第八届全国重味物理和量子色动力学研讨会（重庆）
2026年4月24日-28日

# New Perspectives on Precision Nucleon Tomography

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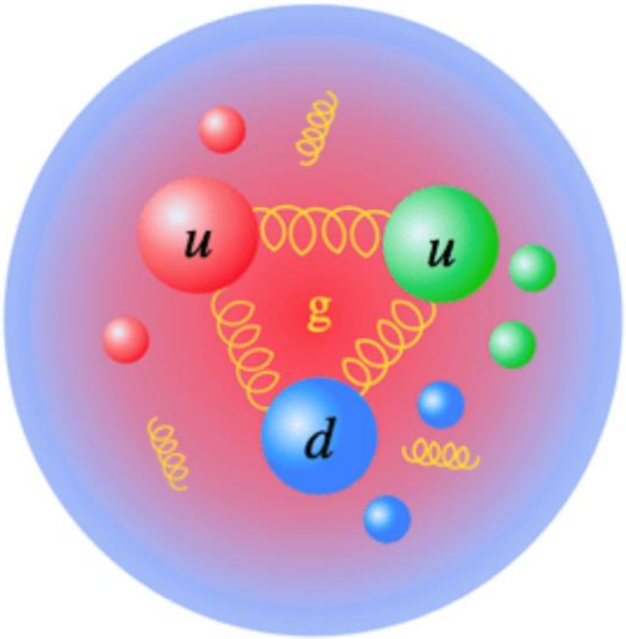
Phys. Rev. Lett. 136 (2026) 151902
Phys. Rev. Lett. 136 (2026) 021901
Phys. Rev. Lett. 135 (2025) 171903
JHEP 11 (2025) 082
2602.20249，2602.22972，2510.13951

# QCD中两类重要的演生现象

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left( i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

