Adding vacuum branching to jet evolution in a dense medium

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Abstract

We study the fragmentation of a jet propagating in a dense quark-gluon plasma. We show that the “vacuum-like” emissions triggered by the parton virtualities can be factorized from the medium-induced radiation responsible for the energy loss within a controlled, “double-logarithmic”, approximation in perturbative QCD. We show that the collisions with the plasma constituents modify the vacuum-like parton shower already at leading twist, in two ways: the radiation phase-space is reduced and the first emission outside the medium can violate angular ordering. We compute the jet fragmentation function and find results in qualitative agreement with measurements at the LHC.

Keywords: Quark Gluon Plasma; Jets; Jet quenching; Bremsstrahlung.

1. Introduction

The energy lost by a jet propagating through the dense environment of an ultrarelativistic heavy ion collision and, more generally, the medium-induced modifications in the jet branching pattern, are among the main observables used in the study of the quark-gluon plasma (QGP) expected to be created in the intermediate stages of such a collision. For the respective data at RHIC and the LHC to be fruitfully exploited, it is essential to have a good theoretical understanding of the interactions between the jet and the QGP, from first principles. It is in particular of utmost importance to understand how the physics of parton branchings is modified by these interactions. On conceptual grounds, it is quite clear that the overall jet structure should get built via the interplay between two mechanisms for radiation: the usual, “vacuum-like”, bremsstrahlung through which a virtual parton evacuate his virtuality (until this becomes as small as the hadronisation scale) and the additional, “medium-induced”, radiation, which is triggered by the collisions between the partons from the jet and those from the plasma. Taken separately, these two mechanisms are by now rather well understood (notably due to recent progress with understanding color decoherence [1, 2, 3] and multiple medium-induced branchings [4, 5, 6, 7, 8, 9]), but it appears as a challenge to construct a unified theoretical picture which consistently encompasses both sources of radiation and their potential interplay. There are several reasons for such a difficulty: the respective underlying mechanisms are characterized by different evolution variables — parton virtualities for the vacuum-like emissions (VLEs), respectively, in-medium propagation time for the medium-induced ones (MIEs) —, by different coherence properties (see
2. Vacuum-like emissions in the double logarithmic approximation

It is conceptually simpler to consider a jet initiated by a quark-antiquark antenna in a color singlet state with opening angle \( \theta_{q\bar{q}} < 1 \), e.g. produced by the decay of a boosted W/Z boson or a virtual photon. (For a generic jet which is produced by a parton, the role of \( \theta_{q\bar{q}} \) would be played by the jet radius \( R \).) The quark and the antiquark are assumed to have equal energies: \( E_q = E_{\bar{q}} \equiv E \), with \( E \) a very high energy compared to the typical scales of the medium (see below). Also, the antenna is assumed to be produced directly inside the medium (a static and uniform plasma characterized for the present purposes by the jet quenching parameter \( \hat{q} \)) and to cross the medium along a distance \( L \). Finally, for simplicity we shall work in the limit of a large number of colors \( N_c \gg 1 \), where a gluon emission can be pictured as the splitting of one dipole into two. The quark and antiquark legs of this antenna have a large virtuality \( Q^2 \approx (E\theta_{q\bar{q}})^2 \), so they can radiate gluons like in the vacuum, i.e. via bremsstrahlung (see the left Figure 1 for an illustration).

The formation time. Consider first a VLE which occurs inside the medium, meaning that the respective formation time \( t_f \) is smaller than \( L \). \( t_f \) is determined by the condition that the transverse separation \( \Delta r \sim \theta t_f \) between the gluon and its parent parton at the time of emission be as large as the gluon transverse wavelength \( 2/k_{\perp} \), with \( k_{\perp} \approx \omega \hat{q} \) its transverse momentum w.r.t. its emitter. This argument applies to both vacuum-like and medium-induced emissions and implies \( t_f \approx 2\omega/k_{\perp}^2 = 2/(\omega \hat{q})^2 \). Then, gluons emitted inside the medium have a minimum \( k_{\perp} \) set by the momentum acquired via multiple collisions during formation: \( k_{\perp}^2 \approx \hat{q} t_f \). This translates into an upper limit \( t_f \lesssim \sqrt{2\omega}/\hat{q} \) on the formation time, leaving two possibilities: (a) MIEs, for which \( k_{\perp} \approx k_f \), so the corresponding formation time saturates the upper limit, and (b) VLEs, which are comparatively harder, \( k_{\perp} \gg k_f \), meaning that they occur much faster than MIEs with the same energy:

\[
t_f = \frac{2}{\omega \hat{q}} \ll \sqrt{\frac{2\omega}{\hat{q}}} \quad \Rightarrow \quad \omega \gg \left( \frac{2\hat{q}}{\omega^2} \right)^{1/2} \equiv \omega_0(\theta) \quad \text{(VLE)}
\]  (1)

This constraint, which can be also formulated as a lower limit on the emission angle, applies only so long \( \sqrt{2\omega/Q} < L \), i.e. for energies \( \omega \leq \omega_c \equiv \hat{q} L^2/2 \). Emissions with larger energies \( \omega \geq \omega_c \) behave exactly as in the vacuum: their emission angle can be arbitrarily small and their formation time can be larger than \( L \). We shall assume that \( E > \omega_c \), which is indeed the case for the high energy (\( E > 100 \text{ GeV} \)) jets at the LHC.
The vetoed region. Eq. (1) immediately implies the existence of a vetoed region in the \((\omega, \theta)\) phase-space for VLEs \([13]\): for a given energy \(\omega \leq \omega_0\), there are no VLEs with formation time within the range \(\sqrt{2\omega/\hat{q}} < t_f < L\). As visible in Fig. 1(right), this excluded region exists only for angles larger than a special value \(\theta_* \equiv 2/\sqrt{\hat{q}L}\), which is quite small, \(\theta_* < 0.1\), for the phenomenologically relevant values for \(\hat{q}\) and \(L\).

