Jet quenching from the lattice

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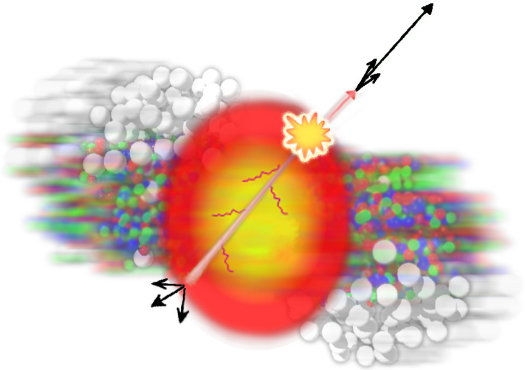
Based on: M.P., K. Rummukainen and A. Schäfer, PRL **112** (2014) 162001

Outline

Momentum broadening of a hard parton in the QGP

Jet quenching is related to *energy loss* and *momentum broadening* experienced by a hard parton moving in deconfined medium Bjorken, 1982



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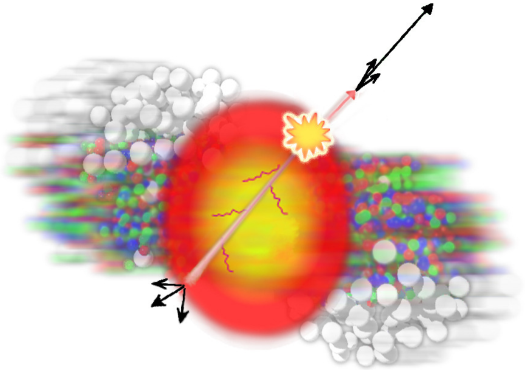

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Multiple soft-scattering description, in the *eikonal approximation* Baier et al., 1997

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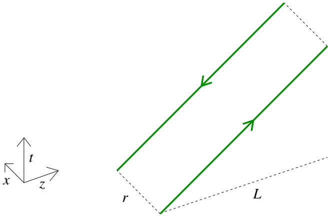
$C(p_\perp)$ is related to two-point correlator of *light-cone Wilson lines*



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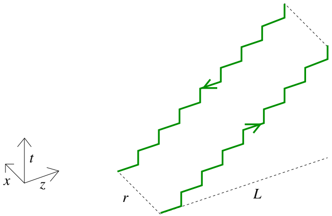
A direct lattice evaluation of light-cone Wilson line correlators *very impractical*



Outline

Key idea

Energy scale hierarchy in high-temperature, perturbative QCD:

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

IR divergences accounted for by 3D effective theories Braaten and Nieto, 1995 Kajantie et al., 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! Caron-Huot, 2008

Proof

Spatially separated ($|t| < |z|$) light-like Wilson lines Ghiglieri *et al.*, 2013

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

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

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

$$G^<(t, x_\perp, z) = T \sum_{n \in \mathbb{Z}} \int \mathrm{d}^2 p_\perp \mathrm{d}p'^z \tilde{G}_\mathrm{E}(2\pi n T, p_\perp, p'^z + 2\pi i n T t/z) e^{i\left(x_\perp \cdot p_\perp + z p'^z\right)}$$

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

Outline

Electrostatic QCD on the lattice

Super-renormalizable EQCD Lagrangian

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

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

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

Standard Wilson lattice regularization Hietanen *et al.*, 2008

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

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

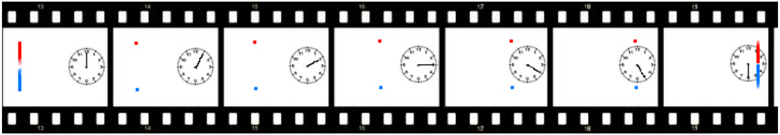
Closely related studies in MQCD Laine, 2012 Benzke *et al.*, 2012

Operator implementation

Effective theory: purely spatial

but

Operator describes *real time* evolution



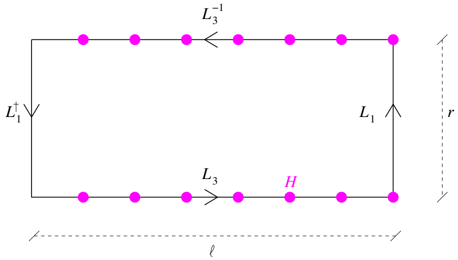
Operator implementation

Light-cone Wilson line correlator

$$\langle W(\ell, r)\rangle = \left\langle \mathrm{Tr}\left(L_3 L_1 L_3^{-1} L_1^\dagger\right)\right\rangle \sim \exp\left[-\ell V(r)\right]$$

with

$$L_3 = \prod U_3 H \qquad L_1 = \prod U_1 \qquad H = \exp(-a g_{\mathrm{E}}^2 A_0)$$



