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New picture of jet quenching dictated by color coherence

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ABSTRACT

We propose a new description of the jet quenching phenomenon observed in nuclear collisions at high energies in which coherent parton branching plays a central role. This picture is based on the appearance of a dynamically generated scale, the jet resolution scale, which controls the transverse resolution power of the medium to simultaneously propagating color probes. Since from the point of view of the medium all partonic jet fragments within this transverse distance act coherently as a single emitter, this scale allows us to rearrange the jet shower into effective emitters. We observe that in the kinematic regime of the LHC, the corresponding characteristic angle is comparable to the typical opening angle of high-energy jets such that most of the jet energy is contained within a non-resolvable color coherent inner core. Thus, a sizable fraction of the jets is unresolved, losing energy as a single parton without modifications of their intra-jet structure.

1. Introduction

The phenomenon of "jet quenching", in other words the modifications of the structure of jets in a heavy-ion environment, is one of the main tools to determine the properties of QCD matter under extreme conditions. The suppression of high transverse momentum particles observed in Au+Au collisions at RHIC stands out as one of its key discoveries [1–4]. A similarly strong suppression is observed in Pb + Pb collisions at the LHC [5,6]. Reconstructed jet observables, which hold the promise to be extremely versatile probes for an unprecedented characterization of the medium, have recently been measured as well [7,8]. Clearly, the success of this program relies crucially on a detailed understanding of the interaction of jets with QCD matter. However, the approaches successfully applied at RHIC need important refinements to describe the sub-leading structure of the jet, treated so far in an oversimplified manner. This calls for a complete theory of jets in a medium.

The perturbative QCD description of jets in the vacuum is built up of partial information from limiting cases where first-principle calculations are possible and improves systematically when increasing precision is needed. A similar approach is being followed for the medium case. One of the essential features of the vacuum branching process is color coherence in multi-gluon radiation, a problem which has recently been addressed for the medium in a series of papers [9–15]. Based on the insights obtained from these studies of the *antenna radiation*, in this Letter we put forward a new and appealing picture of the problem of in-medium jet evolution. This provides an extension of the antenna radiation, a computational setup, to the whole jet evolution, introducing the concept of effective emitters for the medium radiation.

The underlying physical picture arising from these studies is simple: for medium-induced gluon radiation, a jet is composed of a set of colored emitters, which may not correspond to the actual number of partons in the shower. A given medium configuration defines an effective number of emitters off of which induced radiation takes place, while inside each of these effective sources the angular-ordered vacuum radiation occurs. The resolution defining these emitters is determined dynamically by the medium properties and not by the kinematics of the radiated gluon, as for the vacuum. A key observation is that the medium gives rise to a transverse resolution scale which determines the role of the coherence effects: partons separated in transverse plane less than this characteristic size remain color correlated and hence emit induced gluons as a single parton.[1]

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[1] For parametric estimates we will be using the 'multiple-soft scattering' approximation throughout, but the discussion can easily be refined to include hard interactions with the medium.

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Two generic properties for the in-medium jet evolution are direct consequences of this effect: i) the total energy loss of the jet is smaller than in the case of totally incoherent emission off each of its constituent partons; ii) each of the effective emitters fragments as in vacuum. In particular, the leading particles of the jet define a coherent “inner core” of the reconstructed jet, shielded by coherence against medium modifications of its structure and only losing energy by induced radiation as a single parton. As will be shown below, for typical LHC kinematics there is a significant probability that the experimentally reconstructed jet with cone parameter R accommodates only one resolved charge which contains the leading constituents carrying nearly all of the total jet transverse energy.

2. From the antenna to the jet

The dynamics of a QCD jet in vacuum is described in terms of the scales of the problem. The initial hardness, given by the jet transverse mass $E\Theta_{\rm jet}$, where E is the jet energy and $\Theta_{\rm jet}$ its aperture, is distributed among several constituents in the course of a branching process. Multiple emissions in the shower, which become important when $E\Theta_{\rm jet}/Q_0 \gg 1$, where Q_0 is a non-perturbative cut-off, are governed by color coherence which can most easily be understood in the context of the *antenna radiation*, the soft gluon radiation off a pair of highly energetic color correlated partons. The antenna serves as the building block for a probabilistic scheme of jet evolution.

In the radiation process from any such antenna of opening angle Θ, the emitted gluon transverse wavelength $\lambda_\perp$, which is related to its transverse momentum by $\lambda_\perp \sim 1/k_\perp$, needs to be compared to the transverse separation of the pair at the time of formation of the gluon, $r_\perp = \Theta t_{\rm f}$, with $t_{\rm f} \sim \omega/k_\perp^2$ and ω the gluon frequency. If $\lambda_\perp > r_\perp$, the gluon cannot resolve the two components of the antenna which act coherently as a single emitter; in the opposite case, when $\lambda_\perp < r_\perp$, the radiative spectrum is the superposition of independent gluon emissions off each of the antenna components. In other words, radiation with $\lambda_\perp > r_\perp$ is only sensitive to the total charge. This relation takes a particularly simple form for the angular distribution of gluons, namely gluons emitted at small angles $\theta < \Theta$ resolve the individual charges while those with $\theta > \Theta$ behave as if emitted off the total charge. This generic feature is responsible for the angular ordering constraint [16].

