

Nucleon Energy Correlators

Xiaohui Liu

QCD Evolution Workshop 2023

IJCLab, Orsay, France

XL, Zhu, [Phys.Rev.Lett. 130 \(2023\) 9, 9](#)

Liu, XL, Pan, Yuan, Zhu, [Phys.Rev.Lett. 130 \(2023\) 18, 181901](#)

Cao, XL, Zhu, [2303.01530](#), PRD

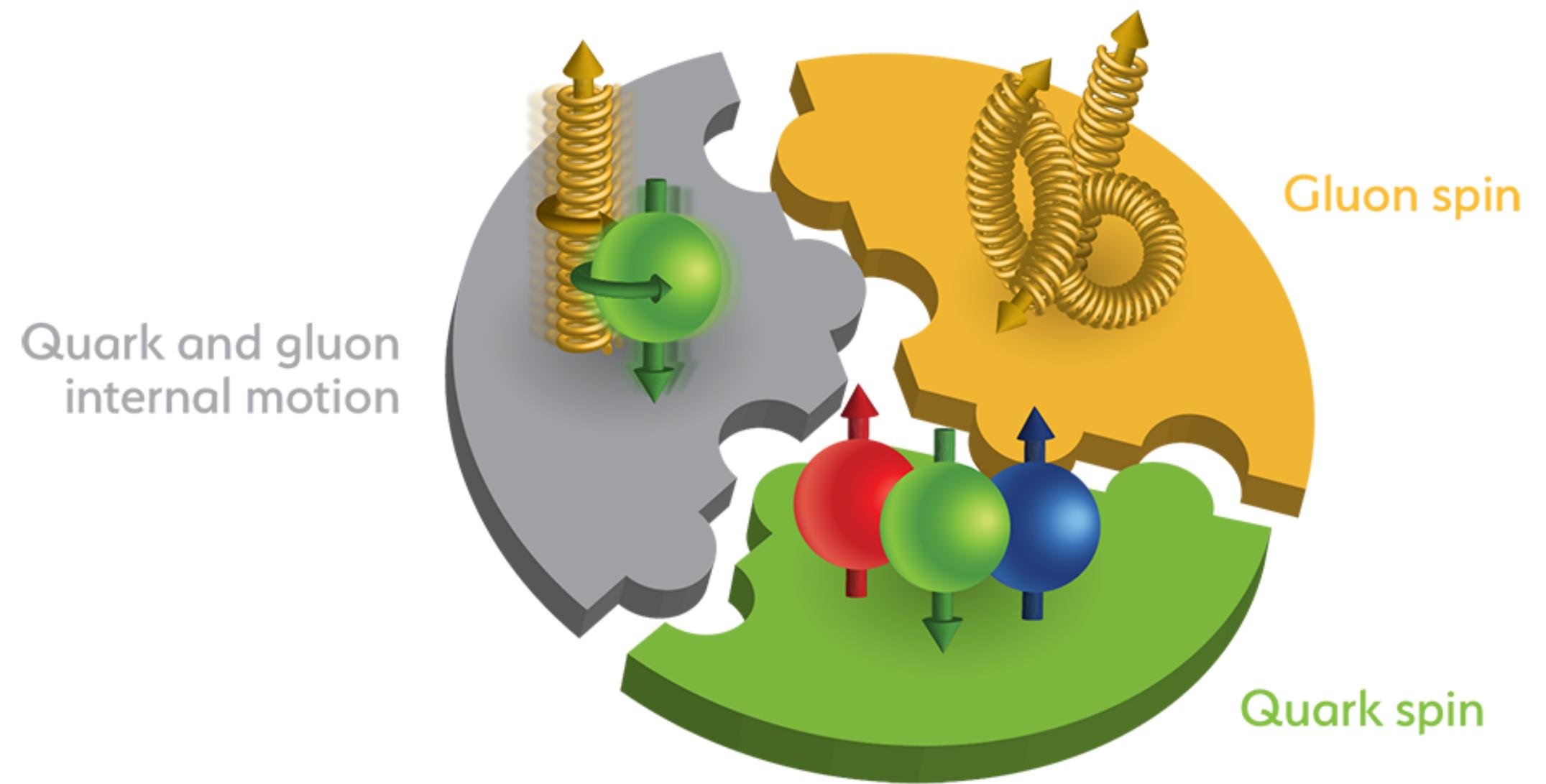
[more to come ...](#)



Outline

- The concept and features of the nucleon energy correlators
- Application to structure studies
- Conclusion

Nucleon/Nucleus Structure



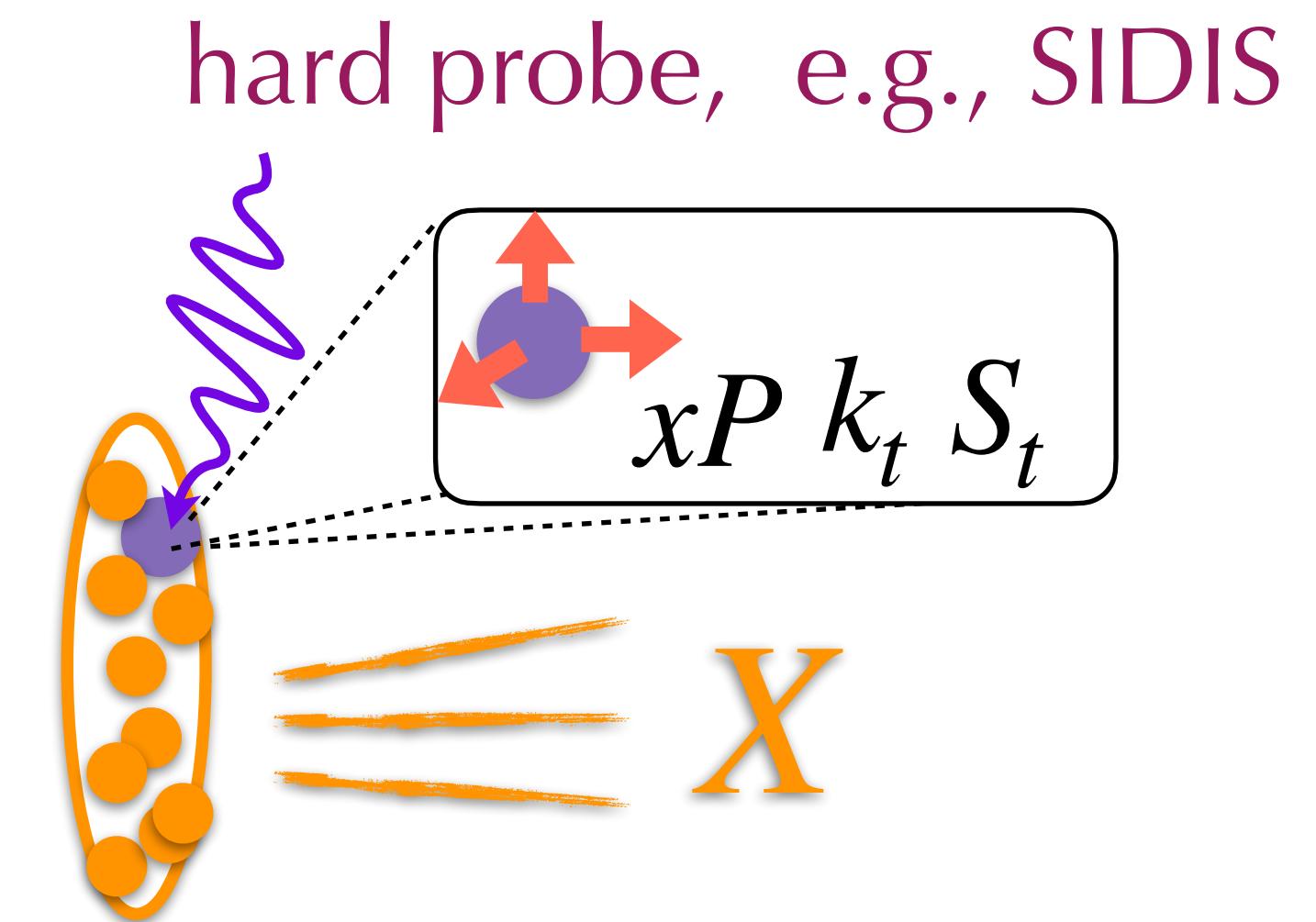
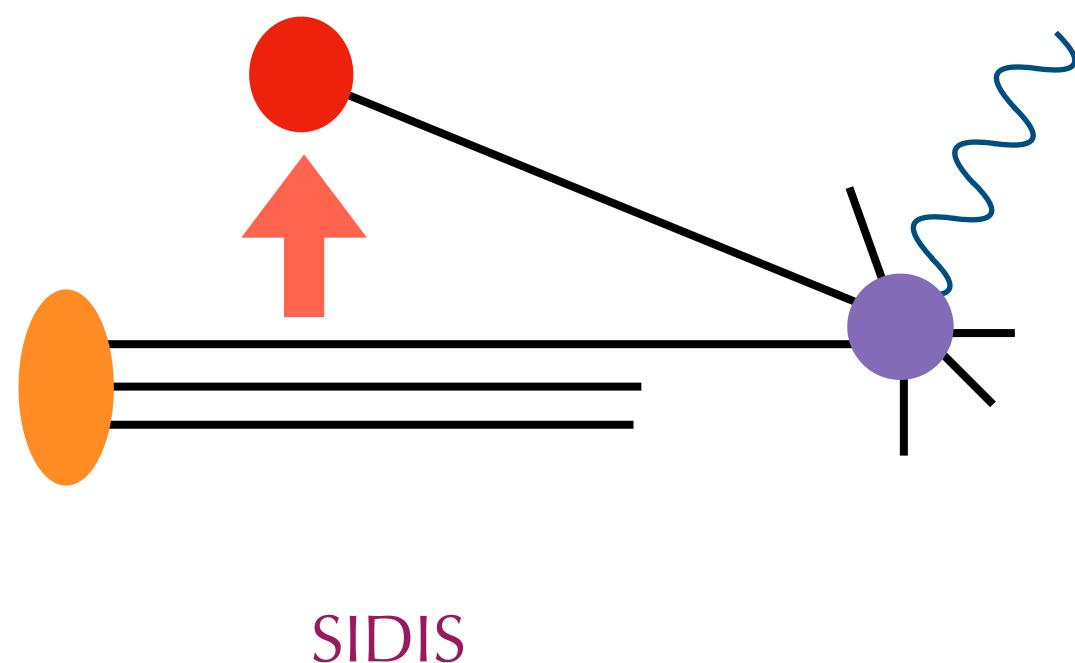
Major focus of EicC, EIC ...

Nucleon/Nucleus Structure

TMD-PDFs

$$f_{q/p}(x, k_t) = \int_{-\infty}^{\infty} \frac{dy^- dy_t}{(2\pi)^3} e^{ixp^+ y^-} e^{ik_t \cdot y_t} \frac{\gamma^+}{2} \langle P | \bar{\psi}(0) \mathcal{L} \psi(y_t, y^-) | P \rangle$$

$$q_t \sim k_t \sim \Lambda_{\text{QCD}}$$

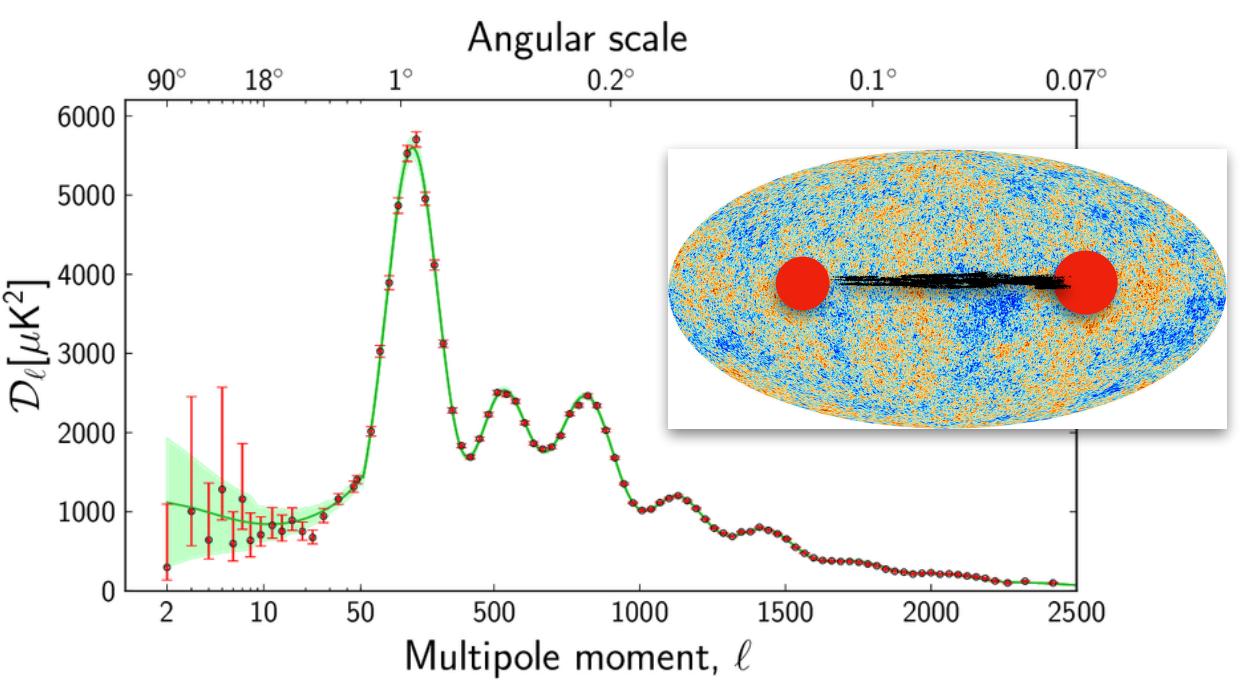


- Very successful for structure studies
- Soft contribution, e.g., $\sigma(k_T) \propto \frac{1}{k_t^2} e^{-\frac{q^2}{k_t^2}}, \dots$
- Not differential enough, **lose information**