**强子结构**



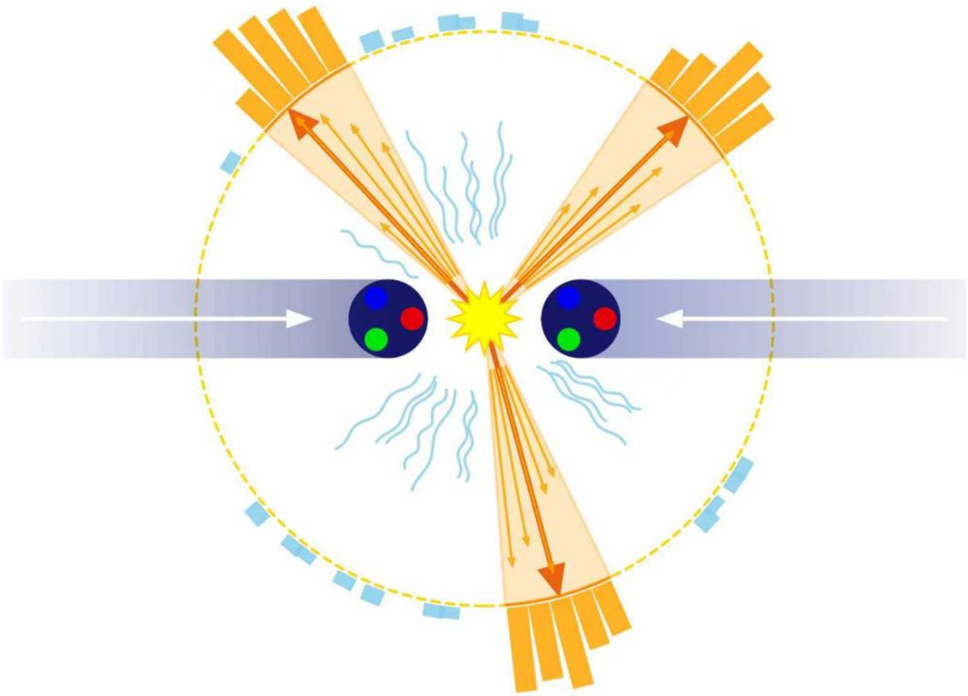

**色禁闭**

**渐近自由**

**红外奇点**

**……**

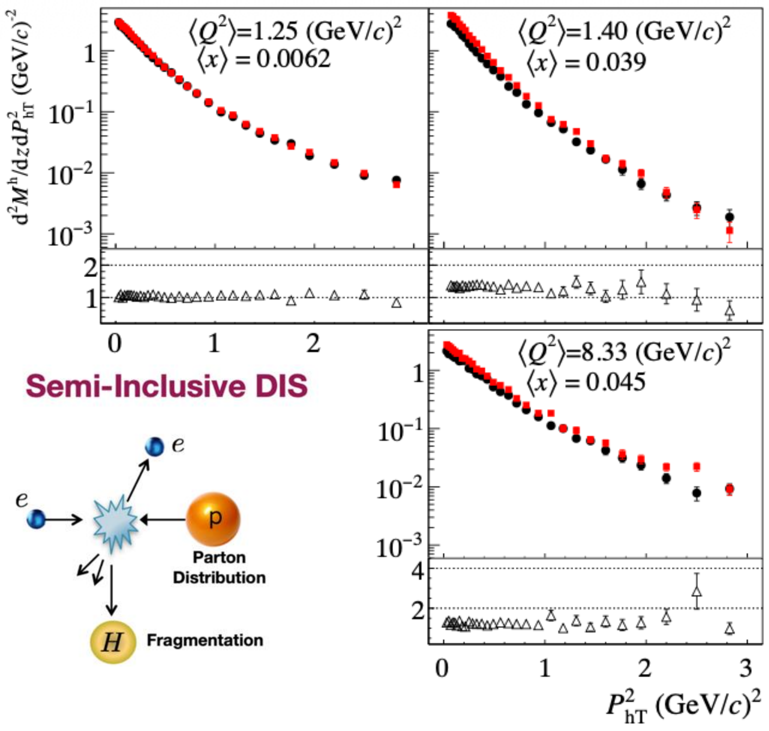
**喷注产生**



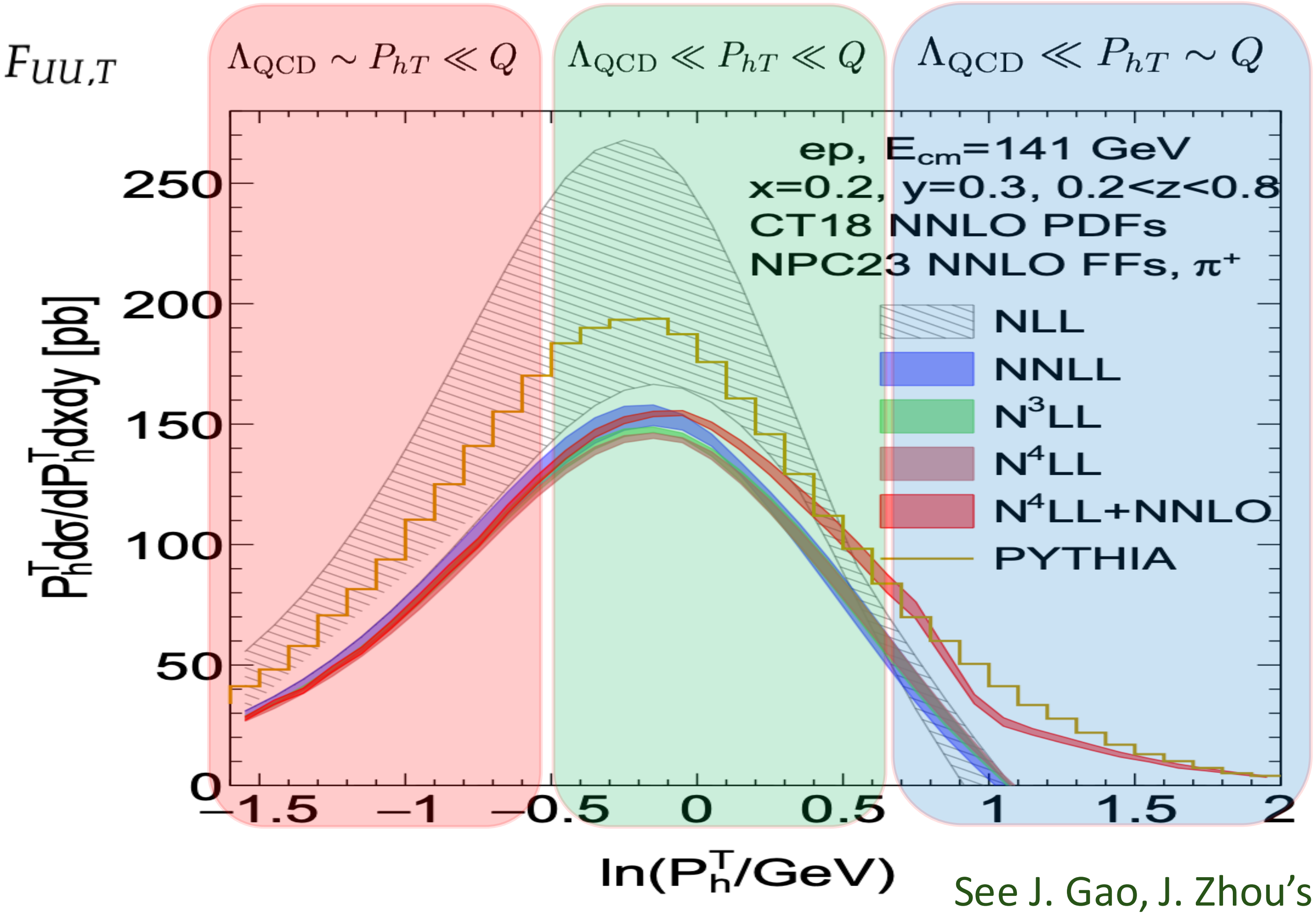
# Quark TMDs in e-p collisions

**One of the most fundamental measurements in SIDIS related to TMDs is the study of the unpolarized $P_{hT}$ differential cross section**

$$\frac{d^4\sigma_{\mathrm{SIDIS}}}{dx\,dy\,dz_h\,dP_{hT}} = 4\pi P_{hT}\frac{\alpha_{em}^2}{x\,y\,Q^2}\left(1-y+\frac{1}{2}y^2\right)F_{UU,T}$$



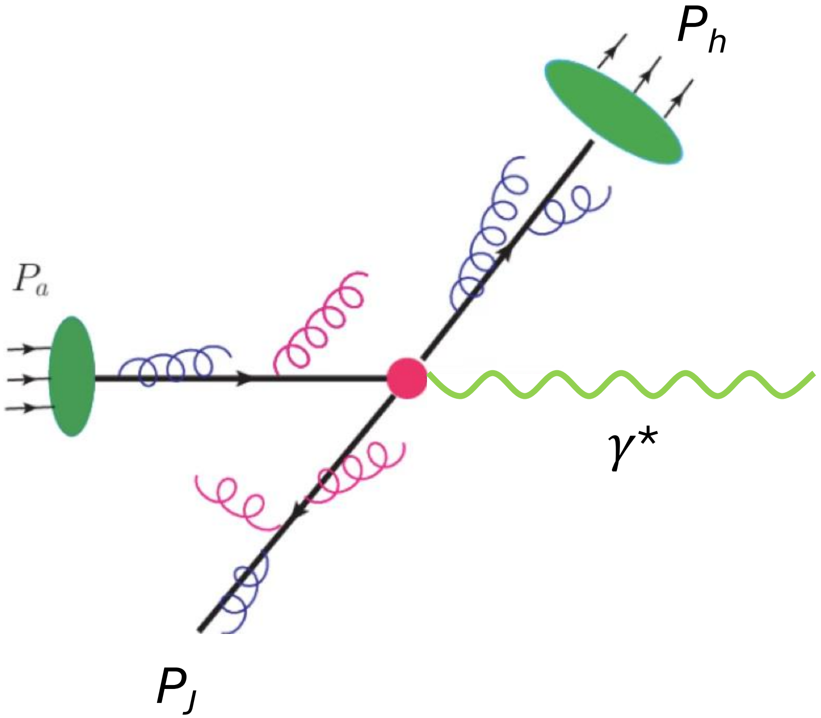

Gao, Li, Zhu, Zhu '26



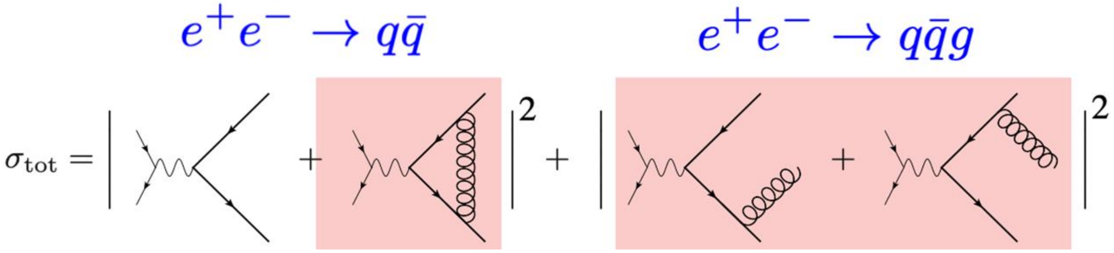

See J. Gao, J. Zhou's talks

# NNLO QCD corrections for $P_{hT}$ distribution

**Hadron + jets @ NNLO**




- **A key challenge is handling infrared (IR) divergences, which must cancel between real and virtual configurations.**



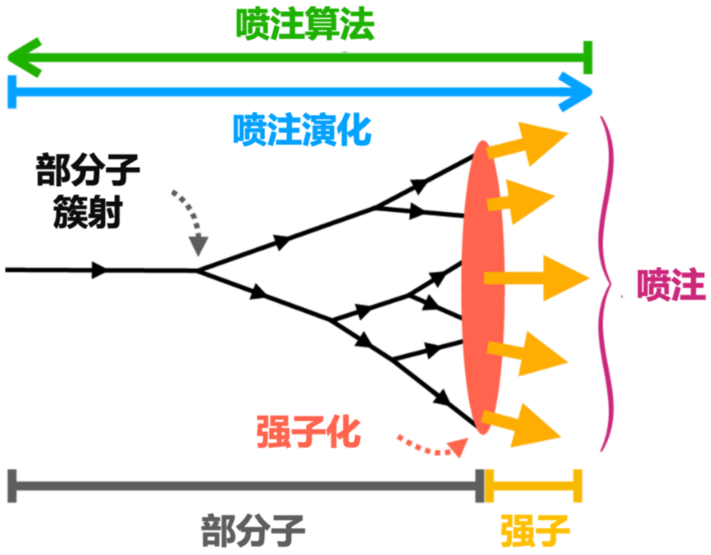

- **FMNLO framework for hadron production at NLO** Liu, Shen, Zhou, Gao '23
- **Transverse momentum (qT) subtraction for hadron production at NNLO** Gao, Li, Zhu, Zhu '26
- **qT subtraction works well for colorless or colored (but massive) system**
  - **N3LO Drell-Yan** Chen, Gehrmann, Glover, Huss, Yang, Zhu '23
  - **N3LO di-photon** Czakon, Eschment, Generet, Poncelet '26
- **For processes with jets, qT is unsuitable because qT=0 for radiation emitted inside jets.**

