In medium evolution of energy-energy correlators

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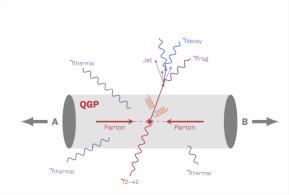
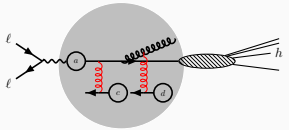
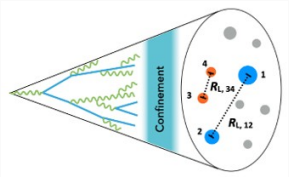
In collaboration with Bianka Meçaj, and Ivan Vitev

Based on WK, B. Meçaj, I. Vitev, JHEP 04 (2026) 155
WK, I. Vitev, PLB 854 (2024) 138751

Scan the QCD medium with energy correlators







- Dynamics of energetic partons is modified by QCD media.

  Hot medium: quark-gluon plasma (QGP). ▸ Alice Ohlson's talk

  Cold medium: interior of nucleus in e+A.

- Energy correlator (EEC): an elegant way to study dynamics at different scale ($\mu = \theta E$) [I. Moult, H.-X. Zhu 2506.09119 for a review]

$$\Sigma(\cos\theta = \vec{n}_1 \cdot \vec{n}_2) = \langle \hat{\mathcal{E}}_{n_1} \hat{\mathcal{E}}_{n_2} \rangle\,, \quad \hat{\mathcal{E}}_n = \lim_{r\to\infty} r^2 \int_0^\infty dt\, n_i \hat{T}^{0i}(t, r\vec{n})$$

- Questions: 1) How are EECs modified by QCD medium?
  2) Do EECs test new aspects of jets in medium?

Diagnose QCD medium in small system with EEC

- Factorized calculations of EEC measured in jets $(y, p_T^{\rm jet}, R)$ in hadronic/nuclear collider

$$\frac{d\Sigma_{AB}}{d\theta\, dp_T^{\rm jet}\, dy} = \sum_{a,b,i,X} \int dx_a\, dx_b\, dz_J\; f_{a/A}(x_a,\mu)\, f_{b/B}(x_b,\mu)\, \mathcal{H}_{ab\to iX}\left(\frac{p_T^{\rm jet}}{z_J},\, y, \mu\right)$$
$$\times \underbrace{\left[\mathcal{J}^{\rm vac}_{{\rm EEC},i}(\theta; z_J, p_T^{\rm jet}, R, \mu) + \Delta\mathcal{J}^{\rm med}_{{\rm EEC},i}\right]}_{\text{The EEC jet function}}$$

- This work studies medium modifications to EEC jet function under conditions:

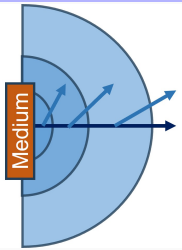
  1) $p_T^{\rm jet}/L \gg \hat{q}L$. L: size of medium; $\hat{q}L$: $k_\perp^2$ broadening.
  2) And, small/moderate medium opacity.

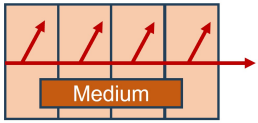
1. Why take the large jet energy limit $p_T^{\text{jet}}/L \gg \hat{q}L$?

Take $p_T^{\text{jet}}/L \gg \hat{q}L$ to maximally exploit the scale-resolving power of EEC

Medium Modified Scale Evolution

$$\mu \frac{d\hat{O}}{d\mu} = (\gamma + \Delta\gamma)\hat{O}$$





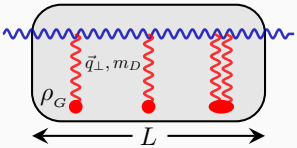
Jet Transport in medium

$$\frac{\partial f_i}{\partial t} + \vec{v} \cdot \nabla f_i = \hat{C}_i[f_i] + \hat{R}_{ij}[f_j]$$

- Modes with $\frac{k^0}{k^2} \gg L$ probe the entire medium coherently.
  $\Rightarrow$ Modified resolution scale dependence for observable when $\mu^2 < \frac{k^0}{L}$.
- Modes with $\frac{k^0}{k^2} \ll L$ are sensitive to local properties of the medium.
  $\Rightarrow$ Cumulative effect of jet transport in medium: $k^2 \sim \hat{q}L$.