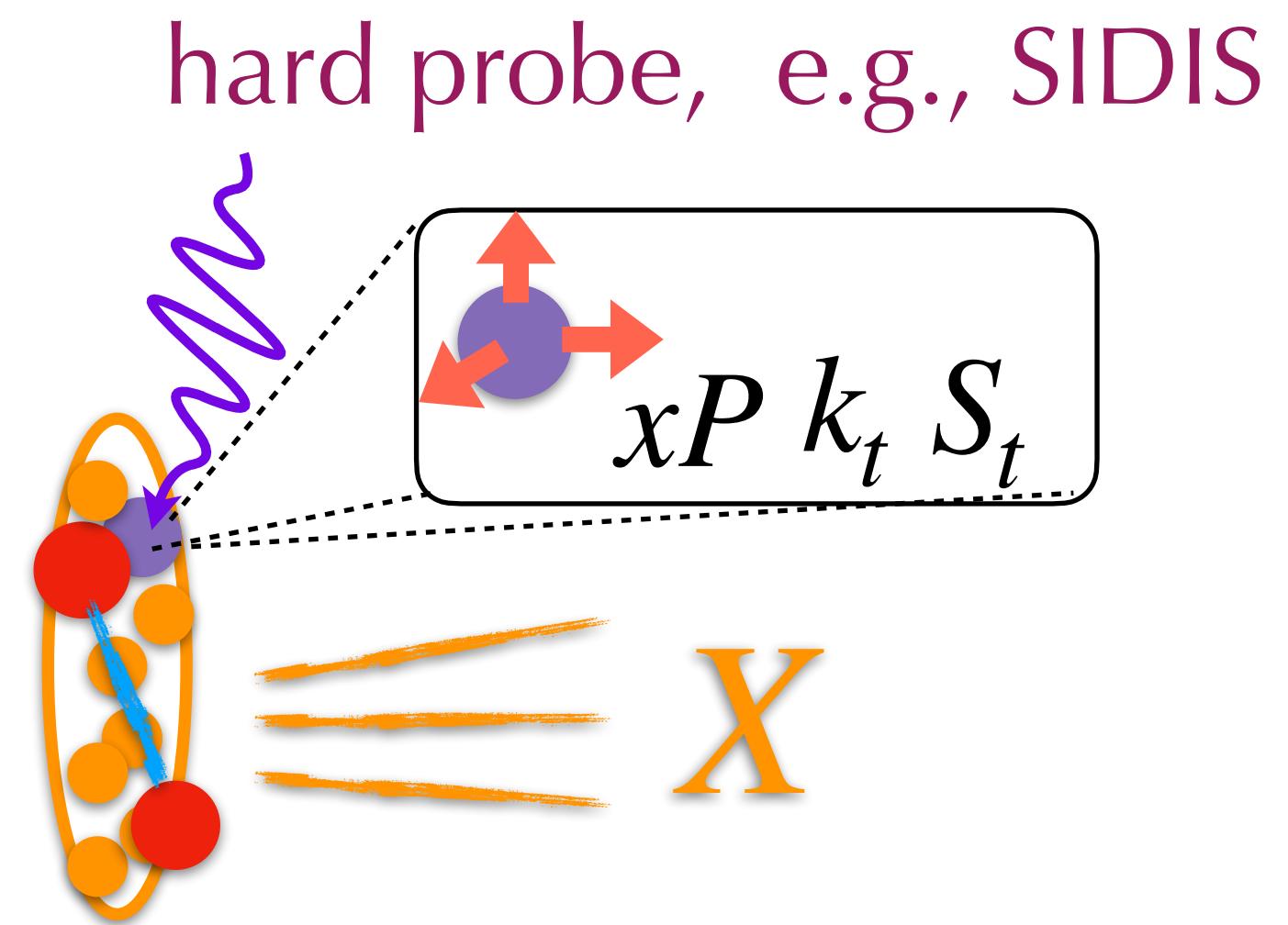
Nucleon/Nucleus Structure

TMD-PDFs

$$f_{q/p}(x, k_t) = \int_{-\infty}^{\infty} \frac{dy^- dy_t}{(2\pi)^3} e^{ixp^+ y^-} e^{ik_t \cdot y_t} \frac{\gamma^+}{2} \langle P | \bar{\psi}(0) \mathcal{L} \psi(y_t, y^-) | P \rangle$$



$\delta T(n_1) \delta T(n_2)$



- Very successful for structure studies
- Soft contribution, e.g., $\sigma(k_T) \propto \frac{1}{k_t^2} e^{-\frac{Q^2}{k_T^2}}$, ...
- Not differential enough, **lose information**

Nucleon Energy Correlators

An extension of the energy correlators

Andres, Basham, Belitsky, Brown, Chen, Dixon, Dominguez,
Elayavalli, Ellis, Hofman, Hohenegger, Holguin, Jaarsma,
Kologlu, Korchemsky, Kravchuk, Komiske, Lee, Li, Love, Luo,
Maldacena, Meçaj, Marquet, Moult, Pathak, Procura, Simmons-
Duffin, Sokatchev, Thaler, van Velzen, Waalewijn, Yang, Zhang,
Zhiboedov, Zhu + ...

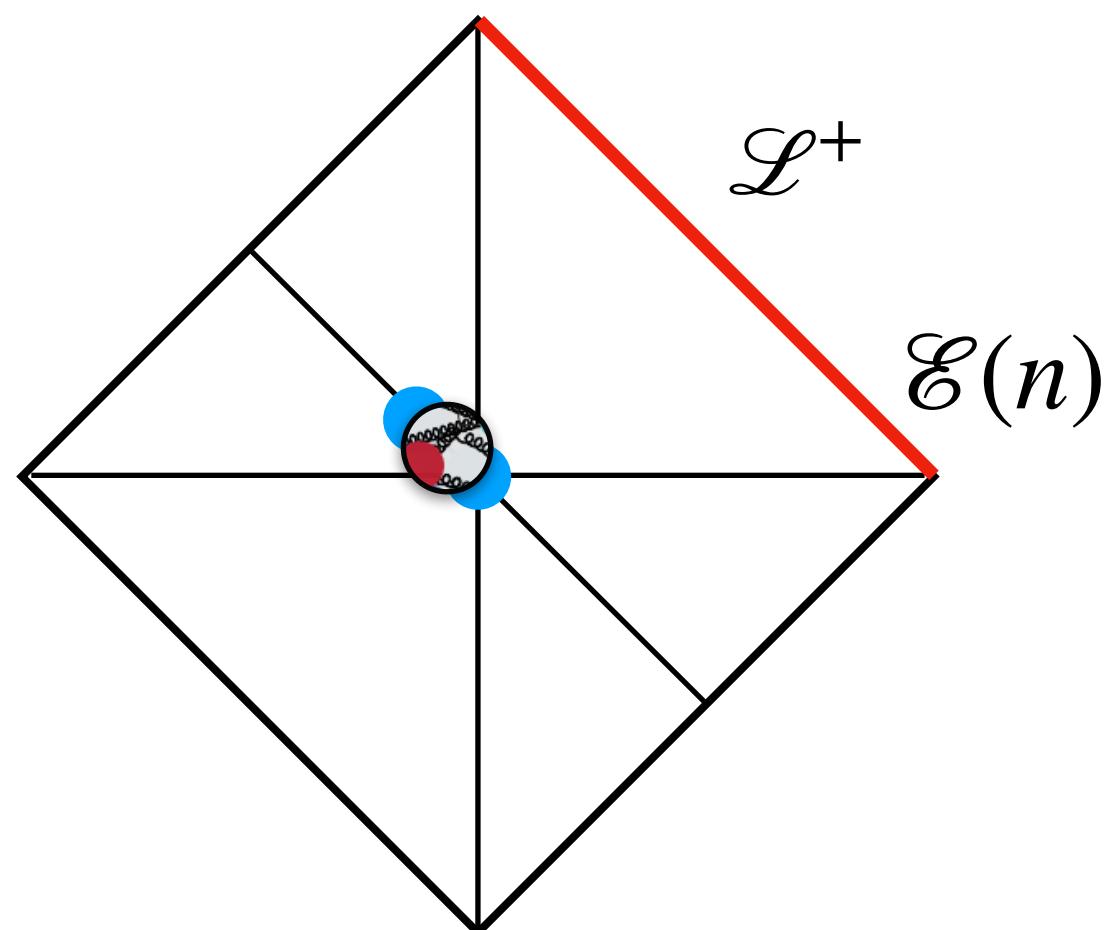
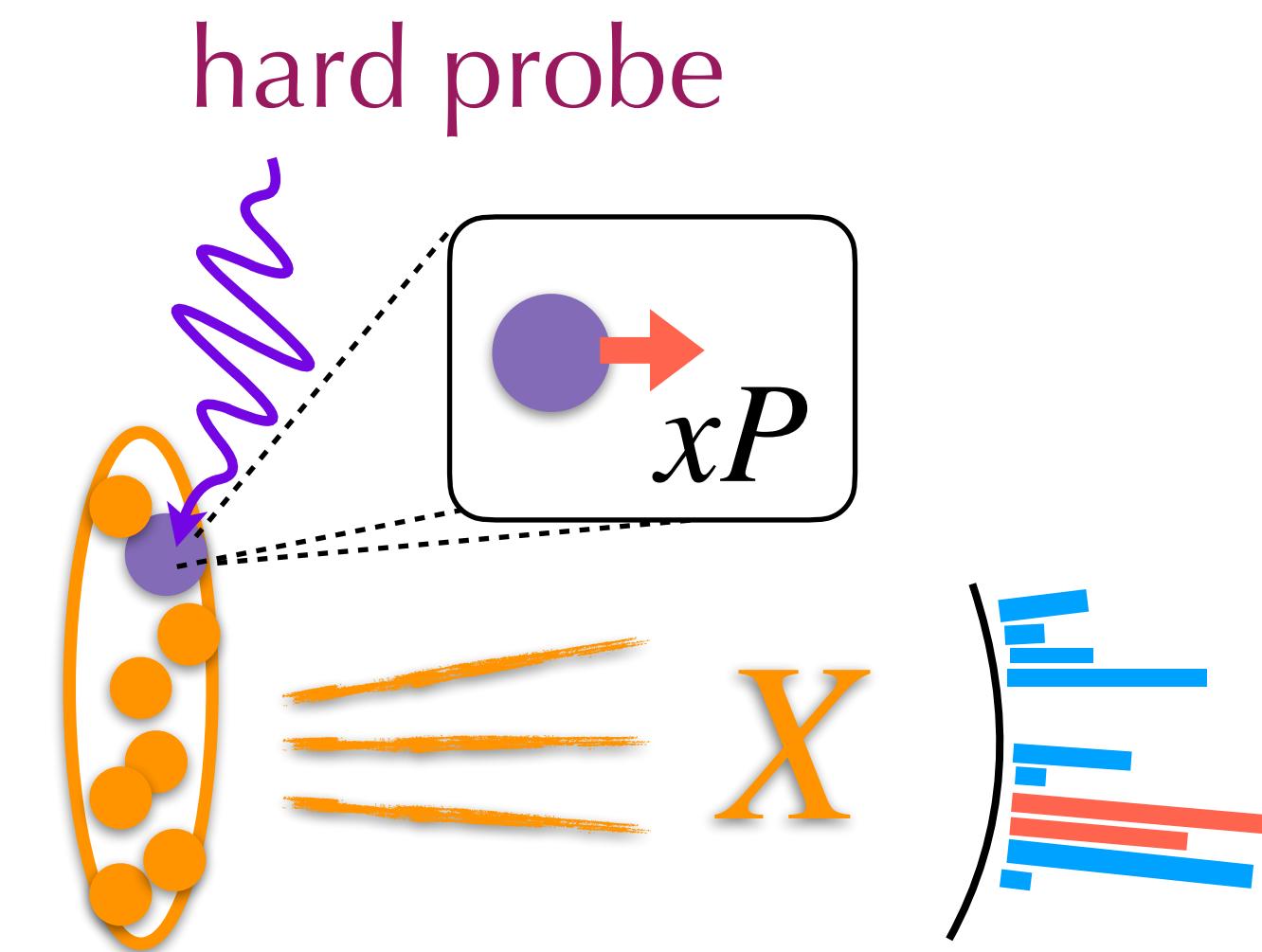
Nucleon Energy Correlators

Nucleon EEC

XL and Zhu, Phys. Rev. Lett. 130 (2023), 9, 9

$$f_{q,EEC}(x, \theta) = \int_{-\infty}^{\infty} \frac{dy^-}{2\pi} e^{ixp^+y^-} \frac{\gamma^+}{2} \langle P | \bar{\psi}(0) \mathcal{E}(\theta) \mathcal{L} \psi(y^-) | P \rangle$$

$$\mathcal{E}(n) = \lim_{r \rightarrow \infty} \int_0^\theta d\vec{n} \int_0^\infty dt T_{0\vec{n}}(t, \vec{n} \cdot \vec{r}) r^2 \quad \mathcal{E}(\theta) |X\rangle = \sum_i \frac{E_i}{E_P} \Theta(\theta - \theta_i) |X\rangle$$



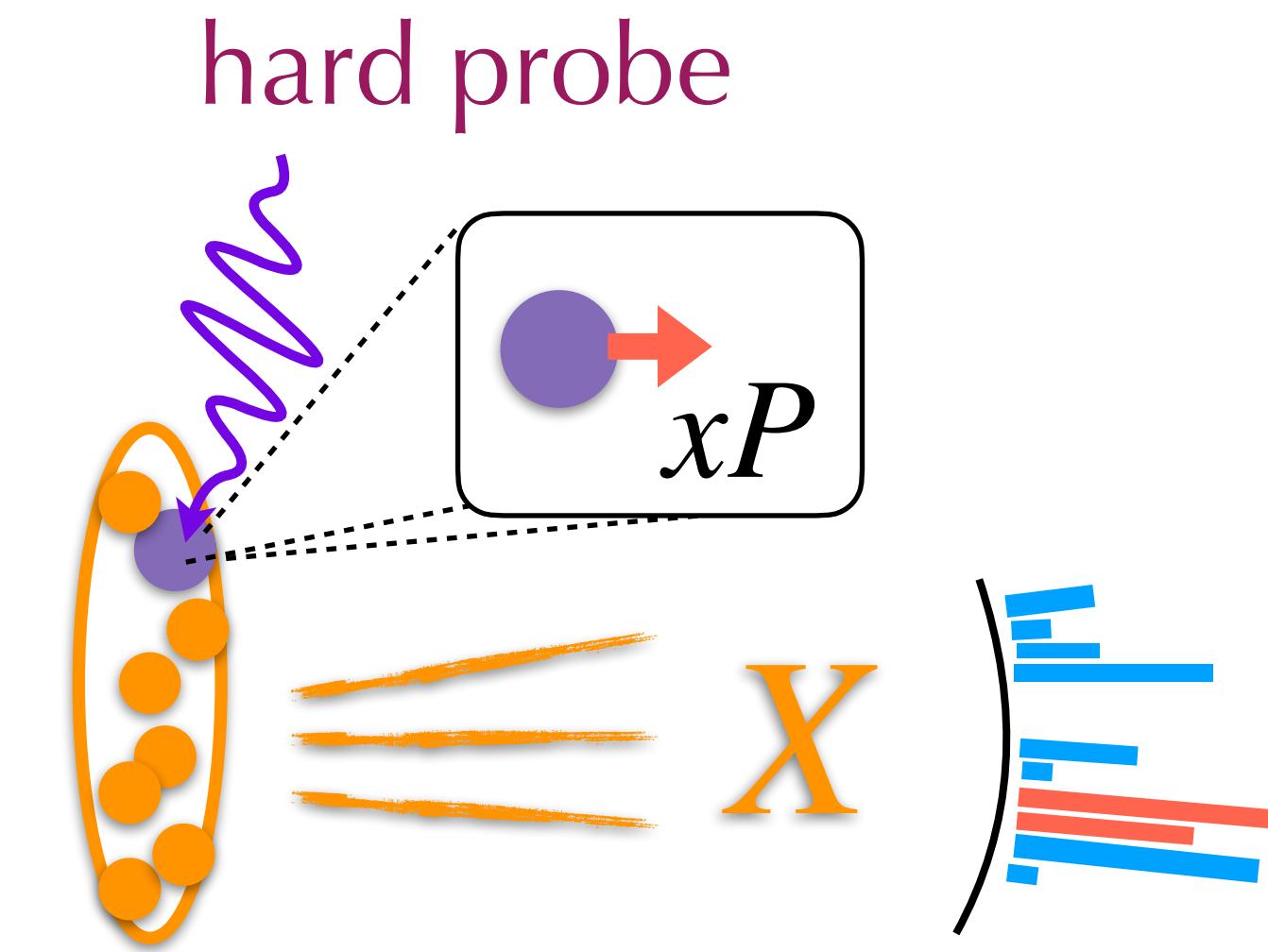
- The active parton k_t unconstrained, NOT TMD
- Transverse dynamics through $\mathcal{E}(\theta)$

Nucleon Energy Correlators

Nucleon EEC

XL and Zhu, Phys. Rev. Lett. 130 (2023), 9, 9

$$f_{q,EEC}(x, \theta) \propto \sum_{i \in X} \frac{E_i}{E_P} \Theta(\theta - \theta_i) \delta(xP - p) \langle P | a_p^\dagger | X \rangle \langle X | a_p | P \rangle$$



- “Energy weighted collinear PDF”
- NOT TMD, insensitive to soft radiations,
e.g. no Sudakov suppression
- Evolves like PDF, modified-DGLAP (MLLA)

