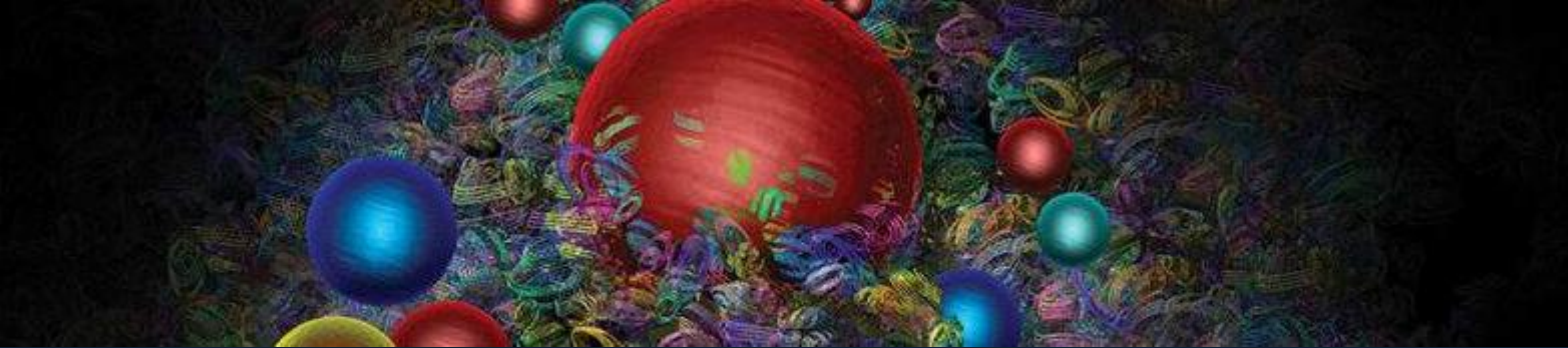


Proton tomography with global analysis of generalized parton distributions

Yuxun Guo

U.C. Berkeley/ Lawrence Berkeley Lab.

Y. Guo, F. Aslan, M. G. Santiago and X. Ji. PRL (2025)

Based on works in collaboration with X. Ji, J. Yang, F. Aslan, M. G. Santiago

BERKELEY LAB

PHENOMENOLOGY LATTICE QCD THEORY QUARK-GLUON TOMOGRAPHY COLLABORATION

Vector Quarkonia as Pressure Gauges Workshop

CNF and JLab Theory Center, Newport News, VA, 23606

Mar. 27th, 2026

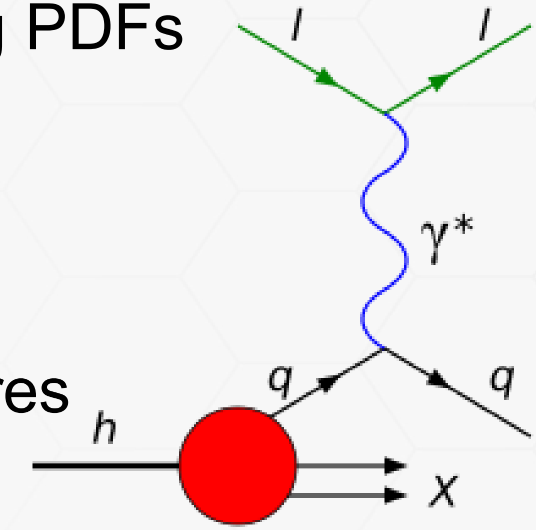
CENTER for NUCLEAR FEMTOGRAPHY

Jefferson Lab

Nucleon spin structures and tomography

The limitation of inclusive measurements and the corresponding PDFs has been evident by the end of last century.

For instance, we cannot explain the proton/neutron spin structures assuming they are point-like particles.



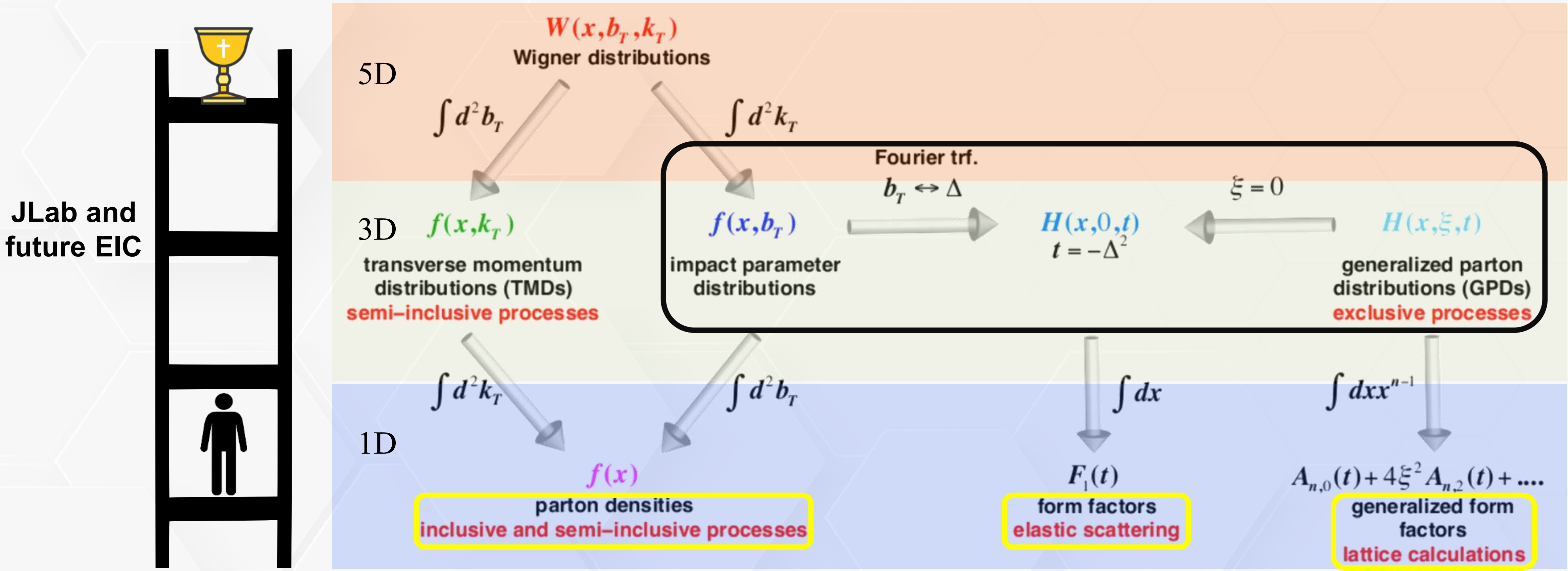
Transverse motions

$\frac{\hbar}{2} =$ quark spin + gluon spin + quark orbital AM + gluon orbital AM

