Jet EEC in Cold Nuclear Matter

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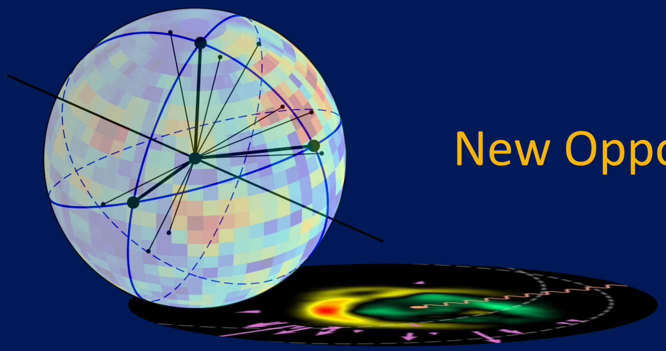
Reference: arXiv:2411.04866

In collaboration with Yu Fu and Berndt Müller



New Opportunities in Particle and Nuclear Physics with Energy Correlators

May 16, 2025

Outline

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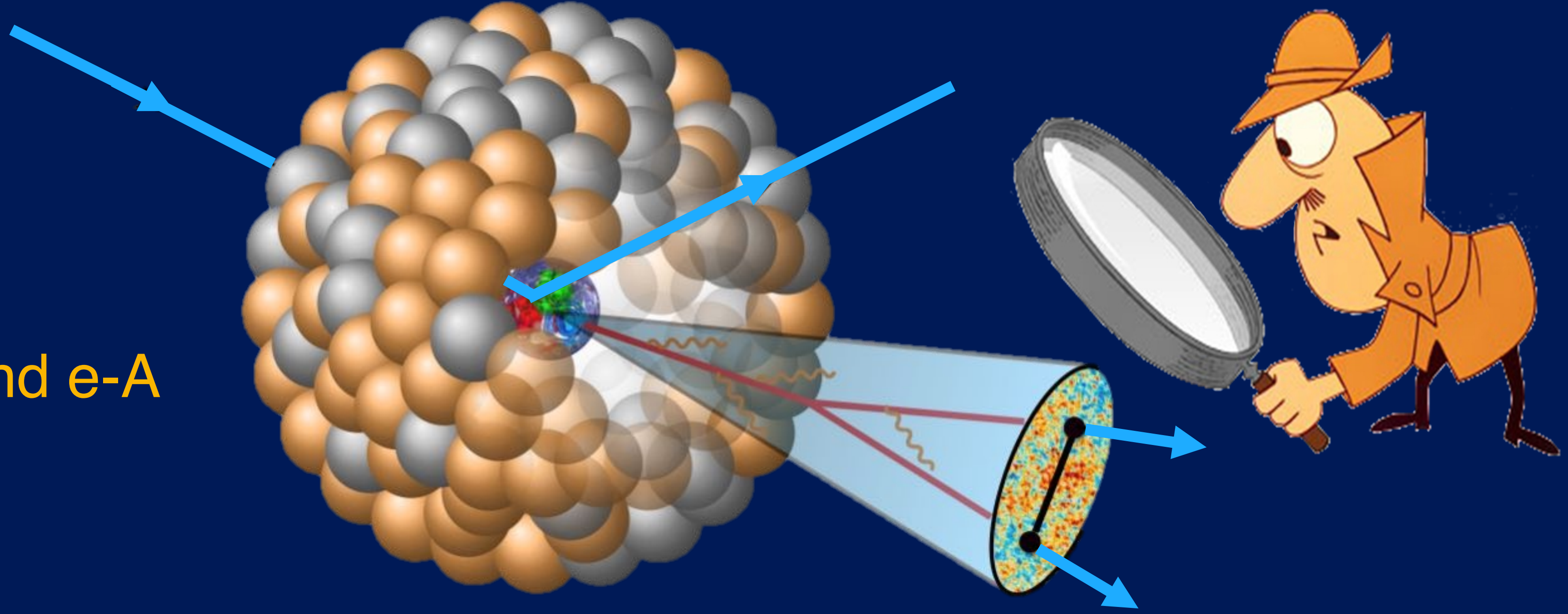
  - Jet EECs in CNM
  - Higher-twist formalism
- Jet EECs in SIDIS – e-p and e-A
  - EEC ratio in SIDIS
- Jet EECs in p-A collisions: comover effect
  - EEC ratio in p-Pb and p-p
- Summary



