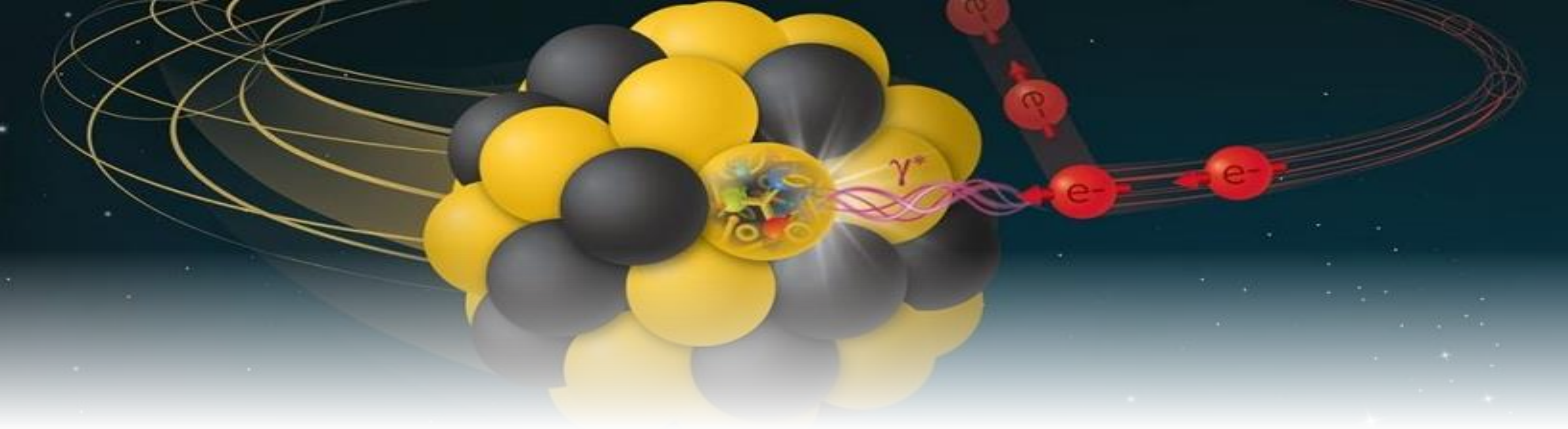


Global analysis of GPDs with GUMP program

— near forward and beyond

Yuxun Guo

Lawrence Berkeley National Laboratory

Precision QCD Predictions for ep Physics at the EIC (II)

CFNS, Stony Brook University, New York

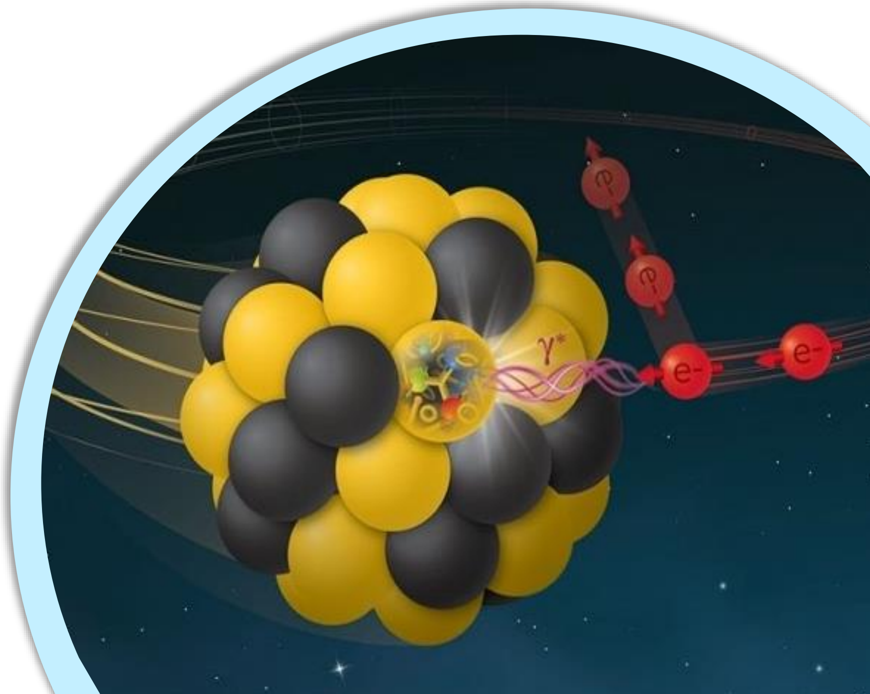
Sep. 18 – 22nd, 2023

BERKELEY LAB

Center for Frontiers in Nuclear Science

Outline

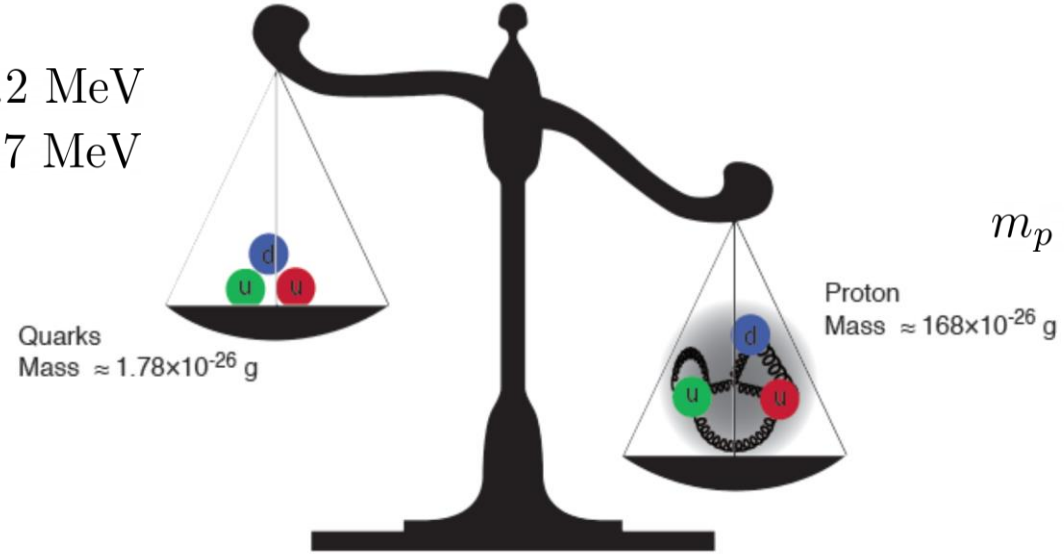
- » Intro - why 3D structure?
- » Nucleon 3D structure from experiments
- » Lattice inputs of GPDs
- » 3D global analysis program
- » Summary and outlook



Why 3D structure? – nucleon mass

Nucleon mass is largely from strong interaction:

$$m_u \approx 2.2 \text{ MeV}$$
$$m_d \approx 4.7 \text{ MeV}$$
$$m_g = 0$$



$$m_p \approx 938 \text{ MeV}$$

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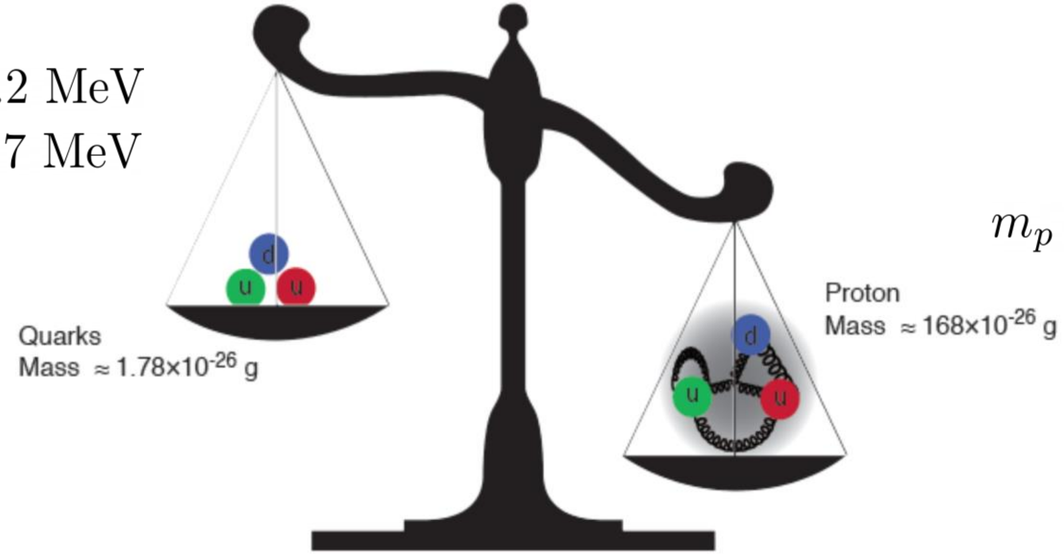

$m_p \approx 938$ MeV

which can be studied with QCD Hamiltonian,

X. Ji Phys. Rev. Lett. 74 1071 (1995)

$$H_{\text{QCD}} = \int \mathrm{d}^3\boldsymbol{x}\, T^{00}_{\text{QCD}}(0,\boldsymbol{x}) = \underbrace{H_q}_{\text{Quark energy}} + \underbrace{H_m}_{\text{Quark mass}} + \underbrace{H_g}_{\text{Gluon energy}} + \underbrace{H_a}_{\text{Quantum anomalous energy}}$$

Energy-momentum tensor form factors

Matrix element of EMT can be expressed as gravitational form factors:

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

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Quantum anomalous energy and mass form factors:

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Gravitational form factors are fundamental for nucleon structures!

Why 3D structure? – nucleon spin

Naïve quark model

quark spin

$$\frac{\hbar}{2} \overset{?}{=}$$

Why 3D structure? – nucleon spin

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Proton spin crisis

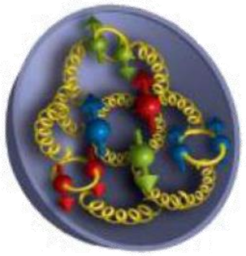
Why 3D structure? – nucleon spin

Naïve quark model gluon contribution

quark spin gluon spin

$$\frac{\hbar}{2} \overset{?}{=}$$

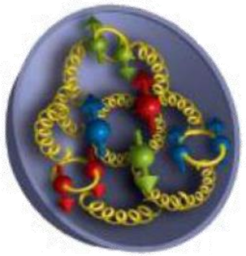
$+$



Proton spin crisis

Why 3D structure? – nucleon spin

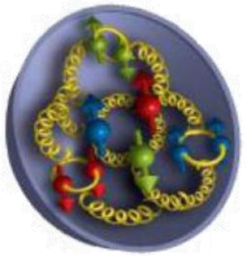
Naïve quark model | gluon contribution | transverse motion

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

Why 3D structure? – nucleon spin

Naïve quark model　　gluon contribution　　transverse motion

quark spin　　gluon spin　　quark orbital AM　　gluon orbital AM

$\frac{\hbar}{2} \stackrel{?}{=}$  $+$  $+$  $+$ 

Jaffe-Manohar sum rule

R. Jaffe and A. Manohar
Nucl. Phys. B 337, 509 (1990)

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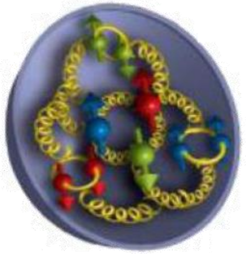

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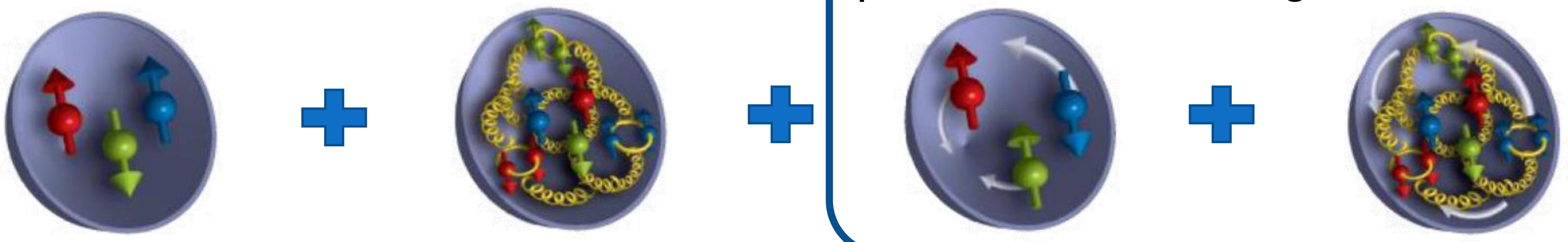

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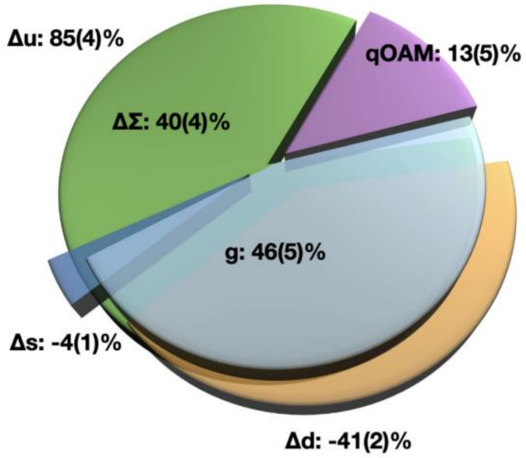
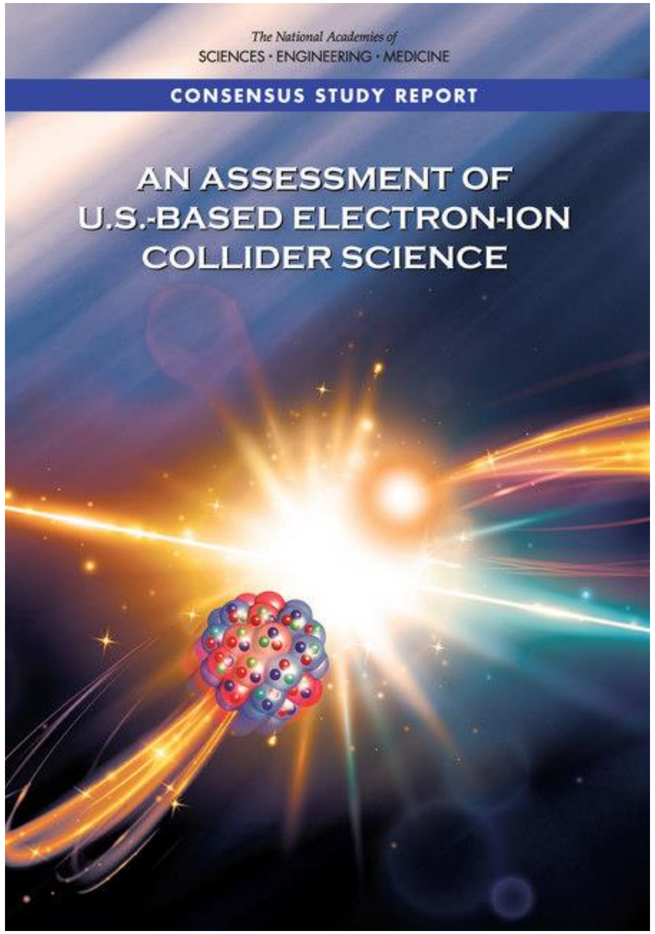


Proton spin decomposition from lattice
by χQCD collaboration

G. Wang et. al. Phys. Rev. D 106, 014512 (2022)
See also ETMC Collaboration Phys. Rev. D 101 9, 094513 (2020)

Nucleon 3D structure with EIC



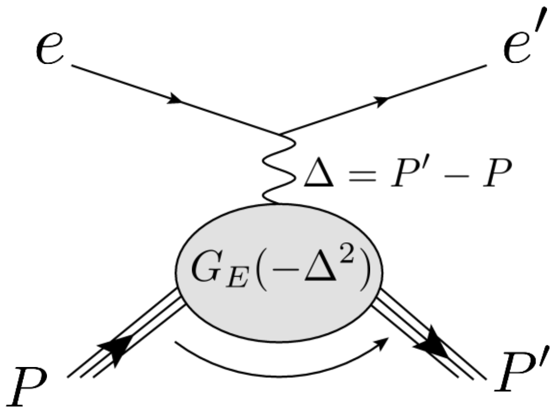
Finding 1:

An EIC can uniquely address three profound questions about nucleons — neutrons and protons — and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

3D distributions of quarks and gluons

Diffractive process is a classic approach to accessing the 3D structures.



elastic scattering

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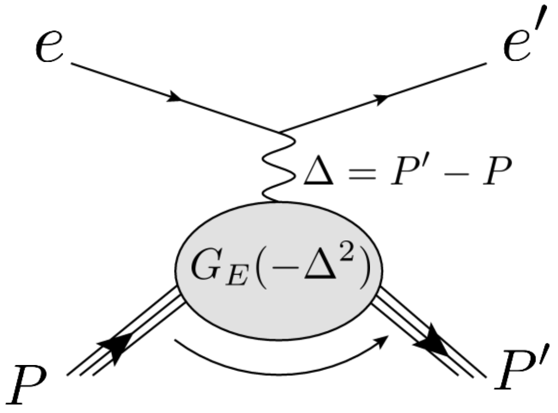

elastic scattering

$$\rho_{\mathrm{NR}}(\boldsymbol{r}) = \int \frac{\mathrm{d}^3\boldsymbol{\Delta}}{(2\pi)^3} e^{-i\boldsymbol{\Delta}\cdot\boldsymbol{r}} G_E(-\boldsymbol{\Delta}^2)$$

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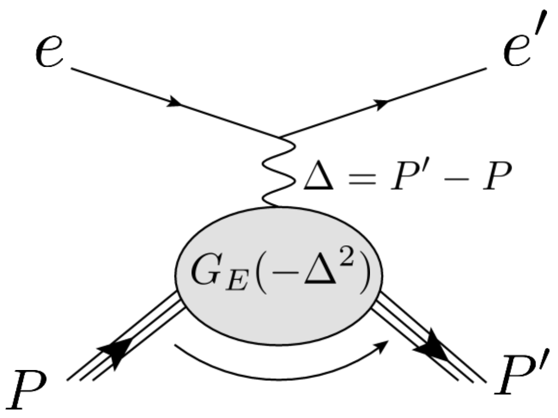

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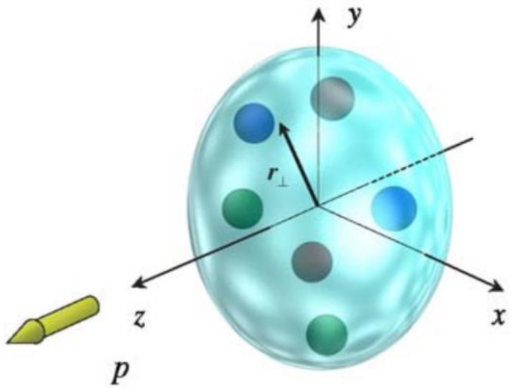

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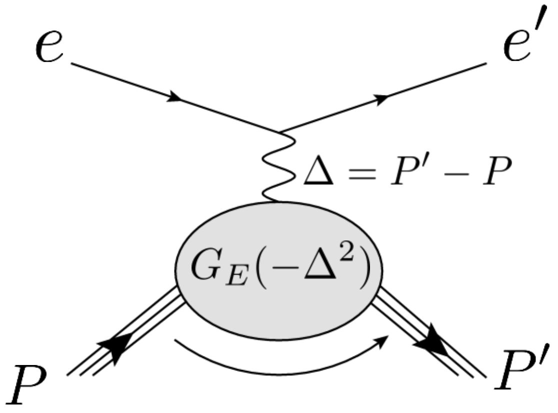

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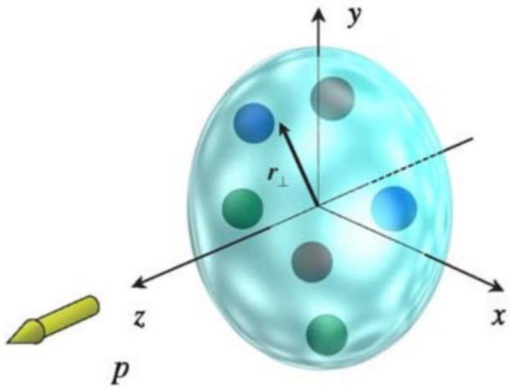

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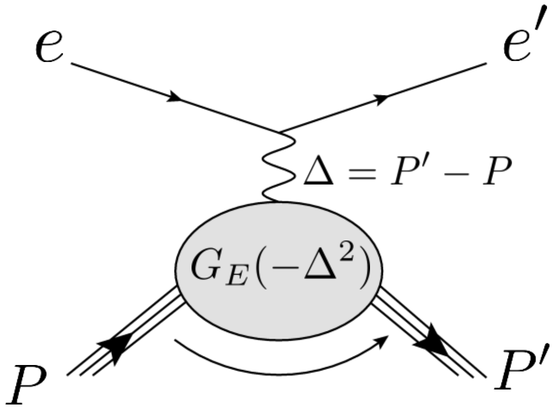

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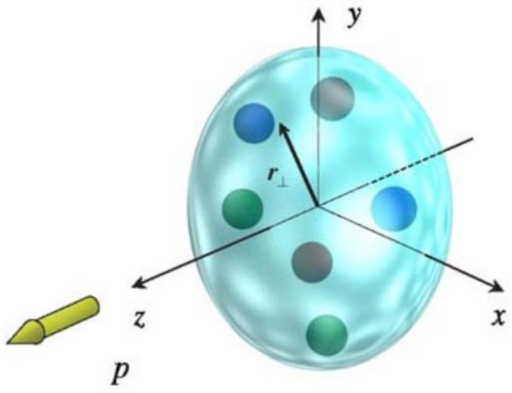

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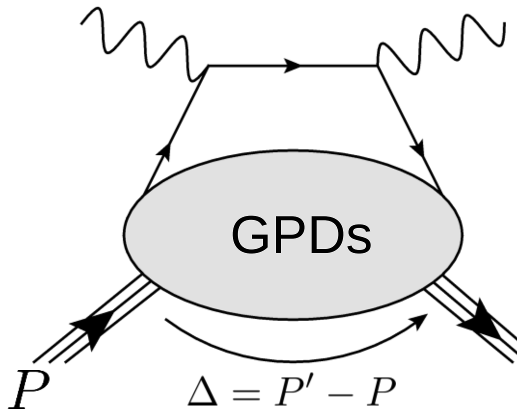

generalized parton distribution

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

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

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3D mass & spin structures with GPDs

GPDs are 3D distributions unifying parton distributions and form factors

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

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Charge FFs

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We cannot easily access GFFs in experiment, but we can access GPDs!

