PROCEEDINGS OF SCIENCE

PoS(High-pT physics09)017

"Jets" and their distortion in heavy-ion collisions

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After a discussion on the meaning of "jets" in the context of nucleus–nucleus collisions, the distortions of the profile of a parton shower induced by the presence of a medium is investigated in a QCD-inspired model that implements the conservation of energy at each step of the shower evolution.

4th international workshop High-pT physics at LHC 09
February 4-7, 2009
Prague, Czech Republic

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The large amount of data already registered in heavy-ion collisions at RHIC and the prospect of an extended kinematical reach at the LHC are shifting the focus of studies of particles with high transverse momenta. While single-particle inclusive distributions of identified hadrons were at first the main topic of interest, attempts are now being made at evidencing structures involving several particles [1 – 3], using techniques [4] primarily developed to identify jets in hadronic collisions. The purpose of these endeavors is to perform “jet physics” in nucleus–nucleus collisions, measuring for instance the medium-induced modification of fragmentation functions of partons into hadrons.

This necessitates in parallel the development of theoretical and/or phenomenological models, which would help relate the measurements to properties of the medium created in the collisions of heavy ions at high energies. A step towards such a theoretical approach will be addressed in Section 2, in which the possible distortions of a parton shower are studied within a QCD-inspired model. Before that, I shall stress in Section 1 the implicit ideas and assumptions that underly the philosophy of studying “jets” in heavy-ion collisions, as well as some of the biases that enter their modeling.

1. On “jets” in a medium

Collisions of heavy nuclei at ultrarelativistic energies result in a high multiplicity of emitted particles. This trivial statement naturally means that trying to identify experimentally jet-like structure is a daunting task, since the “underlying event”—which to a very good extent can be reliably accounted for in proton-(anti)proton collisions [4]—now contributes so much to the signal in the detectors, that even its fluctuations might mimick some local excess of energy-momentum flow.

The high-multiplicity environment also implies fundamental difficulties on the modeling side, some of which I wish to spell out here. In that view, let me first recall the salient features of the description of jets “in vacuum” (i.e., as produced in e^+e^- or $pp/p\bar{p}$ collisions) within the modified leading logarithmic approximation (MLLA) of perturbative QCD [5, 6].

Let E and Θ_0 be the jet energy and opening angle, and for any jet particle with energy k_0 and momentum $k_\perp$ transverse to the direction of the energy flow (“jet axis”) let

$$\ell \equiv \ln\frac{E}{k_0} = \ln\frac{1}{x}, \quad y \equiv \ln\frac{k_\perp}{Q_0}, \tag{1.1}$$

where Q_0 is some infrared cutoff parameter and $k_\perp \geq Q_0$. To double logarithmic accuracy in ℓ and single logarithmic accuracy in y, the soft partons emitted in the jet evolution interfere destructively in some regions of phase space. This *color coherence* effect results in the simple interpretation of the parton shower evolution in terms of a probabilistic cascade in which the successive parton branchings, governed by the leading-order Altarelli–Parisi splitting functions, are independent and satisfy angular ordering [5, 6]. As was quickly realized [7], this probabilistic view allows the implementation of jet evolution in a Monte-Carlo simulation. Additionally, one can compute analytically within MLLA or even including next-to-MLLA corrections the inclusive longitudinal [6] and transverse [8] distributions of hadrons within a jet—or rather, the parton distributions, which are then mapped onto hadrons using the local parton-hadron duality (LPHD) hypothesis—, leading to a satisfactory agreement with experimental data.

Last but not least, the nice description within (N)MLLA of the characteristics of jets measured in elementary-particle collisions ultimately relies on two implicit yet essential premises:

- first, that one can define a jet in a way that is manageable and stable both experimentally and theoretically [9, 10];
- second, that the object thus specified can be “isolated” from its environment—be it the underlying event in a hadronic collision, or the other jet(s) in events with at least two jets—, so that the properties which are attributed to the jet are actually intrinsic to it. This requirement restricts the range of characteristics that can meaningfully be assigned to a jet [6].

Turning now to the case of heavy-ion collisions, one can question which of the above features survive.

The assumption that there exists an object (the “jet”), with definite characteristics that depend on the properties of the medium created in the nucleus-nucleus collision, yet which can be investigated theoretically as an independent entity, lies at the core of “jet physics” studies performed in heavy-ion collisions, including that reported in Section 2.