R. Jaffe and A. Manohar, Nucl. Phys. B 337 (1990)

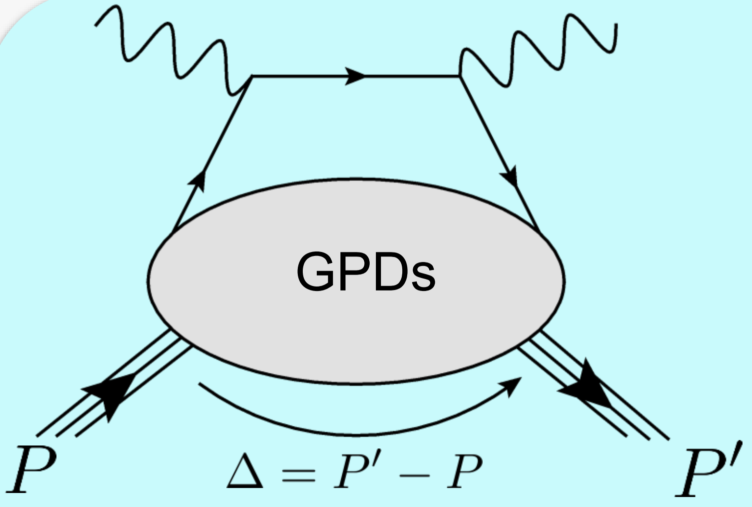
Road map of multidimensional nucleon structure

Deciphering the multidimensional structures of the nucleons naturally requires an extensive set of distributions and corresponding inputs.



Generalized parton distributions (GPDs)

Generalized parton distributions are parton distributions with momentum transfer



D. Muller et. al. Fortsch.Phys. 42 101 (1994)

X. Ji Phys. Rev. Lett. 78, 610 (1997)

GPDs unify the parton distributions and form factors

$$F(x, \Delta^\mu) = F(x, \xi, t)$$

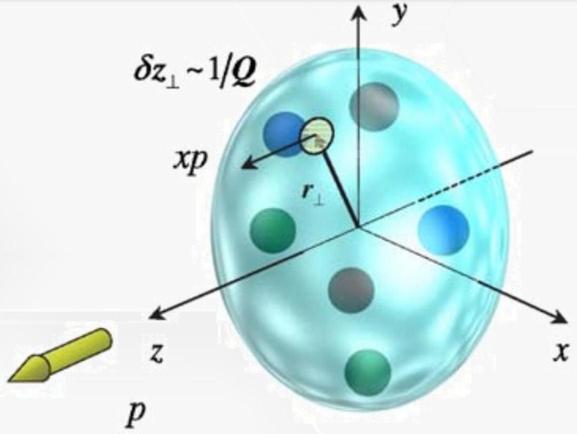
x : average parton momentum fraction

ξ : skewness – longitudinal momentum transfer $\xi \equiv -n \cdot \Delta/2$

t : total momentum transfer squared $t \equiv \Delta^2$

They can then provide parton dist. in coordinate space

$$\rho_q^{\rm Unp}(x, \boldsymbol{b}) = \int \frac{{\rm d}^2\boldsymbol{\Delta}}{(2\pi)^2} e^{-i\boldsymbol{\Delta}\cdot\boldsymbol{b}} H_q(x, -\boldsymbol{\Delta}^2) = \mathscr{H}_q(x, \boldsymbol{b})$$



Energy-momentum tensor form factors

The energy-momentum tensor (EMT) is the tool to study the mechanical properties of the nucleon. Its nucleon matrix element can be written as:

$$\langle P'|\,T^{\mu\nu}_{q,g}\,|P\rangle = \bar{u}(P')\left[A_{q,g}(t)\gamma^{(\mu}\bar{P}^{\nu)} + B_{q,g}(t)\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M_N}\right.$$
$$\left. + C_{q,g}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M_N} + \bar{C}_{q,g}(t)M_N g^{\mu\nu}\right]u(P)$$

Momentum form factors: $A_{q,g}(t)$ X. Ji Phys. Rev. Lett. 78, 610 (1997)

Angular momentum form factors: $J_{q,g}(t) = \frac{1}{2}\left(A_{q,g}(t) + B_{q,g}(t)\right)$

(Not-a-)stress tensor form factors: $C_{q,g}(t)$ X. Ji and C. Yang, Nucl. Phys. B 1024 (2026)

EMT is coupled to gravity but gravitational scattering with nucleon is impossible.

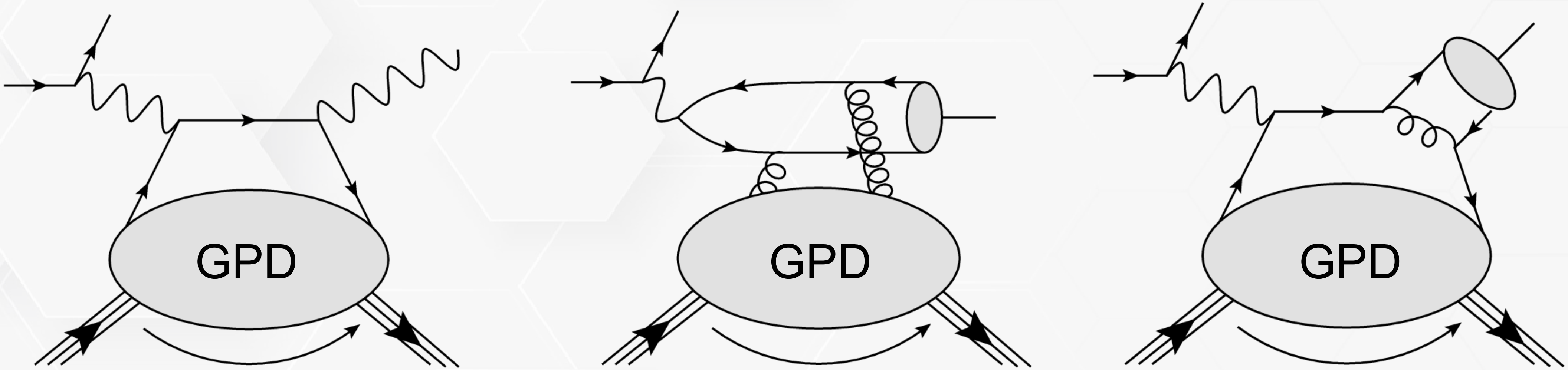
But they can be obtained with GPDs: $\int \mathrm{d}x\; xH(x,\xi,t) = A(t) + (2\xi)^2 C(t)$

X. Ji, J Phys. G 24 1181-1205 (1998)

Proton tomography with GPD

Inverse problem for exclusive processes

It has long been discussed that GPDs can be constrained by hard exclusive process such as Deeply virtual Compton scattering and meson productions



