Theory and phenomenology of Generalised Partons Distributions

Cédric Mezrag

CEA Saclay, Irfu DPhN

October 17^{th}, 2025

2025 International Workshop and School on Hadron Structure and Strong Interactions

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- Renormalisation can be performed in the same way as for local operators, trading products for convolutions in momentum space
- We derived the evolution equations, in analogy with the renormalisation group equation.
- The anomalous dimensions are momentum dependent and are called splitting functions.
  NB : For those willing to perfom the one-loop $\mathcal{P}_{qq}$ computation, you can follow appendix B of arxiv:2206.01412

Non-singlet Splitting function

$$\mathcal{P}^{\pm,[0]}\left(y,\kappa=\frac{\xi}{x}\right)=\theta(1-y)\mathcal{P}_1^{\pm,[0]}(y,\kappa)+\theta(\kappa-1)\mathcal{P}_2^{\pm,[0]}(y,\kappa)\ .$$

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where

$$\mathcal{P}_1^{-,[0]}(y,\kappa)=2C_F\left\{\left(\frac{2}{1-y}\right)_+-\frac{1+y}{1-\kappa^2y^2}+\delta(1-y)\left[\frac{3}{2}-\ln\left(\left|1-\kappa^2\right|\right)\right]\right\},$$

$$\mathcal{P}_2^{-,[0]}(y,\kappa)=2C_F\left[\frac{1+(1+\kappa)y+(1+\kappa-\kappa^2)y^2}{(1+y)(1-\kappa^2y^2)}-\left(\frac{1}{1-y}\right)_{++}\right],$$

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and

$$\int_x^1 dy\left(\frac{1}{1-y}\right)_+f(y)=\int_x^1 dy\frac{f(y)-f(1)}{1-y}+f(1)\ln(1-x)$$

$$\int_x^\infty dy\left(\frac{1}{1-y}\right)_{++}f(y)=\int_x^\infty\frac{dy}{1-y}\left[f(y)-f(1)\left(1+\theta(y-1)\frac{1-y}{y}\right)\right]+f(1)\ln(1-x)\,,$$

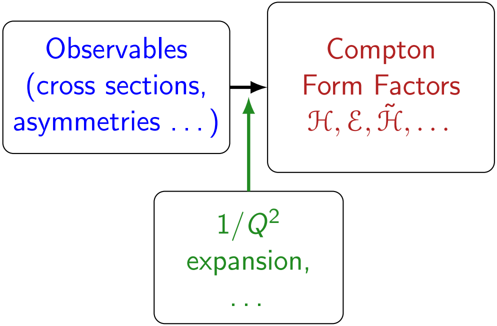
Probing GPDs through exclusive processes

I really recommend reading the Ph.D. thesis of H. Dutrieux:
https://inspirehep.net/literature/2614733

Experimental connection to GPDs

Observables
(cross sections,
asymmetries . . .)

Experimental connection to GPDs



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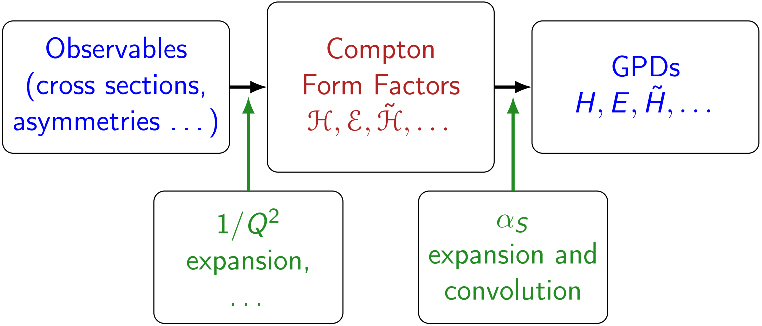

