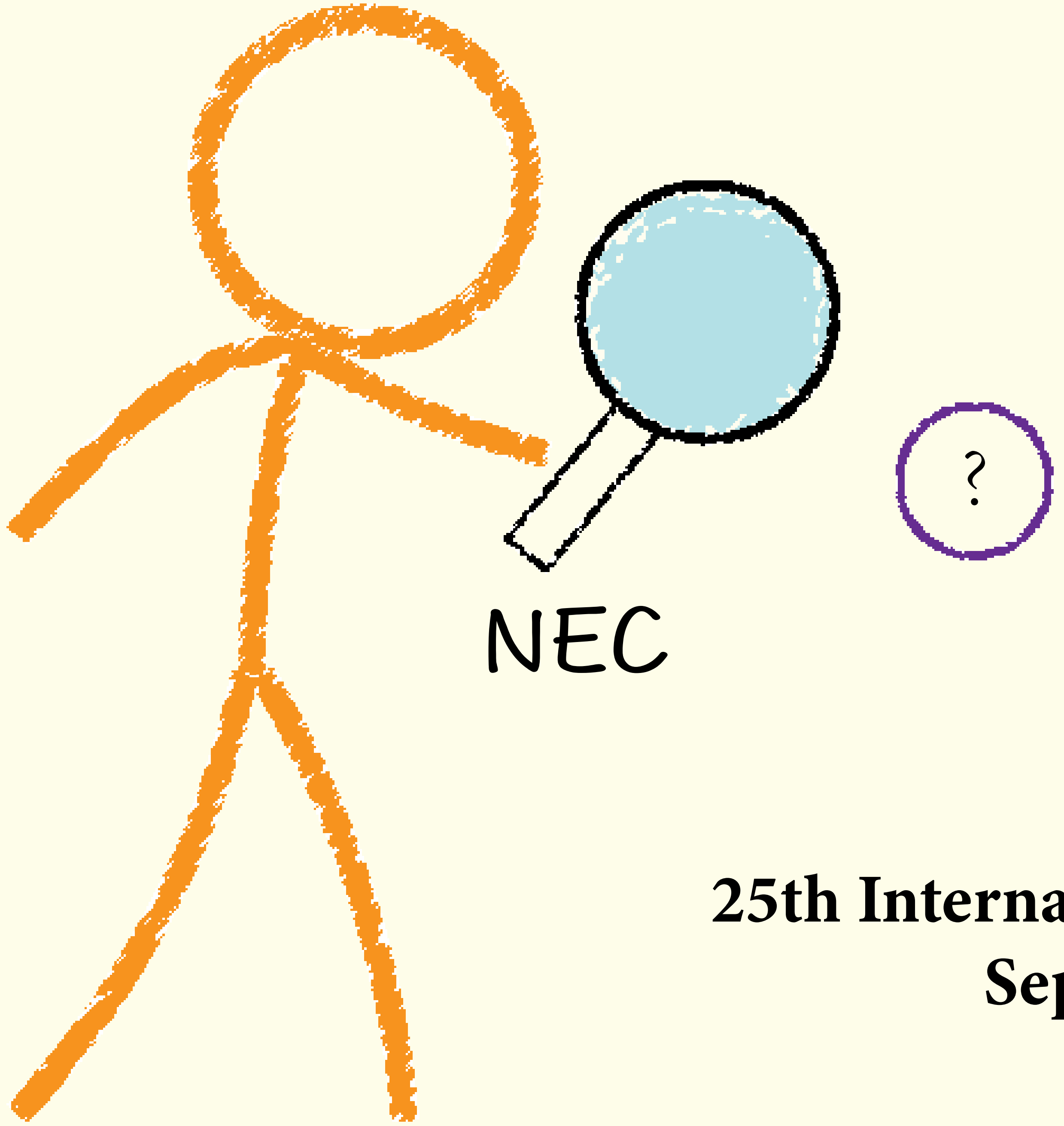
# Nucleon Energy correlators

## -a new way to study nucleon structure




Liu, Zhu, PRL 130 (2023) 9, 9
HC, Liu, Zhu, PRD 107 (2023) 114008
Liu, Liu, Pan, Yuan, Zhu, PRL 130 (2023) 18, 18
Li, Liu, Yuan, Zhu arxiv:2308.1094

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Beijing Normal University

**25th International Spin Symposium**
**September 24-29**

# Outline

1. Conventional approach to nucleon structure
2. Concept and feature of Nucleon Energy Correlators
3. Numerical result
4. Application
5. Conclusion

# Why are we interested in Nucleon Structure?

Still many question yet to answer

    Spin components

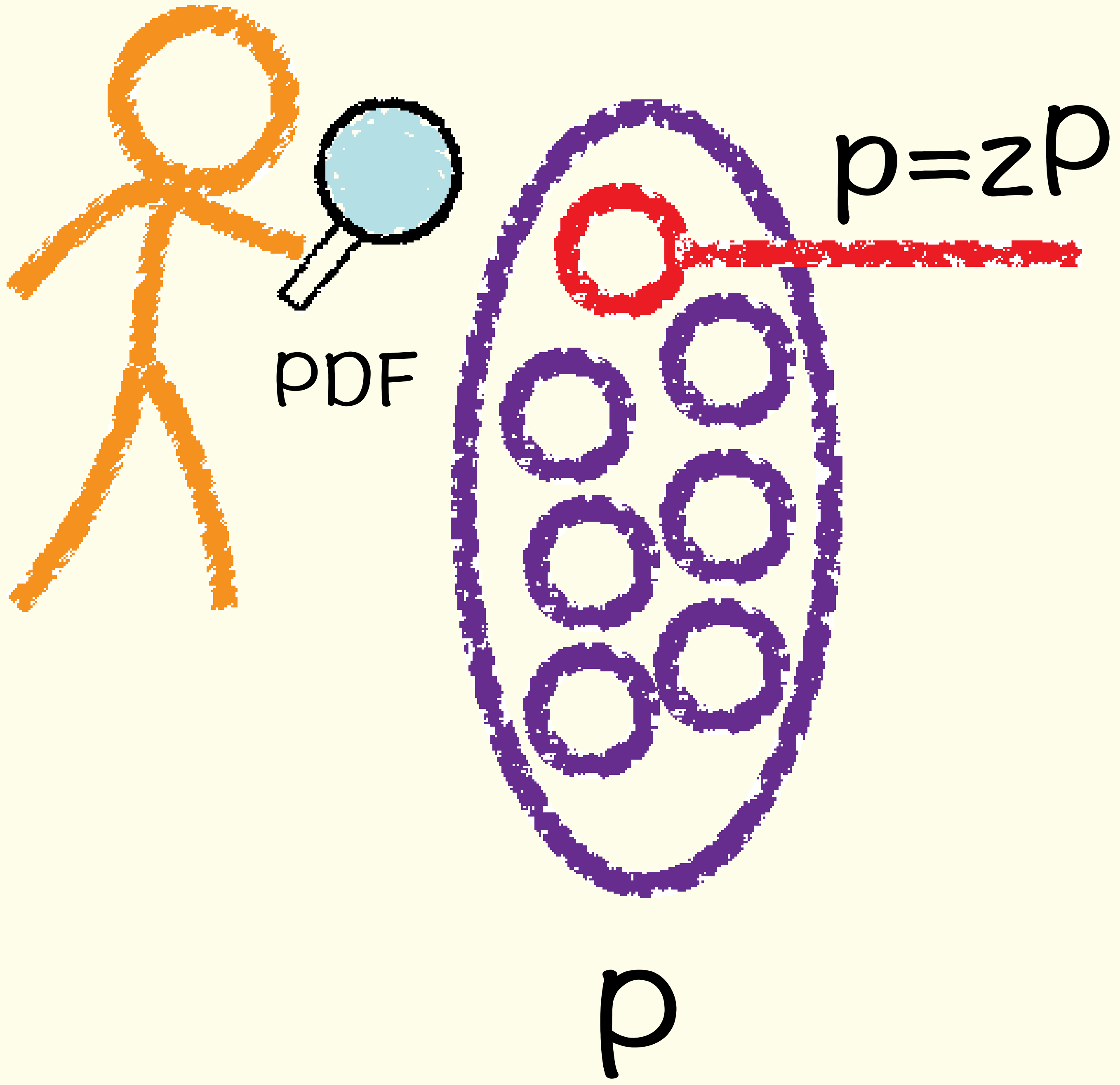
    Mass decomposition

    ...

Major focus of EIC.

# Conventional approach to nucleon structure

Parton distribution function(PDF)



