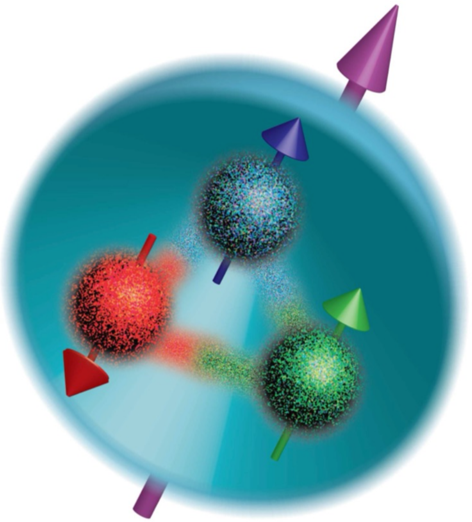
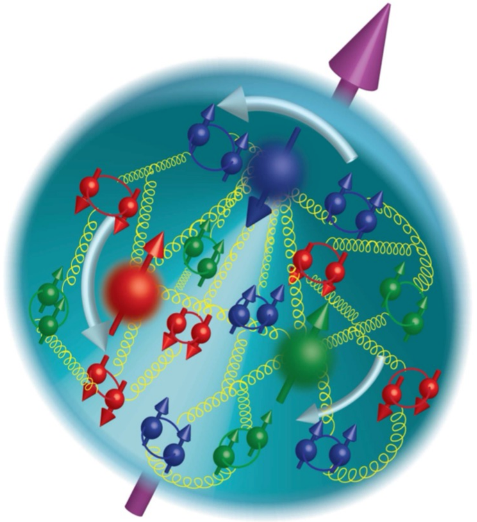
Lattice Parton Collaboration

北京航空航天大学
BEIHANG UNIVERSITY

核子自旋结构的第一性原理研究





张其安

北京航空航天大学

On behalf of Lattice Parton Collaboration (LPC)

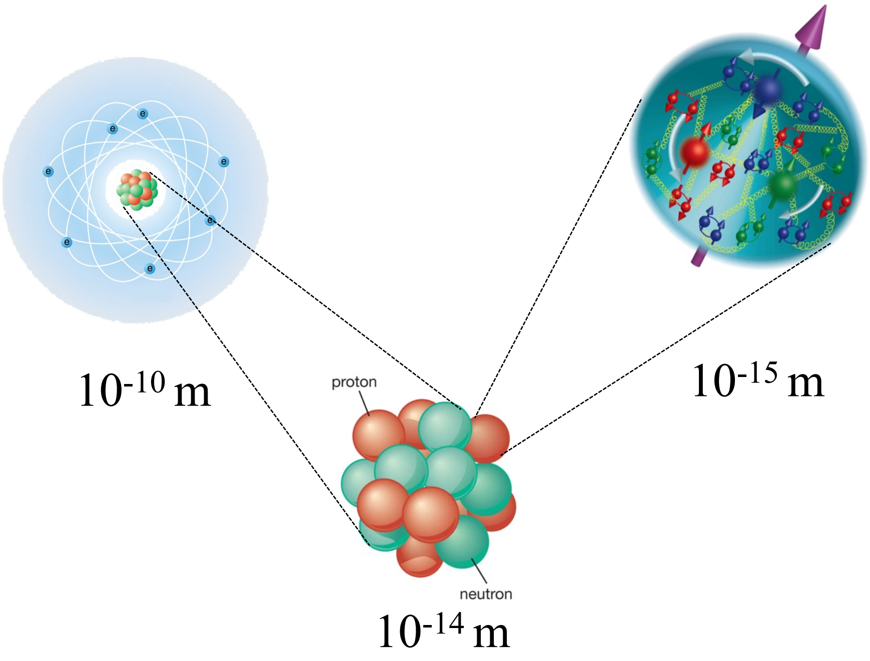
Aug. 15, 2026 @ 超子-核子谱仪物理研讨会，天津

OUTLINE

- Motivation
- Polarized PDF Ratio: Spin Alignment of Quarks
- Quark TMDPDFs: 3D Momentum Tomography of Nucleon
- AI for Lattice QCD
- 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

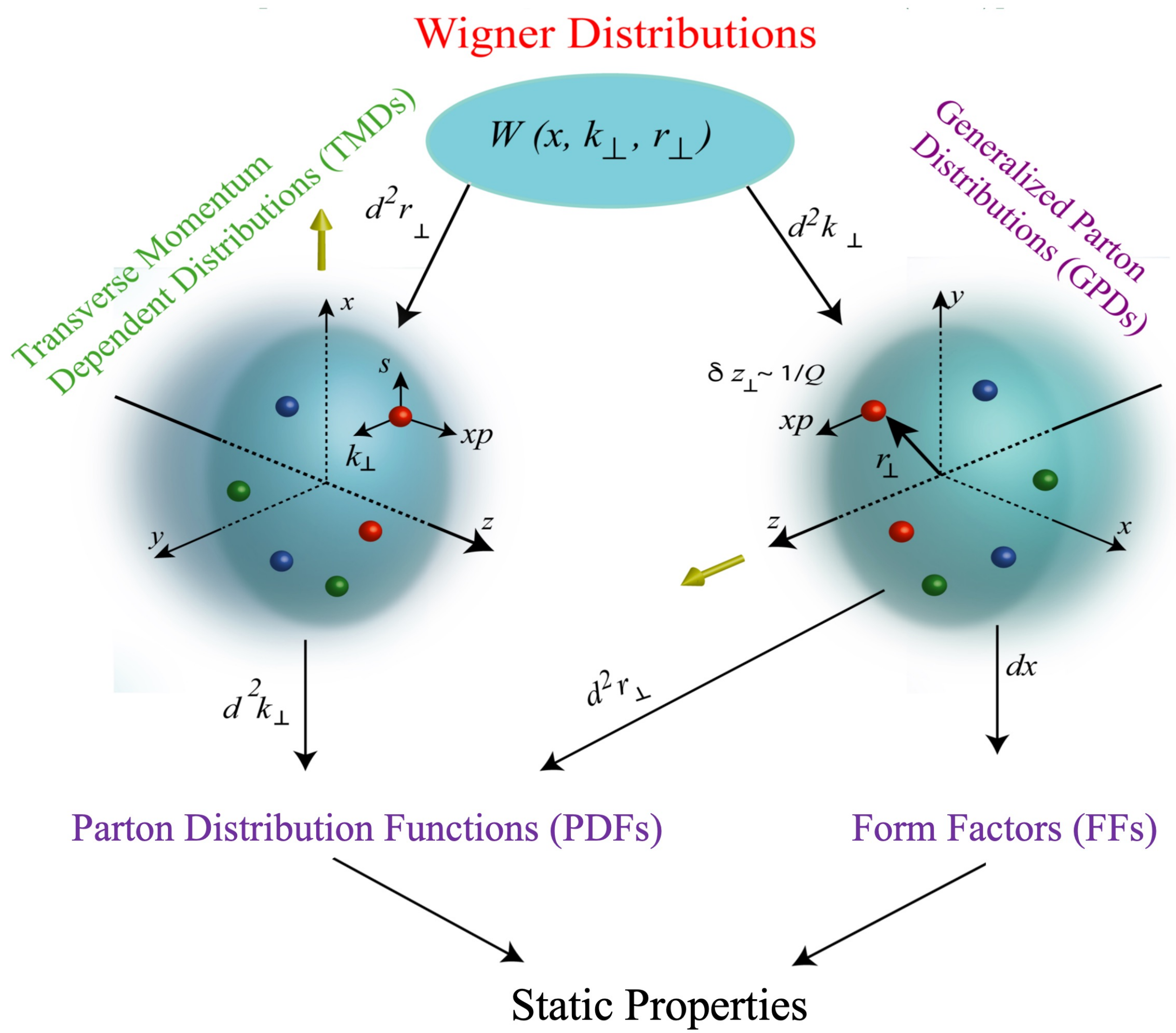


- How does quarks & gluons form the nucleon, how do they distribute?
- How do these distributions and partonic orbital motion generate the nucleon spin?

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

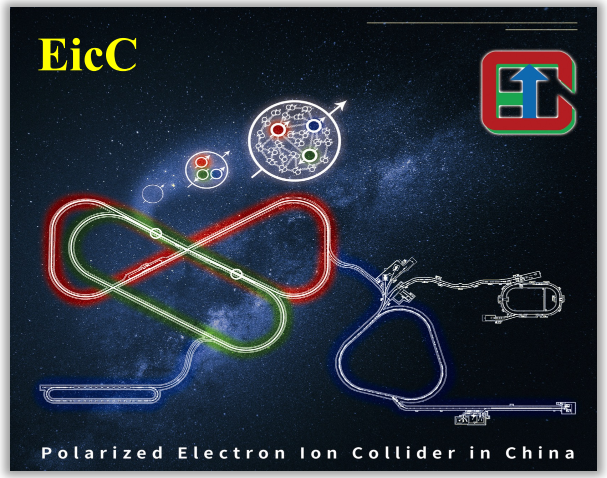
Adapted from the White Paper of EIC, EPJA52, 268 (2016).

The Landscape of Nucleon Structure



(Spins, charge, magnetic moment, charge radius, …)

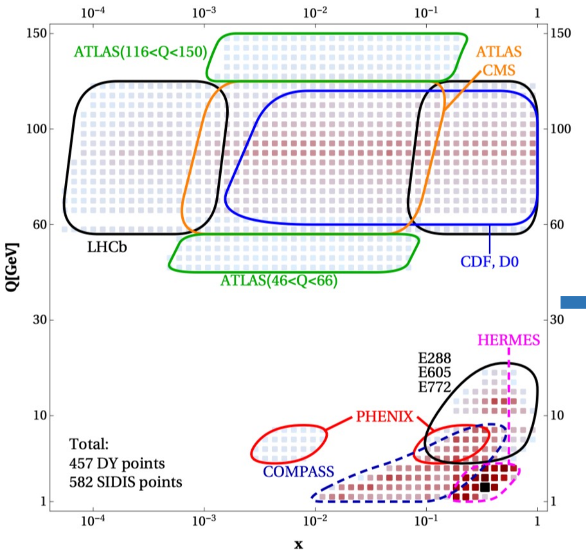
- 3D Structures: TMDs and GPDs



- 1D Structure: PDFs

How do we access the Nucleon Structures?

Exp.

