Medium-Modified Parton Evolution at EIC/EicC

The 1st Annual Conference on Electron-Ion Collider Physics in China, Qingdao, Apr 19–22, 2026

Weiyao Ke, Central China Normal University

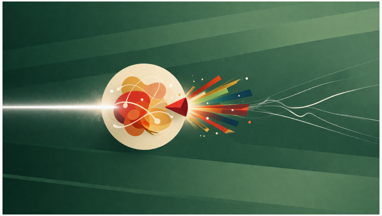
WK, I. Vitev, PLB 854 (2024) 138751

WK, Y. Zhang, H. Xing, X.-N. Wang

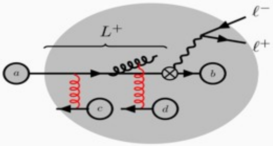
PRD 110 (2024) 034001

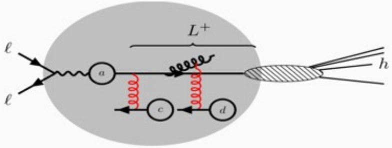
WK, J. Terry, I. Vitev, JHEP 02 (2025) 102

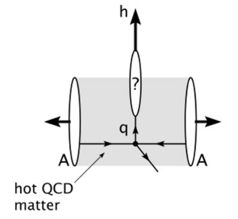
WK, B. Mecaj, I. Vitev, 2512.11952 (JHEP)



Parton propagation in a nuclear medium





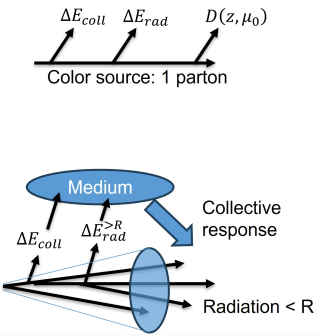


In reactions with nuclei, hard processes are surrounded by nuclear medium.

- Left: parton multiple interactions in the initial-state of Drell-Yan (p+A).
- Middle: parton multiple interactions in the final-state of DIS (e+A).
- Right: quark-gluon plasma effects in A+A, p+A collisions.

In e+A, observables receives dynamical correction relative to e+p.

Why important: dynamical medium effects convolve with structural effects



- For example, consider a SIDIS process tagged by a final-state strange meson (from discussion with Zhihong Ye)

$$\frac{d\sigma}{dx_B\, dy\, dz_h} = \sigma_0 \sum_{ij} f_{i/A}(x_B, \mu) \otimes H_{ji}(x, z, Q, \mu) \otimes D_{K/j}(z_h, \mu).$$

  To study s-quark nuclear PDF, medium modifications of $D_{K/j}(z_h, \mu)$ needs to be considered (energy loss).
- Medium also modify jet observables. But for specific observables, its impact is subdominant compared to nPDF (EIC ℓ-jet correlation, [Fang, Ke, Shao, Terry JHEP 05 (2024) 066]).

Dynamical corrections contain statistical properties of the medium

- Consider collinear parton interact with medium $\mathcal{L}_{\mathrm{int}} = g\phi_c^2(x)A_{\mathrm{med}}(x)$.
- Measure jet observable $\hat{O}[\phi]$, inclusive over the medium. Often treat medium as classical background, and perform ensemble average

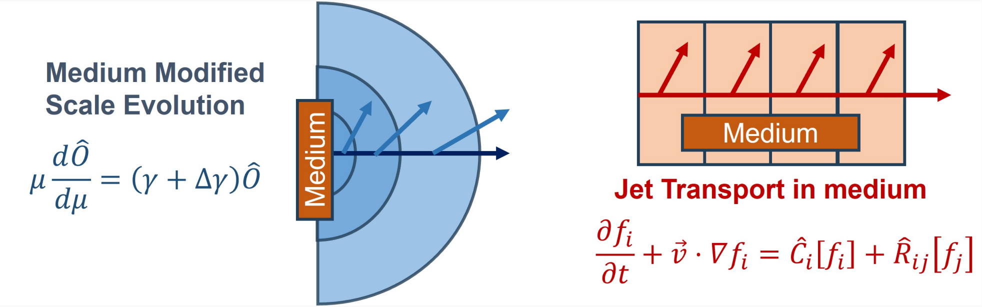
$$\overline{O} = \int \mathcal{D}[\phi_+, \phi_-]\hat{O}[\phi] \underbrace{\int \mathcal{D}[A]e^{-W[A]}}_{\text{medium ensemble avg.}} e^{iS[\phi_+]-iS[\phi_-]+ig\int d^4x\left[\phi_+^2(x)-\phi_-^2(x)\right]A(x)}$$

