Multiplicity distributions inside parton cascades developing in a medium

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Abstract. The jet-quenching explanation of the suppressed high-p_T hadron yields at RHIC implies that the multiplicity distributions of particles inside a jet and jet-like particle correlations differ strongly in heavy-ion collisions at RHIC or at the LHC from those observed at e^+e^- or hadron colliders. We present a framework for describing the medium-induced modification, which has a direct interpretation in terms of a probabilistic medium-modified parton cascade, and which treats leading and subleading partons on an equal footing. We show that our approach implies a characteristic distortion of the single inclusive distribution of soft partons inside the jet. We determine, as a function of the jet energy, to what extent the soft fragments within a jet can be measured above some momentum cut.

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Introduction. Among the most notable results from the first years of running at RHIC stand the deficit in high transverse-momentum hadrons and the suppression of leading back-to-back hadron correlations observed in central Au–Au collisions with respect to expectations from scaling the yields measured in *pp* collisions [1]. These observations are consistent with the "jet-quenching" picture: before they hadronize in the vacuum, partons produced in the dense matter created in head-on Au–Au collisions lose a significant fraction of their energy through an enhanced radiation of soft gluons [2, 3, 4].

Irrespective of the details of the implementation of the medium-enhanced radiation of gluons — either through coherent multiple soft-momentum transfers [5, 6], or through single hard scattering [3] — jet-quenching models of inelastic (radiative) energy loss are quite successful in explaining present light-hadron data from RHIC [7, 8, 9]. However, there remains much room for technical improvement over the existing formulations of inelastic energy loss. Thus, a generic feature of these approaches is that they only consider the medium-induced enhancement in gluon radiation for the leading parton, discarding the medium influence on subleading partons. Such an approximation may remain under control when dealing with leading-hadron production; yet, predictions involving subleading particles become questionable, be it for jet shapes, which may become experimentally accessible at the LHC, or for intrajet two-particle correlations. Similarly, in existing models energy-momentum conservation is not explicitly conserved at each parton splitting, but only globally, through various *ad hoc* corrections.

A novel formulation of medium-induced parton energy loss was recently introduced in Ref. [10], which aims at correcting some of the shortcomings of standard approaches. Thus, it is the first one that deals equally with the various splittings of both leading and subleading partons inside a shower. Furthermore, it automatically conserves energy-momentum at each parton splitting.

Formalism. One of the most testing ground of the color structure of QCD is provided by the jets that are created in e^+e^- or in $pp/p\bar{p}$ collisions. The asymptotic shape of the distribution of hadron momenta inside a jet can be computed exactly, especially at small momentum fractions $x = p/E_{\rm jet}$, by resumming infrared-singular terms to all orders, within the so-called Modified Leading Logarithmic Approximation (MLLA) of QCD [11, 12, 13]. Color coherence thus results in destructive interference between partons, leading to a suppression of small-x hadrons. This amounts, to double and single logarithmic accuracy in $\ln(1/x)$ and $\ln(Q/\Lambda_{\rm eff})$ — where $Q \sim E_{\rm jet}$ is the jet virtuality and $\Lambda_{\rm eff}$ an infrared cutoff which is eventually fitted to experimental data — to an angular ordering of the sequential parton decays within the shower, with leading-order splitting functions. An important prediction of this angular-ordered probabilistic parton cascade is, to next-to-leading order $\sqrt{\alpha_S}$, the characteristic "hump-backed plateau" shape of the distribution of parton momenta inside a jet, represented as a function of $\ln(1/x)$. The parton shower, evolved down to an infrared cutoff $\sim \Lambda_{\rm eff}$, is eventually identified to a hadron jet, by mapping locally each parton onto a hadron ("Local Parton–Hadron Duality", LPHD): for each hadron type, the hadron distribution equals K^h times the parton distribution, where K^h is a proportionality factor of order unity. This resummation and the LPHD prescription give a good description of the measured longitudinal distributions of hadrons $D^h(x,Q^2)$ over a wide energy range, both in e^+e^- [14, 15] and in $p\bar{p}$ [16] collisions. For instance, Fig. 1 shows $D^h(x,Q^2)$ for inclusive hadrons inside 17.5 GeV jets in e^+e^- annihilations [14], together with the MLLA prediction with $K^h = 1.35$.