2. Why consider small opacity?

- **Opacity (χ):** average number of scatterings between jet and medium.



$$\chi = \text{Length} \times \text{Density} \times \text{Cross-section}$$
$$= \int_0^\infty dz^+ \times \rho_G(z^+) \times \int \frac{d^2 q_\perp}{(2\pi)^2} \frac{g_s^2 C_a}{(q_\perp^2 + m_D^2)^2} = \frac{\alpha_s C_a \rho_G}{m_D^2} L \sim \frac{\hat{q}}{m_D^2} L$$

  - $\rho_G(z^+) = \sum_b n_b(z^+) g_s^2 C_b / d_A$: density profile of medium.
  - $m_D^2 = (1 + N_f/6) g_s^2 T^2$: plasma screening mass (squared).

- **The opacity expansion**: compute in series of small χ. Suitable for small collision systems (p+A, O+O, L small) or dilute medium (e+A, ρ_G small).

Compute EEC jet function to $\mathcal{O}(\alpha_s \cdot \chi)$

- The vacuum jet function + medium-correction is

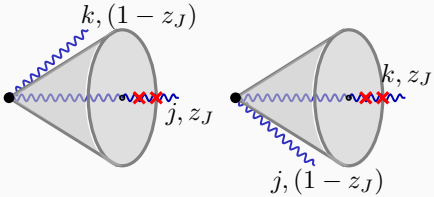
$$\mathcal{J}_{\mathrm{EEC},i} = \mathcal{J}^{\mathrm{vac}}_{\mathrm{EEC},i}(\theta;\, z_J,\, p_T, R, \mu) + \mathcal{J}^{\mathrm{med}}_{\mathrm{EEC},i}(\theta;\, z_J,\, p_T, R, \mu; \text{Medium-related scales})$$

- First organize the vacuum part into

$$\begin{aligned}
\mathcal{J}^{\mathrm{vac}}_{\mathrm{EEC},i}(\theta;\, z_J,\, p_T, R, \mu) &= \delta(1 - z_J)\mathcal{J}^{\mathrm{vac},(0)}_{\mathrm{EEC},c}(\theta; p_T, R, \mu) && \text{Non-pert. contribution } O(\alpha_s^0) \\
&+ \mathcal{J}^{\mathrm{vac},(1)}_{\mathrm{EEC},i}(\theta; z_J, p_T, R, \mu) && \text{Radiations out of the cone } O(\alpha_s^1) \\
&+ \delta(1 - z_J)\mathcal{J}^{vac,(1)}_{\mathrm{EEC},i}(\theta; p_T, R, \mu) && \text{Radiations in the cone } O(\alpha_s^1)
\end{aligned}$$

- Medium contribution can be organized as $O(\chi)$ correction to each terms.

Vacuum: radiations out of the cone, and the hard-collinear functions



+ Scaleless virtual correction

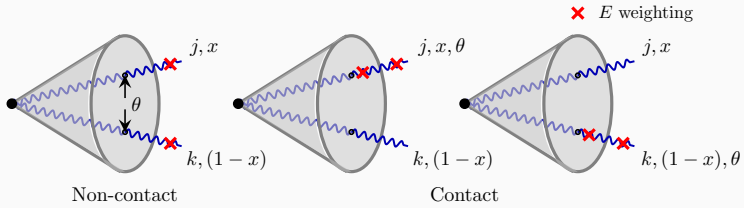
- Out-of-cone radiation only change jet energy fraction and flavor relative to the hard parton. They factor out as hard collinear functions $\mathcal{H}_{ij}$

$$\mathcal{J}^{\mathrm{vac},(0)+(1)}_{\mathrm{EEC},i}(\theta; z_J, p_T, R, \mu) = \sum_j \underbrace{\mathcal{H}_{ji}(z_J, p_T, R, \mu)}_{\textbf{out-of-cone}} \times \underbrace{\mathcal{J}^{\mathrm{vac}}_{\mathrm{EEC},j}(\theta; p_T, R, \mu)}_{\textbf{Exclusive jet function}} + \mathcal{O}(\alpha_s^2)\,.$$

