# Probing linearly polarized gluon inside nucleon through Nucleon Energy Correlators

**Xiao Lin Li**

Beijing Normal University

In collaboration with Xiaohui Liu, Feng Yuan, Hua Xing Zhu

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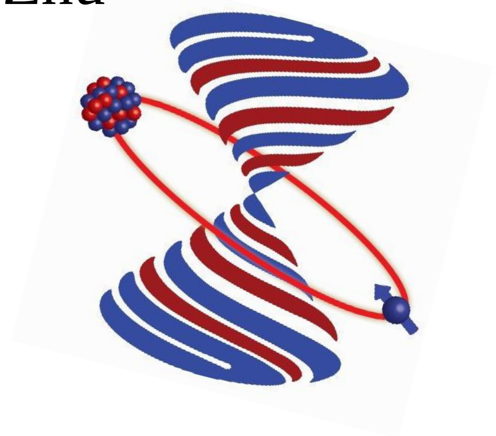
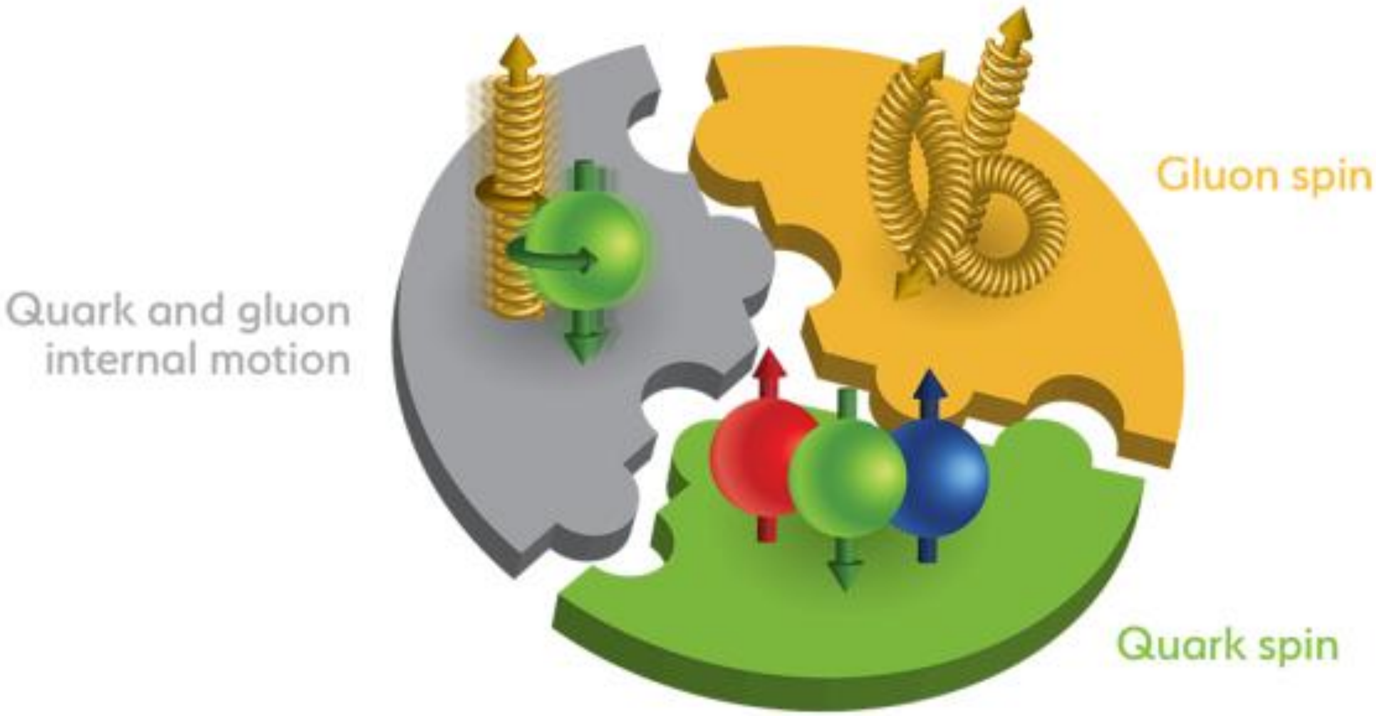


# Outline

1. Motivation
   - concept of linearly polarized gluon
   - conventional probe using TMD-PDFs
2. Measurement of Nucleon Energy-Energy Correlator
3. Numerical result
4. Summary

# Nucleon Structure



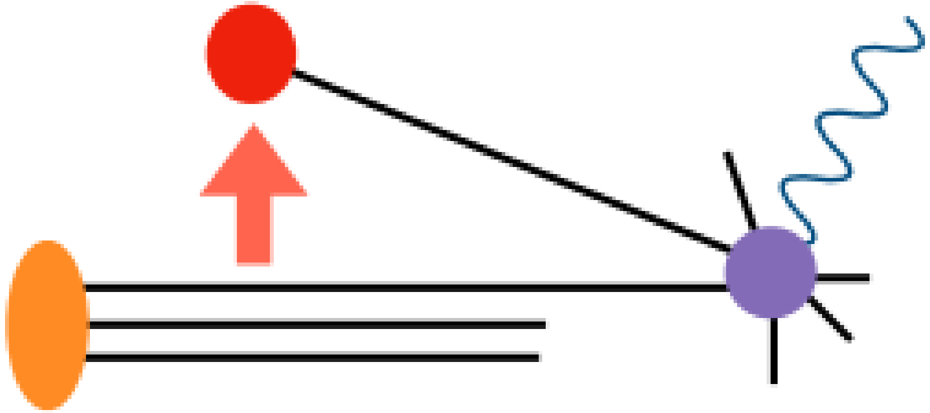

Major focus of EIC, EicC

- ✓ Spin components
- ✓ Mass decomposition
- ✓ …

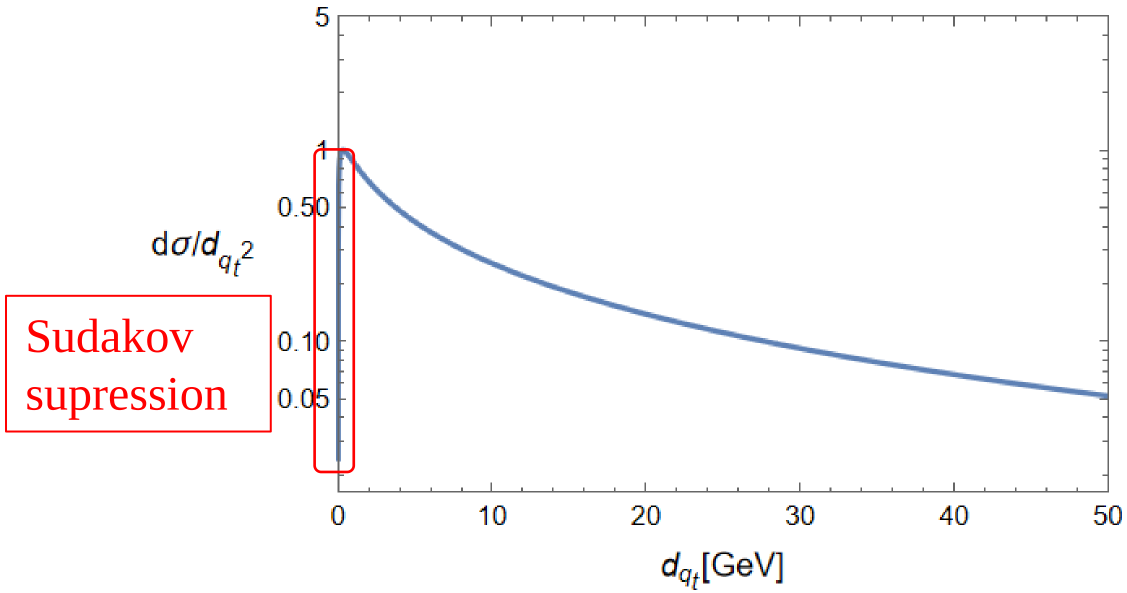
# Conventional approach to nucleon structure