X. Ji, Phys. Rev. D 55, 7114 (1997)

A.V. Radyushkin Phys. Lett. B 385 333-342 (1996)

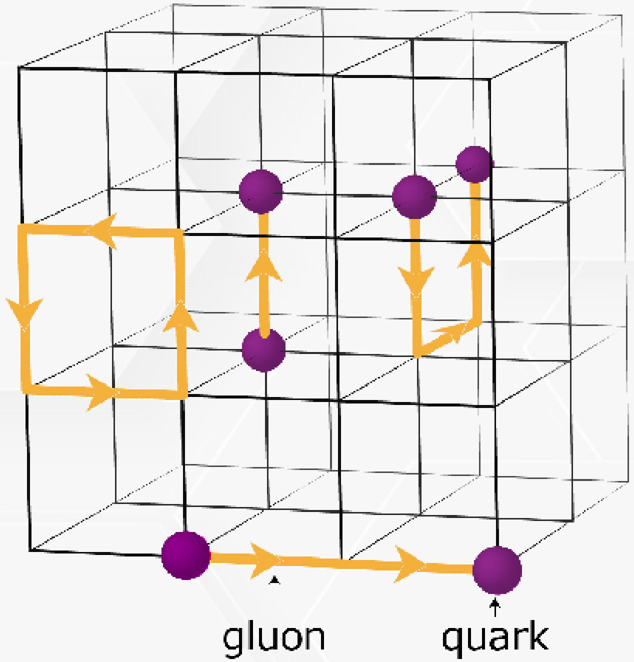
J. C. Collins et. al. Phys. Rev. D 56 2982-3006 (1997)

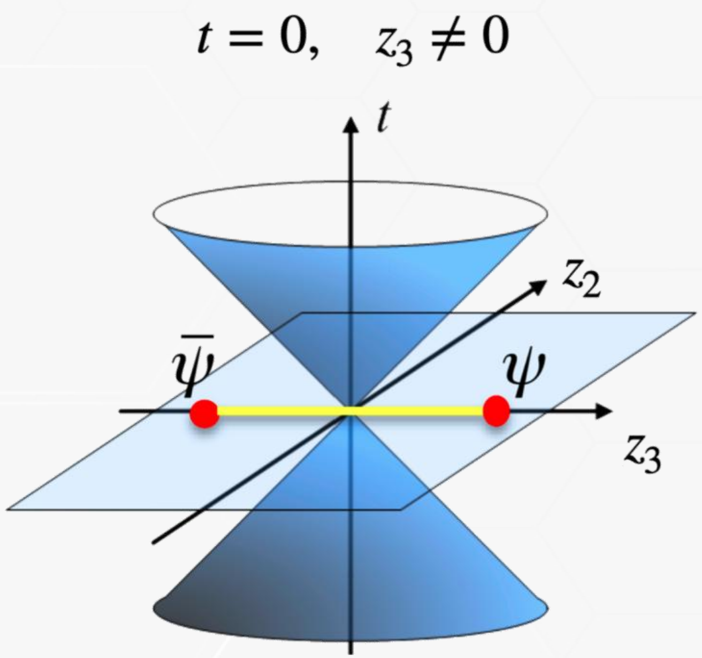
Unfortunately, they generally integrate over parton of all momentum fractions

$$\mathcal{H}_{CFF}(\xi,t)=-\sum_q Q_q^2\int_{-1}^{1}\mathrm{d}x\left(\frac{1}{x-\xi+i0}+\frac{1}{x+\xi-i0}\right)H_q(x,\xi,t)\ ,$$

Nucleon and parton structure on lattice

In the literature, simulating QCD on finite and discretized 4-dimensional Euclidean lattice has been extensively studied.





X. Ji et. al., Rev. Mod. Phys. 93 (2021)

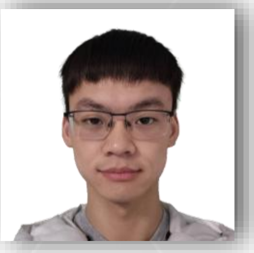
Recent developments of Large Momentum Effective Theory (LaMET) allow us to simulate (light-like) parton structure with space-like lattice correlations!

GPDs through Universal Moment Param. (GUMP)

The GPDs through Universal Moment Param.(GUMP) programs aims to obtain the GPDs from global analysis utilizing moment-space parameterization

Goal: To obtain the state-of-the-art phenomenological **Generalized Parton Distributions (GPDs)** through global analysis of both **experimental data** and **lattice QCD simulations**, utilizing a ***universal moment parameterization*** method.

Collaborators:



Yuxun Guo
Lawrence Berkeley Lab.

Xiangdong Ji
University of Maryland

M. Gabriel Santiago
Temple University

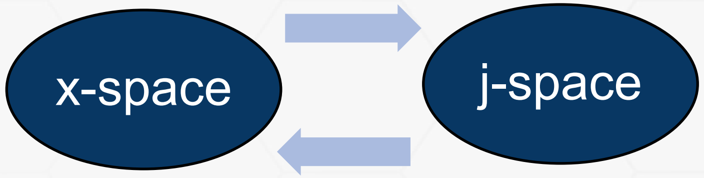
Fatma P. Aslan
Center for Nuclear Femtography

GPDs parameterized in moments

GPDs can be formally expanded in the conformal moment space:

$$F(x,\xi,t)=\sum_{j=0}^{\infty}(-1)^j p_j(x,\xi)\mathcal{F}_j(\xi,t)$$

D. Mueller and A. Schafer 2005



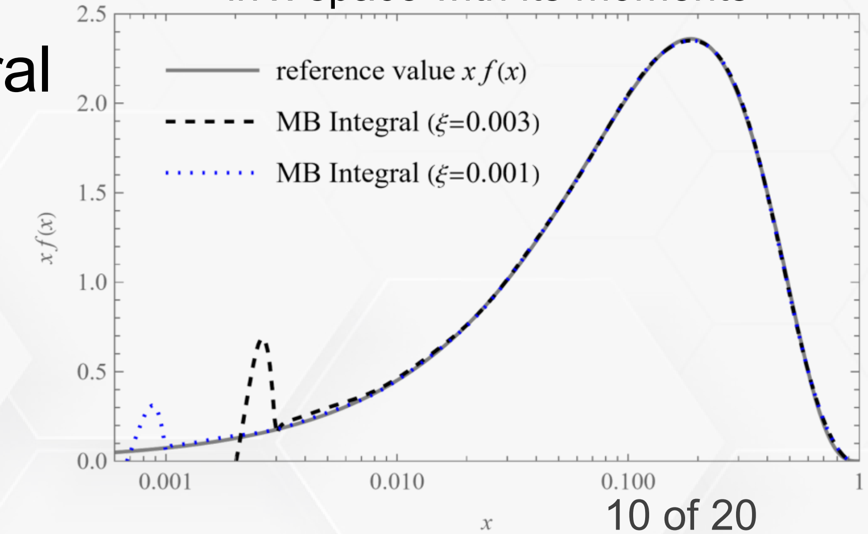
$p_j(x,\xi)$: Orthogonal basis in terms of Gegenbauer polynomials