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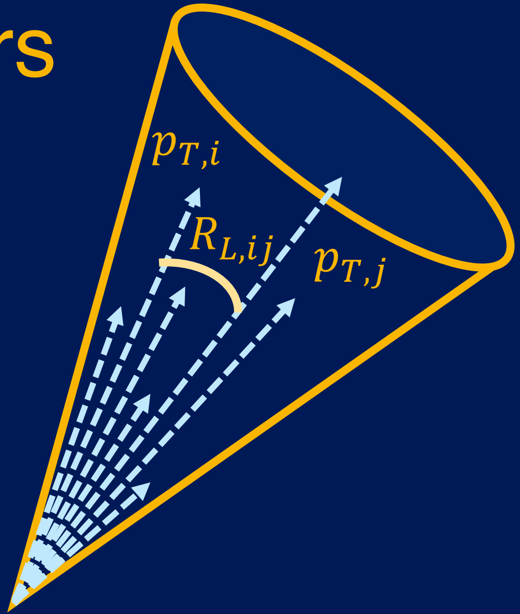
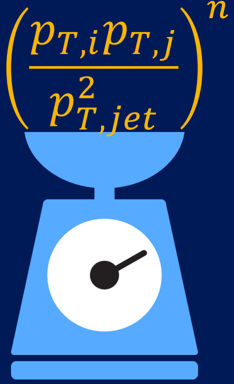
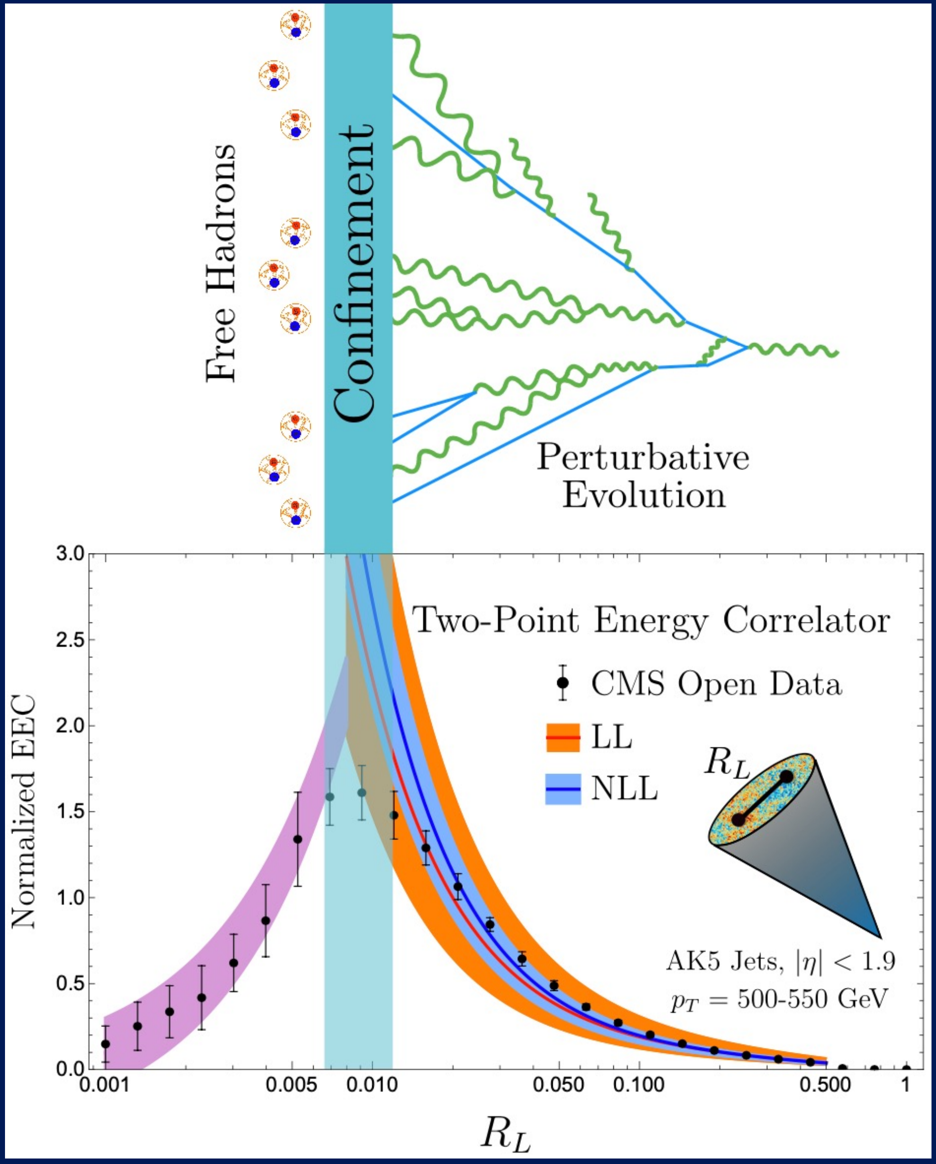
Jet Energy-energy correlators



- Jet substucture observable
  - Reduced sensitivity to soft radiation
  - Weight exponent: tune sensitivity
  - No need for grooming
- $Q \to \Lambda_{QCD} \sim p_T^{jet} R_L$: Phase transition
  - Separation of perturbative and non-perturbative regimes
- mapping time evolution of jet formation into EEC angular scaling with $\tau = \frac{1}{p_T R_L^2}$



$$\frac{d\sigma_{EEC}}{dR_L} = \sum_{i \neq j} \int d\sigma(R'_L) \left(\frac{p_{T,i}\, p_{T,j}}{p_{T,jet}^2}\right)^n \delta(R'_L - R_{L,ij})$$



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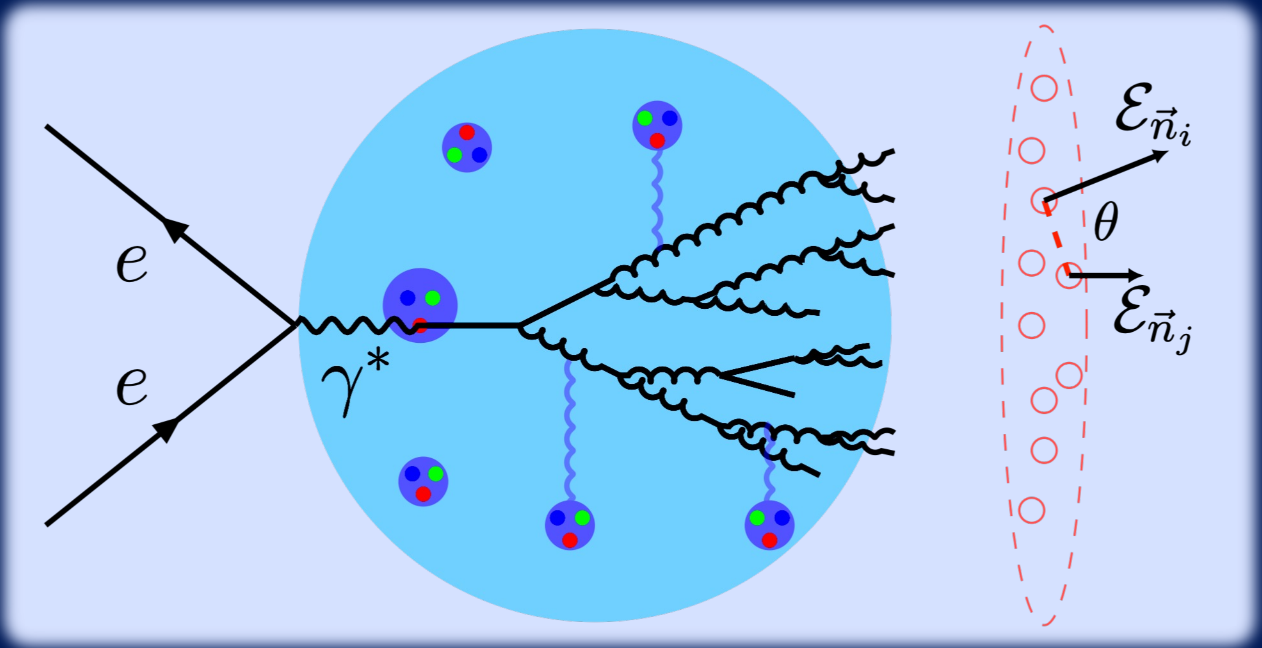
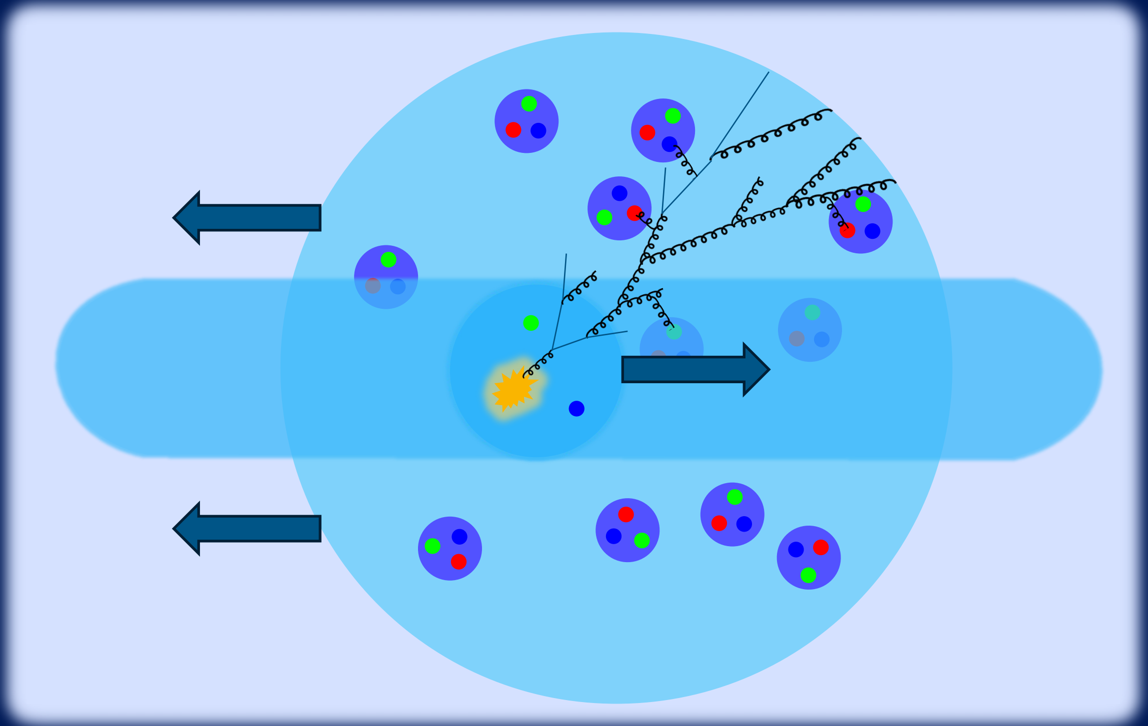
Jet EECs in CNM

