Phenomenology of light quark jet quenching in AdS/CFT

Andrej Ficnar, Jorge Noronha and Miklos Gyulassy

1 Department of Physics, Columbia University, New York, NY 10027, USA
2 Instituto de Física, Universidade de São Paulo, 05315-970 São Paulo, Brazil
E-mail: aficnar@phys.columbia.edu

Abstract. We explore phenomenological signatures of light quark jet quenching within the AdS/CFT correspondence. Firstly, we note that the numerical studies indicate a linear path dependence of the instantaneous energy loss of light quarks modeled as falling strings. Secondly, we propose a phenomenological model for generic description of their energy loss and use it to compute the nuclear modification factor $R_{AA}$ for light quarks in an expanding plasma with Glauber initial conditions. Comparing with the light hadron $R_{AA}$ data at the LHC, a qualitative agreement is shown. Thirdly, we show how the observed quantitative disagreement can be partially alleviated by including the effects from higher derivative corrections to $AdS_5$.

1. Introduction

The AdS/CFT correspondence [1, 2, 3], a conjectured duality between $\mathcal{N} = 4$ $SU(N_c)$ super-Yang-Mills theory and type IIB string theory on $AdS_5 \times S^5$ space, has been a very useful tool in the study of many properties of the strongly-coupled quark-gluon plasma [4] created in heavy ion collisions at RHIC and LHC. The correspondence allows one to study this strongly coupled gauge theory in the $N_c \gg \lambda \gg 1$ limit by performing classical, two-derivative (super)gravity calculations.

One of the important applications of the AdS/CFT correspondence has been the study of jet quenching in strongly-coupled systems [5]. In the light of the new LHC results on the suppression of light hadrons in AA collisions [6, 7], a more consistent treatment of energy loss of light quarks in gauge/gravity duality has become necessary, in order to be able to compute jet quenching observables such as the nuclear modification factor $R_{AA}$. Here we propose a possible way to compute the $R_{AA}$ using the input from the numerical studies of the energy loss of light quarks in AdS/CFT and analyze its features.

2. Light quarks in AdS/CFT and their energy loss

In AdS/CFT, degrees of freedom of mass $m_Q$ in the fundamental representation in the boundary theory (‘quarks’) at a finite temperature $T$ correspond to a setup with a D7-brane that spans from the boundary ($r = 0$) to some $r_m \propto 1/m_Q$ [8] in the presence of a black brane in the $AdS_5$ geometry with an event horizon at $r_h \propto 1/T$ [2]. For light quarks, since the D7-brane fills the entire geometry between the boundary and the black hole, one can study their energy loss by studying the free motion of the strings that have both of their endpoints on the D7-brane (representing dressed $q\bar{q}$ pairs), the so-called falling strings [9].
One of the first results on the energy loss of light quarks in AdS/CFT was their maximum stopping distance in a strongly coupled $\mathcal{N} = 4$ SYM plasma, which was shown in [9] to scale with energy as $\Delta x_{\text{max}} \sim E^{1/3}$. However, to compute observables such as $R_{AA}$, one needs the knowledge of the instantaneous energy loss, for which the spacetime momentum currents $\Pi_{\mu}^{n}$ on the string worldsheet need to be analyzed.

In case of a non-stationary environment of falling strings, the spacetime momentum currents become non-trivial, time-dependent quantities and the details of the geometry on the worldsheet become important in connecting them to the energy loss. This was examined in [10], where a general expression was derived for calculating the instantaneous energy loss in time-dependent string configurations, which shows that the energy loss, in general, receives a correction to the simple $\Pi_{\sigma}^{\sigma}$ component of the flux.

If one defines a light quark jet as a part of the falling string within a certain fixed $\Delta x \sim 1/(\pi T)$ distance from the endpoint (as in [9]), it was demonstrated [10] that this correction becomes especially important at late times and substantially decreases the magnitude of the Bragg-like peak reported in [9] (see Figure 1). We also note that, although the early time behavior of the energy loss is sensitive to the initial conditions, numerical studies suggest that it is linear in time, $dE/dt \sim t$ [10].

3. Computing the light quark $R_{AA}$

In order to compute the nuclear modification factor of light quarks in AdS/CFT, we need to have a definite temperature $T$, initial energy $E_0$ and path length $x$ dependence of the instantaneous energy loss of a light quark moving through an $\mathcal{N} = 4$ SYM plasma. For that purpose, motivated by [11], we model the phenomenologically relevant part of the energy loss in the following way:

$$\frac{dE}{dx}(E_0, T, x) = -c(E_0, T)x^{1/3}\Theta[L_s(E_0, T) - x].$$

(1)