It is also tacitly assumed that this “jet” can be, at least in thought, isolated from a “background event”, so that one can meaningfully study their respective influences on each other: on the one hand, the perturbation of the medium induced by the propagation of the jet—possibilities include shock-waves along a Mach cone [11, 12] or Cherenkov-like radiation of gluons [13 – 15]—; on the other hand, the distortions of the “jet” by the medium through which it propagates. The picture underlying the last point implies that the adopted definition of a “jet” also makes sense in the absence of a medium, i.e. in collisions of elementary particles, so that one has a reference with respect to which the medium-induced modifications can be investigated.

There very probably exists a satisfactory definition of a “jet”, and quite possibly several ones. This belief is driven by the fact that the modification of the single-particle inclusive distribution, which is a clear observable, at high transverse momentum by the medium-enhanced radiation of soft gluons [16 – 18] is a theoretically well-defined phenomenon.
The looked-for definition of a “jet” would however rather imply some object involving more than one particle, with transverse momenta quite probably above a given lower cutoff. The answer should definitely be driven by experimental attempts, by the practical feasibility. Meanwhile, theorists and phenomenologists can only speculate about the modeling of the “jet” in heavy-ion collisions.

Given the expected properties of the “background event”, namely that it reflects a medium which has a finite size with a non-trivial geometry and which is rapidly expanding, so that its properties change in space and time, the most natural approach is to look for a description of the “jet” which can be implemented in a Monte Carlo simulation [19, 20]. One could then embed the simulation of the “jet” into that of the “background event” [21, 22], to compare the result with the experimental data.

This requirement of a Monte Carlo approach is not assumption-free. If the “jet” is a multi-hadron object, then this involves almost automatically the occurrence of branchings in its evolution. From the technical point of view, a consistent probabilistic implementation necessitates that the

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branchings are *independent* from each other. For in-vacuum jets, this independence follows from the effects of color coherence. Yet whether this coherence is retained within a colored medium is far from obvious. Moreover, the physics of the enhanced radiation of gluons by a high-momentum parton in a colored medium is precisely that of a coherent emission à la Landau–Pomeranchuk–Migdal (LPM) [16], at least for part of the emitted gluon spectrum. It was recently argued that a probabilistic implementation of the LPM effect, relying on formation time arguments, can be found [23]. An alternate approach is the formulation of the LPM effect as a modification of parton splitting functions [24]. These are encouraging results, which however might not be applicable to the whole phase space of produced gluons. Additionally, if color coherence in the “jet” development is not retained in a colored medium, one also loses the angular ordering of successive branchings, which means that the “jet” structure becomes more complicated.

Eventually, the choice of the physics ingredient which is put forward in the definition of the “jet” is not neutral either. The picture of the medium-induced modifications of a “jet” that has been adopted till now [25, 26] mostly emphasizes the conservation of energy-momentum. That is, the “jet” is seen as an object inside which, through the influence of the medium, energy and momentum are redistributed, so that the meaningful comparison would be between jets in vacuum and in heavy-ion collisions with the same energy. The choice is greatly motivated by considerations on the (parton) production cross-sections, yet it should be kept in mind that there is some arbitrariness in it. In particular, the exchange of energy and/or momentum of the “jet” with the “background event”—either the loss of energy by the jet through elastic scatterings in the medium [27], or the gain in mean-square transverse momentum due multiple collisions on the medium scattering centers [28]—complicates the separation between both components of the event if one really insists on conserving energy and momentum inside the “jet”.

2. A “medium-modified parton shower” approach

Under all the caveats on the validity of the approach which were recalled in Section 1, let me introduce my model of a “medium-modified parton shower” and some of its possible consequences [26, 29].

The idea is to mimick the medium-enhanced radiation of gluons by a fast parton by modifying the $q \to qg$ and $g \to gg$ splitting functions, enhancing their singular parts. To allow analytical computations, this enhancement is obtained by a multiplication of the singular parts by a constant factor $1 + f_{\text{med}}$. That is, energy is conserved at each branching, while the splitting probability is enhanced: one modifies the structure of the cascade, considered as an isolated entity; in particular, there is no transfer of momentum between the medium and the “jet”.

Under this setup, one can compute the longitudinal and transverse distributions of partons inside the resulting shower, repeating the steps that turned out to be successful in the description of in-vacuum jets. Note that imposing the conservation of energy while increasing the splitting probability automatically results in an increase of the “jet” multiplicity [30 – 32].

