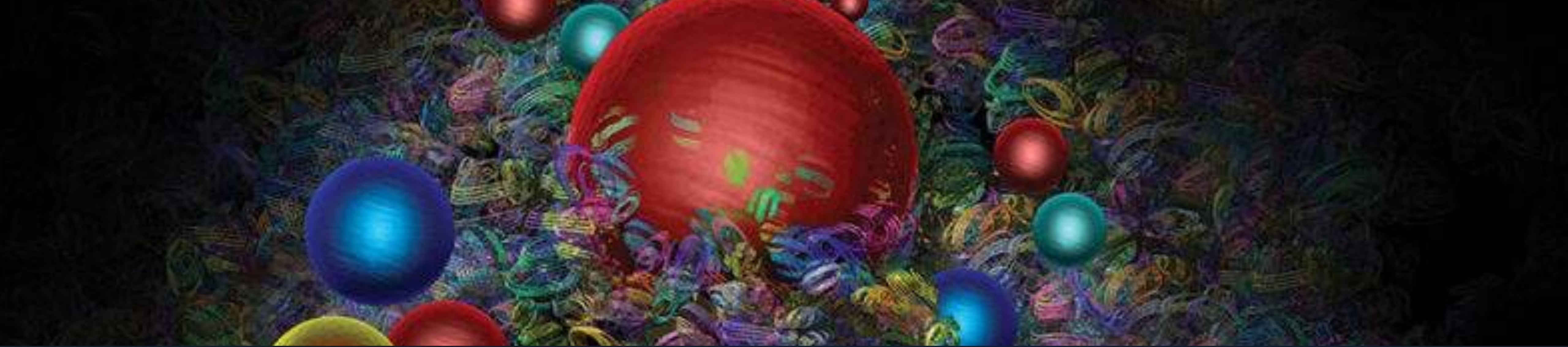


GPD Global Analysis and Proton Tomography

Yuxun Guo

RIKEN BNL and BNL

Guo, Aslan, Ji and Santiago (2025)

Guo, Ji, Santiago, and Shiells (2023)

Guo, Ji, and Shiells (2022)

Based on works in collaboration with X. Ji, F. Aslan, M. G. Santiago, K. Shiells

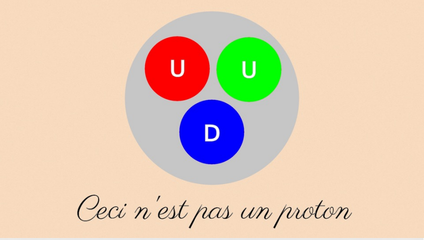
QUARK-GLUON TOMOGRAPHY COLLABORATION

RBRC RIKEN BNL Research Center

Brookhaven National Laboratory

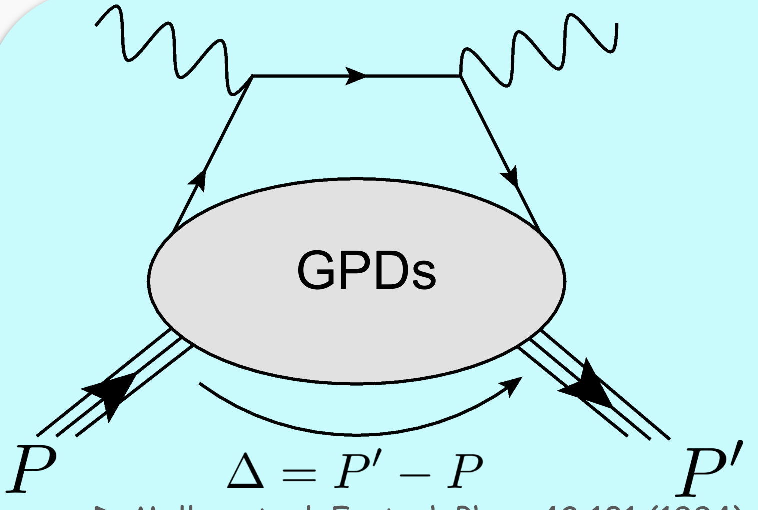
Towards improved hadron femtography with hard exclusive reactions edition V, University of Virginia, Charlottesville, VA 22904

