

Proton Energy Correlators

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第五届重味物理与量子色动力学研讨会
华中科技大学



北京師範大學
BEIJING NORMAL UNIVERSITY

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

Liu, XL, Pan, Yuan, Zhu, [Accepted by PRL \(2023\)](#)

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

[more to come ...](#)

“ *Acknowledgement.*



We thank for the
hospitality of the committee for the “Heavy flavor and
QCD” workshop held in Changsha where this work was
initiated.
”

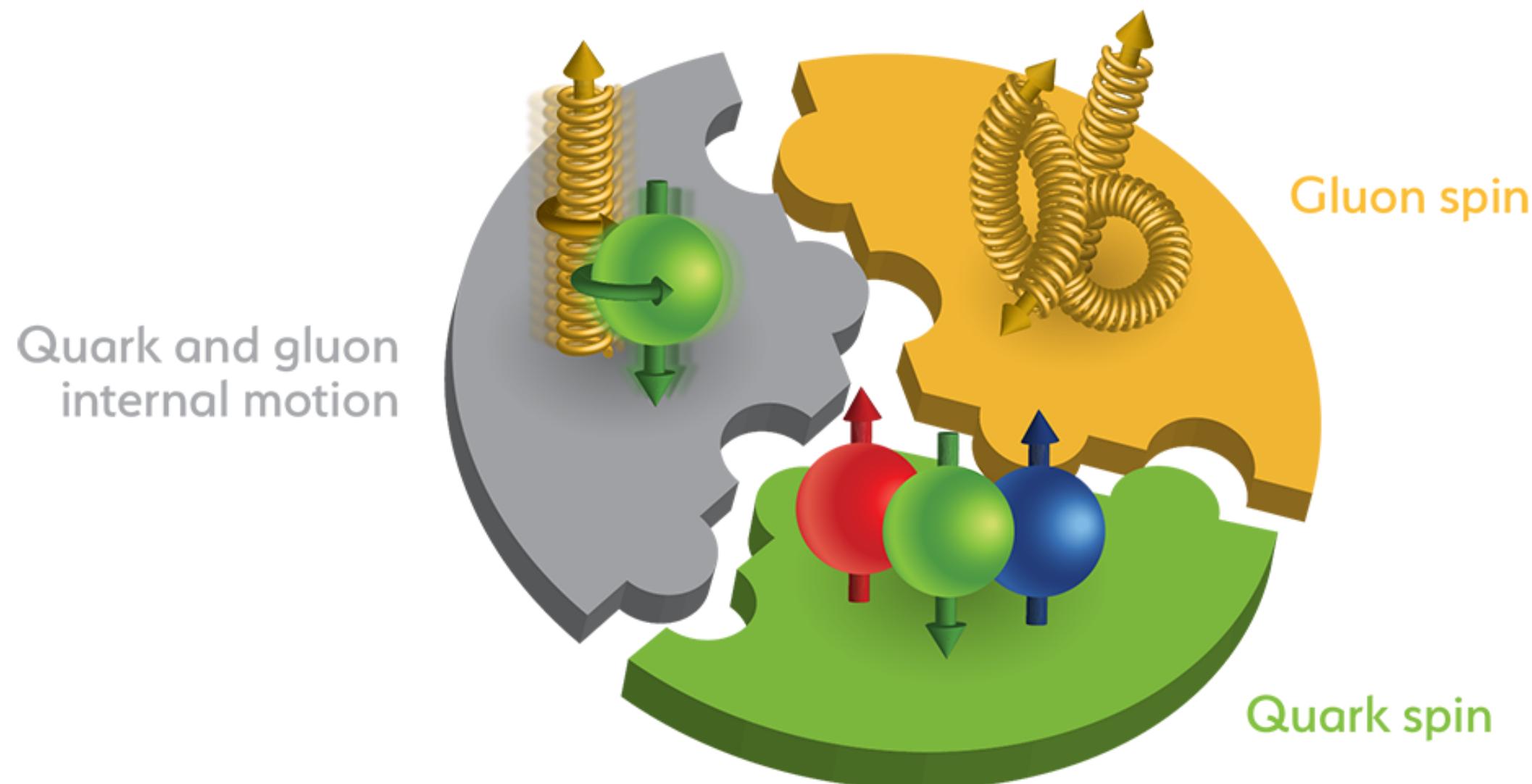
XL, Zhu, [Phys. Rev. Lett. 130 \(2023\)](#)

Outline

- The concept and features of the proton energy correlators
- Applications to proton/nucleus structures
- Conclusion

Nucleon/Nucleus Structure

Major focus of EicC, EIC ...



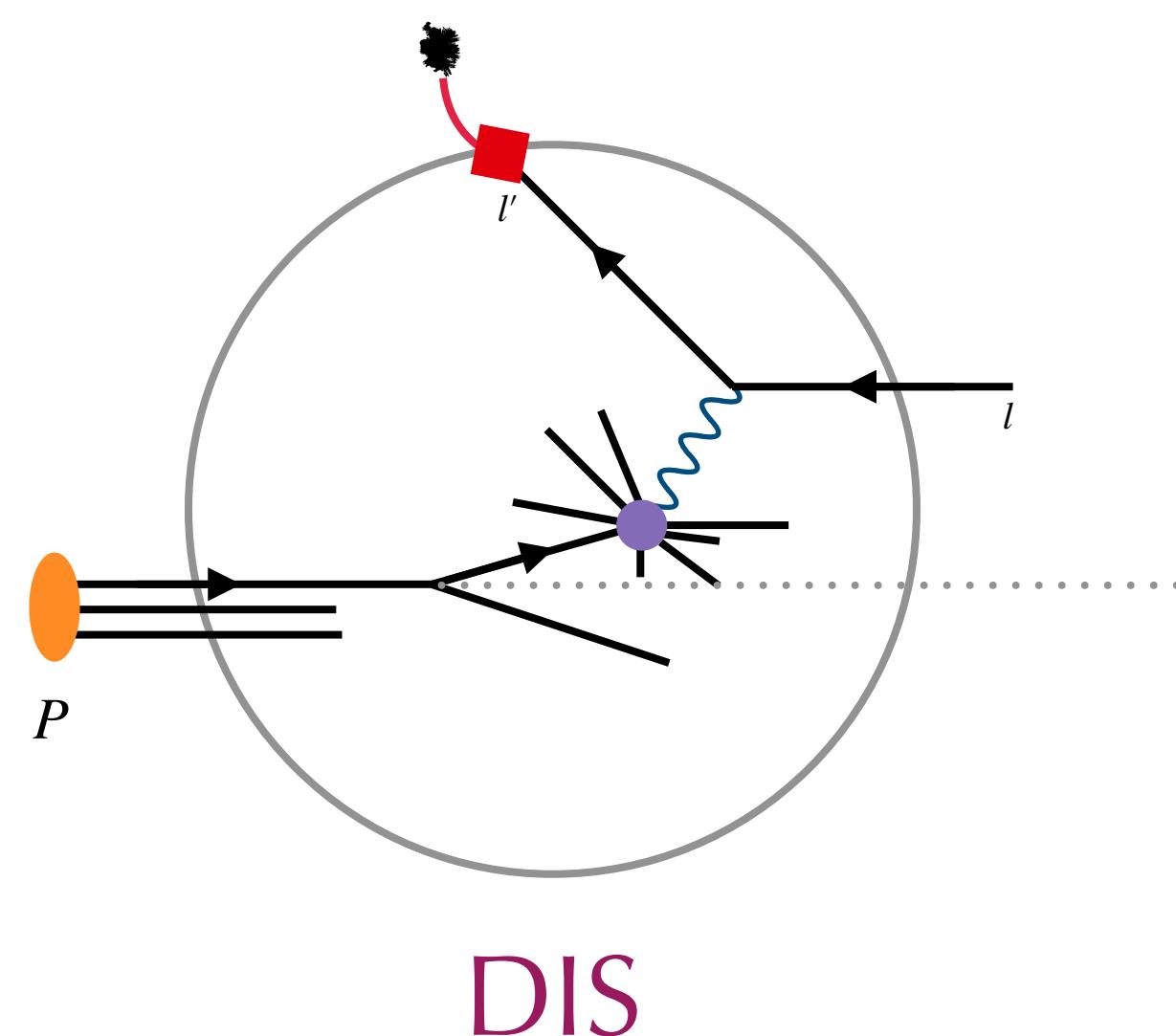
- A lot yet to answer
- Spin components
 - $1/2 = 30\% + ? + ?$
- Mass decomposition
 - proton mass $\sim 1\text{GeV}$, quark mass $\sim \text{keV}$
- ...

Nucleon/Nucleus Structure

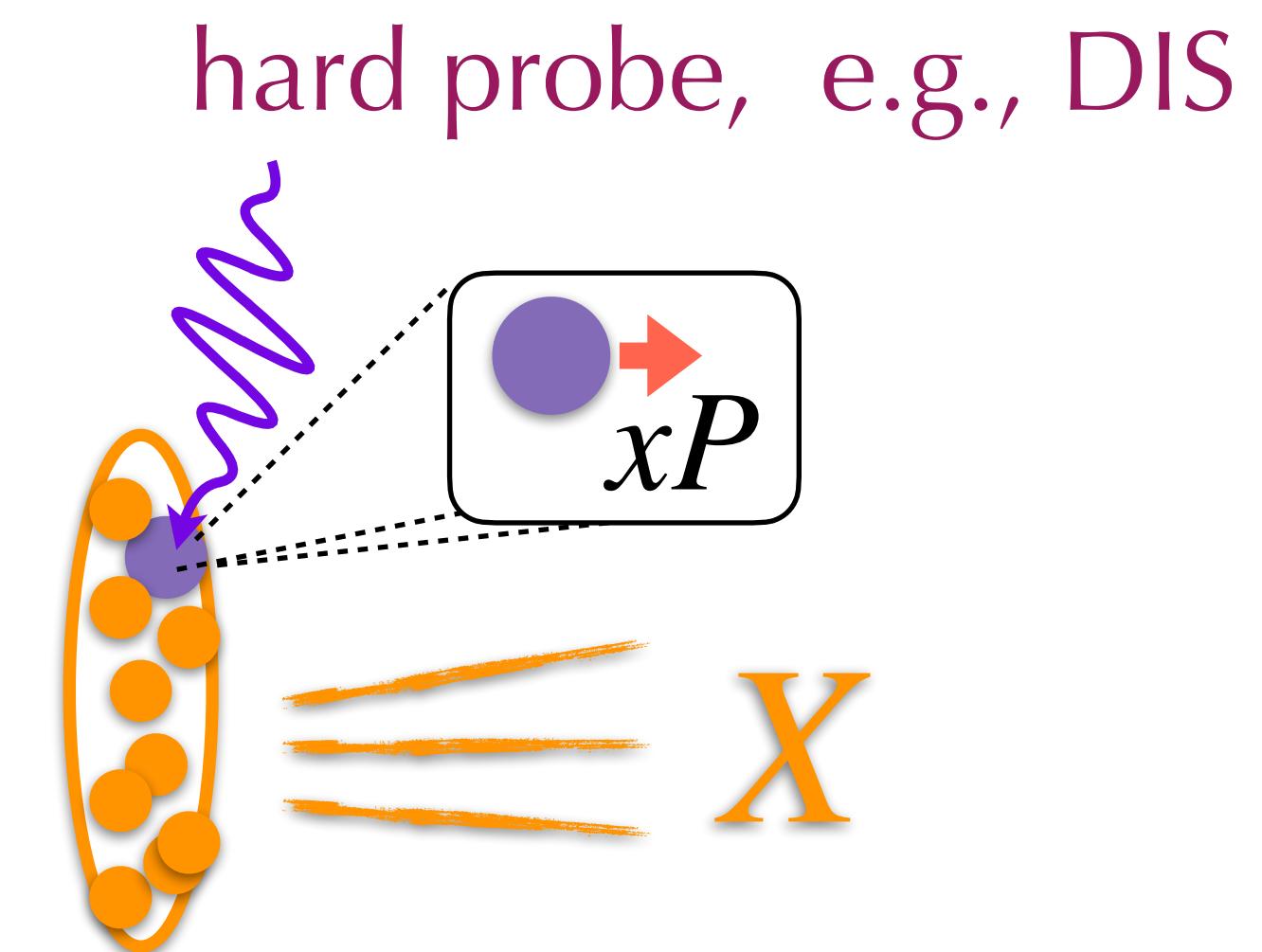
Collinear Parton Distribution Functions (PDFs)

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

$$\propto \delta(xP - p) \langle P | a_p^\dagger a_p | P \rangle$$



- inclusive over X , clean.
- not differential enough, **lose information**

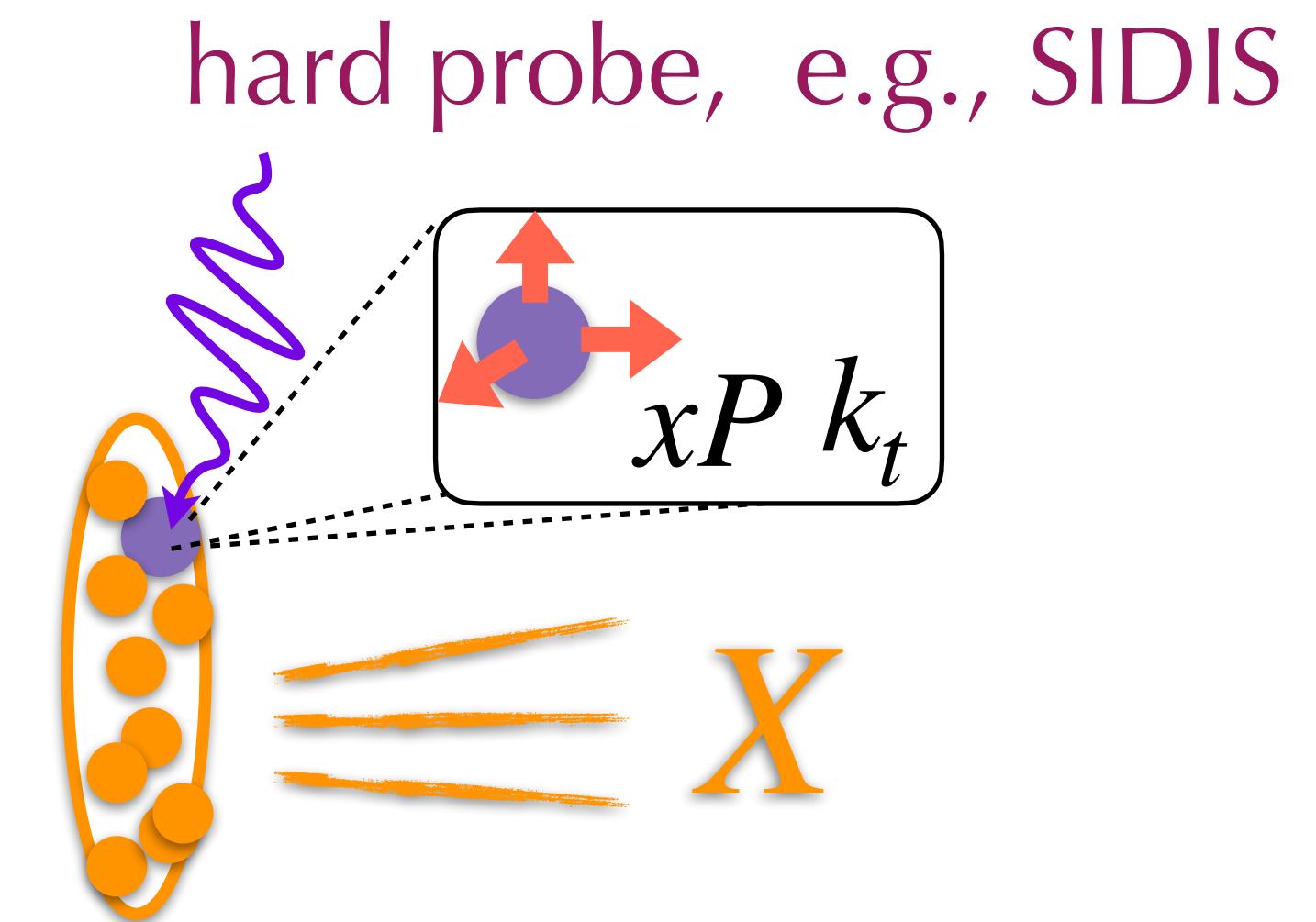
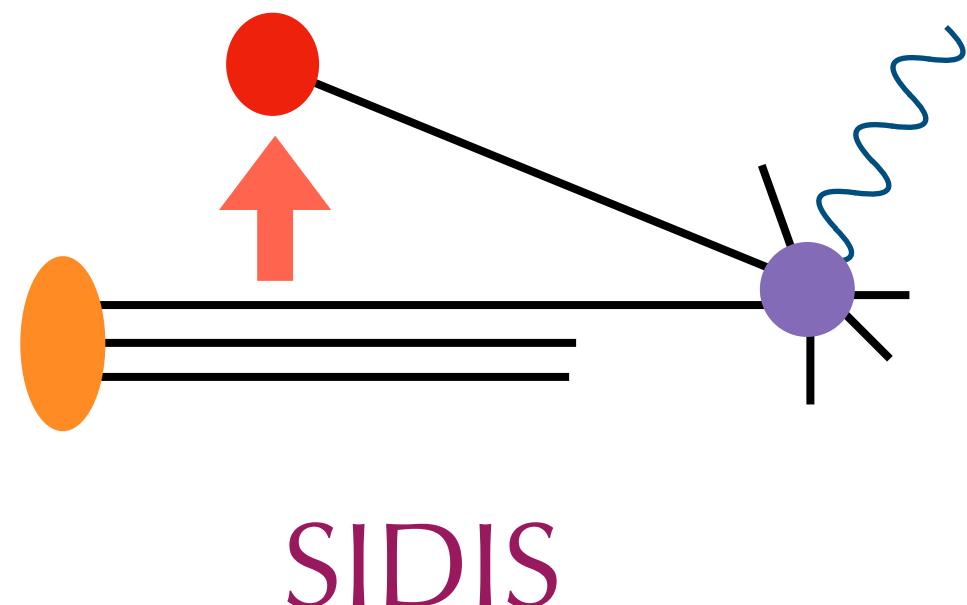


