Short path length pQCD corrections to energy loss in the quark gluon plasma.

Isobel Kolbe[1,2], W. A. Horowitz[1]
[1]University of Cape Town, Rondebosch, Cape Town, South Africa
[2]Isobel.kolbe@gmail.com

DEPARTMENT OF PHYSICS
UNIVERSITY OF CAPE TOWN

2015 KOBE JAPAN

NITheP National Institute for Theoretical Physics

Abstract

Recent surprising discoveries of collective behaviour of low-p_T particles in *pA* collisions at LHC hint at the creation of a hot, fluid-like QGP medium. The seemingly conflicting measurements of non-zero particle correlations and R_{pA} that appears to be consistent with unity demand a more careful analysis of the mechanisms at work in such ostensibly minuscule systems. We study the way in which energy is dissipated in the QGP created in *pA* collisions by calculating, in pQCD, the short separation distance corrections to the well-known DGLV energy loss formulae that have produced excellent predictions for *AA* collisions. We find that, shockingly, due to the large formation time (compared to the *1/μ* Debye screening length) assumption that was used in the original DGLV calculation, a highly non-trivial cancellation of correction terms results in a null short path length correction to the DGLV energy loss formula. We investigate the effect of relaxing the large formation time assumption in the final stages of the calculation -- doing so throughout the calculation adds immense calculational complexity -- and find, since the separation distance between production and scattering centre is integrated over from *0 to ∞*, ≥ *100%* corrections, even in the large path length approximation employed by DGLV.

Model Agreement

Fig 1. shows three important things:

1. Photon R_{AA} of 1 – particle suppression is a final state effect. Therefore, the model controls initial state effects well.
2. Energy is lost as a parton, not as a hadron. Whatever energy is lost, is lost before hadronization occurs.
3. GLV energy loss approach[1] agrees well with experimental data. The set of simplifying approximations that were made appear valid.

Together, these three constitute evidence for the creation of a medium. However, it is clear that the medium must be very large; of the order of the size of two Gold nuclei, and this property is used explicitly in the calculations that lead to the theoretical prediction.

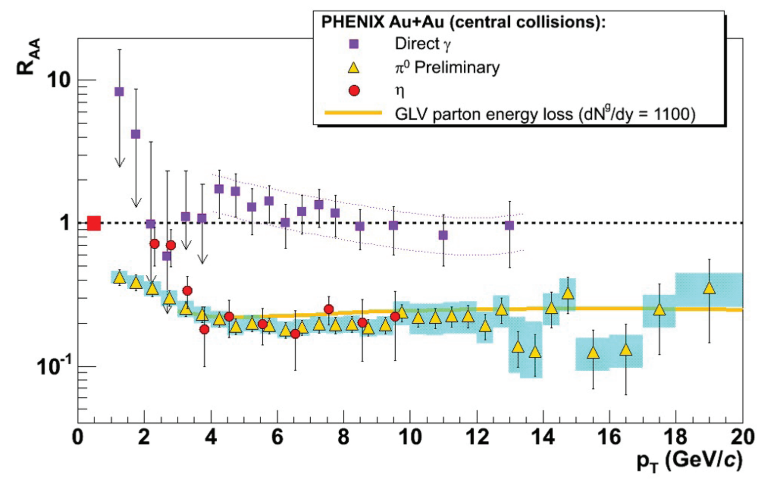

Fig 1. Tshirt; R_{AA} for AuAu at RHIC compared to GLV energy loss for ,Υ π^0 and η.

Motivation

Figure 2 shows recent results from CMS. Hard Probes 2013 also saw ALICE announcing an R_{AA}~*1,5* for high p_T particles[3], an effect which, in *PbPb* experiments has been attributed to the existence of a medium.
Following this trend, at the Quark Matter conference in 2014, CMS[4] released results indicating that they had observed elliptic flow – a distinctly collective phenomenon, in *pPb* collisions.
These results are unexpected, but also remain unexplained; *pA* collisions were intended as a calibrative tool to determine the nature of the scaling of R_{AA}. Formalisms that explain the presence of collective behaviour in *AA* experiments invariantly take the size of the medium to be large. However, the size of any medium created in a *pA* experiment must be of the order of the size of a proton, and no larger. If indeed the effects observed at the LHC are due to the presence of a medium, then it is now necessary to ensure that descriptions of large systems that yield the observed collective behaviour effects remain consistent with small systems.
Flow and high p_T enhancement are not sufficient conditions for the existence of a medium, but since energy loss of a hard probe is considered a necessary feature of the QGP, it must also be evident in small systems – and described by the same physics. For this reason, a detailed analysis of energy loss in such notably small systems is required if an attempt is to be made to understand the new physics of *pA* collisions.