- μ-dependence of $\mathcal{H}_{ij}$ follows standard time-like DGLAP equation

$$\frac{\partial}{\partial \ln \mu^2} \begin{bmatrix} \mathcal{H}_{jq}(z_J, p_T, R, \mu) \\ \mathcal{H}_{jg}(z_J, p_T, R, \mu) \end{bmatrix} = \frac{\alpha_s(\mu)}{2\pi} \begin{bmatrix} \hat{P}_{qq}(z) & \hat{P}_{gq}(z) \\ 2N_f \hat{P}_{qg}(z) & \hat{P}_{gg}(z) \end{bmatrix} \otimes_{z_J} \begin{bmatrix} \mathcal{H}_{jq}(z_J, p_T, R, \mu) \\ \mathcal{H}_{jg}(z_J, p_T, R, \mu) \end{bmatrix}.$$

Vacuum: radiations in the cone, and the exclusive EEC jet function



- **Non-contact**: energy weighted on different branch of the splittings

$$\mathcal{J}^{\mathrm{nc,vac},(1)}_{\mathrm{EEC},i}(\theta; p_T) = \sum_{(jk)} \frac{\alpha_s}{2\pi^2} \int_0^1 dx P^i_{jk}(x) \int \frac{d^2 k_\perp}{k_\perp^2} \underbrace{x(1-x)}_{E \text{ weighting}} \delta\left(\theta^2 - \theta_{jk}^2\right) \propto \frac{\alpha_s}{2\pi} \frac{1}{\theta^2}$$

- **Contact**: energy weighted on the same parton.

$$\mathcal{J}^{\mathrm{c,vac},(1)}_{\mathrm{EEC},i}(\theta; p_T) = \frac{\alpha_s}{2\pi^2} \int \frac{d^2 k_\perp}{k_\perp^2} \int_0^1 dx \Theta^<_{jk} P^i_{jk}(x) \Big[\underbrace{\mathcal{J}^{\mathrm{vac}(0)}_{\mathrm{EEC},j}(\theta; x p_T)}_{\approx x^2 \mathcal{J}^{\mathrm{vac}(0)}_{\mathrm{EEC},j}(\theta; p_T)} + \underbrace{\mathcal{J}^{\mathrm{vac}(0)}_{\mathrm{EEC},k}(\theta; (1-x) p_T)}_{\approx (1-x)^2 \mathcal{J}^{\mathrm{vac}(0)}_{\mathrm{EEC},k}(\theta; p_T)} \Big]$$

Apply LO energy-scaling of EEC ▷

Scale dependence of the exclusive EEC jet function

- RGEs of the exclusive jet function, and initial conditions at $\mu = \theta p_T$.

$$\frac{\partial \mathcal{J}_i^{\rm vac}(\theta, p_T, \mu)}{\partial \ln \mu^2} = -\sum_j \mathcal{J}_j^{\rm vac}(\theta, p_T, \mu) \frac{\alpha_s(\mu)}{4\pi} \gamma_{ji}^{(0)}(N)\,,$$

$$\mathcal{J}_i^{\rm vac}(\theta, p_T, \mu = \theta p_T) = \frac{\alpha_s(\mu)}{2\pi} \frac{1}{\theta^2} \left[A_i + \text{“terms suppressed by } \frac{\Lambda}{\theta p_T}\text{”}\right]$$

- Anomalous dimensions are moments of the splitting functions [L. J. Dixon, I. Moult, H.-X. Zhu, PRD100(2019)014009]. The leading-order ones:

$$\gamma_{ji}^{(0)}(N) = (-2) \int_0^1 dz x^{N-1} [P_{ji}(x)]_+$$

For EEC ($N = 3$): $\gamma_{qq}^{(0)}(3) = \frac{25}{6} C_F\,,\ \gamma_{gg}^{(0)}(3) = \frac{14}{5} C_A + \frac{2}{3} N_f\,,\ \gamma_{gq}^{(0)}(3) = -\frac{7}{6} C_F\,,\ \gamma_{qg}^{(0)}(3) = -\frac{14}{15} T_F N_f\,.$