Jun. 14-19th, 2026



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

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

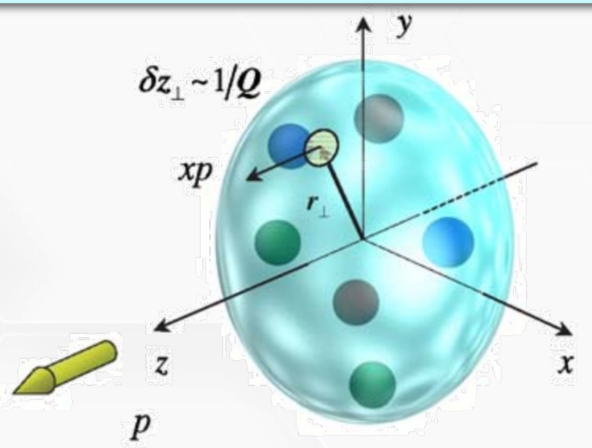
x : average parton momentum fraction

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

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



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 arXiv: 2508.16727

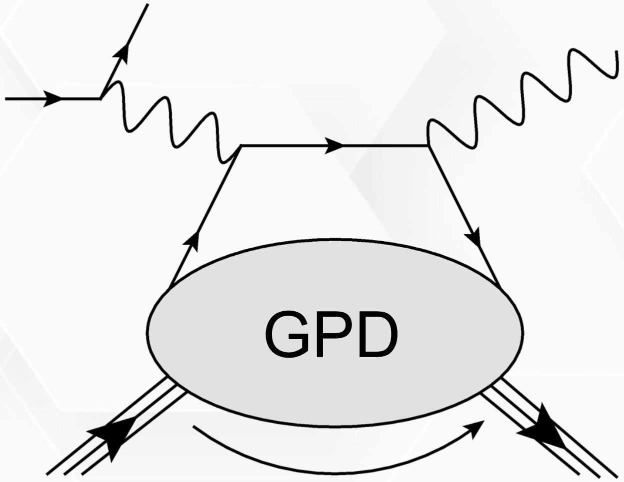
EMT is coupled to gravity but gravitational scattering with nucleon is impossible.

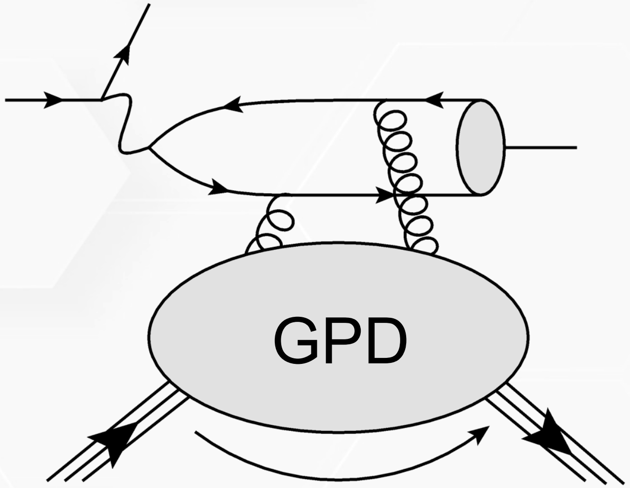
But they can be obtained with GPDs: $\int \mathrm{d}x\; xH(x,\xi,t) = A(t) + (2\xi)^2 C(t)$

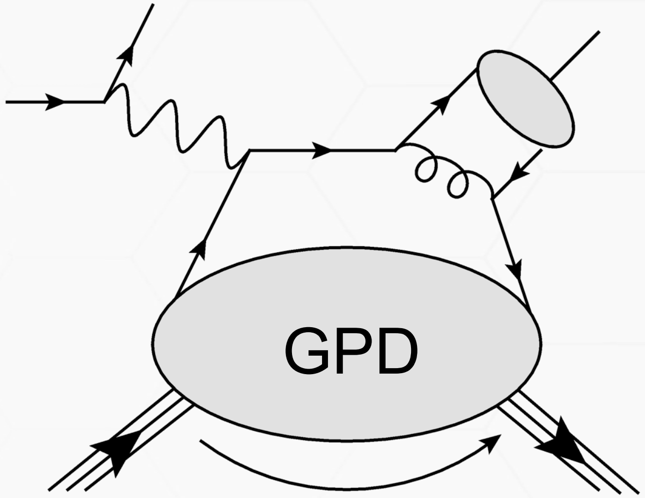
X. Ji, J Phys. G 24 1181-1205 (1998)

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)

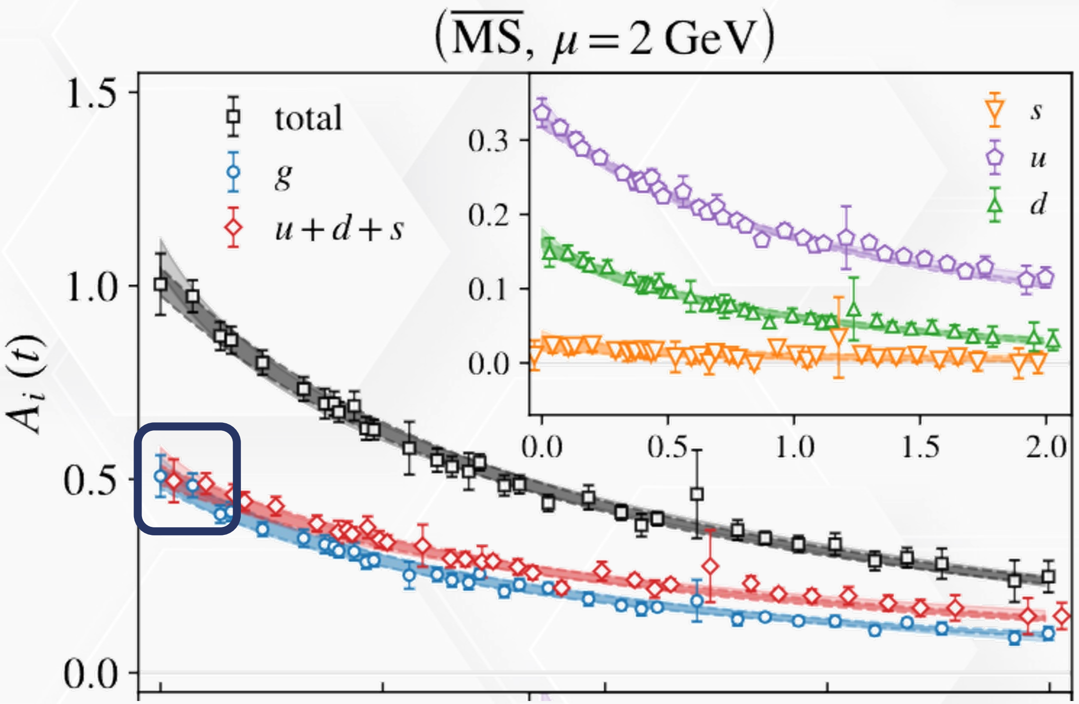
Unfortunately, they generally integrate over parton of all momentum fractions

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

Complementarity of lattice and exp.