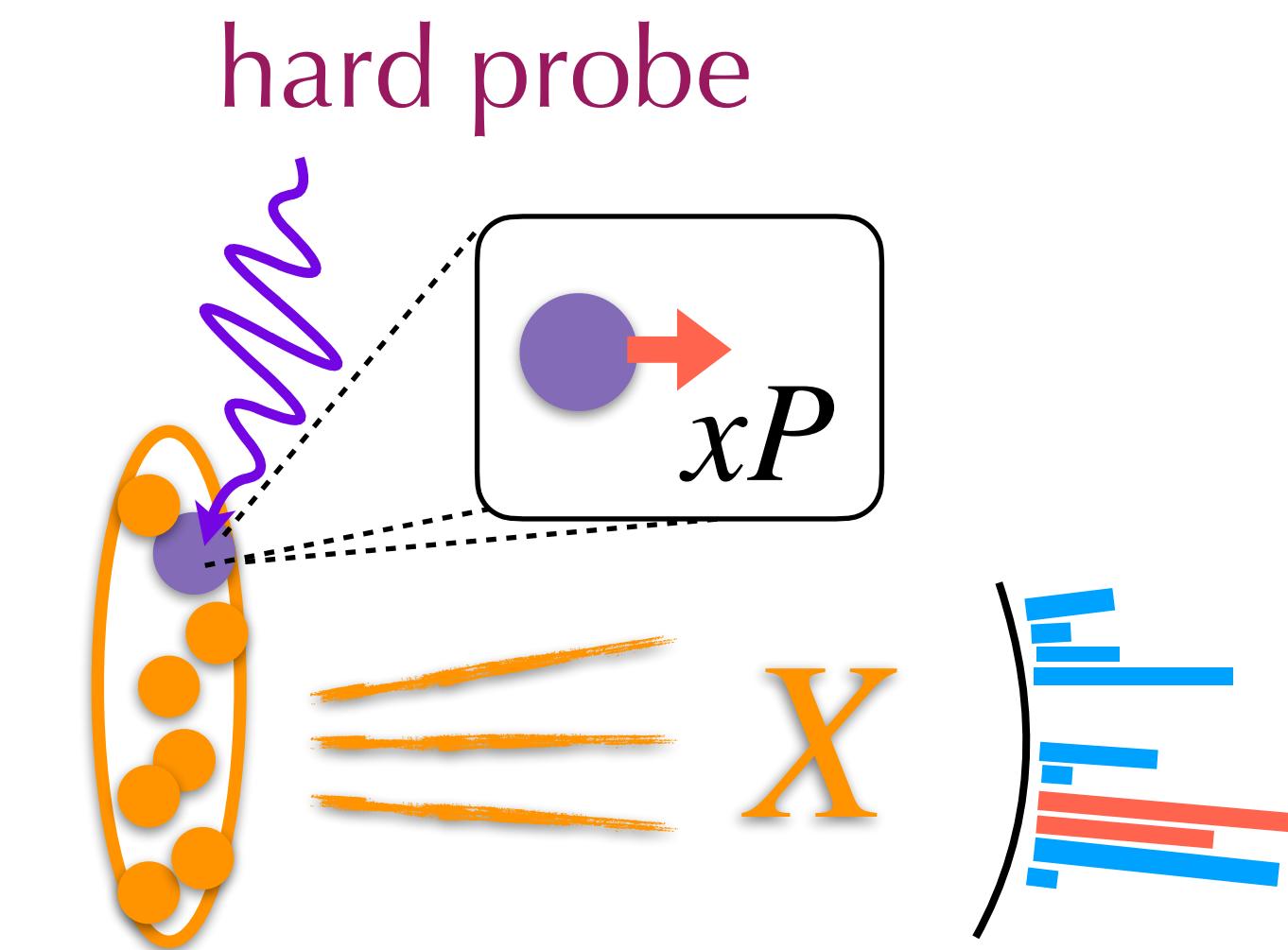
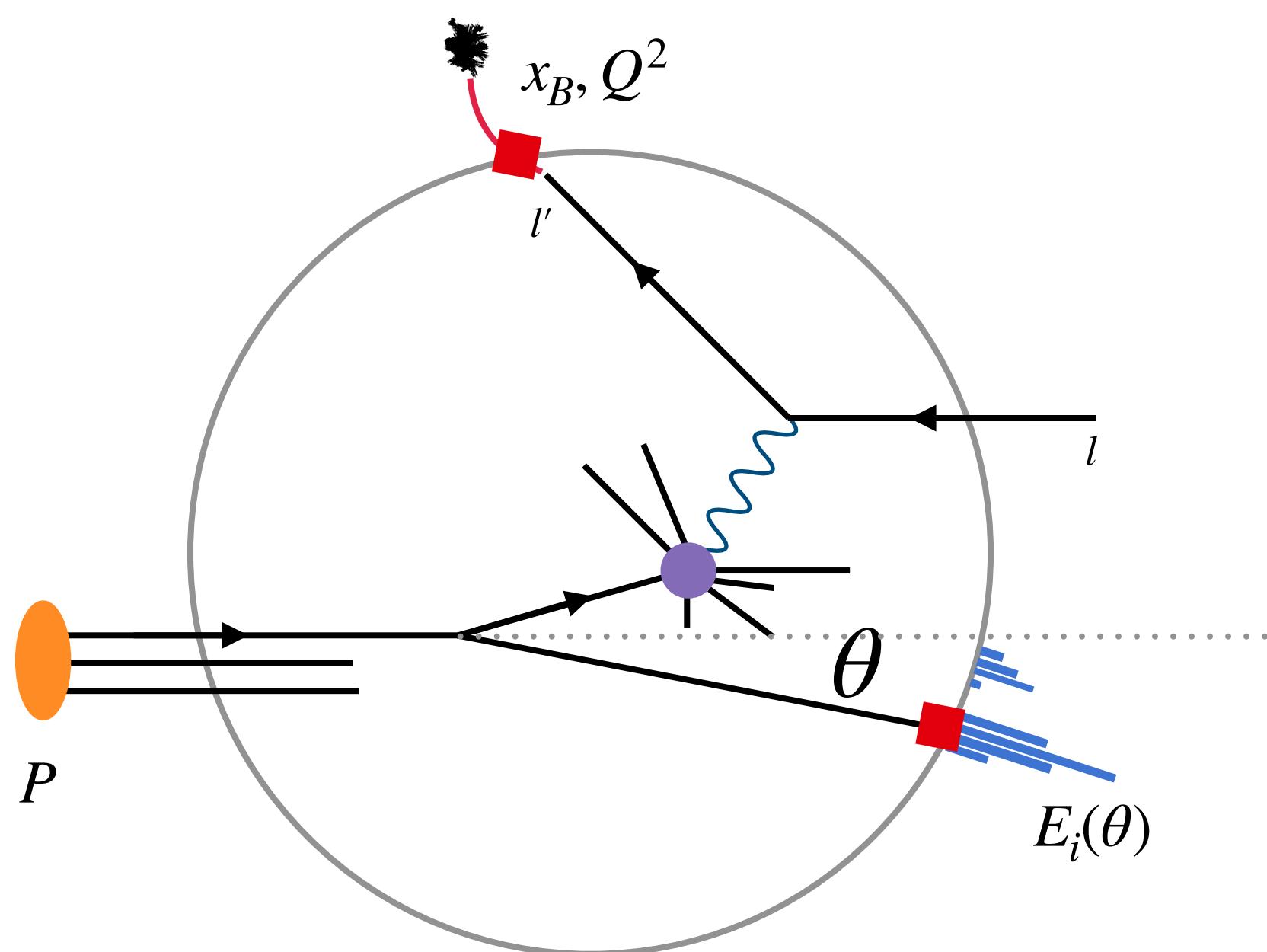
$$df(z, \ln \frac{Q\theta}{z u \mu}) / d \ln \mu = \int \frac{d\xi}{\xi} P\left(\frac{z}{\xi}\right) f(\xi, \ln \frac{Q\theta}{z u \mu})$$

Nucleon Energy Correlators

Nucleon EEC

XL and Zhu, Phys. Rev. Lett. 130 (2023), 9, 9

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



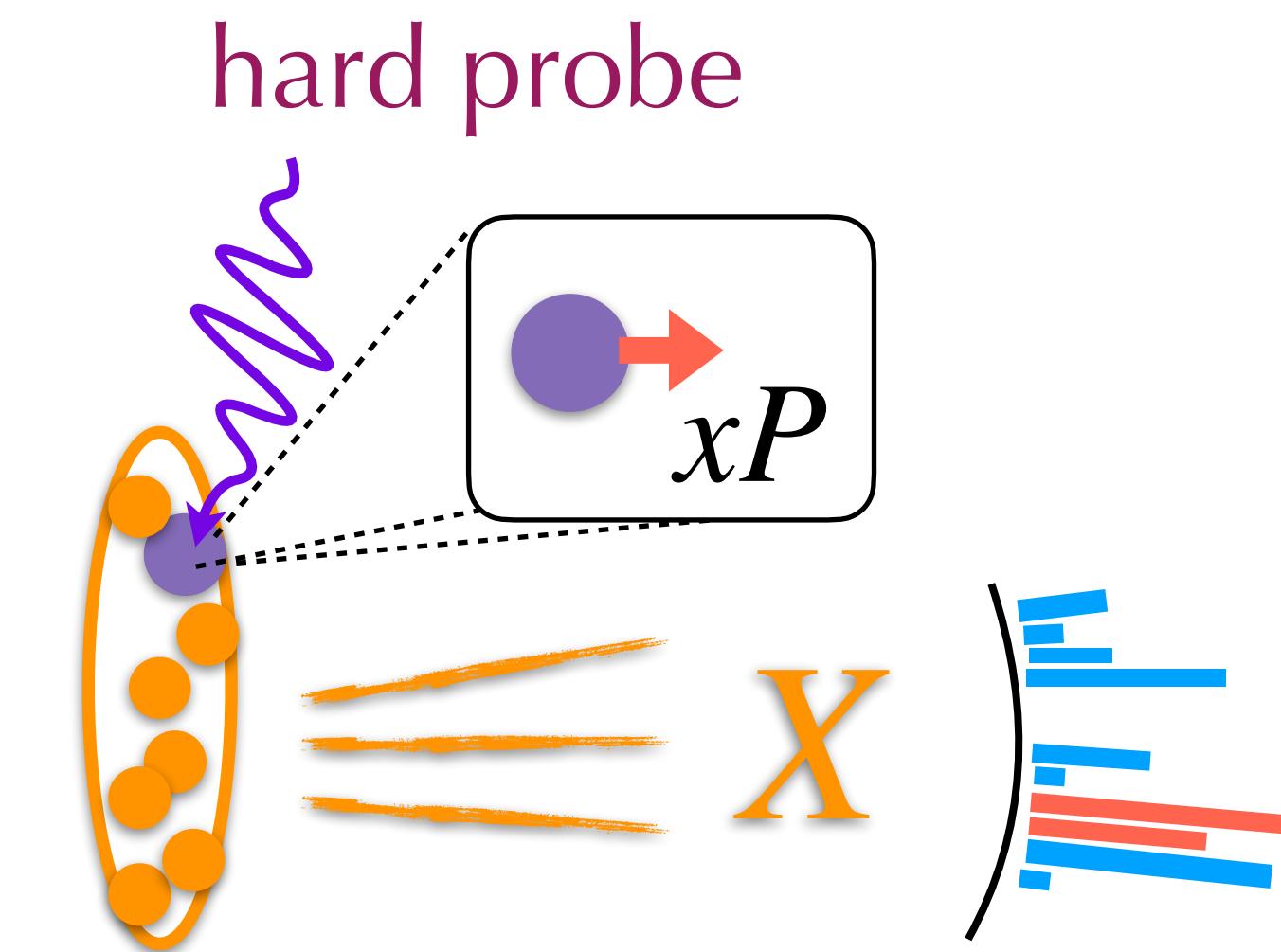
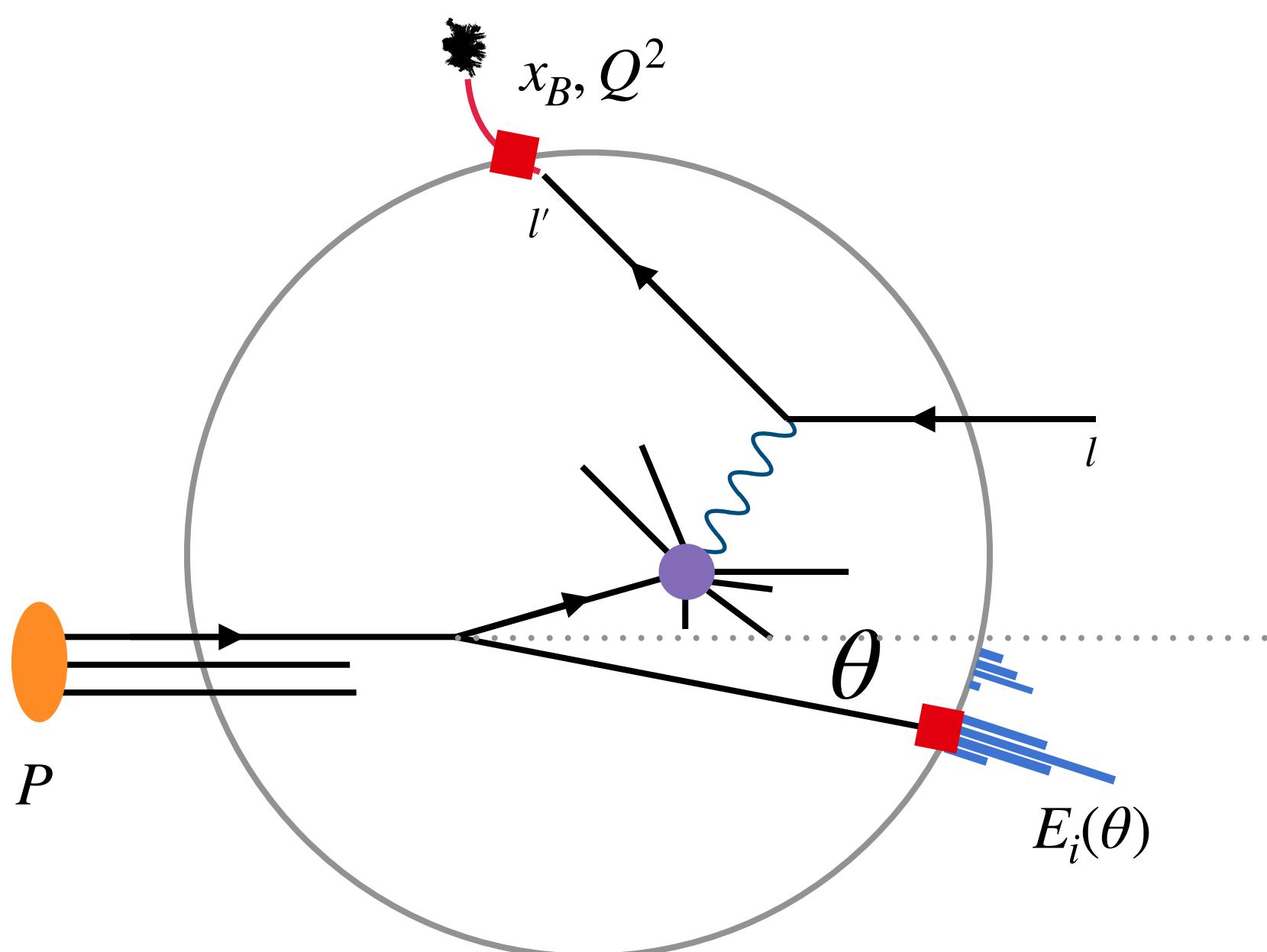
- Full inclusive measurement, **no jet/hadrons**, weighted by E_i
- Different θ 's probe different physics

Nucleon Energy Correlators

Nucleon EEC

XL and Zhu, Phys. Rev. Lett. 130 (2023), 9, 9

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



- When $\theta Q \ll Q$, factorization can be shown using SCET

$$\Sigma(x_B, Q^2, \theta) = \int \frac{dz}{z} \hat{\sigma}\left(\frac{x_B}{z}, Q^2, \mu\right) f_{\text{EEC}}(z, \theta, \mu)$$