- Medium correction to $\overline{O}$ depends on $-\frac{g^2}{2}(\phi_+^2 - \phi_-^2)_x\Gamma(x,y)(\phi_+^2 - \phi_-^2)_y$, etc, which encodes statistical correlation functions

$$\Gamma(x,y) = \langle A(x)A(y)\rangle = \int \mathcal{D}[A]e^{-W[A]}A(x)A(y)\,,\ \Gamma(q_\perp) \sim \frac{\rho_{\mathrm{eff}}}{(q_\perp^2 + \xi^2)^2}$$

- **Opacity expansion**: an expansion in $\Gamma(x,y)$ correlated with radiative correction.

The space-time picture of medium modification: two limiting cases



- Thin-medium limit: radiations probe the entire medium in a coherent way.
- Large-medium limit, radiations depends on local properties of the medium.
- In realistic problem, both type of radiations exist.

Medium modified scale evolution versus jet transport

- Cumulative effect of transport: momentum broadening $\langle k_\perp^2 \rangle = \hat{q}L$,
- Scales of fluctuations that sees the medium coherently

$$\frac{2k^0}{k^2} \sim L \longrightarrow k^2 \sim \frac{2k^0}{L}.$$

- Compare transport effect versus medium-modified scale evolution effect

$$r = \frac{2E/L}{\hat{q}L} = \begin{cases} \gg 1 & \text{Medium-modified scale evolution} \\ \ll 1 & \text{Transport phenomena dominants} \end{cases}$$

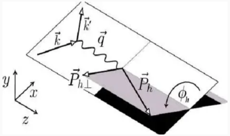
Typical number of r in HIC and EIC

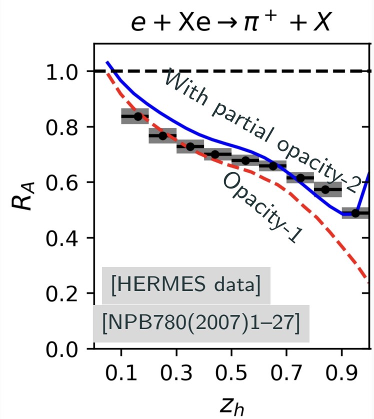
Quark-gluon plasma (LHC)	$\langle \hat{q} L \rangle$	$\frac{2E}{L}$	$r = \frac{2E/L}{\langle \hat{q} L \rangle}$
Central Pb+Pb	8 GeV^2	1 GeV^2, at E=10 GeV	$\mathcal{O}(0.1)$
Central Pb+Pb	8 GeV^2	10 GeV^2, at E=100 GeV	$\mathcal{O}(1)$
High-multiplicity p+Pb	1.5 GeV^2	10 GeV^2, at E=50 GeV	$\mathcal{O}(10)$

Cold nuclear matter	$\langle \hat{q} L \rangle$	$\frac{2E}{L}$ at $y_e = 0.3$	$r = \frac{2E/L}{\langle \hat{q} L \rangle}$
^{131}Kr at HERMES	0.25 GeV^2	1.0 GeV^2	4
^{208}Pb at EicC	0.3 GeV^2	3.5 GeV^2	$\mathcal{O}(10)$
^{208}Pb at EIC	0.3 GeV^2	33 GeV^2	$\mathcal{O}(100)$

EIC and EicC provide a wide range of r to understand medium-modified scale evolution.

