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# Jet quenching with strong coupling

Daniel Pablos

*Department of Physics, McGill University, 3600 University Street, Montréal, QC, H3A 2T8, Canada*

**Abstract**

I will motivate the use of holographic techniques to the study of jet quenching and introduce some of the recent theoretical progress made in the determination of the characteristic features of strongly coupled jet energy loss. Phenomenological applications and their current reach will also be discussed.

*Keywords:* jet quenching, strong coupling, holography

## 1. Motivation

One of the main reasons why one would want to study jet quenching phenomena at strong coupling is that the QGP appears to be an almost ideal strongly coupled liquid itself. The fact that signals of flow are present also in small systems such as pp and pA, reinforces the idea that there is a common hydrodynamic origin for these strong collective phenomena across all system sizes (see e.g. [1]). Indeed, such small systems are supposed to reach hydrodynamization at very short time scales, a situation which is completely natural in the strongly coupled regime where the mean free path tends to zero. The appearance of hydrodynamics at early times despite the presence of large pressure gradients can be explained by holographic computations at large coupling both for conformal [2] and non-conformal [3] gauge theories.

Even if the QGP produced in our accelerators is dominated by temperature regimes in which quasi-particle excitations are absent, probing this system with a microscope should give rise to the quark and gluon degrees of freedom at very short distances, or very large momentum transfers, as expected from an asymptotically free theory such as QCD. The crucial point is then whether the typical momentum exchanges between a fast projectile and the medium are high enough to probe the quasi-particle degrees of freedom and to allow the application of perturbative QCD, or otherwise the momentum range of such transfers occurs at a scale that is low enough for non-perturbative physics to play a dominant role.

By assuming that the relevant energy scale of the plasma is its temperature, which is of the order of the confinement scale, it is clear that there is a strong motivation for the study of jet quenching at large coupling. We can do so by exploiting the use of new techniques that go beyond the perturbative frameworks, which have the potential to provide us with a consistent description of the jet/plasma interplay that does not rely on the presence of quasi-particles. Moreover, these studies and their derived phenomenology can give important insights on what signatures to expect that are characteristic of strongly coupled energy loss dynamics. Building holographic models, and understanding why they succeed or fail in describing experimental data, is tantamount to being able to assess the sensitivity that some observables might present on perturbative

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processes, which will allow us to determine the relative importance of the different energy loss mechanisms that could coexist and the relevance of the length scales at which they emerge.

The rest of the text is distributed as follows: in Section 2 a short introduction of the gauge/gravity duality tools for jet quenching is presented, followed by some recent developments in the extraction of the characteristic properties of jet modifications in Section 3. Section 4 will be devoted to phenomenological efforts in describing jet data by implementing the theoretical insights and Section 5 will briefly summarise the conclusions and motivate future directions.

## 2. Holographic setup

Gauge/gravity duality provides a description of a strongly coupled non-abelian gauge theory living in a 4-dimensional flat space in terms of a semi-classical weakly coupled string theory in 5 dimensions living in a geometry which behaves asymptotically as Anti-de Sitter (AdS) space. This represents the strongest realisation so far of the so called holographic principle, which states that information within a region of space can be constrained by the data at the boundary. Beyond the profound impact it has had at a fundamental level, which is yet to be fully understood, it allows for a very convenient way to reinterpret the challenging non-perturbative behaviour of quantum field theories in terms of considerably simpler geometry problems in general relativity. Even though the most well studied QFT is not QCD itself, but the one with highest degree of symmetry, namely the conformal $\mathcal{N} = 4$ SYM theory, it is reasonable to expect that important qualitative lessons can be learnt from the study of these simpler theories, specially when they are put at finite temperature where the differences between them and QCD above the deconfinement scale are less pronounced.

Following the holographic dictionary, having a plasma at temperature $T$ at the boundary is dual to a black hole within the AdS geometry (Schwarzschild anti-de Sitter, or SAdS) with Hawking temperature $T$, that sits at a distance $r_H = 1/\pi T$ from the boundary in the holographic dimension. Dressed quarks are dual to open strings with one if its endpoints attached to a probe flavour brane, in the so called quenched approximation where the presence of these flavour branes does not affect the background geometry. The depth at which the flavour brane sinks into the holographic dimension is proportional to the mass of the quark, yielding a qualitative difference between the heavy and light quark behaviours given that for a light enough quark the flavour brane becomes space-filling and the endpoint can fall below the black hole horizon. Moreover, given that the bulk metric perturbations induced by the presence of the string encode the variations of the stress energy tensor at the boundary, one can keep track of the modifications that the quark propagation produces in the plasma such that the medium response effects can be computed. For a proper introduction to holography and a review on the implications it has in heavy-ion collisions the reader is deferred to [4].

This gauge/gravity duality framework yields a new form of intuition on the physics of energy loss at strong coupling. By designing sensible problems using the holographic toolbox, we can learn much about the characteristic properties of jet quenching in a strongly coupled plasma. Considerable recent progress has been made in this direction, as shall be presented next.

## 3. Theoretical progress

### *3.1. Heavy and light quark fluctuations*

A key ingredient for the problem of energy loss consists in the determination of the quark diffusion coefficients responsible for its momentum fluctuations due to the presence of a thermal bath [6, 7]. While the contribution to the energy loss of heavy quarks coming from the pull exerted by the black hole on the string, expressed in terms of a longitudinal drag force, was computed some time ago in [8, 9], stochastic processes have been shown to play an important role in the description of heavy quark suppression [10]. Naively neglecting such thermal fluctuations yields an incorrect picture, specially for the softer part of the spectrum - a fact that reminds us about the importance of considering all the physics processes that are relevant for a specific observable. The setup generally used to describe heavy quark energy loss in holography has a natural limit of validity, which is expressed in terms of a maximum value for the Lorentz