# Generalised Partons Distributions at the time of high precision experiments


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June $6^{th}$, 2024

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# Introduction

- Generalised Parton Distributions (GPDs):

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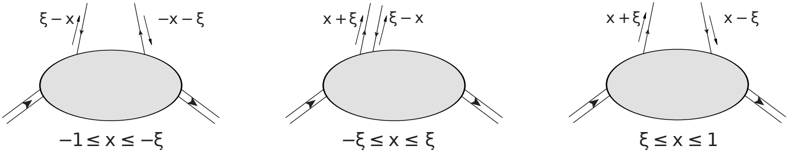
  - "hadron-parton" amplitudes which depend on three variables $(x, \xi, t)$ and a scale $\mu$,




  - ★ $x$: average momentum fraction carried by the active parton
  - ★ $\xi$: skewness parameter $\xi \simeq \frac{x_B}{2-x_B}$
  - ★ $t$: the Mandelstam variable

- Generalised Parton Distributions (GPDs):
  - "hadron-parton" amplitudes which depend on three variables $(x, \xi, t)$ and a scale $\mu$,
  - are defined in terms of a non-local matrix element,

$$\frac{1}{2}\int \frac{e^{ixP^+z^-}}{2\pi}\langle P+\frac{\Delta}{2}|\bar{\psi}^q(-\frac{z}{2})\gamma^+\psi^q(\frac{z}{2})|P-\frac{\Delta}{2}\rangle \mathrm{d}z^-|_{z^+=0,\mathbf{z}=0}$$
$$= \frac{1}{2P^+}\left[H^q(x,\xi,t)\bar{u}\gamma^+u + E^q(x,\xi,t)\bar{u}\frac{i\sigma^{+\alpha}\Delta_\alpha}{2M}u\right].$$

$$\frac{1}{2}\int \frac{e^{ixP^+z^-}}{2\pi}\langle P+\frac{\Delta}{2}|\bar{\psi}^q(-\frac{z}{2})\gamma^+\gamma_5\psi^q(\frac{z}{2})|P-\frac{\Delta}{2}\rangle \mathrm{d}z^-|_{z^+=0,\mathbf{z}=0}$$
$$= \frac{1}{2P^+}\left[\tilde{H}^q(x,\xi,t)\bar{u}\gamma^+\gamma_5 u + \tilde{E}^q(x,\xi,t)\bar{u}\frac{\gamma_5\Delta^+}{2M}u\right].$$

D. Müller *et al.*, Fortsch. Phy. 42 101 (1994)
X. Ji, Phys. Rev. Lett. **78**, 610 (1997)
A. Radyushkin, Phys. Lett. **B380**, 417 (1996)

4 GPDs without helicity transfer + 4 helicity flip GPDs

# Generalised Parton Distributions

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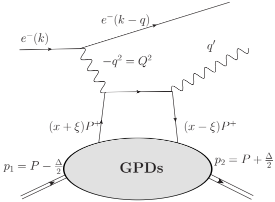
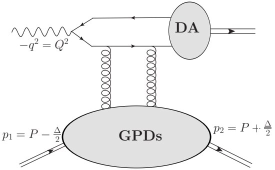
  - are related to PDF in the forward limit $H(x, \xi = 0, t = 0; \mu) = q(x; \mu)$
  - are universal, *i.e.* are related to the amplitude of various exclusive processes through convolutions

$$\mathcal{H}(\xi, t) = \int \mathrm{d}x \; C(x, \xi) H(x, \xi, t)$$



# Main current and future facilities

- Current experimental facilities: fixed targets

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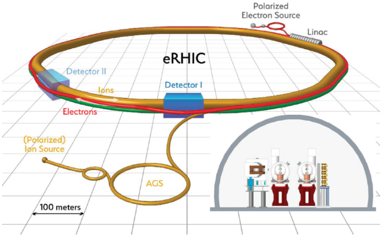
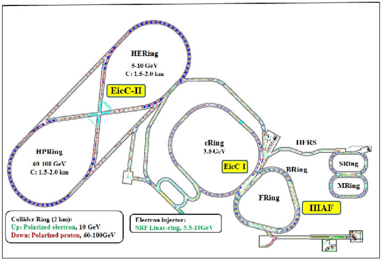
- Future facilities: colliders



# Properties

- Polynomiality Property:

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

X. Ji, J.Phys.G 24 (1998) 1181-1205
A. Radyushkin, Phys.Lett.B 449 (1999) 81-88

Special case :

$$\int_{-1}^{1} \mathrm{d}x\; H^q(x,\xi,t;\mu) = F_1^q(t)$$

Lorentz Covariance

# Properties

- Polynomiality Property:

Lorentz Covariance

- Positivity property:

$$\left| H^q(x,\xi,t) - \frac{\xi^2}{1-\xi^2} E^q(x,\xi,t) \right| \leq \sqrt{\frac{q\left(\frac{x+\xi}{1+\xi}\right) q\left(\frac{x-\xi}{1-\xi}\right)}{1-\xi^2}}$$

A. Radysuhkin, Phys. Rev. **D59**, 014030 (1999)
B. Pire *et al.*, Eur. Phys. J. **C8**, 103 (1999)
M. Diehl *et al.*, Nucl. Phys. **B596**, 33 (2001)
P.V. Pobilitsa, Phys. Rev. **D65**, 114015 (2002)

Positivity of Hilbert space norm

# Properties

- Polynomiality Property:

Lorentz Covariance

- Positivity property:

Positivity of Hilbert space norm

- Support property:

$$x \in [-1; 1]$$

M. Diehl and T. Gousset, Phys. Lett. **B428**, 359 (1998)

Relativistic quantum mechanics

# Properties

- Polynomiality Property:

  Lorentz Covariance

- Positivity property:

  Positivity of Hilbert space norm

- Support property:

  Relativistic quantum mechanics

- Continuity at the crossover lines
  $\rightarrow$ GPDs are continuous albeit non analytical at $x = \pm\xi$

  J. Collins and A. Freund, PRD 59 074009 (1999)

  Factorisation theorem

# Properties

- Polynomiality Property:

Lorentz Covariance

- Positivity property:

Positivity of Hilbert space norm

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Relativistic quantum mechanics

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Factorisation theorem

- Scale evolution property
  $\rightarrow$ generalization of DGLAP and ERBL evolution equations

D. Müller *et al.*, Fortschr. Phys. 42, 101 (1994)

Renormalization

# Properties

- Polynomiality Property:

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Positivity of Hilbert space norm

- Support property:

Relativistic quantum mechanics

- Continuity at the crossover lines

Factorisation theorem

- Scale evolution property

Renormalization

**Problem**

- There is hardly any model fulfilling *a priori* all these constraints.
- Lattice QCD computations remain very challenging.

- In the limit $\xi \to 0$, one recovers a density interpretation:
  - 1D in momentum space $(x)$
  - 2D in coordinate space $\vec{b}_\perp$ (related to $t$)

M. Burkardt, Phys. Rev. **D62**, 071503 (2000)

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M. Burkardt, Phys. Rev. **D62**, 071503 (2000)

- Possibility to extract density from experimental data

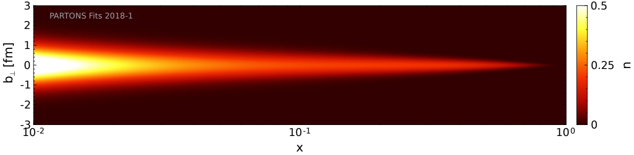


figure from H. Moutarde *et al.*, EPJC 78 (2018) 890

# Interpretation of GPDs I

## 2+1D structure of the nucleon

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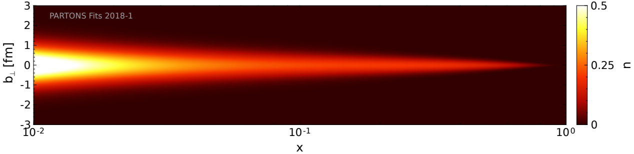


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- Correlation between x and $b_\perp \to$ going beyond PDF and FF.

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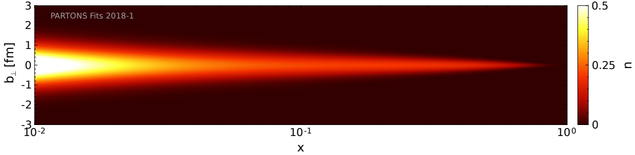


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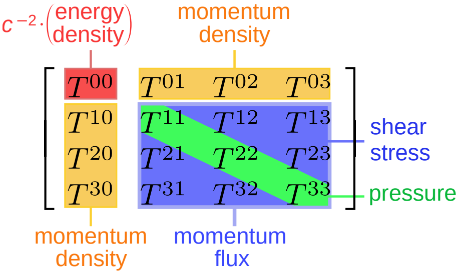
- Correlation between x and $b_\perp \to$ going beyond PDF and FF.
- Caveat: no experimental data at $\xi = 0$
  $\to$ extrapolations (and thus model-dependence) are necessary