Medium-induced/modified collinear evolution





- Medium-induced evolution in the limit $Q^2 > 2\nu/L \gg \xi^2$ [WK, I. Vitev PLB854(2024)138751],

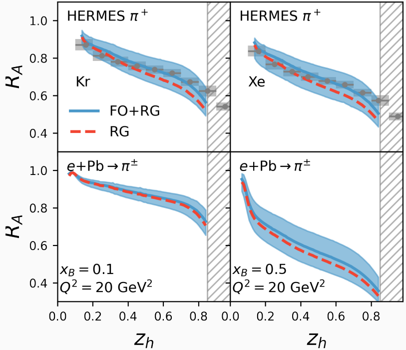
$$\frac{\partial F_q(z,\mu^2)}{\partial \ln \mu^2} = v\left(4C_F C_A \frac{\partial}{\partial z} - \frac{2C_F(2C_A + C_F)}{z}\right) F_q + v\frac{C_F T_R F_g}{z} + \mathcal{O}(v^2),$$

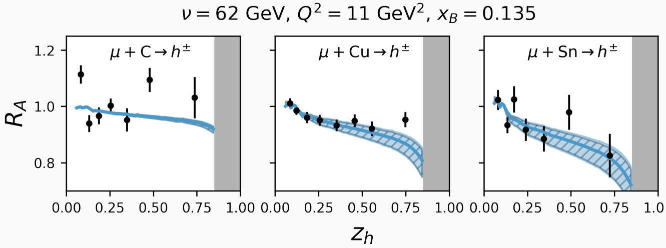
$$\frac{\partial F_g(z,\mu^2)}{\partial \ln \mu^2} = v\left(4C_A^2 \frac{\partial}{\partial z} - \frac{2N_f C_F}{z}\right) F_g + v\frac{2C_F^2 \sum_{q,\bar{q}} F_q}{z} + \mathcal{O}(v^2).$$

- Thin medium criteria $v = \alpha_s^2 B(Q^2 L/2\nu)\frac{\frac{1}{2}\rho L}{2\nu/L} \ll 1.$
- Resum emissions between $2\nu/L > p^2 > \xi^2$, and causes energy loss.

$$R_A = \left[\frac{1}{\sigma}\frac{d\sigma}{dx_B\, dy\, dz_h}\right]_{e+A} \Big/ \left[\frac{1}{\sigma}\frac{d\sigma}{dx_B\, dy\, dz_h}\right]_{e+d}$$

Modified parton evolution and fragmentation (1D)

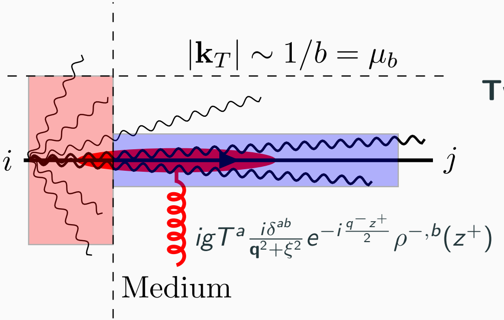




◁ HERMES & EIC, △ EMC (nuclear target)

- Medium modification $e{+}A$ at HERMES, EMC, and EIC.
- Only requires two cold nuclear matter parameters: effective medium density $\rho \approx 0.4/\mathrm{fm}^3$ and medium screening mass $\xi^2 \approx 0.12$ GeV^2.

Medium modified TMD fragmentation (3D)



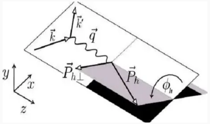
Two leading-log effects at first order in opacity

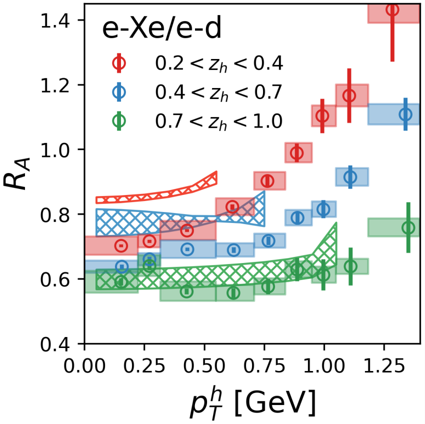
- Medium-induced collinear evolution.
- Momentum broadening due to forward scattering with medium and induced soft radiation.

