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Jet structure in Heavy-Ion Collisions - A theory overview

Yacine Mehtar-Tani

Institute for Nuclear Theory, University of Washington,
Seattle, WA 98195-1550, USA

Abstract

We review the recent developments in the theory of jet-quenching. First, we analyze the coherent vacuum cascade and incoherent medium-induced cascade separately. Then, we discuss the interplay between the two kinds of cascades and the resulting partial decoherence of the inner jet structure. Finally, we report on recent calculations of higher-order corrections. In particular, the dominant radiative corrections to jet observables that yield the renormalization of the quenching parameter are addressed.

Keywords: Perturbative QCD, Jet-quenching, Heavy-Ion Collisions

1. Introduction

In a seminal work [2], Bjorken suggested that in high energy hadronic collisions a deconfined QCD matter might form and would be revealed by the suppression of high-pt particle spectra. This phenomenon is commonly referred to as "jet-quenching" and was successfully observed in ultra-relativistic heavy-ion collisions at RHIC and LHC (see Ref. [1] for an experimental review).

Jet-quenching is caused by energy loss of energetic partons produced early in the collision. Hard partons lose energy while propagating through the QCD medium in two possible ways: elastically by scattering off the color charges of the produced QCD medium [3, 4], or by medium-induced gluon radiation [5, 6, 7, 8, 9, 10, 11, 12]. The average radiative energy loss increases quadratically with the medium length, i.e., L^2. Hencefore, for large media it represents the dominant source of energy loss, compared to elastic energy loss that scales as L.[1]

The unprecedented energies reached by the LHC, allowed for the first time to produce jets in heavy-ion collisions in large numbers [13]. Jets are collimated beams of energetic particles and as such encode more information than single inclusive particle spectra, providing better tools to probe the quark-gluon plasma. Although the theory of parton energy loss has been successful in describing single particle spectra, it was not designed to describe in-medium parton shower, and hence jets, mainly because it is based on leading order calculations, that is, the single gluon radiation spectrum. Therefore, in the absence of a consistent theory of jets in a medium, phenomenological studies of jet observables relied to a large extend on modeling of medium modified parton showers. Consequently, there exists a multitude of Monte Carlo even generators, based on different assumptions as for how to extend the leading order medium-induced gluon radiation spectrum to multiple parton branchings [16].

In this contribution, we report on recent progress toward understanding the space-time structure of parton showers in the presence of QCD medium (see Refs. [17, 18] for recent reviews). We shall leave aside practical questions concerning, for instance, medium evolution, geometry, kinematics, particle species dependence, Monte Carlo implementation, etc, and focus on conceptual issues regarding the structure of medium-modified parton shower.

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[1] In the case of heavy-quark production inelastic processes are suppressed due to the dead-cone effect. Hence, elastic processes are essential to account for the correct suppression.

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2. Parton cascades of two kinds

In vacuum, a jet is described by a virtuality ordered and collimated parton shower. In the presence of a dense medium, another type of parton shower forms induced by multiple interactions with medium. This medium-induced parton cascade is of a fundamentally different nature than the vacuum shower as it evolves in real time and develops at large angles.

2.1. Vacuum cascade

A jet originates from a high energy parton created in a hard process. Because of its high virtuality the energetic parent parton tends to branch with a probability that is proportional to the coupling constant and enhanced by a collinear logarithmic singularity ($\theta \to 0$),

$$\mathrm{d}P \sim \bar{\alpha} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}\theta}{\theta}, \tag{1}$$

with $\bar{\alpha} \equiv \alpha_s N_c/\pi$ for gluon branching. This elementary process captures two characteristic features of QCD jets, that is, multiple parton branching are highly probable and collimated along the original parton momentum direction. The dominant logarithmic contribution to inclusive jet observables, such as the fragmentation function, is given by strongly ordered successive branchings in virtuality from high $Q^2 \equiv E\Theta_{\text{jet}}$ (where E is the jet energy and Θ_{jet} is the jet opening angle, often referred to as p_t and R, respectively, in the literature) to low virtuality, down to a non-perturbative scale $Q_0 \sim \Lambda_{\text{QCD}}$. This ordering results from a strong ordering in formation time along the cascade [21].