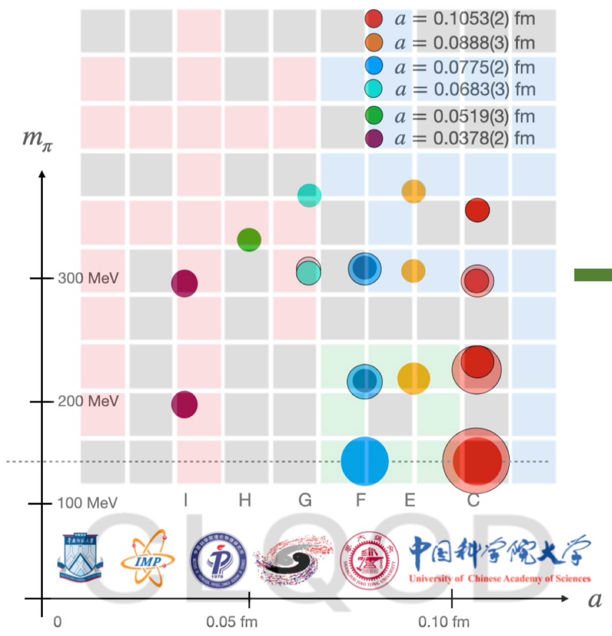


Cross Sections, Asymmetries, … → Global Analysis / Fitting

$$\chi^2 = \sum_i^{N_{\text{meas}}} \frac{(O_i - E_i)^2}{E_i}$$

→ Parameters

Lat.



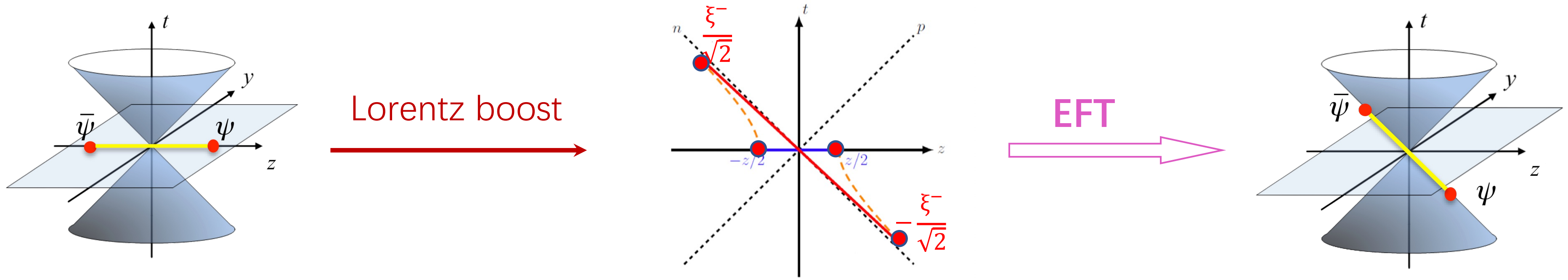
Correlation Function → Effective Theory

$$\langle \tilde{O} \rangle_{\text{lat.}} = C \otimes \langle O \rangle_{l.c.}$$

→ Distributions

LaMET: A New Horizon for Nucleon Structure from Lattice

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



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

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

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

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

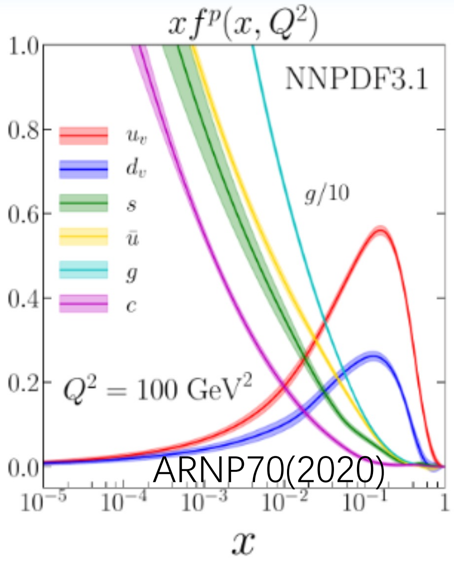
$$q(y, \mu) = \int_{-\infty}^{+\infty} \frac{dx}{|x|} \mathcal{C}\left(\frac{y}{x}, \frac{\mu}{xP^z}\right) \tilde{q}(x, P^z) + \mathcal{O}\left(\frac{M^2}{(P^z)^2}, \frac{\Lambda_{\mathrm{QCD}}^2}{(yP^z, (1-y)P^z)^2}\right)$$

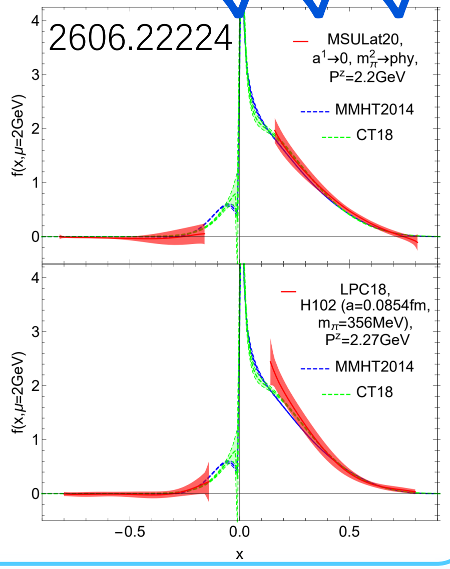
Status of the 1D & 3D Nucleon Structure

Unpolarized

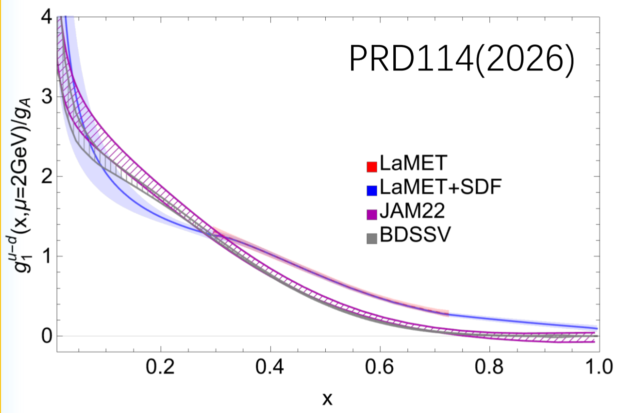
Polarized

1D

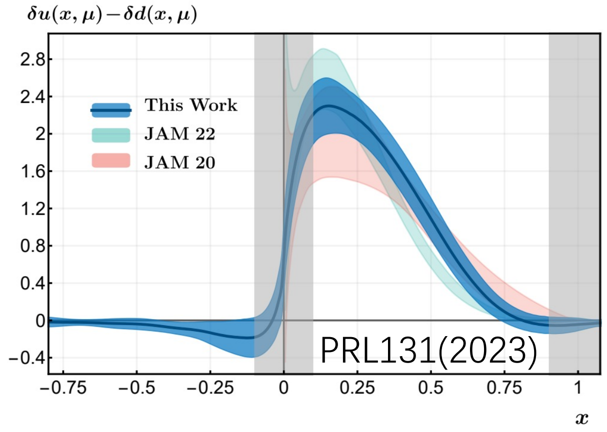




Helicity PDF (lat. vs fit)

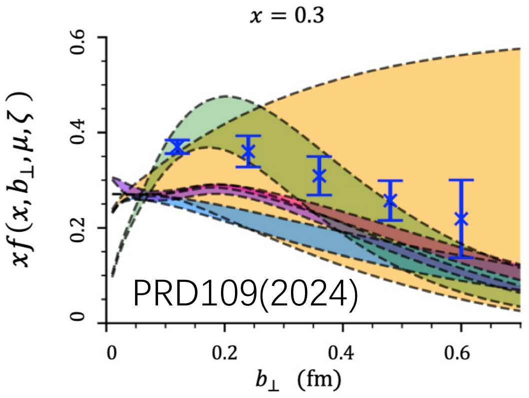


Transversity PDF (lat. vs fit)

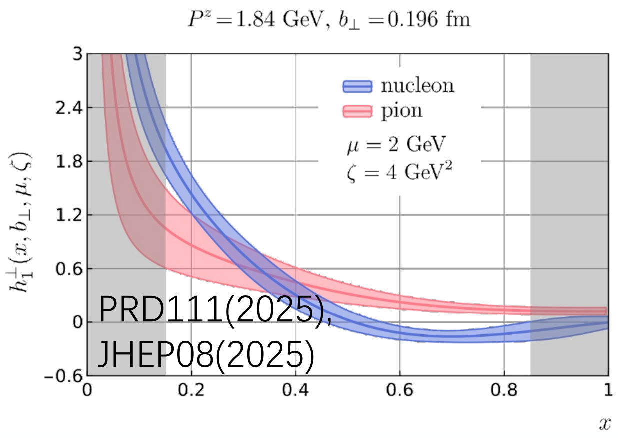


3D

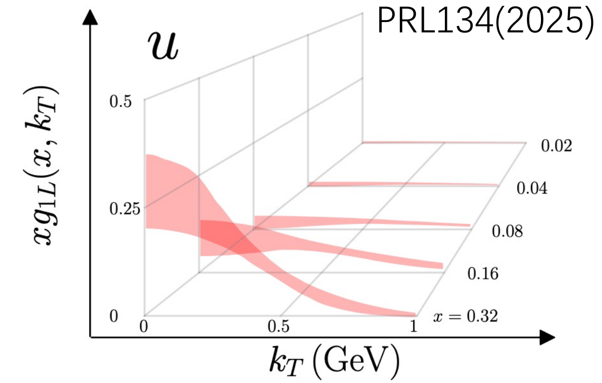
Unpolarized TMDPDF (lat. vs fit)



Boer-Mulders function (lat.)