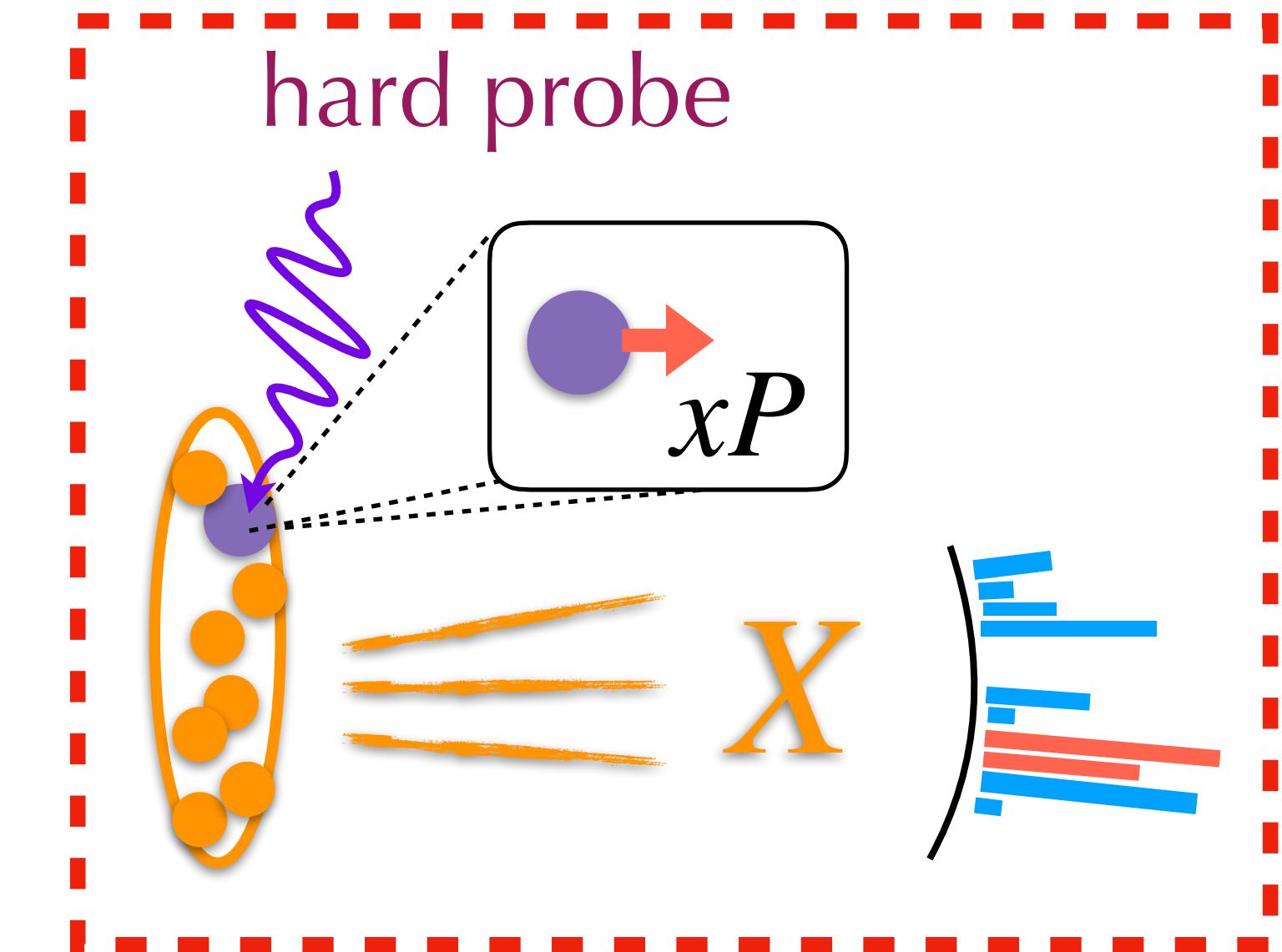
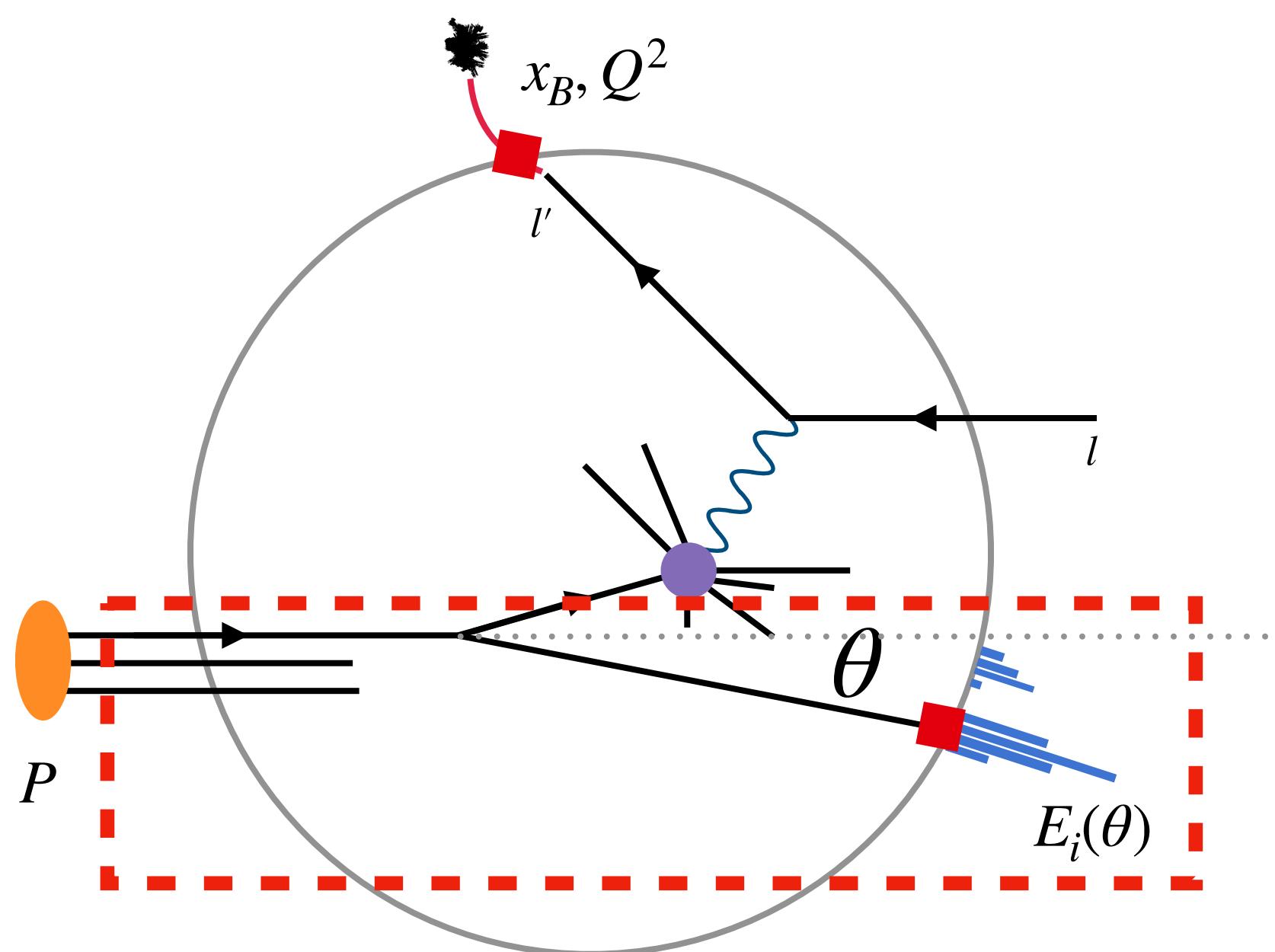
Cao, XL, Zhu, 2303.01530

Nucleon Energy Correlators

Nucleon EEC

XL and Zhu, Phys. Rev. Lett. 130 (2023), 9, 9

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



- When $\theta Q \ll Q$, factorization can be shown using SCET

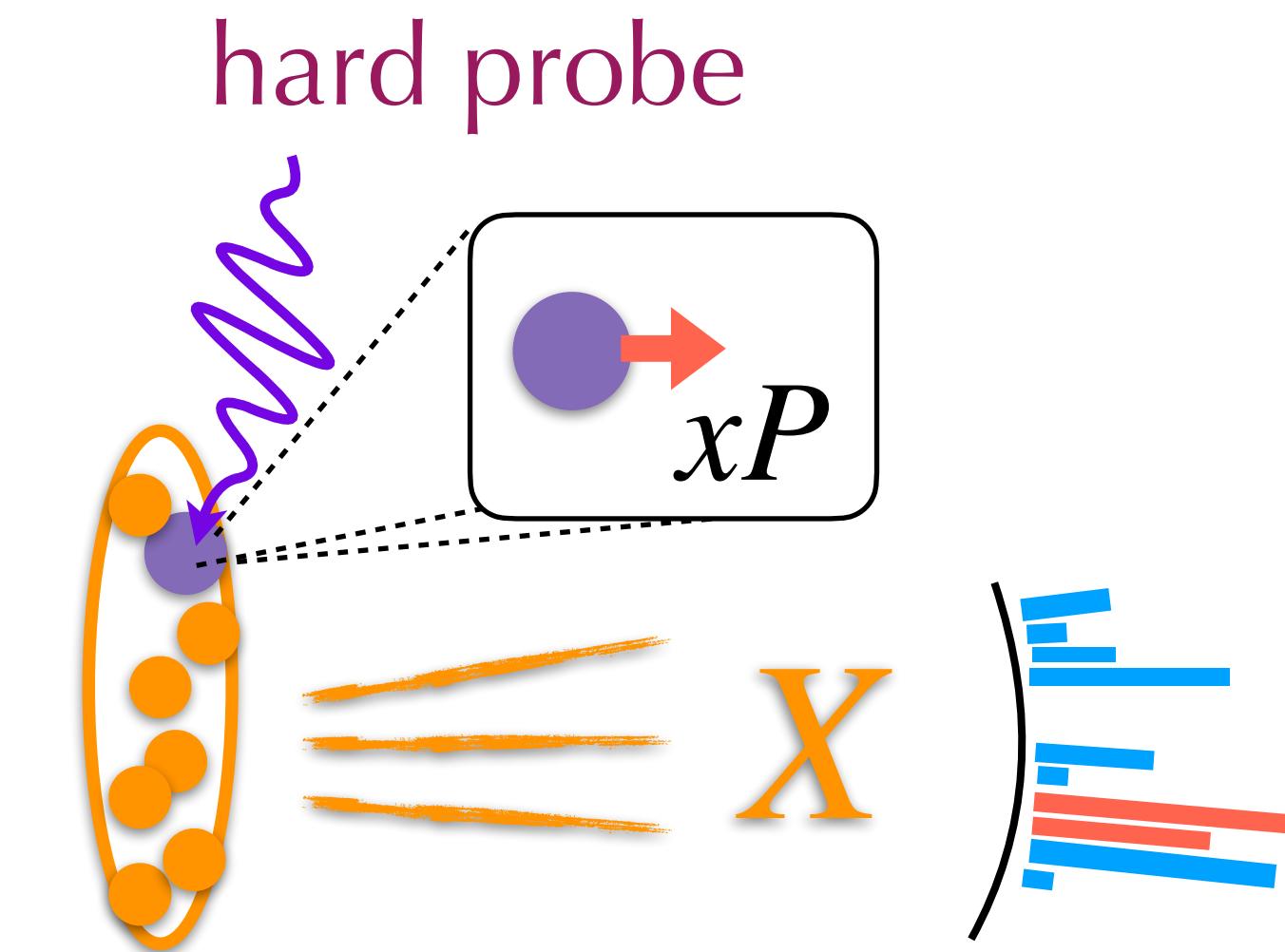
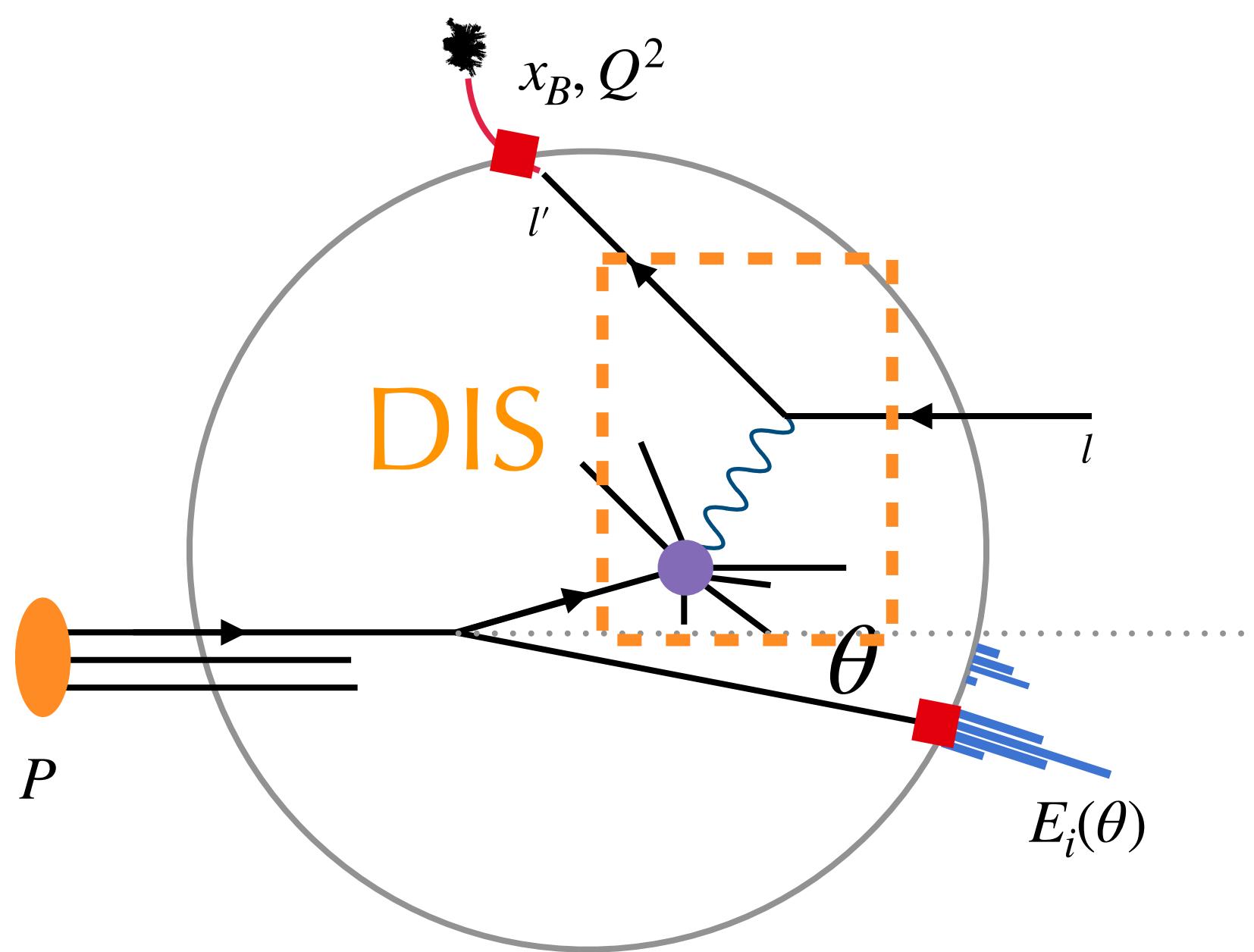
$$\Sigma(x_B, Q^2, \theta) = \int \frac{dz}{z} \hat{\sigma} \left(\frac{x_B}{z}, Q^2, \mu \right) f_{\text{EEC}}(z, \theta, \mu)$$

Nucleon Energy Correlators

Nucleon EEC

XL and Zhu, Phys. Rev. Lett. 130 (2023), 9, 9

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



- When $\theta Q \ll Q$, factorization can be shown using SCET

$$\Sigma(x_B, Q^2, \theta) = \int \frac{dz}{z} \hat{\sigma} \left(\frac{x_B}{z}, Q^2, \mu \right) f_{\text{EEC}}(z, \theta, \mu)$$

