核子自旋结构研究的近期进展

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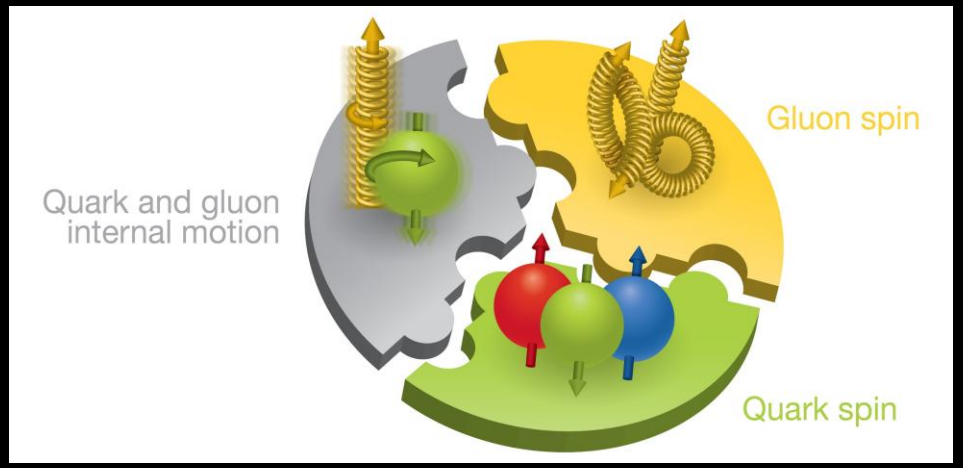
Outline:

- 研究背景
- 核子横向自旋物理
- 轨道角动量测量
- 线性极化效应
- 总结

研究背景

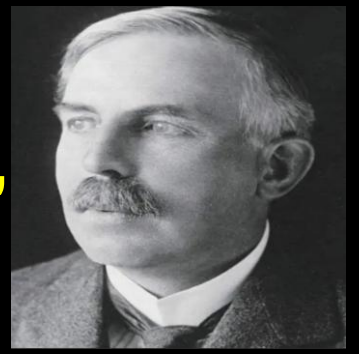


- 核子自旋结构高度非平庸，夸克自旋只贡献约30%
- EIC (造价28亿美元，今年开工建造) 与EicC 物理的核心目标之一

质子三维成像刻画（TMD）

Nucleon Polarization	Quark Polarization: U	Quark Polarization: L	Quark Polarization: T
U	f_1 unpolarized		$h_1^\perp$ Boer-Mulders
L		g_{1L} helicity	$h_{1L}^\perp$ longi-transversity (worm-gear)
T	$f_{1T}^\perp$ Sivers	g_{1T} trans-helicity (worm-gear)	h_1 transversity; $h_{1T}^\perp$ pretzelosity

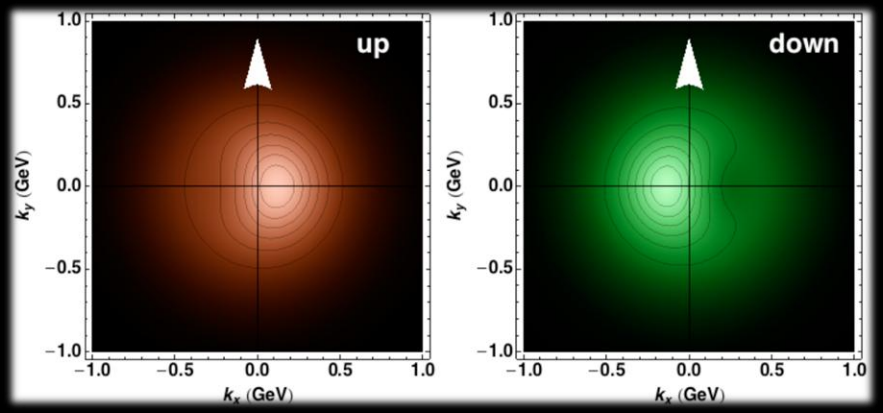
“All science is either physics or stamp collecting.”



“Anomalous Hall Effect” inside a proton

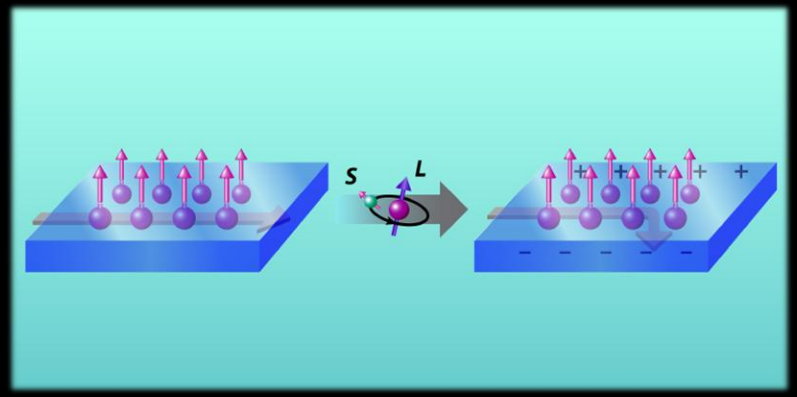
Boer-Mulders effect:

correlation between quark transverse spin and quark transverse momentum in proton