Transversity TMDPDF (fit)



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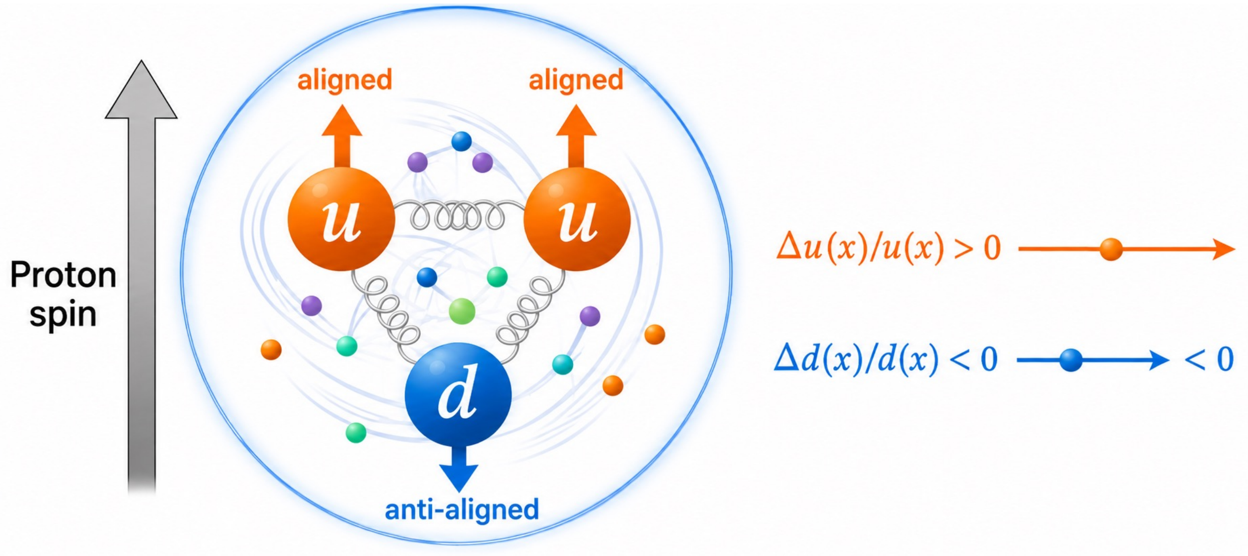
Spin Alignment of the Quarks



- Quark helicity PDF:

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

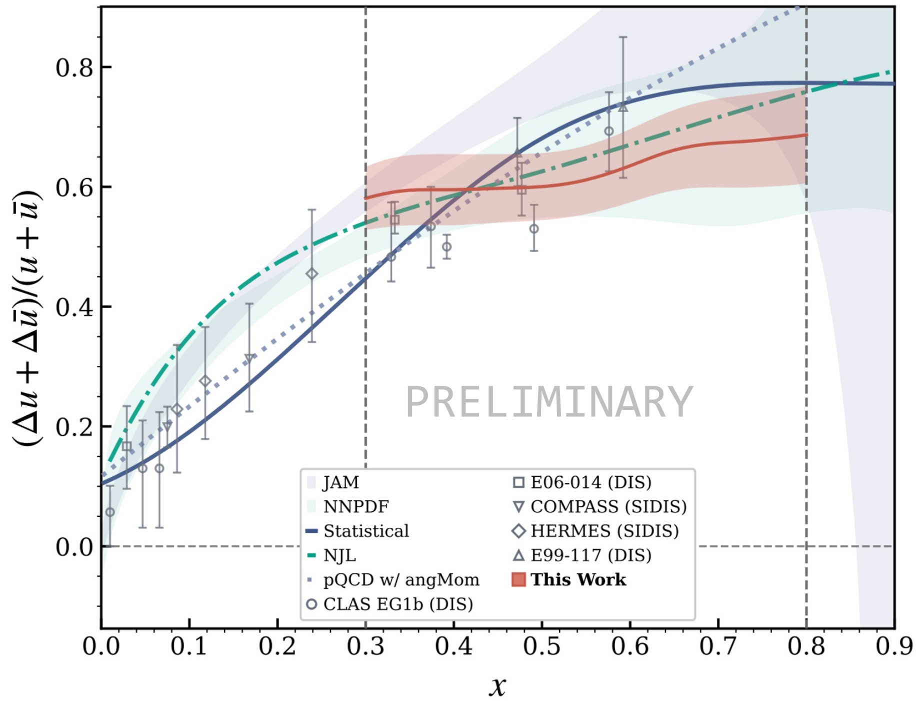
- Quark unpolarized PDF:

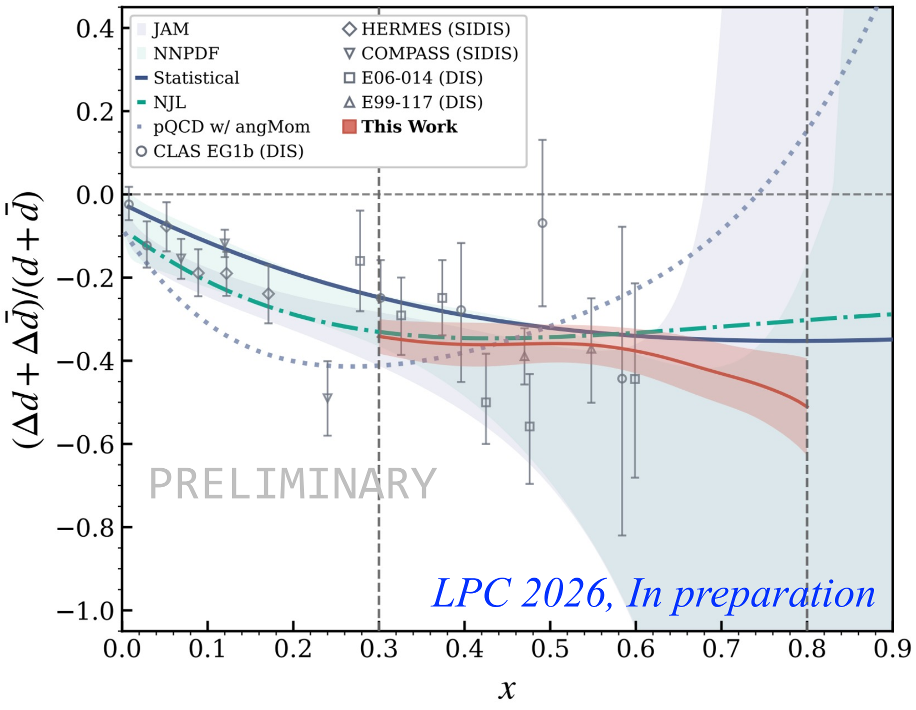
$$q(x) = q^{\uparrow}(x) + q^{\downarrow}(x)$$

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

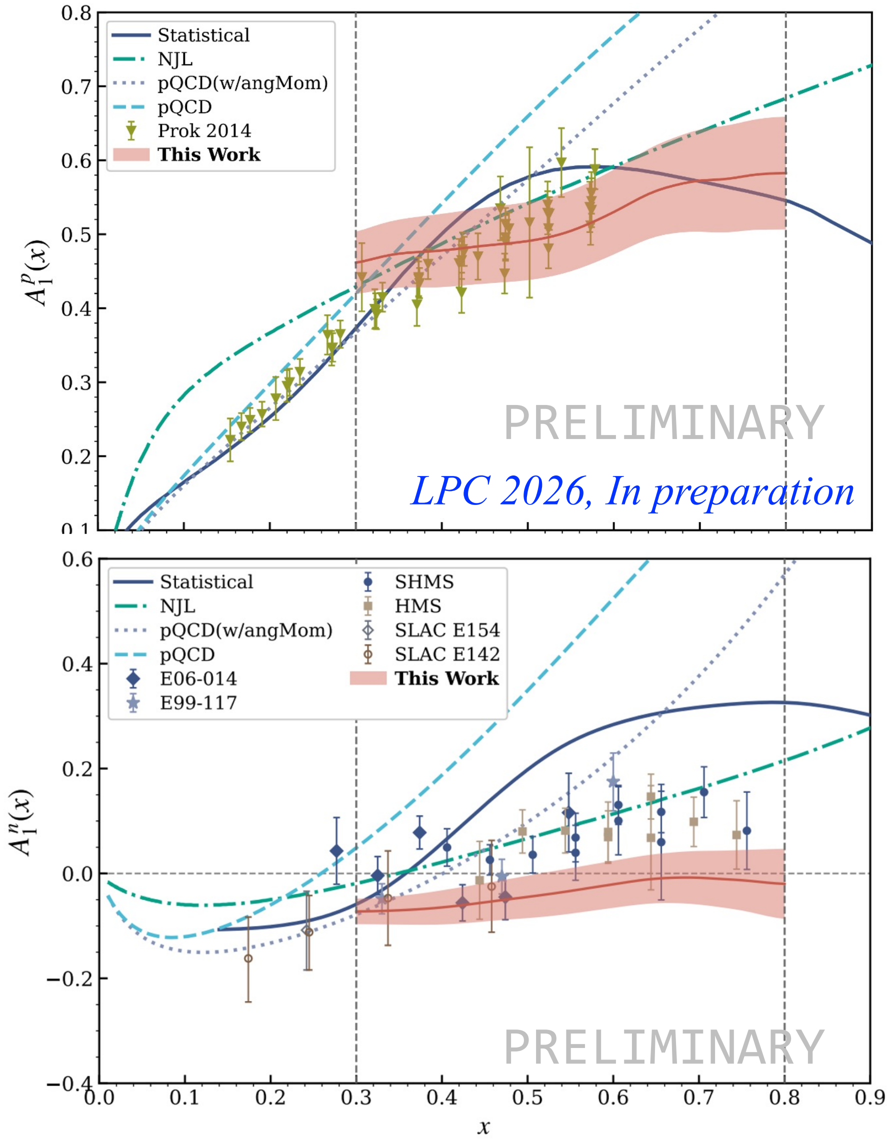
Ratios of Polarized PDFs from Lattice QCD

- 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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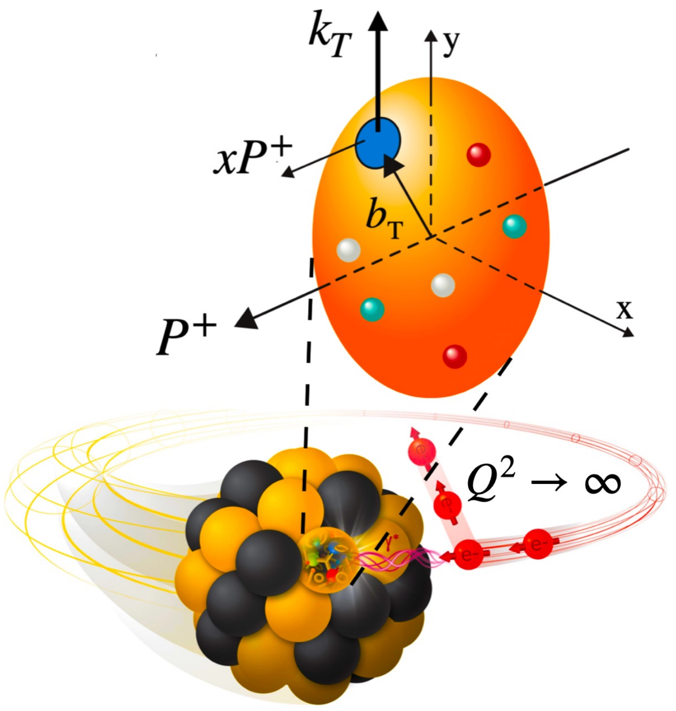
TMDs: 3D Momentum Tomography of Nucleon



