Nucleon Energy Correlators for the Color Glass Condensate

Hao-yu Liu（刘昊昱）

(Beijing University of Chemical Technology)

With Xiaohui Liu, Ji-chen Pan, Feng Yuan and Hua Xing Zhu

中国物理学会高能物理分会第十四届全国粒子物理学术会议,青岛

15th Aug, 2024

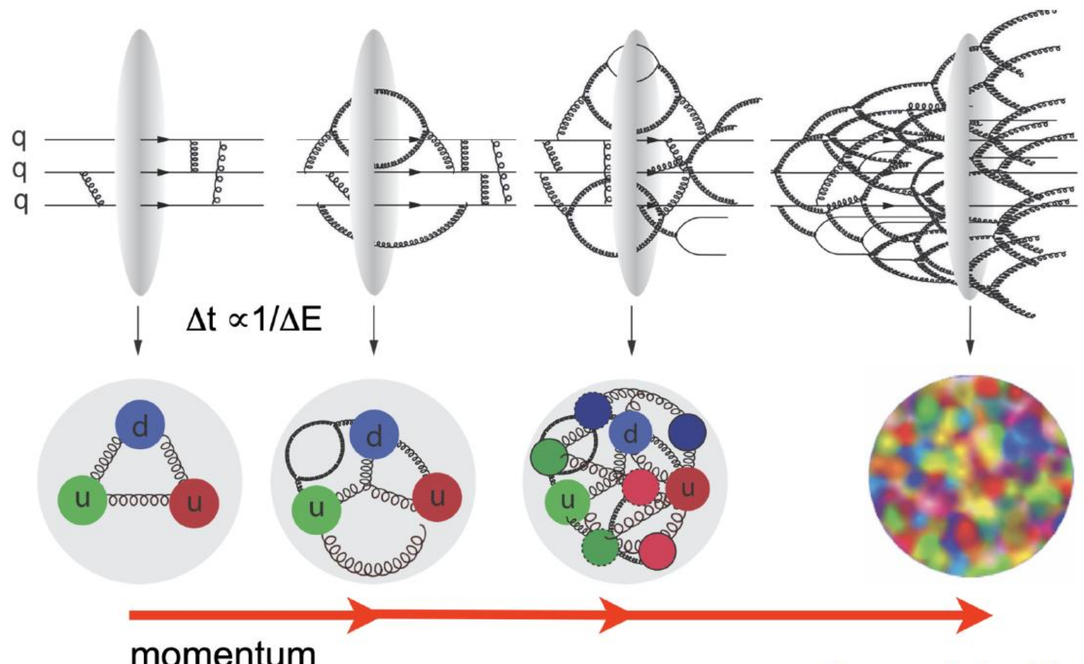
Based on [HL, X.Liu, J.Pan, F.Yuan, H.Zhu,arXiv:2301.01788]

Email address: lhy1991dbc@126.com

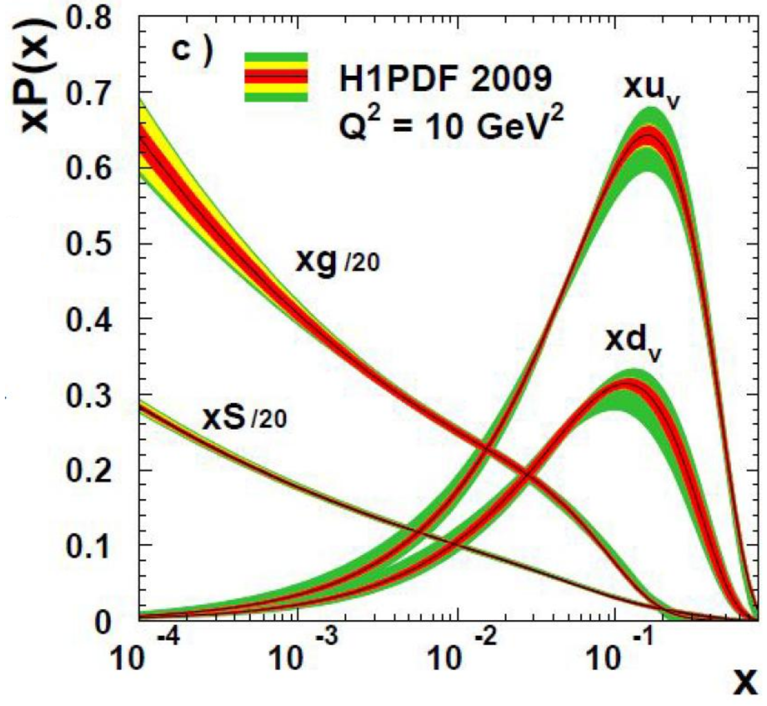
Outline

- Review of CGC effective theory
- Nucleon energy correlator
- Nucleon energy correlator for small x
- Summary

Gluon Saturation



Artwork by T.Ullrich



[Gelis, Iancu, Jalilian-Marian, Venugopalan ,2010]

The gluon density increases with Bjorken x decreases → Gluon saturation

Unitarity

splitting ⟷ (balance) recombination

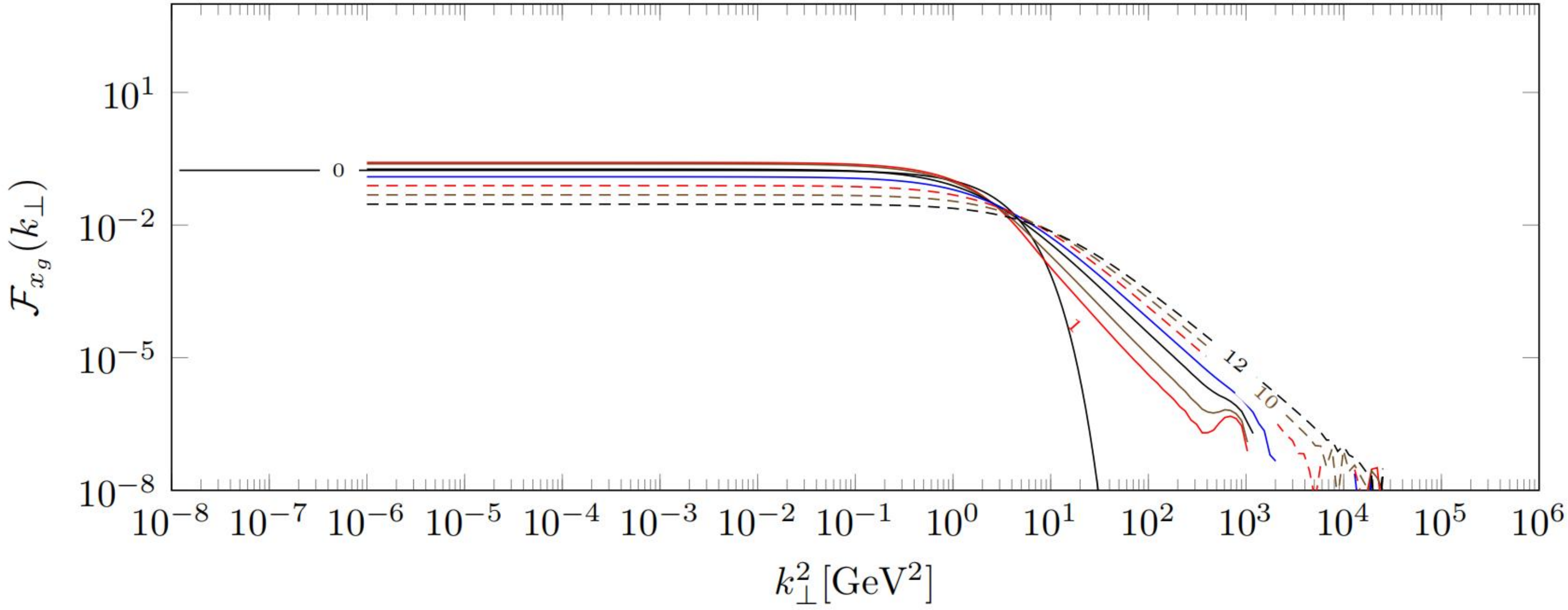
Typical Transverse Momentum   Saturation scale