- extract Transverse Momentum Dependent (TMD)-PDFs

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



Semi-Inclusive DIS



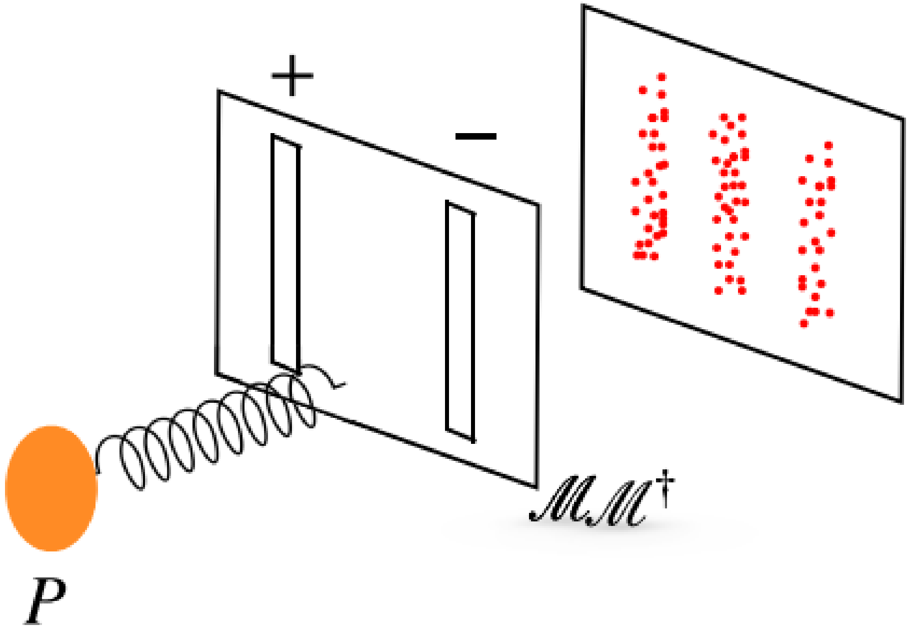

exponentially suppressed in non-pert. region when Q is large $e^{-\frac{Q^2}{q_t^2}}$

# Conventional approach to nucleon structure

- Gluon TMD-PDFs

| | | Gluon Operator Polarization | |
|---|---|---|---|
| | | Un-Polarized | Helicity 2 |
| Nucleon Polarization | Un-Polarized | $f_1^g =$ Unpolarized | $h_1^{\perp g} = \; + \;$ Linearly Polarized |

From TMD Handbook



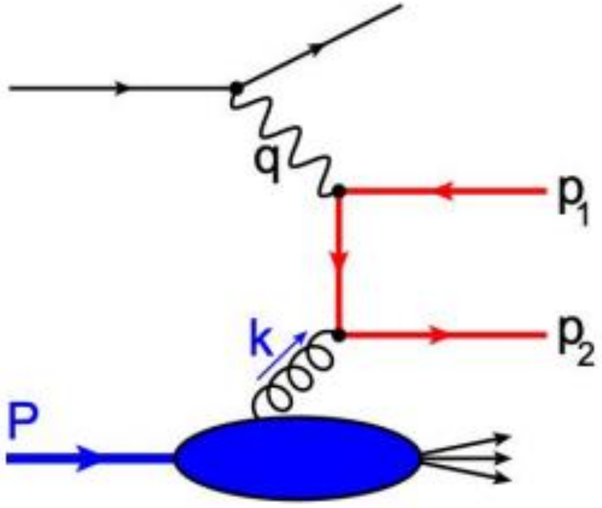

- interference of positive and negative helicities

$$|e^{i\phi} + e^{-i\phi}|^2 \rightarrow 2 + 2\cos(2\phi)$$

Un-polarized PDF    linearly polarized PDF

# Conventional approach to nucleon structure

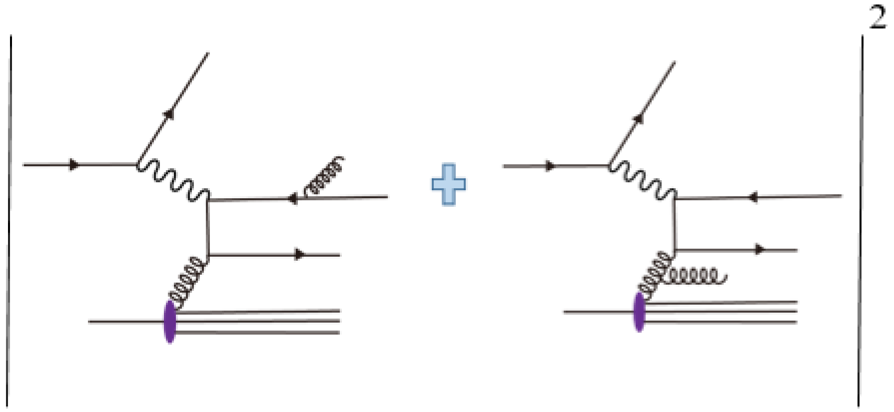
- conventional probe of the linearly polarized gluon is to study the dijet production in DIS process




$$\boxed{\frac{d\sigma}{dPS} = A\, f_1^g(x, p_T^2) + B\, h_1^{\perp g}(x, p_T^2)\, \mathbf{cos(2\phi)}}$$

- experimentally, by looking for $\cos(2\phi)$ signal, we can extract gluon PDF

- However, at high orders, the naïve factorization break down



- ✓ This gives arise to the eikonal factor

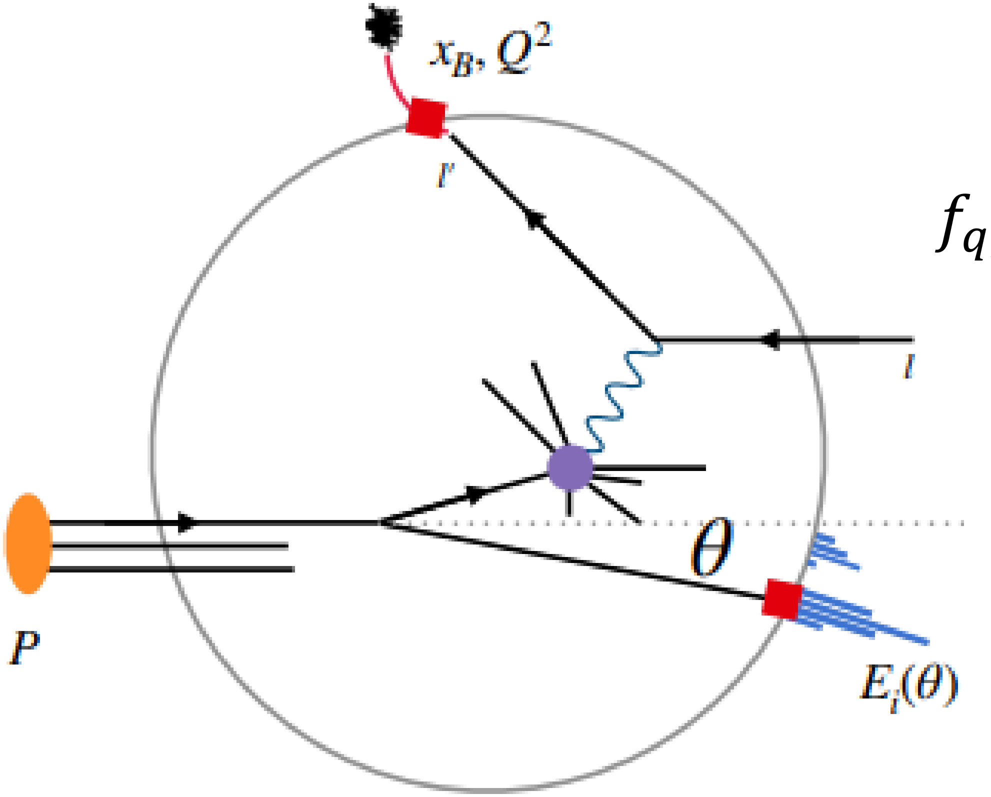
[Y. Hatta, et al. PRD, 104,054037 (2021)]