$\mathcal{F}_j(\xi,t)$: Moments of GPDs to be parameterized

Whereas GPDs in x-space can be reconstructed by resumming all the moments through a complex integral in the moment space.

$$F(x,\xi,t)=\frac{1}{2i}\int_{c-i\infty}^{c+i\infty} dj\,\frac{p_j(x,\xi)}{\sin(\pi[j+1])}\mathcal{F}_j(\xi,t)\ ,$$

Example of reconstructed GPD in x-space with its moments



GUMP parameterization

Moments of GPDs are polynomials of ξ, so they can be written as

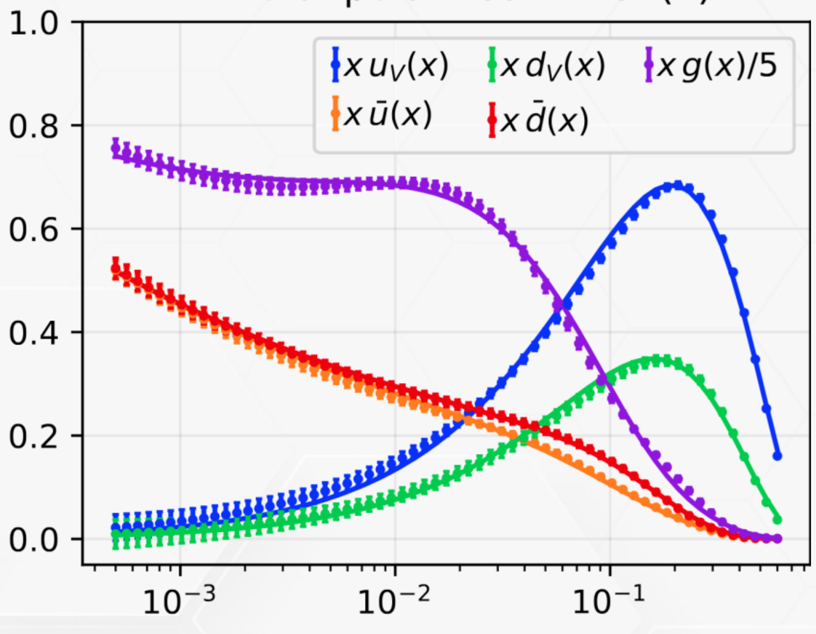
$$\mathcal{F}_j(\xi,t)=\mathcal{F}_{j,0}(t)+\xi^2\mathcal{F}_{j,2}(t)+\xi^4\mathcal{F}_{j,4}(t)+\cdots$$

The first term describes GPDs at $\xi=0$, and is parameterized as:

$$\mathcal{F}_{j,0}(t)=N\frac{B(j+1-\alpha(t),1+\beta)}{B(2-\alpha,1+\beta)}R(t)$$

Beta function $NB(j+1-\alpha,1+\beta)$	Regge trajectory $\alpha(t)=\alpha+\alpha' t$	Residual terms $R(t)$
Correspond to the simple PDF ansatz in the forward limit $Nx^{-\alpha}(1-x)^{\beta}$	Modification from Regge theory in the form of $x^{-\alpha(t)}$	Extra factorized t dependence for more flexibility $\exp(-bt)$ $(1-t/M^2)^{-p}$

Fit to unpolarized PDFs $f(x)$



Full next-to-leading (NLO) accuracy

In the past years, we actively include more processes with improved accuracy:

Full GPD evolutions to the next-to-leading order (NLO)

— *Include both evolving-moment and evolving-Wilson-coefficient method*

NLO deeply virtual J/ψ production (DVJ/ψP) with mass corrections

— *In a hybrid framework to also include the mass corrections*

Y. Guo et. al. Phys. Rev. D 112 (2025)

NLO deeply virtual Compton scattering (DVCS) and meson productions (DVMP)

— *Covering most of the existing JLab and HERA measurements of DVCS and ρ productions*

Extend to other observables such as asymmetries measurements.

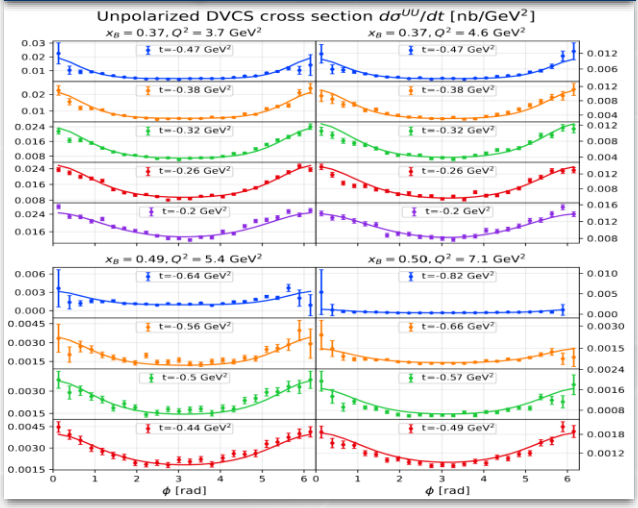
Y. Guo, F. Aslan, M. G. Santiago and X. Ji. PRL (2025)

NLO corrections appear significant for the HERA (future EIC) kinematics !