Anomalous Hall effect:

correlation between electron spin and electron transverse motion in solid



◆ **Similarities Between Boer-Mulders effect and AHE**(Quarks in the proton as analogous to electrons in a solid)

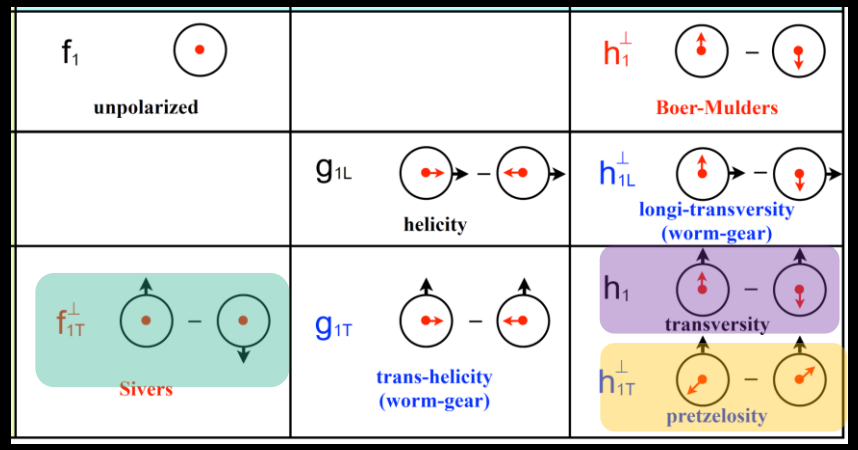
- Both are driven by spin-orbit coupling
- Neither requires an external magnetic field
- Both are T-odd effects
- Both have topological underpinnings, quantum phase plays the crucial role

The common origin of three T-odd TMDs

- We proved （on the operator level）：

$$x f_{1T}^{\perp g} = x h_1^g = x h_{1T}^{\perp g} = \frac{k_\perp^2 N_c}{4\pi^2 \alpha_s} O_{1T,x}^{\perp}(k_\perp^2)$$