$$\frac{1}{P_J \cdot k P \cdot k} \propto \Sigma_n c_n \cos n\phi$$

- ✓ Contaminate the signal

# Nucleon Energy-Energy Correlators(NEEC)

X. Liu and H.X. Zhu PRL,130, 091901 (2023)



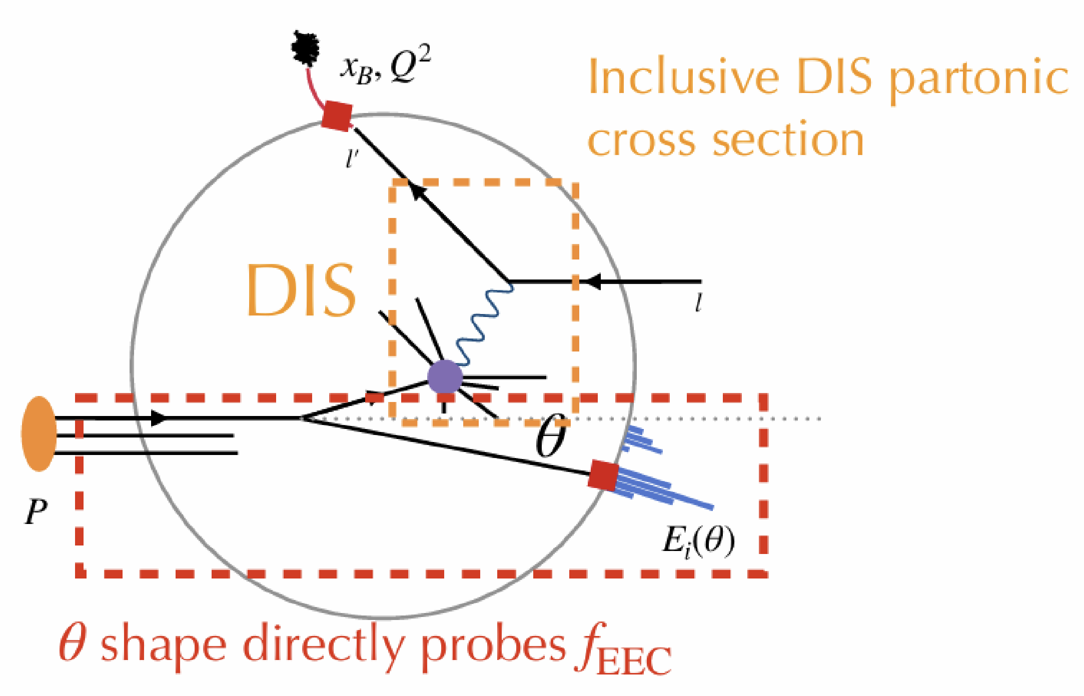

see xiao hui's talk on Fri.

$$f_{q,EEC}(z,\theta) = \int \frac{dy^-}{2\pi} e^{-izP^+y^-} \left\langle P \middle| \bar{\psi}(y^-) \frac{\gamma^+}{2} \hat{\mathcal{E}}(\theta) \psi(0) \middle| P \right\rangle$$

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

- Energy correlator in the forward region
- weighted by $E_i$, insensitive to soft radiations ,e.g. no Sudakov suppression, which is very different from TMD

# Nucleon Energy-Energy Correlators




- When $\theta Q \ll Q$, DIS type factorization

$$\sum\nolimits_N (Q^2, \theta) = \int u^{N-1}\, \hat{\sigma}(u, Q^2, \mu) f_{EEC}\left(N, \ln\frac{\theta Q}{u\mu}\right)$$

- Derived by SCET

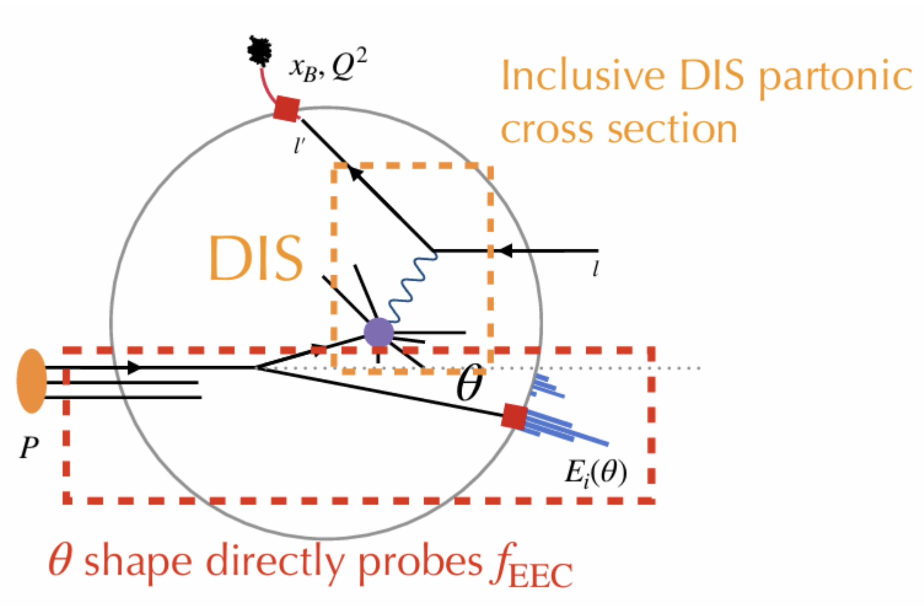
H.T. Cao, X.H. Liu and H.X. Zhu, PRD, 107,114008(2023)