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

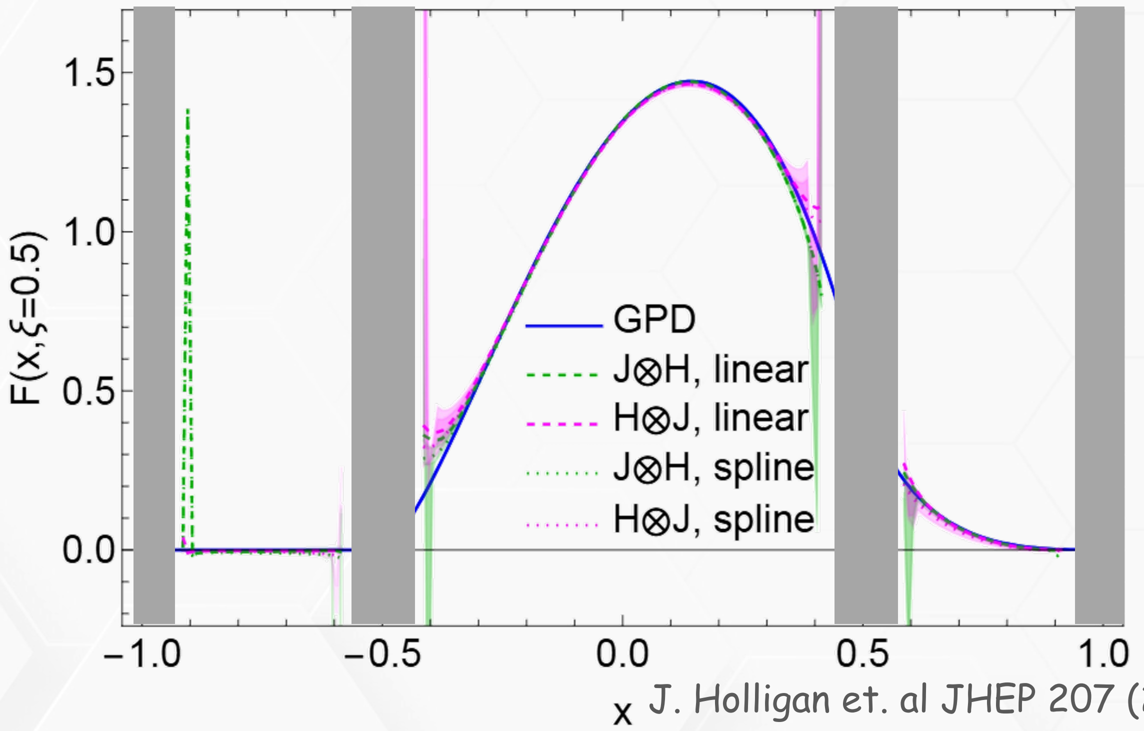
Systematics hard to put under control.



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)

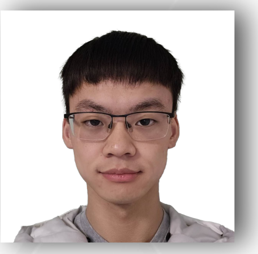
It's important to combine lattice inputs with experiments for better determination!

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
Berkeley/ LBL

Xiangdong Ji
University of Maryland

M. Gabriel Santiago
Temple University

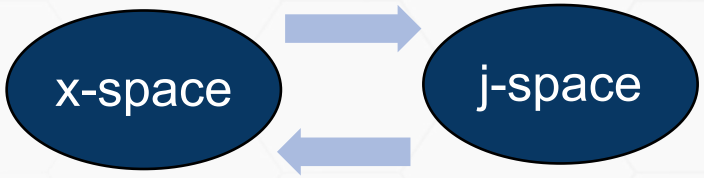
Fatma P. Aslan
Center for Nuclear Femtography