# Winner-take-all qT subtraction for jets

Fu(符荣峻), Rahn, DYS, Waalewijn, Wu PRL135 (2025) 171903

- **Winner-take-all recombination scheme** Bertolini, Chan, Thaler '13

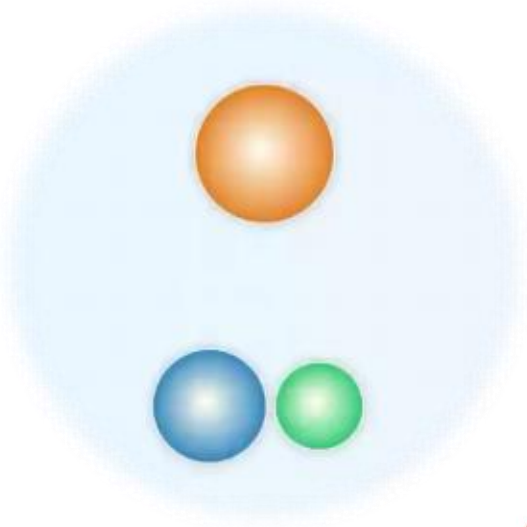
Also see S. Y. Wei's talk



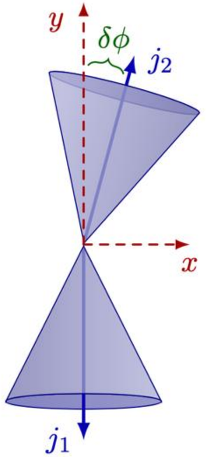

**“赢者通吃”动量重组方案**

$$p_{t,r} = p_{t,i} + p_{t,j}$$
$$\phi_r = (w_i\phi_i + w_j\phi_j)\,/\,(w_i + w_j)$$
$$y_r = (w_i y_i + w_j y_j)\,/\,(w_i + w_j)$$

$$\omega_i = (p_{t,i})^n \qquad n \to \infty$$



- **Factorization theorem is significantly simplified** Chien, Rahn, DYS, Waalewijn & Wu '22 JHEP + Schrignder '21 PLB
  - **NNLL resummation for $\delta\phi$ @ ep & eA** Fang(方申), Ke, DYS, Terry '24 JHEP
  - **N3LL + NNLO resummation for $\delta\phi$ @ ep** Fang(方申), Gao(高梅森), Li, DYS '25 JHEP



# Winner-take-all qT subtraction for jets

Fu(符荣峻), Rahn, DYS, Waalewijn, Wu PRL135 (2025) 171903

- **We propose two ways of extending qT subtraction to processes with jets**

**The key ingredient is the use of a recoil-free WTA jet axis!**

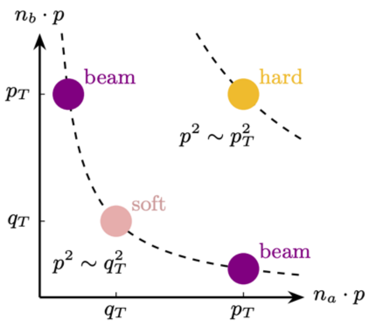
- **Azimuthal decorrelation: $\delta\phi$ or $q_x$**
  - **Suitable for processes that are planar at LO: pp → 2 jets, $\gamma^* p \to jj$, $e^+e^-$ → 3 jets, etc.;**
  - **Standard TMD PDFs and soft functions: known at N3LO** Luo, Yang, Zhu, Zhu, '19; Ebert, Mistlberger, Vita '20 …
  - **TMD jet functions: partially known at NNLO;** Reyes, Scimemi, Waalewijn, Zoppi '19; Bell, Brune, Das, Wald '23; Fang, Gao, Li, DYS '24
- **Total transverse momentum $q_T$**
  - **Suitable for LO non-planar process, such as pp → V/H + 2 jets, pp → 3 jets, etc.**
  - **Soft function is new: Outside the jet ($b_T$), Inside the jet ($b_x$)**

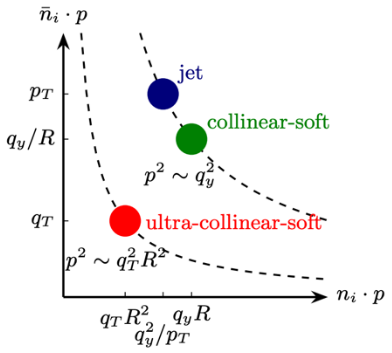
# NNLO new soft functions

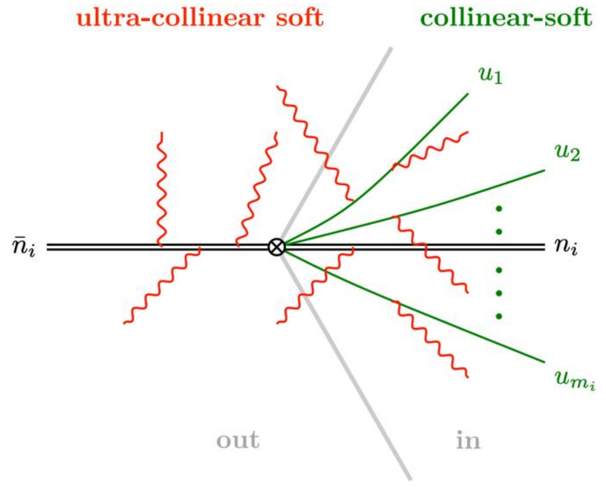
Fu(符荣峻), Rahn, DYS, Waalewijn, Wu 2602.20249

➢ **In small R limit, soft function refactorizes into simpler global and (ultra)-collinear-soft contributions**

- **soft**: $p_s^\mu \sim q_T\,(1,1,1)$,
- $n_i$-**collinear-soft**: $p_{cs}^\mu \sim |q_y|/R\,(R^2,1,R)_{n_i\bar{n}_i}$,
- $n_i$-**ultra-collinear-soft**: $p_{ucs}^\mu \sim q_T\,(R^2,1,R)_{n_i\bar{n}_i}$ ,



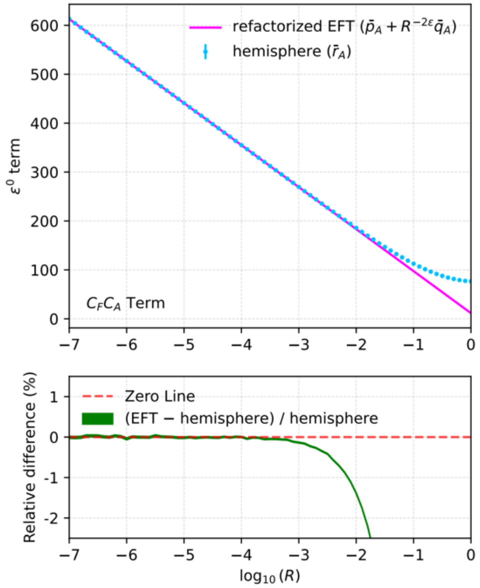




Multi-Wilson lines: Becher, Neubert, Rothen, DYS '16 PRL

Two-loop collinear-soft function

$$
\begin{aligned}
S_i^{\text{hemi},(2)}(b_\perp, b^+) = {} & \left(\frac{\mu|b_\perp|}{b_0}\right)^{4\epsilon}\left(\frac{\nu|b_\perp|R_i}{b_0}\right)^{\eta}\omega^2\left[\omega^2\left(\frac{\nu|b_\perp|R_i}{b_0}\right)^{\eta}C_i^2\frac{h_{\text{in}}^2}{2}\right. \\
& \left. + C_iC_A(h_A+v_A^{\text{in}}) + C_i n_f T_F h_f\right] \\
& + \left(\frac{i\,b^+\mu}{b_0R_i}\right)^{4\epsilon}\left[C_i^2\frac{s_{\text{out}}^2}{2} + C_iC_A(g_A+v_A^{\text{out}}) + C_i n_f T_F g_f\right] \\
& + \left(\frac{\mu|b_\perp|}{b_0}\right)^{2\epsilon}\left(\frac{ib^+\mu}{b_0R_i}\right)^{2\epsilon}\left(C_iC_A r_A(r) + C_i n_f T_F r_f(r)\right) \\
& + \left(\frac{\mu|b_\perp|}{b_0}\right)^{2\epsilon}\left(\frac{ib^+\mu}{b_0R_i}\right)^{2\epsilon}\left(\frac{\nu|b_\perp|R_i}{b_0}\right)^{\eta}\omega^2 C_i^2 h_{\text{in}} s_{\text{out}}.
\end{aligned}
$$