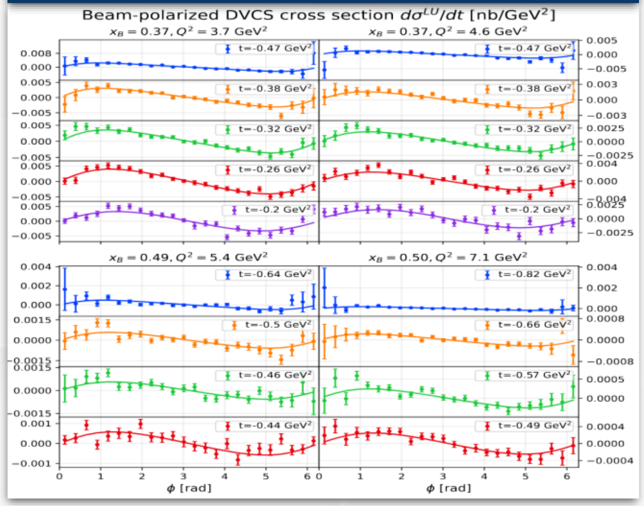
Experimental inputs for GPDs

We include various kinds of exclusive measurements from JLab and HERA

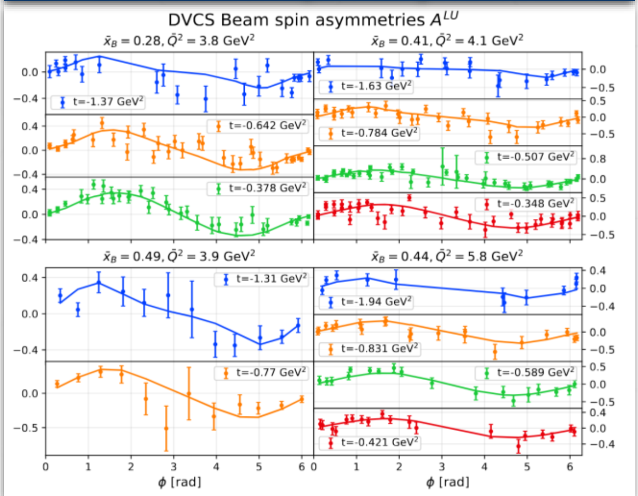
Unpolarized DVCS



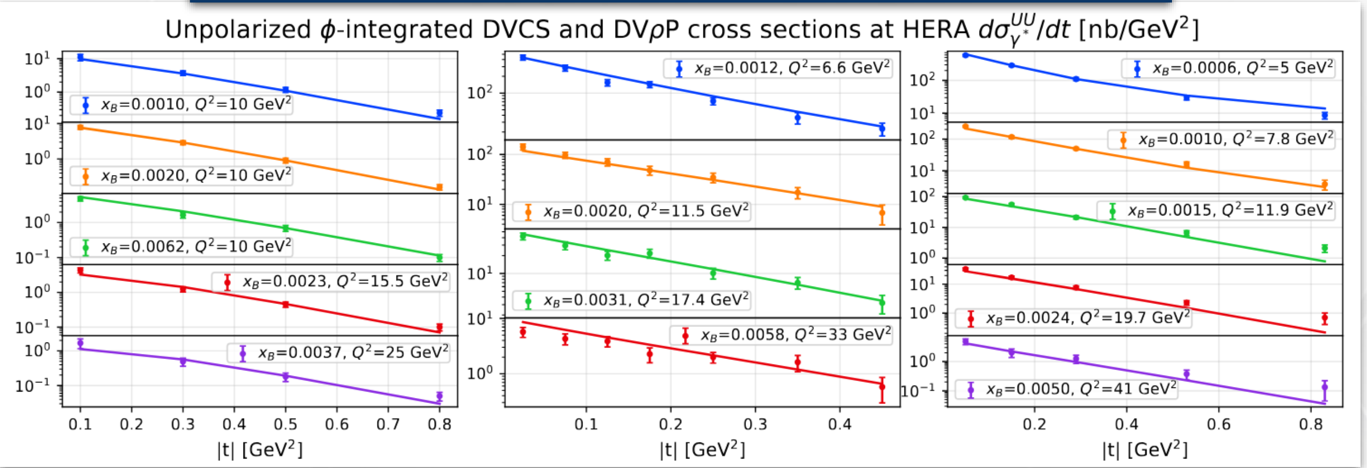
Beam Polarized DVCS



DVCS Beam-spin asymmetries



DVCS and DVMP at HERA



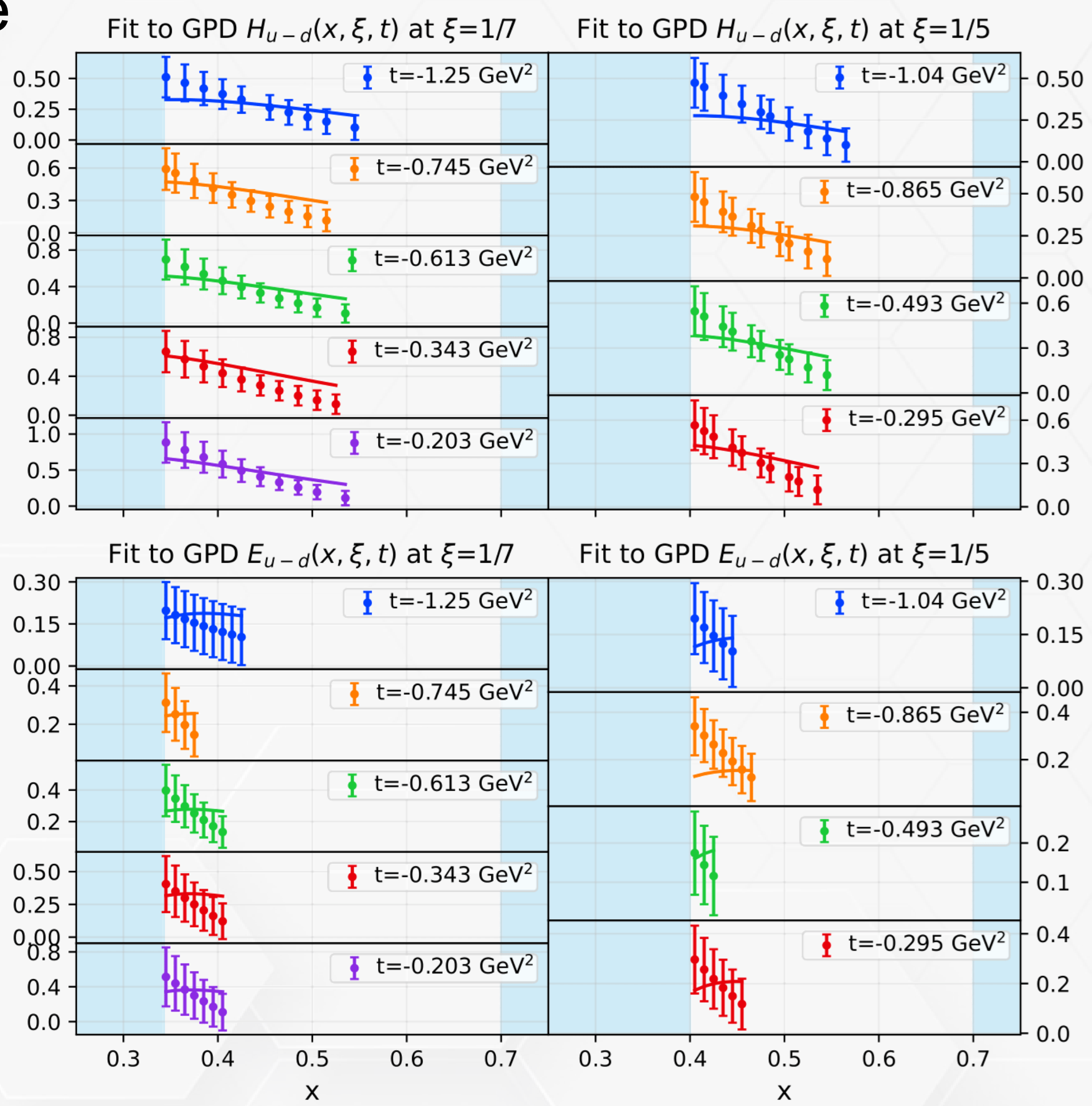
GPDs at non-zero skewness from lattice

Importantly, we also include the recent lattice simulations of GPDs at non-zero skewness.