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M. Burkardt, Int. J. Mod. Phys. A 18 173-208 (2003)

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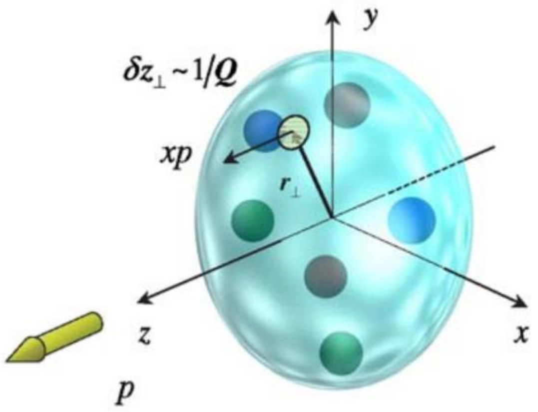

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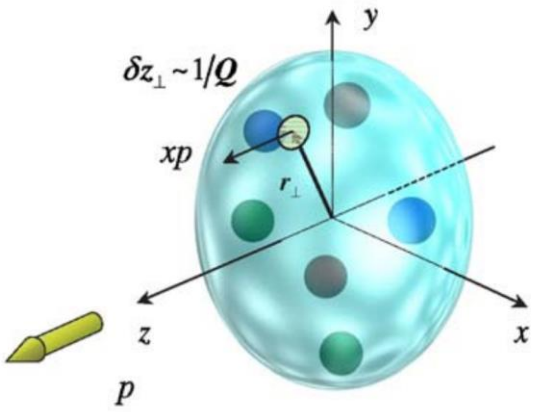

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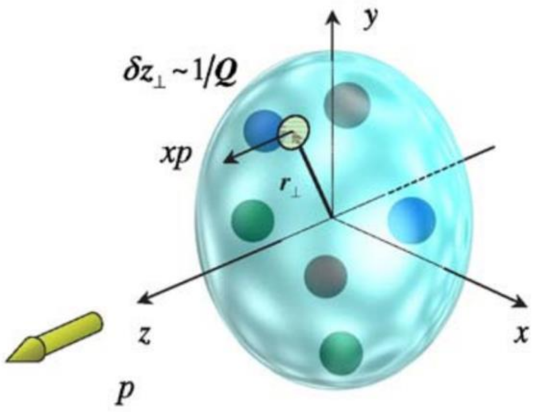

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$$J_q^T(x) = \int \mathrm{d}^2\boldsymbol{b}(b^y \times xP^+)\rho_q^T(x, \boldsymbol{b})$$

Y. Guo et. al. Nucl. Phys. B 969 115440 (2021)

3D Structures from Experiment

Deeply virtual processes

Recall that diffractive processes can provide us access to the 3D structures.

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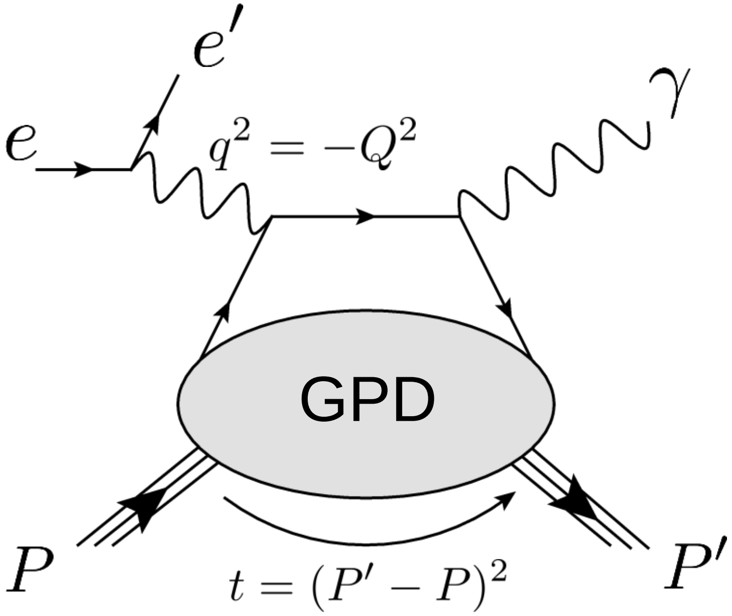

Deeply virtual Compton scattering

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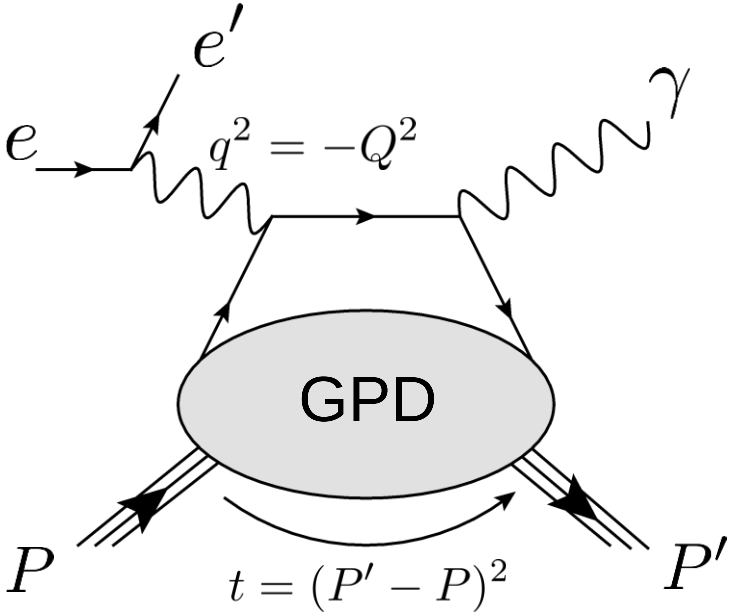

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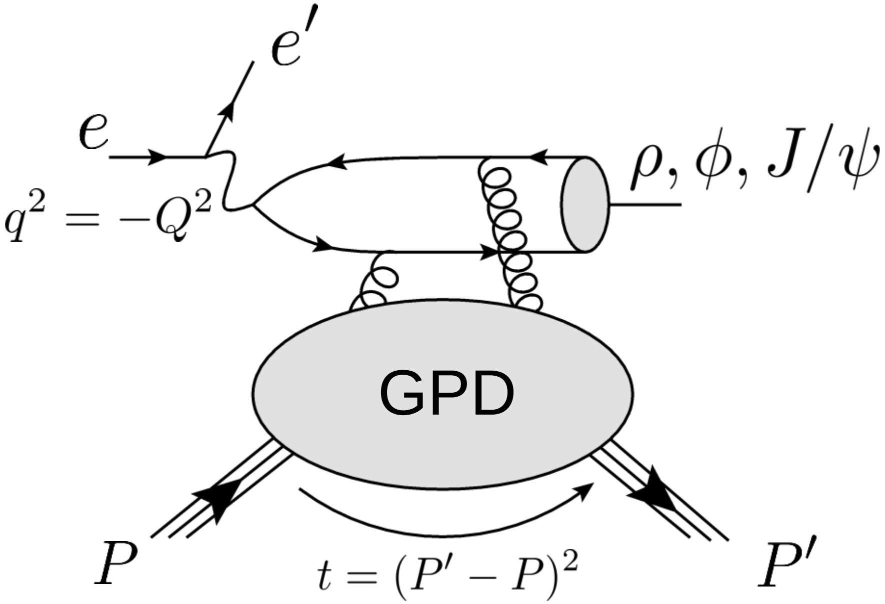

Deeply virtual meson production

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

Deep exclusive measurements

HERA
(***H**adron-**E**lektron-**R**ing**a**nlage*)

H1, ZEUS (Col), HERMES (FT)

- Col. w. electron/positron beam
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CERN
(European Organization for Nuclear Research)

COMPASS

- FT w. Muon/antimuon beam
- DVCS measurements (2016)
- Running ended in 2022

Deep exclusive measurements

HERA
(***H**adron-**E**lektron-**R**ing**a**nlage*)

H1, ZEUS (Col), HERMES (FT)

- Col. w. electron/positron beam
- DVCS and DVMP measurements
- Running ended in 2007

CERN
(European Organization for Nuclear Research)

COMPASS

- FT w. Muon/antimuon beam
- DVCS measurements (2016)
- Running ended in 2022

CEBAF
(Continuous Electron Beam Accelerator Facility)

Hall A, B, C and D

- FT with electron/photon beam
- Large exclusive measurements
- Still are and will be running

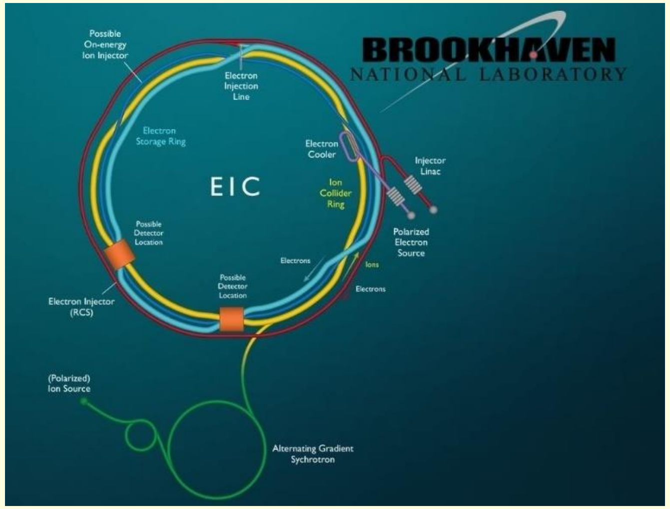
Deep exclusive measurements

HI
(*Hadron-Elekt*

H1, ZEUS (Co

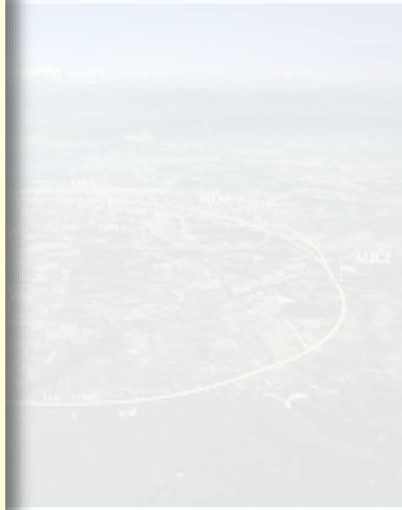
- Col. w. electr
- DVCS and DV
- Running ende

EIC
(Electron-Ion Collider)



- High Lum. (100~1000 times HERA)
- Polarization configurations
- Plan to operate in the next decade

ERN
Organization for
Research)



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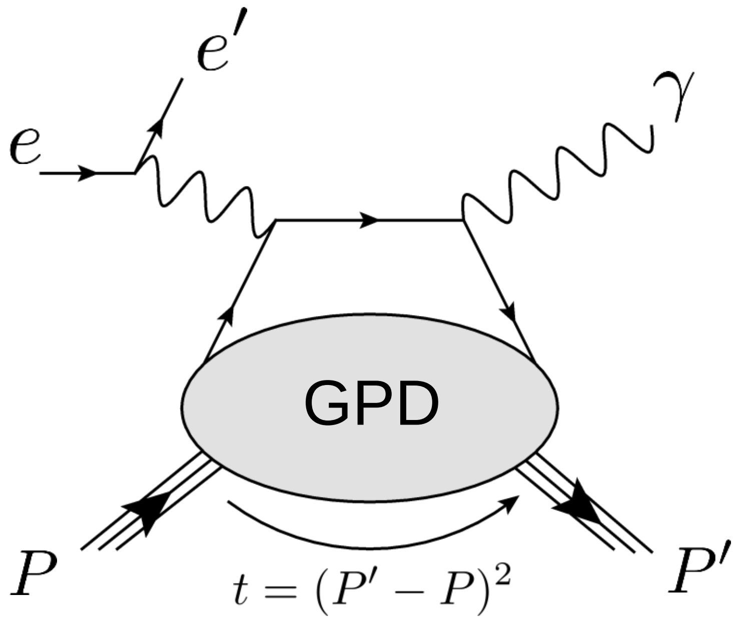
Quarks structures from DVCS

DVCS is considered the golden channel to probe GPDs.



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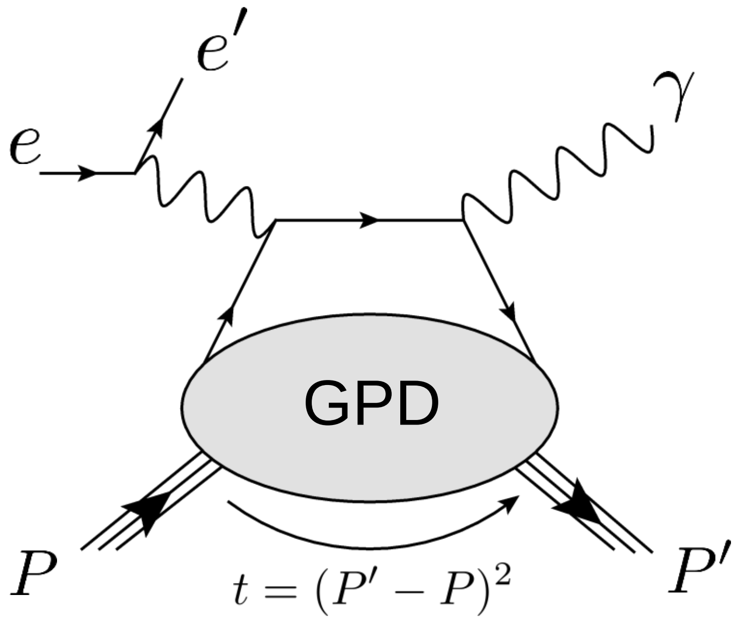
Sensitive to quark GPDs



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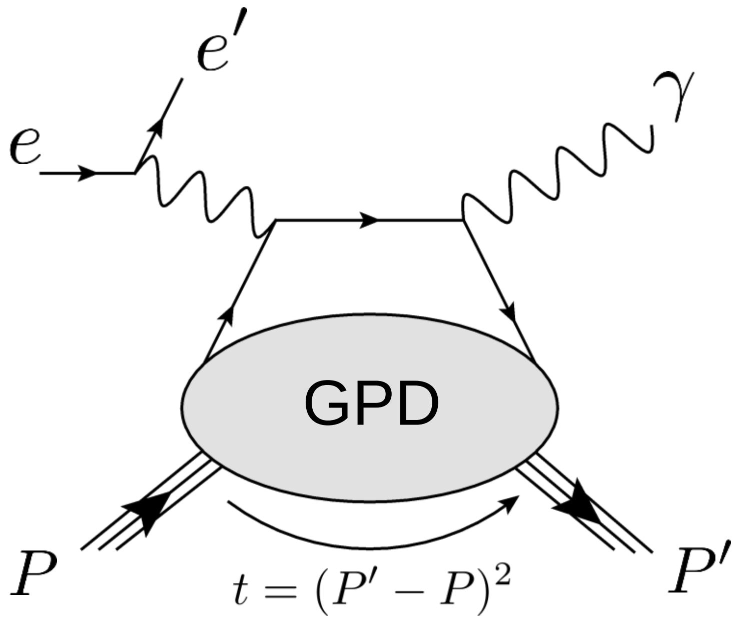

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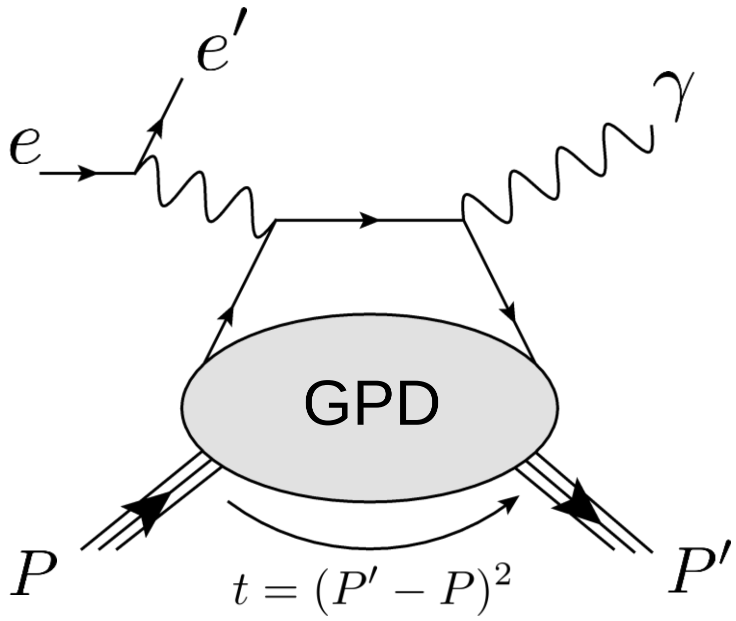
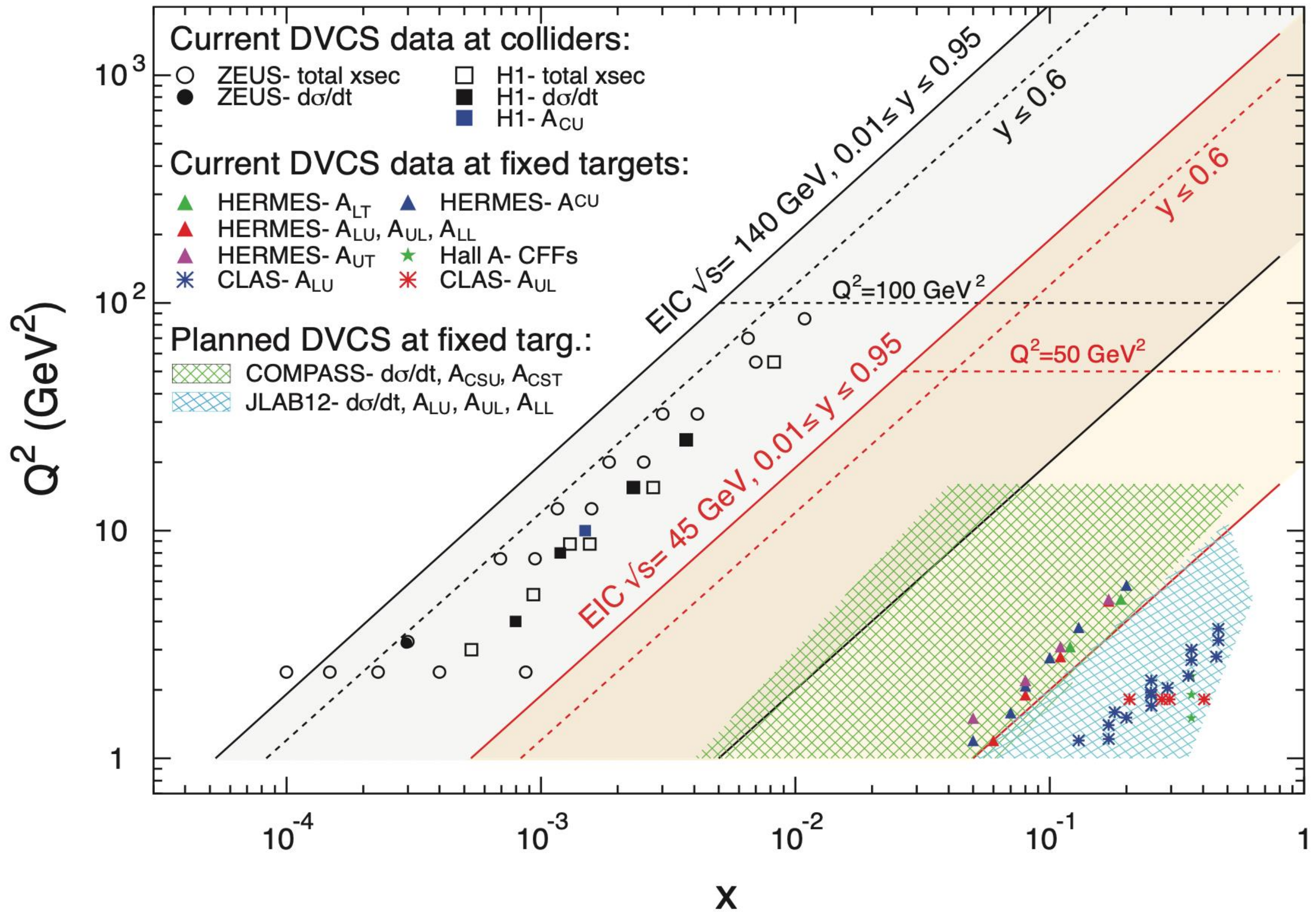


Shohini's talk

DVCS measurements



EIC white paper arXiv:1212.1701

Plots in 2012 -> some recent update:

JLab has upgraded to 12 GeV (2014)

Also considering upgrading to 20+ GeV

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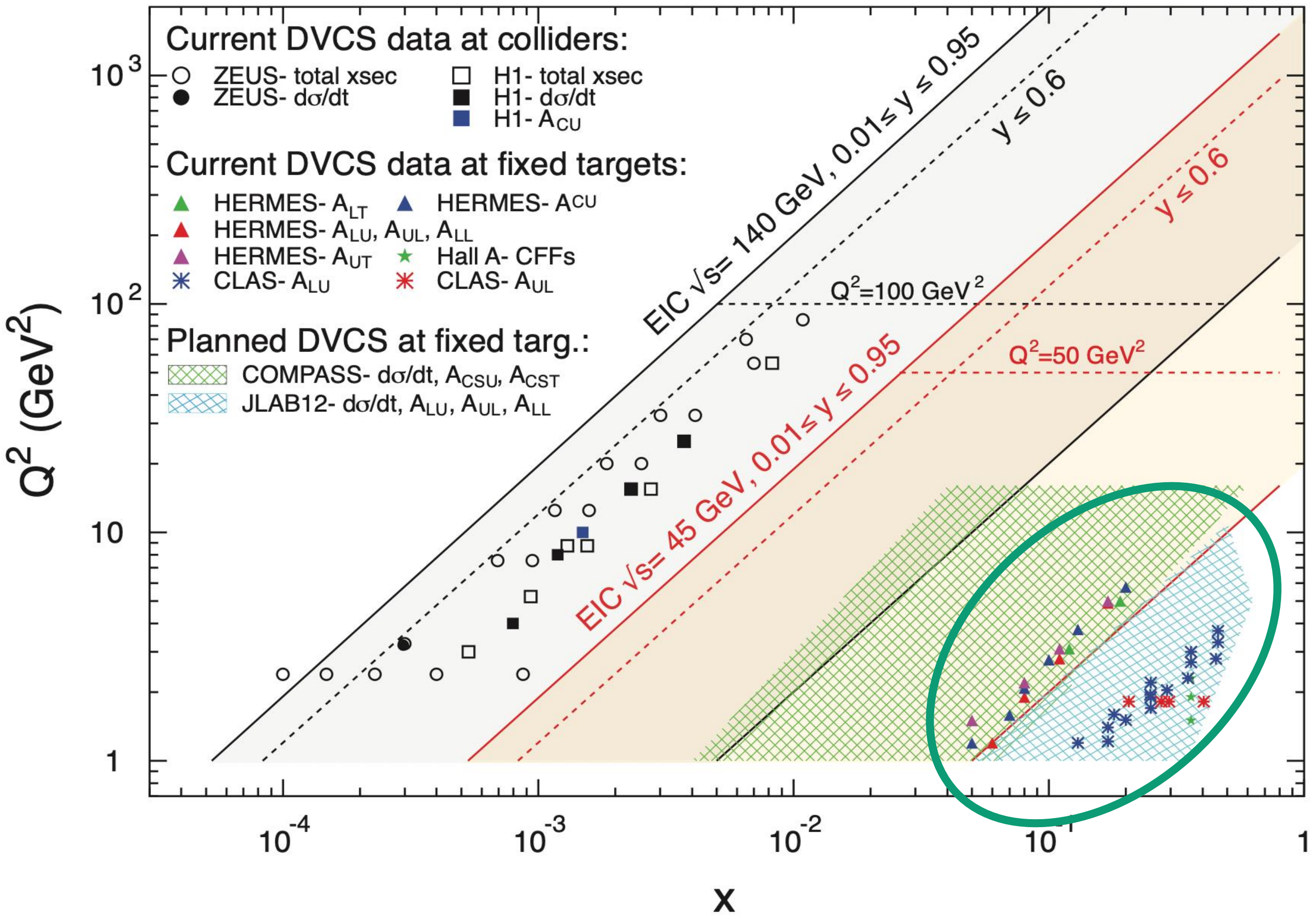