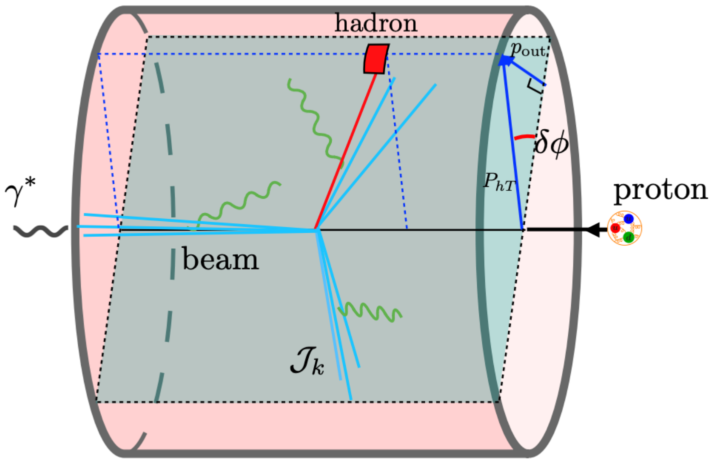


# NNLO QCD corrections for $P_{hT}$ distribution

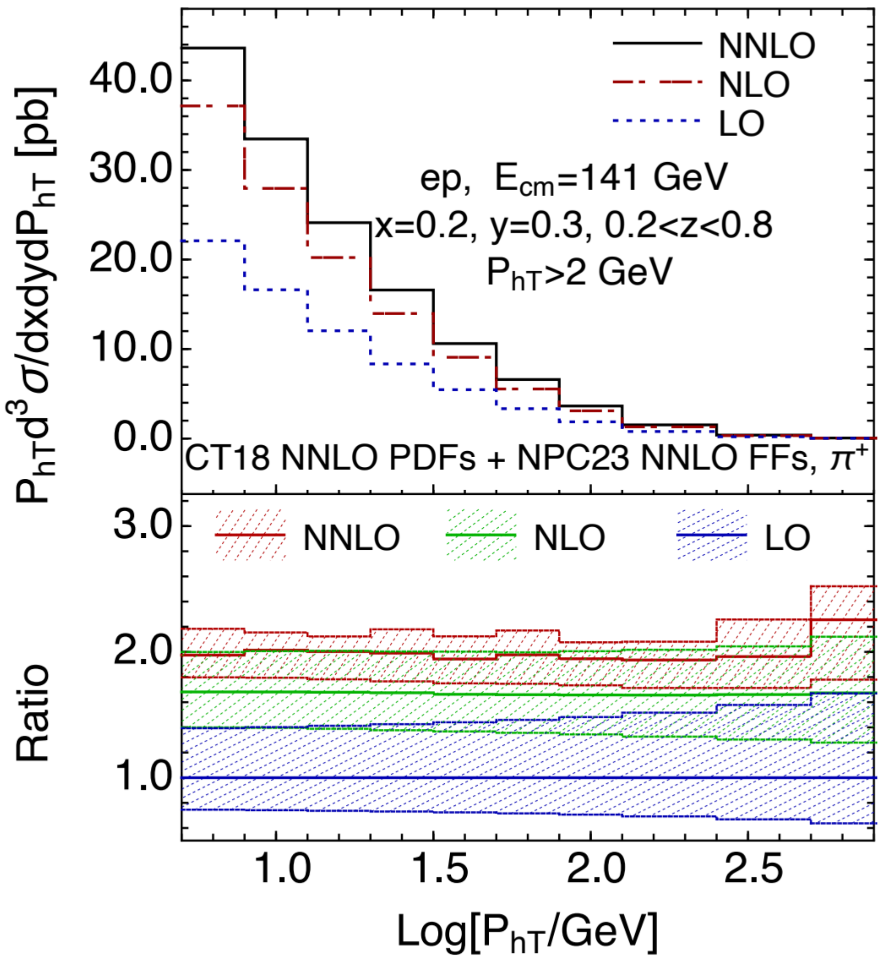
Dong(董亮), Fang(方申), Gao, DYS, Li, Zhu (朱雨蛟) 2602.22972

- **We present the first complete calculation of hadron production in DIS at finite transverse momentum to NNLO**

$$\frac{d\sigma}{d\mathcal{O}} = \int_0^{\delta\phi^{\rm cut}} d\delta\phi \frac{d\sigma}{d\delta\phi\, d\mathcal{O}} + \int_{\delta\phi^{\rm cut}}^{\delta\phi^{\rm max}} d\delta\phi \frac{d\sigma}{d\delta\phi\, d\mathcal{O}}$$



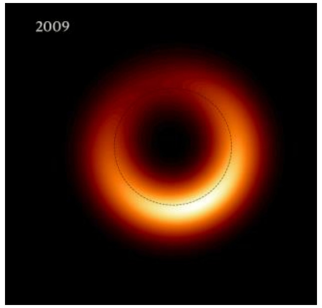

$$\frac{d\sigma_{\rm LP}}{dx\, dy\, dz\, d^2\vec{P}_{hT}\, dp_{\rm out}} = \int \frac{db}{2\pi} e^{ip_{\rm out} b/\zeta} \times \sum_{ijk} \int d\xi\, H_{ei\to ejk}(Q,\xi,\zeta) \times \mathcal{B}_{i/p}(\xi,b)\, \mathcal{D}_{h/j}(\zeta,b)\, \mathcal{J}_k(b)\, S_{ijk}(b)$$



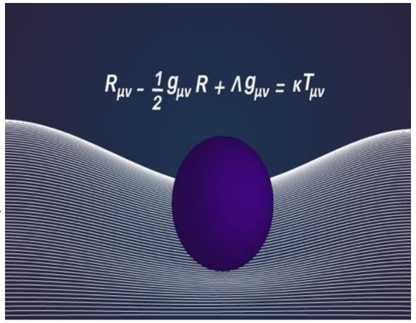

- **First N3LO SIDIS** Dong(董亮), Fang(方申), Gao, DYS, Li, Zhu (朱雨蛟) Zhu 2603.29673

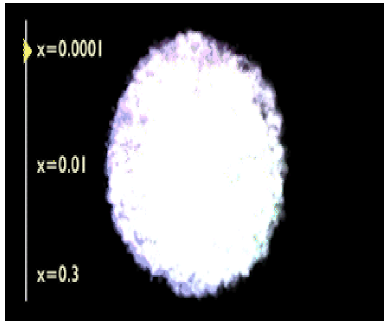
# 核子成像与喷注探针

- **核子成像** Also see J. Zhou’s talk



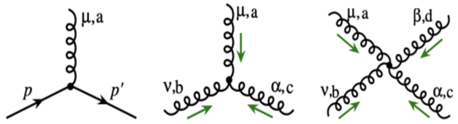

黑洞成像将深化人类对引力的理解



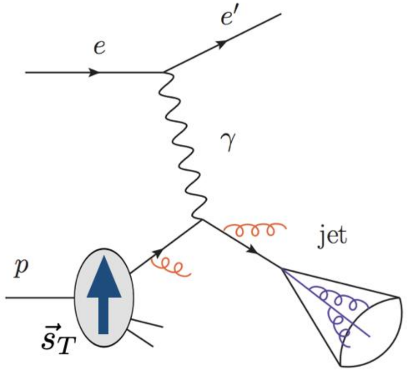



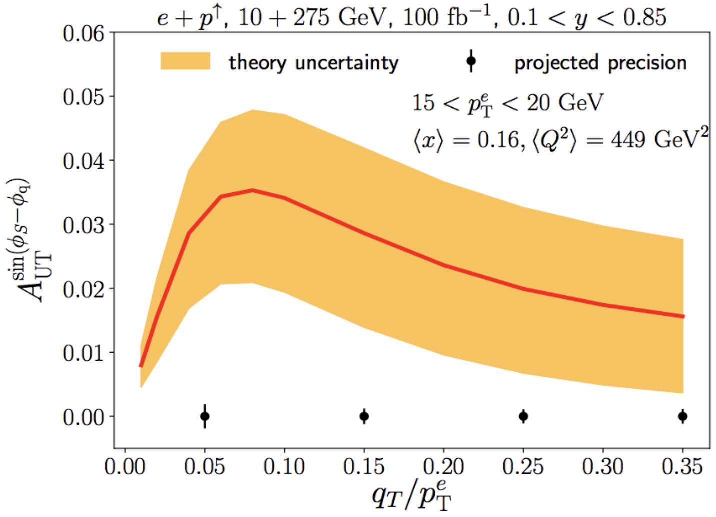

核子成像将深化人类对强力的理解

$$-\frac{1}{4}G^2_{\mu\nu,a}[A] + \sum_f \overline{\psi}_f \left(iD_\mu[A]\gamma^\mu - m_f\right)\psi_f$$