Factorization in the vacuum, and the expected medium corrections

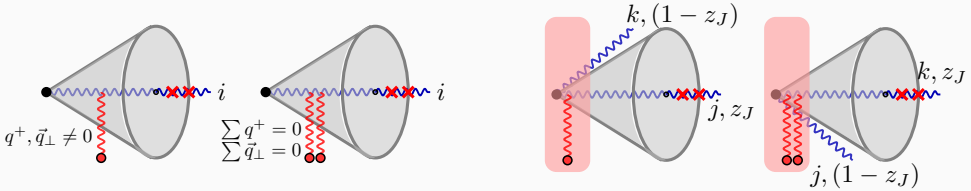
- The (resumed) EEC jet function in the vacuum, for angular region $\Lambda/p_T \ll \theta < R$

$$\mathcal{J}^{\text{vac}}_{\text{EEC},i}(\theta; z_J, p_T, R, \mu_H) = \mathcal{H}_{ji}(z_J, p_T, R, \mu_H) \Big[\exp\Big\{ \int_{2p_T \tan\frac{R}{2}}^{\theta E} \frac{\alpha_s(\mu)}{2\pi} \gamma^{(0)}(3)\, d\ln\mu \Big\} \Big]_{kj} \frac{\alpha_s(\theta E)}{2\pi} \frac{A_k}{\theta^2} .$$

- Medium effects can potentially show up in each sector:

$$\mathcal{J}^{\text{med}}_{\text{EEC},i}(\theta; z_J, p_T, R, \mu) = \overbrace{\Delta z_{\text{coll}}(-\delta'(1-z))\mathcal{J}^{\text{vac},(0)}_{\text{EEC},i}(\theta; p_T, R, \mu)}^{\text{Collisional energy loss}} + \overbrace{\mathcal{J}^{\text{med},(1)}_{\text{EEC},i}(\theta; z_J, p_T, R, \mu)}^{\text{Radiative } E\text{-loss \& conversion}}$$
$$+\delta(1-z_J)\Big[\underbrace{\mathcal{J}^{\text{contact,med},(1)}_{\text{EEC},i}(\theta; p_T, R, \mu) + \mathcal{J}^{\text{non-contact,}med,(1)}_{\text{EEC},i}(\theta; p_T, R, \mu)}_{\text{Medium-induced radiations in the cone}} \Big]$$

Medium modifications I: hard collinear function $\mathcal{H}_{ji} + \Delta\mathcal{H}_{ji}$

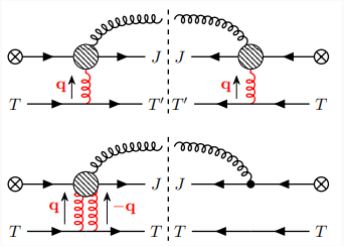


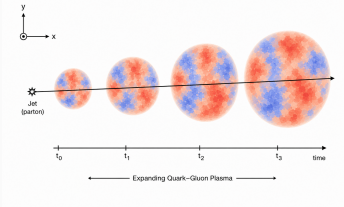
- Collisional energy loss: energy loss rate $d\Delta E_{\rm coll}/dL$ from the Hard-Thermal-Loop calculation [E. Braaten, M. H. Thoma, PRD44(1991)R2625] .
- Radiative energy loss: medium-induced radiations out of the cone

$$\Delta E_{\rm rad} \propto C_R C_A \rho_{\rm eff} L_{\rm eff}^2 \frac{2}{\beta_0}\left[\alpha_s\left(m_D\right) - \alpha_s\left(\left(\#L_{\rm eff}\tan\frac{R}{2}\right)^{-1}\right)\right]$$

- A shift of parton energy: $\left(\mathcal{H}_{ji} + \Delta\mathcal{H}_{ji}\right) \otimes d\sigma = \left(\mathcal{H}_{ji} \otimes d\sigma\right)_{p_T \to p_T + \Delta E_{\rm coll} + \Delta E_{\rm rad}}$

