Jet Modifications and Medium Response - Theoretical Overview

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Abstract. A personal view on the current status of the theoretical description of jet quenching physics in heavy-ion collisions is presented.

1 Introduction

The essential property of jets created in heavy-ion collisions is that they possess and energy E which is much larger than any relevant medium scale, say the temperature T. We know that an energetic object will suffer a process of energy loss as it interacts with deconfined QCD matter, in which its energetic modes will be degraded down to the medium scale. From a perturbative QCD (pQCD) perspective, this process is described by the stimulated emission of quanta, which in turn emit more quanta and develop a turbulent cascade with a sink at $E \sim T$ [1]. From a non-perturbative perspective, the energetic parton is dual to a string that falls towards a black hole with Hawking temperature T, exciting hydrodynamic modes at distances $\sim 1/T$ as it crosses the horizon [2]. For many years, we have had experimental evidence that the process of energy loss does take place in heavy-ion collisions. This fact represents one of the strongest affirmations of the creation of deconfined QCD matter in accelerators. We have learned that the reduction of high-p_T yields are accompanied by an excess of soft particles at large angles around the hard object, and that the magnitude of both effects is closely related to the system size, or centrality.

The medium that the jets traverse is not static, but seems to be very well described by an hydrodynamic explosion. The way the jet gets modified (its radiation, its broadening) should thus depend on the local properties of the flowing medium. Additionally, the energy and momentum deposited in the medium by the jet should produce ripples whose evolution also depends on the local properties of the flowing medium. So far, though, we still *do not have experimental evidence of* these *jet-fluid correlations*. The usage of hydrodynamics to successfully describe the final soft particle distributions in large collision systems has been extended to small systems as well, where fluid-like effects are also present. However, recent theoretical results illustrate the apparent inapplicability of hydrodynamics in small systems [3]. A logical question arises: if the collective effects in small systems that so much resemble those in large systems are not described by hydrodynamics, is hydrodynamics really responsible for

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the collective effects in large systems? From this perspective, having evidence that jet (and jet-induced) modifications are sensitive to the spatio-temporal evolution of a flowing medium represents a crucial pillar in the establishment of the fluid QGP paradigm.

Even though the QGP would seem to be well described by hydrodnamics at long distances, $\sim 1/T$, QCD asymptotic freedom predicts that at short-enough distances one resolves individual quark and gluon degrees of freedom. High-energy jets are capable of triggering high-enough momentum exchanges $q < \sqrt{ET}$, which are well within the perturbative regime and can resolve the short-length structure of the QGP due to their small wavelength. Jets are our best chance to look for evidence that the QGP is not bet described as a liquid at all length scales, and in this way try to understand how the liquid picture emerges as one zooms out.

Another aspect of jets having a large energy is that their production is associated to a large virtuality scale, $E \sim Q$. Even though multiple parton emissions are suppressed by powers of α_s, they are enhanced due to large logarithmic corrections related to the large scale separation between Q and the hadronization scale $\Lambda_{\rm QCD}$. The momentum fraction distribution of the produced partons depends on the scale it is probed at – the famous violation of Bjorken scaling. Therefore, jets present a multi-parton structure as they interact with the medium. This interplay, which as we will see has important phenomenological implications, needs to be understood before other more subtle effects can be addressed.

2 Jet production and evolution in heavy-ion collisions

2.1 Initial state effects

At high p_T, jet production is well described by pQCD. The production timescale is short, and so it is safe to assume that it is decoupled from the presence of the medium. However, the nuclear wave function of the incoming projectiles is modified with increasing atomic number. These modifications, labelled as initial state effects, have been shown to have an imprint on jet observables, specially at large x (dominated by the valence quarks), for any value of Q^2. This modification of the jet production spectra translates into effects on jet suppression, $R_{\rm AA}$, mimicking the effects of energy loss at very large p_T [4, 5], or at moderate p_T and large rapidity [6, 7]. Initial state effects have recently been shown to also induce finite jet v_2 in nucleon-nucleus collisions in the absence of energy loss [8]. While these initial state effects have typically been disregarded in jet quenching phenomenology studies, it is now clear that they need to be included and quantified for a correct interpretation of results.

