Jet Transverse Momentum Broadening

Hannah Clayton[1,*], Matthew D. Sievert[2,†], W. A. Horowitz[1,‡]

[1]University of Cape Town, South Africa [2]New Mexico State University, USA

[*]clyhan001@myuct.ac.za, [†]msievert@nmsu.edu, [‡]wa.horowitz@uct.ac.za

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Introduction

In deeply inelastic lepton-nucleus scattering, hadron-nucleus and heavy-ion collisions, multiple scatterings of energetic partons in the nuclear medium lead to a broadening of the average jet transverse momentum. This jet broadening phenomenon offers a useful tool for probing the properties of nuclear media, including the quark-gluon plasma formed in high-energy heavy-ion collisions. Many theoretical frameworks have been developed in the study of multiple scatterings and their subsequent effects. We will focus on the Djordjevic-Gyulassy-Levai-Vitev (DGLV) energy loss model [1] [2], as well as the Twist-4 collinear factorization framework [3] [4]. Notably, DGLV assumes a factorization of the hard production process and the subsequent jet evolution in medium. In contrast, factorization is not assumed, but appears to hold, in semi-inclusive deep inelastic scattering (SIDIS) at Twist-4. The Twist-4 derivation [4] includes cross talk between the production and evolution that is missing in the energy loss formalism; we aim to quantify the importance of these neglected terms in energy loss calculations and, ultimately, to derive energy loss formulae that respect a rigorous factorization.

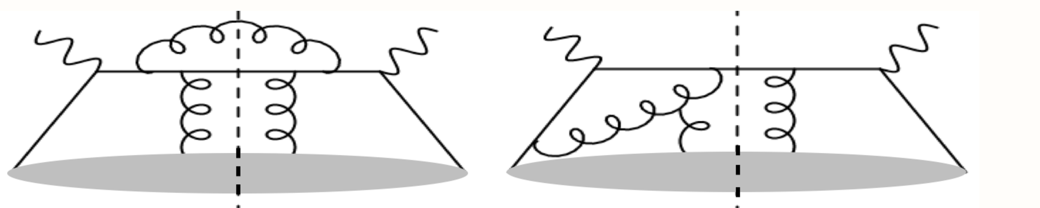

Figure 1: Two of the contributing Feynman diagrams to the transverse momentum broadening in SIDIS at Twist-4 (reproduced from [3]). The left diagram is topologically equivalent to the one used for energy loss in Figure 2. The right diagram includes cross talk between the parton production and subsequent evolution, which is neglected in the energy loss formalism.

In this work, we present predictions for the jet broadening in heavy-ion collisions calculated using the DGLV energy loss model. We investigate the asymptotic behaviour of these jet broadening results from the energy-loss perspective, with a view to making preliminary comparisons with transverse momentum jet broadening in SIDIS at Twist-4 presented by Kang et al. [4].

Model and results

We consider two ways in which jet broadening can occur from an energy loss perspective. First, a parton propagating through the medium can undergo elastic scatterings off medium constituents, in which transverse momentum is transferred from the in-medium gluon to the parton. We refer to this as the "collisional" or "leading order (LO)" momentum broadening. Second, interactions with the medium can stimulate the emission of gluons off the parton, where some transverse momentum is carried away by the emitted gluon. This broadening is referred to as "radiative" or "next-to-leading order (NLO)". The radiative broadening can be computed using the DGLV energy loss model.

DGLV energy loss

The study of medium-induced parton energy loss offers a valuable technique for the characterisation of the highly-dense matter produced in ultra-relativistic heavy ion collisions. The initial hard collisions produce high-energy partons, which then lose energy via elastic scattering and medium-induced radiation as they propagate through the dense medium. In this section, we present the Djordjevic-Gyulassy-Levai-Vitev (DGLV) formalism for the radiative energy loss.

Gyulassy et al. [1] used the opacity series expansion method to compute the radiative energy loss for a fast massless parton in the QCD medium, in the soft gluon emission limit ($x \ll 1$). Djordjevic and Gyulassy [2] later generalized the massless result of GLV to derive the heavy quark medium-induced radiative energy loss to all orders in opacity $(L/\lambda)^n$, for $x \ll 1$.

