Are Jets Narrowed or Broadened in eA SIDIS?

DIS 2022

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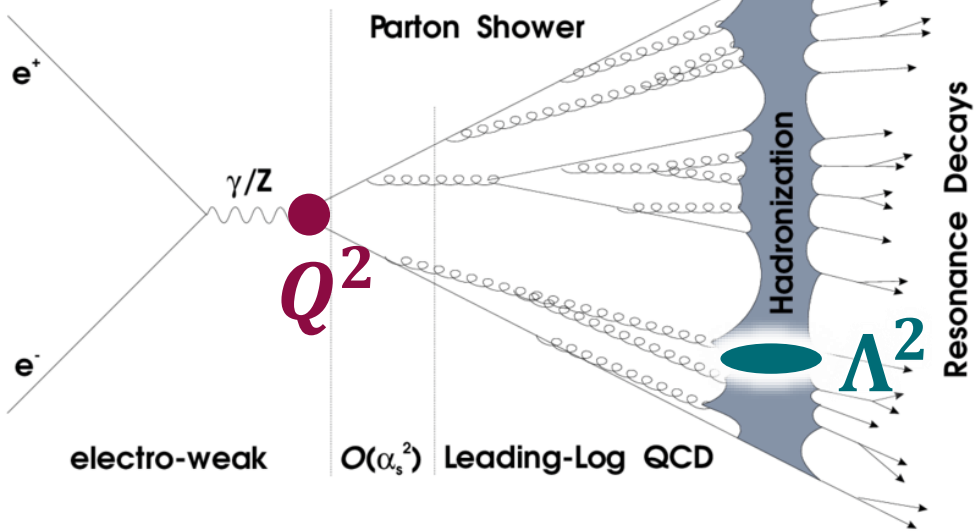
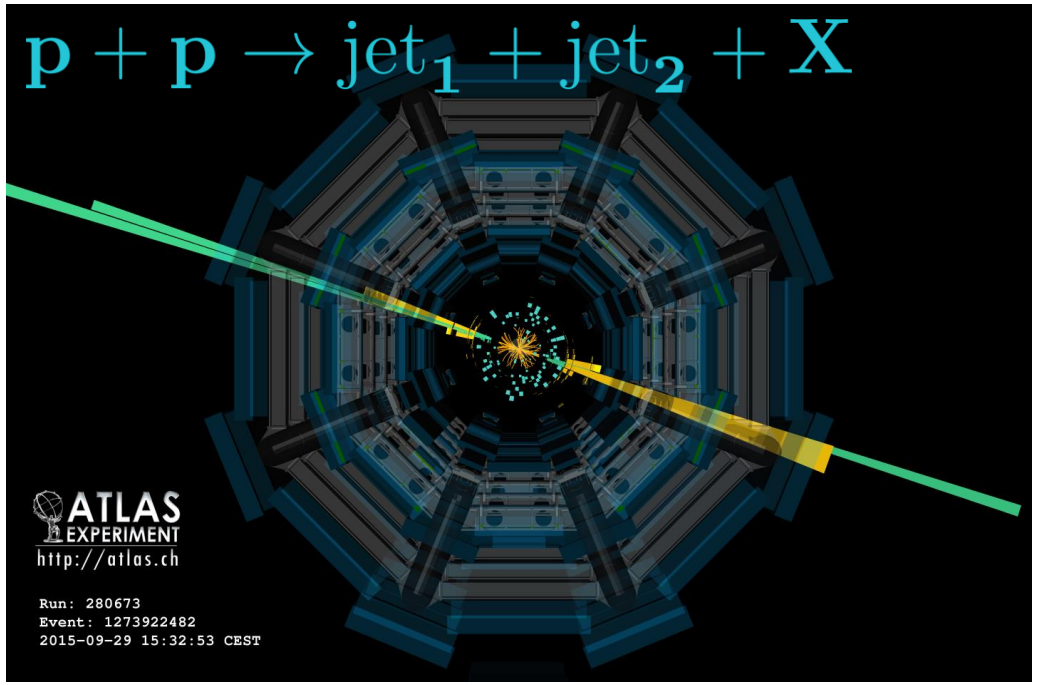
based on arXiv: 2110.14737 (accepted in Eur. Phys. J. C)

What Are Jets? A Microcosm of QCD

$$e^+ + e^- \to jet_1 + jet_2 + X$$



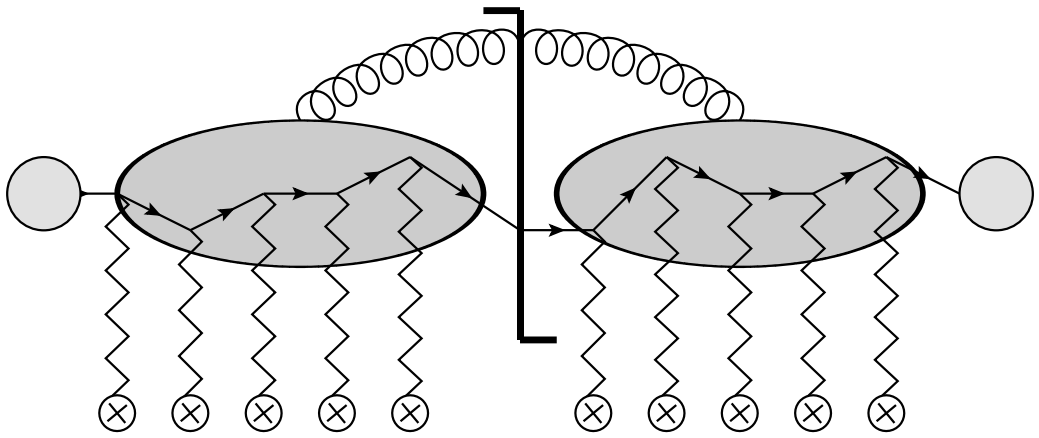


- Basic **jet production**: **hard parton-parton scattering** at high virtuality Q^2
- **Cascade of radiation** falling in virtuality down from Q^2 to the **hadronization scale** Λ^2
- Jets and substructure: **radiative QCD evolution** from perturbative to nonperturbative