- Rigorous QCD derivation by relating to the fracture fuction through sum rules

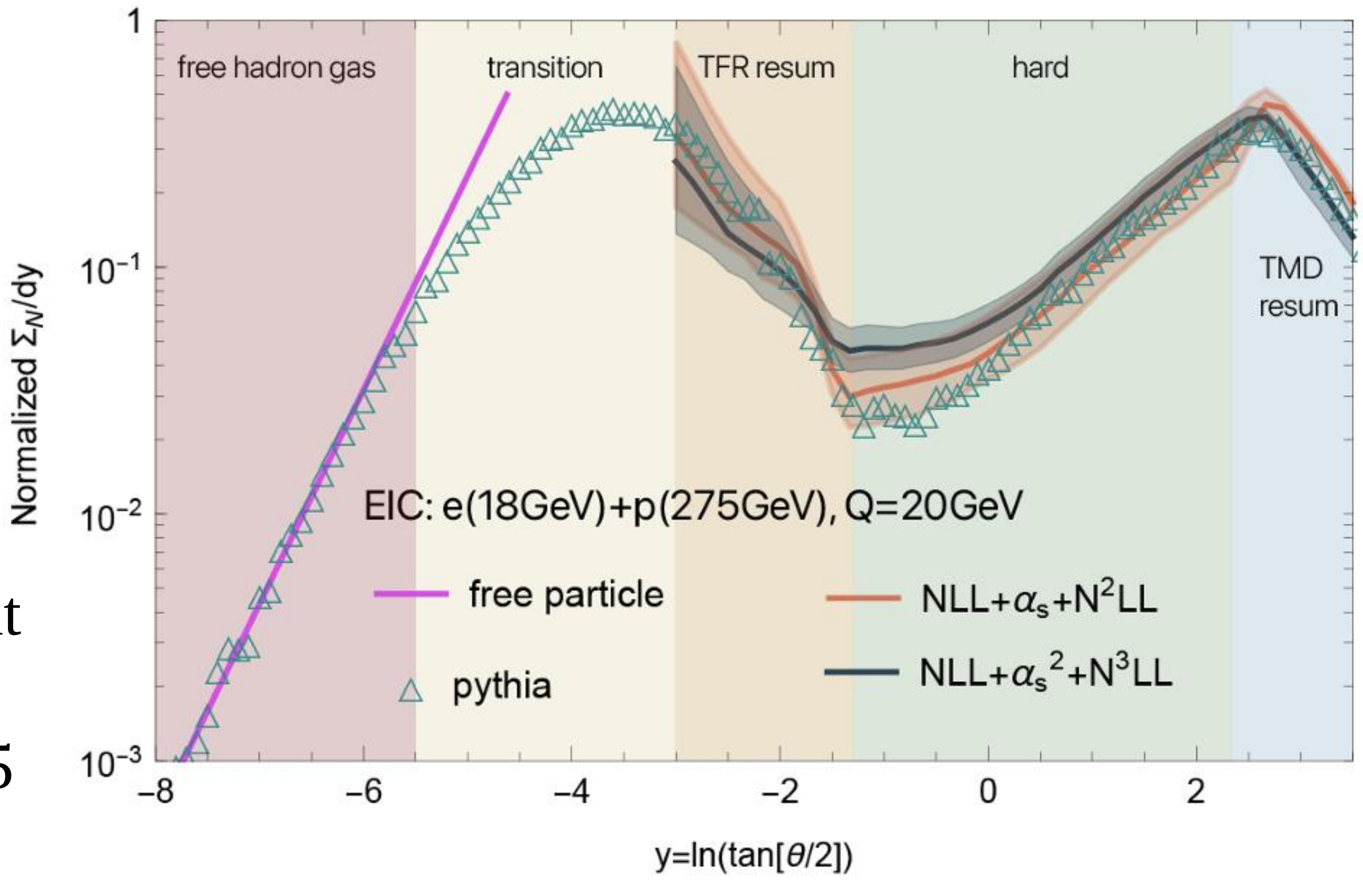
K.B. Chen, J.P. Ma and X.B. Tong, JHEP, 2406.08559(2024)

# Nucleon Energy-Energy Correlators

H.T. Cao, H.T. Li et al. PRD,109, 096004 (2024)

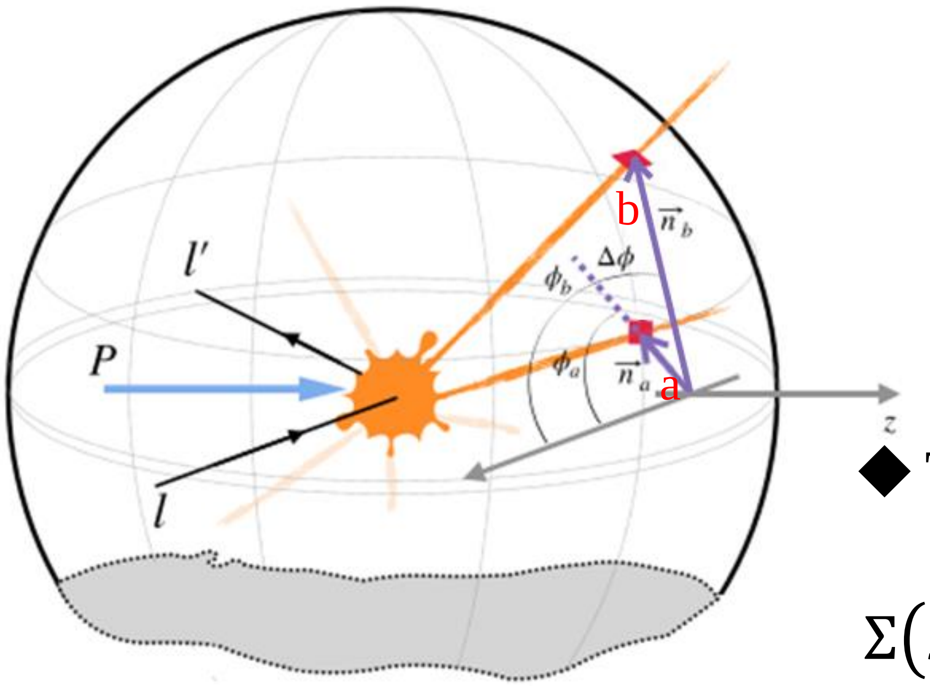



Target Fragmentation Region(TFR)

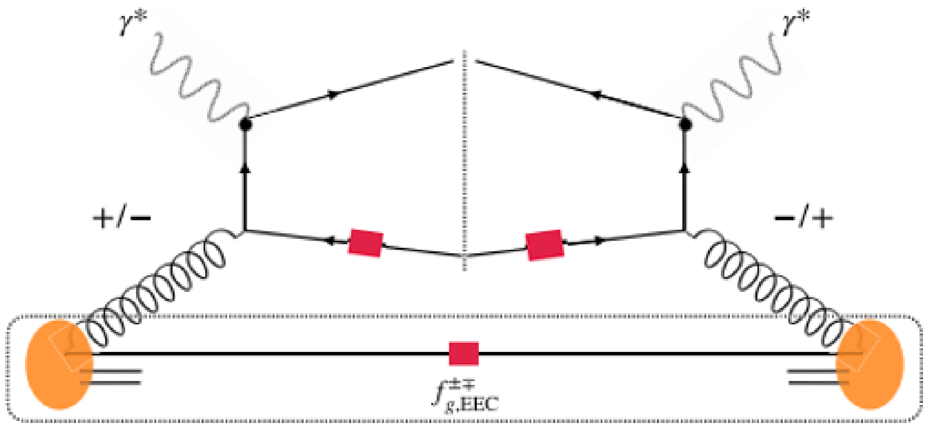



- the theoretical predictions are consistent with the pythia fitting results
- Not that forward in TFR region,$y \lesssim 2.5$