From the results of Djordjevic and Gyulassy et al. we define the distribution of inclusive gluon radiation to first order in opacity for a heavy quark of mass M as

$$\frac{d^5N_g^{(1)}}{dx\,d^2\mathbf{k}_\perp d^2\mathbf{q}_\perp} = \frac{4\alpha_s\,L}{3\pi^3 x\lambda}\frac{1}{\mathbf{k}_\perp^2+m_g^2+M^2x^2}\frac{\mu^2}{(\mathbf{q}_\perp^2+\mu^2)^2}\times$$
$$\times\, 2\frac{\mathbf{k}_\perp\cdot\mathbf{q}_\perp(\mathbf{k}_\perp-\mathbf{q}_\perp)^2+(m_g^2+M^2x^2)\mathbf{q}_\perp\cdot(\mathbf{q}_\perp-\mathbf{k}_\perp)}{(\frac{4Ex}{L})^2+((\mathbf{k}_\perp-\mathbf{q}_\perp)^2+M^2x^2+m_g^2)^2}\,, \tag{1}$$

where E is the initial parton energy, x is the fractional energy radiated, $|\mathbf{q}_\perp|$ is the magnitude of the transverse momentum transfer between a target parton and a jet, $|\mathbf{k}_\perp|$ is the magnitude of the transverse momentum of the radiated gluon, λ is the mean free path of the gluon, L is the effective length of the medium through which the parton travels, μ is the chromoelectric Debye screening mass, and $m_g = \mu/\sqrt{2}$ is the asymptotic plasmon mass.

Transverse momentum broadening

We now consider the transverse momentum broadening of a single deconfined parton due to the presence of the medium.

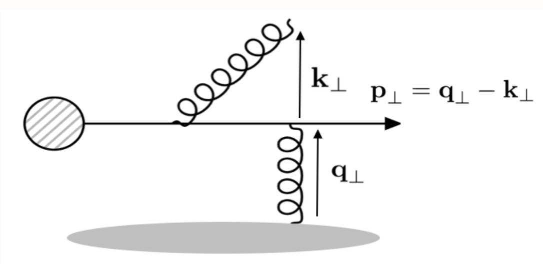

Figure 2: After the initial hard process, the deconfined parton traverses the medium. Transverse momentum can be transferred to this parton via collisions with the medium ($\mathbf{q}_\perp$) or the stimulated emission of soft gluons ($\mathbf{k}_\perp$).

The collisional (LO) and radiative (NLO) broadening of the parton are computed (at first order in opacity) as

$$\langle p_T^2\rangle_{LO} \equiv \frac{L}{\lambda}\int d^2\mathbf{q}_\perp\,\mathbf{q}_\perp^2\frac{d^2\sigma^{qg\to qg}}{d^2\mathbf{q}_\perp}\,, \tag{2}$$

$$\langle p_T^2\rangle_{NLO,1} \equiv \int dx\,d^2\mathbf{q}_\perp d^2\mathbf{k}_\perp\,(\mathbf{q}_\perp-\mathbf{k}_\perp)^2\frac{d^5N_g^{(1)}}{dx\,d^2\mathbf{k}_\perp d^2\mathbf{q}_\perp}\,, \tag{3}$$

where $d^2\sigma^{qg\to qg}/d^2\mathbf{q}_\perp = 2\alpha_s^2/(\mathbf{q}_\perp^2+\mu^2)^2$ is the cross section for elastic quark-gluon scattering.

Finally, the vacuum-subtracted total transverse momentum broadening is the difference between the momentum broadening in nucleus-nucleus and proton-proton collisions,

$$\begin{aligned}\langle p_T^2\rangle_{tot} &\equiv \langle p_T^2\rangle_{tot,AA} - \langle p_T^2\rangle_{tot,pp}\\ &= e^{-\langle N_g\rangle_{0+1}}\langle p_T^2\rangle_{LO} + (1-e^{-\langle N_g\rangle_{0+1}})\langle p_T^2\rangle_{NLO,0+1}\\ &\quad -(1-e^{-\langle N_g\rangle_0})\langle p_T^2\rangle_{NLO,0}\,,\end{aligned} \tag{4}$$

where $\langle N_g\rangle$ is the average number of stimulated gluon emissions, and numerical subscripts indicate orders in opacity.