2.1 Modification of the longitudinal distribution of partons

The splitting functions enter evolution equations for the distributions $\mathscr{D}_{A_0}^{A}(x, E\Theta, Q_0)$ of partons of type A with the energy fraction x inside a shower with opening angle Θ initiated by parton A_0

with energy E [6]. These equations (or rather, an approximation thereof) can be solved, leading in the limit $Q_0 = \Lambda_{\rm QCD}$ to the *limiting spectrum* $\tilde{\mathscr{D}}^{\rm lim}(\ell,y) = x\mathscr{D}_g^{\rm MLLA}(\ell,y)$ with its characteristic “hump-backed plateau” shape [6]. Note that $y \approx \ln(k_0\Theta/Q_0)$, see Eq. (1.1), and that the “partonic” limiting spectrum is mapped through LPHD on the hadronic one $K^h\tilde{\mathscr{D}}^{\rm lim}$.

The effect on the ℓ-distribution of modifying the Altarelli–Parisi splitting functions through the introduction of the $1+f_{\rm med}$ factor has been studied in Ref. [26], and consists in redistributing partons from low-ℓ values to larger ones, as is illustrated in the case of a 100 GeV jet in Fig. 1. This follows at once from the assumed ingredients of the model: if the splitting probability increases, this decreases the probability that partons with high energy fractions x survive the evolution. Since energy is to a large extent conserved, this must in turn result in a significant growth of the multiplicity at low x, i.e. large ℓ. The advantage of the model is that the redistribution is encoded in the analytical formula that gives the distorted longitudinal spectrum, which can then be used for other purposes.

2.2 Transverse momentum distribution

The calculation of the distribution in transverse momentum with respect to the jet axis for hadrons inside a jet relies on integrating over one hadron (h_2) the double differential two-particle cross-section, weighted by the hadron energy fraction x_2 [6]. The process under consideration, which is represented e.g. in Fig. 1 of Ref. [33], is the following. A hard process gives rise to an “initial” parton A_0 with the typical energy scale $E\Theta_0$. This parton emits with the probability $D_{A_0}^A(u, E\Theta_0, uE\Theta)$, which is governed by the splitting functions, a parton A that carries a fraction u of the energy of the initial parton and has the virtuality $uE\Theta < E\Theta_0$. Parton A can then further evolve and split into two partons B (energy uzE) and C (energy $u(1-z)E$) forming an angle of typical order Θ; the corresponding probability again involves the parton splitting function $P_{BA}(z)$. Eventually, the partons hadronize: B gives some hadron h_1 with the energy x_1E, C gives h_2 with the energy x_2E. The probability for these hadronization processes $A \longrightarrow h_i$ is given by the fragmentation

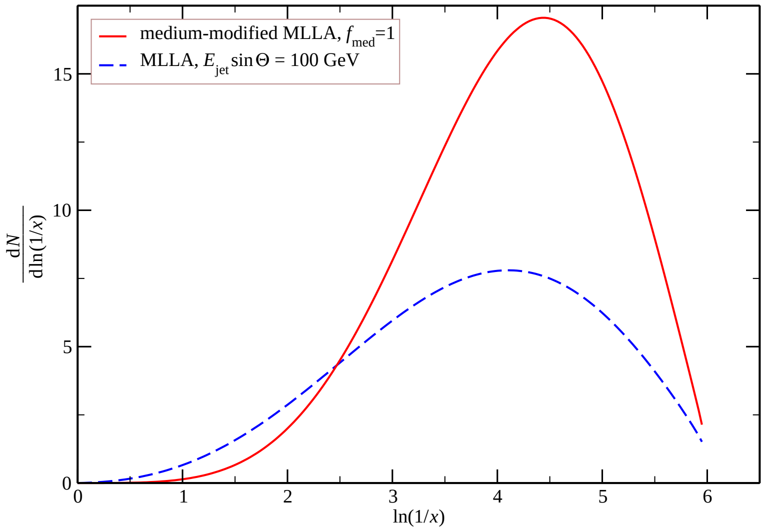

Figure 1: Longitudinal distribution inside a parton shower initiated by a parton such that $Y_\Theta \equiv \ln\dfrac{E\sin\Theta}{Q_0} = 6$

function $D_A^{h_i}(x_i/u, uE\Theta, Q_0)$. All in all, the distribution $F_{A_0}^h(x,\Theta,E,\Theta_0)$ of the energy fraction of hadrons within a subjet with an opening angle $\Theta < \Theta_0$ reads [6]

$$F_{A_0}^h(x,\Theta,E,\Theta_0) \equiv \sum_{A=q,g} \int_x^1 \mathrm{d}u\, D_{A_0}^A(u,E\Theta_0,uE\Theta)\, D_A^h\left(\frac{x}{u},uE\Theta,Q_0\right). \tag{2.1}$$

