Revisiting heavy quark radiative energy loss in nuclei within the high-twist approach

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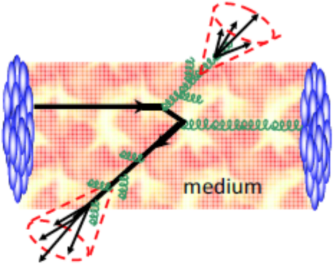
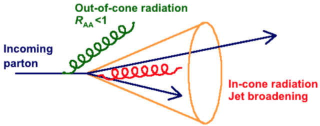
Outline

- Introduction
- SIDIS at Next-to-Leading Order & Twist 4
- Improved high-twist factorization formalism: gauge invariance
- Summary & Outlook

Parton energy loss in medium and jet quenching



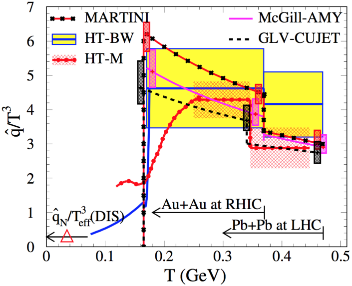


- Energetic partons will lose energy when traveling through hot QGP or large cold nuclei (eA DIS process)
- Medium-induced gluon radiations give rise to jet energy loss

Jet transport parameter $\hat{q}$

$$\hat{q} = \frac{4\pi C_F \alpha_s}{N_c^2 - 1} \int dy^- \left\langle F^{ai+}(0) F_i^{a+}(y^-) \right\rangle e^{i\xi p^+ y^-},$$

- Average squared transverse momentum transfer per unit distance in the medium, reflecting the ability of the medium to "quench" jets.
- Proportional to the gluon density of the medium.
- Medium property can be probed by parton energy loss mechanisms



$\hat{q} = 1.3 \pm 0.3 \mathrm{GeV}^2/\mathrm{fm}$ Au+Au at RHIC $\sqrt{s} = 0.2\mathrm{TeV/n}$;
$\hat{q} = 2.2 \pm 0.5 \mathrm{GeV}^2/\mathrm{fm}$ Pb+Pb at LHC $\sqrt{s} = 2.76\mathrm{TeV/n}$;
Extracted from HT-BW model via R_{AA}. PRC 90, 014909

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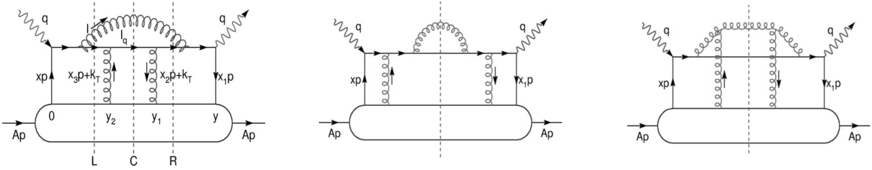
SIDIS at NLO & Twist 4



Identify one hadron in final state

- * Light quark: $l(L_1) + A(p) \rightarrow l(L_2) + h(l_h) + X$, via γ^* exchange. Nucl. Phys. A696, 788 (2001)
- * Heavy quark: $l(L_1)+A(p) \rightarrow \nu_l(L_2)+H(l_H)+X$, via $W^\pm$ exchange. Nucl. Phys. A757, 493 (2005)

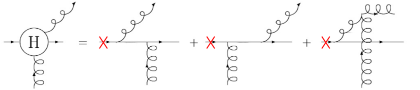
- Single rescattering approximation: dilute medium, $l_{mfp} \gg L$
- Dynamic scattering center: momentum and energy ($\sim q$) transfer
- Hard radiated gluon: finite z_g
- Typical transverse momentum transfer from the medium is much smaller than radiated gluon transverse momentum: $k_T \ll l_T$