Modification of Jets due to Final-State Interactions

- At high p_T, jets lose energy primarily by **radiating** a shower of soft gluons
  - In vacuum: **Sudakov factor**
  - In medium: **LPM effect**
- The **interference pattern** of the shower carries information about the **medium**
  - **Position-space** information: $\rho(\vec{x})$
  - **Momentum space** information: $v(\vec{q})$

Induced Radiation
+ accompanying $\boldsymbol{p_T}$ ***broadening***



Landau, Pomeranchuk, Dokl. Akad. Nauk Ser. Fiz ***92*** *(1953)*

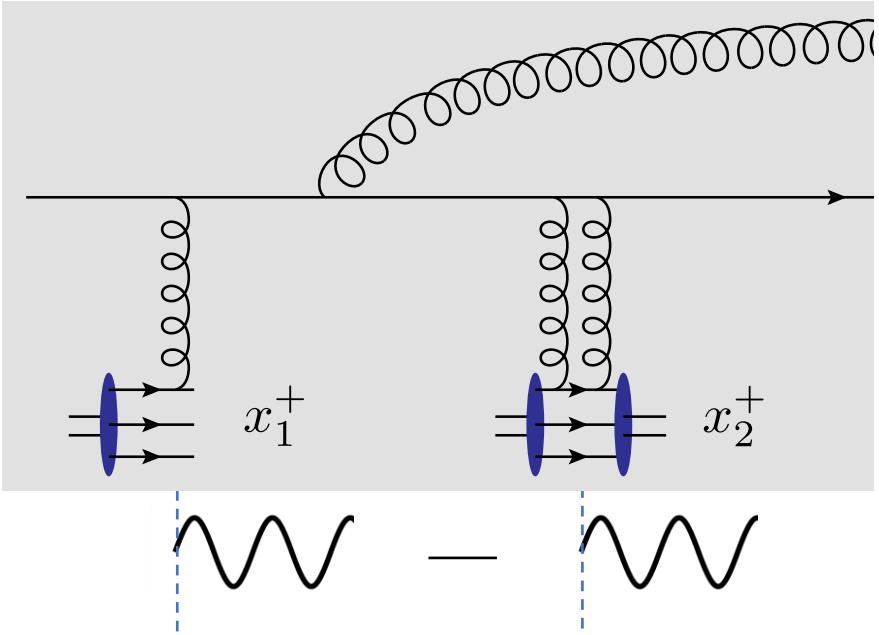
Migdal, Phys. Rev. ***103*** *(1956)*

Jets as Interferometers for QCD Tomography

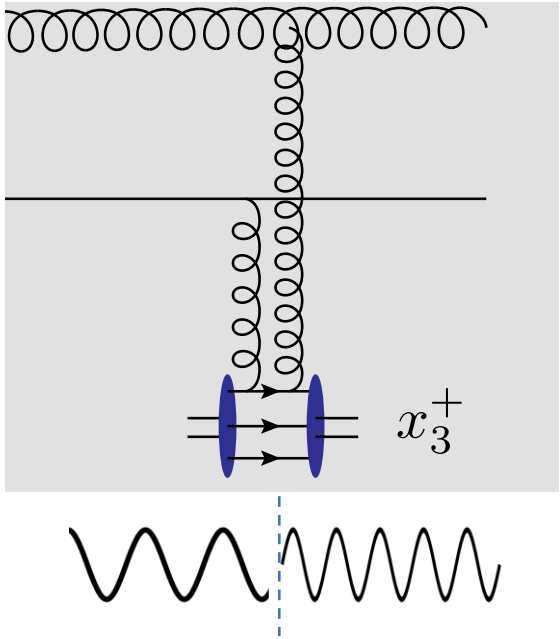
- **Edge phases** of the emission region
- **Phase slip** from scattering

Formation Time

$$\frac{1}{\ell_f} = \frac{(k - xp)_T^2 + x^2 m^2}{2x(1-x)E}$$

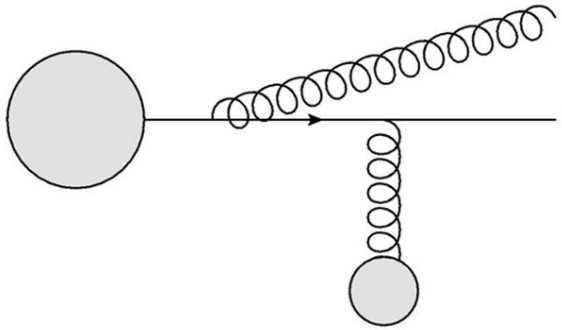


$$e^{i(z_1 / \ell_f)} - e^{i(z_2 / \ell_f)}$$



$$e^{i\, z_3\, (1 / \ell'_f - 1 / \ell_f)}$$

One Standard Approach: Medium-Modified Fragmentation



$$D(x,t) = \Delta(t) D(x,t_0) + \Delta(t) \int_{t_0}^{t} \frac{dt_1}{t_1} \frac{1}{\Delta(t_1)} \int \frac{dz}{z} P(z) D\left(\frac{x}{z}, t_1\right)$$

N. Armesto et al., JHEP **02** (2008)

- Compute jet production plus **final-state gluon emission**
- Interpret as a **medium-modified DGLAP** splitting function
- **Iterate multi-gluon emission** using modified DGLAP kernel