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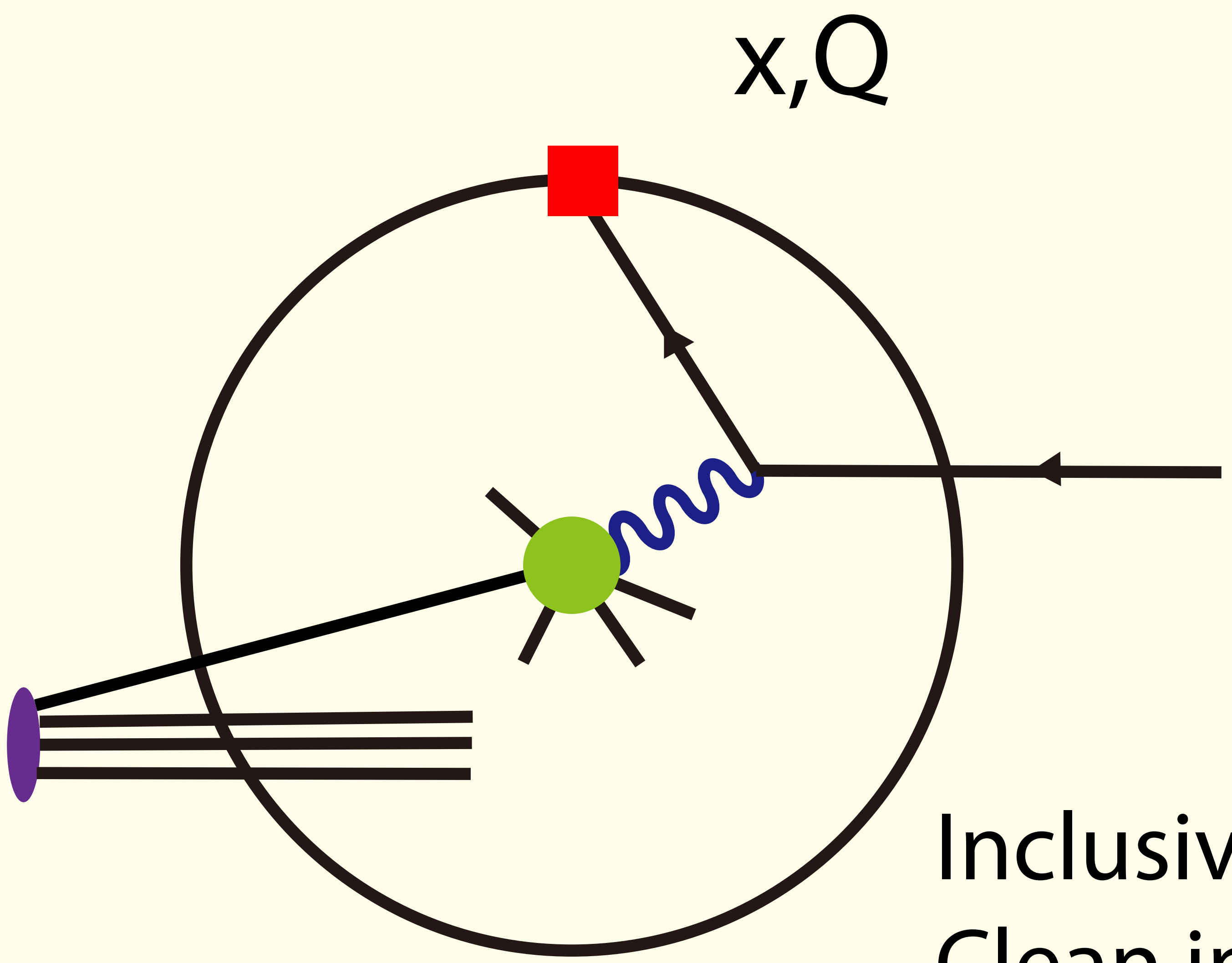
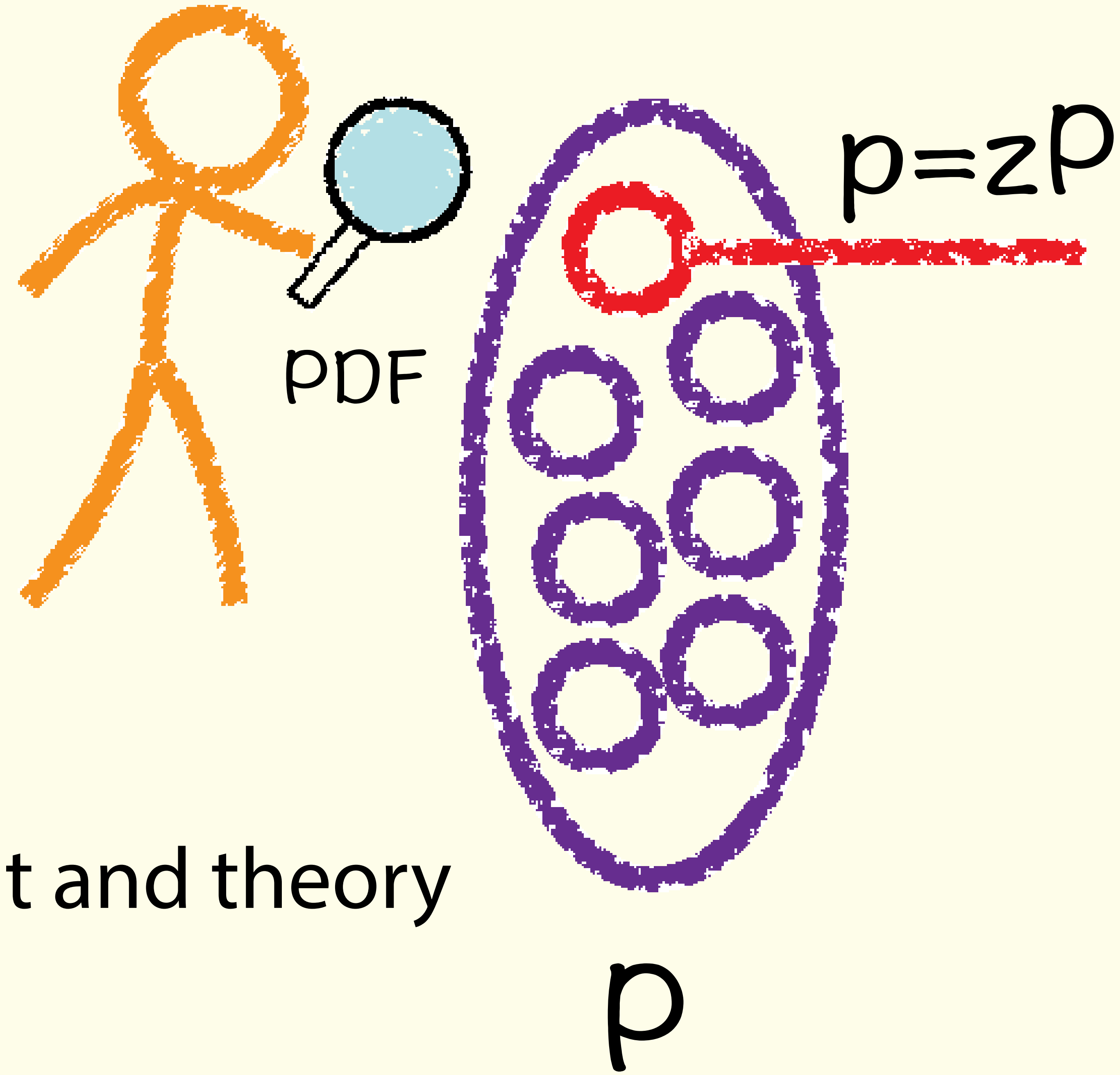
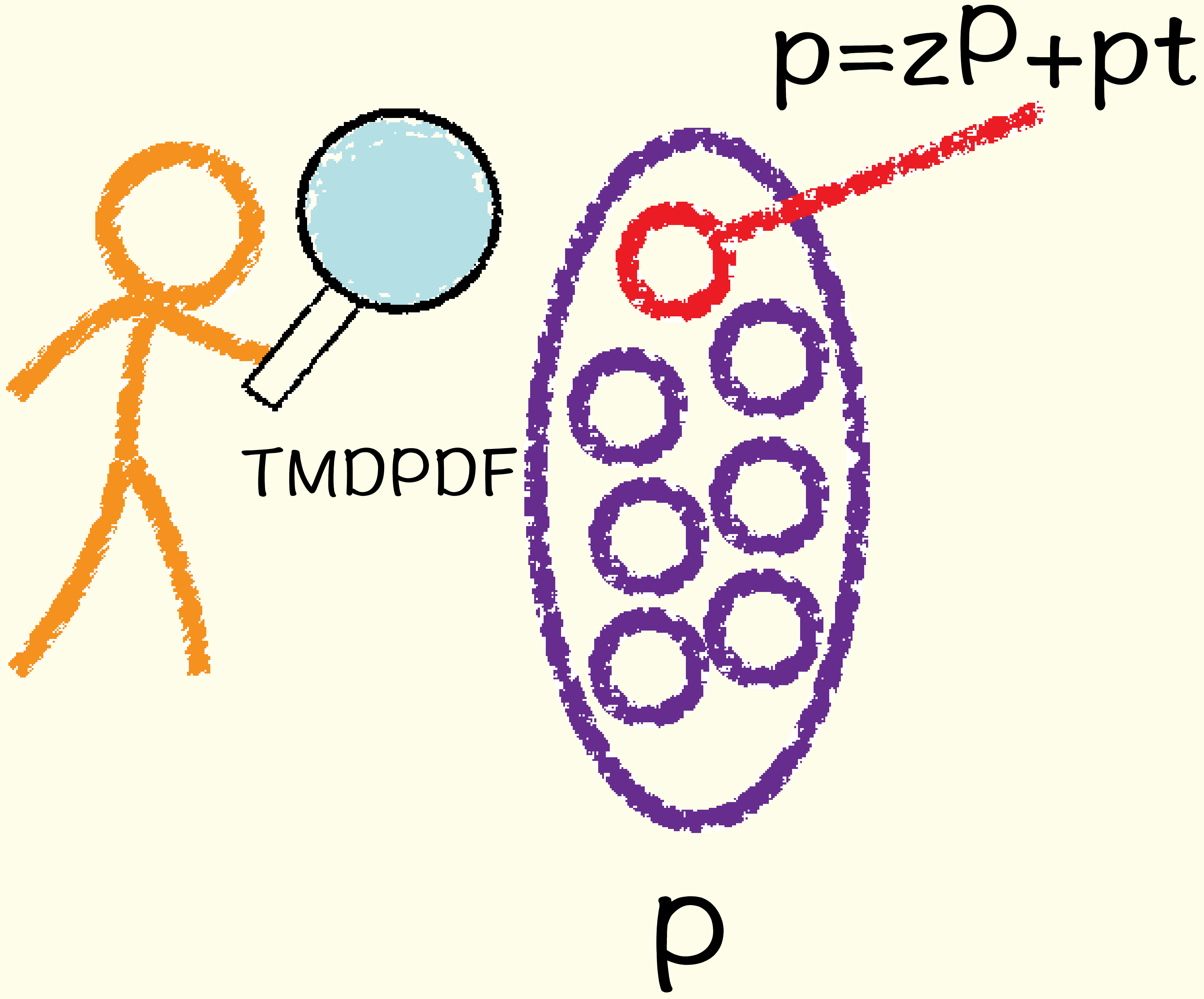