Collinear Expansion and Factorization

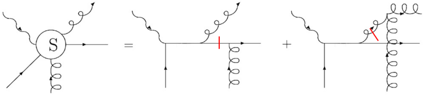
- $W_{\mu\nu} \propto \mathrm{Tr}[\hat{H}^{\alpha\beta}_{\mu\nu}(x_1 p^+, k_2, k_3)\langle A \mid \bar{\psi}(0) A_\beta(y_2) A_\alpha(y_1) \psi(y) \mid A\rangle]$
- $\hat{H}^{\alpha\beta}_{\mu\nu}(x_1 p^+, k_2, k_3) = \hat{H}^{\alpha\beta}_{\mu\nu}(k_\perp = 0) + \frac{\partial \hat{H}^{\alpha\beta}_{\mu\nu}}{\partial k_{\perp\rho}} \mid_{k_\perp = 0_\perp} k_{\perp\rho}$ $+ \frac{1}{2} \frac{\partial^2 \hat{H}^{\alpha\beta}_{\mu\nu}}{\partial k_{\perp\rho} \partial k_{\perp\sigma}} \mid_{k_\perp = 0_\perp} k_{\perp\rho} k_{\perp\sigma} + \ldots$
- $k_\perp = 0$ term contributes to gauge link of initial quark PDF without L enhancement.
- $k_{\perp\rho}$ term contributes zero for unpolarized beam, vanishing on taking a spin average.
- $W^D_{\mu\nu} \propto \int \mathrm{d}z_H \int_{z_H}^1 \frac{\mathrm{d}z}{z} D_{Q\to H}(\frac{z_H}{z}) \int \frac{\mathrm{d}y^-}{2\pi} \mathrm{d}y_1^- \mathrm{d}y_2^-$ $\left(-\frac{1}{2} g^{\rho\sigma}\right) \left[\frac{\partial^2}{\partial k_\perp^\rho \, \partial k_\perp^\sigma} \bar{H}^D_{\mu\nu} \right]\Big|_{k_\perp = 0}$ $\times \frac{1}{2} \langle A \mid \bar{\psi}(0) \gamma^+ F_\sigma{}^+(y_2^-) F^{+\sigma}(y_1^-) \psi(y^-) \mid A\rangle$

SIDIS at NLO & Twist 4 with central-cut

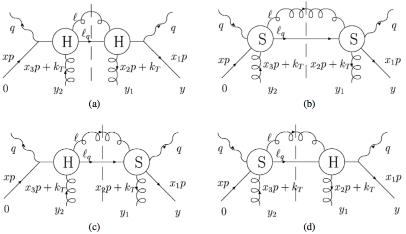
Twist: Dimension-Spin+Momentum in operator definition



The cross marks indicate the propagators where the hard poles arise

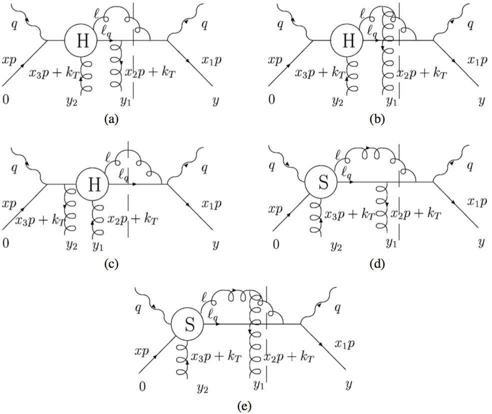


The short bars indicate the propagators where the soft poles arise



- Power suppressed compared with twist-2 contribution
- Nuclear size enhancement $\propto L$
- LPM interference effect $\propto L^2$

SIDIS at NLO & Twist 4 with asymmetric-cut



Interference between vacuum and medium induced radiation

Note: Virtual corrections and gluon fragmentation are also needed

Nucleus modified Splitting Functions & FFs

- Splitting Functions

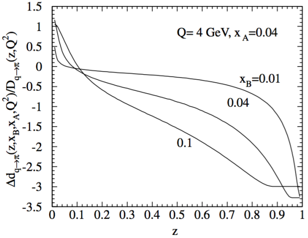
$$\Delta\gamma_{q\to qg}(z,x,x_L,\ell_T^2) = \left[\frac{1+z^2}{(1-z)_+}T_{qg}^A(x,x_L) + \delta(1-z)\Delta T_{qg}^A(x,\ell_T^2)\right]\frac{C_A 2\pi\alpha_s}{(\ell_T^2+\langle k_T^2\rangle)N_c\widetilde{f}_q^A(x,\mu_I^2)}$$

$$\Delta\gamma_{q\to gq}(z,x,x_L,\ell_T^2) = \Delta\gamma_{q\to qg}(1-z,x,x_L,\ell_T^2).$$

- Quark-gluon correlation function at Twist-4, analogous to PDFs at Twist-2

$$T_{qg}^A(x,x_L) = \int\frac{dy^-}{2\pi}dy_1^-dy_2^-\,e^{i(x+x_L)p^+y^-}\left(1-e^{-ix_Lp^+y_2^-}\right)\left(1-e^{-ix_Lp^+(y^--y_1^-)}\right)$$
$$\times\frac{1}{2}\langle A|\bar\psi_q(0)\gamma^+F_\sigma{}^+(y_2^-)F^{+\sigma}(y_1^-)\psi_q(y^-)|A\rangle\theta(-y_2^-)\theta(y_2^--y_1^-)$$

$$\tilde{D}_{q\to h}(z_h,\mu^2) \equiv D_{q\to h}(z_h,\mu^2) + \int_0^{\mu^2}\frac{\mathrm{d}l_T^2}{l_T^2}\frac{\alpha_s}{2\pi}\int_{z_h}^1\frac{\mathrm{d}z}{z}\Big[\Delta\gamma_{q\to qg}(z,x,x_L,l_T^2)$$
$$D_{q\to h}(z_h/z,\mu^2) + \Delta\gamma_{q\to gq}(z,x,x_L,l_T^2)D_{g\to h}(z_h/z,\mu^2)\Big].$$



Jet transport parameter $\hat{q}$

Parton energy loss and jet transport coefficient $\hat{q}$ are both related to the quark-gluon correlation functions.