$$C_{ij}^{\text{vac+med}}(z, b, \mu, \frac{\zeta}{\nu^2}) = e^{\sum_\ell \rho_\ell^- L^+ [\Sigma_{i\ell}(b, \mu_b, \frac{\sqrt{\zeta_{\text{LPM}}\zeta_{\text{med}}}}{\mu_b^2}) - \Sigma_{i\ell}|_{b=0}]} U_{\text{TMD}}(\mu_b, \mu, \frac{\zeta}{\nu^2})$$

$$C_{ik}(z, \alpha_s(\mu_b)) \otimes U_{ks}^{\text{DGLAP}}(z, \mu_b, \mu_0) \otimes M_{si}^{\text{med}}(z, \mu_b, Q^2, 2E/L, \xi^2)$$

Medium (dynamical) Modified TMD fragmentation (3D)



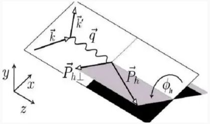


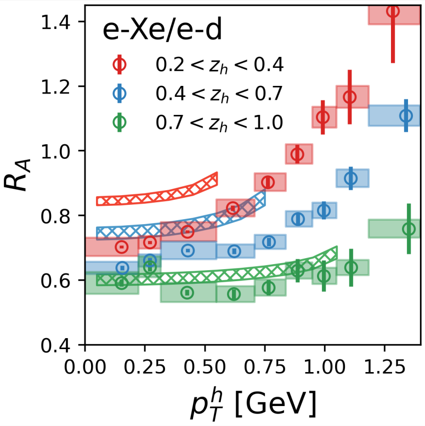
$$R_A = \left[\frac{1}{\sigma}\frac{d\sigma}{dx_B dQ^2 dz_h dp_T^h}\right]_{e+A} \Big/ \left[\frac{1}{\sigma}\frac{d\sigma}{dx_B dQ^2 dz_h dp_T^h}\right]_{e+d}$$

e+Xe to pion at HERMES, three different z_h bins.

- Uncertainty in collinear FF in the vacuum (NNFF1.0nlo).

Medium (dynamical) Modified TMD fragmentation (3D)



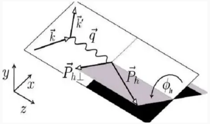


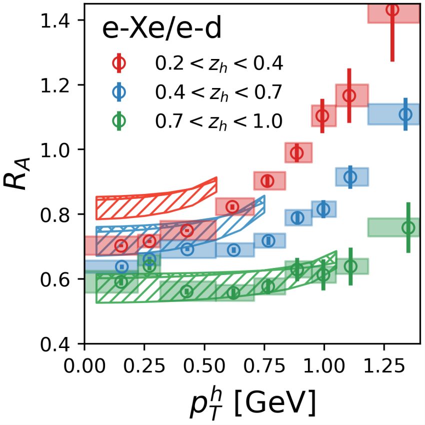
$$R_A = \left[\frac{1}{\sigma}\frac{d\sigma}{dx_B dQ^2 dz_h dp_T^h}\right]_{e+A} \Big/ \left[\frac{1}{\sigma}\frac{d\sigma}{dx_B dQ^2 dz_h dp_T^h}\right]_{e+d}$$

e+Xe to pion at HERMES, three different z_h bins.

- Uncertainty in collinear FF in the vacuum (NNFF1.0nlo).
- Uncertainty in collinear nuclear PDF (nCTEQ15WZnlo).

Medium (dynamical) Modified TMD fragmentation (3D)



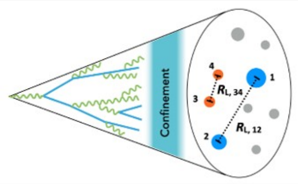


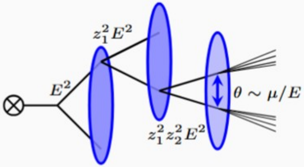
$$R_A = \left[\frac{1}{\sigma}\frac{d\sigma}{dx_B dQ^2 dz_h dp_T^h}\right]_{e+A} \Big/ \left[\frac{1}{\sigma}\frac{d\sigma}{dx_B dQ^2 dz_h dp_T^h}\right]_{e+d}$$

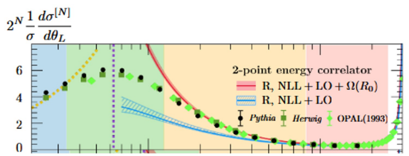
e+Xe to pion at HERMES, three different z_h bins.

