Realistic medium-averaging in radiative energy loss

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Abstract

We present results from a jet energy loss calculation using the Gyulassy-Levai-Vitev (GLV) formalism and bulk medium evolution from the covariant transport MPC. At both RHIC and LHC energies we find that realistic transverse expansion strongly reduces elliptic flow at high $p_T$ compared to calculations with transversely “frozen” profiles. We argue that this is a generic feature of GLV energy loss. Transverse expansion also leads to stronger high-$p_T$ suppression, while fluctuations in energy loss with the location of scattering centers weaken the suppression. But, unlike the reduction of $v_2$, these effects nearly disappear once $\alpha_s$ is adjusted to reproduce $R_{AA}$ in central collisions.

Keywords: Relativistic heavy-ion collisions, parton energy loss, momentum anisotropy, elliptic flow

1. Introduction

Understanding parton energy loss in ultrarelativistic heavy-ion reactions has been the focus of considerable recent theoretical effort. A variety of phenomenological approaches (e.g., [1, 2, 3]) formulate the problem in terms of a local energy loss rate $dE/dL = -f(E(L), T(L), L)$ along the Eikonal parton trajectory, given by the local temperature, position, and parton energy. In the small-coupling regime, more rigorous treatment is possible based on perturbative QCD[4, 5, 6]. This includes quantum interference effects and also fluctuations, namely, energy loss along a given jet trajectory becomes a stochastic variable that is in general a function of the scattering and emission history of the jet.

A critical step in computing heavy-ion observables from any energy loss model is spatial and temporal averaging over the bulk medium formed in the collision. We employ here the Gyulassy-Levai-Vitev (GLV) framework[6] in which a high-energy parton loses energy through gluon radiation induced by interactions with static Yukawa scatterers in the medium. It is natural to combine this approach with parton transport for the bulk evolution, such as Molnar’s Parton Cascade[7] (MPC), because it directly provides scattering center information.

Our approach is similar to recent work by Buzzatti and Gyulassy[8], but with a few key differences. Unlike [8], at present we only focus on light partons, and do not include multiple gluon radiation, elastic energy loss, or energy loss fluctuations due to variations in radiated gluon momentum. However, we do include realistic 3D medium evolution with both longitudinal and transverse expansion, which turns out to influence energy loss and, especially, elliptic flow.

2. Radiative energy loss and medium averaging

We consider here the leading $n = 1$ (single scattering) term in the GLV opacity expansion of the radiated gluon spectrum[6]

$$\frac{dN^{(1)}}{dx d^2k} = \frac{C_R \alpha_s}{\pi^2} \chi \int d^2q \frac{\mu^2(z)}{\pi(q^2 + \mu^2(z))^2} \frac{kq}{k^2(k-q)^2} \left[ 1 - \cos \left( \frac{(k-q)^2 z}{2xE} \right) \right]$$

(1)
where the original hard scattering is at $z = 0$, $\mu(z)$ is the local Debye screening mass, $\sigma = 9\pi\alpha_s^2/(2\mu^2)$ is the (screened) total $gg \rightarrow gg$ scattering cross section, and $\chi = \int dz p(z)$ is the opacity. We integrated this spectrum numerically with kinematic bounds $k < xE$, $q < \sqrt{6ET}$, and $xE \geq \mu$ to obtain a momentum-averaged energy loss $\Delta E^{(1)}(z) = \int dx d^2k E_x (dN^{(1)}/dx d^2k)$ for fixed $z$, i.e., retained energy loss fluctuations due to variations in $z$ only. The probability for the scattering to occur at $z$ is $p(z) = \rho(z)\sigma(z)/\chi$, so the fully averaged energy loss is $\Delta E^{(1)} = \int dz p(z) \Delta E^{(1)}(z)$.

