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Nuclear Physics A 967 (2017) 81–88

NUCLEAR PHYSICS A

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Jet energy loss and equilibration

Korinna C. Zapp

Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Av. Elias Garcia 14-1, 1000-149 Lisboa, Portugal
Theory Department, CERN, CH-1211 Genève 23, Switzerland

Abstract

The field of jet quenching studies is witnessing an interesting development marked by the appearance of jet sub-structure observables. I give my personal view on this class of observables and comment on how they are connected to thermalisation.

Keywords: heavy ion collisions, jet quenching, jet sub-structure, thermalisation

1. Introduction

The theory of jet quenching has come a long way since the discovery of the phenomenon at RHIC in single-inclusive hadron observables and two-hadron correlations around the year 2000. Today the study of jet quenching is largely concerned with observables based on reconstructed jets. These have the advantage of being largely insensitive to hadronisation and allow to ask new questions, e.g. about the distribution of energy in the vicinity of a hard, fragmenting parton. Describing jets does, however, also require different theoretical tools. For single-inclusive hadrons it was enough to consider the propagation of a single hard parton (figure 1), for jets one has to take the scale evolution into account, keep track of radiated gluons, control the interplay between vacuum-like and medium-induced emissions, understand the response of the medium to the passage of a jet etc. (figure 2). The recent calculation of the interference in two-gluon emission (cf. [1, 2] and references therein) constitutes an important step forward.

It is important to keep in mind is that jets are defined by the jet algorithm. This implies that jets are a proxy for hard partons, but there is no strict correspondence between the two. Reconstructing jets reduces the complexity of the event and facilitates studies of global event properties. On the other hand, a lot of physics is contained in the sub-structure of jets. In particular, as will be argued in the following, the sub-structure of quenched jets in heavy ion collisions carries information about the medium.

The production and sub-structure of jets in p+p collisions is well understood in perturbative QCD. Jet production matrix elements are calculated at fixed order and are available at next-to-leading order for up to five jets. The parton showers provide a process independent resummation to leading logarithmic accuracy of collinear logarithms giving rise to the characteristic jet sub-structure. In addition, resummations of sub-leading logarithms are available for many observables. Leading or next-to-leading order matrix elements supplemented with parton showers are implemented in multi-purpose event generators. This provides a solid and well calibrated baseline for understanding medium modifications of jets.

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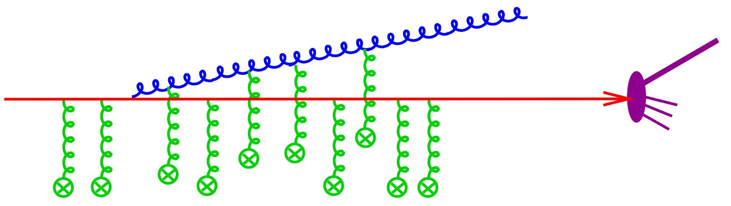

Fig. 1. Cartoon of quenching of single-inclusive hadrons in the eikonal limit due to gluon radiation off a hard quark due to multiple scattering in the medium.

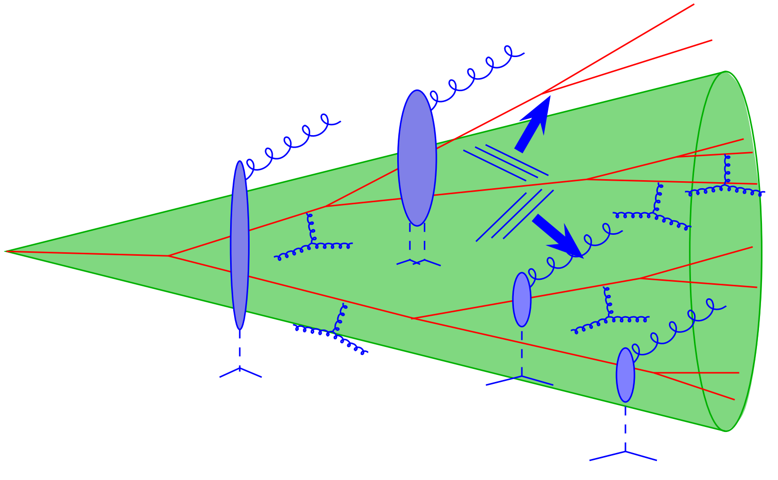

Fig. 2. Cartoon of medium modifications experienced by a reconstructed jet due to different elastic and inelastic energy loss processes.