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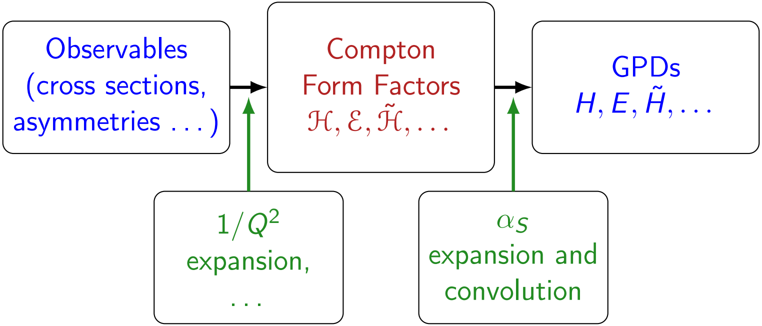
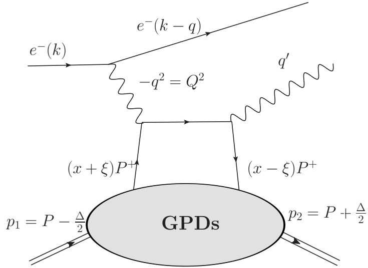


- CFFs play today a central role in our understanding of GPDs
- Extraction generally focused on CFFs

Deep Virtual Compton Scattering



- Best studied experimental process connected to GPDs
  $\rightarrow$ Data taken at Hermes, Compass, JLab 6, JLab 12

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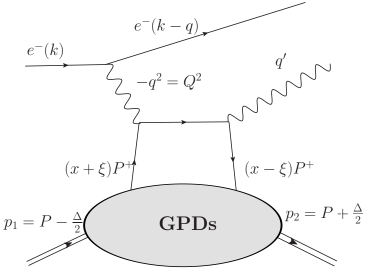

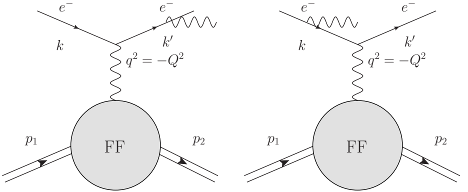

- Best studied experimental process connected to GPDs

  → Data taken at Hermes, Compass, JLab 6, JLab 12
- Interferes with the Bethe-Heitler (BH) process
  - Blessing: Interference term boosted w.r.t. pure DVCS one
  - Curse: access to the angular modulation of the pure DVCS part difficult

M. Defurne *et al.*, Nature Commun. 8 (2017) 1, 1408

Amplitude

$$\text{cross-sections} = \sum |BH + DVCS|^2$$
$$= \sum |BH|^2 + \underbrace{BH^* DVCS + DVCS^* BH}_{\text{interference term}} + |DVCS|^2$$

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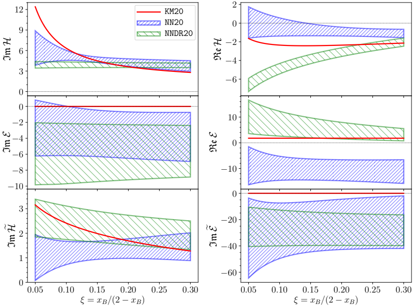
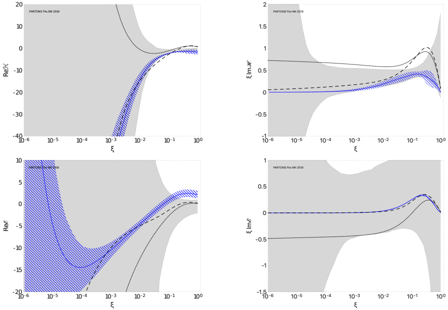
$$\mathcal{H}(\xi, t, Q^2) = \int_{-1}^{1} \frac{\mathrm{d}x}{\xi} T\left(\frac{x}{\xi}; \alpha_s\right) H(x, \xi, t)$$

and similar definitions for $\mathcal{E}$, $\tilde{\mathcal{H}}$ and $\tilde{E}$.