# Nucleon Energy-Energy Correlators




$$\boxed{\overrightarrow{n_m} = \sin\theta_m(\cos\phi_m, \sin\phi_m)}$$



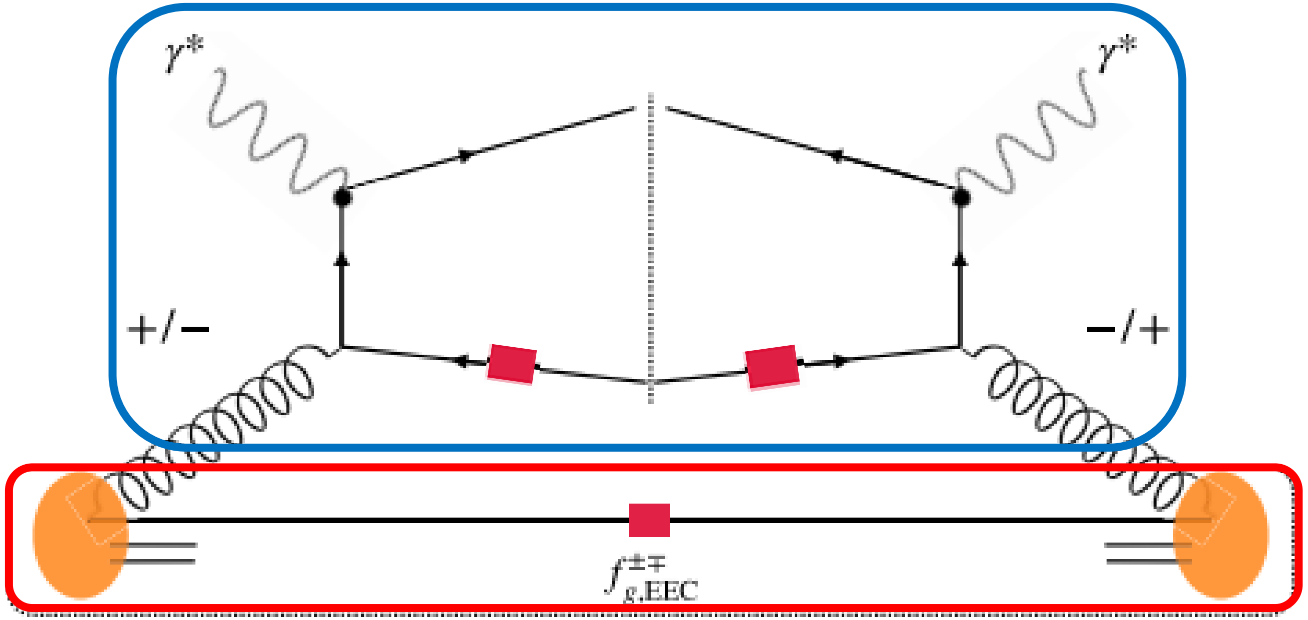

◆ The energy-weighted cross section $Q\theta_a \sim \mathcal{O}(\Lambda_{QCD})$

$$\Sigma(x_B, Q^2, \cos\theta_{a,b}, \phi) = \sum_{ab} \int d\sigma(x_B, Q^2) \frac{E_a}{E_P}\frac{E_b}{E_P} \delta(\overrightarrow{n_a} - \overrightarrow{n_i})\, \delta(\overrightarrow{n_b} - \overrightarrow{n_j}) \mathcal{F}(\phi; \overrightarrow{n_{a,b}})$$

- the measurement in the Breit frame
- the azimuthal angle $\phi$ between detectors a and b
- extract linearly polarized PDFs, demand one of the angle to be very small

# Nucleon Energy-Energy Correlators

- NEEC factorization




- $\theta_a \ll \theta_b$ , the cross section $\Sigma_{\mu\upsilon}$

$$\Sigma_{\mu\upsilon} = \frac{y^2}{16\pi Q^2}\int d\Phi_X\, H_q f_{q,EEC}(x,\overrightarrow{n_a}) + \boxed{H_{g,\alpha\beta}}\boxed{f^{\alpha\beta}_{g,EEC}(x,\overrightarrow{n_a})}$$

- measure the energy flow along the detector b

# Nucleon Energy-Energy Correlators

- the gluon NEEC operator definition

$$\boldsymbol{f}^{\alpha\beta}_{g,EEC}(\boldsymbol{x},\overrightarrow{\boldsymbol{n}_a}) = \int \frac{dy^-}{4\pi x P^+} e^{-ixP^+\frac{y^-}{2}} \langle P | \mathcal{F}^{+\alpha}(y^-)\hat{\varepsilon}(\overrightarrow{n_a})\mathcal{F}^{+\beta}(0) | P \rangle$$

- the most general parametrization of the gluon NEEC

$$\boldsymbol{f}^{\alpha\beta}_{g,EEC}(\boldsymbol{x},\overrightarrow{\boldsymbol{n}_a}) = -g_T^{\alpha\beta} \boldsymbol{f}_{g,EEC} + \left(\frac{n^\alpha_{a,T} n^\beta_{a,T}}{n^2_{a,T}} - \frac{g_T^{\alpha\beta}}{2}\right) \boldsymbol{d}_{g,EEC}$$

- ✓ $\mathcal{F}$ : gauge field strength tensor
- ✓ *as obvious from this decomposition*

$$\epsilon_{\pm,\alpha}\epsilon^*_{\pm,\beta} f^{\alpha\beta}_{g,EEC} = \boldsymbol{f}_{g.EEC}$$

$$\epsilon_{\mp,\alpha}\epsilon^*_{\pm,\beta} f^{\alpha\beta}_{g,EEC} = \frac{1}{2} e^{\mp 2i\phi_a} \boldsymbol{d}_{g,EEC}$$

- hard coefficient can also be written in the similar form

$$\boldsymbol{H}_{i,\alpha\beta} = -g_T^{\alpha\beta} A(z,c_b) + \left(\frac{n^\alpha_{b,T} n^\beta_{b,T}}{n^2_{b.T}} - \frac{g_T^{\alpha\beta}}{2}\right) B(z,c_b) + \boxed{\cdots}$$

- ✓ No contribution.
  when contract with the NEEC is vanish

# Nucleon Energy-Energy Correlators

- take this form,

$$\Sigma_{\mu\upsilon} = \frac{y^2}{16\pi Q^2}\int d\Phi_X\, H_q f_{q,EEC}(x,\overrightarrow{n_a}) + \boldsymbol{H}_{g,\alpha\beta}\boldsymbol{f}^{\alpha\beta}_{g,EEC}(x,\overrightarrow{n_a})$$

- we can show that the only possibility to get $\cos(2\phi)$ through these tensor contraction

$$f^{\alpha\beta}_{g,EEC}(x,\overrightarrow{n_a}) = -g_T^{\alpha\beta} f_{g,EEC} + \left(\frac{n^\alpha_{a,T} n^\beta_{a,T}}{n^2_{a,T}} - \frac{g_T^{\alpha\beta}}{2}\right) d_{g,EEC}$$

Only about $\phi_a$

$$\boldsymbol{H}_{i,\alpha\beta} = -g_T^{\alpha\beta} A(z,c_b) + \left(\frac{n^\alpha_{b,T} n^\beta_{b,T}}{n^2_{b.T}} - \frac{g_T^{\alpha\beta}}{2}\right) B(z,c_b)$$