The formalism developed in Ref. [10] to describe the medium-induced distortion of jets reduces to the MLLA baseline in the absence of a medium. This new approach involves different approximations from the standard models of parton energy loss that are currently used in the phenomenology of RHIC data. Thus, present model comparisons to RHIC data start with a medium-modified energy spectrum of radiated gluons, $\mathrm{d}I^{\rm tot} = \mathrm{d}I^{\rm vac} + \mathrm{d}I^{\rm med}$ [2, 3, 4]. The part corresponding to the "normal" vacuum radiation shows a double logarithmic dependence $\mathrm{d}I^{\rm vac} = \frac{\alpha_s}{\pi^2}\frac{\mathrm{d}\omega}{\omega}\frac{\mathrm{d}\mathbf{k}}{\mathbf{k}^2}$; its integral over $\mathbf{k}$ gives rise to the leading $\ln Q^2$ term in the DGLAP evolution equation. This contrasts to the $\mathbf{k}$-integration of $\mathrm{d}I^{\rm med}$, which is infrared- and ultraviolet-safe [6] and leads to a nuclear-enhanced "higher-twist" contribution, $\propto \hat{q}L/Q^2$, where $\hat{q}$ is the transport coefficient that characterizes the medium, subleading in an expansion in $1/Q^2$, but enhanced with respect to other such terms by a factor proportional to the geometrical extension $\sim L$ of the target. In practice, however, the parton virtuality does not enter the existing comparisons to experimental data, where one rather considers the $\mathbf{k}$-integrated gluon distribution $\omega\,\frac{\mathrm{d}I^{\rm med}}{\mathrm{d}\omega}$, neglecting the Q^2-dependence. In addition, existing approximations only include the extra source of gluon radiation $\mathrm{d}I^{\rm med}$ for the leading parton, dropping it for the further medium-induced splittings of subleading partons in the shower.

The obvious way to improve over this state of the art is to replace the double differential gluon spectrum $\mathrm{d}I^{\rm vac}$ by $\mathrm{d}I^{\rm tot}$ in *all* leading and subleading splitting processes of a medium-modified parton cascade. This can only be done within a Monte-Carlo approach, which we intend to develop in future studies. The first, still fully analytical step in that direction consists in using an extra approximation: instead of using the computed $\mathbf{k}$-integrated medium-induced distribution, we replaced it by a constant $f_{\rm med}$. In the kinematic regime tested at RHIC, this assumption amounts to a similar uncertainty as that

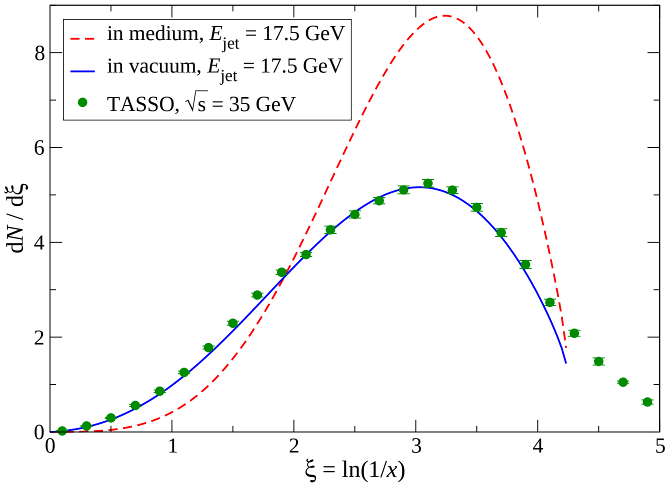

FIGURE 1. Longitudinal distribution $\mathrm{d}N/\mathrm{d}\ln(1/x)$ of inclusive hadrons inside a jet of energy $E_{\mathrm{jet}} = 17.5$ GeV, as a function of $\ln(1/x) = \ln(E_{\mathrm{jet}}/p)$, as measured by TASSO [14] and within MLLA (solid curve: $f_{\mathrm{med}} = 0$; dashed curve: $f_{\mathrm{med}} = 0.8$).

arising from whether one should use the multiple-soft scattering approach or the single hard scattering picture. We have then used the medium-induced spectrum $\omega\frac{\mathrm{d}I^{\mathrm{med}}}{\mathrm{d}\omega}$ on the same level as $\omega\frac{\mathrm{d}I^{\mathrm{vac}}}{\mathrm{d}\omega}$, i.e., as a leading logarithmic correction [10]. With this ansatz, our formalism ensures energy-momentum conservation at each parton splitting, and treats all leading and subleading parton splittings on the same footing.