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

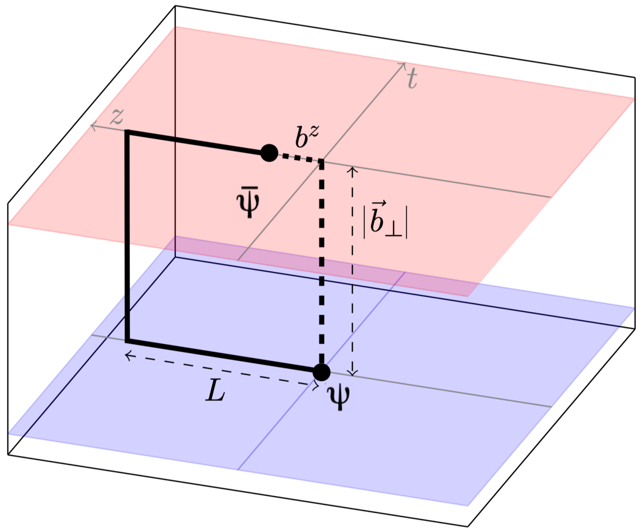
Leading Quark TMDPDFs

Nucleon Spin   Quark Spin

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

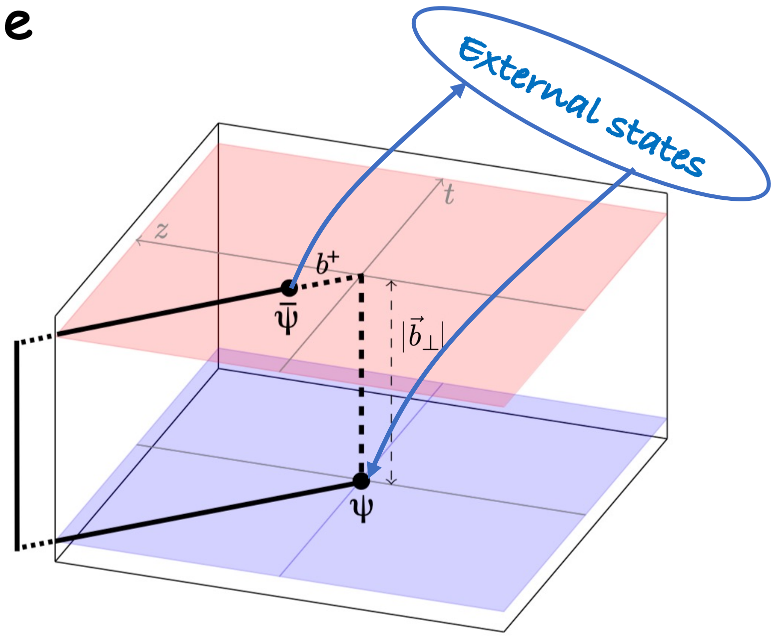
TMDs from Lattice QCD within LaMET

Quasi-TMDs: Equal-time correlators, Lattice calculable



Lorentz boost

$L \to \infty$
$P^z \to \infty$



Factorization in LaMET:

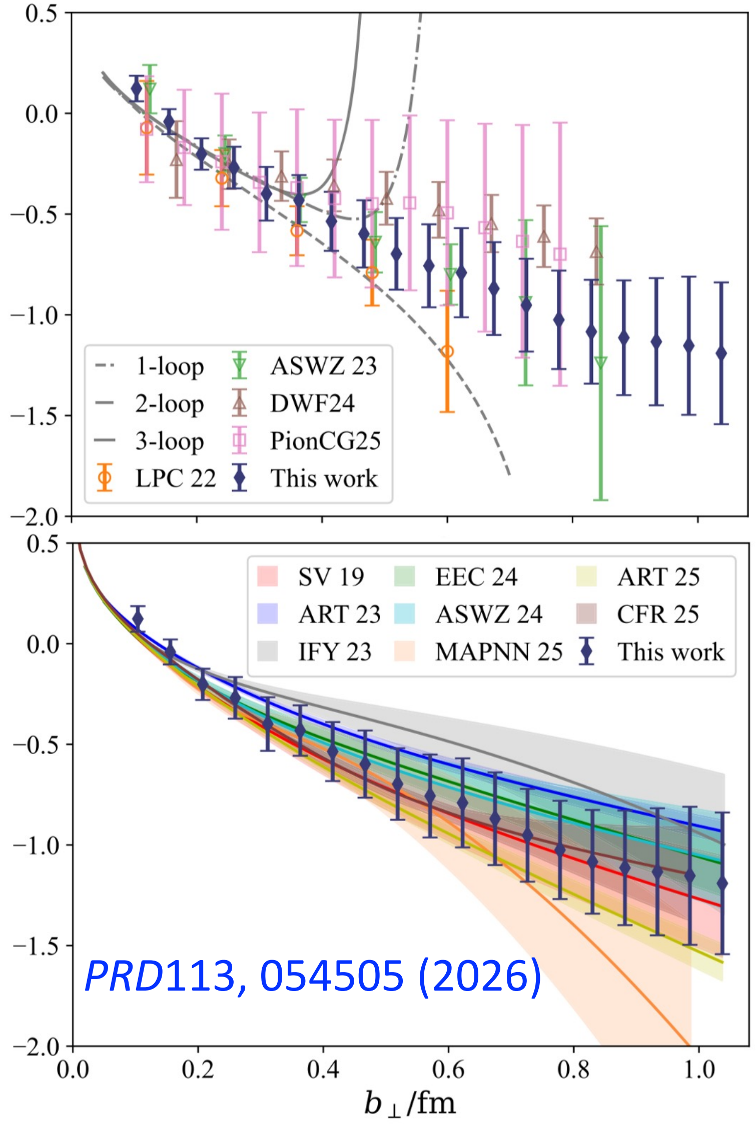
PLB811, 135946 (2020); JHEP04, 178, (2022)

Perturbative matching kernel

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

Quasi TMDs Intrinsic Soft Function Collins-Soper kernel Light-cone TMDs

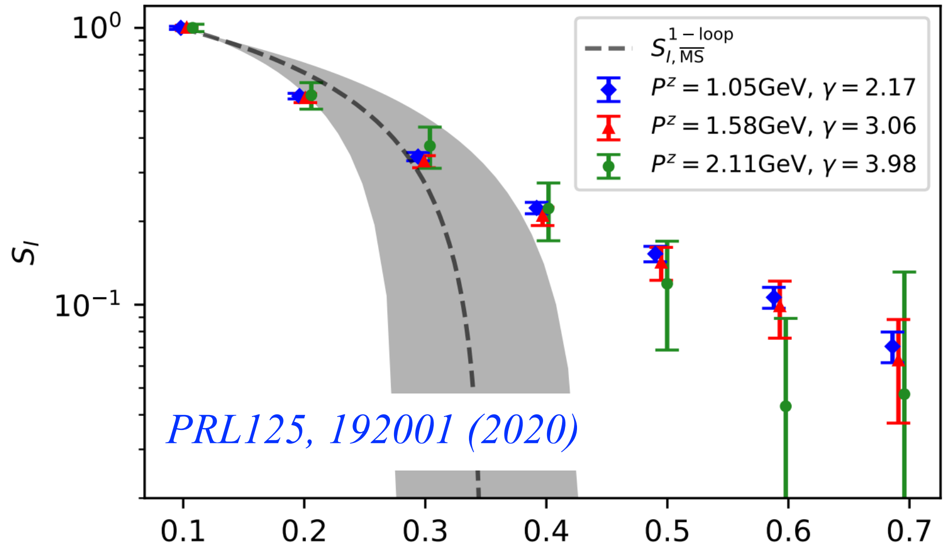
Collins-Soper Kernel from Lattice QCD



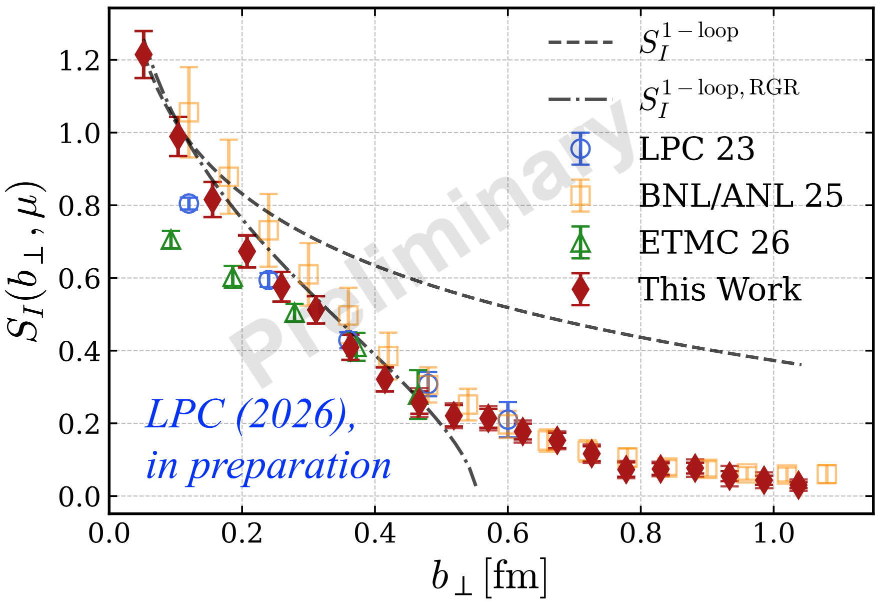
- A benchmark quantity for lattice TMD studies
  - ✓ Continuum, physical mass, and infinite-momentum limits are now being addressed
  - ✓ Lattice QCD provides first-principles constraints up to $b_T \sim$ 1fm
  - ✓ Agreement with global fits provides mutual validation
- A precise CS kernel is a key step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

Intrinsic Soft Function from Lattice QCD

LPC, 2020



LPC, 2026



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

Exploratory LQCD Studies for TMDPDFs (LPC 2024-2025)

- *Single lattice spacing*
- *Limited statistics*
- *Incomplete systematic uncertainties*