Nucleon/Nucleus Structure

TMD-PDFs

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

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

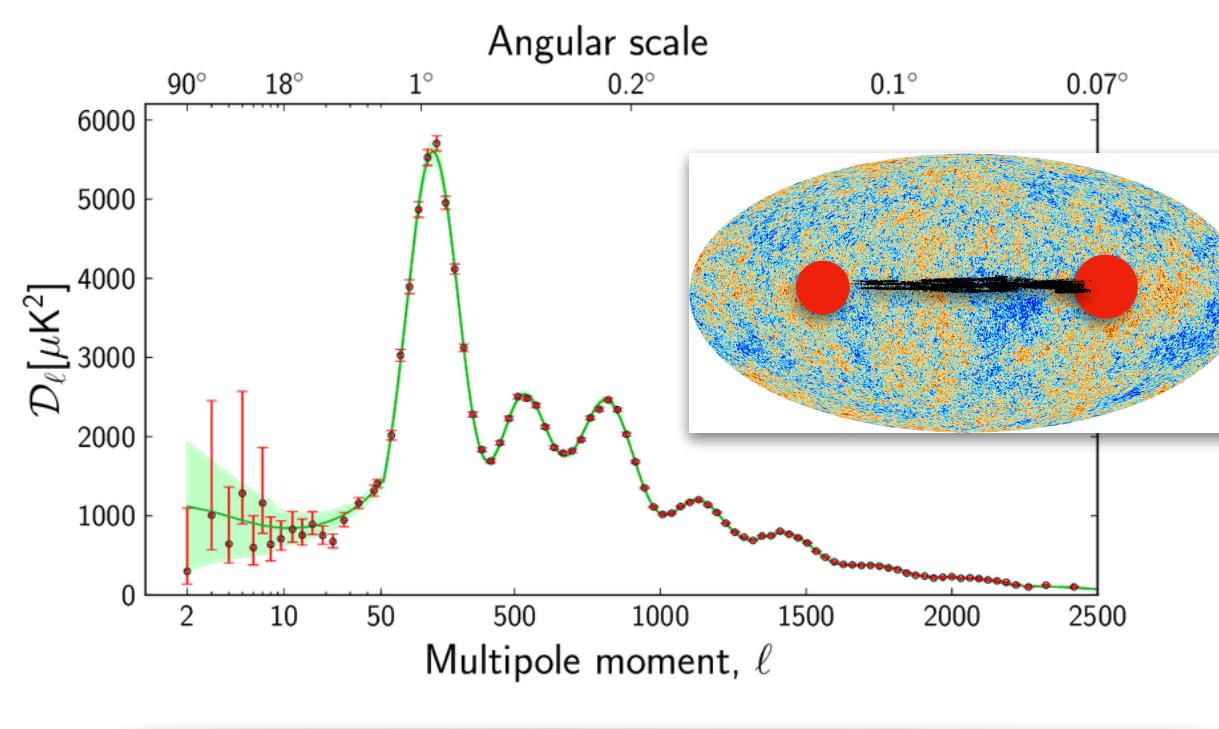


- Very successful for structure studies
- Usually involves 2 non-pert. object
 $\sigma = \hat{\sigma}(x, z) D(z, \vec{q}_T) \otimes f_{q/p}(x, \vec{k}_T)$
- Not differential enough, **lose information**

Nucleon/Nucleus Structure

TMD-PDFs

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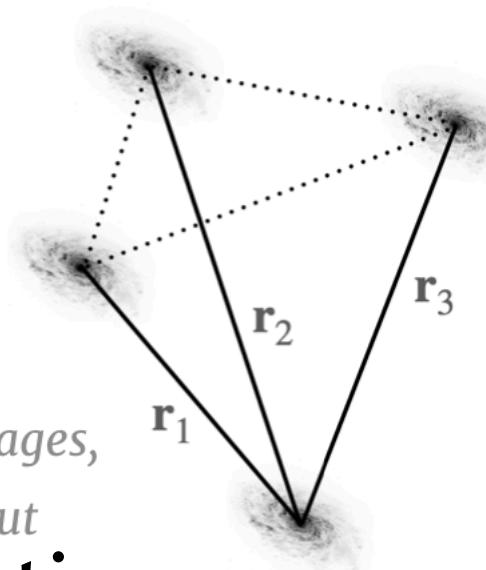


$\delta T(n_1) \delta T(n_2)$

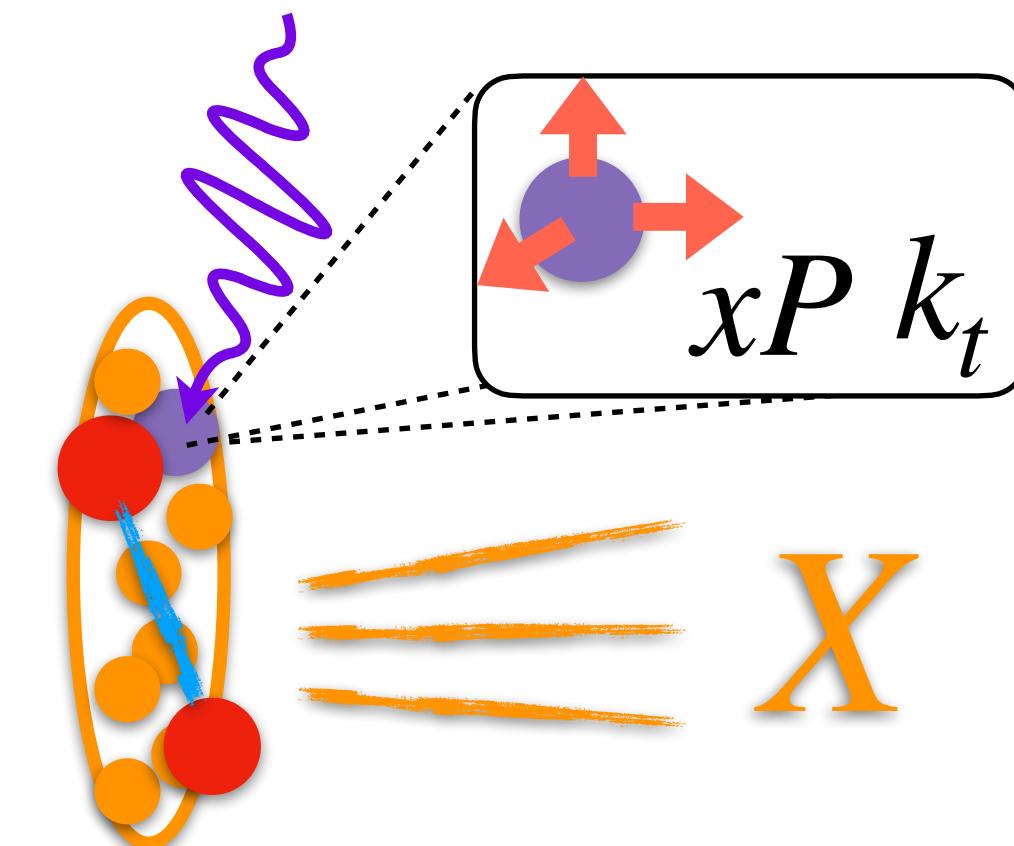
COSMOLOGY
Asymmetry Detected in the Distribution of Galaxies

Two new studies suggest that certain tetrahedral arrangements of galaxies outnumber their mirror images, potentially reflecting details of the universe's birth. But confirmation is needed.

4-pt-correlation
2206.04227



hard probe, e.g., SIDIS



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 - Usually involves 2 non-pert. object
- $$\sigma = \hat{\sigma}(x, z) D(z, \vec{q}_T) \otimes f_{q/p}(x, \vec{k}_T)$$
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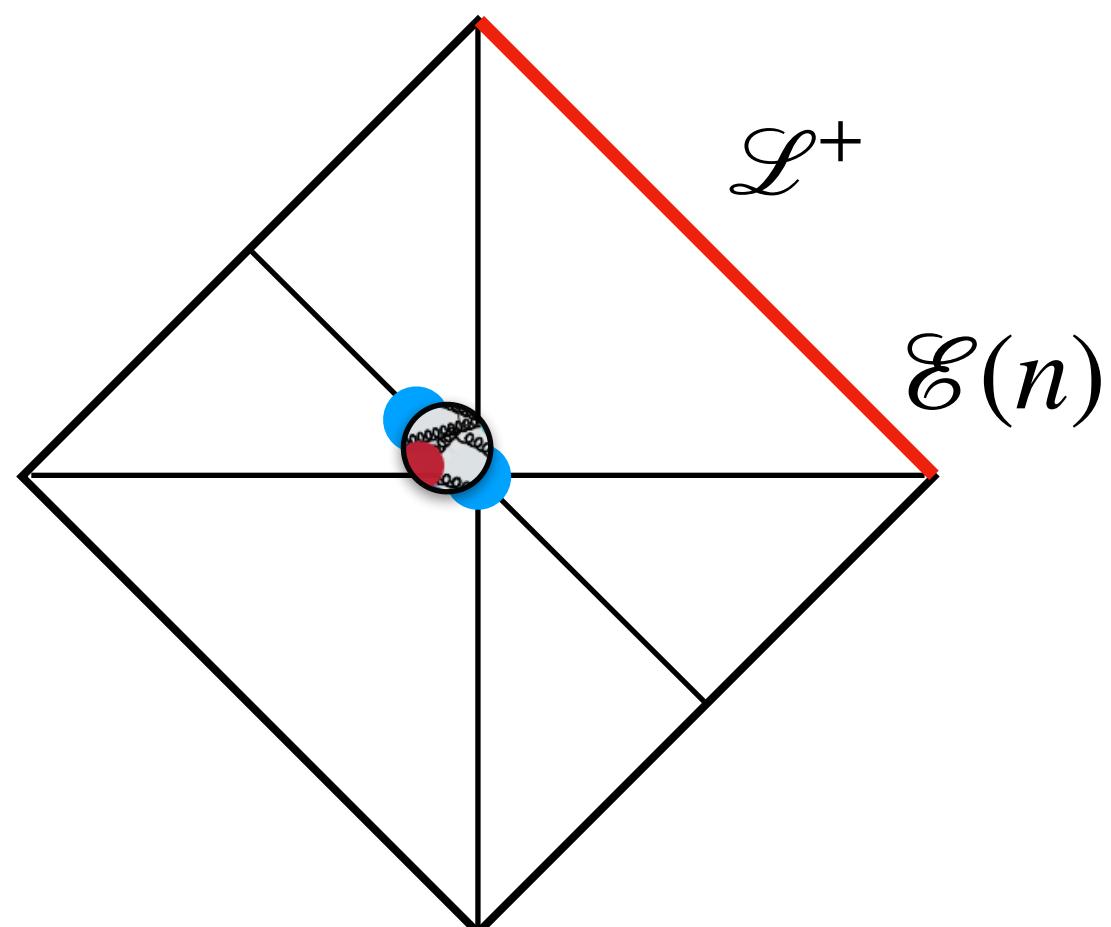
Proton Energy Correlators

Proton EEC

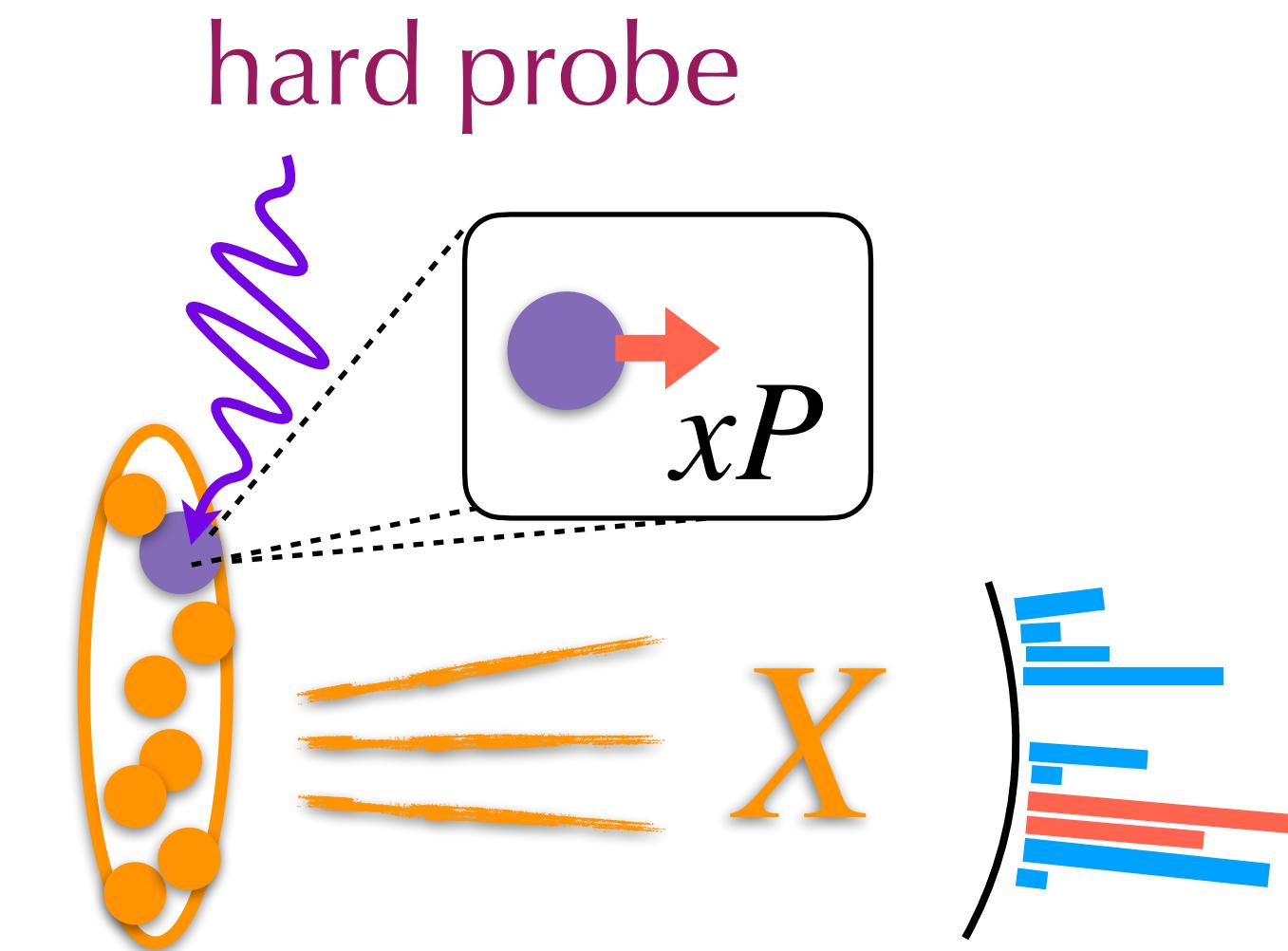
XL and Zhu, 2209.02080, Phys. Rev. Lett. 130 (2023)

