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Jet (de)coherence in Pb–Pb collisions at the LHC

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Abstract

Jets are collimated QCD multi-particle states that are abundantly produced in heavy-ion collisions at the LHC. Their description in the vacuum is governed by the hardest scale of the problem, typically the jet virtuality. In the presence of an interacting background field, e.g. such as expected in a quark–gluon plasma, one also has to consider a hard scale arising from the medium interactions. We show how a factorization of small-angle jet evolution and large-angle medium-induced emissions can be realized and calculate three key observables: the jet nuclear modification factor, modification of the intra-jet structure and the amount of out-of-cone radiation.

Keywords: QCD jet physics; Jet quenching; Quark–gluon plasma

1. Introduction

Jets emerging from heavy-ion collisions are unique probes of the underlying dynamics [1,2]. Being multi-particle configurations, their detailed substructure is very sensitive to interactions with the dynamical medium, characterised by the transport coefficient $\hat{q}$, in course of the branching process. The complexity of the resulting multi-scale evolution is reduced by the presence of a hard scale, related to the jet energy, which is much larger than any characteristic momentum scale of the medium [3]. This scale separation guarantees the validity of a perturbative framework.

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Since any colored high-energy particle propagating through the medium (color current) perturbs the background field and leads to stimulated radiation, former studies mainly addressed the jet modifications in medium arising from induced radiation [4]. The dynamical interplay of jet and medium scales in course of the evolution is, however, to a large extent unknown, although models based on perturbative arguments exist [5]. The problem has been worked out in detail on the level of a time-like single emission off a dipole [6,7]. It was shown that the decoherence of the dipole was governed by the "decoherence parameter," defined as

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

where $r_\perp = \theta_0 L$ is the transverse size of a dipole of opening angle θ_0 at the end of the medium of length L, and $Q_s = \sqrt{\hat{q}L}$ is the characteristic transverse momentum scale from the medium. Whenever the dipole is hard enough, such that $r_\perp^{-1} \gg Q_s$, the decoherence parameter is small meaning that the medium only resolves the total charge of the dipole. In this case, it is also the total charge that gives rise to medium-induced radiation. In the opposite case, whenever the medium scale is large, $r_\perp^{-1} \ll Q_s$, the individual charges of the dipole are resolved and can induce radiation. In addition to reorganizing sources of medium-induced radiation, decoherence also modifies the ordering properties of the jet evolution. This can e.g. be understood [6] as a modification of the angular ordering in vacuum [8].

This general picture has also been mapped out in the context of jet evolution [3], where it was pointed out that a large fraction of jets created in central Pb–Pb collisions are not resolved by the medium, i.e. their relevant decoherence parameter $\Delta_{\rm med}$ is small. In Fig. 1 we show an illustration of how the medium resolves structures inside the jet at length scales related to $\Lambda_{\rm med} \sim Q_s^{-1}$. Also calculations at leading-logarithmic approximation of pQCD reveal that the main energy fraction is located in jet substructures located at small angles relative to the jet axis [9]. On the other hand, jet substructures carrying soft momenta occupy a larger angular range and could therefore be affected by effects of decoherence in the medium.

In these proceedings we briefly review a systematic approach for calculating modifications of jet observables, see [10] for further details. We argue that for inclusive observables, such as the jet spectrum at high-p_T, most of the important effects are captured by assuming a coherent jet interaction with the medium, see right panels of Fig. 1. This is due to the fact that the energetic core of the jet is typically not resolved by the medium [3]. For a correct description of the jet substructure, on the other hand, one needs to take into account the decoherence of sub-jet structures, see the left panel of Fig. 1 [10].

2. Discussion and observables

For a dense and large medium, we can treat the propagation of an energetic particle through the medium as a Gaussian diffusive process. In this approximation, the single-gluon spectrum is characterized by the maximal gluon frequency $\omega_c = \hat{q}L^2/2$ [11]. The spectrum has a power-like IR divergence, $\omega\,{\rm d}I/{\rm d}\omega \sim \omega^{-1/2}$, and it was showed that gluons with $\omega \ll \omega_c$ form quasi-instantaneously [12]. This allows to write a coupled rate equation for the medium-induced partonic distributions after passing the medium, $\omega\,{\rm d}N_i^{\rm med}/{\rm d}\omega \equiv D_i^{\rm med}(x, p_\perp, L)$ for $i = q, g$, where $p_\perp$ is the initial energy of the partonic color current transverse to the beam axis and $\omega = x p_\perp$ [13,14], see also [10].

In the present work, the rate equation evolves the distributions in "time" $\tau = \bar{\alpha}\sqrt{2\omega_c/p_\perp}$ through a medium of constant density, where $\bar{\alpha} = \alpha_s C_F/\pi$. We have also introduced an infrared