Recent CFF extractions



M. Cuič *et al.*, PRL 125, (2020), 232005



H. Moutarde *et al.*, EPJC 79, (2019), 614

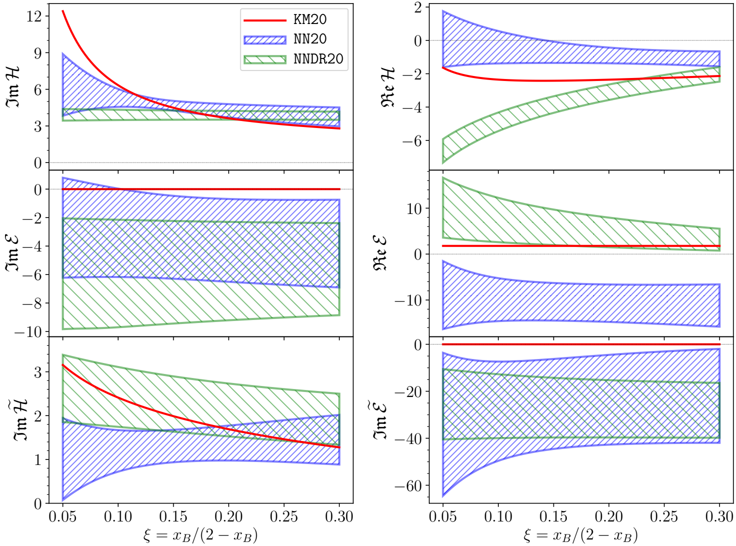
- Recent effort on bias reduction in CFF extraction (ANN)

  additional ongoing studies, J. Grigsby *et al.*, PRD 104 (2021) 016001

- Studies of ANN architecture to fulfil GPDs properties (dispersion relation,polynomiality,. . .)
- Recent efforts on propagation of uncertainties (allowing impact studies for JLAB12, EIC and EicC)

  see *e.g.* H. Dutrieux *et al.*, EPJA 57 8 250 (2021)

Let us discuss these results



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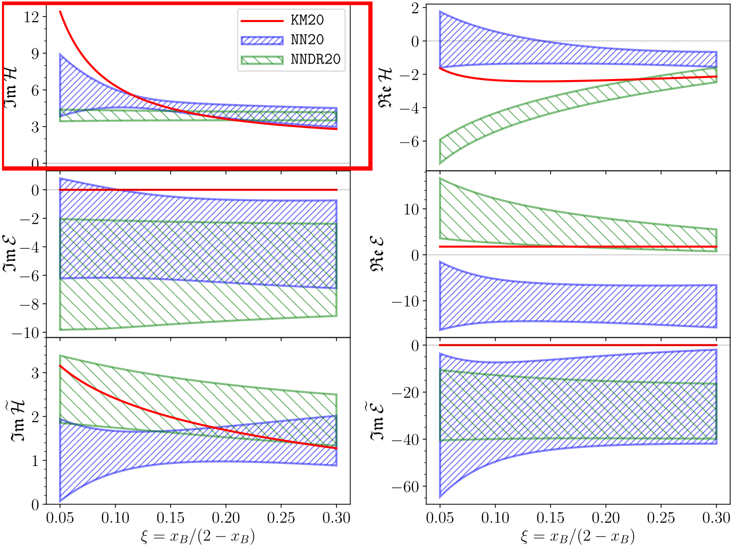
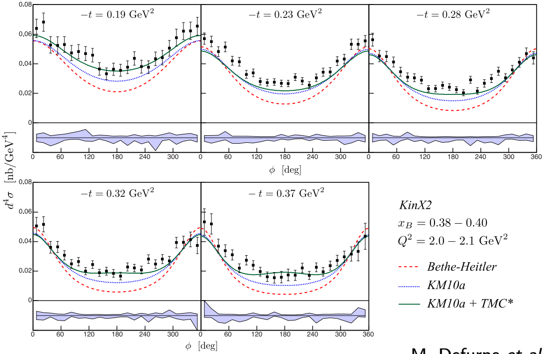