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

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



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

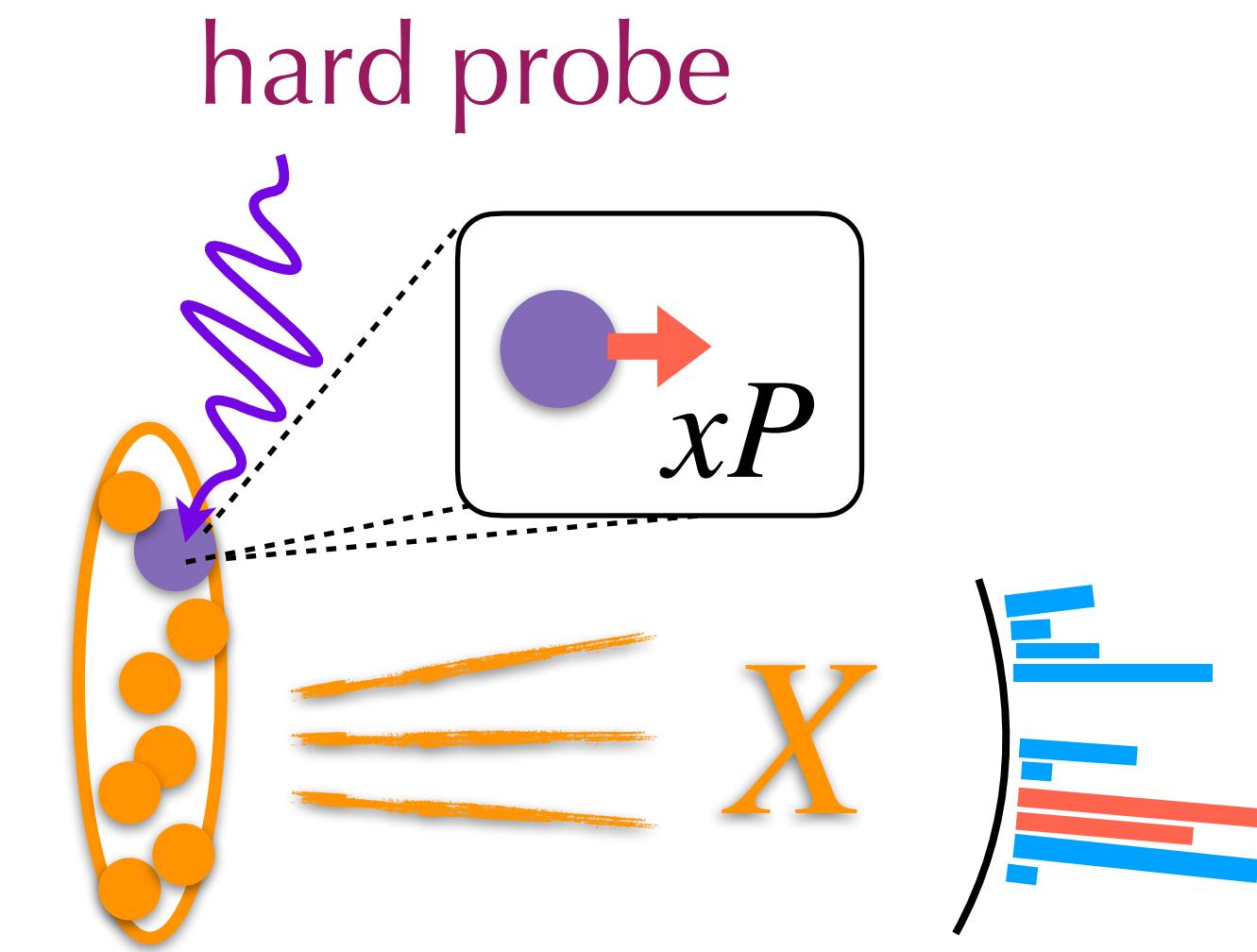


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$$f_{q,EEC}(x, \theta) \propto \sum_{i \in X} \frac{E_i}{E_P} \delta(\theta_i - \theta) \delta(xP - p) \langle P | a_p^\dagger | X \rangle \langle X | a_p | P \rangle$$

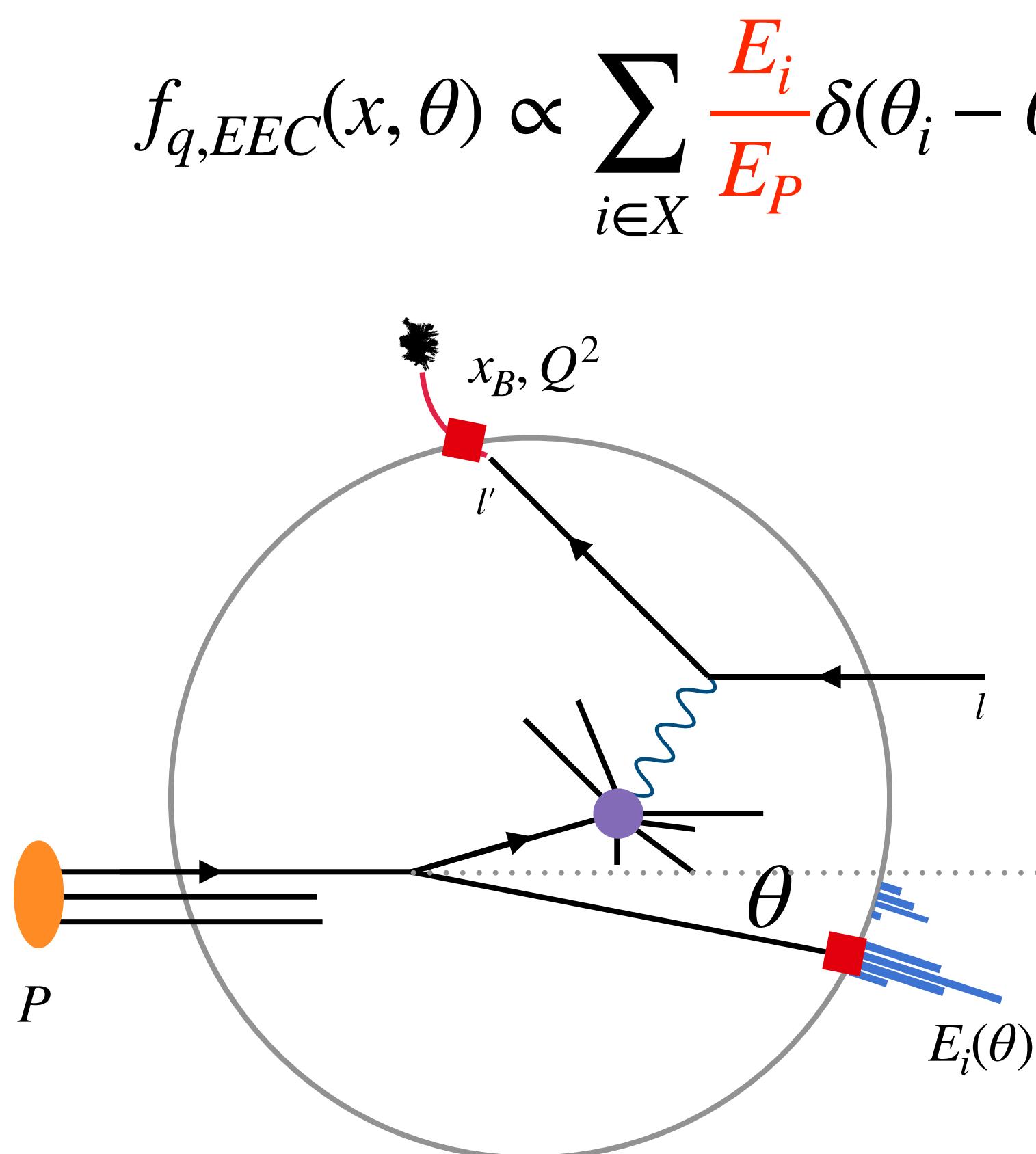


- “Energy weighted PDF”
- Evolves like PDF, DGLAP

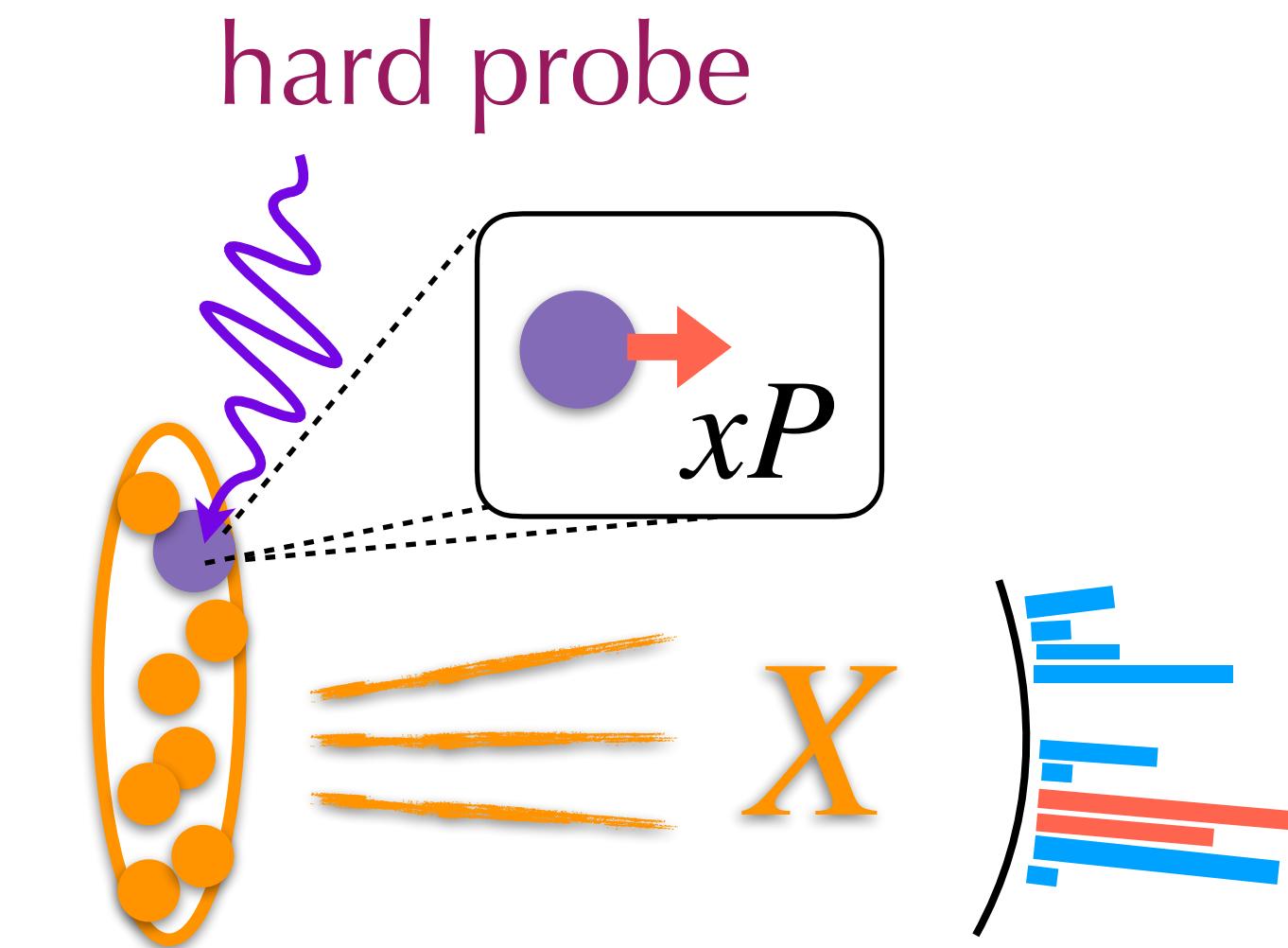
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- $\Sigma(x_B, Q^2, \theta) = \sum_i \int \frac{E_i}{E_P} d\sigma(x_B, Q^2, p_i) \delta(\theta - \theta_i)$
 - When $\theta Q \ll Q$,
- $$\Sigma(x_B, Q^2, \theta) = \int \frac{dz}{z} \hat{\sigma} \left(\frac{x_B}{z}, Q^2, \mu \right) f_{\text{EEC}}(z, \theta, \mu)$$
- Full inclusive measurement, **no jet/hadrons**, weighted by E_i

