Illuminating nucleon-gluon interference via calorimetric asymmetry

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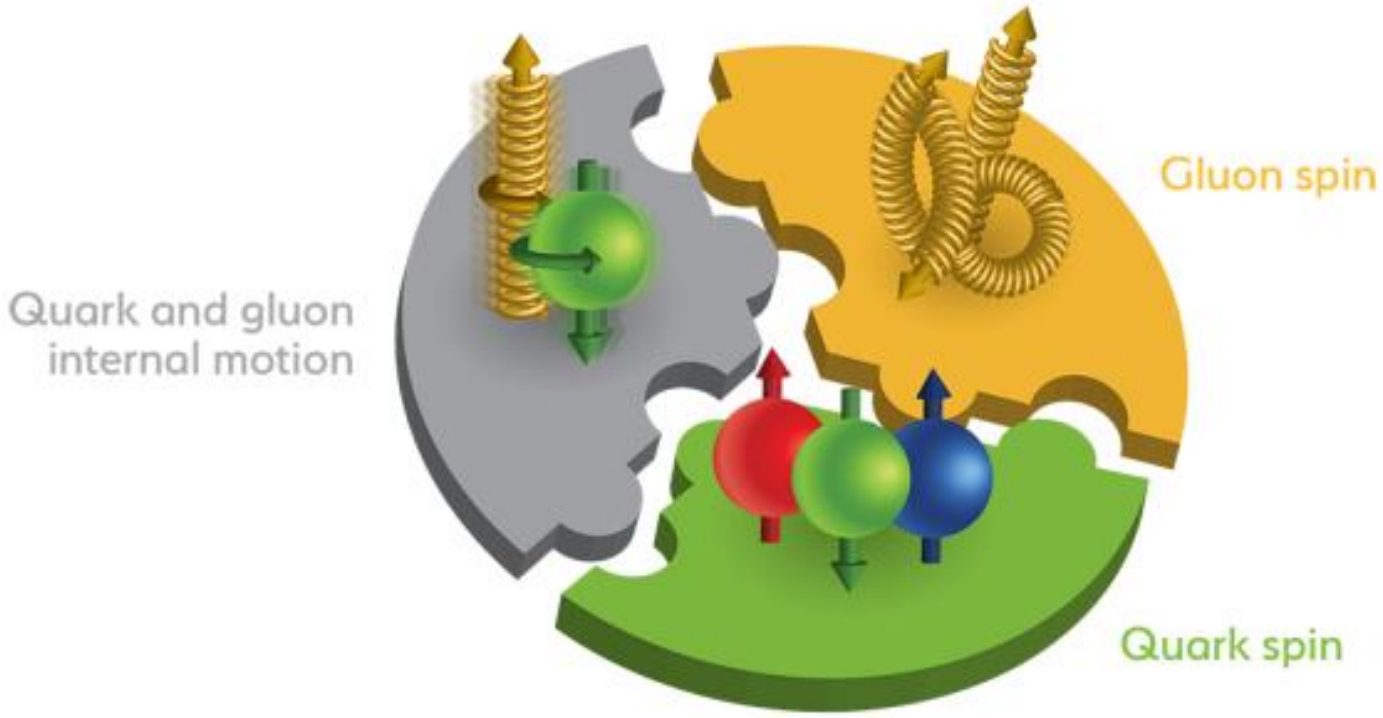
Phys. Rev. D 108, L091502(2023)

SCET 2024, Salamanca, Apr. 17

Outline

- **Motivation**
  - **concept of linearly polarized gluon**
  - **conventional probe using TMD-PDFs**
- **Measurement of Nucleon Energy-Energy Correlator**
- **Numerical result**
- **Summary and Outlook**