Inclusive DIS partonic
cross section

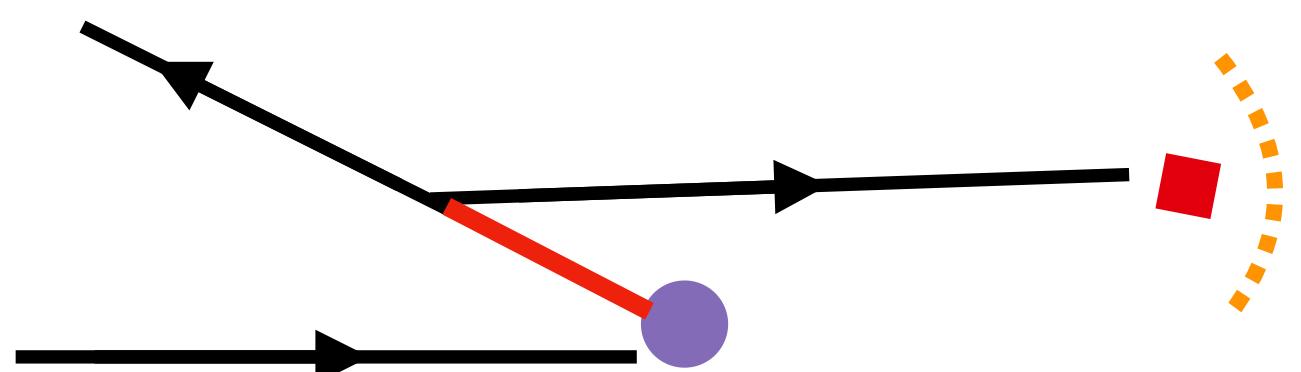
Nucleon Energy Correlators

Nucleon EEC

XL and Zhu, Phys. Rev. Lett. 130 (2023), 9, 9

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

Breit Frame
NLO



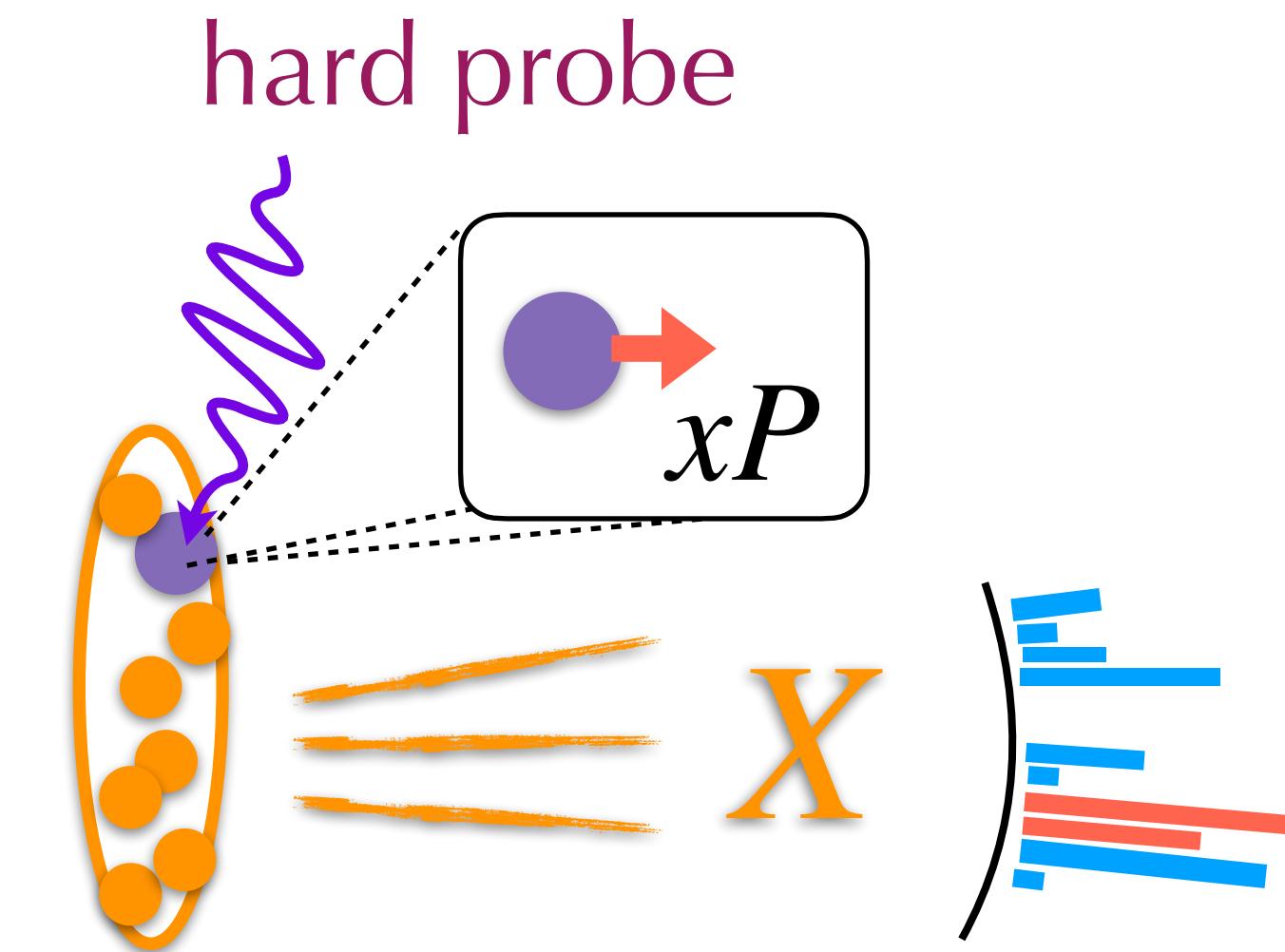
$$\sim \frac{1}{Q^2} \times Q^2 \theta^2 \rightarrow 0$$

- When $\theta Q \ll Q$, factorization can be shown using SCET

$$\Sigma(x_B, Q^2, \theta) = \int \frac{dz}{z} \hat{\sigma} \left(\frac{x_B}{z}, Q^2, \mu \right) f_{\text{EEC}}(z, \theta, \mu)$$

Inclusive DIS partonic
cross section

θ shape directly
probes f_{EEC}

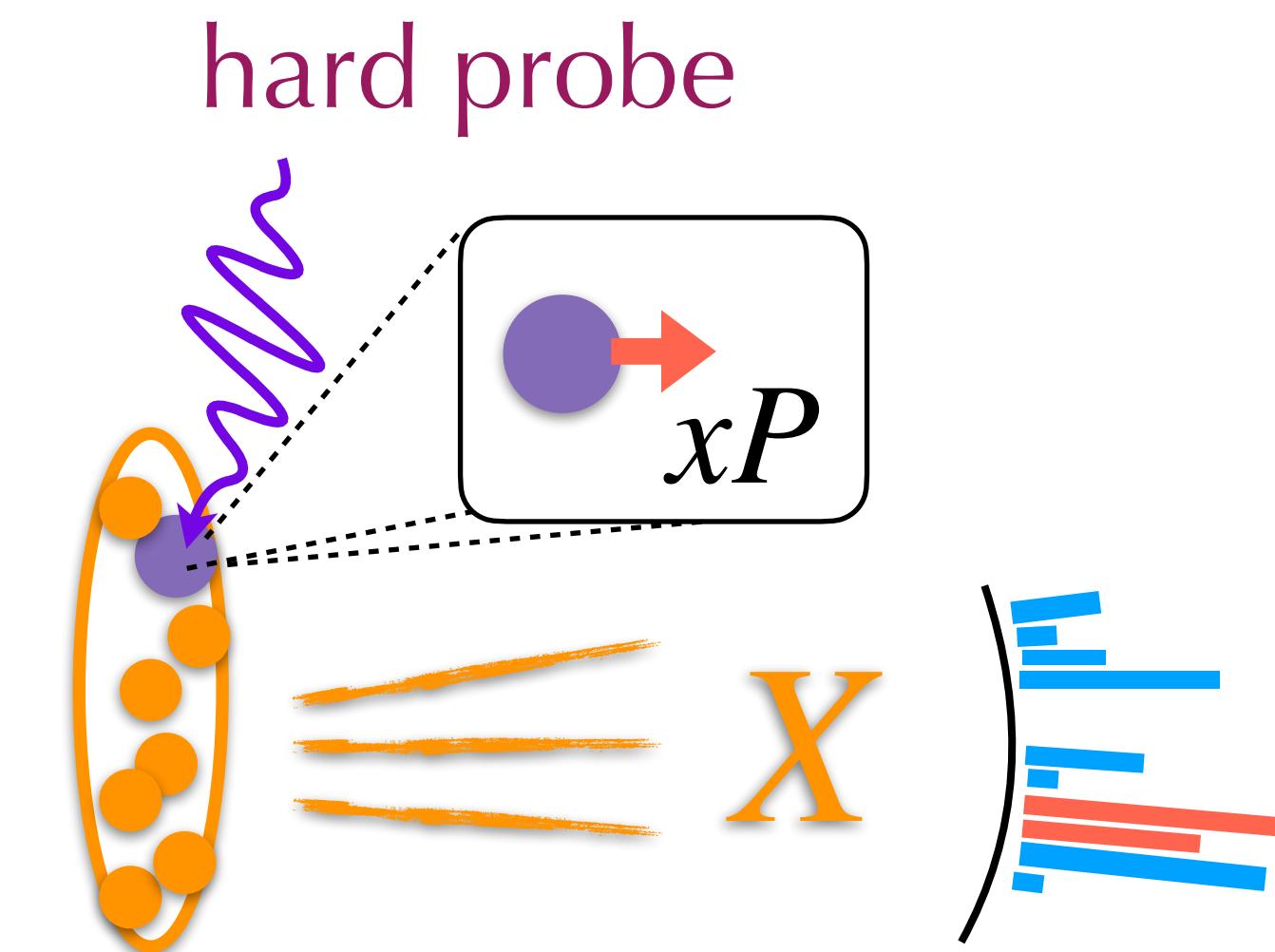
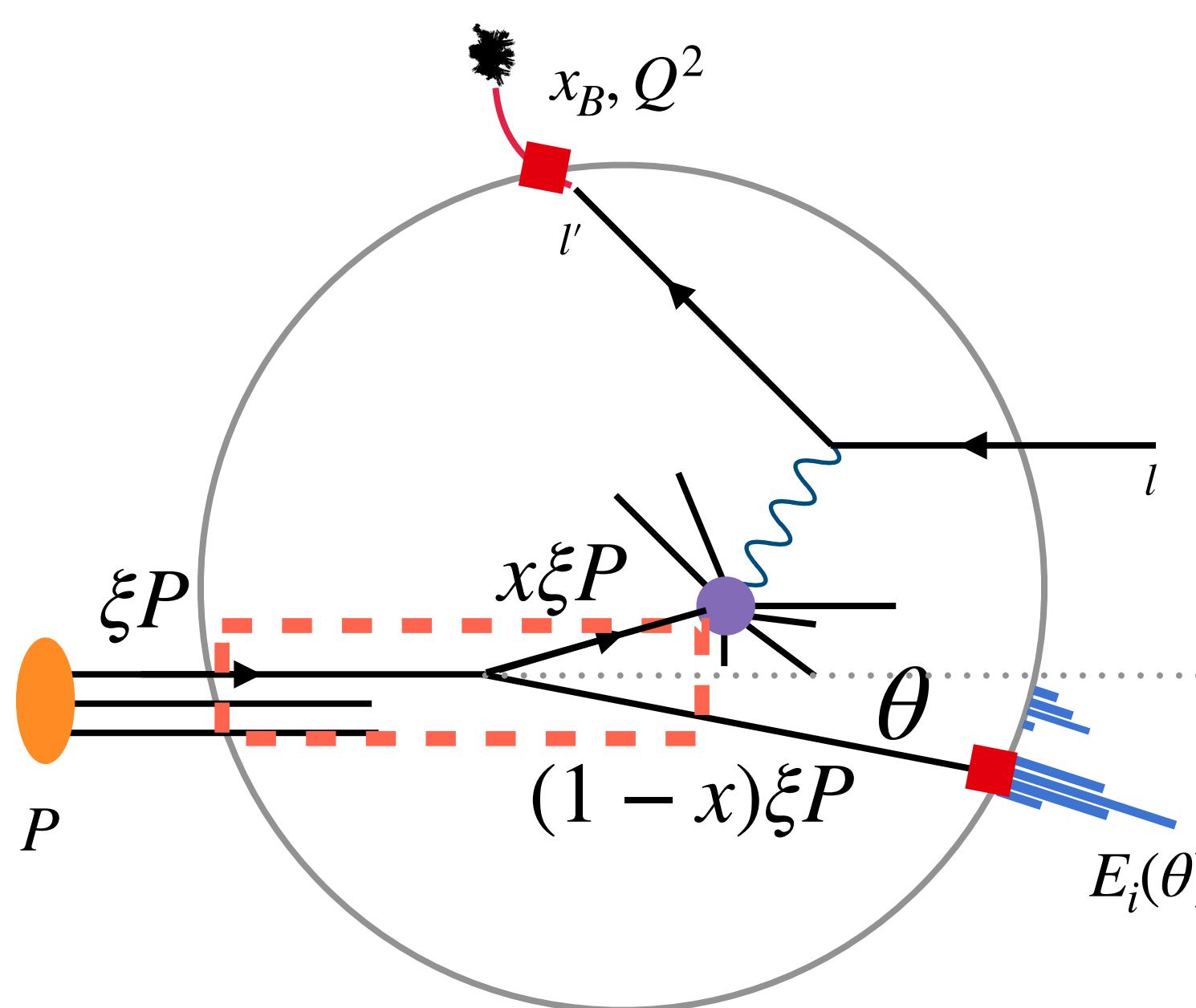