Dilute → Collinear factorization

Dense → ?

2-4 GeV $Q_s \gg \Lambda_{QCD}$

Gluon Distribution in CGC



[D. Zaslavsky, 1409.8259]

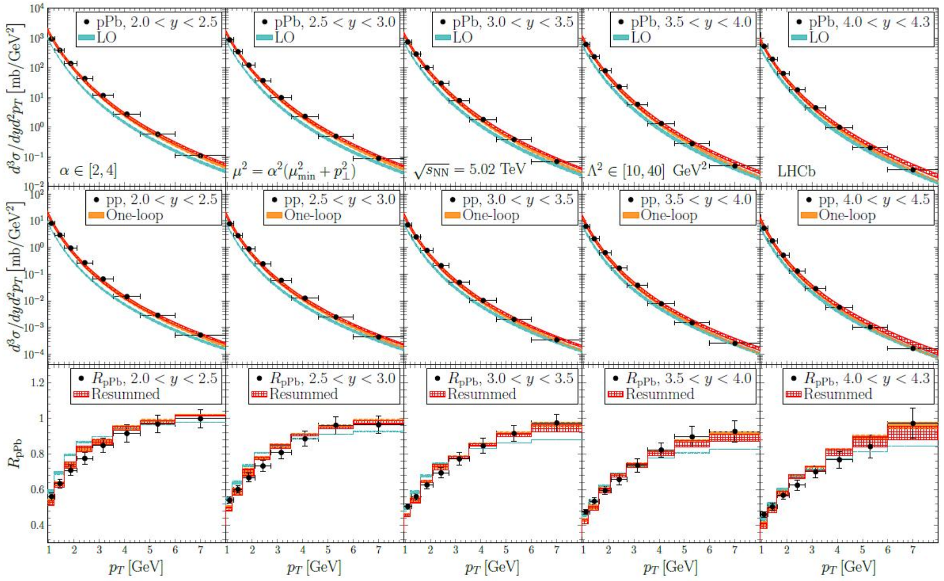
$$\mathcal{F}_{x_g}(\mathbf{k}_\perp) = \int \frac{d^2\mathbf{x}_\perp d^2\mathbf{y}_\perp}{(2\pi)^2} e^{-i\mathbf{k}_\perp\cdot(\mathbf{x}_\perp - \mathbf{y}_\perp)} S^{(2)}_{x_g}(\mathbf{x}_\perp, \mathbf{y}_\perp)$$

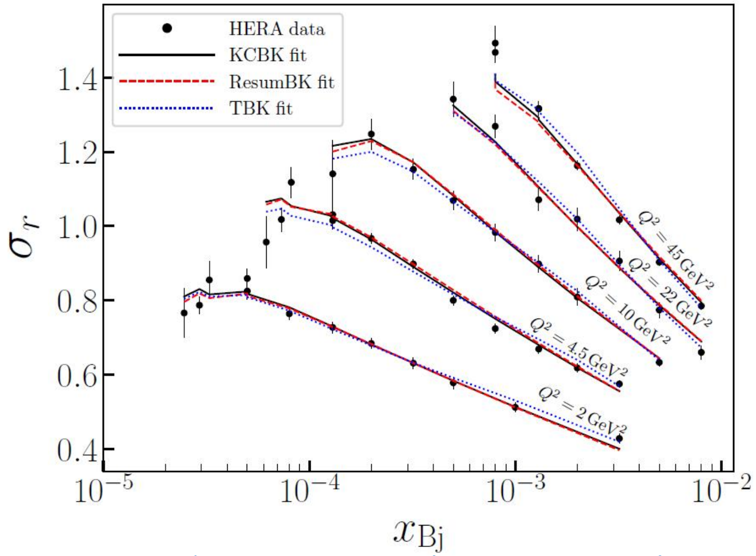
Transverse Momentum distribution by CGC (Color Glass Condensate)

Effective theory of QCD

One of the most appropriate theories for saturation

Searching for deterministic evidence of saturation



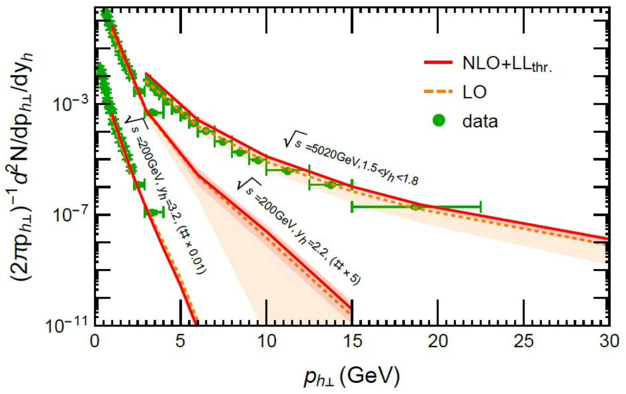


Inclusive DIS

[B. Ducloué, H. Hänninen, T. Lappi, Y. Zhu, 2017]

[G. Beuf, H. Hänninen, T. Lappi, H. Mäntysaari, 2020]

Single hadron production in pA



[G.Chirilli,B.Xiao,F.Yuan, 2012]

[Y.Shi, L.Wang, S.Wei, B.Xiao, 2021]

[Iancu, Mueller, Triantafyllopoulos, 2016]

[HL, Y.Ma, K.Chao, 2019]

[HL, Z.Kang, X.Liu, 2020]