Nucleon Structure



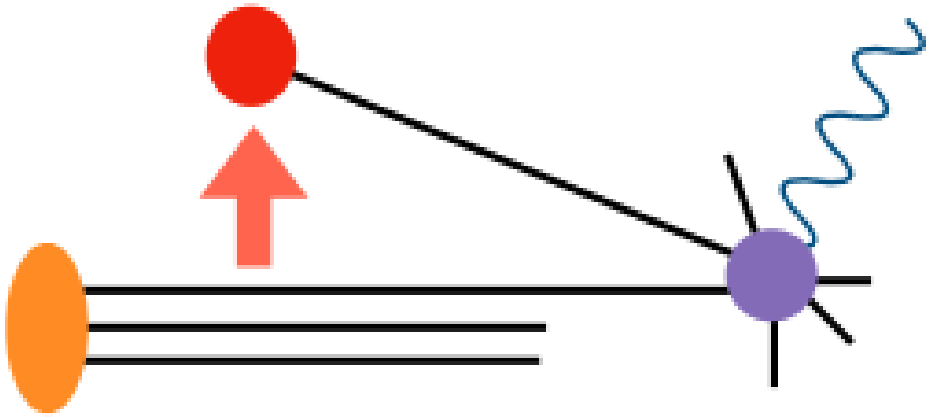
Major focus of EIC …

- ✓ Spin components
- ✓ Mass decomposition
- ✓ …

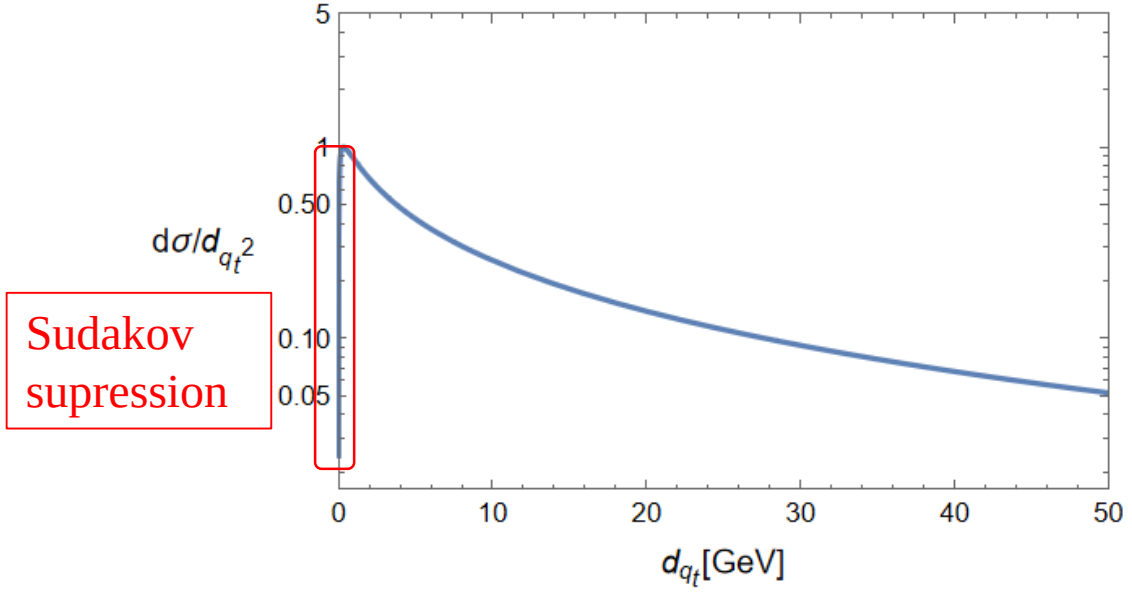
Conventional approach to nucleon structure

- extract Transverse Momentum Dependent (TMD)-PDFs

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



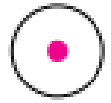
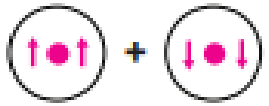
Semi-Inclusive DIS

