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

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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, the large formation time (compared to the $1/\mu$ Debye screening length) assumption that was used in the original DGLV calculation, results in a highly non-trivial cancellation of correction terms. We investigate the effect of relaxing the large formation time assumption in the final stages of the calculation and find that, not only is the effect of the small separation distance correction important even in large (~ 5 fm) systems, but also that the correction term dominates over the leading term at high energies.

1. Introduction

Recently, the discovery of a number of key signatures of the quark-gluon plasma (QGP) (collective behaviour [1], strangeness enhancement [2,3], and quarkonium suppression [4]) at the Relativisitc Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) have raised alarming questions regarding the presence of a QGP in small colliding systems like pp and p/dA. Jet quenching provides a means of probing the dynamics of the degrees of freedom of the QGP and is therefore also a key observable [5, 6], with early experimental analysis showing signs of centrality dependent jets in p/dA collisions at RHIC and LHC [7, 8].

Perturbative Quantum Chromodynamics (pQCD) has provided a basis for a number of energy loss models [9–12] that have been extremely successful, qualitatively describing the momentum dependence and angular distribution of the suppression of high-momentum, $\sim 5-150$ GeV single particle pions [13, 14] and charged hadrons [15–17] from primordial hard light flavors and gluons and electrons [18–20] as well as D [21] and non-prompt J/ψ mesons [22] from open heavy flavor decays at mid rapidity in A+A systems from $\sqrt{s} = 0.2$ ATeV to 2.76 ATeV. The QGP signatures seen in p/dA collisions then call for quantitative theoretical predictions for jet tomography in small colliding systems.

However, the usual DGLV opacity expansion [23, 24] derivation of the energy loss assumes a large separation distance $\Delta z \equiv z_1 - z_0 \gg \lambda_{mfp} \gg 1/\mu$ between the initial production position z_0 of the hard parent parton and the position z_1 where it scatters off a QGP medium quasiparticle.

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The mean free path of the high-p_T particle is $\lambda_{mfp} = 1/\rho\sigma \sim 1-2$ fm while the Debye mass in an infinite, static thermal QGP of temperature $T \sim 350$ MeV is $\mu = gT \sim 0.5$ GeV, as derived from thermal field theory [25]. In pp and p/dA collisions, one expects a system of radius $\lesssim 2$ fm, suggesting that a high-p_T parton that does scatter cannot have a large separation distance between production and scattering.

In order to apply DGLV energy loss to small systems, we derive the $N = 1$ opacity generalization for all separation distances. The correction has two curious properties. The first is that the vast majority of correction terms are suppressed under the usual assumptions of eikonality, collinearity, and large gluon formation time common to all pQCD-based energy loss formalisms [26], resulting in only two diagrams with non-zero correction terms. The second is that those correction terms that do remain dominate the large separation distance DGLV expression at high (~ 100 GeV) parton energies. We will show that this second surprise is due to the breakdown of the large formation time approximation in the DGLV formalism. While the sensitivity of all energy loss formalisms to the collinear approximation has already been shown [26, 27], the present sensitivity to the large formation time approximation is both new and different from the collinear sensitivity.

2. Setup

We follow the DGLV calculation [24], treating the high-p_T eikonal parton produced at an initial point $(t_0, z_0, \mathbf{x}_0)$ inside a finite QGP, where we have used $\mathbf{p}$ to mean transverse 2D vectors, $\vec{\mathbf{p}} = (p_z, \mathbf{p})$ for 3D vectors and $p = (p^0, \vec{\mathbf{p}}) = [p^0 + p^z, p^0 - p^z, \mathbf{p}]$ for four vectors in Minkowski and light cone coordinates respectively. As in the DGLV calculation, we consider the target to be a Gyulassy-Wang Debye screened potential [28] with Fourier and color structure given by

$$\begin{aligned} V_n &= V(\vec{\mathbf{q}}_n) e^{-i\vec{q}_n \cdot \vec{x}_n} \\ &= 2\pi\delta(q^0) v(\mathbf{q}_n, q_n^z) e^{-i\vec{q}_n \cdot \vec{x}_n} T_{a_n}(R) \otimes T_{a_n}(n). \end{aligned} \tag{1}$$

The color exchanges are handled using the applicable $SU(N_c)$ generator $T_a(n)$ in the d_n dimensional representation of the target or $T_a(R)$ in the d_R dimensional representation of the high-p_T parent parton.