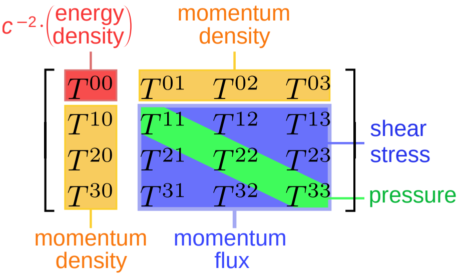

How energy, momentum, pressure are shared between quarks and gluons

Caveat: renormalization scheme and scale dependence

C. Lorcé *et al.*, PLB 776 (2018) 38-47,
M. Polyakov and P. Schweitzer, IJMPA 33 (2018) 26, 1830025
C. Lorcé *et al.*, Eur.Phys.J.C 79 (2019) 1, 89

# Interpretation of GPDs II

## Connection to the Energy-Momentum Tensor

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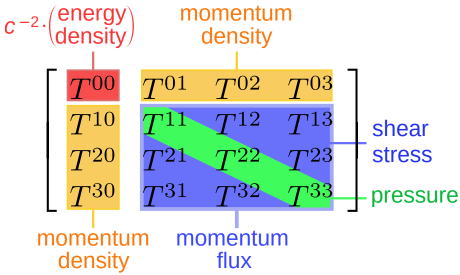
$$\langle p', s' | T^{\mu\nu}_{q,g} | p, s\rangle = \bar{u}\left[P^{\{\mu}\gamma^{\nu\}} A_{q,g}(t;\mu) + \frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} C_{q,g}(t;\mu) + M g^{\mu\nu}\bar{C}_{q,g}(t;\mu) + \frac{P^{\{\mu} i\sigma^{\nu\}\Delta}}{2M} B_{q,g}(t;\mu) + \frac{P^{[\mu} i\sigma^{\nu]\Delta}}{2M}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

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$$\int_{-1}^{1} \mathrm{d}x\, x\, H_q(x,\xi,t;\mu) = A_q(t;\mu) + (2\xi)^2 C_q(t;\mu)$$

$$\int_{-1}^{1} \mathrm{d}x\, x\, E_q(x,\xi,t;\mu) = B_q(t;\mu) - (2\xi)^2 C_q(t;\mu)$$

- Ji sum rule
- Fluid mechanics analogy

X. Ji, PRL 78, 610-613 (1997)
M.V. Polyakov PLB 555, 57-62 (2003)

Accessing GPDs from experimental data

# PARTONS and Gepard

## Integrated softwares as a mandatory step for phenomenology

| PARTONS | Gepard |
|---|---|
| partons.cea.fr | gepard.phy.hr |
| B. Berthou *et al.*, EPJC 78 (2018) 478 | K. Kumericki, EPJ Web Conf. 112 (2016) 01012 |

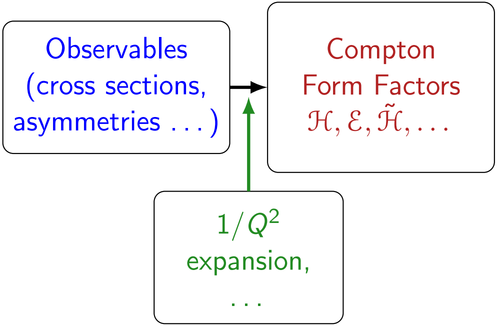
- Similarities : NLO computations, BM formalism, ANN, . . .
- Differences : models, evolution, . . .

### Physics impact

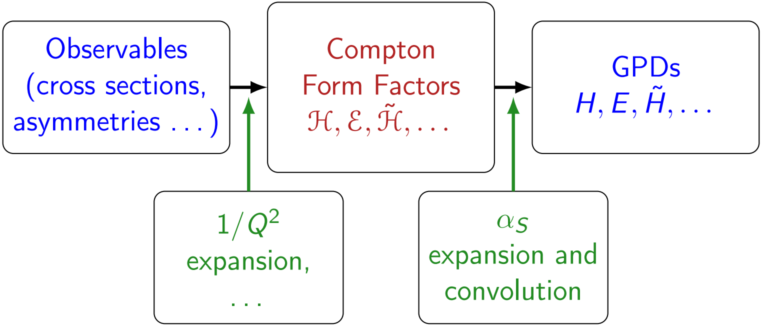
These integrated softwares are the mandatory path toward reliable multichannel analyses.