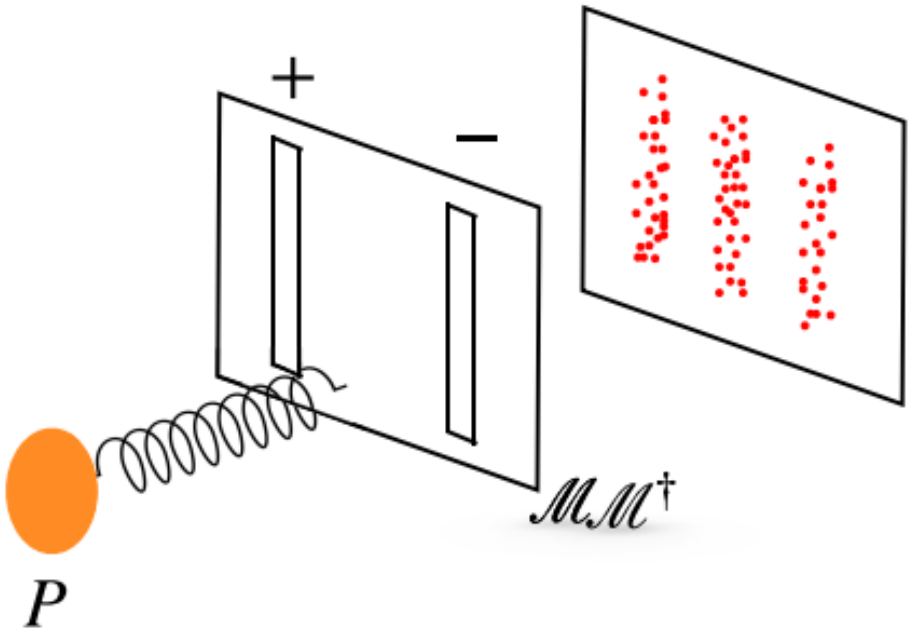


exponentially suppressed in non-pert. region when Q is large $e^{-\frac{Q^2}{q_t^2}}$

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



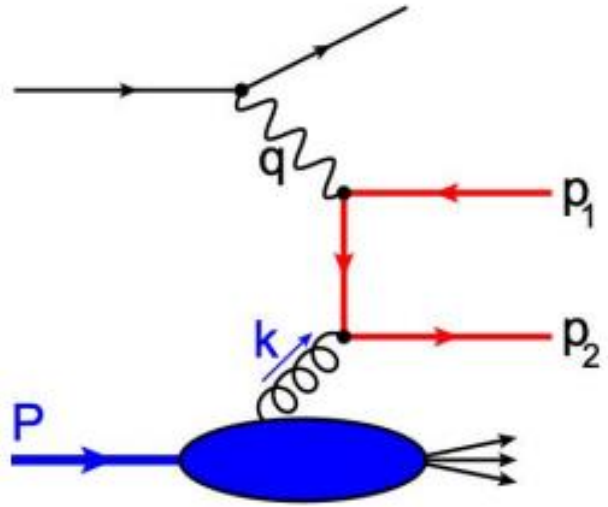
- interference of positive and negative helicities