As customary, in non-static media we reinterpret $\rho(z)$ in the GLV formula as $\rho(z, t = t_0 + z)$ along the parton trajectory. The density evolution was obtained from the parton transport MPC, employing $2 \rightarrow 2$ interactions for massless gluons. The scattering rate was adjusted to generate substantial $v_2(p_T \approx 3 \text{ GeV}) \sim 0.25$ in collisions with $b = 8$ fm impact parameter, and we set growing $\sigma_{gg \rightarrow gg} \propto t^{2/3}$ to keep the shear viscosity to entropy ratio approximately constant\cite{9}. Initial conditions for Au+Au at $\sqrt{s_{NN}} = 200 $ GeV and Pb+Pb at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ were based on diffuse Woods-Saxon nuclei. For the transverse density, binary collision profiles were used, while the impact parameter dependence of rapidity densities $dN(b)/dy$ was proportional to $N_{part}$ with $dN(0)/dy = 1100$ (Au+Au) and 2400 (Pb+Pb) to match the observed charged particle yields. Because we are only interested in observables at midrapidity, we set up boost invariant conditions in the coordinate rapidity window $|\eta| < 5$, with formation time $\tau_0 = 0.6$ fm.
Using tabulated densities from the transport, we set the local temperature assuming a massless gas of gluons \( \rho = 2T^4 \) and the Debye mass via \( \mu = gT = 2T \). At early times \( \tau < \tau_0 \) we assume linear density build-up\([8]\) \( \rho = \tau\rho(\tau_0, \tau_0)/\tau_0 \). We roughly account for additional energy loss off dynamical (recoiling) scattering centers\([10]\) \( [(q^2 + \mu^2)^2 \rightarrow q^2(q^2 + \mu^2)] \) in \([1]\) and elastic scattering\([11]\) via rescaling our opacities \( \chi \rightarrow \chi/Z \) with \( Z = 0.35 \). Initial jet momentum distributions in \( p+\bar{p}, \) Au+Au and Pb+Pb were computed from leading-order (LO) perturbative QCD with one-loop running coupling \( \alpha_s(Q^2) \), using CTEQ5L parton distribution function parameterizations with \( Q^2 = p^2_{T,\text{parton}} \).

Nuclear effects such as shadowing were ignored but isospin (proton-neutron differences) was included. After energy loss, jets were fragmented independently using LO BKK95 fragmentation function parameterizations with scale factor \( Q^2 = p^2_{T,\text{hadron}} \) and we assumed \( n_0 = (\pi^+ + \pi^-)/2 \) for the neutral pion yield. This procedure reproduces high-\( p_T \) \( n_0 \) and charged particle spectra in \( p+\bar{p} \) at RHIC and LHC with modest \( K_{NLO} \approx 2.5 \) to account for higher-order contributions.

Below we focus on two basic high-\( p_T \) observables for neutral pions at midrapidity, the nuclear suppression factor \( R_{AA} \) and the momentum anisotropy (elliptic flow) \( v_2 \approx \langle \cos 2\phi \rangle_{p_T} \). Only energy loss was considered, i.e., contributions by the radiated gluons to the final spectrum and feedback on the bulk medium due to the jet were ignored.

3. Main results

We considered four scenarios based on i) whether the medium is only undergoing Bjorken expansion (“1D” as in \([8]\)) or transverse expansion as well (“3D”); and ii) whether average energy loss is used or the stochastic \( \Delta E(z) \). Figure\([1]\) shows our results for \( R_{AA} \) at RHIC, for the same \( \alpha_s = 0.29 \). In the stochastic case energy loss effects are noticeably weaker, which is natural for convex parton spectra (“curving up” at high \( p_T \)). We also find that realistic transverse expansion significantly enhances jet quenching, which is a generic GLV feature coming from the interference term in \([1]\). Scatterings at large \( z \) induce larger energy loss, and with a transversely expanding density profile there is higher chance to scatter further away from the production point than in the transversely static case.

Unfortunately, without precise control over \( \alpha_s, R_{AA} \) alone cannot differentiate between these four scenarios. As shown in Fig.\([2]\) after a slight tuning of \( \alpha_s \) to reproduce the suppression in central collisions, differences in \( R_{AA} \) largely disappear. On the other hand, striking difference in \( v_2 \) remains between 1D and 3D evolution at both RHIC and LHC energies, as shown in Figs.\([3]\) and\([4]\). The strong 40–50% reduction of \( v_2 \) at high-\( p_T \) with realistic transverse evolution is another generic consequence of interference in GLV. Scattering points that lead to most energy loss are biased to occur away from the production point and so later in time, by when the expansion makes the system more cylindrical, reducing the spatial azimuthal asymmetry that drives elliptic flow. We expect that this strong effect will be manifest in more full-fledged GLV calculations as well, such as \([8]\).
At the conference we also presented results based on scattering center ensembles from the transport (not just density information) but due to page limitations these will be written up elsewhere.

4. Conclusions

We investigated GLV energy loss using bulk medium evolution data from the covariant transport MPC. We find that realistic transverse expansion strongly suppresses elliptic flow at high $p_T$ compared to calculations with transversely “frozen” profiles (as in [8]). We argue that this is a generic feature of GLV energy loss, raising the question whether GLV produces too little elliptic flow at high $p_T$.

Transverse expansion also enhances the high-$p_T$ suppression, while fluctuations in energy loss with the location of scattering centers reduce energy loss effects. However, unlike for $v_2$, these effects nearly disappear once calculations are adjusted to reproduce $R_{AA}$ in central collisions.

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