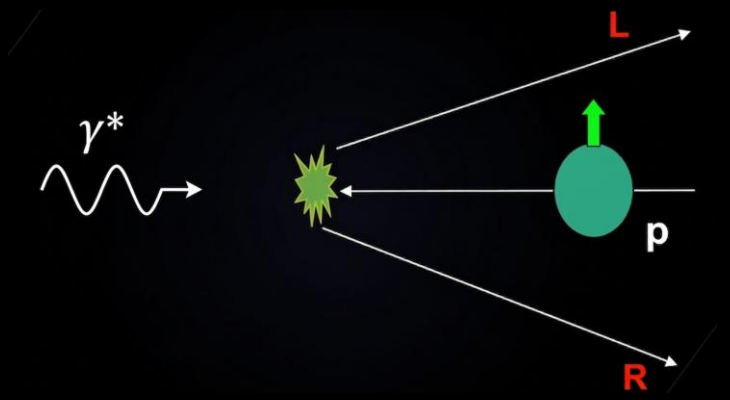
Boer, Echevarria, Mulders, ZJ; PRL，2017

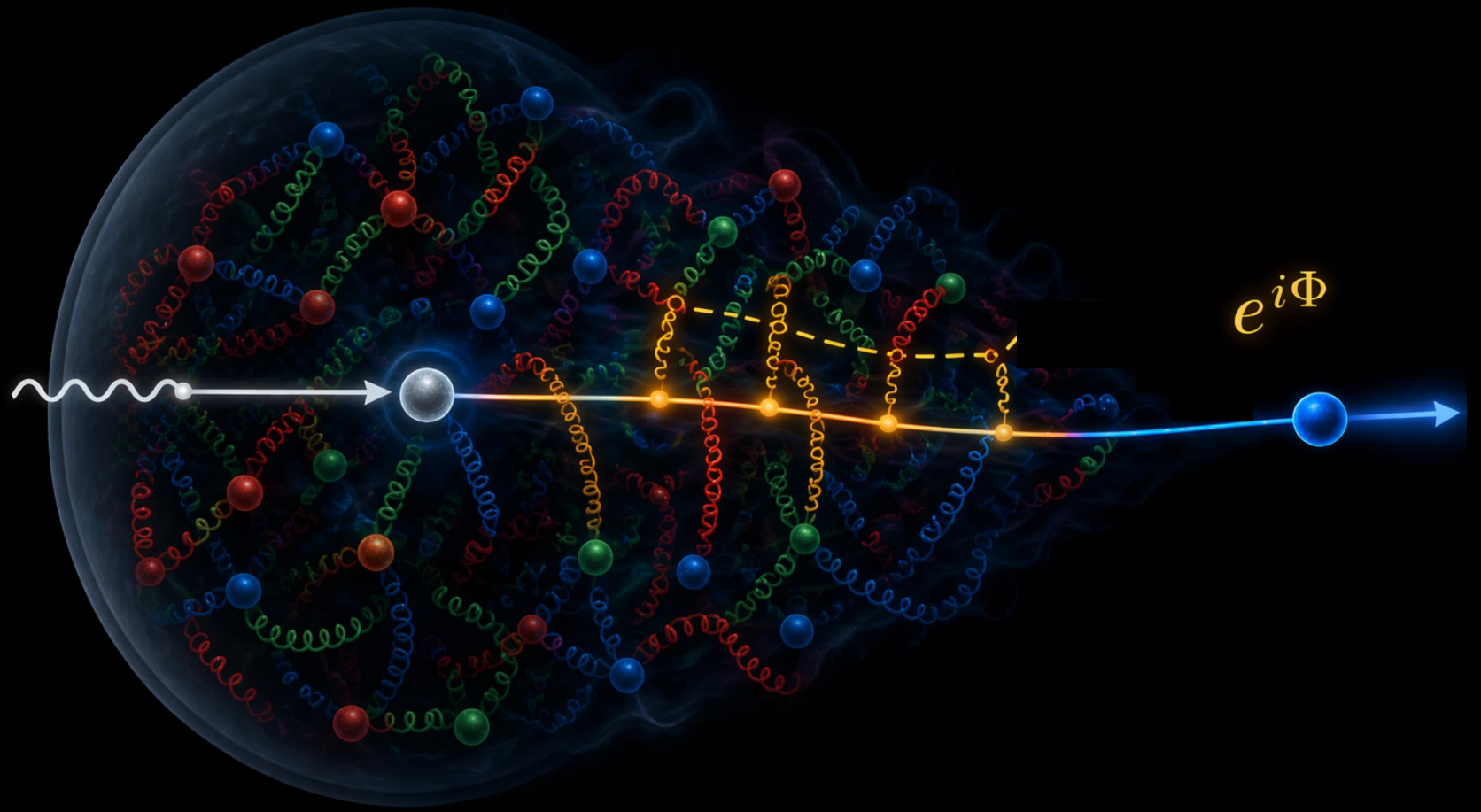


- For a long time, these three functions were mistakenly thought to be independent. But our work revealed their **intrinsic connection**!

Left-Right asymmetry

TSSA in SIDIS process:

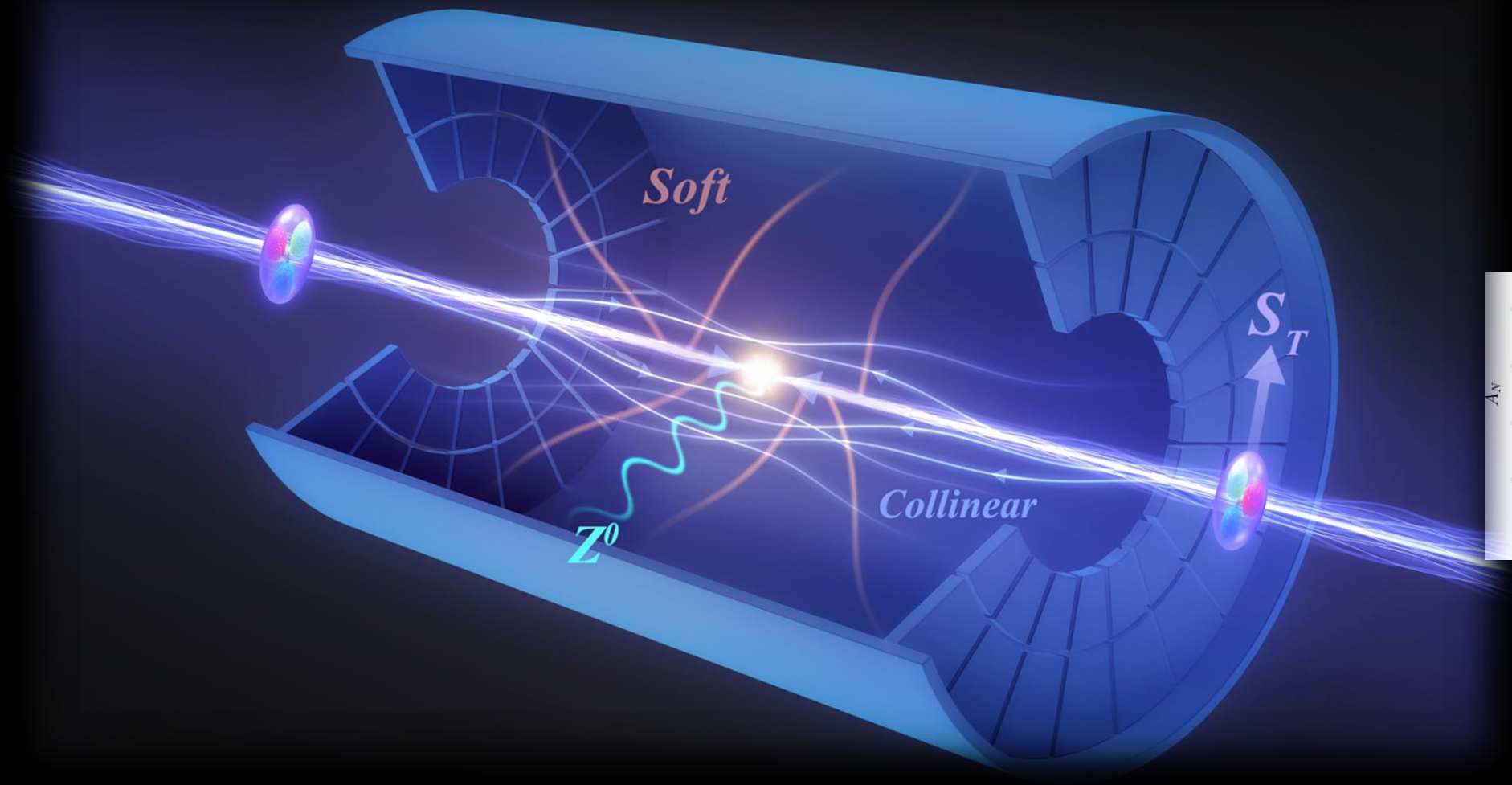




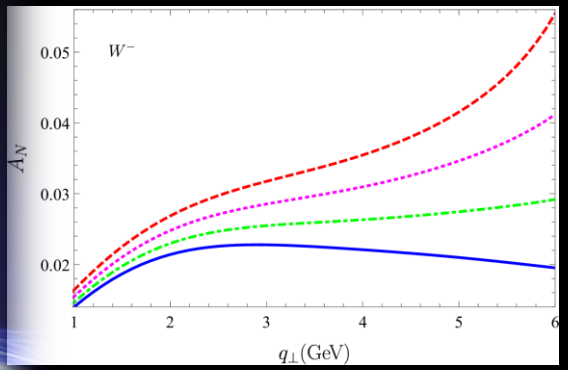
QCD analog of the Aharonov–Bohm effect**!**

A novel strategy to enhance the asymmetry: 0-jettiness

Fang, Lin, Shao and ZJ, PRL, 2026

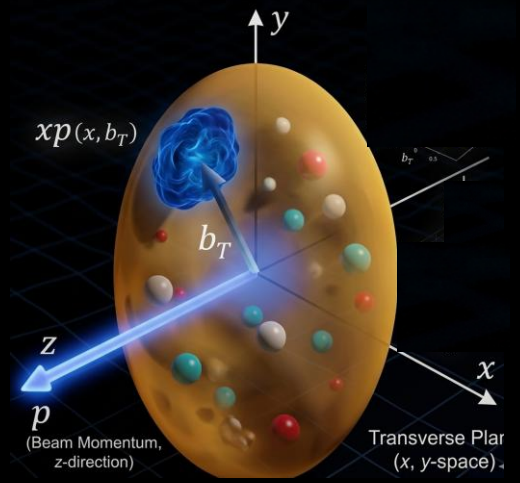


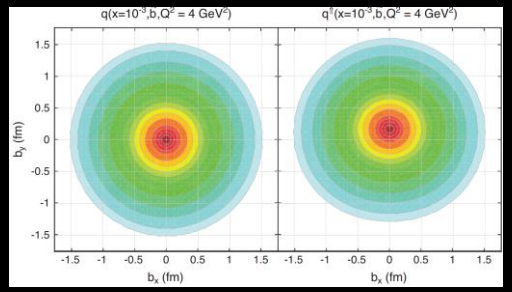
For more details:
邵鼎煜's talk



Energy evolution of proton transverse deformation

- Transverse spatial distribution of gluons





- Non-axisymmetric distribution is closely related to orbital angular momentum.
- Evolving picture of the gluonic landscape inside proton

Hatta, ZJ, PRL，2022

$$\partial_Y \mathcal{E}(k_\perp) = \frac{\bar{\alpha}_s}{\pi} \int \frac{d^2k'_\perp}{(k_\perp - k'_\perp)^2} \left[\mathcal{E}(k'_\perp) - \frac{k_\perp^2}{2k'^2_\perp} \mathcal{E}(k_\perp) \right] - 4\pi^2 \alpha_s^2 \overline{\mathcal{F}}_{1,1}(k_\perp) \mathcal{E}(k_\perp)$$

