Exclusive processes at EIC

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October 9^{th}, 2024

Introduction

Generalised Parton Distributions

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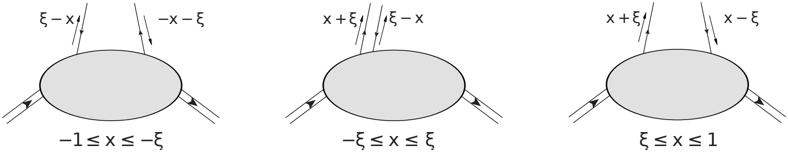
  - "hadron-parton" amplitudes which depend on three variables (x, ξ, t) and a scale μ,



  - ★ x: average momentum fraction carried by the active parton
  - ★ ξ: 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, ξ, t) and a scale μ,
  - are defined in terms of a non-local matrix element,

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

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

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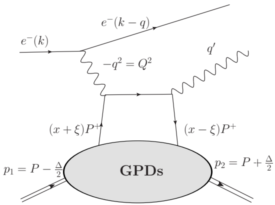
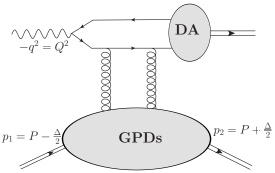
  - are related to PDF in the forward limit $H(x, \xi = 0, t = 0; \mu) = q(x; \mu)$
  - are universal, *i.e.* are related to the amplitude of various exclusive processes through convolutions

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





- Polynomiality Property:

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

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

- 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

- Support property:

  Relativistic quantum mechanics

- Continuity at the crossover lines

  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:

  Lorentz Covariance

- Positivity property:

  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)

Interpretation of GPDs I

2+1D structure of the nucleon

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- Possibility to extract density from experimental data

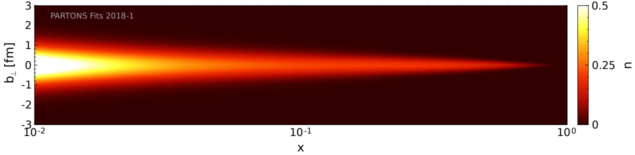

figure from H. Moutarde *et al.*, EPJC 78 (2018) 890

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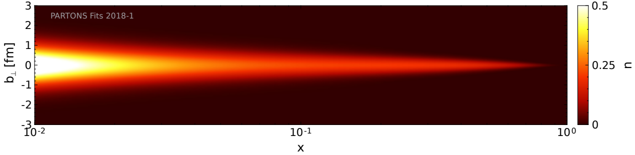

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- Correlation between x and $b_\perp \to$ going beyond PDF and FF.

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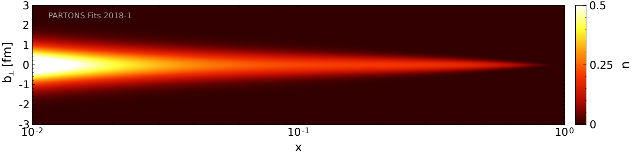

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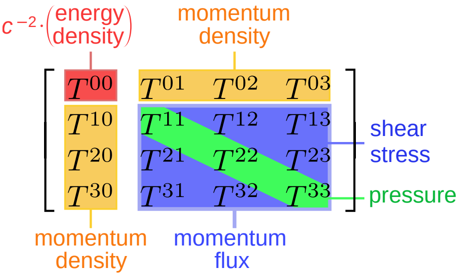
- Correlation between x and $b_\perp \to$ going beyond PDF and FF.
- Caveat: no experimental data at $\xi = 0$
  $\to$ extrapolations (and thus model-dependence) are necessary

Interpretation of GPDs II

Connection to the Energy-Momentum Tensor



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

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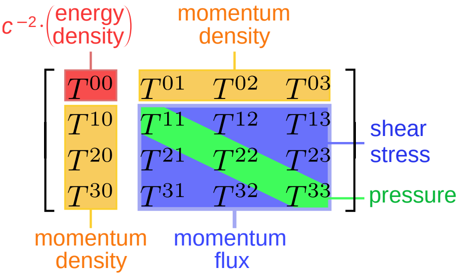

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$$\langle p', s' | T^{\mu\nu}_{q,g} | p, s\rangle = \bar{u}\left[P^{\{\mu}\gamma^{\nu\}} A_{q,g}(t;\mu) + \frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} C_{q,g}(t;\mu) + M g^{\mu\nu}\bar{C}_{q,g}(t;\mu) + \frac{P^{\{\mu} i\sigma^{\nu\}\Delta}}{2M}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