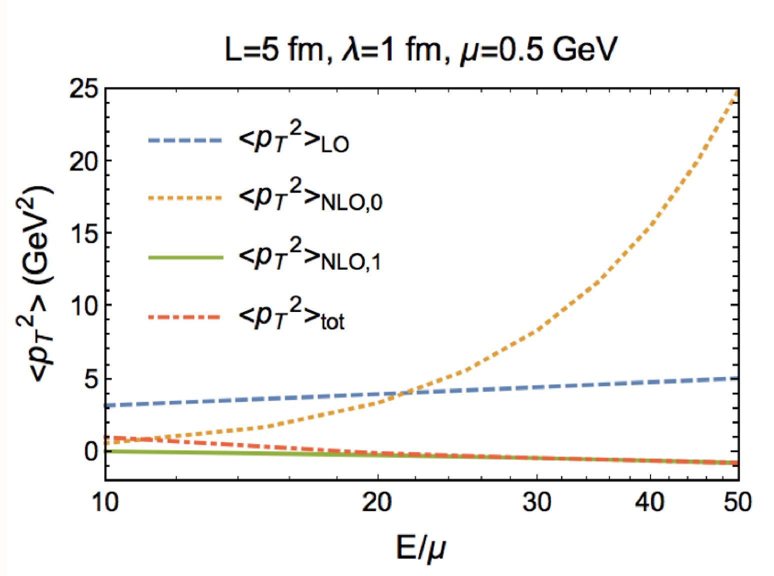

Figure 3: The LO, NLO and vacuum-subtracted total transverse momentum picked up by a charm quark ($M = 1.5$ GeV). We observe $\log(E/\mu)$ and $(\log(E/\mu))^2$ scaling for $\langle p_T^2\rangle_{LO}$ and $\langle p_T^2\rangle_{NLO,1}$ respectively, which agrees with the estimates in (5) and (6).

Asymptotic scaling

In preparation for making comparisons with the momentum broadening within the Twist-4 collinear factorization framework, where $E \gg \mu$, we consider the asymptotic behaviour of the collisional and radiative broadenings presented in (2) and (3). While the integral for the collisional broadening can be computed analytically in the limit $E \gg \mu$, more careful work is required for the radiative component. By ignoring the kinematic limits and performing a suitable shift of integration variables, we determined an approximate form for the radiative broadening. In the massless limit ($M = m_g = 0$) of (1), we obtained

$$\langle p_T^2\rangle_{LO} \overset{E\gg\mu}{\simeq} \frac{L\mu^2}{\lambda}\log(E/\mu)\,, \tag{5}$$

$$\langle p_T^2\rangle_{NLO,1} \overset{E\gg\mu}{\simeq} \frac{8\alpha_s}{3\pi}\frac{L\mu^2}{\lambda}(\log(E/\mu))^2\,. \tag{6}$$

These scalings were verified numerically in Figures 4 and 5, where the massless limit of (1) was used to compute $\langle p_T^2\rangle_{NLO,1}$ with the appropriate finite kinematic limits ($q_{max} = \sqrt{3E\mu}$ and $k_{max} = 2x(1-x)E$). However, there is a disagreement in the overall sign for the NLO broadening, which can be attributed to finite kinematic effects.