Significant effects in constraining GPDs at non-zero skewness!

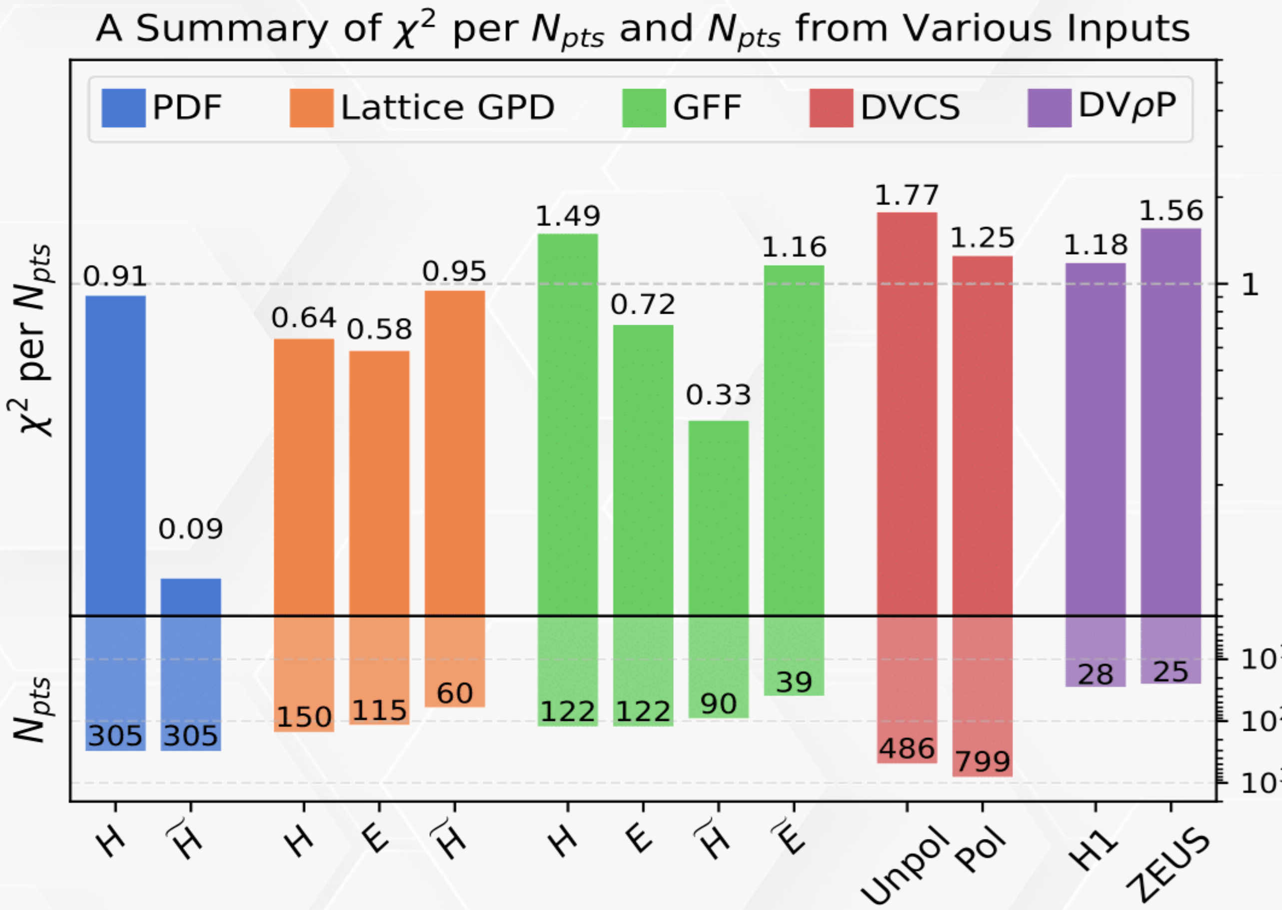
Note: besides the 30% relative uncertainty added to all the lattice data, we have a very conservative selection:

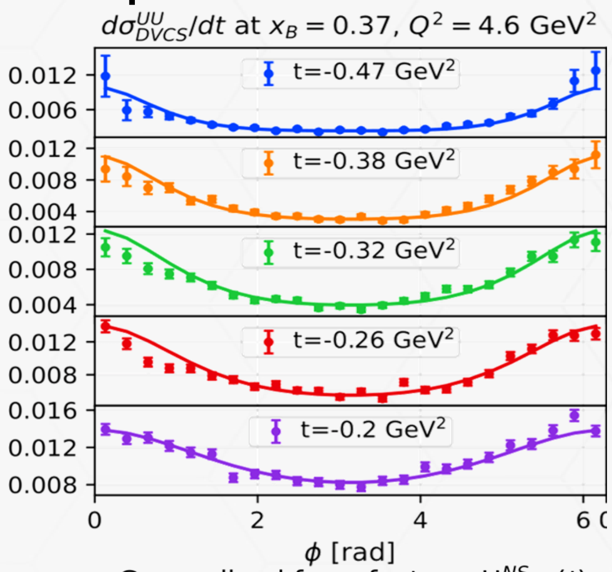
1) Only used the data between 0.3<x<0.7 and |x-xi|>0.2.
2) Exclude region where GPDs get negative or very small (lattice artifacts or intrinsic GPD behaviors?)