Inclusive
Clean in both experiment and theory
Lose information



# Conventional approach to nucleon structure

Transverse momentum dependent (TMD) PDF



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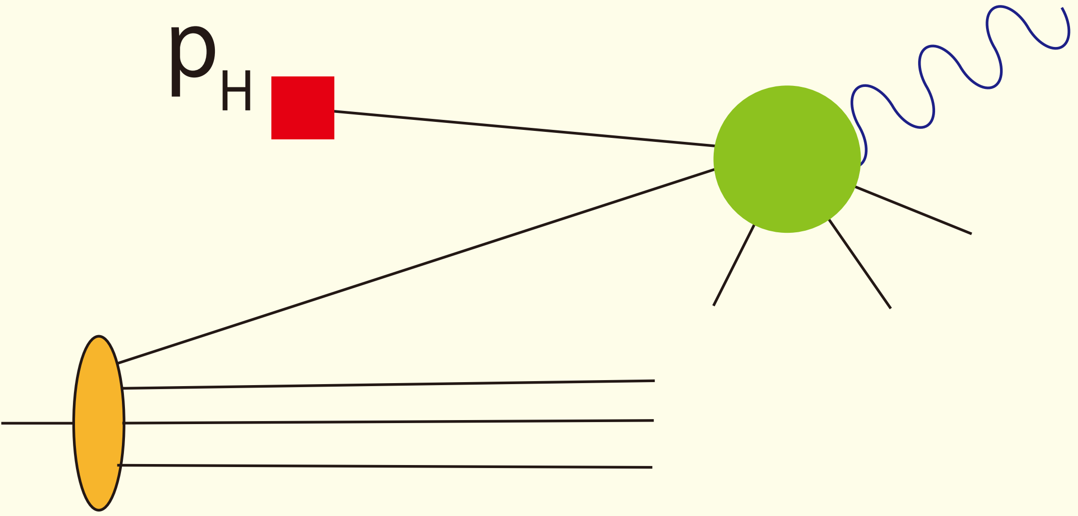
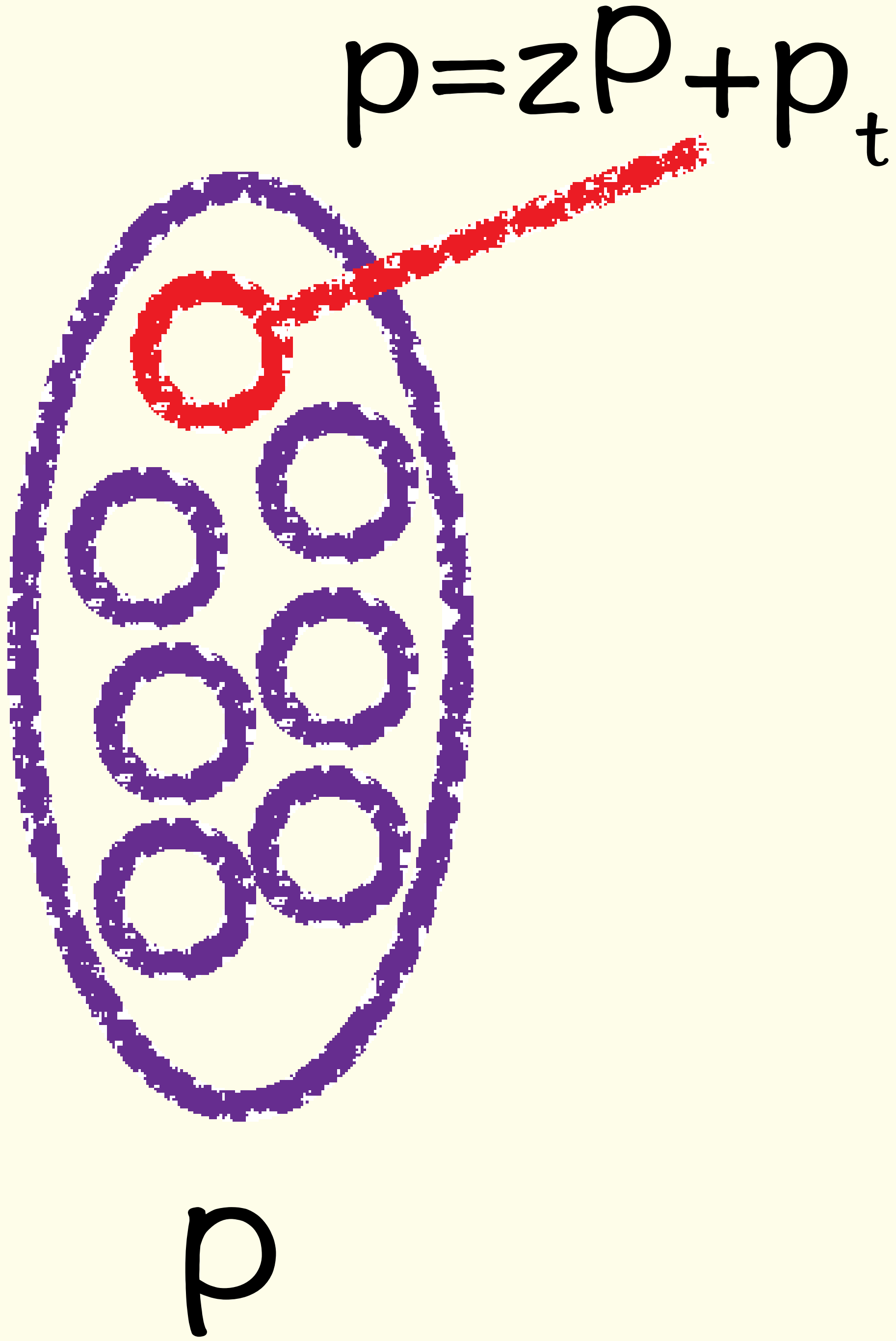


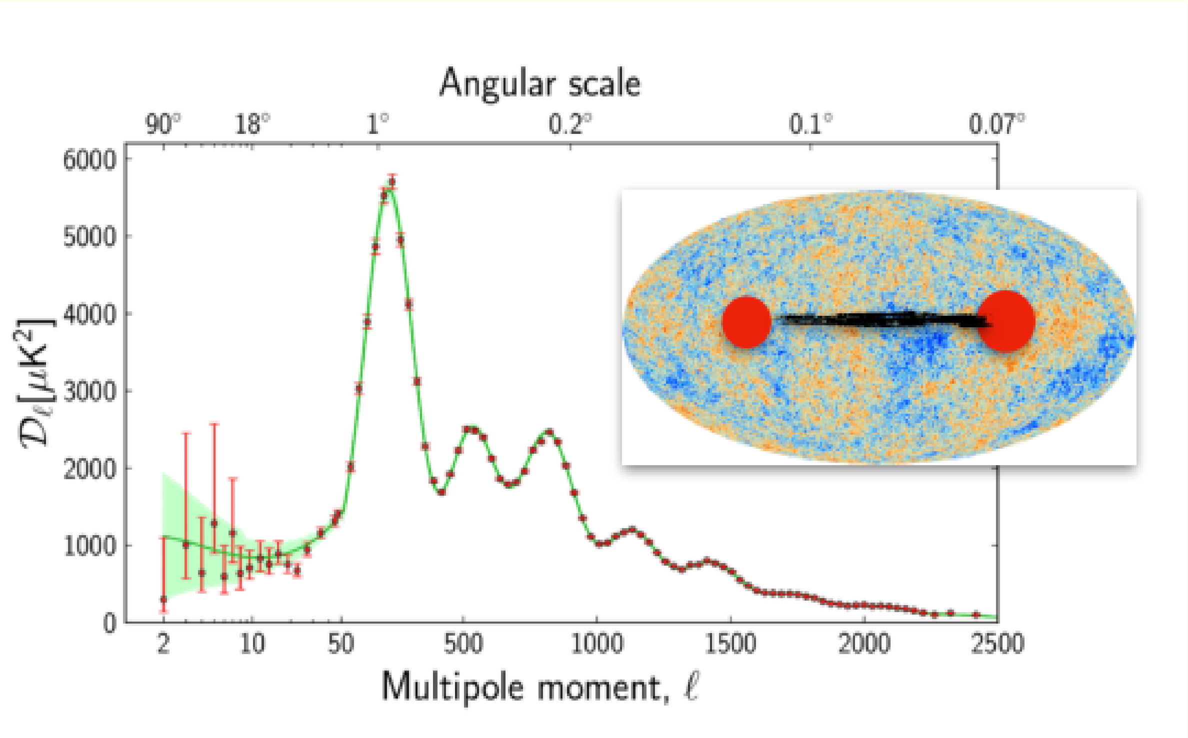

Semi-Inclusive DIS

1. Usually needs 2 non-pert object
2. exponentially suppressed in non-pert region when Q is large
3. Loses information



# Conventional approach to nucleon structure

Transverse momentum dependent (TMD) PDF

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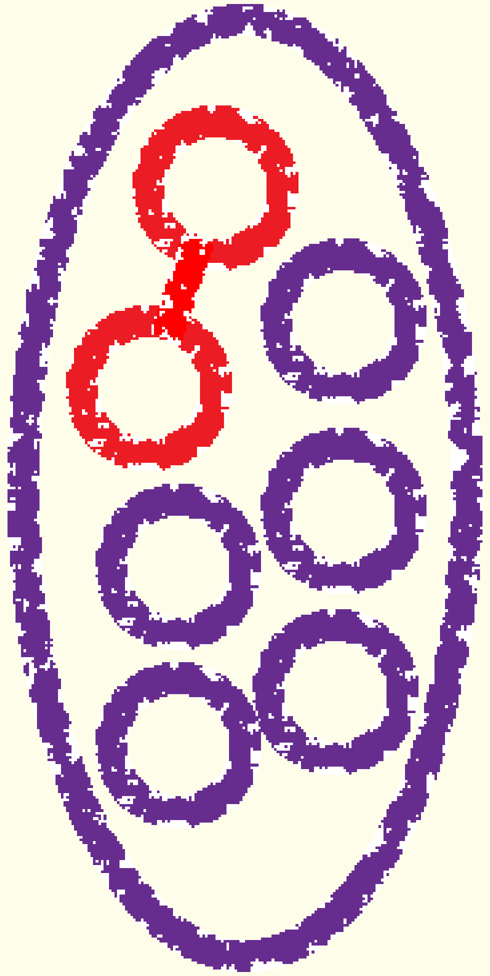
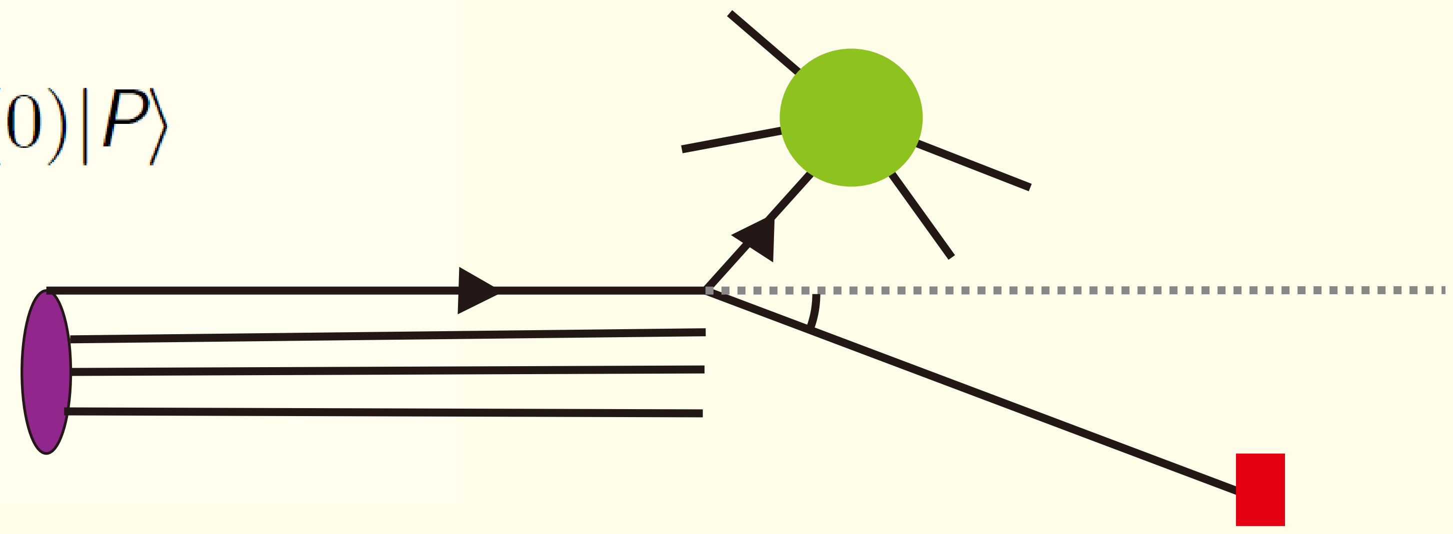


# Nucleon Energy Correlators

Follow the idea of Energy Correlators[Dixon, Moult, Zhu...], Nucleon Energy Correlators was proposed[Liu,Zhu(2023)] . It can be regarded as the target EC, which is an inclusive version of the fracture funciton / target fragmentaiton function, without tagging an explicit hadron.

$$f_{q,\mathrm{EEC}}(z,\theta) = \int \frac{dy^-}{4\pi} e^{-izP^+\frac{y^-}{2}} \langle P|\bar{\chi}_n(y^-)\frac{\gamma^+}{2}\hat{\mathcal{E}}(\theta)\chi_n(0)|P\rangle$$

$$\hat{\mathcal{E}}(\theta)|X\rangle = \sum_{i\in X} \frac{E_i}{E_P}\Theta(\theta-\theta_i)|X\rangle$$



We do not constrain on the parton transverse momentum. The transverse dynamics are encoded in the energy density operator