Quasi-TMDPDFs

Collins-Soper Kernel

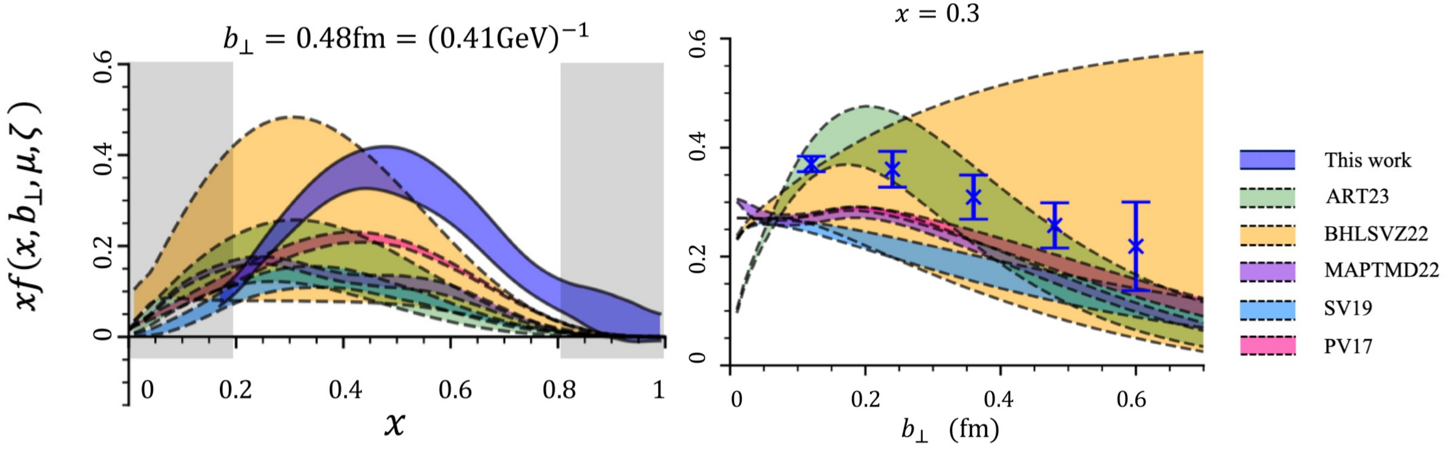
Intrinsic Soft Function

Matching in LaMET:

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

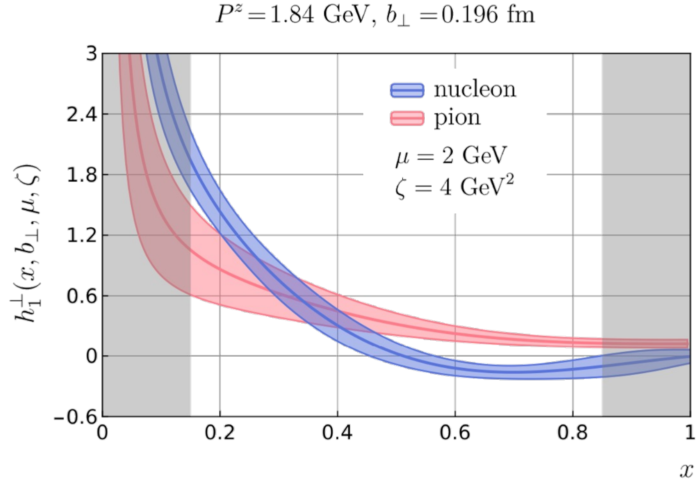
Unpolarized TMDPDF

LPC, PRD109, 114513 (2024)



Quark Spin-transverse-momentum Correlation

LPC, PRD111, 094507 (2025); JHEP 08, 086 (2025)



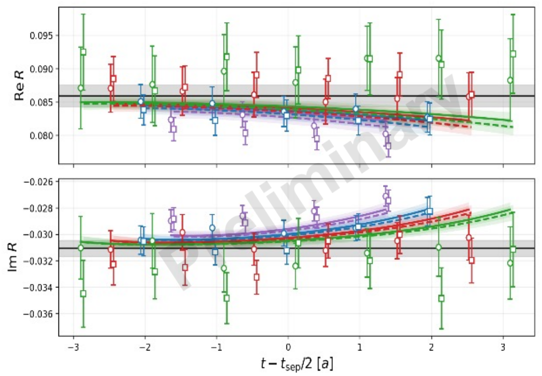
Precision Calculation for Polarized TMDPDFs (LPC 2026)

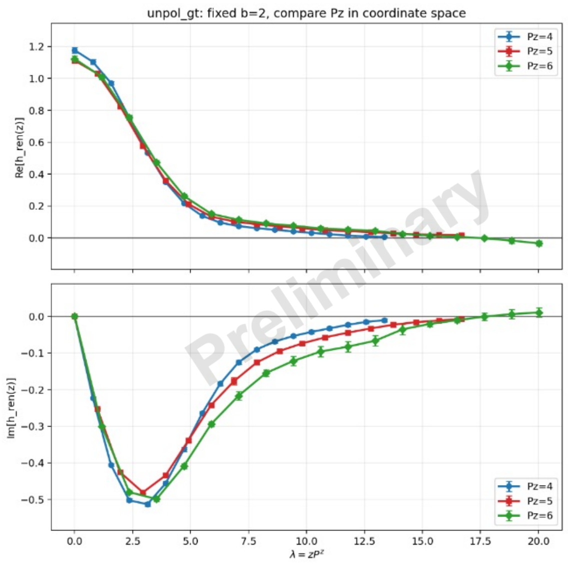
- E.g.: Unpolarized TMDPDF

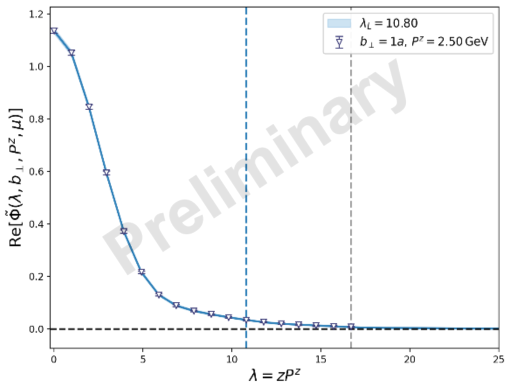
✓ Multi lattice spacings ⇒ Continuum Limit

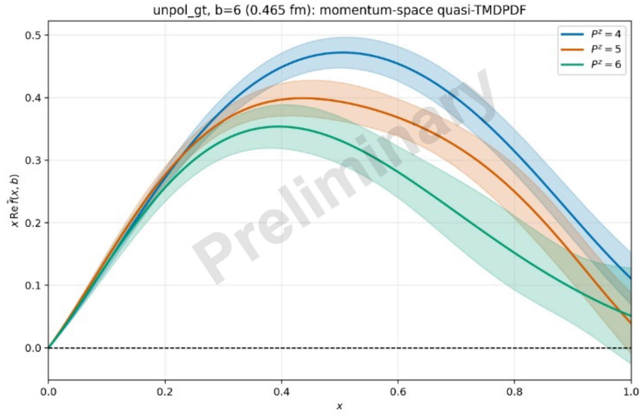
✓ Multi pion masses ⇒ Chiral Limit

✓ Large statistics









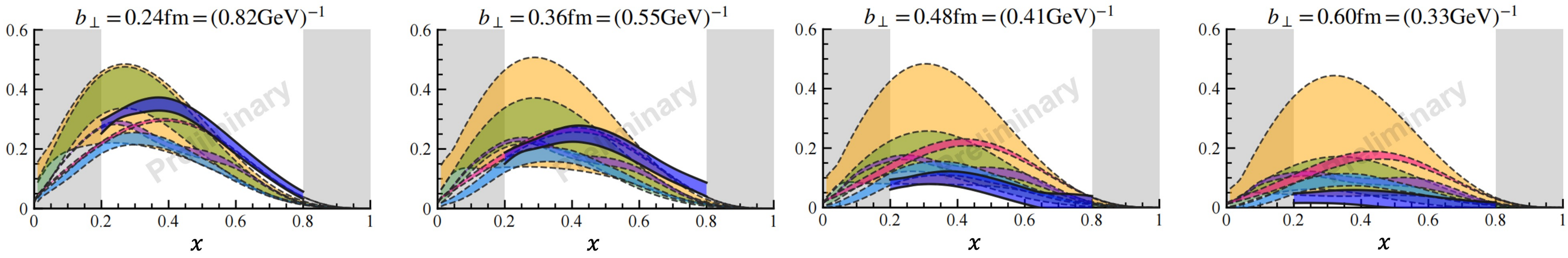
LPC (2026), in preparation

Ground-state fit the ratio of 3pt/2pt → Nonlocal renormalization to get coordinate-space distribution → Large-λ extrapolation → Fourier transform to get momentum-space quasi-TMDPDF

