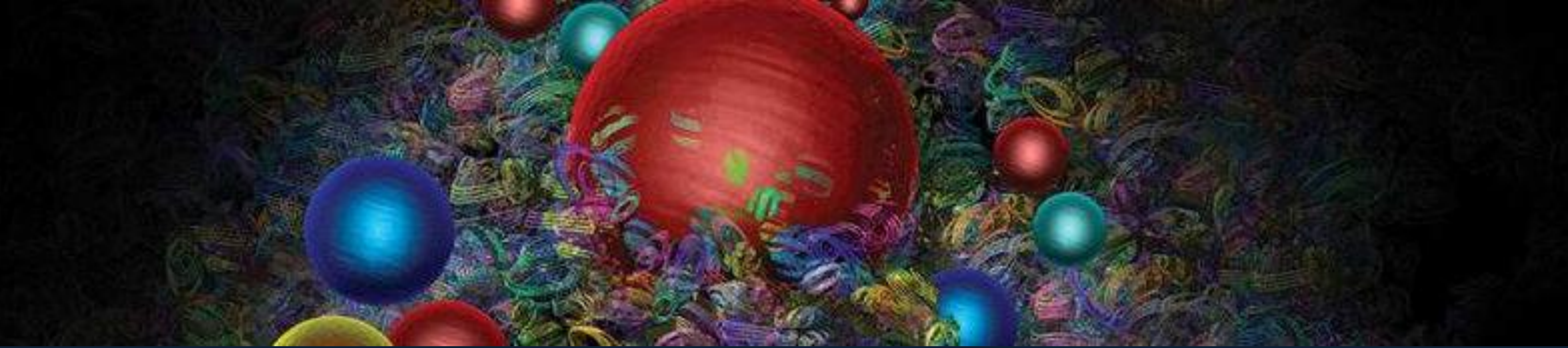


Proton tomography with generalized parton distributions at current and future facilities

Yuxun Guo

U. C. Berkeley

Y. Guo et. al. Phys. Rev. Lett. (2025)
Y. Guo, F. Yuan and W. Zhao. Phys. Rev. Lett. (2025)

Based on works in collaboration with X. Ji, Y. Liu, J. Yang, F. Yuan, W. Zhao, F. Aslan, M. G. Santiago

中国高能核物理网络论坛
HIGH ENERGY NUCLEAR PHYSICS IN CHINA
HENPIC

High-Energy Nuclear Physics
in China (HENPIC) Seminar
Jan. 08th, 2025

Berkeley
UNIVERSITY OF CALIFORNIA

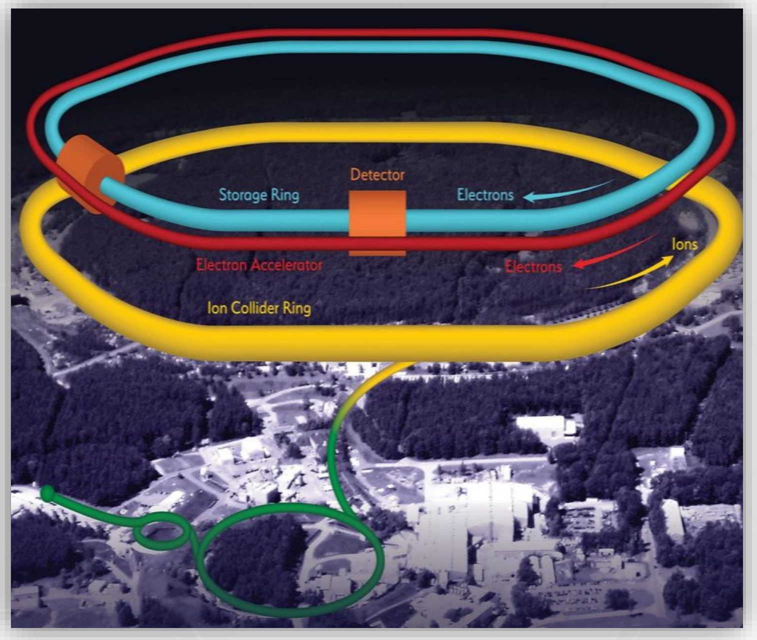
Outline

- Generalized Parton Dist. and Gravitational form factors
- Proton tomography from exclusive processes
- Global analysis of GPDs
- Proton GFFs from heavy quarkonium productions
- Summary and outlook

Internal structure of the nucleon

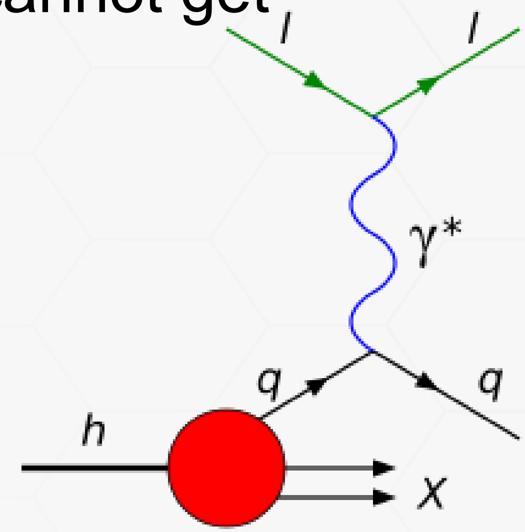
Understanding the dynamics of the quarks and gluons has been one of the central topics in modern high-energy particle and nuclear physics.

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F^{a,\mu\nu} F^{a}_{\ \mu\nu} + \bar{\psi}\left(i\gamma^{\mu} D_{\mu} - m\right)\psi$$

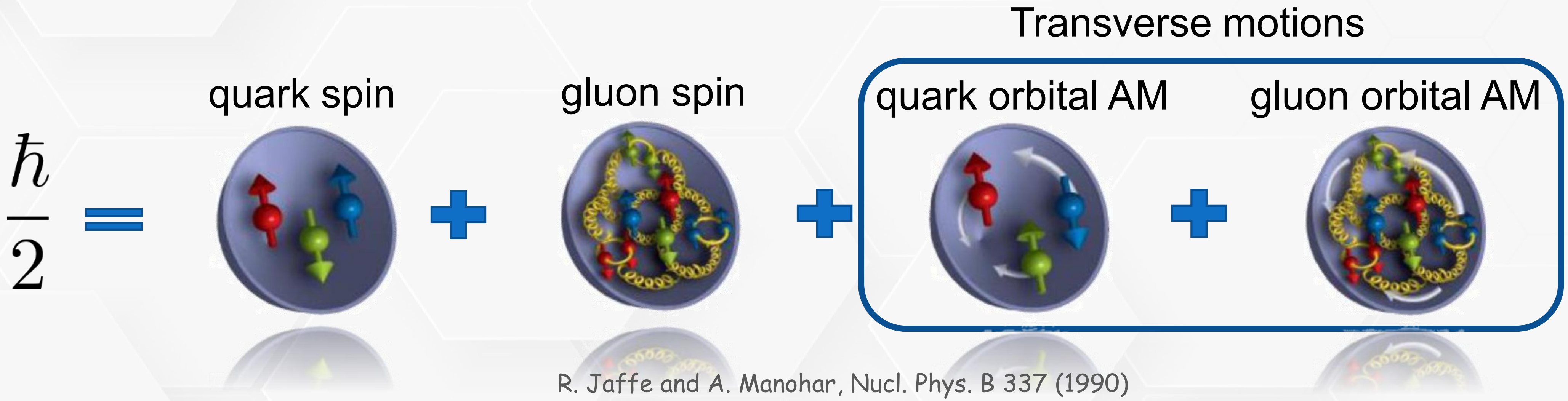


Nucleon spin structures and tomography

We have gradually realized by the end of last century that we cannot get everything we want with only inclusive measurements like DIS



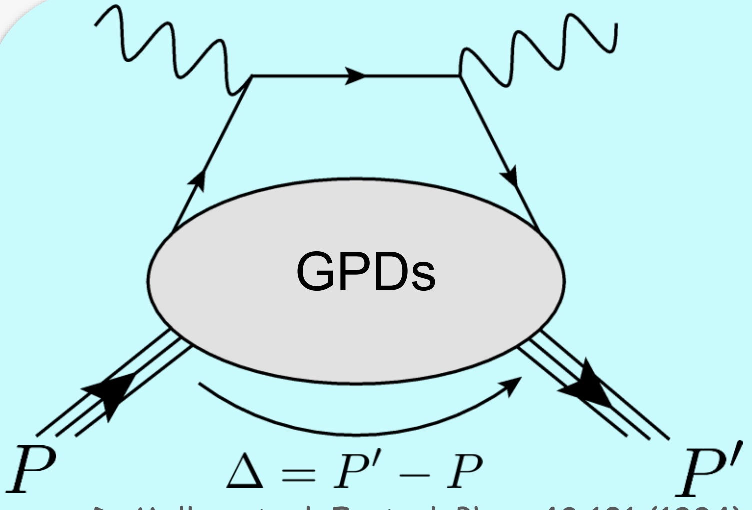
For instance, we cannot explain the proton/neutron spin structures assuming they are point-like particles.



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

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

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

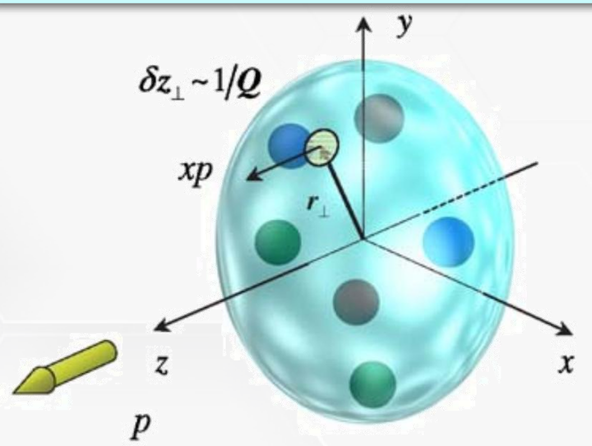
x : average parton momentum fraction

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.