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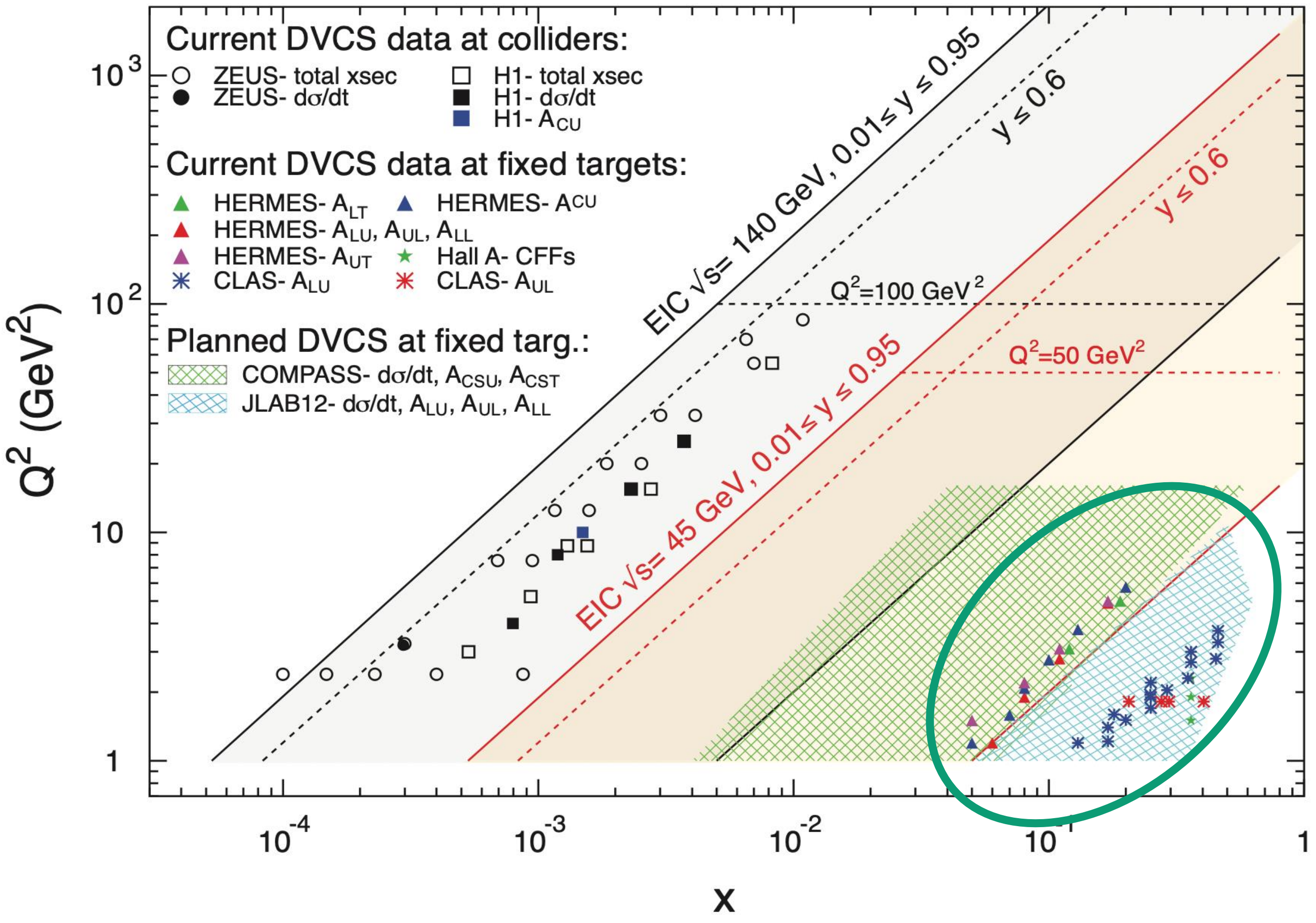

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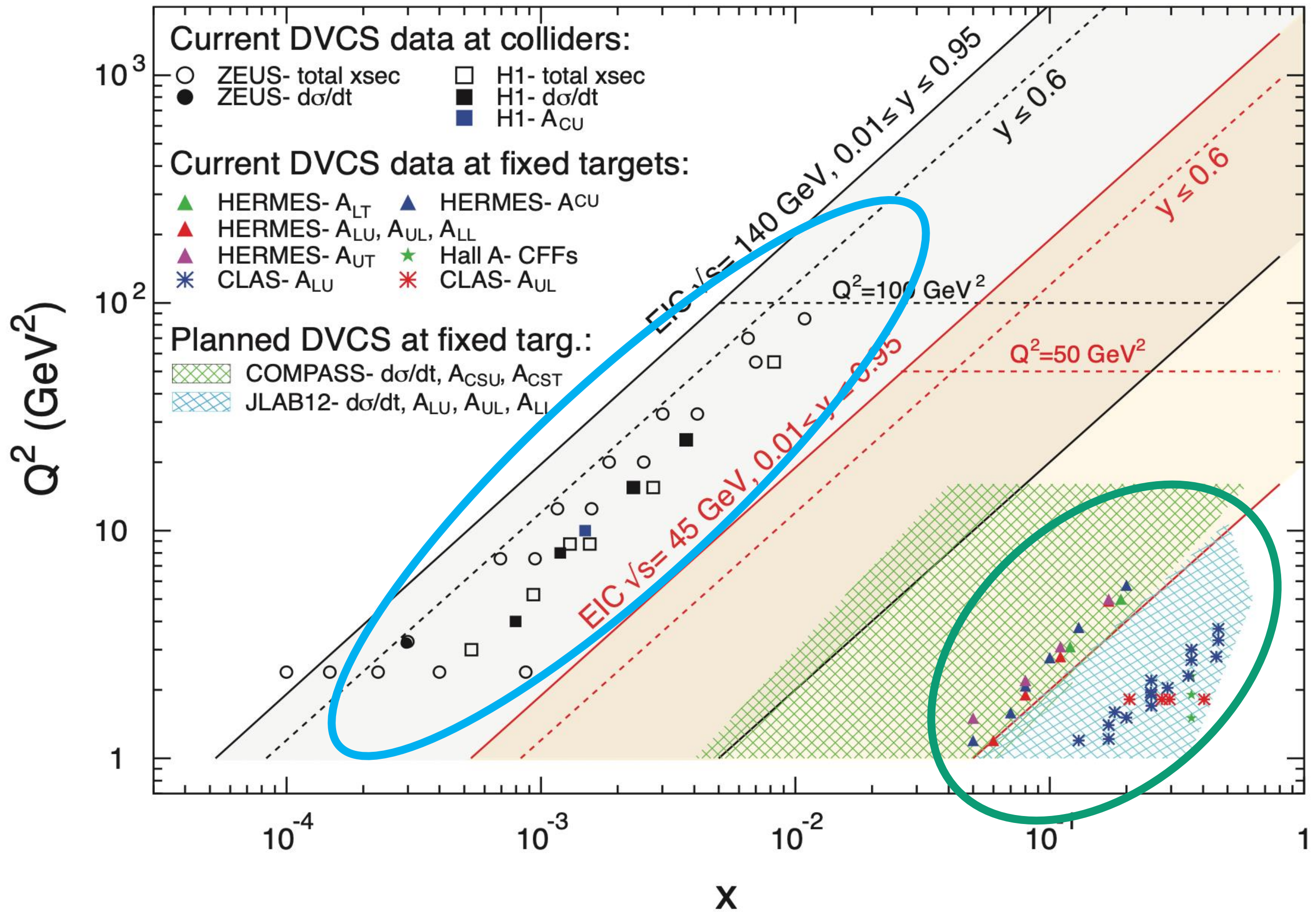

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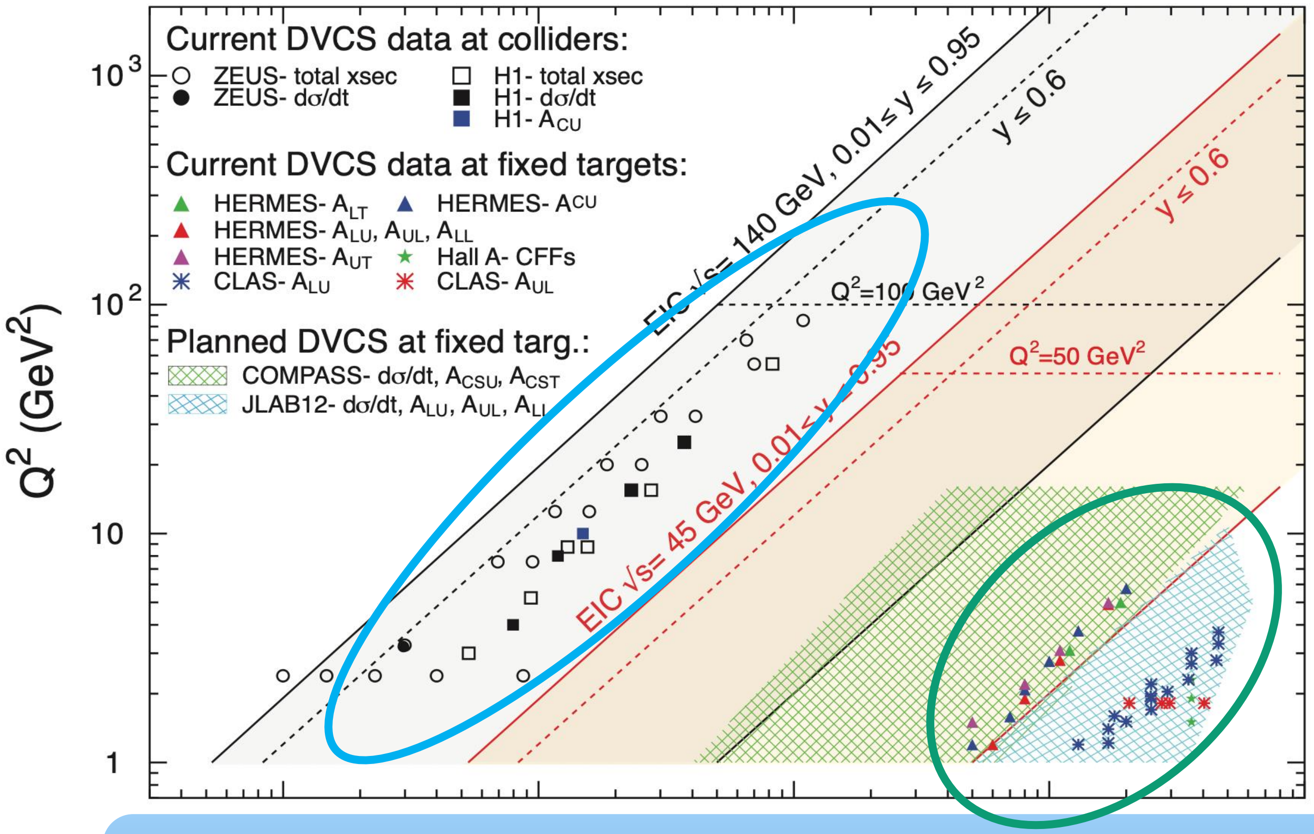

EIC is essential for exploring the sea quarks and gluons!

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Compton form factors and deconvolution

DVCS probes the GPDs via the Compton form factors

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

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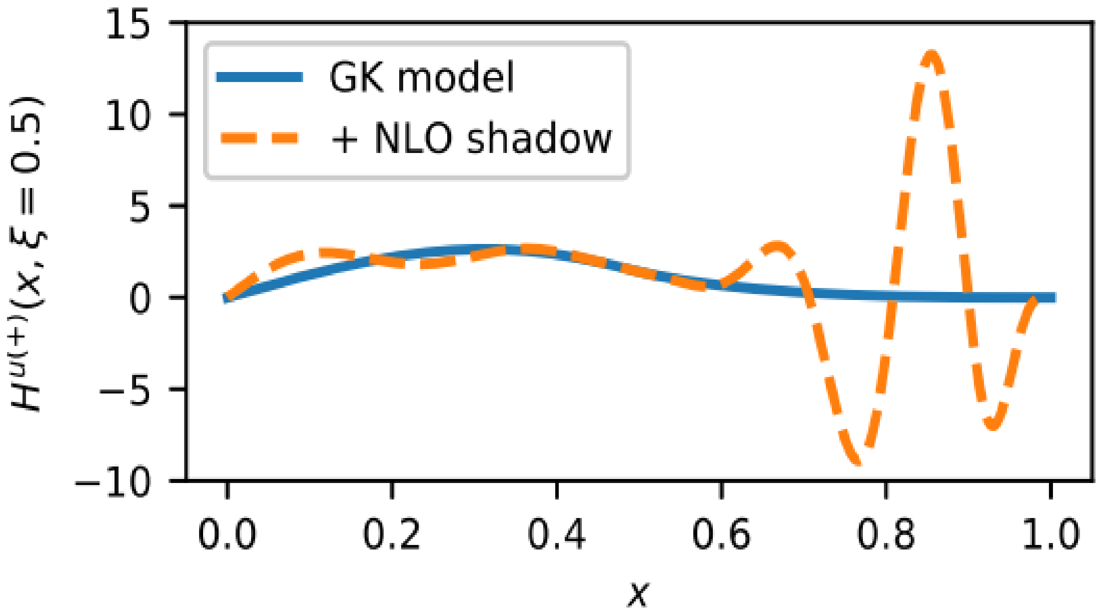

V. Bertone et. al. SciPost Phys.Proc. 8 (2022) 107

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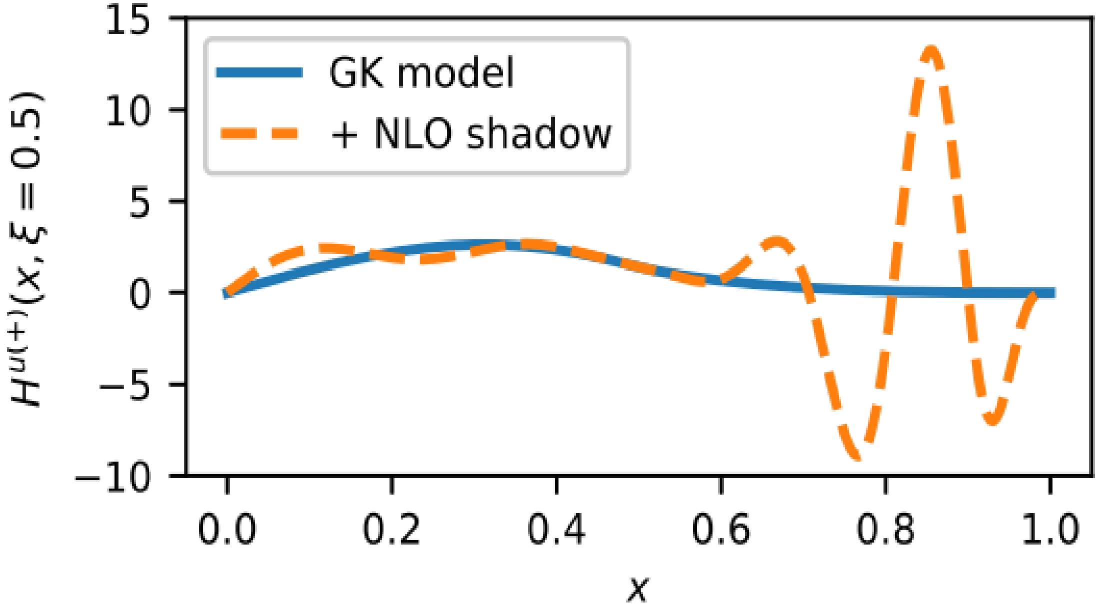

Dr. Qiu's talk

V. Bertone et. al. SciPost Phys.Proc. 8 (2022) 107

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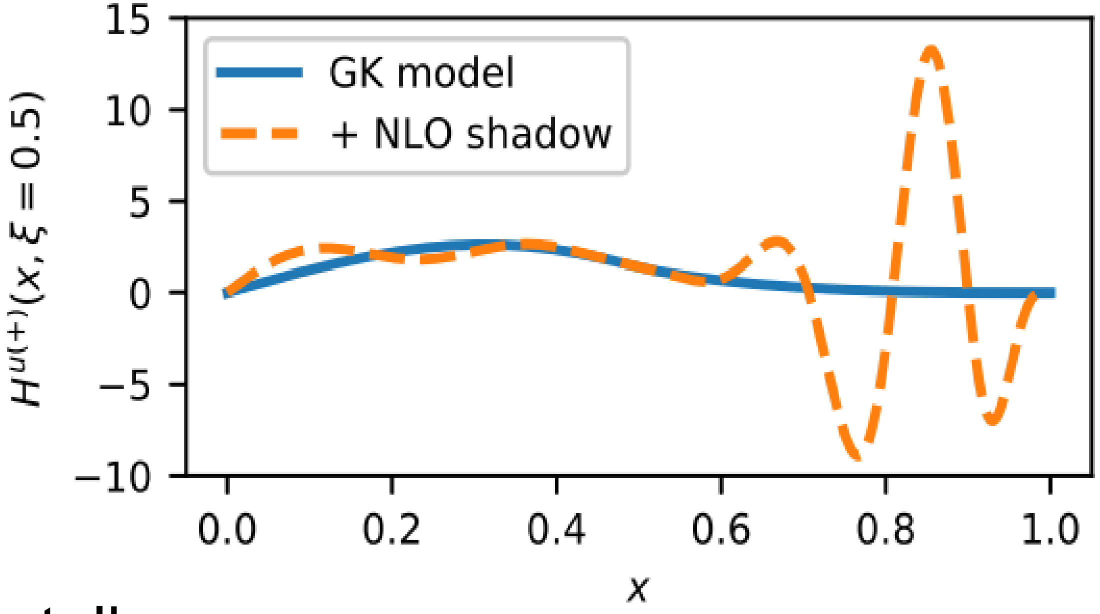
Global analysis needed



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Gluon 3D structures from experiment

Gluon can only be directly probed by strongly interacting particles – meson ...

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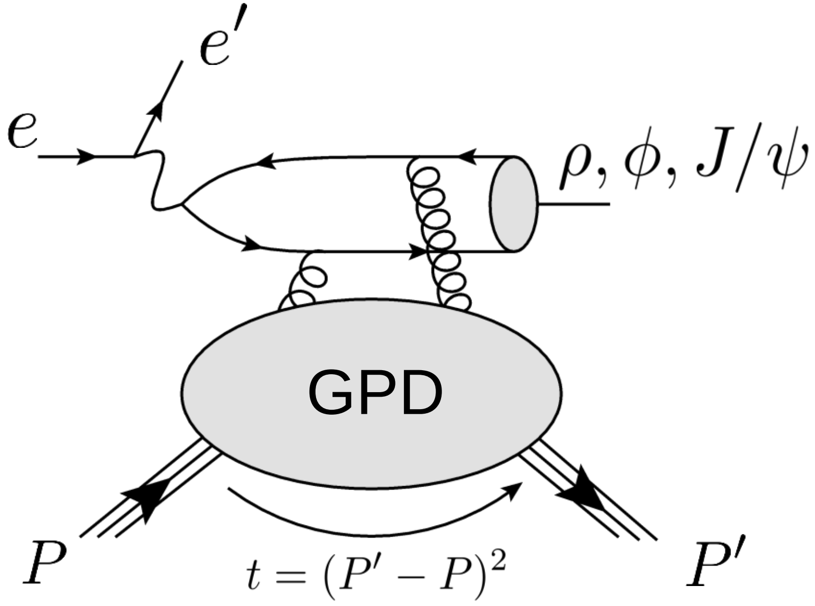

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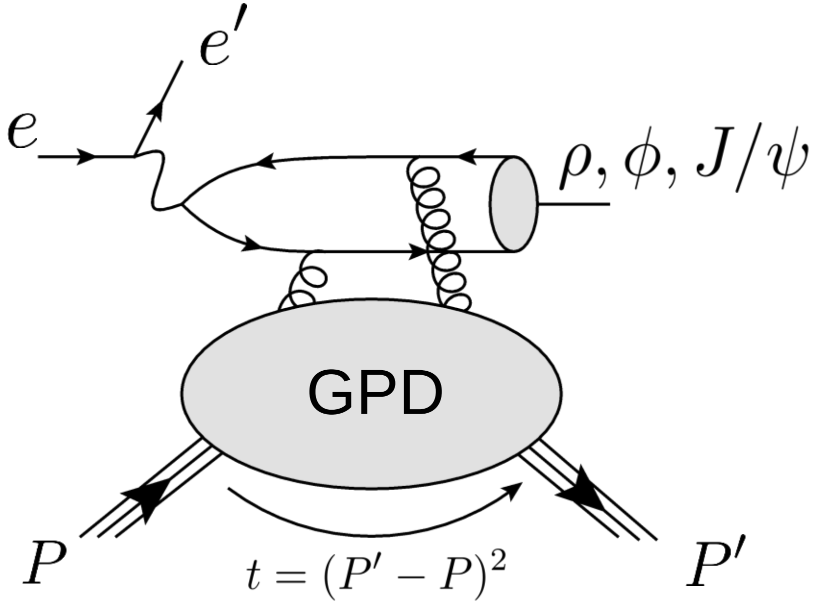

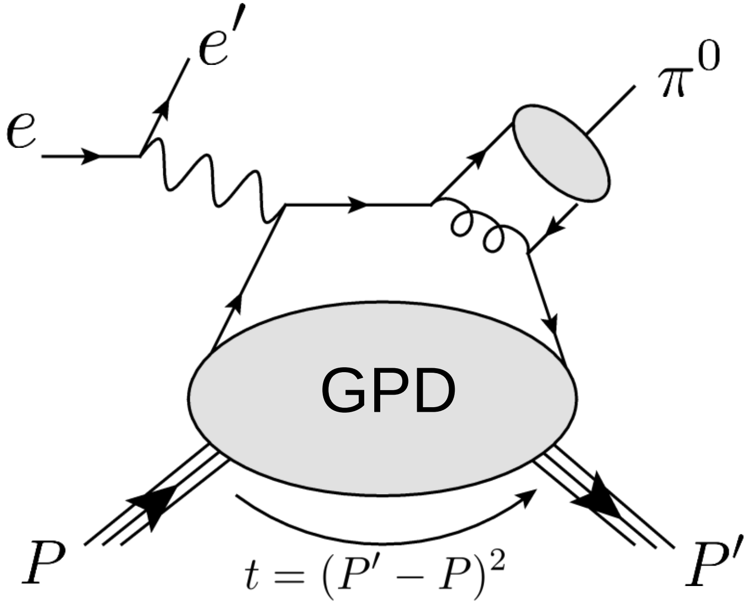

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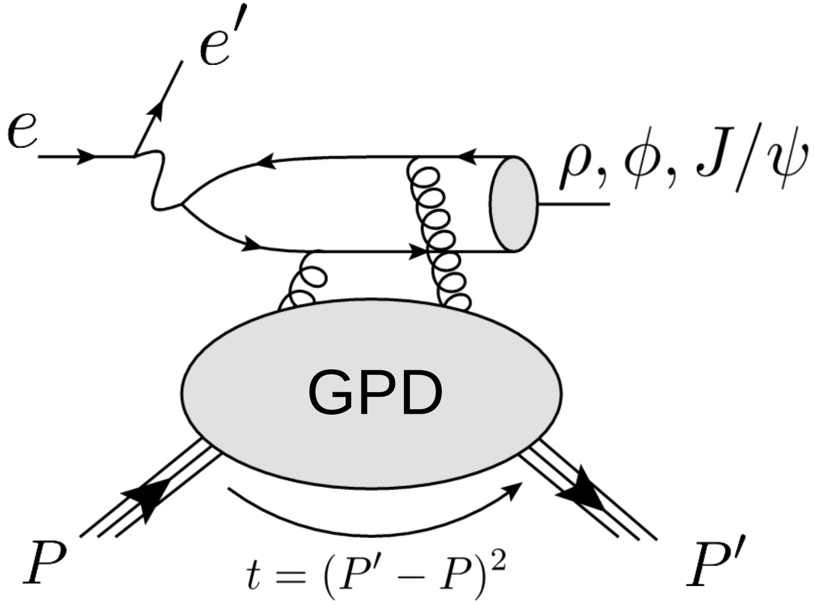

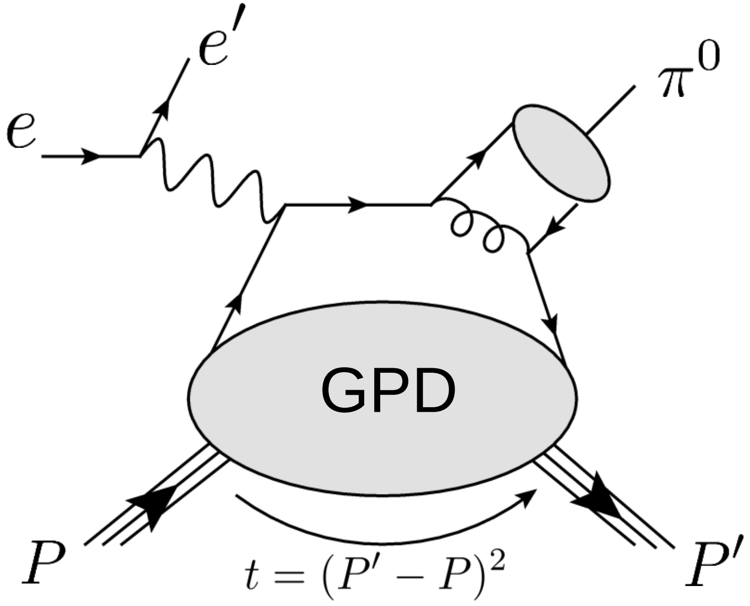

Heavy meson preferred to suppress the intrinsic quark contributions.