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



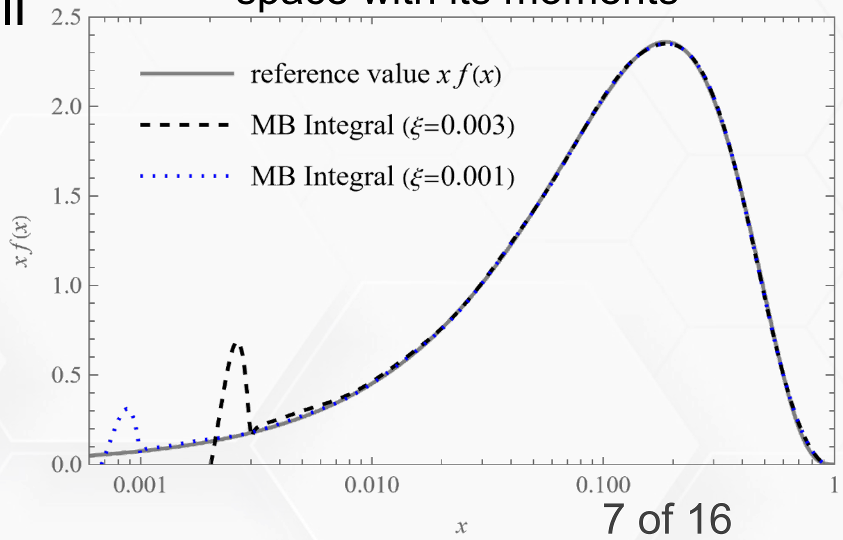
$p_j(x,\xi)$: Orthogonal basis in terms of Gegenbauer polynomials

$\mathcal{F}_j(\xi,t)$: 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
$NB(j+1-\alpha,1+\beta)$

Correspond to the simple PDF ansatz in the forward limit

$$Nx^{-\alpha}(1-x)^{\beta}$$

Regge trajectory
$\alpha(t)=\alpha+\alpha' t$

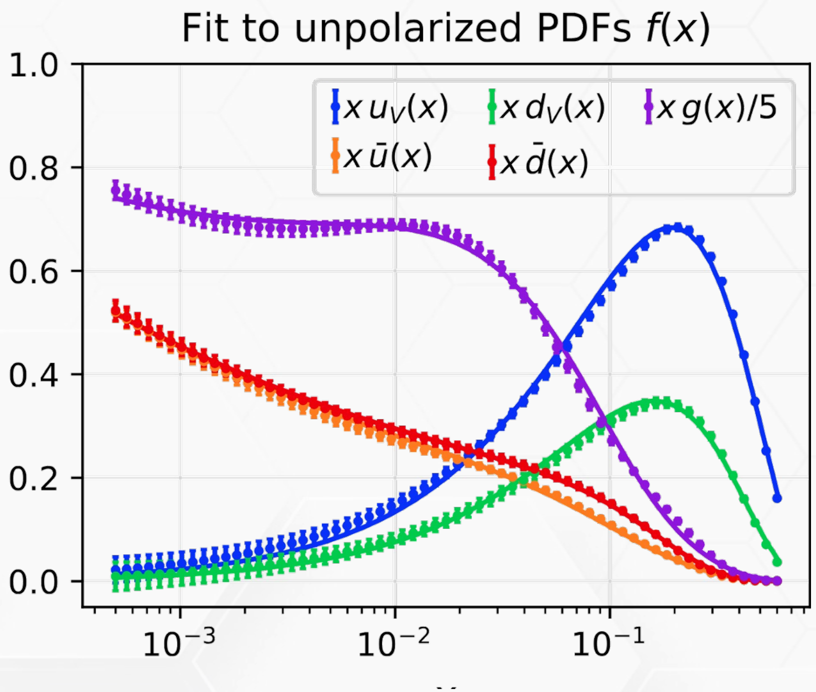
Modification from Regge theory in the form of

$$x^{-\alpha(t)}$$

Residual terms
$R(t)$

Extra factorized t dependence for more flexibility

$$\exp(-bt)$$
$$(1-t/M^2)^{-p}$$



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*

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

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

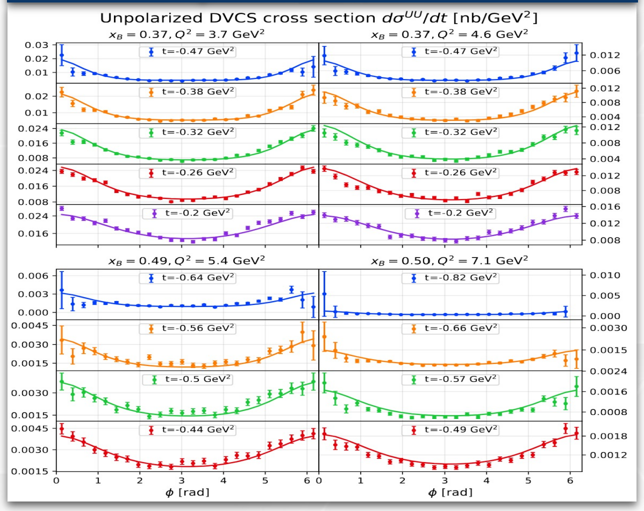
Extend to other observables such as asymmetries measurements.