Kinematic corrections in t/Q^2 and M^2/Q^2

V. Braun *et al.*, PRL 109 (2012), 242001



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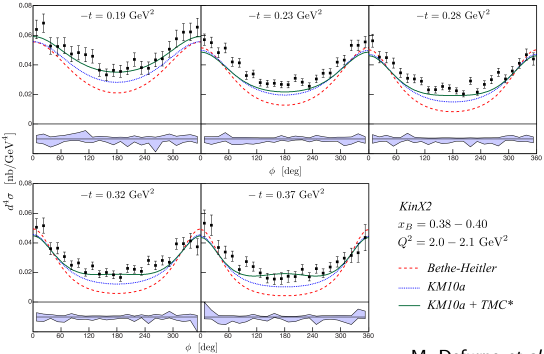

M. Defurne *et al.* PRC 92 (2015) 55202

- Sizeable even for $t/Q^2 \sim 0.1$
- Not currently included in global fits.

- At all orders in α_S, dispersion relations relate the real and imaginary parts of the CFF.

I. Anikin and O. Teryaev, PRD 76 056007
M. Diehl and D. Ivanov, EPJC 52 (2007) 919-932
H. Dutrieux *et al.*, EPJC 85 (2025) 1, 105
V. Martinez Fernandez and C. Mezrag, arXiv:2509.05059

$$\mathcal{S}(t, Q^2) = \int_{-1}^{1} \mathrm{d}\omega\, T(\omega) D(\omega) = \Re\mathcal{H}(\xi) - \frac{2}{\pi} \fint_0^1 \frac{x^2 \Im\mathcal{H}(x)}{(\xi - x)(\xi + x)} \frac{\mathrm{d}x}{\xi}$$

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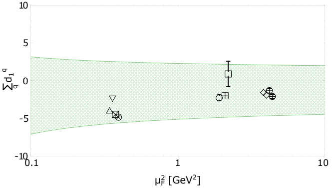


figure from H. Dutrieux *et al.*, Eur.Phys.J.C 81 (2021) 4

- First attempt from JLab 6 *GeV* data

Burkert *et al.*, Nature 557 (2018) 7705, 396-399

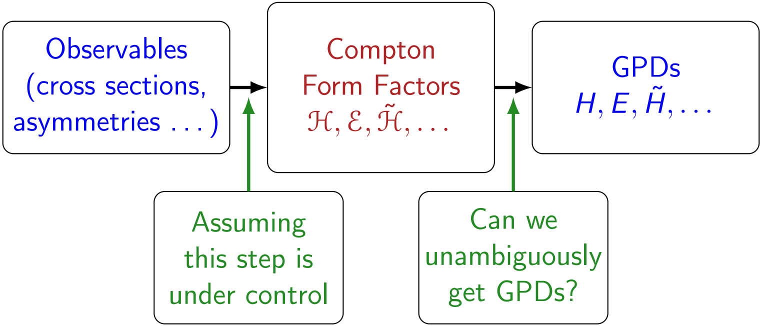
- Tensions with other studies
  $\rightarrow$ uncontrolled model-dependence

K. Kumericki, Nature 570 (2019) 7759, E1-E2
H. Moutarde *et al.*, Eur.Phys.J.C 79 (2019) 7, 614
H. Dutrieux *et al.*, Eur.Phys.J.C 81 (2021) 4

- Scheme/scale dependence

The DVCS deconvolution problem I

From CFF to GPDs



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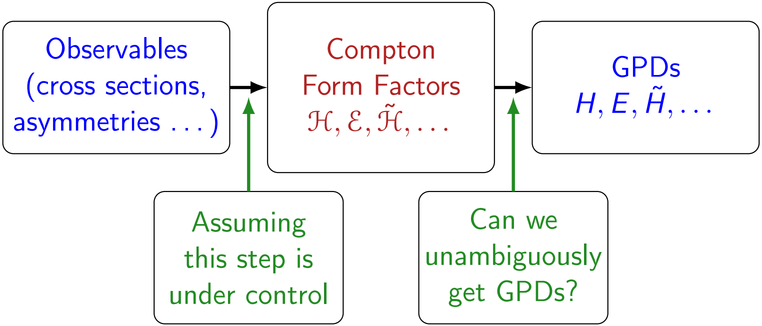