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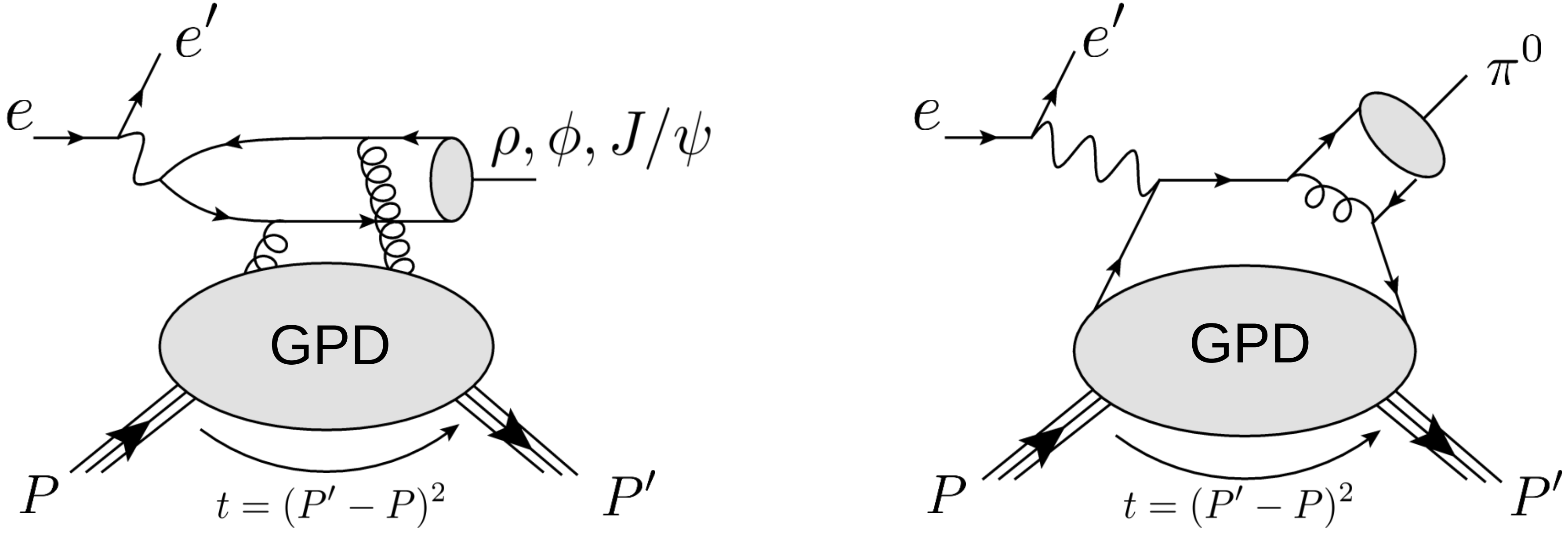
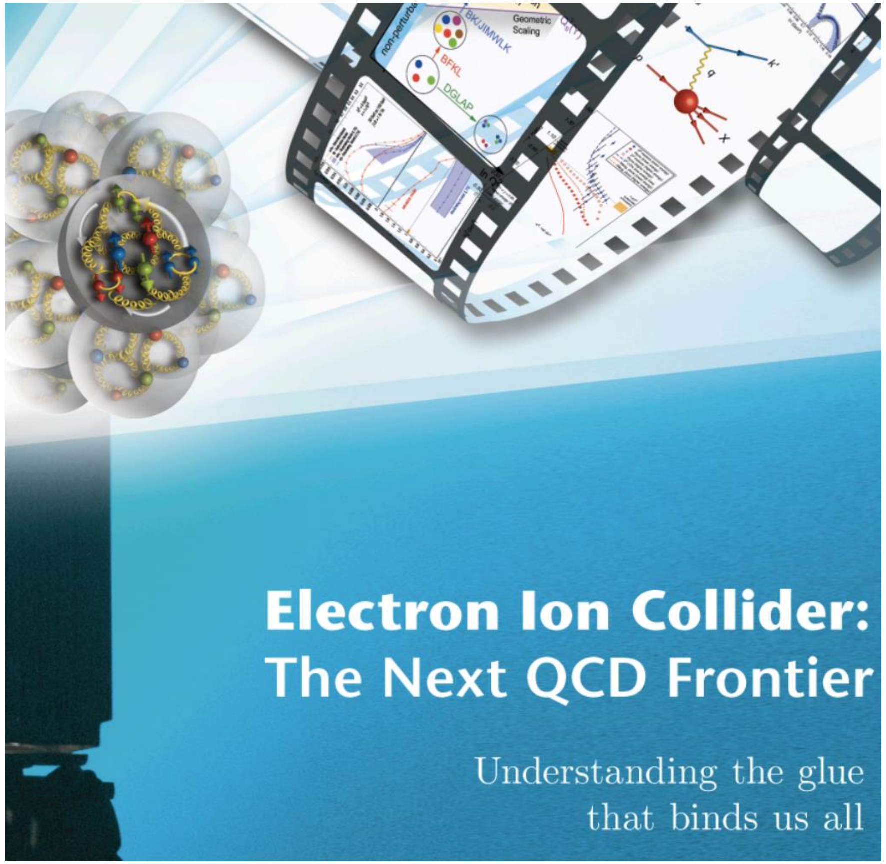


Heavy meson preferred to suppress the intrinsic quark contributions.

Higher energy required. (Hard to reach with fixed target)

Gluon 3D structures from experiment

Main task of EIC – exploring the gluons (with meson production, jet production …)



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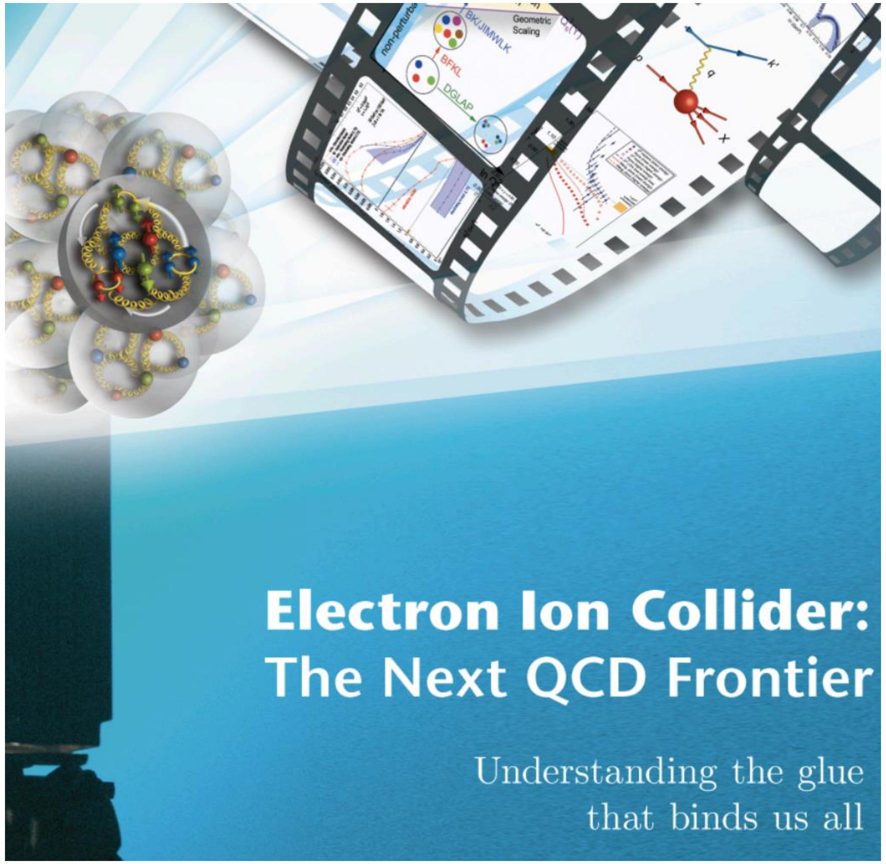

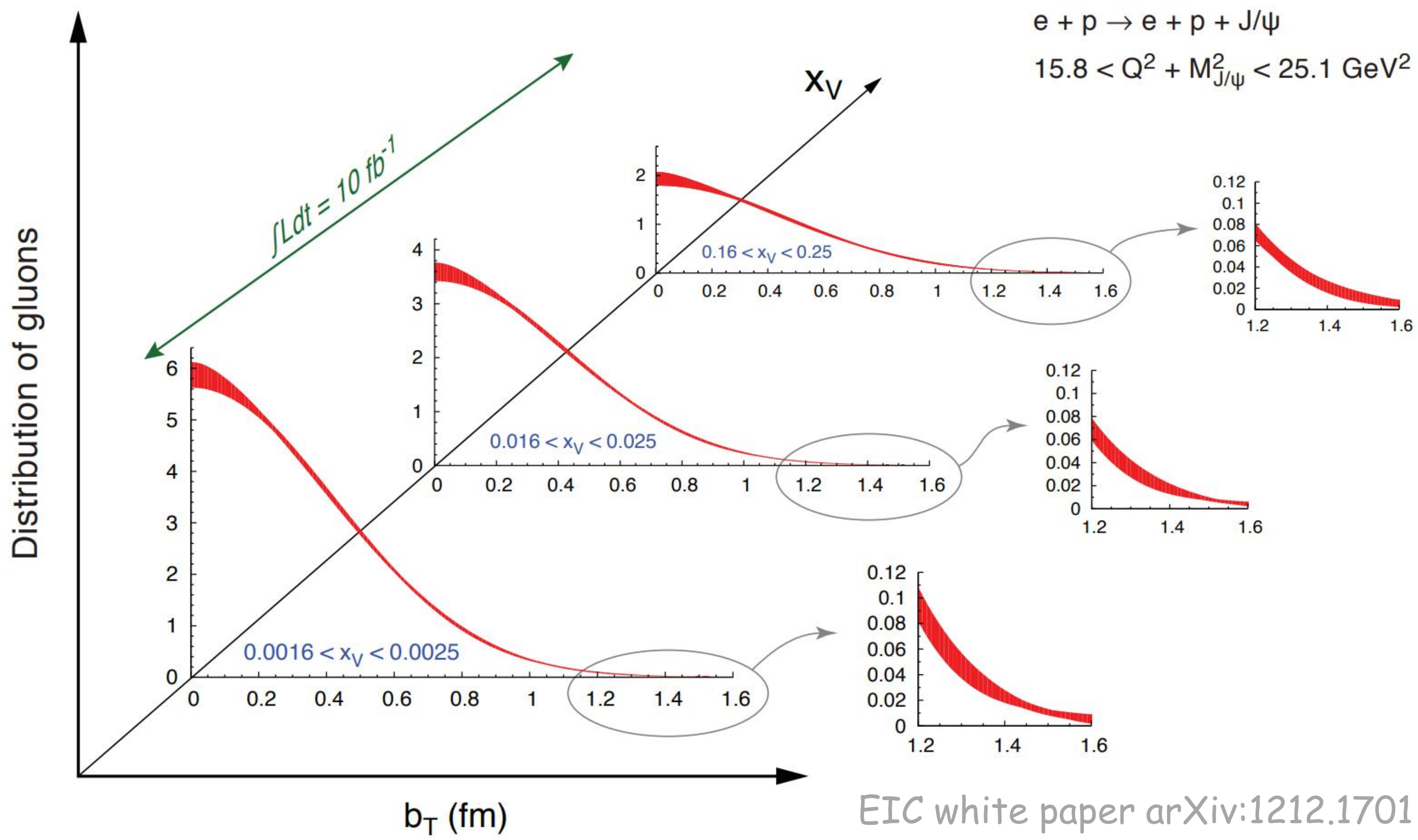

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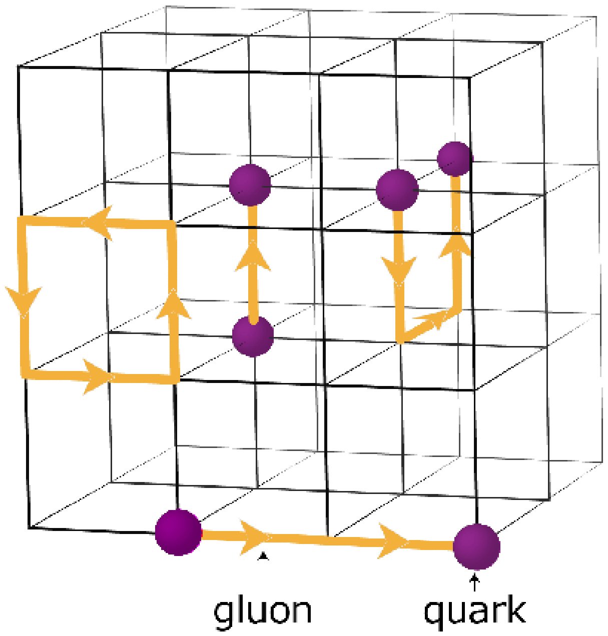
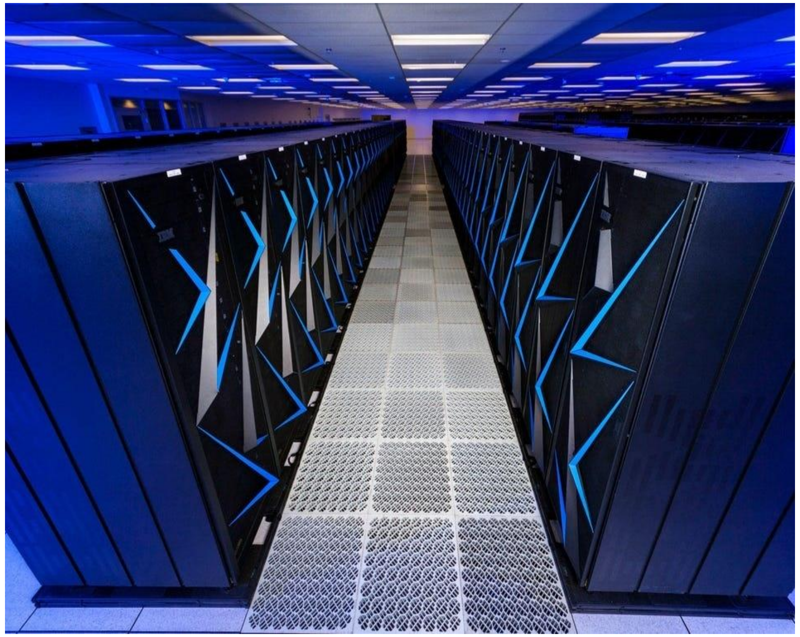
3D Structures with Lattice QCD

Lattice QCD

Simulation of discretized, finite-volume system with super computers.





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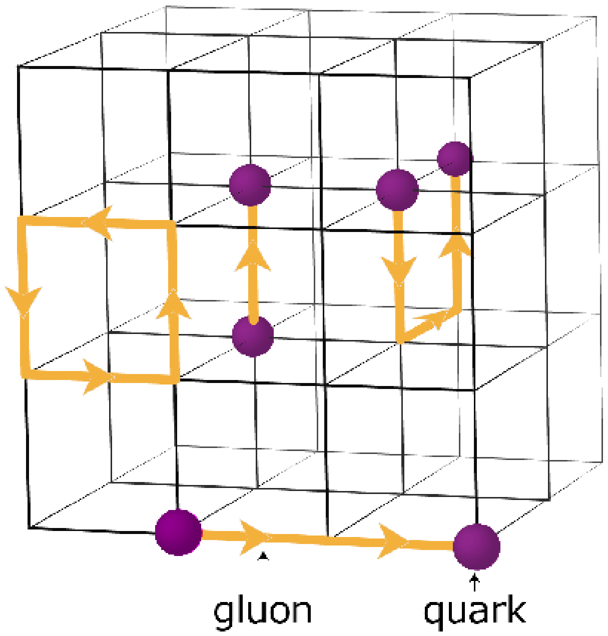

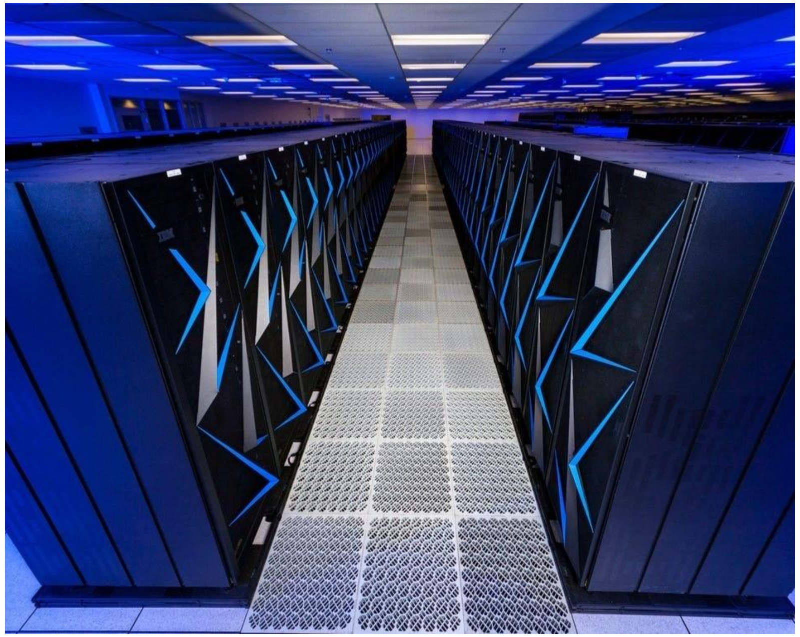

From first-principle and systematically improvable.

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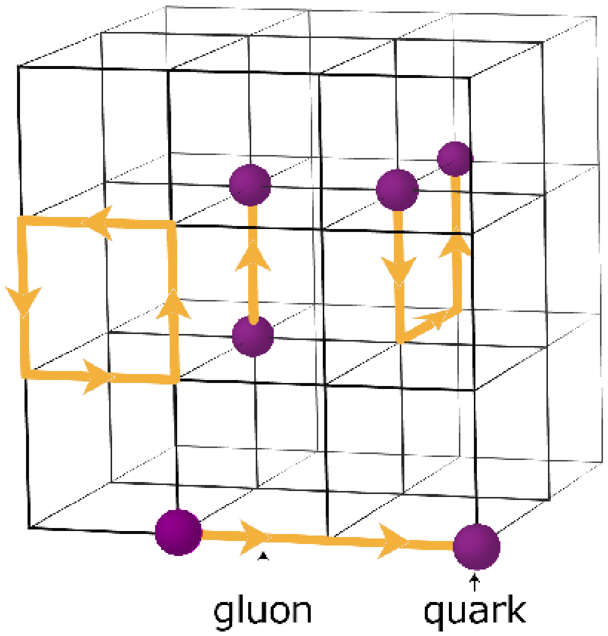
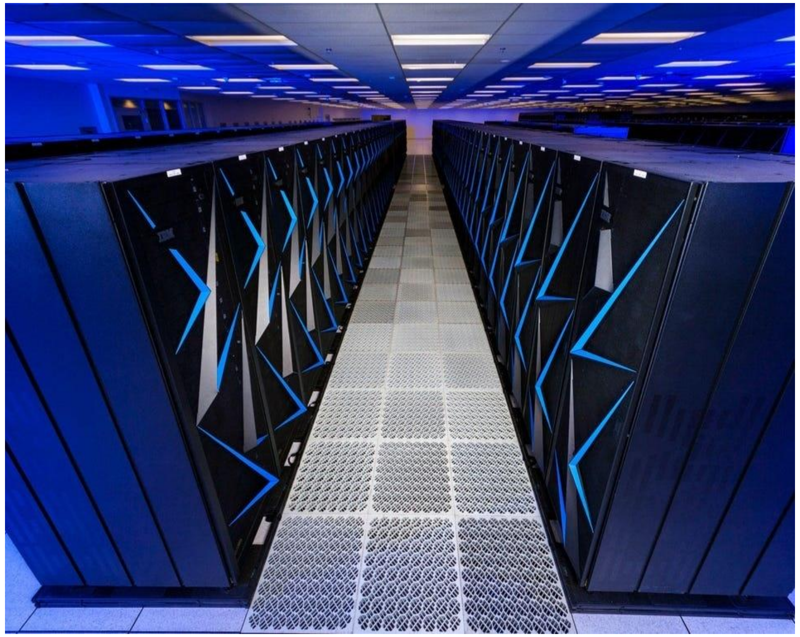




From first-principle and systematically improvable.