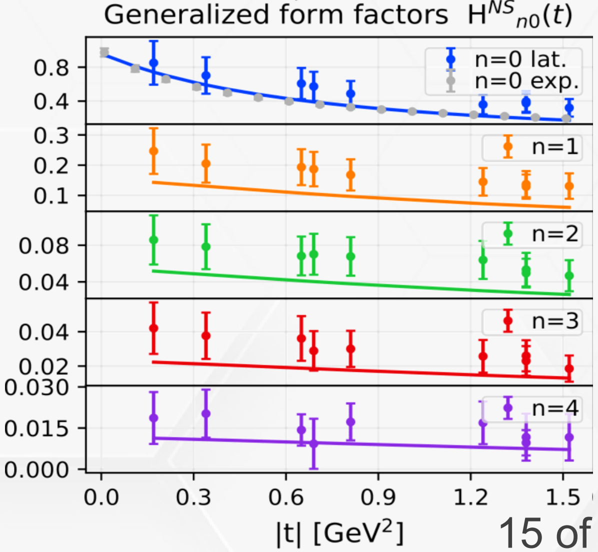


Excellent descriptions of exp. and lattices

Generally, we observe excellent agreement across various inputs:







Y. Guo, F. Aslan, M. G. Santiago and X. Ji. PRL (2025)

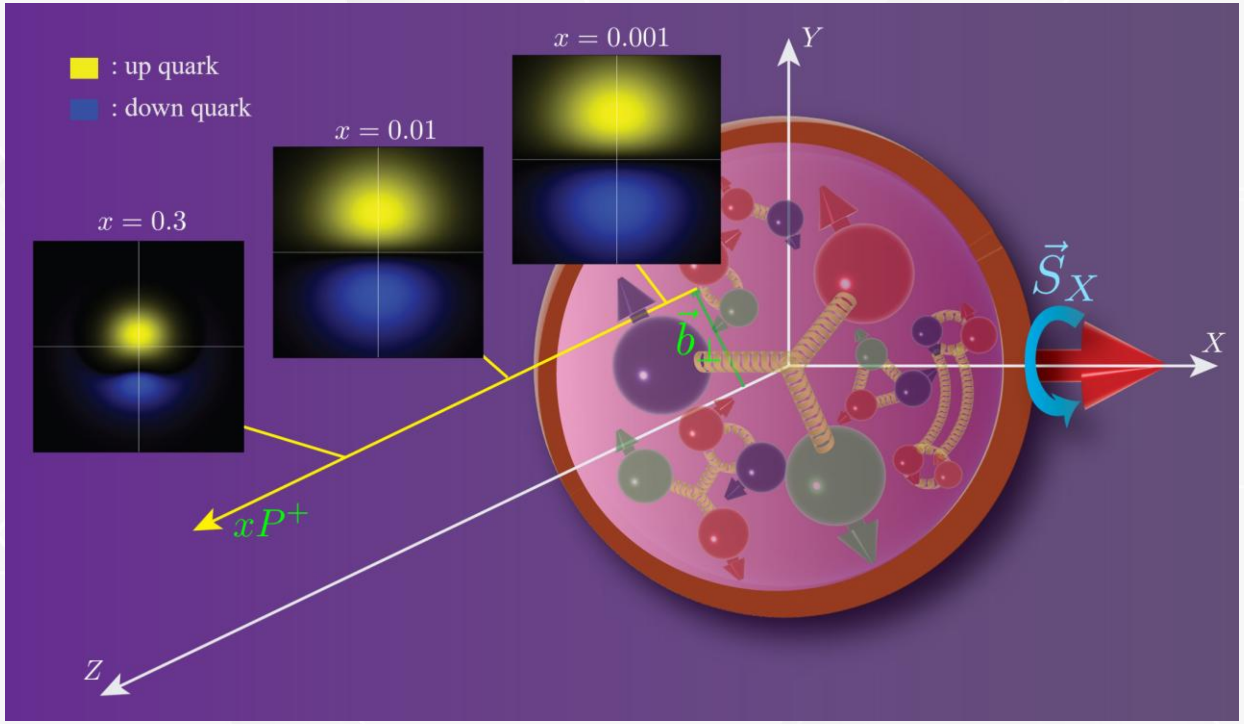
Reduced chi squared of 1.09 for 2,646 data points

Nucleon tomography with GUMP1.0 GPDs

The tomography of the quark in the nucleons can be obtained via GPDs. In particular, for transversely polarized proton, the intrinsic quark distributions are

$$\rho^{X}_{q,\mathrm{In}}(x,\boldsymbol{b}) = \int \frac{\mathrm{d}^2\boldsymbol{\Delta}}{(2\pi)^2} e^{-i\boldsymbol{\Delta}\cdot\boldsymbol{b}} \left[H_q(x,-\boldsymbol{\Delta}^2) + \frac{i\Delta_y}{2M} \left(H_q + E_q\right)(x,-\boldsymbol{\Delta}^2) \right]$$

Y. Guo, X. Ji and K. Shells. Nucl. Phys. B 969 (2021)



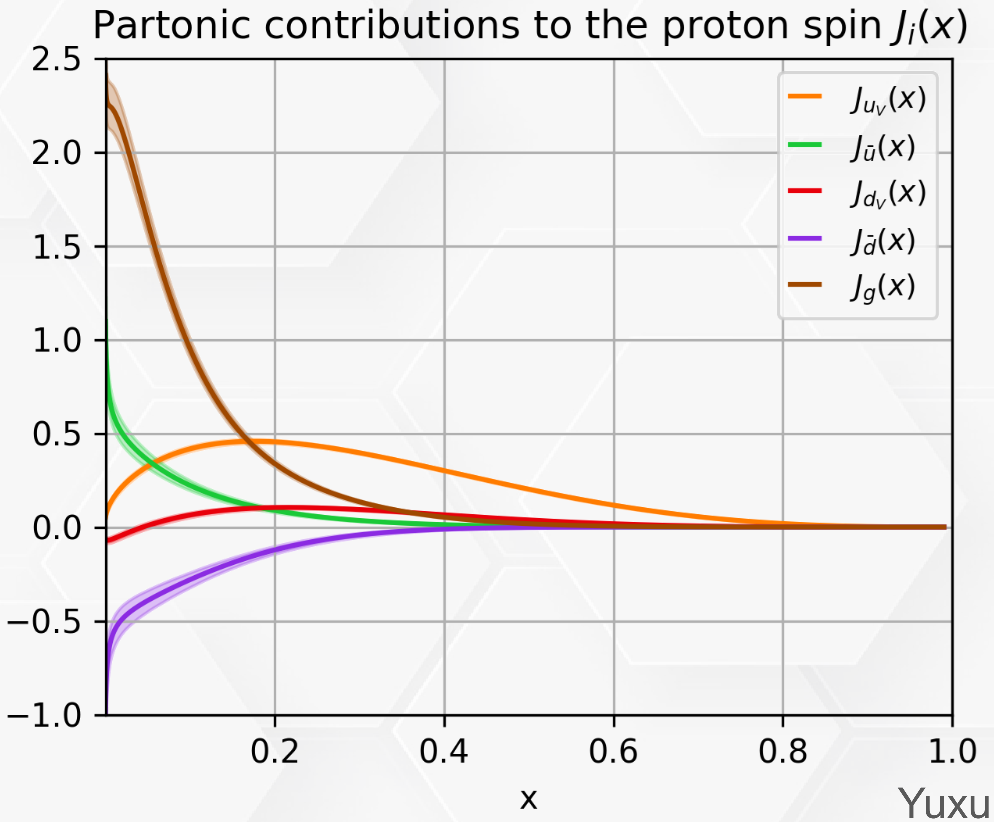
Distributions of quark in the transverse space of a polarized proton with respect to the center of the proton.

