Short Path Length Energy Loss in the Quark-Gluon Plasma from pQCD

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Abstract. An outline for research to be done is given. In the heavy ion experiments at RHIC and the LHC, it is widely believed that a state of matter known as the quark-gluon plasma (QGP) has been produced. The so-called hard particles, or particles with very high momentum that are produced as a consequence of the asymptotic freedom of QCD, can be used as tomographic probes of the QGP. We will study the way in which energy is dissipated in this QGP by calculating, in pQCD, short path length corrections to the well-known energy loss formulae. This calculation is necessary to address the discovery at the LHC that shockingly small systems appear to exhibit collective behaviour.

1. Introduction

In the heavy ion collisions at both the LHC and RHIC, there is overwhelming evidence that a new state of matter has been created, known as the quark-gluon plasma [1]. Naturally, one would like to study this new phase of matter. However, one of the major challenges such a study is faced with is the extremely short life time of the QGP which excludes the possibility of using an externally produced probe. For this reason, one is reliant on the use of self-generated probes if one is to attempt a characterization of the medium. That is, one must depend on probes that are produced along with the medium.

‘Hard partons’ or partons (such as a quark or a gluon) with very high transverse momentum can be used as tomographic probes of this new medium in the same way that X-rays are used in medicine, in that one can study the degree to which energy is lost as the parton propagates through the medium [2]. The hard partons that are used in this treatment are a quark-antiquark pair that are produced along with the medium. In rare cases, this pair will be created on the periphery of the medium with the effect that one of the pair will move off away from the medium, passing through numerous stages of thermalization and hadronization before being detected as a high $p_T$ jet in the detector, while the other will have to traverse the medium before being subjected to the same process. This leads to back-to-back jets of which one has a much lower total energy than the other. This phenomenon is known as jet quenching [3].

Jet quenching has been used [4] to explain the discovery [5–8] of high $p_T$ hadron suppression in RHIC experiments. This was done using a pQCD model developed by Gyulassy, Vitev and Lévai (GLV) which is a radiative energy loss model [3].

Several calculations, each improving on or correcting previous works, of the radiative energy loss of a parton moving through the QGP in the GLV model have been done [3,9,11]. Figure 1
Figure 1. GLV energy loss model prediction compared to RHIC data [12]

shows the considerable success that this model has enjoyed.

It is important to note that Figure 1 also shows that the model controls initial state effects well since we see no suppression of the photon (which is colourless and can therefore move through the medium unperturbed). This is further evidenced in that the suppression of the $\pi^0$ and $\eta$ particles is similar even though their masses differ substantially ($\sim 135$ MeV and $\sim 548$ MeV respectively), suggesting that this suppression is a final state effect rather than an initial state effect.

Originally, since this suppression is not seen in smaller systems such as in the $d + Au$ at RHIC [13], it was believed that no medium had been created in these collisions. However, recently, the CMS Collaboration [14] as well as the ALICE Collaboration [15] have released results indicative of collective behaviour in these exceptionally small systems, suggesting that the medium is in fact being created, which is motivation for studying the effects of energy loss in small systems.

The higher luminosities - and therefore higher statistics- of Run II of the LHC will improve the measurements of energy loss. It is therefore highly probable that there will be concrete data for jet quenching in small systems within the coming years.

We will thus attempt to correct the GLV calculation shown in Figure 1 for short path lengths (such as those present in the very small systems that are displaying collective behaviour).

2. Method and Calculations

The energy loss calculation shown in Figure 1 as the ‘GLV parton energy loss’ was performed using a number of assumptions:

(i) For the Debye screening length $\mu_D$, the mean free path $\lambda_{MFP}$ and the size of the system $L$, the following length scales were assumed

\[ \frac{1}{\mu_D} \ll \lambda_{MFP} \ll L. \]  (1)
The Debye screening length and mean free path can be calculated from thermal considerations [9] and are therefore known, while the system was considered extremely large since it was on the order of the radius of the heavy ions of the collision.

(ii) The majority of the energy loss is due to radiative loss rather than elastic collisions. This means, amongst others, that only diagrams with up to two or three scattering interactions need to be calculated since very few elastic scatterings occur in the time during which the parton traverses the medium.

This calculation has been done using a reactor operator approach [3, 9] in excess of nine orders of opacity [16], with diagrammatic calculations of up to third order in opacity.

We will relax assumption (i) to account for the smaller system sizes. That is, in our calculation, we will assume rather that

$$\frac{1}{\mu D} \ll \lambda_{MFP} \sim L$$  \hspace{1cm} (2)$$

This assumption will be used when considering the poles of a number of contour integrals that need to be calculated. Previously, assumption (i) meant that a number of terms pertaining to the potential were neglected since their contribution to the matrix element of the diagram were considered small. We will now keep these terms, meaning that our calculation is largely an addition of terms. It is therefore not necessary to redo the entire calculation.

That said, we have reproduced almost all of the results (that is, we have calculated the majority of the diagrams) obtained by [9].

3. Outlook
As part of a Master’s project, we will adjust the assumptions made in the GLV model to compensate for the recent discovery of exceptionally small systems that exhibit collective behaviour. This will entail a number of highly technical calculations but will in essence only involve the retention of previously discarded terms.

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