Search for saturation in pA collisions and DIS, many hints, no solid evidence

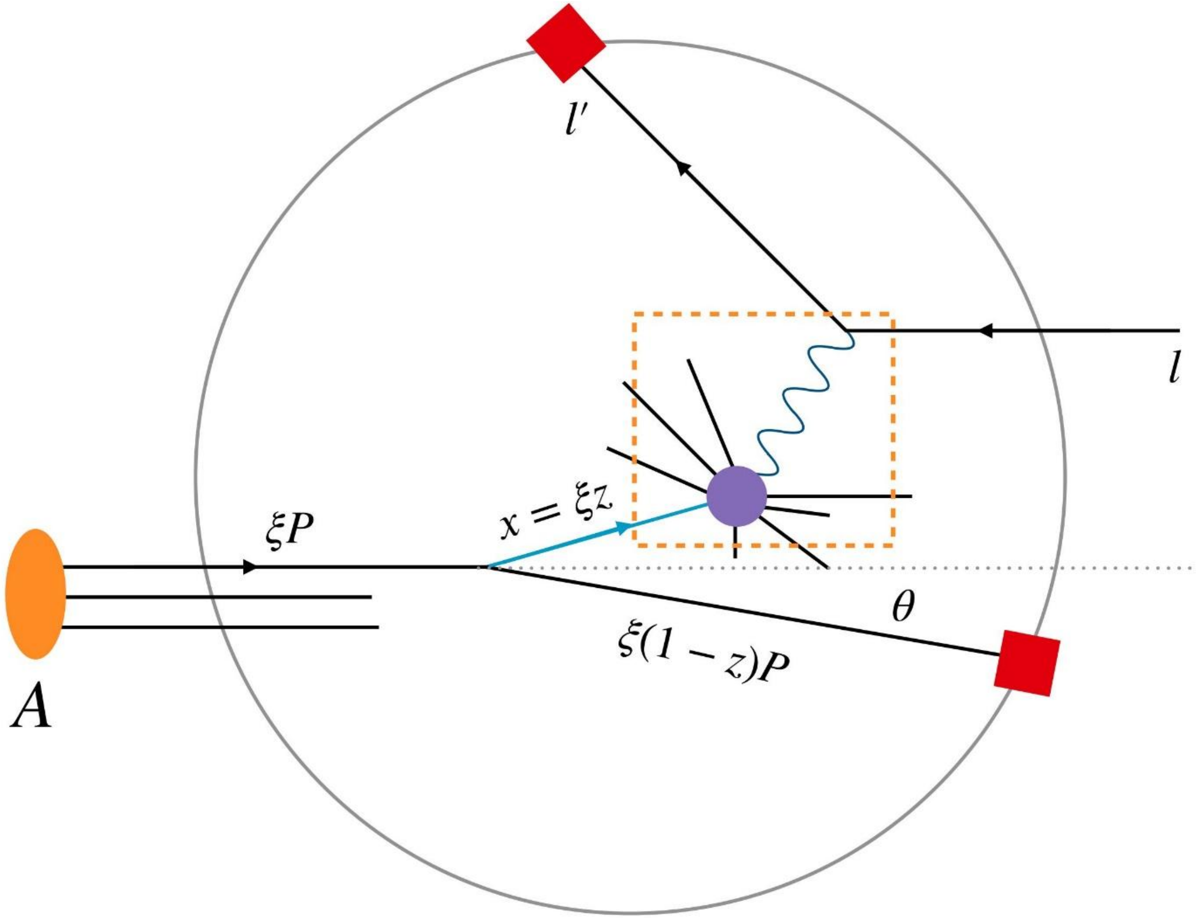
One of the main objects for EIC

Any new prob?

The measurement of Nucleon energy correlator

[X.Liu, H.Zhu, 2022] [H.Cao,X.Liu, H.Zhu, 2023]

Similar to normal DIS



One detector for lepton $x_B = \frac{-q^2}{2P\cdot q}$ $Q^2 = -q^2$

Another detector for the energy deposits at θ

$$\sum_i E_i$$

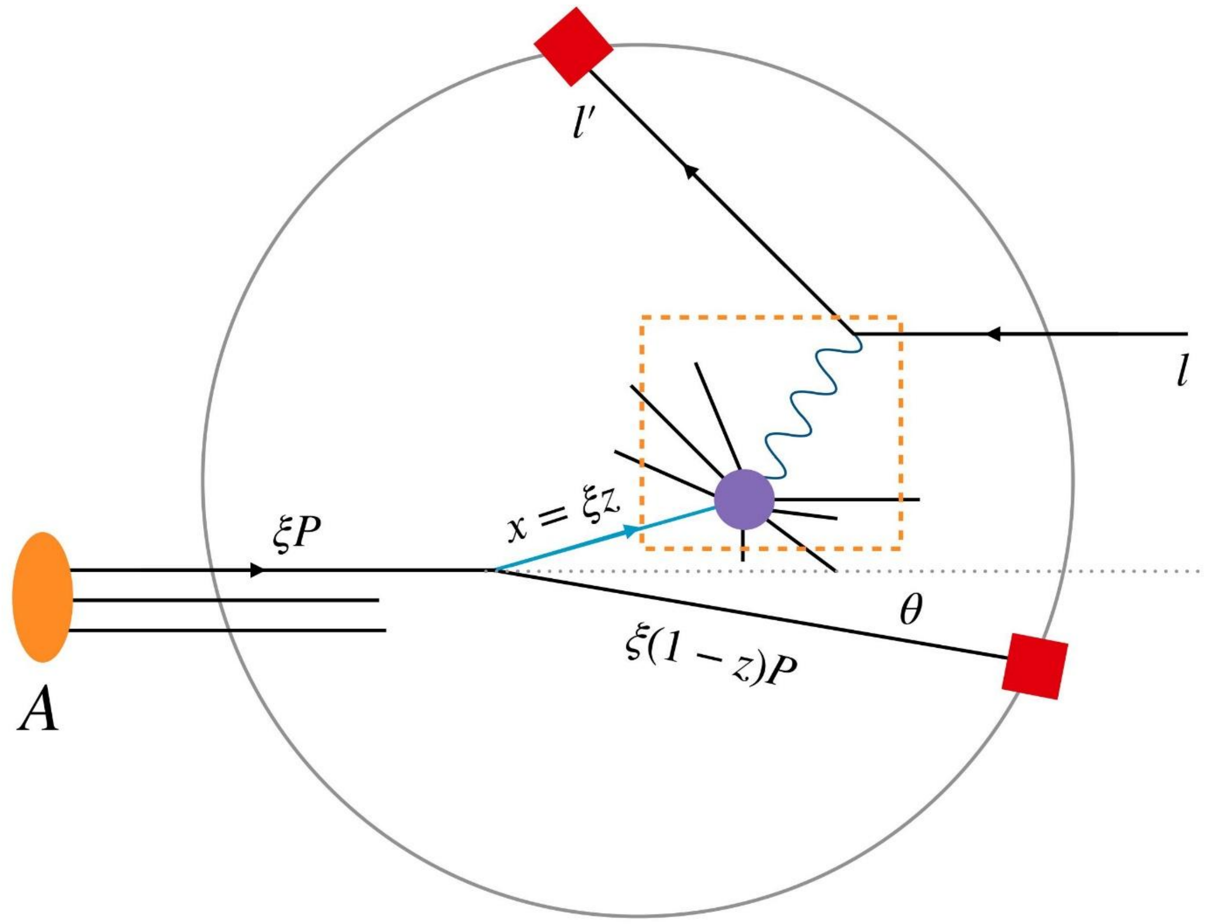
The weighted cross section

$$\Sigma(Q^2, x_B, \theta) = \sum_i \int d\sigma(x_B, Q^2, p_i)\, \frac{E_i}{E_A}\, \delta(\theta^2 - \theta_i^2)$$