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

Un-polarized PDF linearly polarized PDF

Conventional approach to nucleon structure

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

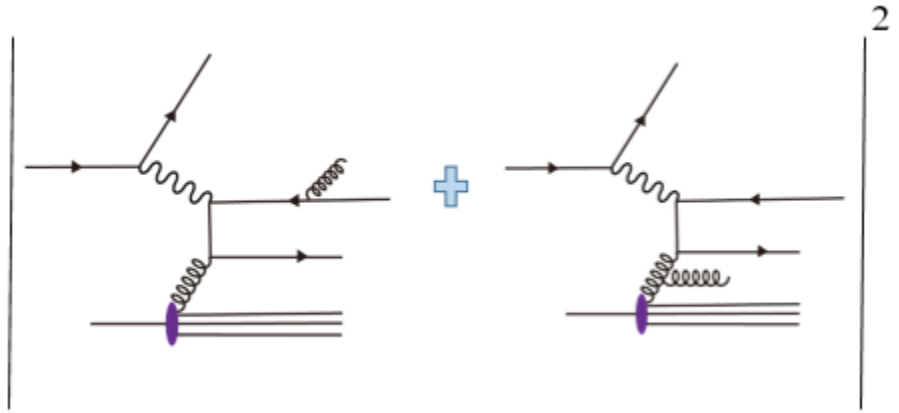


See Ding Yu's talk

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

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

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



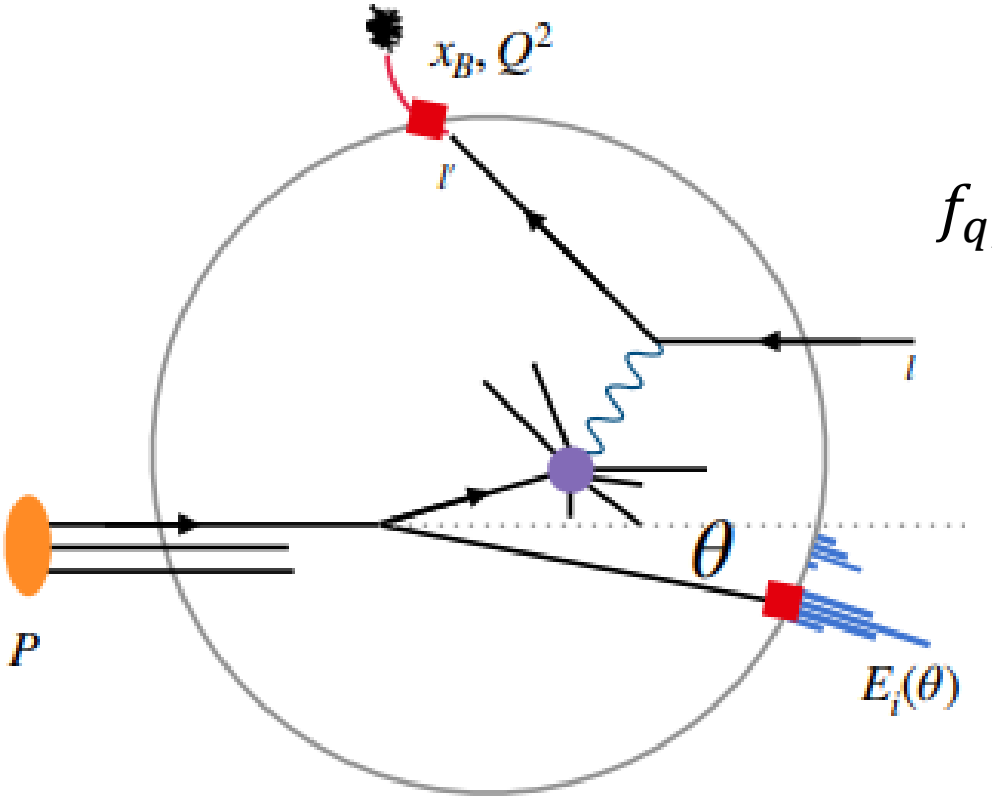
- ✓ This gives arise to the eikonal factor [Y. Hatta, et al. PRD, 104,054037 (2021)]

