



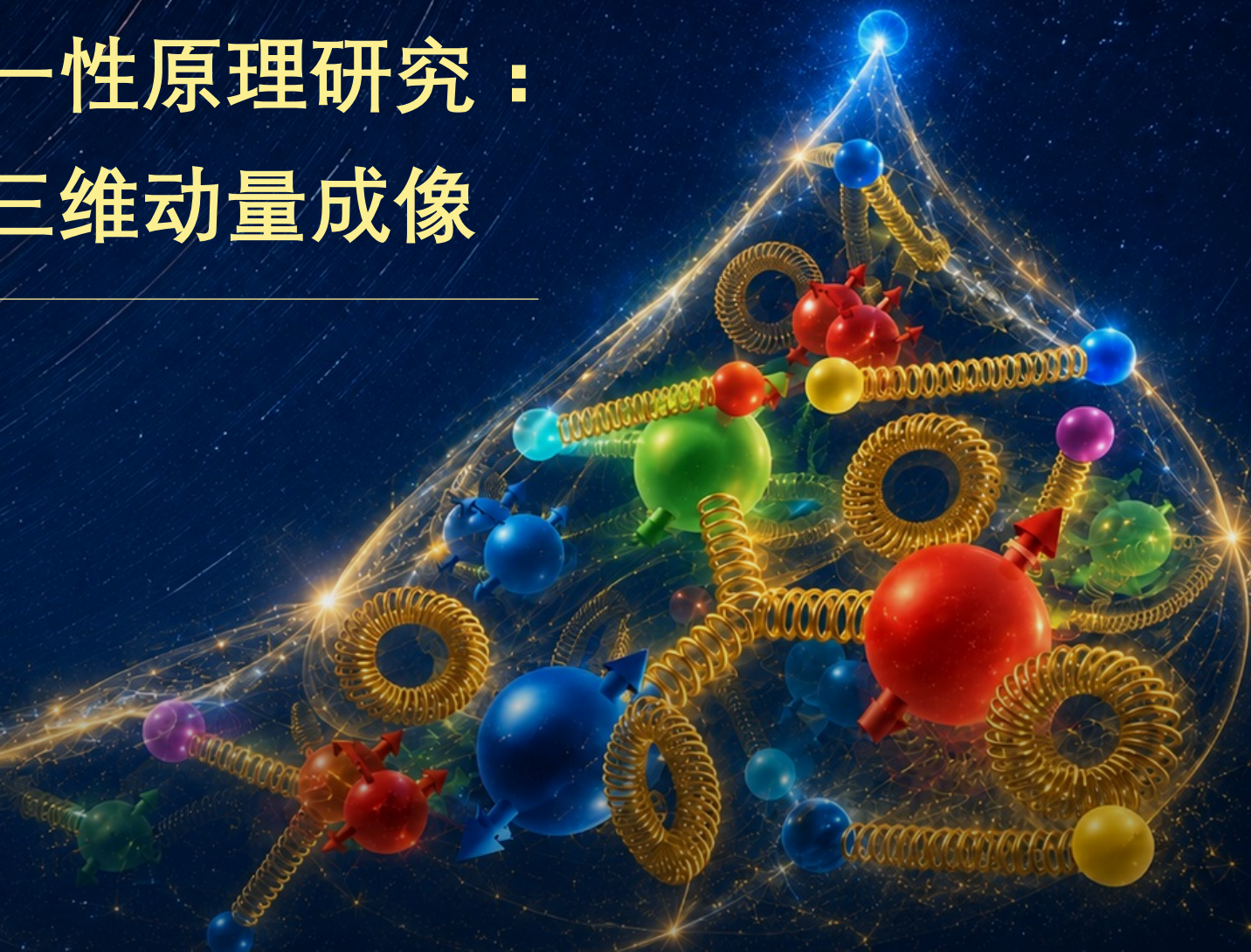
北京航空航天大学
BEIHANG UNIVERSITY

核子部分子结构的第一性原理研究： 从极化部分子分布到三维动量成像

张其安, 北京航空航天大学



2026/07/15 @ 广州

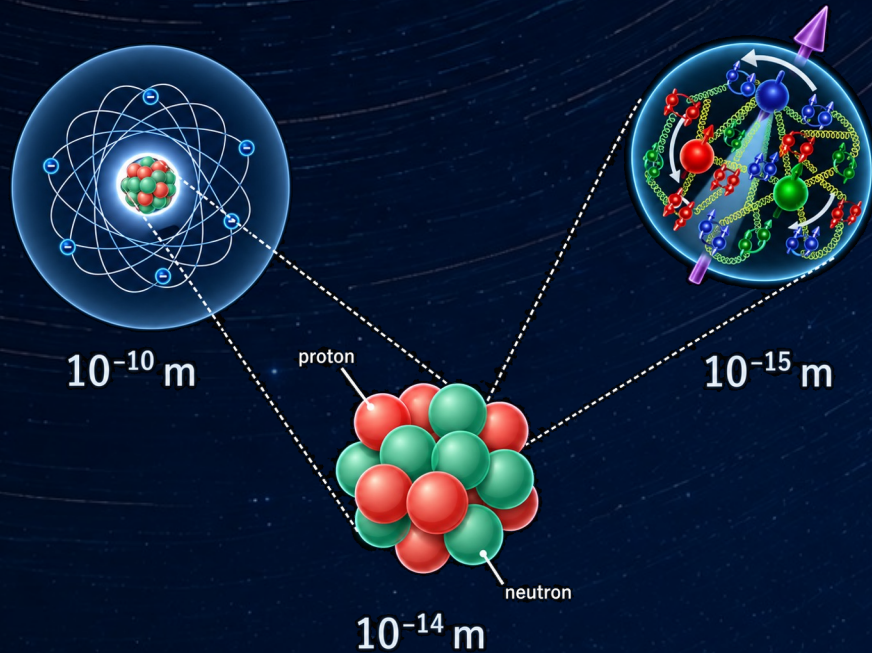


OUTLINE

- **Motivation**
- **Polarized PDF Ratio: Spin Alignment of Quarks**
- **Quark TMDPDFs: 3D Momentum Tomography of Nucleon**
- **Summary and Outlook**

Nucleons: Building Blocks of the Visible Universe

Despite more than half a century of exploration, the nucleon is still a very mysterious object, and the most abundant piece of matter in the visible Universe