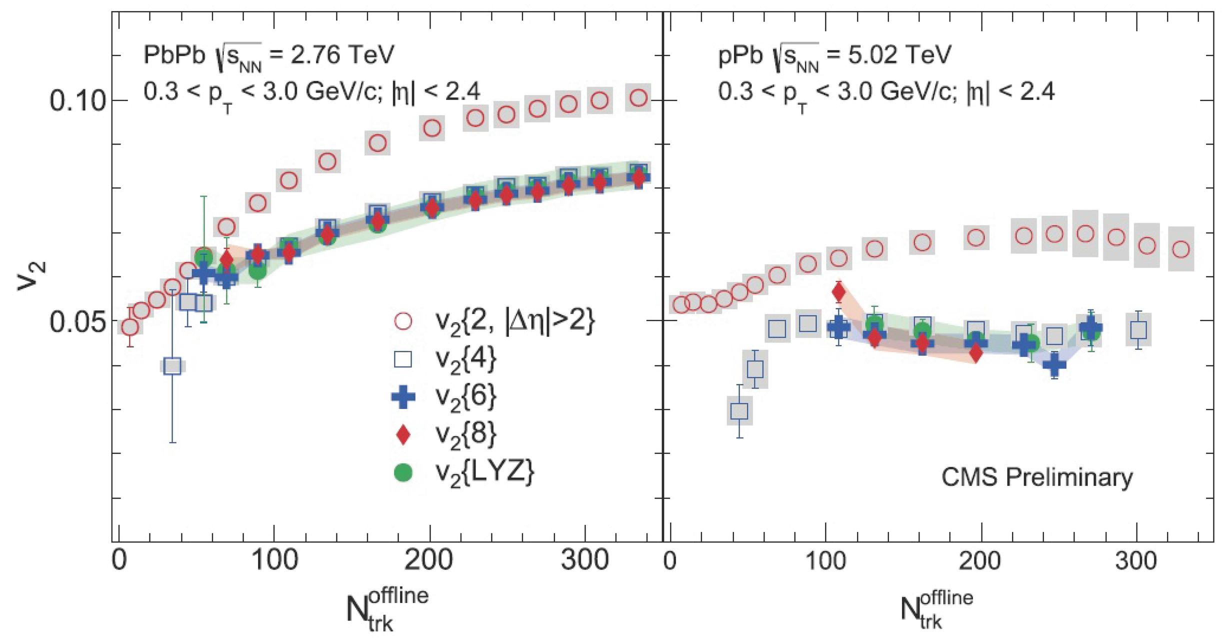

Fig2. FlowResults: Multi-particle correlations in *pPb* experiments at the CMS detector[4].

Approach

In order to address the problem of adjusting the DGLV[5] calculation (which is a heavy quark generalization of the result in **Figure 1**), the scale of the problem needs to be adjusted. The scale chosen by DGLV led to a simplification in the calculation because certain residues were exponentially suppressed and could therefore be neglected. These terms had their origin in the form of the random color-screened potentials that are used in the GLV model to model the interactions in the QGP. These potentials have the form

$$V_n = V(\vec{\mathbf{q}}_n)e^{-i\vec{q}_n\cdot\vec{x}_n}$$
$$= 2\pi\delta(q^0)v(\mathbf{q}_n, q_n^z)e^{-i\vec{q}_n\cdot\vec{x}_n}T_{a_n}(R)\otimes T_{a_n}(n).$$

In order to generalize DGLV, we changed the length scale of the problem, taking instead:

$$\frac{1}{\mu} \ll \lambda_{mfp} \ll L \quad \Rightarrow \quad \frac{1}{\mu} \ll L.$$

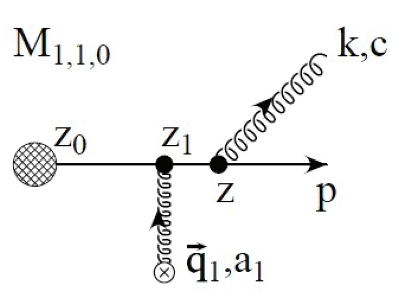

Fig 3. M110: Single scattering soft gluon radiation amplitude that contributes to short path length correction. [5]