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

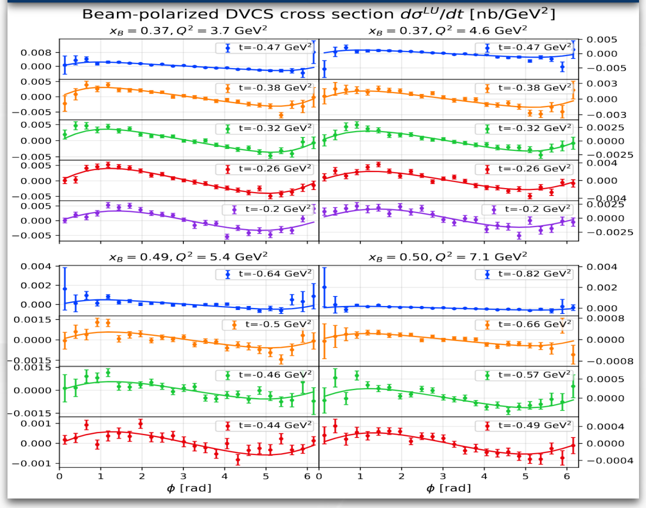
Experimental inputs for GPDs

We include various kinds of exclusive measurements from JLab and HERA

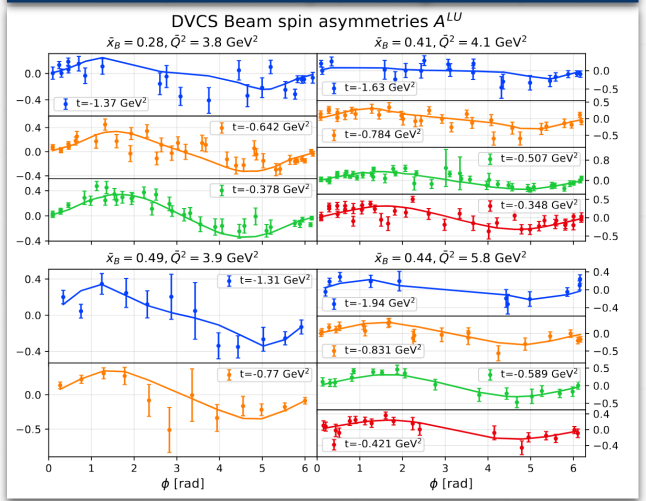
Unpolarized DVCS



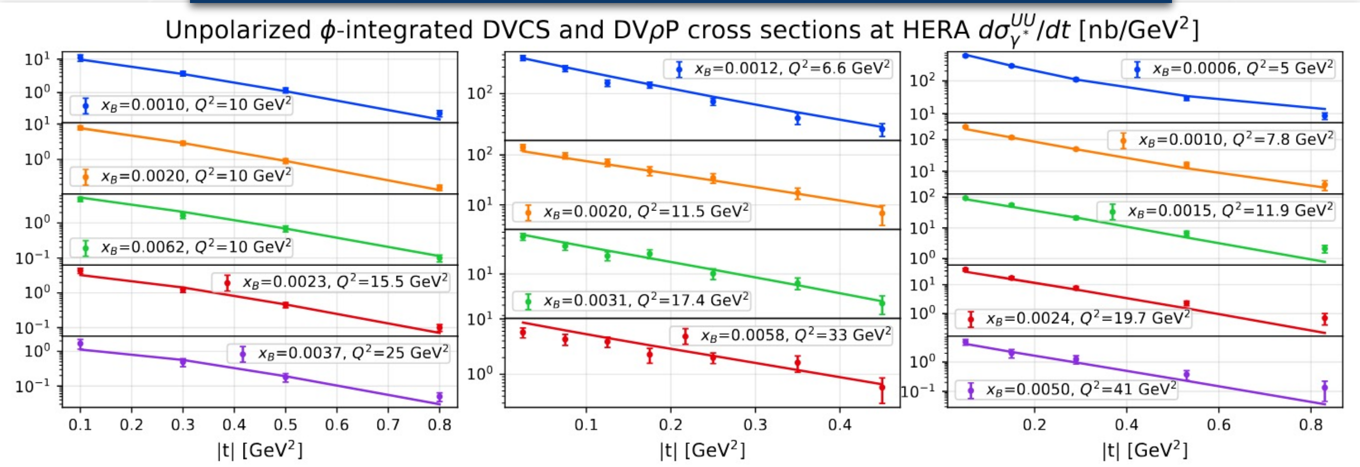
Beam Polarized DVCS



DVCS Beam-spin asymmetries



DVCS and DVMP at HERA