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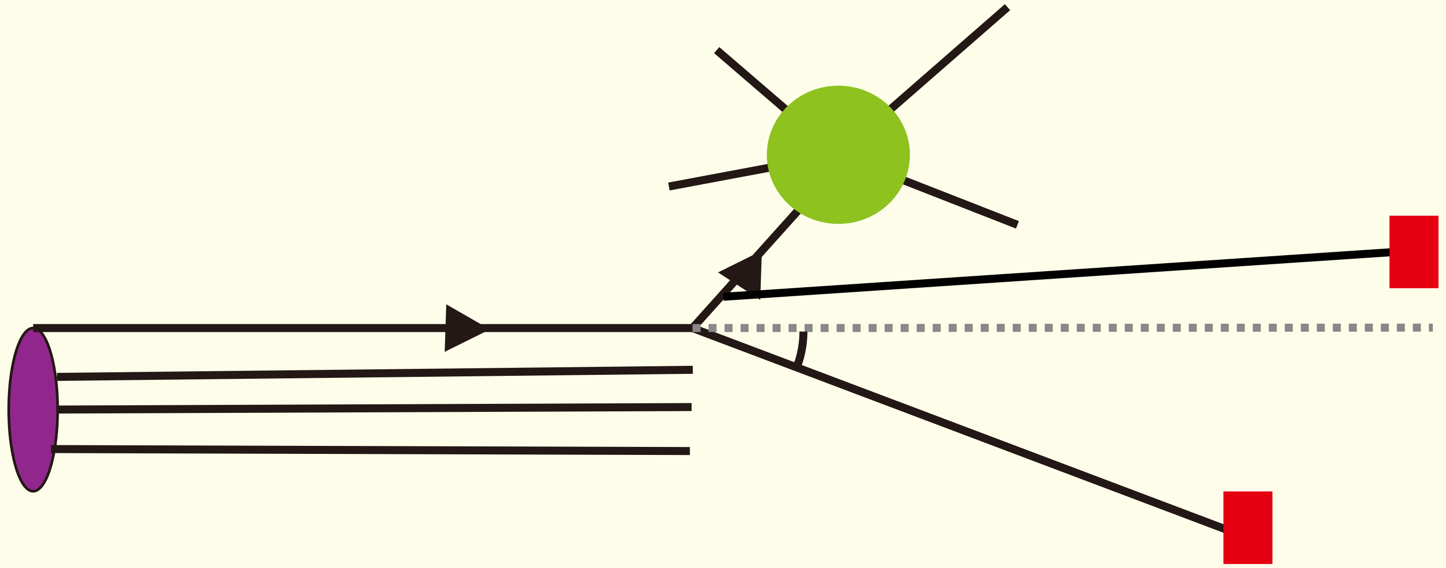
$$f_q(z) = \int \frac{dy^-}{4\pi} e^{-izP^+\frac{y^-}{2}} \langle P|\bar{\chi}_n(y^-)\frac{\gamma^+}{2}\chi_n(0)|P\rangle$$

Comapre it with pdf

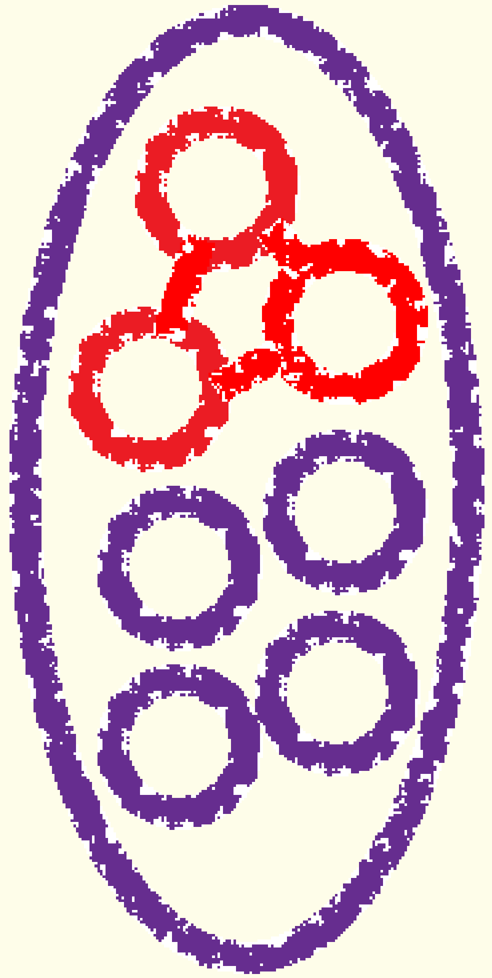
the only difference is the energy density operator.

# Higher-Point correlator

Multi-point correlation is straightforwardly generalized with

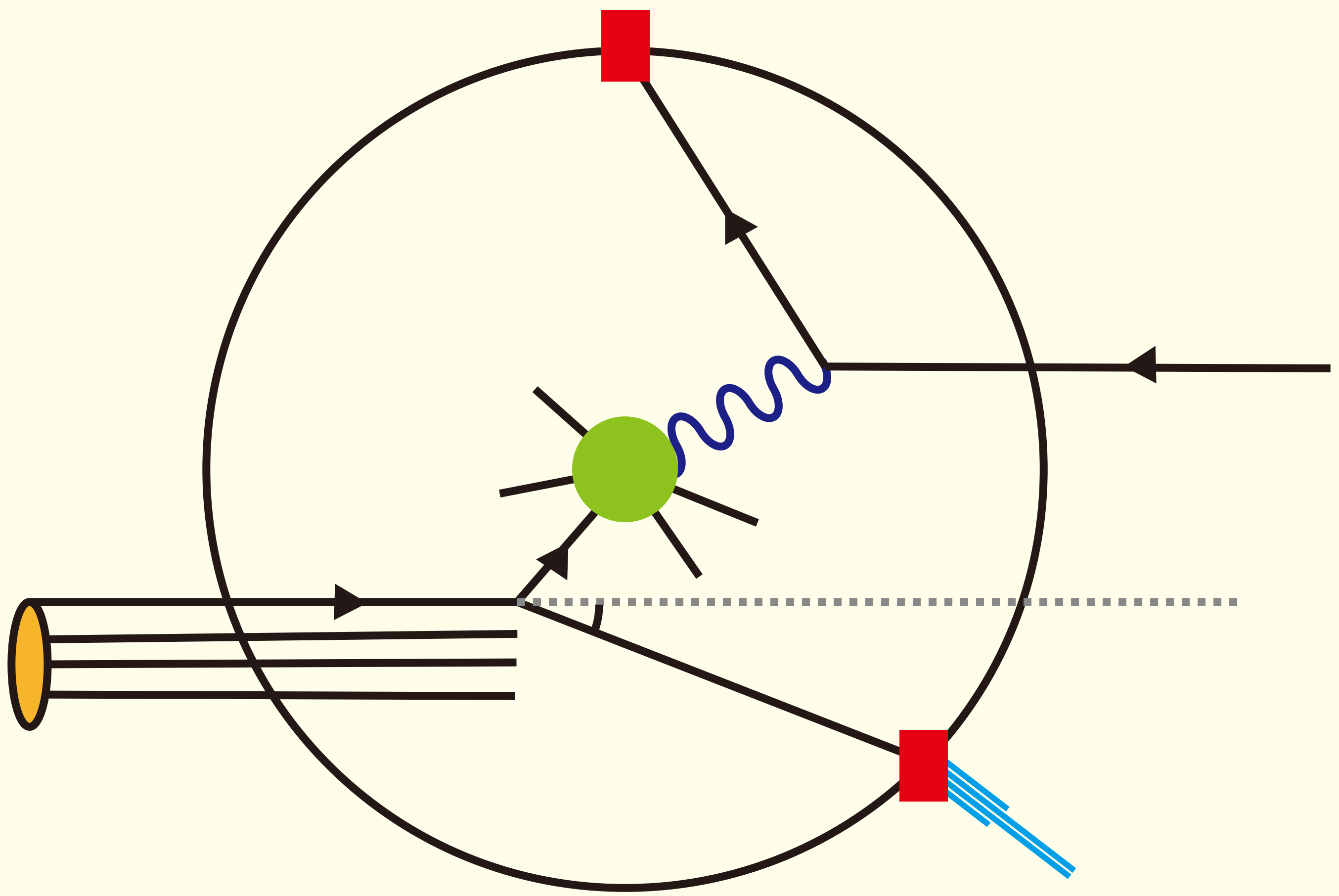


Nucleon internal dynamics will be imprinted in
the detailed structure of these correlation functions.



# How to probe NEEC

We first claim NEEC can be probed with



We first claim NEEC can be probed with

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

# How to probe NEEC

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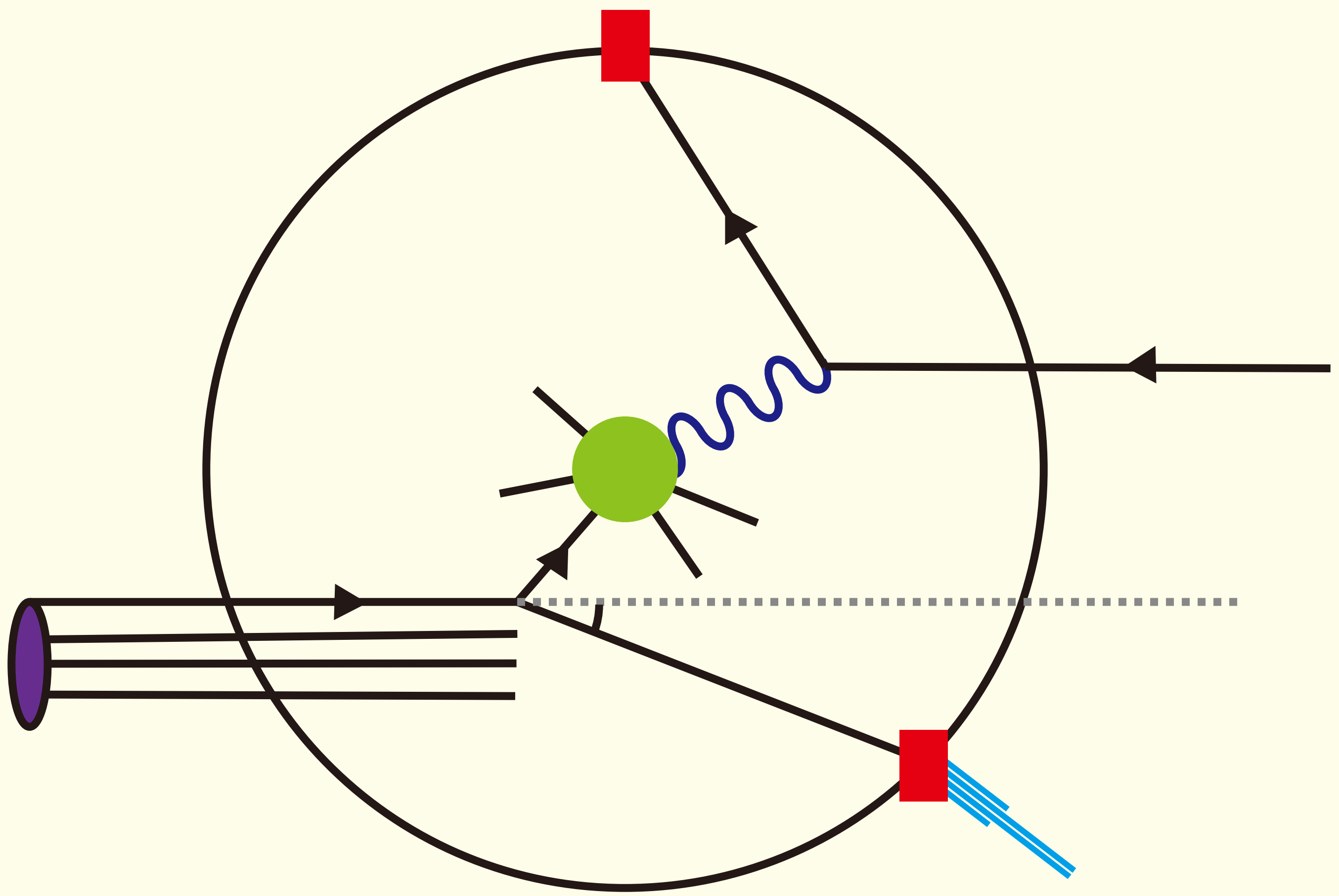