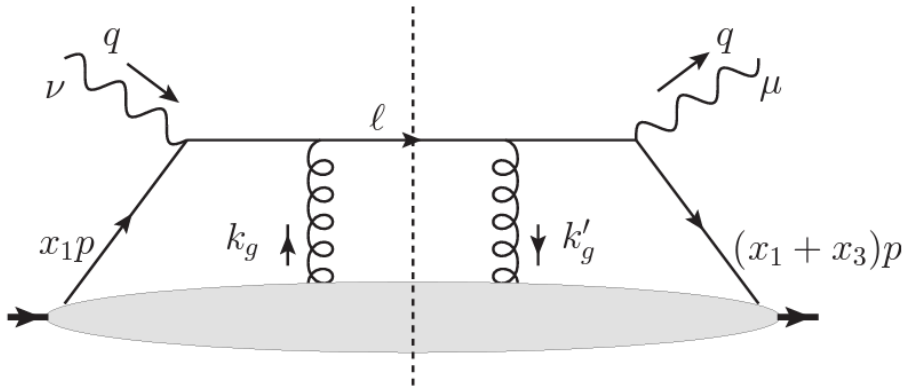
$$\Delta(t) = \exp\left[-\int_{t_0}^{t} \frac{dt'}{t'} \int dz \frac{\alpha_s(t',z)}{2\pi} P(z,t')\right]$$

$$\frac{\mathrm{d}N_{\mathrm{med}}^{(i)}}{\mathrm{d}x\,\mathrm{d}^2\boldsymbol{k}_\perp} = \frac{\alpha_s}{2\pi^2} \frac{1}{\boldsymbol{k}_\perp^2} P_i^{\mathrm{med,\ real}}(x, \boldsymbol{k}_\perp)$$

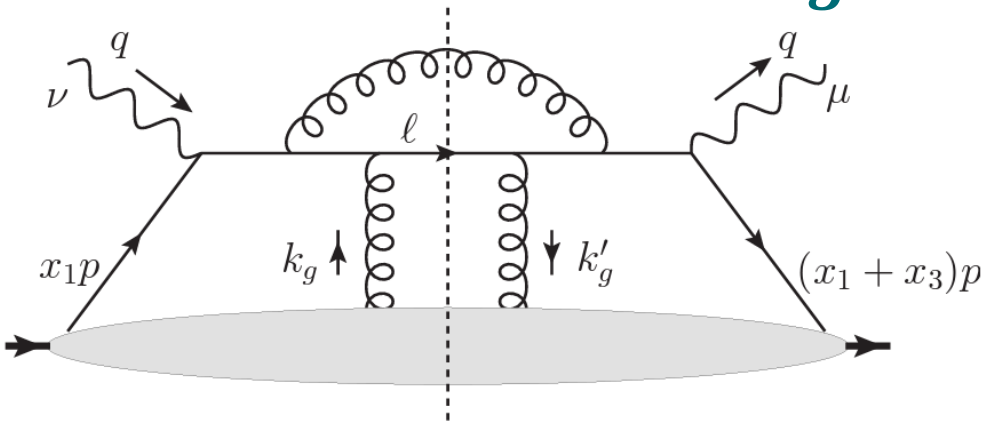
Y.-T. Chien, et al., Phys. Rev. **D93** (2016)

A Different Approach: Collinear Twist-4

LO: Collisional Broadening



LO: Radiative Broadening



Z.-B. Kang, et al., Phys. Rev. Lett. **112** (2014), Phys. Rev. **D94** (2016)

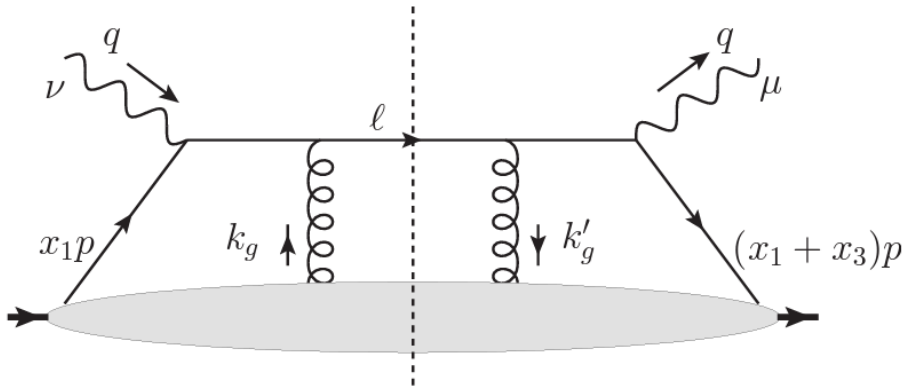
- Observable: jet transverse momentum broadening in eA: $\langle p_T^2 \rangle_{eA} - \langle p_T^2 \rangle_{ep}$
  - Utilizes photon as "reference direction" to measure broadening
  - Enhancement of higher-twist effects in eA relative to ep
  - Length-enhanced subset of higher-twist corrections dominate: $\sim Q_s^2 \,/\, Q^2$

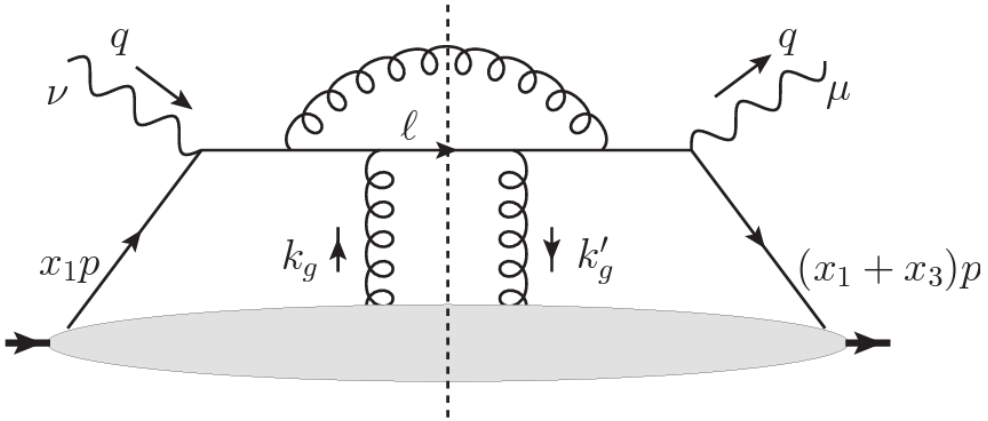
*T. Altinoluk, R. Boussarie, JHEP **10** (2019)*

