

Parton showers with medium-modified splitting functions

Gennaro Corcella*

Museo Storico della Fisica, Centro Studi e Ricerche E. Fermi,

Piazza del Viminale 1, I-00184 Roma, Italy,

Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56123 Pisa, Italy,

INFN, Sezione di Pisa, Largo Fibonacci 3, I-56127, Pisa, Italy

E-mail: gennaro.corcella@sns.it

I discuss the recent implementation of medium-modified splitting functions within the HERWIG angular-ordered parton shower algorithm and present a few results on transverse momentum, energy and angular distributions.

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*Speaker.

Much work has been carried out through the years in order to theoretically describe jet quenching, one of the most striking observations of heavy-ion collisions, namely the suppression of particle multiplicity at large transverse momentum (p_T), as well as other related phenomena, such as the disappearance or distortion of the spectra of particles at opposite directions with respect to a reference one [1]. A higher energy loss in a dense medium is a possible explanation of jet quenching: partons which in the vacuum are potentially produced at large p_T can further radiate, which determines suppression of the high- p_T spectrum and enhancement of the low- p_T one.

In order to describe the higher branching probability in a medium, a simple prescription consists in adding to the Altarelli–Parisi splitting functions a term depending on the medium properties [2, 3], i.e.

$$P(z) \rightarrow P(z) + \Delta P(z, p^2, E, \hat{q}, L). \quad (1)$$

In (1), p^2 is the branching-parton virtuality, E its energy, L the medium length, \hat{q} the transport coefficient, defined as the average transverse momentum transferred from the medium to the parton per unity of free path. The correction $\Delta P(z, p^2, E, \hat{q}, L)$ can be computed by means of the so-called BDMPS approximation [4], namely multiple collinear radiation off static scattering centres, in the presence of a screened Coulomb potential.

Such modified splitting functions can be implemented in Monte Carlo parton shower generators, which can thus be used by the heavy-ion community to compare with data from RHIC and, ultimately, LHC experiments. Medium modifications have been included in the framework of the PYTHIA event generator [5], which orders cascades in virtuality, with an option to veto branchings which do not satisfy angular ordering. This implementation is known as Q-PYTHIA [6, 7]. More recently [8], medium-modified splittings have also been implemented in the HERWIG showering algorithm [9], which, unlike PYTHIA, systematically includes angular ordering, thus leading to colour coherence in the large- N_C limit. Following [8], hereafter I shall present the main results yielded by medium-modified HERWIG parton showers.

For the sake of comparison with the Q-PYTHIA results in [6], I shall study the cascades initiated by a single gluon, whose energy will be fixed to $E = 10$ and 100 GeV, with the hadronization switched off. As discussed in [8], since this is not a standard HERWIG option, it was necessary to add a fictitious process and set by the hand the upper limit of the evolution variable $Q^2 \simeq E^2(1 - \cos \theta)$ to $Q_{\max}^2 = 2E^2$, where E is the energy of the branching parton and θ the emission angle. Moreover, care must be taken about the fact that the medium length varies along the shower: in fact, if L_0 is the length for the first splitting, in a subsequent emission, a parton ‘sees’ an effective length $L = L_0 - 2zE/k_T^2$, z and k_T being its energy fraction and transverse momentum, since it has travelled for a distance $2zE/k_T^2$, the so-called parton formation length, before radiating again. As L is not positive definite, whenever the medium length becomes negative, the shower will be vacuum-like.

Hereafter, I shall consider the options of media with $\hat{q} = 1$ and 10 GeV²/fm, $L_0 = 2$ and 5 fm. For simplicity, such medium configurations will be labelled in terms of the so-called accumulated transverse momentum $\hat{q}L_0 = 2, 5, 20$ and 50 GeV².

A fundamental quantity in shower algorithms is the Sudakov form factor $\Delta_S(Q_1^2, Q_2^2)$, namely the probability of evolution between Q_1^2 and Q_2^2 with no intermediate branching. Fig. 1 presents the gluon Sudakov form factors $\Delta_S(Q^2, Q_{\max}^2)$, for $E = 10$ and 100 GeV, fixed $L = L_0$ and the values