Only about $\phi_b$

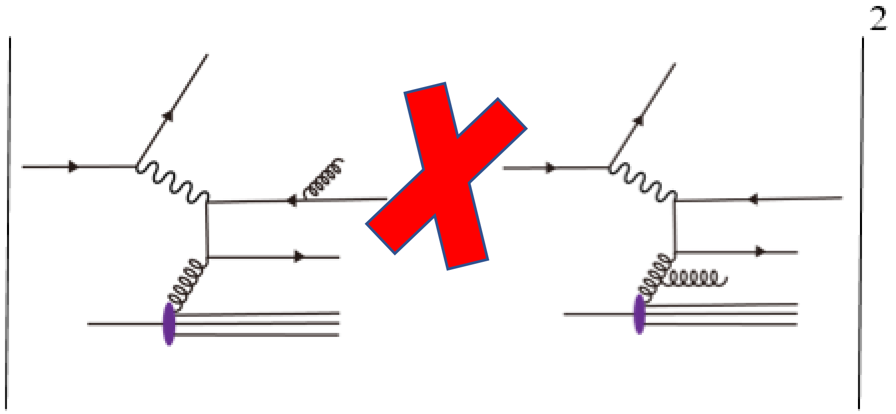
# Nucleon Energy-Energy Correlators

- To all orders, the cross section fulfills the general form

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

$z \equiv \frac{x_B}{x}, \frac{x_B}{z}$ originated from $\frac{E_b}{E_P}$

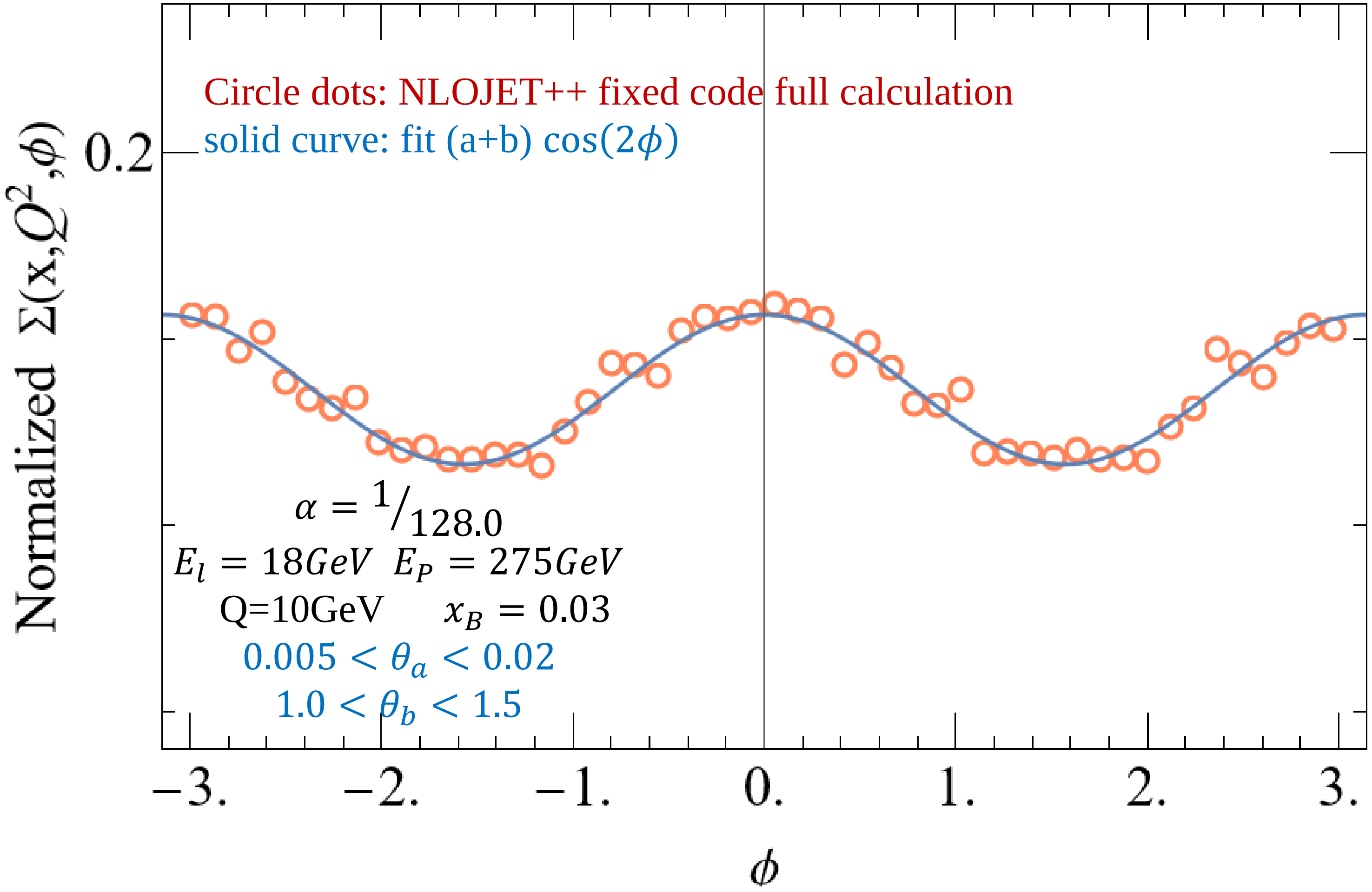
- Because of we do not have soft radiation, this *$cos(2\phi)$* structure hold to all orders

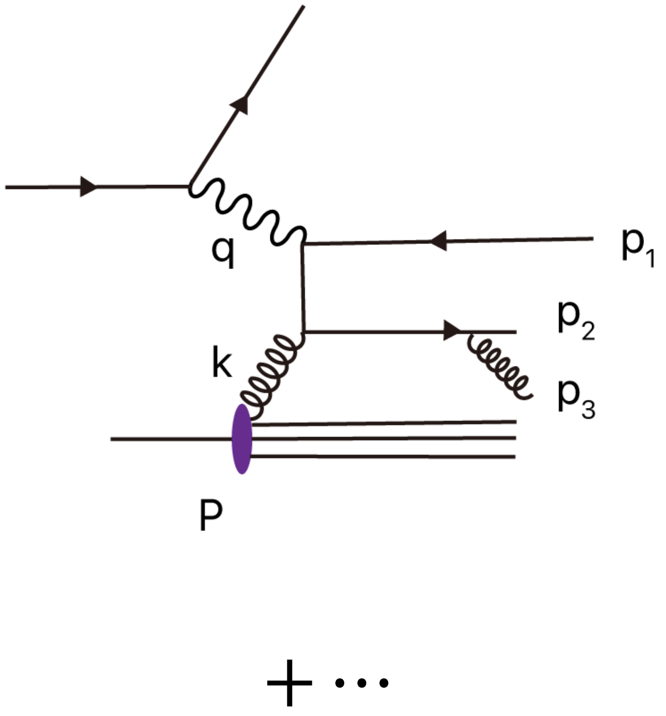



- will not spoil $\cos(2\phi)$ signature
- This is very different TMD

# Numerical result

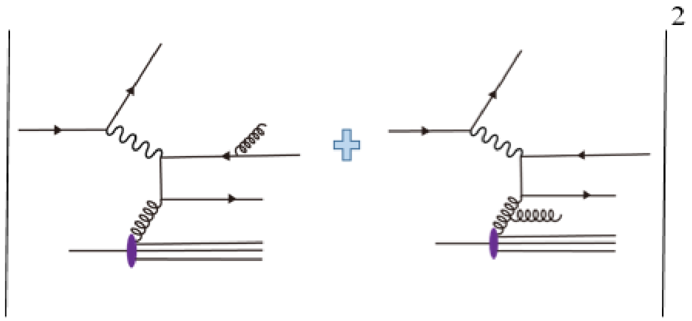
- Here we validate our factorization theory of the all orders structure using perturbative calculation based on NLOJET++ fixed code at LO