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

- ✓ This is not related to the polarization of the gluon

Nucleon Energy-Energy Correlators

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



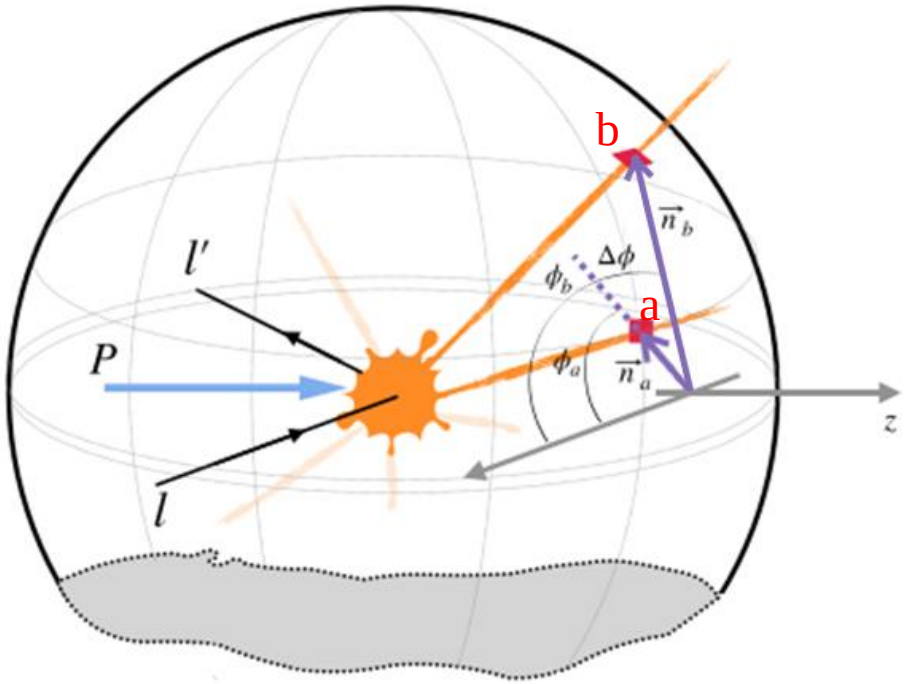
See Hua Xing's talk

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

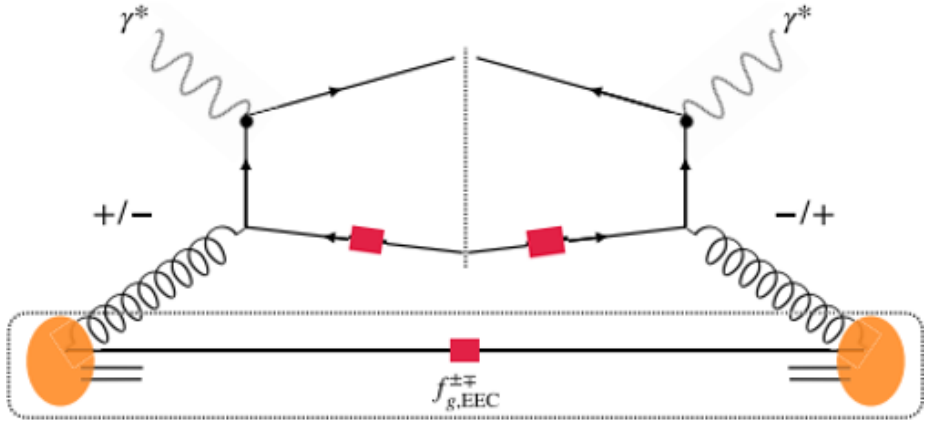
$$\mathfrak{E}(\theta)|X\rangle = \sum_{i \in X} \frac{E_i}{E_P} \delta(\theta_I - \theta)|X\rangle$$

- one thing to notice, because of this energy weight, the nucleon energy correlator will be insensitive to soft radiation , which is very different from TMD!!

Nucleon Energy-Energy Correlators



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



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

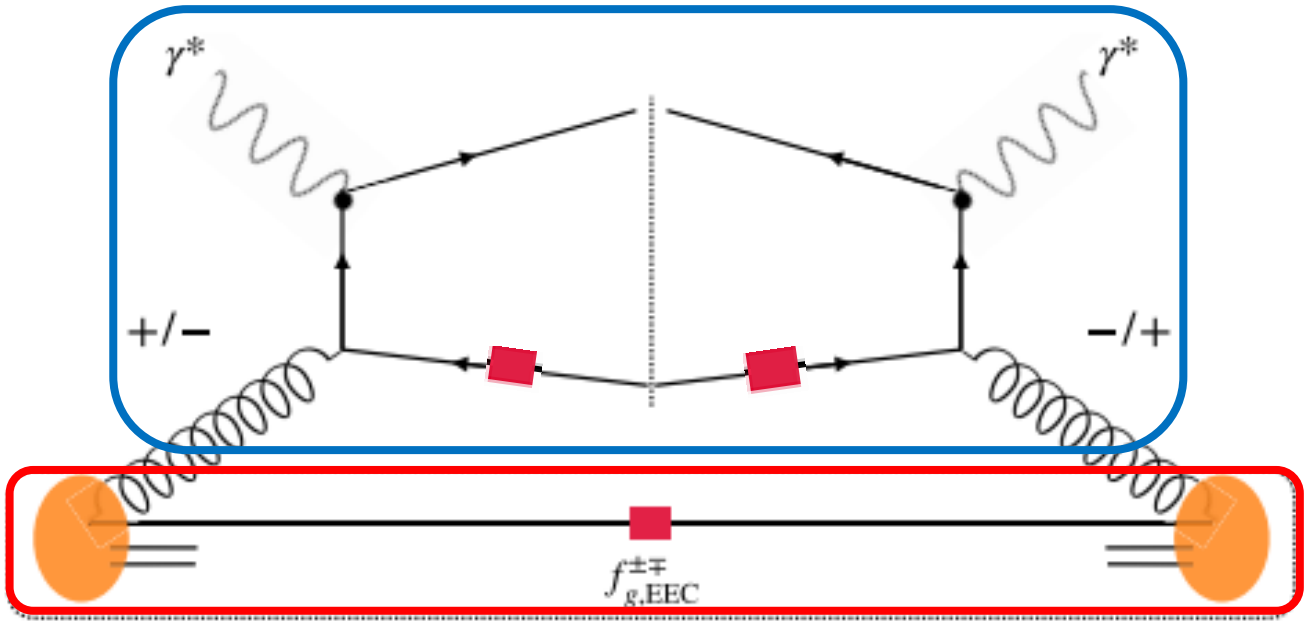
$$\Sigma(x_B, Q^2, \cos\theta_{a,b}, \phi)$$
$$= \sum_{ab} \int d\sigma(x_B, Q^2)\, \frac{E_a}{E_P}\frac{E_b}{E_P}\, \delta(\overrightarrow{n_a} - \overrightarrow{n_i})\, \delta(\overrightarrow{n_b} - \overrightarrow{n_j}) \times \mathcal{F}(\phi; \overrightarrow{n_{a,b}})$$