Nucleon Energy Correlators

Nucleon EEC

XL and Zhu, Phys. Rev. Lett. 130 (2023), 9, 9

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



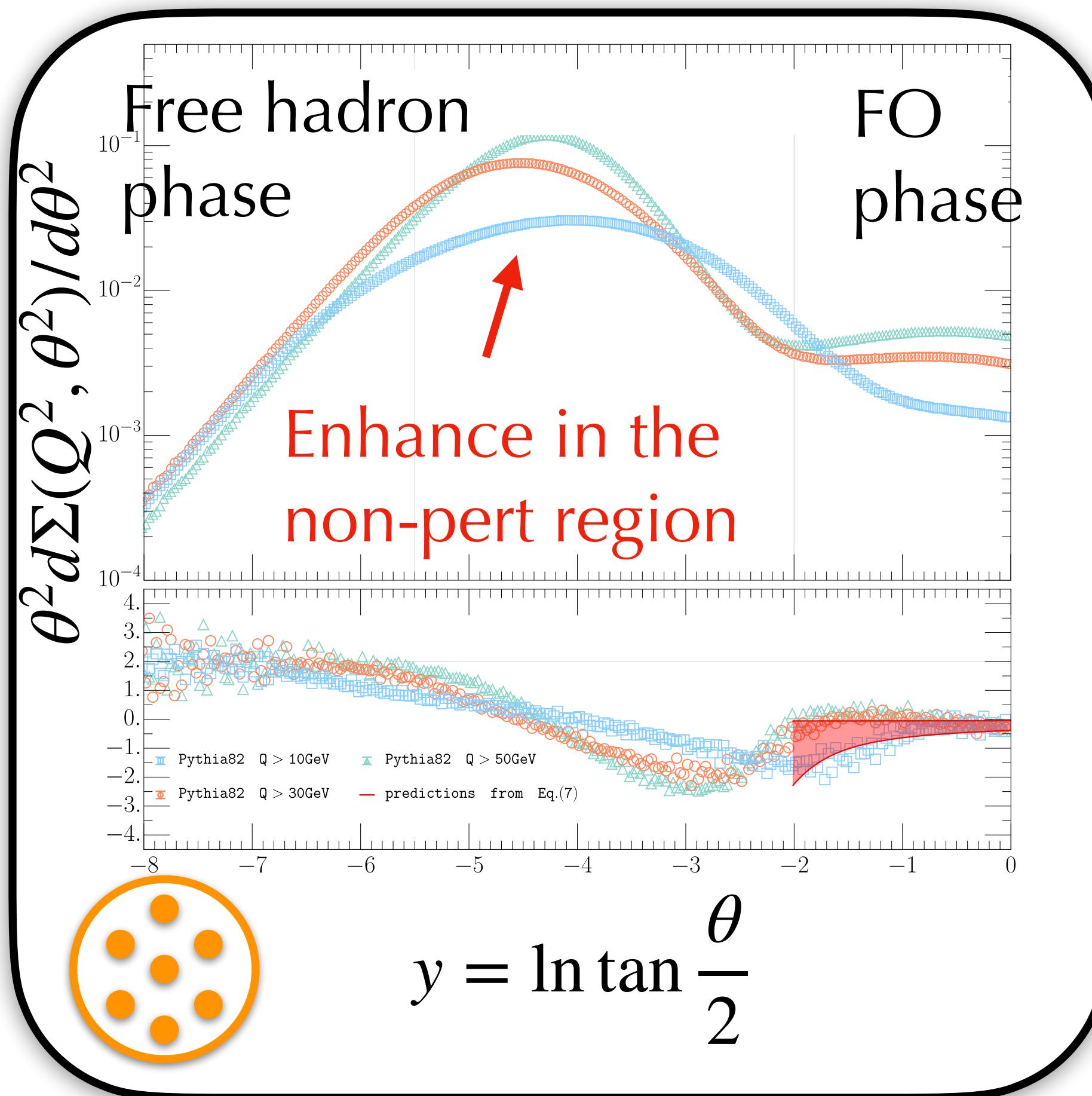
- $Q\theta \gg \Lambda_{\text{QCD}}, \quad df_{\text{EEC}}(\theta)/d\theta^2 \propto \left[\frac{1}{\theta^2} (1-x)P(x) \right] \times [\xi f(\xi)]$
- 1-loop Cao, XL, Zhu, 2303.01530 , 2-loop Chen, XL, Pan, Yang Zhu, in preparation

All orders follow modified DGLAP

Nucleon Energy Correlators

Nucleon EEC

XL and Zhu, Phys. Rev. Lett. 130 (2023), 9, 9



- Enhanced when θ decreases, follows DGLAP

- "phase transition" between FO and free hadron

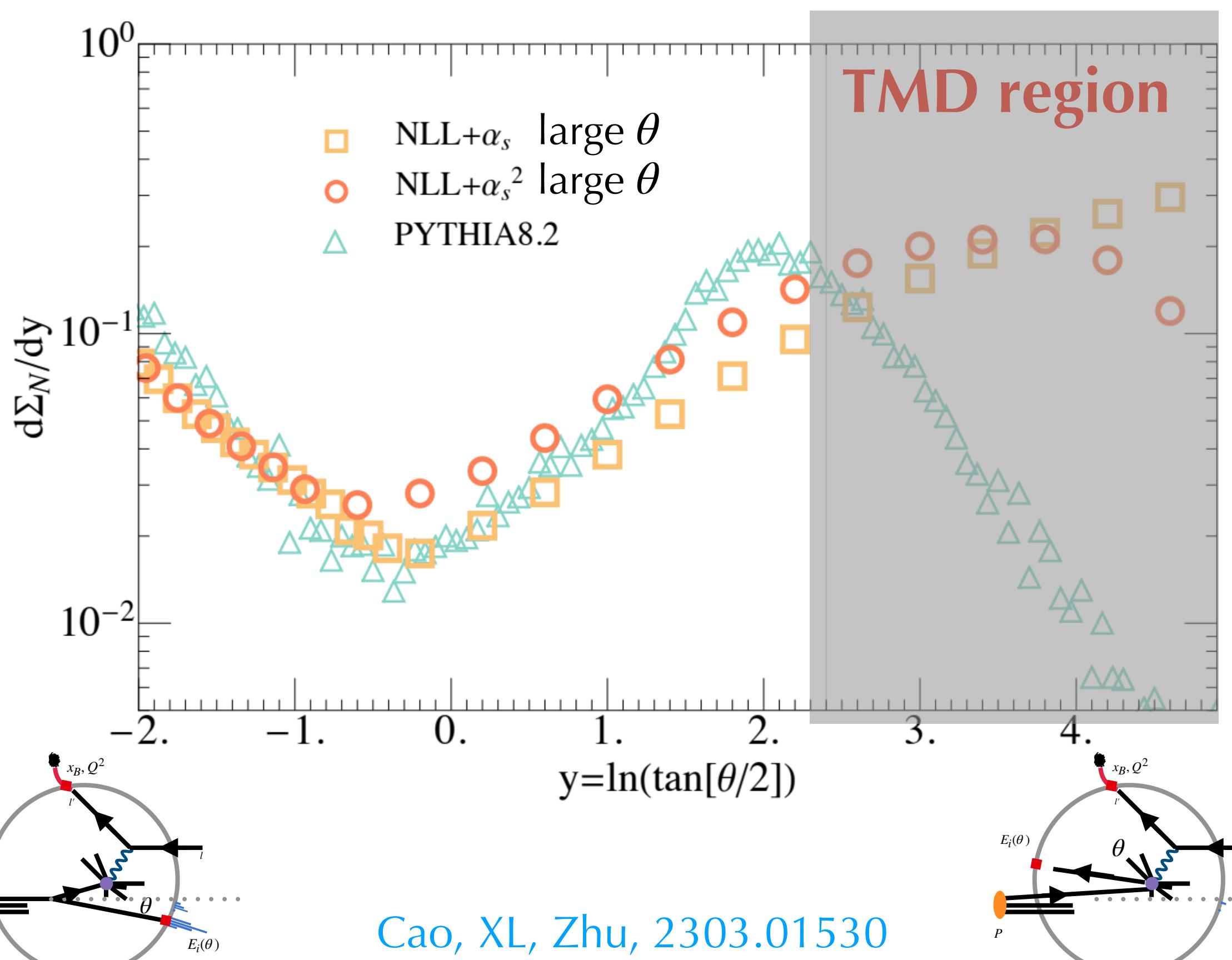
$$\propto \theta^2 \frac{d}{d\theta^2} \frac{a}{\pi(\tilde{P}\theta)^2} \sim \frac{1}{\theta^2} \sim e^{2y}$$

- Sensitive to the non-pert structures

Nucleon Energy Correlators

Nucleon EEC

XL and Zhu, Phys. Rev. Lett. 130 (2023), 9, 9



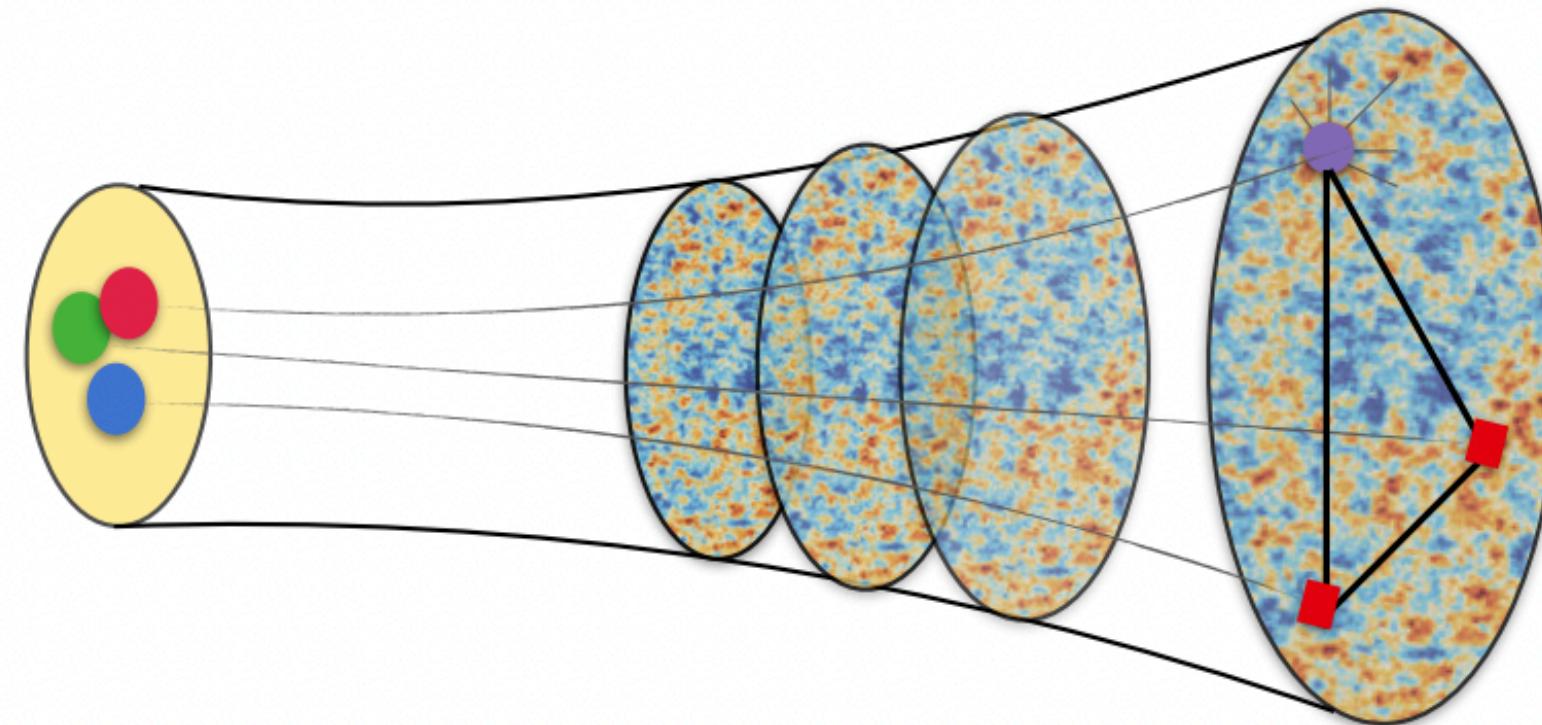
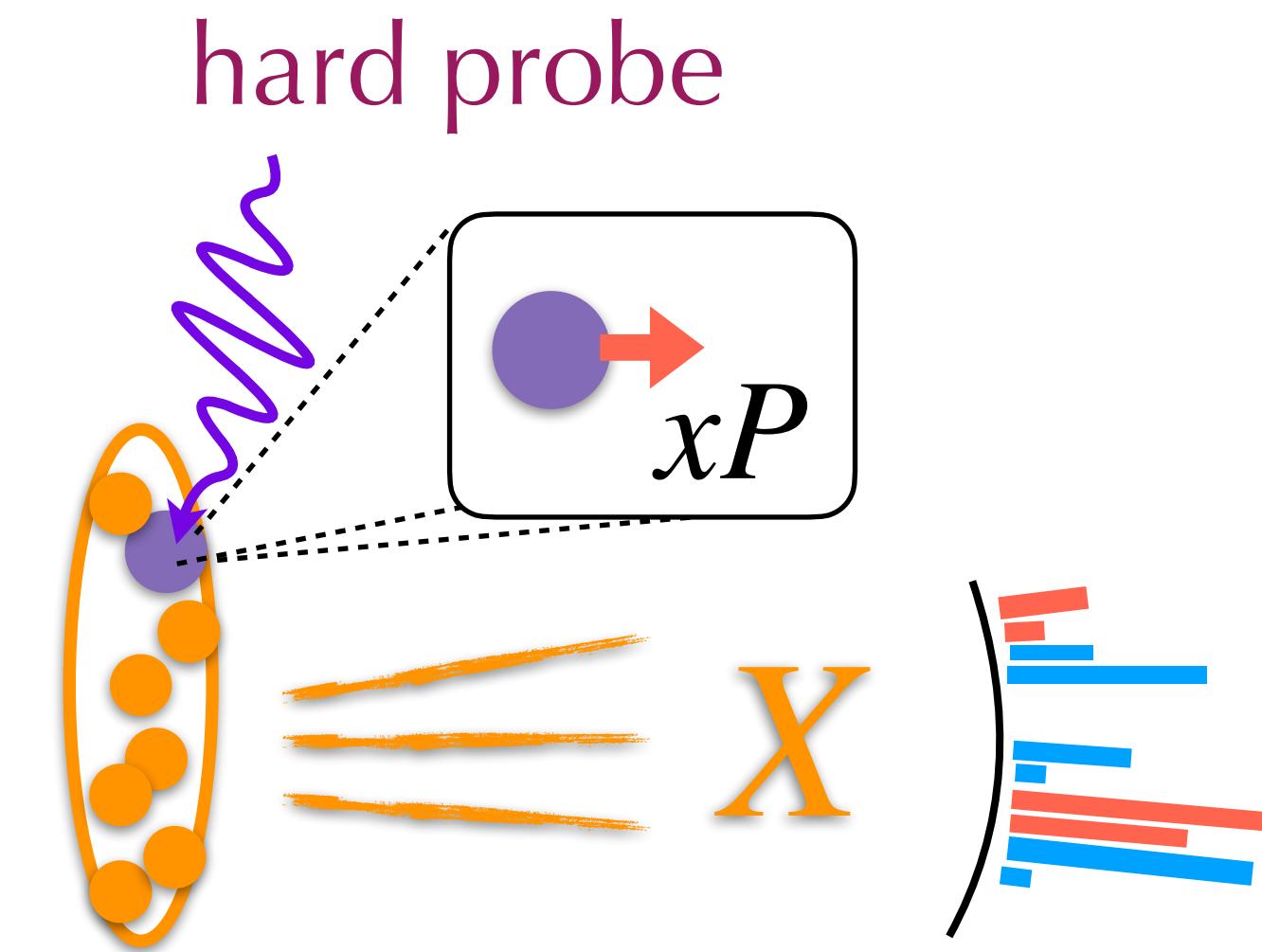
- FO+resumamtion prediction
- Good agreement with Pythia
- Enhancement in the small θ region
- Working on NNLL (2-loop f_{EEC})
Chen, XL, Pan, Yang, Zhu, **in preparation**
- 3-loops and NNNLL f_{EEC} seems also possible

Nucleon Energy Correlators

Nucleon EEC

XL and Zhu, 2209.02080, Phys. Rev. Lett. 130 (2023)

