北京航空航天大學
BEIHANG UNIVERSITY

Mapping Transverse-Momentum Dynamics in QCD from First Principles

Nucleon TMDs from Lattice QCD



Qi-An Zhang

Beihang University

Lattice Parton Collaboration

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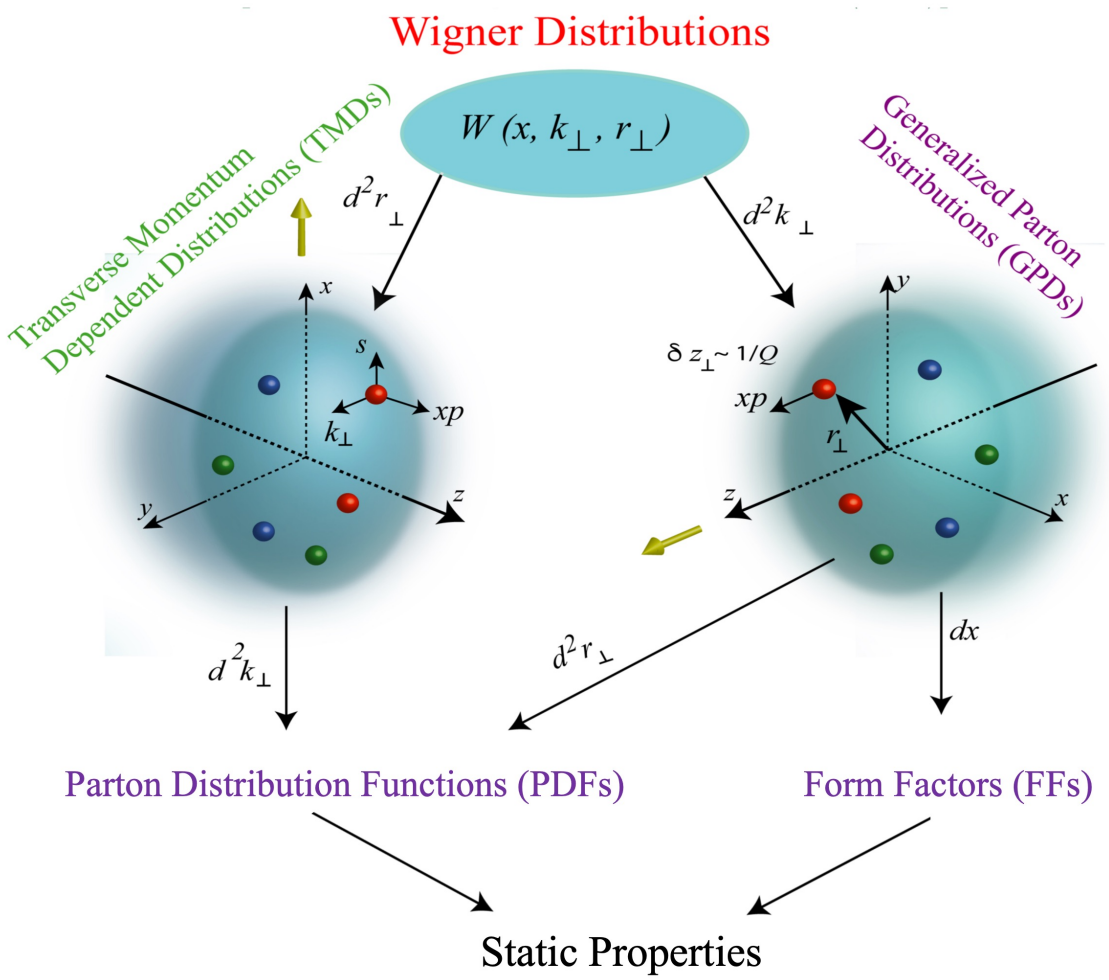
OUTLINE

- Motivation
- Theoretical framework
- Lattice results
  - Collins-Soper Kernel, Intrinsic soft function
  - Unpolarized TMDPDFs and jet-SIDIS at the EIC
  - Helicity TMDPDFs and spin-momentum structure
  - Boer-Mulders Function
- Summary and Outlook

From Nucleon Structure to 3D Imaging



- *How do quarks & gluons form the nucleon, and how are they distributed?*
- *How does nucleon mass & spin emerge from strong interactions?*

— Central science questions driving the EIC program.

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

Hadron's partonic structure in 3D:

- TMDs: 3D structure in momentum space
- GPDs: 3D structure in mixed momentum and coordinate space

Leading Twist Quark TMDPDFs

$$\Phi_{ij}(x,k_\perp) = \int \frac{d\xi^-}{2\pi}\frac{d^2\xi_\perp}{2\pi} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \langle P,S|\bar\psi_j(0)\mathcal{U}(0,\xi)\psi_i(\xi)|P,S\rangle|_{\xi^+=0}$$

Individual TMDs can be projected out of the correlator:

- **Unpolarized Quarks:**

$$\frac{1}{2}\mathrm{Tr}[\gamma^+\Phi(x,k_\perp)] = f_1(x,k_\perp^2) - \frac{\varepsilon_\perp^{ij}k_{\perp i}S_{\perp j}}{M} f_{1T}^\perp(x,k_\perp^2)$$

- **Longitudinally Polarized Quarks:**

$$\frac{1}{2}\mathrm{Tr}[\gamma^+\gamma_5\,\Phi(x,k_\perp)] = \lambda_N g_{1L}(x,k_\perp^2) - \frac{k_\perp\cdot S_\perp}{M} g_{1T}^\perp(x,k_\perp^2)$$

- **Transversely Polarized Quarks:**

$$\frac{1}{2}\mathrm{Tr}[i\sigma^{i+}\gamma_5\,\Phi(x,k_\perp)] = S_\perp^i h_1(x,k_\perp^2) + \frac{k_\perp^2}{M^2}\left(\frac{1}{2}g_\perp^{ij} - k_\perp^i k_\perp^j\right)S_{\perp j} h_{1T}^\perp(x,k_\perp^2)$$
$$+ \frac{\lambda_N}{M} k_\perp^i h_{1L}^\perp(x,k_\perp^2) - \frac{\varepsilon_\perp^{ij}k_\perp^j}{M} h_1^\perp(x,k_\perp^2)$$

Leading Quark TMDPDFs — Nucleon Spin, Quark Spin

Nucleon Polarization	Un-Polarized (U)	Longitudinally Polarized (L)	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

TMD Handbook, arXiv:2304.03302

Extractions for Leading Quark TMDPDFs

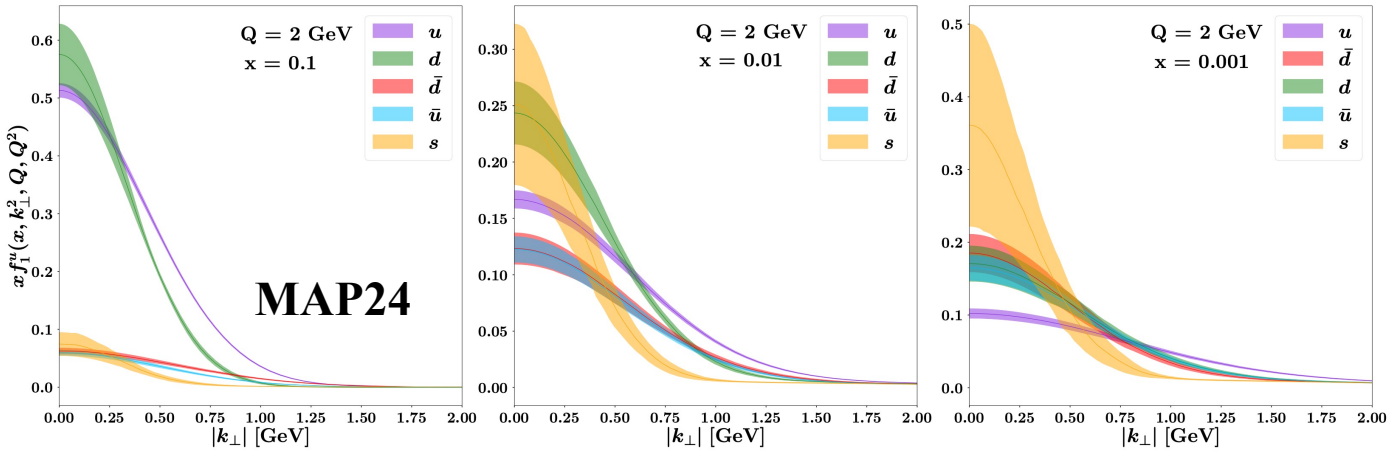
TMDPDFs	Global fit	Lattice QCD (x-dependent)
Unpolarized f_1	2206.07598; 2305.07473; 2405.13833; 2502.04166; 2503.11201; 2510.13771; 2510.17243	2211.02340
Helicity g_{1L}	2409.08110; 2409.18078	2505.18430
Transversity h_1	1505.05589; 2310.15532; 2412.18324	
Sivers $f_{1T}^{\perp}$	2009.10710; 2103.03270; 2304.14328; 2412.18324	
Boer-Mulders $h_1^{\perp}$	2004.02117; 2407.06277	2502.11807
Worm-gear $g_{1T}^{\perp}$	2110.10253; 2210.07268; 2403.12795	
Worm-gear $h_{1L}^{\perp}$		
Pretzelosity $h_{1T}^{\perp}$	1411.0580	

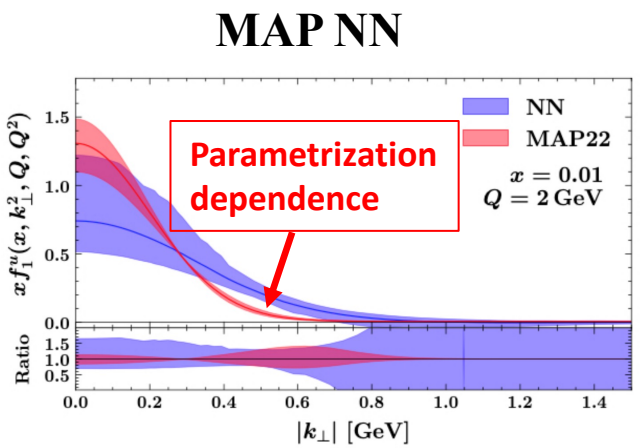
Adapted from Barbara Pasquini, talk on DIS2025

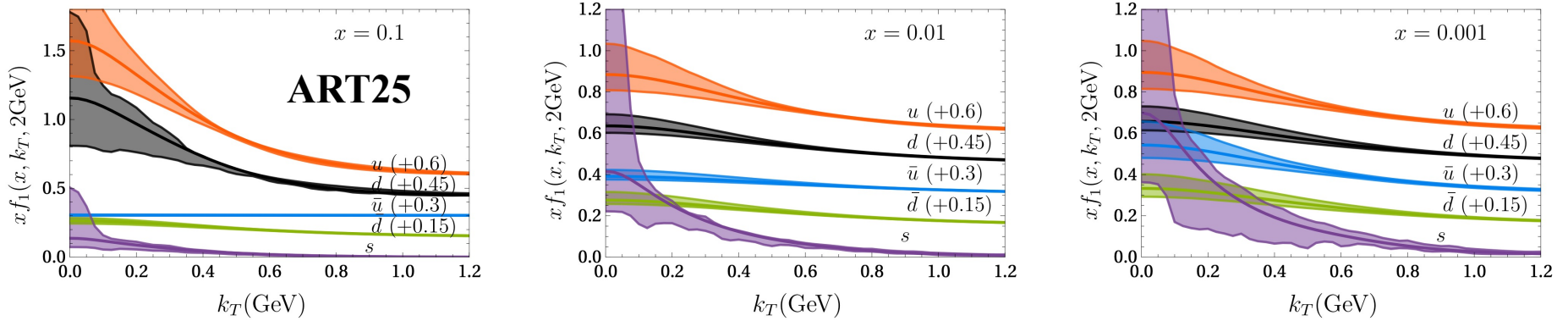
Not mentioned: pion TMDs, TMD fragmentation functions, nuclear TMDs

Phenomenological Extractions

Unpolarized f_1:



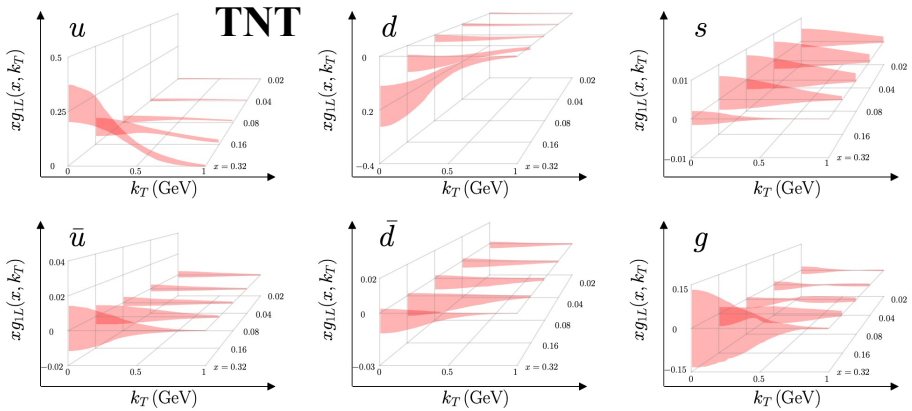




- MAP24, JHEP 08 (2024) 232
- MAPNN, Phys. Rev. Lett. 135, 021904 (2025)
- ART25, JHEP 11 (2025) 134