Colour (de)coherence. For emissions by a colour-singlet antenna, even a VLE obeying (1) could be still affected by the medium, via color decoherence \([1,2,3]\). In the vacuum, gluon emissions at large angles \(\theta \gg \theta_{q\bar{q}}\) are suppressed by the destructive interferences between the quark and the antiquark. But an antenna propagating through a dense QGP can lose its coherence via rescattering off the medium: the quark and the antiquark suffer independent color rotations, hence the probability that the antenna remains in a color singlet state decreases with time. The two legs of the antenna start behaving like independent color sources after a time \(t \sim t_{coh}\), where \(t_{coh} \equiv (4/\hat{q}^2\theta_{q\bar{q}}^2)^{1/3}\) \([2]\). This scale would be comparable to \(L\) for \(\theta_{q\bar{q}} \sim \theta_*,\) in practice though, one generally has \(\theta_{q\bar{q}} \gg \theta_*\), meaning that our original antenna will lose coherence pretty fast. In spite of that, it cannot radiate vacuum-like gluons at large angles \(\theta \gg \theta_{q\bar{q}}\), as noticed in \([13]\). Indeed one can easily check that VLEs with \(\theta \gg \theta_{q\bar{q}}\) would have formation times even smaller than the decoherence time, \(2/\omega^2 \ll t_{coh}(\theta_{q\bar{q}})\), hence they are killed by interference, like in the vacuum. This implies that color decoherence plays no special role for VLEs occurring inside the medium: only emissions with \(\theta \lesssim \theta_{q\bar{q}}\) are allowed whether or not they occur at times larger than the decoherence time \(t_{coh}(\theta_{q\bar{q}})\).

Multiple emissions inside the medium. So far, we have considered a single emission inside the medium, but the previous arguments remain valid for an arbitrary numbers of successive VLE which are strongly ordered in both energies and angles: \(\theta_{q\bar{q}} \gg \theta_1 \gg \cdots \gg \theta_n \gg \theta_\omega\) and \(E \gg \omega_1 \gg \cdots \gg \omega_n \gg \omega_\omega(\theta_\omega)\). These are precisely the cascades which give the dominant, double-logarithmic, contribution to the jet multiplicity (or fragmentation function) \(D(\omega) = \omega (dN/d\omega)\) when \(\omega \ll E\) in pQCD. The fact that the angular ordering of successive emissions can be preserved inside the medium (like in the vacuum) is highly non-trivial and follows from our previous observation that color decoherence via rescattering plays no role for the VLEs.

First emission outside the medium. The partons produced inside the medium via VLEs can act as sources for medium-induced radiation (and thus contribute to the energy loss by the jet), but they can also radiate gluons directly outside the medium. The first such an emission, whose formation time is, by definition, larger than \(L\), is rather special \([13]\). Indeed, all the in-medium sources with \(\theta \gg \theta_\omega\) satisfy \(t_{coh}(\theta) < L\) and thus lose color coherence after propagating over a distance \(L\) in the medium. Accordingly, the first emission outside the medium can violate angular ordering. (A similar idea appears in \([14]\).) This is important since it...
re-opens the angular phase-space for the subsequent cascades developing outside the medium (which are of course angular-ordered). A gluon cascade with these characteristics is illustrated in Fig. 1 (left).

Jet fragmentation function. These physical considerations can be easily transposed into a calculation of the jet multiplicity in the double logarithmic approximation (DLA), with the results shown in Fig. 2 [13]. The left figure refers to the two-dimensional gluon distribution \( T(\omega, \theta) \equiv d^2N/d\omega d\theta \); we more precisely show the ratio \( T(\omega, \theta)/T_{vac}(\omega, \theta) \) between the distribution generated in the presence of the medium and that in the vacuum. This ratio is 1 for all the points either inside the medium or with \( \omega > \omega_m \). However, one sees significant deviations from unity for points outside the medium with energies \( \omega < \omega_m \) for intermediate values of \( \omega < \omega_c \). For smaller energies and larger angles, \( \theta > 0.2 \), one rather sees a strong enhancement, owing to emissions violating angular ordering.

Given the two-dimensional distribution \( T(\omega, \theta) \), the fragmentation function \( D(\omega) \) is obtained by integrating over the angles. The right plot in Fig. 2 shows the ratio \( D(\omega)/D_{vac}(\omega) \). One sees a slight suppression (relative to vacuum) at intermediate energies, roughly from 2 GeV up to \( \omega_c \), and a substantial enhancement at lower energies \( \omega < 2 \) GeV. This enhancement is attributed to small-angle emissions inside the medium, radiating at larger angles outside the medium due to the lack of angular ordering. These results are in qualitative agreement with the respective LHC measurements for the most central PbPb collisions [15, 16]. Since based on a probabilistic picture, our approach is suitable for Monte-Carlo implementations, which would allow to go beyond the present, double-logarithmic, approximation.

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