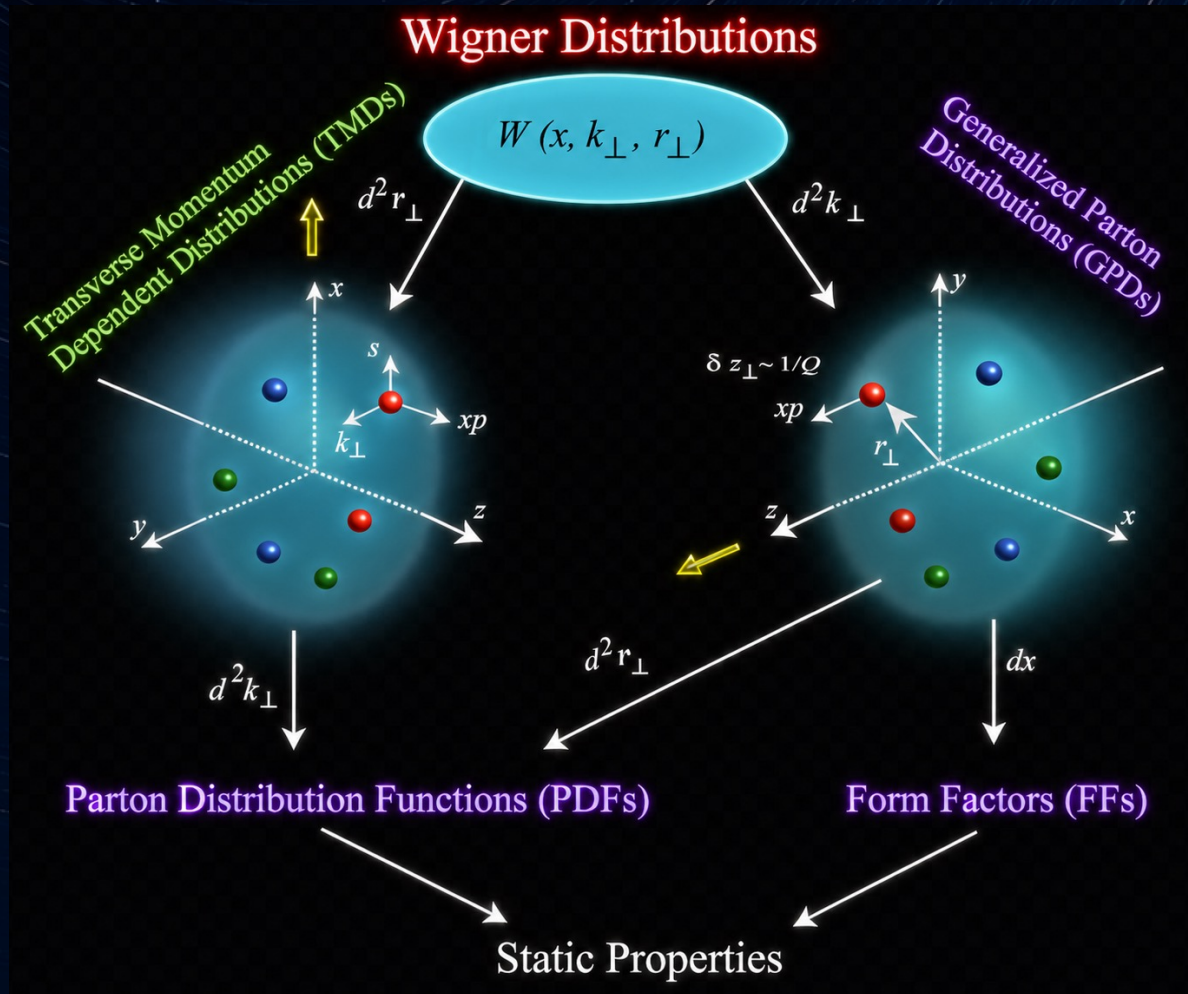


- How do quarks & gluons form the nucleon, how do they distribute?
- How do these distributions and partonic orbital motion generate the nucleon spin?

— *1st of the 3 central science questions driving the EIC program.*

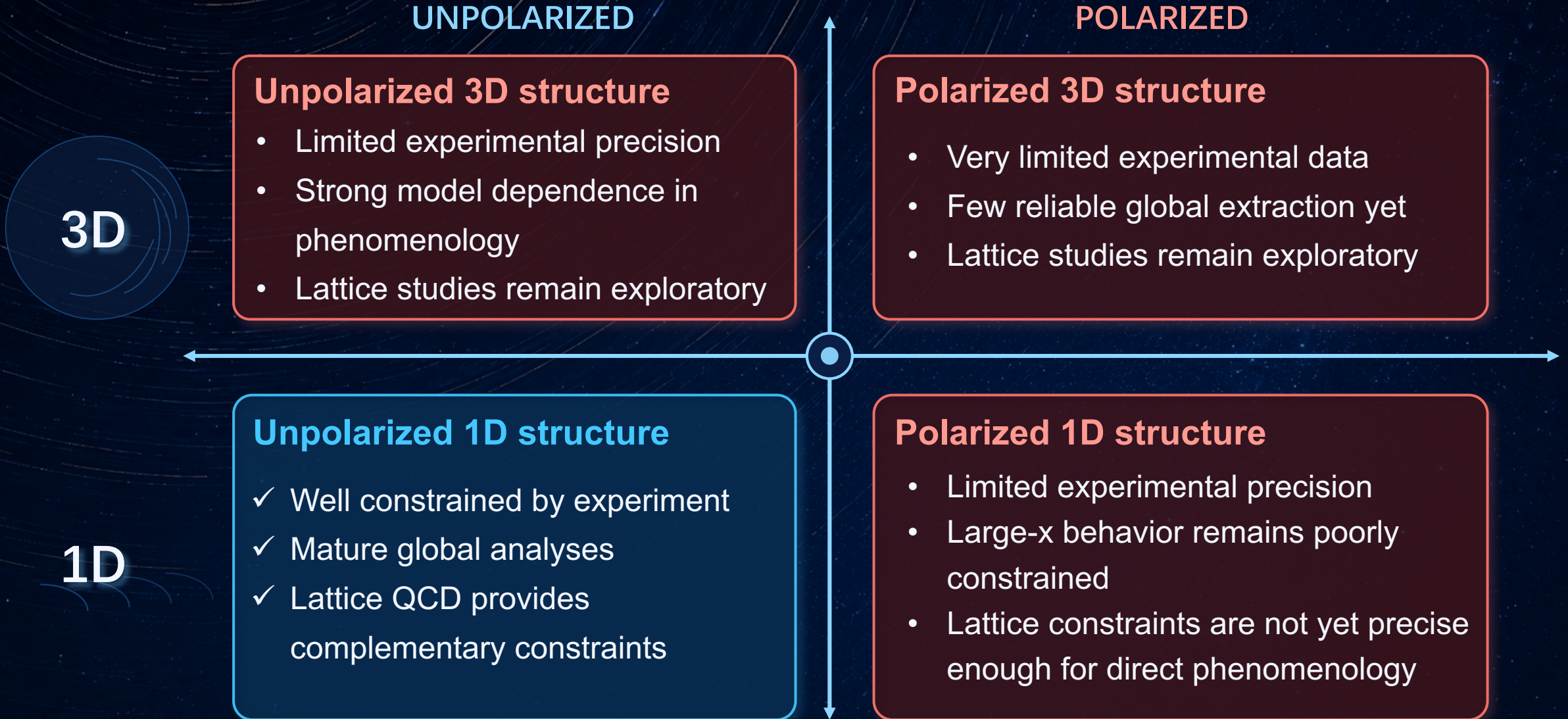
Adapted from the White Paper of EIC, EPJA52, 268 (2016).

The Landscape of Nucleon Structure



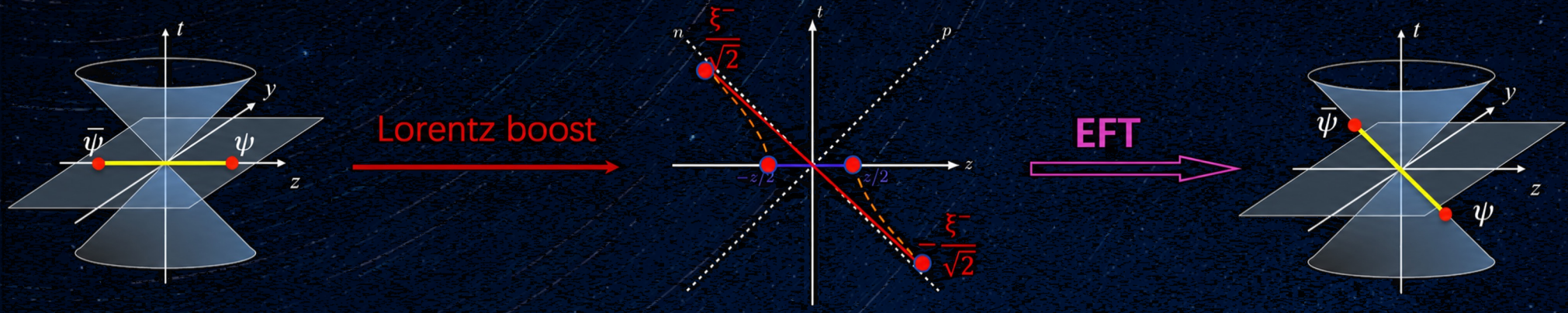
- Wigner distribution (5-D)
Not directly accessible in experiments
- TMDs and GPDs (3-D)
- PDFs and Form Factors (1-D)
- Spins, charge, magnetic moment, charge radius, ... (0-D)
Have been determined with high precision