e-A and p-A collisions: probe CNM

- ➢ e-A collisions
  - ❖ SIDIS: Clean environment (EIC)



- ➢ p-A collisions: comover effect
  - ❖ Comovers: particles produced in the interaction of protons with nuclei that are unrelated to hard scattering

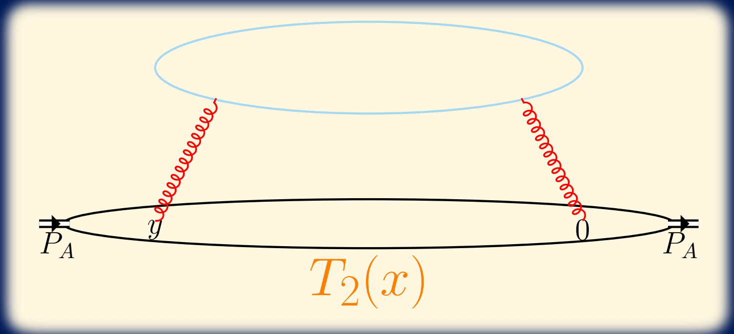


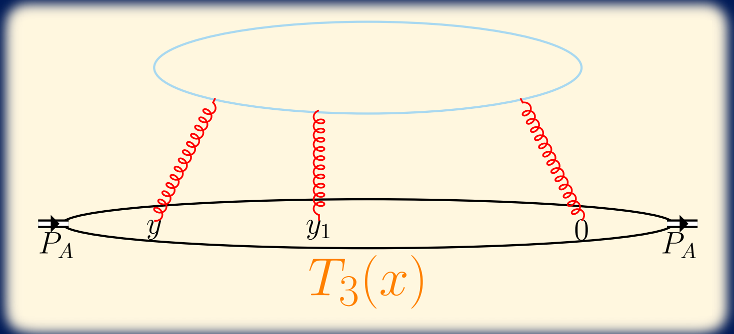
Higher-Twist (HT) formalism

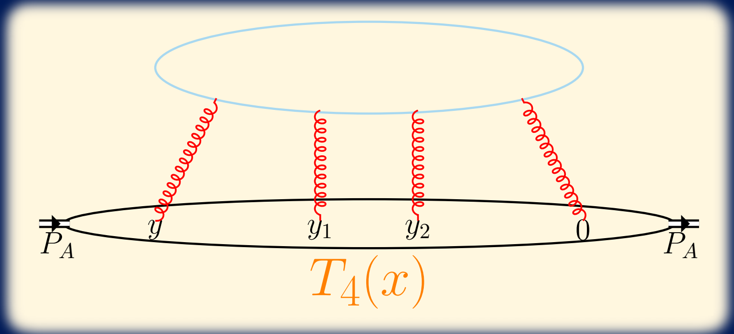
Perturbative Expansion

$$\sigma \sim \left[\alpha_s^0 C_2^{(0)} + \alpha_s^1 C_2^{(1)} + \alpha_s^2 C_2^{(2)} + \ldots\right] \otimes T_2(x)$$
$$+ Q^{-1} \left[\alpha_s^0 C_3^{(0)} + \alpha_s^1 C_3^{(1)} + \alpha_s^2 C_3^{(2)} + \ldots\right] \otimes T_3(x)$$
$$+ Q^{-2} \left[\alpha_s^0 C_4^{(0)} + \alpha_s^1 C_4^{(1)} + \alpha_s^2 C_4^{(2)} + \ldots\right] \otimes T_4(x)$$

Twist Expansion
(Power suppressed)







Twist-4 gluon-gluon correlator:

$$T_4(x) \propto \int dy^- dy_1^- dy_2^- \langle F(0^-)\, F(y_2^-)\, F(y_1^-)\, F(y^-)\rangle \propto A^{1/3}$$

$$\Longrightarrow \frac{1}{Q^2} \xrightarrow{\text{nuclear size}} \frac{A^{1/3}}{Q^2}$$

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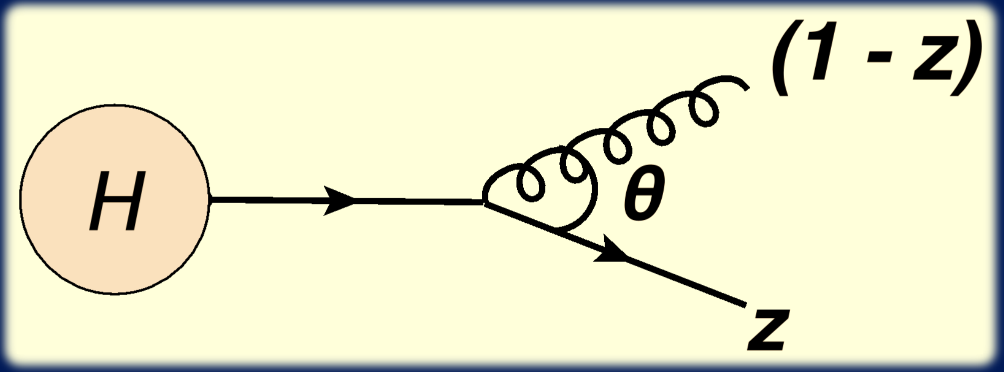
Jet EEC at Leading Order in pQCD