- **喷注及其精细结构为抽取核子分布函数提供了新的探针**
- **与传统SIDIS观测量相比可以有效分离出末态的非微扰信息**




Liu, Ringer, Vogelsang, Yuan 19
Arratia, Kang, Prokudin, Ringer 19

$$p(p_A, S_A) + e(p_B, \lambda_e) \to \left[\text{jet}(p_C)\, h\,(z_h, \boldsymbol{j}_\perp)\right] + e(p_D) + X$$

| JFF \ PDF | $\tilde{f}_1$ | $\tilde{f}_{1T}^{\perp(1)}$ | $\tilde{g}_{1L}$ | $\tilde{g}_{1T}^{(1)}$ |
|---|---|---|---|---|
| $\mathcal{D}_1$ | 1 | $\sin(\phi_q - \phi_{S_A})$ | 1 | $\cos(\phi_q - \phi_{S_A})$ |
| $\mathcal{D}_{1T}^\perp$ | $\sin(\hat\phi_h - \hat\phi_{S_h})$ | $\sin(\hat\phi_h - \hat\phi_{S_h})\sin(\phi_q - \phi_{S_A})$ | $\sin(\hat\phi_h - \hat\phi_{S_h})$ | $\sin(\hat\phi_h - \hat\phi_{S_h})\cos(\phi_q - \phi_{S_A})$ |
| $\mathcal{G}_{1L}$ | 1 | $\sin(\phi_q - \phi_{S_A})$ | 1 | $\cos(\phi_q - \phi_{S_A})$ |
| $\mathcal{G}_{1T}$ | $\cos(\hat\phi_h - \hat\phi_{S_h})$ | $\cos(\hat\phi_h - \hat\phi_{S_h})\sin(\phi_{S_A} - \phi_q)$ | $\cos(\hat\phi_h - \hat\phi_{S_h})$ | $\cos(\hat\phi_h - \hat\phi_{S_h})\cos(\phi_q - \phi_{S_A})$ |

| JFF \ PDF | $\tilde{h}_1^{\perp(1)}$ | $\tilde{h}_{1L}^{\perp(1)}$ | $\tilde{h}_1$ | $\tilde{h}_{1T}^{\perp(2)}$ |
|---|---|---|---|---|
| $\mathcal{H}_1^\perp$ | $\cos(\hat\phi_h - \phi_q)$ | $\sin(\phi_q - \hat\phi_h)$ | $\sin(\phi_{S_A} - \hat\phi_h)$ | $\sin(2\phi_q - \hat\phi_h - \phi_{S_A})$ |
| $\mathcal{H}_{1L}^\perp$ | $\sin(\hat\phi_h - \phi_q)$ | $\cos(\phi_q - \hat\phi_h)$ | $\cos(\phi_{S_A} - \hat\phi_h)$ | $\cos(2\phi_q - \hat\phi_h - \phi_{S_A})$ |
| $\mathcal{H}_1$ | $\sin(\hat\phi_{S_h} - \phi_q)$ | $\cos(\phi_q - \hat\phi_{S_h})$ | $\cos(\phi_{S_A} - \hat\phi_{S_h})$ | $\cos(2\phi_q - \hat\phi_{S_h} - \phi_{S_A})$ |
| $\mathcal{H}_{1T}^\perp$ | $\sin(2\hat\phi_h - \hat\phi_{S_h} - \phi_q)$ | $\cos(2\hat\phi_h - \hat\phi_{S_h} - \phi_q)$ | $\cos(2\hat\phi_h - \hat\phi_{S_h} - \phi_{S_A})$ | $\cos(2\hat\phi_h - \hat\phi_{S_h} + \phi_{S_A} - 2\phi_q)$ |

Kang, Lee, DYS, Zhao ‘21

# Accessing Nucleon Transversity via One-Point Energy Correlators

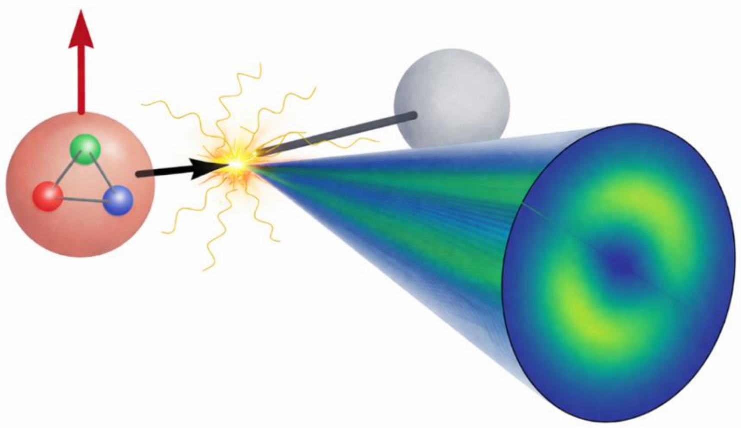
Gao(高梅森), Kang, Li(李婉辰), DYS PRL 136 (2026) 151902

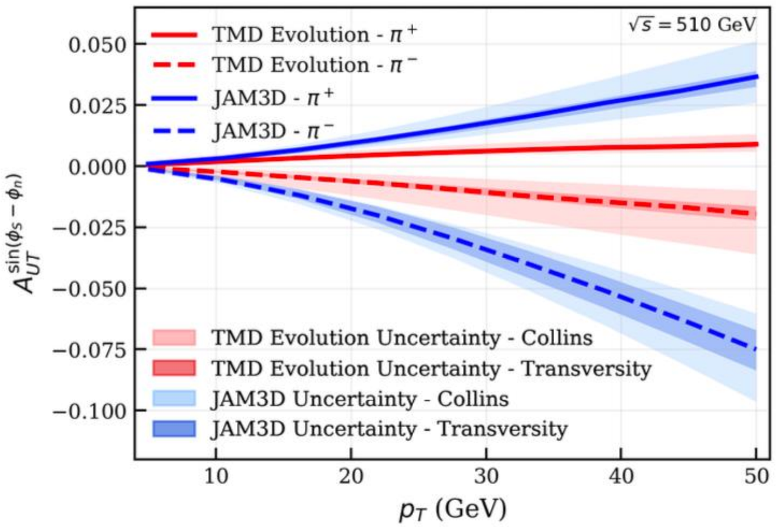
- **Transversity distribution $h_1^q$ is a fundamental, yet less known, parton distribution.**
- **Its chiral-odd nature prevents access via inclusive DIS**
- **Nucleon tensor charge $\delta q$ is essential for BSM search, Lattice QCD benchmarks**
- **We introduce the one-point energy correlator (OPEC) to probe the nucleon transversity**