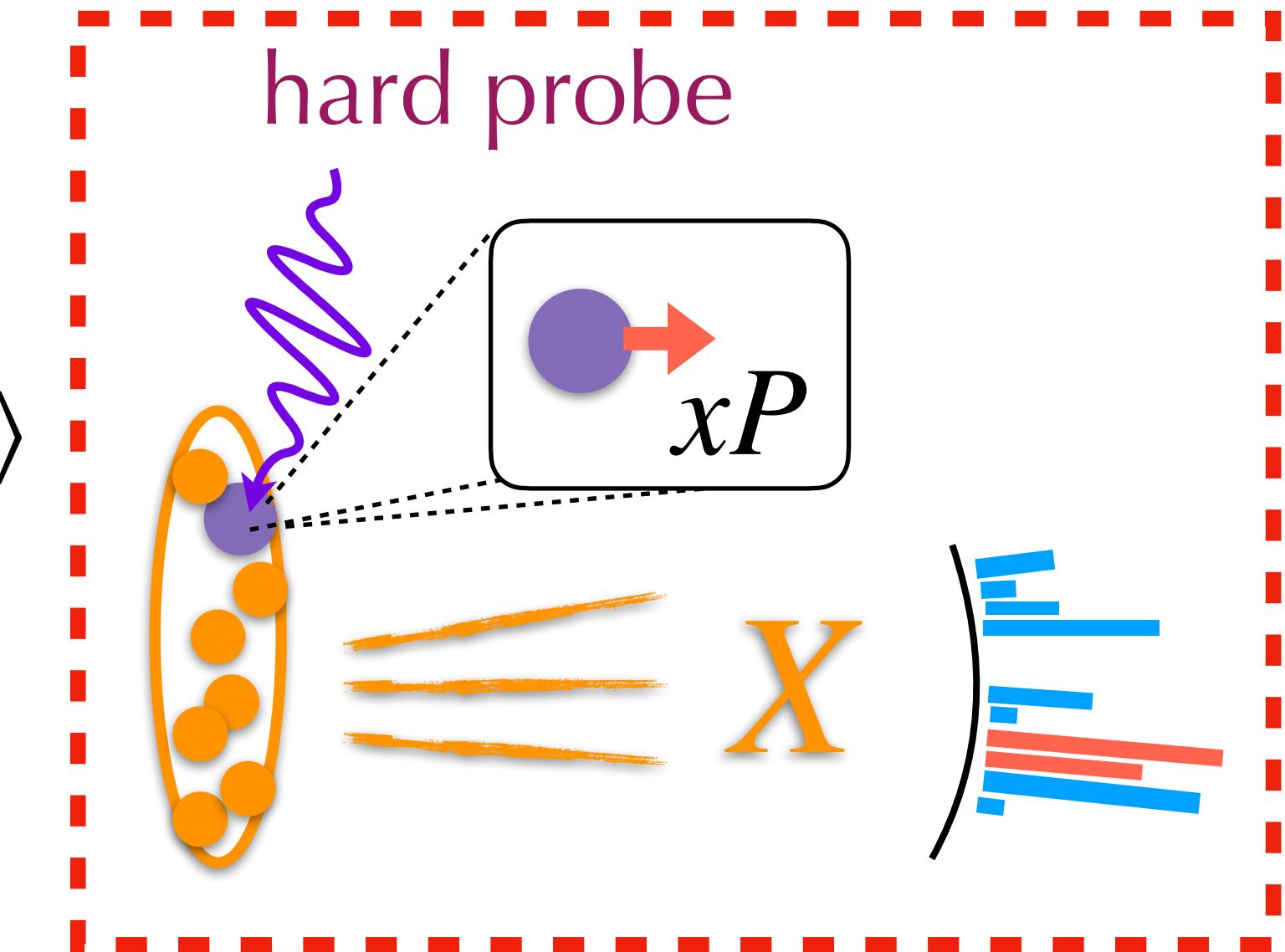
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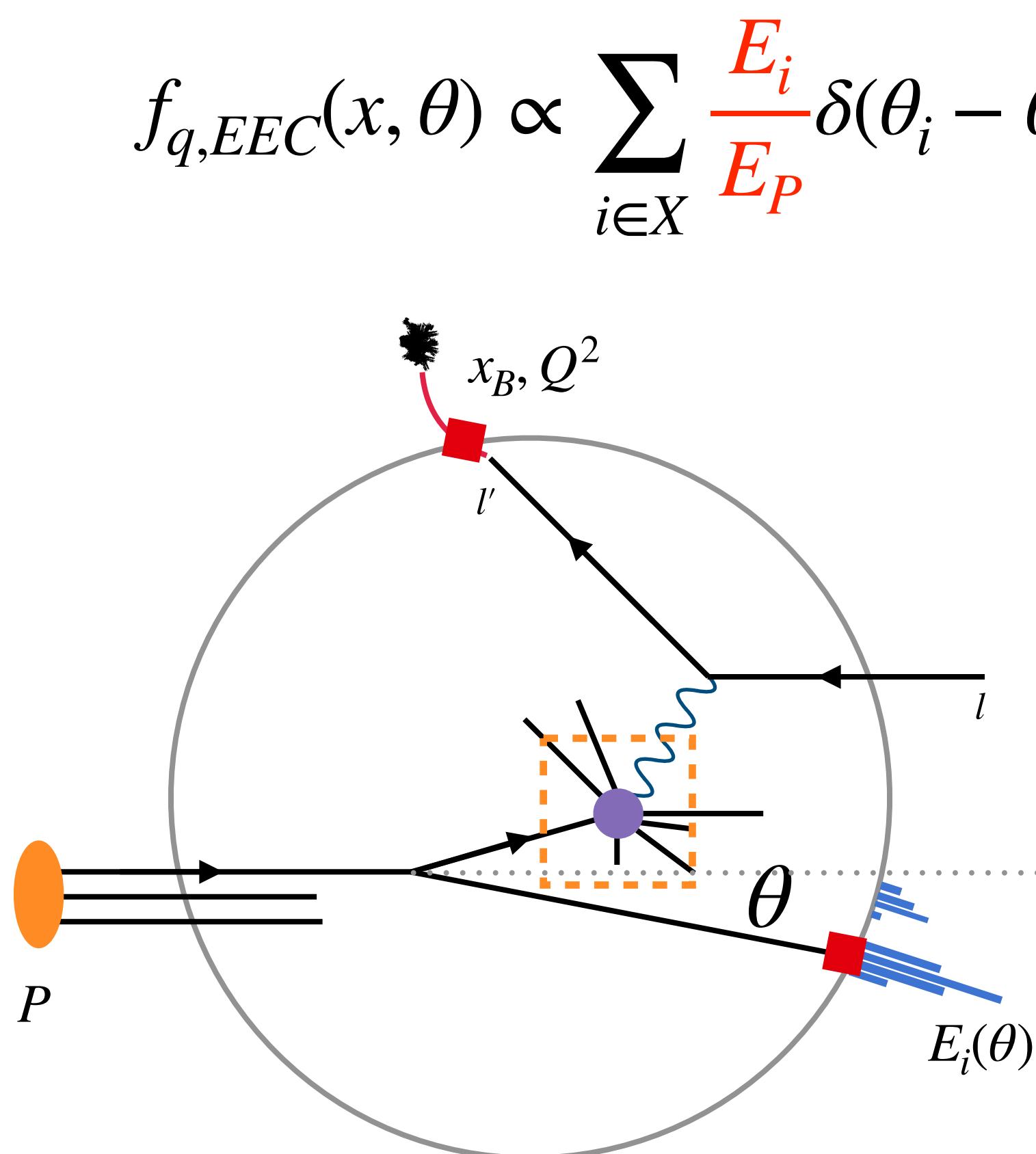
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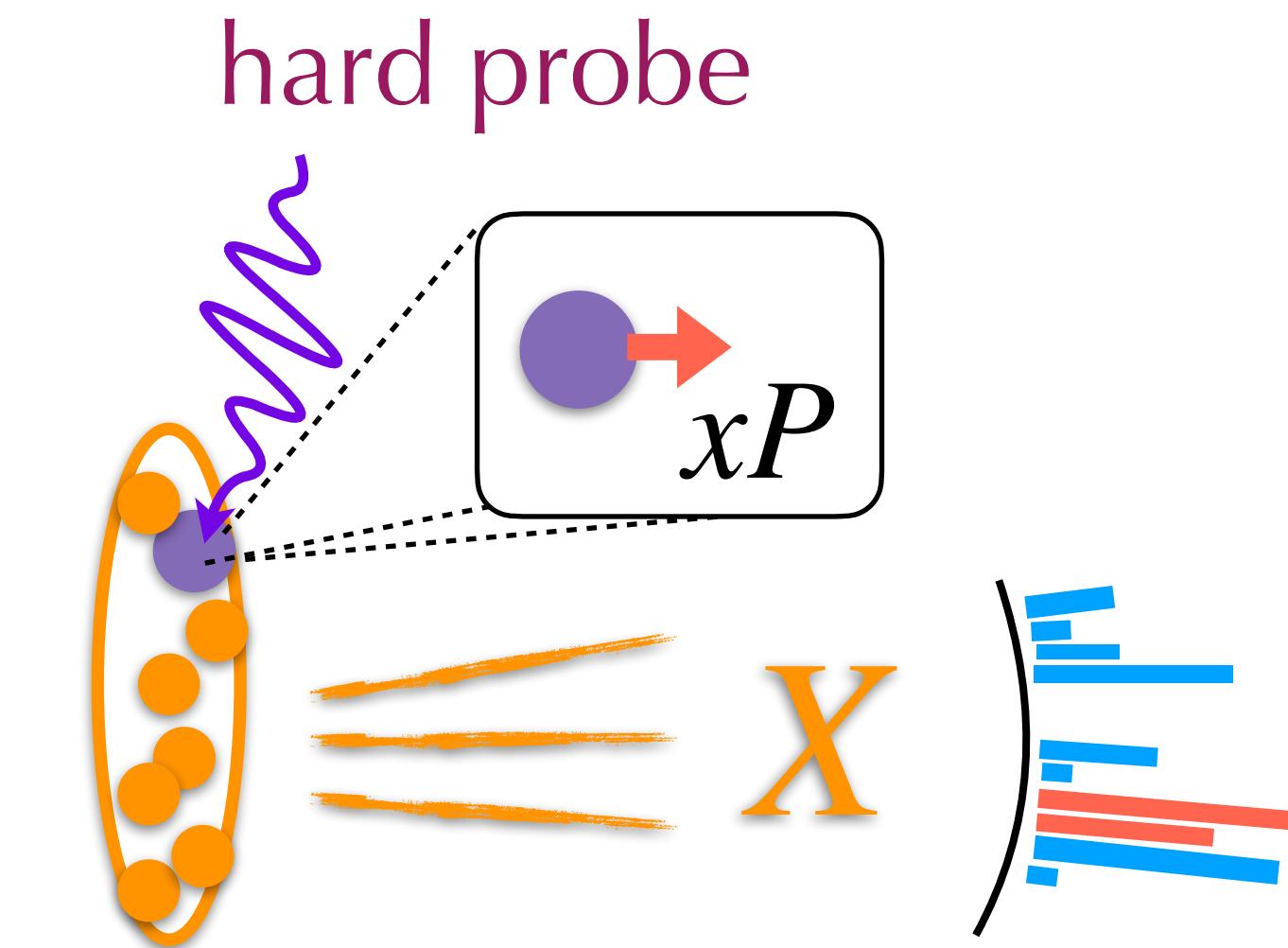
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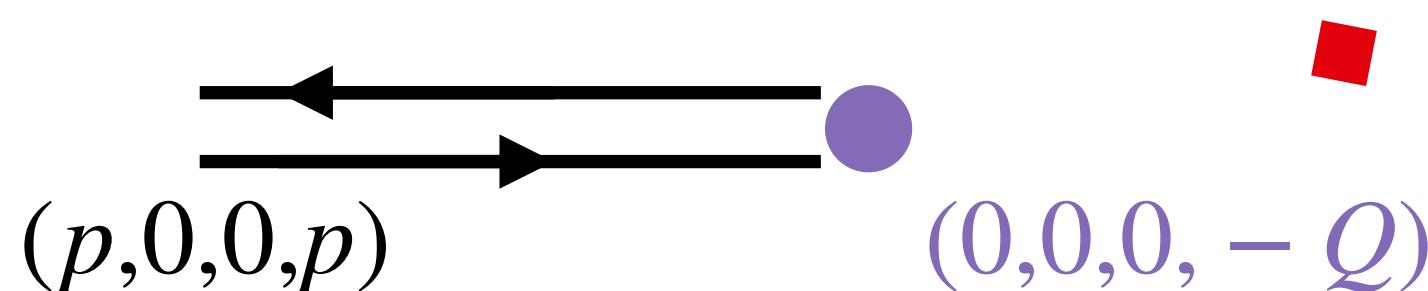
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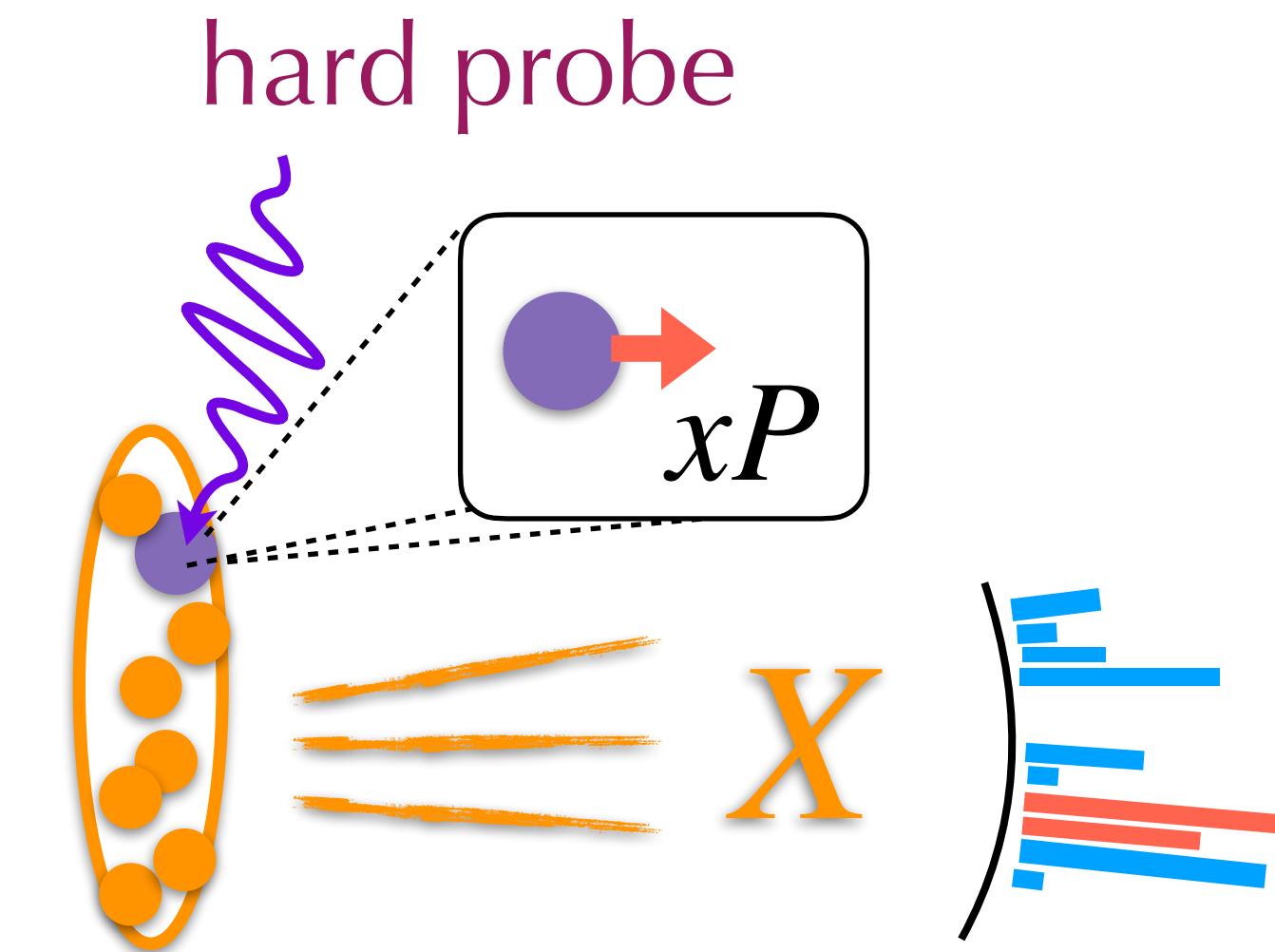
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Breit Frame

LO



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

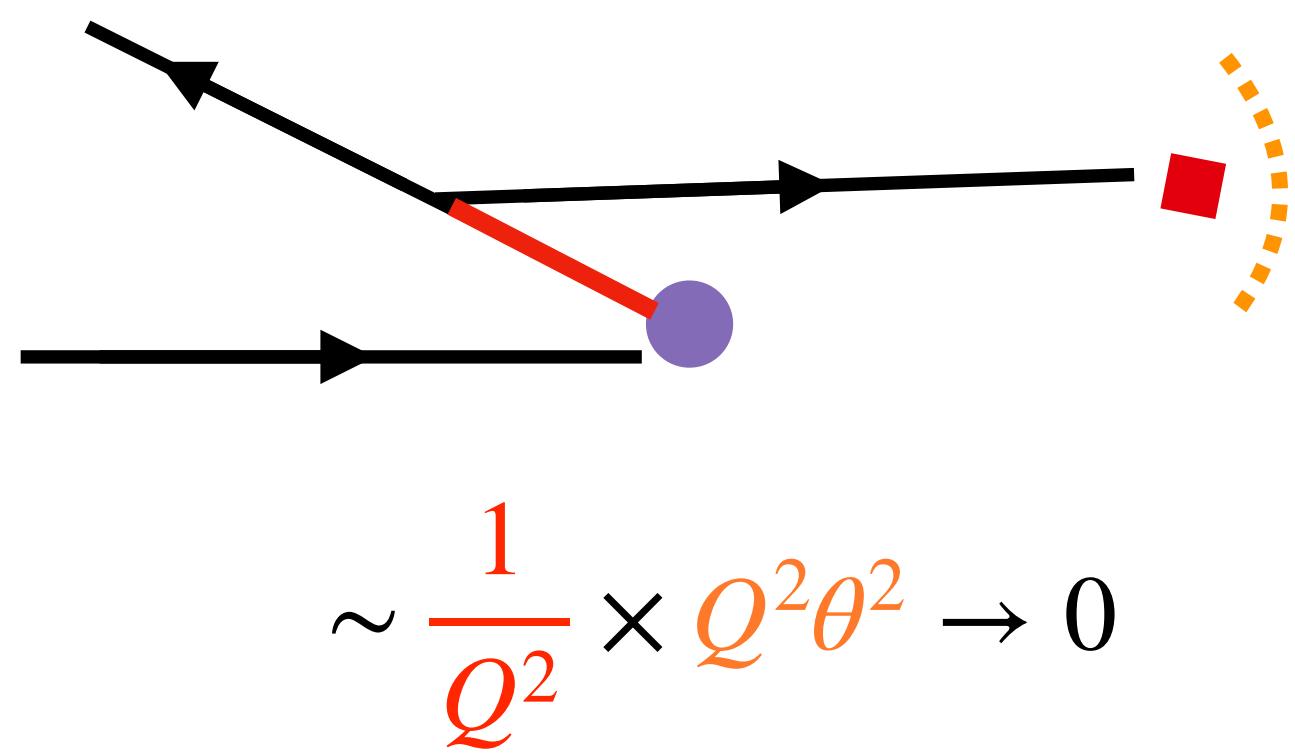
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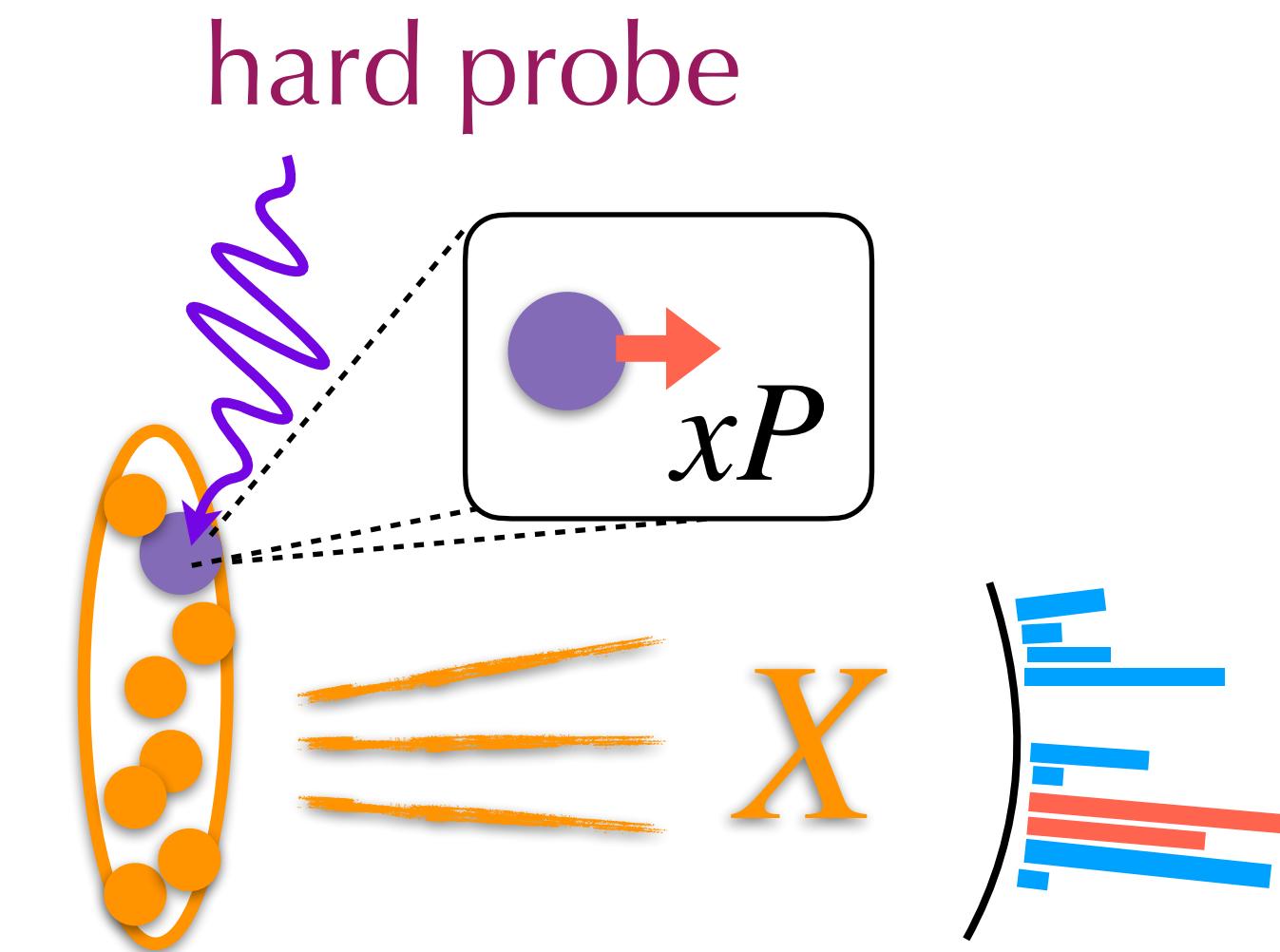
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Breit Frame

