Color decoherence of in-medium jet evolution

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Abstract

We give a brief overview of recent theoretical studies on the alteration of color coherence in the process of jet fragmentation in the presence of a dense QCD medium. Two regimes emerge depending on the interplay between the typical size of the jet inside the medium $r_\perp = \theta_{jet} L$, where θ_{jet} is the jet opening angle and L the length of medium, and the in-medium transverse color correlation length $Q_s^{-1} \equiv (\hat{q}L)^{-1/2}$, where $\hat{q}$ is the jet quenching parameter. When $Q_s^{-1} \gg r_\perp$ the medium does not resolve the inner structure of the jet. In this coherence regime the medium will induce radiation off the total charge of the jet while its fragmentation will proceed coherently as in vacuum. In the opposite case $Q_s^{-1} \ll r_\perp$, the medium resolves more charges inside the jet which will decohere due to rapid color randomization from the jet and fragment independently. A probabilistic picture of in-medium jet fragmentation can be formulated in the total decoherence regime.

1. Introduction

The strong suppression of high-pt hadrons, commonly known as ”jet-quenching”, is one of the main experimental evidences in ultra-relativistic heavy ion collisions (HIC) at RHIC and the LHC in favor of the creation of a dense phase of deconfined QCD matter in the intermediate stages of the collisions [1, 2, 3, 4, 5, 6, 7]. This phenomena is due to the energy loss suffered by high-pt partons, produced in the early stage of the collision, via gluon radiation stimulated by the interactions with the hot colored medium. The theory of radiative parton energy loss has been developed in late 90’s. It is commonly referred to as BDMPSZ theory, from the names of the original authors [8, 9, 11, 12].

In particular, at the LHC, high-energy jets are abundantly produced in HIC, thus allowing for more differential studies of the medium effects on the propagation of hard particles. Such studies include jet shapes, fragmentation functions, the jet modification factor, etc. [4, 5, 6, 7]. However, in contrast to this wealth of experimental results, the theoretical tools are not yet sufficiently developed to permit a fully satisfactory understanding of the data. This contribution reports on recent works which represents a major step towards the construction of a complete theory for in-medium jet evolution from first principles [14, 15, 16, 17, 18, 19, 13, 21].

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2. From the antenna to in-medium jet structure

A jet is a transversally extended object that is built-up by multiple parton branching. The QCD building block of jet evolution in vacuum is the well-known antenna radiation probability that involves two partons branching into three. It allows to account for color coherence in the jet responsible for angular ordering of successive branchings. We have thus naturally investigated the alteration of the antenna radiation pattern in the medium in order to understand how color coherence is altered by the interaction of a jet with medium color charges [14, 15, 16, 17, 18]. .

In the presence of a medium, the response of such a system dependents on the transverse scales (that are generated dynamically) of the problem.

One can identify two distinct regimes in the radiation pattern of the antenna characterized by the quantity

$$\Delta_{\rm med} = 1 - \exp\left(-\frac{1}{12} Q_s^2\, r_\perp^2\right) ,$$

In terms of characteristic transverse distances, on one hand there is the antenna size, $r_\perp$, and, on the other hand, the transverse color correlation length of the medium, given by the inverse of the characteristic medium scale Q_s^{-1}, which is related to the maximum transverse momentum that a induced particle can accumulate traversing the total medium length. First let us consider the case, when $r_\perp < Q_s^{-1}$, i.e., the limit of small antenna sizes ($\Delta_{\rm med} \sim 0$). In this situation the antenna interacts as a coherent objet with the medium and the medium cannot resolve its inner structure. It follows that the medium interactions only can stimulate coherent radiation off the total charge of the antenna. In the opposite case, $r_\perp > Q_s^{-1}$ ($\Delta_{\rm med} \sim 1$), the medium probes the inner structure of the antenna. We have called it the "decoherence" regime. Interferences are strongly suppressed and independent radiation is induces off each of the constituents. In both cases, the spectrum is governed by the hardest of these two momentum scales, $Q_{\rm hard} = \max\left(r_\perp^{-1}, Q_s\right)$, which specifies the maximal transverse momentum of produced gluons. Most importantly, vacuum coherence is restored for $k_\perp > Q_{\rm hard}$. Thus, $\Delta_{\rm med}$ takes the meaning of a decoherence parameter.

More generally, and by analogy with the antenna, the same scales can be identified in the case of a jet of energy E and opening angle θ_{jet} (in addition to the jet transverse mass $M_\perp = \theta_{jet} E$ and the non-perturbative scale at which hadronization occurs), $Q_0 \sim \Lambda_{\rm QCD}$), namely, the inverse jet transverse size, $r_\perp^{-1} = (\theta_{jet} L)^{-1}$ and the medium scale Q_s. A full theory of in-medium jets should involve these four scales and describe the interplay bewteen them in particular the transition between the coherence and the decoherence regimes.

3. Probabilistic picture in the decoherence regime

In the full-decoherence regime color coherence is destroyed by the medium and as we shall see in-medium multiple branchings factorize. This situation is realized by formally taking $L \to \infty$ (or $\hat{q} \to \infty$).