Status of the 1D & 3D Nucleon Structure



LaMET: A New Horizon for Nucleon Structures from LQCD

Large-momentum effective theory (LaMET): connecting Euclidean lattice and physical observables



- Equal-time distributions can be directly computed in lattice QCD:

*Ji, PRL110, 262002 (2013), see
Rev.Mod.Phys.93, 035005 (2021)
for review*

$$\tilde{q}(x, P^z) = \int \frac{dz}{2\pi} e^{-izP^z} \langle P^z | \bar{\psi}(z) \Gamma \mathcal{U}(z, 0) \psi(0) | P^z \rangle$$

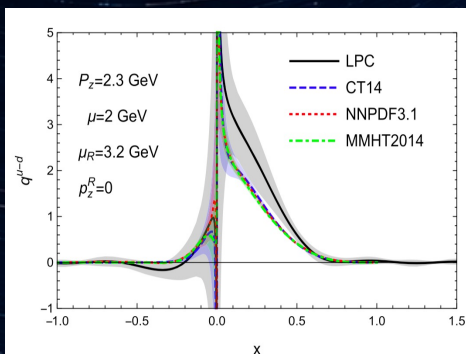
- Recovering light-cone distributions in the large-momentum limit:

$$q(y, \mu) = \int_{-\infty}^{+\infty} \frac{dx}{|x|} \mathcal{C}\left(\frac{y}{x}, \frac{\mu}{xP^z}\right) \tilde{q}(x, P^z) + \mathcal{O}\left(\frac{M^2}{(P^z)^2}, \frac{\Lambda_{\text{QCD}}^2}{(yP^z, (1-y)P^z)^2}\right)$$

LaMET: A New Horizon for Nucleon Structure from Lattice

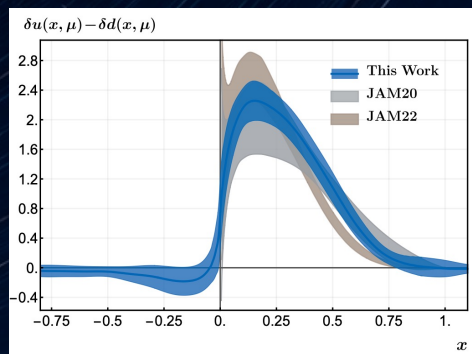
- Significant progress has been made on PDFs, LCDAs, TMDs, and more: @ 孙鹏、华俊's talk