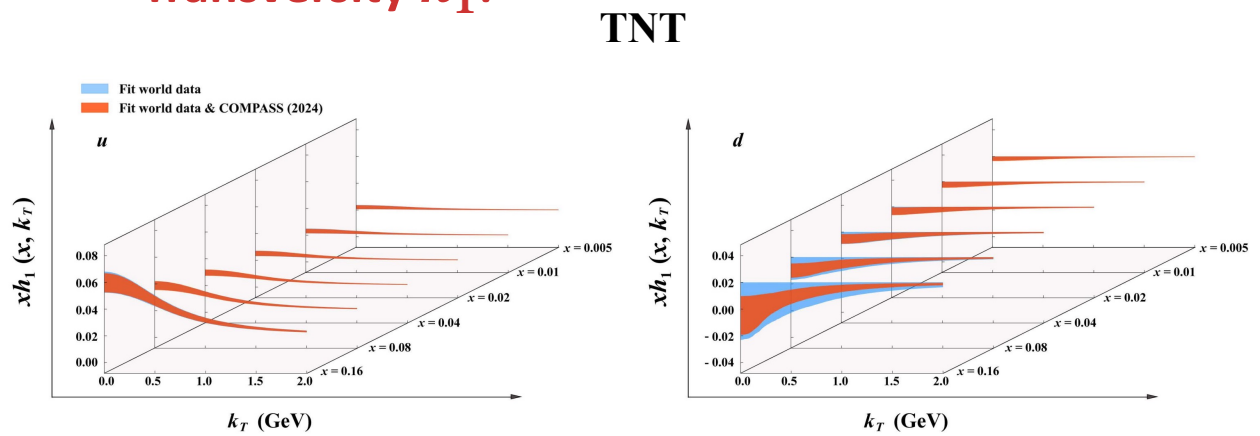
Phenomenological Extractions

Helicity g_1:

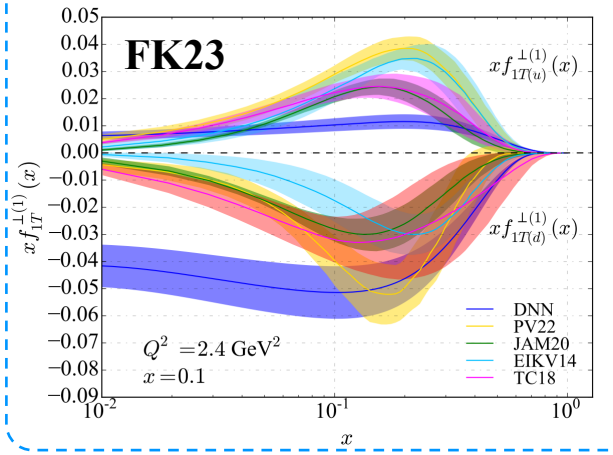


- TNT, Phys. Rev. Lett. 134, 121902 (2025)
- MAP-Heli, Phys. Rev. Lett. 134, 121901 (2025)
- TNT, arXiv:2412.18324 [hep-ph]

Transversity h_1:

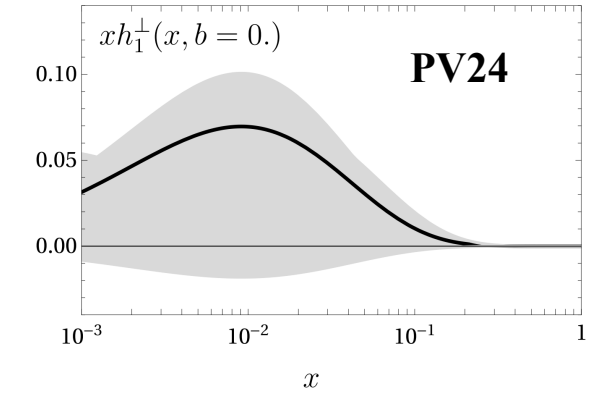


Sivers $f_{1T}^{\perp}$:



- FK23, Phys. Rev. D 108, 054007 (2023)

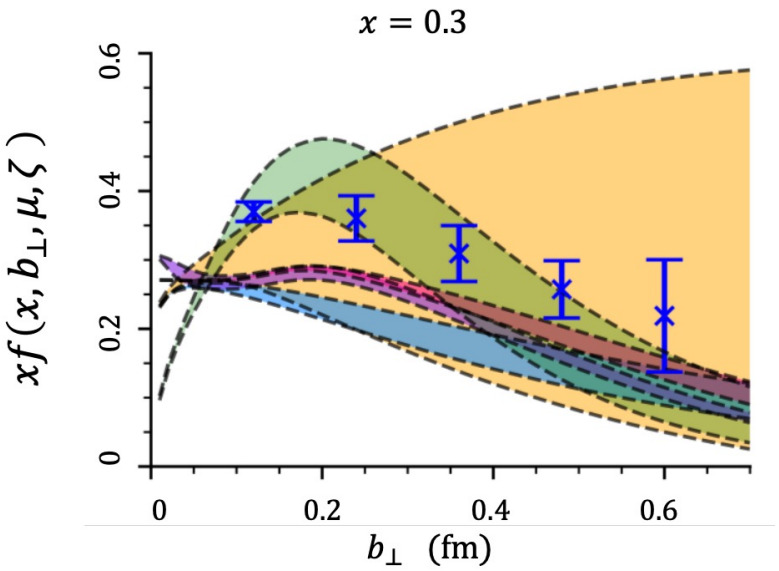
Boer-Mulders $h_1^{\perp}$:



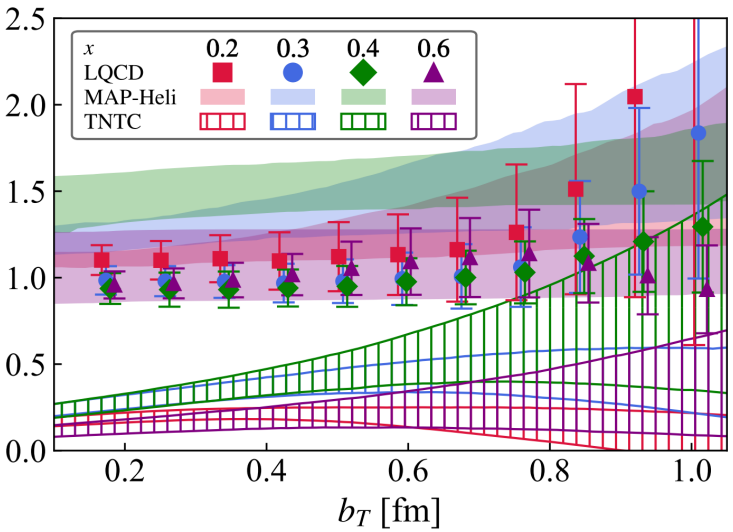
- PV24, JHEP 12 (2024) 059

Lattice QCD Calculations

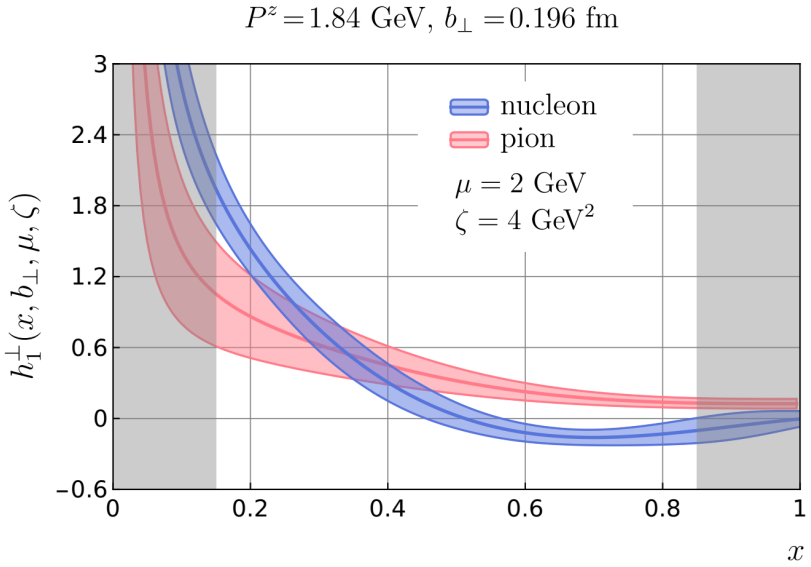
Unpolarized f_1: LPC24



Ratio of Hel. to Unpol. g_1/f_1: BNL/ANL25



Boer-Mulders $h_1^\perp$: LPC25



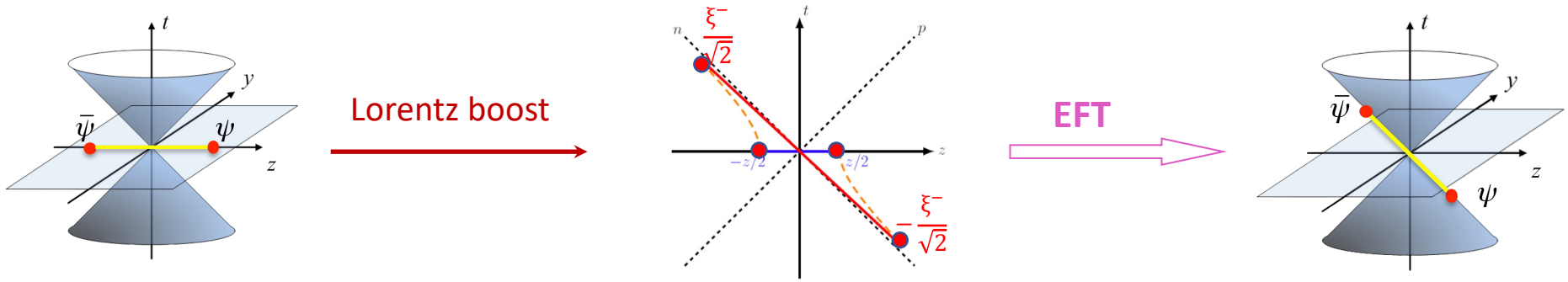
Remaining limitations:

- Single lattice spacing
- Limited statistics
- Incomplete systematic uncertainties

- LPC24: PRD109, 114513 (2024)
- BNL/ANL25: PRL135, 201901 (2025)
- LPC25: JHEP08, 086 (2025)

LaMET: Theoretical framework for lattice calculations

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 (quasi-distributions) can be directly computed in lattice QCD:

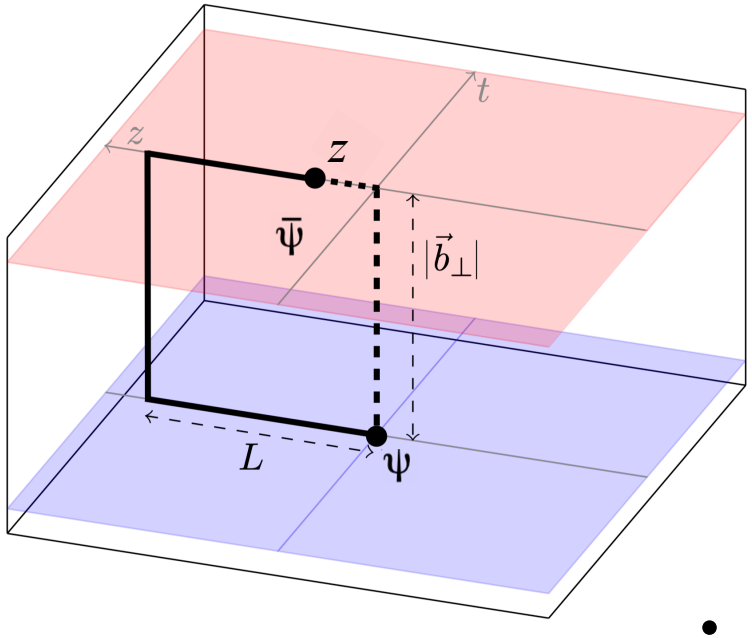
$$\tilde{q}(x, P^z) = \int \frac{dz}{2\pi} e^{-izP^z} \langle P^z | \bar{\psi}(z) \Gamma \mathcal{U}(z,0) \psi(0) | P^z \rangle$$