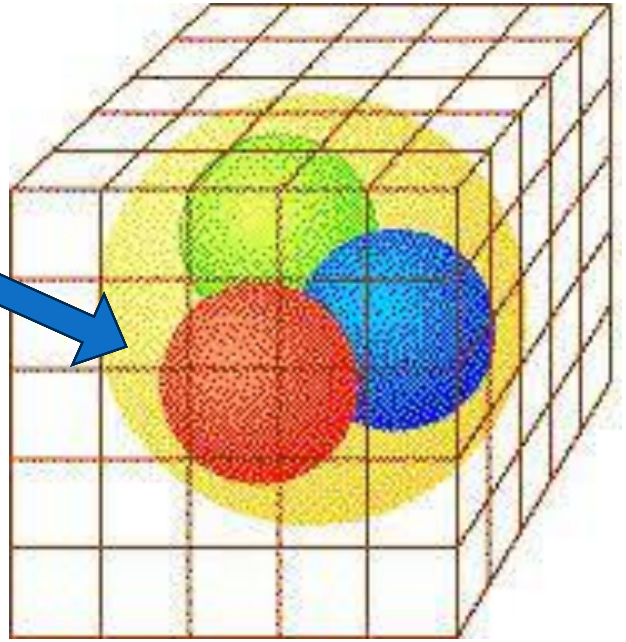
Nucleon form factors on lattice

Lattice QCD is most efficient in capturing the feature of the whole nucleon.

$$\hat{O}_q^{\mu}=\sum_q e_q\bar{\psi}_q\gamma^{\mu}\bar{\psi}_q$$

$$\hat{O}_q^{\mu\nu}=\sum_q \bar{\psi}_q\gamma^{(\mu}i\overleftrightarrow{D}^{\nu)}\bar{\psi}_q$$

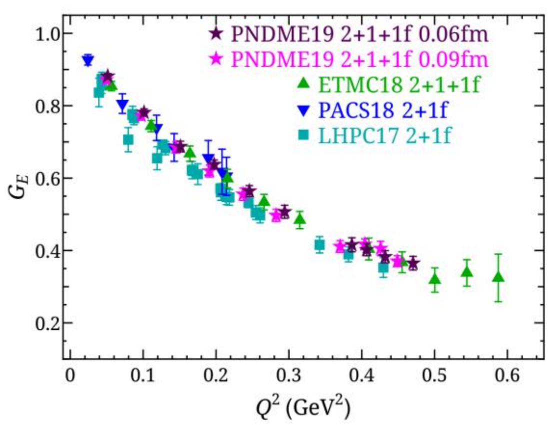
•••

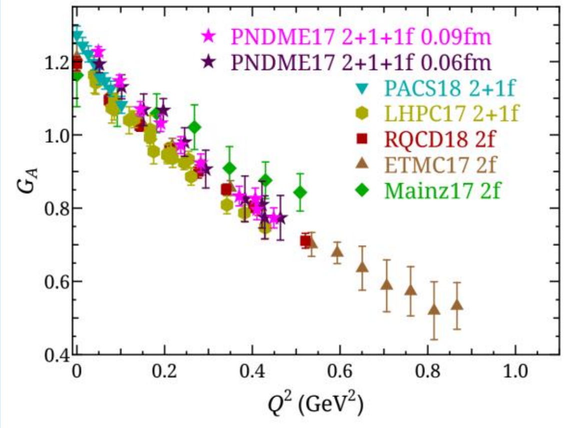


Relatively easy so long as you can prepare a static nucleon on the lattice

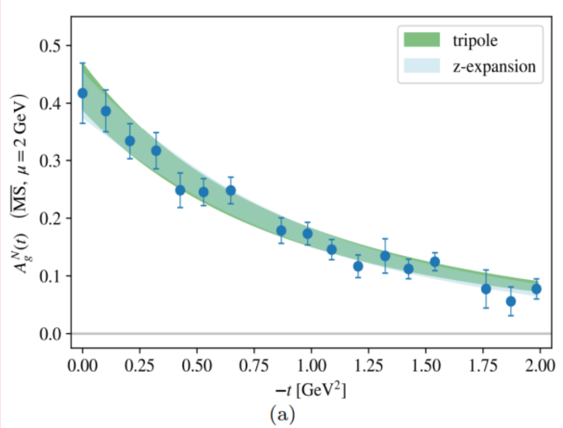
Nucleon form factors on lattice

Isovector (axial) charge form factors with lattice QCD





Gluon gravitational form factors



D. A. Pefkou et. al .
Phys. Rev. D 105, 054509 (2022)

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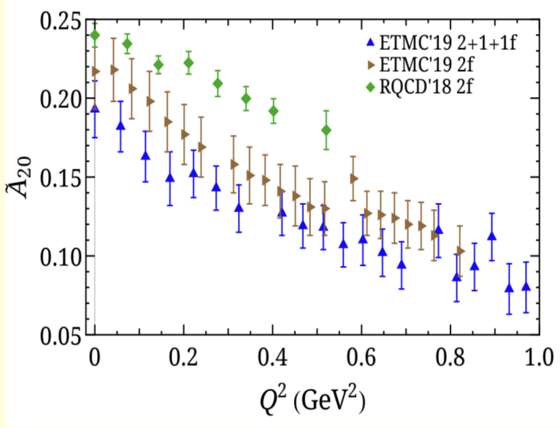

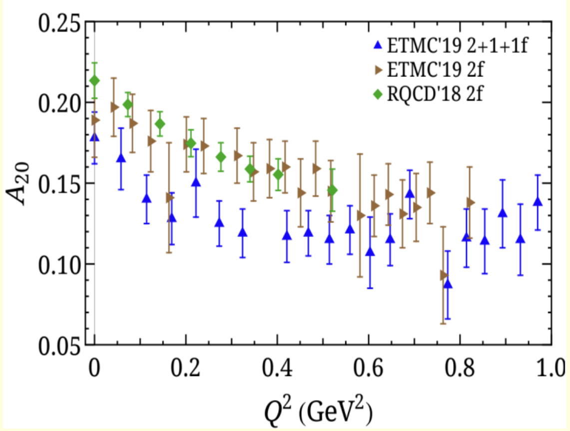

Reviewed in M. Constantinou et. al. Prog. Part. Nucl. Phys. 121 103908 (2021)
Collected results from lattice community including ETMC, LHPC, Mainz, PACS, PNDME ,RQCD

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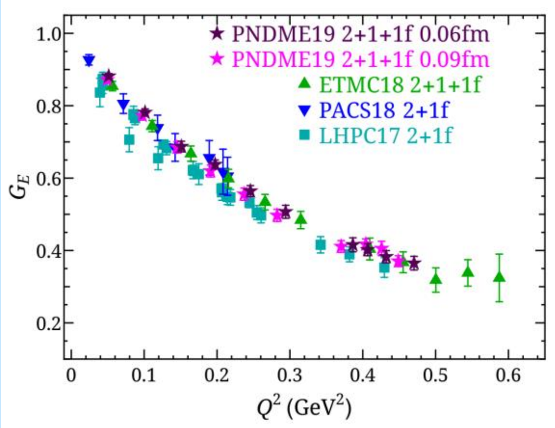

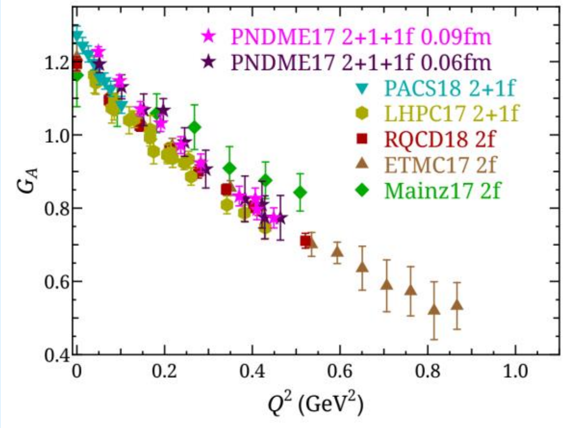

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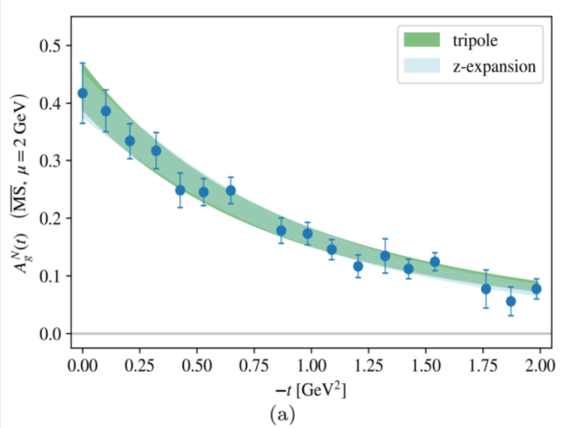

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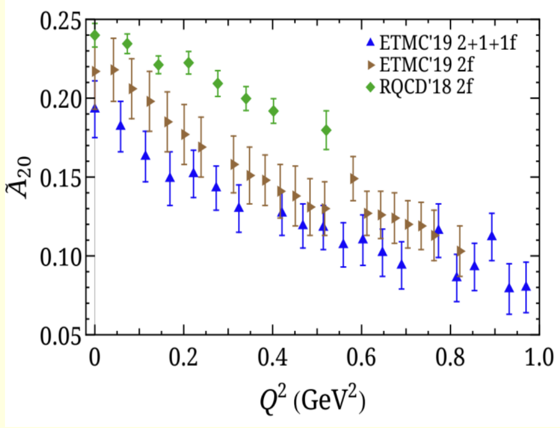

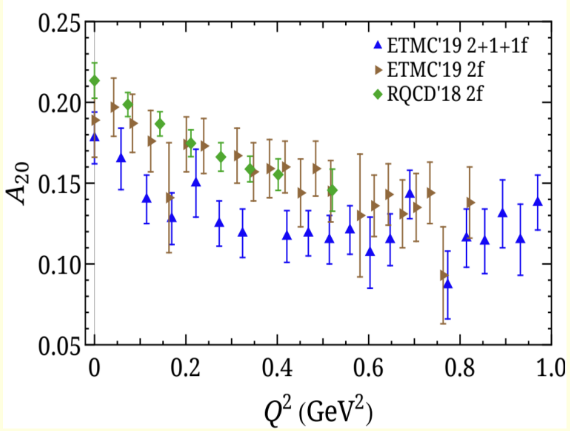

Many are almost impossible

to get from experiments!

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Measuring the real-time dynamics, on the other hand, is much harder on lattice.

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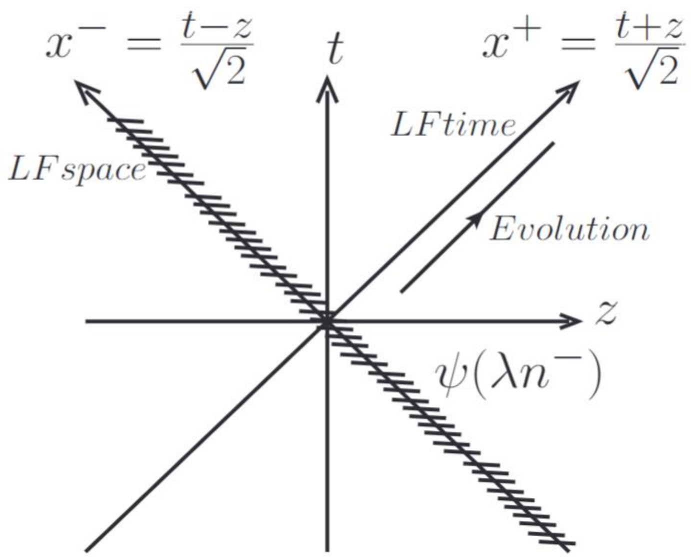

Partons live on light front.

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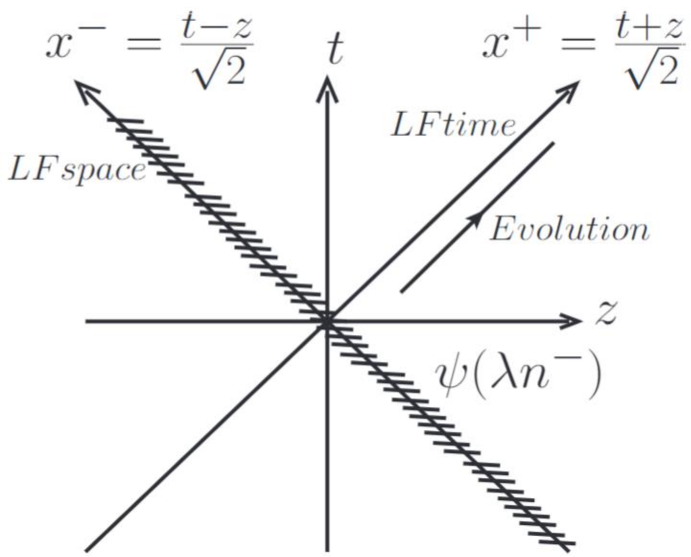

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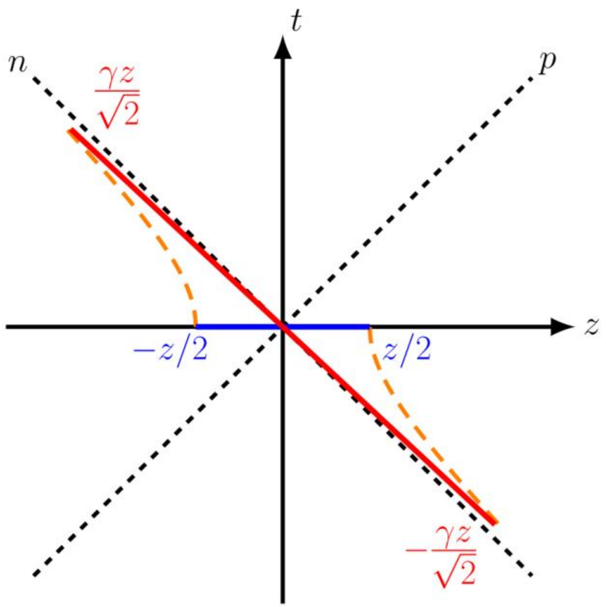

Large Momentum Effective Theory (LaMET)

X. Ji et. al. Rev. Mod. Phys. 93 3, 035005 (2021)

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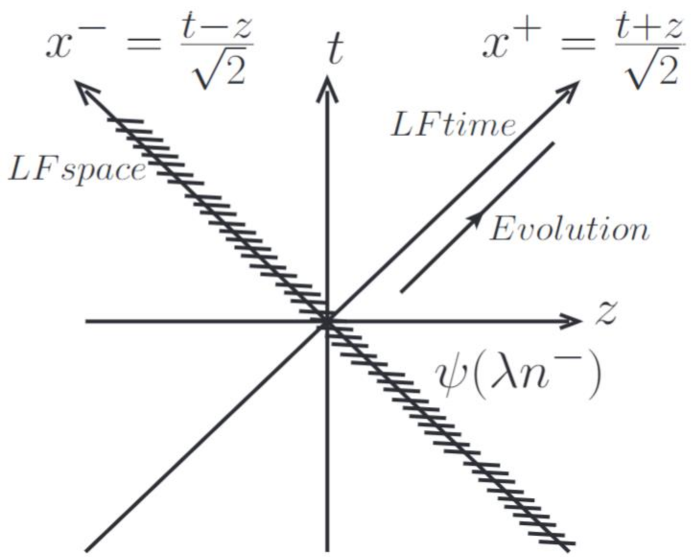

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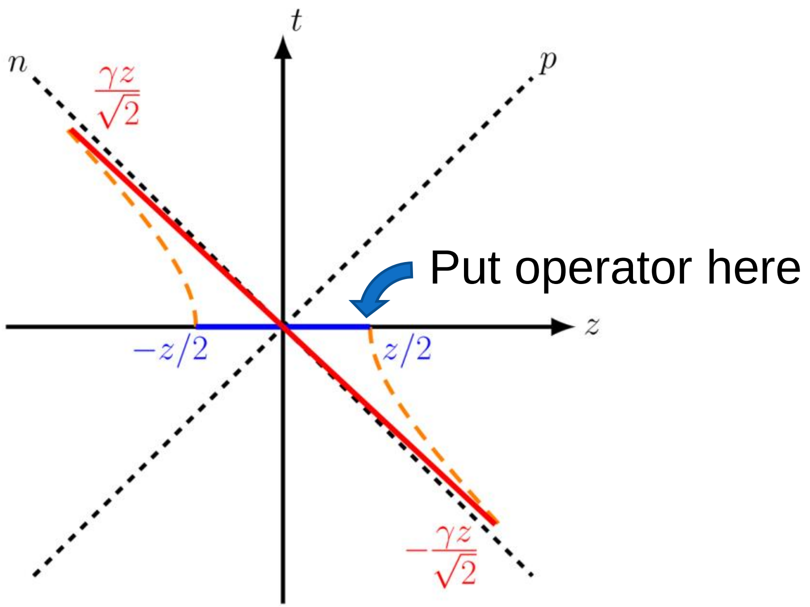

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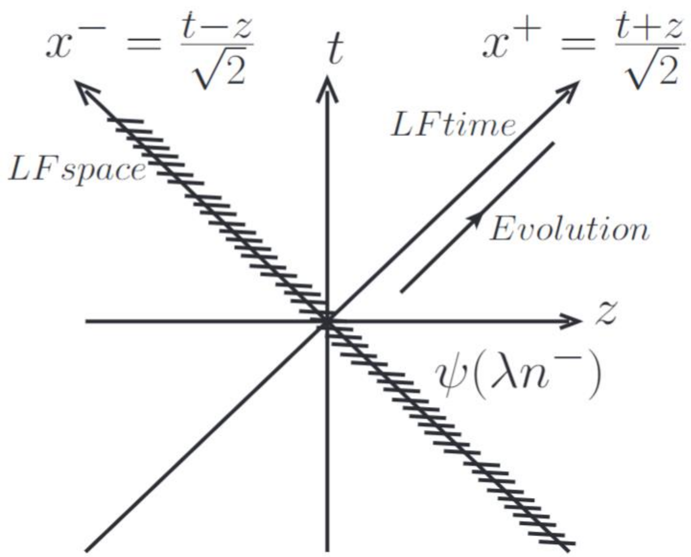

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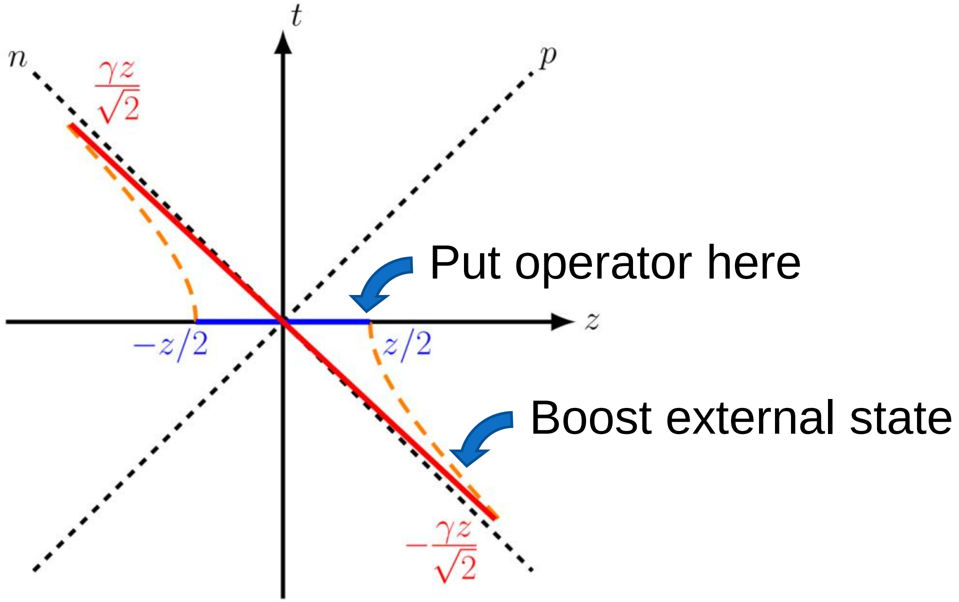

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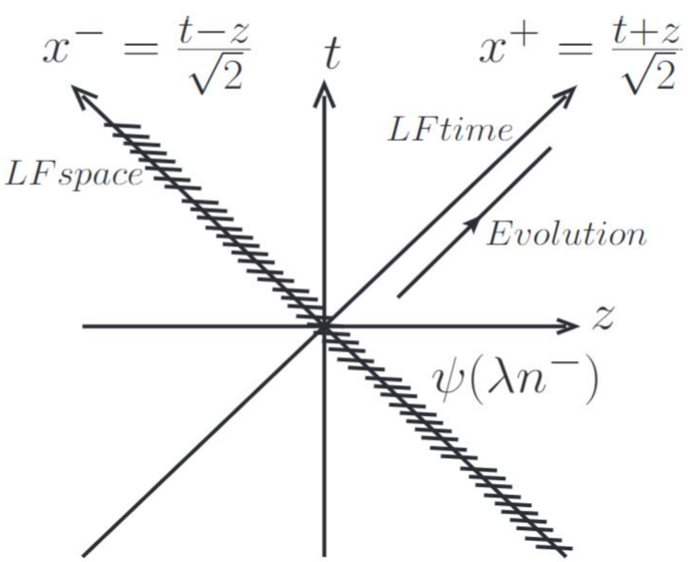

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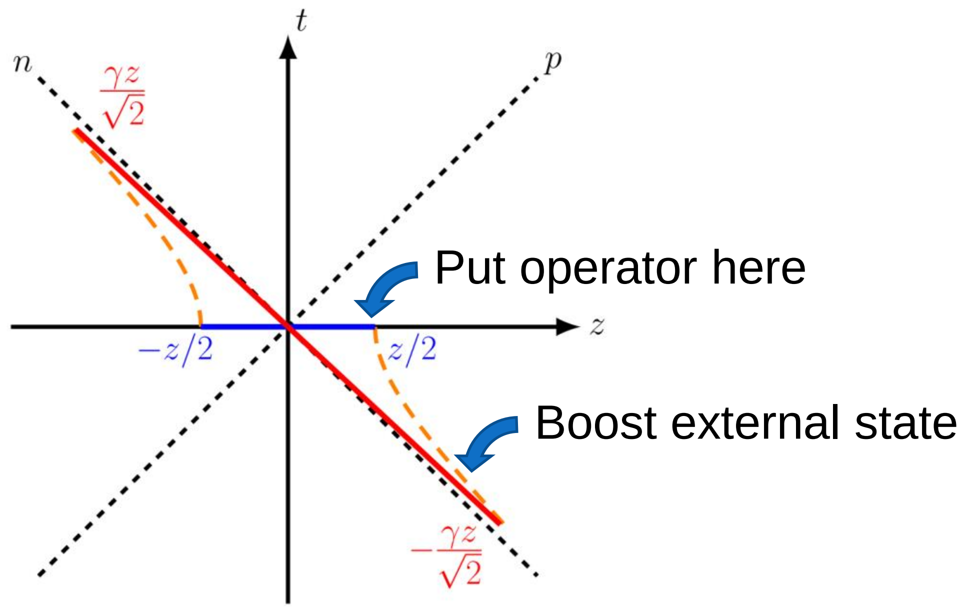

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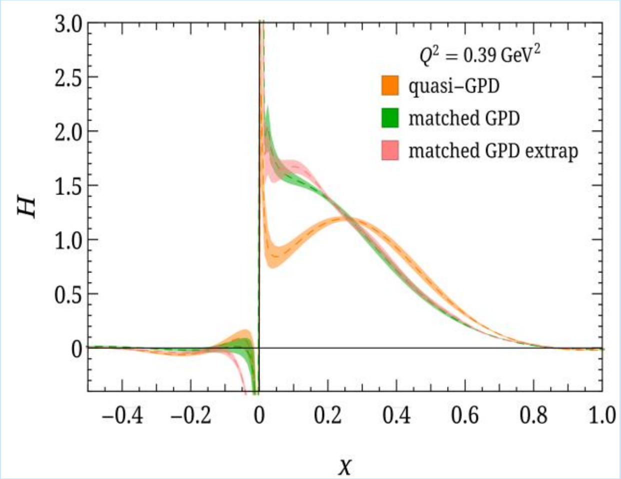
Massive progresses have been made for PDFs/DAs. Here we focus on GPDs.

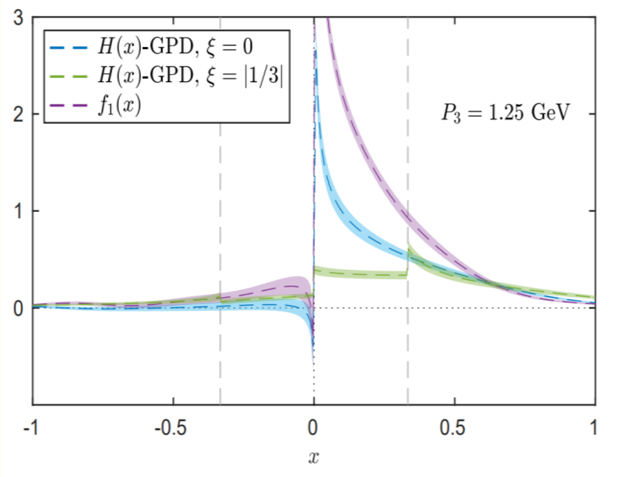
Parton distributions on lattice

Isovector H GPDs



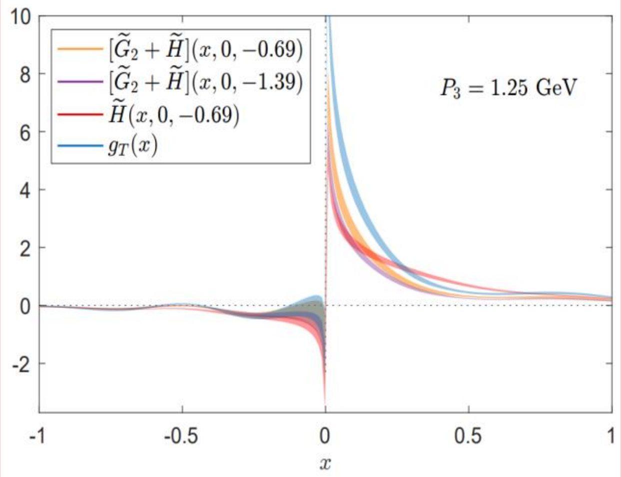
Huey-Wen Lin
Phys.Rev.Lett. 127 18, 182001 (2021)

Isovector H GPDs (skewness)



C. Alexandrou et. al. (ETMC)
Phys.Rev.Lett. 125 26, 262001 (2020)

Isovector Twist-3 GPDs

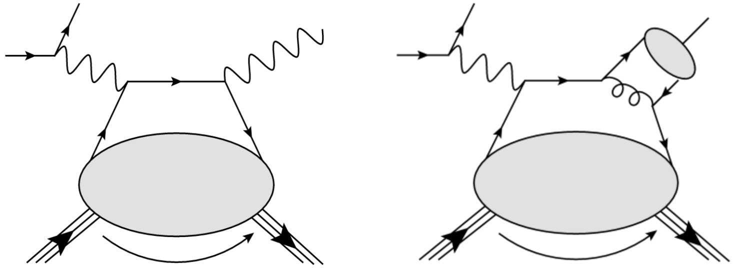


S. Bhattacharya et. al.
PoS LATTICE2021 054 (2022)

3D GPD global analysis

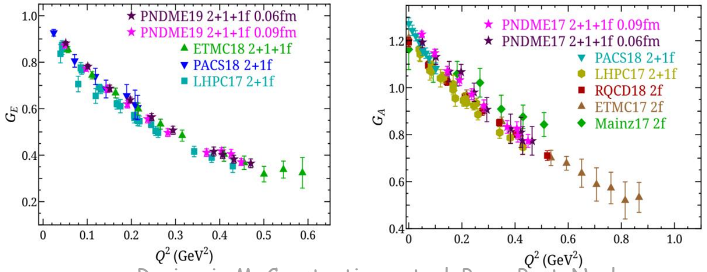
Composite tasks for GPD study

The high-dimensional nature of GPD requires composite inputs.