In light cone coordinates the momenta (defined in **??**) of the emitted gluon, the final high-p_T parton, and the exchanged medium Debye quasiparticle are

$$k = \left[xP^+, \frac{m_g^2 + \mathbf{k}^2}{xP^+}, \mathbf{k}\right], p = \left[(1-x)P^+, \frac{M^2 + \mathbf{k}^2}{(1-x)P^+}, -\mathbf{k}\right], q = [q^+, q^-, \mathbf{q}], \tag{2}$$

where the initially produced high-p_T particle of mass M has large momentum $E^+ = P^+ = 2E$ and negligible other momentum components. Notice that we include the Ter-Mikayelian plasmon effect with an effective emitted gluon mass m_g [24, 25].

A shorthand for energy ratios will prove useful notationally. Following [24], we define $\omega \approx xE^+/2 = xP^+/2$, $\omega_0 \equiv \mathbf{k}^2/2\omega$, $\omega_i \equiv (\mathbf{k} - \mathbf{q}_i)^2/2\omega$, $\omega_{(ij)} \equiv (\mathbf{k} - \mathbf{q}_i - \mathbf{q}_j)^2/2\omega$, and $\tilde{\omega}_m \equiv \left(m_g^2 + M^2x^2\right)/2\omega$.

Additionally, a number of crucial assumptions are made in line with [24]: 1) the eikonal, or high energy, approximation, for which E^+ is the largest energy scale of the problem; 2) the soft (radiation) approximation $x \ll 1$; 3) collinearity, $k^+ \gg k^-$; 4) that the impact parameter varies over a large transverse area; and, most crucially for the present work, 5) the large formation time assumption $\omega_i \ll \mu_i$, where $\mu_i^2 \equiv \mu^2 + \mathbf{q}_i^2$. These assumptions allow us to 1) (eikonal) ignore the spin of the high-p_T parton; 2) (soft) assume the source current for the parent parton varies slowly with momentum $J(p - q + k) \approx J(p + k) \approx J(p)$; 3) (collinearity) complete a separation of energy scales

$$E^+ \gg k^+ \gg k^- \equiv \omega_0 \sim \omega_{(i\ldots j)} \gg \frac{(\mathbf{p} + \mathbf{k})^2}{P^+}; \tag{3}$$

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and 4) take the ensemble average over the phase factors, which become $\langle e^{-i(\mathbf{q}-\mathbf{q}')\cdot\mathbf{b}}\rangle = \frac{(2\pi)^2}{A_\perp}\delta^2(\mathbf{q}-\mathbf{q}')$.

Within the above setup, we re-evaluated the 10 N=1 in opacity diagrams without the large separation distance $\Delta z \gg 1/\mu$ assumption.

3. Calculation and Results

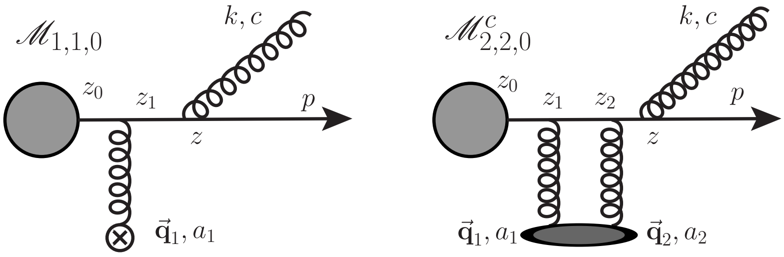

Figure 1: $\mathscr{M}_{1,1,0}$ (top panel) and $\mathscr{M}^c_{2,2,0}$ (lower panel) are the only two diagrams that have non-zero short separation distance corrections in the large formation time limit. $\mathscr{M}^c_{2,2,0}$ is the double Born contact diagram, corresponding to the second term in the Dyson series in which two gluons are exchanged with the single scattering center.