- Parton energy loss: carried away by the radiated gluons

$$\begin{aligned}\frac{\Delta E}{E} &= \langle \Delta z_g \rangle = \frac{\alpha_s}{2\pi} \int \frac{dl_T^2}{l_T^2} \int dz z \Delta\gamma_{q\to gq}(z, l_T^2) \\ &= \alpha_s^2 \int dl_T^2 \int_0^1 dz \frac{C_A}{N_c} \frac{1+(1-z)^2}{l_T^4} \frac{T_{qg}^A(x_B, x_L)}{f_q^A(x_B)}.\end{aligned}$$

- Decomposition:

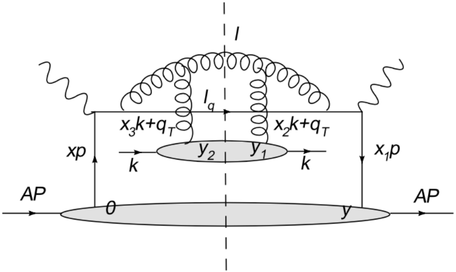
$$\begin{aligned}\frac{2\pi\alpha_s}{N_c} \frac{T_{qg}^A(x_B, x_L)}{f_q^A(x_B)} &= \frac{2\pi\alpha_s}{N_c} \pi \int dy^- \rho_N^A(y)[1-\cos(x_L p^+ y^-)] \\ &\quad \times [(x_L G_N(x_L) + c(x_L)[x G_N(x)]_{x\approx 0}] \\ &= \int dy^- [1-\cos(x_L p^+ y^-)][\hat{q}_F(x_L, y) + c(x_L)\hat{q}_F(0, y)]\end{aligned}$$

- Jet transport parameter:

$$\hat{q}_R(x_L, y) = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \rho_N^A(y) x_L G_N(x_L),$$

W.-T Deng and X.-N. Wang, Phys. Rev. C 81, 024902

Applied in hot medium



X-F Chen et al, Phys. Rev. C 81, 064908

- Apply the modified splitting function in the hot medium.
- Coupled to the dynamical evolution models of the bulk matter.

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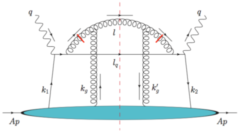
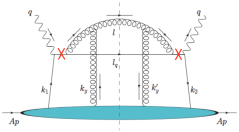
SIDIS at NLO & Twist 4 ensuring gauge invariance

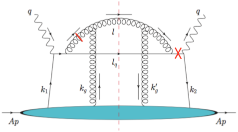
Z-B Kang, E-k Wang, X-N Wang, and H-x Xing, PRL 112,102001 &
Z-B Kang, J-W Qiu, X-N Wang, and H-x Xing, PRD 94, 074038



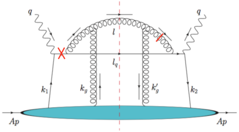
(a) The hard-soft process. We assign the four initial partons' momenta as $k_1 = xp, k_2 = x_1 p, k_g = x_3 p + k_T$ and $k'_g = x_2 p + k_T$, respectively.



(b) The double hard process. We assign the four initial partons' momenta as $k_1 = xp, k_2 = x_1 p + k_{3T} - k_{2T}, k_g = x_3 p + k_{3T}$ and $k'_g = x_2 p + k_{2T}$, respectively.



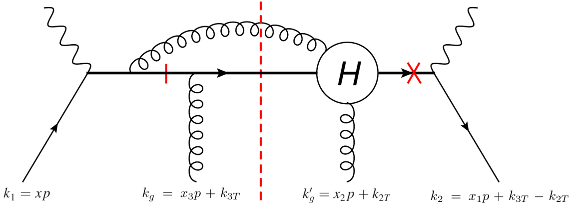
(c) The interference between hard-soft and double hard process. We assign the four initial partons' momenta as $k_1 = xp, k_2 = x_1 p + k_{3T} - k_{2T}, k_g = x_3 p + k_{3T}$ and $k'_g = x_2 p + k_{2T}$, respectively.