The energy weight suppresses the soft contributions

No Sudakov logs suppression

The factorization of the weighted cross section



Factorization when $\Lambda_{\mathrm{QCD}} \ll \theta Q \ll Q$

$$\Sigma(Q^2, x_B, \theta) = \int \frac{dx}{x} \hat{\sigma}_{i,\mathrm{DIS}}\left(\frac{x_B}{x}, Q\right) f_{i,\mathrm{EEC}}(x, \theta)$$

Nucleon energy correlator

inclusive partonic DIS cross section

Suppose collinear factorization still holds for small x

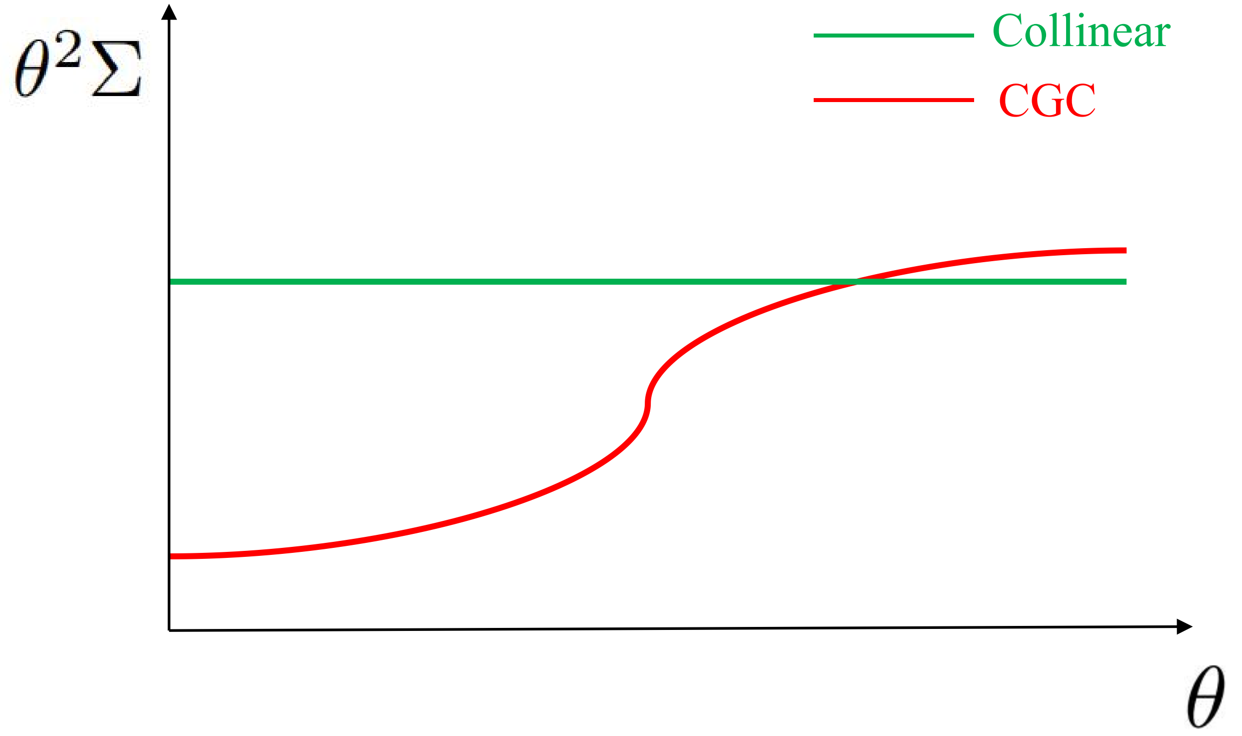
$$f_{q,\mathrm{EEC}}(x, \theta) = \frac{\alpha_s T_R}{2\pi\theta^2} \int_x^1 \frac{d\xi}{\xi} (1-\xi)(\xi^2 + (1-\xi)^2) \left[\frac{x}{\xi} f_g\left(\frac{x}{\xi}\right)\right]$$

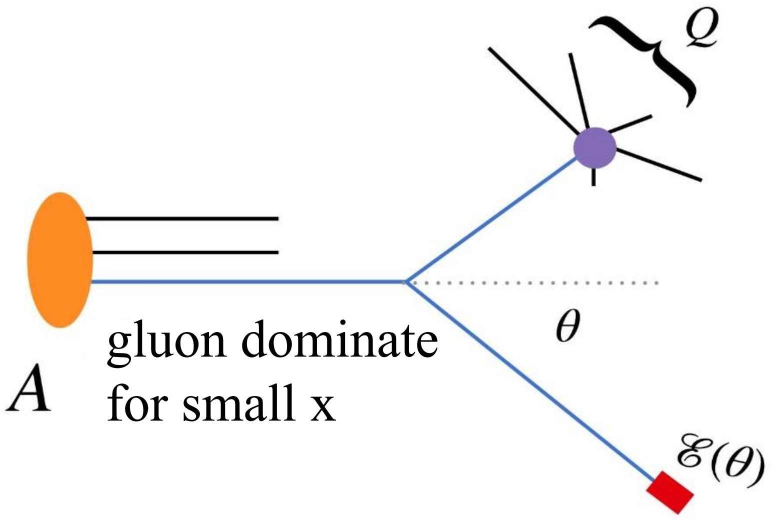
collinear PDF

$\frac{1}{\theta^2}$ scaling

$\theta^2 \Sigma$ insensitive to θ

Naïve analysis





$q_t \sim \Lambda_{\rm QCD}$ for collinear

Splitting function → $\frac{1}{\theta^2}$ scaling

$\theta^2\Sigma$ insensitive — Leading order

No Sudakov suppression — Higher order

$q_t \sim Q_s$ →

hardly hits the detector for $\theta Q \ll Q_s$ → suppression

Similar to the collinear case for $\theta Q \gg Q_s$ → insensitive

$\theta^2\Sigma$

Nucleon energy correlator by CGC

$F_{g,x_B}(\vec{g}_t)$ gluon transverse momentum distribution in CGC

$$f_{q,\mathrm{EEC}}(x_B,\theta) = \frac{N_C S_\perp}{8\pi^4}\int d^2\vec{g}_t \int_{\xi_{\mathrm{cut}}}^{1} \frac{d\xi}{\xi} \mathcal{A}_{qg}(\xi,\theta,\vec{g}_t)\, F_{g,x_B}(\vec{g}_t)$$