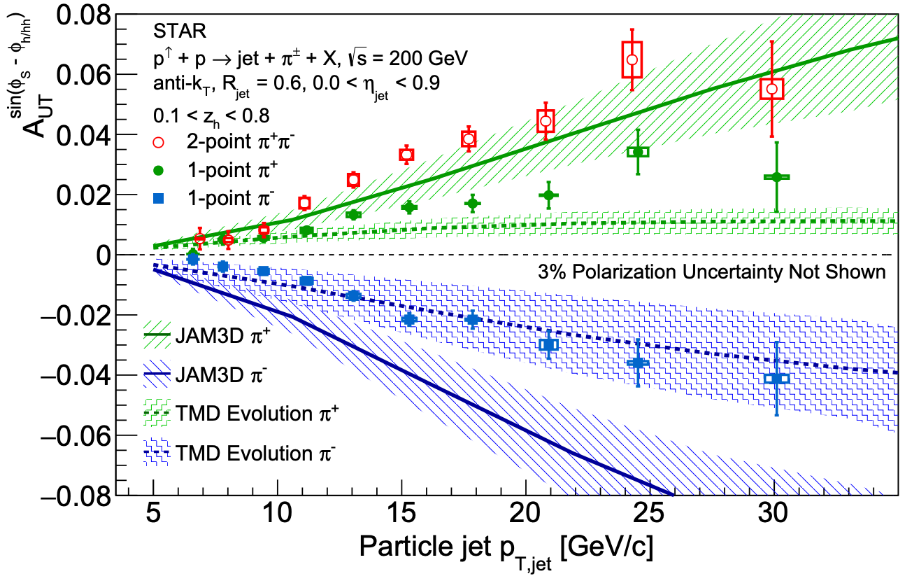
$$\Delta^q(z,\hat{\boldsymbol{n}}) = \sum_X \sum_{i\in J} \langle \Omega|\bar{\chi}_n \delta_{Q,\mathcal{P}_n} \delta^{(2)}(\hat{\boldsymbol{n}} - \hat{\boldsymbol{n}}_i)|JX\rangle \frac{E_i}{E_J} \langle JX|\chi|\Omega\rangle$$

Also see H. X. Zhu & X. H. Liu's talks

RHIC-STAR 2604.15543

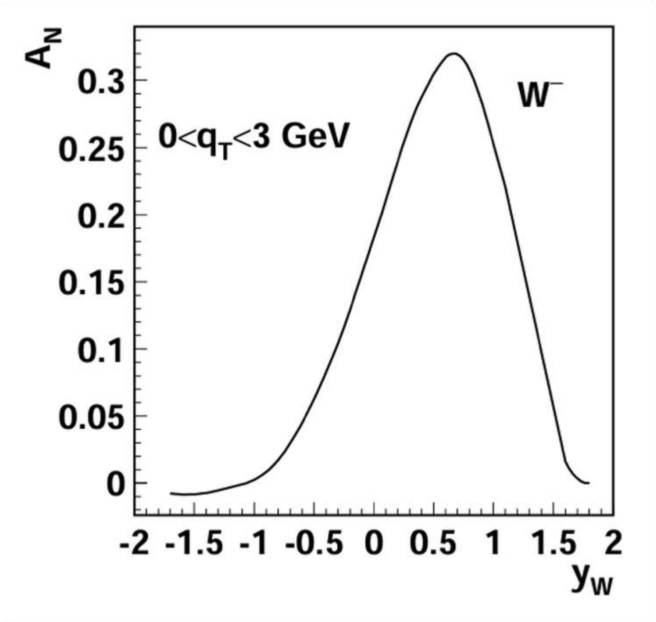




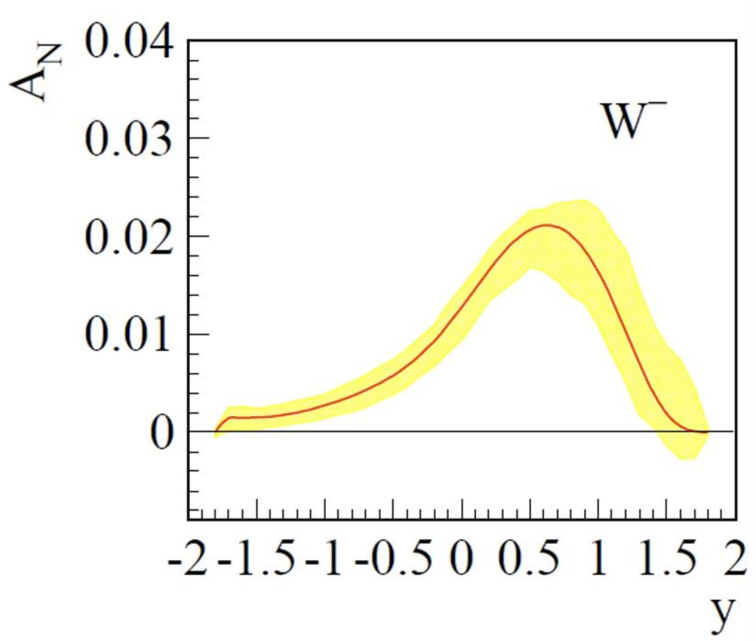
# Spin asymmetry and QCD evolution

## Without evolution




Kang & Qiu ‘09

## With evolution




Echevarria, Idilbi, Kang, Vitev ’14

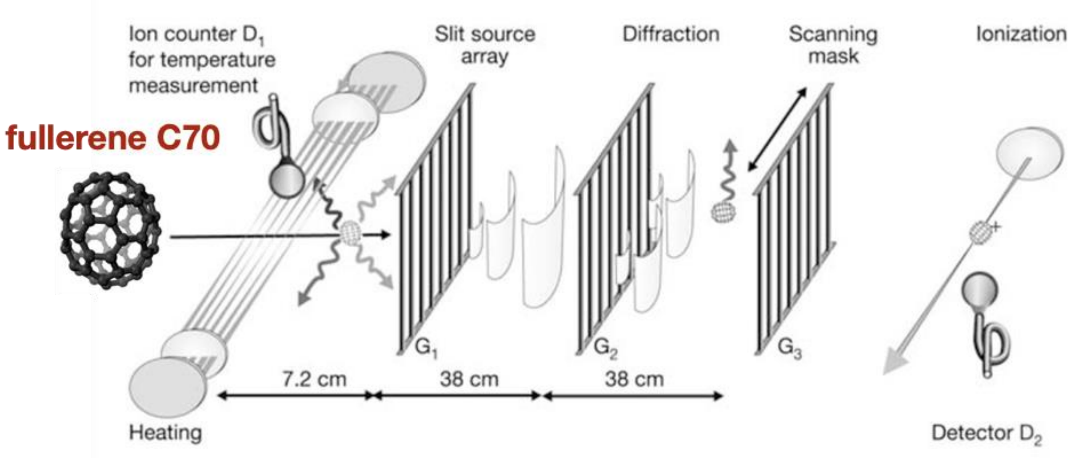
- Soft and collinear radiation destroy superposition
- Soft radiation decohere the directions of the momenta and the gauge representations of the particles
- Collinear radiation decohere the energies and the spin

Carney, Chaurette, Neuenfeld, Semenof ’17
Neill, Waalewijn ’19
S.J. Lin, M.J. Liu, DYS, S.Y. Wei ‘25
J.Y. Gu, S.J. Lin, DYS, S.X. Yang, L.T Wang ’25
… …