- Direct sensitivity to medium parameter $\hat{q}$ and in-medium splitting amplitude

Final-State… or Initial-State…?

$$\langle p|\,\bar{\psi}(0)\gamma^+ F^+{}_\mu(y_1^-)F^{\mu+}(y_2^-)\psi(y_3^-)\,|p\rangle \longrightarrow \textit{Quantum Evolution}$$





Z.-B. Kang, et al., Phys. Rev. Lett. **112** (2014), Phys. Rev. **D94** (2016)

$$\mu_f^2 \frac{\partial}{\partial \mu_f^2} T_{qg}(x_B,0,0,\mu_f^2) = \frac{\alpha_s}{2\pi}\int_{x_B}^1 \frac{dx}{x}\left[\mathcal{P}_{qg\to qg}\otimes T_{qg} + P_{qg}(\hat{x})T_{gg}(x,0,0,\mu_f^2)\right]$$

Not DGLAP!

$$\mathcal{P}_{qg\to qg}\otimes T_{qg} \equiv P_{qq}(\hat{x})T_{qg}(x,0,0) + \frac{C_A}{2}\left\{\frac{4}{(1-\hat{x})_+}T_{qg}(x_B,x-x_B,0) - \frac{1+\hat{x}}{(1-\hat{x})_+}\left[T_{qg}(x,0,x_B-x)\right.\right.$$
$$\left.\left. + T_{qg}(x_B,x-x_B,x-x_B)\right]\right\} + 2C_A\delta(1-\hat{x})T_{qg}(x,0,0).$$

Uncomfortable Questions…

- Jet **broadening** and jet **quenching** arise from **final-state interactions**….
  - ➢ But does that mean they have to belong to **fragmentation functions**…?
  - ➢ And was it **safe to assume DGLAP would hold** for the modifications…?

- A collinear twist-4 analysis suggests that final-state interactions are properly encoded as **double parton distributions** associated with the "initial state".

  M. Diehl, J. Gaunt, P. Plossl, A. Schafer, SciPost Phys **7** (2019)

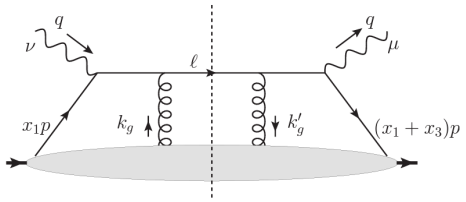
  - ➢ PDFs are **not just parton densities**: final-state interactions are non-negligible

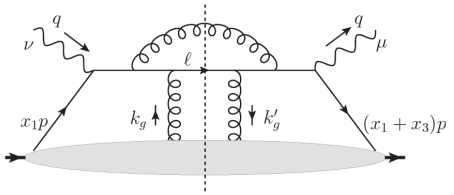
    (see e.g. Sivers function in TMDs)

  - ➢ Distinction not just academic: **different Q^2 evolution** from non-DLGAP structure

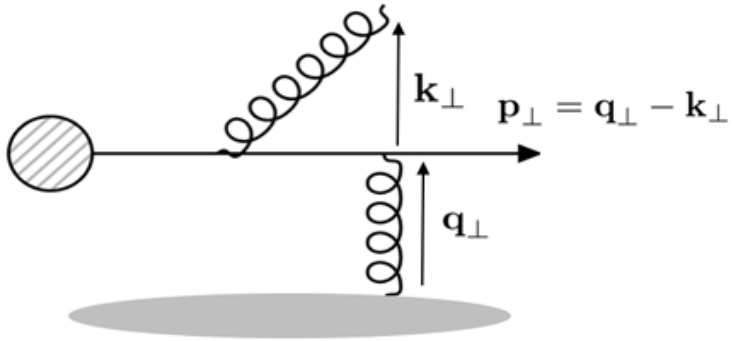
A Point of Comparison: $\langle p_T^2 \rangle$ in eA Collisions

$$\frac{d\langle \ell_{hT}^2 \sigma^D \rangle}{d\mathcal{PS}} = \sigma_h \sum_q e_q^2 \int_{x_B}^1 \frac{dx}{x} T_{qg}(x,0,0,\mu_f^2) \int_{z_h}^1 \frac{dz}{z} D_{h/q}(z,\mu_f^2)\delta(1-\hat{x})\delta(1-\hat{z})$$
$$+ \sigma_h \frac{\alpha_s}{2\pi} \sum_q e_q^2 \int_{z_h}^1 \frac{dz}{z} D_{h/q}(z,\mu_f^2) \int_{x_B}^1 \frac{dx}{x} \left\{ \ln\left(\frac{Q^2}{\mu_f^2}\right) \left[\delta(1-\hat{x}) P_{qq}(\hat{z}) T_{qg}(x,0,0,\mu_f^2)\right.\right.$$
$$\left. + \delta(1-\hat{z})\left(\mathcal{P}_{qg\to qg} \otimes T_{qg} + P_{qg}(\hat{x}) T_{gg}(x,0,0,\mu_f^2)\right)\right]$$
$$\left. + H_{qg}^{C-R} \otimes T_{qg} + H_{qg}^{C-V} \otimes T_{qg} - H_{qg}^{A} \otimes T_{qg}^{A} + H_{gg}^{C} \otimes T_{gg} \right\},$$