Unpolarized PDF



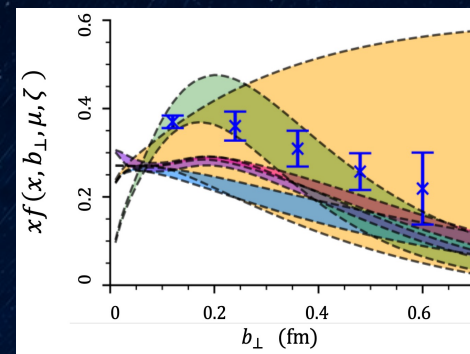
LPC, 2020

Transversity PDF



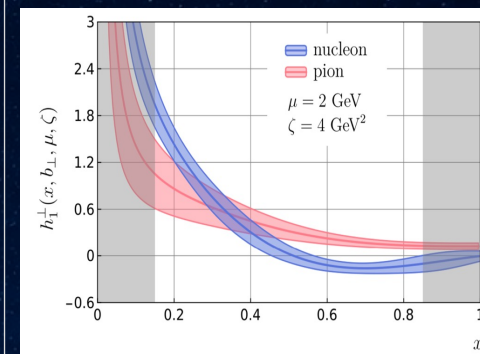
LPC, 2024

Unpolarized TMDPDF



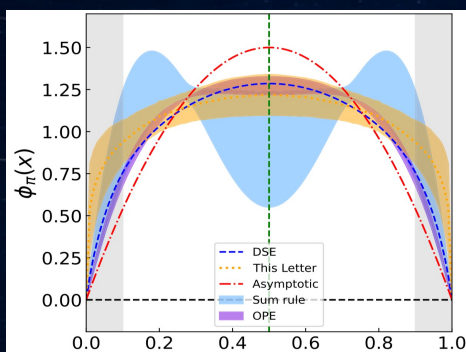
LPC, 2024

Boer-Mulders Function



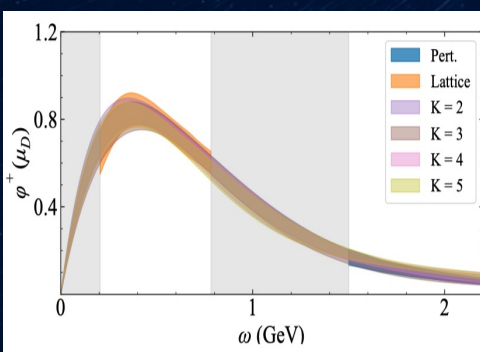
LPC, 2025

Light Meson LCDA



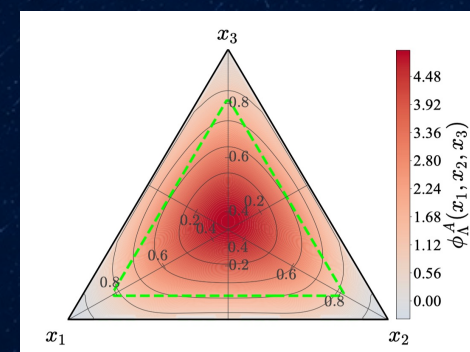
LPC, 2022

Heavy Meson LCDA



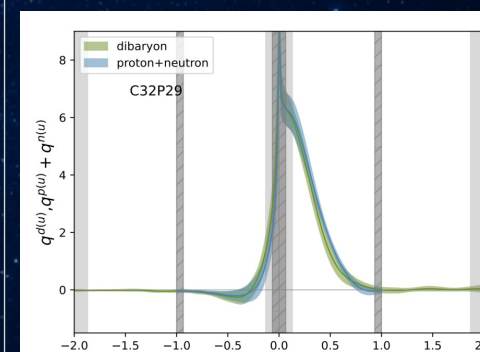
LPC, 2026

Baryon LCDA



LPC, 2026

Deuteron PDF

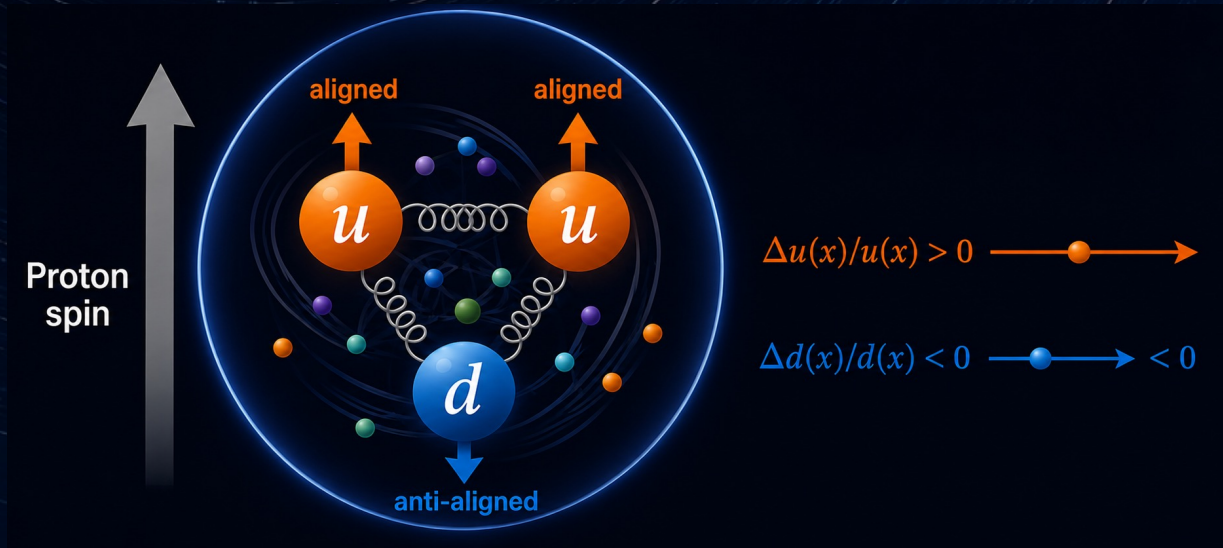


LPC, 2025

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Ratios of Polarized PDFs



- Quark helicity PDF:

$$\Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$$

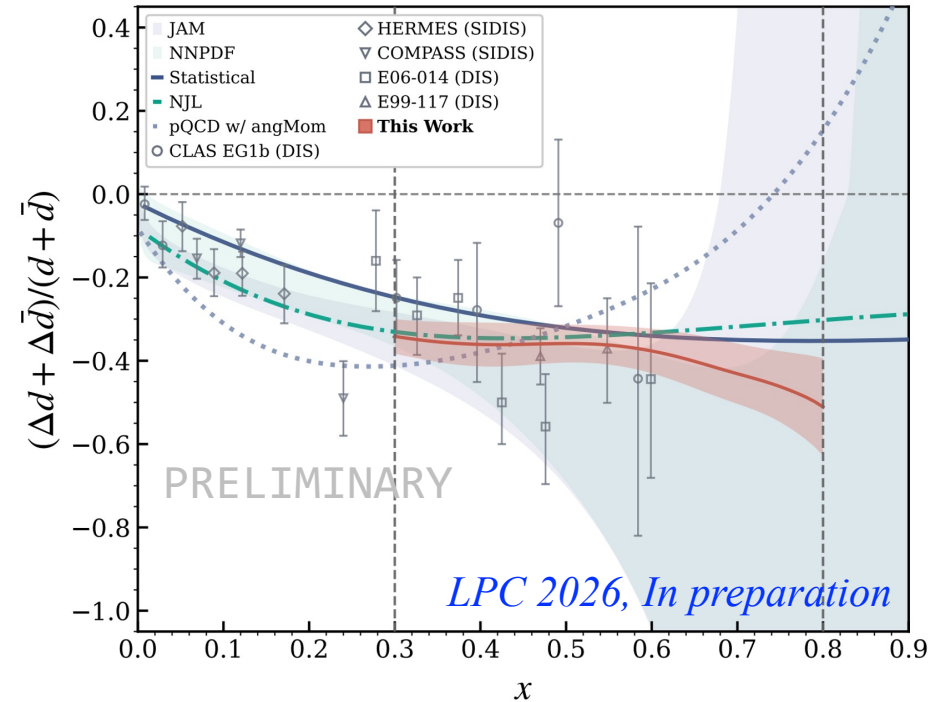
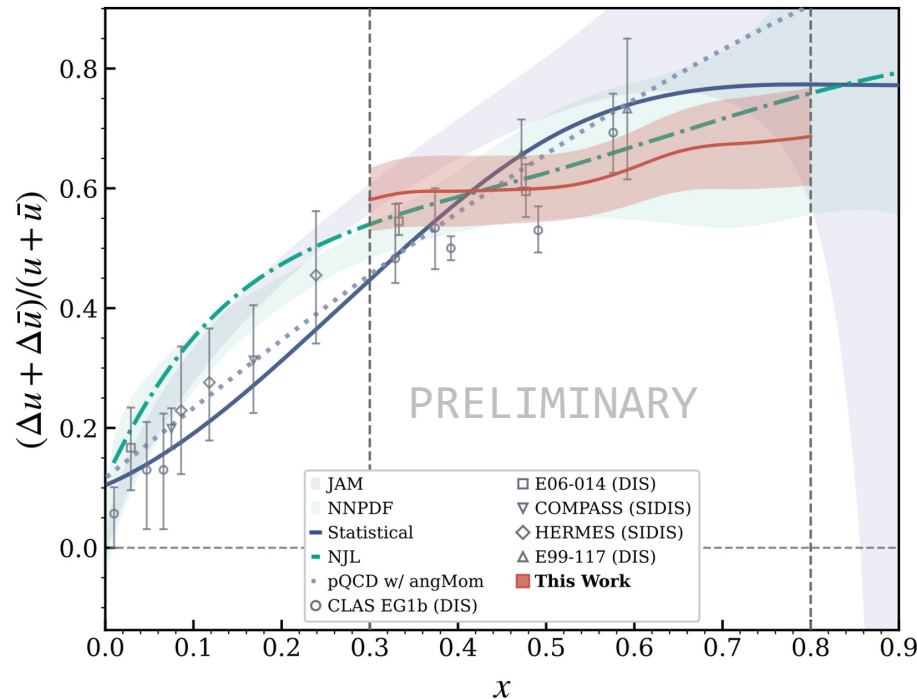
- Quark unpolarized PDF:

$$q(x) = q^{\uparrow}(x) + q^{\downarrow}(x)$$

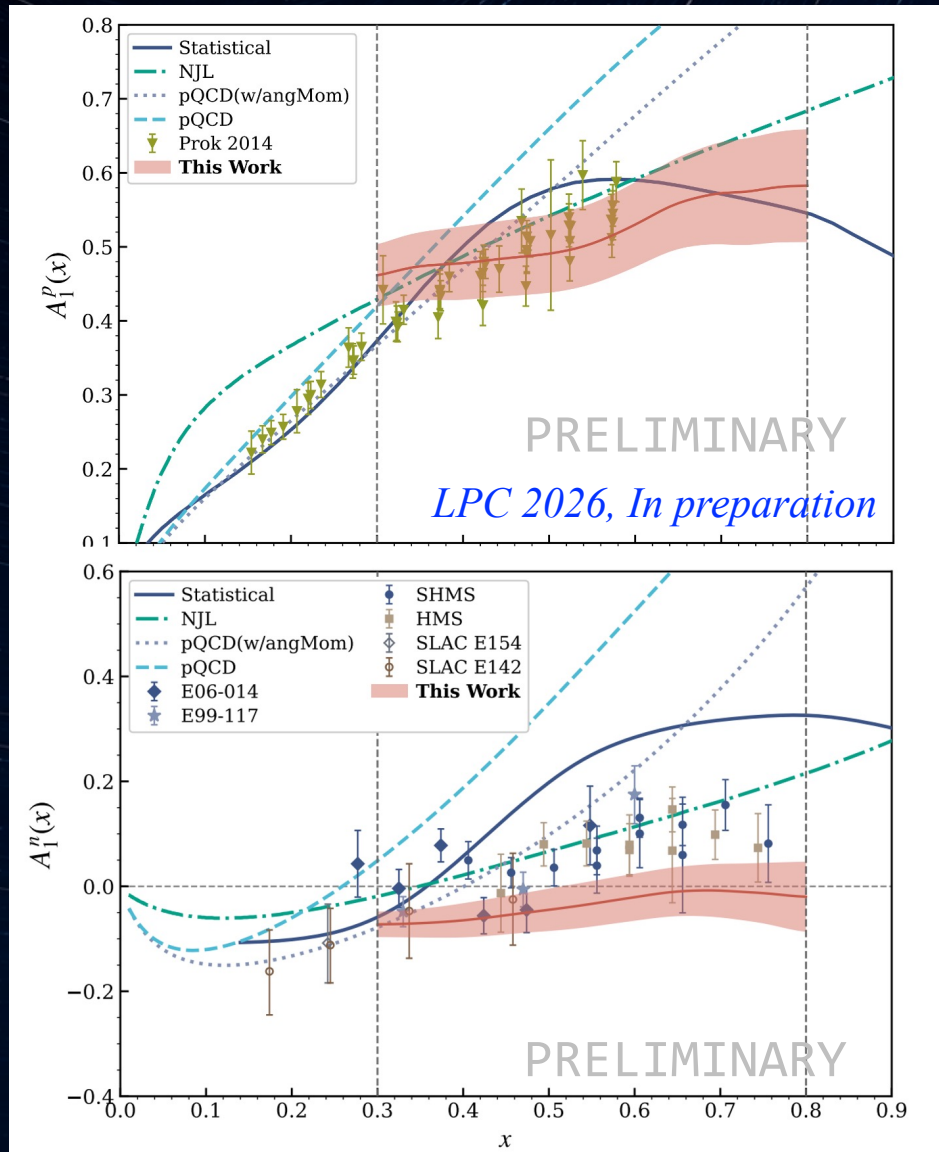
$\Delta q(x)/q(x)$ encodes the longitudinal spin alignment of quarks inside the proton, providing a clean probe of its spin-flavor structure