Theory inputs for the medium-induced radiations





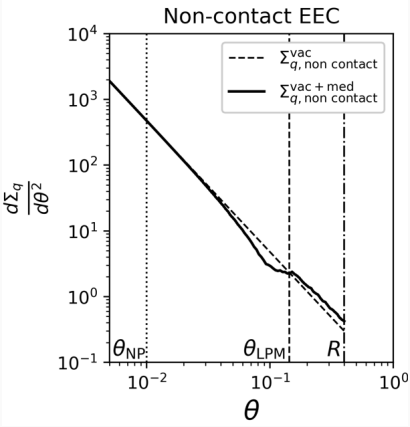
- $\frac{dN_{ij}}{dxd^2k_\perp}$ are the medium-induced radiation spectrum. For example, for $q \to q + g$ at first order in opacity:

$$\left(\frac{dN}{dxd^2\mathbf{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2} C_F \frac{1+(1-x)^2}{x} \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\mathbf{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\text{medium}}}{d^2\mathbf{q}_\perp} \left[\frac{\mathbf{B}_\perp}{B_\perp^2} \cdot \left(\frac{\mathbf{B}_\perp}{B_\perp^2} - \frac{\mathbf{C}_\perp}{C_\perp^2} \right) \right.$$
$$\times \left(1 - \cos[(\Omega_1 - \Omega_2)\Delta z]\right) + \frac{\mathbf{C}_\perp}{C_\perp^2} \cdot \left(2\frac{\mathbf{C}_\perp}{C_\perp^2} - \frac{\mathbf{A}_\perp}{A_\perp^2} - \frac{\mathbf{B}_\perp}{B_\perp^2} \right) \left(1 - \cos[(\Omega_1 - \Omega_3)\Delta z]\right)$$
$$+ \frac{\mathbf{B}_\perp}{B_\perp^2} \cdot \frac{\mathbf{C}_\perp}{C_\perp^2} \left(1 - \cos[(\Omega_2 - \Omega_3)\Delta z]\right) + \frac{\mathbf{A}_\perp}{A_\perp^2} \cdot \left(\frac{\mathbf{D}_\perp}{D_\perp^2} - \frac{\mathbf{A}_\perp}{A_\perp^2} \right) \left(1 - \cos[\Omega_4 \Delta z]\right)$$
$$\left. - \frac{\mathbf{A}_\perp}{A_\perp^2} \cdot \frac{\mathbf{D}_\perp}{D_\perp^2} \left(1 - \cos[\Omega_5 \Delta z]\right) + \frac{1}{N_c^2} \frac{\mathbf{B}_\perp}{B_\perp^2} \cdot \left(\frac{\mathbf{A}_\perp}{A_\perp^2} - \frac{\mathbf{B}_\perp}{B_\perp^2} \right) \left(1 - \cos[(\Omega_1 - \Omega_2)\Delta z]\right) \right],$$

G. Ovanesyan, I. Vitev, PLB 706 (2012) 371-378

- The formula integrates over QGP density profile (from a hydrodynamic simulation [iEBE-VISHNU, CPC199(2016)61-85]).

Medium modifications II: the initial condition to first order in opacity



[Ke, Mecaj, Vitev, JHEP04(2026)155]

Medium non-contact EEC jet function

$$\mathcal{J}^{\rm nc,med(1)}_{{\rm EEC},i}(\theta) = \int dx d^2k_\perp d^2q_\perp \frac{dN^{\rm real\ emission}_{\rm med,i\to j+k}}{dx d^2k_\perp d^2q_\perp} x(1-x)\delta(\theta^2-\theta_{ij}^2)$$

- The LPM interference factor defines an characteristic angle $\theta_{\rm LPM} = \sqrt{\frac{8\pi}{E_{\rm jet}L}}$, $\quad (E_{\rm jet} = p_T^{\rm jet})$

$$1-\cos\left[\frac{k_\perp^2 L}{2x(1-x)E_{\rm jet}}\right] = 1-\cos\left[4\pi x(1-x)\frac{\theta^2}{\theta^2_{\rm LPM}}\right]$$

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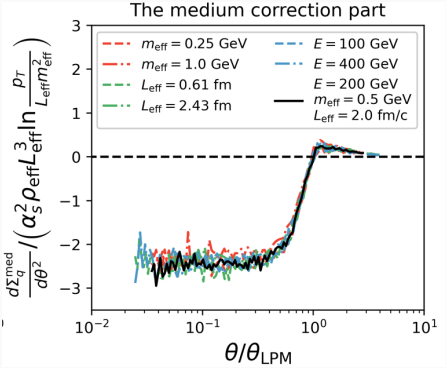

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- Magnitude of the correction: $\propto \alpha_s^2 \rho_G L^3 \ln \frac{p_T^{\rm jet} L}{m_D^2}$. The log due to $1/q_\perp^4$ tail of the scattering between jet and medium.