NLO



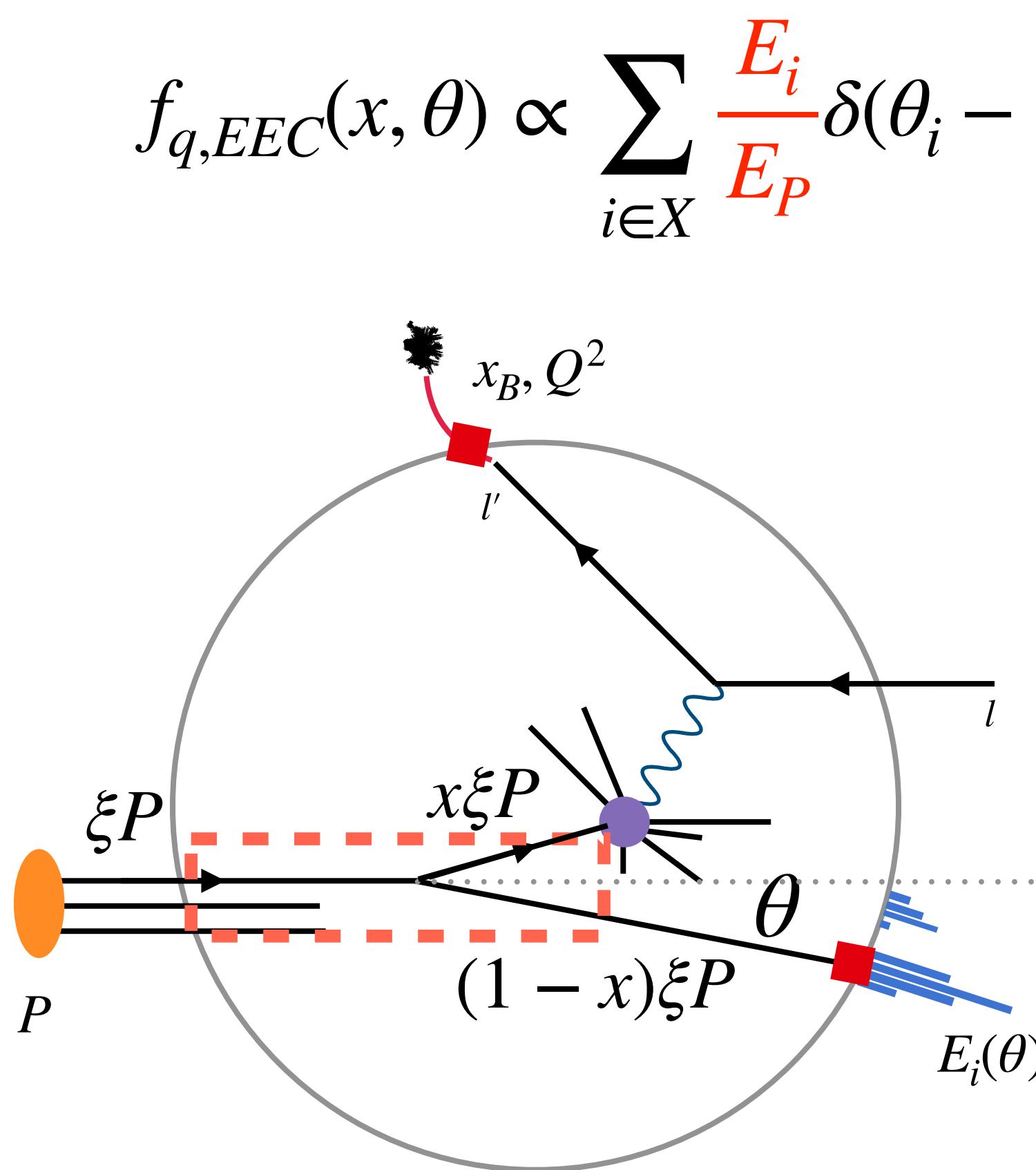
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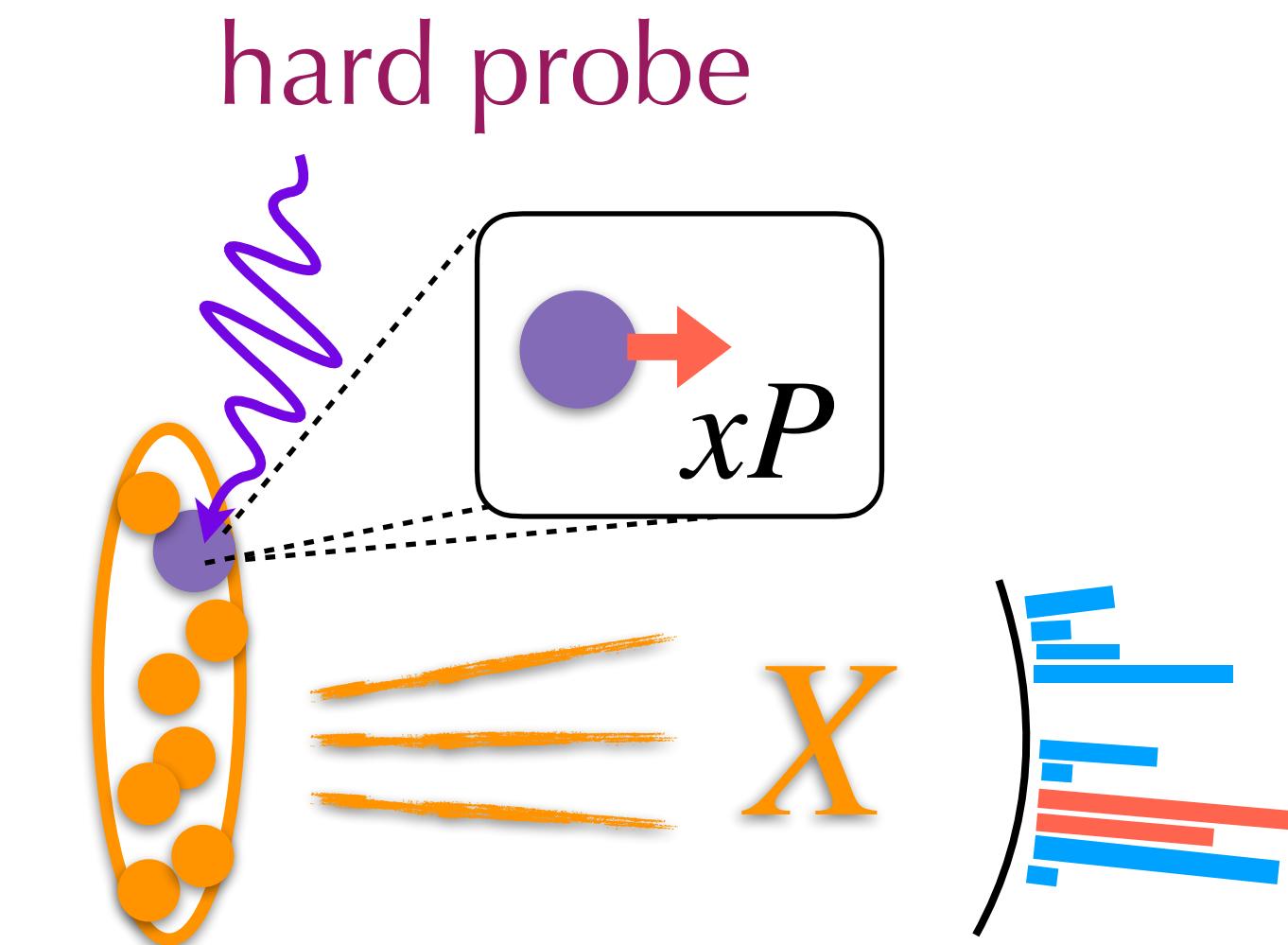
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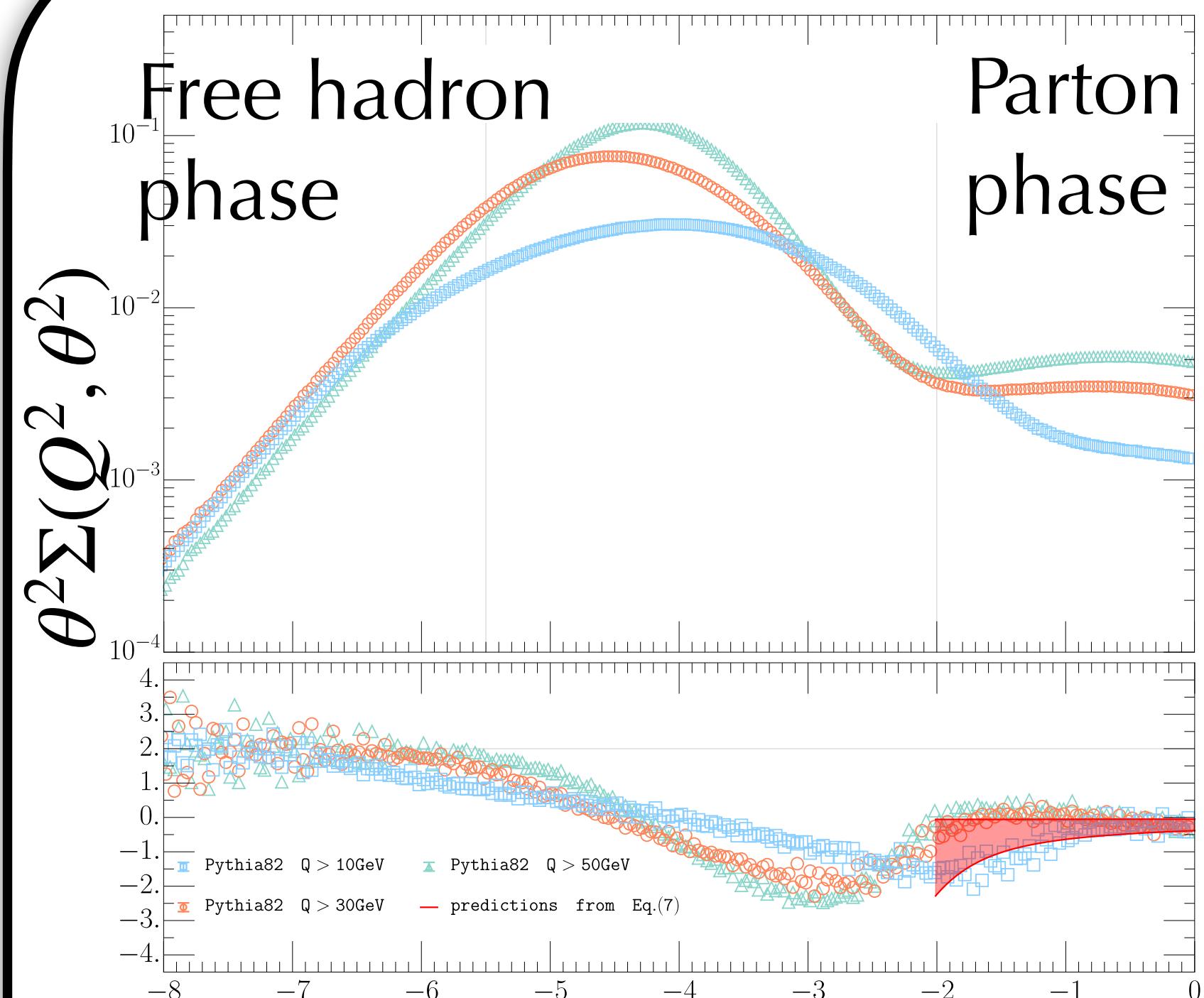
- $Q\theta \gg \Lambda_{\text{QCD}}$, $f_{\text{EEC}}(\theta) \propto \left[\frac{1}{\theta^2} (1 - x) P(x) \right] \times [\xi f(\xi)]$
- Angular correlation between final energy - initial energy density. Encode the angular distribution through $\mathcal{E}(\theta)$, induced by intrinsic transverse momentum
- 1-loop Cao, XL, Zhu, 2303.01530 , 2-loop Chen, XL, Pan, Yang Zhu, in preparation

All orders $\propto \theta^{-2+\gamma[\alpha_s]}$ mod PDFs mixing

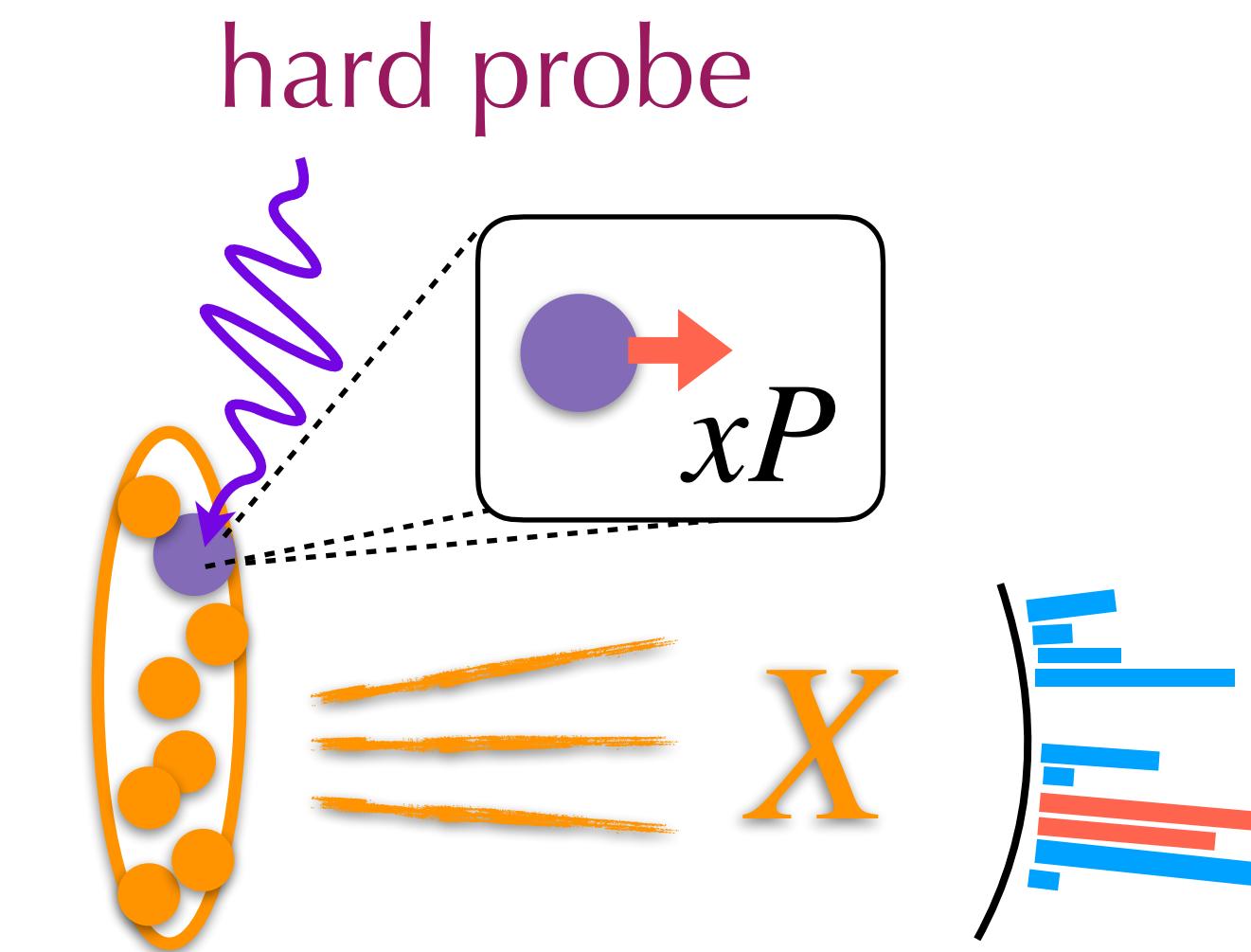
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$$(xP - p) \langle P | a_p^\dagger | X \rangle \langle X | a_p | P \rangle$$