Ratios of Polarized PDFs from Lattice QCD

- u -quark polarization ratio is positive and rises with x
- d -quark polarization ratio remains negative throughout the accessible x region



Predictions for Nucleon Spin Asymmetries



- A_1 is the ratio between polarized structure function g_1 and unpolarized structure function F_1 :

$$A_1^N(x, Q^2) \simeq \frac{g_1^N(x, Q^2)}{F_1^N(x, Q^2)}$$

- Neglecting the strange quark, sea quark flavor separation and higher-twist corrections, the proton and neutron asymmetries:

$$A_1^p(x) \simeq \frac{4\Delta u(x) + \Delta d(x)}{4u(x) + d(x)},$$

$$A_1^n(x) \simeq \frac{\Delta u(x) + 4\Delta d(x)}{u(x) + 4d(x)}.$$

Y. Prok et al. (CLAS), PRC 90, 025212 (2014).

D. Flay et al. (JLab Hall A), PRD 94, 052003 (2016).

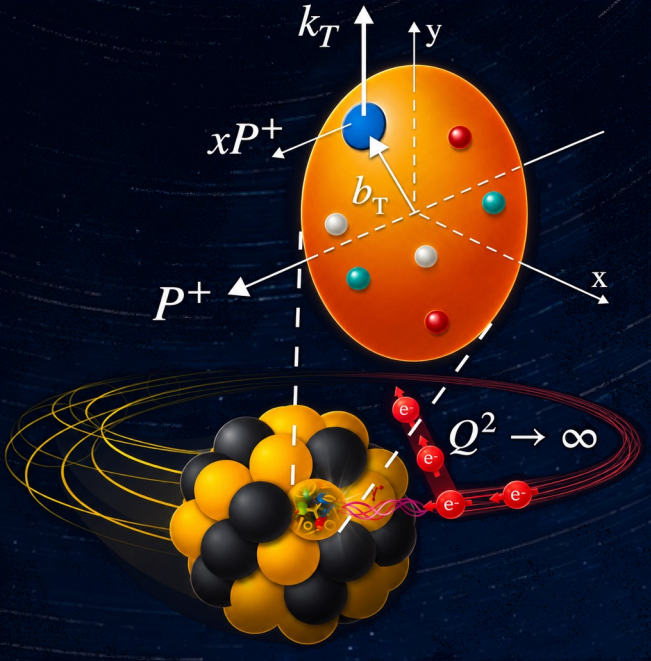
X. Zheng et al. (JLab Hall A), PRL 92, 012004 (2004);

X. Zheng et al., PRC 70, 065207 (2004).

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TMDs: 3D Momentum Tomography of Nucleon

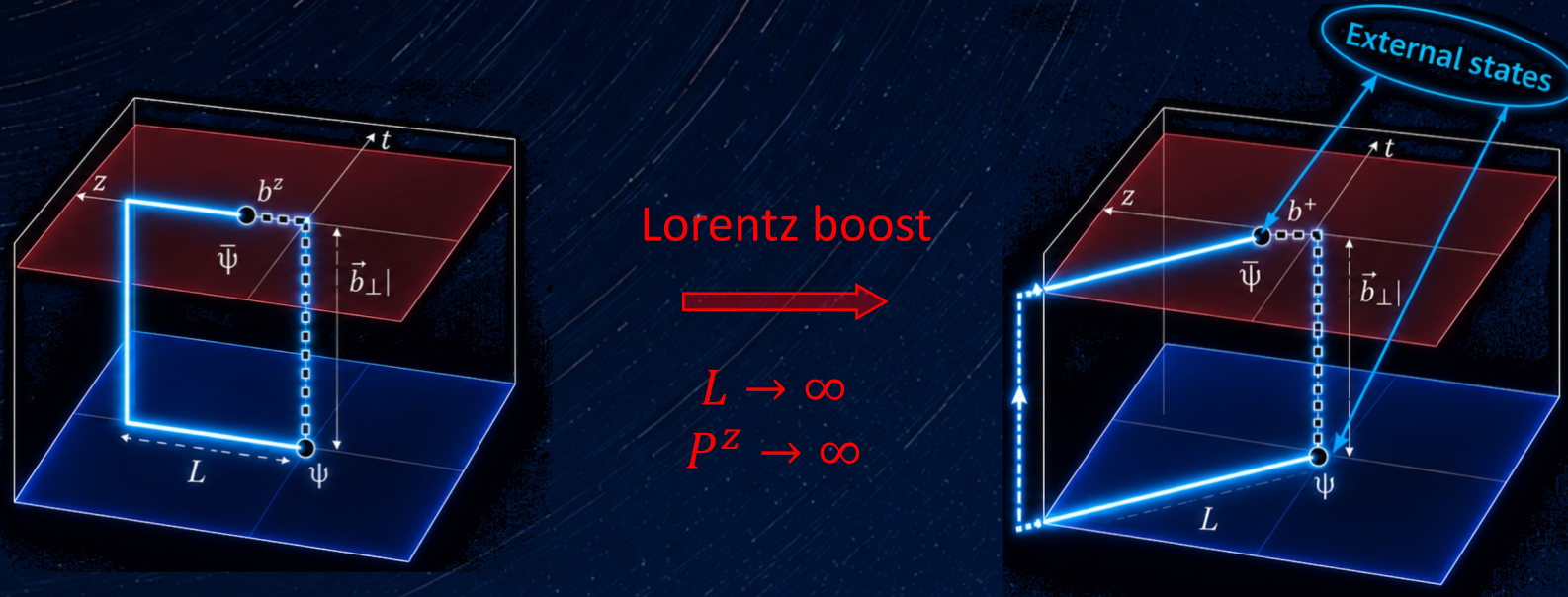


TMDs: Spin-dependent 3D momentum space images from semi-inclusive scattering

Leading Quark TMDPDFs		↑ Nucleon Spin → Quark Spin		
		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \text{Unpolarized}$		$h_1^\perp = \text{Boer-Mulders}$
	L		$g_1 = \text{Helicity}$	$h_{1L}^\perp = \text{Worm-gear}$
	T	$f_{1T}^\perp = \text{Sivers}$	$g_{1T}^\perp = \text{Worm-gear}$	$h_1 = \text{Transversity}$ $h_{1T}^\perp = \text{Pretzelosity}$