Here $L_s$ is the stopping distance, $\Theta$ is the step function and we have also utilized the conjectured linear path dependence from the previous section. The initial energy and temperature dependence has been packed into an unknown function $c(E_0, T)$ which will be determined from the dependence of the stopping distance on the initial energy and temperature [9]:

$$L_s(E_0, T) = \frac{\kappa}{T}\left(\frac{E_0}{\sqrt{\lambda T}}\right)^{1/3}.$$  

(2)

Here $\lambda$ is the 't Hooft coupling and $\kappa$ is a numerical factor that in general depends on the initial string configuration (for the maximum stopping distance it was shown to be $\approx 0.5$ [9]). Combining (1) and (2), we can fix the unknown function $c(E_0, T)$ and finally obtain:

$$\frac{dE}{dx} = -\chi E_0^{1/3} x^{1/3} T^{8/3},$$

(3)

where we have defined an effective coupling $\chi \equiv 2\lambda^{1/3}/\kappa^2$, which determines the overall magnitude of the energy loss and is the only free parameter in this formula. For $\kappa \approx 0.5$ [9] and an unphysically small $\lambda = 1$, we have $\chi \approx 8$. As noted in [10], formula (3) has a surprising similarity to the typical qualitative behavior of energy loss of light quarks in pQCD in the strong LPM regime [11].

With this formula, we can compute the $R_{AA}$ for light quarks following the procedure in [12]: we use Glauber initial conditions for determining the temperature profile of the expanding plasma and average over the jet azimuthal directions and production points in the transverse plane. The results are shown in in Figure 2, where we see that the value of $\chi = 8$ gives an
$R_{AA}$ of a rather low magnitude, indicating strong quenching. However, using a lower value of $\chi = 1$ we see that $R_{AA}$ has the correct qualitative behavior as displayed by the LHC data on the suppression of light hadrons in AA collisions [7]. This suggests that the main problem could be simply in the low magnitude of $R_{AA}$, or, equivalently, too strong quenching.

4. Higher derivative corrections
To make our setup more realistic, in the hope of better fitting the $R_{AA}$ data (i.e. decreasing the strength of the quenching while keeping the correct qualitative behavior), one can include higher derivative $R^2$ corrections to the gravity sector of $AdS_5$, which are the leading $1/N_c$ corrections in the presence of a $D7$-brane. These we will model by a Gauss-Bonnet term, i.e. we will consider the action of the form:

$$S = \frac{1}{2\kappa_5^2} \int d^5x \sqrt{-G} \left[ R + \frac{12}{L^2} + L^2 \kappa \left( R^2 - 4R_{\mu\nu}^2 + R_{\mu\nu\rho\sigma}^2 \right) \right],$$

where $\kappa$ is a dimensionless parameter, constrained to be $-\frac{7}{36} < \kappa \leq \frac{9}{100}$ to avoid causality violations [13] and to have positive energy density on the boundary [14]. A black brane solution in this case is known analytically [15]. Following a similar procedure as in [9], by analyzing null geodesics in geometry given by (4) and relating its parameters to the energy of the string, we can estimate the maximum stopping distance of falling strings up to linear order in $\kappa$ [16]:

$$\Delta x_{\text{max}} = \frac{C}{T} \left( \frac{E}{T \sqrt{\lambda}} \right)^{1/3} \left( 1 - \mathcal{F} \kappa \right) + \mathcal{O}(\kappa^2),$$

where $\mathcal{C} \sim 1/2$ and $\mathcal{F}$ is a numerical factor $>1$, for which our preliminary estimate gives $\mathcal{F} = 11/6$. We see that the $\sim E^{1/3}$ scaling is still present and that for negative values of $\kappa$ we can increase the stopping distance by up to $\sim 30-40\%$, compared to the case of pure $AdS_5$ with no higher derivative corrections. In addition to the $\sim E^{1/3}$ scaling, there are indications that, at linear order in $\kappa$, we can also have an additional new energy scaling (though numerically suppressed), details of which, together with the precise value of the parameter $\mathcal{F}$ in (5), will be presented in a future publication [16].

From (5) we see that the Gauss-Bonnet parameter $\kappa$ affects the $\kappa$ coefficient in (2) and hence the effective coupling $\chi$, which governs the strength of the quenching. For $\kappa = -1/5$, this gives $\kappa = 0.65$ instead of $\approx 0.5$ in the pure $AdS$ case and, as we can see from Figure 3, this has the effect of increasing the magnitude of $R_{AA}$ by almost 100%, while preserving the correct qualitative behavior.

5. Conclusions and outlook
In [10] it was shown that, defining the light quark jet in $AdS$/CFT as a part of the falling string within a certain fixed $\Delta x$ distance from the endpoint, its instantaneous energy loss seems to display a linear path dependence. Using this in a phenomenological model (3) for the energy loss, we have computed the nuclear modification factor $R_{AA}$ for light quarks in an expanding plasma with Glauber initial conditions [12]. While the shape of our model calculations for $R_{AA}$ seems to qualitatively agree with the LHC light hadron $R_{AA}$ data [6, 7], the overall magnitude is too low. We have also shown that taking into account higher derivative $R^2$ corrections to the gravity sector of $AdS_5$ can increase the stopping distance (5) and hence increase the magnitude of $R_{AA}$ while preserving its qualitative behavior.