- Uncertainty in collinear FF in the vacuum (NNFF1.0nlo).
- Uncertainty in collinear nuclear PDF (nCTEQ15WZnlo).
- Uncertainty in cold nuclear matter parameters (vary by 50%).

Energy correlators as a scale dependent probe of medium modified shower







K. Lee, A. Pathak, I. Stewart, Z. Sun PRL133 (2024) 231902

- Energy correlators [See I. Moult, H.-X. Zhu 2506.09119 for a review]

$$\Sigma(\theta^2, E) = \frac{1}{N_{\rm jet}} \sum_{ij} E_i E_j \delta(\theta^2 - \theta_{ij}), \quad \text{LO: } \Sigma(\theta^2, E) \propto E^2 \frac{\alpha_s}{\theta^2}$$

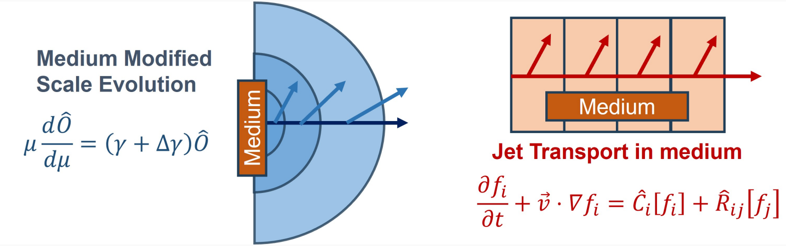
- Multiple emissions within $\theta_{\rm EEC} < \theta_r < R$ reduce the measured energy flows

$$\frac{\partial J_{N,i}(E)}{\partial \ln \mu^2} = J_{N,j}(E) \frac{\alpha_s}{4\pi} \underbrace{(-2) \int_0^1 dx x^{N-1} P_{ij}(x)}_{\gamma_{ij}(N)}$$

Anomalous dimension in the vacuum (e.g., pure glue)

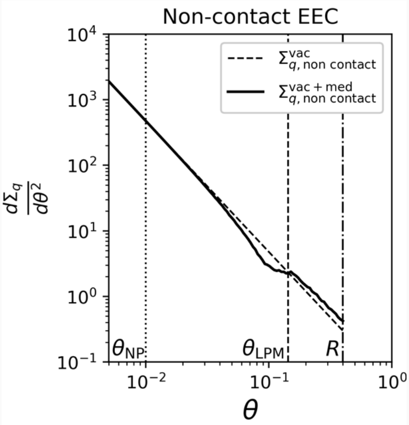
$$\Sigma_N(\theta^2) \propto E^2 \frac{\alpha_s}{\theta^2} \left[\frac{\theta^2}{R^2}\right]^{\frac{\alpha_s}{4\pi}\gamma_{gg}(N)}$$

EEC is ideal to differentiate transport phenomena versus scale evolution

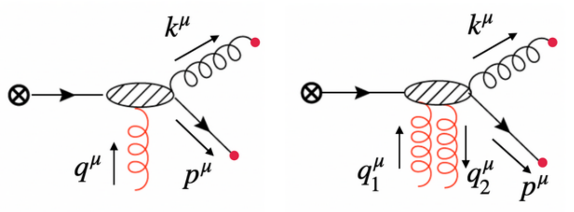


- If medium correction follows a scale evolution, then EEC look into different stage of the shower.
- If medium correction follows a transport equation. The multiple radiations are not necessarily correlated in a scale-dependent way $\Rightarrow$ independent mixture of medium-induced splittings at different time.