However, an accurate description of parton showers does not reduce to a simple iteration of the single parton branching probability ordered in virtuality due to interference effects in the muti-parton system. The jet is a color coherent system of partons, and as a consequence, large angle soft gluon radiation, characterized by a transverse wave length $\lambda_\perp \sim 1/k_\perp$ larger than the transverse size of emitting system, does not "resolve" the individual radiating color charges. The resulting radiation intensity is suppressed compared to incoherent radiation off individual charges. In turn, it is proportional to the total color charge that is that of the original parton. Color coherence of the parton shower which is a consequence of color charge conservation, can be accounted for by imposing a strict angular ordering of successive parton branchings in place of the less restrictive virtuality ordering prescription [19, 20] (see Fig. 2.1). Therefore, the QCD evolution equation that describes the evolution of the fragmentation function, the Modified-Leading-Log-Approximation (MLLA) equation differs from the DGLAP equation in the choice of the jet angle as an evolution variable instead of the jet virtuality [21].

To summarize, jets in vacuum are characterized by a strongly collimated parton shower and a suppression of large angle soft gluon radiation. These important features are to be contrasted with the medium-induced shower that we shall discuss in the following section.

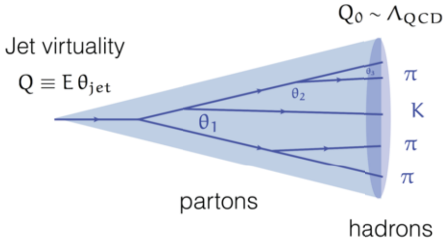

Figure 1: Illustration of the vacuum cascade: three successive branchings, ordered in angle, are depicted: $\theta_3 \ll \theta_2 \ll \theta_1 \ll \Theta_{\text{jet}}$. Virtuality decreases from Q down to a non-perturbative scale Q_0 where hadronization takes place.

2.2. Medium-induced cascade

A high energy parton passing through a hot QCD medium undergoes multiple scatterings. In the weak coupling regime the in-medium correlation length given by the inverse Debye mass, $1/m_D \sim 1/gT$ is much smaller than the typical in-medium mean-free-path, $\ell_{\text{mfp}} \sim 1/g^2T$. This allows us to treat multiple scatterings as effectively independent. Hence, the coupling of energetic partons with the medium can be characterized by local transport coefficients whose the most significant ones are the so-called jet-quenching parameter, $\hat{q} \equiv \mathrm{d}\langle k_\perp^2\rangle/\mathrm{d}t$ [6] and $\hat{e} \equiv \mathrm{d}\langle E\rangle/\mathrm{d}t$ [22], that are related to transverse momentum broadening and collisional energy loss, respectively.

Multiple interactions of the hard parton with the medium constituents can trigger gluon radiation coherently over a time $t_f \sim \omega/k_\perp^2 \sim \sqrt{\omega/\hat{q}}$, where ω is the frequency of the radiated gluon. For $\ell_{\text{mfp}} \ll t_f(\omega) \ll L$, the radiation probability reads (cf. Ref. [23] for a review)

$$\mathrm{d}P \sim \bar{\alpha} \frac{\mathrm{d}\omega}{\omega} \frac{\mathrm{d}t}{t_f(\omega)}, \tag{2}$$

where t runs up to the length of the medium L. Note that hard gluon radiation, corresponding to large formation times, are suppressed compared to incoherent radiation whose rate is $\omega \mathrm{d}P/\mathrm{d}\omega\mathrm{d}t \sim \alpha_s/\ell_{\text{mfp}}$. This is the QCD analog of the Landau-Pomeranchuk-Migdal (LPM) effect. The maximum suppression is achieved