- At leading order in α_s:
  - Jet with $q \to q + g$ splitting
  - Energy flows determine by momentum and angular distributions of offsprings



- Energy weighted differential cross section:

$$\frac{d\Sigma}{d\theta} = \int_0^1 dz \frac{d\sigma_{qg}}{d\theta} \, z\,(1-z)$$

  - σ_{qg} - inclusive cross section with $q \to q + g$ splitting
  - z – large momentum fraction carried by the offspring quark

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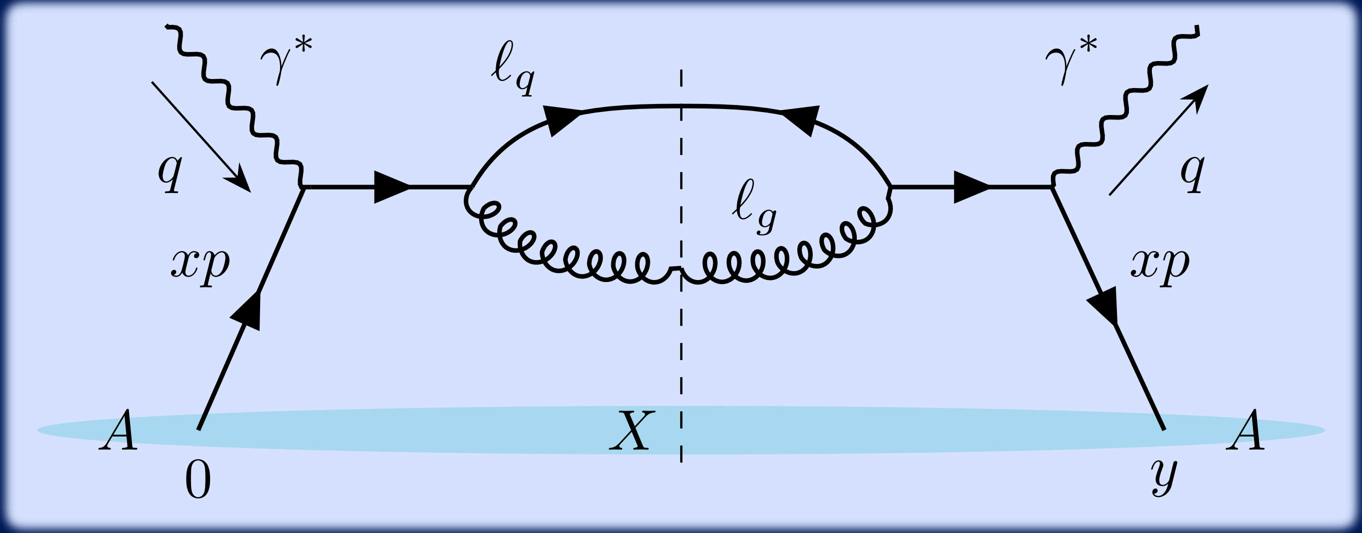
Notation and Kinematics



Breit Frame: $z = \frac{\ell_q^-}{q^-}$

$$p = (p^+, 0^-, \vec{0}_\perp)$$
$$q = \left(-\frac{Q^2}{2q^-}, q^-, \vec{0}_\perp\right)$$
$$\ell_q = \left(\frac{\ell_{q\perp}^2}{2zq^-}, zq^-, \vec{\ell}_{q\perp}\right)$$

- Differential Hadronic tensor:

$$\frac{dW^{\mu\nu}_{EEC}}{d\cos\theta} = \int d^4y\, e^{iq\cdot y} \frac{d^4\ell_q}{(2\pi)^4}\, \delta(\ell_q^2)\, \frac{d^4\ell_g}{(2\pi)^4}\, \delta(\ell_g^2)\, \Gamma(\ell_q, \ell_g) \sum_X \langle p/A|J^\mu(y)|q,g,X\rangle\langle q,g,X|J^\nu(0)|p/A\rangle$$

- $\Gamma(\ell_q, \ell_g) = \frac{\ell_q^- \ell_g^-}{(q^-)^2}\, \delta\left(\cos\theta - \frac{\vec{\ell_q}\cdot\vec{\ell_g}}{|\vec{\ell_q}|\,|\vec{\ell_g}|}\right)$

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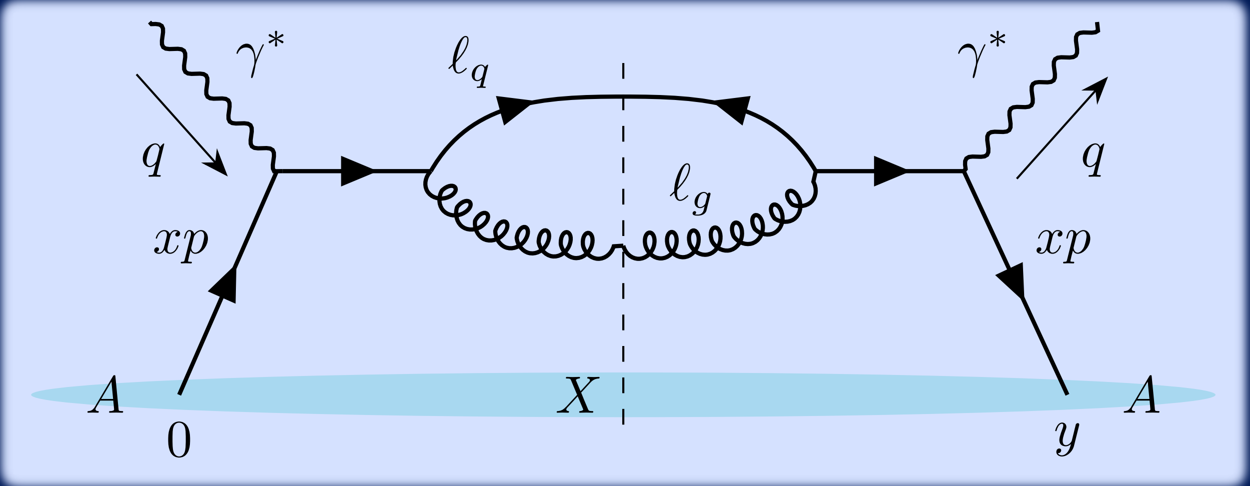
e-p and e-A collisions at Leading Twist



$$\left.\frac{dW^{\mu\nu}_{EEC}}{d\theta}\right|^{LT} \approx \int dx\, f_q(x)\, \bar{H}^{\mu\nu}_0(x)\, K_{LT}(\theta)$$