One of the fundamental questions addressed with jet quenching is whether jets resolve the partonic structure of the medium. Ideally, this gives access to the scale dependence of medium properties. The relevant scale defining the resolution is the momentum transfer between the jet and the medium. This resolution works in both directions: the jet does or does not resolve the structure of the medium and the medium does or does not resolve the sub-structure of jets. A low momentum transfer implies that the jet sub-structure is unresolved, but the jet carries colour charge and can interact coherently. This leads to mostly soft large angle gluon radiation, but does not affect the inner jet structure. If, on the other hand, the jet structure is resolved with a large momentum transfer, the individual partons interact incoherently with the medium. This gives rise to modifications of the jet structure that are in principle experimentally accessible. Observables that are sensitive to the jet sub-structure should thus be able to distinguish these two scenarios and thus help to clarify the above question what jets interact with. A few words of caution are expedient here. Of course, between these extreme cases exists a regime where the jet is partially resolved and smaller sub-systems inside the jet stay coherent. Also, in the limits of sufficiently small or large momentum transfer the structure of both jet and medium are resolved or unresolved, but it is conceivable that an intermediate regime exists in which one is resolved but the other is not.

The magnitude of the momentum transfer is also connected to the question which is the right language to describe the interactions between jets and the background medium. Small momentum transfers imply that the coupling between jet and medium is large. In this case strong coupling techniques such as AdS/CFT are the most appropriate language. The advantages of this approach are that (i) it allows to study the exact solution of a gauge theory at strong coupling and (ii) there are no uncertainties in the jet-medium interaction. The downsides are that (i) jets are a weak coupling phenomenon that doesn't exist at strong coupling and (ii) QCD and $\mathcal{N} = 4$ SYM are different theories even at finite temperature. The strategy is thus to prepare an initial state that shares characteristics with jets and study the evolution of this "holographic jet" at strong coupling (for reviews see e.g. [3, 4]).

In the other scenario of large momentum transfer the jet interacts with individual quasi particles in the medium and the interactions can, at least in principle, be calculated using perturbative techniques. In practice this is an intractable problem and different approaches, techniques and approximations have lead to a multitude of results and tools.

Although the weakly and strongly coupled regimes have an arguably very different phenomenology, they also share a few important similarities. One of them is that both at weak and at strong coupling there is an intimate connection between jet quenching and thermalisation. Not only are both the early stages of a heavy ion collision and jets propagating in a dense background far-from-equilibrium systems on their way to thermalisation. Also the theoretical tools used to describe the two systems are very closely related. At strong coupling the evolution of blobs of super-symmetric energy density describe both jet energy loss and thermalisation. At weak coupling the extended phase where the occupancy $f \ll 1/\alpha_s$ is described by an effective kinetic theory [5, 6], governed by the Boltzmann equation

$$-\frac{\mathrm{d}f_{\mathbf{p}}}{\mathrm{d}\tau} = C_{1\leftrightarrow 2}[f_{\mathbf{p}}] + C_{2\leftrightarrow 2}[f_{\mathbf{p}}] + C_{\mathrm{exp}}[f_{\mathbf{p}}]\,. \tag{1}$$

In this theory the change in the gluon distribution is given by a splitting/merging term $C_{1\leftrightarrow 2}[f_{\mathbf{p}}]$, an elastic scattering term $C_{2\leftrightarrow 2}[f_{\mathbf{p}}]$ and the expansion $C_{\mathrm{exp}}[f_{\mathbf{p}}]$. $C_{1\leftrightarrow 2}$ encodes the emission or absorption of a gluon in the presence of multiple scattering and includes the LPM effect. $C_{1\leftrightarrow 2}$ and $C_{2\leftrightarrow 2}$ are also responsible for parton energy loss and are thus relevant for jet quenching.

2. Jet sub-structure in heavy ions

As argued in the introduction jet sub-structure observables should be able to help clarify to what extent jets remain coherent while passing through a medium. These observables are built from the jet constituents (e.g. partons or calorimeter cells) and characterise the momentum distribution inside jets and/or find particular structures inside jets. They have been studied extensively in the context of p+p collisions over the last years. One of the classical use cases is the discrimination between QCD jets and boosted heavy objects that decay hadronically. In the latter case the two jets originating from the decay merge due to the boost and are identified as a single jet. However, the inner structure of this jet still shows a characteristic two-prong structure that is different from ordinary QCD jets and can be identified with dedicated sub-structure observables (for a review cf. [7]).