Interpretation of GPDs II

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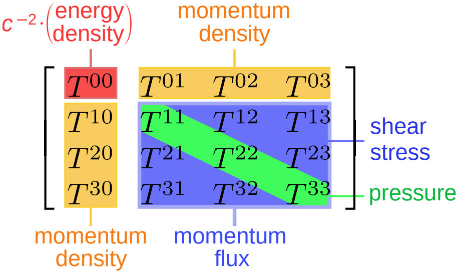

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$$\int_{-1}^{1} \mathrm{d}x\, x\, H_q(x,\xi,t;\mu) = A_q(t;\mu) + (2\xi)^2 C_q(t;\mu)$$

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

- 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

partons.cea.fr

B. Berthou *et al.*, EPJC 78 (2018) 478

Gepard

gepard.phy.hr

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.

Eur. Phys. J. C (2022) 82:819
https://doi.org/10.1140/epjc/s10052-022-10651-z

THE EUROPEAN PHYSICAL JOURNAL C

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Special Article - Tools for Experiment and Theory

EpIC: novel Monte Carlo generator for exclusive processes

E. C. Aschenauer[1,a], V. Batozskaya[2,b], S. Fazio[3,c], K. Gates[4,d], H. Moutarde[5,e], D. Sokhan[4,5,f], H. Spiesberger[6,g], P. Sznajder[2,h], K. Tezgin[1,i]

[1] Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA
[2] National Centre for Nuclear Research (NCBJ), Pasteura 7, 02-093 Warsaw, Poland
[3] University of Calabria and INFN-Cosenza,, 87036 Rende (CS), Italy
[4] University of Glasgow, Glasgow G12 8QQ, UK
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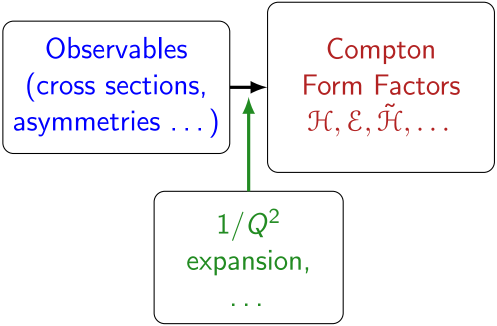
Received: 13 June 2022 / Accepted: 27 July 2022

Experimental connection to GPDs

Observables
(cross sections,
asymmetries . . .)

Experimental connection to GPDs



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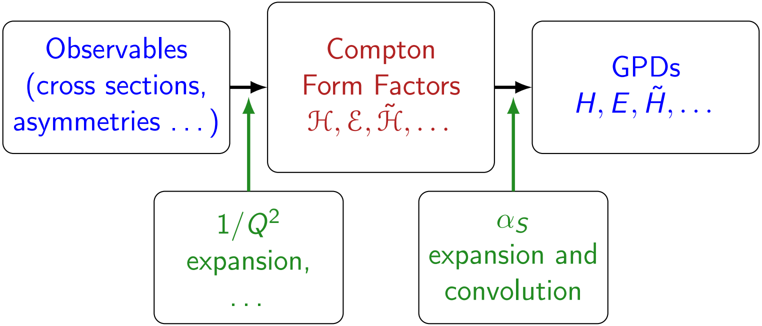
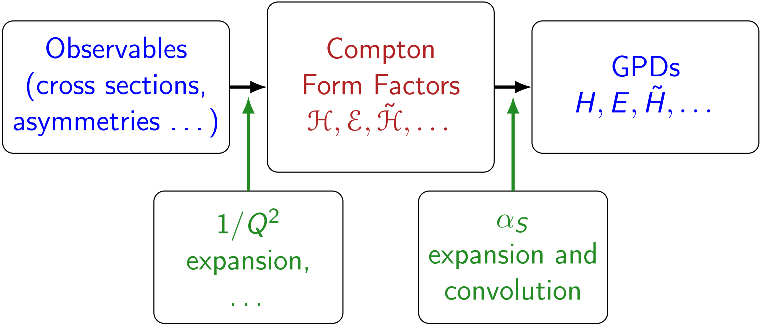
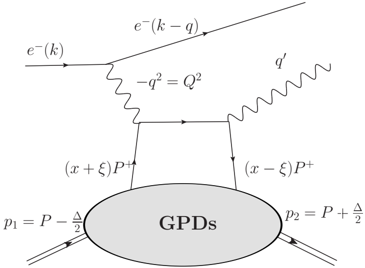