In the original evaluation of the 10 diagrams contributing to the $N = 1$ in opacity energy loss derivation, the large separation distance approximation $\Delta z \gg 1/\mu$ allowed the neglect of terms proportional to $\exp(-\mu\Delta z)$. In our reevaluation of these 10 diagrams, we retained all terms proportional to $\exp(-\mu\Delta z)$. However, we found an enormous simplification due to the large radiated gluon formation time approximation $\omega_i \ll \mu_i$: all but 2 of the 10 diagrams' 18 new small distance correction pole contributions are suppressed under the large formation time assumption. We show the two diagrams with non-zero contributions at the amplitude level $\mathscr{M}_{1,1,0}$ and $\mathscr{M}^c_{2,2,0}$ in the large formation time approximation in 1.

The full result for these two amplitudes under our approximation scheme is then

$$\begin{aligned}\mathscr{M}_{1,1,0} &\approx -J(p)e^{ipx_0}2gT_{a_1}ca_1\int\frac{d^2\mathbf{q}_1}{(2\pi)^2}v(0,\mathbf{q}_1)e^{-i\mathbf{q}_1\cdot\mathbf{b}_1}\\ &\times\frac{\mathbf{k}\cdot\boldsymbol{\epsilon}}{\mathbf{k}^2+m_g^2+x^2M^2}\left[e^{i(\omega_0+\tilde{\omega}_m)(z_1-z_0)}-\frac{1}{2}e^{-\mu_1(z_1-z_0)}\right]\end{aligned} \tag{4}$$

$$\begin{aligned}\mathscr{M}^c_{2,2,0} &\approx J(p)e^{i(p+k)x_0}\int\frac{d^2\mathbf{q}_1}{(2\pi)^2}\int\frac{d^2\mathbf{q}_2}{(2\pi)^2}e^{-i(\mathbf{q}_1+\mathbf{q}_2)\cdot\mathbf{b}_1}\\ &\times igT_{a_2}T_{a_1}ca_2a_1v(0,\mathbf{q}_1)v(0,\mathbf{q}_1)\frac{\mathbf{k}\cdot\boldsymbol{\epsilon}}{\mathbf{k}^2+m_g^2+x^2M^2}\\ &\times\left[e^{i(\omega_0+\tilde{\omega}_m)(z_1-z_0)}+e^{-\mu_1(z_1-z_0)}\left(1-\frac{\mu_1e^{-\mu_2(z_1-z_0)}}{2(\mu_1+\mu_2)}\right)\right].\end{aligned} \tag{5}$$

It should be noted that the large formation time assumption allows one to neglect terms in both the original DGLV and the current short separation distance correction. The double differential single inclusive gluon emission distribution is given by [24]

$$d^3N_g^{(1)}d^3N_J = \frac{d^3\vec{\mathbf{p}}}{(2\pi)^3 2p^0}\frac{d^3\vec{\mathbf{k}}}{(2\pi)^3 2\omega}\left(\frac{1}{d_T}\operatorname{Tr}\langle|\mathscr{M}_1|^2\rangle+\frac{2}{d_T}\Re\operatorname{Tr}\langle\mathscr{M}_0^*\mathscr{M}_2\rangle\right), \tag{6}$$

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from which the energy loss, given by the energy-weighted integral over the gluon emission distribution $\Delta E = E\int dx\, x dN_g/dx$, can be calculated from the amplitudes.

Our main analytic result is then the $N = 1$ first order in opacity small distance generalization of the DGLV induced energy loss of a high-p_T parton in a QGP:

