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Drag induced radiative energy loss of semi-hard heavy quarks

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Abstract

We revisited gluon bremsstrahlung off a heavy quark in nuclear matter within higher twist formalism. In this work, we demonstrate that, in addition to transverse momentum diffusion parameter ($\hat{q}$), the gluon emission spectrum for a heavy quark is quite sensitive to $\hat{e}$, which quantify the amount of *light-cone* drag experienced by a parton. This effect leads to an additional energy loss term for heavy-quarks. From heavy flavor suppression data in ultra-relativistic heavy-ion collisions one can now estimate the value of this sub-leading non-perturbative jet transport parameter ($\hat{e}$) from our results.

Keywords: energy loss, drag, heavy-quark, bremsstrahlung radiation.

1. Introduction

By now a substantial amount of work has already been done to understand unexpectedly large suppression of single electrons or open heavy mesons coming from the fragmentation of a heavy-quark in nuclear medium. There are two main categories associated with these developments [1]: (*a*) Calculations that extended radiated energy loss formalism for light flavors to include mass dependent terms, as well as a drag term [2, 3]. (*b*) Calculations that have totally ignored the role of radiative loss and only focussed on drag loss. In both sets of calculations, radiative loss is the results of transverse momentum diffusion experienced by the heavy quark, which is denoted by the jet transport coefficient $\hat{q}$. Till now no calculation of heavy flavor energy loss has investigated the possibility that the drag coefficient $\hat{e}$ (or the longitudinal diffusion coefficient $\hat{e}_2$) may also lead to an additional prominent source of radiative energy loss, beyond that provided by $\hat{q}$. In the higher twist framework, the drag (and longitudinal diffusion) coefficient $\hat{e}$ ($\hat{e}_2$) defined as the loss of light-cone momentum (fluctuation in light-cone momentum) per unit light-cone length as,

$$\hat{e} = \frac{d\langle \Delta p^- \rangle}{dL^-}, \qquad \hat{e}_2 = \frac{d\langle \Delta p^{-2} \rangle}{dL^-}. \tag{1}$$

Here we assume that the parton is moving in the negative light-cone direction. Though this sub-leading transport coefficients have little effect to the off-shellness of a near on-shell *massless* quark, it has a considerable impact on the off-shellness of a near on-shell *massive* quark. In particular this sub-leading transport coefficients will *only* have an effect on the radiative energy loss of a patron where the momentum p is comparable to the mass M. We also point out that this mass dependent effect is by no means limited only to the higher-twist scheme, but intrinsic to all other formalisms that have considered the radiative loss from a heavy-quark in a nuclear medium. To delineate the relative importance of these additional new drage terms, we have used power-counting techniques borrowed from Soft-Collinear-Effective-Theory (SCET). This helps one to identify the regime where these mass dependent terms really cause detectable effects on the actual gluon bremsstrahlung spectrum. In this work, being a first attempt, we have considered only the case of single scattering and single emission off the propagating

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heavy quark.

2. Deep inelastic scattering and the semi-hard heavy quark

We consider the case of deep-inelastic scattering of a hard virtual photon off a hard heavy quark within a large nucleus with mass number A [4]. We also factorized the propagation of the heavy-quark from the hard scattering vertex which produces the outgoing slow moving heavy-quark. The exchanged virtual photon possesses no transverse momentum, in the Breit frame,

$$q \equiv [q^+, q^-, q_\perp] = [q^+, q^-, 0]\,. \tag{2}$$

The scattering process under consideration is the following:

$$e(L_1) + A(P) \to e(L_2) + J_Q(L_Q) + X. \tag{3}$$

As there is no valence heavy-quark within the nucleon, the photon will have to strike a heavy quark from rare $Q\bar{Q}$ fluctuations within the sea of partons. In the rest frame of the nucleus we assume that the quark and antiquark are almost at rest *i.e.* $\left(p_Q^+, p_Q^-, p_{Q\perp}\right) \sim \left(M/\sqrt{2},\ M/\sqrt{2},\ 0\right)$. Now if the nucleus is boosted by a large boost factor γ in the " + " direction, momentum components of the incoming heavy quark will then scales as,

$$p_Q = \left[p_Q^+, p_Q^-, p_{Q\perp}\right] \equiv \left[\gamma\frac{M}{\sqrt{2}},\ \frac{1}{\gamma}\frac{M}{\sqrt{2}},\ 0\right]. \tag{4}$$