The proton is transversely polarized to the +X directions. Thus, quarks are shifted in Y directions that generate orbital angular momenta!

Partonic contributions to the proton spin

The partonic contributions to the proton spin can also be obtained from the extracted GUMP1.0 GPDs. Specifically, they are given by

$$J_{q/g}(x) = \frac{1}{2}\left(H_{q/g} + E_{q/g}\right)(x, \xi = 0, t = 0)$$



- Parametric biases/errors not considered
- Consistent with most existing constraints
- Some tension with the lattice GFFs
- Proton spin sum rule satisfied!

Summary and Outlook

To summary

Summary

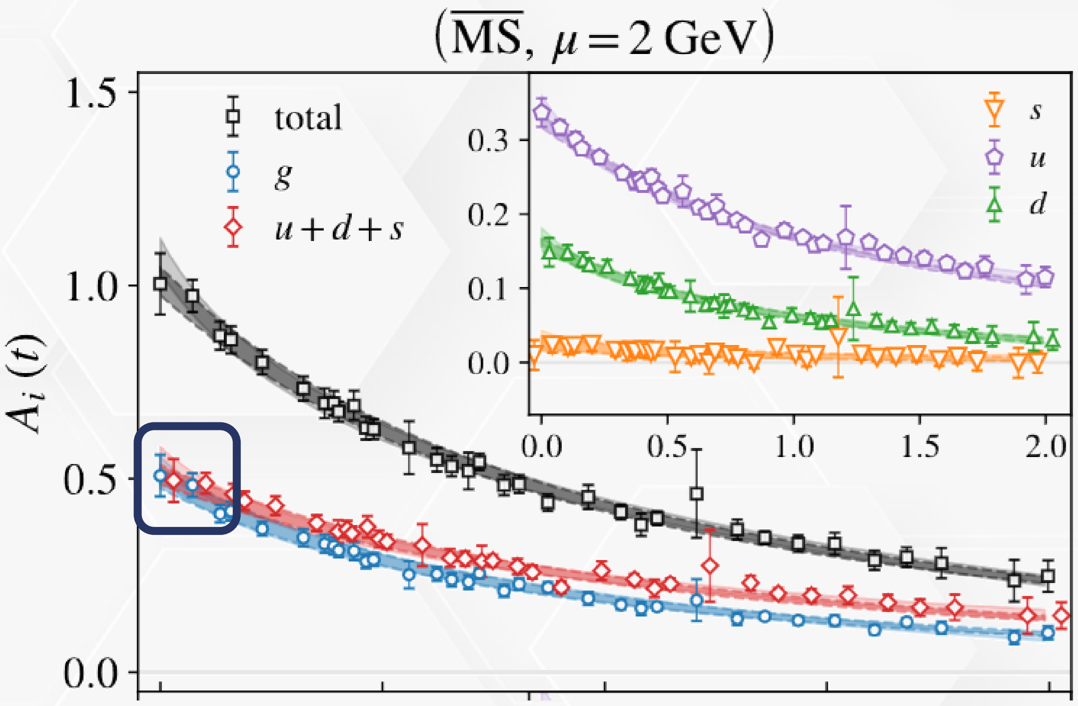
What's more?

Thank you!

Complementarity of lattice and exp.

However, lattice is limited itself, particularly when approaching the light-cone.

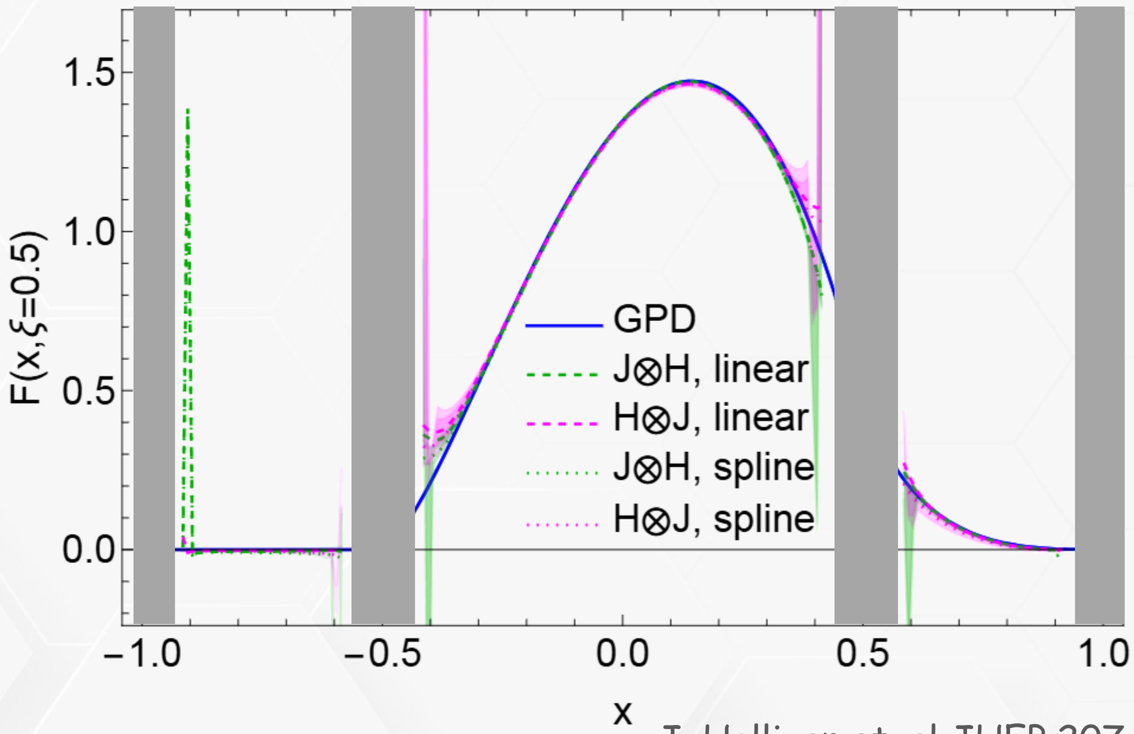
Systematics hard to put under control.



D. Hackett et. al Phys. Rev. Lett. 132 (2024)

Breakdown of LaMET near end-points

$$[-1+x_0, -\xi-x_0] \cup [-\xi+x_0, \xi-x_0] \cup [\xi+x_0, 1-x_0]$$



J. Holligan et. al JHEP 207 (2025)

It's important to combine lattice inputs with experiments for better determination!

Lattice inputs for GPDs

Similarly, a comprehensive inputs from lattice are considered in this work.