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

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

TMDs from Lattice QCD within LaMET

Start from **quasi-TMDs:**



- Quasi-TMDPDF (inclusive)

$$\tilde{f}(x, b_\perp, \mu, P^z) = \lim_{L\to\infty} \int \frac{dz}{2\pi} e^{-ixP^z z} \times \langle P^z | \bar{\psi}(z\hat{n}_z) \Gamma U_{\sqsubset}(z, b_\perp; \pm L) \psi(b_\perp \hat{n}_\perp) | P^z \rangle_R$$

- Quasi-TMD wave function (exclusive)

$$\tilde{\phi}(x, b_\perp, \mu, P^z) = \lim_{L\to\infty} \int \frac{dz}{2\pi} e^{ixP^z z} \times \langle 0 | \bar{\psi}(z\hat{n}_z) \Gamma U_{\sqsubset}(z, b_\perp; L) \psi(b_\perp \hat{n}_\perp) | P^z \rangle_R$$

- Staple-shaped Wilson link:

$$U_{\sqsubset}(z, b_\perp; \pm L) \equiv U_z^\dagger(z\hat{n}_z \to L\hat{n}_z) U_\perp(L\hat{n}_z, L\hat{n}_z + b_\perp \hat{n}_\perp) U_z(L\hat{n}_z + b_\perp \hat{n}_\perp, b_\perp \hat{n}_\perp)$$

TMDs from Lattice QCD within LaMET

- UV and rapidity evolution of TMDs:

$$\mu\frac{d}{d\mu}\ln f^{\rm TMD}(x,b_\perp,\mu,\zeta) = \gamma_F(\mu,\zeta)$$

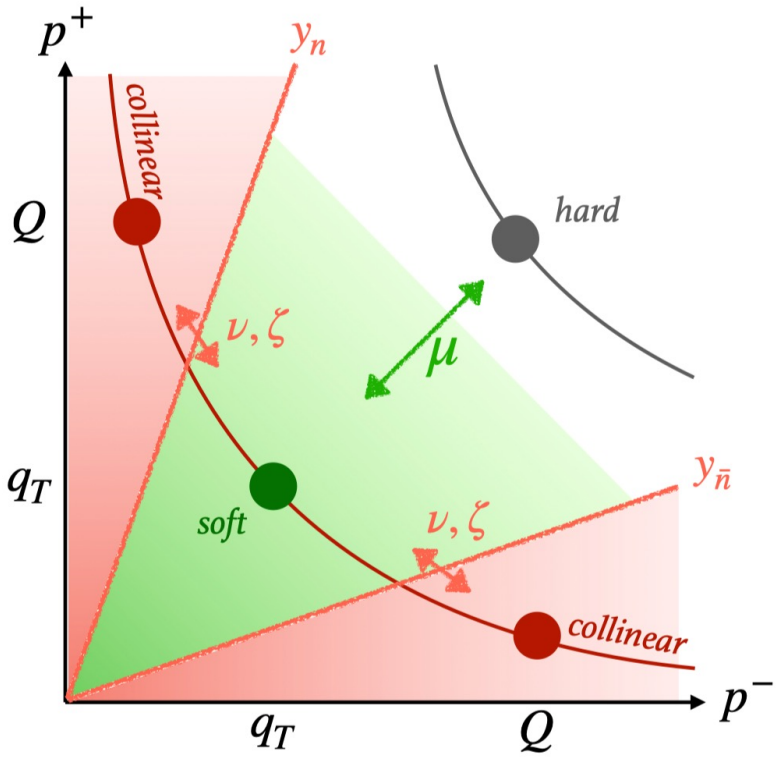
$$2\zeta\frac{d}{d\zeta}\ln f^{\rm TMD}(x,b_\perp,\mu,\zeta) = K(b_\perp,\mu)$$

- LaMET: rapidity evolution → momentum evolution

$$\tilde{f}(x,b_\perp,\mu,\zeta_z)\sqrt{S_I(b_\perp,\mu)} = H(\zeta_z,\mu)\exp\left[\frac{1}{2}K(b_\perp,\mu)\ln\frac{\zeta_z}{\zeta}\right]f^{\rm TMD}(x,b_\perp,\mu,\zeta)$$

- Collins-Soper kernel from lattice QCD:

$$\frac{d\ln f^{\rm TMD}}{d\ln\sqrt{\zeta}} = K \quad \Longleftrightarrow \quad \frac{d}{d\ln P^z}\ln\frac{\tilde{f}}{H} = K$$



TMDs from Lattice QCD within LaMET

- 4-quark form factor with large P^z:

$$F_\Gamma(b_\perp, P^z) = \langle -P^z | (\bar{q}_1 \Gamma q_1)(b_\perp)(\bar{q}_2 \Gamma q_2)(0) | P^z \rangle$$

Fully Euclidean, lattice calculable

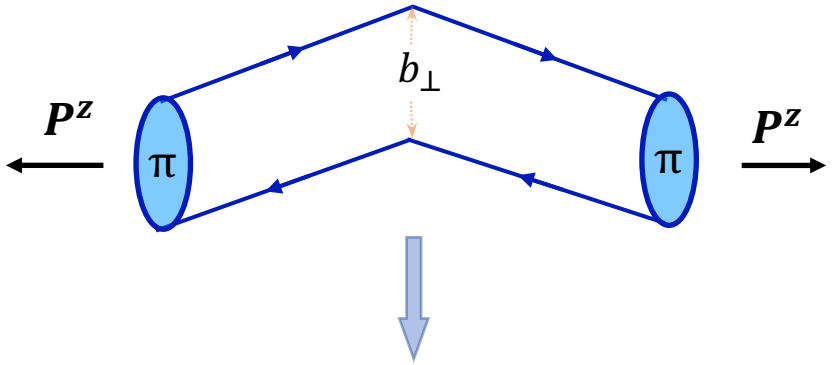
- In the large momentum limit:

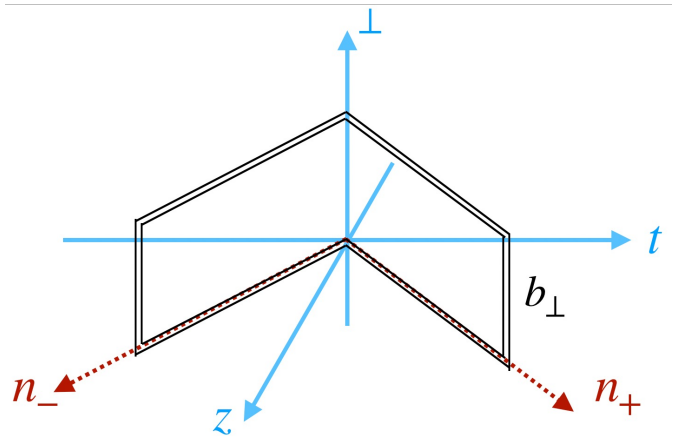
$$F_\Gamma(b_\perp, P^z) = S_I(b_\perp, \mu) \int dx\, dx' \times H_\Gamma(x, x', P^z, \mu)\, \tilde{\phi}(x, b_\perp, P^z)\, \tilde{\phi}^\dagger(x', b_\perp, P^z)$$

- Intrinsic soft function from lattice QCD:

$$S_I(b_\perp, \mu) = \frac{F_\Gamma(b_\perp, P^z)}{\int dx\, dx'\, H_\Gamma\, \tilde{\phi}(x, b_\perp, P^z)\, \tilde{\phi}^\dagger(x', b_\perp, P^z)}$$

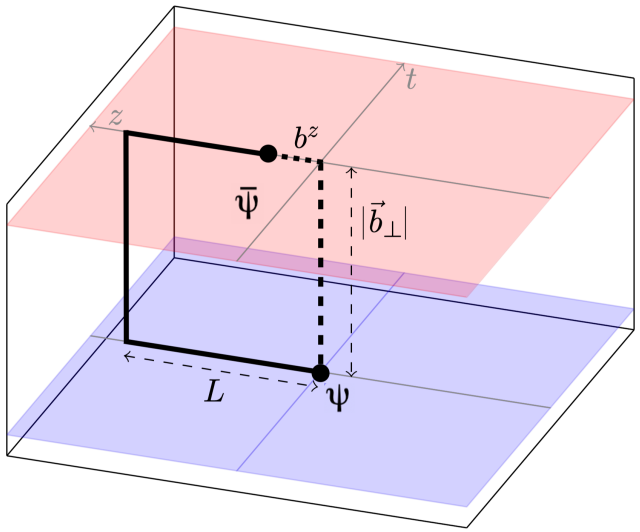
Ji, Liu, Liu, Nucl. Phys. B 955 (2020) 115054





TMDs from Lattice QCD within LaMET

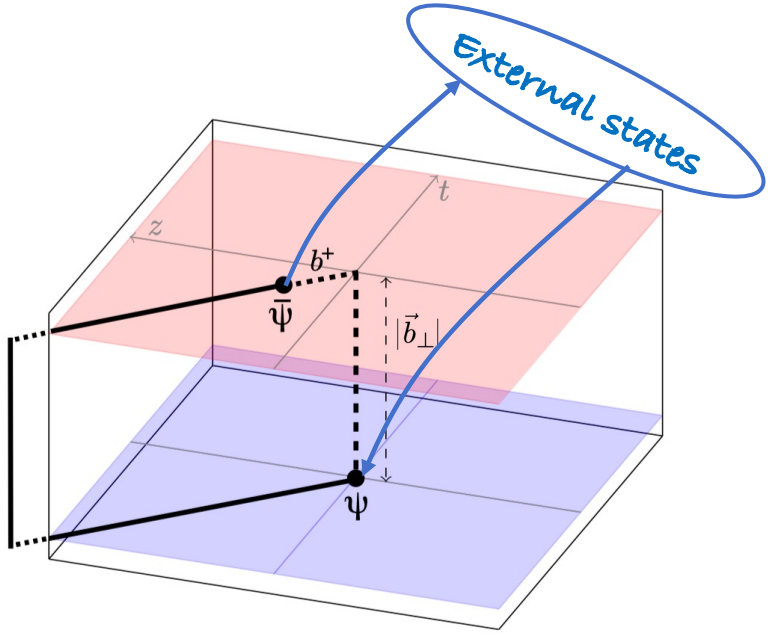
- Quasi TMDs in the large momentum limit:



Lorentz boost

$L \to \infty$

$P^z \to \infty$



Factorization in LaMET:

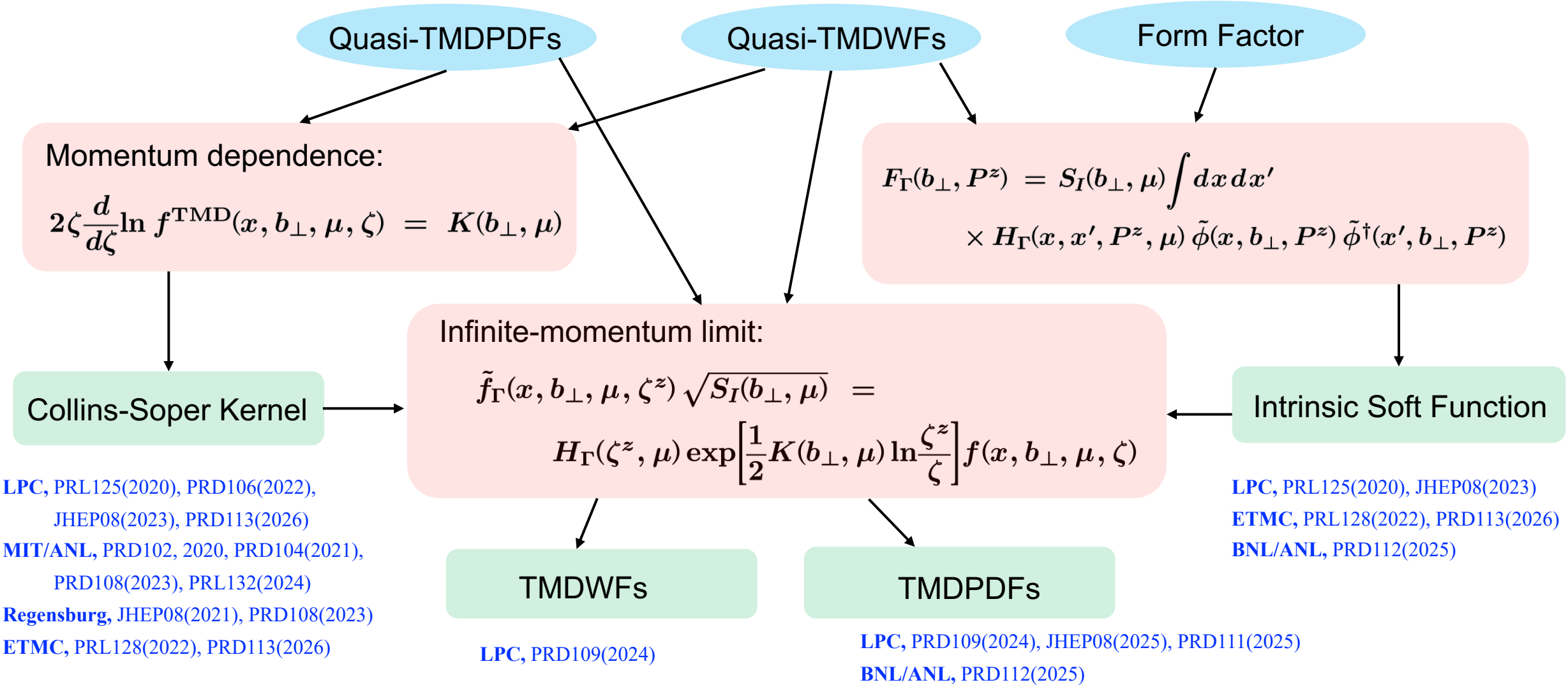
PLB811, 135946 (2020); JHEP04, 178, (2022)