(d) The interference between double hard and soft-hard process. We assign the four initial partons' momenta as $k_1 = xp + k_{2T} - k_{3T}, k_2 = x_1 p, k_g = x_3 p + k_{3T}$ and $k'_g = x_2 p + k_{2T}$, respectively.

$$\frac{1}{2}\,\frac{\partial^2}{\partial k_T^\alpha \partial k_T^\beta}\bar{H}^D_{\mu\nu}(k_T)\bigg|_{k_T=0} \to \frac{\partial^2}{\partial k_{2T}^\alpha \partial k_{3T}^\beta}\bar{H}^D_{\mu\nu}(k_{2T},k_{3T})\bigg|_{\substack{k_{2T}=0\\ k_{3T}=0}}$$

Example: soft-hard double scatterings



Two factorized scatterings at amplitude level

- Left: first hard scattering $W + q \to Q + g$ (NLO, $\alpha\alpha_s$) and then soft rescattering $Q + g \to Q$ (LO QCD, α_s) by exchanging a soft gluon: on-shell initial quark $k_1^2 = 0$ for the first scattering $\to k_1 = xp$.
- Right: first hard scattering $W + q \to Q$ (LO EW, α) and then hard rescattering $Q + g \to Q + g$ (NLO, α_s^2): on shell initial gluon $k_g'^2 = 0$ for the second scattering, up to the order in which we perform collinear expansion, $\mathcal{O}(k_{2T})$ and $\mathcal{O}(k_{3T})$ if $k_{2T} \neq k_{3T}$.
- Momentum conservation: $k_2 = x_1p + k_{3T} - k_{2T}$.

Results and corrections

$$T_{qg}^{A,C}(x, x_L, M^2) \approx \frac{\tilde{\mathrm{C}}}{x_A} f_q^A(x)(1 - \mathrm{e}^{-\tilde{x}_L^2/x_A^2}) a(z, \frac{M^2}{\vec{\ell}_T^2})$$

$$a(z, \frac{M^2}{\vec{\ell}_T^2}) = \frac{(1+z)}{2} + [\ldots] \frac{(1-z)^2}{1+z^2} \frac{M^2}{\vec{\ell}_T^2} + [\ldots] \frac{(1-z)^4}{1+z^2} \frac{M^4}{\vec{\ell}_T^4}$$

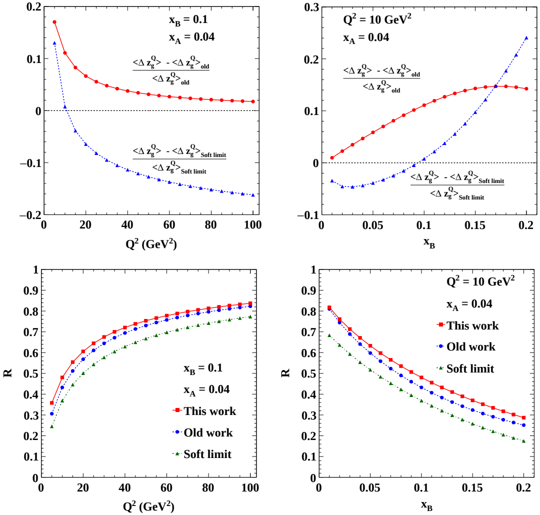
$$\Delta a = \left[z - \frac{1}{2} + \frac{\mathrm{C_F}}{\mathrm{C_A}}(1-z)^2\right] \left[(1+z)^2 + (1-z)^4 \frac{M^2}{\vec{\ell}_T^2}\right] \frac{(1-z)^2}{1+z^2} \frac{M^2}{\vec{\ell}_T^2}.$$

$$\langle \Delta z_g^Q \rangle = \frac{\tilde{\mathrm{C}} \mathrm{C_A} \alpha_s^2 x_B}{N_c Q^2 x_A} \int_0^1 \mathrm{d}z \frac{1+(1-z)^2}{z(1-z)} \int_{\tilde{x}_M}^{\tilde{x}_\mu} \mathrm{d}\tilde{x}_L \frac{(\tilde{x}_L - \tilde{x}_M)^2}{\tilde{x}_L^4} (1 - \mathrm{e}^{-\frac{\tilde{x}_L^2}{x_A^2}}) a,$$

- Light quark energy loss and mDGLAP Eqs for FF remains the same
- New correction terms in the heavy quark energy loss, which vanishes in the soft gluon radiation limit $z \to 1$.

Y.-L Du, Y.-Y He, X.-N Wang, H.-X Xing, H.-S Zong, PRD 98, 054015 (2018)

Relative correction of energy loss and Ratio R



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- Gauge invariance is ensured by a delicate setup of the initial partons' transverse momenta in SIDIS at twist 4.
- New correction terms only in the heavy quark energy loss, which vanishes in the soft gluon radiation limit.
- Significant correction in the small Q^2 and large x_B (small heavy quark energy) regions compared with the old result and that with soft gluon approximation.
- Necessity to go beyond the soft gluon limit: a global fitting on light and heavy quark energy loss.

Future work:

- Numerical simulation on heavy quark energy loss in transport models
- A complete & gauge invariant calculation of parton energy loss at NLO & twist 4.


THANK
YOU!