- PDF (Twist 2): $f_q(x)$
- Partonic hard scattering: $\bar{H}^{\mu\nu}_0(x)$
- Angle-dependence: $K_{LT}(\theta) = \frac{\alpha_s}{2\pi}\, C_F\, \int_0^1 dz\, \frac{z(1-z)}{\theta}\, P_{qg}(z)$
  - At LO, EEC obeys $1/\theta$ power law
  - Resum higher-order processes modifies angle scaling to $1/\theta^{1-\gamma(3)}$
- Only difference in eA – nPDF: $f_q^A(x) = R_p^A(x)\, f_q(x)$

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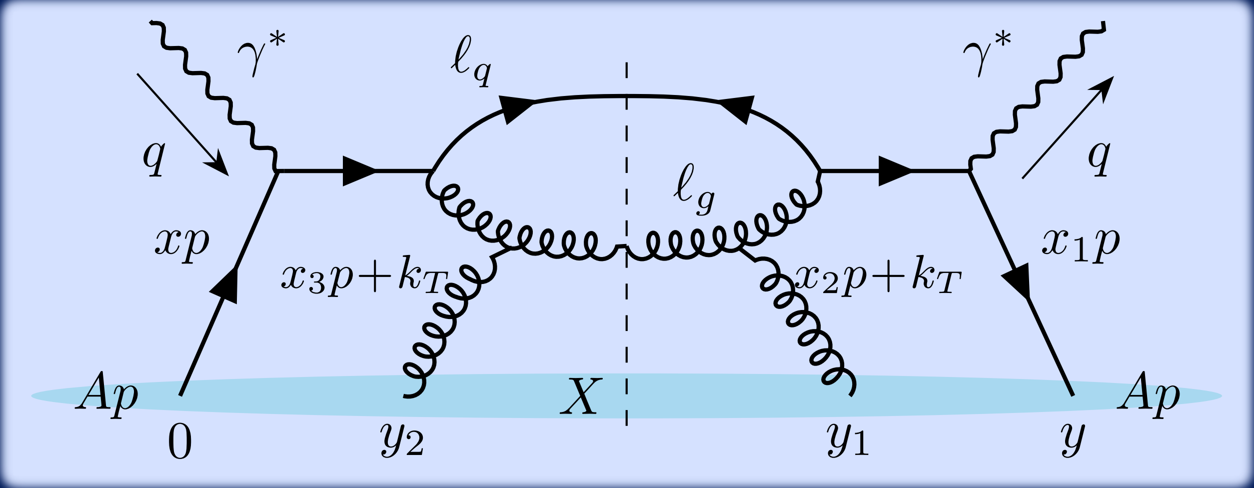
e-A collisions at Next-to-Leading Twist



$$\left.\frac{dW^{\mu\nu}_{EEC}}{d\theta}\right|^{NLT} \approx \int dx\, f_q^A(x)\, \overline{H}_0^{\mu\nu}(x)\, K_{NLT}(\theta, Q)$$

- Collinear approximation: $\ell_\perp^2 \ll Q^2$
  - For $\theta = 0.4$: $\ell_\perp^2 \sim \theta^2\, Q^2 < \left(\frac{0.4}{2}\right)^2\, Q^2 = 0.04\, Q^2$
- $K_{NLT}(\theta, Q) = \frac{\alpha_s}{2\pi}\, C_A \int_0^1 dz \frac{16\, P_{qg}(z)}{\theta^3\, z\,(1-z)\, Q^2} \int_0^L d\xi^-\, \hat{q}(\xi^-) \sin^2\left(\frac{z\,(1-z)\,Q\theta^2}{4\sqrt{2}}\, \xi^-\right)$
- Jet transport coefficient, $\hat{q}(\xi^-)$: $T_4(x) \sim \int d\xi^- f_q^A(x)\, \hat{q}(\xi^-)$

Jet EEC: e-A collisions

- $\frac{d\Sigma_{eA}^{LT+NLT}}{dx_B dQ^2 d\theta} = \frac{\alpha_s\,\alpha_{EM}^2\,e_q^2}{4\pi\,x_B^2\,s^2\,Q^2}\,f_q^A(x_B)\,L_{\mu\nu}\,\overline{H}_0^{\mu\nu}(x_B)\,(K_{LT}(\theta,Q)+K_{NLT}(\theta,Q))$

- LT: $\frac{1}{\theta}$ power law

- NLT: $\frac{1}{\theta^3}\sin^2(\#\,\theta^2) \xrightarrow{\theta\to 0} \frac{1}{\theta^3}\,(\#\,\theta^4) \sim \theta$

- LT + NLT: $\frac{1}{\theta}\,(1+\#\,\theta^2) \Longrightarrow$ agrees with light-ray OPE prediction (Andres et al, arXiv:2411.15298)

- Competition between $\frac{1}{\theta}$ and θ: EEC enhancement manifests when $\theta > \theta_0$, with $K_{LT}(\theta_0) = K_{NLT}(\theta_0)$