Inclusive

No jet, No hadron

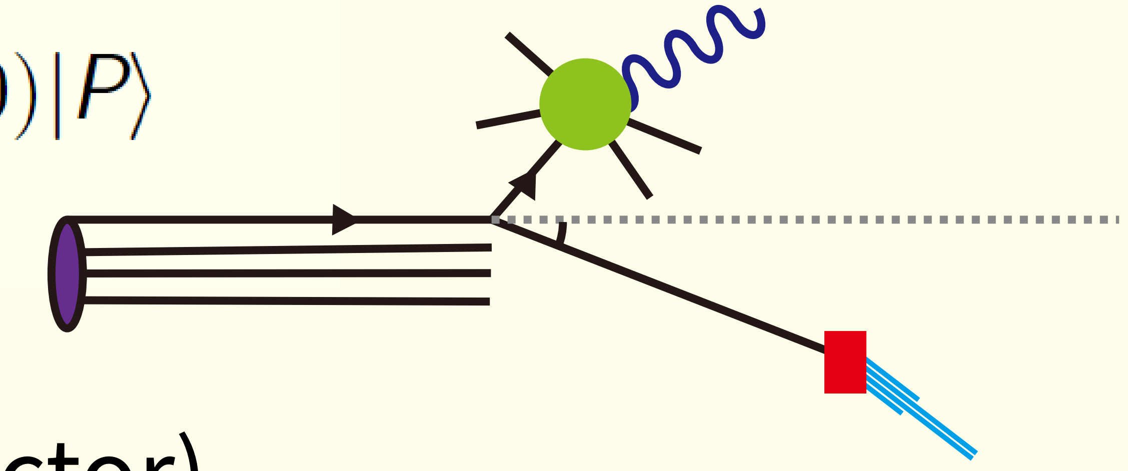
We first claim NEEC can be probed with

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

# Factorization

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

$$= \frac{\alpha^2}{Q^4} L_{\mu\nu}(Q^2, x_B) \int d^4x e^{iq\cdot x} \langle P | j^{\mu\dagger}(x)\, \hat{\mathcal{E}}(\theta)\, j^{\nu}(0) | P \rangle$$



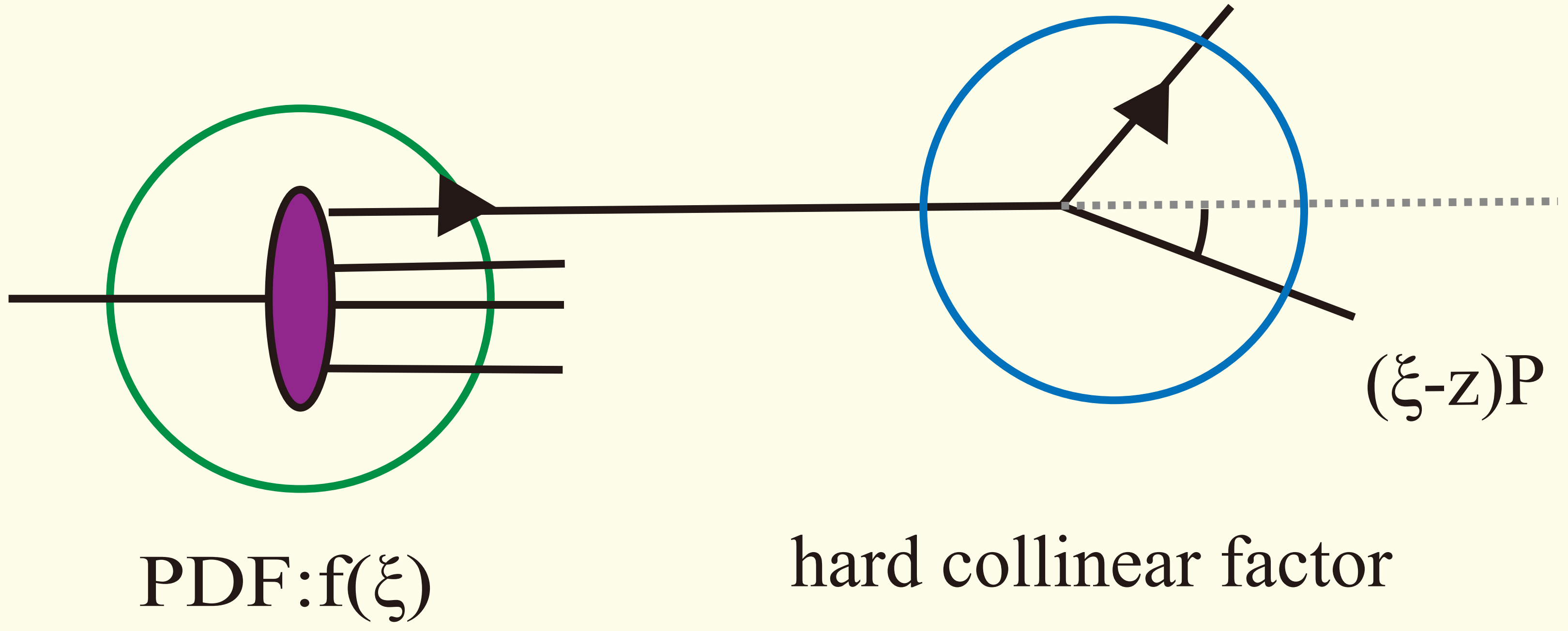
When we remove the Energy density operator (detector)
in collinear region, The weighted cross section will recover to the cross section of inclusive DIS.

$$\Sigma(Q^2, x_B, \theta) = \int_{x_B}^{1} \frac{dz}{z} \hat{\sigma}_i \left(\frac{x_B}{z}\right) f_{i,\mathrm{EEC}}(z, P^+\theta)$$

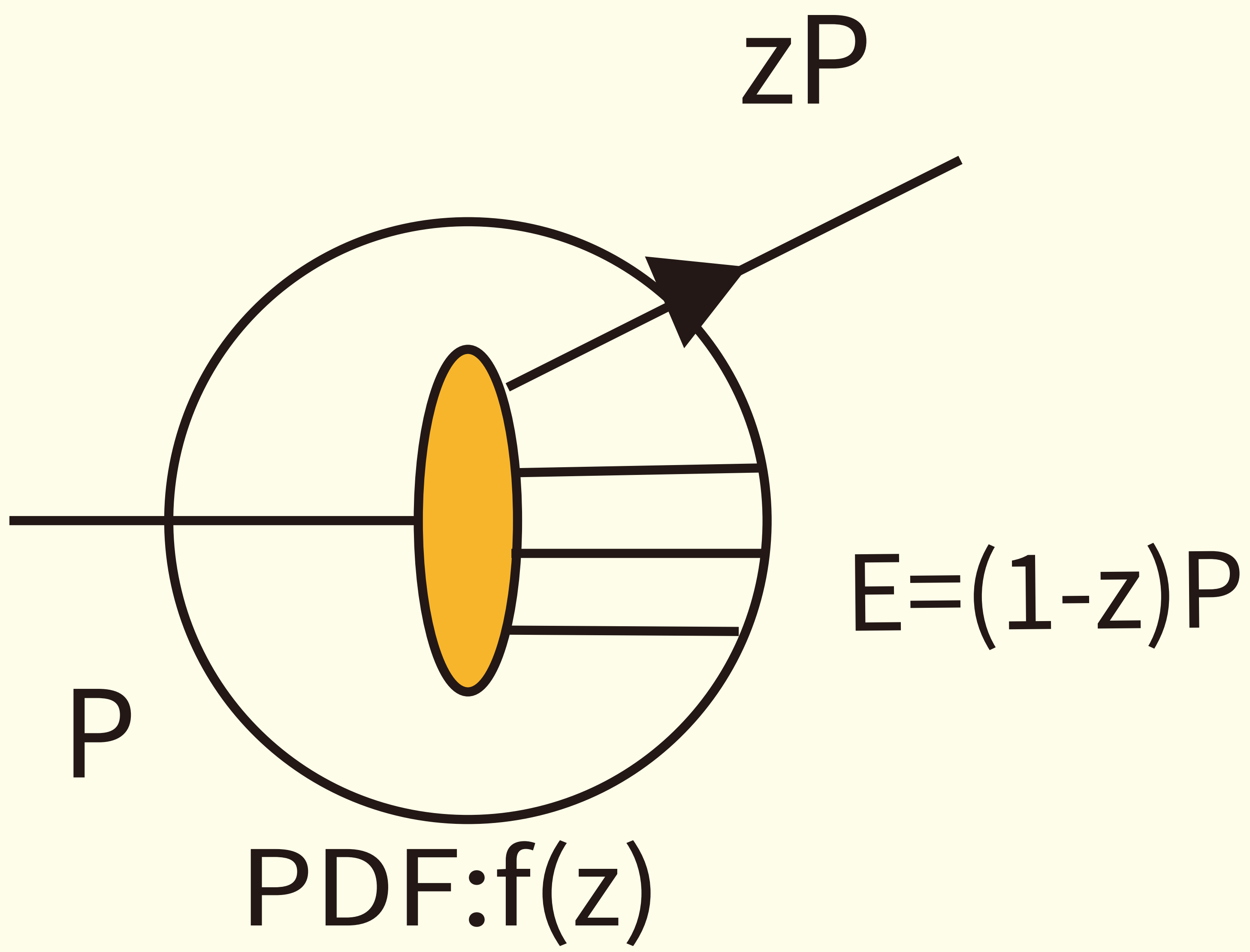
Unlinke TMD region, There will be gluon contribution.
From the consistency relation, NEEC will satisfy the DGLAP equation as PDF

# Factorization

When $\theta<<1$ but it is large enough that $\Lambda_{QCD} << \theta Q$, We can further split the collinear mode into the hard collinear mode ($C_1$), pt~ $\Lambda_{QCD}/Q$ and SCET$_2$ mode ($C_2$) pt~$\theta Q$ mode NEEC can be futher matched to pdf