In the p+p community jet sub-structure observables are often discussed in conjunction with so-called grooming techniques such as filtering [8], trimming [9] or pruning [10]. These are designed to separate the hard jet structure from soft contamination due to pile-up or underlying event. This is potentially interesting in a heavy ion context, but systematic studies are presently still missing.

On the experimental side there has been a number of measurements of jet sub-structure observables over the last years [11, 12, 13, 14, 15], some of which show large medium modifications. In the remainder of this chapter I will discuss in more detail the groomed shared momentum fraction z_g. This is a classic example for a sub-structure observable, that may give insight into the structure of the medium. Moreover, there is a recent measurement of this observables in heavy ion collisions showing a characteristic modification relative to p+p [14].

z_g is defined by the Soft Drop procedure [16, 17], which is designed to identify the hardest two-prong structure inside a jet. To this end jets are reconstructed with the anti-$k_\perp$ algorithm and subsequently re-clustered with Cambridge/Aachen (an algorithm based entirely on angles). Then the last re-clustering step is undone, giving the two prongs with the largest angular separation. If the $p_\perp$ sharing between the two prongs satisfies

$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} > z_{\mathrm{cut}} \tag{2}$$

the algorithm terminates. Otherwise, the softer of the prongs is rejected and the last clustering step of the harder is undone, until a configuration satisfying the Soft Drop condition of equation 2 is reached[1]. Rejecting soft prongs, that are more likely to come from a predominantly soft background contamination, is an example for grooming.

The z_g distribution is calculable in perturbative QCD [18]. To lowest order the result is independent of α_s:

$$p(z_g) = \frac{P(z_g) + P(1 - z_g)}{\int_{z_{\mathrm{cut}}}^{1/2} \mathrm{d}z\, [P(z) + P(1 - z)]} \Theta(z_g - z_{\mathrm{cut}}) \,. \tag{3}$$

As shown in [18], including resummation effects in the high-energy limit does not alter this result. The authors also show that the distributions obtained with Monte Carlo event generators are well described by equation 3 for jets with a $p_\perp$ of a few hundred GeV at top LHC energies (figure 3). Corrections to equation 3 arise for instance from cases where one prong is incompletely reconstructed because some particles fall outside the jet cone, or where the prongs found by the Cambridge/Aachen algorithm do not match the prongs generated by the jet evolution. Nevertheless, it can be concluded that for sufficiently hard jets evolving in vacuum the z_g distribution is directly sensitive to the QCD splitting function.

A first measurement of the z_g distribution in heavy ion collisions by CMS shows a significant modification compared to p+p (figure 4). The low z_g part of the distribution is enhanced and the large z_g part suppressed, indicating a preference for more asymmetric configurations in Pb+Pb collisions. It should be noted that both the Pb+Pb and the p+p distributions are separately normalised to unity before the ratio is taken, therefore an enhancement (suppression) in some region of the distribution necessarily leads to a suppression (enhancement) elsewhere. Interestingly, the modification of the z_g distribution disappears when increasing the jet $p_\perp$.

The connection of the z_g distribution to the QCD splitting function in p+p collisions raises the question, whether in heavy ion collisions z_g can be used to measure the in-medium splitting function. For this it is essential to better understand coherence of jets or significant sub-systems inside jets [19, 20], since, as

[1] The Soft Drop procedure allows for an angular dependence in equation 2, which was not exploited in the CMS measurement and is therefore not considered here.

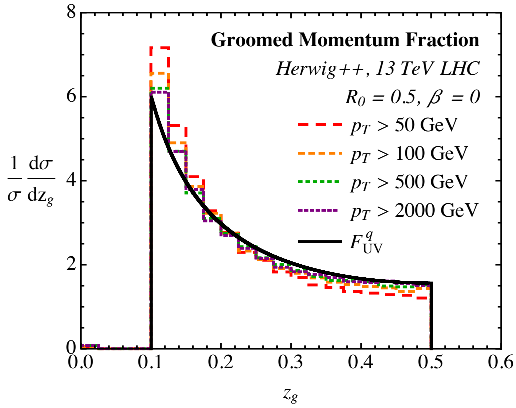

Fig. 3. Comparison of the analytical result for the z_g distribution (black line) to Monte Carlo results generated with Herwig++. Reprinted figure with permission from A. J. Larkoski, S. Marzani, J. Thaler, Phys. Rev. D91 (11) (2015) 111501, arXiv:1502.01719, doi:10.1103/PhysRevD.91.111501. Copyright (2015) by the American Physical Society.