- The NLT modification depends on $\hat{q}$ and path length L

Combine LT and NLT results to get full result up to NLT accuracy

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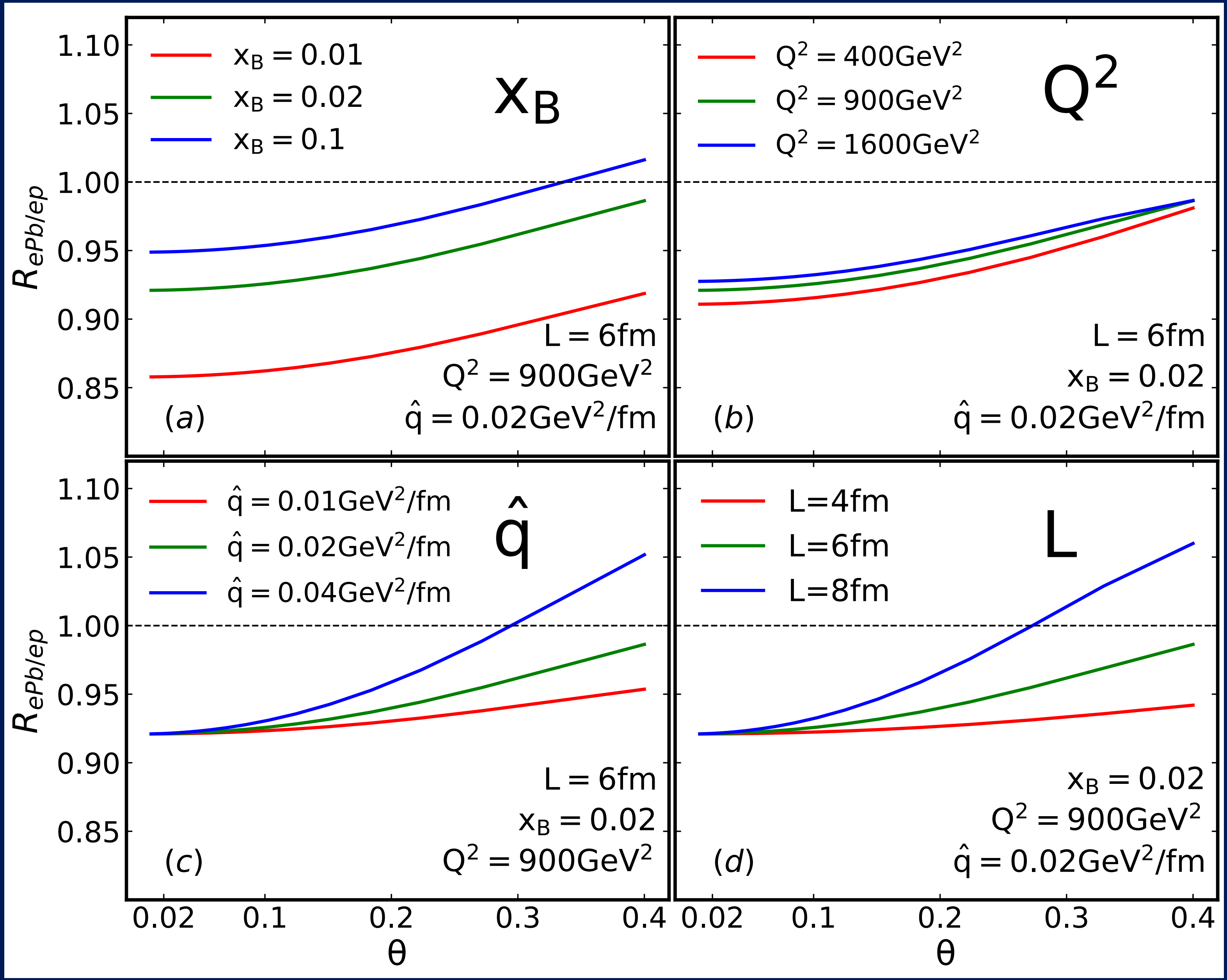
EEC ratio in SIDIS



- $R_{eA/ep}(\theta) = \dfrac{d\Sigma_{eA}^{LT+NLT}/dx_B\, dQ^2\, d\theta}{d\Sigma_{ep}/dx_B\, dQ^2\, d\theta}$

- NLT modification(final state interaction) $\sim \theta$
  - enhance in large θ

- At small θ, no enhancement
  - Ratio $<$ 1: nuclear shadowing in nPDF

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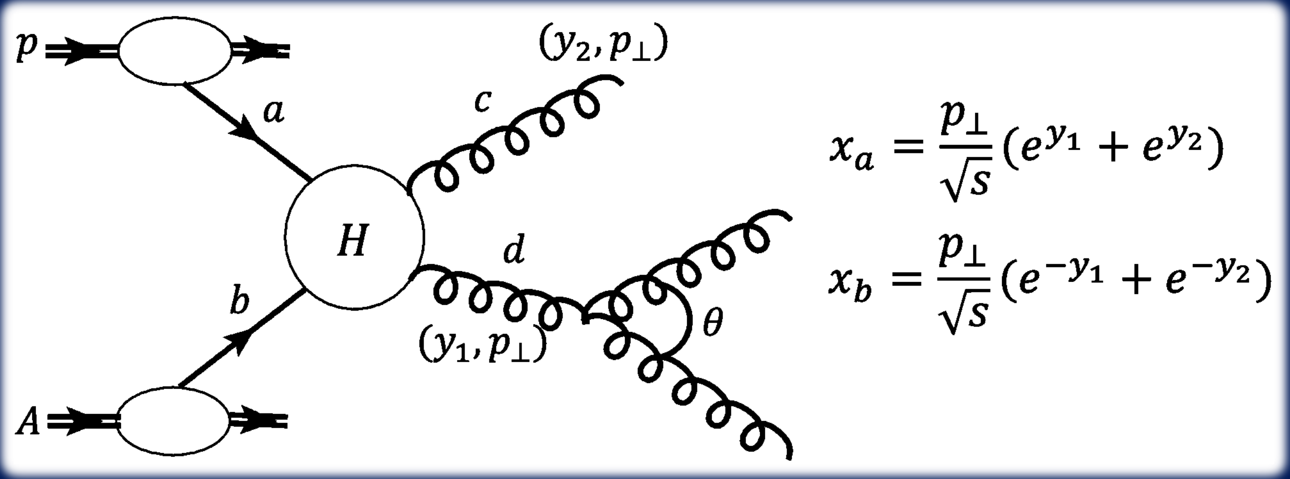
Jet EEC: p-A collisions

In pA collisions with a (ab→ cd) partonic process:



- Inclusive jet production cross section:
  - $$\frac{d\sigma^{pA}}{dy_1\, dp_\perp^2}\bigg|_{y_1=0} = f_{a/p}(x_a) \otimes f_{b/A}(x_b) \otimes H_{ab\to cd}$$
- For jet EEC:
  - $$\frac{d\sigma^{pA}_{EEC}}{dy_1\, dp_\perp^2\, d\theta}\bigg|_{y_1=0} = f_{a/p}(x_a) \otimes f_{b/A}(x_b) \otimes H_{ab\to cd}\ K(\theta, p_\perp)$$
- From previous discussion:
  - $$K_{LT} \sim \frac{1}{\theta}, \quad K_{NLT} \sim \frac{1}{\theta^3} \int_0^L d\xi^- \ \hat{q}(\xi^-) \sin^2(\#\, \theta^2\, \xi^-)$$

Same kernels calculated for DIS can be used as the final state modifications only make through $\hat{q}$

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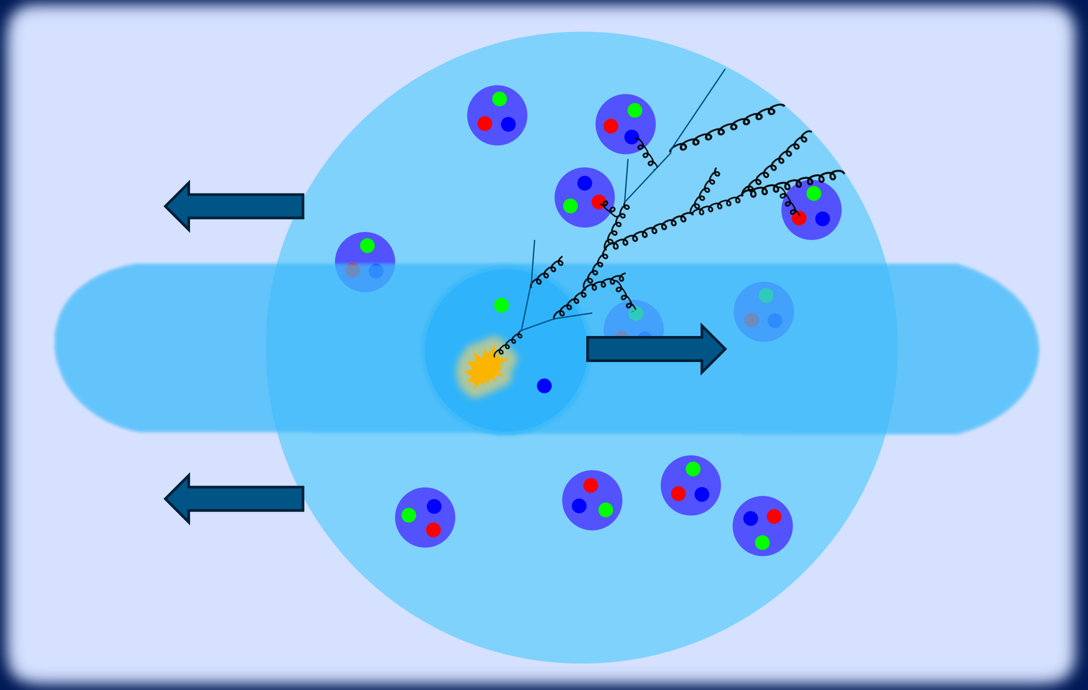
Comover Effect