Phenomenological predictions. The replacement of the medium-induced contribution to the gluon spectrum $\omega\frac{\mathrm{d}I^{\mathrm{med}}}{\mathrm{d}\omega}$ by a constant f_{med} in the kinematically relevant range of ω amounts to considering "medium-modified parton splitting functions" that differ from the standard ones by enhancing their singular parts by a factor $(1+f_{\mathrm{med}})$.[1] This formulation allows us to follow the same line of technical arguments as that used for the calculation of jet multiplicity distributions in the absence of a medium [13], and to compute the momentum distribution of partons within a parton cascade. To exemplify the effect of the medium-enhanced gluon radiation on the hump-backed plateau of particle production, we compare in Fig. 1 the longitudinal distribution inside a jet with energy $E_{\mathrm{jet}} = 17.5$ GeV in the cases $f_{\mathrm{med}} = 0$ (no medium) and $f_{\mathrm{med}} = 0.8$ (which allows us to reproduce the light-hadron suppression measured at RHIC [10]). One clearly sees that the effect of the medium is a strong distortion of the distribution, with a depletion of the number of particles at large x, and correspondingly a largely enhanced emission of particles at small x: due to energy-momentum conservation in the parton cascade, the energy which in the vacuum is taken by a single large-x parton is redistributed over many small-x partons in the presence of a medium.

Once the longitudinal multiplicity distribution inside a jet is known, a straightforward integration yields the number of hadrons inside the jet with transverse momenta larger

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[1] Such a modification of parton splitting functions was discussed in Ref. [17], where it results from considering nuclear-enhanced twist-four parton matrix elements in studies of deeply inelastic eA scattering.

than a given cut. One can calculate this multiplicity for jets with the same energy both in the presence of medium effects (in which case, the lower cut gives some control on the high-multiplicity soft background over which the jet develops) and in vacuum, and compute their ratio. For jets with $E_{\rm jet} = 17.5$ GeV and medium effects modeled by a constant coefficient $f_{\rm med} = 0.8$, one finds [10] that the ratio is smaller than 1 for $p_T^{\rm cut} \gtrsim 1.5$ GeV/c, while the medium-induced enhancement in soft-particle production becomes dominant for smaller values of the transverse-momentum cut. The crossover value is close to that reported by the STAR Collaboration in attempts at measuring the excess of particles inside the back jet over the soft background [18]. Although we did not consider several effects (varying $E_{\rm jet}$ and in-medium path lengths, geometry…) that should be included in a more thorough comparison between our calculation and the STAR data, the reasonable agreement we find is a further hint that energy is indeed redistributed from high- to low-x partons through the influence of the medium. For jets of energy $E_{\rm jet} = 100 - 200$ GeV, which should be accessible at the LHC, the crossover between enhancement and depletion should take place at transverse momenta $p_T^{\rm cut} \sim 4 - 7$ GeV/c [10]. This should leave a window above the upper kinematic boundary of the soft background, in which there is an enhancement of the jet multiplicity, thereby allowing a more detailed characterization of the medium-enhanced radiation.

Conclusion. We have reported a first step towards a description of parton cascades developing in a medium, which conserves energy-momentum at each successive parton splitting, and treats all partons in the shower on the same footing [10]. The simplified analytical formalism we have presented, which will serve as a reference for future more realistic Monte-Carlo implementations, is able to reproduce semi-quantitatively several characteristic features of RHIC data, such as the suppression of high-momentum particle yields and the enhanced soft-particle distribution associated to high-p_T trigger particles.

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