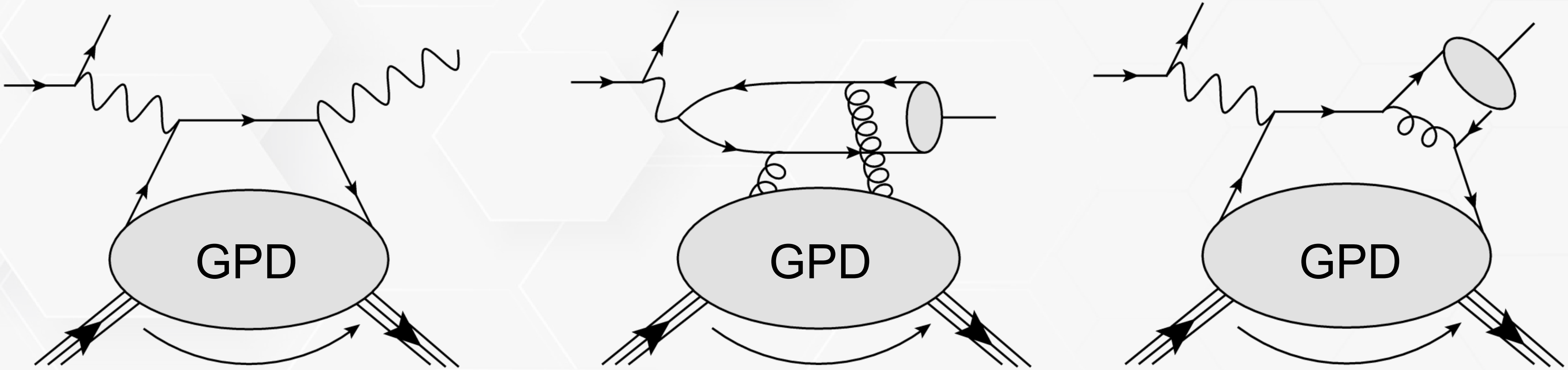
But they can be obtained with GPDs: $\int \mathrm{d}x\; xH(x,\xi,t) = A(t) + (2\xi)^2 C(t)$

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

GPD from exclusive process and more

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)

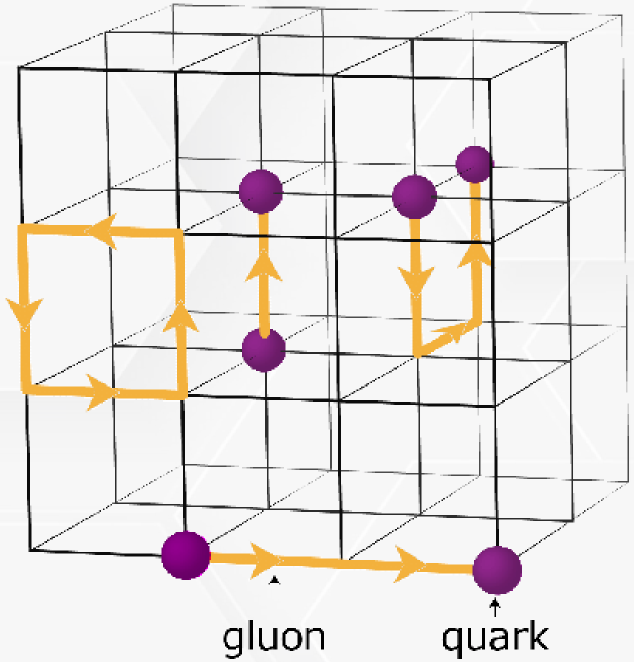
A.V. Radyushkin Phys. Lett. B 385 333-342 (1996)
J. C. Collins et. al. Phys. Rev. D 56 2982-3006 (1997)

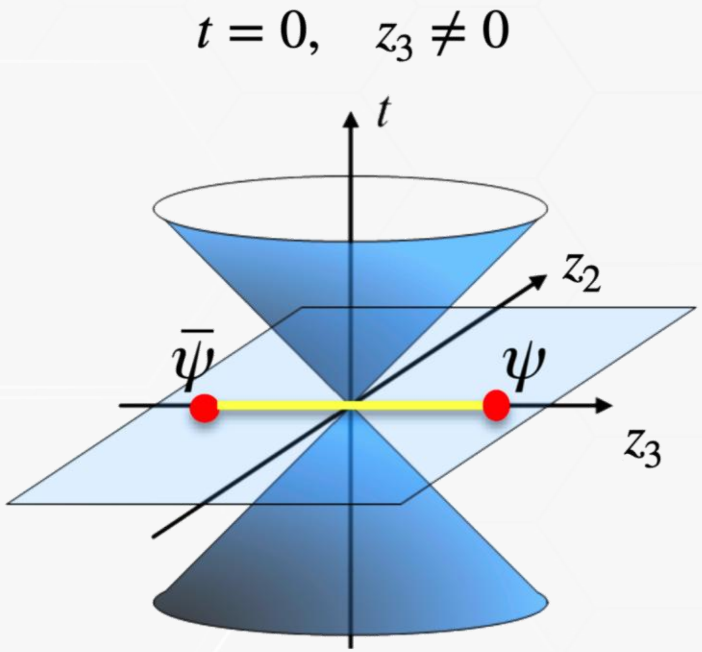
Unfortunately, they generally integrate over parton of all momentum fractions

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

Nucleon and parton structure on lattice

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





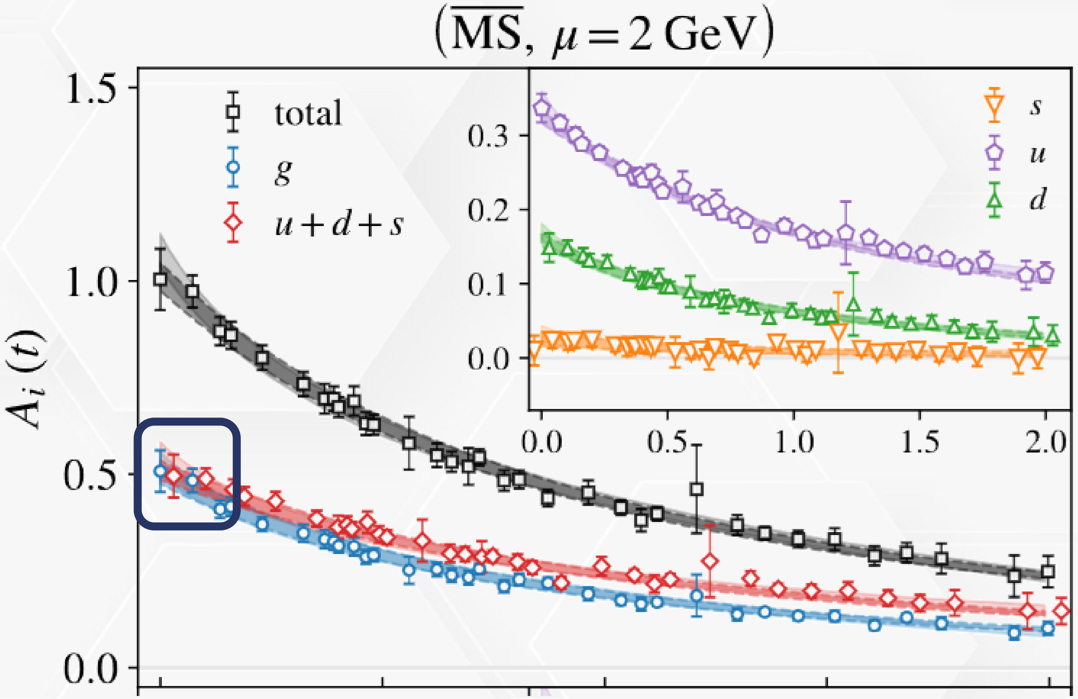
X. Ji et. al., Rev. Mod. Phys. 93 (2021)

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

Complementarity of lattice and exp.

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

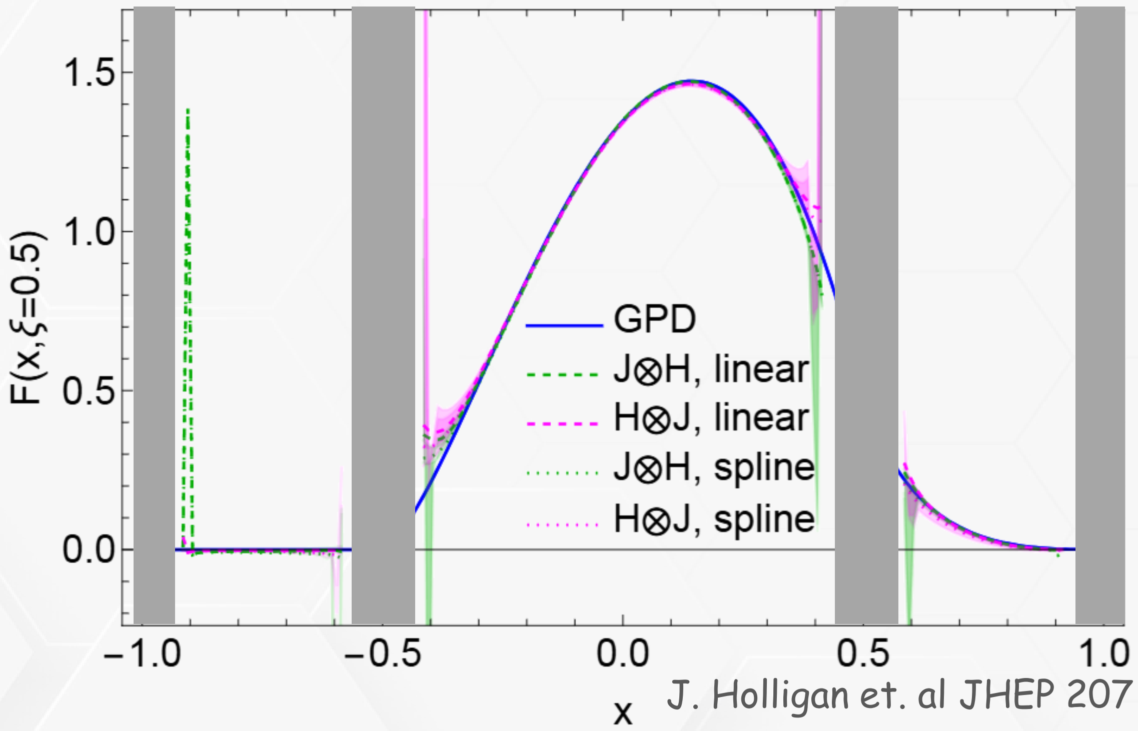
Systematics hard to put under control.



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!