TMDs from LQCD within LaMET

Quasi-TMDs: Equal-time correlators with staple-shaped Wilson lines, **lattice calculable**



Factorization in LaMET:

PLB811, 135946 (2020); JHEP04, 178, (2022)

Perturbative matching kernel

$$\tilde{f}_\Gamma(x, b_\perp, \mu, \zeta^z) \sqrt{S_I(b_\perp, \mu)} = H_\Gamma(\zeta^z, \mu) \exp\left[\frac{1}{2} K(b_\perp, \mu) \ln \frac{\zeta^z}{\zeta}\right] f(x, b_\perp, \mu, \zeta) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{\zeta^z}, \frac{M^2}{(P^z)^2}, \frac{1}{b_\perp^2 \zeta^z}\right)$$

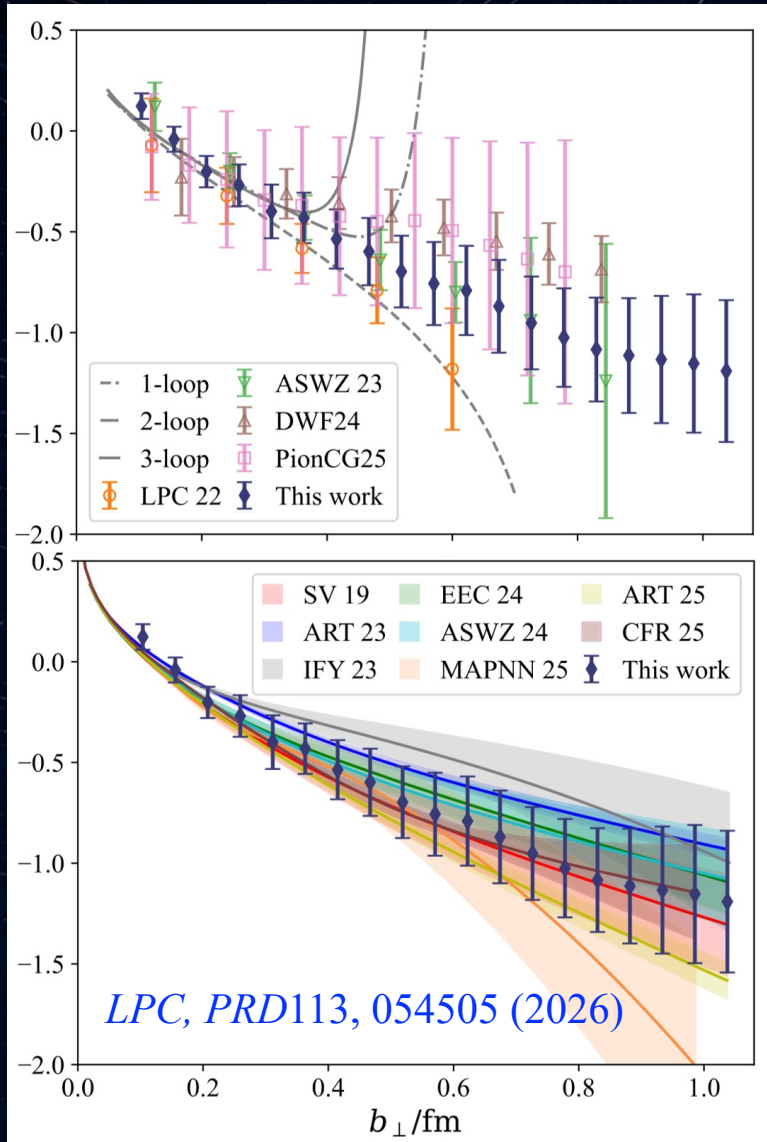
Quasi TMDs

Intrinsic Soft Function

Collins-Soper kernel

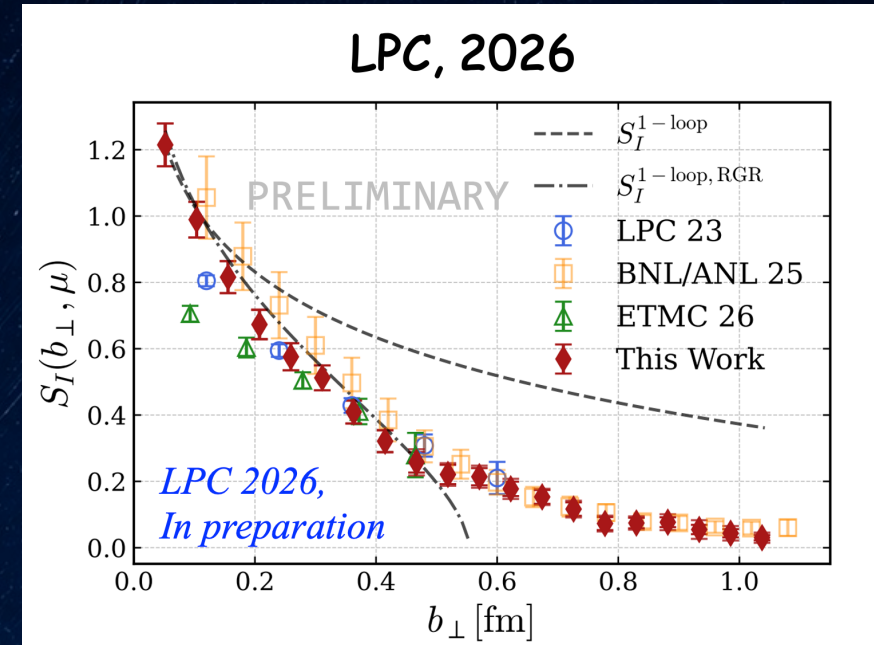
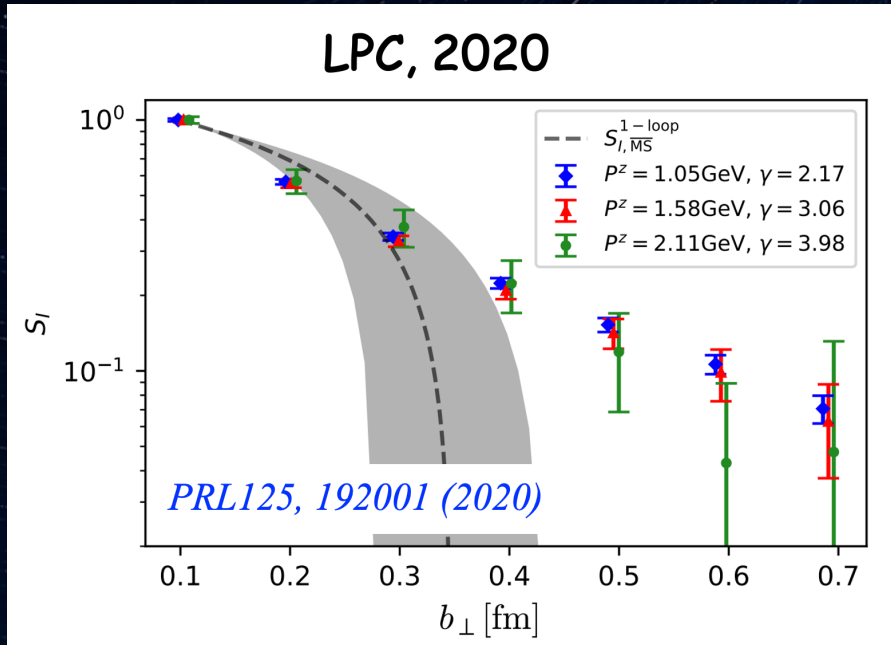
Light-cone TMDs