- Comovers: particles produced in the interaction of protons with nuclei that are unrelated to hard scattering
- Average path length within the comover region: limited by the transverse area of pPb interaction
  - $\langle L_{co} \rangle \sim R_p \approx 1\ \text{fm}$
- Estimate $\hat{q}$ at the comover region:
  - from Pb + Pb: $\hat{q} \approx 8\,T^3 \sim s$
  - charged particle multiplicity as a proxy for entropy density
  - $\frac{dN_{ch}}{d\eta} \sim s\, R_{rms}^2\, \tau$

$$\Rightarrow \hat{q}_{co} = \hat{q}\, \frac{\frac{dN_{ch}^{pPb}}{d\eta}}{\left(R_{rms}^{p}\right)^2} \Bigg/ \frac{\frac{dN_{ch}^{PbPb}}{d\eta}}{\left(R_{rms}^{Pb}\right)^2} \approx 0.6\ \text{GeV}^2/\text{fm}$$



$$K_{NLT} = \frac{1}{\theta^3}\int_0^{\langle L_{co}\rangle} d\xi^-\, \hat{q}_{co}(\xi^-)\sin^2(\#\,\theta^2\xi^-) + \frac{1}{\theta^3}\int_{\langle L_{co}\rangle}^{L} d\xi^-\, \hat{q}_{Pb}(\xi^-)\sin^2(\#\,\theta^2\xi^-)$$