2.2 In-medium vacuum-like evolution

The virtuality scale associated to jet production triggers a parton evolution as determined by the DGLAP equations. The way in which this evolution takes place within the medium is still not completely understood theoretically, but solid arguments exist to state that jets experience part of their in-medium evolution as if they were in vacuum [9]. The relevant scales for this discussion revolve around the formation time τ_f, which is the quantum mechanical time that it takes for an emission to decohere from its parent parton. We say that a potential emission is vacuum-like (VLE) if its formation time is much shorter than the time it takes for the medium to trigger an emission via bremsstrahlung. There naturally exists a large phase-space for these in-medium VLE due to the largeness of the transverse momentum of the emission inherited by DGLAP dynamics compared to that acquired via multiple soft scatterings (whose rate is encapsulated in the jet transport coefficent $\hat{q}$). Of course, large momentum exchanges that can compete with the large virtuality scale can also occur, but they are rare and are unlikely to occur during the fast decay processes of the early-times jet evolution. Another important aspect of the interplay between VLE and the medium is related to color coherence. It has been shown that a given color dipole, generated by VLE, will have both its legs losing energy as independent objects as long as the dipole decoherence time is shorter than the medium length L. Alternatively, this can be expressed by requiring that their relative angle is larger than the critical angle $\theta_c \sim 1/\sqrt{\hat{q}L^3}$. At the same time, medium induced emissions cannot occur at angles smaller than θ_c.

Even though most jet quenching models include the presence of VLE, albeit under different assumptions, there is still no (direct) experimental evidence that this factorized picture exists in real collisions. A recent study [10] has proposed using jet clustering techniques to analyze the properties of the most energetic splittings within the jet. Using different jet quenching Monte Carlos, it was found that at high-enough momenta all models present the same angular distribution for the triggered splitting, signaling the dominance of vacuum physics in that region of phase-space. Experimentally accessing these high-momenta splittings will be possible with new data from the LHC, and will allow us to constrain the scales at which the alleged factorization is supposed to occur.

2.3 Wide versus narrow, gluon versus quark

The presence of this initial parton distribution, triggered by VLE, heavily affects the total energy loss of a jet. This implies that the medium is sensitive to vacuum-set scales, and so to jet substructure fluctuations. The most evident consequence is the selection bias towards jets that experienced a narrower fragmentation (if the jet production spectra is steeply falling, as in the case of inclusive jet selections). Crucially, this statement depends on whether the VLE are resolved by the medium, i.e. if their $\theta > \theta_c$. Together with the high-p_T yields reduction and associated excess of soft particles, we can say that another *experimental fact is that jets in heavy-ion collisions present a narrower core than in pp*. It would thus seem that there is evidence that the medium is capable of resolving at least some of these VLE, allowing us to learn more about their interplay with the medium scales.

However, there exists a confounding factor, related to species dependence. We know that a gluon-initiated jet is typically wider than a quark-initiated jet due to its larger Casimir. We also expect that a gluon-initiated jet will interact more strongly with the medium, also due to its larger Casimir. This means that, even if the medium only resolved the total charge of the jet (as if $\theta_c \to \infty$), one can obtain jet core narrowing just by the medium-modification of the relative species abundance of the typical quark- and gluon-initiated jets (a quark vs gluon selection bias effect, in essence). A very easy solution to this conundrum consists in selecting species enriched samples, in which the modification of the relative species abundance plays little or close to no role. There are several options to get quark enriched samples, such as using boson-jet events [11], heavy-flavour tagged jets [12], or performing rapidity scans for a fixed jet p_T [7]. The strategy is clear: if one has a very high quark-fraction, and narrowing is still observed, it is due to the medium resolving the jet substructure fluctuations.

On this matter, a qualitative observation can be made based on the recent measurement of jet suppression of large radius R jets that contain different number of hard subjets inside [13]. Large-R jets containing just one hard subjet are much less suppressed than those containing two or more. Even though the gluon fraction of single-subjet large-R jets is smaller than those with multiple subjets, simple estimates based on the quenching weights formalism indicate that there is no physical solution for these data if one assumes that the internal structures of the large-R jets were not resolved. Although with many caveats, this is an illustration that these type of measurements might already be indicating that structures form within the medium and are resolved by the medium.