Medium modifications III: the modified anomalous dimension

- Extract $\Delta\gamma_{ji}$ from the contact part of exclusive EEC jet function:

$$\mathcal{J}^{\mathrm{c,med}(1)}_{\mathrm{EEC},i}(\theta) = \int_0^1 dx \left[\int d^{2-2\epsilon}k_\perp \Theta^<_{jk} \frac{dN^{\text{real emission}}_{\mathrm{med,i\to j+k}}}{dx d^{2-2\epsilon}k_\perp} \right]_+ \left[x^{N-1}\mathcal{J}^{(0)}_{\mathrm{EEC},j}(\theta, E) + (1-x)^{N-1}\mathcal{J}^{(0)}_{\mathrm{EEC},k}(\theta, E) \right]$$

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- Performs power expansion in $\frac{m_D^2}{p_T^{\mathrm{jet}}/L}$ and obtain $\Delta\gamma_{ji}$ as coefficients of $1/\epsilon$ poles

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

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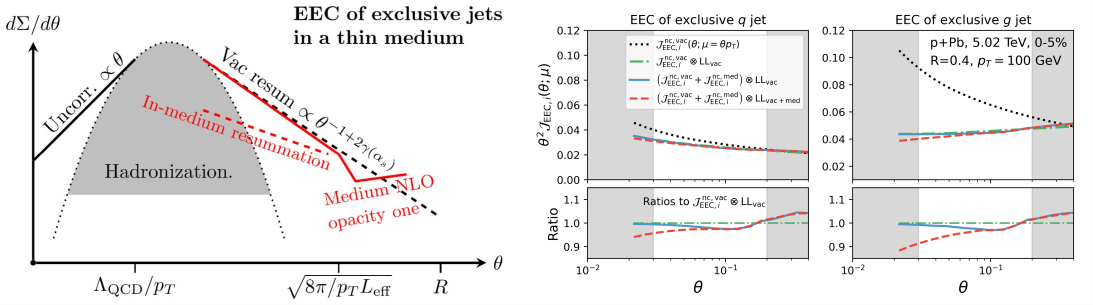
[Ke, Mecaj, Vitev, JHEP04(2026)155]

- $\Delta\gamma_{ji}$ only depends on global medium properties due to the coherent nature,

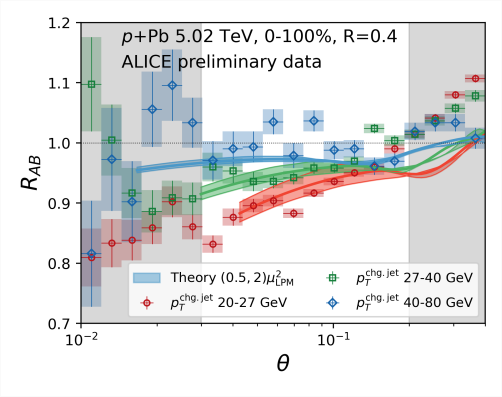
$$w_{\mathrm{med}} = \frac{4\pi\alpha_s(\mu^2)\,\rho_{\mathrm{eff}}\,L_{\mathrm{eff}}}{2p_T^{\mathrm{jet}}/\,L_{\mathrm{eff}}} \ll 1, \quad \text{with } 0 = \int_0^\infty \rho_G(z^+) z^+ \ln\frac{z^+}{L_{\mathrm{eff}}} dz^+, \quad \rho_{\mathrm{eff}} = \int_0^\infty \frac{dz^+}{L_{\mathrm{eff}}}\frac{z^+}{L_{\mathrm{eff}}}\rho_G(z^+)$$

Effects of the modified initial condition and modified anomalous dimension



- Modes resolve medium size: $k^2 \sim k^0/L$. Typical angles $\theta \sim \sqrt{k^2}/k_0^2 \sim 1/\sqrt{p_T L}$.
- Modes coherent over medium: $\Lambda^2 \ll k^2 \ll k^0/L$. Modify γ_{ji} between $\frac{\Lambda}{p_T} \ll \theta \ll \frac{1}{\sqrt{p_T L}}$

Compare to preliminary ALICE measurement in p+Pb



- The middle window: $\frac{\Lambda_{\mathrm{QCD}}}{p_T^{\mathrm{jet}}} \ll \theta \ll \sqrt{\frac{8\pi}{p_T^{\mathrm{jet}} L}}$. Consistent with the p_T^{jet} dependence.