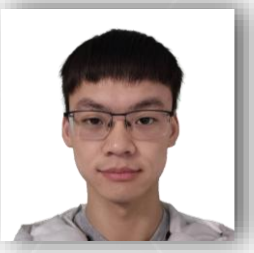
Global analysis of GPDs

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:



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Temple University

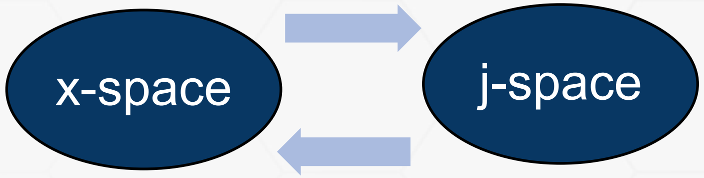
Fatma P. Aslan
Center for Nuclear Femtography

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



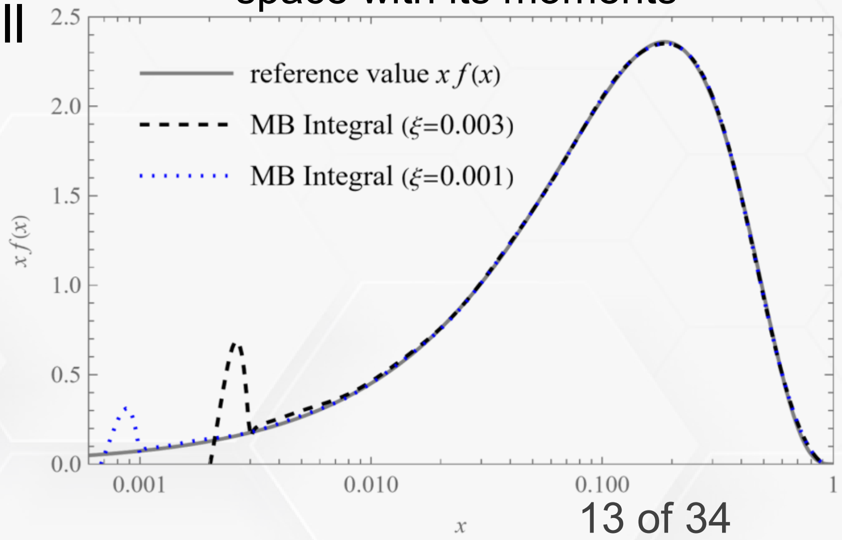
$p_j(x,\xi)$: Orthogonal basis in terms of Gegenbauer polynomials

$\mathcal{F}_j(\xi,t)$: 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

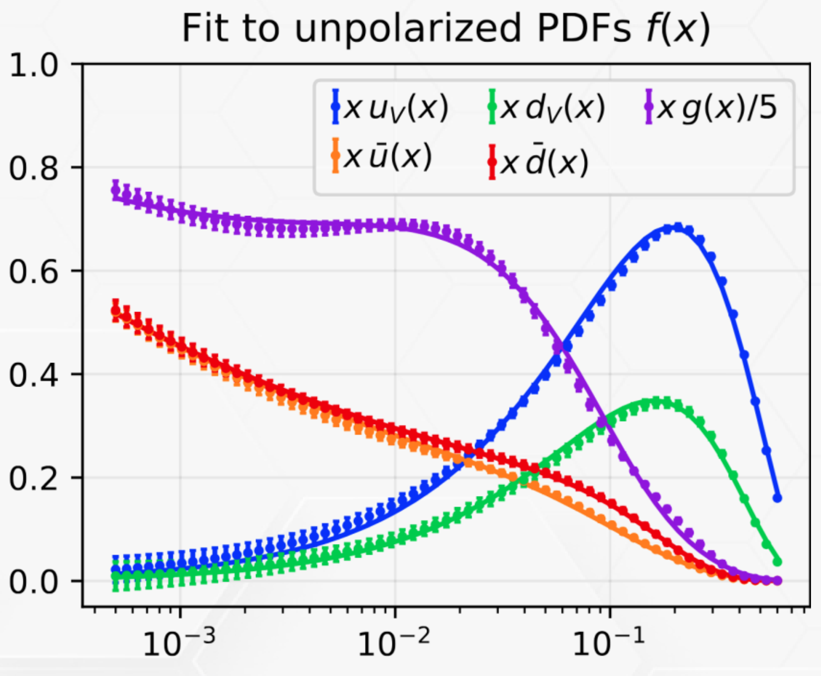
$$x^{-\alpha(t)}$$

Residual terms
$R(t)$

Extra factorized t dependence for more flexibility

$$\exp(-bt)$$

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

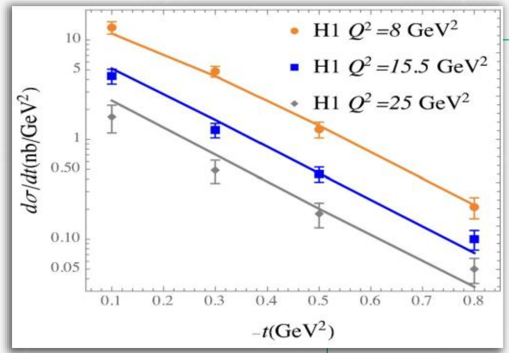


Proof-of-principle analysis (GUMP 0.5)

In one of our first work, we performed a comprehensive analysis including:

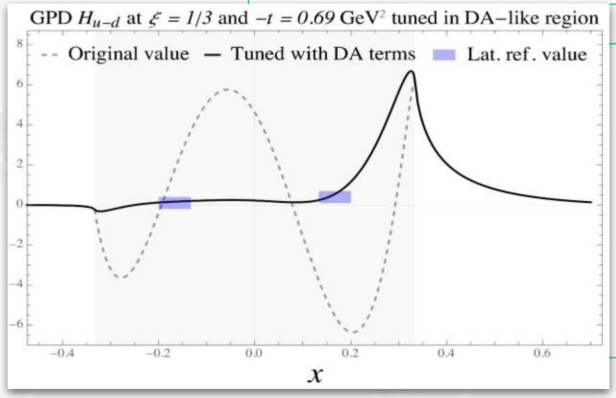
Y. Guo et. al. JHEP 05 (2023)

Y. Guo et. al. JHEP 09 (2022)



Experimental data and constraints

- ❑ *Polarized and unpolarized PDFs from global analysis*
- ❑ *Neutron/ Proton charge form factors from global analysis*
- ❑ Deeply virtual Compton scattering data at JLab and HERA



Lattice QCD simulations

- ❑ Lattice simulations of nucleon generalized form factors
- ❑ Lattice simulations of unpolarized and helicity GPDs at (non-)zero skewness

- ➢ Only leading order in perturbative expansion
- ➢ Lacking meson production constraints
- ➢ Lattice simulations not as abundant

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 (DV$J/\psi$P) 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.