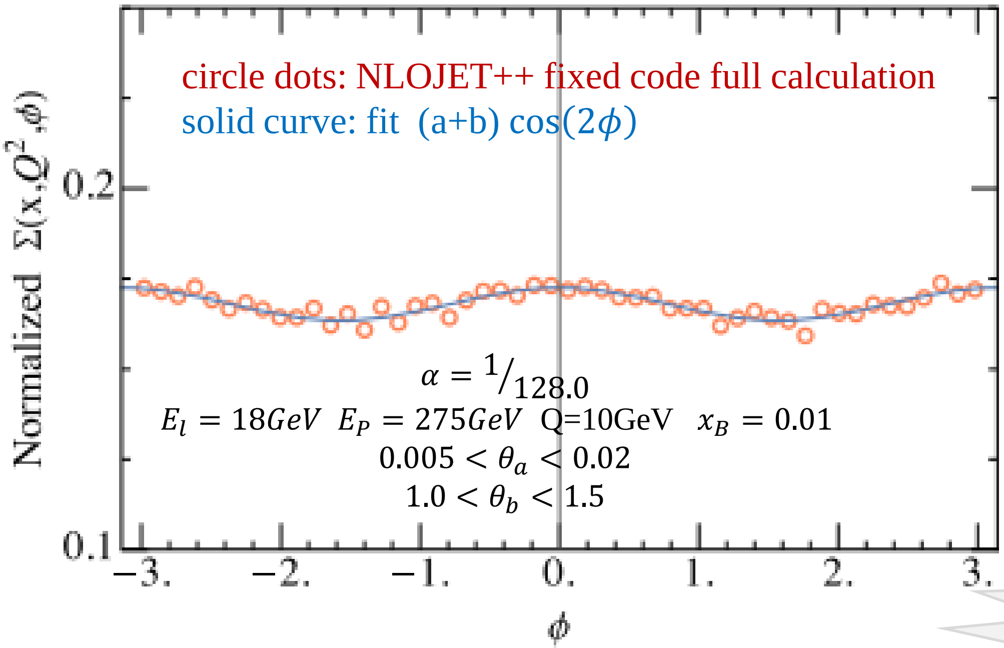

**But this is trivial**

# Numerical result

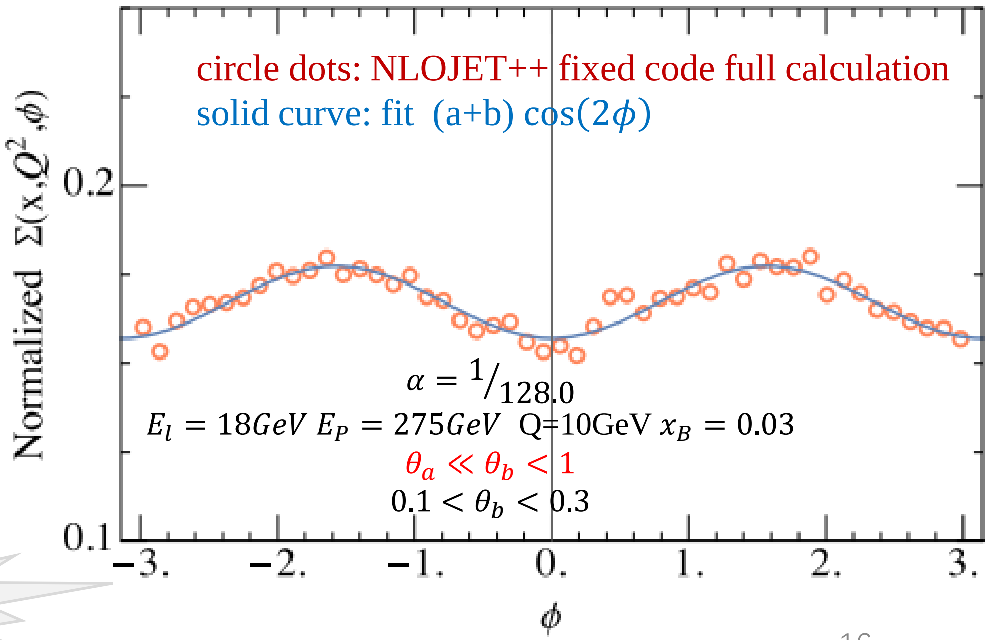



- Non trivial verification starts with NLO
- we have additional radiations that can cross talk between initial state gluon and final state jet, that will potentially breaks the factorization just like the TMD

✓ indicate cross talk is power suppressed in our method




✓ We also show the result into the squeezed limit, two detectors are both put in forward region




**High non-trivial!!**

# Summary

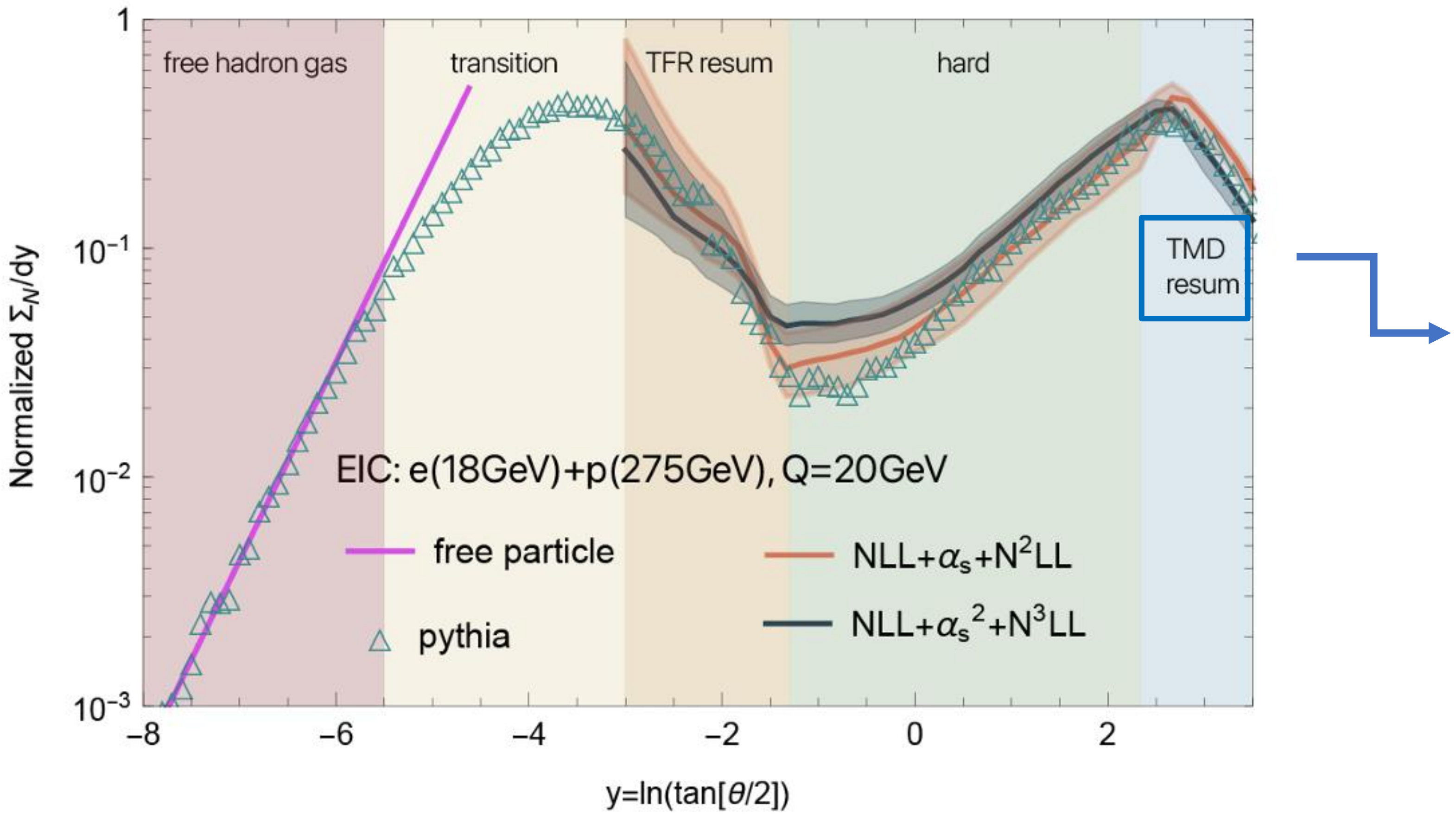
- We propose to study the linearly polarized gluons through the observation of helicity-dependent NEEC in the DIS process
- the $\cos 2\phi$ asymmetry is preserved by rotational symmetry and factorization
- hold to all orders, free of soft radiation contamination and free of Sudakov suppression
- looking ahead, we plan to present the evolution of the helicity-dependent NEEC, to make all order predictions for the azimuthal distribution


IMP
LIGHT CONE 2024
Hadron Physics in the EIC era
The Institute of Modern Physics,
Chinese Academy of Sciences,
Huizhou Campus, China.
November 25-29, 2024

Thanks!