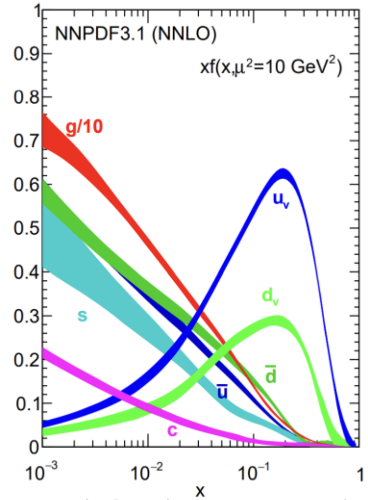
X. Ji, Phys. Rev. D 55, 7114 (1997) A.V. Radyushkin, Phys. Lett. B 385 333 (1996)
J. C. Collins et. al. Phys. Rev. D 56 2982 (1997)

Deeply virtual exclusive processes



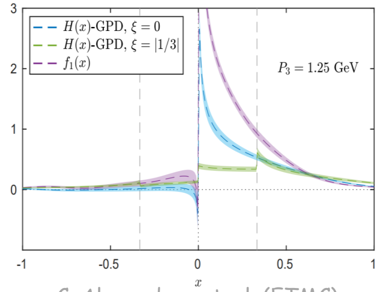
Review in M. Constantinou et. al. Prog. Part. Nucl. Phys. 121 103908 (2021). And references therein

Nucleon form factors from lattice



NNPDF et al., Eur. Phys. J. C 77, 663 (2017)

Parton Distribution Function



C. Alexandrou et. al. (ETMC)
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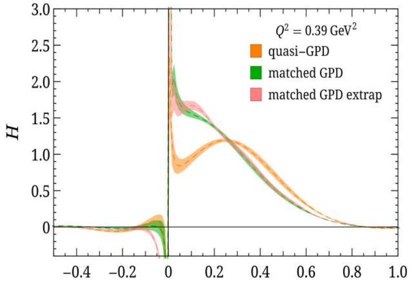

Huey-Wen Lin
Phys. Rev. Lett. 127, 182001 (2021)

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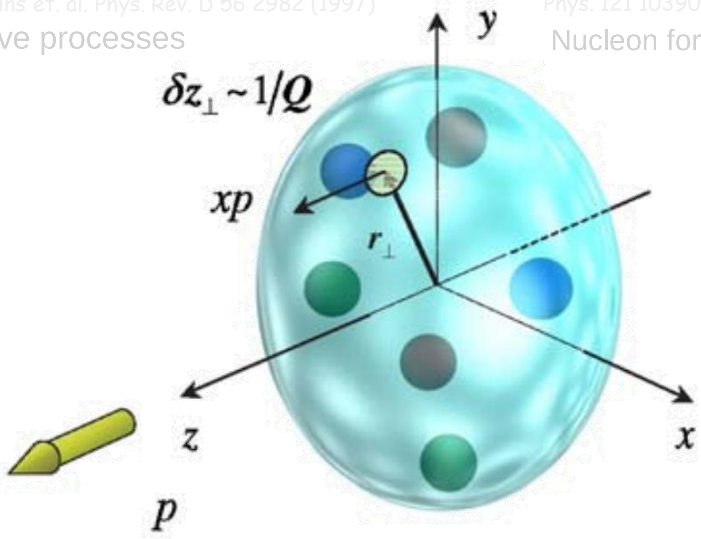

3D Quark-Gluon Tomography

C. Alexandrou et. al. (ETMC)
Phys. Rev. Lett. 125, 262001 (2020)

Huey-Wen Lin
Phys. Rev. Lett. 127, 182001 (2021)

x-dependence from lattice

Global GPD Global analysis efforts

K. Kumericki et al.
Nucl. Phys. B 794 244-323 (2008)

M. Almaeen et al.
arxiv: 2207.10766

B. Berthou et al.
Eur. Phys. J. C 78 6, 478 (2018)

Machine Learning Approach

Eric Moffat et al.
Phys. Rev. D 108 3, 036027 (2023)

GUMP

Y. Guo et. al. JHEP 09 215 (2022)
Y. Guo et. al. JHEP 05 150 (2023)

GPD global analysis

While each task faces its own challenge, the global analysis is the gatekeeper.

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- Compute GPD observables
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- Massive degrees of freedom

Compute GPD observables
- Both x & moment space with evolution

Constraints on GPDs
- Various inputs from very different system

Compare and iterate
- Computation efficiency!

Parameterization of GPD

We employ the established conformal partial wave expansion of GPD

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

D. Mueller and A. Schafer Nucl. Phys. B 739 1-59 (2006)

Advantages:

- Polynomiality condition: $\int_{-1}^{1}\mathrm{d}x x^{n-1}F(x,\xi,t)=\sum_{k=0,\mathrm{even}}^{n}\xi^k F_{n,k}(t)$ X. Ji, J. Phys. G 24 1181-1205 (1998)
- Conformal moments are (LO) multiplicatively renormalizable

I. Balitsky and V. Braun Nucl. Phys. B 311 541-584 (1989)

GPDs through Universal Moment Parameterization (GUMP)

Collaborators: Xiangdong Ji, Kyle Shiells, Gabriel Santiago, Jinghong Yang

Y. Guo et. al. JHEP 09 215 (2022)
Y. Guo et. al. JHEP 05 150 (2023)

Inputs for the global analysis

Experiments

- PDFs from global analysis

JAM, Phys. Rev. D 106 3, L031502 (2022)

  - Polarized and unpolarized PDFs from JAM

Z. Ye et. Al., Phys. Lett. B 777 8-15 (2018)

- Charge form factors from global analysis
  - YAHL global analysis of EM form factors
  - Flavor separation combing proton and neutron data

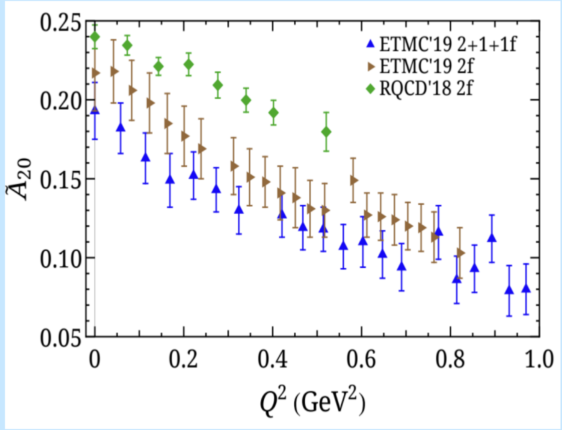
CLAS, Phys. Rev. Lett. 123 3, 032502 (2019)
JLab Hall A, PoS Hadron2017 170 (2018)

- DVCS cross-section measurements
  - Combined data from CLAS and Hall A (UU and LU)
  - H1 experiments at HERA

H1, Phys. Lett. B 681 391-399 (2009)

Lattice

- Different setups used in lattice simulations induce systematical uncertainties and deviations.



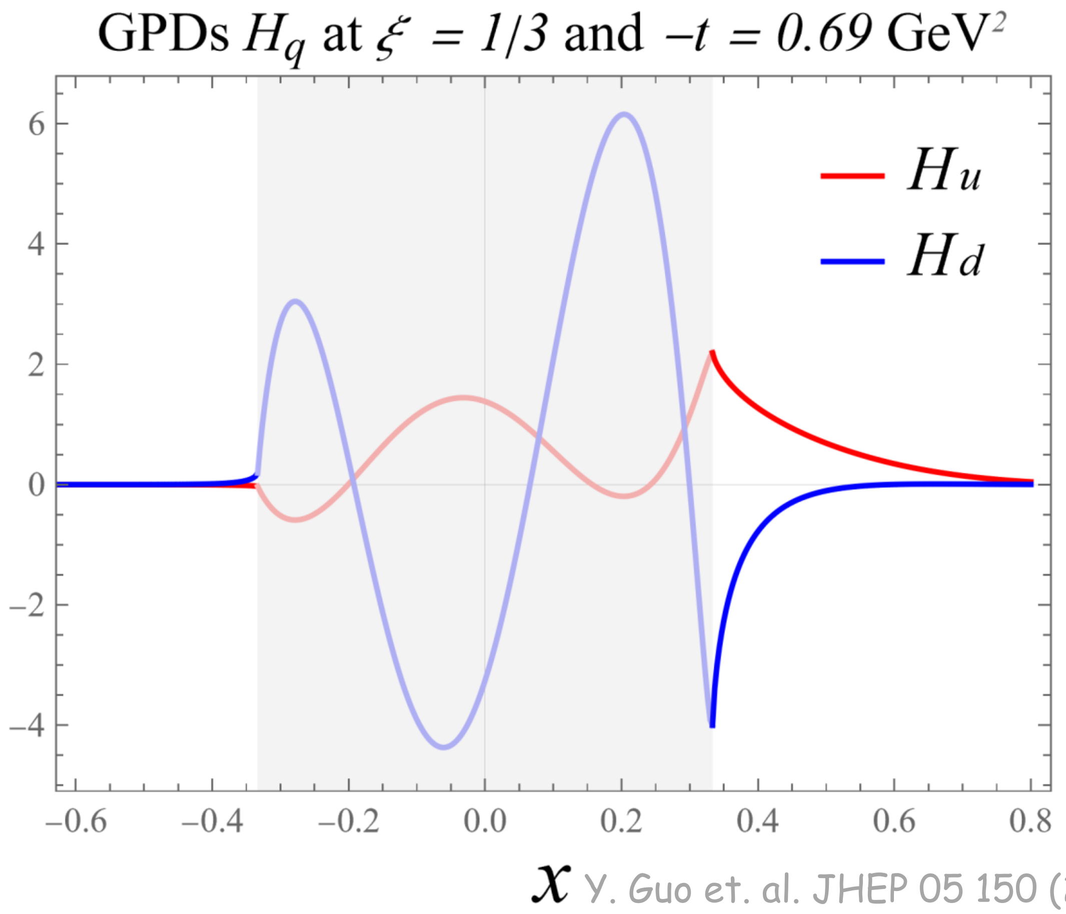
M. Constantinou et. al. Prog. Part. Nucl. Phys. 121 103908 (2021)

- Lattice form factors and GPDs from a single group.

C. Alexandrou et. al. Phys. Rev. Lett. 125 26, 262001 (2020)
C. Alexandrou et. al. PoS LATTICE2021 250 (2022)

Extracted GPDs

The extracted GPDs encounter degeneracy - the inverse problem.



Y. Guo et. al. JHEP 05 150 (2023)

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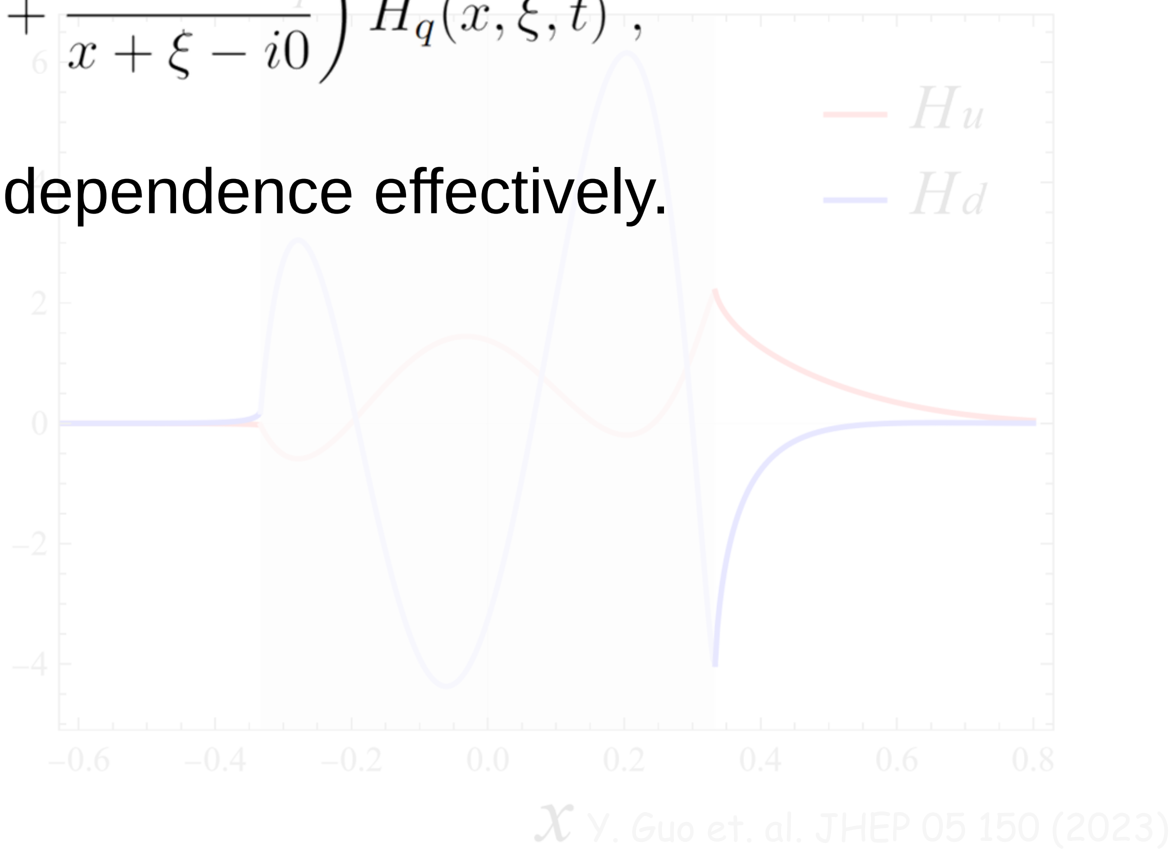
$$\mathcal{H}_{CFF}(\xi,t) = -\sum_q Q_q^2 \int_{-1}^{1} \mathrm{d}x \left(\frac{1}{x-\xi+i0} + \frac{1}{x+\xi-i0} \right) H_q(x,\xi,t) \,,$$

The left-hand side does not constrain the x-dependence effectively.



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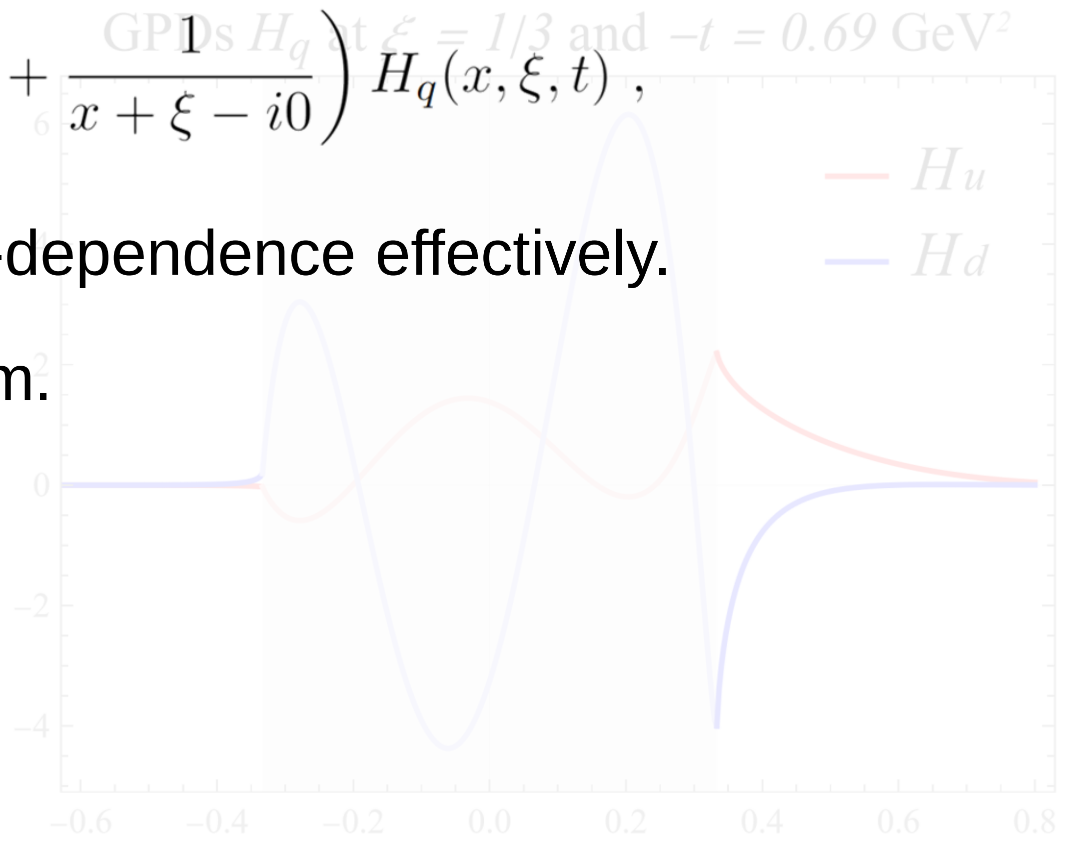
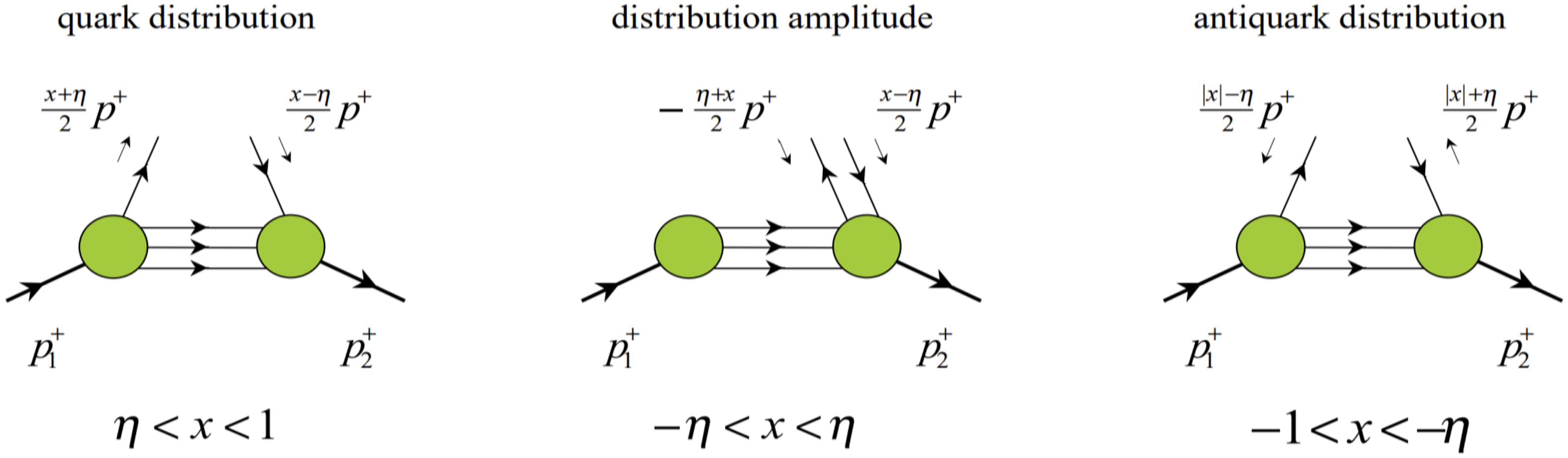


Y. Guo et. al. JHEP 05 150 (2023)

Partonic interpretations of GPDs

GPDs involve different partonic interpretations



A. Belitsky et al., Phys. Rept. 418 1-387 (2005)

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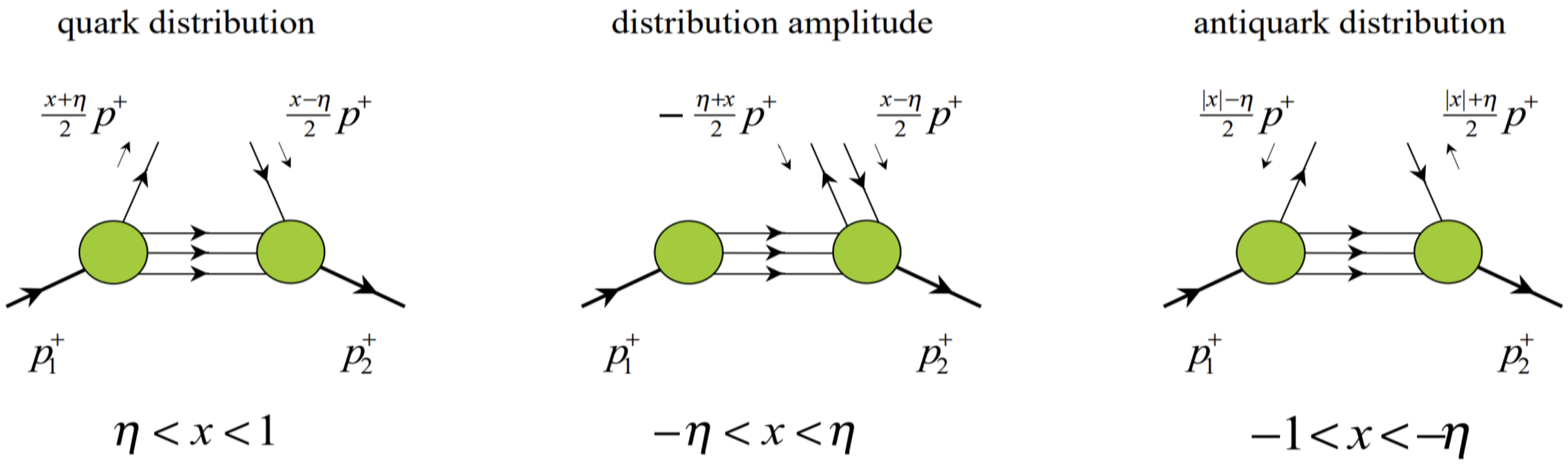