Collins-Soper Kernel from Lattice QCD



- A benchmark quantity for lattice TMD studies
 - ✓ Continuum, physical mass, and infinite-momentum limits are now being addressed
 - ✓ Lattice QCD provides first-principles constraints up to $b_{\perp} \sim 1\text{fm}$
 - ✓ Agreement with global fits provides mutual validation
- A precise CS kernel is a key step toward first-principles predictions of TMD observables

Intrinsic Soft Function from Lattice QCD

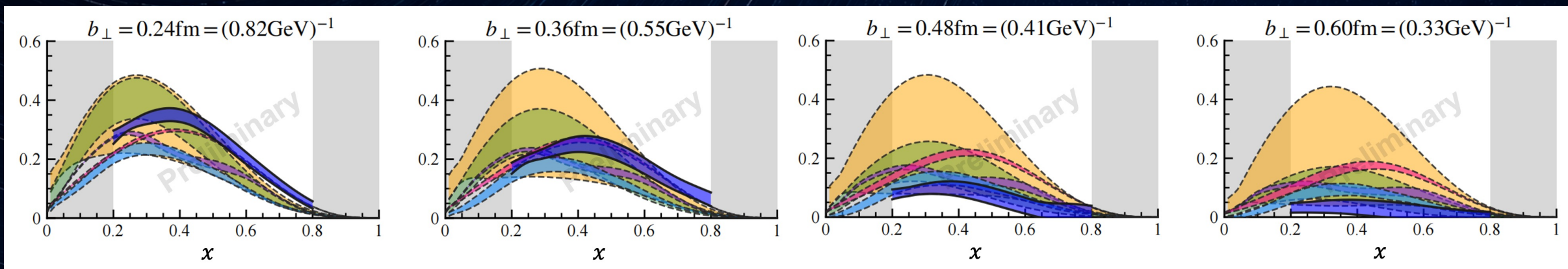


- ✓ Continuum, physical mass and infinite-momentum limits
- ✓ Precise first-principles prediction up to $b_T \sim 1\text{fm}$
- ✓ Essential input for the lattice calculation of TMDPDFs

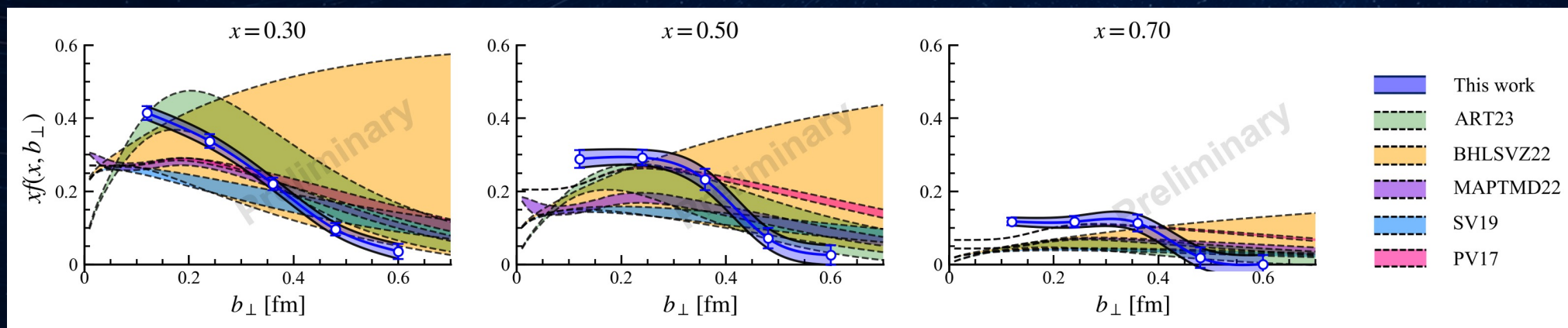
Unpolarized TMDPDFs from Lattice QCD

- x-dependence

LPC (2026), in preparation



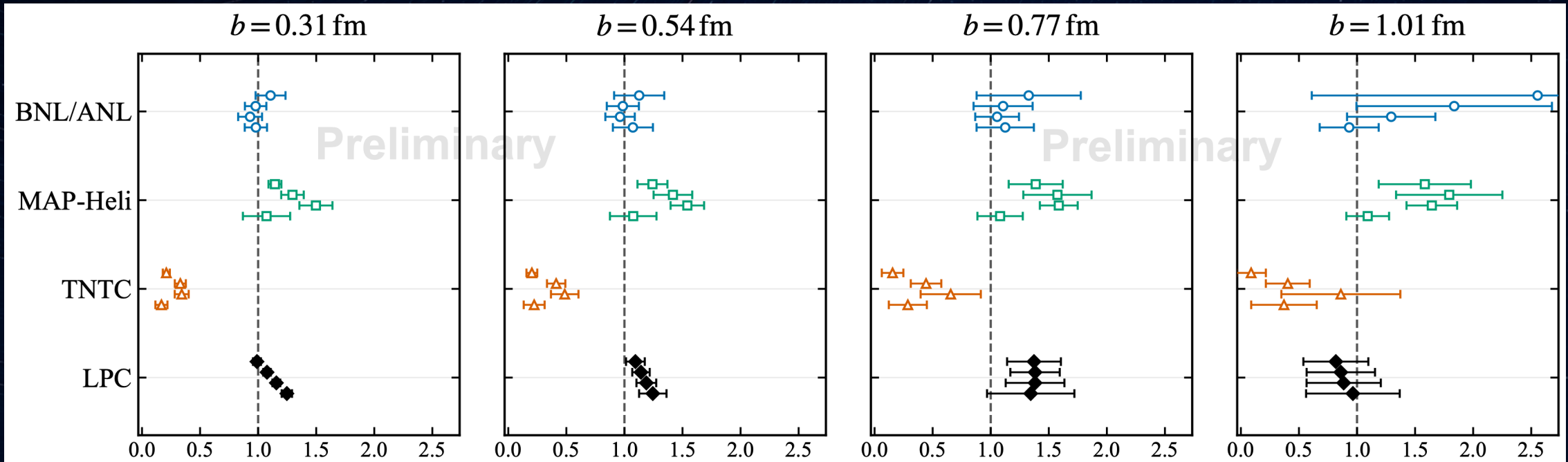
- $b_\perp$ -dependence



Helicity-to-Unpolarized TMD Ratio

- Preliminary results on the ensemble with $a=0.077\text{fm}$, $m_\pi=300\text{ MeV}$

LPC (2026), in preparation



- More systematic analyses are in progress

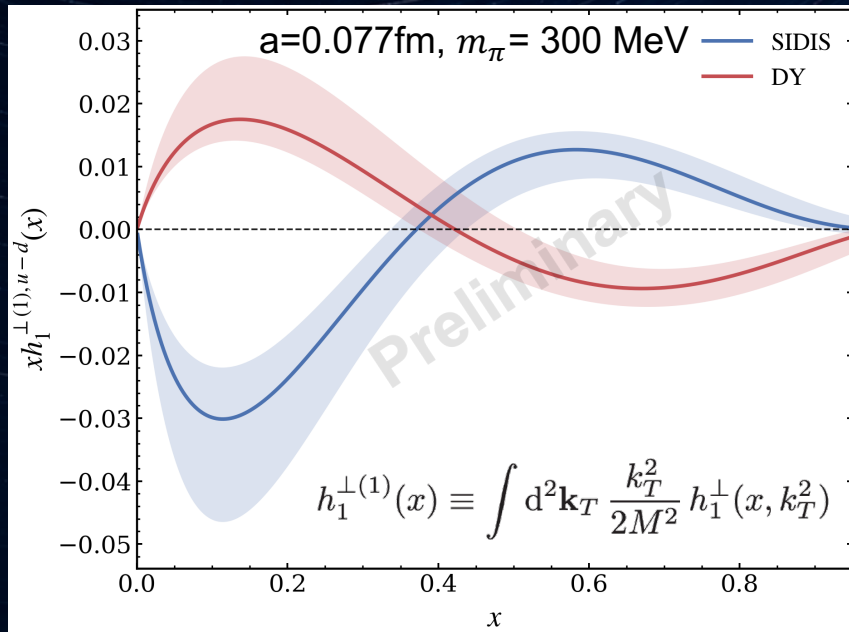
BNL/ANL (LQCD): PRL135, 20 (2025)
MAP (Global fit): PRL134, 121901 (2025)
TNTC (Global fit): PRL134, 121902 (2025)

