Testing the mechanism of QGP-induced energy loss

Ivan Vitev

Los Alamos National Laboratory, Theoretical Division and Physics Division, Los Alamos, NM 87545, USA

Received 18 November, 2005

Abstract. We present an analytic model of jet quenching, based on the (D)GLV energy loss formalism, to describe the system size dependence of QGP-induced parton absorption in relativistic heavy ion collisions. Numerical simulations of the transverse momentum dependence of jet quenching are given for central Au+Au and Cu+Cu reactions. Low \( p_T \) dijet correlations are shown to be sensitive to the reappearance of the lost energy as soft hadrons. At high \( p_T \) we find that the attenuation of dihadrons is similar to that of single inclusive particles. Comparison to recent data from PHENIX and STAR is given as a test of the jet quenching theory.

Keywords: energy loss, jet quenching, A+A, dijet correlations
PACS: 12.38.Mh; 24.85.+p; 25.75.Nq

1. Introduction

In this contribution key results from the many-body QCD dynamics of partons in dense nuclear matter are summarized. The emphasis is on the systematic understanding of the signatures of final state radiative energy loss effects [1, 2] in the quark-gluon plasma (QGP). Theoretical predictions are confronted by the recent RHIC data.

Tomographic determination of the properties of the medium created in nucleus-nucleus collisions can only be achieved through detailed numerical simulations [1, 2, 3, 4, 5]. It is, however, useful to elucidate such studies with a simplified analytic model, which incorporates the essential features of jet quenching calculations [1]. We consider inclusive particle production, where the fragmentation functions \( D_{h/c}(z) \) are convoluted with the power law partonic cross sections as follows

\[
\frac{d\sigma^h}{dyd^2p_T} = \sum_c \int_{\tau_{\text{min}}}^1 dz \frac{d\sigma^c(p_c = p_T/z)}{dyd^2p_{Tc}} \frac{1}{z^2} D_{h/c}(z) \approx \sum_c \frac{A}{p_{Tc}^{n-2}} (z^{(n-2)} D_{h/c}(z)).
\]
In Eq. (1) \( z_{\text{min}} = p_T/p_{T,\text{max}} \) and \( n \) is the partonic cross section power law index. The second input to the analytic model comes from the Gyulassy-Levai-Vitev energy loss formalism [6], extended by Djordjevic et al. to the case of heavy quarks [7]. For the fractional energy loss \( \epsilon = \Delta E/E \) in \((1+1)\)D Bjorken expansion we find in the limit of large parton energy \( 2E/\mu^2 \gg 1 \),

\[
\frac{\Delta E}{E} \approx \frac{9C_R \pi \alpha_s^3}{4} \frac{1}{A_{\perp}} \frac{dN^g}{dy} L \frac{1}{E} \ln \frac{2E}{\mu^2 L} + \cdots .
\]

The key to understanding the dependence of jet quenching on the nuclear species is the \( A \) or \( N_{\text{part}} \) dependence of the characteristic parameters in Eq. (2). We recall that \( dN^g/dy \propto dN^h/dy \propto A \propto N_{\text{part}}, \quad L \propto A^{1/3} \propto N^{1/3}_{\text{part}}, \quad A_{\perp} \propto A^{2/3} \propto N^{2/3}_{\text{part}} \). Therefore, the fractional energy loss, which is boost and gauge invariant when it enters physical observables, scales as \( \epsilon = \Delta E/E \propto A^{2/3} \propto N^{2/3}_{\text{part}} \).