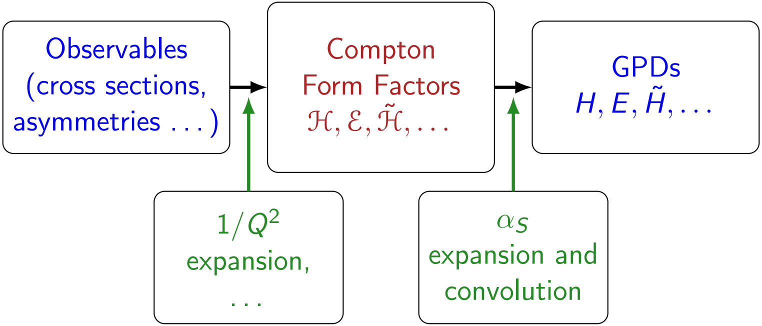
# Experimental connection to GPDs

Observables
(cross sections,
asymmetries . . . )


Observables
(cross sections,
asymmetries . . . )
Compton
Form Factors
$\mathcal{H}, \mathcal{E}, \tilde{\mathcal{H}}, \ldots$
$1/Q^2$
expansion,
. . .

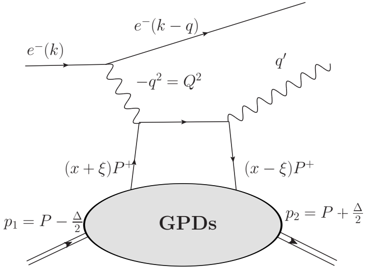
# Experimental connection to GPDs



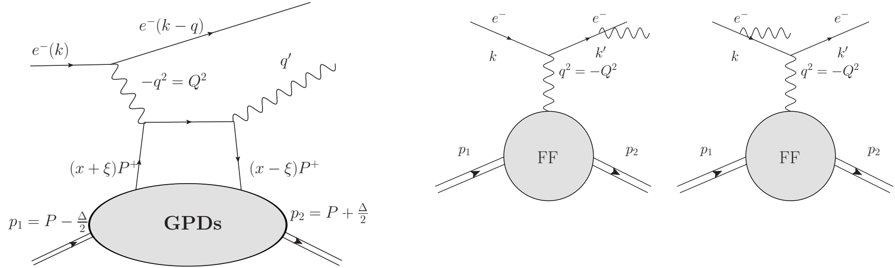



- CFFs play today a central role in our understanding of GPDs
- Extraction generally focused on CFFs

# Deep Virtual Compton Scattering



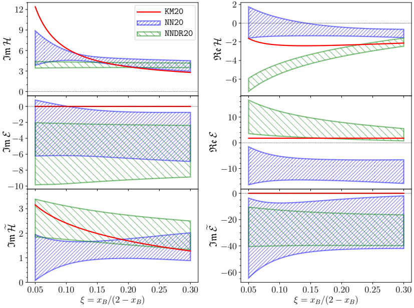

- Best studied experimental process connected to GPDs
  → Data taken at Hermes, Compass, JLab 6, JLab 12



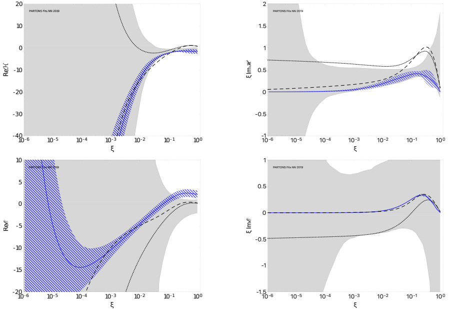

- Best studied experimental process connected to GPDs
  $\rightarrow$ Data taken at Hermes, Compass, JLab 6, JLab 12
- Interferes with the Bethe-Heitler (BH) process
  - Blessing: Interference term boosted w.r.t. pure DVCS one
  - Curse: access to the angular modulation of the pure DVCS part difficult

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

# 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)

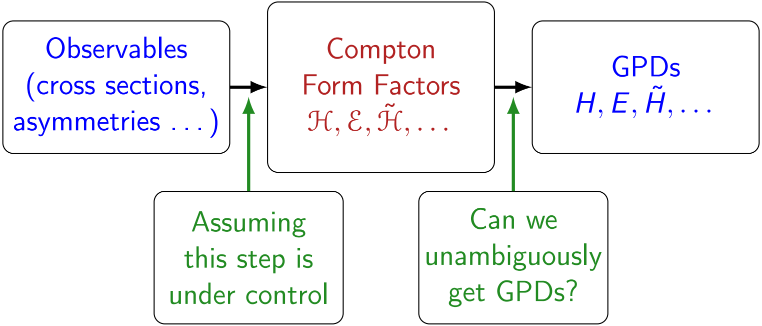
  additional ongoing studies, J. Grigsby *et al.*, PRD 104 (2021) 016001

- 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)