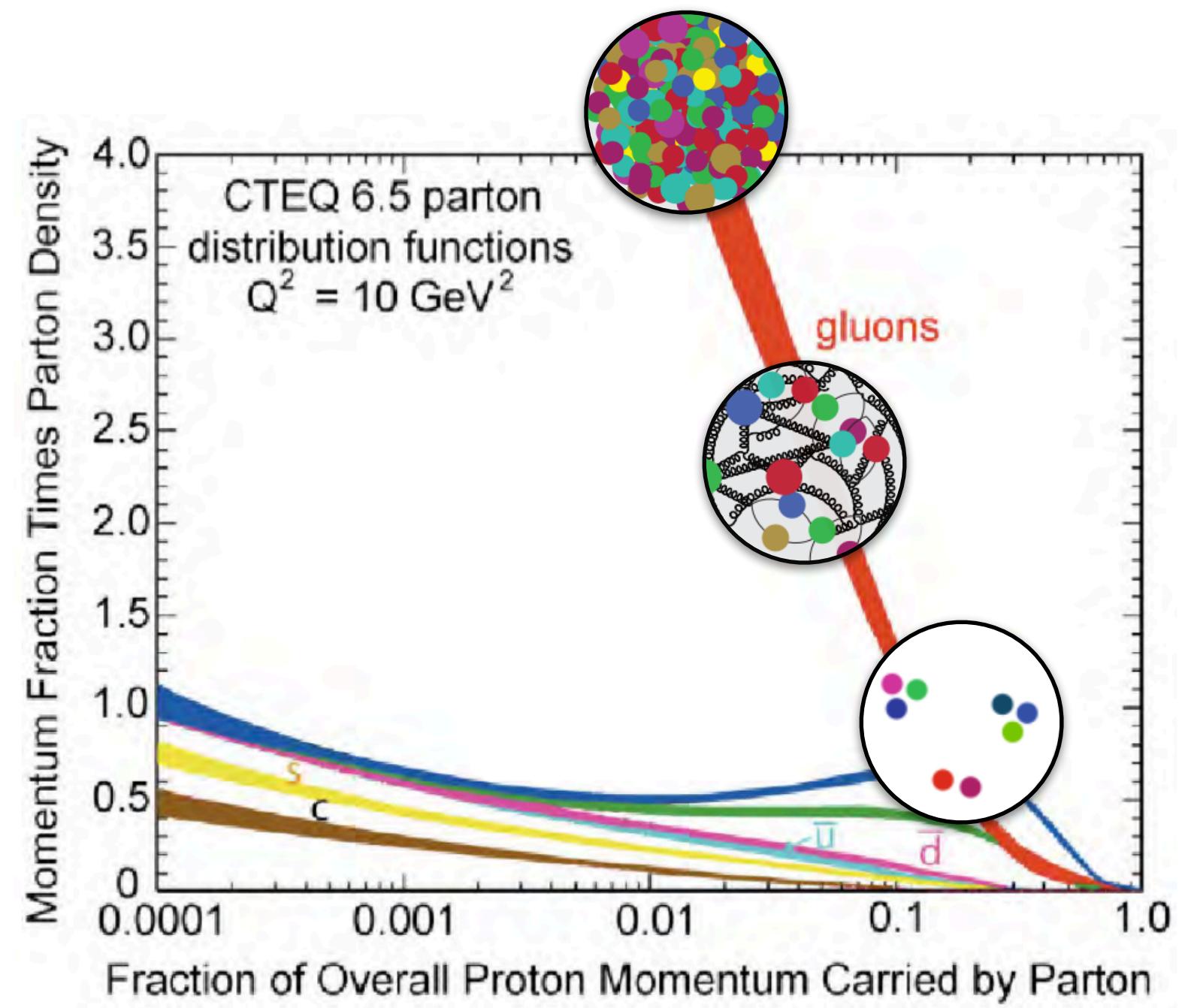
$$f_{q,EEC}(x, \theta) = \int_{-\infty}^{\infty} \frac{dy^-}{2\pi} e^{ixp^+y^-} \frac{\gamma^+}{2} \langle P | \bar{\psi}(0) \mathcal{E}(\theta) \mathcal{L} \psi(y^-) | P \rangle$$



- differential through \mathcal{E} , multi-point correlation will give CMB-like distribution of a nucleon
 $\langle P | \bar{\psi}(0) \mathcal{E}(\theta_1, \phi_1) \dots \mathcal{E}(\theta_N, \phi_N) \psi(y^-) | P \rangle$