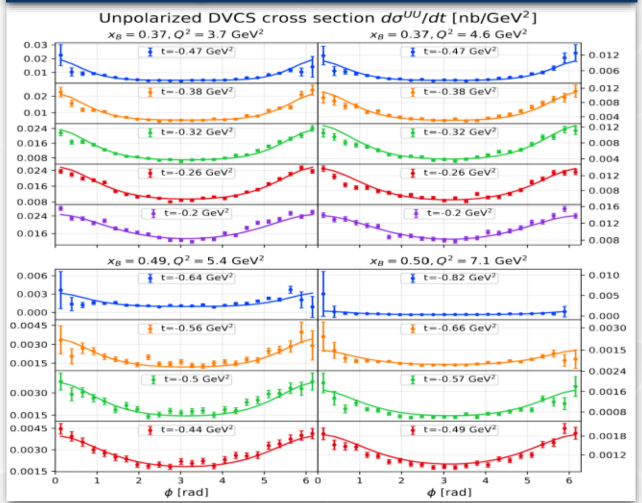
Y. Guo et. al. arXiv: 2509.08037

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

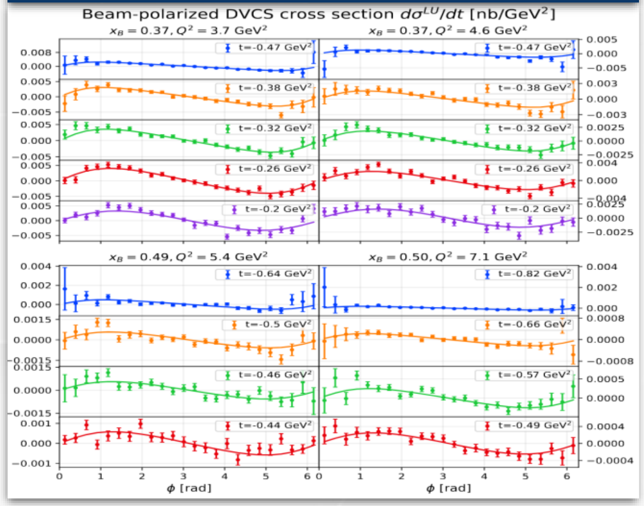
Experimental inputs for GPDs

We include various kinds of exclusive measurements from JLab and HERA

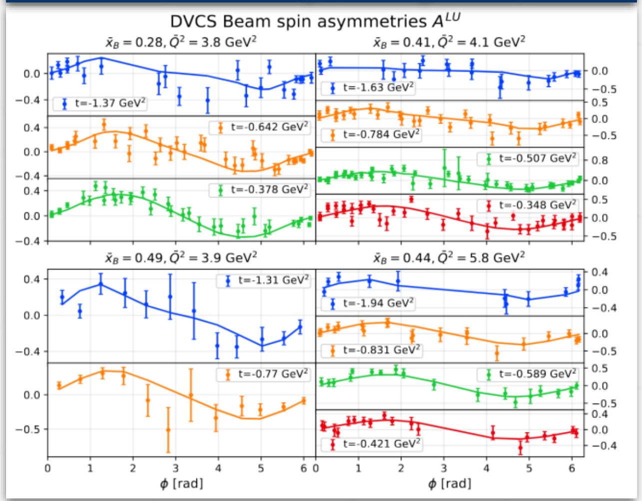
Unpolarized DVCS



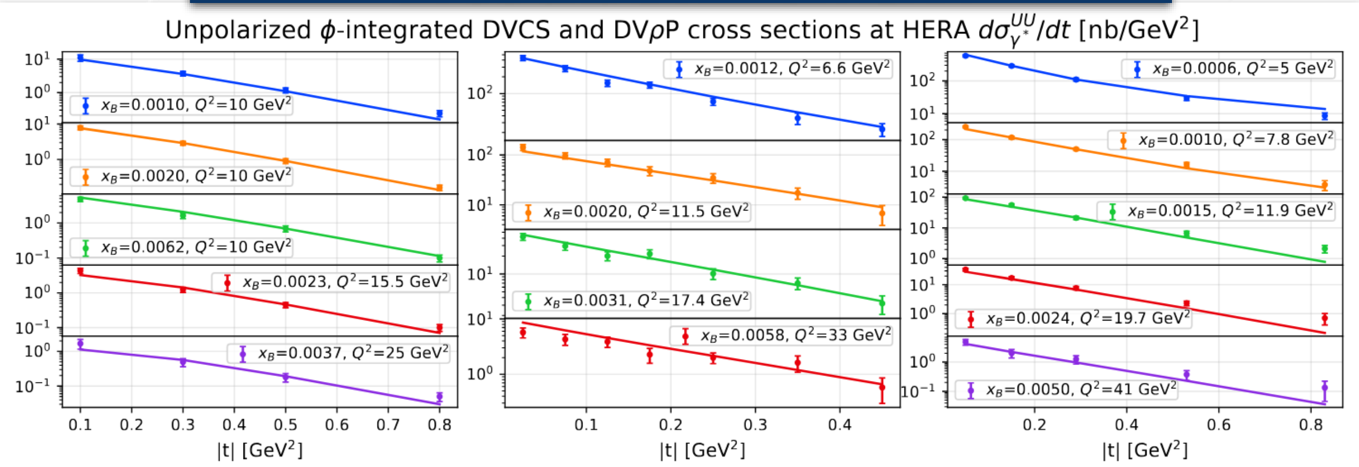
Beam Polarized DVCS



DVCS Beam-spin asymmetries

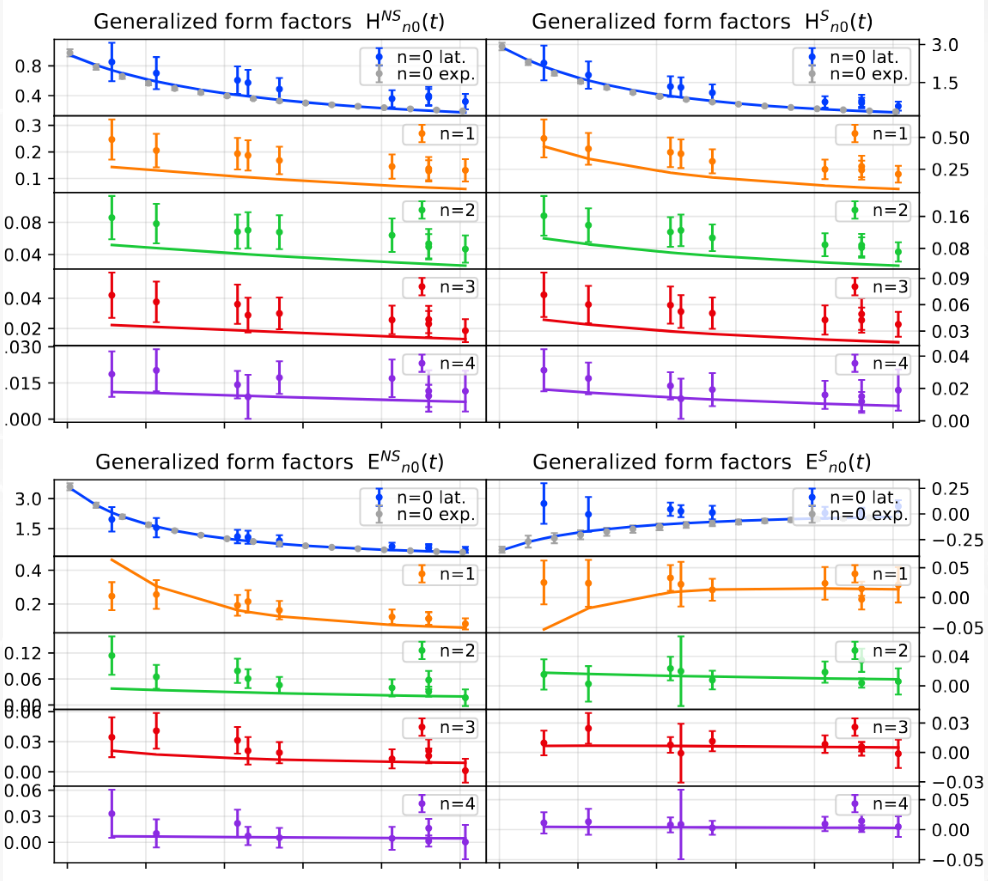


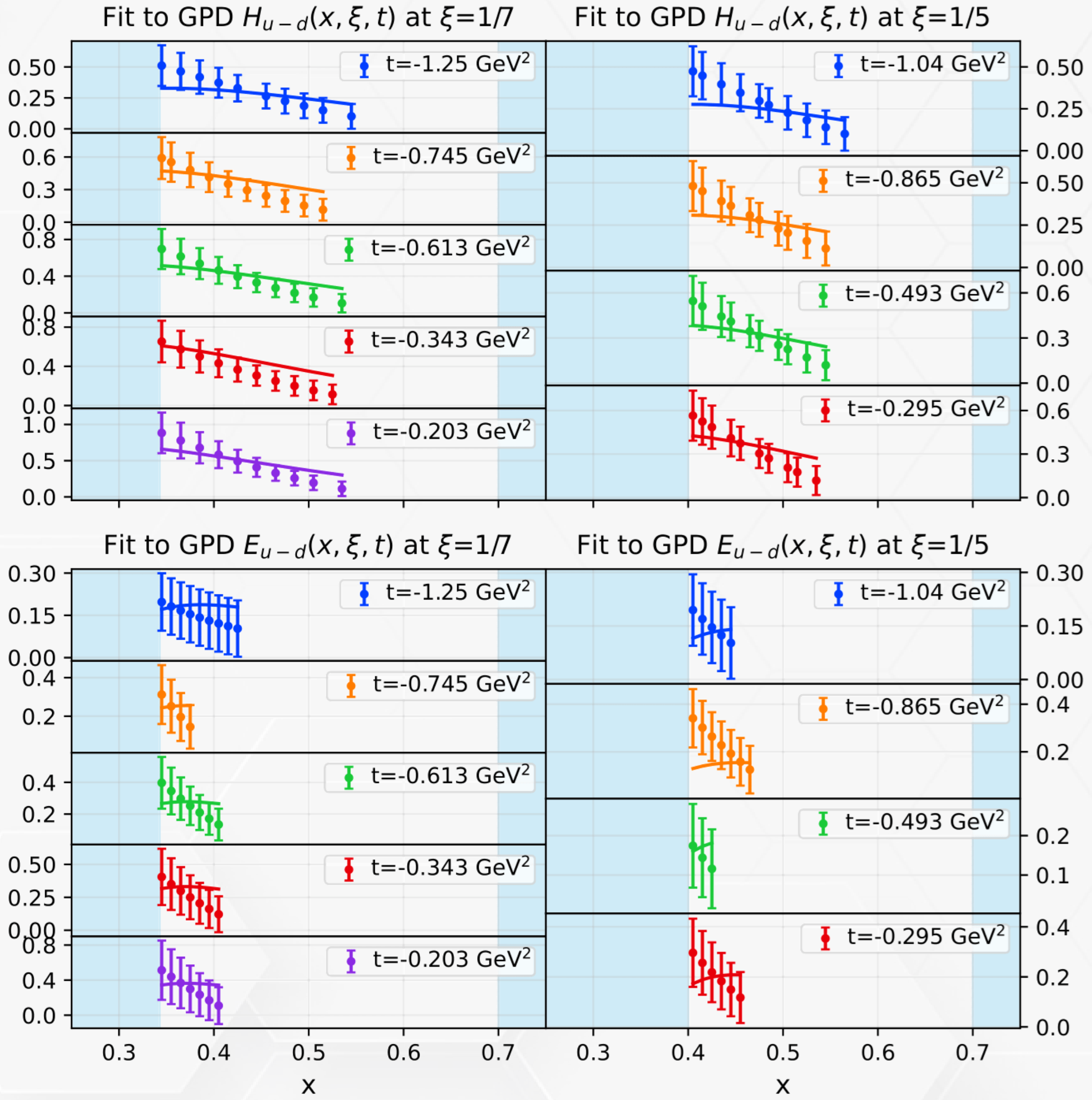
DVCS and DVMP at HERA



Lattice inputs for GPDs

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





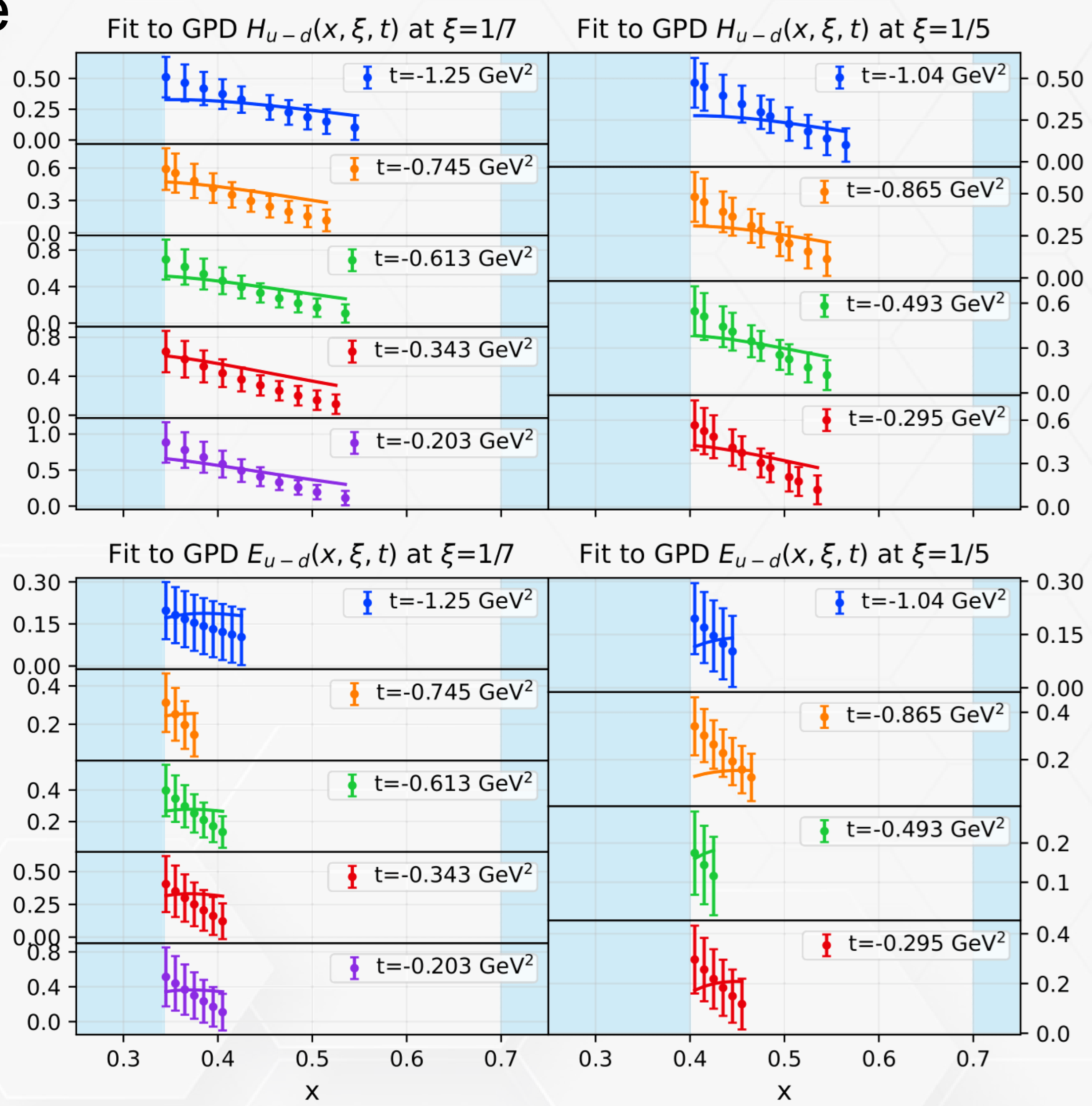
GPDs at non-zero skewness from lattice

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

Significant effects in constraining GPDs at non-zero skewness!