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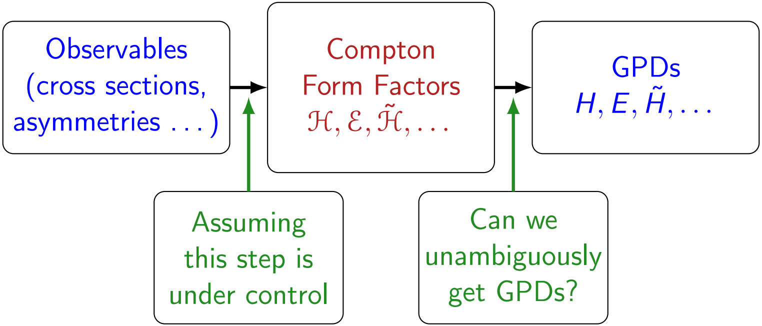

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- Are QCD corrections improving the situation?

CFF Definition

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Shadow GPD definition

We define shadow GPD $H^{(n)}$ of order n such that when T is expanded in powers of α_s up to n one has:

$$0 = \int_{-1}^{1} \frac{\mathrm{d}x}{\xi} T^{(n)}\left(\frac{x}{\xi}, \frac{Q^2}{\mu_0^2}, \alpha_s(\mu_0^2)\right) H^{(n)}(x, \xi, t, \mu_0^2) \quad \text{invisible in DVCS}$$

$$0 = H^{(n)}(x, 0, 0) \quad \text{invisible in DIS}$$

A part of the GPD functional space is invisible to DVCS and DIS combined

Finding Shadow GPDs I

- We want our shadow GPDs to fulfill all the good theoretical properties of standard GPDs, especially polynomiality

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which is in one to one correspondance with the polynomiality property

N. Chouika *et al*, EPJC 77 (2017)

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Adding Mellin moments (computed on the Lattice) provides other sets of order N equations.

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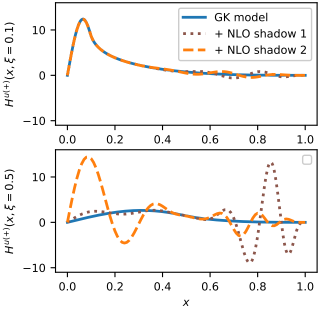
- We expect CFF computed from evolved NLO shadow GPDs to exhibit an α_s^2 behaviour under evolution (provided that the logs remain small enough).



- NLO analysis of shadow GPDs:
  - Cancelling the line $x = \xi$ is necessary but **no longer** sufficient
  - Additional conditions brought by NLO corrections reduce the size of the “shadow space”...
  - ... but do not reduce it to 0
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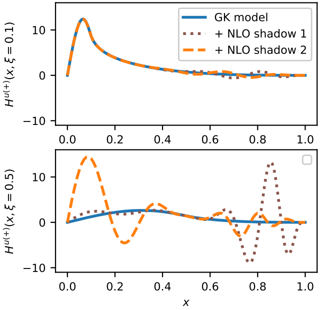
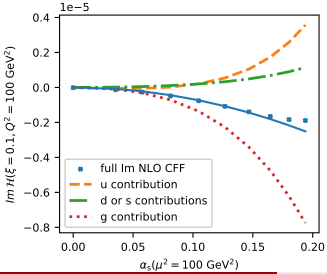
H. Dutrieux *et al.*, PRD 103 114019 (2021)

The DVCS deconvolution problem II





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- Evolution
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A. Freund PLB 472, 412 (2000)
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  - but in practice it is not the case

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A tale of two eigenvalues

$$\begin{pmatrix} a \pm \delta \\ 0 \pm \delta \end{pmatrix} = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \epsilon \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