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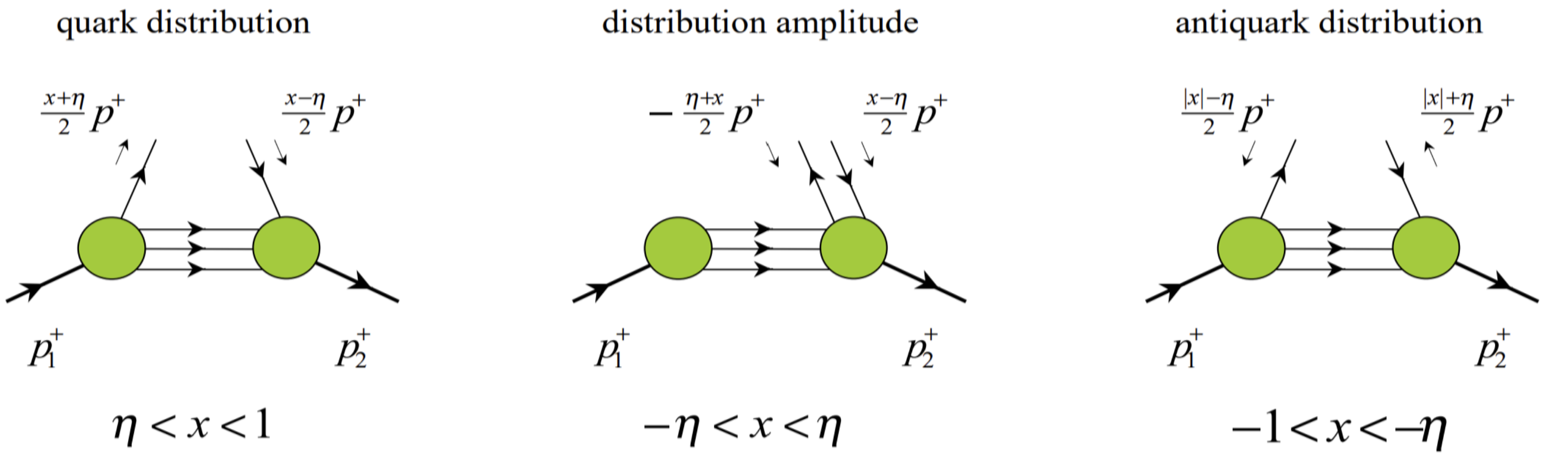

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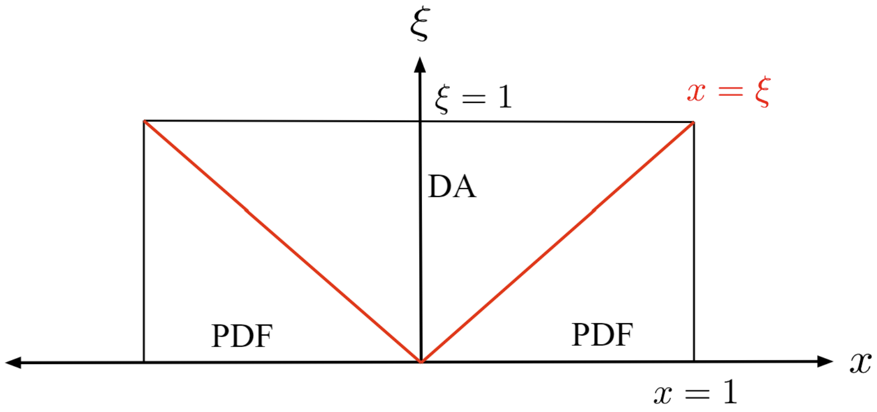

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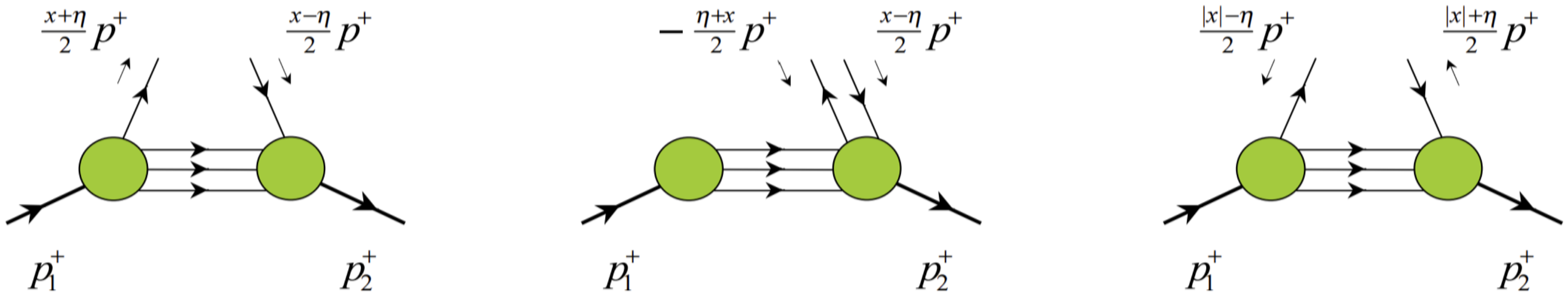
quark distribution | distribution amplitude | antiquark distribution



$\eta < x < 1$ | $-\eta < x < \eta$ | $-1 < x < -\eta$

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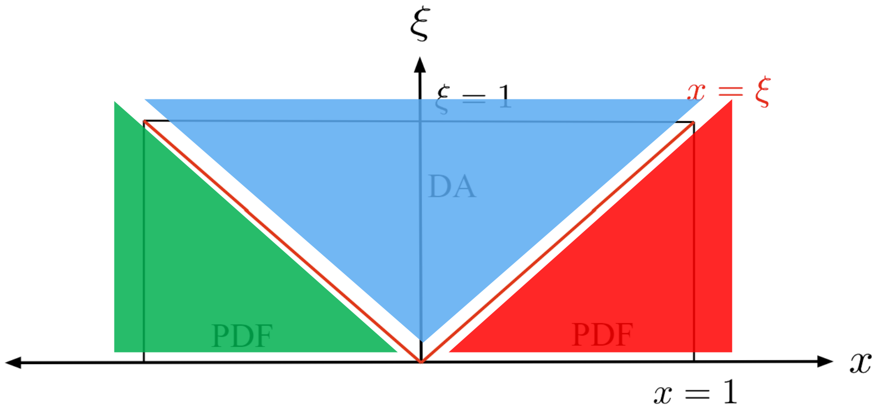

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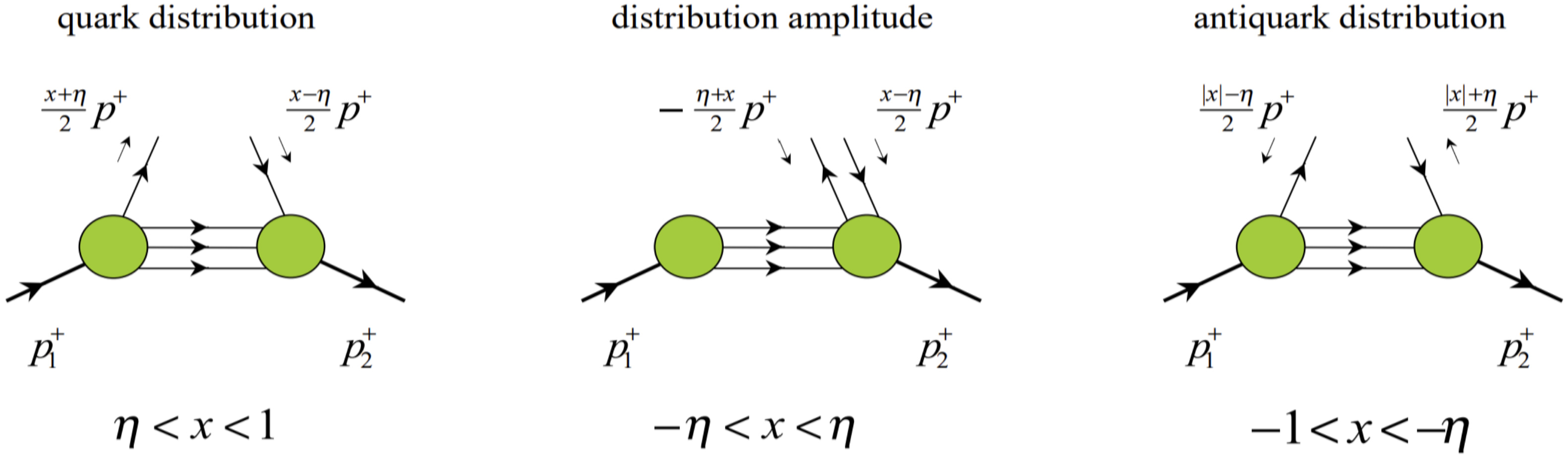

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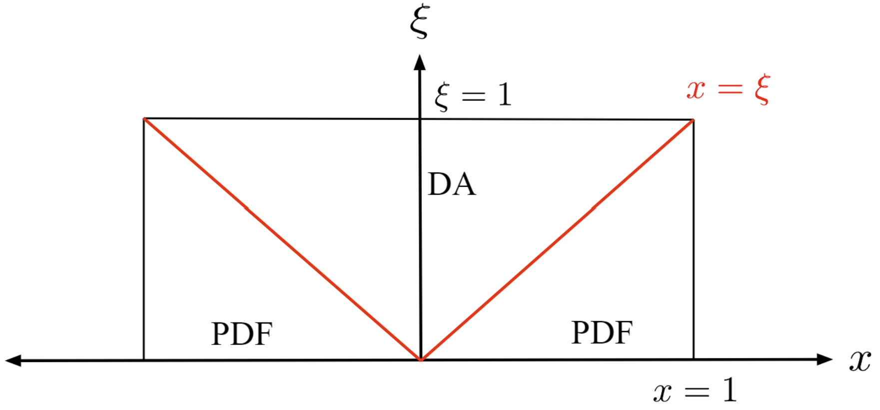

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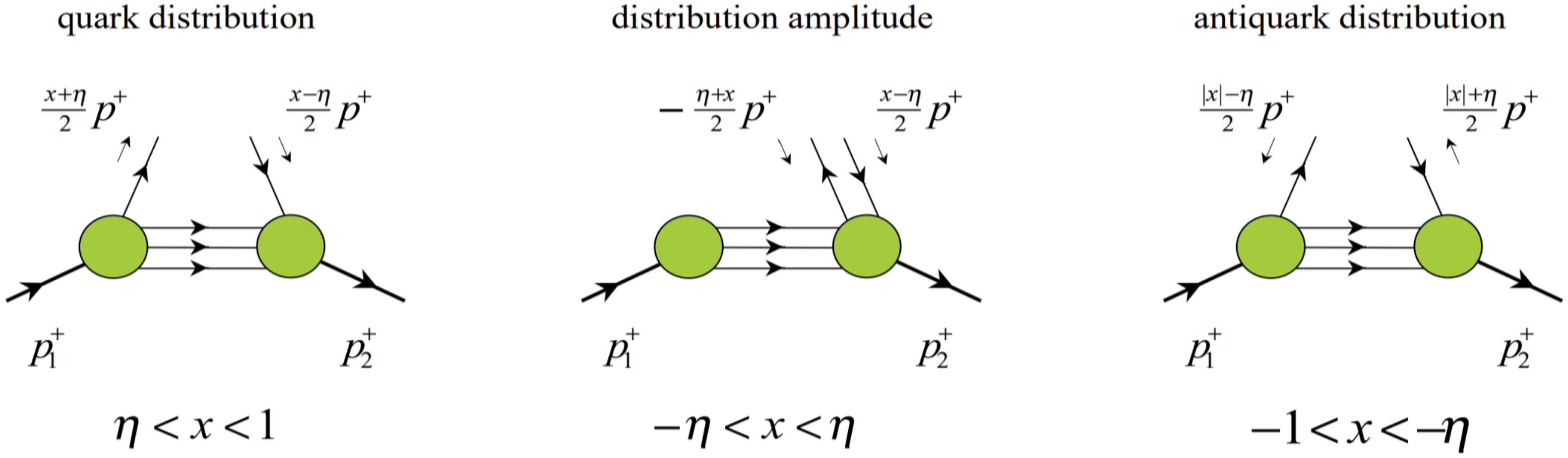

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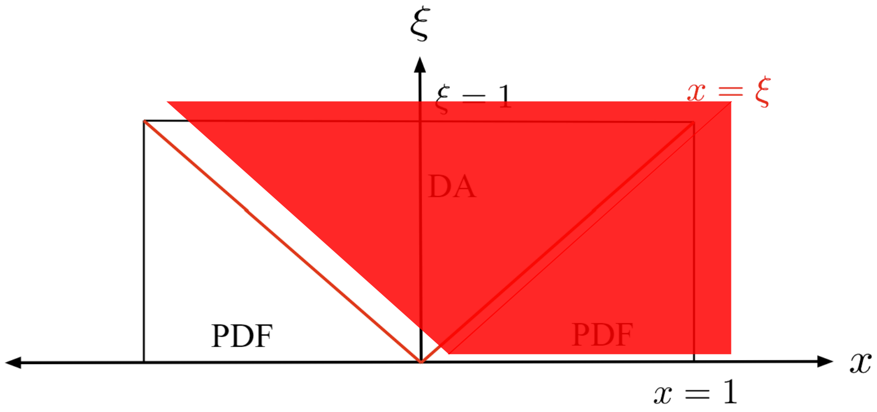

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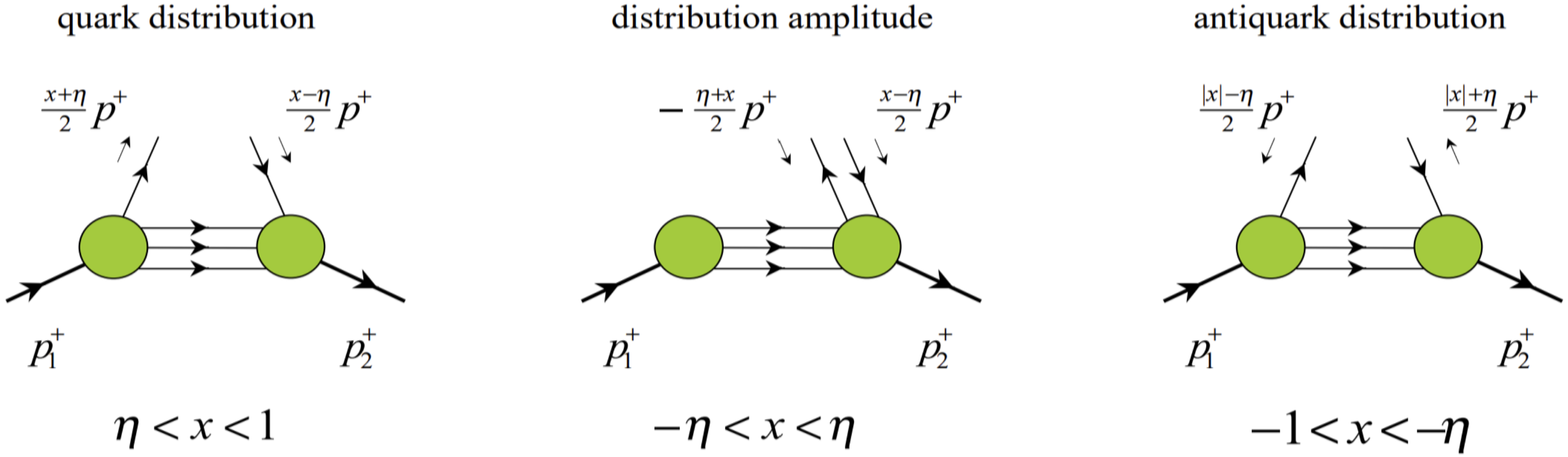

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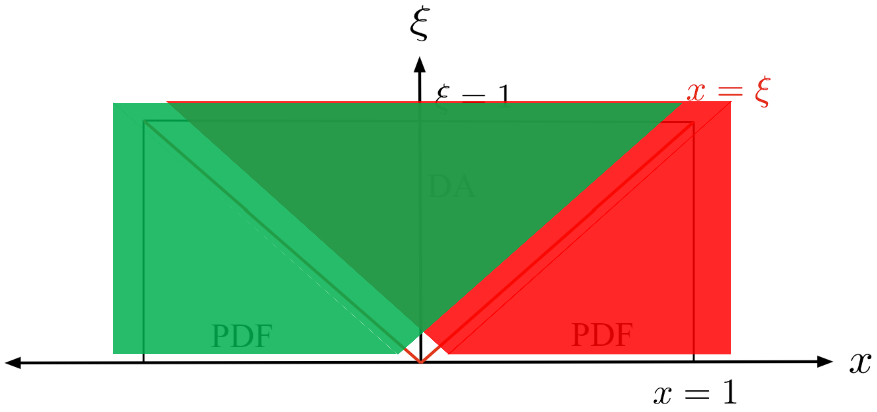

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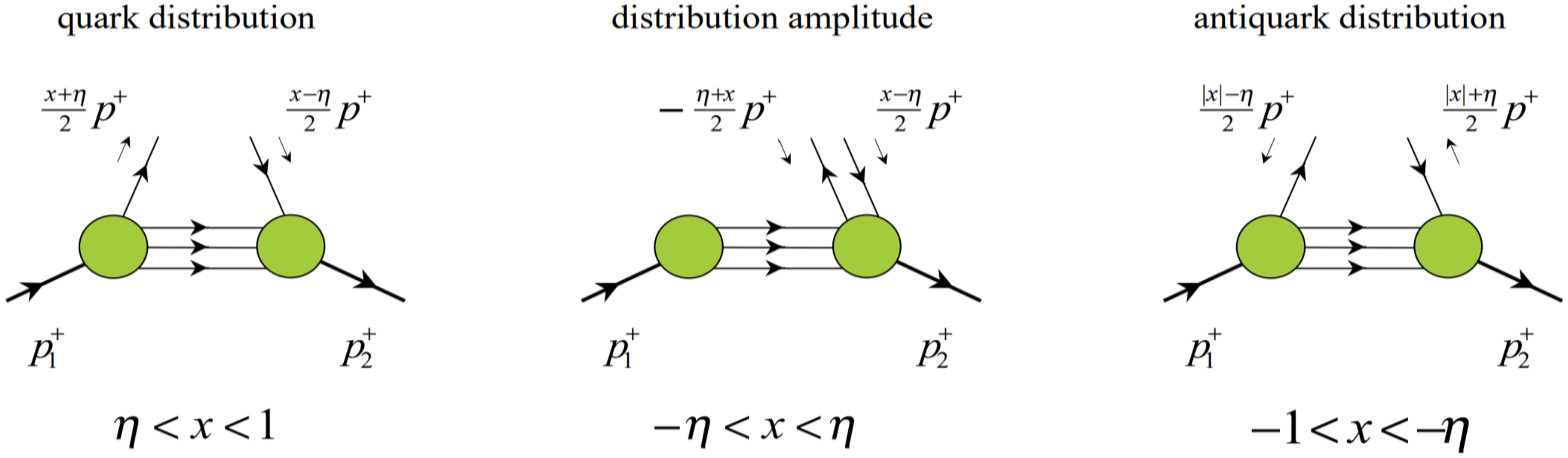

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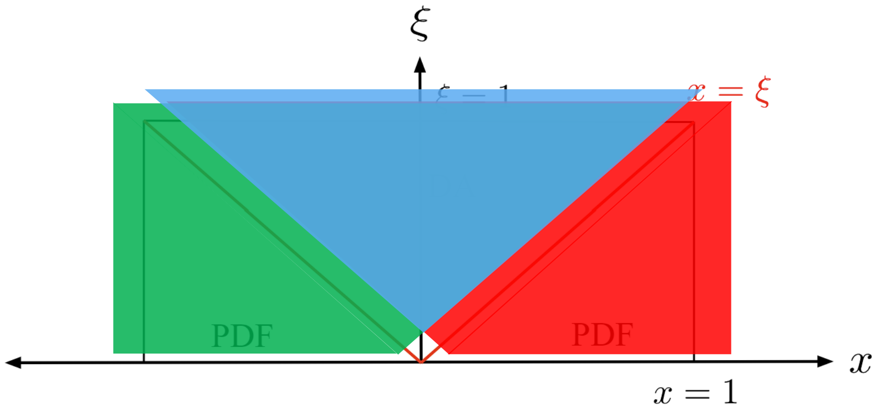

GPD in DA-like region

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The DA-like region becomes non-trivial as xi increases

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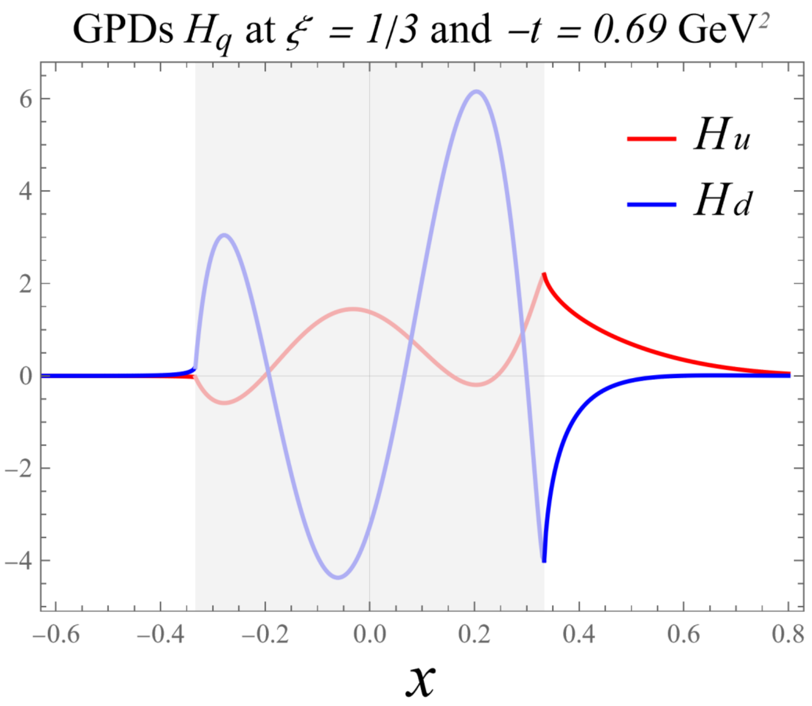

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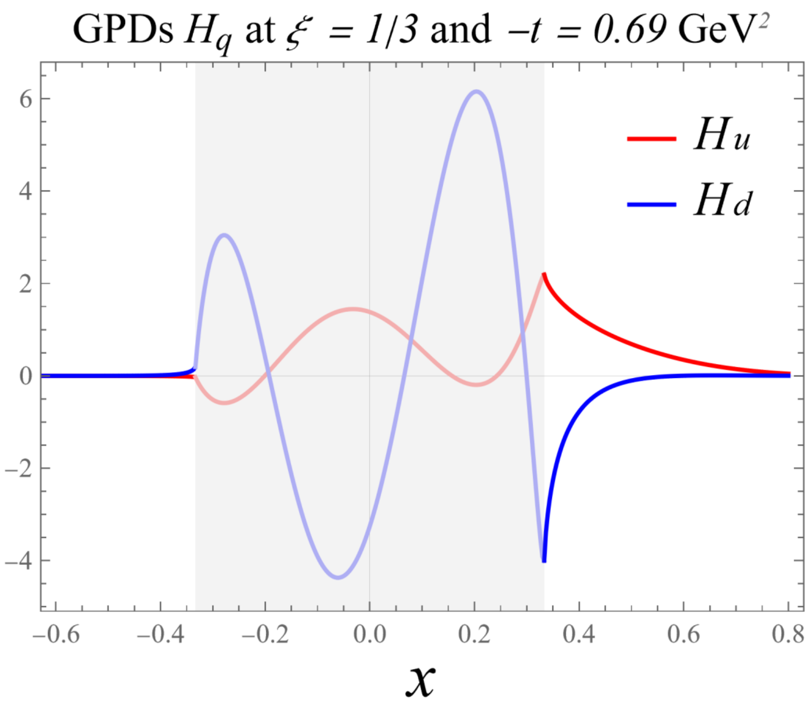