Quark orbital angular momentum

Canonical vs. Kinematic: Two Faces of Quark OAM

- Jaffe-Manohar，1990（Canonical OAM）

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + l_q + \Delta g + l_g$$

- Ji，1996（kinematical OAM）

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \mathrm{L}_q + J_g$$

Canonical	V.S.	Kinematical
$\vec{r} \times (\vec{p} - e\vec{A})$		$\vec{r} \times \vec{p}$

	JM	Ji
Operator commutation relation	Yes	No
Gauge invariance	No	Yes

- Probing kinematical OAM(DVCS，DVMP）：

$$J_q = \lim_{t\to 0} \frac{1}{2} \int dx x [H_q(x,t,\xi) + E_q(x,t,\xi)]$$ Ji, 1997

First observable of canonical quark OAM since 1990

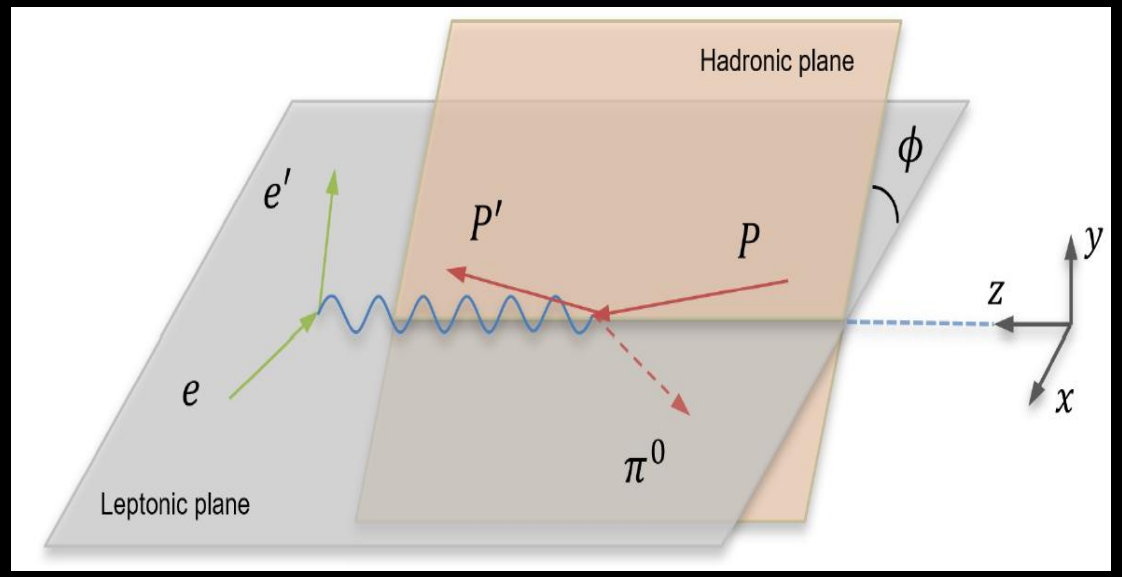
$$\frac{d\sigma}{dtdQ^2dx_Bd\phi} = \frac{(N_c^2-1)^2\alpha_{em}^2\alpha_s^2 f_\pi^2 \xi^3 \Delta_\perp^2}{2N_c^4(1-\xi^2)Q^{10}(1+\xi)} \left[1+(1-y)^2\right] \times \left\{ \left[|\mathcal{F}_{1,1}+\mathcal{G}_{1,1}|^2 + |\mathcal{F}_{1,4}+\mathcal{G}_{1,4}|^2 + 2\frac{M^2}{\Delta_\perp^2}|\mathcal{F}_{1,2}+\mathcal{G}_{1,2}|^2 \right] \right.$$

$$\left. + \cos(2\phi)a\left[-|\mathcal{F}_{1,1}+\mathcal{G}_{1,1}|^2 + |\mathcal{F}_{1,4}+\mathcal{G}_{1,4}|^2\right] + \lambda \sin(2\phi)\, 2a\, \mathrm{Re}\left[(i\mathcal{F}_{1,4}+i\mathcal{G}_{1,4})\left(\mathcal{F}_{1,1}^*+\mathcal{G}_{1,1}^*\right)\right] \right\}$$