2.4 Looking for evidence of decoherence

The two point energy correlators (EEC) have been put forward as a convenient way with which to study the emergent medium scales associated to jet modification. In general, the anomalous dimension that governs the power-law behaviour of the angular distribution depends on the species initiator, but medium effects are expected to have little sensitivity to changes in the quark-fraction. By studying the modification to the partonic splitting function induced by medium effects as determined by several medium models, it has been shown that both θ_c and the angular scale associated to the finite medium length, $\theta_L = \theta|_{\tau_f<L}$, leave their imprints in the EEC [14]. In particular, the scale θ_c can be extracted by studying the peak position and separating between two main regimes, depending on the other scales of the system (jet energy E, medium length L and jet transport parameter $\hat{q}$): the decoherent regime, where all emissions in the medium are resolved ($\theta_L \gg \theta_c$), and the partially coherent regime, where only some of the emissions are resolved ($\theta_c \gg \theta_L$). However, these first studies have ignored energy loss per se, and so the effect of selection bias for inclusive jet samples has not been taken into account. Such an approximation is more appropriate to describe the EEC that would be measured in boson-jet events, where the spectrum is not steeply falling.

Another recent proposal of an observable that is sensitive to θ_c is jet v_2 as a function of the jet radius R. We currently understand jet v_2 as a geometrical selection bias in which we have an excess of jets travelling in the short direction of the medium compared to the long one. One expects that jet v_2 should be larger than hadron v_2, for the simple reason that the larger number of energy loss sources contained in a jet object will induce a stronger dependence on the traversed length for the final jet energy. Of course, this is so as long as $R > \theta_c$, since otherwise the jet effectively acts a single coherent object from the point of view of the medium. Given the marked length dependence of θ_c, one can study jet $v_2(R)$ for different centralities, i.e. different average traversed lengths and so different typical values of θ_c, in order to reveal such a behaviour [15].

2.5 Cascading down to T

While semi-hard VLE do not in general emit soft gluons independently, due to coherence, soft induced radiation do experience successive independent democratic branchings. The one-gluon distribution admits a description in terms of a rate equation, exhibiting a turbulent cascade behaviour within the multiple soft scattering approximation. This is the main thermalization mechanism in pQCD. Very recently, it has been shown that hard induced emissions can also be assumed to happen independently [16], which is something that was de facto assumed for simplicity in all jet quenching models.

The role of single scatterings, i.e. the Bethe-Heitler (BH) regime for small emitted energies and the Gyulassy-Levai-Vitev (GLV) regime for high emitted energies has been recently analyzed in detail in a consistent framework [17]. The new analytical results can account for all the different regimes, including for the first time the BH regime, such that their relative contribution, at each emitted energy and at each time step in the evolution can be assessed. The cascade picture is modified by the addition of single scatterings in two ways. First, the rarer hard scatterings (GLV) modify the distribution of the initiator, effectively adding a new source of induced radiation. Second, the common soft scatterings (BH) modify the soft tail, breaking the turbulent flow. These new advancements are specially important to understand jet thermalization in pQCD when path-lengths are not too large, such as when considering realistic geometries (i.e. beyond the fixed medium length scenario) or in small systems.

However, when BH becomes important, also $2 \leftrightarrow 2$ scatterings are important, implying that both recoils and thermal masses need to be taken into account. Recent numerical results that consistently include these and all the other known relevant effects (including 2 → 1 recombination processes) for the energy loss of a single color charge offer a detailed understanding of the pQCD thermalization process within the effective kinetic theory (EKT) framework [18]. This comprehensive analysis of the dynamics features the cascade, the modified chemistry around the jet and naturally accounts for medium response, or how the jet drags the medium along with it. Further steps will involve considering the energy loss of a full jet, where coherence effects will have to play a role.

Up to very recently, most first-principle calculations (such as the ones just mentioned) have assumed a static QGP brick scenario. However, accessing the imprints of the spacetime evolution of the QGP left on the jet properties have required new theoretical tools (see the latest work [19] and references therein). There are now new calculations of the single and multiple scatterings regimes using a scattering potential that features gradients in temperature and density (i.e. not uniform) and that can accommodate flowing matter (i.e. not static). Some of the preliminary results on the associated phenomenology show that the transverse energy profile within the jet will be slightly pushed along the gradients direction, and that the EEC sensitivity to gradient effects is relatively robust under VLEs, the omnipresent source of uncertainties when attempting to extract precise information about the jet/medium interaction, over a relatively large phase-space [20].