- $Q\theta \gg \Lambda_{\text{QCD}}$, $f_{\text{EEC}}(\theta) \propto \left[\frac{1}{\theta^2} (1-x) P(x) \right] \times [\xi f(\xi)]$
- Angular Bjorken scaling rule in relatively large θ
- Manifest the phase transition between **parton** and **free hadron**

$$\propto \theta^2 \theta^{-2+\gamma[\alpha_s]} \text{mod PDFs mixing} \sim e^{\gamma[\alpha_s]y}$$

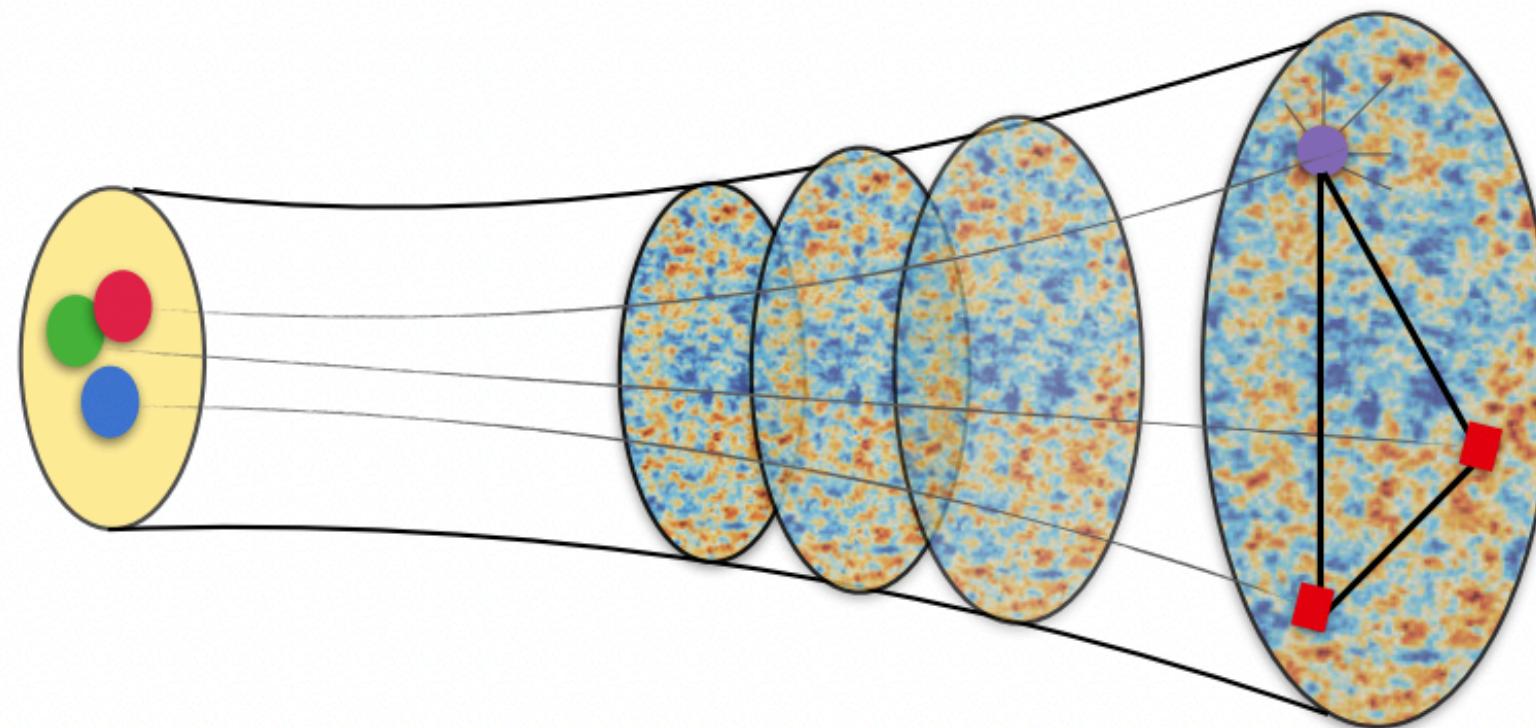
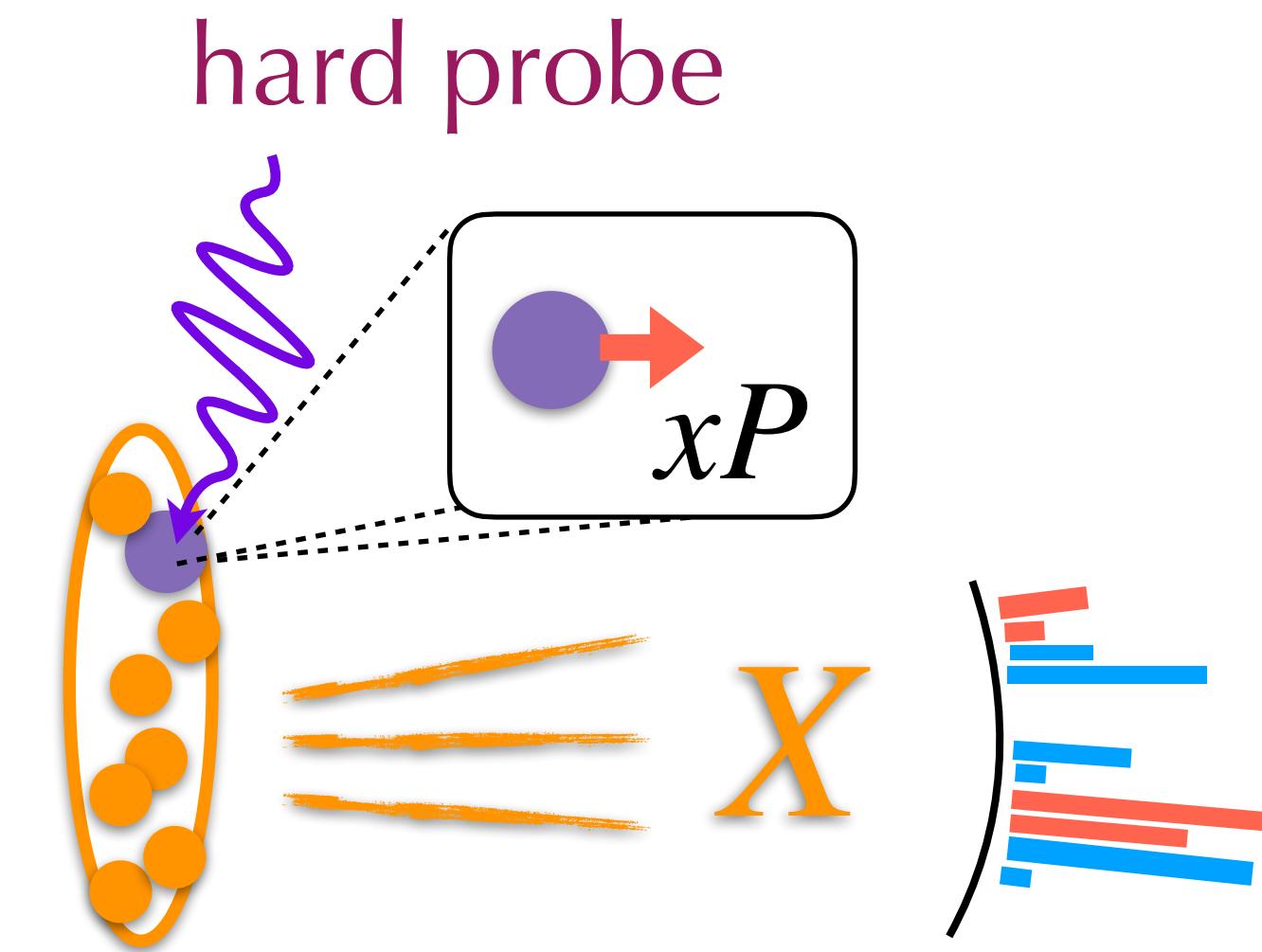
$$\propto \theta^2 \frac{d}{d\theta^2} \frac{a}{\pi(\tilde{P}\theta)^2} \sim \frac{1}{\theta^2} \sim e^{2y}$$

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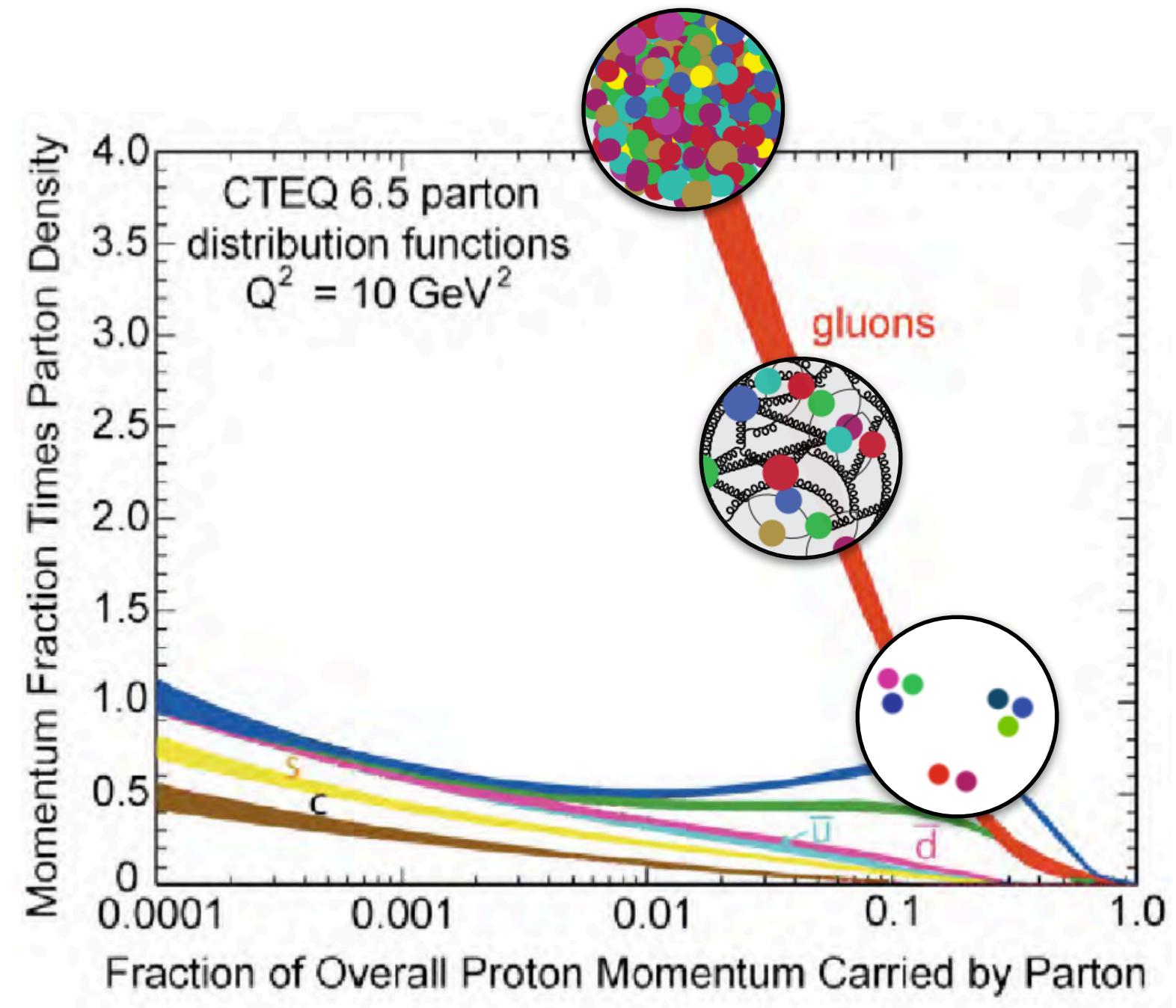
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- differential through \mathcal{E} , multi-point correlation will give CMB-like distribution of a nucleon
 $\langle P | \bar{\psi}(0) \mathcal{E}(\theta_1) \dots \mathcal{E}(\theta_N) \psi(y^-) | P \rangle$

Applications

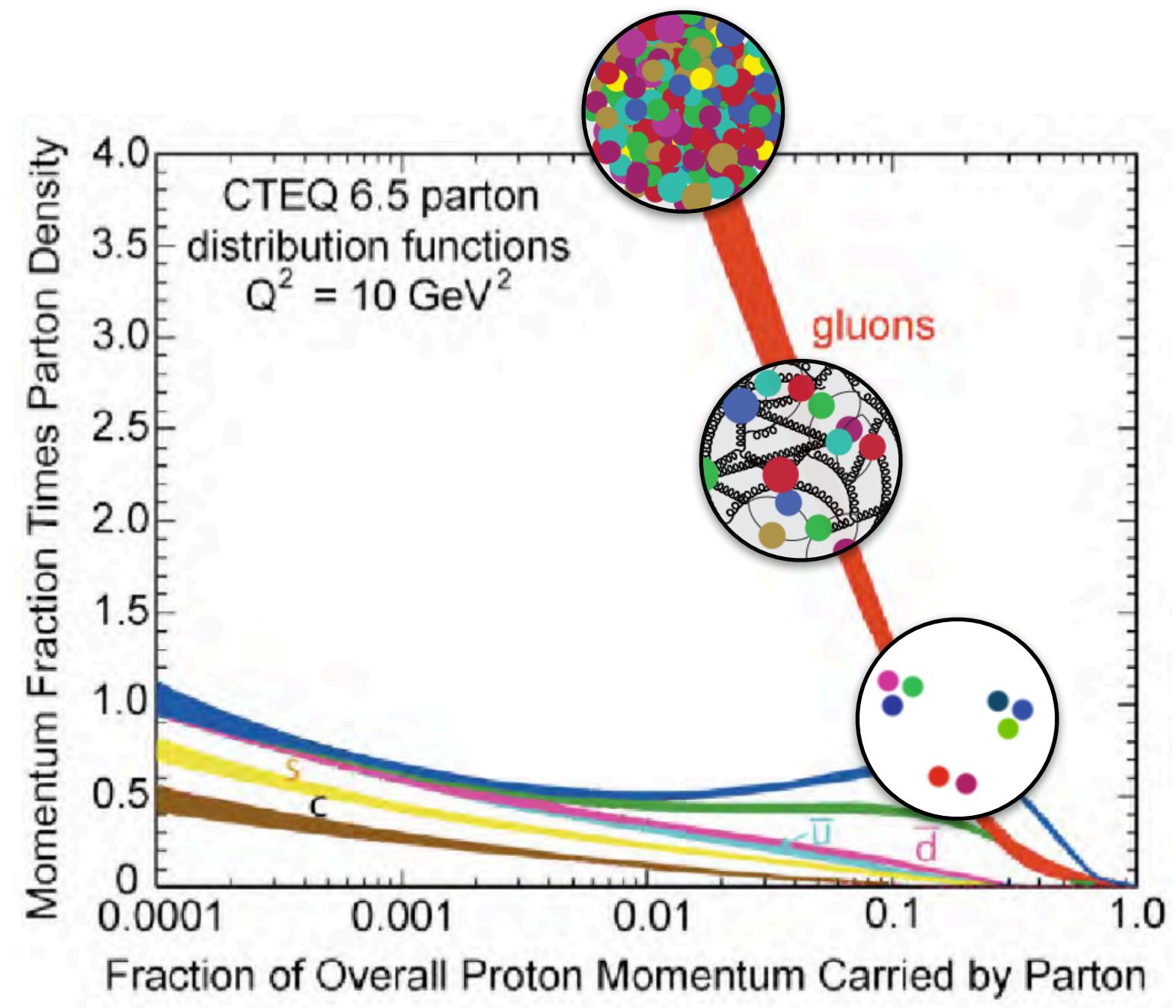
Application to the gluon saturation



Gluon saturation at small x

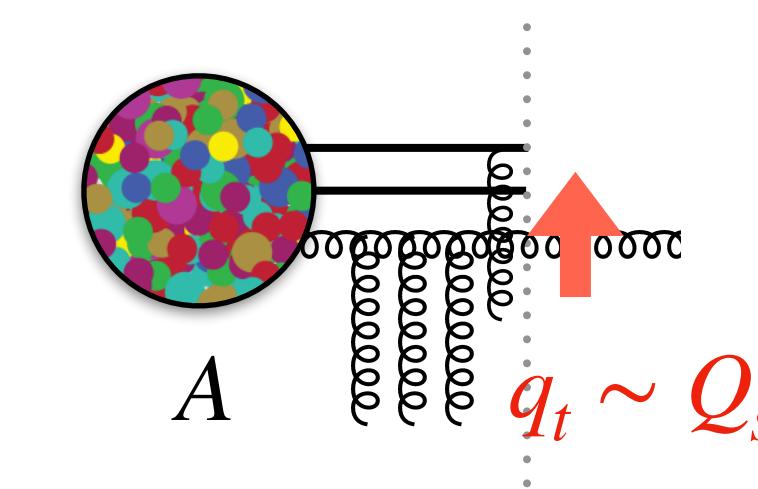
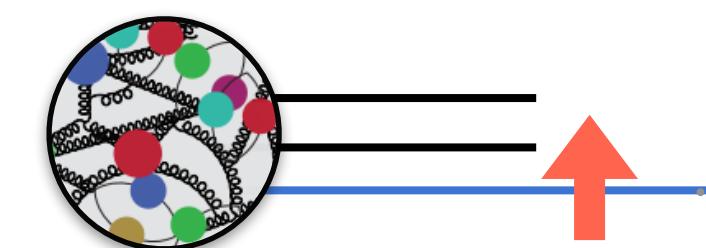
- Many hints but yet to be nailed down
- One major pillar of the EIC