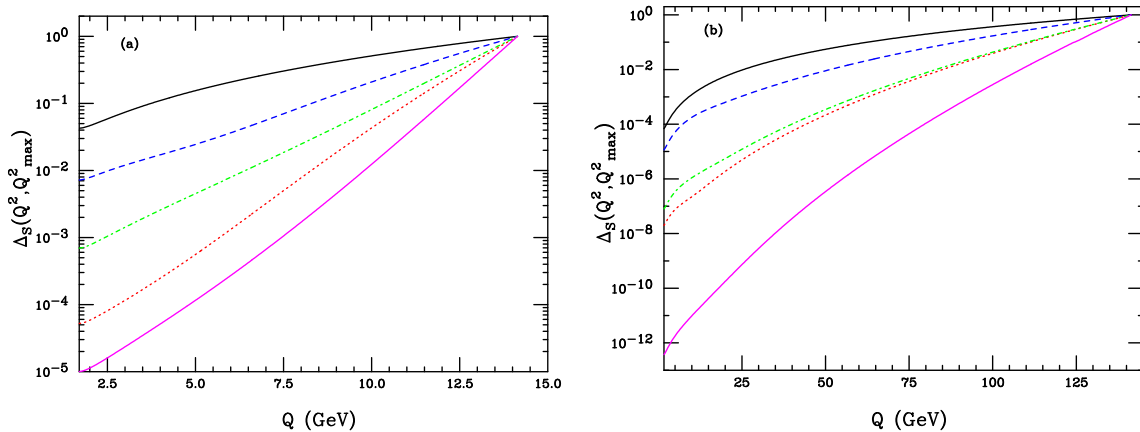


Figure 1: Gluon Sudakov form factors, in the vacuum (solid, black) and in media with $\hat{q}L_0 = 2$ (dashes, blue), 5 (dots, red), 20 (dot-dashes, green) and 50 (magenta, solid) GeV^2 . The gluon energy is $E = 10$ GeV (a) and 100 GeV (b).

Table 1: Average parton multiplicities in showers initiated by gluons of energy of 10 and 100 GeV, in the vacuum and in a medium with assigned values of $\hat{q}L_0$.

E	$\hat{q}L_0 = 0$	$\hat{q}L_0 = 2 \text{ GeV}^2$	$\hat{q}L_0 = 5 \text{ GeV}^2$	$\hat{q}L_0 = 20 \text{ GeV}^2$	$\hat{q}L_0 = 50 \text{ GeV}^2$
10 GeV	2.56	3.05	4.14	3.60	4.56
100 GeV	6.95	7.41	8.79	8.93	11.70

of \hat{q} and L_0 given above. From Fig. 1 one learns that medium-induced effects are quite large: the Sudakov form factors exhibit suppressions of a few orders of magnitude, with respect to the vacuum, corresponding to an enhancement of the branching probability, and thus of the radiative energy loss.

As a further check of the higher emission probability, Table 1 quotes the the average parton multiplicity in the vacuum and in a dense medium. The enhancement factor runs from 20% ($\hat{q}L_0 = 2 \text{ GeV}^2$) up to about 80% ($\hat{q}L_0 = 50 \text{ GeV}^2$) for $E = 10$ GeV, and between 7% and 70% for 100 GeV. In Figs. 2–3 I present the differential multiplicity with respect to the parton transverse momentum (p_T), angle (θ) and logarithmic energy fraction, defined as $\xi = \ln(E/|p|)$, where E is the initiating-gluon energy and $|p|$ the modulus of the three-momentum of the partons in the cascade. All plotted distributions are normalized to unity.

Overall, the medium-modified spectra present the features which one should expect and in agreement with the jet-quenching observations: suppression (enhancement) of the parton multiplicity at large (small) p_T , broader angular distributions, small- ξ suppression. However, compared with the distributions presented in [6] and obtained with the Q-PYTHIA code, some differences can be noticed. As discussed in [8], on average the emission probability in PYTHIA is larger than in HERWIG, as a consequence of the different evolution variables and the range wherein they are allowed to vary. For example, the vacuum spectra here obtained for $E = 10$ GeV exhibit a sharp peak at $p_T = \theta = \xi = 0$, corresponding to a fraction of events wherein the gluon evolves down to the infrared cutoff with no emission. This feature is less evident when running Q-PYTHIA [6].

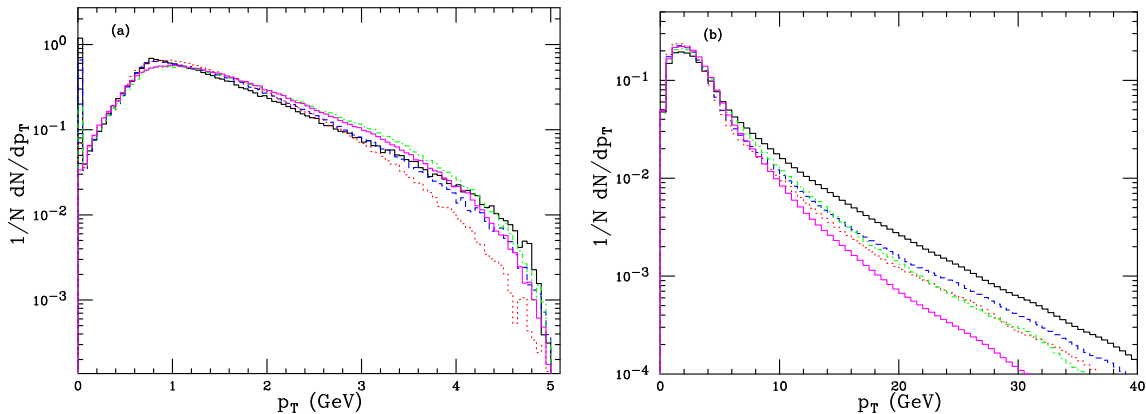


Figure 2: Transverse momentum multiplicity in a shower initiated by a gluon of energy 10 GeV (a) and 100 GeV (b), in the vacuum (solid, black) and in media with accumulated transverse momentum $\hat{q}L_0 = 2$ (dashes, blue), 5 (dots, red), 20 (dot-dashes, green) and 50 (solid, magenta) GeV^2 .