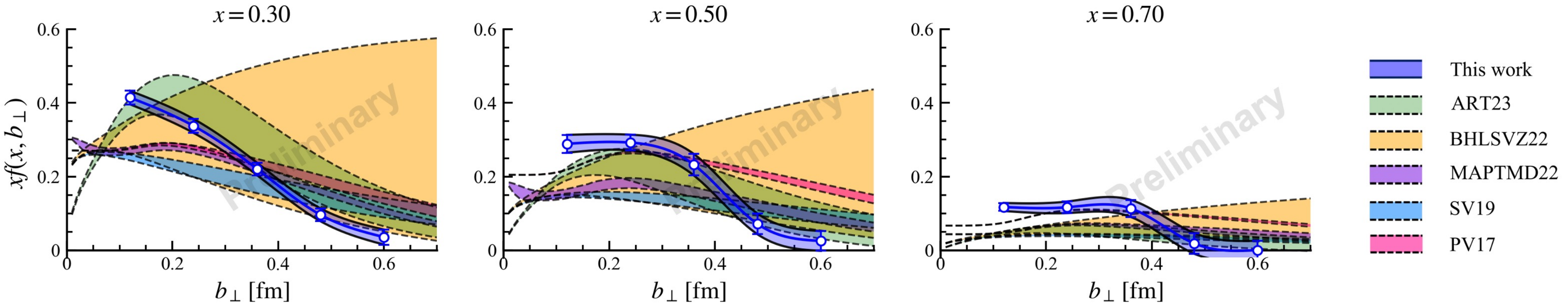
Unpolarized TMDPDFs from Lattice QCD

- x-dependence

LPC (2026), in preparation



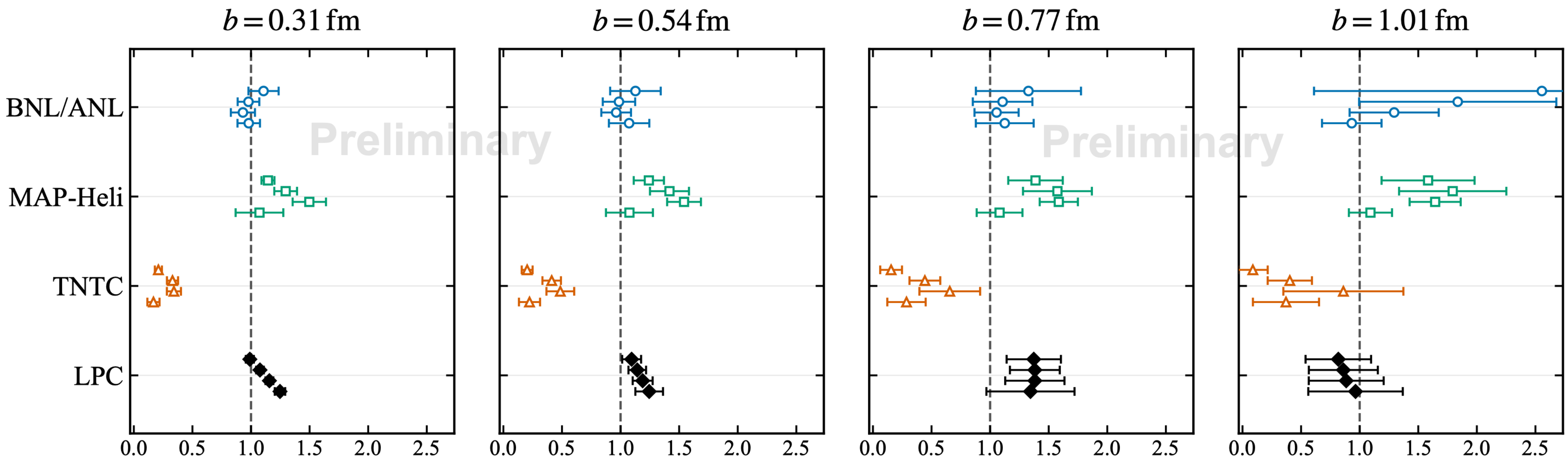
- b_T-dependence



Spin Alignment in TMDs

- **Helicity-to-Unpolarized TMD Ratio:**

LPC (2026), in preparation



- More systematic analyses are in progress ……

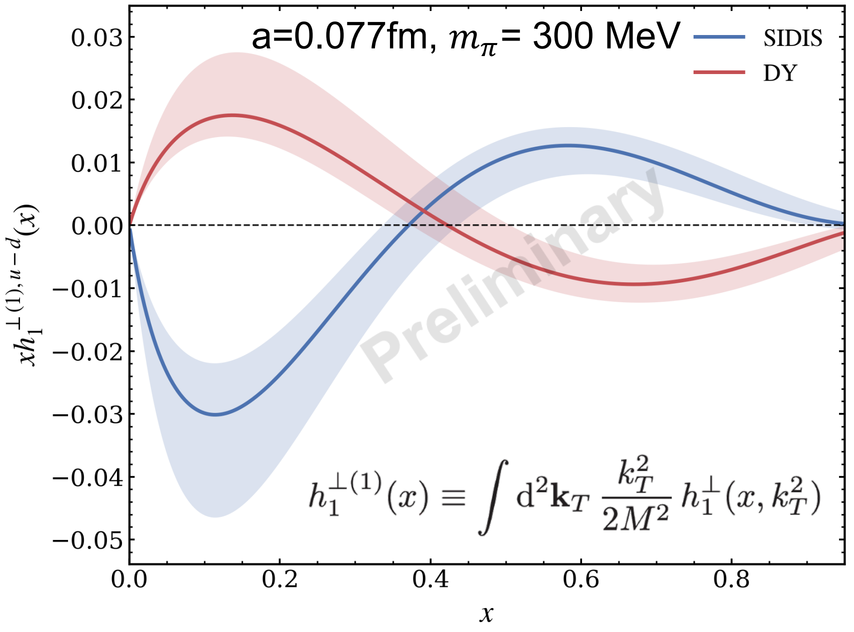
BNL/ANL (LQCD): PRL135, 20 (2025)
MAP (Global fit): PRL134, 121901 (2025)
TNTC (Global fit): PRL134, 121902 (2025)

Quark Spin-transverse-momentum Correlation

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

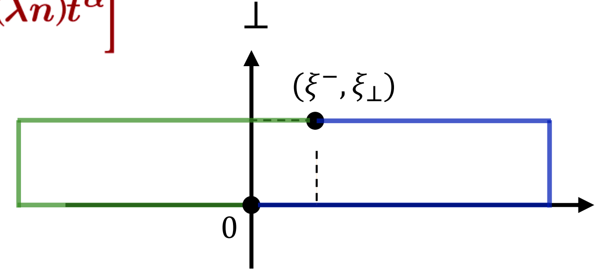
$$\tilde{h}_1^{\perp(1)}(x,b_\perp^2,P^z,\mu)=\frac{1}{iM\epsilon_\perp^{ij}b_{\perp j}}\frac{E}{P^z}\int\frac{dz}{2\pi}e^{ixP^zz}\frac{\sum_S \mathrm{Tr}\left[P_+u(P,S)\langle N(P,S)|O^{i\sigma^{\perp z}\gamma_5}(z,b_\perp)|N(P,S)\rangle\bar{u}(P,S)\right]_R}{\sum_S \mathrm{Tr}\left[P_+u(P,S)\bar{u}(P,S)\right]_R}$$

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



- Gauge links generate initial and final state interactions and distinguish the SIDIS & Drell-Yan processes

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



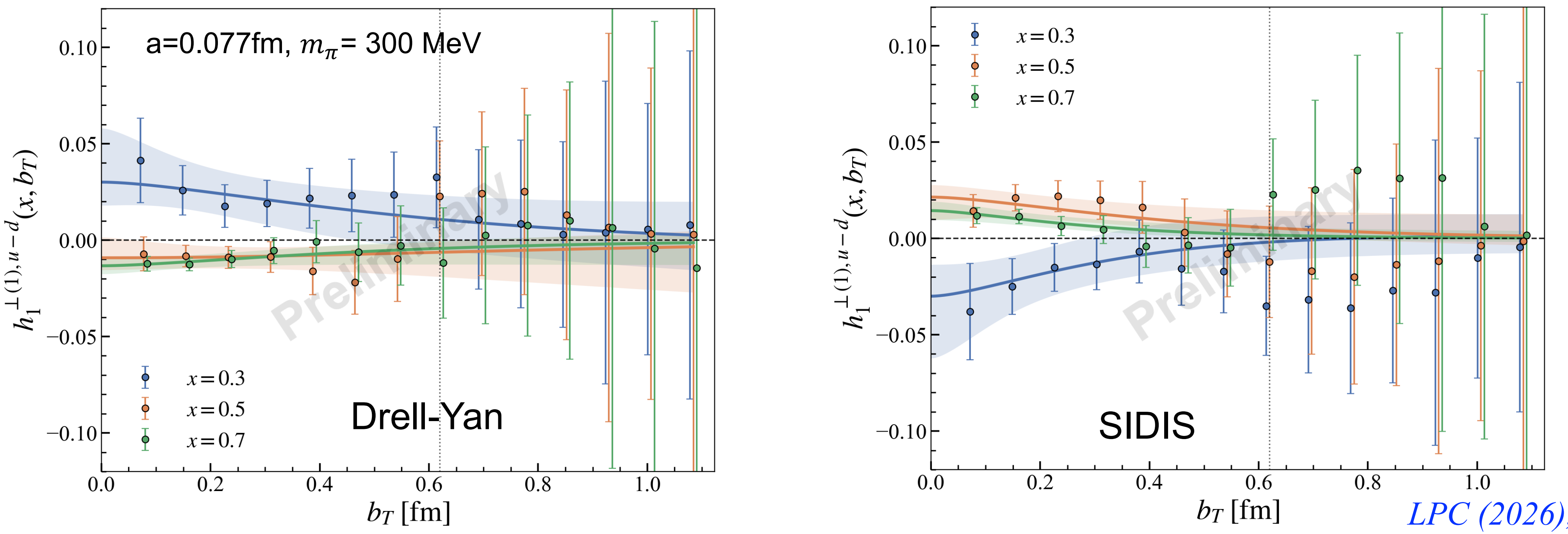
LPC (2026), in preparation

Quark Spin-transverse-momentum Correlation

- Rebuild the full distribution of $h_1^{\perp}(x, k_\perp^2)$ from model parametrization

Bacchetta, Conti, Radici, PRD78, 074010 (2008)

$$h_1^{\perp,u-d}(x,k_\perp^2) = \frac{M_N^2}{2\pi k_\perp}\int db_\perp b_\perp^2 J_1(k_\perp b_\perp) h_1^{\perp(1)}(x,b_\perp^2)$$
$$\equiv H_S(x)\frac{4M^2}{\pi L_S^4(x)}\left(1+\frac{k_\perp^2}{L_S^2(x)}\right)^{-3} - H_A\frac{4M^2}{\pi L_A^4(x)}\left(1+\frac{k_\perp^2}{L_A^2(x)}\right)^{-3}$$



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Quark Spin-transverse-momentum Correlation

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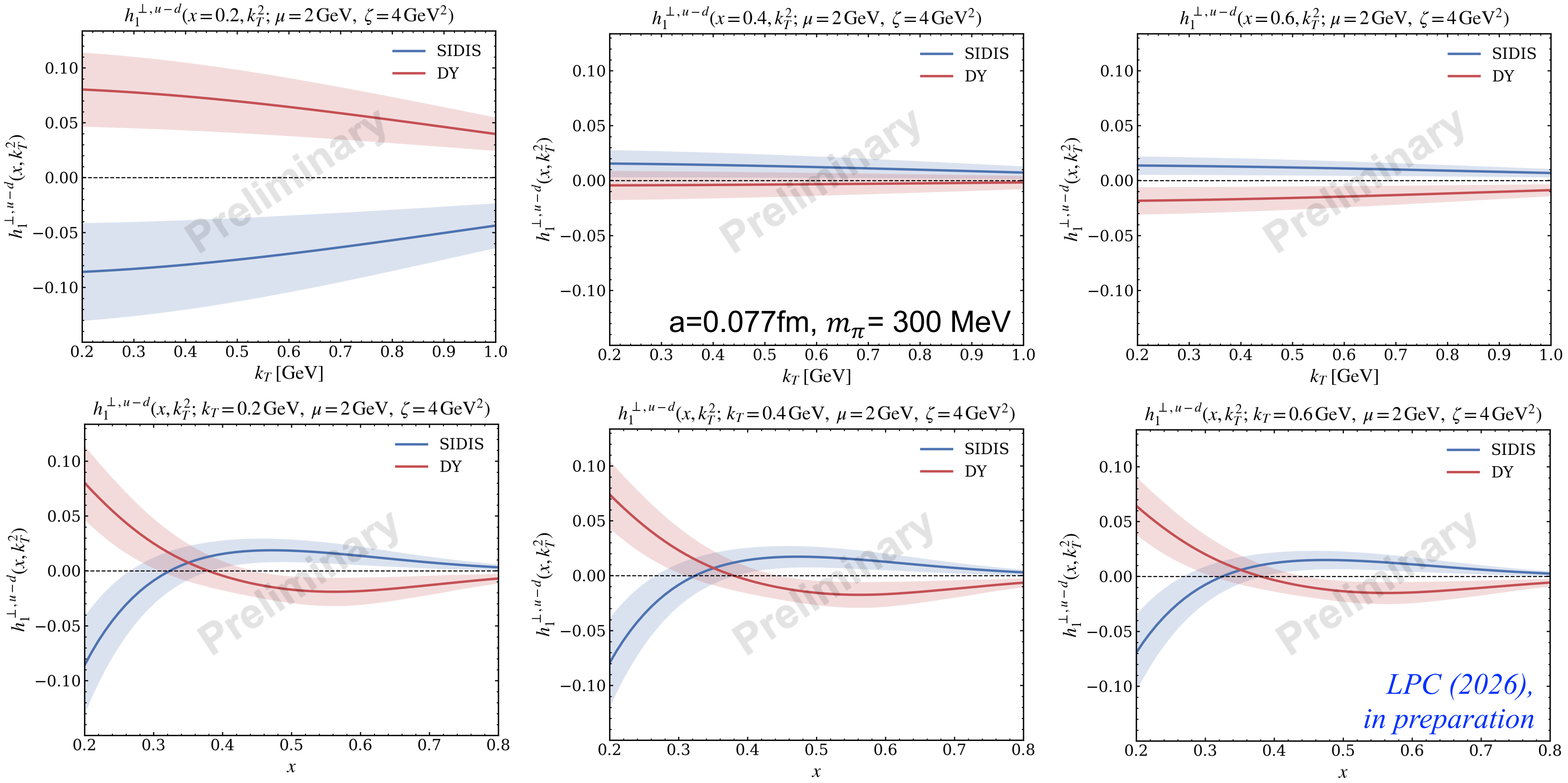