3 Hydrodynamization of jet energy

Adding gradient and flow effects in broadening and radiation provides key information about the fluid QGP, but when quanta reach the thermal scale they become part of the medium itself. The usual procedure is to treat those modes as sources of energy and momentum into the hydrodynamic equations of motion (e.o.m.). Most implementations assume a Gaussian functional form for this source term (with the notable exception of the causal diffusion equation used in [21]), but one clearly needs a better motivated form. To this end, detailed studies of jet equilibration within EKT can provide some answers. Recent analysis involving minijet energy loss within an expanding background have shown that the minijet does indeed hydrodynamize slower than the background and that such hydrodynamization time scales with $\sqrt{E}$ [22]. A way forward could consist in determining the Green's functions that map the jet modes to the hydrodynamic modes in a similar fashion to what was done in the KøMPøST framework [23]. *Accurately determining the way that a jet feeds the hydrodynamic modes* represents today one of the main sources of theoretical uncertainties in jet quenching physics, and its importance is obviously *related to* that of *the hydrodynamization process of the bulk of the system itself.*

A perturbation on top of a fluid will excite sound and diffusive modes. The evolution of the generated wake is sensitive to QGP properties, such as its viscosity. The final hadron distribution generated by the wake will thus be a result of the interplay of the evolution time until each perturbed fluid cell reaches the freezeout hypersurface as well as the local background flow at that point in spacetime. The fact that the sound modes will spread the energy in rapidity, away from the location where the jet excited the fluid, will break longitudinal boost invariance, which means that one needs to resort to the computationally expensive 3+1D hydrodynamical numerical simulations. This motivates the development of semi-analytical approaches, using superpositions of wake profiles generated with linearized hydrodynamics [24], that can efficiently generate all the casuistics that results from the convolution of the spacetime profile of background flow and a given jet's production point and orientation.

Experimental evidence of jet-induced medium response, directly connected to the existence of a fluid QGP, is still missing. A number of smoking guns have been put forward over the last years. The most promising are the depletion of soft particles in the direction opposite to the jet due to the diffusion wake in boson-jet events [25] and dijet events [4], the modified baryon to meson ratios around the axis due to the coalescence of the excited recoils at intermediate p_T [26], or the novel idea about the imprints left on Λ polarization due to the jet-induced vortex ring [27]. For a more detailed review on these efforts we refer the reader to [28]. A recent experimental result on the study of very low-p_T jets exploiting semi-inclusive events [29] has shown a strong enhancement of the yields of jets around $p_T \gtrsim 10$ GeV as compared to pp. This is consistent with the accumulation of energy around the medium scale due to energy loss. The more striking result is the fact that the angular distribution of jets with $R = 0.5$ has been very strongly broadened. Given that the strong broadening is absent for the smaller $R = 0.2$ jets, a preliminary conclusion that can be extracted from this measurement is that the effect is mostly due to the smearing of the jet axis by the accumulation of thermalized particles within the jet cone rather than a deflection caused by a single hard scattering. In order to be able to elucidate the mechanism behind this effect it will be very interesting to learn about the substructure of these low-p_T jets.

4 Looking for point-like scatterers

In pQCD, the transverse momentum distribution is dominated by soft scatterings, leading to a Gaussian broadening behaviour describing diffusion. However, there is also broadening in a strongly coupled plasma, where in particular the corresponding $\hat{q}$ is not proportional to the number density of scatterers [30]. Therefore, Gaussian broadening is not evidence per se that one is probing the individual quark and gluon degrees of freedom, as it also arises in a fluid with no quasi-particles.

Large-enough momentum transfers will feature the typical p_T^{-4} Rutherford behaviour that can only arise due to the scattering with a point-like object. While this physics is naturally included in all the models that account for the recoils produced in such a $2 \leftrightarrow 2$ scattering process, the momentum transfers are allowed to go as down as the non-perturbative Debye mass scale. For this reason, finding signatures in jet observables of the presence of momentum transfers that are large (and so, perturbative) enough is not straightforward. Using the hybrid strong/weak coupling model to incorporate these elastic scatterings [31], with a lower cutoff on the exchanged momentum, serves as a convenient scenario with which to test the specific phenomenological implications of the presence of the point-like scatterers, since prior to this addition both energy loss and broadening where described at strong coupling. Most observable effects associated to these scatterings are caused by the sprouting of new subjets, made of recoil particles, around the jet direction. However, the selection bias effect that suppresses those jets with a larger number of VLE-subjets works in the opposite direction, implying that a crisp, net enhancement on the number of subjets is not expected in inclusive jet samples.

5 Conclusions

Many pieces are falling into place to develop more accurate jet quenching models with the potential to discover medium response and the existence of point-like scatterers in the QGP. The interplay between the vacuum-like evolution and medium-induced radiation, the determination of the functional form of the sources into the hydrodynamic e.o.m. and the incorporation of quenching in the initial stages remain as some of the main obstacles that we hope to overcome in the next few years.

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