$\theta^2\Sigma$

$$\mathcal{A}_{qg}(\xi,\theta,\vec{g}_t) = \frac{1}{\theta^2}(1-\xi)\vec{k}_t^2(\vec{k}_t-\vec{g}_t)^2 \times \left| \frac{\vec{k}_t}{\xi\vec{k}_t^2+(1-\xi)(\vec{k}_t-\vec{g}_t)^2} - \frac{\vec{k}_t-\vec{g}_t}{(\vec{k}_t-\vec{g}_t)^2}\right|^2$$

$g_t \sim Q_s \qquad k_t = \frac{1-\xi}{\xi}\frac{Q}{2}\theta$

Expansion under different approximations

$\theta Q \ll Q_s$

$\mathcal{A}_{qg}(\xi,\theta,\vec{g}_t) \Rightarrow \theta^0$ Suppression

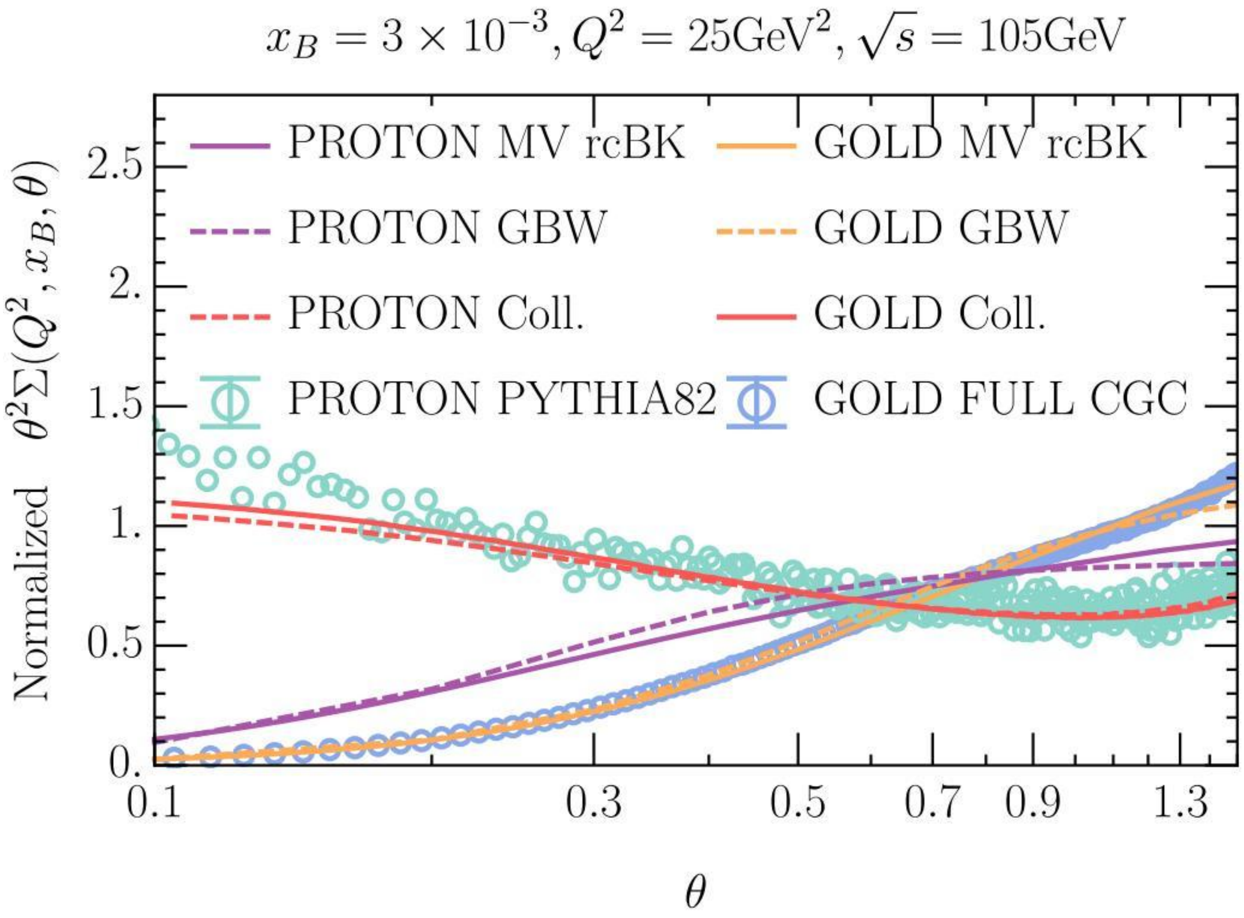
$\theta Q \gg Q_s$

$\mathcal{A}_{qg}(\xi,\theta,\vec{g}_t) \Rightarrow \frac{1}{\theta^2}$ insensitive to θ