From Eqs. (1) and (2) we can easily derive the system size dependence of the nuclear modification factor

\[
R_{AB} = \frac{1}{N_{AB \text{ col}}} \frac{d\sigma^h_{AB}/dyd^2p_T}{d\sigma^h/adyd^2p_T} = (1 - \epsilon_{\text{eff}})^{n-2}, \quad \ln R_{AA} = -\kappa N^{2/3}_{\text{part}},
\]

where \( \kappa \approx (n - 2)\epsilon_{\text{eff}}/N^{2/3}_{\text{part}} \). The left panel of Fig. 1 shows the predicted \( N_{\text{part}} \) dependence of jet quenching at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). Central collisions for systems ranging from Be+Be to U+U are also shown. The right panel of Fig. 1 confronts the theoretical model [1] with preliminary STAR [8] and PHENIX [9] measurements in Au+Au and Cu+Cu collisions. Within the systematic uncertainty, given by the difference in the measured \( R_{AA} \) by the two experiments, there is a good description of the centrality dependence of jet quenching.
Fig. 2. Left panel: predicted quenching for single inclusive $\pi^0$ ($\pi^+ + \pi^-$) production in central Au+Au and central Cu+Cu collisions to high $p_T = 20$ GeV [1, 2]. Data is from PHENIX [11]. Right panel: comparison of the preliminary 0-10% central Au+Au and Cu+Cu data from PHENIX [9] to the energy loss calculations with $dN^g/dy = 1150, 370$, respectively [1].

2. Numerical results for the quenching of jets and dijets

Numerical evaluation of the nuclear modification factor $R_{AA}(p_T)$ in ultrarelativistic heavy ion collisions is carried out as in [2, 5]. The perturbative QCD hadron production cross sections are modified by several, often competing, effects. Initial state multiple scattering leads to transverse momentum broadening of the incoming quarks and gluons and Cronin-like enhancement at intermediate transverse momenta. While nuclear shadowing is incorporated, its effects were found to be small, $|S(x, Q^2) - 1| < 0.2$. In fact, dynamical nuclear enhanced power corrections $\sim \xi^2 A^{1/3}/Q^2$ may play a dominant role in the modification of the DIS structure functions [10]. Their effect is negligible for $p_T > 5$ GeV hadron production [10].

When energy is lost in a deconfined medium of high color charge density $\rho \sim dN^g/dy/(\tau A_{\perp})$ prior to fragmentation, two contributions arise from the medium-induced splitting of the hard parton. With a suitable change of variables we find [13]

$$D_{h/c}(z) \Rightarrow \int_0^{1-z} d\epsilon P(\epsilon) \frac{1}{1-\epsilon} D_{h/c} \left( \frac{z}{1-\epsilon} \right) + \int_z^1 d\epsilon \frac{dN^g}{d\epsilon}(\epsilon) \frac{1}{\epsilon} D_{h/g} \left( \frac{z}{\epsilon} \right).$$ (4)

Here, $z = \frac{p_T}{p_T} / p_T$ is the unmodified momentum fraction in the vacuum and $P(\epsilon)$ is the probability for fractional energy loss $\epsilon$ due to multiple gluon emission [2, 4]. It is easy to verify the momentum sum rule for the hadronic fragments of the attenuated jet and the radiative gluons

$$\sum_h \int_0^1 dz z D_{h/c}(z) = 1 - \langle \epsilon \rangle + \langle \epsilon \rangle = 1.$$ (5)

For the single inclusive particle production at high $p_T$ the first term in Eq. (4) dominates. The left panel of Fig. 2 shows the predicted transverse momentum
dependence of $R_{AA}(p_T)$ for central Au+Au and Cu+Cu collisions at the top RHIC energy. The sensitivity of the calculation to the variation in the effective gluon rapidity density $dN_g/dy$ is illustrated. The quenching of jets is approximately $p_T$ independent in the range $5 \text{ GeV} < p_T < 20 \text{ GeV}$. Data in central Au+Au collisions is from PHENIX [11]. The left panel of Fig. 2 shows the comparison of the (D)GLV theory to the recent PHENIX data in both central Au+Au and central Cu+Cu collisions to much higher $p_T \sim 20 \text{ GeV}$ [9].

