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Nuclear Physics A 910–911 (2013) 27–34
NUCLEAR PHYSICS A
www.elsevier.com/locate/nuclphysa

Perturbative versus non-perturbative aspects of jet quenching: in-medium breaking of color coherence

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Abstract

The quenching of jets (and high-p_T particle spectra) observed in heavy-ion collisions is interpreted as due to the energy lost by hard partons crossing the Quark Gluon Plasma. Here we review recent efforts to include in its modeling important qualitative features of QCD, like the correlations in multiple gluon emissions and the color-flow pattern in parton branchings. In particular, the modification of color connections among the partons of a shower developing in the presence of a medium is a generic occurrence accompanying parton energy-loss. We show how this effect can leave its fingerprints at the hadronization stage, leading by itself to a softening of hadron spectra and to an enhanced production of soft particles in jet-fragmentation.

Keywords: Quark Gluon Plasma, jet quenching, color flow

1. Introduction

The observation of jet-quenching (in a broad sense) represents a strong signature of the formation of an opaque medium in ultra-relativistic nucleus-nucleus collisions, leading to a sizable energy degradation of the high-p_T partons initially produced in hard pQCD events and traversing the fireball. Experimental measurements, initially limited to the suppression of high-p_T hadron production [1, 2, 3], are nowadays available also for the quenching of reconstructed jets [4, 5, 6] in the dense environment produced in heavy-ion collisions.

The standard theoretical interpretation views the phenomenon as due to parton energy-loss: the interaction of a high energy quark or gluon (produced in a hard pQCD process) with the color field of the medium induces the radiation of (mostly) soft ($\omega \ll E$) and collinear ($k_\perp \ll \omega$) gluons; the emitted gluons, carrying color charge, can further rescatter in the medium, accumulating an additional $q_\perp$ which favors their kinematic decoherence. A schematic picture is given in Fig. 1. The above transverse momentum broadening was shown to be of relevance to explain dijet-imbalance measurements by ATLAS (and CMS) in terms of the out-of cone radiation of many soft partons [7].

Within the above picture, several models were developed in order to provide a consistent explanation of the experimental data collected at RHIC and LHC. We refer the reader to Ref. [8] for a quantitative comparison of the various models available in the literature. Here we prefer to put the emphasis on the conceptual framework they are based on, suggesting how they can be improved in order to account for important qualitative QCD effects which get modified in the presence of a medium.

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http://dx.doi.org/10.1016/j.nuclphysa.2012.12.007

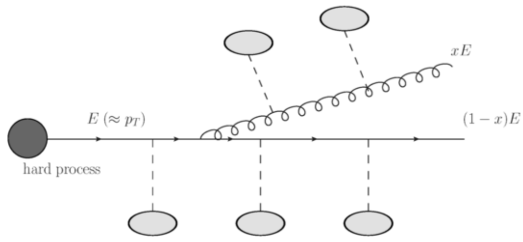

Figure 1: Schematic cartoon of parton energy loss due to medium-induced gluon radiation.

If one ignores possible modifications of the PDFs (which will be small for high-p_T observables), the inclusive cross-section for the production of a hadron X in nucleus-nucleus collisions is generally assumed to be described by the following factorized expression

$$\begin{aligned} d\sigma_{\rm med}^{AA\to h+X} &= \sum_f d\sigma_{\rm vac}^{AA\to f+X} \otimes \langle D_{\rm med}^{f\to h}(z,\mu_F^2)\rangle_{AA} \\ &= \sum_f \underbrace{d\sigma_{\rm vac}^{AA\to f+X}}_{pQCD} \otimes \underbrace{\langle P(\Delta E)\rangle_{AA}}_{\text{e.loss prob.}} \otimes \underbrace{D_{\rm vac}^{f\to h}(z,\mu_F^2)}_{\text{vacuum FF}}, \end{aligned} \quad (1)$$

where the medium-modified Fragmentation Function (FF) arises simply from the action of a vacuum FF on a final-state parton having suffered some in-medium energy loss according to the probability density $P(\Delta E)$.

The above factorized expression ignores the role of color correlations, whose effect will be the subject of our presentation. Firs of all, most calculations of medium-induced gluon radiation focused so far limited on the evaluation of the single inclusive gluon spectrum. Multiple gluon emission was in general described by a simple poissonian distribution

$$P(\Delta E) = \sum_{n=0}^{\infty} \frac{e^{-\langle N_g\rangle}}{n!} \prod_{i=1}^{n} \left[\int d\omega_i \frac{dN_g}{d\omega_i}\right] \delta\left(\Delta E - \sum_{i=1}^{n} \omega_i\right), \quad (2)$$

treating successive emissions as uncorrelated. Secondly, the use of a vacuum FF to describe the transition from partons to hadrons is simply justified through kinematic considerations: the time required for a high-energy parton of virtuality Q to hadronize, of order Q^{-1} in its rest frame, is Lorentz boosted in the lab-frame to $\Delta t_{\rm lab}^{\rm hadr} \sim (E/Q)(1/Q)$, much larger than the plasma lifetime in the $E \to \infty$ limit. However the color-exchange interactions of the hard parton with the medium can dramatically change the color connections in the developing shower and this may lead to an effect in the final hadron spectra, independently on when hadronization occurs. Correlations between successive gluon emissions (leading to the *angular-ordering* [9] of vacuum showers) and the color-flow pattern of QCD processes, essential for our understanding of strong interactions in the vacuum, were not accounted for in previous "jet-quenching" studies. Here we recall, first, how they provide an essential guidance to interpret the experimental data in elementary collisions. We then discuss their effect in the nucleus-nucleus case.

Let us start from the angular distribution of gluon radiation in the vacuum, considering for simplicity the emission from a color-singlet $q\overline{q}$ pair (left panel of Fig. 2). The q and the $\overline{q}$ form an *antenna* which radiates coherently. During the gluon formation time $t_f = 2\omega/k_\perp^2$ the pair must in fact have reached a separation $d_\perp = t_f\theta_{q\overline{q}}$ larger than the transverse wave-length $\lambda_\perp \sim 1/k_\perp \sim 1/\omega\theta_{gq}$ of the gluon, so that the latter can resolve the individual color charges (instead of seeing a neutral object). The request $\lambda_\perp < d_\perp$ forces then the gluon to be radiated within the cone $\theta_{gq} < \theta_{q\overline{q}}$. Such an *angular ordering* of soft gluon emission in the vacuum leads to important phenomenological consequences. It is at the basis of the development of well collimated jets in hard pQCD events. Furthermore it also explains how hadrons are distributed inside a jet (*intra-jet* coherence). The ordering condition $\lambda_\perp < d_\perp$, entailing $1/k_\perp < (2\omega/k_\perp^2)\,\theta_{q\overline{q}}$, together with the constraint $k_\perp \gtrsim \Lambda_{\rm QCD}$, leads to a lower bound for the energy of the radiated gluon $\omega \gtrsim \Lambda_{\rm QCD}/\theta_{q\overline{q}}$. The angular-ordering condition of QCD radiation was found to nicely accommodate the experimental data – see the