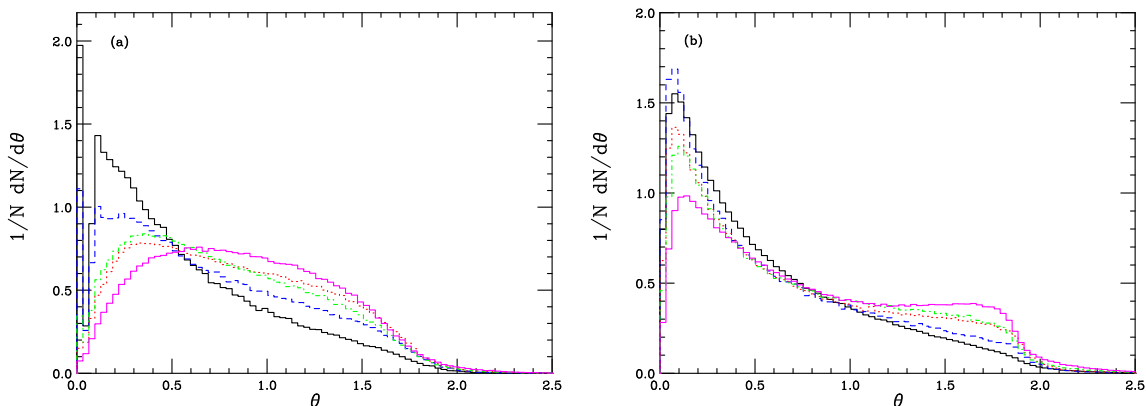


Figure 3: Angular distributions for showers initiated by a gluon of energy 10 GeV (a) and 100 GeV (b). The lines are labelled as in Fig. 2.

As for the angular distributions, Fig. 3 shows that the multiplicity is negligible for $\theta > 2$; in fact, unlike PYTHIA, HERWIG presents a dead zone for large-angle radiation and we are studying the shower produced by a single parton, with no matrix-element matching. Ref. [8] also discussed medium-modified showers for fixed length $L = L_0$ and reasonable results were obtained, namely stronger medium effects once L does not decrease throughout the cascade.

In summary, I reviewed the main issues involved in the modification of the HERWIG angular-ordered shower algorithm for the sake of including the effects of a dense medium and possibly describing jet quenching. The release of such a code, which will be called Q-HERWIG [10], is currently in progress. Furthermore, in order to draw a final conclusion on the comparison with Q-PYTHIA, it will be compelling turning hadronization on and tune the two programs to the same data set. In this way, light will be shed even on the role played by the evolution variable in medium-modified cascades.

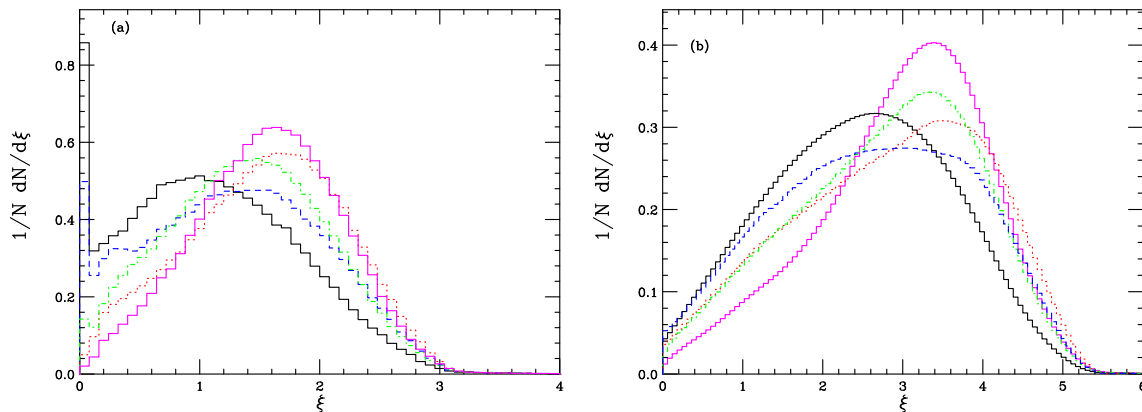


Figure 4: As in Figs. 2 and 3, but showing the logarithmic energy-fraction ξ .

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