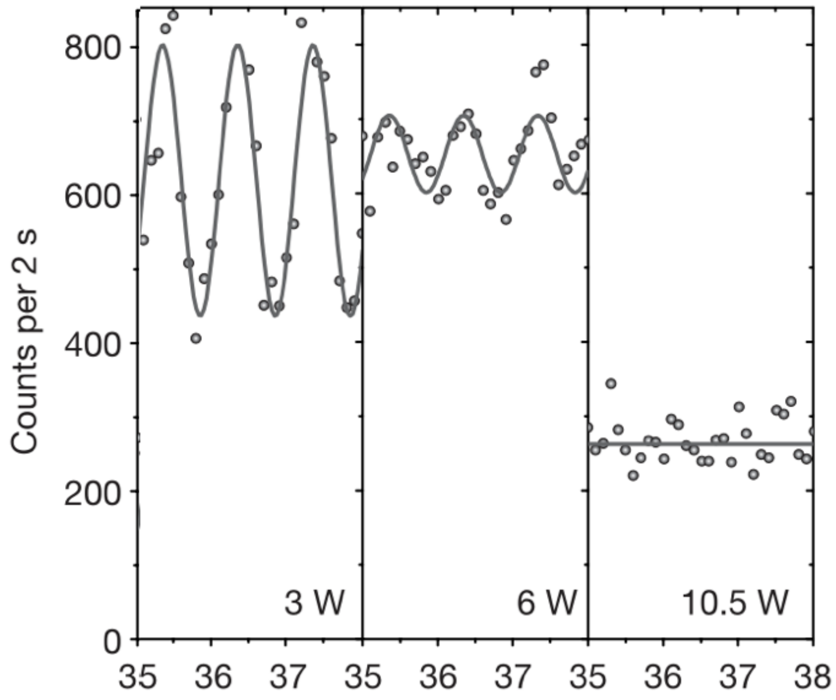
**Evolution reduces the asymmetry**

# 热光子辐射引起的退相干

Hackermuller, Hornberger, Brezger, Zeilinger, Arndt  Nature ‘04




- 塔尔博特-劳厄干涉仪
- 在进入干涉仪之前，C70分子会穿过一束激光以提高温度
- 温度调节范围从低于1000K（低温）至3000K（高温）



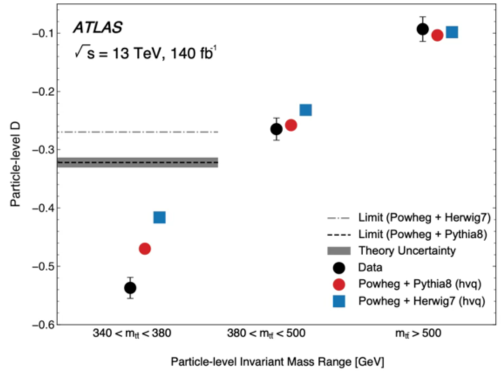

- 低温：
  - 分子辐射可忽略不计
  - 结果：观测到清晰的干涉条纹

- 高温：
  - 分子发射携带路径信息的热光子
  - 结果：干涉条纹可见度降至0%

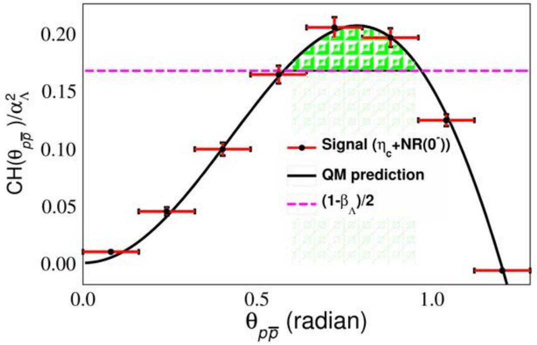
**辐射可以导致退相干**

# Quantum information science meets high energy physics

**The study of quantum information in high-energy collider physics is rapidly transitioning from a theoretical curiosity to an experimental reality.**

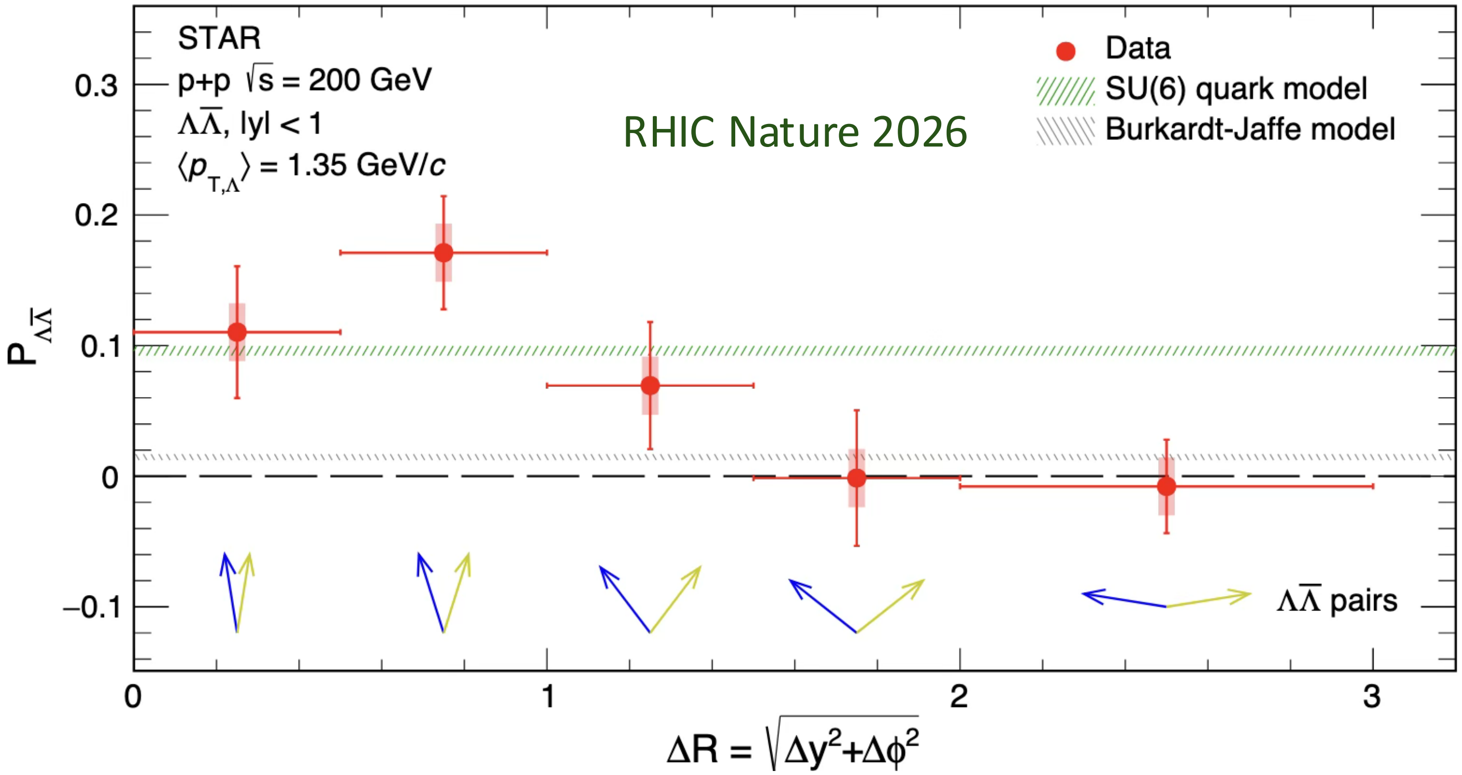



ATLAS Nature 2024




BESIII Nature Communications 2025

"Measuring spin correlation between quarks during QCD confinement"



# Effective field theory for decoherence

S.J. Lin(林士佳), M.J. Liu(刘铭钧), DYS, S.Y. Wei 25 JHEP; J.Y. Gu, S.J. Lin(林士佳), DYS, S.X. Yang(杨斯翔), L.T Wang 25

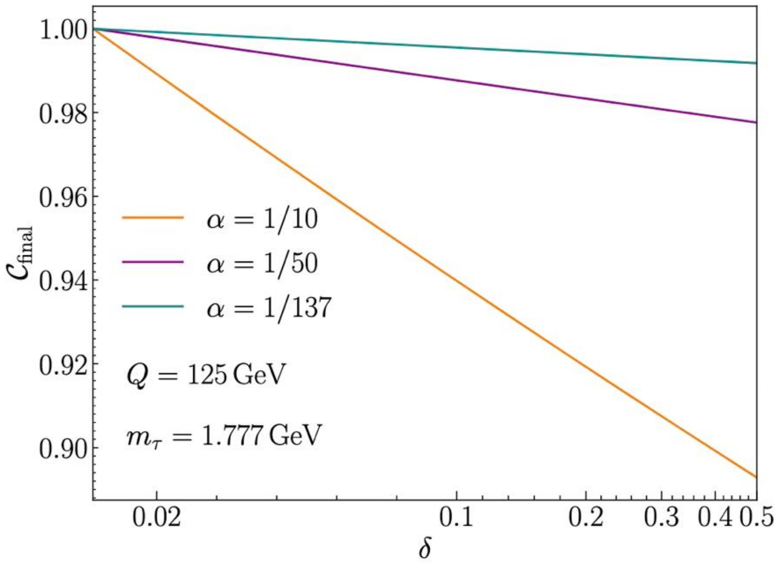
- **A systematic framework calculating decoherence in high energy collisions by combing SCET with the formalism of open quantum systems.**
- **The renormalization group evolution constitutes a quantum channel, where the RG flow parameter, rather than time, drives a Markovian loss of quantum coherence.**
- **E.g. Applications in QED processes** $e^+e^- \to l^+l^- + n\gamma$
- **Lindblad equation and jump operators**

$$\frac{\mathrm{d}\hat{\rho}_{\text{eff}}}{\mathrm{d}t} = -\frac{\alpha}{2\pi}\hat{\rho}_{\text{eff}} + \frac{\alpha}{4\pi}\left[(\hat{\sigma}_3 \otimes \mathbb{I})\,\hat{\rho}_{\text{eff}}\,(\hat{\sigma}_3 \otimes \mathbb{I}) + (\mathbb{I} \otimes \hat{\sigma}_3)\,\hat{\rho}_{\text{eff}}\,(\mathbb{I} \otimes \hat{\sigma}_3)\right]$$

$$t \equiv \log(Q\delta/\mu) \qquad \hat{L}_1 = \sqrt{\alpha/4\pi}\,\hat{\sigma}_3 \otimes \mathbb{I} \qquad \hat{L}_2 = \sqrt{\alpha/4\pi}\,\mathbb{I} \otimes \hat{\sigma}_3$$