Differentiating this distribution with respect to to $\ln\Theta$—or equivalently, at fixed ℓ, $\ln k_\perp$—yields the double differential single-particle inclusive distribution of hadrons inside a jet initiated by the parton A_0 with opening angle Θ_0 and energy E [6]:

$$\frac{\mathrm{d}^2N}{\mathrm{d}x\,\mathrm{d}\ln k_\perp} \simeq \frac{\mathrm{d}^2N}{\mathrm{d}x\,\mathrm{d}\ln\Theta} = \frac{\mathrm{d}}{\mathrm{d}\ln\Theta} F_{A_0}^h(x,\Theta,E,\Theta_0). \tag{2.2}$$

Within a small-x approximation and MLLA, this can be rewritten as [33]

$$\left(\frac{\mathrm{d}^2N}{\mathrm{d}\ell\,\mathrm{d}y}\right)_{g,q} = \frac{\mathrm{d}}{\mathrm{d}y}\left[\frac{\langle C\rangle_{g,q}}{N_c} K^h \tilde{\mathscr{D}}^{\lim}(\ell,y)\right], \tag{2.3}$$

where $K^h\tilde{\mathscr{D}}^{\lim}$ is the limiting spectrum for hadrons (see above) while the average color current $\langle C\rangle_{A_0}$ inside a jet initiated by A_0 follows from the splitting functions. If one wants the distribution of partons, instead of hadrons, one should just divide by the constant K^h.

The transverse momentum distribution inside a jet is finally given by the integral of Eq. (2.3) over ℓ:

$$\left(\frac{\mathrm{d}N}{\mathrm{d}\ln k_\perp}\right)_{g,q} = \int \mathrm{d}\ell \left(\frac{\mathrm{d}^2N}{\mathrm{d}\ell\,\mathrm{d}\ln k_\perp}\right)_{g,q}. \tag{2.4}$$

The various steps in the computation can be repeated using "medium-modified" splitting functions instead of the Altarelli–Parisi functions. Let me present the results, for gluon-initiated parton showers with the energy 100 GeV. Figure 2 displays, for various values of the energy fraction x, the

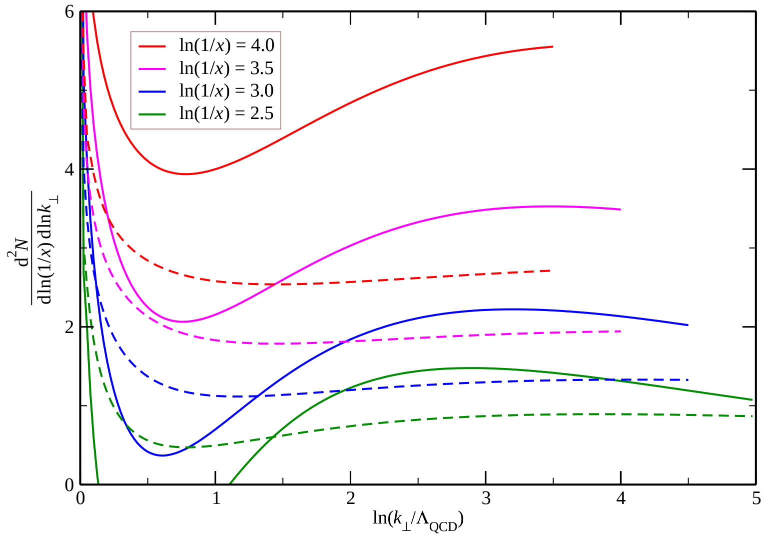

Figure 2: Double differential distribution inside a parton shower initiated by a gluon such that $Y_\Theta = 6$, for various values of ℓ. Dashed lines: MLLA; full lines: "medium-modified MLLA" with $f_{\text{med}} = 1$.

double differential single-particle distribution (2.3). The dashed curves, representing in-vacuum jets, reproduce the calculations of Ref. [33]: at fixed ℓ, the distribution is rather flat for $y \gtrsim 1$, while the divergence as $y \to 0$ reflects that of the running QCD coupling constant $\alpha_s(k_\perp)$ when $k_\perp \to \Lambda_{\rm QCD}$, and thus signals the breakdown of the perturbative regime and thereby the validity of the computation.

The effect of increasing the singular parts of the splitting function is to deplete the low-$k_\perp$ region, while increasing the high-$k_\perp$ one. The effect seems to be proportionally more marked for small ℓ values than at low x. Actually, for the lowest ℓ value reported here, the “influence of the medium” gives negative values to the particle distribution for $k_\perp \lesssim 3\Lambda_{\rm QCD}$. This is slightly disturbing, although obviously in a regime where even the vacuum calculation is not to be taken too literally. One should therefore only see the general qualitative trend of redistributing partons from low to large transverse momenta, without attaching too much value to the quantitative aspects.