Application to the gluon saturation

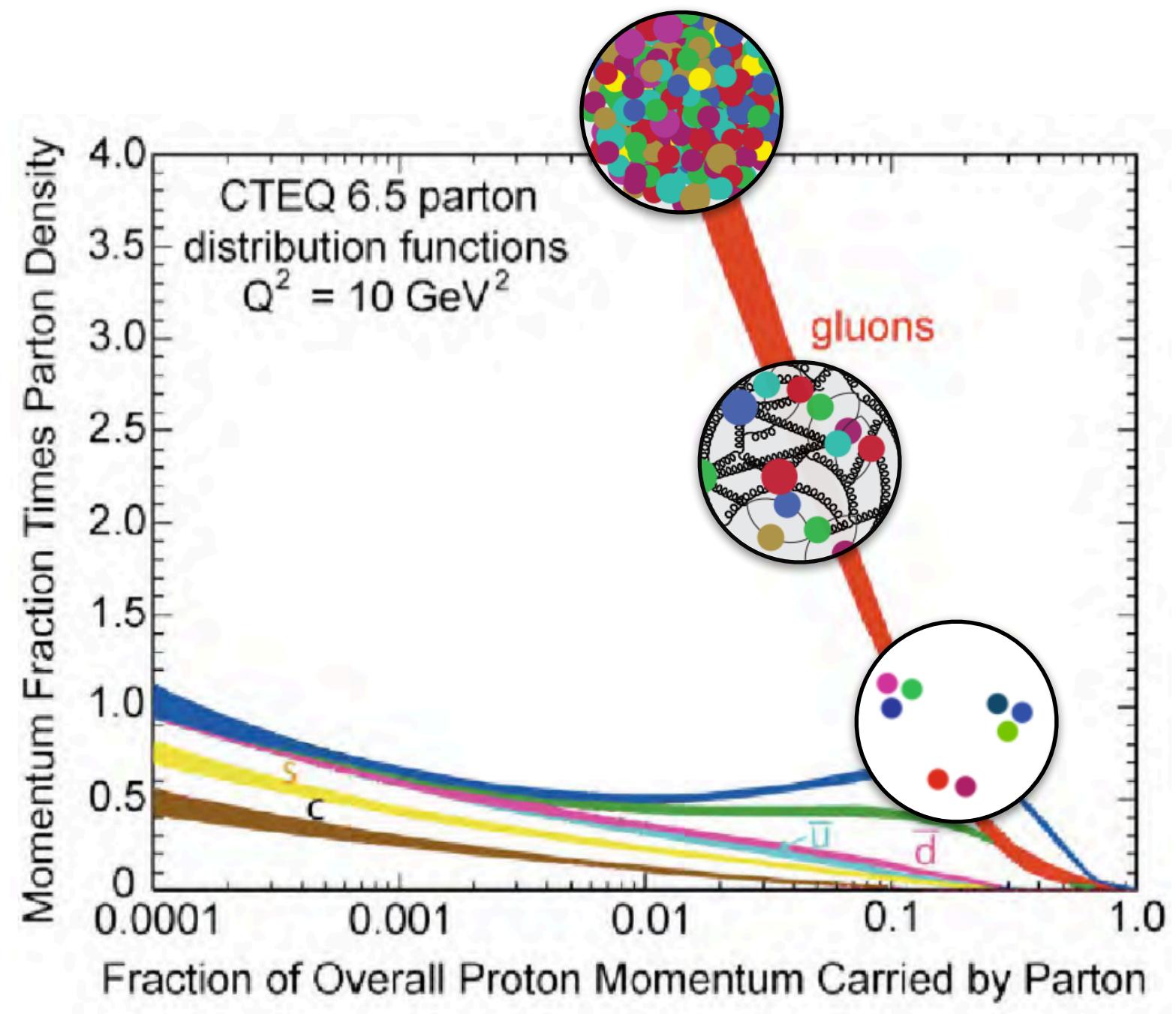


Gluon saturation at small x

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

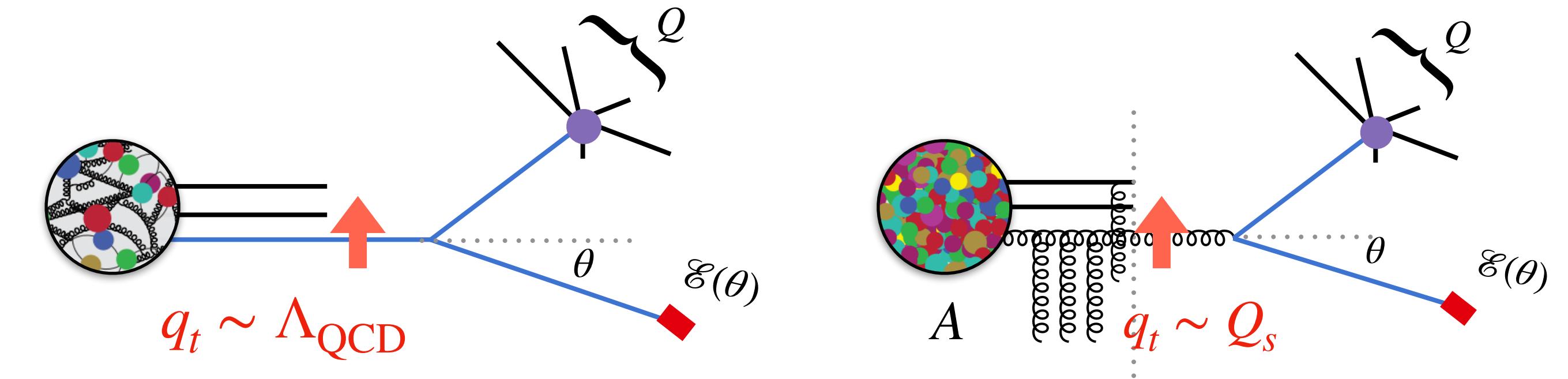


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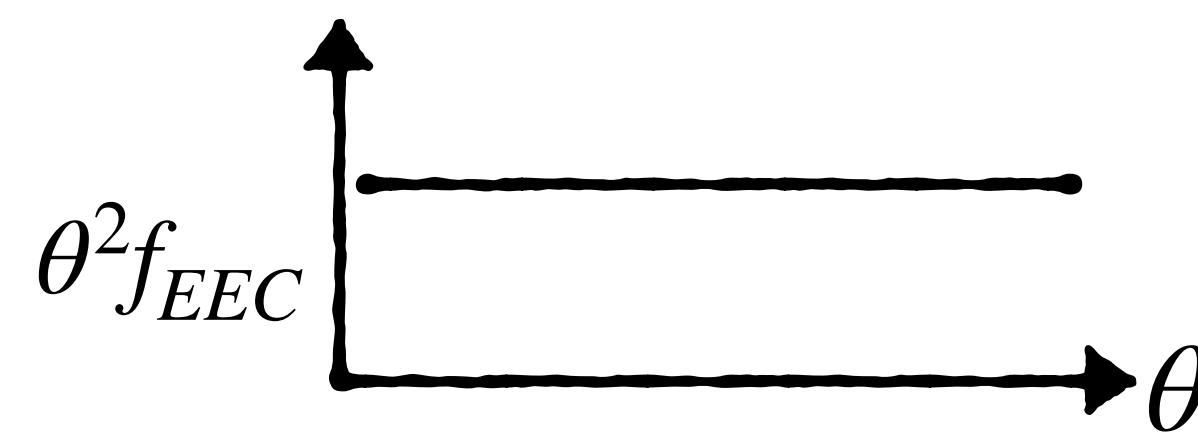


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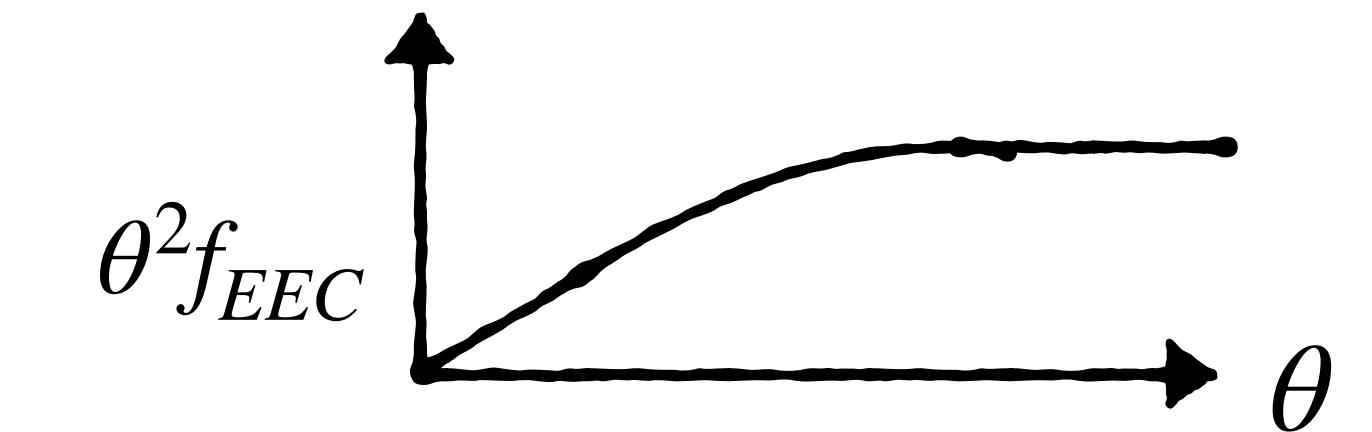
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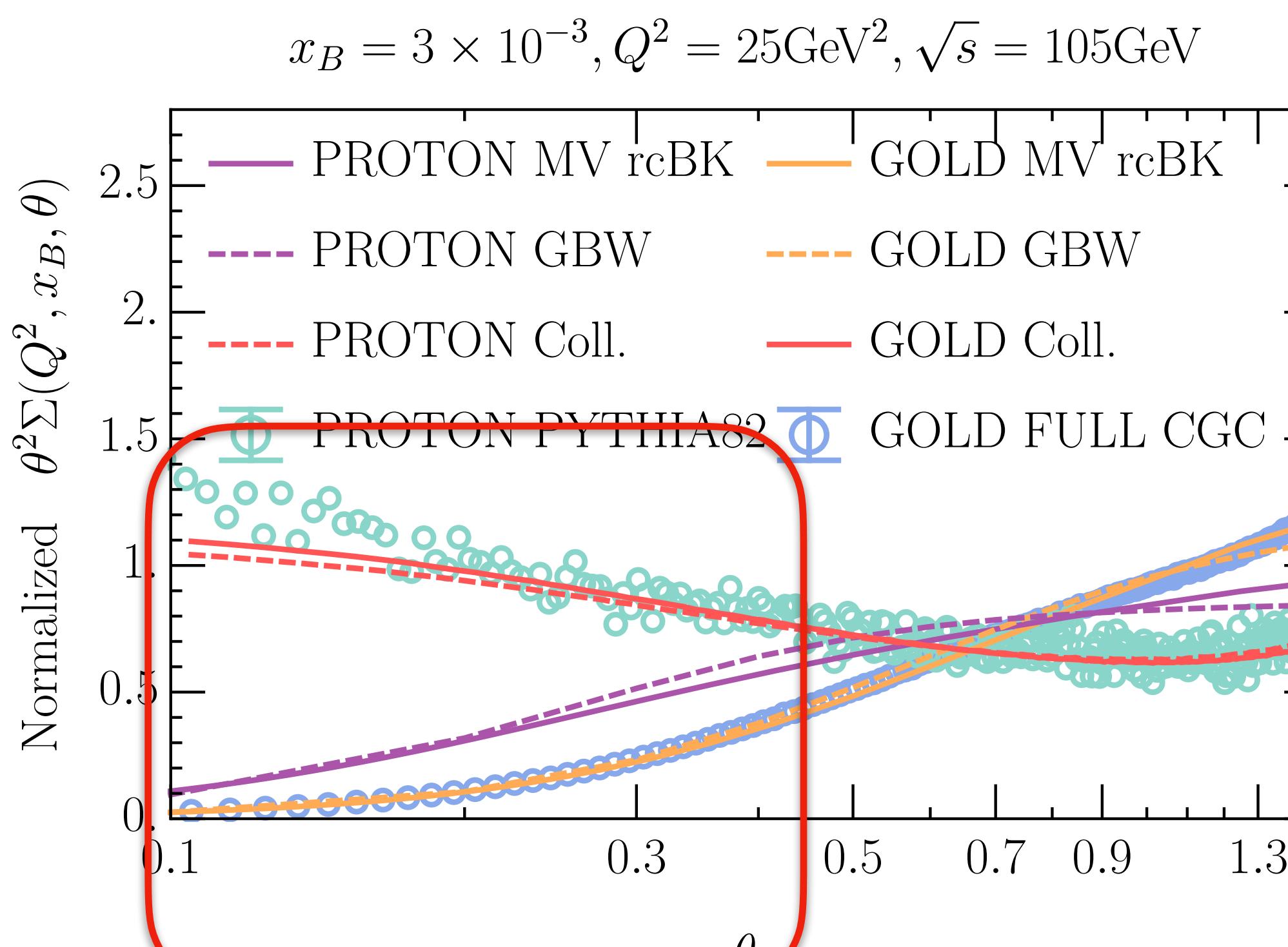
$q_t \ll Q\theta$ Ignored