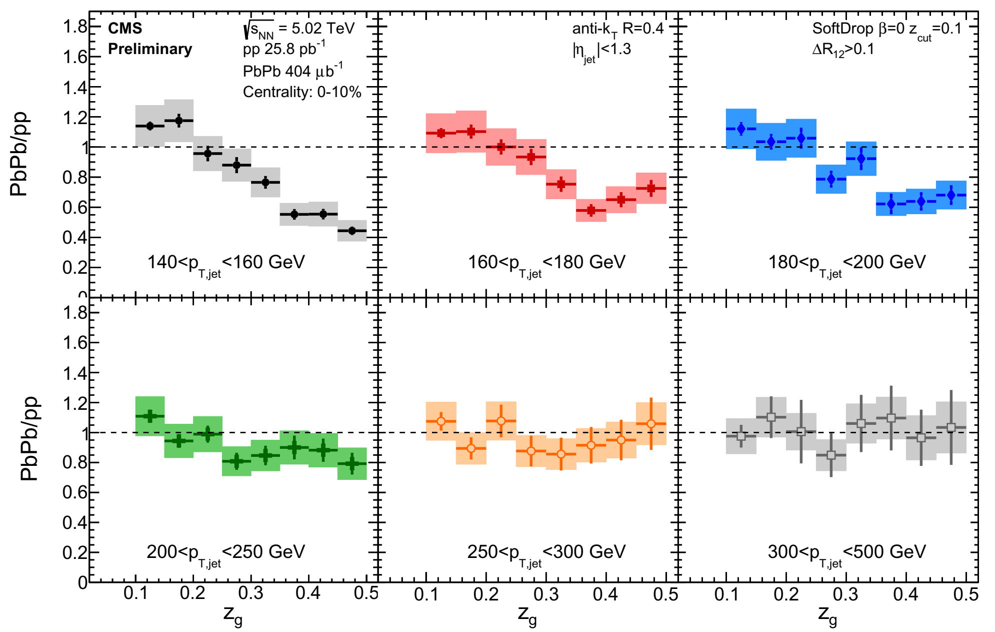

Fig. 4. Modification of the z_g distribution in central Pb+Pb relative to p+p collisions in different jet $p_\perp$ bins measured by CMS. Figure reproduced from CMS-PAS-HIN-16-006.

argued above, coherence can prevent the jet sub-structure from being modified by medium induced radiation. But even in the presence of medium induced radiation inside the jet cone it has to be clarified whether it can give rise to hard large-angle structures that are picked up by the Soft Drop algorithm [21, 22]. Finally, a better understanding of the interplay between vacuum-like and medium induced emissions is required. Particularly important in this context is the question how and to what extent the hard, i.e. vacuum-like, jet sub-structure influences possible induced radiation (for a first discussion cf. [23]) and how this affects the z_g distribution.

Some studies have shown that jet sub-structure observables are sensitive to the medium response [24, 25, 26]. The term medium response denotes the medium's reaction to the energy and momentum deposited by the jet. Experimentally an enhancement of soft particle production at large angles from the jets has been observed [27, 28], that is attributed to medium response. The sensitivity of jet shape and other dedicated observables to medium response furnishes the chance to directly observe the medium's reaction to a perturbation, i.e. the thermalisation of energy and momentum lost by a jet.

Medium response leads to additional activity in addition to the jet and the (fluctuating) background, which is correlated with the jet but not entirely contained in the jet cone. While the average background is subtracted from the jets (with unfolding to deal with the fluctuations), this correlated background component cannot be naively subtracted and should rather be regarded as belonging to the jet. One should keep in mind that also the correlated background fluctuates and that these fluctuations are related to energy loss fluctuations and are phenomenologically relevant.

Initially, theoretical studies of medium response were almost entirely focused on the possible formation of a Mach cone and a wake and did not employ realistic models for the jet. At strong coupling the energy and momentum lost by the jet are transferred into hydrodynamic modes [29, 30]. Also at weak coupling a fast thermalisation of soft fragments was found [31] and several groups have studied the hydrodynamic response to source terms derived from more realistic jet energy loss calculations [32, 33]. A natural framework to study medium response are transport calculations that treat all partons, whether they are part of the background or a jet, on equal footing. In these codes thermal partons recoiling against an interaction with a jet may undergo further interactions with the medium [34, 35, 36]. More recently, hybrid models have been developed, that use a transport description for the jet but model the medium and its response to the passage of a jet in hydrodynamics [24, 37, 26]. In JEWEL two limiting cases can be studied: one option is to extract a source term that is then used in a hydrodynamic model of the background and the medium response [38], while in the other case recoiling thermal partons are kept in the event and hadronise together with the jet, but don't undergo further interactions[2]. Similarly, in [39] the effect of recoiling partons on single inclusive jet suppression is considered in the two extreme scenarios of immediate thermalisation of recoiling partons and no further interactions.