# The DVCS deconvolution problem I

## From CFF to GPDs



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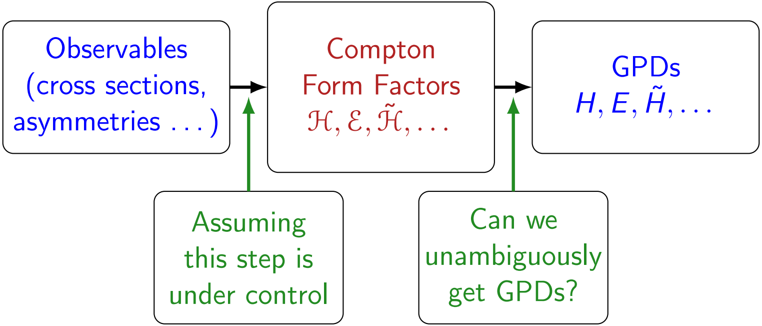
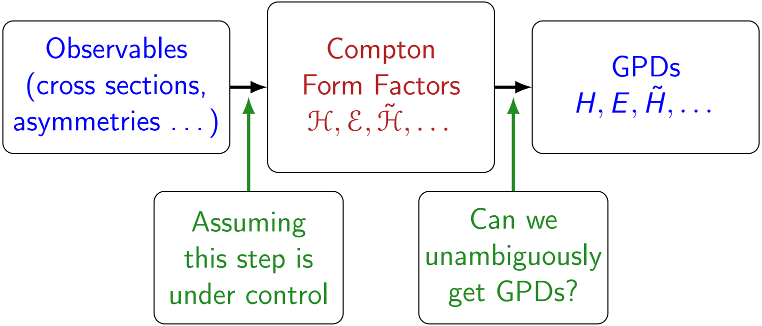



- It has been known for a long time that this is not the case at LO
  Due to dispersion relations, any GPD vanishing on $x = \pm\xi$ would not contribute to DVCS at LO (neglecting D-term contributions).

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  Due to dispersion relations, any GPD vanishing on $x = \pm\xi$ would not contribute to DVCS at LO (neglecting D-term contributions).
- Are QCD corrections improving the situation?

# Introducing shadow GPDs

## CFF Definition

$$\underbrace{\mathcal{H}(\xi, t, Q^2)}_{\text{Observable}} = \int_{-1}^{1} \frac{\mathrm{d}x}{\xi} \underbrace{T\left(\frac{x}{\xi}, \frac{Q^2}{\mu^2}, \alpha_s(\mu^2)\right)}_{\text{Perturbative DVCS kernel}} H(x, \xi, t, \mu^2)$$

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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 $\alpha_s$ 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

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

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

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

- We expanded $f_{\mathrm{shadow}}$ on polynomials of order $N$, so that we have a number of coefficient of order $N^2$.

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

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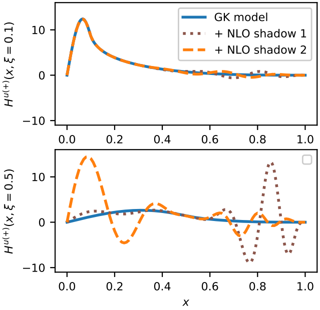
- We expect CFF computed from evolved NLO shadow GPDs to exhibit an $\alpha_s^2$ behaviour under evolution (provided that the logs remain small enough).

# The DVCS deconvolution problem II




- 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 $\rightarrow$ NLO shadow GPDs

H. Dutrieux *et al.*, PRD 103 114019 (2021)

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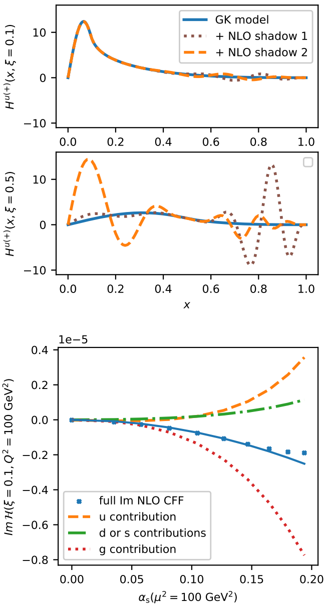


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A. Freund PLB 472, 412 (2000)
E. Moffat *et al.*, PRD 108 (2023)

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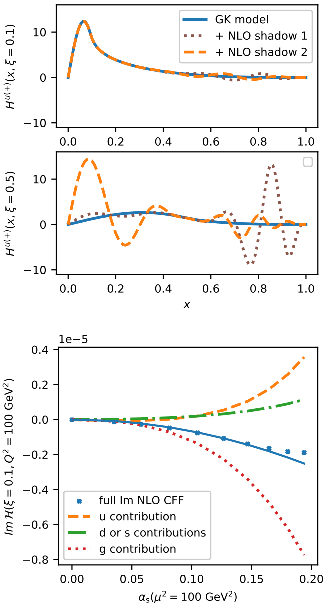


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Theoretical uncertainties promoted to main source of GPDs uncertainties

# 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 $\rightarrow$ 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
  - View lQCD Ioffe-time ratios as an additional process to be included in a global fit

Model $H = H_{\text{visible}} + H_{\text{shadow}}$ with two different neural networks fulfilling by construction all the properties but one, the positivity property.