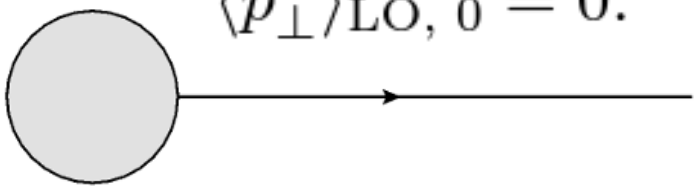
- As a step toward detailed comparison of "energy loss" frameworks and Twist-4:
  - Compare with a standard implementation in the **opacity expansion** M. Gyulassy, P. Levai, I. Vitev, Nucl. Phys. **B594** (2001)
  - Do they agree on **leading-log evolution** for p_T broadening?



Collisional and Vacuum Radiative Broadening

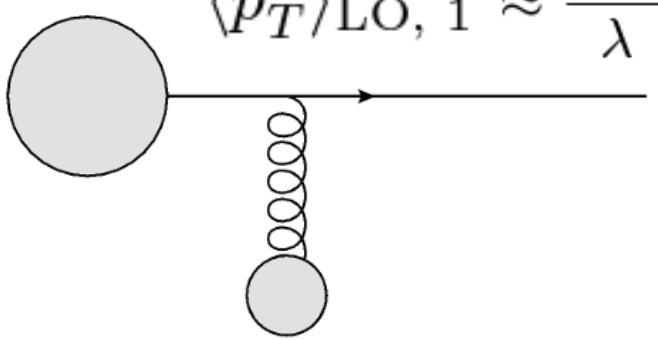
Initial Condition

$$\langle p_\perp^2 \rangle_{\mathrm{LO},\,0} = 0.$$



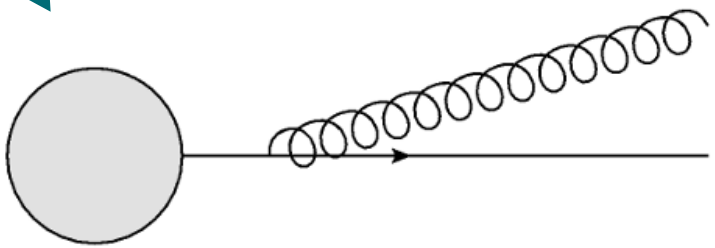
Collisional

$$\langle p_T^2 \rangle_{\mathrm{LO},\,1} \approx \frac{L\mu^2}{\lambda} \boxed{\log\left(\frac{E}{\mu}\right)} = \hat{q}L$$



- Logarithmic
- Length-enhanced

Radiative



$$\frac{d^3 N_g^{(0)}}{dx\, d^2\mathbf{k}_\perp} = \frac{C_R \alpha_s}{\pi^2 x} \frac{\mathbf{k}_\perp^2}{(\mathbf{k}_\perp^2 + m_g^2 + M^2 x^2)^2}$$

- **Quadratic** (!)

$$\langle p_T^2 \rangle_{\mathrm{NLO},\,0} = \int dx\, d^2\mathbf{k}_\perp \left(k_\perp^2 \frac{d^3 N_g^{(0)}}{dx\, d^2\mathbf{k}_\perp} \right) \approx 2 \frac{\alpha_s C_R}{\pi} \boxed{E^2}$$

Medium-Induced Gluon Emission

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

Simple but reasonable assumptions:

- Simple model assuming exponential density distribution $\sim (e^{-\Delta z\,/L})/L$ smooths out interference pattern
- Soft gluon approximation $x \ll 1$
- Collinear approximation $k_\perp \ll x\,E$
- Gyulassy-Wang potential (heavy target partons)

$$\left.\frac{d^2\sigma^{qg\to qg}}{d^2\mathbf{q}_\perp}\right|_1 = \frac{2\alpha_s^2}{(\mathbf{q}_\perp^2 + \mu^2)^2}$$

- Energy conservation $q < \sqrt{3E\mu}$ for a target parton with energy 3μ

Leading Logs: The Quick, Intuitive Way....

k_T^2 moment

$$\langle p_T^2\rangle_{\text{NLO, 1}} = \int_0^1 dx \int^{k_\perp<2xE} d^2k_\perp \int^{q_\perp<\sqrt{3E\mu}} d^2q_\perp \frac{C_R\alpha_s}{\pi^3 x}\frac{L}{\lambda}\frac{1}{\mathbf{k}_\perp^2}\frac{\mu^2}{(\mathbf{q}_\perp^2+\mu^2)^2}\, 2\frac{\mathbf{k}_\perp\cdot\mathbf{q}_\perp(\mathbf{k}_\perp-\mathbf{q}_\perp)^4L^2}{(4Ex)^2+(\mathbf{k}_\perp-\mathbf{q}_\perp)^4L^2}$$

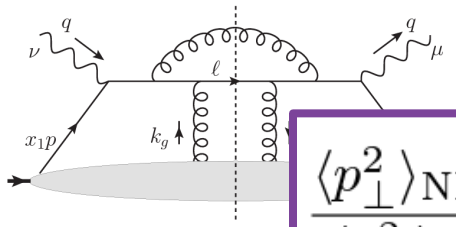
Relax convergent integral

Momentum shift $\boldsymbol{q}_\perp' \equiv \mathbf{k}_\perp - \mathbf{q}_\perp$

$$\langle p_\perp^2\rangle_{\text{NLO, 1}} = \frac{C\pi}{2}\int_{\frac{\mu}{E}}^1 \frac{dx}{x}\int_{\mu^2}^{\infty} dk_\perp^2 \int_0^{2\pi} d\theta \int_0^{3E\mu} dq_\perp'^2\, \frac{\mu^2}{k_\perp^2}\frac{k_\perp^2 - k_\perp q_\perp'\cos\theta}{(k_\perp^2+q_\perp^2-2k_\perp q_\perp'\cos\theta+\mu^2)^2}\frac{q_\perp'^4}{A^2+q_\perp'^4}$$

$$\langle p_T^2\rangle_{\text{NLO, 1}} \approx \frac{4\alpha_s}{3\pi}\mu^2\frac{L}{\lambda}\ln^2\frac{E}{\mu}$$

