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Medium Induced Collinear Radiation via Soft Collinear Effective Theory (SCET)

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Abstract. The propagation of hard partons through the strongly interacting matter created in high energy heavy-ion collisions involves widely separated scales. The methods of Effective Field Theories (EFT) can provide a factorized description at lowest nontrivial order, and a formalism where the corrections to this factorization are calculable systematically order by order in the small ratios between the different scales. We present our preliminary results on the medium induced collinear radiation by using the methods of Soft Collinear Effective Theory (SCET). The radiated gluon is collinear with the incoming hard parton and gets an arbitrary fraction of its energy.

Keywords: Quark-gluon plasma, Jet quenching, Soft Collinear Effective Theory (SCET).

PACS: 12.38.Mh, 21.65.Qr.

INTRODUCTION AND SCET

The strongly interacting, high-density matter produced in ultra-relativistic heavy ion collisions has a lifetime far too short to be tested with external probes. Thus the study of its properties can be only be performed through its decay products and via internally generated probes. One of the most promising tools is the study of medium induced parton energy loss and parton fragmentation, which is a central part of the program of heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) [1] and at the Large Hadron Collider (LHC) [2]. In the high energy limit the parton loses energy dominantly by processes that are the QCD analogue of bremsstrahlung [3]. It is crucial to the calculation of this radiative energy loss process that the incident hard parton, the outgoing parton, and the radiated gluons are all continually being jostled by the medium in which they find themselves: they are *all* subject to transverse momentum broadening.

The calculation of parton energy loss and transverse momentum broadening involves widely separated scales, $Q \gg T$, where Q is the energy of the hard parton and T is the soft scale characteristic of the medium. We can ultimately hope for a factorized description, with physics at each of these scales cleanly separated at lowest nontrivial order in a combined expansion in the small ratio between these scales and in the QCD coupling α evaluated at scales which become large in the high parton energy limit. And, most importantly, we can aspire to having a formalism in which corrections to this factorization are calculable systematically, order by order in these expansions. We continue our effort in this direction: we formulate the calculation of the medium induced collinear radiation in the language of Soft Collinear Effective Theory (SCET) [4], which has rendered the calculation of many other processes involving soft and collinear degrees of freedom systematically improvable. Related works applying SCET to jet propagation in dense media can be found in reference [5].

We applied SCET in reference [6] to treat transverse momentum broadening only in the absence of radiation. In particular the “jet quenching parameter” $\hat{q}$, defined as the mean transverse momentum picked up by the hard parton per unit distance travelled, was found to be given by

$$\hat{q} \equiv \frac{\langle k_{\perp}^2 \rangle}{L} = \frac{1}{L} \int \frac{d^2 k_{\perp}}{(2\pi)^2} k_{\perp}^2 \int d^2 x_{\perp} e^{-ik_{\perp} \cdot x_{\perp}} \mathcal{W}_{\mathcal{R}}(x_{\perp}), \quad (1)$$

where $\mathcal{R}$ is the $SU(N)$ representation to which the collinear particle belongs and $\mathcal{W}_{\mathcal{R}}(x_{\perp})$ is the expectation value of two light-like Wilson lines separated in the transverse plane by the vector $x_{\perp}$. Note that $\mathcal{W}_{\mathcal{R}}(x_{\perp})$ depends only on the properties of the medium and it is independent of the energy of the hard parton, meaning that so is $\hat{q}$ in the limit in which this hard parton energy is taken to infinity. Transverse momentum broadening without radiation thus does “measure” a field-theoretically well-defined property of the strongly coupled medium. The goal of the present work is to extend the transverse momentum broadening analysis, by allowing the hard parton to emit a collinear gluon.

where C_F is the Casimir factor in the $SU(N)$ representation, and we define

$$\mathcal{V}[x_\perp, l_\perp, P] = \mathcal{W}_F(x_\perp) \int \frac{d^2 k_\perp}{(2\pi)^2} \exp[ik_\perp \cdot x_\perp] \left(\frac{k_\perp^2}{Q-P} + \frac{l_\perp^2}{P} \right)^{-2} \times \left[\frac{1}{2} \frac{k_\perp^2}{(Q-P)^2} + \frac{1}{2} \frac{(k_\perp + l_\perp)^2}{Q^2} + \frac{l_\perp^2}{P^2} - \frac{l_\perp \cdot k_\perp}{P(Q-P)} - \frac{l_\perp \cdot (k_\perp + l_\perp)}{QP} \right]. \quad (5)$$

We therefore discover that $|\mathcal{M}_v|^2$, the amplitude for emission in vacuum after the hard parton exits the medium, does depend on the properties of the medium — in fact through the same soft function $\mathcal{W}_F(x_\perp)$ constructed from the expectation value of light-like Wilson lines that controls transverse momentum broadening and appears in (1). This is at first a surprise, since in treatments in the literature (for example in [7]) $|\mathcal{M}_v|^2$ is independent of the properties of the medium. However, in the kinematic limit in which the radiated gluon is much softer than the incoming hard parton, namely $P \ll Q$, we find that (5) becomes independent of the medium, as in the literature. In this limit

$$\mathcal{V}[x_\perp, l_\perp, P] \simeq \mathcal{W}_F(x_\perp) \delta^2(x_\perp) \frac{1}{l_\perp^2} \quad \Rightarrow \quad |\mathcal{M}_v|^2 = \frac{4g^2 C_F}{l_\perp^2} \quad (\text{for } P \ll Q). \quad (6)$$

The medium emission squared $|\mathcal{M}_m|^2$ and the interference $2\text{Re}(\mathcal{M}_m \mathcal{M}_v^*)$ contributions are also computed, and we recover the correct limit [7] when the radiated gluon is much softer than the incoming quark. However the expressions for arbitrary values of P have some interesting different features. The final state collinear quark, after it radiates a collinear gluon, is not necessarily described by a light-like Wilson line as in [7], but more generally as a path integral. This takes into account the region of phase space where the radiated gluon takes away a significant amount of its energy. In addition there are transverse derivatives acting not only on the path integrals describing the motion of the radiated gluon, but also on the fundamental Wilson line and path integral, describing the incoming and outgoing quark, respectively. We will report the detailed expressions in a future publication.

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