Perturbative matching kernel

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

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

LQCD Workflow for TMD Calculations



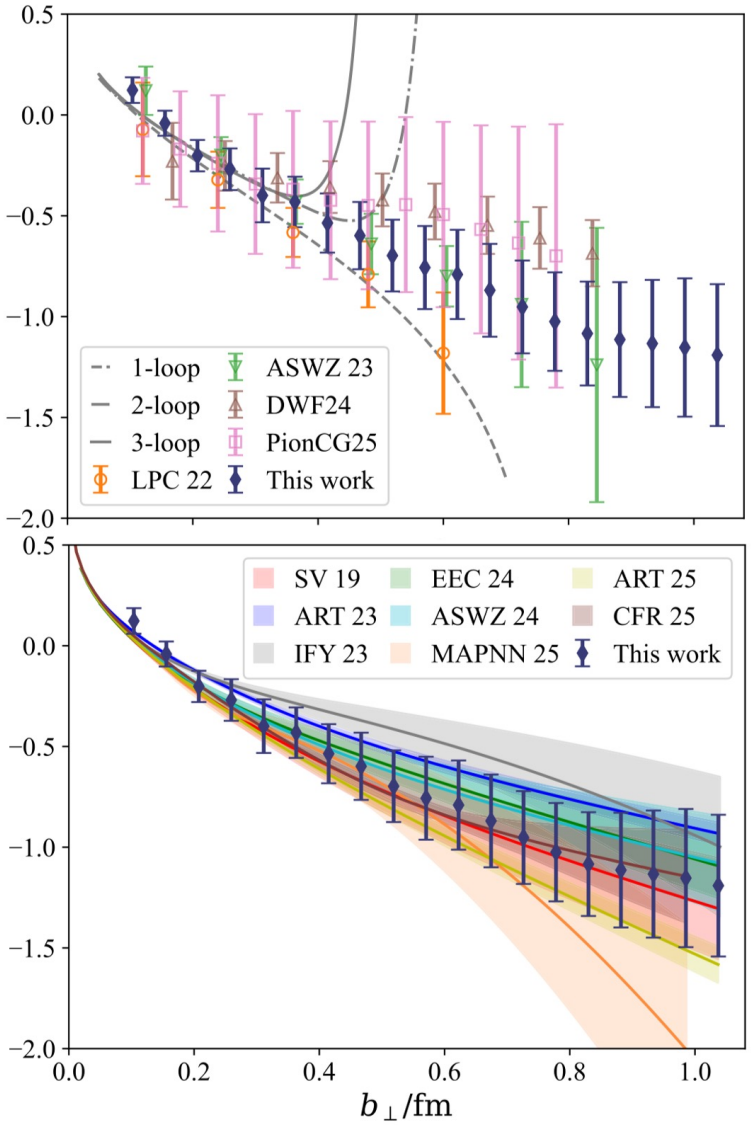
LPC, PRL125(2020), PRD106(2022), JHEP08(2023), PRD113(2026)
MIT/ANL, PRD102, 2020, PRD104(2021), PRD108(2023), PRL132(2024)
Regensburg, JHEP08(2021), PRD108(2023)
ETMC, PRL128(2022), PRD113(2026)

LPC, PRD109(2024)

LPC, PRD109(2024), JHEP08(2025), PRD111(2025)
BNL/ANL, PRD112(2025)

LPC, PRL125(2020), JHEP08(2023)
ETMC, PRL128(2022), PRD113(2026)
BNL/ANL, PRD112(2025)

Collins-Soper Kernel from Lattice QCD

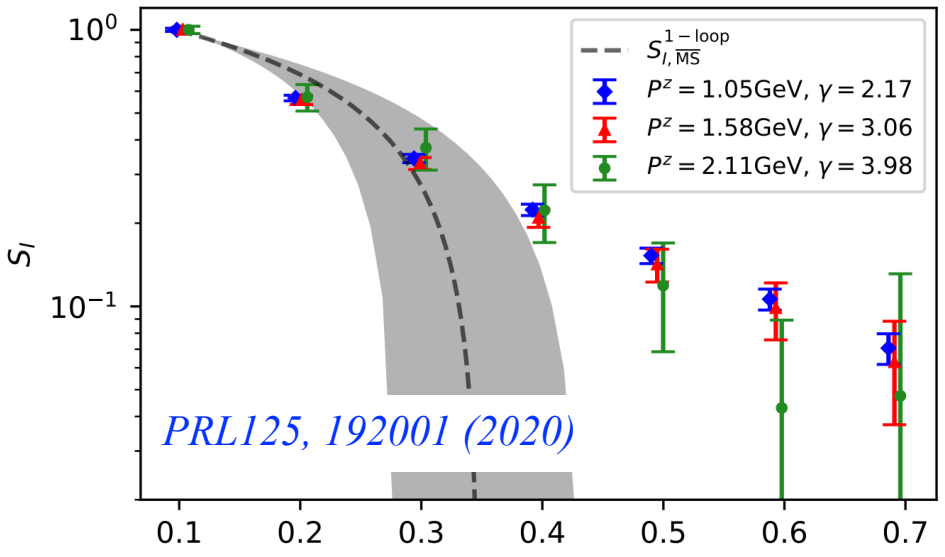


- A benchmark quantity for lattice TMD studies
  - ✓ Continuum, physical mass, infinite-momentum limits
  - ✓ Controlled systematic uncertainties
  - ✓ Lattice QCD provides first-principles constraints up to $b_\perp$ ~ 1fm
  - ✓ Consistency with global extractions provides an important cross-check
- A precise CS kernel is a key step toward first-principles predictions of TMD observables

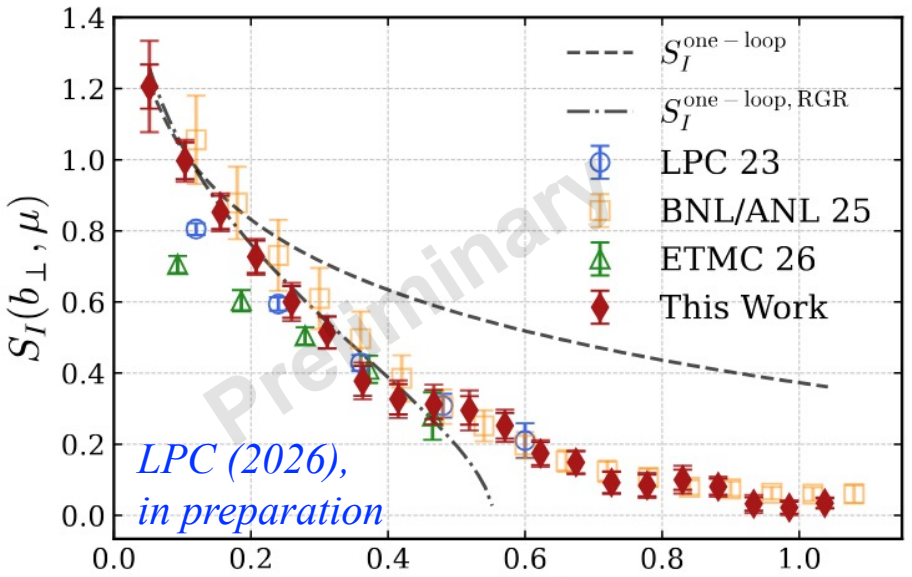
LPC, PRD113, 054505 (2026)

Intrinsic Soft Function from Lattice QCD

LPC, 2020



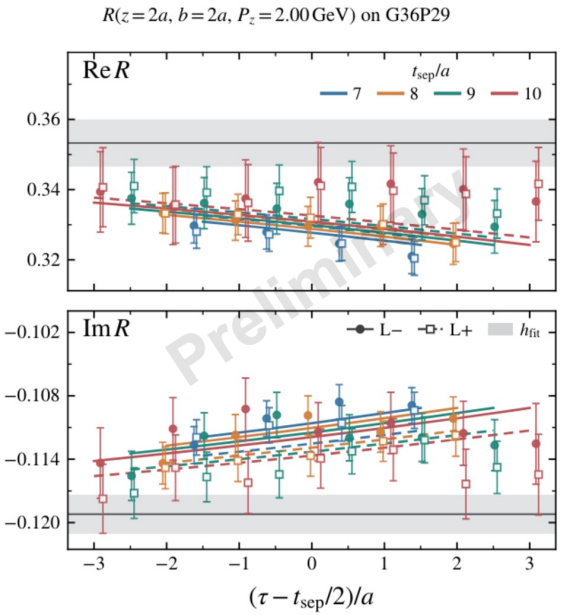
LPC, 2026

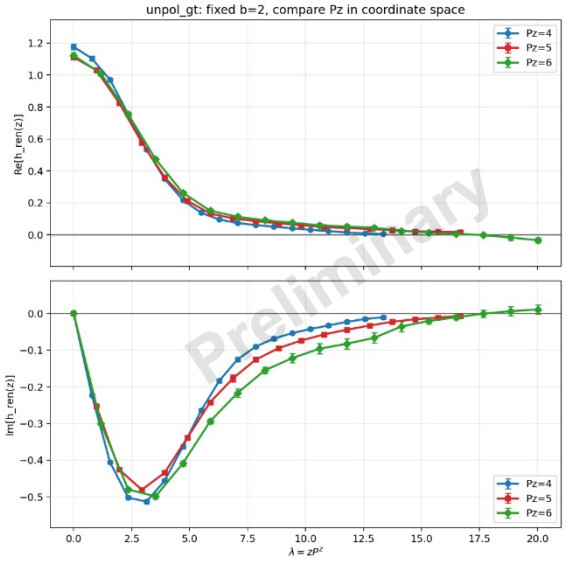


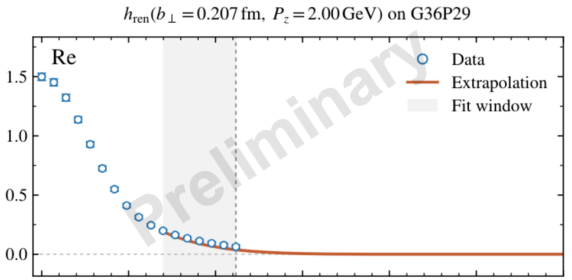
- ✓ Continuum, physical mass, infinite-momentum limits
- ✓ Controlled systematic uncertainties
- ✓ Precise first-principles prediction up to $b_\perp$ ~ 1fm

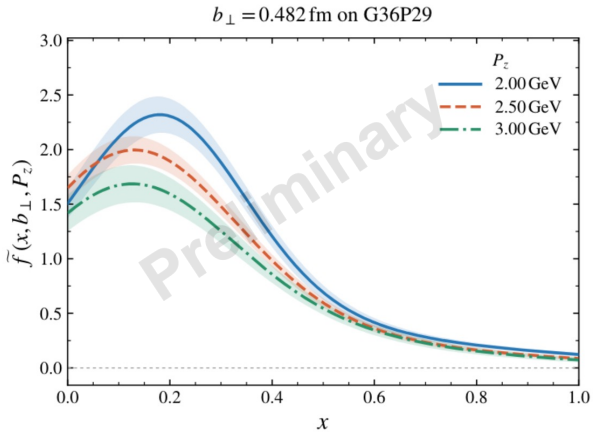
Precise Calculation for Leading Quark TMDs

- E.g.: Unpolarized isovector nucleon TMDPDF









- ✓ Multi lattice spacings ⇒ Continuum Limit
- ✓ Multi pion masses ⇒ Physical mass Limit
- ✓ Large statistics