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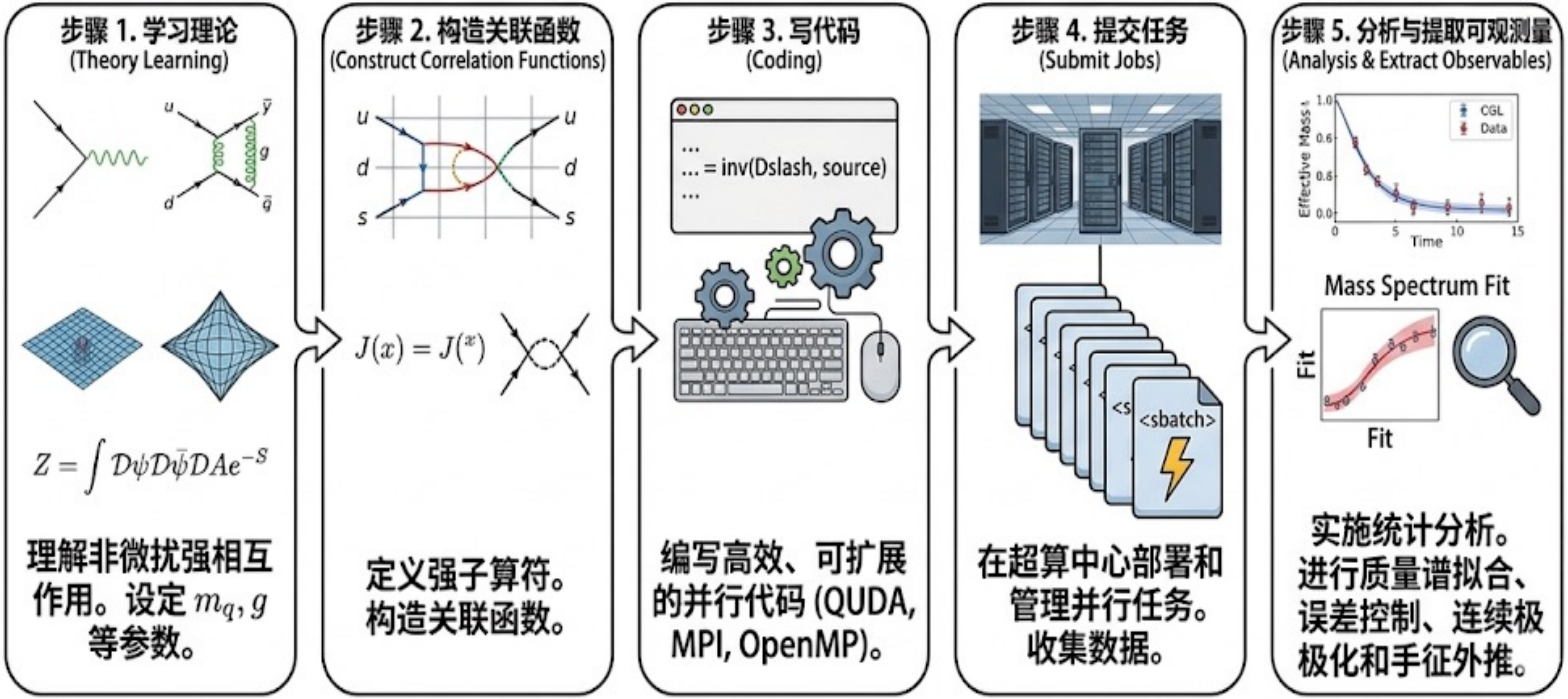
Workflow for Lattice QCD