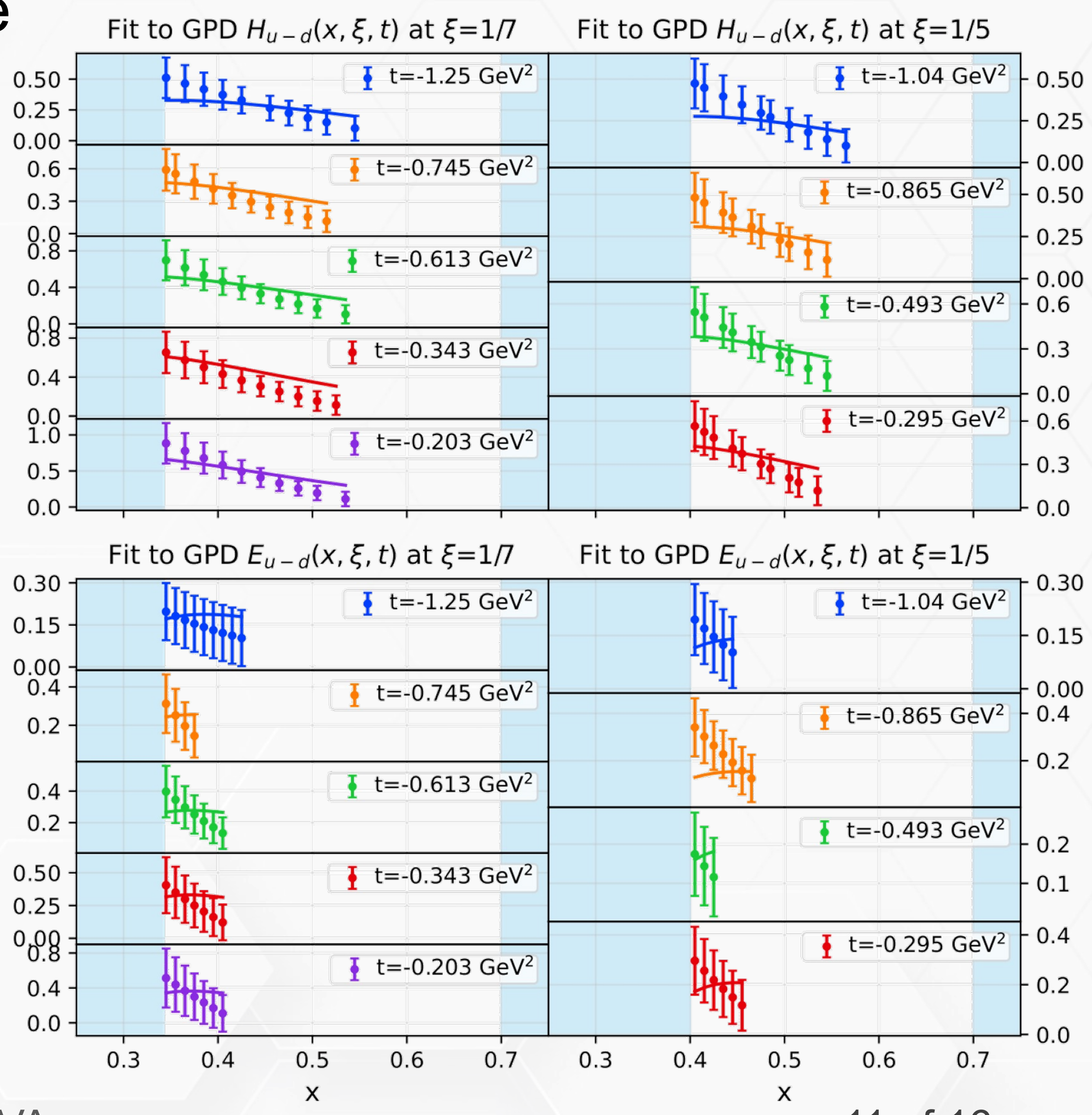
GPDs at non-zero skewness from lattice

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

Significant effects in constraining GPDs at non-zero skewness!

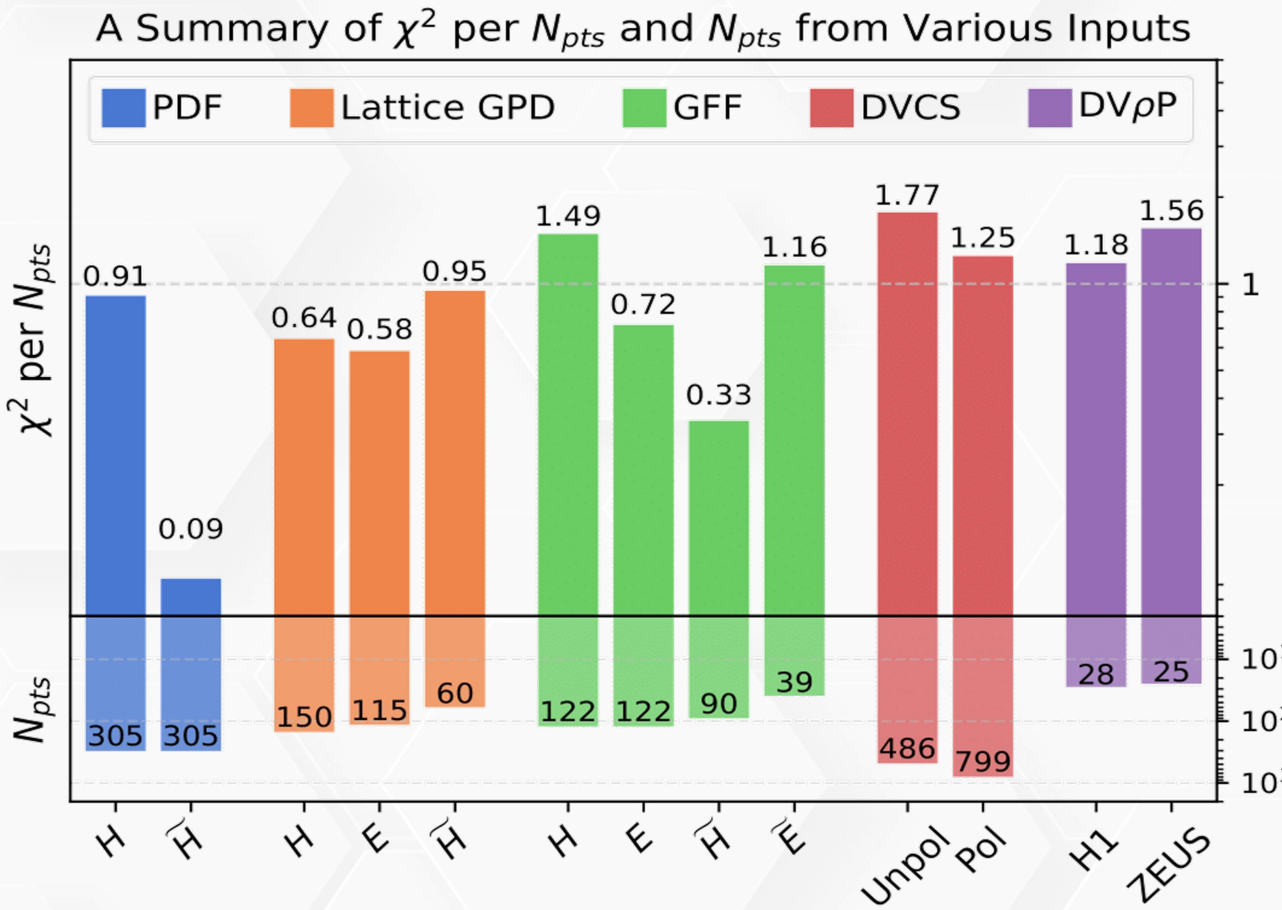
Note: besides the 30% relative uncertainty added to all the lattice data, we have a very conservative selection:

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?)

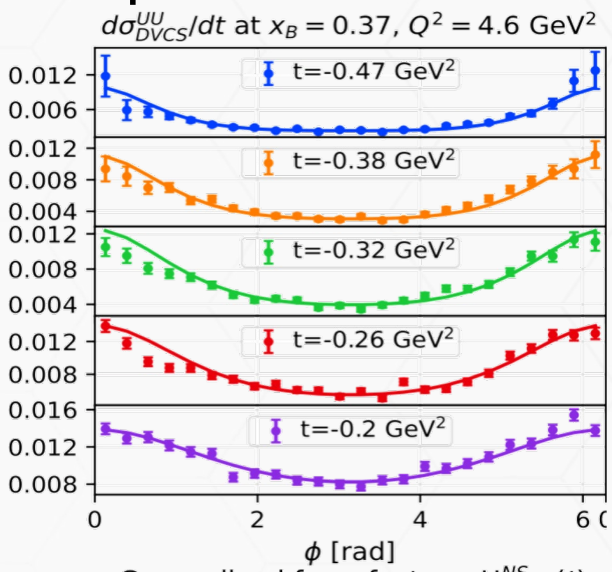


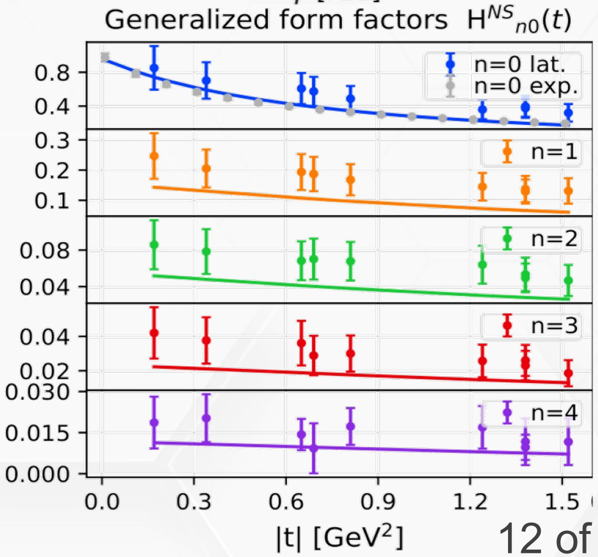
Excellent descriptions of exp. and lattices

Generally, we observe excellent agreement across various inputs:



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





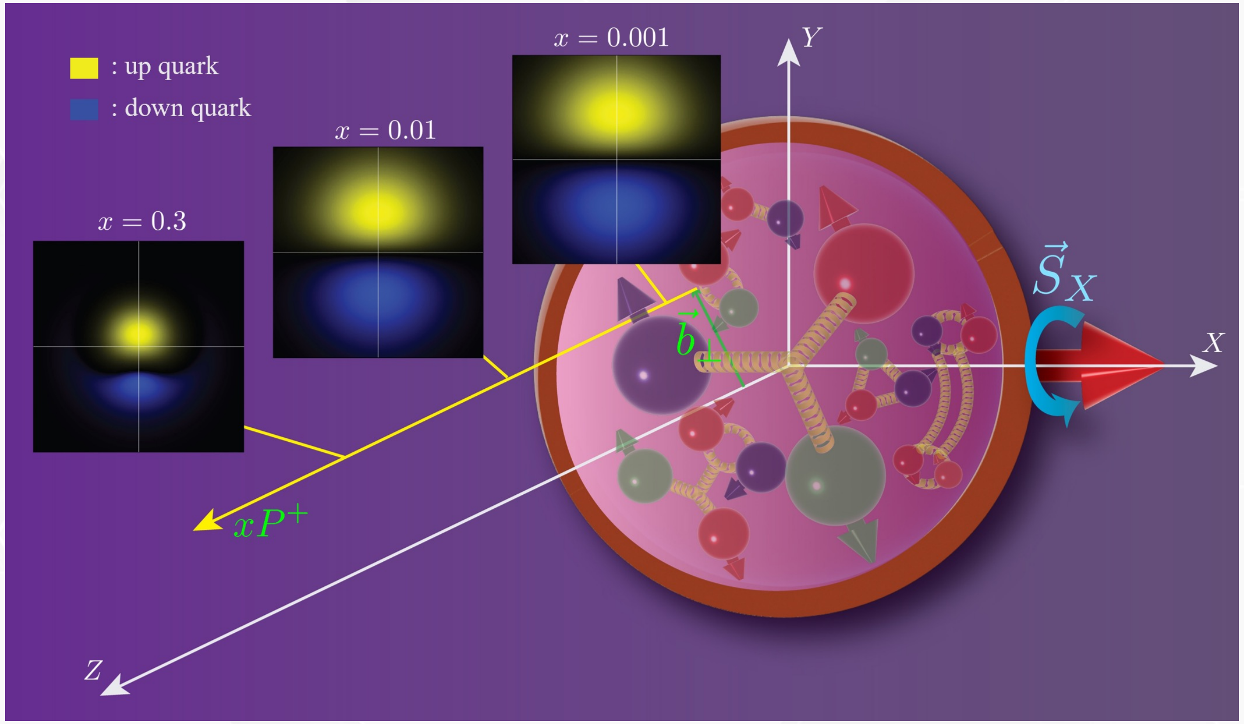
Reduced chi squared of 1.09 for 2,646 data points