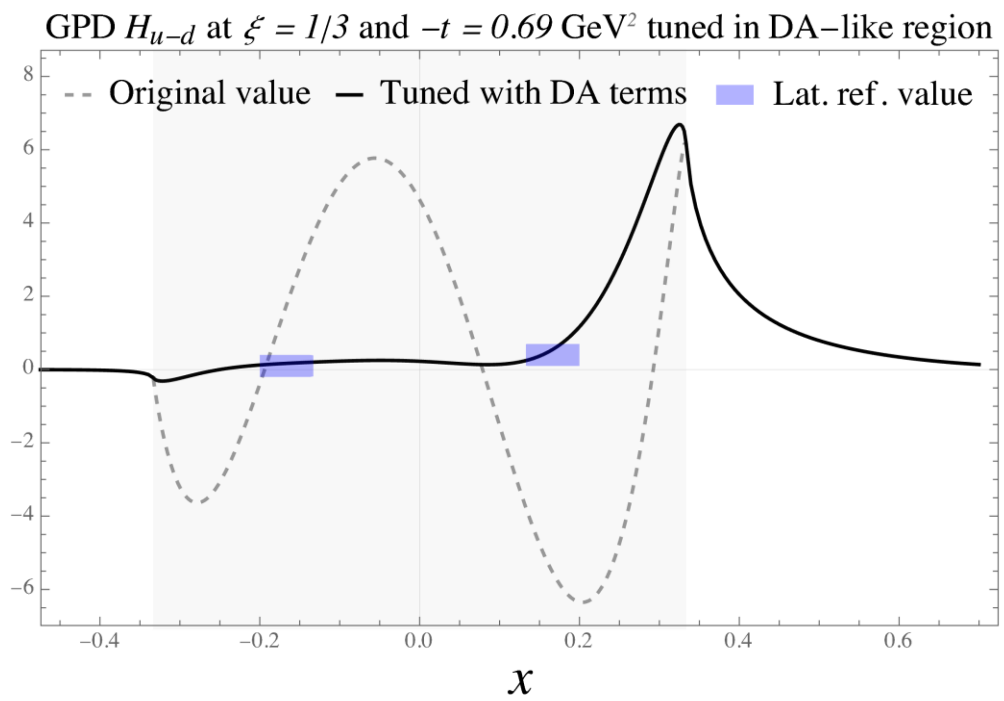

Y. Guo et. al. JHEP 05 150 (2023)

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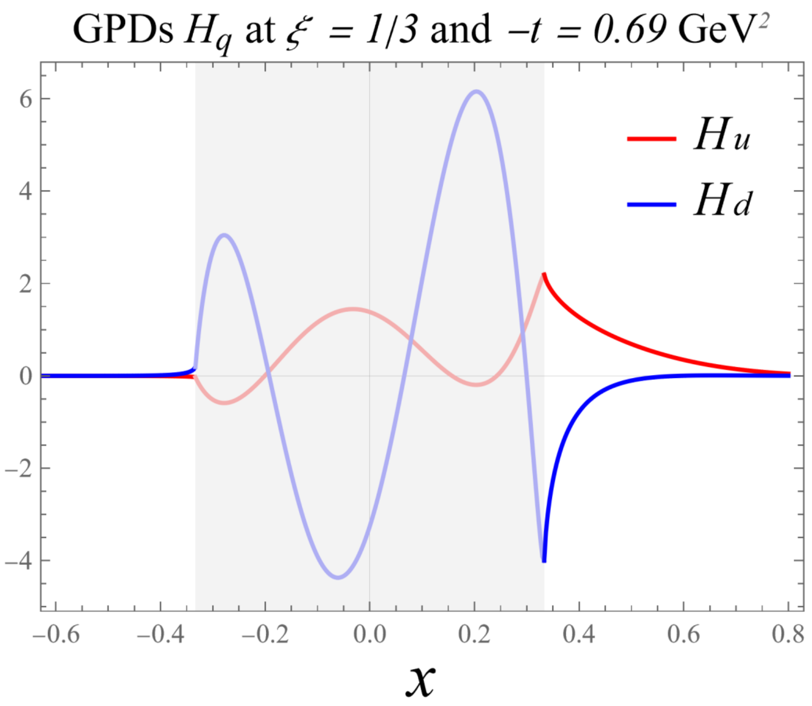

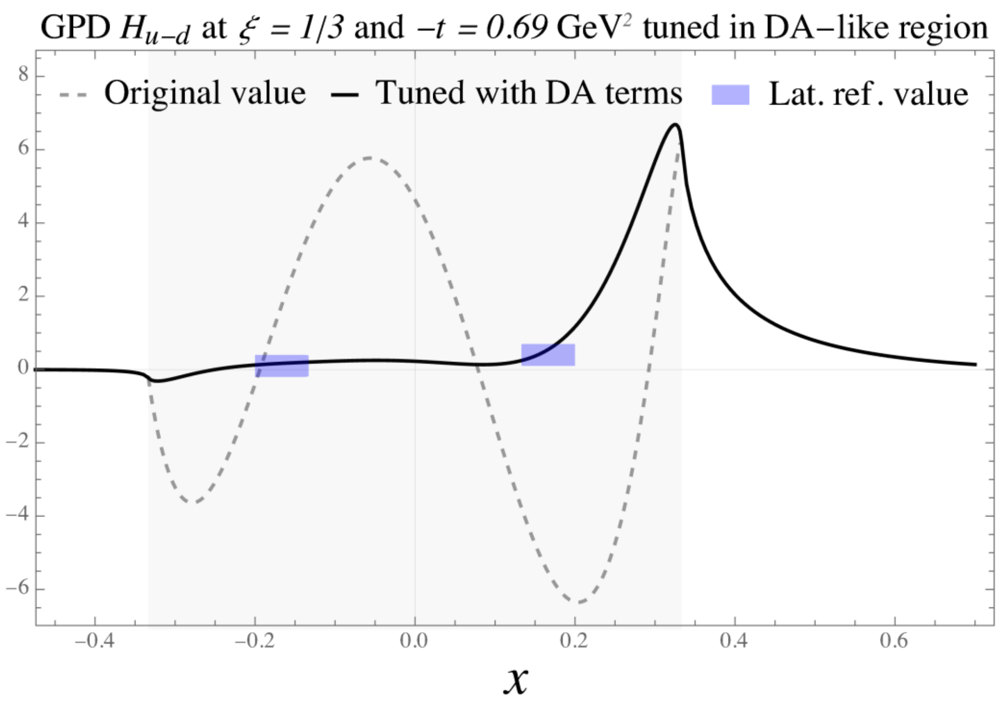

Y. Guo et. al. JHEP 05 150 (2023)

Extra inputs crucial to determine the shape of GPDs in the middle regions.

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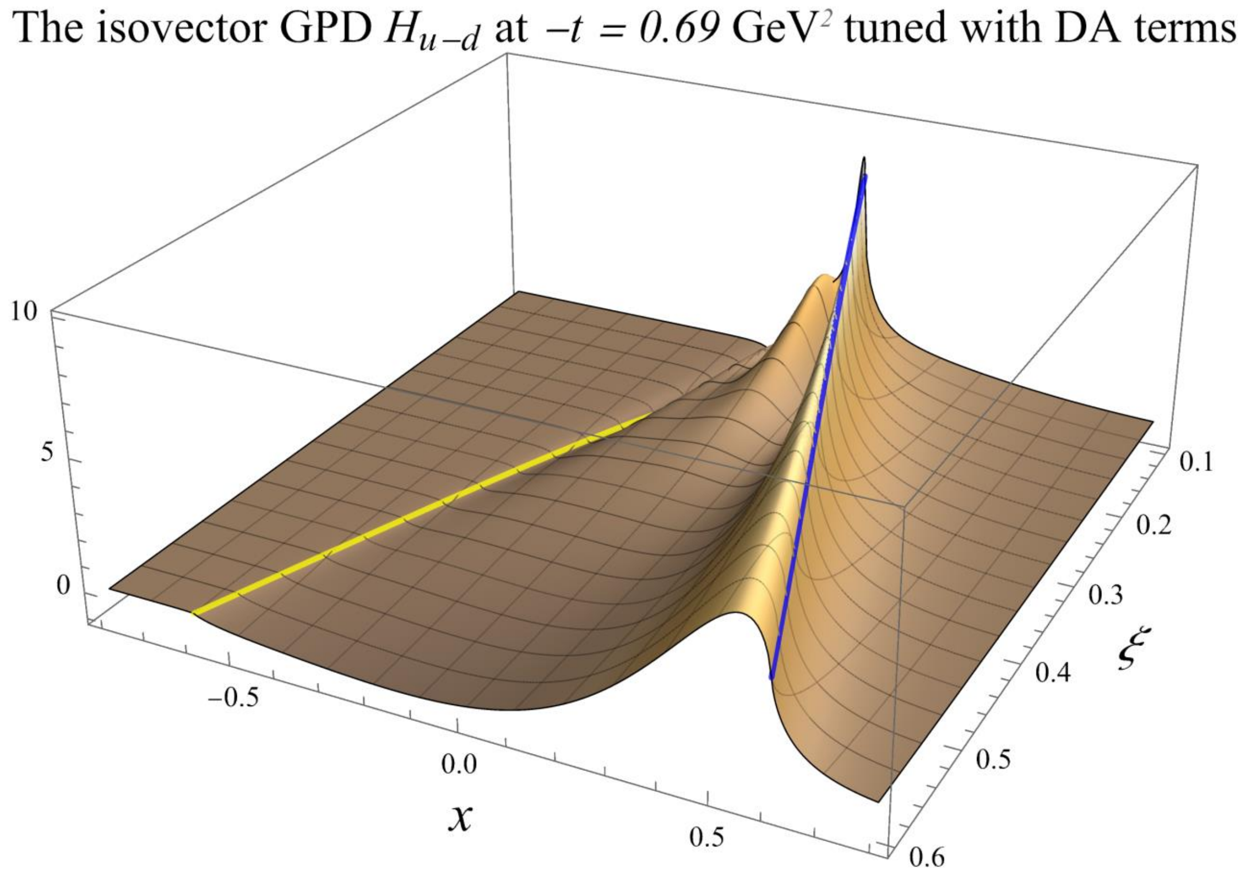

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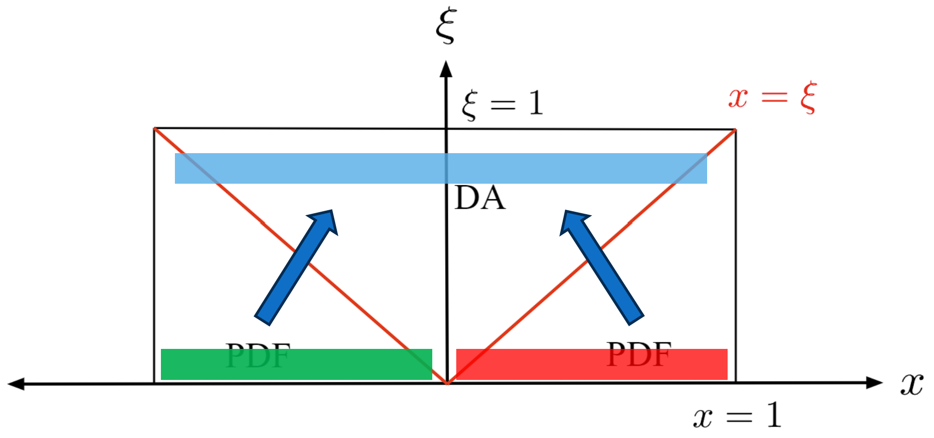

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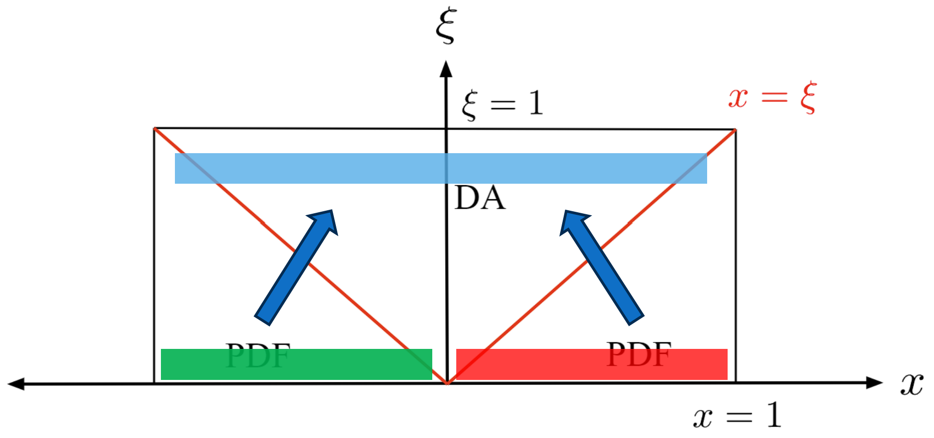

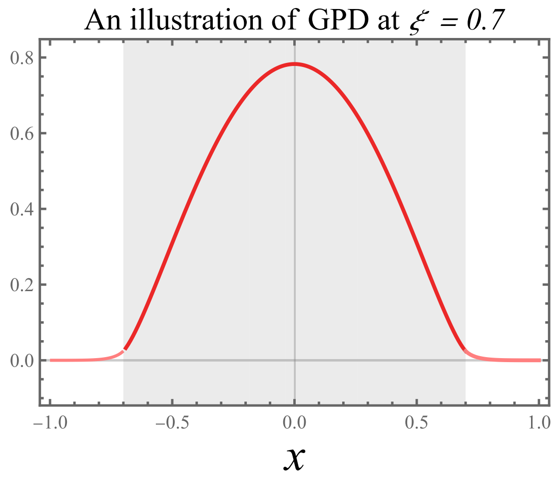

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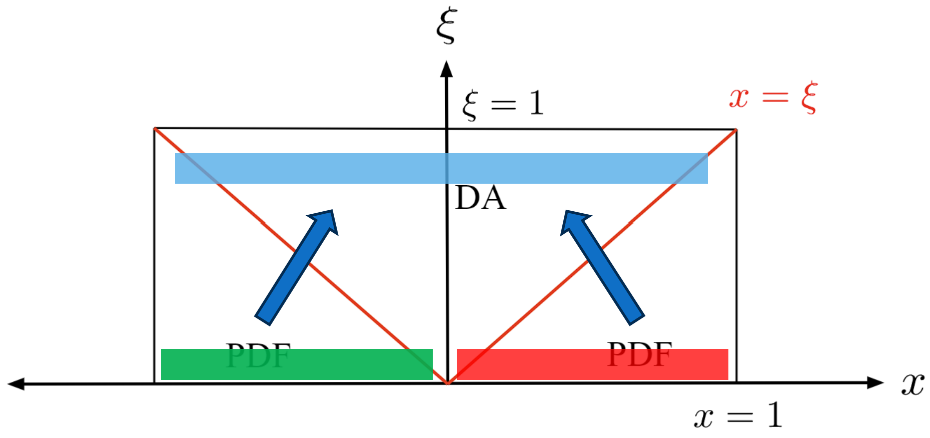
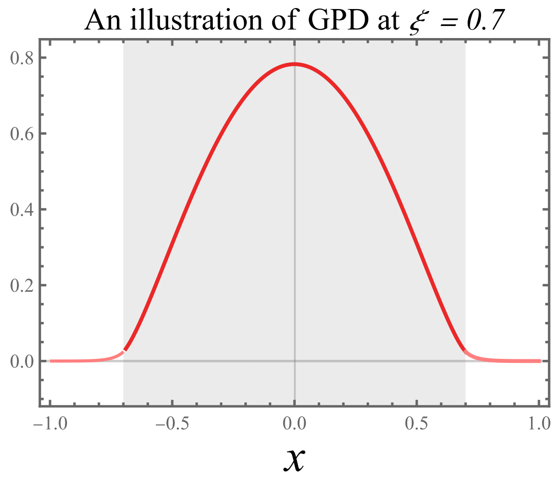
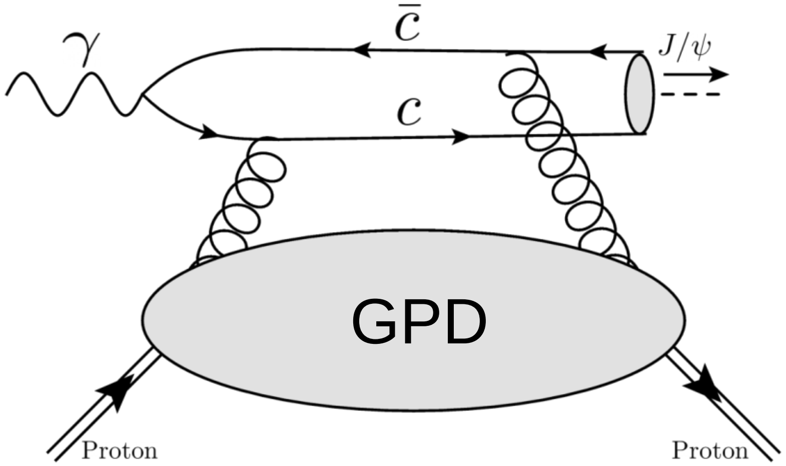




Conjectured behavior based on the suppression of PDF-like region by the endpoints at |x|=1.

J/psi photoproduction near the threshold

Exclusive heavy vector meson, e.g., J/psi productions naturally probe the gluon GPD.



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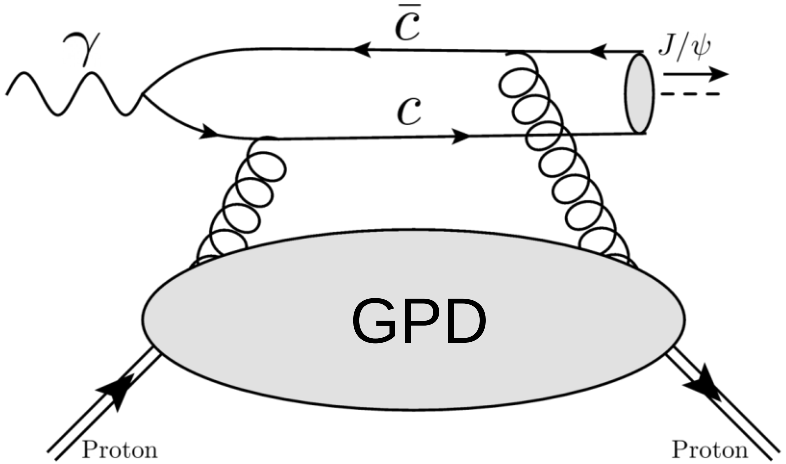

Leading order factorization with GPDs near the threshold

- Same amplitude as the collinear case
- Different (threshold) kinematics from the collinear case
- Large momentum transfer (skewness) in the heavy quark limit

Y. Guo et. al. Phys. Rev. D 103 9, 096010 (2021)

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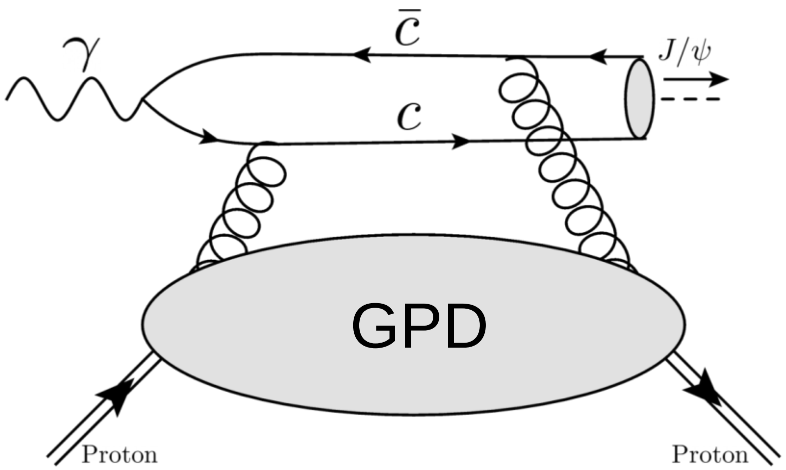

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$$\frac{d\sigma}{dt} \propto \left[\left(1-\xi^2\right) \left|\mathcal{H}_{gC}\right|^2 - 2\xi^2 \mathrm{Re}\left[\mathcal{H}^*_{gC}\mathcal{E}_{gC}\right] - \left(\xi^2 + \frac{t}{4M_p^2}\right) \left|\mathcal{E}_{gC}\right|^2 \right] ,$$

GFFs extraction

In the large-skewness approximation we have

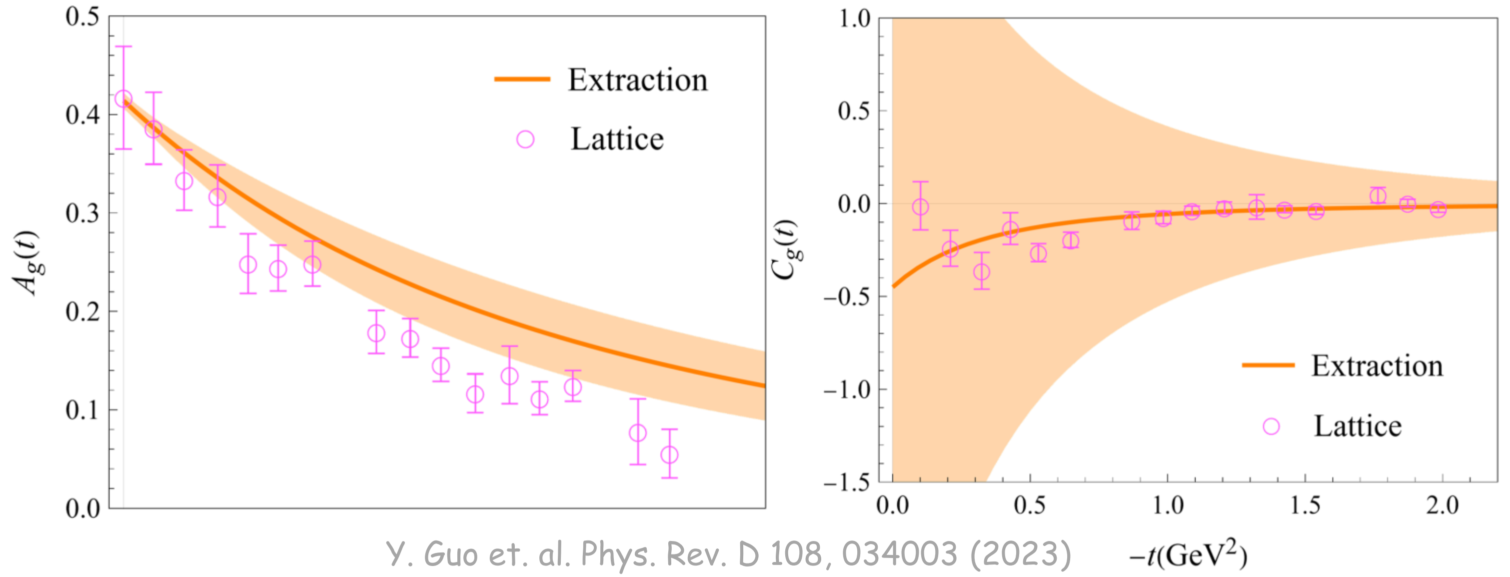
Y. Guo et. al. arxiv: 2308.13006

$$\mathcal{H}_{gC}(\xi,t) \approx \mathcal{C}_g(t) + \xi^{-2}\mathcal{A}_g^{(2)}(t) \qquad \mathcal{E}_{gC}(\xi,t) \approx -\mathcal{C}_g(t) + \xi^{-2}\mathcal{B}_g^{(2)}(t)$$

They are related to the GFFs up to higher-moment contamination:

$$\mathcal{A}_g^{(2)}(t) \approx 2A_g(t) \quad \mathcal{B}_g^{(2)}(t) \approx 2B_g(t)(\approx 0) \quad \mathcal{C}_g(t) \approx 8C_g(t)$$

Potential GFFs extraction with such measurements! (with systematic uncertainties)



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Summary and outlook

Summary

- The global analysis program has been built up.
- 1^{st} global analysis with DVCS and lattice input.
- Currently work on J/psi production and gluon.
- Next-to-leading order effects seem important.

Outlook

- Include gluon distribution (J/psi & others)
- Implementing NLO evolutions.
- Simultaneous quark and gluon extraction.

Thank you!