- (a, b) is our experimental vector (measured), (x, y) is our unknown
- Now let's assume that $\lambda_1 \sim 1$ and $\lambda_2 = \epsilon << 1$
- Finally, our experimental data are known with a finite precision δ and b is compatible with zero.
- Let us put numbers everywhere : $a = 1.4$, $\delta = 0.1$, $\lambda_1 = 2$, $\epsilon = 10^{-3}$

$$x = 0.7 \pm 0.05, \quad y = 0 \pm 100$$

- You should use theory constraints if you know some to get relevant values for y:

$$\sqrt{x^2 + y^2} \leq \rho_{\rm max} \Rightarrow y = 0 \pm \sqrt{\rho_{\rm max}^2 - x^2}$$

- even if $\rho_{\rm max} \simeq 10$, you gain an order of magnitude and theory **is** driving your knowledge of y.

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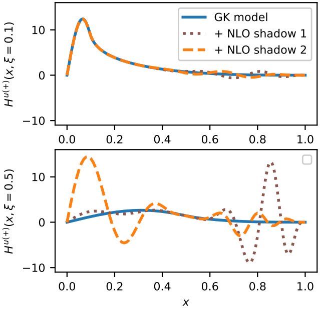

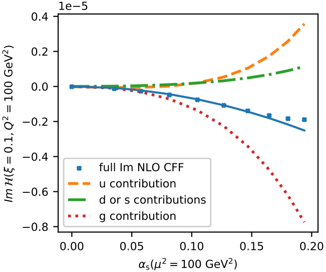

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Theoretical uncertainties promoted to main source of GPDs uncertainties

Improving the deconvolution problem

- Introduce theoretical inputs coming from QCD constraints
  - Change of methods with introduction of theoretical bias
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- Introduce theoretical inputs coming from QCD constraints
  - Change of methods with introduction of theoretical bias
  - Positivity is going to play an important role
- Go to multichannel analysis
  - Shadow GPDs are process-dependent, *i.e.* some processes can see the shadow GPDs of others
  - Some exclusive processes are expected *not* to have shadow GPDs at all (but they are harder to measure).
    - ★ Double DVCS is the most obvious one

      K. Deja *et al.*,PRD 107 (2023) 9, 094035
    - ★ New 2 $\to$ 3 exlusive processes are also good candidates

      R. Boussarie *et al.*, JHEP 02 (2017) 054
      O. Grocholski *et al.*,Phys.Rev.D 104 (2021) 11,
      J.-W. Qiu and Z. Yu, JHEP 08 (2022) 103

GPD properties and replicas techniques

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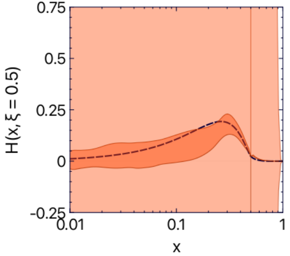

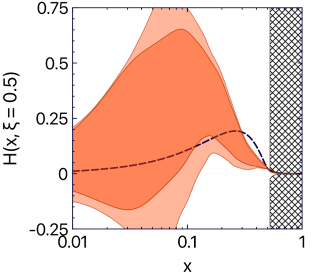

H. Dutrieux *et al.*, EPJC 82 (2022) 3, 252

Impact of Lattice QCD

Lattice QCD can now compute matrix elements connected to GPDs:

$$I(\nu, \xi, t, z^2) = \int \mathrm{d}x C(x, \nu, \xi, z^2, \mu^2) H(x, \xi, t, \mu^2)$$