$\mathcal{F}$: impose the phase-space measurement to construct ϕ

- the measurement in the Breit frame
- the azimuthal angle ϕ between detectors a and b

Nucleon Energy-Energy Correlators

- NEEC factorization



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

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

- measure the energy flow along the detector b

Nucleon Energy-Energy Correlators

- the gluon NEEC operator definition

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

- the most general parametrization of the gluon NEEC

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

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

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

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

- hard cross section can also be written in the similar form

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

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

Nucleon Energy-Energy Correlators

- so take this form we can show that the only possibility to get cos2phi through these tensor contraction

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

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

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

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

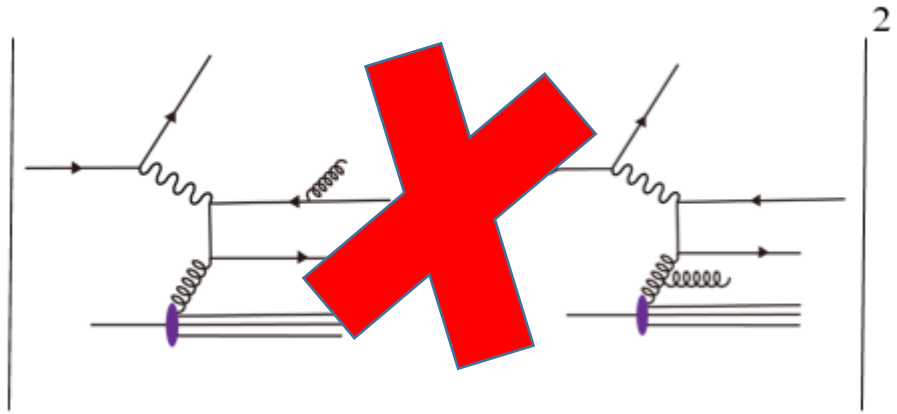
Nucleon Energy-Energy Correlators

- so take this form we can show that the only possibility to get cos2phi through these tensor contraction