Different scaling of θ

Consistent with the naïve argument

Comparing CGC and collinear result



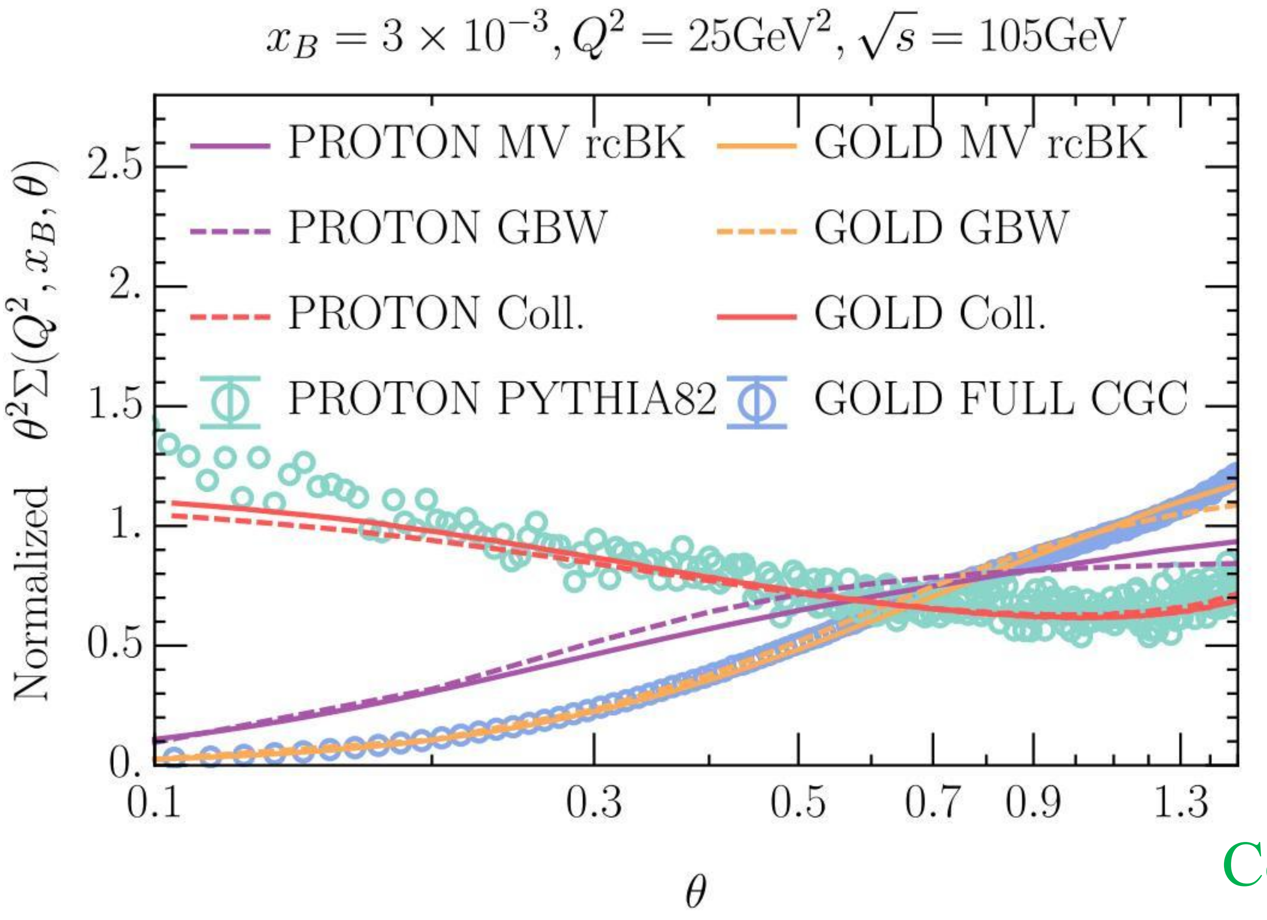
Collinear and CGC prediction for HERA kinematics

CGG result is suppressed for small θ

Collinear factorization can't give this suppression because of the absence of Sudakov factor

NEEC is a clean probe for small-x phenomena

Comparing CGC and collinear result



The spectrum becomes flat for $\theta Q \gg Q_s$

We can estimate Q_s by the tuning point

For the proton

$$\theta \sim 0.15-0.2 \quad Q_s \sim \theta Q \sim 0.75-1.0\,\text{GeV}$$

For the gold nucleus

$$\theta \sim 0.4-0.5 \quad Q_s \sim \theta Q \sim 2-2.5\,\text{GeV}$$

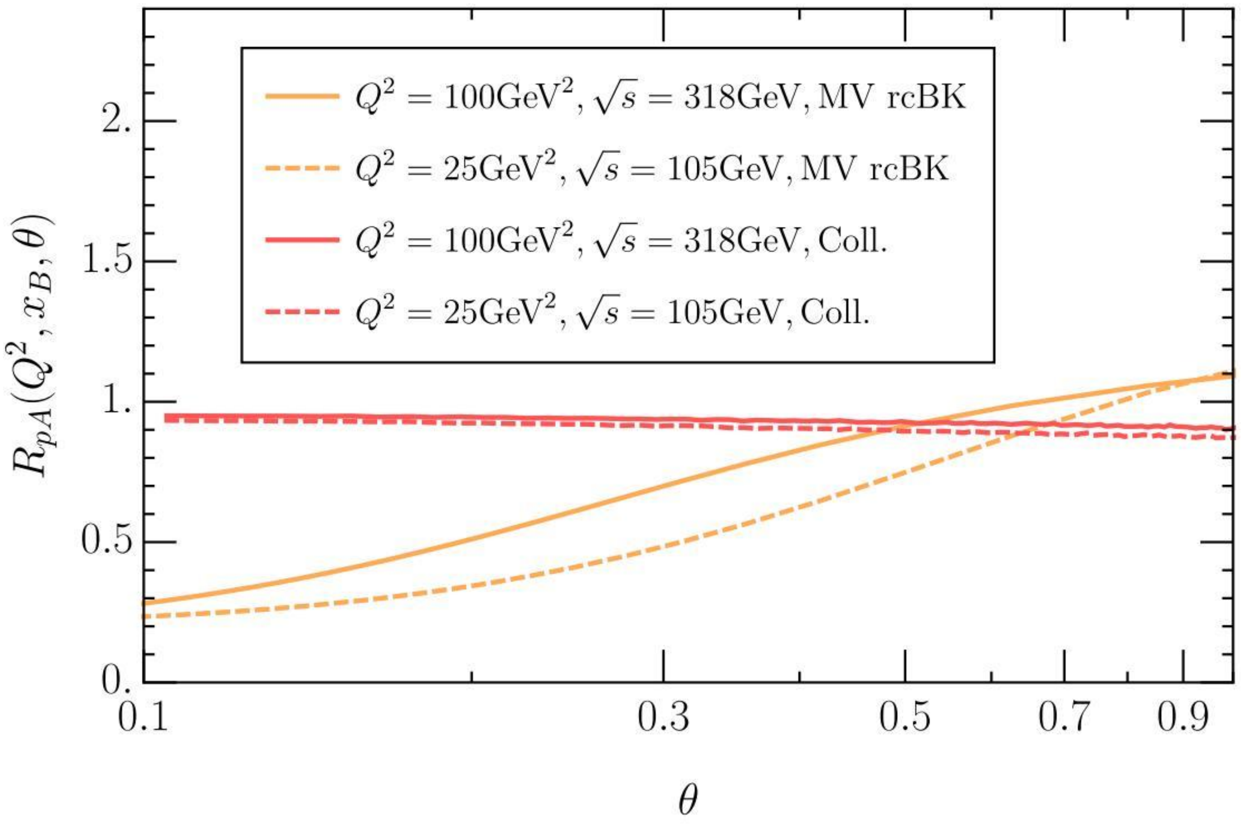
Consistent with the input Q_s parameter

A probe for the onset of gluon saturation

Nuclear Modification Factor

$$R_{pA} = \frac{A^{-1}\Sigma_A(Q^2, x_B, \theta)}{\Sigma_p(Q^2, x_B, \theta)}$$

Take ratios to reduce the systematics



Q_s is larger for large nuclear

$\theta^2\Sigma(Q^2, x_B, \theta)$ is suppressed comparing to proton

There is no suppression for the collinear case

Summary and Outlook

- Nucleon energy correlator is a new probe of the gluon saturation phenomenon in DIS at the future electron-ion colliders. The θ-shape of the weighted cross section behaves differently in the collinear factorization theorem and the CGC.