Ground-state fit the ratio of 3pt/2pt

Nonlocal renormalization to get coordinate-space distribution

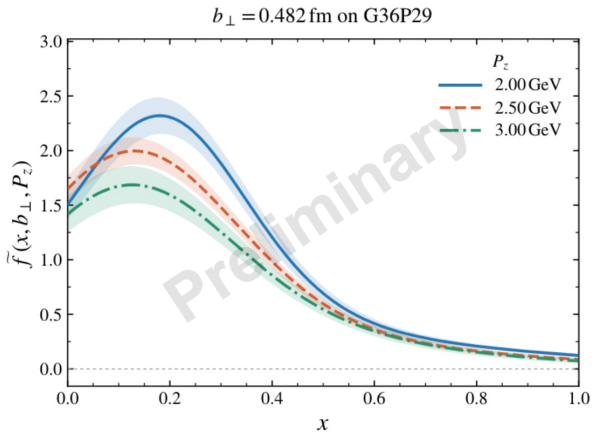
Long-range extrapolation

Fourier transform to get momentum-space quasi-TMDPDF

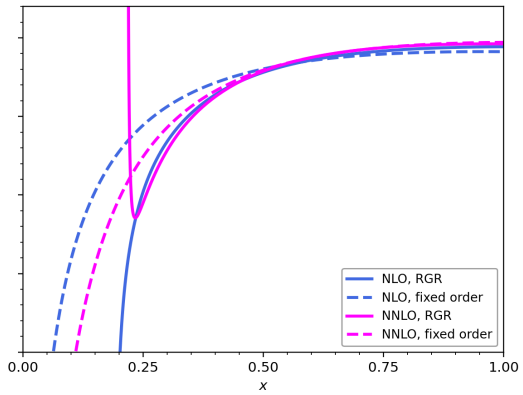
LPC (2026), in preparation

Precise Calculation for Leading Quark TMDs

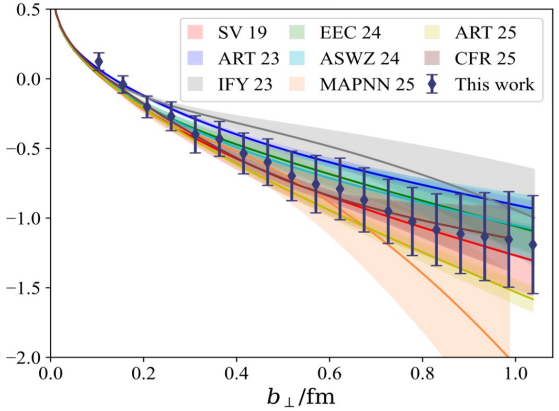
Quasi-TMDPDF



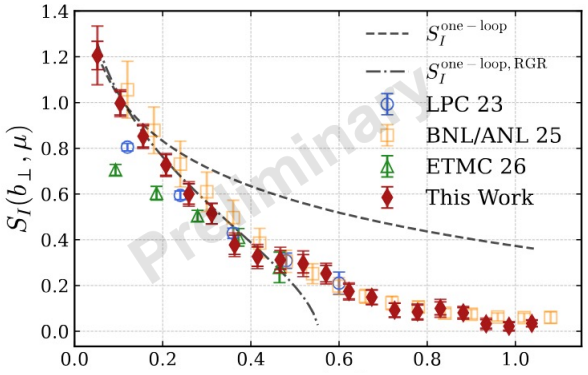
Matching kernel

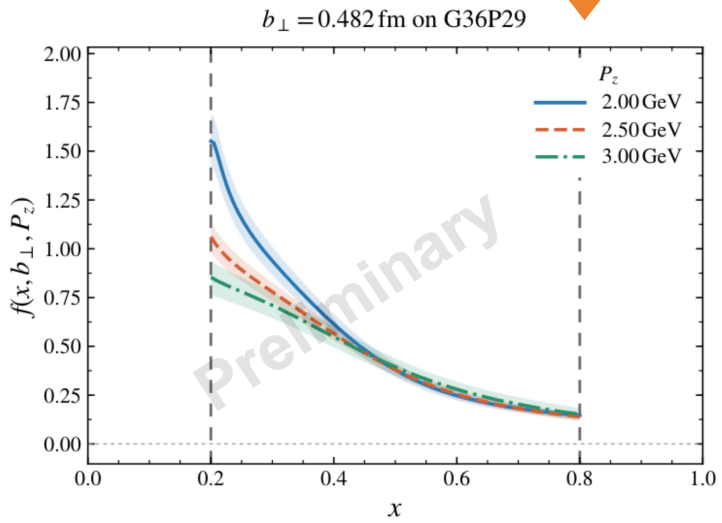


Collins-Soper kernel



Intrinsic soft function





Repeat

Calculations

Ensembles:

C32P23: 0.105fm, 228MeV

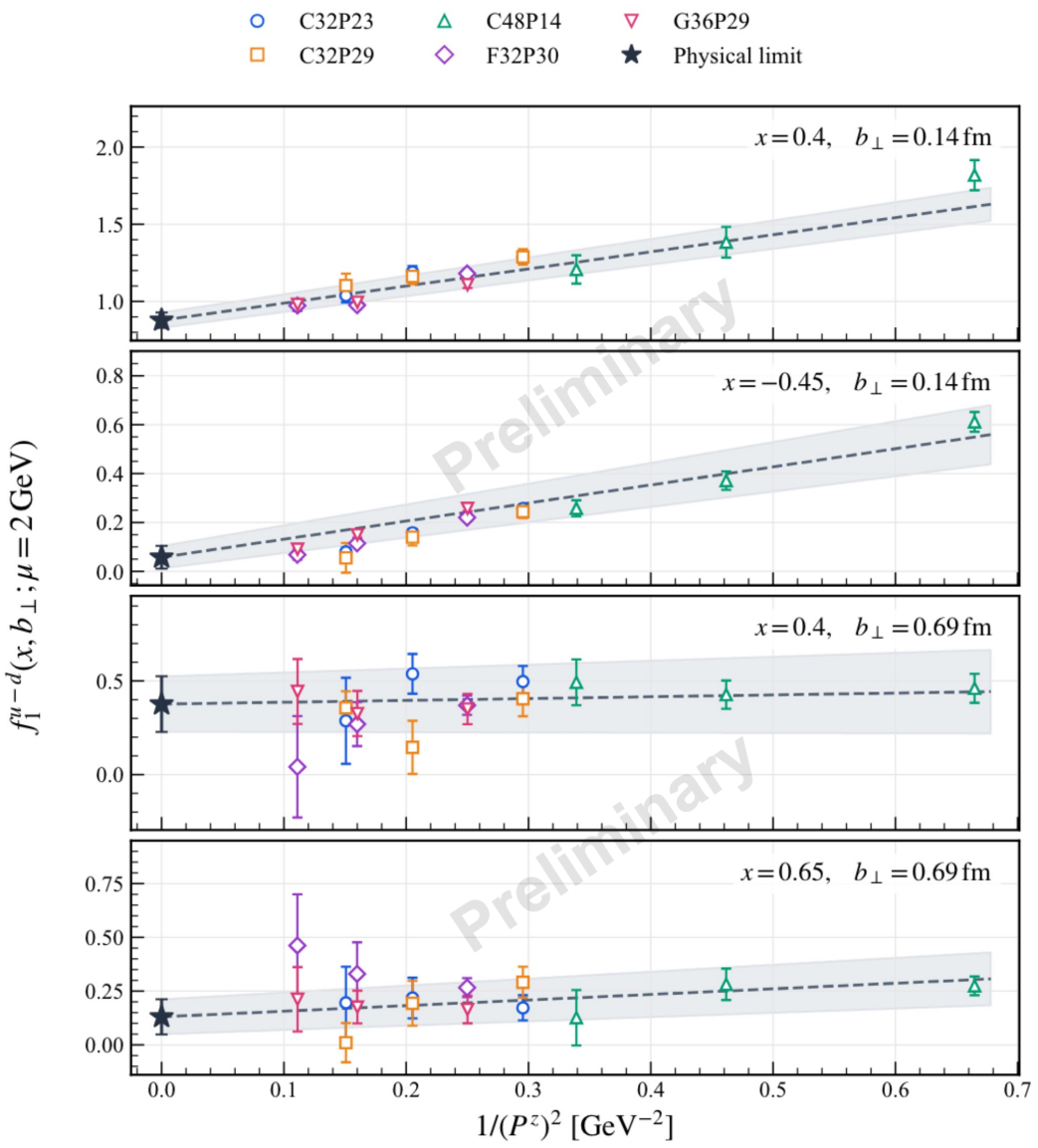
C32P29: 0.105fm, 292MeV

C48P14: 0.105fm, 136MeV

F32P30: 0.077fm, 303MeV

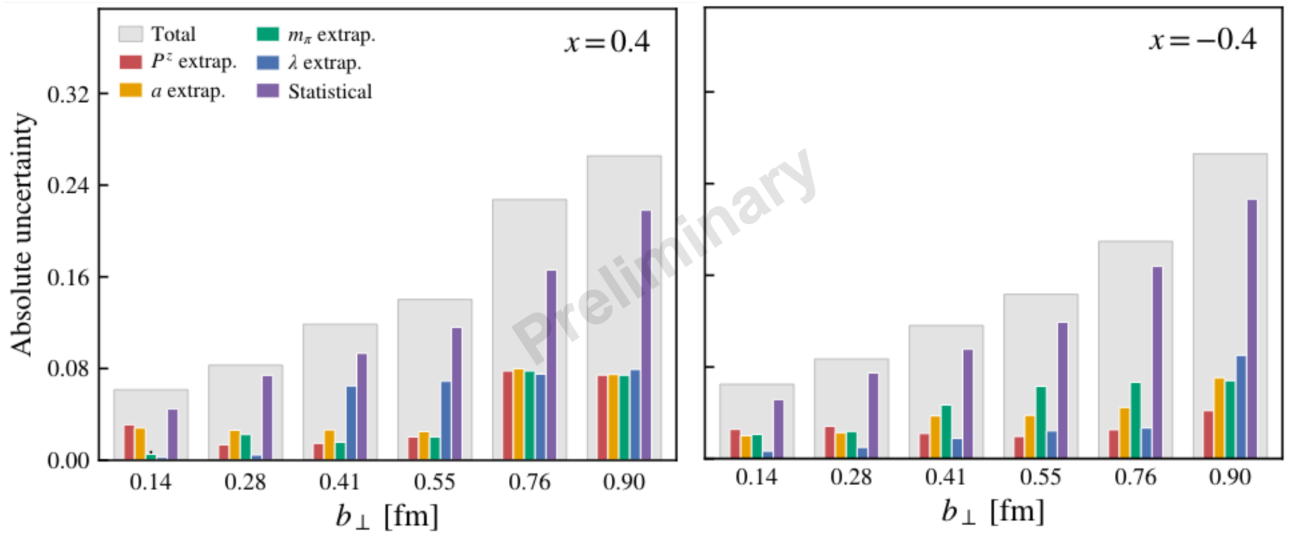
G36P29: 0.069fm, 295MeV

Isovector Unpolarized TMDPDFs from Lattice QCD



Precise physical-limit results:

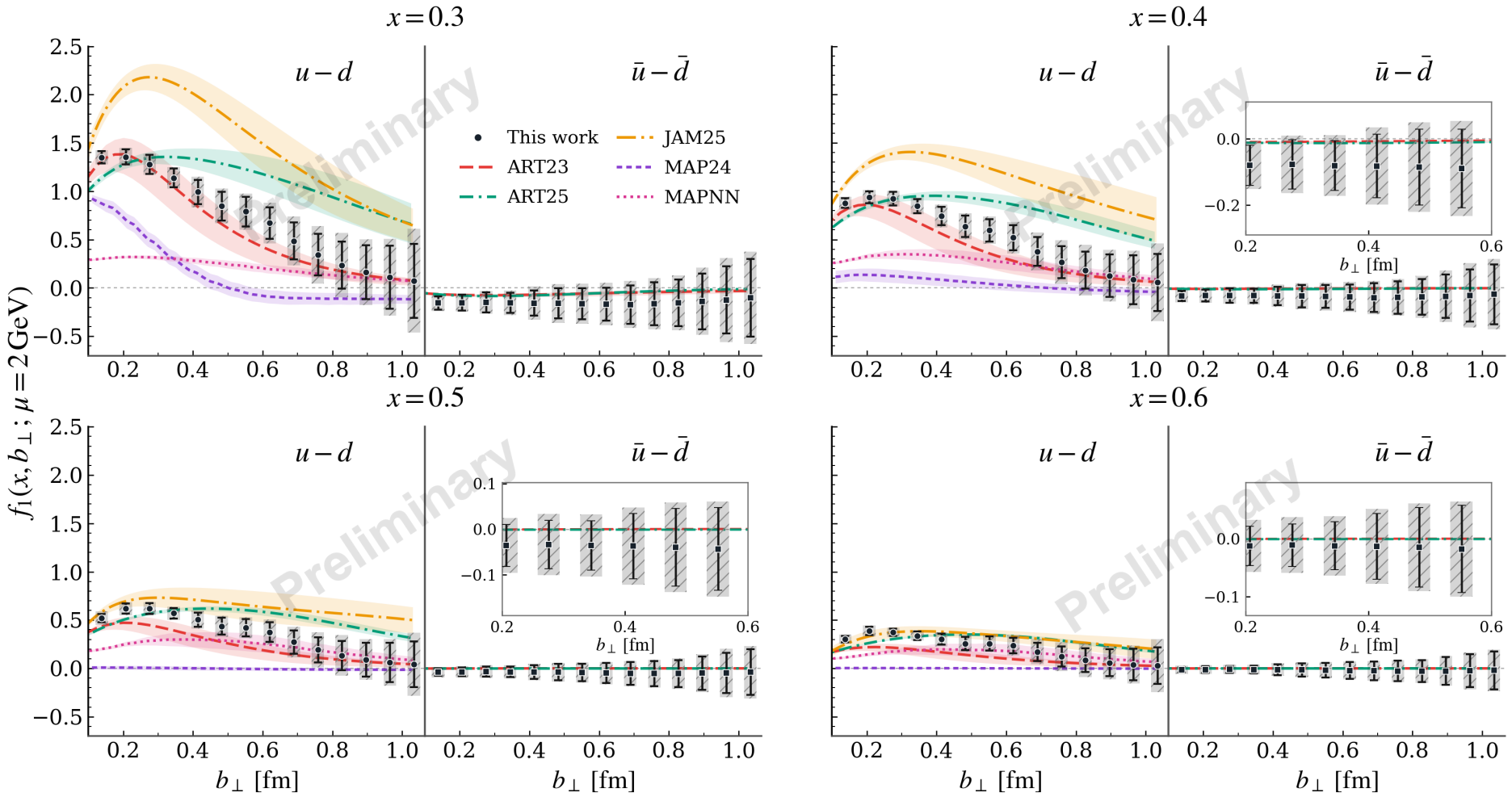
- ✓ Both quark & antiquark TMDPDFs
- ✓ Continuum & physical-mass limit
- ✓ Infinite-momentum limit
- ✓ Controlled systematic uncertainties



LPC (2026), in preparation

Isovector Unpolarized TMDPDFs from Lattice QCD

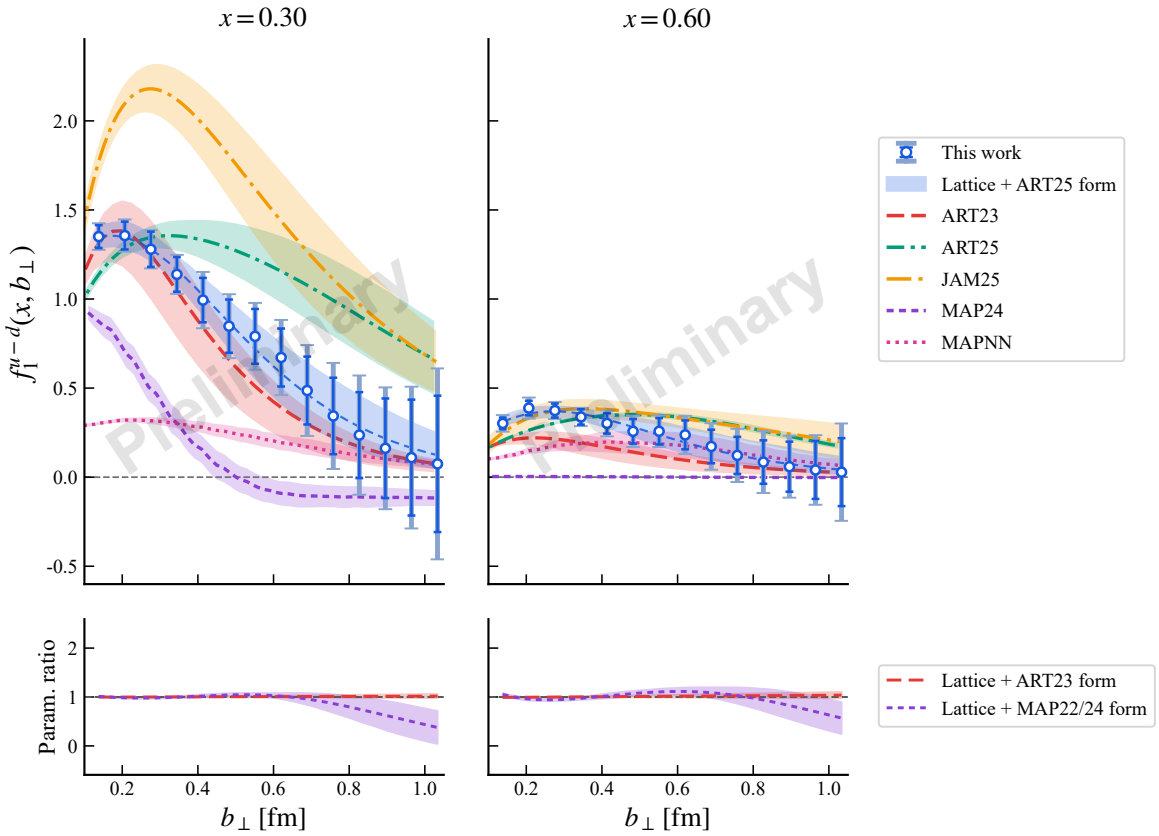
- LQCD result @ continuum/physical-mass/infinite-momentum limit vs. Global fits



- *ART23: 2305.07473*
- *ART25: 2503.11201*
- *JAM25: 2510.13771*
- *MAP24: 2405.13833*
- *MAPNN: 2502.04166*
- *LPC26 (this work), in preparation*

Isovector Unpolarized TMDPDFs from Lattice QCD

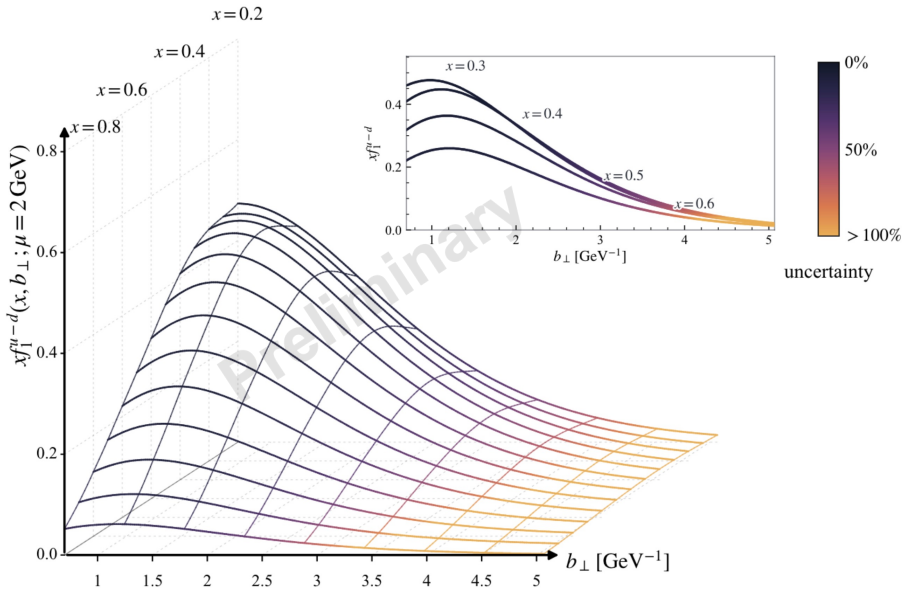
Lattice data constrained global fit:



LPC (2026), in preparation

- Global fits show sizable differences.
- Lattice-constrained fits give remarkably consistent results.

✓ A continuous first-principles map in $(x, b_\perp)$ space



Predictions for the jet-SIDIS Process

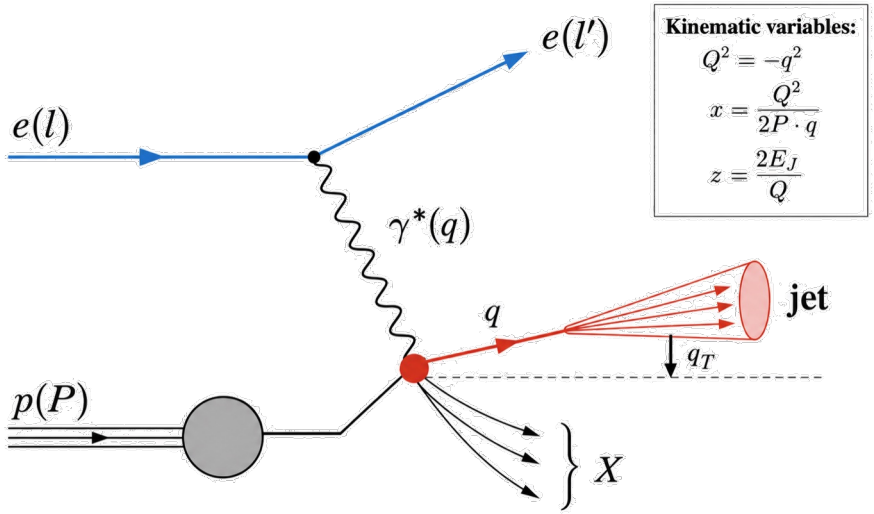
- The jet-SIDIS process will provide a clean platform for test the TMDPDFs:

$$e + p \to e' + \text{jet} + X, \qquad e + n \to e' + \text{jet} + X.$$

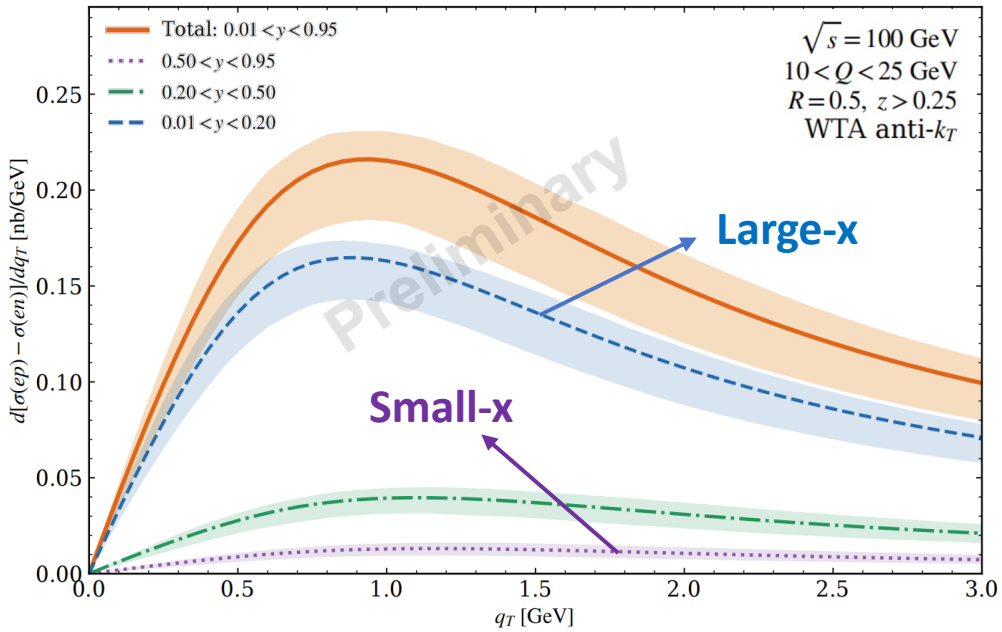
Gutierrez-Reyes, et.al. JHEP 10 (2019) 031

- Differential cross section is dominated by large-x region: $y = \frac{Q^2}{xs}$