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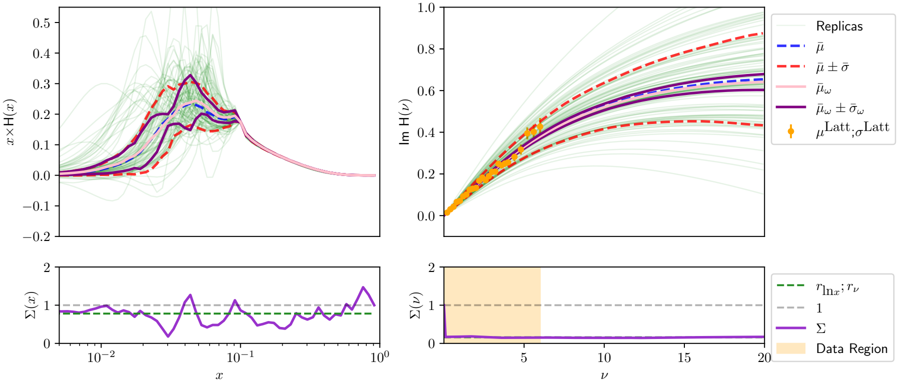

M. Riberdy *et al.*, Eur.Phys.J.C 84 (2024) 2, 201

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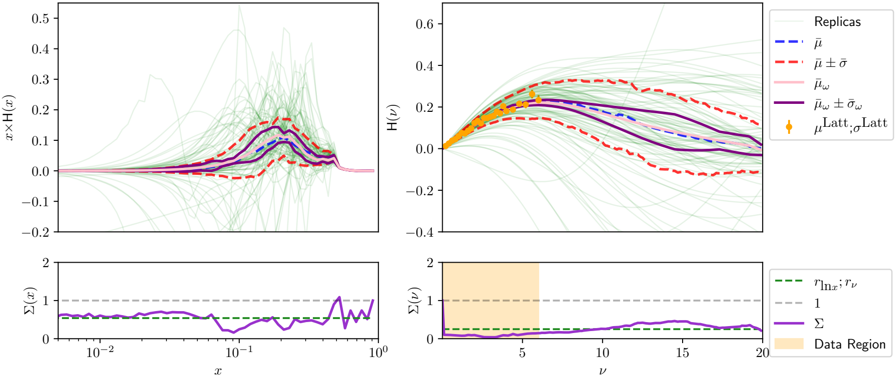

M. Riberdy *et al.*, Eur.Phys.J.C 84 (2024) 2, 201

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- We need to improve the hard kernel where it matters the most
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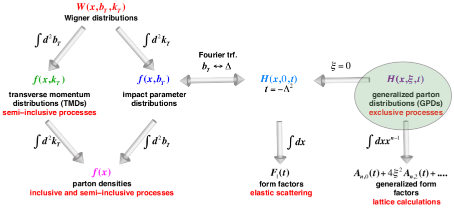
Summary

- Introduction to GPDs and their place in hadron structure studies



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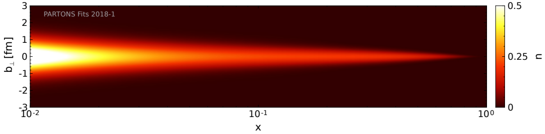

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- Focus on two important properties: polynomiality and positivity

$$\int_{-1}^{1} \mathrm{d}x\; x^m H^q(x,\xi,t;\mu) = \sum_{j=0}^{\left[\frac{m}{2}\right]} (2\xi)^{2j} A^q_{2j,m}(t;\mu) + mod(m,2)(2\xi)^{m+1} C^q_{m+1}(t;\mu)$$

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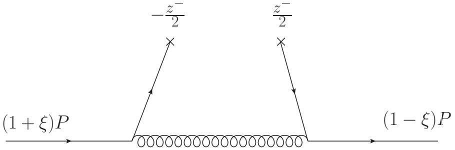

Summary

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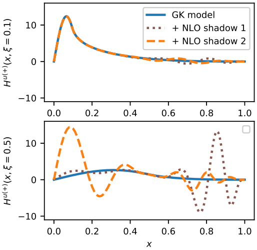
- We have discussed their interpretation as probability densities on the lightcone
- Focus on two important properties: polynomiality and positivity
- We have studied the one loop evolution properties
- And finally we have discussed the origin of uncertainties in attempts to extract GPDs from experimental data.



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A few words at the end

Time is precious,
and asking questions can make you save a lot of it !

Thank you for your attention !

Some final questions ?