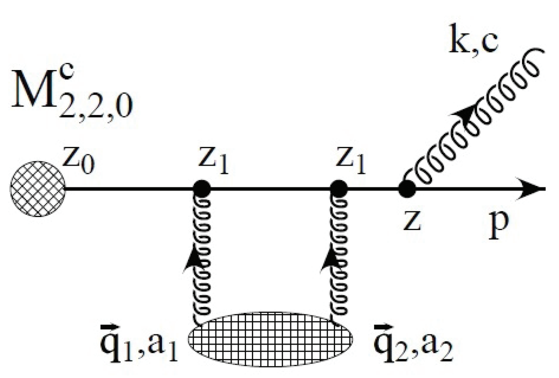

Fig 4. M220: Double scattering soft gluon radiation amplitude that contributes to short path length correction. [5]

Results and Conclusions

The contributions to the short separation distance correction term from the vast majority of the relevant Feynman Diagrams turn out to be suppressed due to the large formation time assumption that is used throughout the DGLV treatment. The only two diagrams that contain non-zero short separation distance correction terms at the amplitude level are shown in **Figure 3, 4**, but if one continues to hold strictly to the large formation time assumption for the duration of the derivation of the energy loss calculation, a remarkable and wholly unpredictable cancellation occurs in the square-sum stage of the calculation, resulting in a null short path-length correction term. In order to investigate the full extent of the effects of the large formation time assumption, we relax the assumption beyond the amplitude stage of the calculation to obtain a new energy loss formula that carries a short path length correction,

$$\begin{aligned}
\Delta E^{(1)}_{ind} =& \frac{C_R\alpha_s LE}{\pi\lambda_g}\int\frac{d^2\mathbf{q}_1}{\pi}\frac{\mu^2}{(\mu^2+\mathbf{q}_1^2)^2}\frac{d^2\mathbf{k}}{4\pi}\int d\Delta z\bar{\rho}(\Delta z)\times\\
&\times\Bigg[-\frac{2(1-\cos\{(\omega_1+\tilde{\omega}_m)\Delta z\})}{(\mathbf{k}-\mathbf{q}_1)^2+M^2x^2+m_g^2}\times\\
&\times\left(\frac{(\mathbf{k}-\mathbf{q}_1)\cdot\mathbf{k}}{m_g^2+\mathbf{k}^2+x^2M^2}-\frac{(\mathbf{k}-\mathbf{q}_1)^2}{(\mathbf{k}-\mathbf{q}_1)^2+M^2x^2+m_g^2}\right)\\
&+\frac{1}{2}e^{-\mu\Delta z)}\Bigg\{\left(\frac{\mathbf{k}}{m_g^2+\mathbf{k}^2+x^2M^2}\right)^2\times\\
&\times\left(1-\frac{2C_R}{C_A}\right)\left(1-\cos\{(\omega_0-\tilde{\omega}_m)\Delta z\}\right)\\
&+\frac{\mathbf{k}\cdot(\mathbf{k}-\mathbf{q}_1)}{(\mathbf{k}^2+m_g^2+x^2M^2)((\mathbf{k}-\mathbf{q}_1)^2+M^2x^2+m_g^2)}\times\\
&\times\left(\cos\{(\omega_0-\tilde{\omega}_m)\Delta z\}-\cos\{(\omega_0-\omega_1)\Delta z\}\right)\Bigg\}\Bigg].
\end{aligned}$$