# Nucleon Energy-Energy Correlators

H.T. Cao, H.T. Li et al. PRD,109, 096004 (2024)

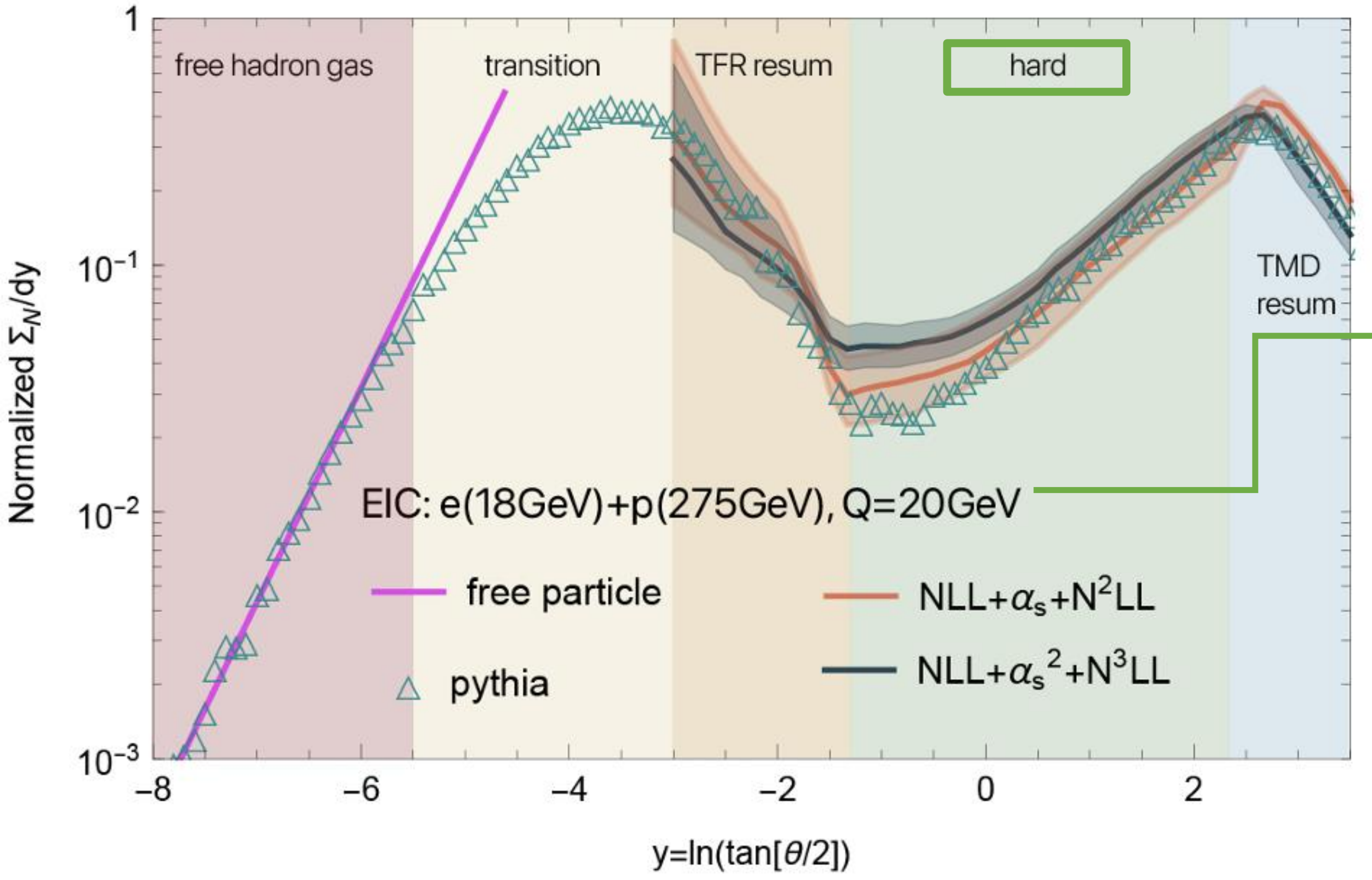



**TMD region**

- conventional TMD physics
- TMD PDF is suppressed by Sudakov

# Nucleon Energy-Energy Correlators

H.T. Cao, H.T. Li et al. PRD,109, 096004 (2024)




**Hard region**

- the distribution to be well described by fixed-order QCD calculations

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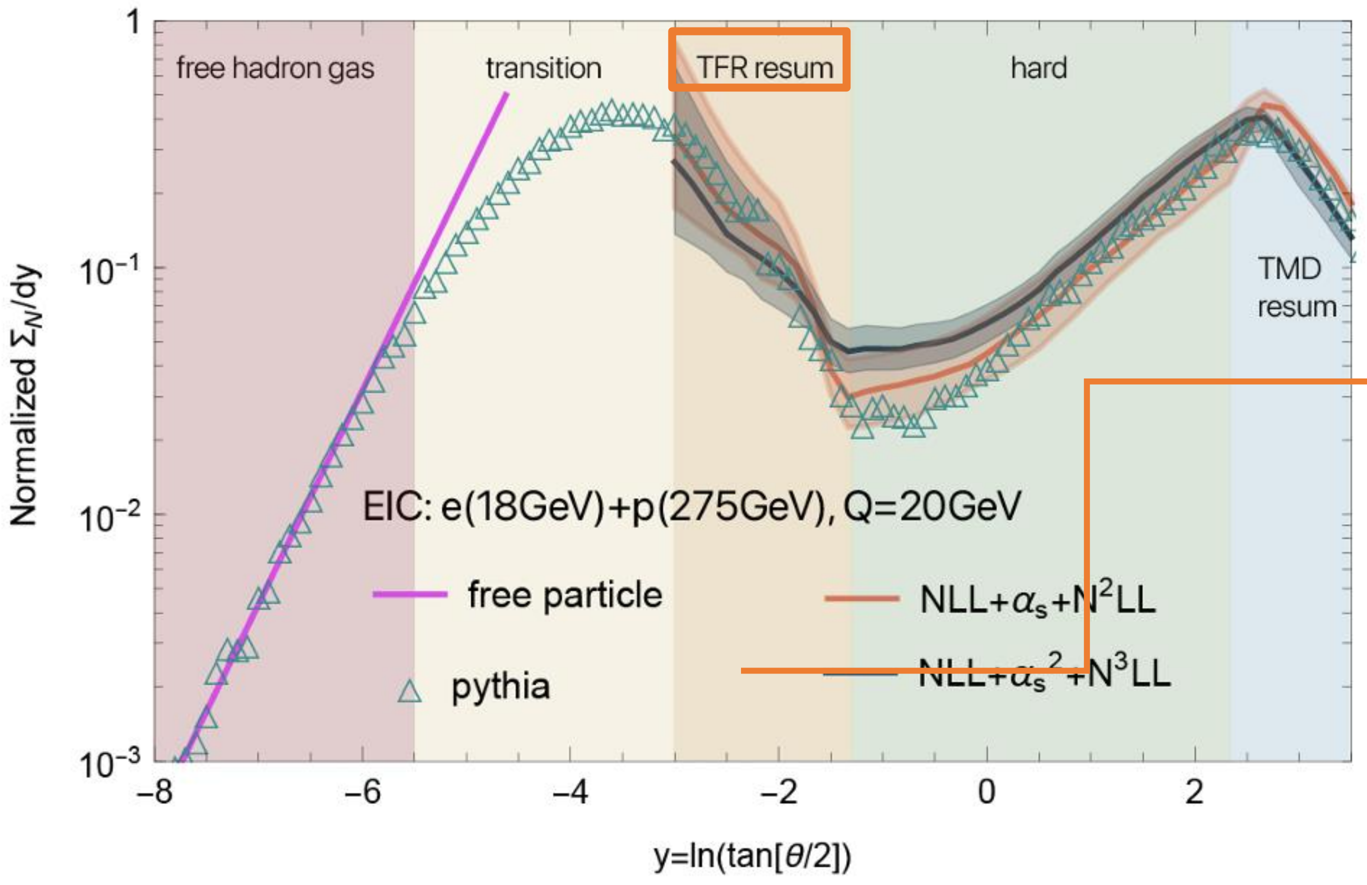
H.T. Cao, H.T. Li et al. PRD,109, 096004 (2024)




**Target Fragmentation Region(TFR)**

$\theta \ll 1$

- Correlation between initial and final states
- Dynamics dominated by collinear splitting