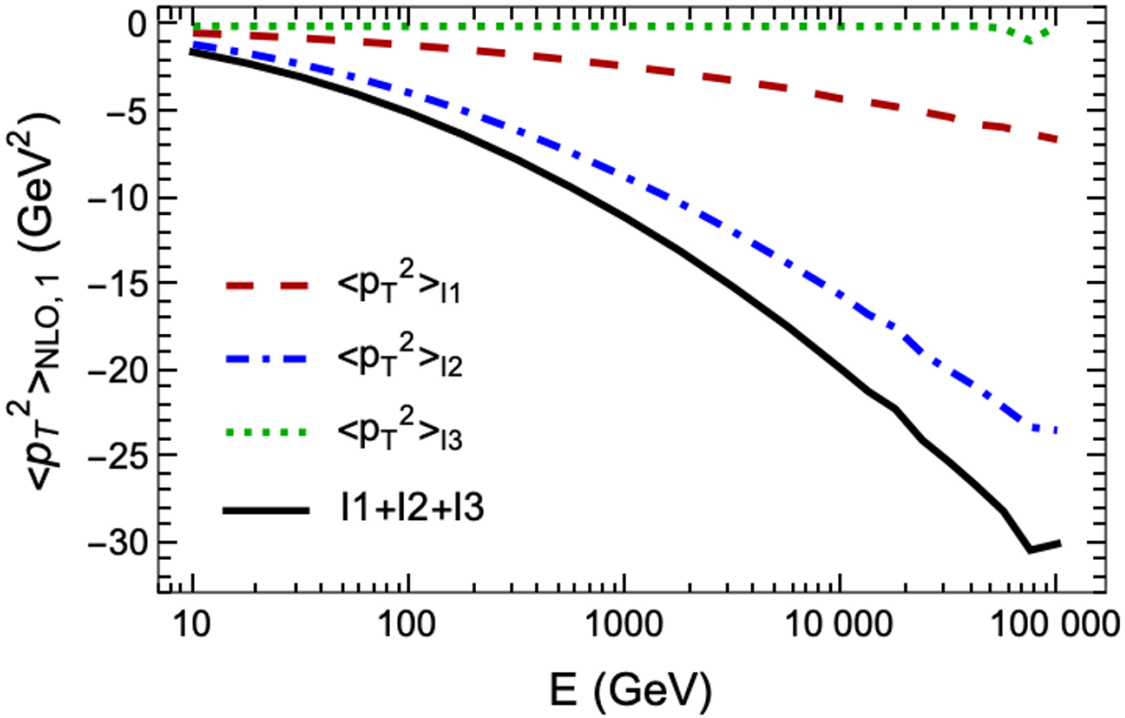
But wrong!

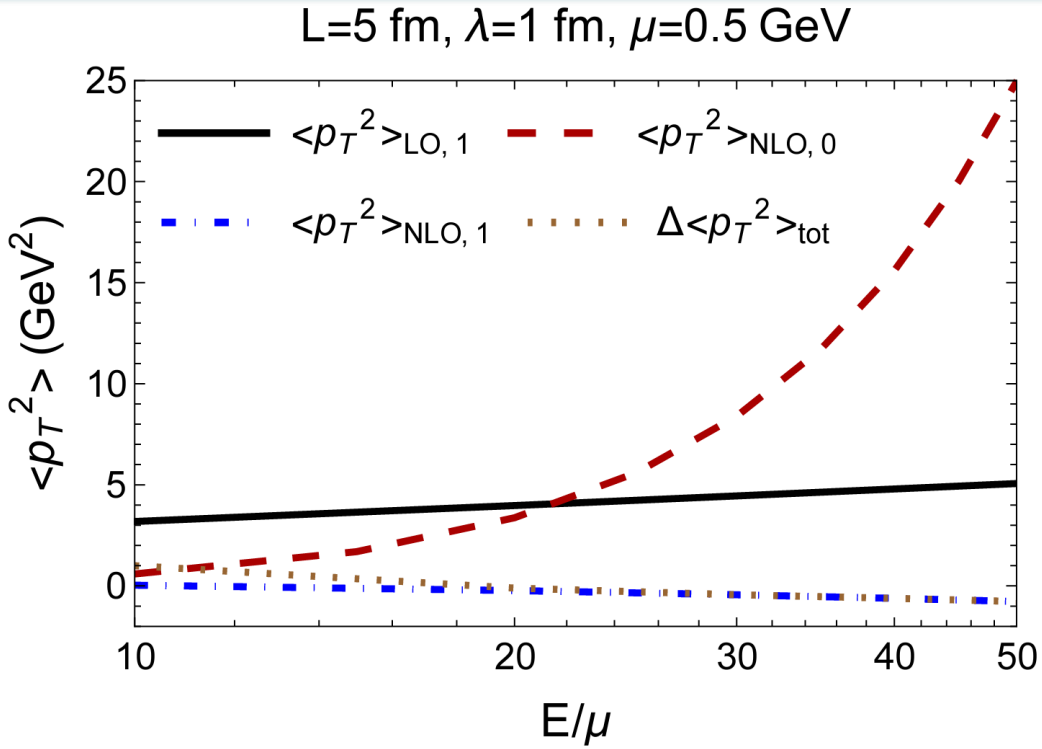


Quantum Evolution?