Understand EEC in small collision system (p+Pb)



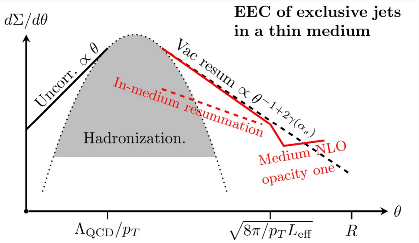
[WK, B. Mecaj, I. Vitev, 2512.11952 (JHEP)]

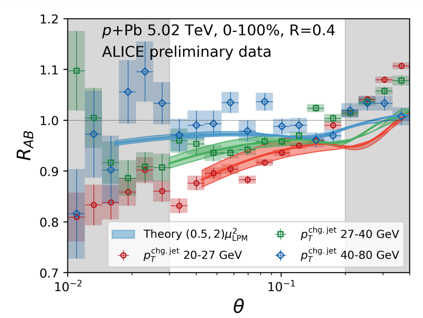


Leading-order and first-order in opacity:

- Magnitude of the correction: $\Delta\Sigma_q \sim \alpha_s^2 \rho_{\rm eff} L_{\rm eff}^3$, with a Coulomb log enhancement ln $\frac{E/L}{\xi^2}$ sensitive to medium screening mass ξ^2.
- Characteristic angle $\theta_{\rm LPM} = \sqrt{\frac{8\pi}{EL}}$.

Medium-modified anomalous dimension





- For $\theta_{\rm EEC} < \theta_r < \theta_{\rm LPM} < R$: medium corrects anomalous dimension (first order in opacity)

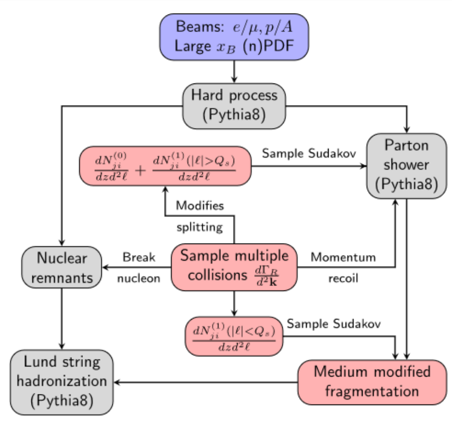
$$\Delta\gamma_{qq}(N) = w_{\rm med}\left(2(N-1)C_F C_A + C_F^2\right)$$
$$\Delta\gamma_{gq}(N) = w_{\rm med}\left(-C_F^2\right)$$
$$\Delta\gamma_{gg}(N) = w_{\rm med}\left(-2N_f T_F C_F\right)$$
$$\Delta\gamma_{qg}(N) = w_{\rm med}\left(-2N_f T_F C_F\right)$$

- Correction directly relates to medium properties (extraction of $\hat{q}$ from EEC in thin medium)

$$w_{\rm med} = \frac{4\pi\alpha_s(\mu^2)\rho_{\rm eff} L_{\rm eff}}{2p_T^{\rm jet}/L^{\rm eff}}$$

◁ EEC ratio [p+Pb]/[p+p], [Ke, Mecaj, Vitev]

Development of event generator based on higher-twist modifications

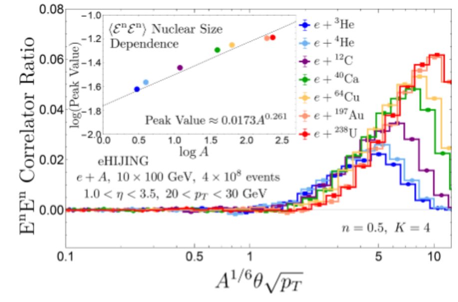


◁ eHIJING based on Pythia8 + medium higher-twist correction to splitting function

[Ke, Zhang, Xing, Wang, PRD110(2024)034001]

▽ Two-point EEC in jets $e + A \to j + X$.

[Devereaux, Fan, Ke, Kyle Lee, Moult, PRC112(2025)035202]



Summary

- At EIC and EicC, the theory of medium-modified scale evolution can be tested in a systematic & differential way.
  - Collinear & TMD fragmentation function in $e{+}A$.
  - EEC provide a scale scan of medium-modified shower..
- Understand medium property, help to separate dynamical medium effects from structural effects.
- Precision data also enable the study of medium properties beyond the statistical correlations and transport coefficients.

Questions?