$$\Delta E^{(1)}_{ind} = \frac{C_R\alpha_s LE}{\pi\lambda_g}\int dx \int \frac{d^2\mathbf{q}_1}{\pi}\frac{\mu^2}{(\mu^2+\mathbf{q}_1^2)^2}\int\frac{d^2\mathbf{k}}{\pi}\int d\Delta z\bar{\rho}(\Delta z)\Bigg[-\frac{2\big(1-\cos\{(\omega_1+\tilde{\omega}_m)\Delta z\}\big)}{(\mathbf{k}-\mathbf{q}_1)^2+m_g^2+x^2M^2}$$
$$\times\left(\frac{(\mathbf{k}-\mathbf{q}_1)\cdot\mathbf{k}}{\mathbf{k}^2+m_g^2+x^2M^2}-\frac{(\mathbf{k}-\mathbf{q}_1)^2}{(\mathbf{k}-\mathbf{q}_1)^2+m_g^2+x^2M^2}\right)$$
$$+\frac{1}{2}e^{-\mu_1\Delta z}\Bigg\{\left(\frac{\mathbf{k}}{\mathbf{k}^2+m_g^2+x^2M^2}\right)^2\left(1-\frac{2C_R}{C_A}\right)\Big(1-\cos\{(\omega_0-\tilde{\omega}_m)\Delta z\}\Big)$$
$$+\frac{\mathbf{k}\cdot(\mathbf{k}-\mathbf{q}_1)}{\big(\mathbf{k}^2+m_g^2+x^2M^2\big)\big((\mathbf{k}-\mathbf{q}_1)^2+m_g^2+x^2M^2\big)}\big(\cos\{(\omega_0-\tilde{\omega}_m)\Delta z\}-\cos\{(\omega_0-\omega_1)\Delta z\}\big)\Bigg\}\Bigg]. \quad (7)$$

The last four lines of 7 show the short separation distance correction term - this correction has precisely the properties one might expect: 1) for large separation distances the correction term goes to zero and 2) for vanishing separation distances the correction term also goes to zero, due to the destructive interference of the LPM effect. However, the correction also has a number of puzzling features: First is the breaking of color triviality to all orders in opacity which comes from the term proportional to $2C_R/C_A$. The second curiosity, only apparent through a numerical investigation, is that the correction term in fact dominates the original DGLV calculation at high energies.

To see this, a numerical investigation of equation (7) was performed in line with that in [24], resulting in figures 2a, 2b and 2c. The numerical analysis used the following values: $\mu = 0.5$ GeV, $\lambda_{mfp} = 1$ fm, $C_R = 4/3$, $C_A = 3$, $\alpha_s = 0.3$, $m_{charm} \equiv m_c = 1.3$ GeV and $m_{bottom} \equiv m_b = 4.75$ GeV, and the QCD analogue of the Ter-Mikayelian plasmon effect was taken into account by setting $m_{gluon} \equiv m_g = \mu/\sqrt{2}$. As in [25], kinematic upper limits were used for the momentum integrals such that $0 \leq k \leq 2x(1-x)E$ and $0 \leq q \leq \sqrt{3E\mu}$, due to finite kinematics. This choice of k_{max} guarantees that the final momentum of the parent parton is collinear to the initial momentum of the parent parton and that the momentum of the emitted gluon is collinear to the momentum of the parent parton. The fraction of momentum carried away by the radiated gluon, x was integrated over from 0 to 1. The distribution of scattering centers was assumed to be exponential in order to account for the rapidly expanding medium, $\bar{\rho}(z) = 2\exp(-2\Delta z/L)/L$.

In Fig. 2a we show the fractional energy loss of charm and bottom quarks of varying energy propagating through a 4 fm long static QGP brick. Notice first that the small distance correction term is generally an energy *gain* due to the sign of the color triviality breaking term and, second, that the size of the correction relative to the long distance DGLV result grows with energy.

In Fig. 2b we plot the fractional energy loss of charm and bottom quarks of energy $E = 10$ GeV for path lengths up to 5 fm. One sees that the small separation distance correction has a non-negligible effect even for large path lengths. Although initially unanticipated, the non-zero effect is due to the integration over all separation distances between the production point and the scattering position; even for large path lengths, some of the interaction distances between the parent parton and the target occur at separation distances that are small compared to the Debye screening scale. Additionally, the relative size of the small distance correction term and the leading DGLV result diminishes at fixed energy as the path length grows.