# Factorization



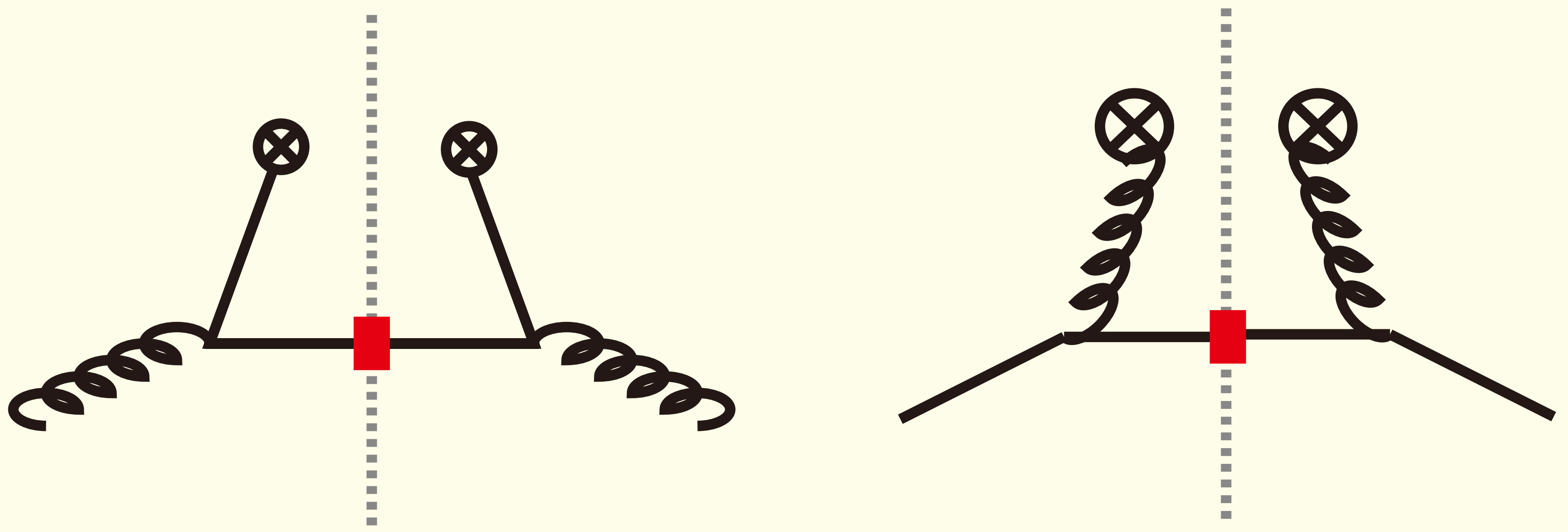

Since the angle in SCET₂ region will always be smaller than θ, it will contributes as

$$f^{(0)}_{i,\mathrm{EEC}}(z,\theta) = f_i(z) - z f_i(z)$$

# Factorization

The The LO contribution of hard collinear region will be zero, which can be noticed by the feynman graphs

The NLO contribution are calculated with graphs like these.

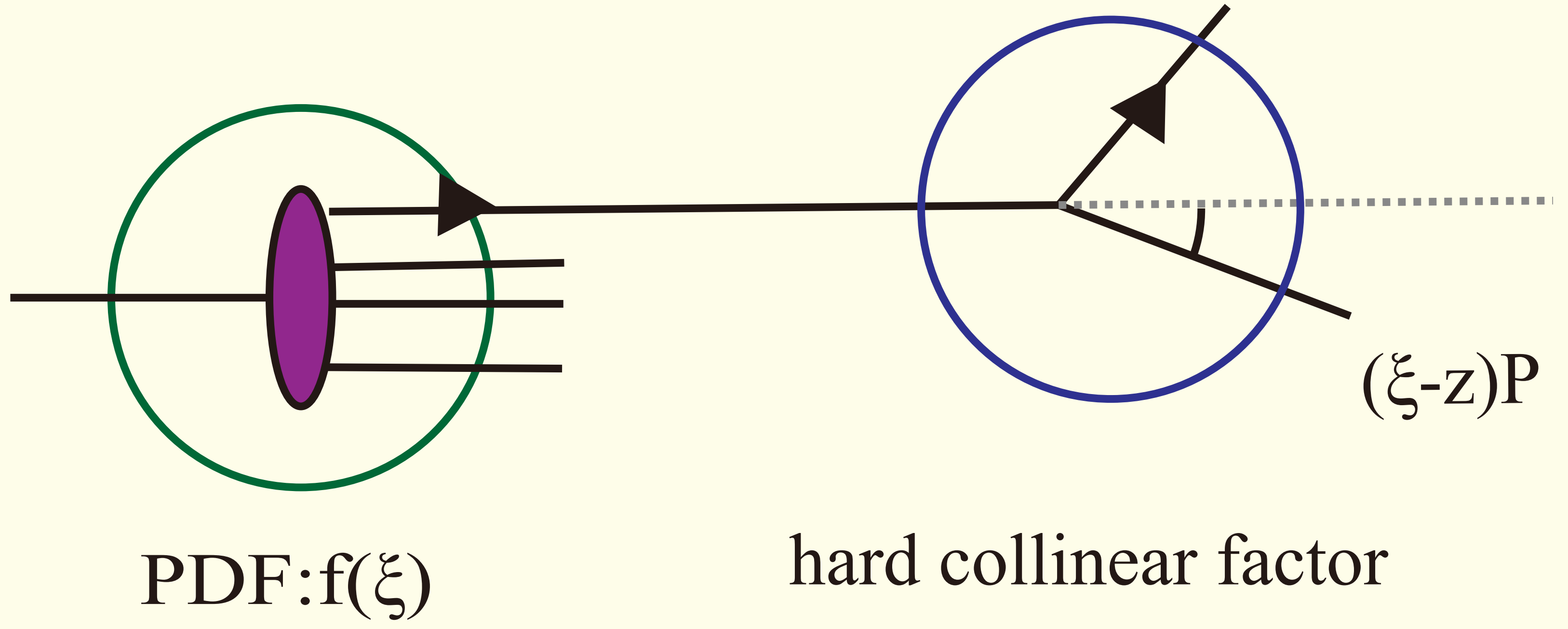


# Factorization

We can understand why this object is called NEEC, which is obvious from the fix order calculation.

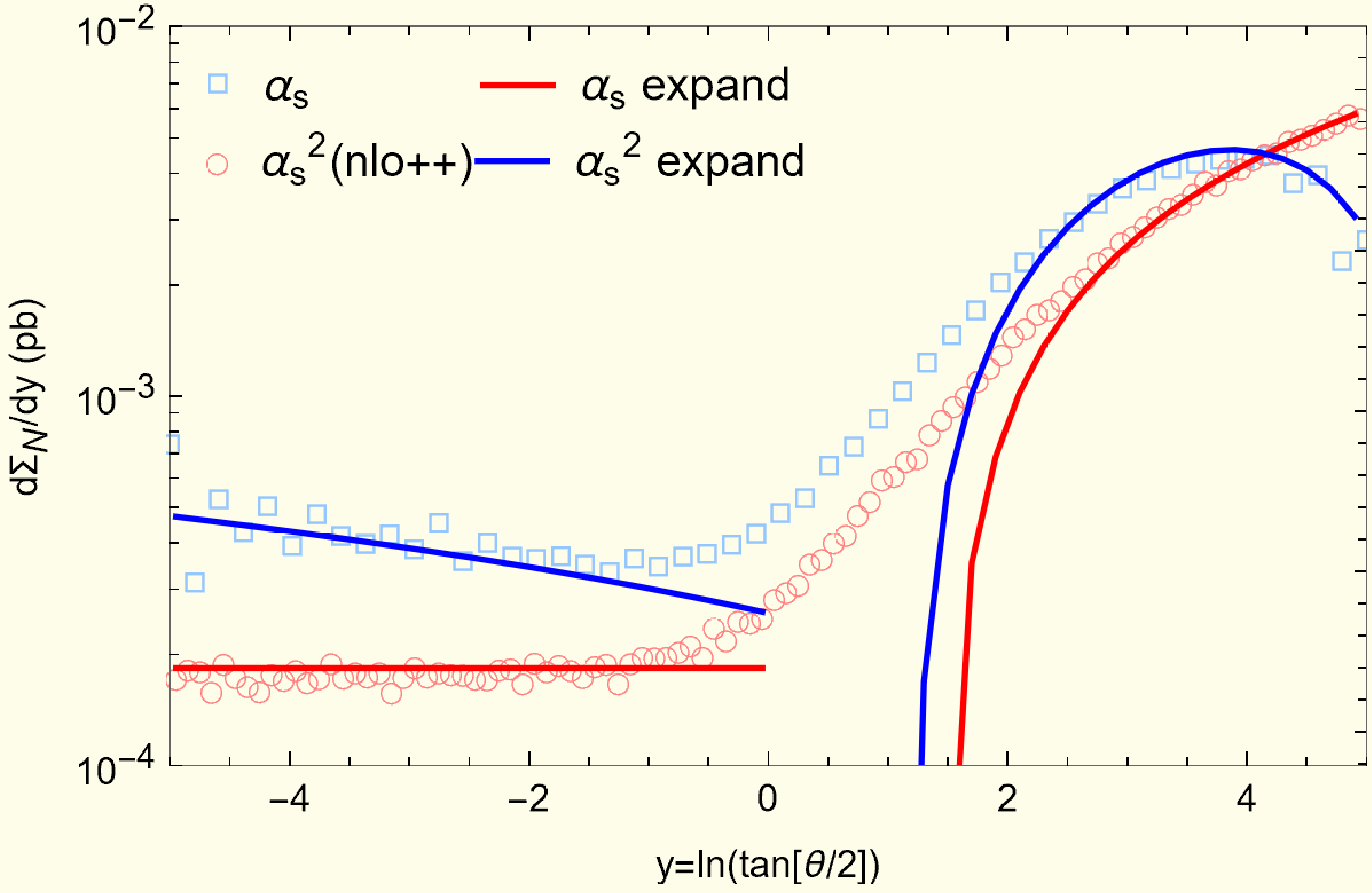
$$\frac{df^{(1)}_{\mathrm{EEC}}(z,\theta)}{d\theta} \propto \left[\left(1-\frac{z}{\xi}\right)\frac{1}{\theta}P\left(\frac{z}{\xi}\right)\right]\xi f(\xi)$$