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.

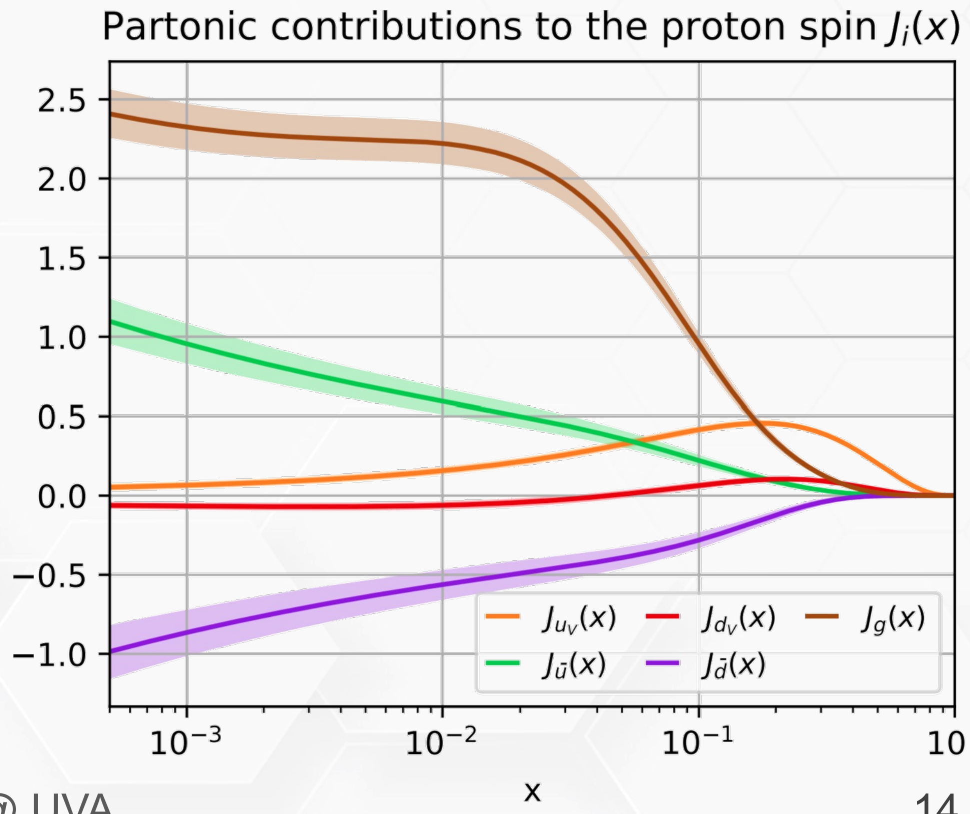
The proton is transversely polarized to the +X directions. Thus, quarks are shifted in Y directions that generate orbital angular momenta!

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 (due to exp.)
- Proton spin sum rule satisfied!



To summary

Summary

- ✓ Global analysis all four leading-twist GPDs for up, down quarks and gluons at NLO
- ✓ NLO GPD evolution with DVCS, DVMP, DVJ/ψP at JLab, HERA and future EIC
- ✓ Include the state-of-the-art lattice calculations of GPDs and moments
- ✓ GUMP1.0 GPDs are released, and more analyses are on-going!

Explore more at https://github.com/yuxunguo/GUMP-Global-GPDs

What's the next step

Extend to more observables

- More meson productions data: vector meson and others, J/ψ photoproduction
- Implementing the strange flavor (ϕ meson productions)
- A more global analysis including the large skewness region (threshold region)

Improving the accuracy

- Next-to-Next-to-Leading-Order (NNLO) hard coefficients
- Possible NNLO GPD evolutions?
- Kinematic corrections in DVCS; Mass corrections for J/ψ production
- Bayesian inference method for fitting

Precision and benchmarking

- Open GPD evolution code in momentum or moment space
- Benchmark of LO/NLO GPD evolution precision

Thank you!