The presence of a deconfined medium introduces a new transverse length scale into the problem, which we simply denote by $\Lambda_{\rm med}$, defining the transverse size of the color correlations of the plasma as seen by a probe. The response of a single, energetic parton immersed in this environment is the radiation of modes with $k_\perp \lesssim 1/\Lambda_{\rm med}$, giving rise to an energy depletion of the projectile. The nature of this radiation has been extensively discussed in the literature and is generically referred to as the BDMPS-Z spectrum [17–21]. For more than one simultaneously propagating parton, this medium-induced component will also be accompanied by a modification of the color correlation structure among the different charges [9–15], which we proceed to discuss.

Let us start by the simplest case of a single antenna in a static and homogeneous medium of length L. The maximal degree of decoherence, due to color randomization, of the two constituents of the antenna is controlled by [9–15]

$$\Delta_{\rm med} \simeq 1 - \exp\left[-\frac{r_\perp^2}{12\Lambda_{\rm med}^2}\right] \equiv 1 - \exp\left[-\frac{\Theta^2}{\theta_c^2}\right], \qquad (1)$$

which varies between 0 (no randomization) and 1 (maximal color randomization), see [9–15] for a further discussion. Here $r_\perp = \Theta L$

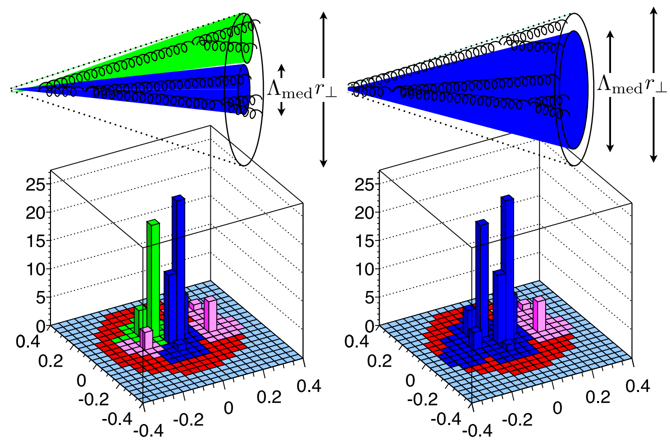

Fig. 1. (Upper panels.) Illustration of the competition of the medium transverse resolution scale and the size of the jet, appearing in Eq. (1). (Lower panels.) Substructure analysis of a sample anti-k$_t$ jet resolved with $R_{\rm med} = 0.1$ (left panel) and 0.15 (right panel), see discussion below Eq. (2). The blue histogram denotes the hardest resolved sub-jet, the green the next-to-hardest one, while the pink histogram denotes soft fragments. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

and the medium resolution scale is given by $\Lambda_{\rm med} = 1/\sqrt{\hat{q}L}$ ($\hat{q}$ being the well-known quenching parameter, characterizing the degree of momentum broadening in the transverse plane per unit length). It is now simple to discuss the two possible scenarios, depicted in Fig. 1, for a jet with opening angle $\Theta = \Theta_{\rm jet}$.

When $\Theta_{\rm jet} \ll \theta_c$, the entire jet is not resolved by the medium. In this singular case, the effects of the medium factorize from the details of jet evolution. Therefore, all its components act as a single emitter. This gives rise to two central consequences. Firstly, the coherent fragmentation of the jet is unmodified and proceeds as in vacuum. Secondly, the jet energy is depleted coherently proportionally to the color charge of the jet initiator. Since medium-induced gluons will typically be deflected to angles $\theta \geqslant \theta_c$ due to momentum broadening [17–22], the jet will correspondingly reduce its total energy without altering its intra-jet structure. Explicitly, for a jet energy loss ΔE, each parton reduces its energy by a constant factor $1 - \Delta E/E$, where E is the total jet energy. These factorization properties are a manifestation of color transparency for highly collimated jets.

When $\Theta_{\rm jet} > \theta_c$ the situation is more complex since some parts of the jet can be resolved by the medium depending on the formation time of the different jet fragments, see upper, left panel of Fig. 1. Nevertheless, the partons within the jet may be reorganized into a reduced *effective number of emitters* which replicate the features described in the previous paragraph. In this case, the jet energy loss is harder to estimate although one should expect deviations of the intra-jet structure away from the vacuum baseline.

3. An estimate of the relevance of color coherence for LHC conditions

As a proof-of-principle study, we have analyzed the transverse structure of vacuum jet showers in the kinematic range of the LHC. Using PYTHIA 8.150 [23], we studied jet events at partonic level in p + p collisions at 2.76 TeV identified via the anti-k$_t$ algorithm, as implemented in FastJet 3.0.3 [24,25]. Since the resolution power of the medium depends upon the geometry encountered by the jet, we have embedded these events into an evolution model for the plasma. Each event was assigned a production point in the transverse plane according to the $N_{\rm coll}$ distribution in the Glauber