$$\frac{\langle p_\perp^2\rangle_{\text{NLO, 1}}}{\langle p_\perp^2\rangle_{\text{LO, 1}}} = \frac{4\alpha_s}{3\pi}\ln\frac{E}{\mu}$$

...Versus the Cautious, Methodical Way

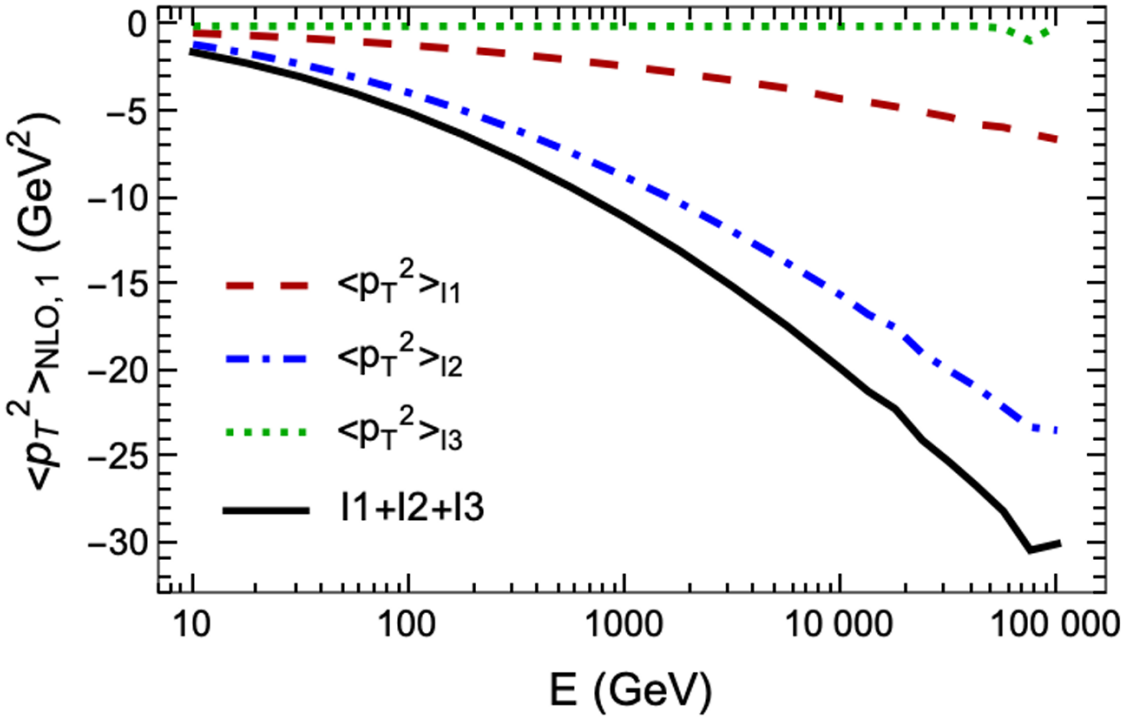


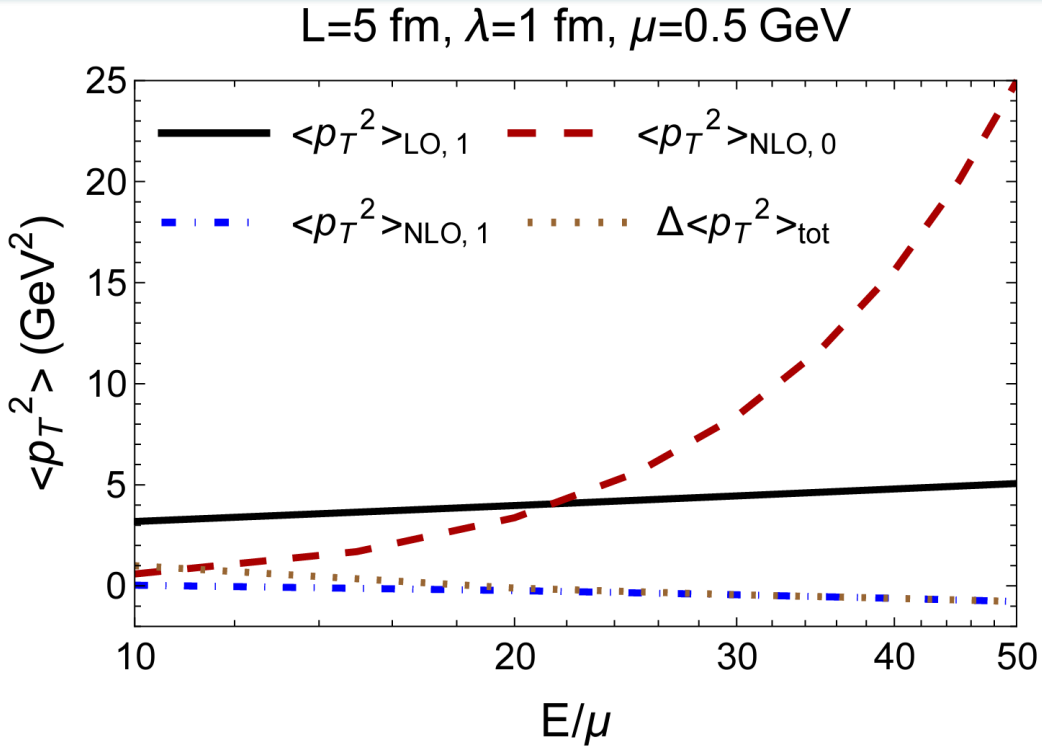


- $\langle p_T^2 \rangle$ is more **sensitive to UV** cutoffs
- Actually **3 logarithmic regions**, with nontrivial **angular dependence**
- Imprecise limits **qualitatively change answer**