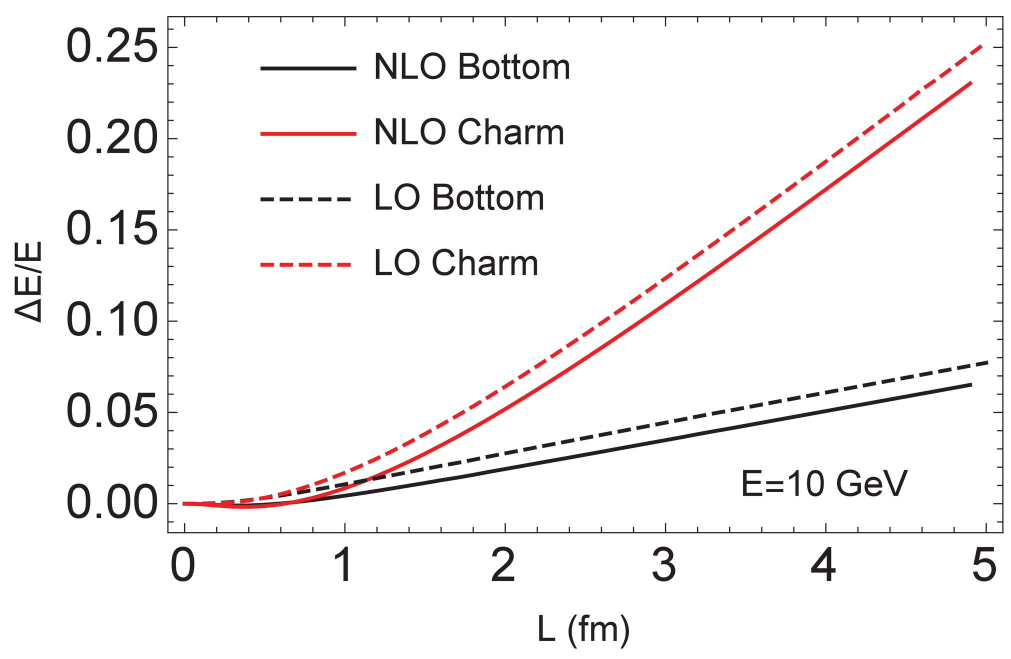

Fig. 5 10GeV: Energy loss per unit energy as a function of the static thickness of the medium for Leading Order (dashed) and Leading Order with NLO corrections (solid) for bottom and charm quarks at 10 GeV.

At low energies the correction seems reasonable as in **Figure 5**, however, at *100 GeV*, we see that the next to leading order terms constitute corrections of more than *100%* in **Figure 6**. We note two important conclusions.

1. The effect of including short separation distances does not seem to decrease with increasing system size as the dz_i integral is performed over z_i, *from 0 to ∞*, and must therefore be taken into account in energy-loss calculations
2. The large formation time assumption has an erroneous effect at large energies, prompting a more careful analysis of the applicability of large formation times.

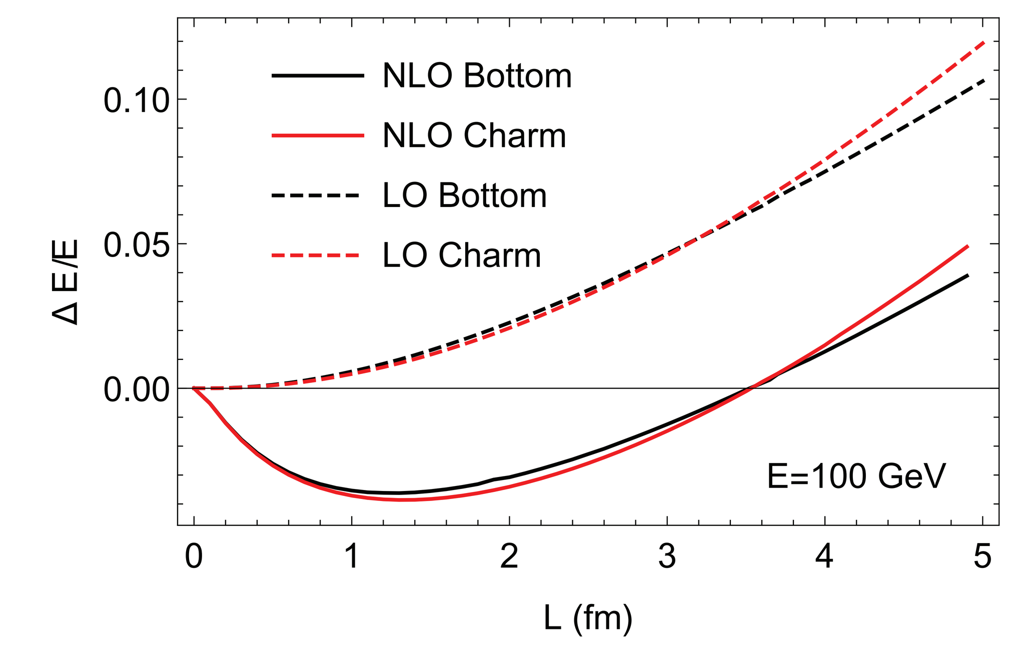

Fig. 6 100GeV: Energy Loss per unit energy as a function of the static thickness of the medium for Leading Order (dashed) and Leading Order with NLO corrections (solid) for bottom and charm quarks at 100 GeV.

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Acknowledgements

We are very grateful for financial support from the National Institute of Theoretical Physics (NITheP). We would also like to thank the National Research Foundation (NRF) and SA-CERN.