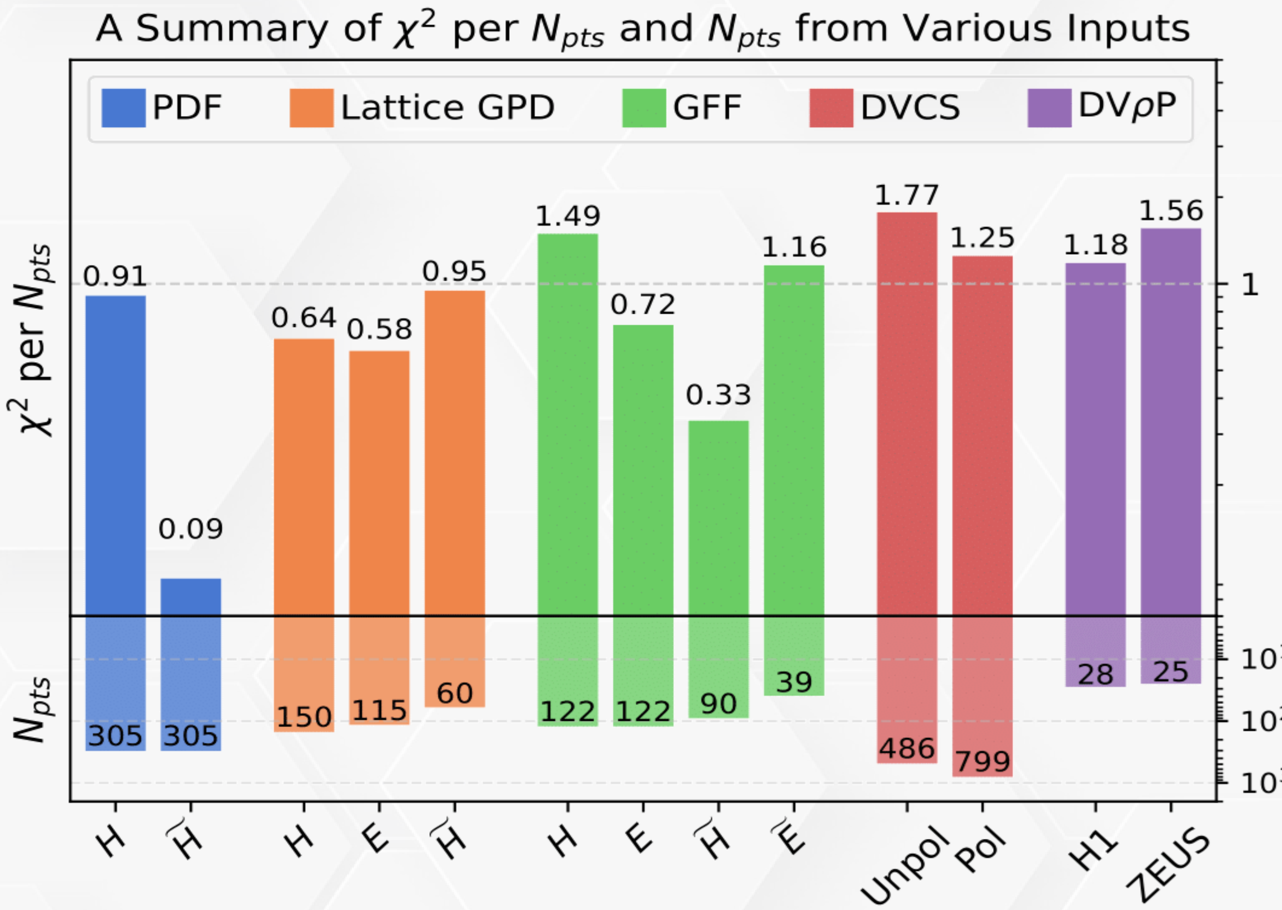
Note: besides the 30% relative uncertainty added to all the lattice data, we have a very conservative selection:

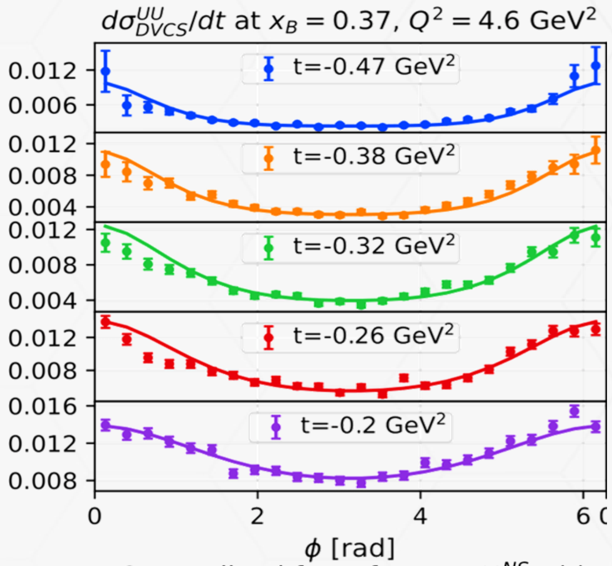
1) Only used the data between 0.3<x<0.7 and |x-xi|>0.2.
2) Exclude region where GPDs get negative or very small (lattice artifacts or intrinsic GPD behaviors?)

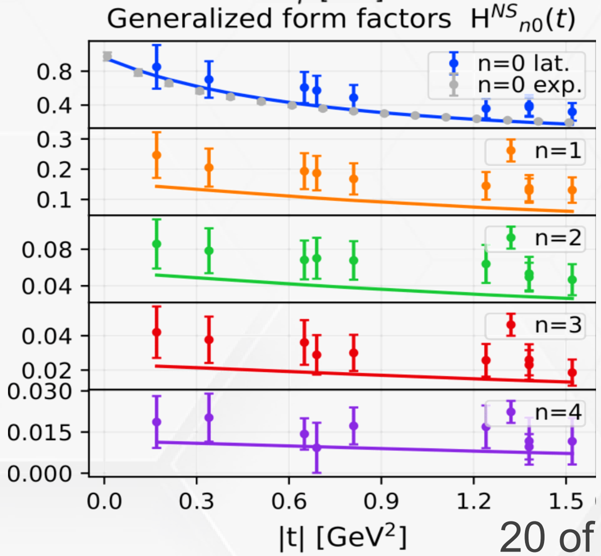


Excellent descriptions of exp. and lattices

Generally, we observe excellent agreement across various inputs:







Y. Guo et. al. arXiv: 2509.08037

Reduced chi squared of 1.09 for 2,646 data points

Nucleon tomography with GUMP1.0 GPDs

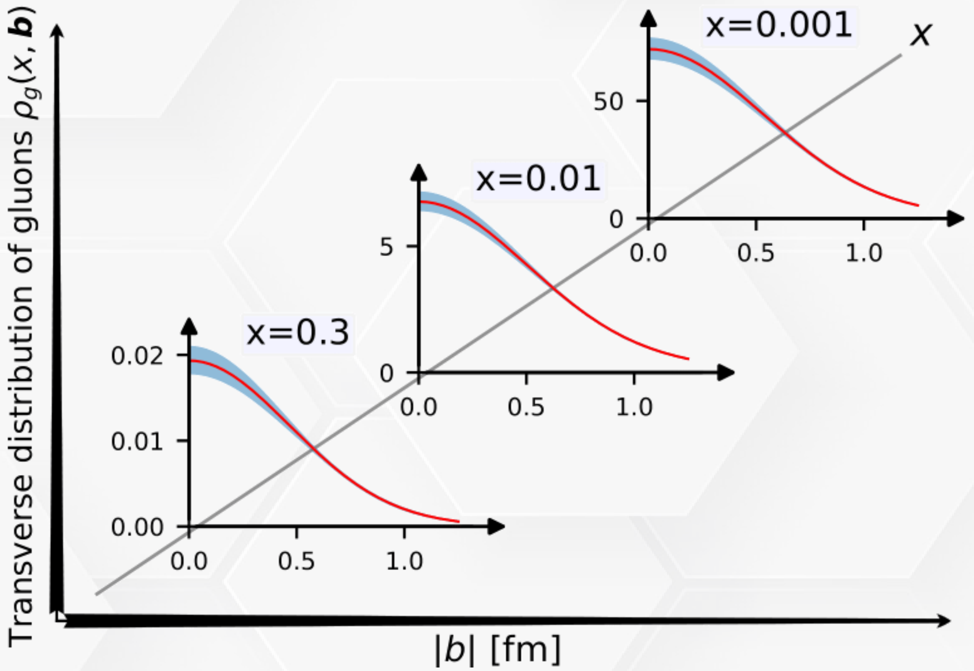
Of course we can also study the nucleon tomography via:

$$\rho_{q/g}(x,\boldsymbol{b}) = \int \frac{\mathrm{d}^2\boldsymbol{\Delta}}{(2\pi)^2} e^{-i\boldsymbol{\Delta}\cdot\boldsymbol{b}} H_{q/g}(x,-\boldsymbol{\Delta}^2)$$