An interesting next step in a more realistic modeling of light quark energy loss would be to study the effect of higher derivative corrections in a non-conformal plasma (the energy loss of heavy quarks in simple non-conformal models was studied in [17, 12]), as well as to examine the falling strings in the Janik-Peschanski metric [18], dual to perfect fluid hydrodynamics, to take into account realistic effects of an expanding plasma [16].
Figure 1. Comparison of the (normalized) instantaneous energy loss as a function of time (i.e. with the correction from [10]; solid blue curve) with the apparent energy loss $\Pi^\text{app}$ (dashed red curve), for a light quark jet defined as a part of the falling string within a certain fixed $\Delta x$ distance from the endpoint.

Figure 2. Nuclear modification factor $R_{AA}$ for light quarks as a function of the final parton energy $E$ for two different values of the effective coupling $\chi$, compared to the LHC data from [7]. The initial jet production time $t_i$, the freeze-out temperature $T_{\text{freeze}}$ and the initial temperature at the center of the plasma $T_{\text{init,center}}$ are indicated in the plot.

Figure 3. Comparison of the light quark $R_{AA}$ at LHC as a function of the final parton energy $E$, computed as in [12], for different values of the effective coupling $\chi$ with and without Gaussian higher derivative corrections (4), compared to the LHC data from [7].

Acknowledgments

We thank W. Horowitz, A. Bussatti, G. Torrieri and S. S. Gubser for helpful discussions. A.F. and M.G. acknowledge support by US-DOE Nuclear Science Grant No. DE-FG02-93ER40764. J.N. is supported by the Brazilian funding agencies FAPESP and CNPq.

References

[1] Maldacena J M 1998 Adv. Theor. Math. Phys. 2 231-252 (Preprint hep-th/9711200)
[2] Witten E 1998 Adv. Theor. Math. Phys. 2 253-291 (Preprint hep-th/9802150)
[3] Gubser S S, Klebanov I R and Polyakov A M 1998 Phys. Lett. B 428 105-114 (Preprint hep-th/9802109)
[4] Gyulassy M and McLerran L 2005 Nucl. Phys. A 750 30-63 (Preprint nucl-th/0405103)
[5] Gubser S S 2006 Phys. Rev. D 74 126005 (Preprint hep-th/0605182); Herzog C P, Karch A, Kovtun P, Kozcaz C and Yaffe L G 2006 JHEP 0607 013 (Preprint hep-th/0605158); Casalderrey-Solana J and Teaney D 2006 Phys. Rev. D 74 085012 (Preprint hep-ph/0605199); Noronha J, Gyulassy M and Torrieri G 2010 Phys. Rev. C 82 054903 (Preprint 1009.2286 [nucl-th])
[6] Aamodt K et al. (ALICE Collaboration) 2011 Phys. Lett. B 696 30 (Preprint 1012.1004 [nucl-ex])
[7] CMS Collaboration 2012 Eur. Phys. J. C 72 1945 (Preprint 1202.2554 [nucl-ex])
[8] Karch A and Katz E 2002 JHEP 0206 043 (Preprint hep-th/0205236)
[9] Chesler P M, Jensen K, Karch A and Yaffe L G 2009 Phys. Rev. D 79 125015 (Preprint 0810.1985 [hep-th])
[10] Ficnar A 2012 Phys. Rev. D 86 046010 (Preprint 1201.1780 [hep-th])
[11] Horowitz W A and Gyulassy M 2011 Nucl. Phys. A 872 265 (Preprint 1104.4958 [hep-ph])
[12] Ficnar, Noronha J and Gyulassy M 2011 J. Phys. G: Nucl. Part. Phys. 38 124176 (Preprint 1106.6303 [hep-ph])
[13] Brigante M, Liu H, Myers R C, Shenker S and Yaida S 2008 Phys. Rev. D 77 126006 (Preprint 0712.0805 [hep-th])
[14] Hofman D M and Maldacena J 2008 JHEP 0805 012 (Preprint 0803.1467 [hep-th])
[15] Cai R-G 2002 Phys. Rev. D 65 084014 (Preprint hep-th/0109133)
[16] Ficnar A, Noronha J and Gyulassy M, to appear.
[17] Ficnar A, Noronha J and Gyulassy M 2011 Nucl. Phys. A 855 372-375 (Preprint 1012.0116 [hep-ph])
[18] Janik R A and Peschanski R 2006 Phys. Rev. D 73 045013 (Preprint hep-th/0512162)