Interplay between bulk medium evolution and (D)GLV energy loss

Denes Molnar and Deke Sun

Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, U.S.A.

Abstract

We study the consistency between high-\(p_T\) nuclear suppression (\(R_{AA}\)) and elliptic flow (\(v_2\)) using Gyulassy-Levai-Vitev (GLV) energy loss or a simpler power-law \(dE/dL\) formula, for a variety of bulk evolution models. The results generally confirm our earlier work [1] that found suppressed elliptic flow for transversely expanding media. One exception is the set of hydrodynamic solutions used recently[2] by Betz and Gyulassy, which give significantly higher \(v_2\) but unfortunately assume unrealistic bag-model equation of state. On the other hand, we show that covariant treatment of energy loss introduces an interplay between jet direction and hydrodynamic flow of the medium, which largely counteracts elliptic flow suppression caused by transverse expansion.

Keywords: Heavy-ion collisions, elliptic flow, parton energy loss

1. Introduction

An important crosscheck of parton energy loss calculations is the consistency between nuclear suppression (\(R_{AA}\)) and differential elliptic flow \(v_2(p_T)\). Recently we found[1] that in realistic applications of Gyulassy-Levai-Vitev (GLV) radiative parton energy loss[3] that include transverse expansion of the bulk medium, high-\(p_T\) elliptic flow is reduced by nearly a half compared to transversely frozen evolution scenarios. This reinforced the conclusions[4] by the PHENIX Collaboration that perturbative QCD energy loss models generally fail to reproduce the azimuthal angle dependent neutral pion suppression. However, a recent work by Betz and Gyulassy claims[2] simultaneous reproduction of this set of observables with simple pQCD-motivated energy loss formulas. This apparent contradiction, on the other hand, may be due to important differences between the two calculations, especially in the energy loss model and bulk medium evolution assumed. Here we pinpoint the origin of the discrepancy, and show that the findings of Ref. [2] are largely due to the hydrodynamic solutions used in that calculation for bulk medium evolution. In addition, we show that covariant treatment of energy loss introduces an interplay between jet direction and hydrodynamic flow of the medium, which largely compensates the elliptic flow suppression we found earlier in [1].

2. Radiative energy loss and bulk medium evolution

2.1. Sensitivity to bulk medium model

Consider the parameterized energy loss model \(dE/dL = \kappa E^a L^b T^c\) by Betz and Gyulassy [2], with “pQCD-like” exponents \(a = 1/3, b = 1,\) and \(c = 2 - a + b = 8/3\) (\(\kappa\) is then dimensionless). Here \(E\) is the jet energy, \(T\) is temperature of the medium, and \(L\) is the pathlength traveled by the jet. To study the sensitivity to the bulk medium evolution, we investigate five different dynamical models for \(\text{Au} + \text{Au}\) at \(\sqrt{s_{NN}} = 200\ \text{GeV}\) at RHIC, impact parameter \(b \approx 7.5\ \text{fm}\). Four of these are solutions of boost-invariant 2+1D hydrodynamics using the VISH2+1 code[5], which are available in tabulated form from the TECHQM Collaboration website [6] in two data sets. Set 1 is for a “bag-model” like
2.2. Energy loss model

Next we test how well the power-law \(dE/dL \propto E^{\alpha}L^{\beta}T^{\gamma}\) formula captures perturbative QCD parton energy loss in the Gyulassy-Levai-Vitev (GLV) formulation\cite{GLV}. The approach is identical to the one in Ref. \cite{1}, i.e., we use the average radiative energy loss along the path of a massless jet parton obtained via integrating the first-order (in opacity) calculation with more realistic lattice QCD EoS, constant \(\eta/s \approx 0.08\) and Glauber initial profile from “Set 2” (double short dashes); and iv) covariant parton transport MPC as in Ref. \cite{1} (solid lines). For comparison, results from Ref. \cite{1} using MPC and GLV energy loss are also shown (solid lines with crosses). In all cases energy loss is scaled to set a fixed \(R_{AA} \approx 0.4\) at \(p_T \approx 15 - 20\) GeV. As in Ref. \cite{1}, data\cite{PHENIX} from PHENIX (boxes) are shown to guide the eye.