- **Each “jump” corresponds to an unresolved collinear photon emission from either of the fermion legs, which induces a stochastic phase-flip quantum channel**
- **Reduction of the concurrence**

$$\mathcal{C}(t) = \mathcal{C}(0)e^{-\frac{\alpha}{\pi}t}$$




**decoherence = RG flow**

anomalous dimensions in RGE determine the information loss

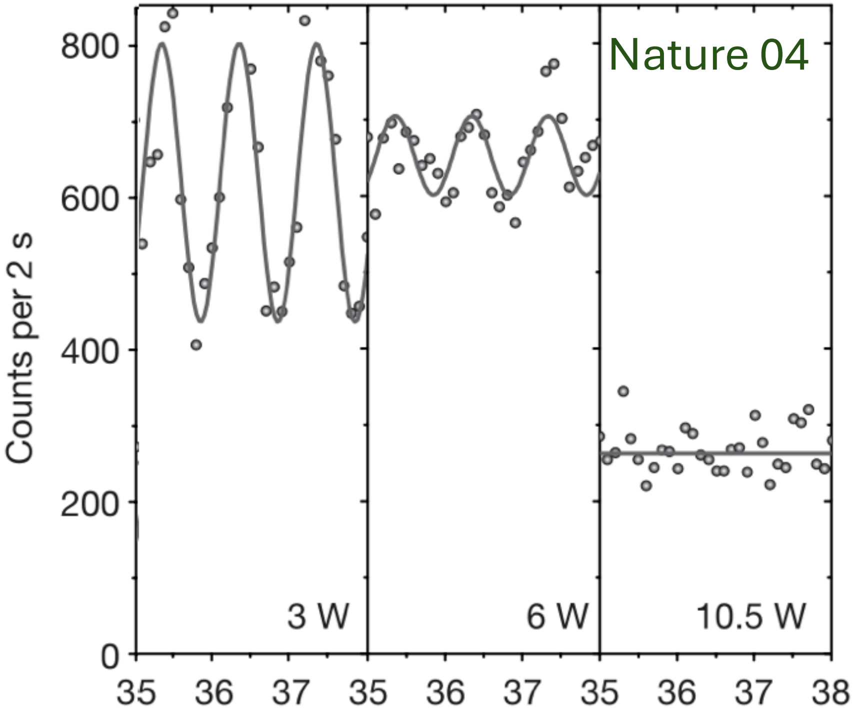
# Nucleon tomogr

沐硕), DYS, Zhou PRL136 (2026)021901

$$\frac{\ \ \vec{S}_T)}{S} = F_{UU} + \sin(\phi_s - \phi_q) F_{UT}^{\sin(\phi_s-\phi_q)}$$

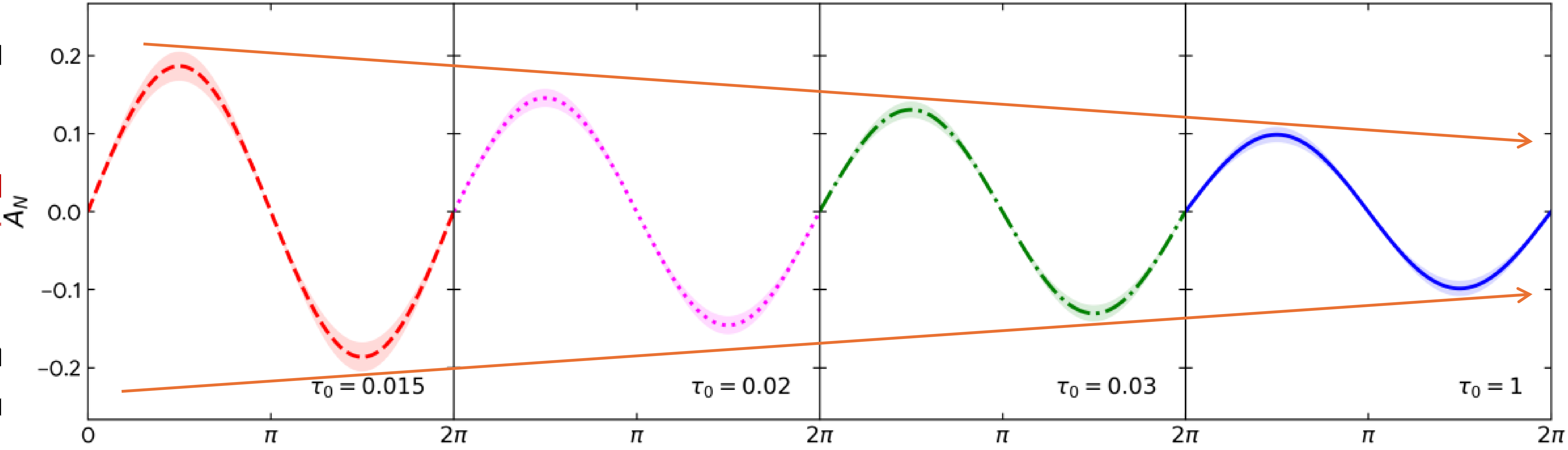
$$f_q(x, k_T) \qquad \frac{1}{M}\epsilon_{\alpha\beta}\, s_T^{\alpha}\, k_T^{\beta}\, f_{1T}^{\perp q}(x, k_T)$$

- TMDs encode the quantum corr polarization and the motion and gluons
- However, at high energies, initia environmental noise, causing de these signals.




- We intr into a tu

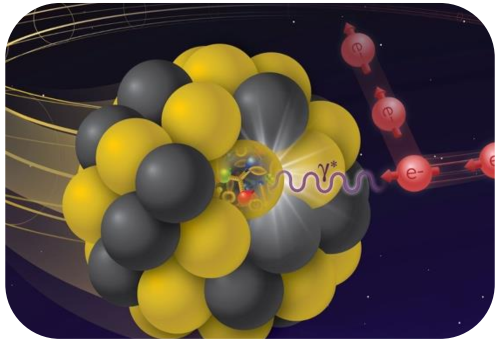
**Modified Sukakov**



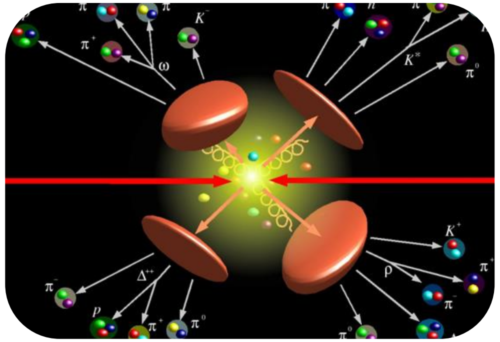

- We den asymm

# 总结与展望

**QCD对撞机物理研究从“总截面”的宏观成功，迈向“微分与极化”的微观精密时代**



QCD因子化
SCET



核子结构与自旋物理

喷注物理与精确计算

纠缠

退相干

量子信息的视角

# 谢谢