When integrating over ℓ, this qualitative reshuffling from low to large $k_\perp$ values results in a broader $k_\perp$ range where the distribution is sizable, as shown on Fig. 3, which shows the transverse momentum distribution (2.4) as a function of $\ln k_\perp$. The jet is thus “broadened” in transverse momentum. One can similarly show that the same model leads to in-medium *angular broadening*, the distribution in the angle Θ with respect to the jet axis being broader for the medium-distorted parton shower as in the vacuum [29].

At the same time however, one can guess on Fig. 3 that at large values of $k_\perp$ the distribution is actually smaller for in-medium “jets” as in the vacuum. This actually reflects the redistribution of partons from high to low x values. The combination of both effects is indeed the softening of the transverse momentum spectrum, as shown in Fig. 4. This softening was previously also observed in simulations with the Q-PYTHIA parton cascade [31].

Note that a proper accounting in analytical calculations of the large transverse momentum region might necessitate the introduction of next-to-MLLA corrections that keep track of energy

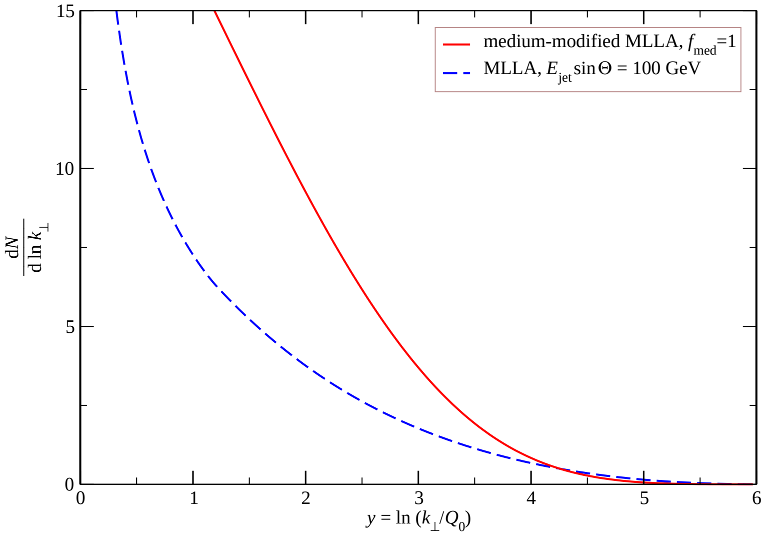

Figure 3: Transverse distribution inside a parton shower initiated by a gluon such that $Y_\Theta = 6$, as a function of $\ln k_\perp$.

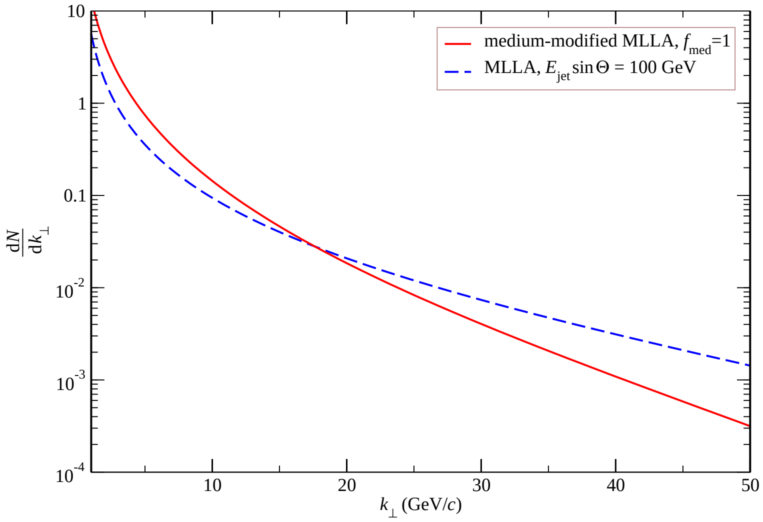

Figure 4: Transverse distribution inside a parton shower initiated by a gluon such that $Y_\Theta = 6$, shown vs. $k_\perp$.

conservation in the branchings with better accuracy [8]. This is however at this time a rather academic point, given the exploratory character of the model. In particular, one can quite safely anticipate that the only experimentally accessible modifications of jet shapes have to be investigated above some lower cutoff in the momentum transverse to the beam axis, as was partly done in Refs. [26, 29], but has to be studied in a more systematic way.

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