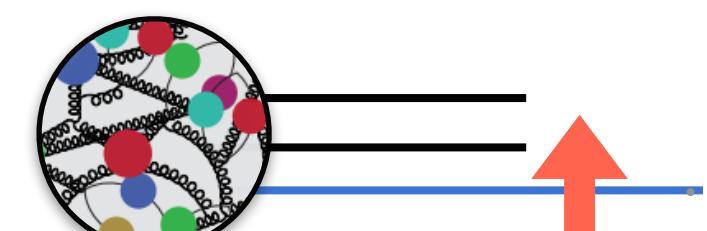
Applications

Application to the gluon saturation

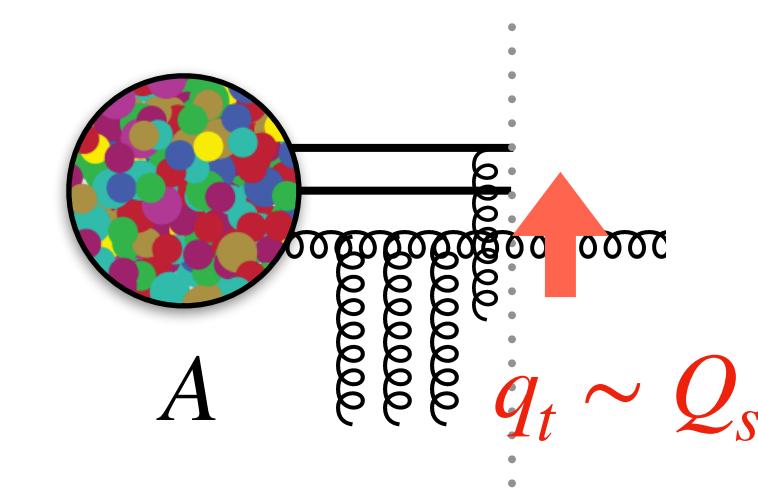


Gluon saturation at small x

- Saturation scale $q_t \sim Q_s \gg \Lambda_{\text{QCD}}$

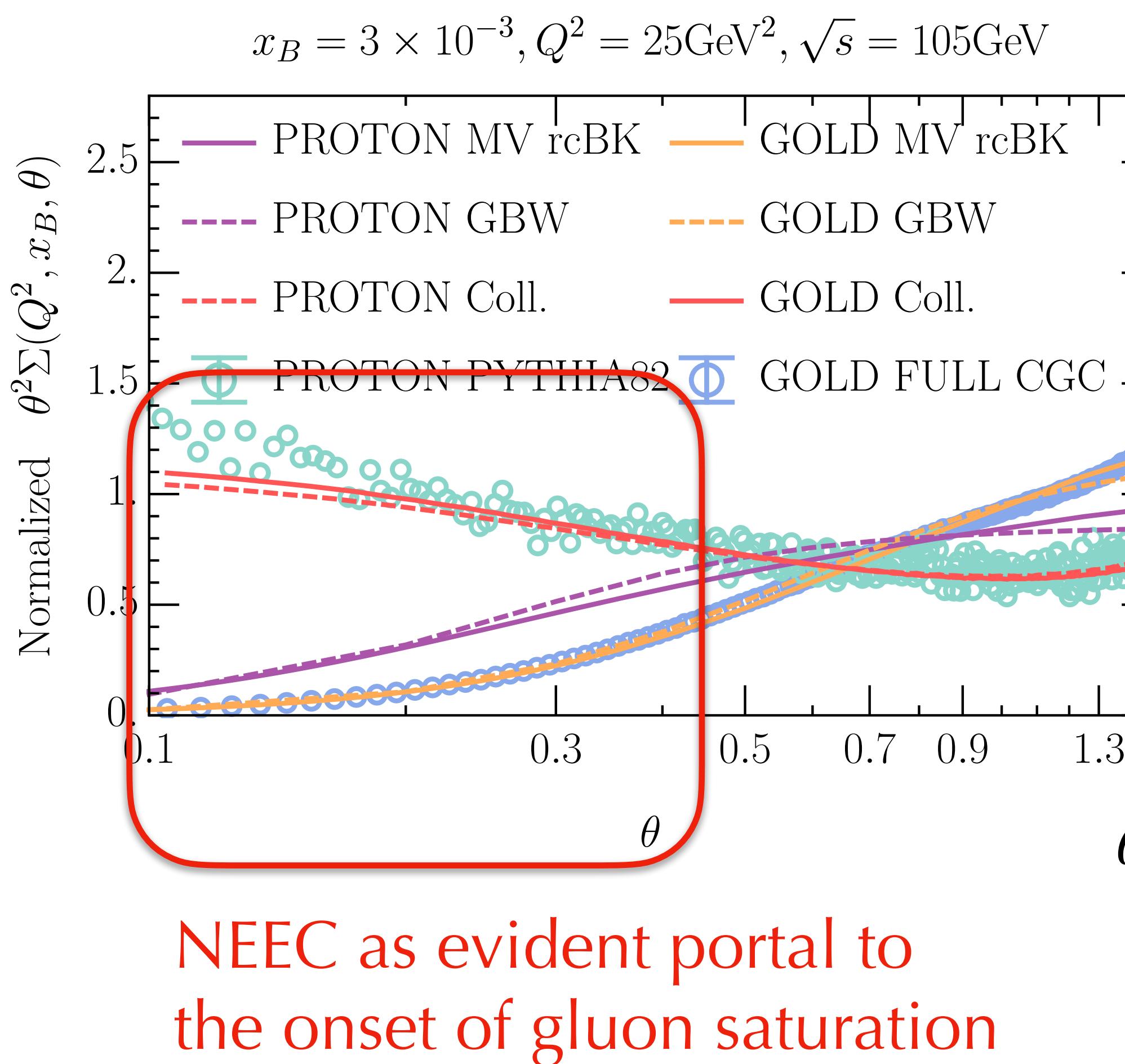


$$q_t \sim \Lambda_{\text{QCD}}$$

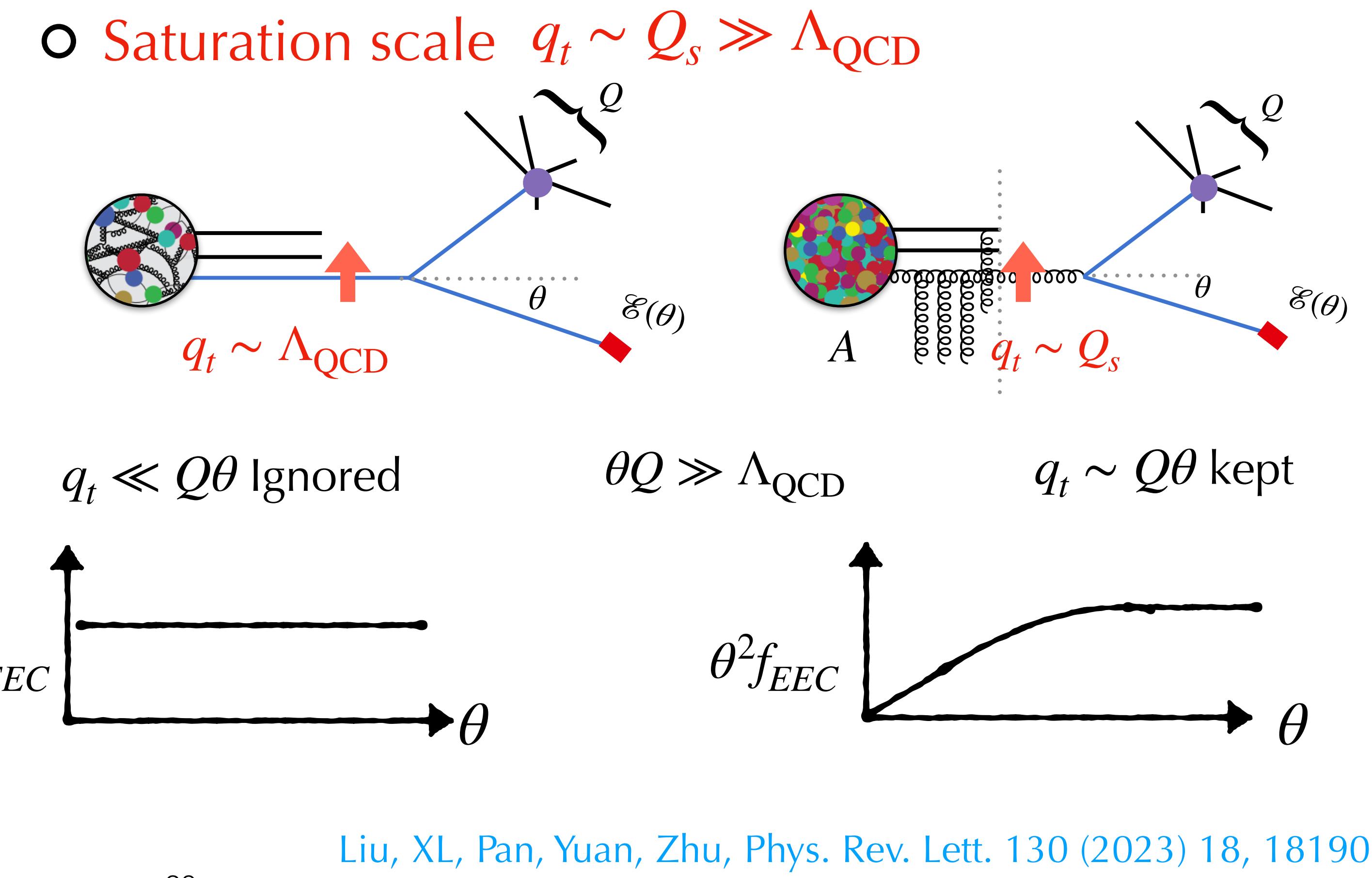


$$q_t \sim Q_s$$

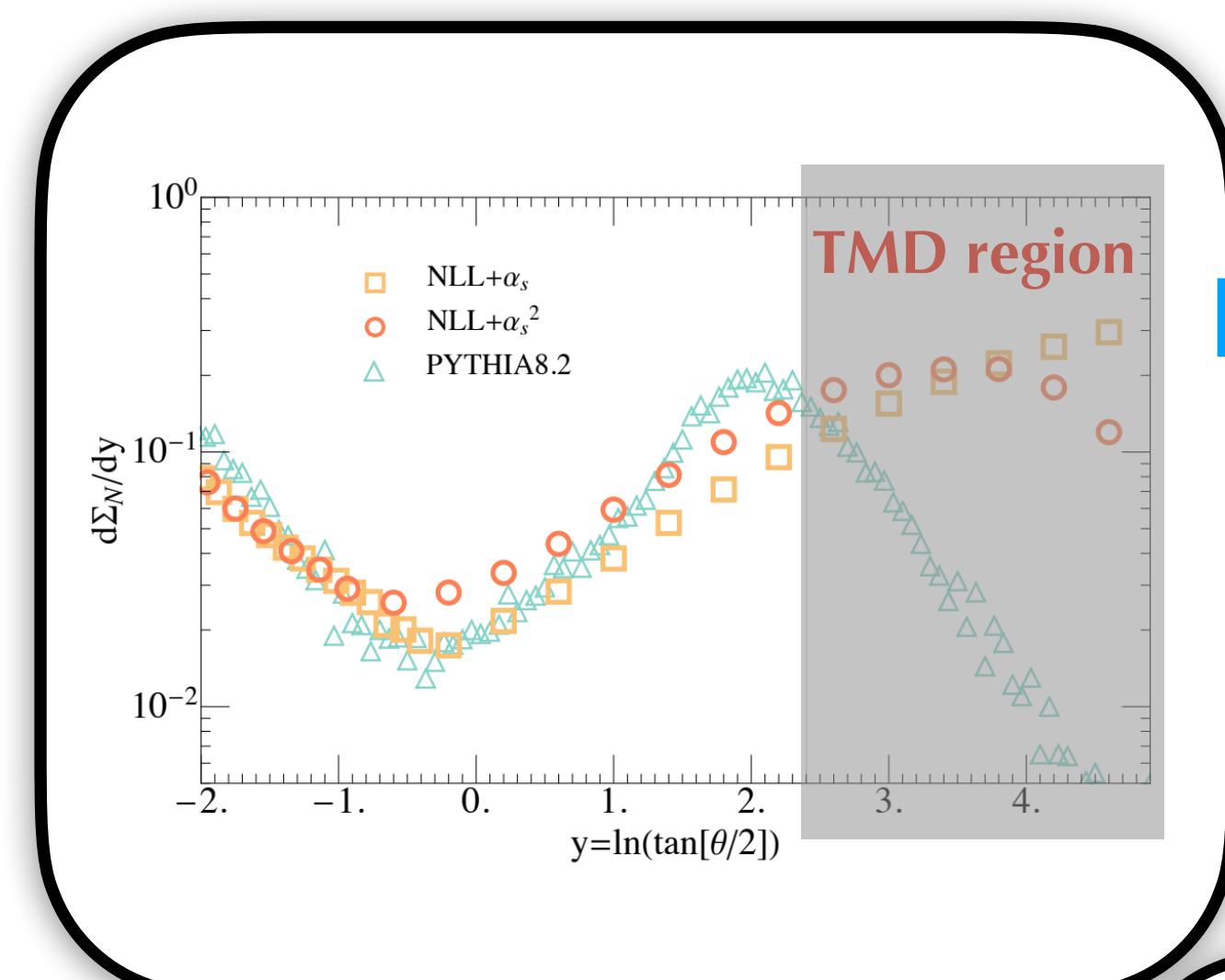
Application to the gluon saturation



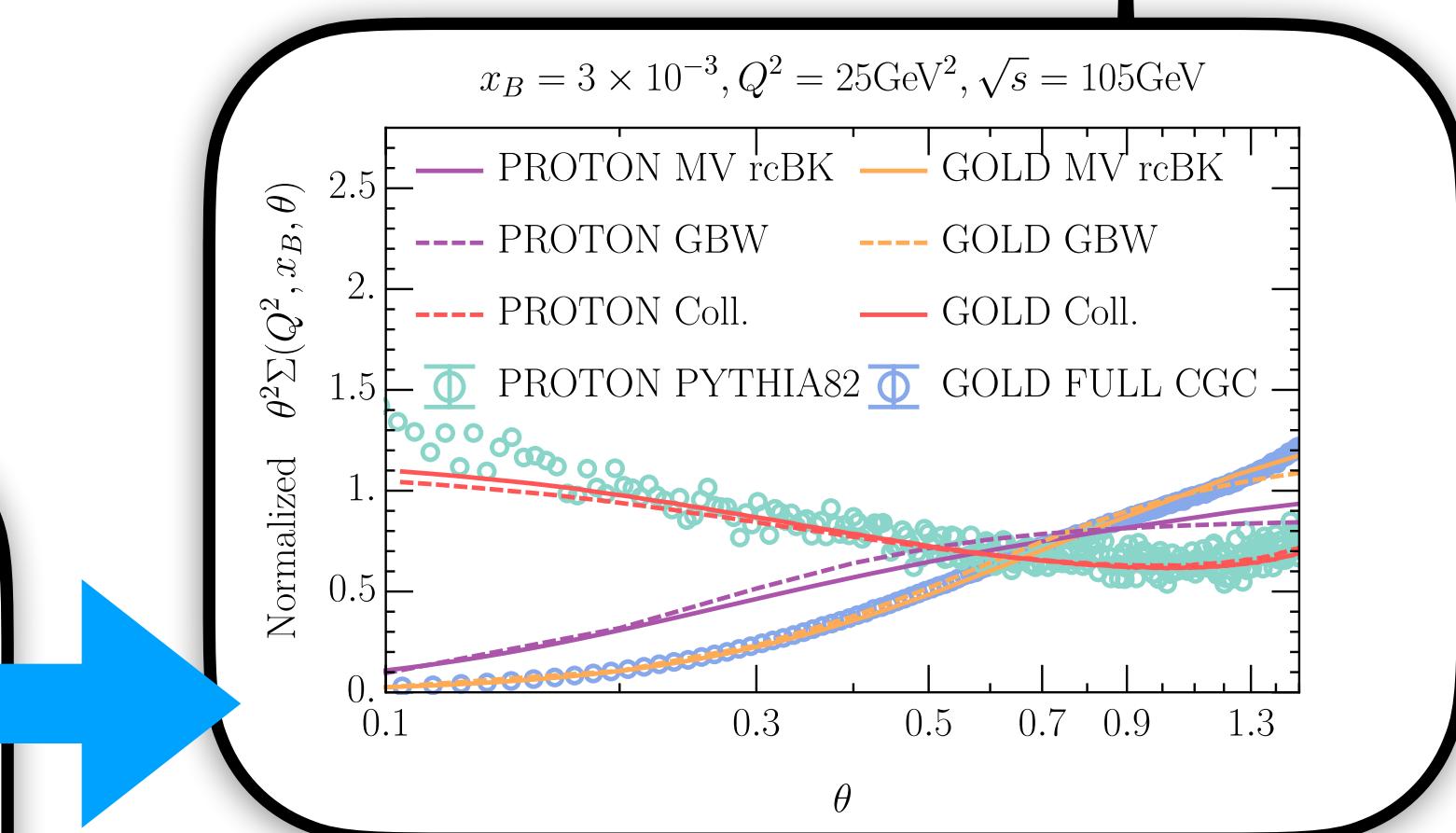
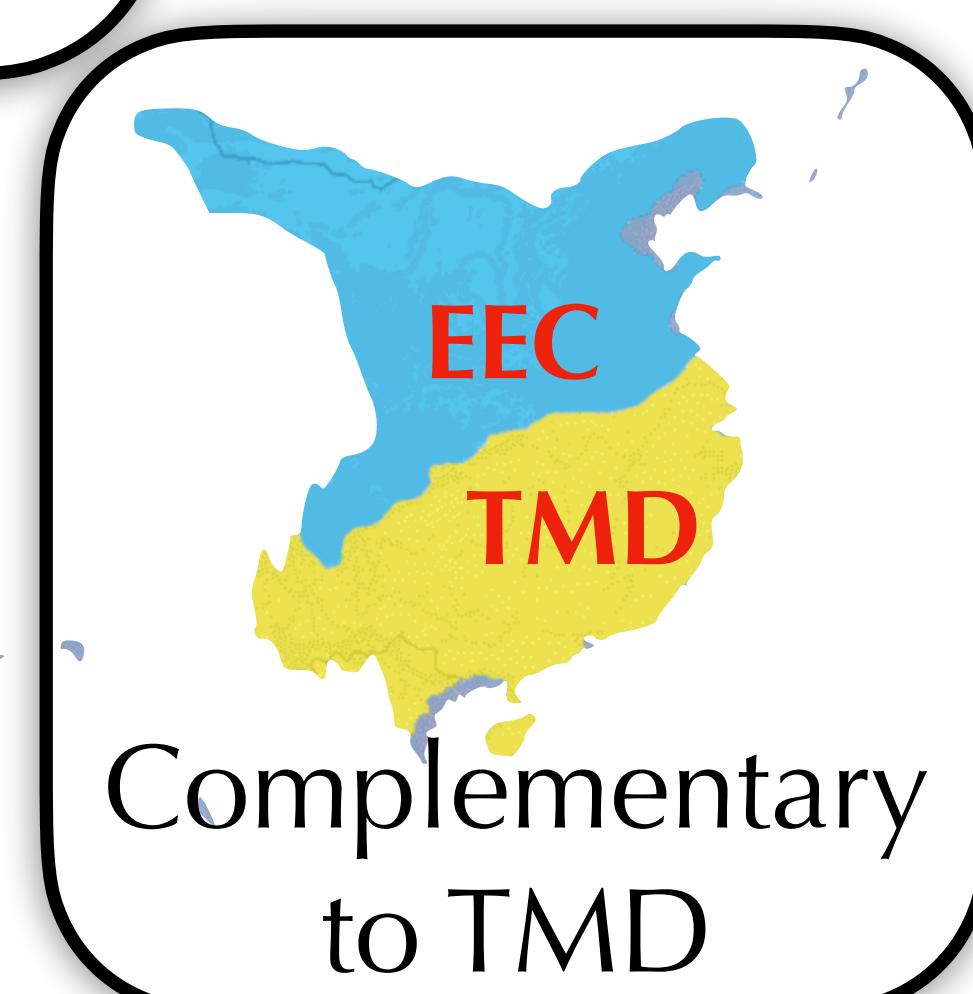
Gluon saturation at small x



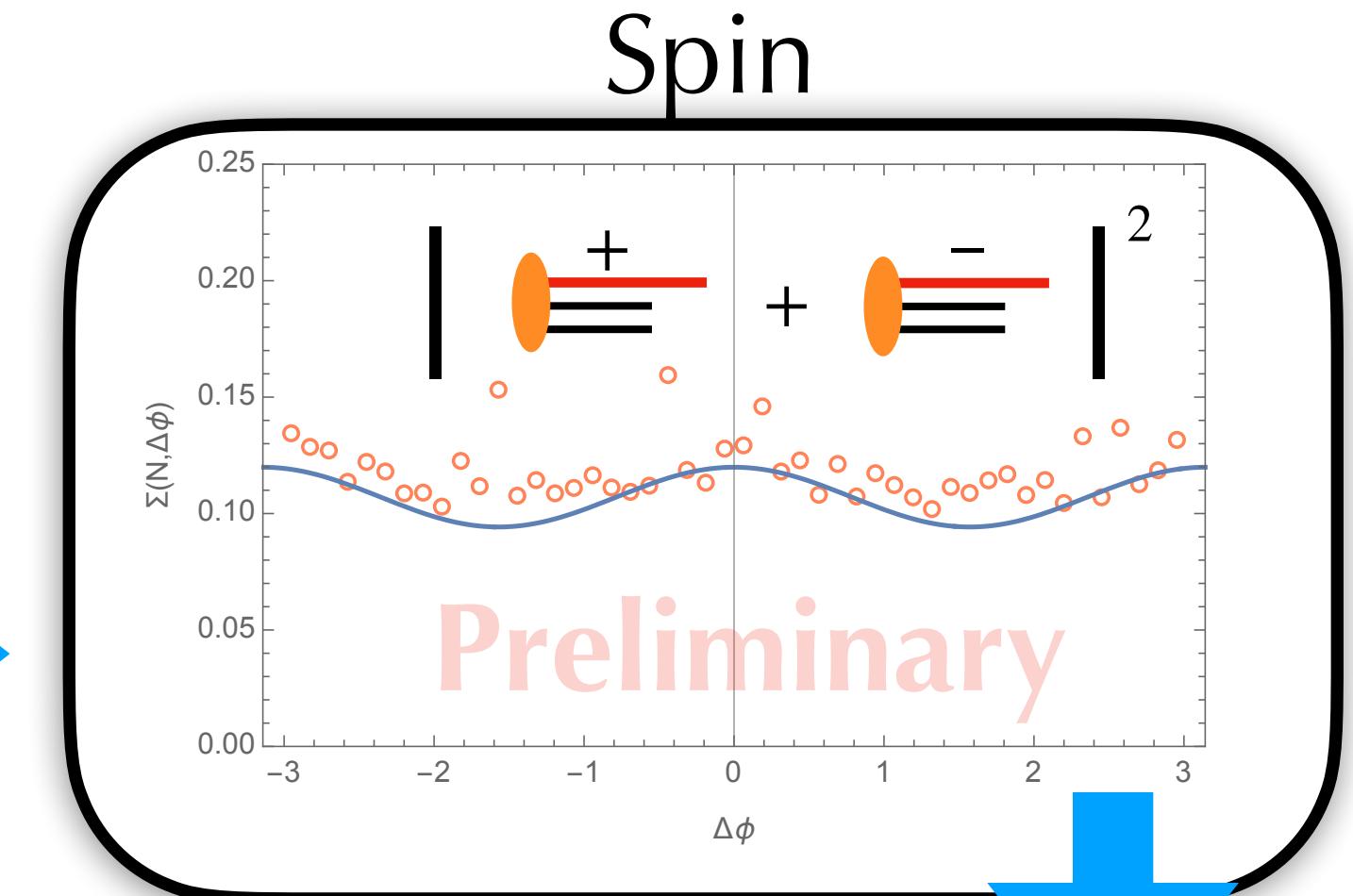
Current status and future plan



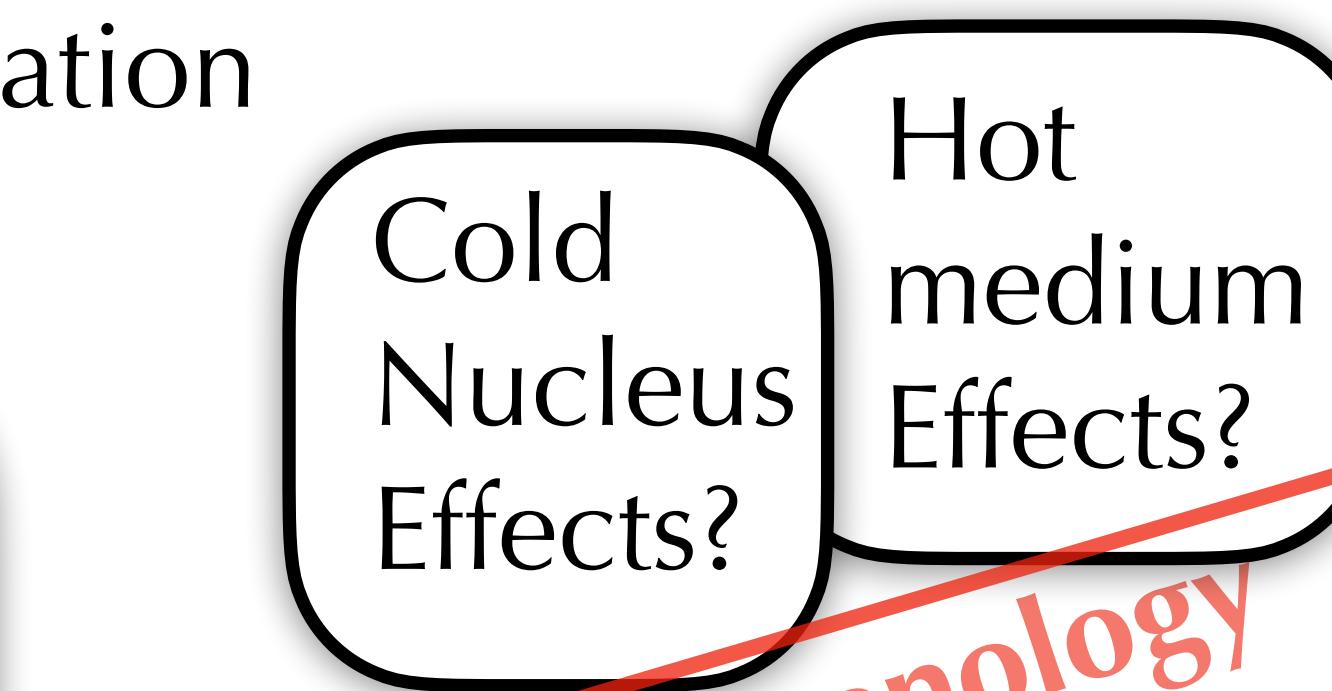
Properties



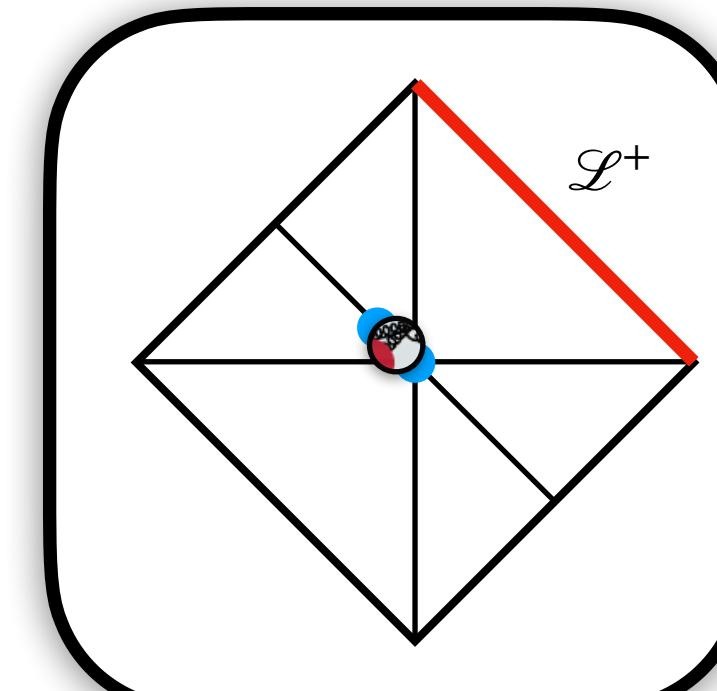
Portal to the gluon saturation



Connection to pQCD, TMD ...



Phenomenology



Theory