$\theta Q \gg \Lambda_{\text{QCD}}$

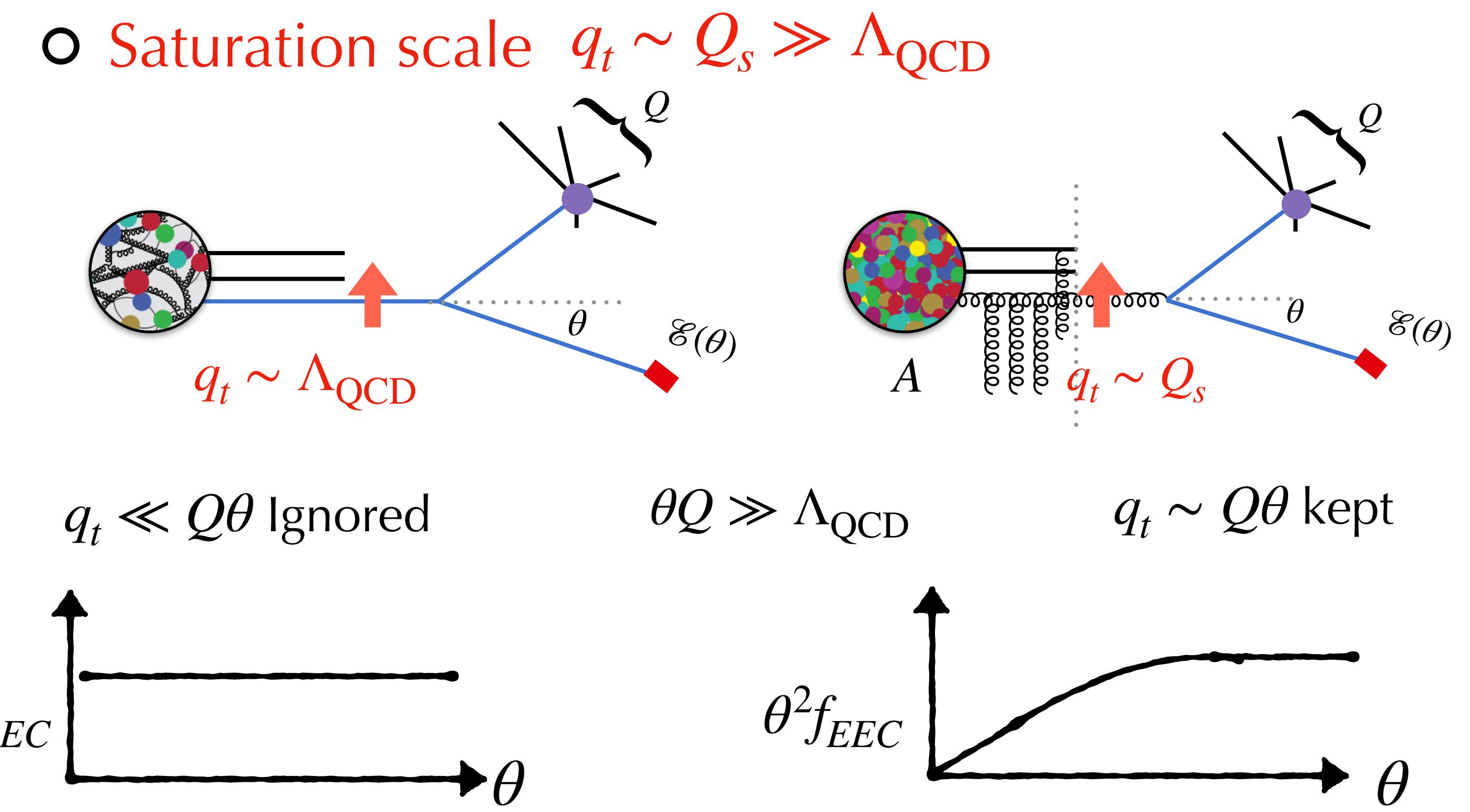


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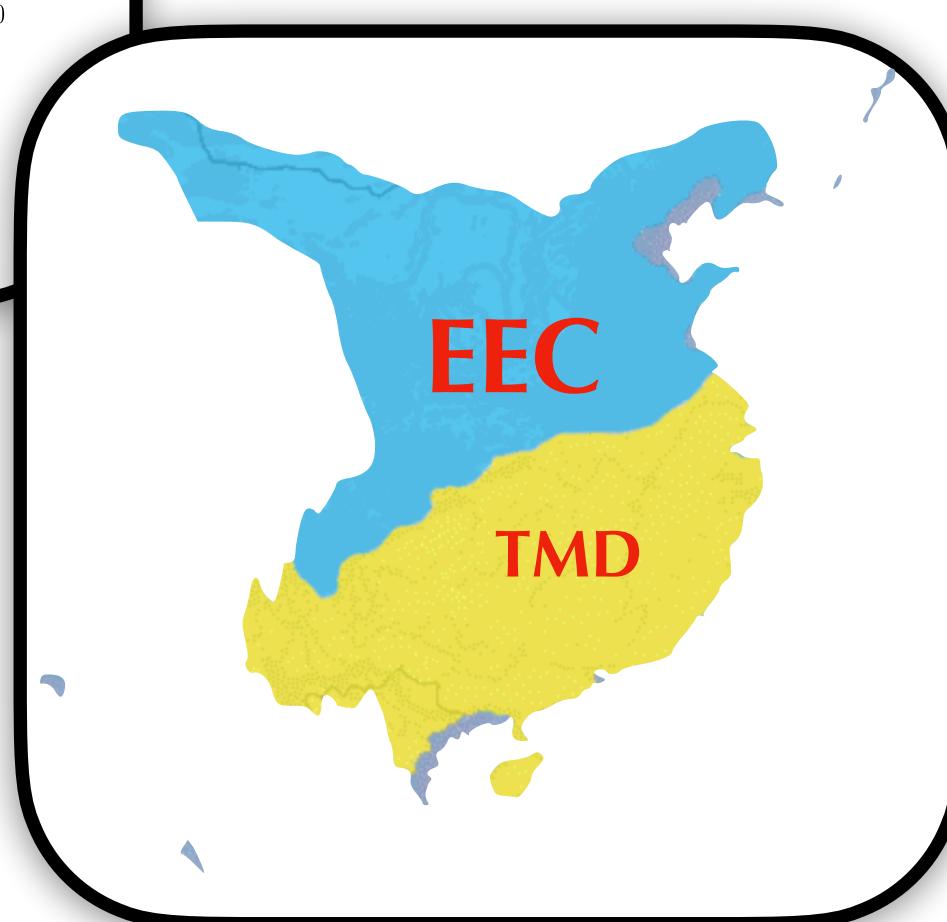
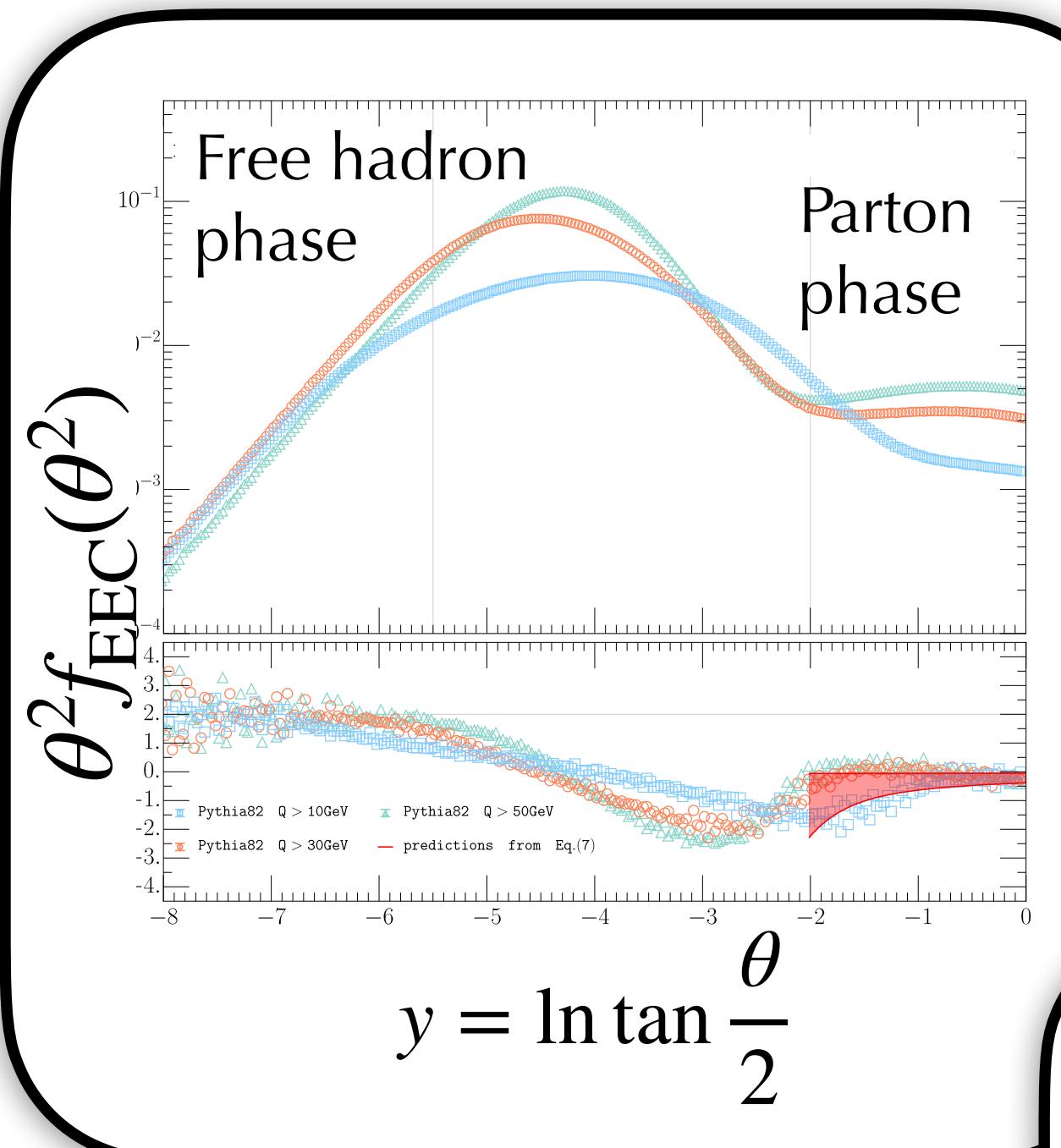


NEEC as evident portal to
the onset of gluon saturation

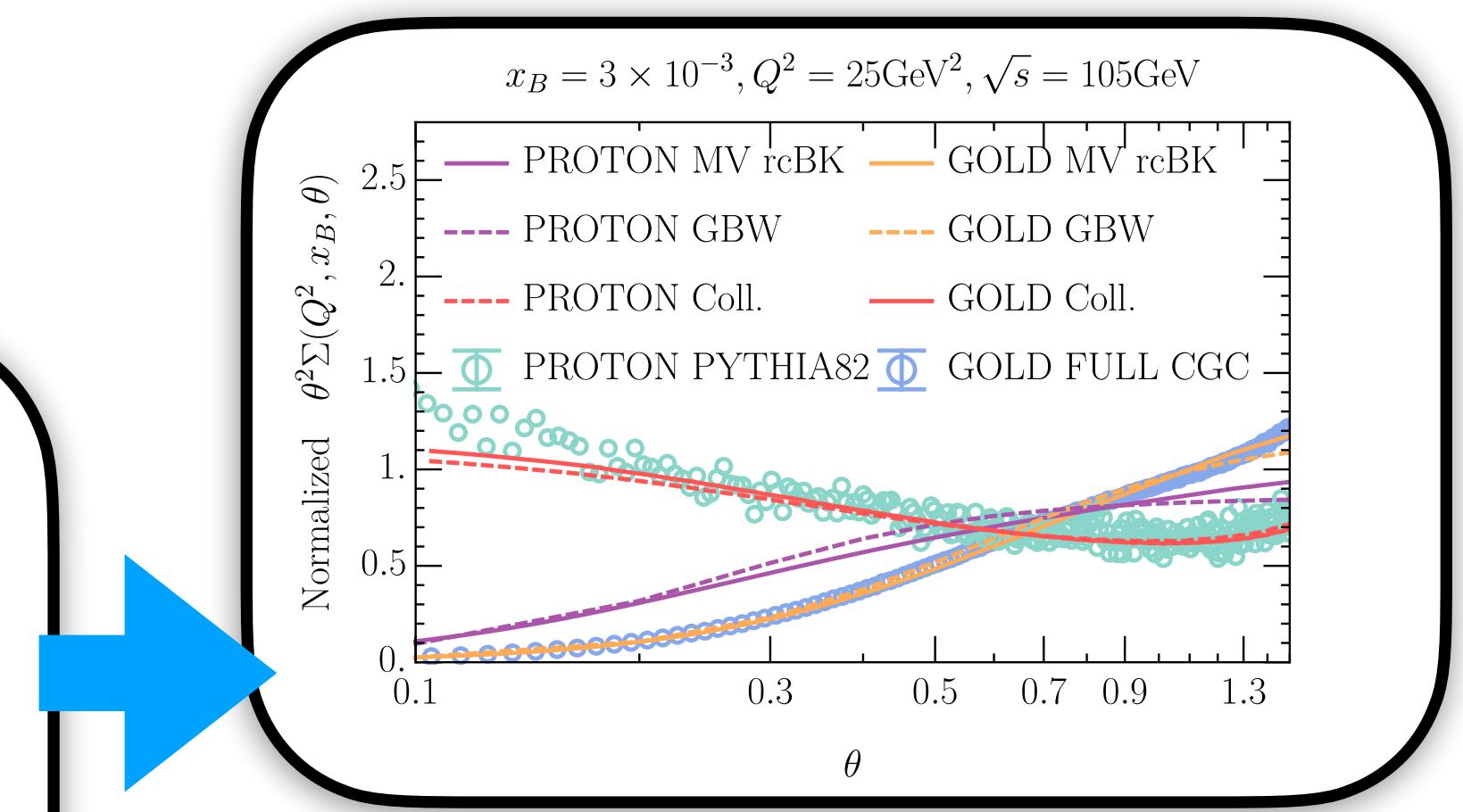
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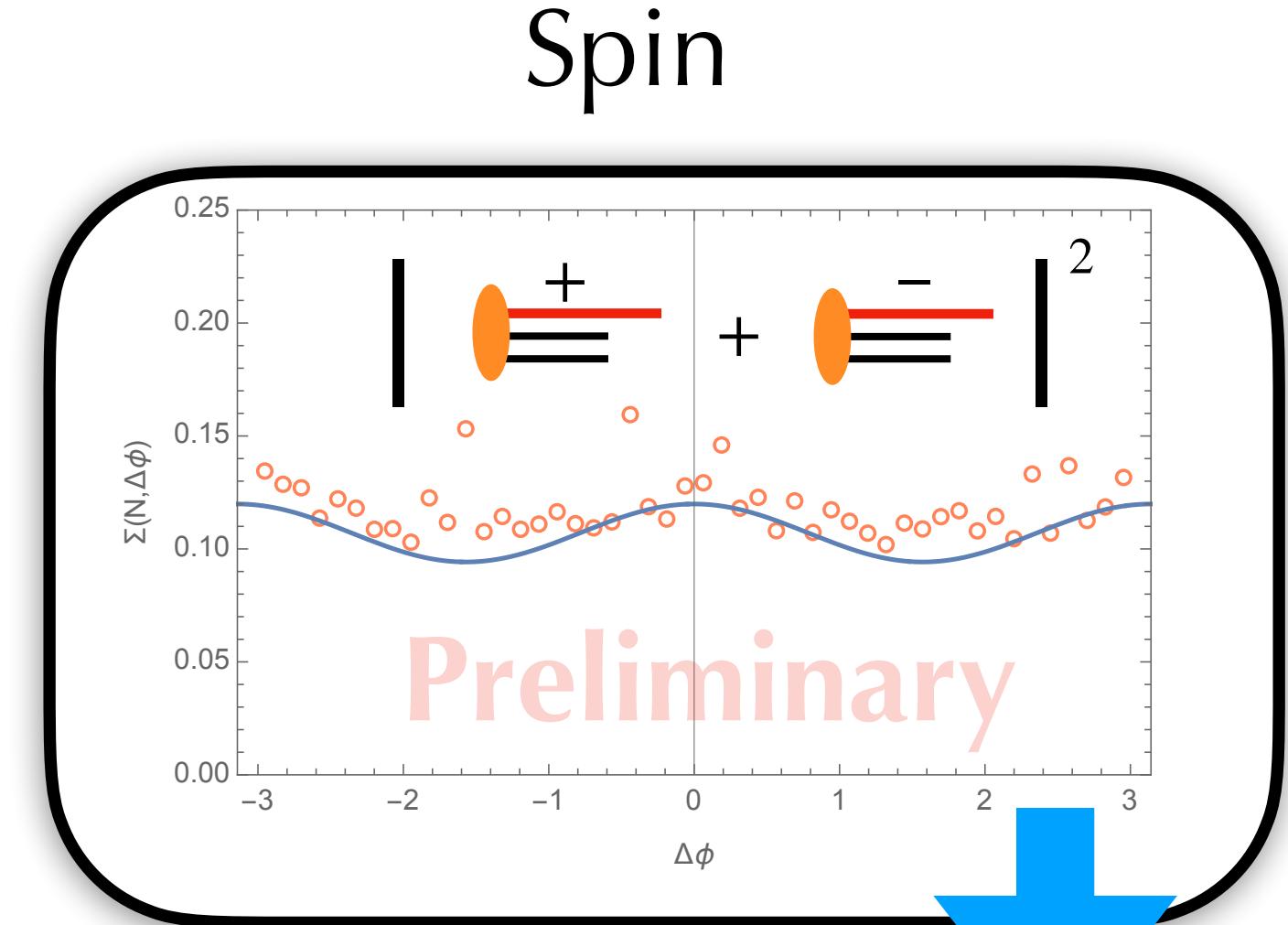
Current status and future plan



Parton-hadron
“phase transition”



Nail down gluon
saturation

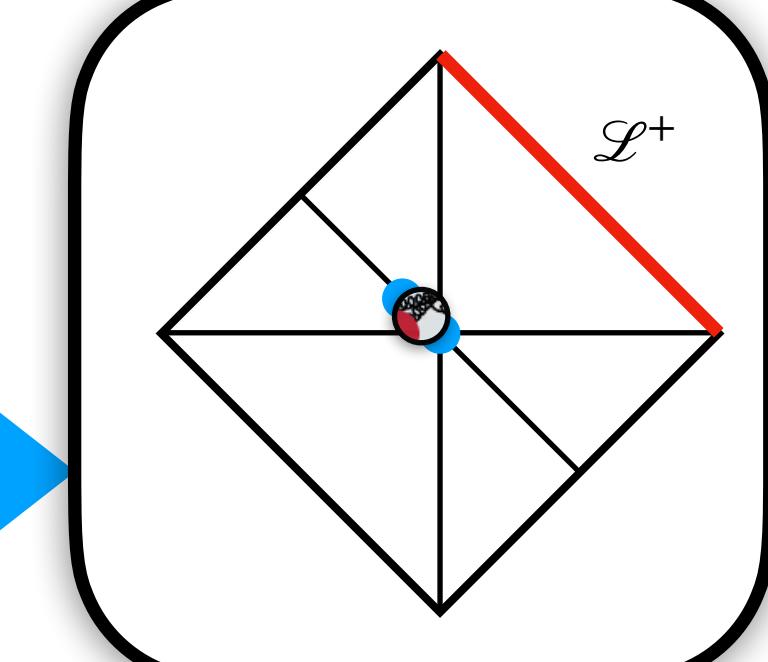


Connection to
pQCD and
topological
structure?

Hot
medium
Effects?

Cold
Nucleus
Effects?

Phenomenology



Theory

Formal
theory
studies