\[
\langle \Delta E^{(1)} \rangle = \frac{C_{\alpha_s}}{\pi^2} \int_0^\infty dt \rho_0(\vec{r}_0 + \vec{v}T, \tau) \sigma_{gg}(\tau) \int dx \, d^2k \int d^2q \frac{\mu^2(\tau)}{\pi(q^2 + \mu^2)} \frac{2kq}{k^2(q^2)} \left(1 - \cos \frac{(k - q)^2\tau}{2xE}\right),
\]

where \(E\) is the jet parton energy, \(\vec{q}\) is the momentum transfer in scattering with the medium, \(\mu\) is the local Debye screening mass, \(\sigma_{gg} = 9\pi\alpha_s^2/2\mu^2\) is the scattering cross section in the medium for gluons, and the momentum integrals are performed observing finite energy and kinematic bounds (\(|k| \leq xE\), \(|q| \leq \sqrt{6xET}\), \(xE \gtrsim \mu\)).

Figure \ref{fig:2} shows neutral pion \(R_{AA}\) and \(v_2\) for the different bulk medium scenarios with GLV energy loss. Qualitatively the results are very similar to those in Fig. \ref{fig:1} confirming that the “pQCD-like” exponents in Ref. \cite{2} are a reasonable approximation to GLV energy loss. After fixing \(R_{AA} \sim 0.4\) at high \(p_T\) (left plot), a residual sensitivity to the bulk evolution still remains in elliptic flow (right plot). The “ideal-fKLN” evolution used in Ref. \cite{2} gives largest \(v_2\), almost as large as the results with transversely frozen dynamics in Ref. \cite{1} (solid line). Hydrodynamic solutions with lattice QCD EoS, on the other hand, give smaller \(v_2\). There is a modest ~ 15% difference between fKLN and Glauber profiles with viscous hydrodynamics (fKLN is higher), which may help constrain the initial geometry.
2.3. Covariant energy loss

Neither of the above calculations observe proper Lorentz covariance, however, because both $dE/dL \propto E^aL^bT^c$ and GLV energy loss Eq. (1) give frame dependent results. We can formulate a frame-independent prescription if we require energy loss contributions to be computed in the frame where the fluid is locally static along the path (LR frame). For massless partons produced at spacetime point $(0, \vec{v})$, scattering occurs at $L(1, \vec{v})$, which transforms the same way as the four-momentum $E(1, \vec{v})$. Therefore, in the massless case $dE/dL$ is a Lorentz scalar, which means that for the $dE/dL$ model we should have

$$\frac{dE}{dL} = \frac{dE_{LR}}{dL_{LR}} = \kappa E^a_{LR} L^b_{LR} T^c = \kappa (1 - \vec{v}\vec{v}_F) \alpha^{a+b} E^a L^b T^c , \quad (2)$$

while for GLV

$$dL_{LR} \rho_{LR} \sigma = dL \rho_{LR} \sigma \gamma_F (1 - \vec{v}\vec{v}_F) = dL \rho \sigma (1 - \vec{v}\vec{v}_F). \quad (3)$$

Here, $\vec{v}_F$ is the local three-velocity of fluid flow, while $\gamma_F \equiv (1 - \vec{v}_F^2)^{-1/2}$. In both cases, a new factor appears that couples the motion of the jet to that of the fluid. For GLV this is very similar to the term introduced in Ref. [10], however, in contrast to the results there we find that jet-medium flow coupling has significant effect on observables.