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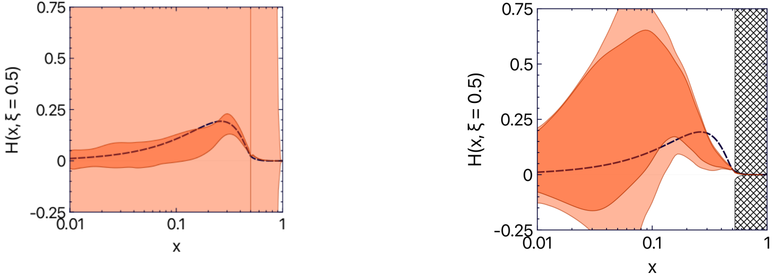


H. Dutrieux *et al.*, EPJC 82 (2022) 3, 252

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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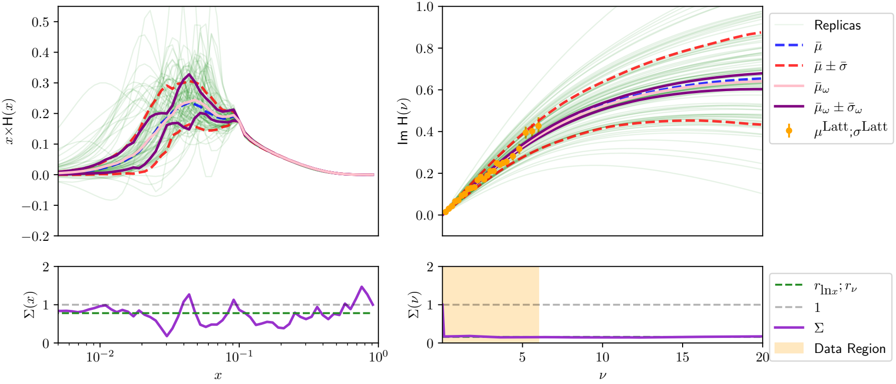


M. Riberdy *et al.*, Eur.Phys.J.C 84 (2024) 2, 201

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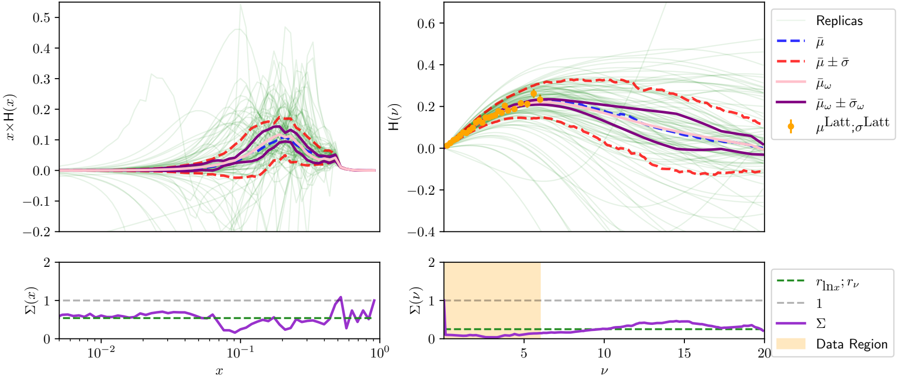