$$\phi = \phi_{l_\perp} - \phi_{\Delta_\perp}$$

Proton helicity

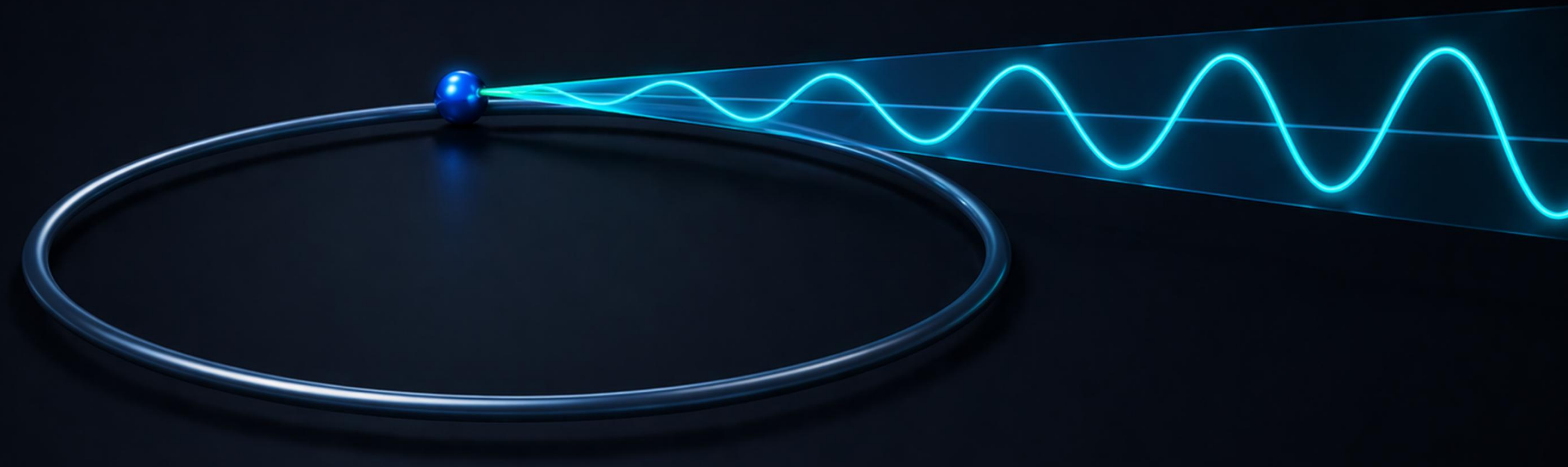
Distinguished experimental signature of $F_{1,4}$



Bhattacharya, Zheng, ZJ, PRL 2024

◆ Can be measured at EIC and EicC。

线性极化效应

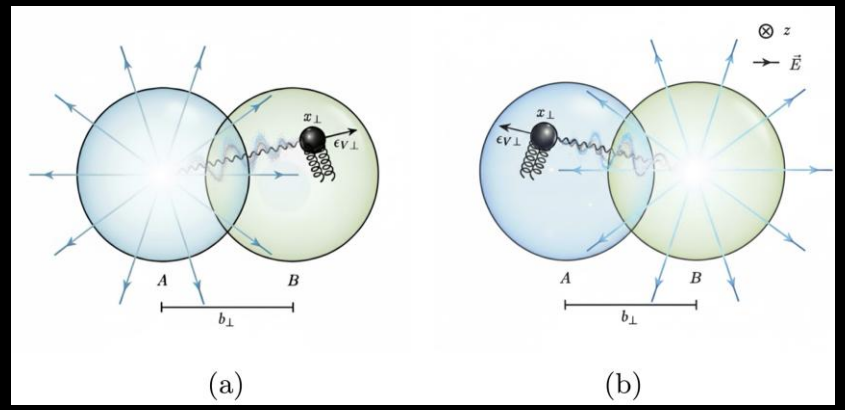


同步辐射示意图

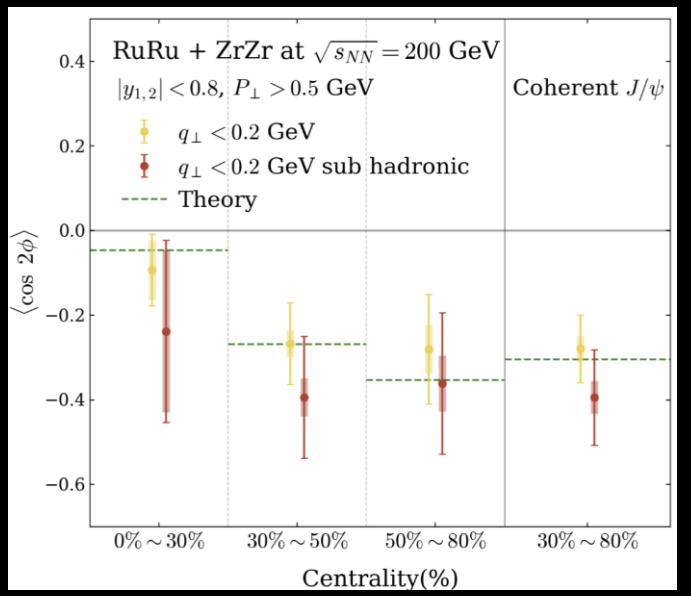
动量-坐标 这间的方位角关联

- 矢量介子极化方向和碰撞参数之间的角度关联

Xiao, Yuan, ZJ; PRL, 2020;
Ding, Yu, Zhang, ZJ, PRD, 2025



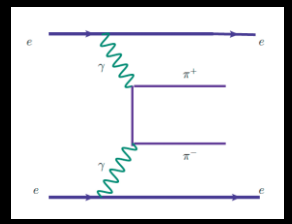
LHC result:



See also predictions by Wang mei Zha et.al.