AI for Lattice QCD

✓ 计算：物理目标 → 计算程序

- 必要的物理知识：量子场论，算符构造，关联函数，…
- 专业的计算程序：Chroma，PyQUDA，…

LQCD MASTER

【 An Autonomous AI Scientist for Lattice QCD 】

✓ 分析：格点数据 → 物理结果

- 超长链条、海量数据、高维结构的复杂分析
- 耗时久，需至少两人检查

PhysMaster

2512.19799, PhysMaster

2603.22471, PhysMaster for LQCD

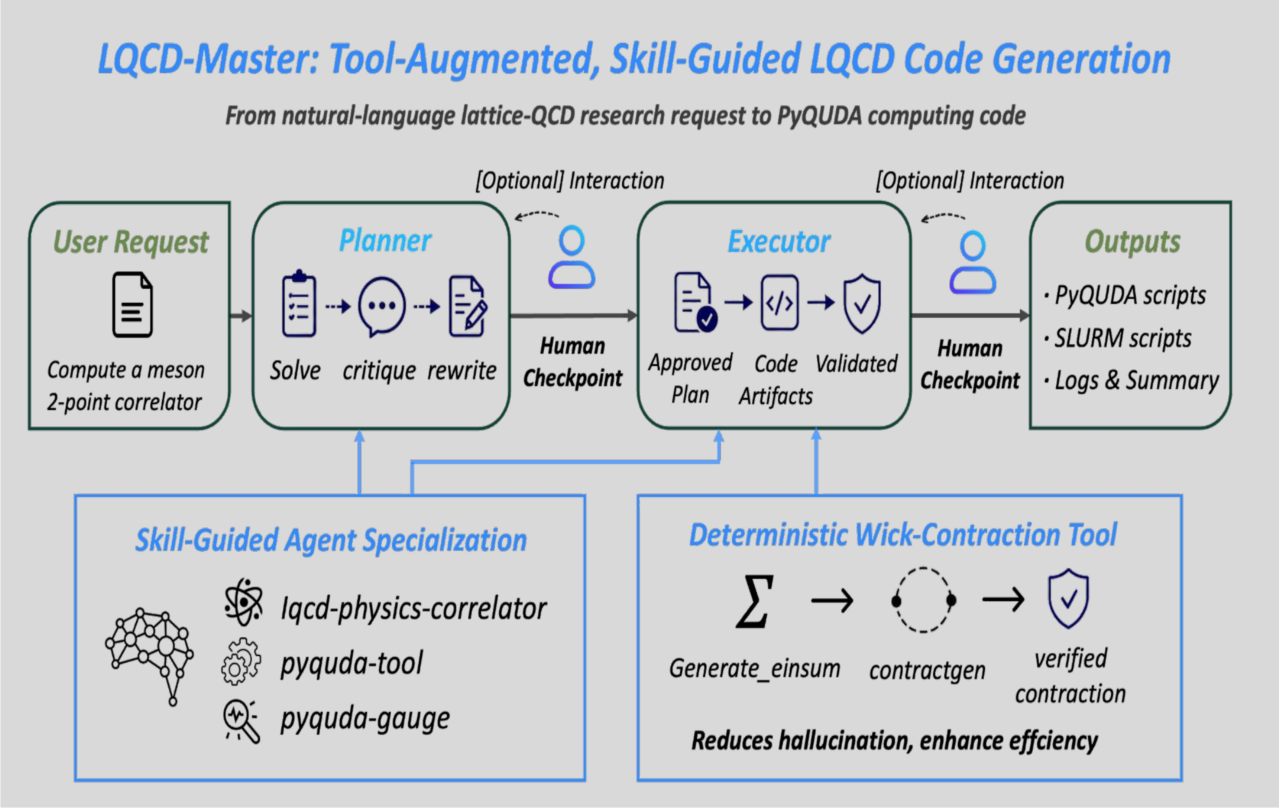
2604.15411, PRL-Bench

2607.15001, LQCDMaster

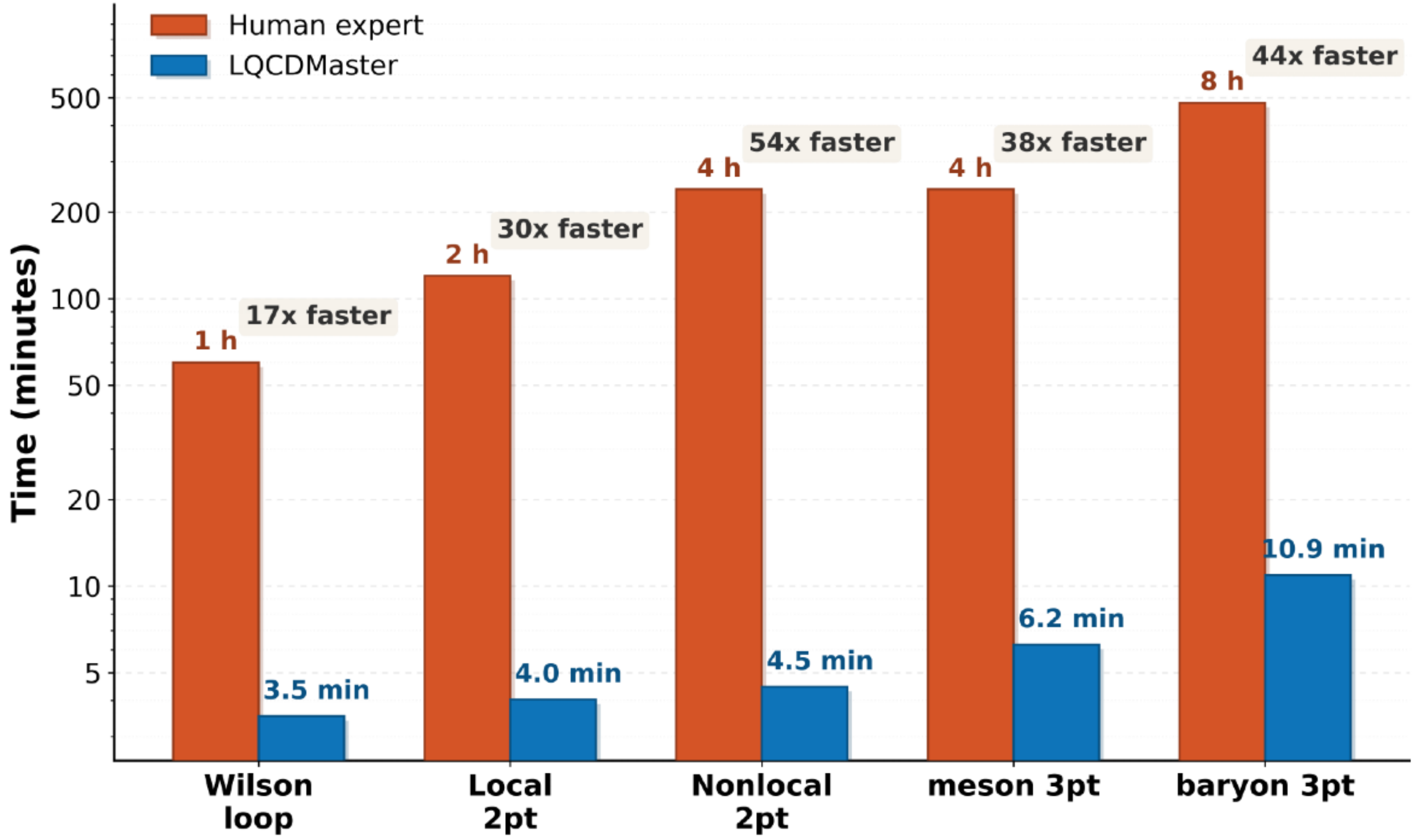
基于智能体的通用技术+工具增强+技能指导，我们设计了LQCDMaster智能体

- ✓ 3-step:
  - Planner
  - Executor
  - Verifior
- ✓ Tool：
  - Generate_einsum
  - Contractgen
- ✓ SKill：
  - lqcd-physics-correlator
  - pyquda-tool
  - Pyquda-gauge

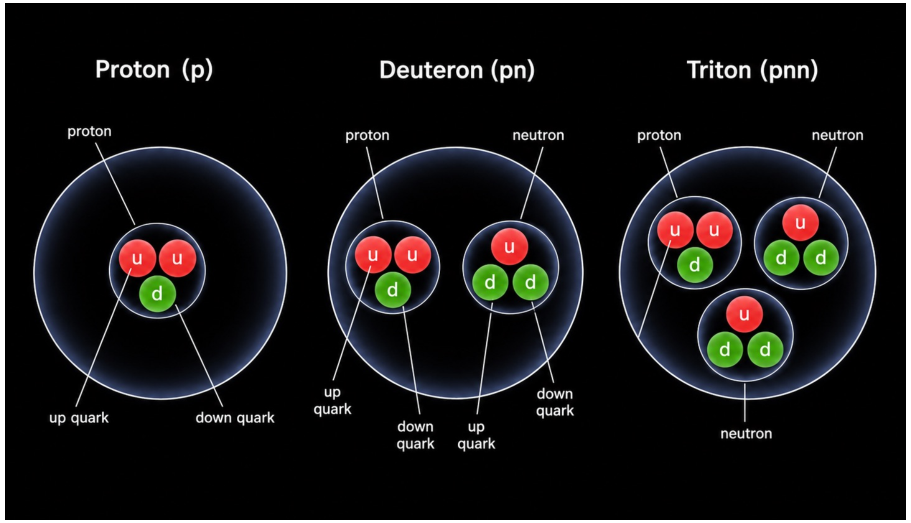
LQCDMaster的流程示意图 2607.15001

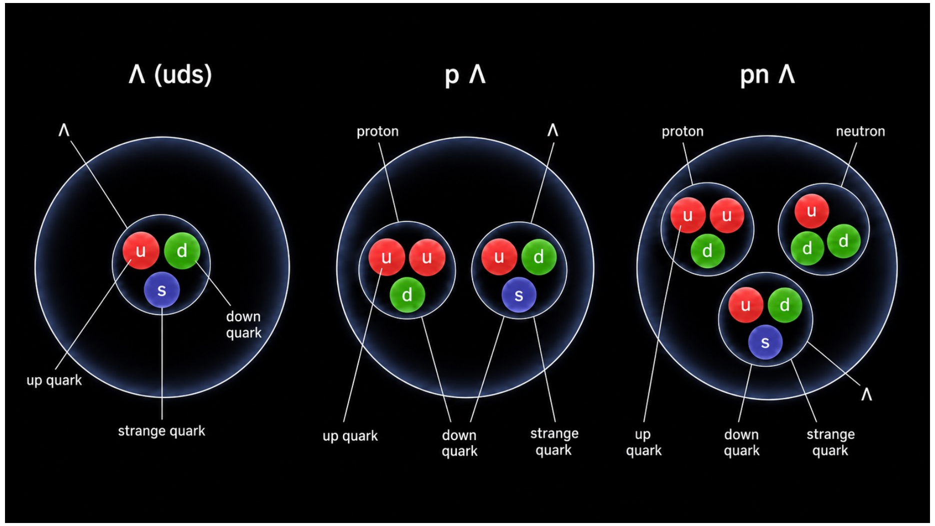


相较于人类专家， LQCDMaster可以实现17-54倍的提速！



LQCD calculation of lowest-lying nucleus





使用自然语言输入

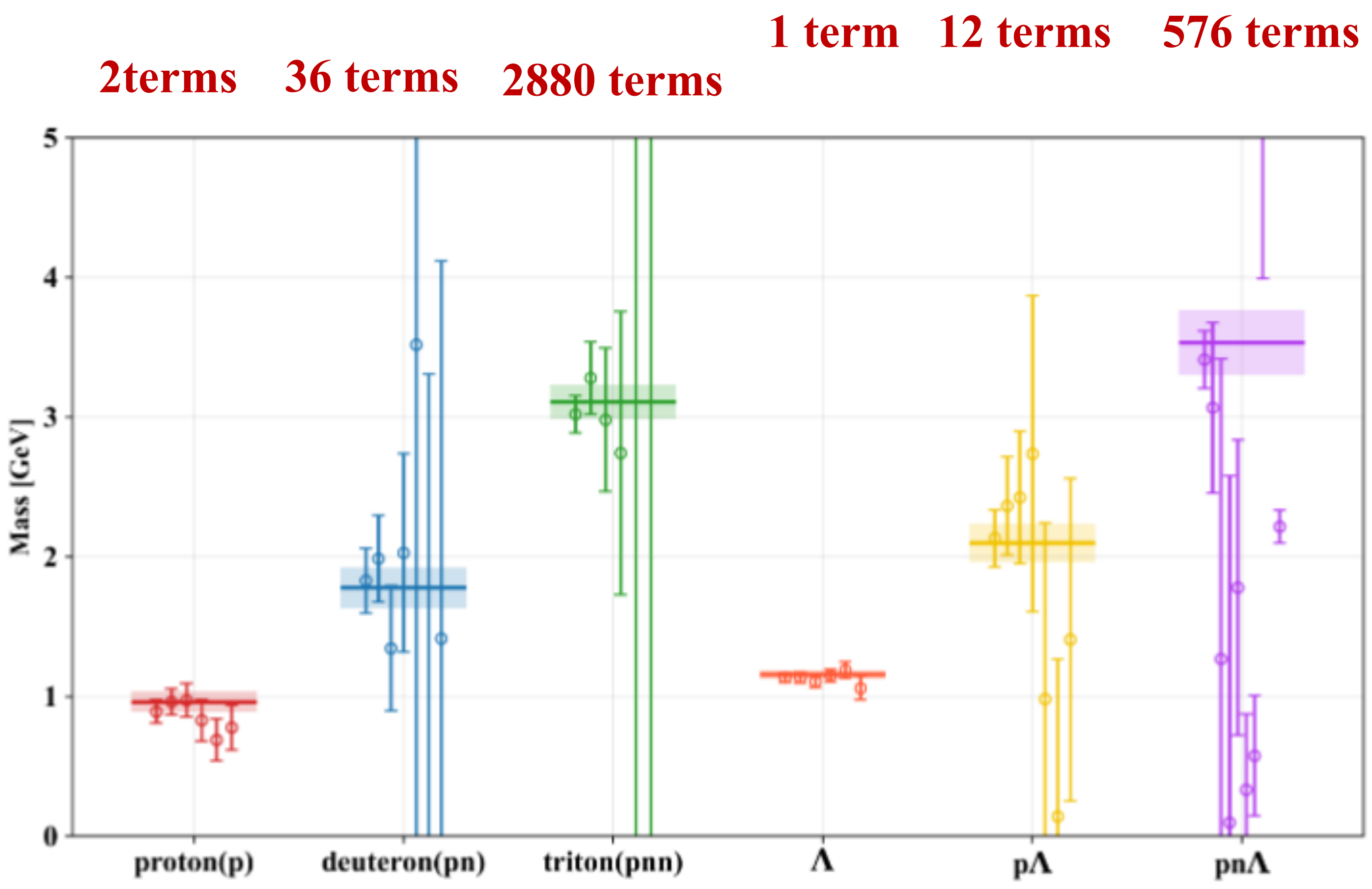
Use multi_hadron_2pt to compute the combined two-baryon two-point function for a local 6-quark operator. The combined interpolating operator at source and sink is:

O = (u^T Cg5 d) d * (u^T Cg5 d) u

Use single-term baryon operators only (no octet flavor combinations). Apply P_plus projector on each baryon block individually (per-baryon block projection, not composite-level). The contraction should be one multi-hadron 2pt object, NOT a product of separate baryon 2pt correlators.

Nuclear mass spectra with LQCDMaster finished within 10 minutes.

LQCD calculation of lowest-lying nucleus



LQCD for Nuclear Spectra:

✓ High theoretical complexity

✓ Predictions consistent with data

✓ Imprecise due to limited computational resources

Nuclear mass spectra with LQCDMaster finished within 10 minutes.

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.

Summary and Outlook

探索AI Agent解决新特定科学问题的方案：eg. 双智能体强化学习拓展设计空间；

领域专精AI自主科学家：LQCDMaster 超长程高效探索+稳健数值计算+可信知识库

我们希望，***PhysMaster / LQCDMaster*** 可以

- ✓ 将智慧、思维活跃的物理学家从繁重的重复劳动中解放出来
- ✓ 加速灵感的生成与验证
- ✓ 解决之前解决不了的问题，拓展科研的边界

Thanks for your attention