Figure 3 shows neutral pion $R_{AA}$ and $v_2$ in Au+Au at RHIC with $b \approx 7.5$ fm, calculated using covariant $dE/dL$ energy loss. Two features are noticeable immediately. First, with covariant energy loss one needs higher scaling...
We study the consistency between high-$p_T$ nuclear suppression ($R_{AA}$) and elliptic flow ($v_2$) using Gyulassy-Levay-Vitev energy loss or a simpler power-law $dE/dL$ formula, for a variety of bulk evolution models. The results generally confirm our earlier work [1] that found suppressed elliptic flow for transversely expanding media. However, one exception is the set of hydrodynamic solutions used recently [2] by Betz and Gyulassy, which give significantly higher $v_2$ enhancement than for the covariant $dE/dL$ model but otherwise it shows the same ordering between the various scenarios.

At the conference we also showed preliminary results for charm and bottom quarks with Djordjevic-Gyulassy-Levai-Vitev (DGLV) energy loss [11]. Due to space constraints these results will be presented elsewhere.

3. Conclusions

Very similar results follow with covariant GLV energy loss, as shown in Figure 4. Elliptic flow is a little bit smaller but unfortunately assume unrealistic bag-model equation of state. On the other hand, we also find that covariant treatment of energy loss introduces an interplay between jet direction and hydrodynamic flow of the medium, which largely cancels out the flow suppression due to transverse expansion found in Ref. [1]. We find the largest $v_2$ for the “ideal-fKLN” profile used in Ref. [2].

At the conference we also showed preliminary results for charm and bottom quarks with Djordjevic-Gyulassy-Levai-Vitev (DGLV) energy loss [11]. Due to space constraints these results will be presented elsewhere.

3. Conclusions

We study the consistency between high-$p_T$ nuclear suppression ($R_{AA}$) and elliptic flow ($v_2$) using Gyulassy-Levay-Vitev energy loss or a simpler power-law $dE/dL$ formula, for a variety of bulk evolution models. The results generally confirm our earlier work [1] that found suppressed elliptic flow for transversely expanding media. However, one exception is the set of hydrodynamic solutions used recently [2] by Betz and Gyulassy, which give significantly higher $v_2$ but unfortunately assume unrealistic bag-model equation of state. On the other hand, we also find that covariant treatment of energy loss introduces an interplay between jet direction and hydrodynamic flow of the medium, which largely compensates for the elliptic flow suppression we found earlier in [1].

Acknowledgements: This work was supported by the US DOE under grant DE-PS02-09ER41665. D.S. was partially supported by the JET Collaboration (DOE grant DE-AC02-05CH11231).

References

[1] D. Molnar and D. Sun, arXiv:1305.1046 [nucl-th]
[2] B. Betz and M. Gyulassy, arXiv:1305.6458 [nucl-th].
[3] M. Gyulassy, P. Levai and I. Vitev, Nucl. Phys. B 594, 371 (2001) [nucl-th/0006010]; A. Buzzatti and M. Gyulassy, Phys. Rev. Lett. 108, 022301 (2012) [arXiv:1106.3061 [hep-ph]].
[4] A. Adare et al. [PHENIX Collaboration], Phys. Rev. C 87, 034911 (2013) [arXiv:1208.2254 [nucl-ex]].
[5] H. Song and U. W. Heinz, Phys. Rev. C 77, 064901 (2008) [arXiv:0712.3715 [nucl-th]].
[6] Tabulated hydrodynamic solutions can be downloaded from the TECHQM Collaboration wiki at https://wiki.bnl.gov/TECHQM
[7] Phys. Rev. C 62, 054907 (2000); D. Molnar, MPC 1.8.11. This transport code is available at http://karman.physics.purdue.edu/OSCAR
[8] A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. 101, 232301 (2008) [arXiv:0801.4020 [nucl-ex]].
[9] A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. 105, 142301 (2010) [arXiv:1006.3740 [nucl-ex]].
[10] R. Baier, A. H. Mueller and D. Schiff, Phys. Lett. B 649, 147 (2007) [nucl-th/0612068].
[11] M. Djordjevic and U. Heinz, Phys. Rev. C 77, 024905 (2008) [arXiv:0705.3439 [nucl-th]].