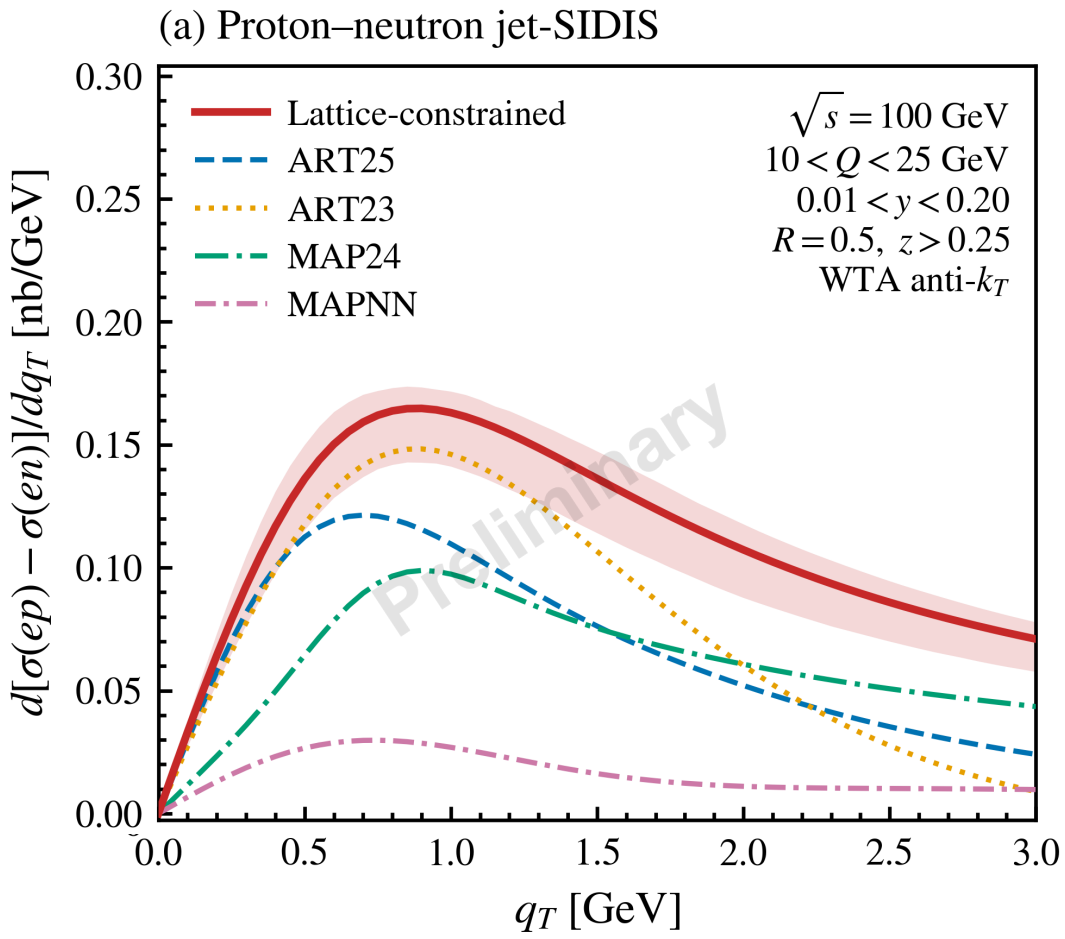
The interval $0.01 < y = \frac{Q^2}{xs} < 0.20$ accounts for about 75% of the total cross-section difference integrated over $0 < q_T < 3$ GeV.



LQCD prediction for $\Delta\sigma = \sigma(ep) - \sigma(en)$



Predictions for the jet-SIDIS Process



LPC (2026), in preparation

- Lattice QCD and global fits predict clearly different q_T spectra.
- Future EIC data can directly test which TMD description is favored by experiment.
- A direct experimental test of first-principles lattice predictions.

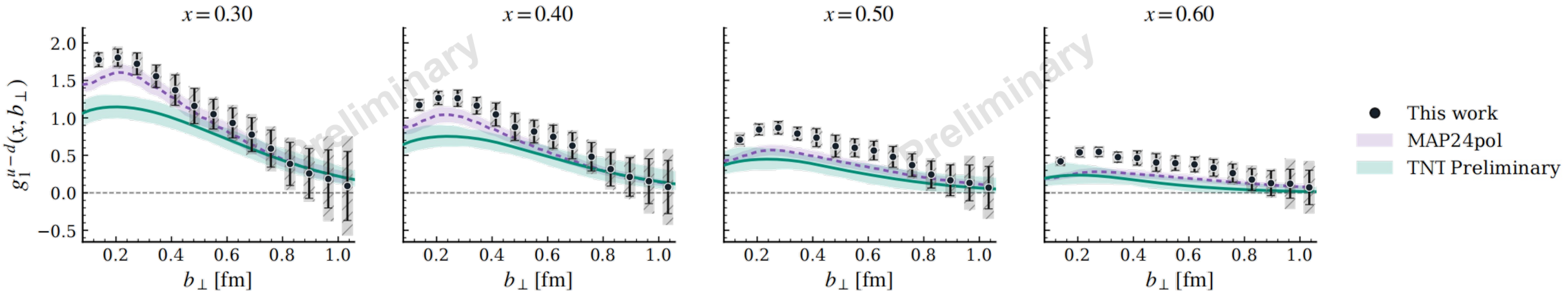
Global-fit curves show central values only.

Helicity TMDPDFs from Lattice QCD

✓ Continuum limit ✓ Physical mass limit ✓ Infinite momentum limit

✓ Systematic uncertainties ✓ $b_T \sim 1$fm

- Overall good agreement with MAP24pol.



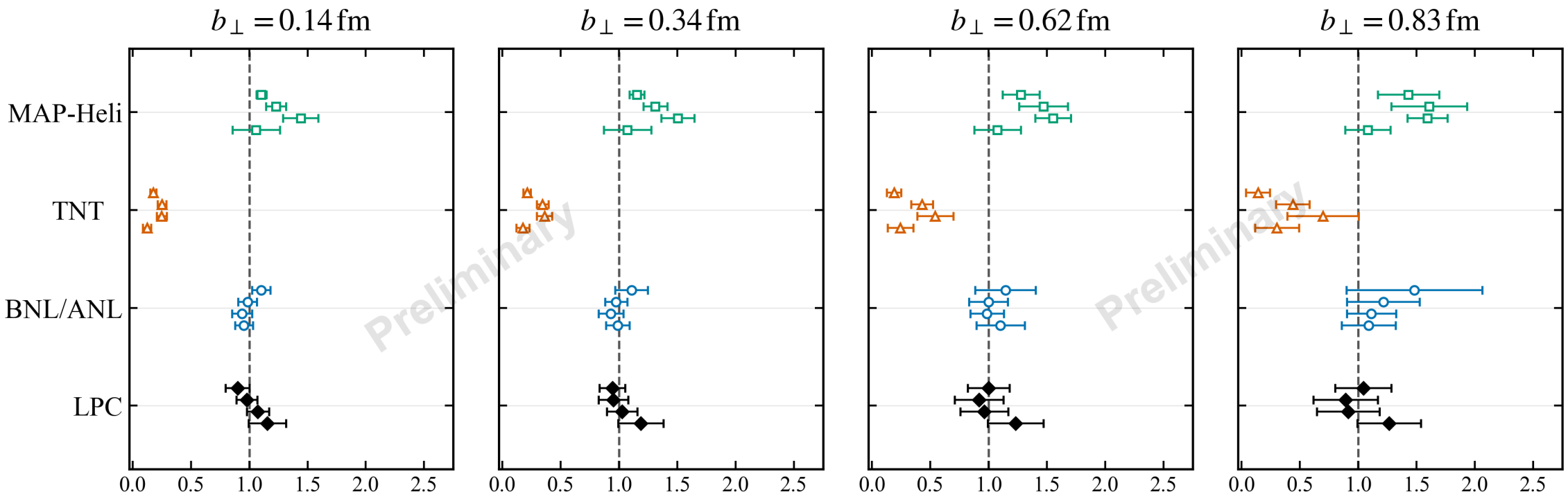
- *MAP-Heli: 2409.18078*
- *LPC26 (this work), in preparation*
- *TNT26: in preparation*

Helicity TMDPDFs from Lattice QCD

- Normalized Helicity-to-Unpolarized TMD Ratio:

$$R^{u-d}_{g_{1L}/f_1}(x, b_T) \cdot g_A \equiv \frac{g^{u-d}_{1L}(x, b_T; \zeta, \mu)}{f^{u-d}_1(x, b_T; \zeta, \mu)} \simeq \frac{\tilde{g}^{u-d}_{1L}(x, b_T, P_z, \mu)}{\tilde{f}^{u-d}_1(x, b_T, P_z, \mu)} .$$

- *MAP-Heli: 2409.18078*
- *TNT: 2409.08110*
- *BNL/ANL: 2505.18430*
- *LPC26 (this work), in preparation*



(The points from top to bottom correspond to x=0.2, 0.3, 0.4, 0.6)

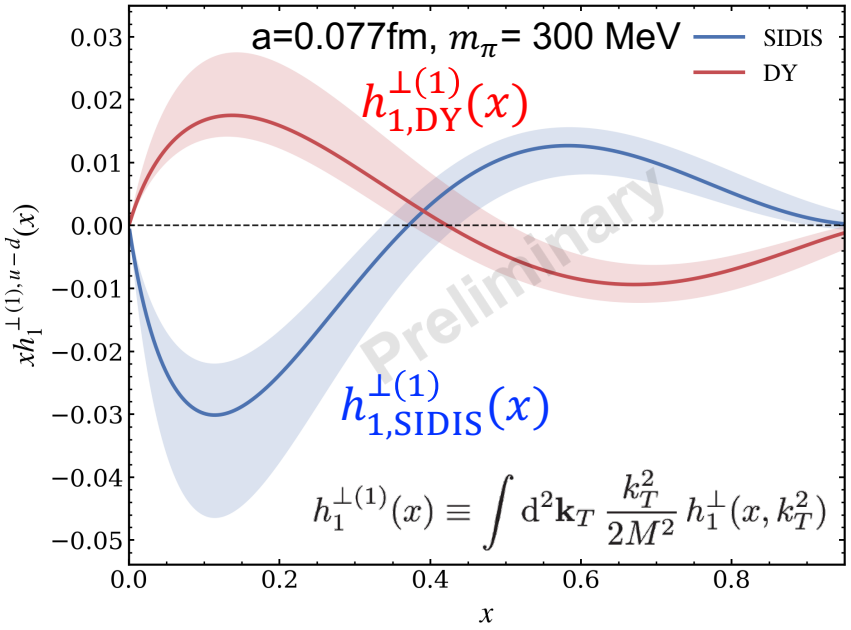
Quark Spin-transverse-momentum Correlation

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

Preliminary: Single ensemble

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

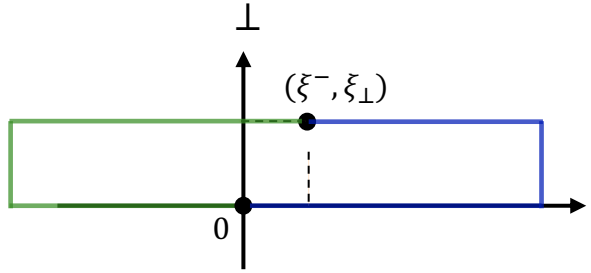
$$\tilde{h}_1^{\perp(1)}(x, b_\perp^2, P^z, \mu)\sqrt{S_I(b_\perp, \mu)} = \exp\left[\frac{1}{2}\ln\frac{\zeta_z}{\zeta} K(b_\perp, \mu)\right] H\left(\frac{x}{y}, \frac{\mu^2}{\zeta_z}\right) h_1^{\perp(1)}(y, b_\perp^2, \mu, \zeta) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}^2}{\zeta_z}, \frac{M^2}{(P^z)^2},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



LPC, in preparation

- **T-odd:** Gauge links encode initial and final state interactions and distinguish the SIDIS & Drell-Yan processes