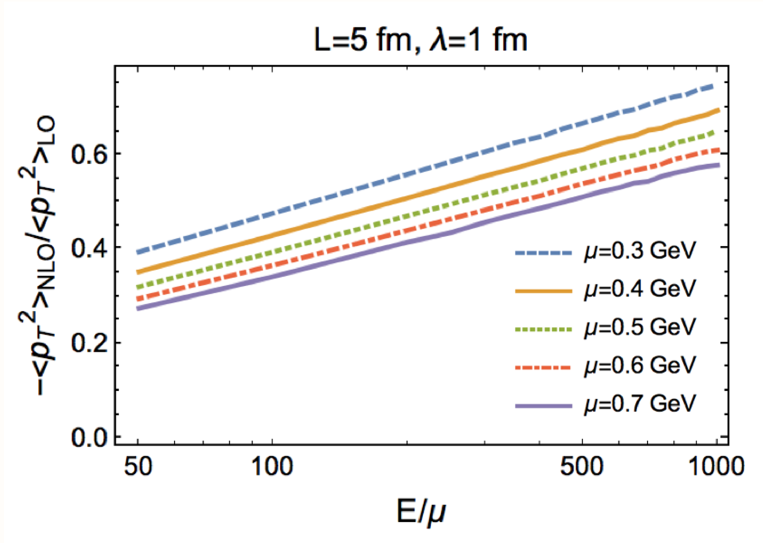

Figure 4: The ratio of NLO to LO transverse momentum broadening as a function of E/μ, for various values of μ. Despite the finite kinematic limits, the expected logarithmic behaviour from the analytic scaling estimates in (5) and (6) is observed clearly.

The ratio $-\langle p_T^2\rangle_{NLO,1}/\langle p_T^2\rangle_{LO}(E/\mu)$ was computed for fixed values of μ and L, and fits of the form $-\langle p_T^2\rangle_{NLO,1}/\langle p_T^2\rangle_{LO}(E/\mu) = a + b\log(E/\mu)$ were performed. The fit parameter b is plotted as a function of the dimensionless quantity μL in Figure 5.

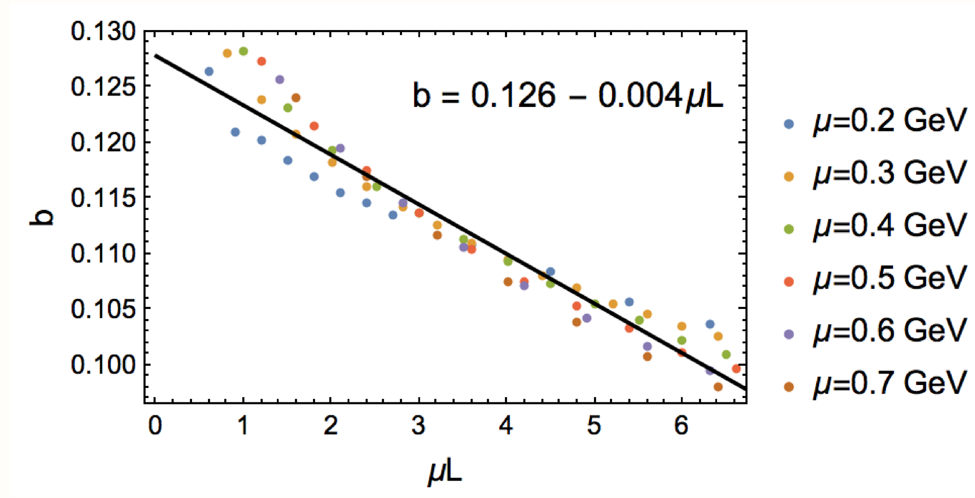

Figure 5: For the chosen plasma parameters, the analytic scaling estimates predict a value for the fit parameter $b = 8\alpha_s/3\pi \simeq 0.255$. This is a factor of 2 larger than the numerical result of $b \simeq 0.126$. However, such a deviation was expected within the approximations used to generate (5) and (6).

Although we observe some slight μL dependence for the fit parameter b shown in Figure 5, it was deemed insignificant when compared with the overall constant intercept value.

Conclusions and future work

Up to the expected accuracy, we have numerically verified that within the DGLV energy loss framework, the ratio of NLO to LO transverse momentum broadening scales like $\log(E/\mu)$ for sufficiently large energies. This is consistent with our expectations for the jet broadening in SIDIS at Twist-4. For the next stage in this work, we will proceed with the numerical analysis of the Twist-4 jet broadening model presented by Kang et al. [4].

References

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