Quark Spin-Transverse-Momentum Correlation

- First transverse moment of quasi Boer-Mulders function and its matching

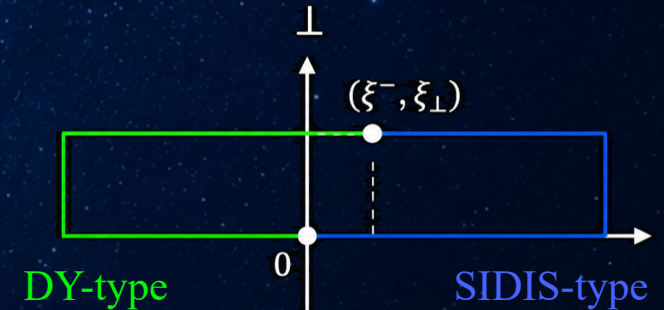
$$\tilde{h}_1^{\perp(1)}(x, b_\perp^2, P^z, \mu) = \frac{1}{iM\epsilon_\perp^{ij}b_{\perp j}} \frac{E}{P^z} \int \frac{dz}{2\pi} e^{ixP^z z} \frac{\sum_S \text{Tr} \left[P_+ u(P, S) \langle N(P, S) | \mathcal{O}^{i\sigma^{1z}\gamma_5}(z, b_\perp) | N(P, S) \rangle \bar{u}(P, S) \right]_R}{\sum_S \text{Tr} [P_+ u(P, S) \bar{u}(P, S)]_R}$$

$$\tilde{h}_1^{\perp(1)}(x, b_\perp^2, P^z, \mu) \sqrt{S_I(b_\perp, \mu)} = \exp \left[\frac{1}{2} \ln \frac{\zeta_z}{\zeta} K(b_\perp, \mu) \right] H \left(\frac{x}{y}, \frac{\mu^2}{\zeta_z} \right) h_1^{\perp(1)}(y, b_\perp^2, \mu, \zeta) + \mathcal{O} \left(\frac{\Lambda_{\text{QCD}}^2}{\zeta_z}, \frac{M^2}{(P^z)^2}, \frac{1}{b_\perp^2 \zeta_z} \right)$$



- Gauge links encode initial and final state interactions, leading to the predicted SIDIS-Drell-Yan sign reversal.

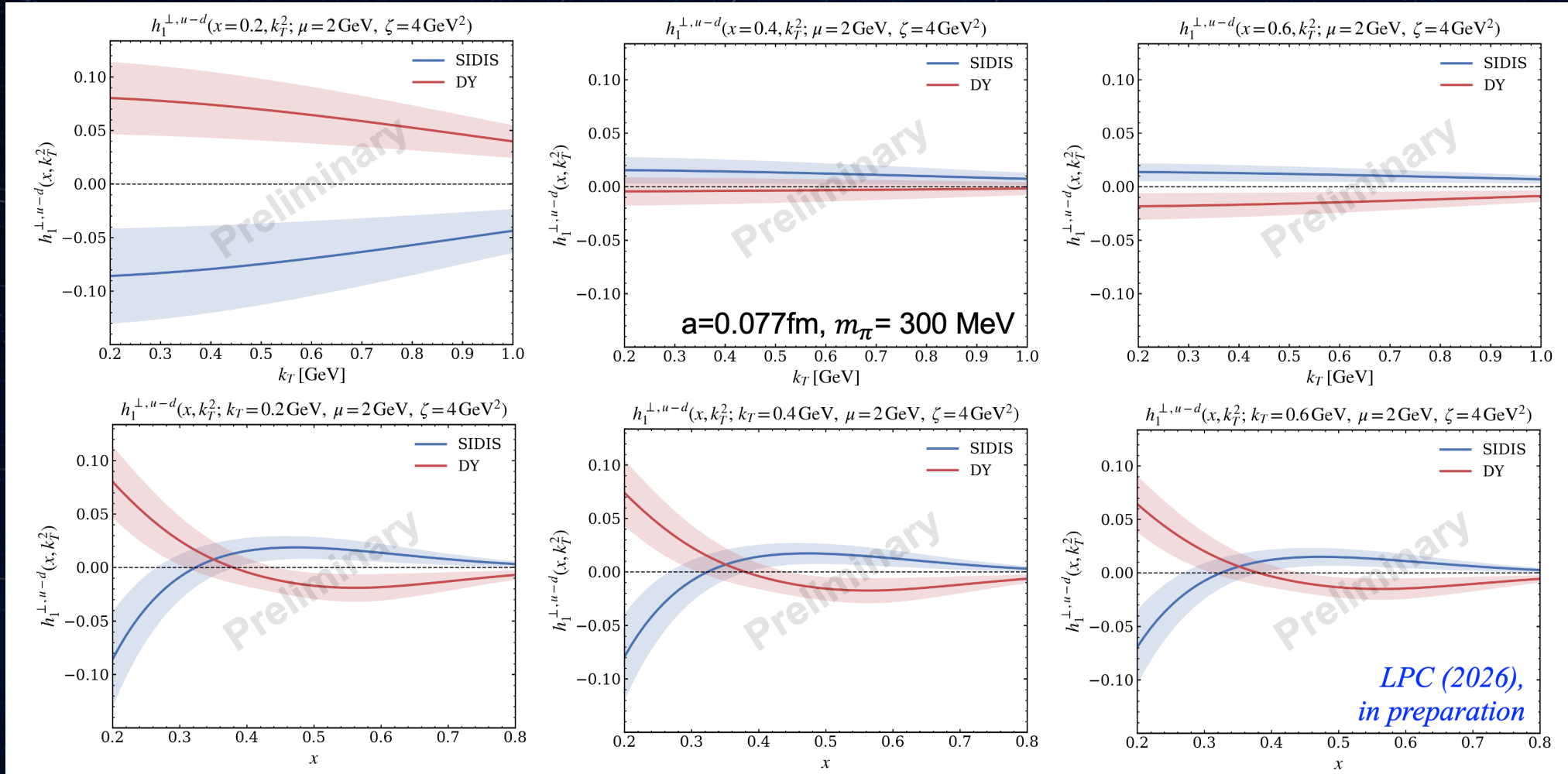
$$\mathcal{U}_n(a, b) = \exp \left[-ig \int_a^b d\lambda n \cdot A^\alpha(\lambda n) t^\alpha \right]$$



LPC (2026), in preparation

Quark Spin-Transverse-Momentum Correlation

- Rebuild the full $k_{\perp}$ -dependent distribution from model parametrization



Summary and Outlook

Polarized PDFs reveal how quark spins align with the nucleon spin, and TMDs promote this one-dimensional picture to a three-dimensional momentum image, exposing fundamental spin-momentum correlations.

Lattice QCD + LaMET is establishing a first-principles pathway from Euclidean correlation functions to physical partonic observables.

Together with global analyses and future EIC measurements, precision lattice calculations will open a new era of multidimensional nucleon imaging.