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

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

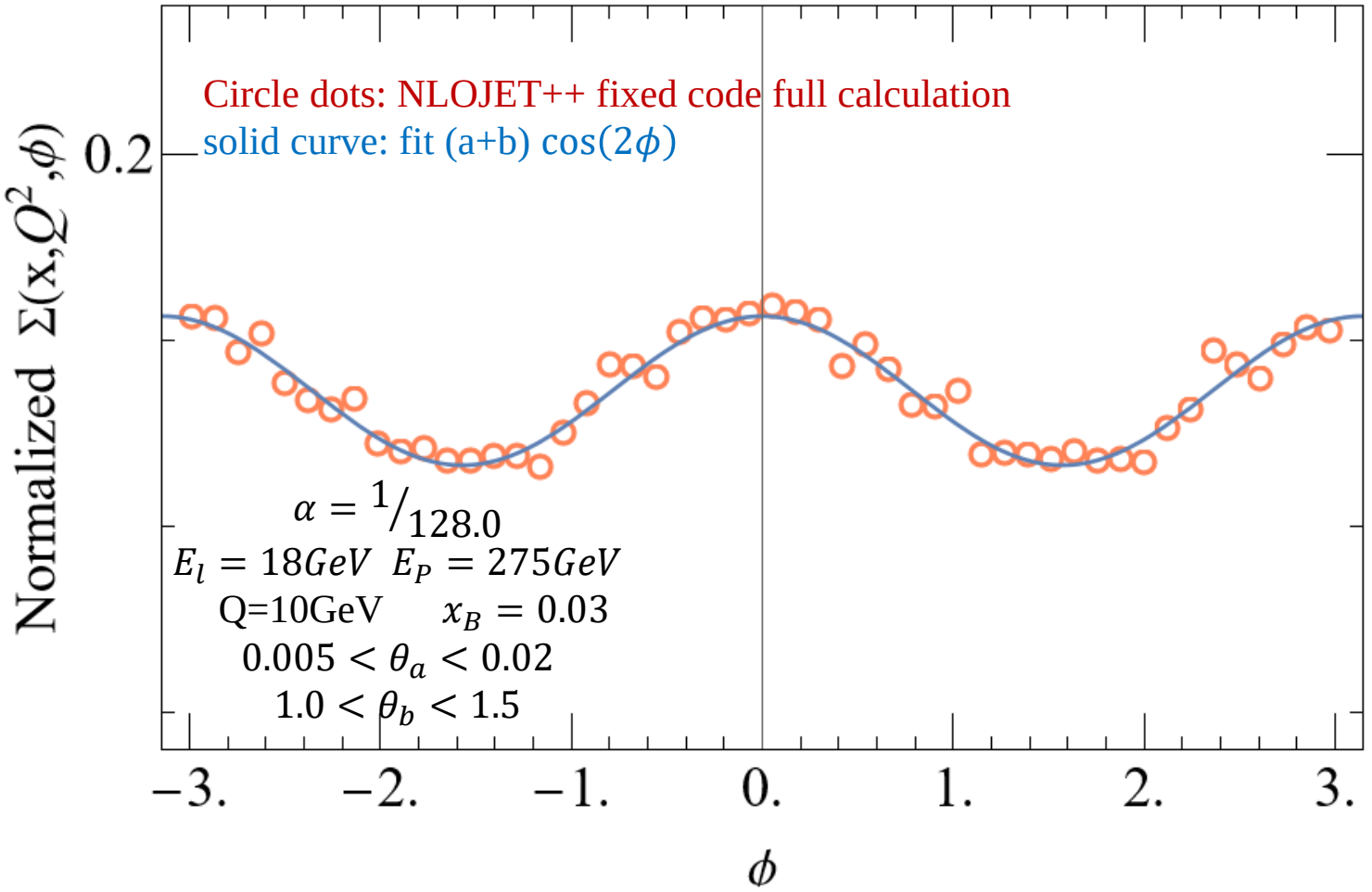
- ✓ Because of we do not have soft radiation, this $\cos(2\phi)$ structure hold to all orders