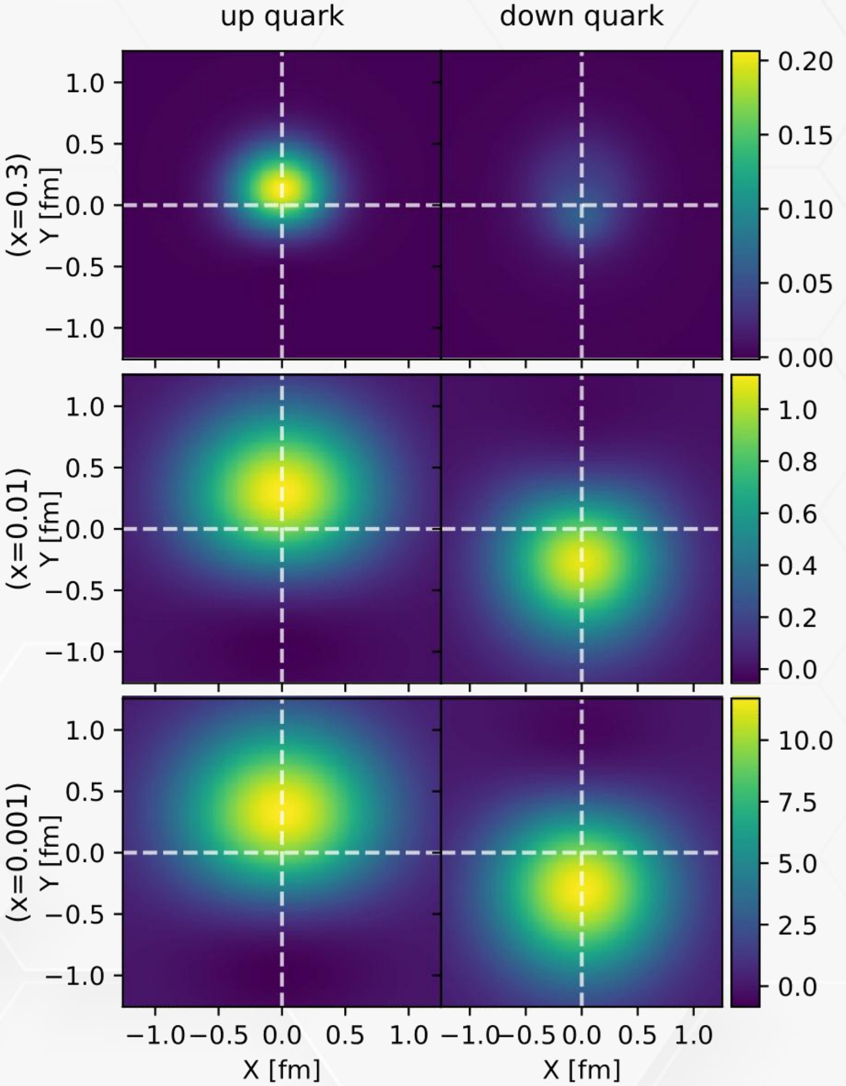
And the ones for transversely polarized proton

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

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



Quark dist. in transversely(X)-polarized proton

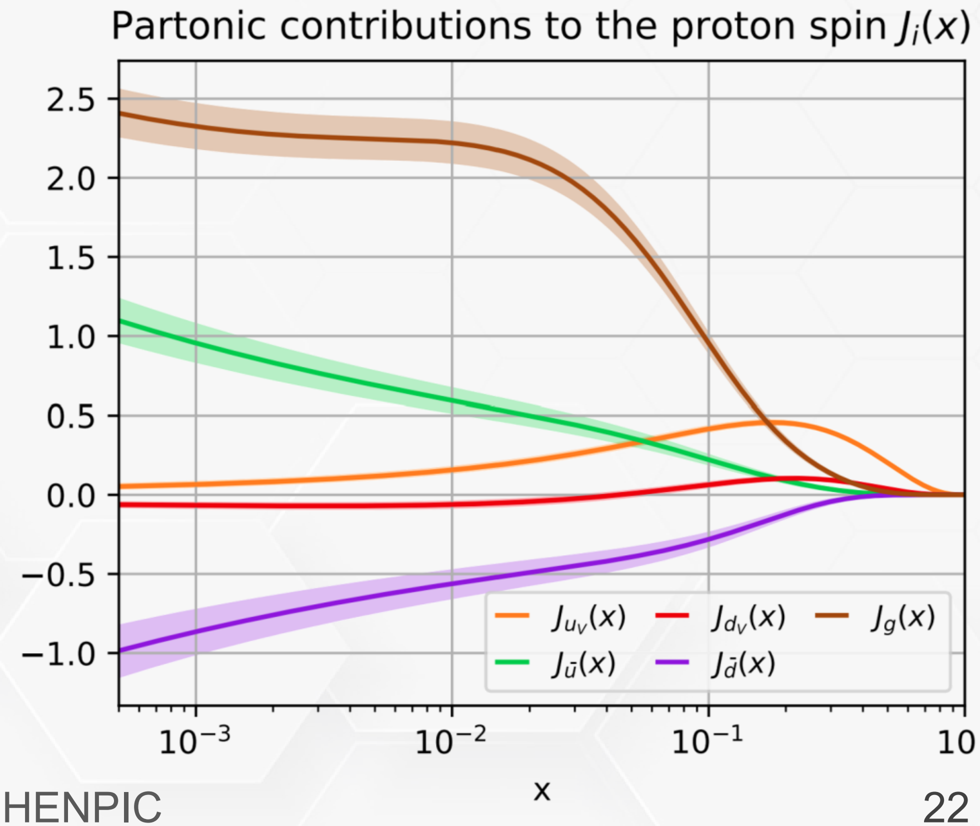


Partonic contributions to the proton spin

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!



Proton GFFs with heavy quarkonium

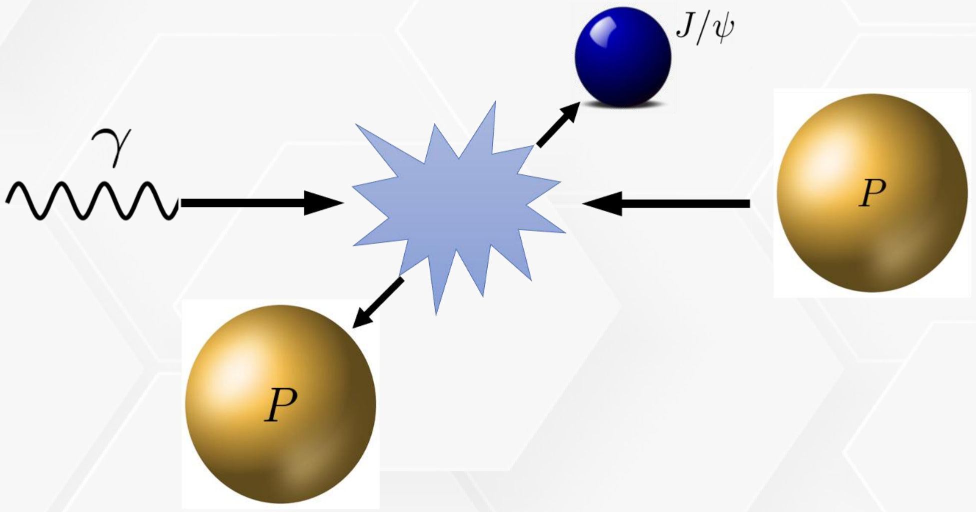
Color dipole as the probe of gluon structure

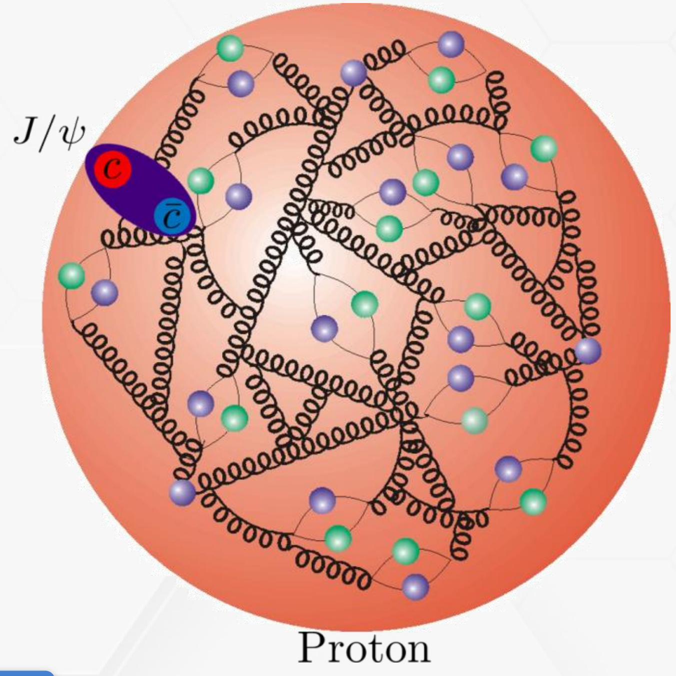
Similarly to the quadratic Stark effect but in QCD, small color dipoles are coupled to the local color electric fields through

M. B. Voloshin Nucl. Phys. B 154 365-380 (1979)
M. Luke et al. Phys. Lett. B 288 355-359 (1992)
D. Kharzeev et al., Eur. Phys. J. C 9 459-462 (1999)

$$\mathcal{H}_{\mathrm{Int}} = \mathbf{E}^a \cdot (\mathbf{r}_c t_c^a - \mathbf{r}_{\bar{c}} t_{\bar{c}}^a)$$

Elastic scattering of J/psi off the nucleon would be ideal, but in real life we consider photo-/electro- production

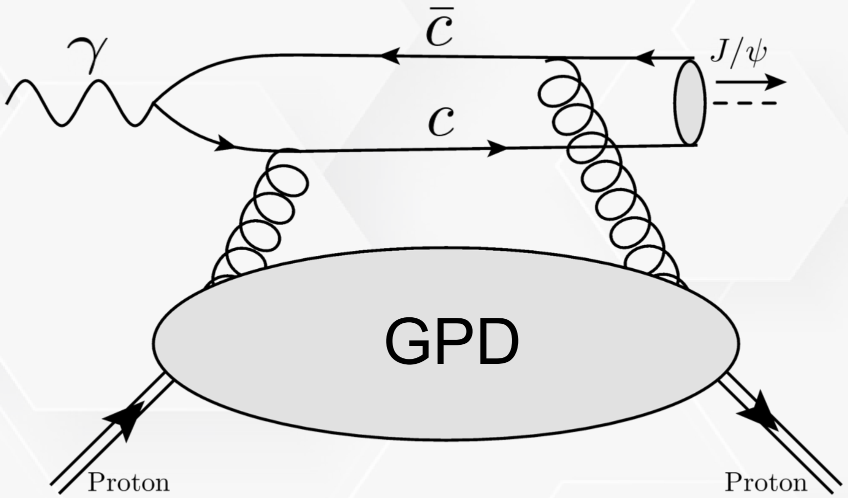




local gluonic distribution ⟷ small dipole ⟷ Heavy meson

Heavy quarkonia production in QCD

This can be rephrased in the language QCD, particularly in the non-relativistic QCD (NRQCD) factorization framework:



D. Y. Ivanov et. al. Eur. Phys. J. C 34, 297 (2004)
Z.-Q. Chen et. al. Phys. Lett. B 797,134816 (2019)
Y. Guo et. al. Phys. Rev. D 103 9, 096010 (2021)

The production of heavy quarkonia can be factorized into local NRQCD matrix elements

For exclusive processes, two-gluon color singlet exchange is required.