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

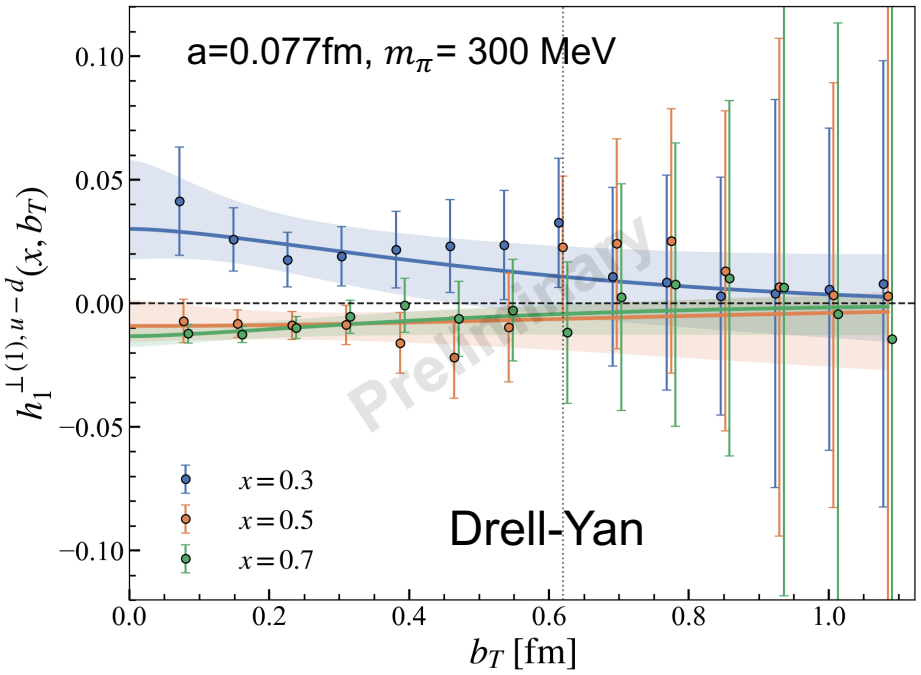


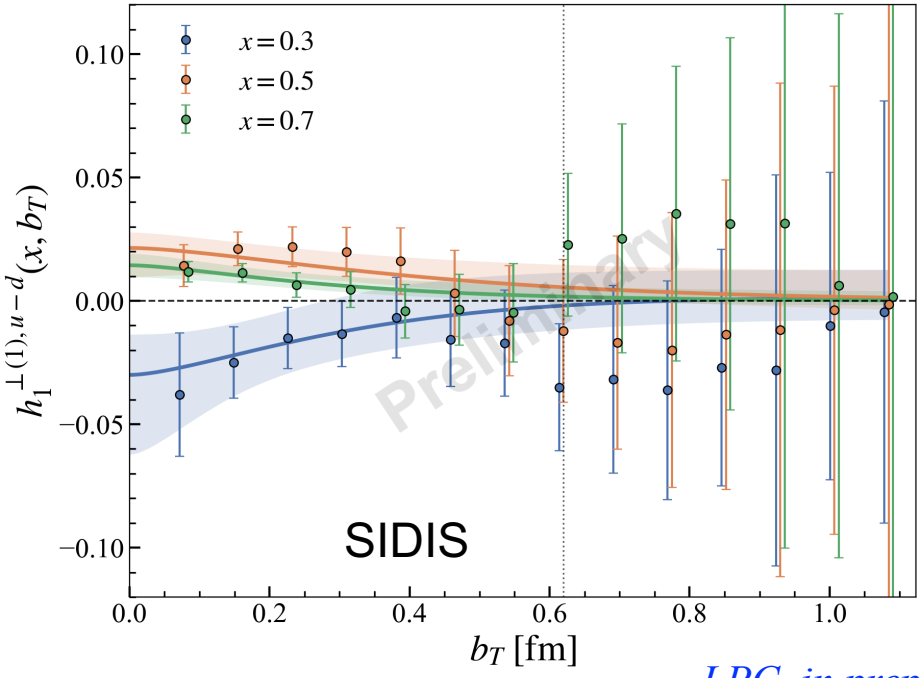
Quark Spin-transverse-momentum Correlation

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

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

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

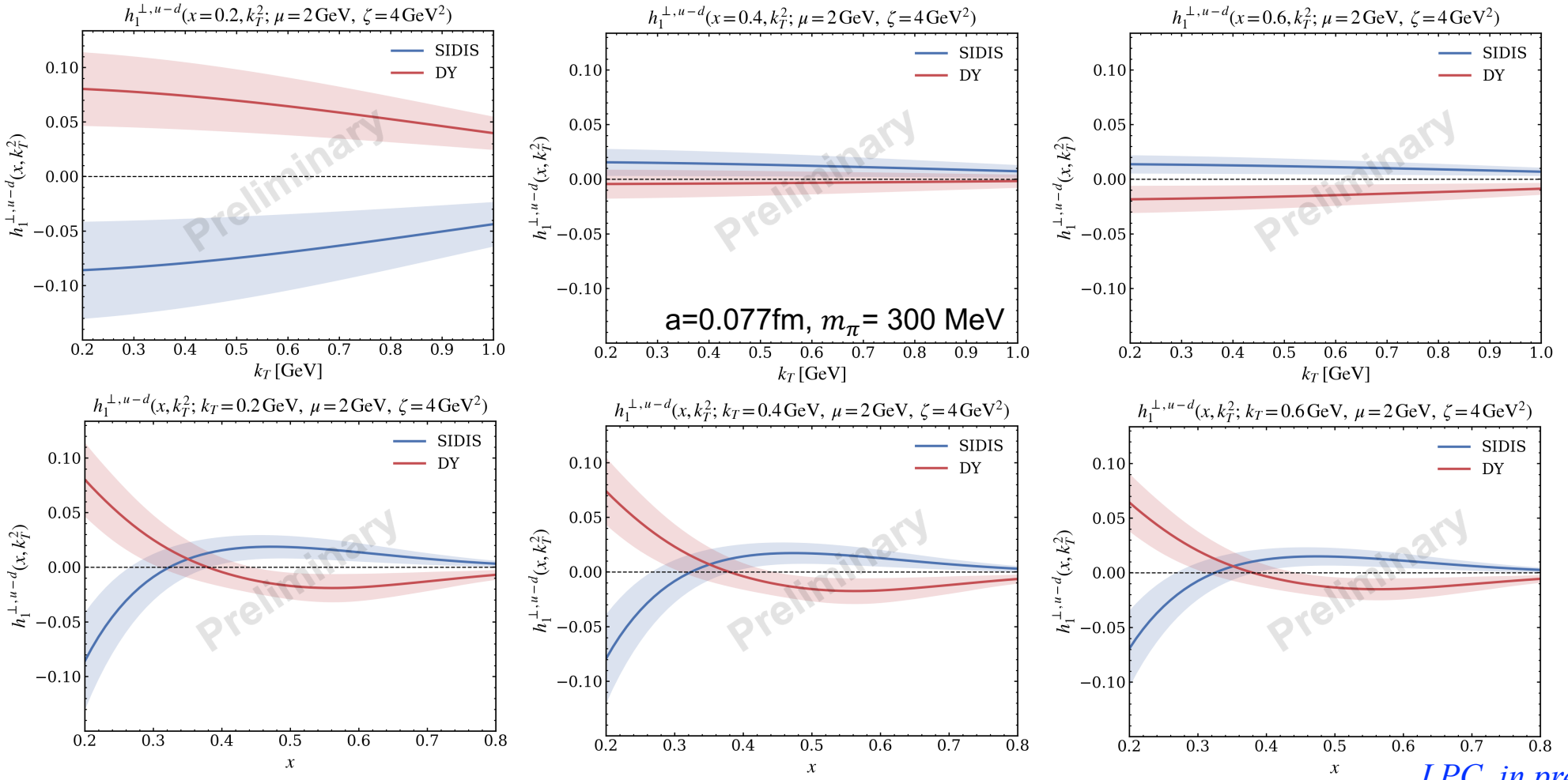




LPC, in preparation

Quark Spin-transverse-momentum Correlation

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



LPC, in preparation

Summary and Outlook

- **CS evolution and soft dynamics:**

Precision lattice determinations of the CS kernel and intrinsic soft function up to $b_\perp \sim 1$ fm with continuum, physical-pion-mass, and large-momentum control.

- **Precision nucleon TMDs:**

First-principles $f_1^{u-d}(x, b_\perp)$ and $g_1^{u-d}(x, b_\perp)$ provide complementary constraints to global analyses.

The lattice calculations is being extended to more TMDs, including T-odd distributions.

- **Toward future experiments:**

Jet-SIDIS at the EIC, T-odd observables, and other spin-dependent measurements connect lattice calculations directly to measurable transverse-momentum phenomena.

Lattice QCD enables experiment-independent, first-principles predictions of the nucleon's spin and momentum structure.

Thanks for your attention!

BACKUP SLIDES

Overview of Collins-Soper Kernel Calculations on the Lattice

Authors/ Collaboration	*Pion mass*	*Continuum*	*Method*	*Matching Kernel*	*Largest* P^z	*Reliable* $b_\perp^{\max}$	*Systematic Uncertainty*	*Highlights*
SWZ PRD102, 2020	1.2 GeV	No	Quasi beam function	LO	2.58 GeV	0.8 fm	No	• First CS kernel extraction via quasi beam function. • Quenched ensemble. • Long-range extrapolation via models.
LPC PRL125, 2020	547 MeV	No	Quasi TMDWF	LO	2.11 GeV	0.4 fm	No	• First extraction via quasi TMDWF. • Dynamical ensemble.
SVZES JHEP08, 2021	422 MeV	No	Mellin moments of quasi TMDPDF	--	2.27 GeV	0.5 fm	Estimated but not included	• Extraction from the ratios of first Mellin moments. • Discussed the sources of systematic uncertainties.
SWZ PRD104, 2021	538 MeV	No	Quasi beam function	NLO	1.5 GeV	0.5 fm	No	• Operator mixing effect in NPR. • Power corrections and higher-twist effects. • Considering NLO matching effects.
PKU/ETMC PRL128, 2022	827 MeV	No	Quasi TMDWF	LO	3.3 GeV	0.3 fm	No	• RI'/MOM renormalization.
LPC PRD106, 2022	670 MeV	No	Quasi TMDWF	NLO	2.58 GeV	0.6 fm	Yes	• Wilson loop renormalization. • Higher-twist effects in operators. • Direction of staple-shaped Wilson link. • Infinite-P^z extrapolation. • Systematic uncertainties are taken into account.
S⁴VWEY PRD108, 2023	686 MeV	No	Mellin moments of quasi TMDPDF	--	1.36 GeV	0.4 fm	No	• Universality of CS kernel from twist-2/3 quasi TMDPDFs of pion and proton

Overview of Collins-Soper Kernel Calculations on the Lattice

Authors/ Collaboration	*Pion mass*	*Continuum*	*Method*	*Matching Kernel*	*Largest* P^z	*Reliable* $b_\perp^{\max}$	*Systematic Uncertainty*	*Highlights*
LPC JHEP08, 2023	220 MeV	No	Quasi TMDWF	NLO	3.16 GeV	0.6 fm	Yes	• Consistency check between two different actions. • Multiple lattice spacings and pion masses, but without extrapolation.
ASWZ PRD108, 2023	148.8 MeV	No	Quasi TMDWF	uNNLL	2.15GeV	0.8 fm	Yes	• Physical pion mass. • $b_\perp$-unexpanded matching coefficient up to NNLL. • Mitigate unexpected imaginary part in matching coefficient.
ASWZ PRL132, 2024	148.8 MeV	Model	Quasi TMDWF	uNNLL	2.3GeV	0.8 fm	Yes	• Multiple lattice spacings, and model constrained continuum limit extrapolation. • Calculation directly at physical pion mass.
BGHMZ PRD112, 2025	300 MeV	No	Quasi TMDWF	NLO	4.3 GeV	-- (Large err.)	Yes	• Coulomb gauge fixed correlators.
ABC^{2}S^{3}T 2509.26316	640 MeV	No	Quasi TMDWF	NLO	3.33GeV	0.5 fm	No	• Higher-twist effects in quasi TMDWF.
LPC 2511.22547	135.5 MeV	Yes	Quasi TMDWF	uNLO	3.0 GeV	1.0 fm	Yes	• Precision calculation at transverse separations beyond the nucleon radius ($b_\perp \approx 1$fm). • Multiple lattice spacings, continuum limit extrapolation. • Multiple pion mass (including physical), and chiral extrapolation.

Overview of Intrinsic Soft Function Calculations on the Lattice

Authors/ Collaboration	*Pion mass*	*Continuum*	*Matching Kernel*	*Largest* P^z	*Reliable* $b_\perp^{\max}$	*Systematic Uncertainty*	*Highlights*
LPC PRL125, 2020	547 MeV	No	LO	2.11 GeV	0.7 fm	No	• First lattice QCD calculation. • Operator mixing effects in NPR.
PKU/ETMC PRL128, 2022	350-827 MeV	No	LO	3.3 GeV	0.7 fm	No	• Higher-twist effects in form factors. • Verified the independent of meson mass.
LPC JHEP08, 2023	670 MeV	No	NLO	2.58 GeV	0.6 fm	No	• Consistency check between different actions.
BGHMZ PRD112, 2025	300 MeV	No	NLO	2.58 GeV for FF, 4.3 GeV for qWF	1.1 fm	No	• Coulomb gauge fixed correlators. • Greatly improved the signal-to-noise ratio problem.
ABC²S³T 2509.26316	640 MeV	No	NLO	3.33 GeV	0.5 fm	No	• Higher-twist effects in quasi TMDWF.
LPC In progress	135.5 MeV	Yes	NLO	3GeV	1 fm	Yes	

Overview of TMDs Calculations on the Lattice

	Authors/ Collaboration	*Pion mass*	*Continuum*	*Matching Kernel*	*Largest P^z*	*Systematic Uncertainty*
Nucleon Unpolarized TMDPDF	**LPC** PRD109, 2024	310, 220 MeV (extra to continuum)	No	NNLO	2.58 GeV	Yes
Nucleon Boer-Mulders Function	**LPC** JHEP08, 2025	338 MeV	No	NNLO	2.21 GeV	No
Pion Unpolarized TMDPDF	**BGHMZ** PRD112, 2025	300 MeV	No	NLO	3.04 GeV	No
Pion Boer-Mulders Function	**LPC** PRD111, 2025	338 MeV	No	NNLO	2.21 GeV	No
Pion TMD Wave Function	**LPC** PRD109, 2024	670 MeV	No	NLO	2.64 GeV	No