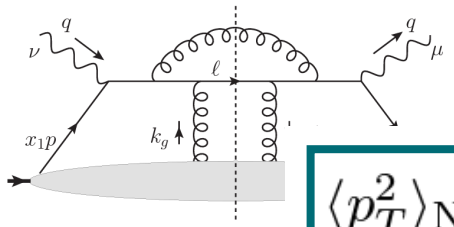
$$\langle p_\perp^2 \rangle_{\mathrm{NLO,\,1}} = \frac{2C_R\alpha_s}{\pi}\frac{L}{\lambda}\Bigg\{ \int_0^{x_{min}} dx \int_0^{k_{max}} dk_\perp \int_0^{2\pi} d\theta \int_0^{q'_{max,+}} dq'_\perp \mathcal{I}$$
$$+ \int_{x_{min}}^{1} dx \int_0^{q_{max}} dk_\perp \int_0^{2\pi} d\theta \int_0^{q'_{max,+}} dq'_\perp \mathcal{I}$$
$$+ \int_{x_{min}}^{1} dx \int_{q_{max}}^{k_{max}} dk_\perp \int_{-\theta_{max}}^{\theta_{max}} d\theta \int_{q'_{max,-}}^{q'_{max,+}} dq'_\perp \mathcal{I}$$

Kinematic Bounds Change the Sign of the Effect





$$\langle p_\perp^2 \rangle_{\mathrm{NLO},\,1} = -\frac{C_R \alpha_s}{4} \frac{L}{\lambda} \mu^2 \quad \log^2\left(\frac{4E}{\mu^2 L}\right)$$



Quantum Evolution?

$$\frac{\langle p_T^2 \rangle_{\mathrm{NLO},\,1}}{\langle p_T^2 \rangle_{\mathrm{LO},\,1}} = -\frac{\alpha_s C_R}{4} \ln \frac{E}{\mu}$$

❖ Tandem analytic / numeric analysis

Comparison to Twist-4

- Collisional broadening: **exact agreement**

$$\frac{d\langle \ell_\perp^2 \sigma\rangle}{dx_B dy} = \frac{d\sigma_0}{dx_B dy}\hat{q}(\mu_f^2)L$$

- Radiative broadening:

$$\left.\frac{d\langle \ell_\perp^2 \sigma\rangle}{dx_B dy}\right|_{\text{NLO}} = \sigma_h \frac{\alpha_s}{2\pi} e_q^2 \log\left(\frac{Q^2}{\mu_f^2}\right)\int_{x_B}^1 \frac{dx}{x}\left[P_{qq}(\hat{x})T_{qg}(x,0,0,\mu_f^2) + P_{qg}(\hat{x})T_{gg}(x,0,0,\mu_f^2)\right]$$

➢ Looks like the **"infinite kinematics" answer...?**

➢ **Convolution** over **hard scattering**

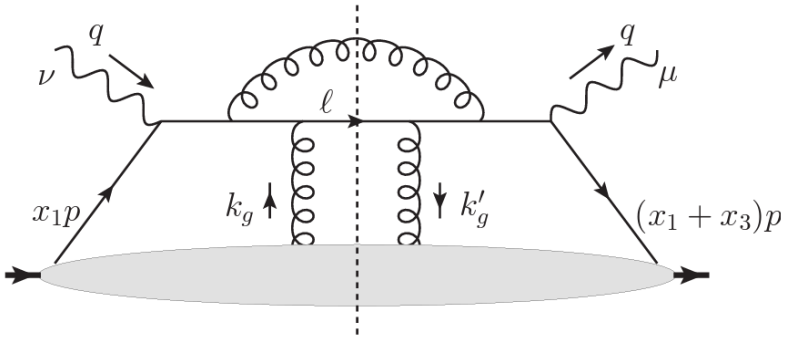
$$\frac{\langle p_T^2\rangle_{\text{NLO, 1}}}{\langle p_T^2\rangle_{\text{LO, 1}}} \approx \boxed{\frac{4\alpha_s}{3\pi}\ln\frac{E}{\mu}} \; \boxed{\frac{\int_{x_B}^1 \frac{dx}{x}\left[\frac{1+\hat{x}^2}{(1-\hat{x}_+} + \frac{3}{2}\delta(1-\hat{x})\right] f_{q/A}(x,\mu^2)}{f_{q/A}(x_B,\mu^2)}}$$

Conclusions

- Jets are promising **tomographic instruments** on similar footing to TMDs and GPDs.

- Jet quenching / broadening in *eA* collisions is a valuable intersection between **collinear factorization** and **higher-twist jet physics**.

- **Transverse momentum broadening** is particularly sensitive to **finite kinematics**
  - ➢ **Qualitatively different** approximations
  - ➢ Trying to **pin down matching** between opacity expansion and twist expansion



Energy Loss (Infinite Kinematics)

$$\frac{\langle p_\perp^2 \rangle_{\mathrm{NLO,\,1}}}{\langle p_\perp^2 \rangle_{\mathrm{LO,\,1}}} = \frac{4\alpha_s}{3\pi} \ln \frac{E}{\mu}$$

Energy Loss (Finite Kinematics)

$$\frac{\langle p_T^2 \rangle_{\mathrm{NLO,\,1}}}{\langle p_T^2 \rangle_{\mathrm{LO,\,1}}} = -\frac{\alpha_s C_R}{4} \ln \frac{E}{\mu}$$

Twist 4

$$\frac{\langle p_T^2 \rangle_{\mathrm{NLO,\,1}}}{\langle p_T^2 \rangle_{\mathrm{LO,\,1}}} \approx \frac{4\alpha_s}{3\pi} \ln \frac{E}{\mu} \times \mathcal{R}_{hard}$$