Qualitatively new information about the mechanisms of jet modification in the QGP can be extracted from two-particle, or dijet, correlations. In the medium-induced energy loss scenario, the second term in Eq. (4) leads to enhancement in the multiplicity of the away-side hadrons associated with a high $p_T$ trigger [13]. With $dN^g/d\epsilon$ calculated in the (D)GLV approach [6, 7], the redistribution of the energy is a parameter free prediction [13]. The dependence of the dihadron modification on the trigger and associated particle momenta, $p_{T1}$ and $p_{T2}$, and collision centrality are shown in the left panels of Fig. 3. Data is from STAR [12]. Another aspect that high $p_T$ dijet correlations can clarify is how opaque is the QGP. The right panel of Fig. 3 compares the quenching of single inclusives to the quenching of dihadrons, $R_{AA}^{h_{1}}/R_{AA}^{h_{1}h_{2}}$. Even without energy loss fluctuations and gluon feedback this ratio is $\sim 1.5$. For $\sqrt{s_{NN}} = 62 \text{ GeV}$, $R_{AA}^{h_{1}}/R_{AA}^{h_{1}h_{2}} \sim 1.2 - 1.35$. Theoretical calculations are, thus, consistent with the preliminary STAR data [14] that improve upon earlier dijet measurements by being able to recover high $p_T$ dijets. Note that for the data point in Fig. 3 $z_{\text{trig}} = p_{T \text{ assoc}}/p_{T \text{ trig}}$. Similar results were found by PHENIX [14].
3. Conclusions

In this contribution we presented results from a theoretical study of the centrality and transverse momentum dependence of jet quenching \[1\]. At high $p_T$ and fixed $\sqrt{s_{NN}}$, in the absence of large additional partonic effects, we find a universal dependence of $R_{AA}$ on $N_{\text{part}}$ [1]. The QGP-induced suppression at RHIC, independent of the system size, is approximately constant versus $p_T$ \[1, 2\]. Such transverse momentum behavior follows from the jet energy dependence of the (D)GLV energy loss \[6, 7\] and its implementation in the factorized perturbative QCD hadron production formalism \[1, 2, 13\]. Dihadron correlations are examined, within the same jet quenching approach, at both low $p_T$ and high $p_T$. The redistribution of the lost energy in low $p_T$ particles is a verified, parameter free, prediction of the model \[13\]. At high transverse momenta, dijet suppression is shown to be only slightly larger than the quenching of single inclusive particles \[5\]. The agreement with the recent STAR data [8] indicates that the QGP, created in Au+Au collisions at RHIC, is not fully opaque.

Acknowledgments

This research is supported in part by the US Department of Energy under Contract No. W-7405-ENG-3 and by the J. Robert Oppenheimer Fellowship of the Los Alamos National Laboratory.

References

1. I. Vitev, Phys. Lett. B 639, 38 (2006).
2. I. Vitev and M. Gyulassy, Phys. Rev. Lett. 89, 252301 (2002).
3. X. N. Wang, nucl-th/0511001 references therein.
4. A. Adil and M. Gyulassy, Phys. Lett. B 602, 52 (2004).
5. I. Vitev, Phys. Lett. B 606, 303 (2005).
6. M. Gyulassy, P. Levai and I. Vitev, Nucl. Phys. B 571, 197 (2000); Phys. Rev. Lett. 85, 5535 (2000); Nucl. Phys. B 594, 371 (2001).
7. M. Djordjevic and M. Gyulassy, Nucl. Phys. A 733, 265 (2004).
8. J. C. Dunlop, nucl-ex/0510073; P. M. Jacobs and M. van Leeuwen, nucl-ex/0511013.
9. M. Shimomura, nucl-ex/0510023; T. Isebe, nucl-ex/0510085.
10. J. W. Qiu and I. Vitev, Phys. Rev. Lett. 93, 262301 (2004); Phys. Lett. B in press, hep-ph/0405068.
11. S. S. Adler et al., Phys. Rev. Lett. 91, 072301 (2003); D. d’Enterria, nucl-ex/0510062.
12. C. Adler et al., Phys. Rev. Lett. 90, 082302 (2003); J. Adams et al., Phys. Rev. Lett. 95, 152301 (2005).
13. I. Vitev, Phys. Lett. B 630, 78 (2005).
14. D. Magistro, nucl-ex/0510002; J. Y. Jia, nucl-ex/0510019.