  [Prelim data: Liang-Gilman 2506.22692]

  [and A. Nambrath's talk at QM25]

- If confirmed $\Rightarrow$ a direct evidence of medium-modified scale evolution.
- Possible robust probe of QGP in small system

$$R_{AB}[\mathrm{PE3C}]/R_{AB}[\mathrm{E2C}] \sim \exp\left(-\frac{4\pi}{\beta_0} 2 C_R C_A \frac{\rho_{\mathrm{eff}} L_{\mathrm{eff}}^2}{p_T^{\mathrm{jet}}} \left[\alpha_s(p_T^{\mathrm{jet}}\theta) - \alpha_s(p_T^{\mathrm{jet}} R)\right]\right)$$

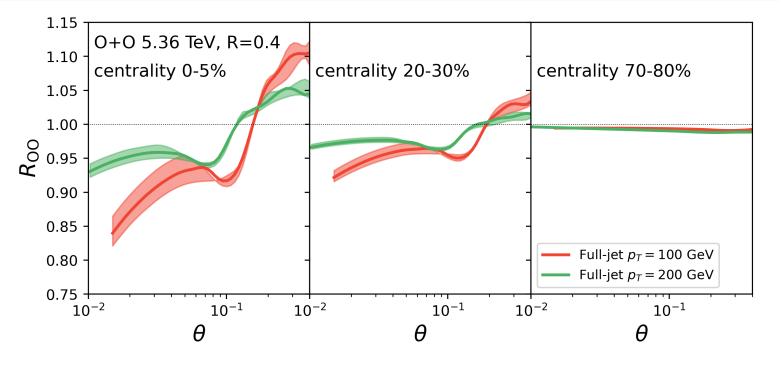
.

Summary

- We studied the medium modified jet EEC when $p_T^{\rm jet}/L \gg \hat{q}L$ and $\hat{q}L/m_D^2 \sim 1$. (Small or dilute systems).
- Emissions resolve the medium size $k^0/k^2 \sim L$ are computed at first order in opacity $\Rightarrow$ corrections at typical angle $\theta_{\rm LPM} = \sqrt{\frac{8\pi}{p_T^{\rm jet} L}}$.
- Emissions coherent over the medium $k^0/k^2 \gg L$ modify the EEC anomalous dimension within $\frac{\Lambda}{p_T^{\rm jet}} \ll \theta \ll \theta_{\rm LPM}$. $\Delta\gamma_{ji}$ only depends on medium global properties.
- Ongoing: use these findings to perform robust characterization of QGP.

Questions?

Projection for full-jet in O+O, 5.36 TeV



Using the same hydrodynamic and jet parameters as the p+Pb calculation, only changing collision energy and nuclear species.

Typical number of v in HIC and EIC

Quark-gluon plasma (LHC)	$\langle \hat{q}L \rangle$	$\frac{2E}{L}$	$v = \frac{\langle \hat{q}L \rangle}{2E/L}$
Central Pb+Pb	8 GeV^2	1 GeV^2, at E=10 GeV	$\mathcal{O}(10)$
Central Pb+Pb	8 GeV^2	10 GeV^2, at E=100 GeV	$\mathcal{O}(1)$
$\star$ O+O, $b = 0$ p+Pb	1.5 GeV^2	10 GeV^2, at E=50 GeV	$\mathcal{O}(0.1)$

Cold nuclear matter	$\langle \hat{q}L \rangle$	$\frac{2E}{L}$ at $y_e = 0.3$	$v = \frac{\langle \hat{q}L \rangle}{2E/L}$
$\star$ ^{131}Kr at HERMES	0.25 GeV^2	1.0 GeV^2	0.25
$\star$ ^{208}Pb at EicC	0.3 GeV^2	3.5 GeV^2	$\mathcal{O}(0.1)$
$\star$ ^{208}Pb at EIC	0.3 GeV^2	33 GeV^2	$\mathcal{O}(0.01)$