Let us first recall the main features of the BDMPS-Z spectrum. The medium-induced inclusive soft gluon spectrum is given at leading order in the coupling constant by

$$\omega \frac{dN}{d\omega} = \frac{\alpha_s C_R}{\pi} \sqrt{\frac{\omega_c}{\omega}} ,$$

for gluon energies $\omega \ll \omega_c \equiv \hat{q} L^2$ and is suppressed as ω^{-2} for $\omega \gg \omega_c$. L is the size of the medium and $\hat{q}$ (known as the 'jet quenching parameter') is a transport coefficient related to the

Debye mass and to the in-medium mean free path: $\hat{q} = m_D^2/\lambda_{\rm mfp}$. The spectrum (1) is the QCD analog of the Landau-Pomeranchuk-Migdal spectrum. It exhibits a suppression of hard modes characterized by the frequency ω_c. Eq. (1) shows that the gluon number scales as the size of the medium L. It can be suggestively rewritten as $\omega dN/d\omega = \bar{\alpha}_s(L/\tau_{\rm br})$, where $\tau_{\rm br} = \sqrt{\omega/\hat{q}}$ is the branching time of the parent parton (in the representation R) which can occur anywhere along the medium length L as long as $\tau_{\rm br} \ll L$. In spite of the apparent suppression introduced by the small coupling constant $\bar{\alpha}_s = C_R\alpha_s/\pi \ll 1$, the perturbative expansion associated with multiple emissions breaks down when $\bar{\alpha}_s(L/\tau_{\rm br}) \sim 1$. In this regime, powers of $\bar{\alpha}_s L/\tau_{\rm br}$ have to be resummed to all orders.

Let us comment more on the gluon formation time: its usual definition, as the inverse of the energy difference at the splitting vertex, yields $t_{\rm f} = \omega/k_\perp^2$. For nearly collinear emissions in the vacuum, this time can be very large. However, as we shall see, for medium–induced emissions, the transverse momentum a peaked around a value $k_{\rm br} = (\hat{q}\omega)^{1/4}$. In other words, most of the gluons with energy ω are formed after a time $\tau_{\rm br}$ and larger formation times are strongly suppressed.

Since each branching can occur quasi-instantaneously ($\tau_{\rm br} \ll L$) anywhere in the medium, two branchings are most likely to be well separated and independent of each other. This dominant and factorizable contribution scales as $dN^{\rm fact} \propto (\alpha_s L)^2$. The two gluons interfere only when the difference between their respective emission times is of the order of their branching times [16], this leads to a scaling for the interferences of the type $dN^{\rm int} \propto (\alpha_s L)(\alpha_s \tau_{\rm br})$, which is suppressed as compared to the factorizable contribution when $\omega \ll \omega_c$ by the factor $dN^{\rm int}/dN^{\rm fact} \sim \tau_{\rm br}/L \ll 1$ In this factorization scheme we addressed only the issue of terms that are enhanced by factor of L. We ignore for the time being logarithmic enhancement, $\alpha_s \ln^2 E$ where E is the energy of the jet, generated by vacuum-like branchings by formally setting $L \to \infty$. Vacuum emissions will be addressed in a future work to complete our picture. This time-scale separation [20] allows us to express the branching process as classical and ordered in light-cone time $t \equiv x^+$ variable along the direction of the jet, in terms of a Master-Equation for a generating functional $Z(p, L; u)$ [21], where $u(p)$ is an arbitrary function of momentum p, i.e,

$$\begin{aligned} Z(p, L - t_0; u) &= \Delta_S(E, L) \int \frac{d^2\boldsymbol{p}'}{(2\pi)^2} P(\boldsymbol{p}' - \boldsymbol{p}, L - t_0)\, u(p') \\ &+ \frac{1}{2}\bar{\alpha}_s \int_{t_0}^{L} dt\, \Delta_S(E, t - t_0) \int_0^1 dz \int \frac{d^2\boldsymbol{p}'}{(2\pi)^2} \int \frac{d^2\boldsymbol{q}}{(2\pi)^2} P(\boldsymbol{p}' - \boldsymbol{p}, t - t_0)\, \mathcal{K}(\boldsymbol{p}' - z\boldsymbol{q}, z, E) \\ &\quad \times Z(q, L - t; u)\, Z(p' - q, L - t; u) \end{aligned} \tag{1}$$

The Generating Functional technique is very useful to compute inclusive jet observables which can be accessed by simply differentiating Z with respect to u then setting $u = 1$, for exemple $\delta Z/\delta u|_{u=1} =< n >$. The quasi-instantaneous k_t-differential splitting kernel can be computed in the harmonic approximation yielding [20]

$$\mathcal{K}(\boldsymbol{p}, z, E) \approx \frac{2}{z(1-z)E} P_{gg}(z) \sin\left(\frac{\boldsymbol{p}^2}{2\boldsymbol{k}_{\rm br}^2}\right) \exp\left(-\frac{\boldsymbol{p}^2}{2\boldsymbol{k}_{\rm br}^2}\right). \tag{2}$$

where $\boldsymbol{k}_{\rm br}^2 = \sqrt{z(1-z)E\hat{q}_{\rm eff}}$ is the typical transverse momentum generated during the branching process and the effective transport coefficient is $\hat{q}_{\rm eff} = C_A\left[1 + z^2 + (1-z)^2\right]\hat{q}/2$ generalize to arbitrary energies the quantities introduced above in the case of a soft gluon radiation ($z \to 0$).

This kernel generalizes the result obtained in [18] in the eikonal limit. When a parton does not branch it rescatters classically in the medium. This process is accounted for by the probability for a gluon to acquire a transverse momentum broadening $\boldsymbol{k}$ during a time interval t, $P(\boldsymbol{k}, t)$. The last but not least element that composes Eq. (1) is the Sudakov-like form factor,

$$\Delta_S(E,t) \equiv \exp\left[-\frac{1}{2}\bar{\alpha}_s t \int_0^1 dz \int \frac{d^2\boldsymbol{p}}{(2\pi)^2}\mathcal{K}(\boldsymbol{p},z,E)\right] \tag{3}$$

It describes the probability that a gluon does not branch during the time t.

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