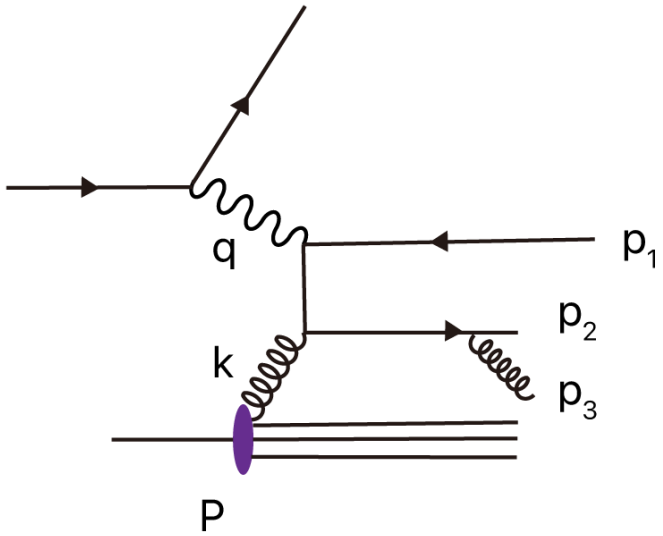


will not spoil $\cos(2\phi)$ signature

Numerical result

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

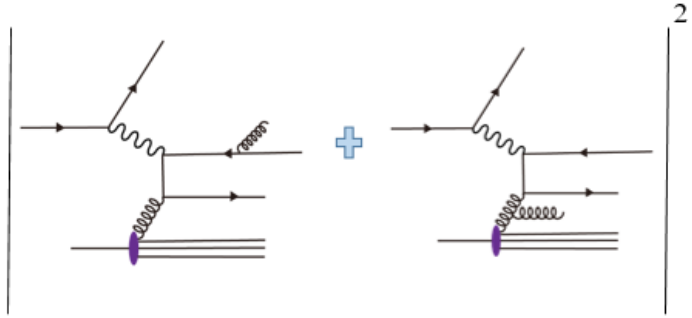




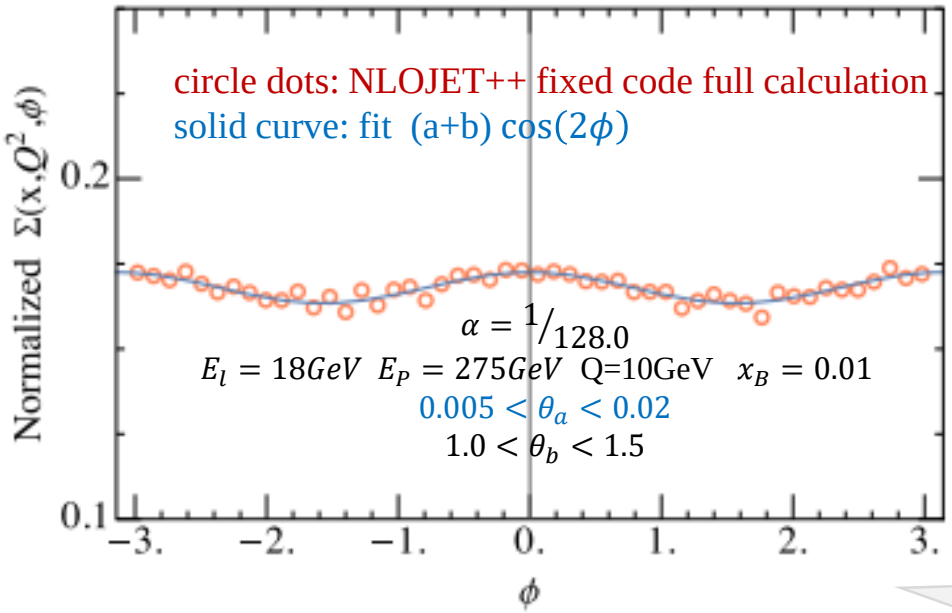
+ …

But this is trivial

Numerical result

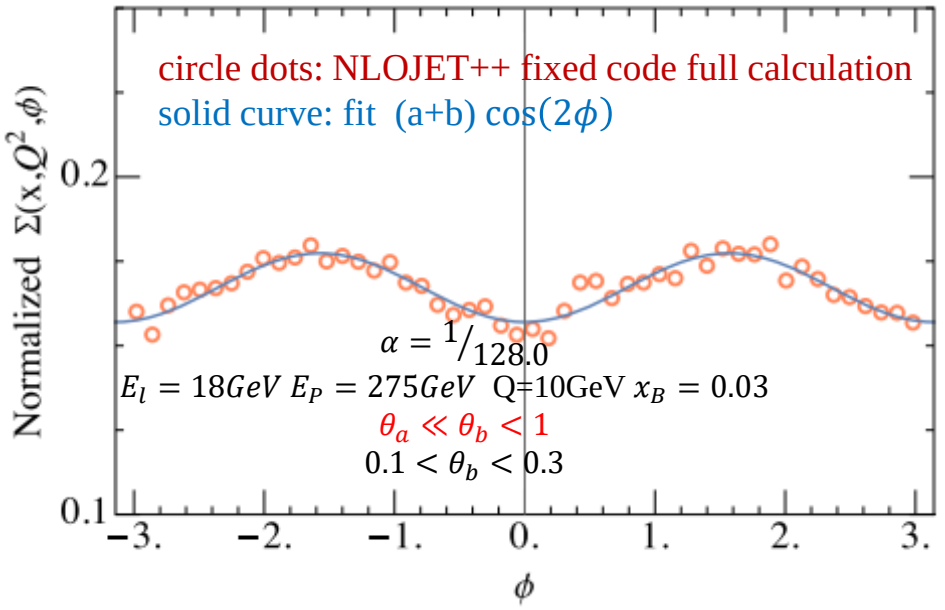


- Non trivial verification starts with NLO
- we have additional radiations that can cross talk between initial state gluon and final state jet, that will potentially breaks the factorization just like the TMD



High non-trivial!!

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



Summary and Outlook

- 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

Thanks for your attention !