In a study using the JEWEL generator [40] it was concluded that medium response is responsible for a large part of the observed modification of the z_g distribution. The mechanism underlying this effect is that components of the correlated background get clustered into the jet and can promote sub-jet configurations above z_{cut} by adding some extra $p_\perp$ to the sub-leading prong. This is likely to happen because of the steeply falling z_g distribution. An enhancement in the low z_g regions induces a suppression at high z_g due to the normalisation of the distribution to unity.

The role of energy loss fluctuations, which lead to fluctuations in the medium response, has been discussed in the JEWEL framework [23] and analytically [41]. In both cases it was concluded that energy loss fluctuations are large and have to be taken into account.

3. Implications for the heavy ion community

The developments of the last years in the field of jet quenching, that are highlighted very clearly by jet sub-structure observables, have implications for work in this community. As with all complex observables

[2]In this case the thermal momentum of the medium partons before interaction with the jet has to be subtracted from the jet at analysis level [25]

it is important to understand in detail how they are measured [3], as even apparently minor details of an experimental analysis can change the interpretation in a non-trivial way. In case of the z_g distribution, for instance, the ΔR cut introduced by CMS plays a central role. Another important point is to understand what a particular observable is sensitive to. Examples for this are again the z_g distribution, which seems to get a surprisingly large contribution from medium response, and the di-jet asymmetry, which was shown to be driven mainly by fluctuations rather than path length differences [23]. This requires advanced theoretical tools that are capable of dealing with all relevant effects. All this can only be achieved in close collaboration between theorists and experimentalists. To structure collaborative efforts and allow the entire community to profit, the Lisbon accord [43], a collaboration involving theorists and experimentalists, has been established. The agenda of the Lisbon accord comprises efforts to

- agree on how measurements should be presented, i.e. what kind of corrections, unfolding etc. should or should not be applied,
- introduce well defined and theoretically sound observables,
- agree on what is good practice for comparisons between theory and data,
- introduce standards, formats and tools to facilitate this,
- and make standard particle physics tools usable for the heavy ion community.

In addition, there is Jetscape [44], a NSF funded collaboration with the aim of providing software packages for the simulation of jets in heavy ion collisions and statistical tools for data comparisons. These tools may be very useful in the future for an insightful mapping out of theoretical uncertainties.

4. Conclusions

Triggered by first measurements, jet sub-structure observables are discussed for the first time in a heavy ion context. This is an exciting and promising development for several reasons.

- Jet sub-structure observables have the potential to elucidate thermalisation. This is to some extent true for all jet quenching observables, but particularly so for jet sub-structure because of its simultaneous sensitivity to hard and soft physics. Notably the effects of medium response on these observables offers a chance to observe the medium's reaction to perturbations.
- They may revolutionise our view of jet-medium interactions, because they are related to the question whether jets resolve quasi-particles in medium. This in turn goes hand in hand with the question in how far colour coherence inside the jet is preserved in the medium.
- Understanding jet sub-structure requires special theoretical techniques. Theoretical tools have to be able to handle multi-particle final states. This implies that the hard vacuum-like structure has to be accounted for alongside the jet-medium interactions. Colour coherence, the interplay between vacuum-like and medium-induced emissions and medium response have to be taken into account.
- Last but not least this development highlights that jet quenching is becoming a quantitative discipline. This has consequences for the way in which theory is compared to data and requires a community effort to agree on standards, ways of presenting measurements, how to achieve fair data-theory comparison, define theoretically sound observables, etc. Obviously, this has to be supported by theorists and experimentalists. The particle physics community has already successfully gone through the same exercise and heavy ion physics may learn from that and profit from tools and standards that have been developed.

[3] Another example for this is the so-called R_{AA}-v_2 puzzle [42].

Acknowledgements

This work was funded by Fundação para a Ciência e a Tecnologia (FCT, Portugal) under project CERN/FIS-NUC/0049/2015 and contract 'Investigador FCT - Starting Grant' IF/00634/2015.

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