In the high energy limit, exchanged gluons are collinear hard

Near threshold, exchanged gluons must also be hard and collinear to create a heavy quarkonium.

$$\mathcal{H}^g_{\rm NRQCD} \sim \left(\frac{\langle O_1\rangle_V}{m_q}\right)^{1/2} \int_{-1}^{1} {\rm d}x C_2^g\left(x,\xi,M_V,Q\right) H^g(x,\xi,t)\ ,$$

Resolution to the inverse problem

How to get the Gravitational form factors (GFFs) if the GPDs are not uniquely determined by just Compton form factors (CFFs)?

Some resolutions in the literature:

Global analysis

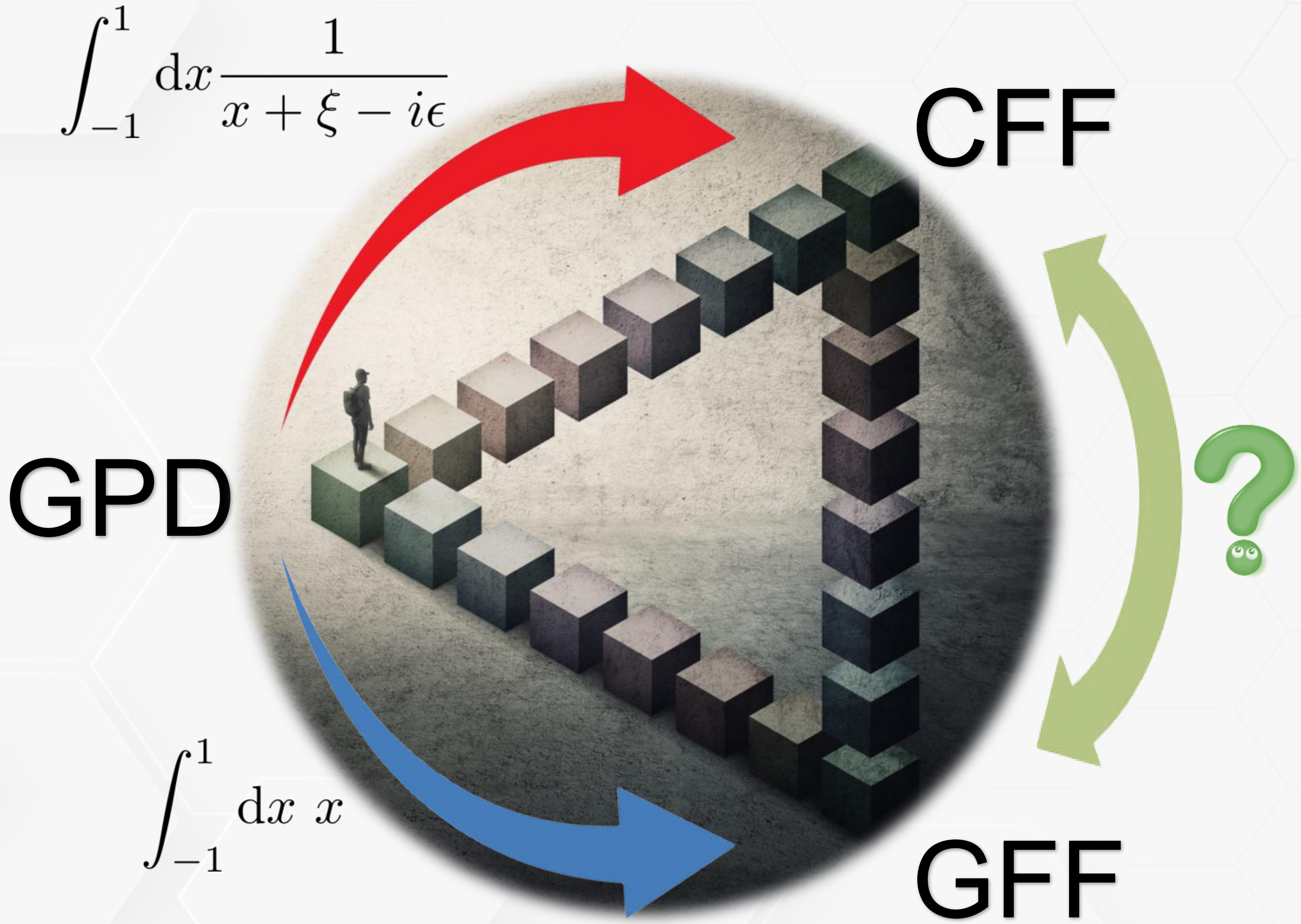
- Might be an overkill for just GFFs?

Dispersion relations

- Need the full imaginary amplitude

Asymptotic expansion

- Works well for large skewness!



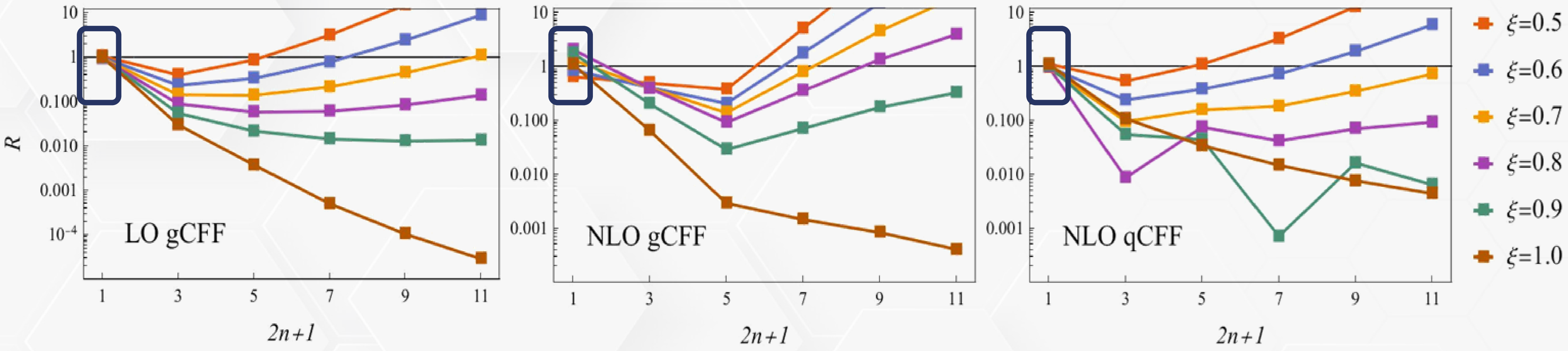
Approximate CFFs with GFFs

Compton-like form factors are related to the generalized form factors through:

$$\mathrm{Re}\mathcal{H}_{g\mathrm{C}}(\xi,t)=\mathcal{C}_g(t)+\sum_{n=1}^{\infty}\xi^{-2n}\mathcal{A}_g^{(2n)}(t)$$

However, the first moments appear to approximate CFFs well for large skewness!

Y. Guo, F. Yuan and W. Zhao. Phys. Rev. Lett. (2025)



See also Y. Hatta et.al. arxiv: 2501.12343

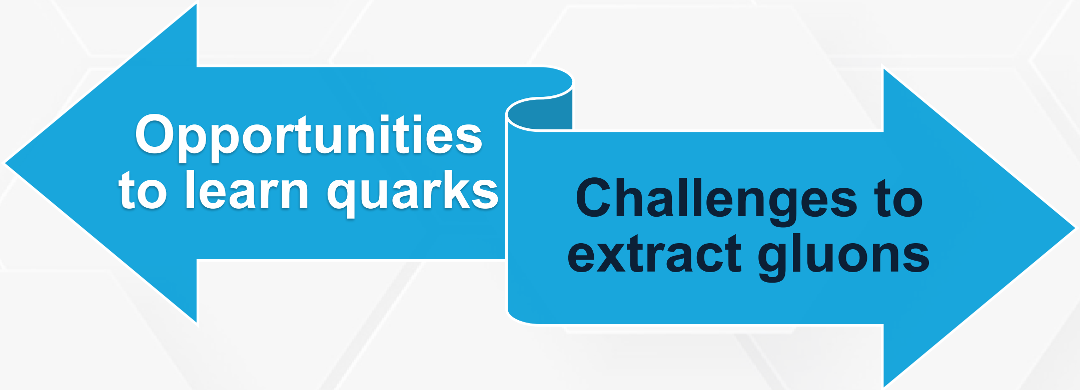
Normalized contribution of each term: $R_{q/g}^{(2n+1)}\equiv\dfrac{\xi^{-2n-2}\bar{C}_{q/g}^{(2n+1)}\bar{H}_{q/g}^{(2n+1)}(\xi,t)}{\mathrm{Re}\mathcal{H}_{q/g\mathrm{C}}(\xi,t)}$

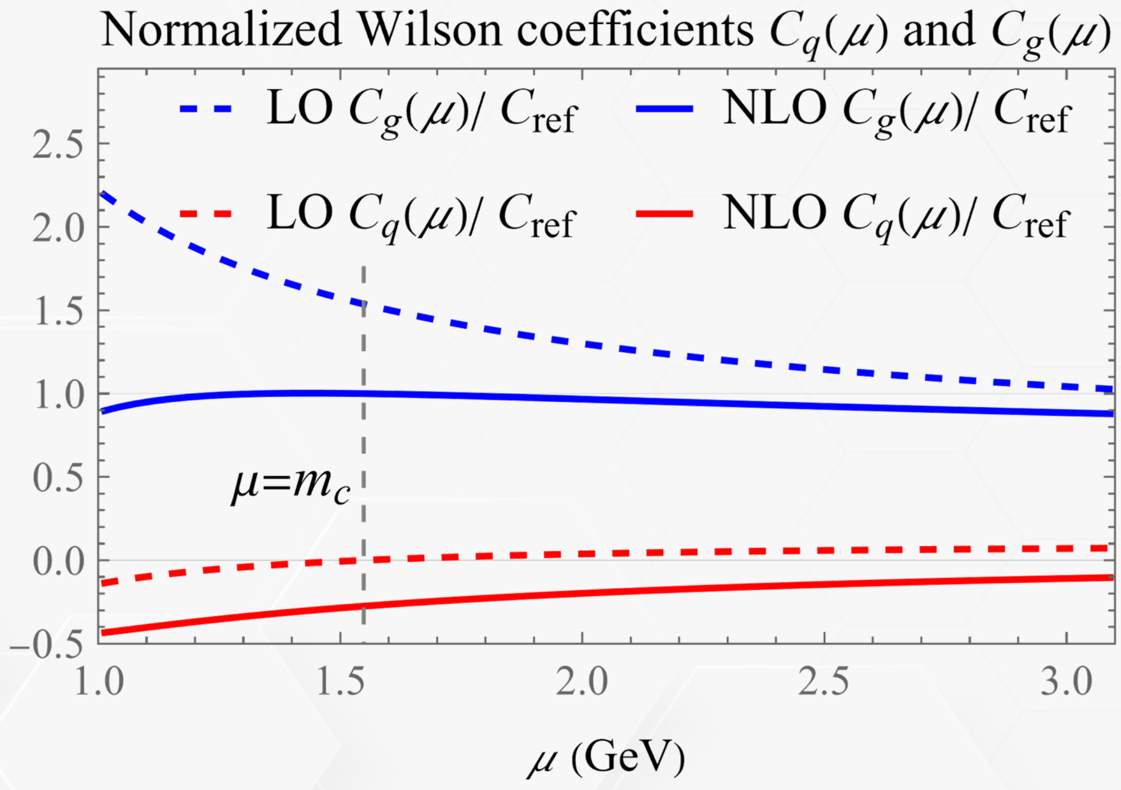
Next-to-leading order effects

The Next-to-leading corrections appear to be sizable:

- ❑ Large scale dependence are found at LO and get significantly reduced at NLO
- ❑ **NLO quark contributions are suppressed by the strong coupling but generally not small.**

$$\bar{C}^{\text{evo}} \equiv \alpha_S(\mu_F)\bar{\boldsymbol{C}}^{(1)}(\mu_F, m_c)\boldsymbol{\mathcal{E}}^{(1)}(\mu_F, m_c)$$





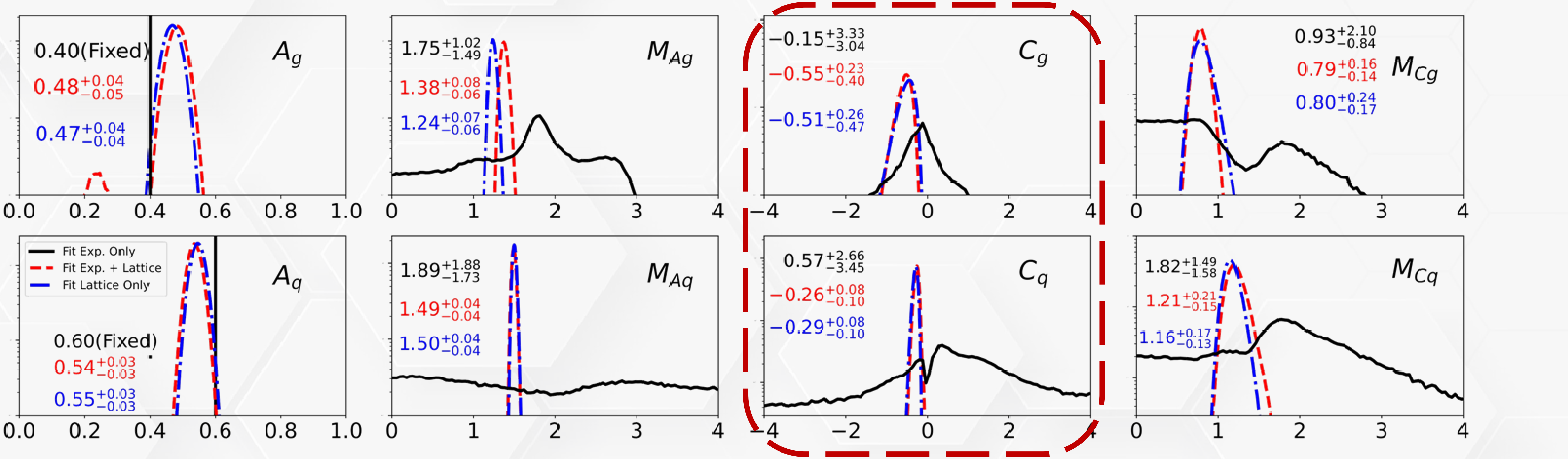
Bayesian inference of proton GFFs

We consider Bayesian inference for a statistically rigorous and interpretable extraction, which gives the posterior distributions of the parameters according to:

$$P\left(\boldsymbol{\theta}|\mathrm{data}\right)=\frac{P\left(\mathrm{data}|\boldsymbol{\theta}\right)}{P\left(\mathrm{data}\right)}P\left(\boldsymbol{\theta}\right)$$

$$P(\mathrm{data})=\int \mathrm{d}\boldsymbol{\theta}\ \mathrm{P}(\mathrm{data}|\boldsymbol{\theta})\mathrm{P}(\boldsymbol{\theta})$$

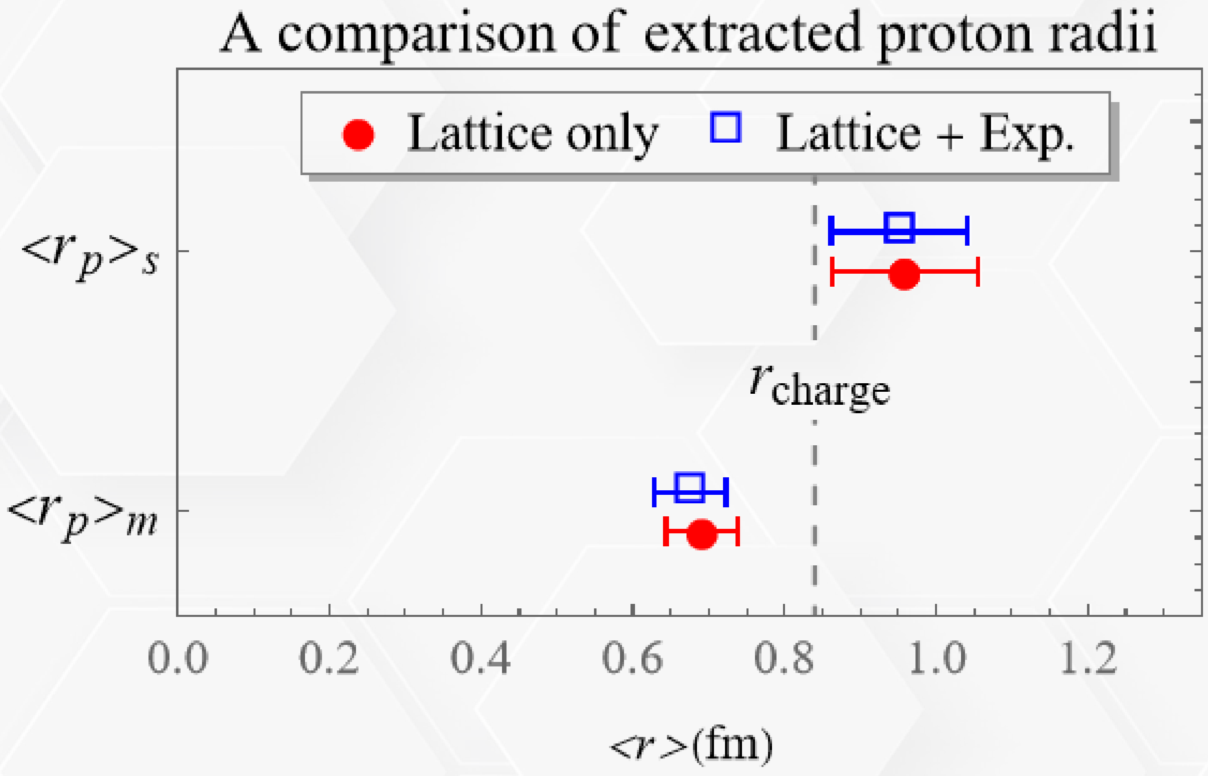
With the parameterization $F_i(t)=F_i(0)\left(1-t/M_{F_i}^2\right)^{-p}$ for $F_i=\{A_q,A_g,C_q,C_g\}$



Y. Guo, F. Yuan and W. Zhao. Phys. Rev. Lett. (2025) and references therein

Implication on the proton radii

We can also calculate the proton radii with the extracted proton GFFs:



$$\left\langle r^2\right\rangle_m = 6\left.\frac{dA(t)}{dt}\right|_{t=0} - 6\frac{C(0)}{M_N^2}$$

$$\left\langle r^2\right\rangle_s = 6\left.\frac{dA(t)}{dt}\right|_{t=0} - 18\frac{C(0)}{M_N^2}$$

Mostly rely on the lattice constraint due to the lack of sensitivity to the dipole/tripole mass of GFFs

Connections to other processes/analyses

This analysis is not limited to just heavy vector meson photo-productions

- Light(er) meson electro-productions at large skewness

Y. Hatta et. al., arXiv: 2501.12343
Y. Hatta and J. Schoenleber Phys. Rev .Lett. 134 (2025)

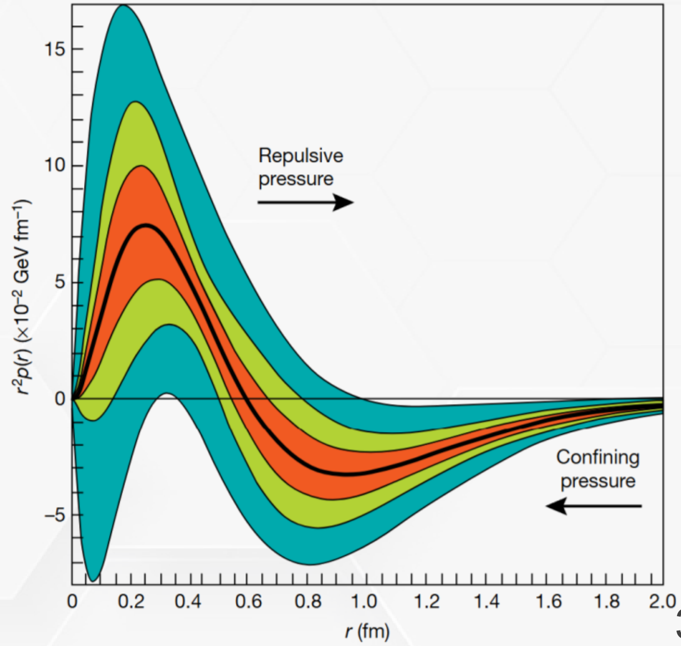
- Time-like Compton scattering (TCS) at large skewness
- Deeply virtual Compton scattering (DVCS) at large skewness

JLab Hall A and F. Georges Phys. Rev. Lett. 128 25, 252002 (2022)

In lower-skewness region, the imaginary part of the amplitudes are no longer small.

Method like dispersion analysis can incorporate the imaginary parts to the extractions.

V. D. Burkert et. al. Nature 557 (2018)



Outlook and summary

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!
- ✓ Also, we consider the threshold production processes for proton GFFs at NLO
- ✓ Promising results in extracting the gluon GFFs of proton, maybe also the quark GFFs

What's more?

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

Improving the accuracy

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

Precision and benchmarking

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

Thank you!