final energy density        initial energy density



# Consistency check

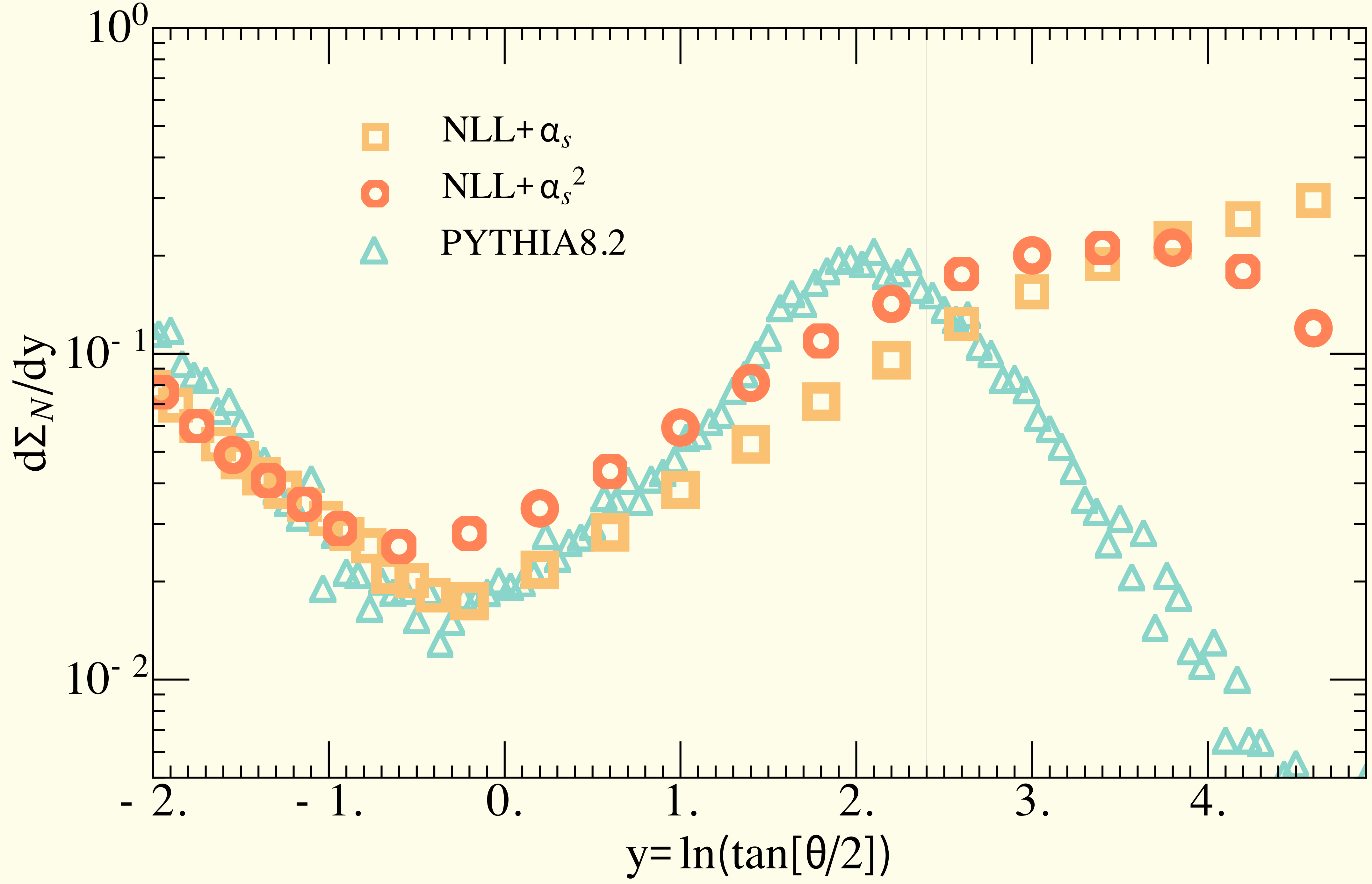
Compare the complete fixed order result with NLL resummed result expanded to $O(\alpha_s)$ and $O(\alpha_s^2)$




N=4
Ep=275GeV
El=18GeV
Q=20GeV

# Numerical result for NLL

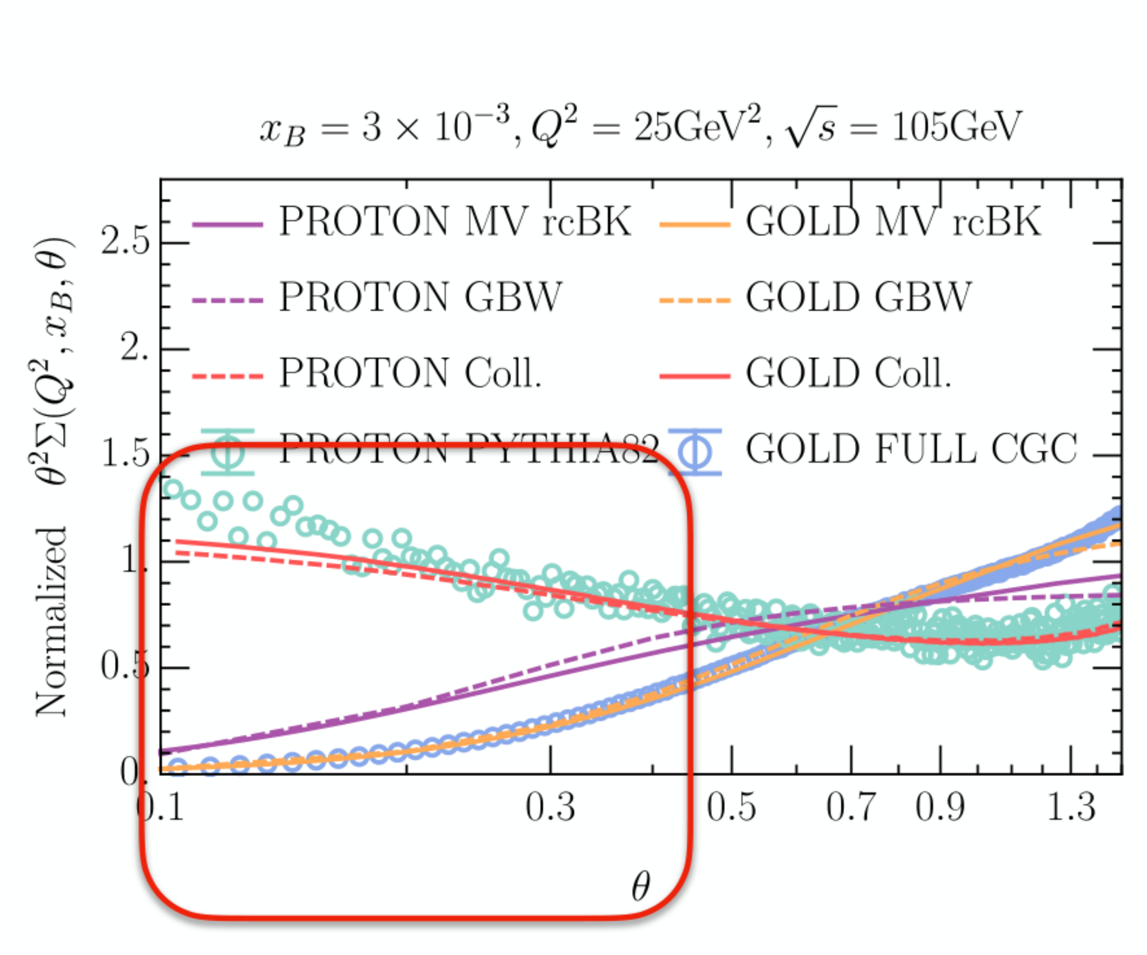
Comparison of the NLL + $\alpha_s$, NLL + $\alpha_s{}^2$ and the Pythia simulation at partonic level. Work in progress. We are still woring on TMD region.

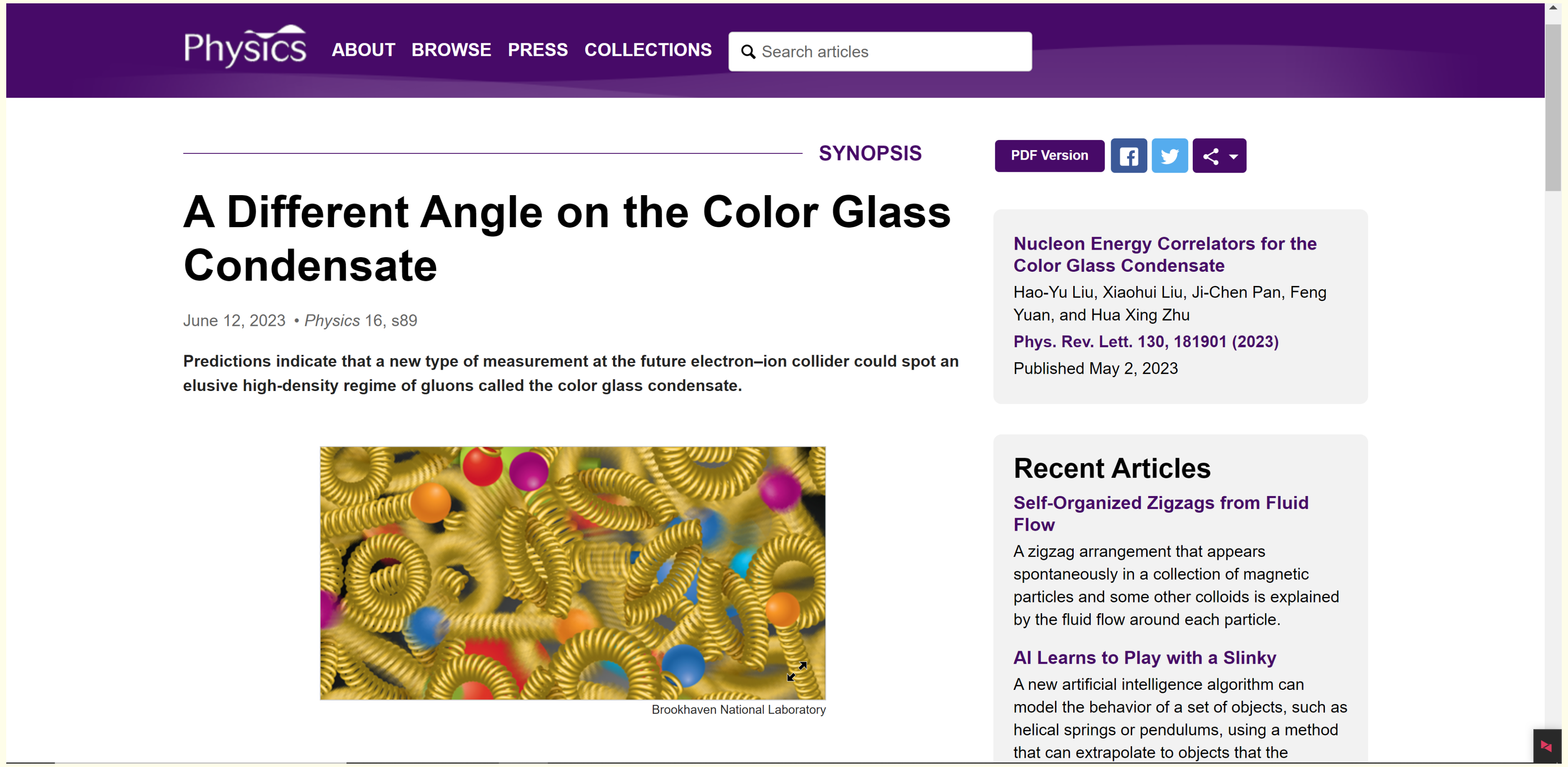



N=3
Ep=275GeV
El=18GeV
Q=10GeV

# Application to the gluon saturation

NEEC as evident portal to the onset of gluon saturation. We can define a turning point around which the slope of the distribution starts to switch its monotonicity.