- The difference is due to the intrinsic transverse momentum of order Qs induced by the non-linear small-x dynamics. The nucleon energy correlator offer a great opportunity to pin down the onset of the gluon saturation phenomenon in eA collisions.

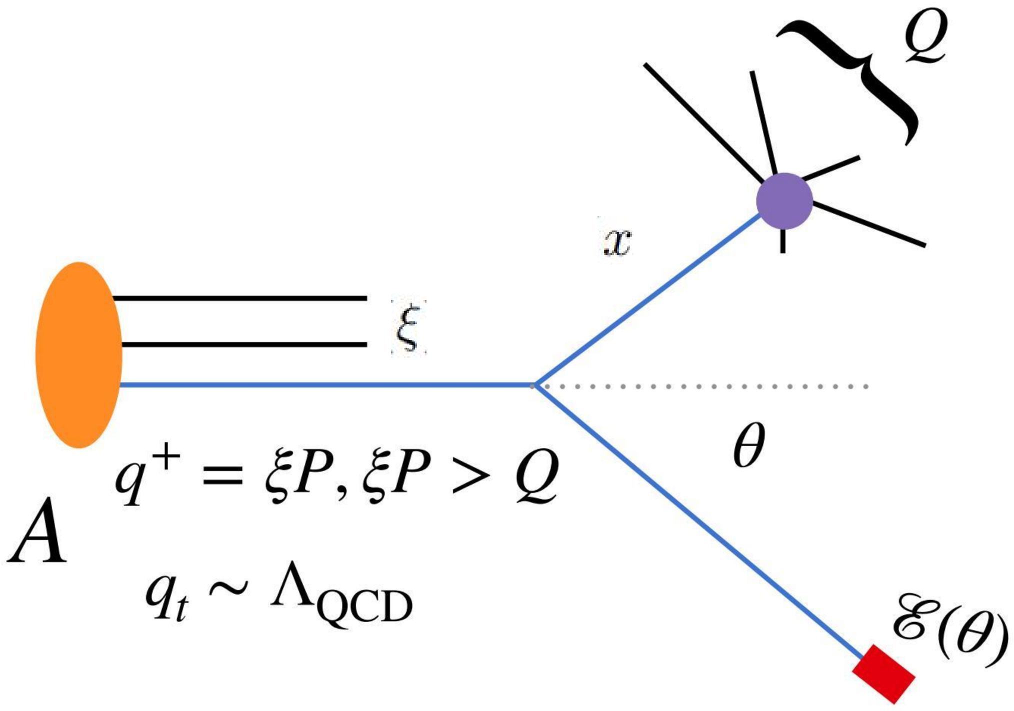
- This probe is fully inclusive and does not involve fragmentation functions or jet clustering, it is both theoretically and experimentally clean.

- Extensions to other observables, such as measuring nucleon energy correlator in prompt photon production, can also be carried out at the LHC.

Thank You!

The Back up

Definition of Nucleon energy correlator



x the momentum fraction that initiates a scattering process

Quark contribution

$$f_{q,\rm EEC}(x,\theta) = \int \frac{dy^-}{4\pi E_A} e^{-ixP y^-} \times \gamma^+ \langle A | \bar{\psi}(y^-) \mathcal{L}^\dagger(y^-)\, \mathcal{E}(\theta) \mathcal{L}(0) \psi(0) | A \rangle$$

$$\mathcal{E}(\theta)|X\rangle = \sum_{i\in X} E_i \delta(\theta_i^2 - \theta^2)|X\rangle$$

When $\theta E_A \gg \Lambda_{\rm QCD}$, $f_{EEC}(x,\theta)$ can be further factorized

$$f_{i,\rm EEC}(x,\theta) = \int \frac{d\xi}{\xi} I_{ij}\left(\frac{x}{\xi},\theta\right) [\xi f_{j/A}(\xi)]$$

$f_{j/A}(\xi)$ collinear PDF

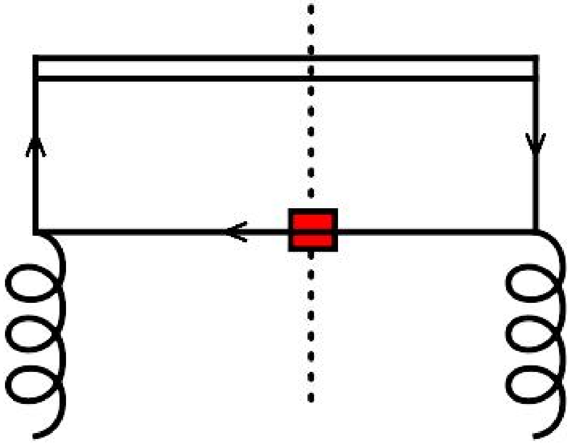
$I_{ij}\left(\frac{x}{\xi},\theta\right)$ matching coefficient

Determined by the splitting function

Nucleon energy correlator in collinear factorization

By SCET

$$f_{q,\mathrm{EEC}}(N,\theta) = \int dz z^{N-1}\frac{1}{2}\int \frac{dq^+ d^2q_t}{q^+(2\pi)^3}\frac{q^+}{P^+}\delta((1-z)P^+ - q^+ - p_X^+)\delta(\theta_q^2-\theta^2)$$
$$\times g_s^2 \mathrm{Tr}[T_a T_a]\frac{1}{2}\mathrm{Tr}[\gamma_t^\mu \gamma_{t,\mu}\not{q}\gamma^+]\left(\frac{-\vec{q}_t^2}{(q^+)^2}+\frac{-\vec{p}_t^2}{(p^+)^2}\right)\left(\frac{p^+}{p^2}\right)^2$$
$$\times\frac{1}{2}\frac{1}{N_C^2-1}\sum_X \langle P|\, A_{t,a,\mu}|X\rangle\langle X|A_t^{a,\mu}|P\rangle \int d\xi P^+\delta((1-\xi)P^+ - p_X^+)$$



$$l_t \sim \Lambda_{\mathrm{QCD}} \qquad p^2 = (l-q)^2 = -2l\cdot q = -\frac{l^+}{q^+}\vec{q}_t^2$$

$$q_t = q_z \sin\theta = \frac{q^+}{2}\theta_q$$

Origin of $\frac{1}{\theta^2}$ scaling

$$f_{q,\mathrm{EEC}}(N,\theta) = \int dx\, x^{N-1}(1-x)\,\frac{\alpha_s}{2\pi}T_R\left\{\frac{1}{\theta^2}\left[x^2+(1-x)^2\right]\right\}\int d\xi \xi^N f_{g/P}(\xi)$$