Momentum components of the incoming photon have been assumed as,

$$q = \left[-\gamma\frac{M}{\sqrt{2}} + \frac{M^2}{2q^-},\ q^- - \frac{1}{\gamma}\frac{M}{\sqrt{2}},\ 0\right]. \tag{5}$$

As there is a large boost factor (γ), one can reasonably assume that $\gamma M \gg M \sim q^- \gg M/\gamma$. This would let us to define the hard scale Q as $Q^2 = -q^2 \simeq \gamma M q^-/\sqrt{2}$. Therefore, final out-going quark have momentum components that scales as,

$$p_f = p_Q + q = \left[\frac{M^2}{2q^-}, q^-, 0\right]. \tag{6}$$

2.1. Power Counting and the small λ parameter

In this study, we have introduced the dimensionless small parameter λ in order to set up the power counting. We borrowed the concept from soft collinear effective theory (SCET) to represent semi-hard scales as λQ and softer scales as $\lambda^2 Q$. Here we have retained leading and next-to-leading terms in λ power counting and neglecting all terms that scale with λ^2 or a higher power of λ. We have chosen the scaling variable λ so that perturbation theory may be applied down to momentum transfer scales even at $\lambda^{3/2} Q \sim \Lambda_{\rm QCD}$. In this study,

$$1 \gg \sqrt{\lambda} \gg \lambda \gg \lambda^{\frac{3}{2}}. \tag{7}$$

The virtuality of the hard photon defines the hardest scale in the problem, Q. The incoming or initial heavy quark has momentum components $p_i \sim (\lambda^{-\frac{1}{2}}, \lambda^{\frac{3}{2}}, 0)Q$, the outgoing heavy quark has momentum components $p \sim (\sqrt{\lambda}, \sqrt{\lambda}, 0)Q$. The mass of the semi-hard heavy quark scales as $M \sim \sqrt{\lambda}Q$. Leading contribution to gluon emission arises from the region where real emitted gluons have momenta which scale as $l \sim (\lambda, \lambda, \lambda)Q$. The fraction of light cone momenta carried out by the gluon is $y = l^-/p^- \sim \sqrt{\lambda}$. Scaling of the virtual Glauber gluons is as follows, $k \sim (\lambda^{\frac{3}{2}}, \lambda^{\frac{3}{2}}, \lambda)Q$ with $k^2 = 2k^+k^- - k_\perp^2 \simeq -k_\perp^2$.

3. Induced gluon radiation off the heavy quark

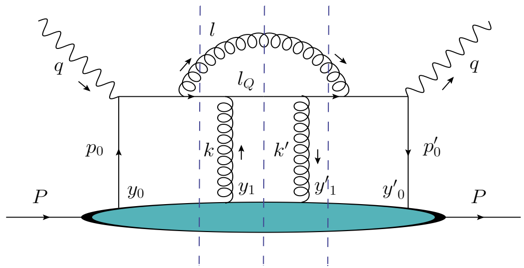

Figure 1: One of the 11 single gluon emission diagram, where gluon emission is induced by single scattering. Dashed lines indicate three separate cuts, denoted as central, left and right.

In total, there are 11 separate topologically distinct diagrams similar to that in Fig. 1 [5]. We have defined the following momentum fractions for convenience,

$$\begin{aligned}
y &= \frac{l^-}{q^-}\,,\ \ \eta = \frac{k^-}{l^-}\,,\ \ \zeta = \frac{1-y}{1-y+\eta y}\,,\\
x_0 &= \frac{p_i^+}{P^+}\,,\ \ x_1 = \frac{k^+}{P^+}\,,\ \ \chi = \frac{y^2M^2}{l_\perp^2}\,,\\
x_L &= \frac{l_\perp^2}{2P^+q^-y(1-y)}\,,\ \ x_D = \frac{k_\perp^2 - 2l_\perp k_\perp}{2P^+q^-}\,,\\
x_K &= \frac{k_\perp^2}{2P^+q^-}\,,\ \ \kappa = \frac{1}{1+(1-y)^2}\,,\\
x_M &= \frac{M^2}{2P^+q^-}.
\end{aligned} \tag{8}$$