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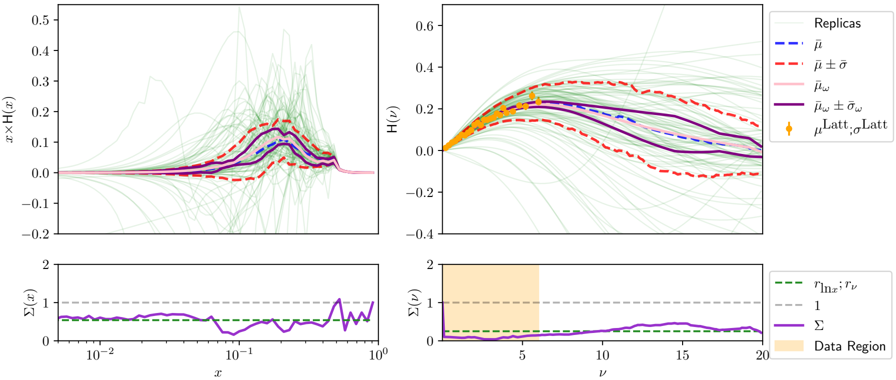
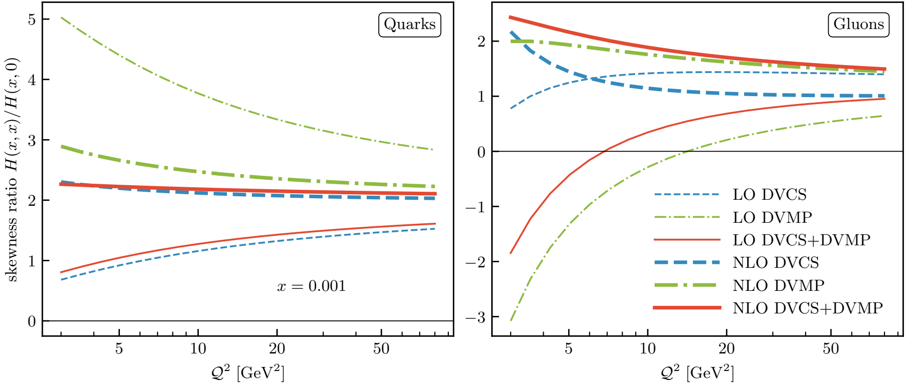



M. Riberdy *et al.*, Eur.Phys.J.C 84 (2024) 2, 201

We can expect a reduction of the deconvolution uncertainties

Multichannel Fit of GPDs

# Recent result of NLO DVCS-DVMP fit



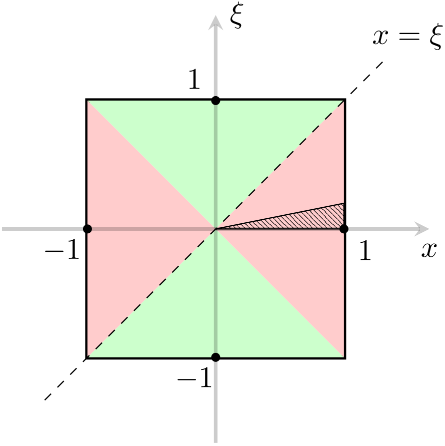

M. Cuic *et al.*, JHEP 12 (2023) 192

- Extraction of quark and gluon GPDs from NLO-DVCS and NLO-DVMP
- Inverse problem regularised through moments parametrisation and truncation

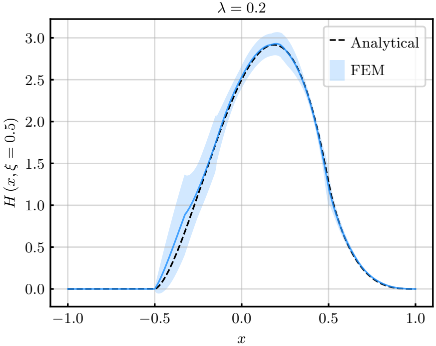
# GPD reconstruction from incomplete knowledge

# Limited Inverse Radon transform for GPDs

Idea : exploit $x$ and $\xi$ entanglement triggered by the Radon Transform.




$\lambda = 0.2$




P. Dall-Olio *et al.*, PRD 109 (2024) 9, 096013

Sullivan process and access to pion GPDs

# Sullivan Process

Can we measure DVCS on a virtual pion ?

D. Amrath *et al.*, EPJC 58 (2008) 179-192
J. M. Morgado Chavez *et al.*, PRL 128 202501

If yes, it is a good way to challenge many computations in the literature.