The main revelation of our numerical analysis is shown in Fig. 2c, which presents the fractional energy loss of 100 GeV charm and bottom quarks propagating up to 5 fm through a QGP. The

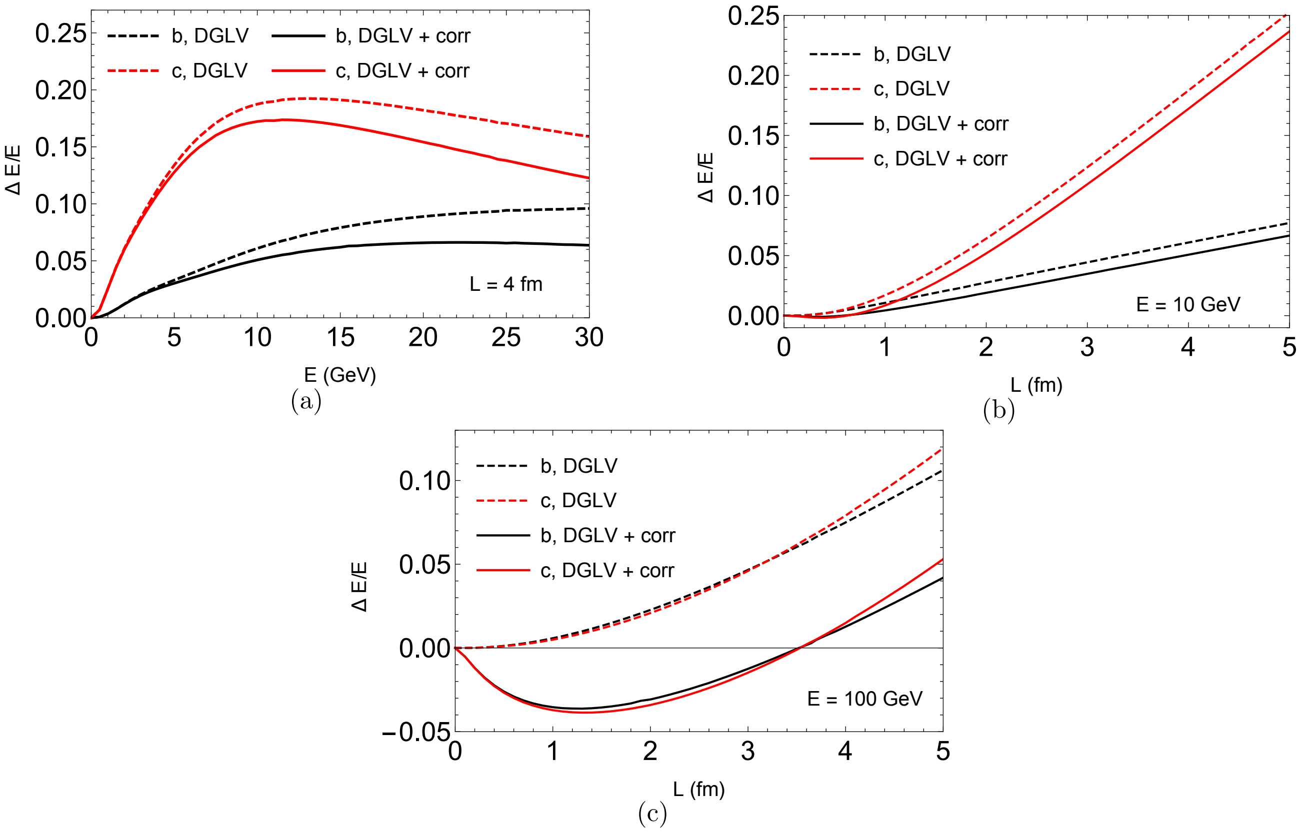

Figure 2: Fractional energy loss of charm and bottom quarks in a QGP with $\mu = 0.5$ GeV and $\lambda_{mfp} = 1$ fm for (a) fixed path length $L = 4$ fm, (b) fixed energy $E = 10$ GeV, and (c) fixed energy $E = 100$ GeV. In the figures, "DGLV" dashed curves are computed from the original $N = 1$ in opacity large separation distance DGLV formula while "DGLV + corr" solid lines are from our all separation distance generalization of the $N = 1$ DGLV result, (**??**).

small distance "correction" term dominates over the leading DGLV result for the first ~ 3 fm of the path.

4. Conclusions

The significant *energy gain* out to large ~ 3 fm paths seems difficult to reconcile with the measured experimental suppression of charged particles in central AA collisions at LHC [15–17]. Furthermore, the dominance of the short separation distance "correction" term at high energies, along with the universal dependence of all pQCD-based energy loss formalisms on the large formation time assumption, calls for a more detailed analysis of the validity of the large formation time assumption in pQCD-based energy loss.

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