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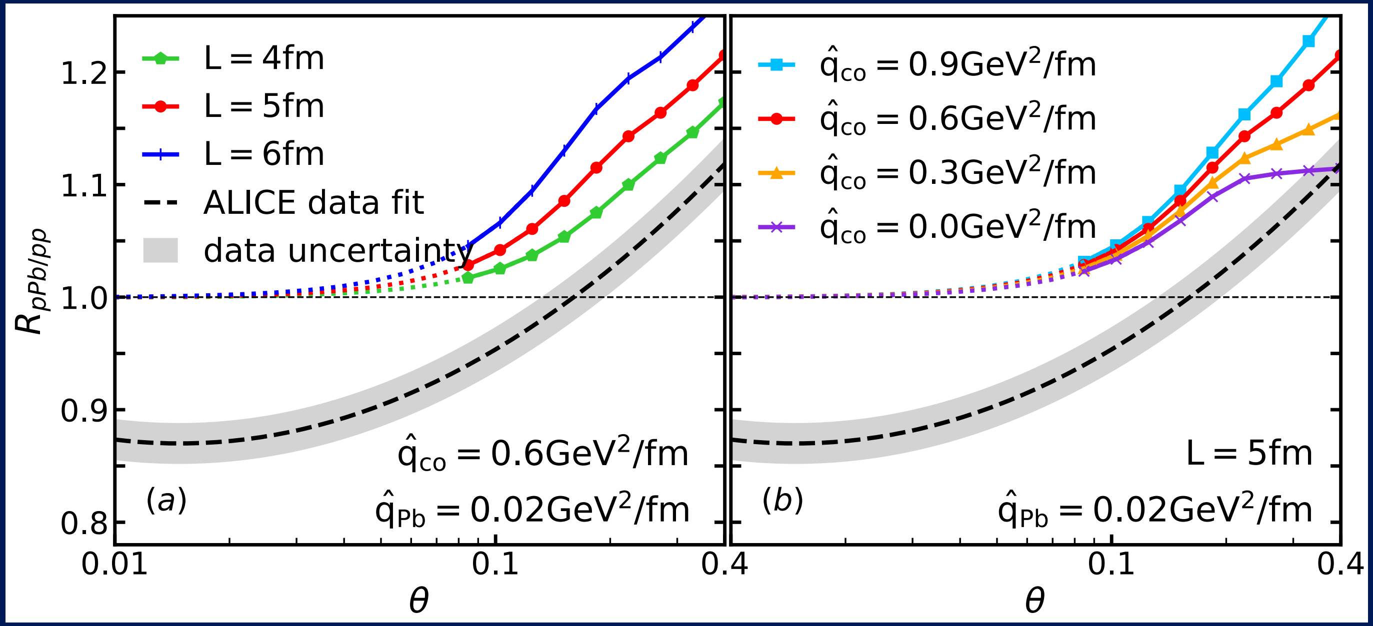
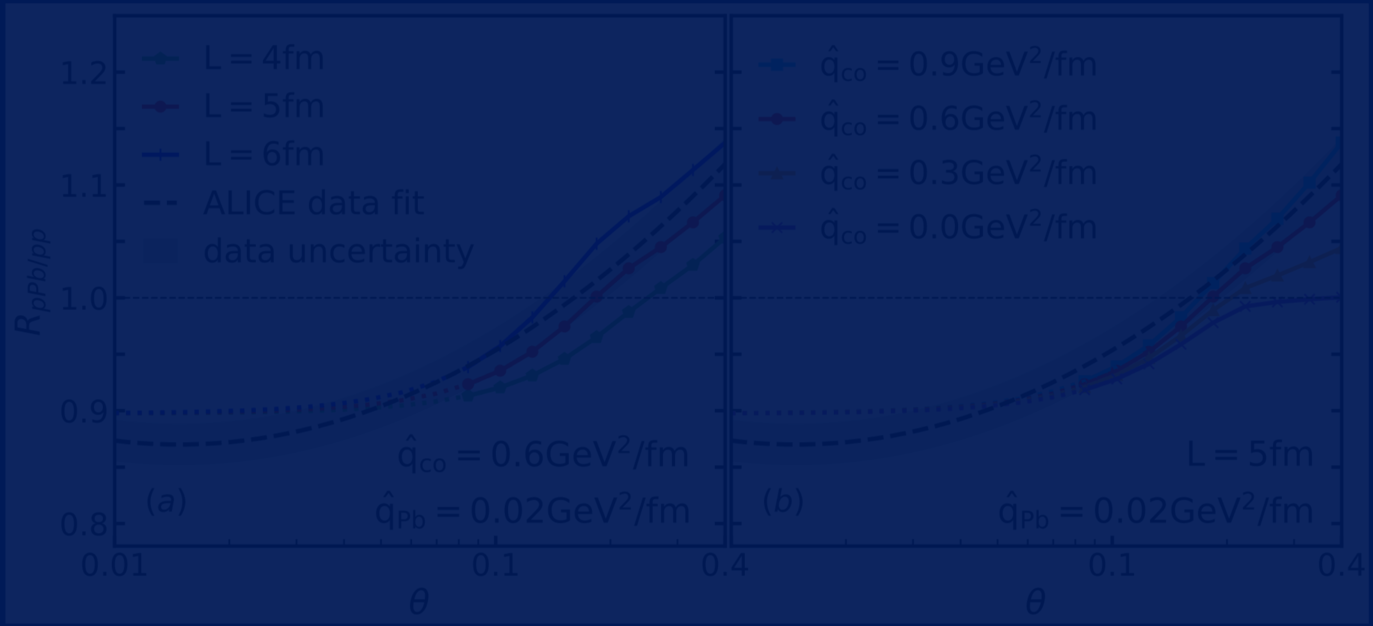
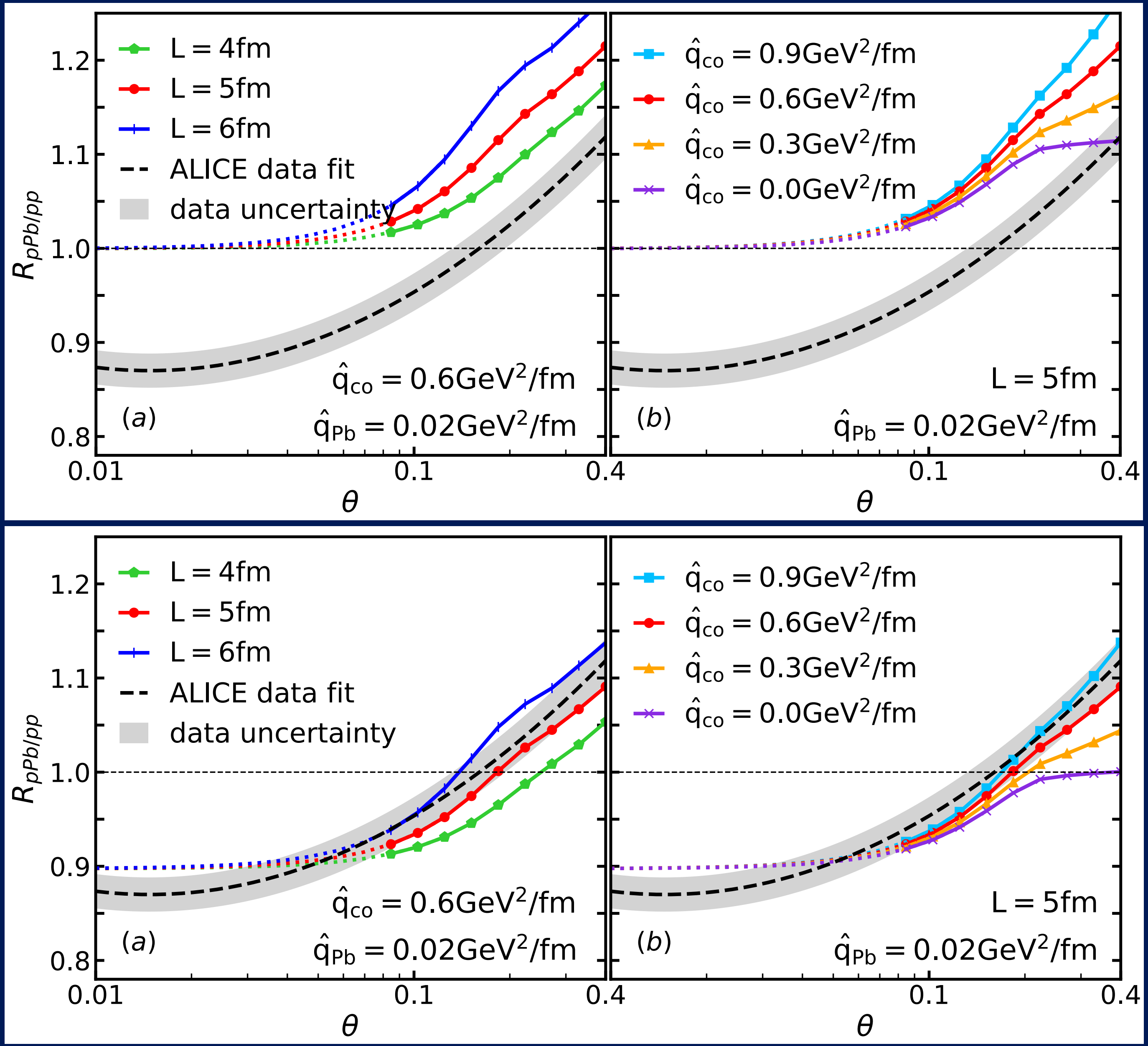
EEC ratio for p-Pb





- $$R^{Exp.}_{pA/pp}(\theta) = \frac{\sigma_{pp}}{\sigma_{pA}} \frac{d\Sigma^{single+double}_{pA}/dy\, dp_T^2\, d\theta}{d\Sigma_{pp}/dy\, dp_T^2\, d\theta}$$
- Mid rapidity
- $p_T = 30\ GeV$
- multiply by 0.9: Capture the overall shape
  - Proper normalization?
  - Non-perturbative effects?
  - Selection Bias?
  - Multiple Scattering (Broadening)?

EEC ratio for p-Pb



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- Mid rapidity
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Summary and Future Directions

- Analytical pQCD calculation of jet EECs in e-A and p-A
- Identified the effects related to initial-state interactions and final-state interactions between jet and medium.
- angular behavior up to NLT is $\frac{1}{\theta}\left(1 + \# \frac{1}{\theta^2} \sin^2(\# \, \theta^2)\right)$
  - NLT angular behavior caused by LPM effect
  - At small angles: $\frac{1}{\theta}(1 + \# \, \theta^2)$, consistent with light-ray OPE result
- pPb ratio: Reproduced overall growth at perturbative region
  - Systematically higher magnitude compared to data
  - Further investigation is ongoing
- Proposed jet EECs in eA and pA helps to measure $\hat{q}$ of cold nuclear matter and separate the cold nuclear matter and comover effects

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