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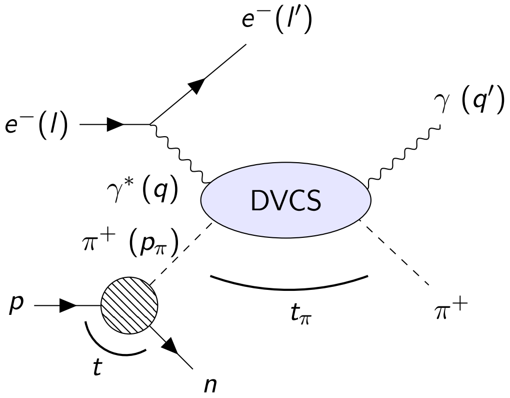
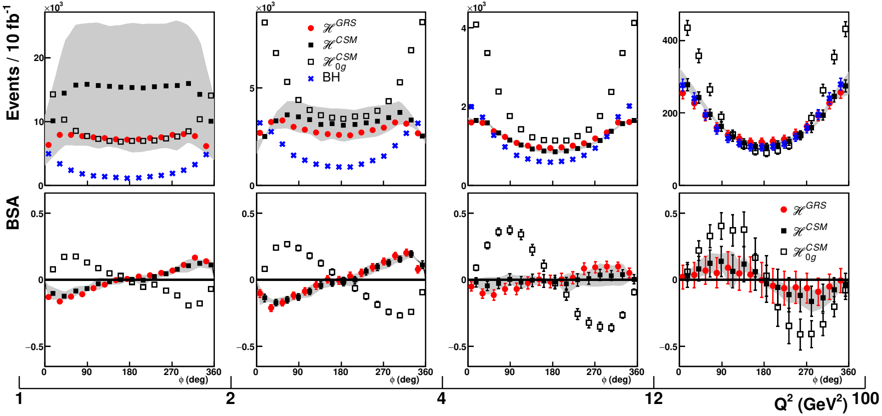



- $e^- p \to e^- \gamma \pi^+ n$
- kinematical cuts to avoid $N^*$ resonances
- Already used to extract pion EFF at JLab
- Considered for pion structure function at EIC and EicC

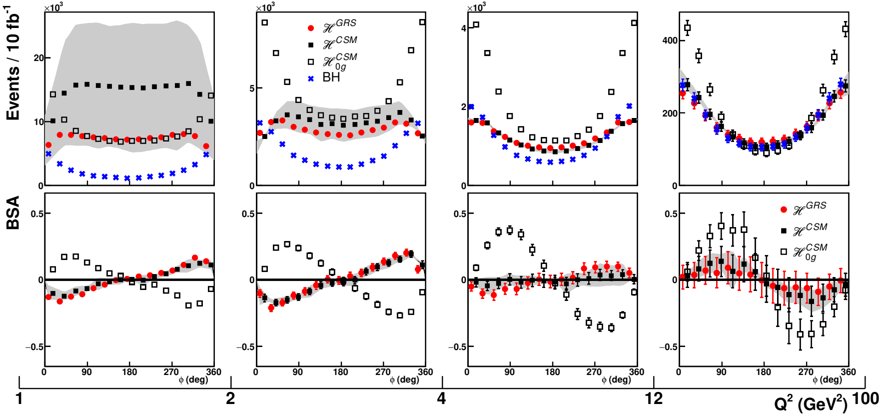
EIC Yellow report, Nucl.Phys.A 1026 (2022) 122447
EicC white paper, Front.Phys.(Beijing) 16 (2021) 6, 64701

J. M. Morgado Chavez *et al.*, PRL 128 202501



# An example on the pion

J. M. Morgado Chavez *et al.*, PRL 128 202501




DVCS off virtual pion may be measurable at EIC and EicC

# Unmentioned topics of PARTONS team

- Event generator EpIC for EIC E.C. Aschenhauer *et al.*, Eur.Phys.J.C 82 (2022) 9, 819
- Impact studies at JLab 12 O. Bessidskaia *et al.*, Phys.Rev.D 107 (2023) 1, 014020
- Small-$x$ GPDs and connection with gluon PDFs H. Dutrieux *et al.*, Phys.Rev.D 107 (2023) 11, 114019
- Feasibility of DDVCS K. Deja *et al.*, Phys.Rev.D 107 (2023) 9, 094035
- Nucleon GPD modelling from LFWFs M. Riberdy *et al.*, in preparation
- Extraction of pressure distributions at NLO H. Dutrieux *et al.*, in preparation
- Structure of heavy mesons on the lattice B. Blossier *et al.*
- Kinematic higher-twist corrections for DVCS, TCS and DDVCS V. Martinez-Fernandez *et al.*
- GPDs in UPC through exclusive quarkonia photoproduction CM *et al.*
- Reconstruction of GPDs from partial DGLAP knowledge P. Dall'Olio *et al.*, PRD 109 (2024) 9, 096013

# Conclusions

## Summary

- A new experimental era is starting with very precise data coming
- It is triggering a precision leap in phenomenology
- The question of theoretical uncertainties (and how to reduce them) becomes crucial

## Perspectives

- Efforts in phenomenology remain to be done (CFF/TFF and GPD)
- Multichannel analysis could help solving the deconvolution problem
- Ab-initio computations will provide insights in the next decade
- No golden solution, at least for now...

The perspective of new and precise data is a real challenge and will trigger leaps in our knowledge of the 3D structure of the nucleon.

Thank you for your attention

# Back up slides