Evolution of Nucleon energy correlator

By the factorization

$$\Sigma(Q^2, x_B, \theta) = \int \frac{dx}{x} \hat{\sigma}_{i,\mathrm{DIS}} \left(\frac{x_B}{x}, Q \right) f_{i,\mathrm{EEC}}(x, \theta)$$

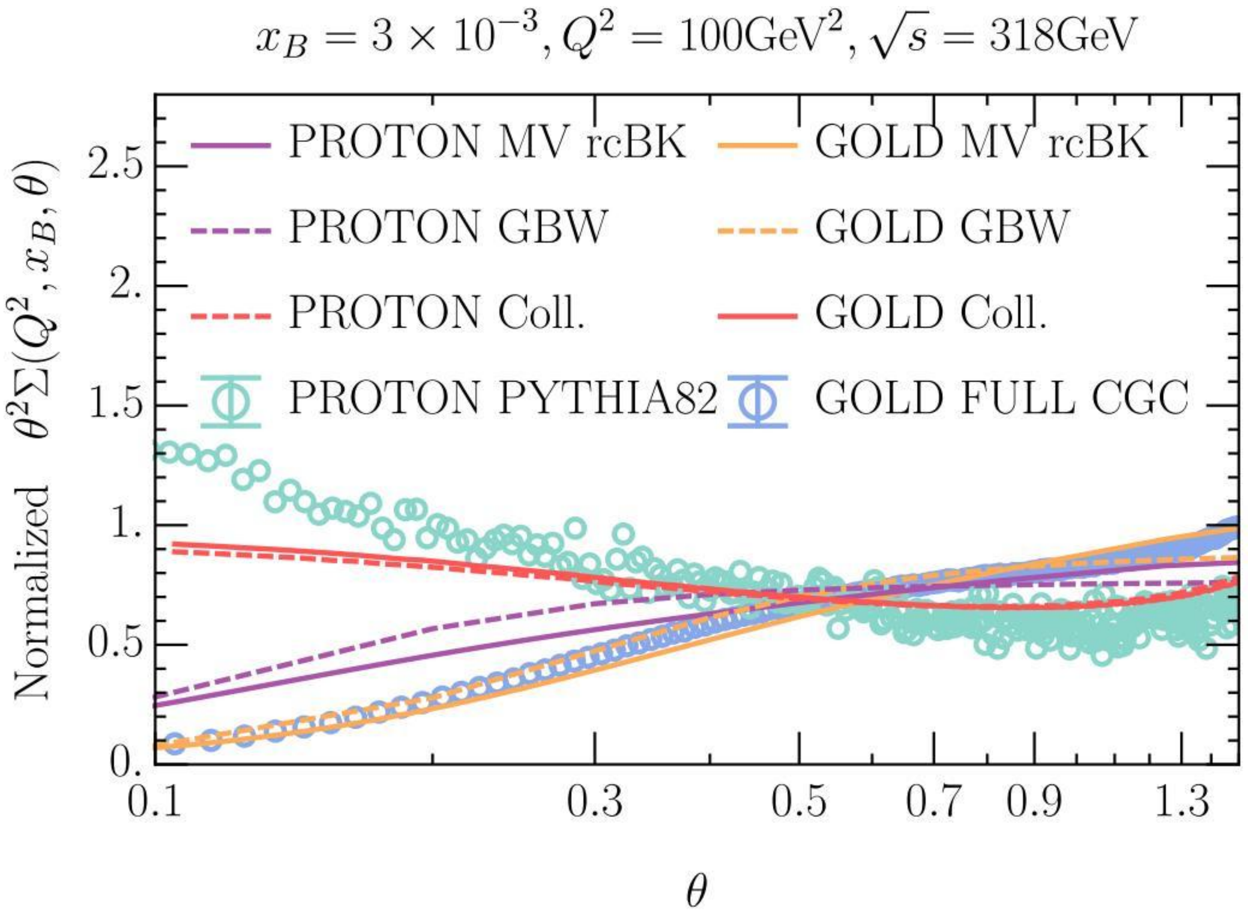
$$d\Sigma / d\ln\mu = 0$$

$$d\hat{\sigma}_{i,\mathrm{DIS}} / d\ln\mu = -P_{ji} \otimes \hat{\sigma}_{j,\mathrm{DIS}}$$

→

$$\frac{df_{i,\mathrm{EEC}}(x, \theta)}{d\ln\mu} = P_{ij} \otimes f_{j,\mathrm{EEC}}$$

Comparing CGC and collinear result

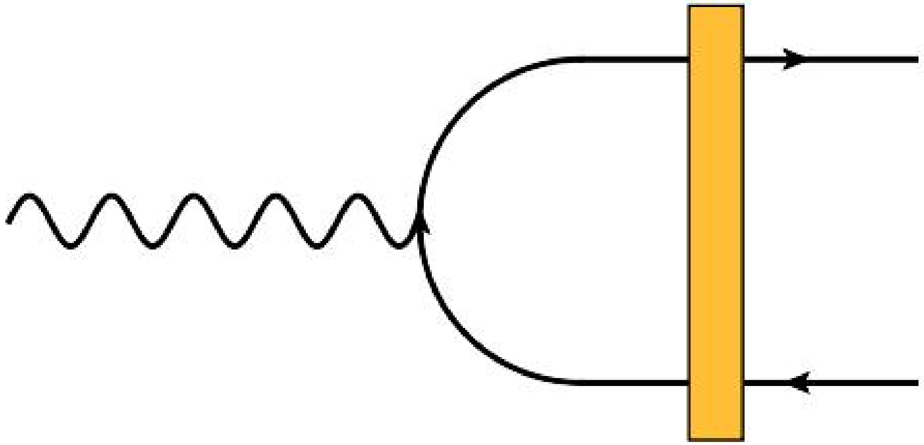


EIC kinematics

θ

Full CGC

$\theta^2\Sigma$ by direct CGC calculation



$$\Sigma_t^{\gamma^*}(Q^2,x_B,\theta)=\sum_q\frac{2N_c\alpha^2e_q^2}{\pi^2x_BQ^2}S_\perp\int dzd^2\vec{k}_t\frac{d^2\vec{l}_t}{(2\pi)^2}F_{g,x_B}(\vec{l}_t)\left[z^2+(1-z)^2\right]\left|\frac{\vec{k}_t}{\vec{k}_t^2+\Delta^2}-\frac{\vec{k}_t-\vec{l}_t}{(\vec{k}_t-\vec{l}_t)^2+\Delta^2}\right|^2$$
$$\times\left[\frac{\vec{k}_t^2+(1-z)^2Q^2}{(1-z)Q}\frac{x_B}{Q}\right]\frac{1}{2\theta}\delta\left(\theta-\tan^{-1}\frac{2k_t(1-z)Q}{k_t^2-(1-z)^2Q^2}\right)\theta\left(\frac{\vec{k}_t^2+(1-z)^2Q^2}{(1-z)Q}<x_B\frac{Q}{x_B}\right)$$