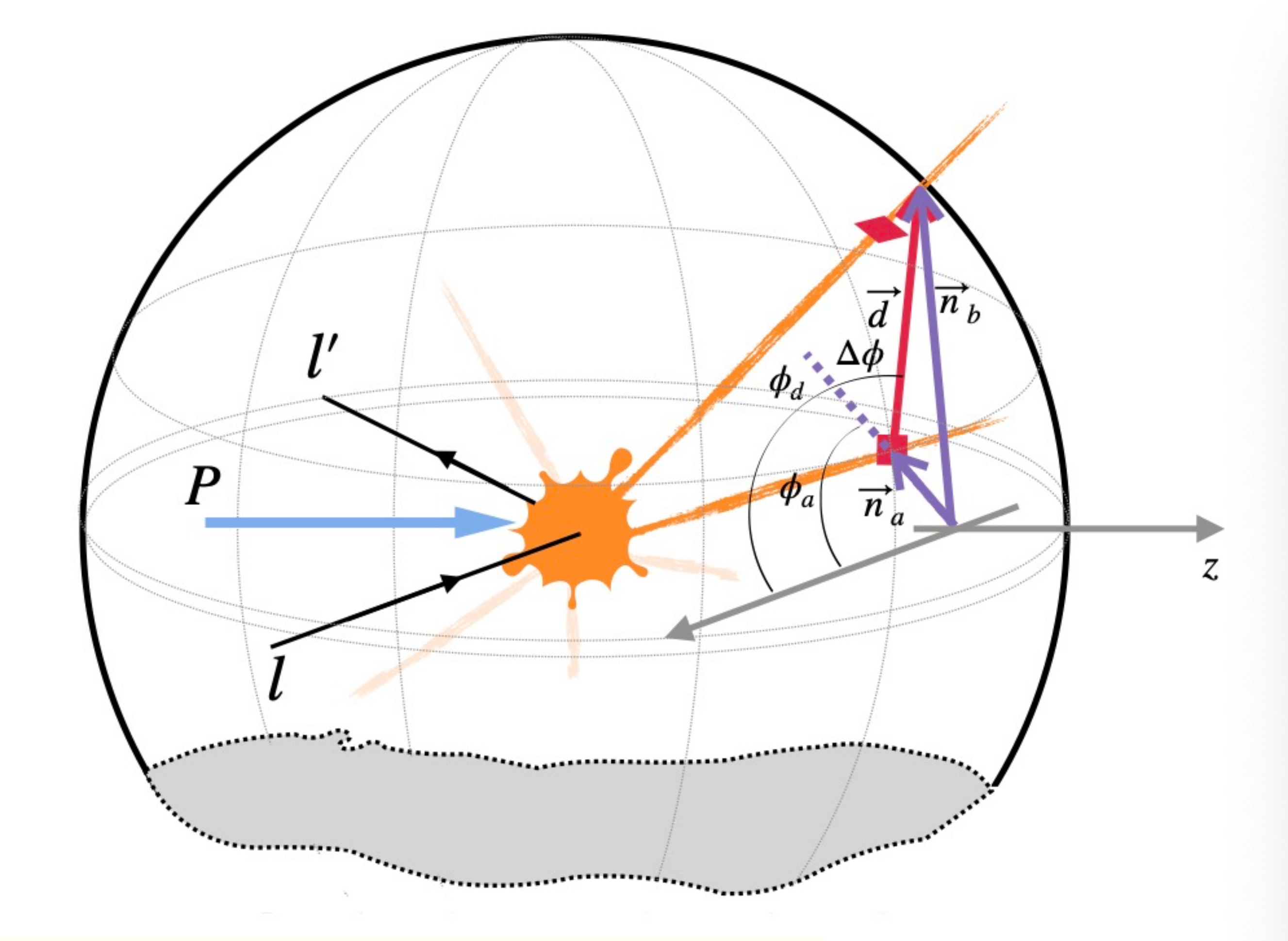

Highlighted by Physics synopsis

# Application to parton polarization

It can be proved for NE3C, When $\theta_b >> \theta_a$ and $1 >> \theta_a$

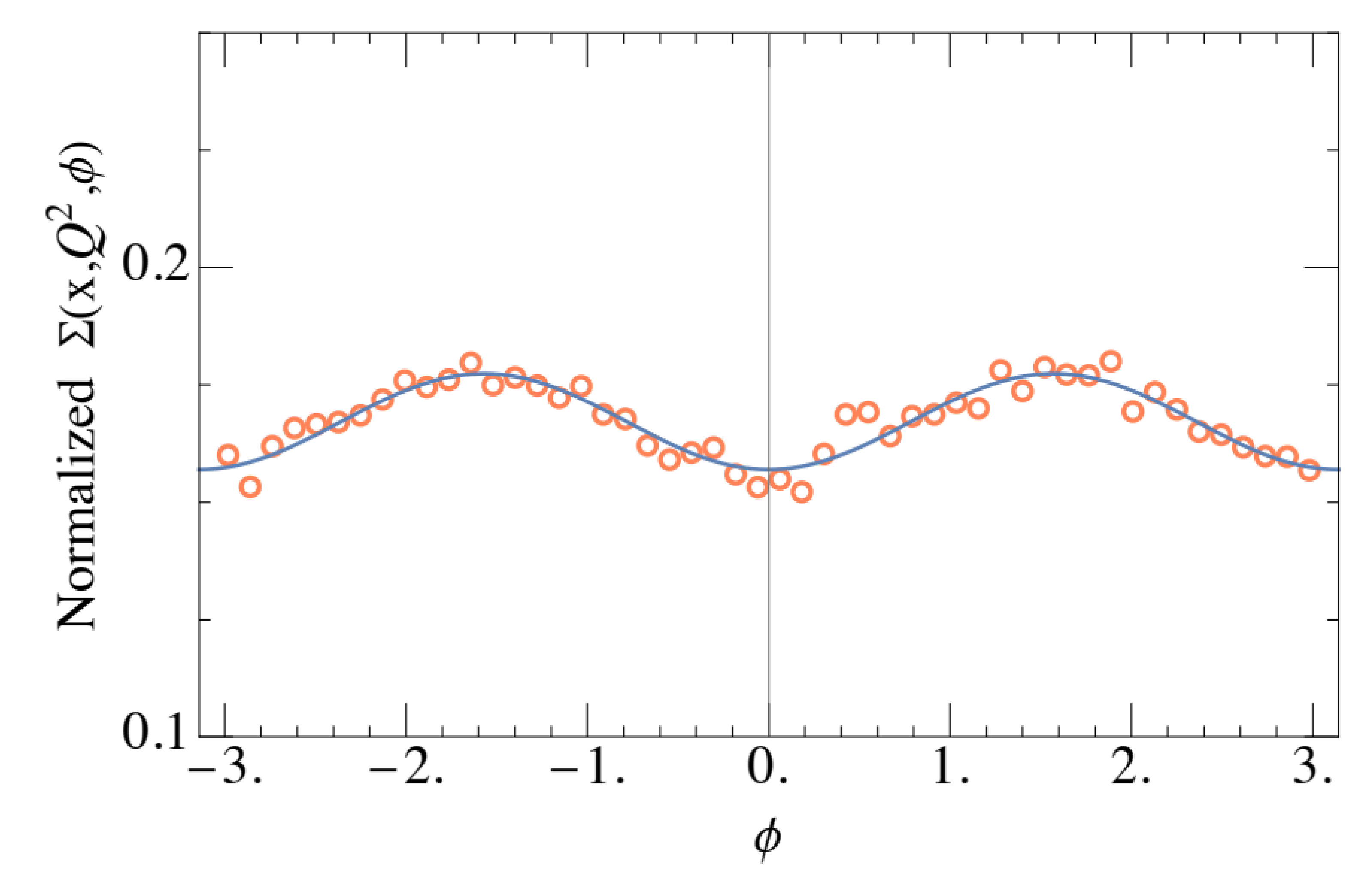
No soft/radiation contamination, cos(2ϕ) to all orders guaranteed by the lorentz structure.

$d_{g,EEC}$:helicity dependent gluon EEC




$$\Sigma(Q^2, x_B, \phi, \theta_{a,b}) \propto \int \frac{dz}{z}\left[\sum_{i=q,g} H_i(y, z, \theta_b)\frac{x_B}{z} f_{i,EEC}\left(\frac{x_B}{z}, \theta_a\right) + \frac{1}{2}\Delta H_g(z, y, \theta_b)\frac{x_B}{z} d_g(\theta_a) cos(2\phi)\right]$$

# Application to parton polarization

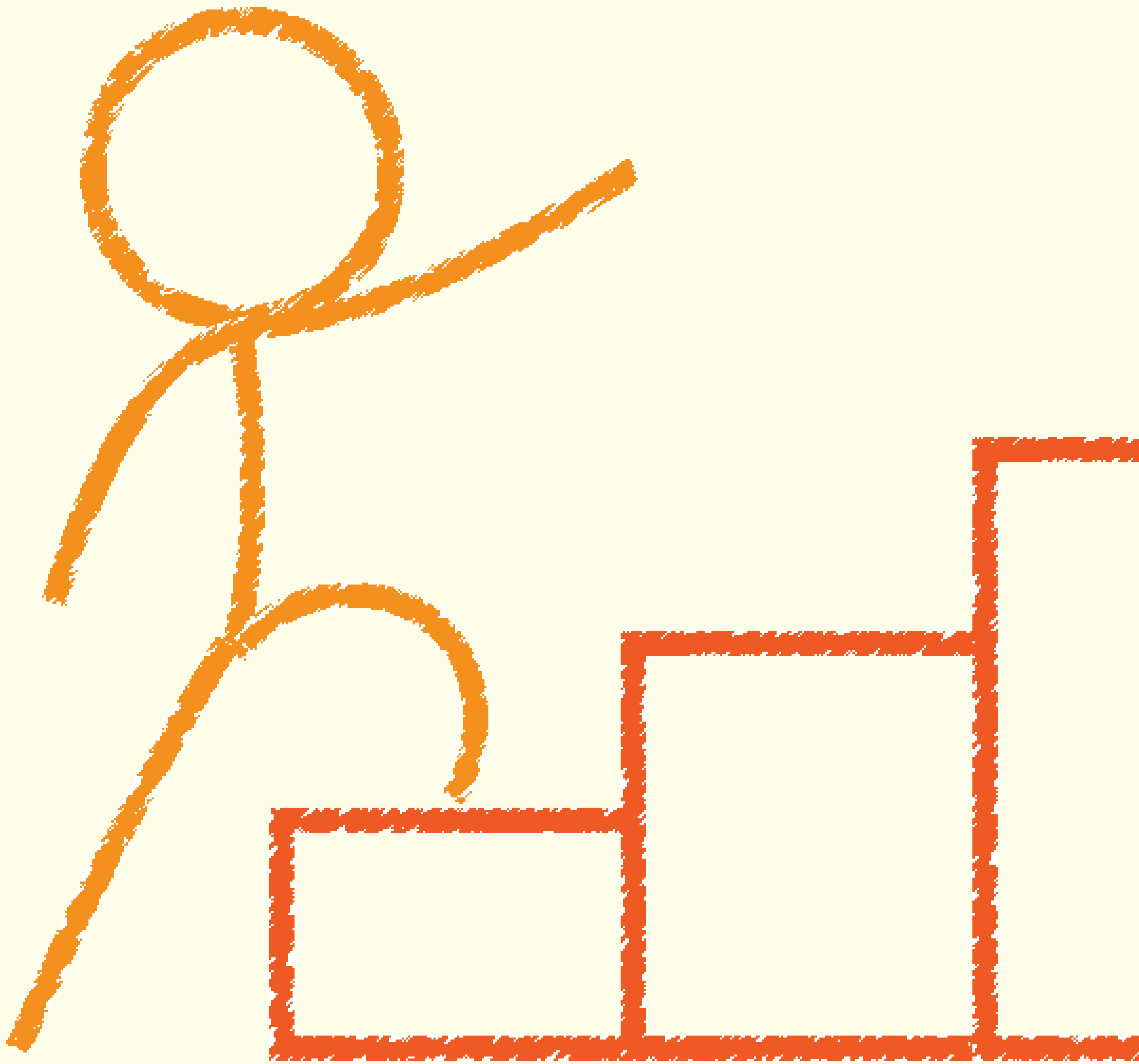



NLO
El=18GeV
Ep=275GeV
$x_B$=0.03
Q=10GeV
0.3>$\theta_a$>0.1
0.02>$\theta_b$>0.005

With explicit cos(2ϕ) modulation, We can estimate the “amount” of linearly polarzed gluons.

# Conclusion

NEEC is a brand new description of the nucleon structures and QCD dynamics.
The factorization therom is ready.
There can be  many things to do with NEEC.



# Thank You