2/fm at RHIC temperatures

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Discussion and conclusions

- Lattice approach *possible* for certain real-time problems
- Here: focus on soft physics in thermal QCD
- Outlined approach is *systematic*
- Tentative estimate of jet quenching parameter
- Results in ballpark of
  - holographic computations Liu, Rajagopal and Wiedemann, 2006 ✓
  - estimates from experiments Eskola *et al.*, 2004 ✓
- Further work in progress