Well-defined renormalization properties D'Onofrio *et al.*, 2014

Outline

$\hat{q}$ *estimate*

Contribution to $\hat{q}$ related to the curvature of $V(r)$ near the origin

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Data fitted with a procedure similar to Laine, 2012

$$V/g_{\mathrm{E}}^2 = Arg_{\mathrm{E}}^2 + B(rg_{\mathrm{E}}^2)^2 + C(rg_{\mathrm{E}}^2)^2 \ln(rg_{\mathrm{E}}^2) + \ldots$$

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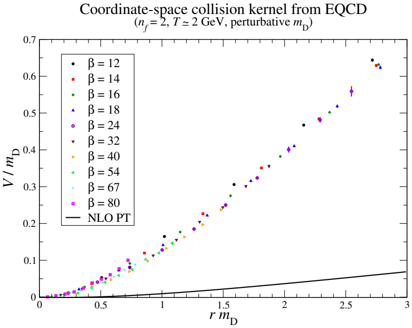
Approximate estimate $\hat{q} \sim 6$ GeV^2/fm at RHIC temperatures

Lattice versus perturbation theory

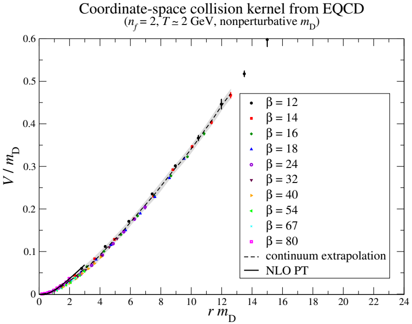
"Naïve" comparison with NLO PT



Lattice versus perturbation theory

Discrepancy reduced if data are plotted in terms of non-perturbative m_{D}

Laine and Philipsen, 2008



(For a discussion of screening masses and real-time rates, see also Brandt *et al.*, 2014)

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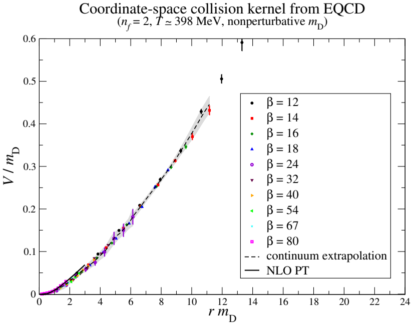

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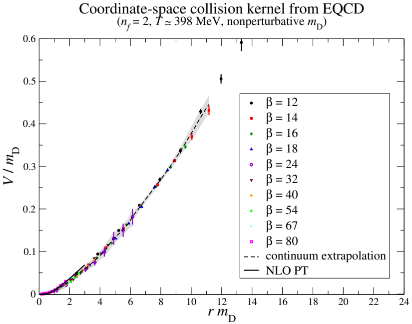

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Using NP value for $m_{\rm D}$ in

$$\hat{q}^{\rm NLO}_{\rm EQCD} = g^4 T^2 m_{\rm D} \mathcal{C}_{\rm f} \mathcal{C}_{\rm a} \frac{3\pi^2 + 10 - 4\ln 2}{32\pi^2}$$

yields again $\hat{q} \sim 6\ {\rm GeV}^2/{\rm fm}$ at RHIC temperatures

Outline

Conclusions

- Lattice approach *possible* for certain real-time problems—see also Majumder, 2012 Ji, 2013
- Here: focus on soft contributions Laine and Rothkopf, 2013 Cherednikov *et al.*, 2013
- A *systematic* approach
- Our results for jet quenching parameter give evidence of large non-perturbative effects
- Results in ballpark of
  - holographic computations Liu, Rajagopal and Wiedemann, 2006 Armesto, Edelstein and Mas, 2006 Gürsoy, Kiritsis, Michalogiorgakis and Nitti, 2009 ✓
  - estimates from phenomenological models Dainese *et al.*, 2004 Eskola *et al.*, 2004 Bass *et al.*, 2008 ✓—but see also Burke *et al.*, 2013 ✗
- Generalization to other observables (e.g. photon production rate, as suggested in Ghiglieri *et al.*, 2013) in progress