Linear Polarization at electron-positron Colliders

- Coherent photons emitted by electrons are also linearly polarized.



$$c_1|M_{++}\rangle + c_2 e^{i\phi}|M_{+-}\rangle$$

$$\langle \cos 2\phi \rangle \propto Re\left[M_{++}M_{+-}^{*}\right]$$

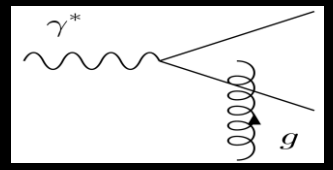
Jia, ZJ, Zhou, PRL, 2025

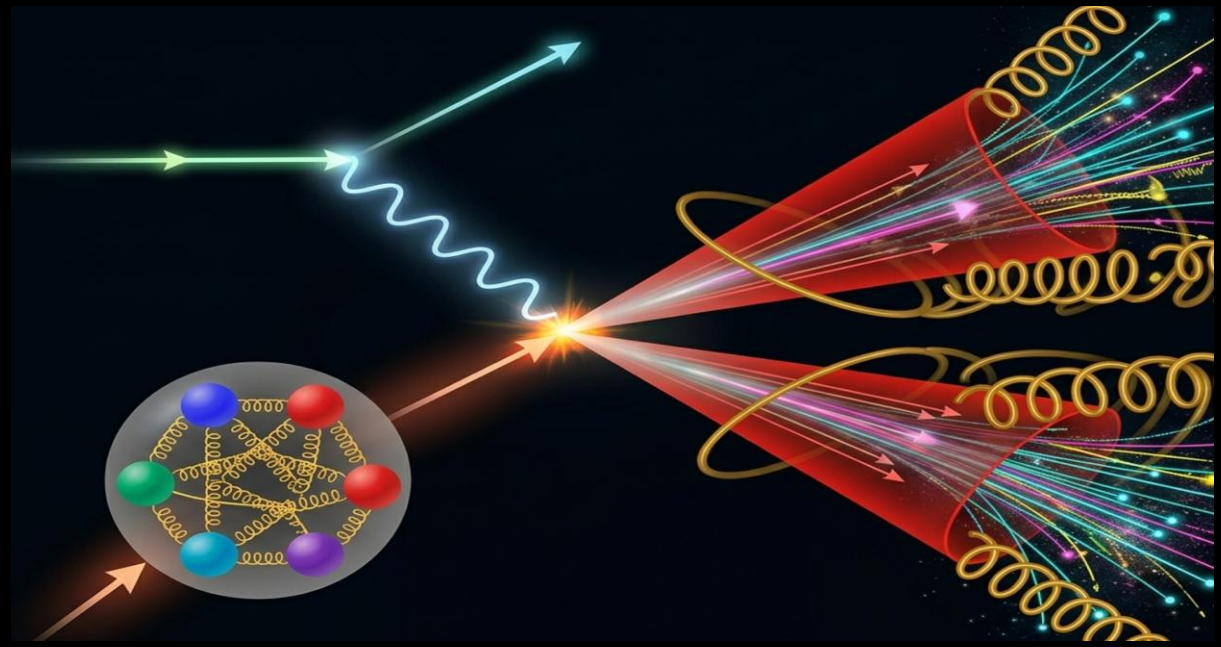
- Linearly polarized photon induced cos2ϕ

→ **the direct extraction of quantum phase**!

How to access gluon linear polarization

- Cos2ϕ asymmetry in di-jet production:





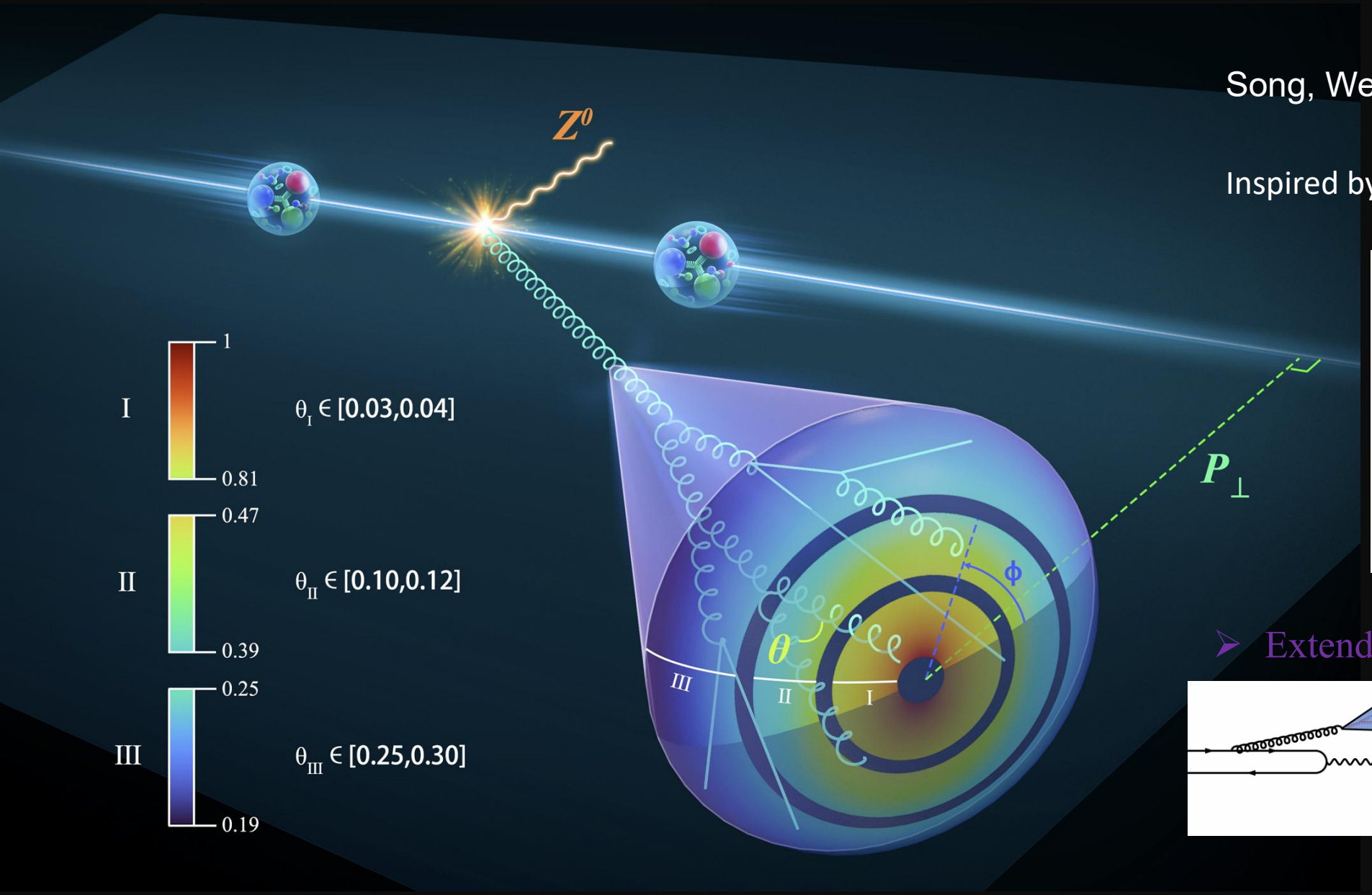
Hatta, Xiao, Yuan, ZJ, PRL, 2021

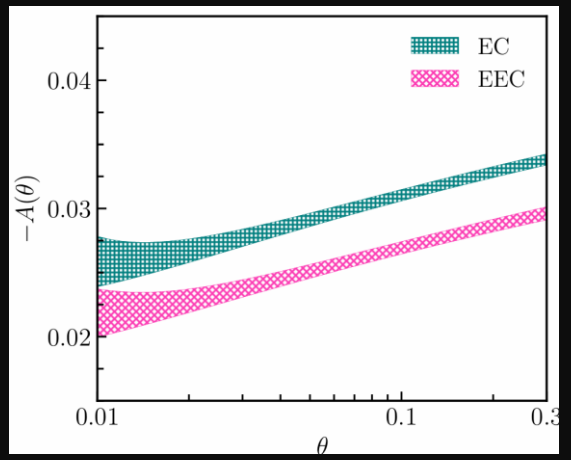
- ISR dilutes the linear polarization of gluons.
- FSR mimics the signature of linear polarization of gluons.

Gluon Polarimetry with Energy-Energy Correlators

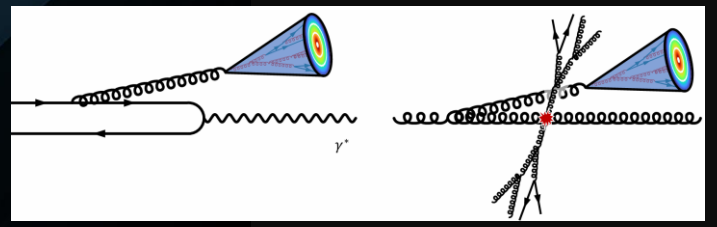
Song, Wei, Yang, ZJ, PRL, 2026

Inspired by Chen, Moult, Zhu, 2021





- Extend to other processes



Summary:

核子结构研究并不是一项集邮活动，有丰富的唯像学等待探索。

Thank you!