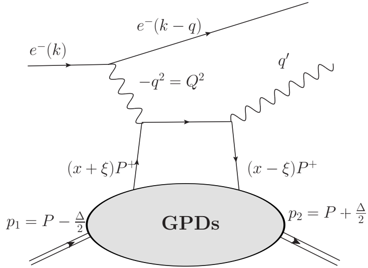
- CFFs play today a central role in our understanding of GPDs
- Extraction generally focused on CFFs

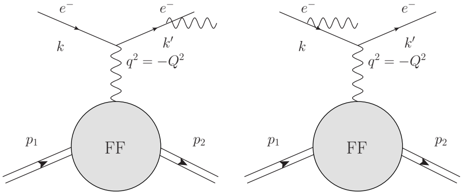


- Best studied experimental process connected to GPDs

  $\rightarrow$ Data taken at Hermes, Compass, JLab 6, JLab 12

Deep Virtual Compton Scattering

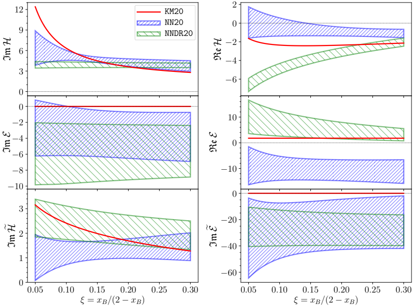




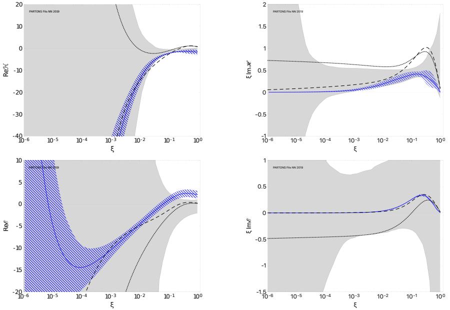
- Best studied experimental process connected to GPDs
  $\rightarrow$ Data taken at Hermes, Compass, JLab 6, JLab 12
- Interferes with the Bethe-Heitler (BH) process
  - Blessing: Interference term boosted w.r.t. pure DVCS one
  - Curse: access to the angular modulation of the pure DVCS part difficult

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)

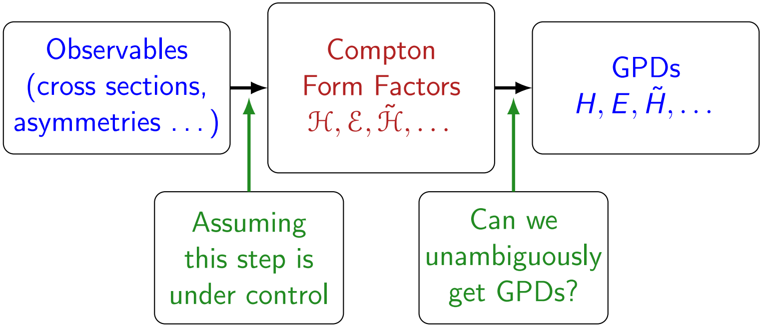
  additional ongoing studies, J. Grigsby *et al.*, PRD 104 (2021) 016001

- 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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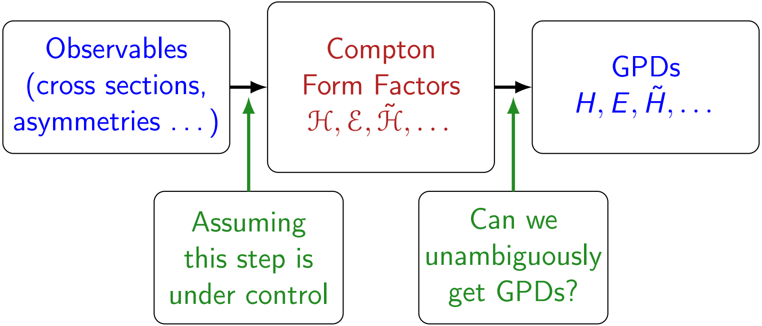

- It has been known for a long time that this is not the case at LO
  Due to dispersion relations, any GPD vanishing on $x = \pm\xi$ would not contribute to DVCS at LO (neglecting D-term contributions).

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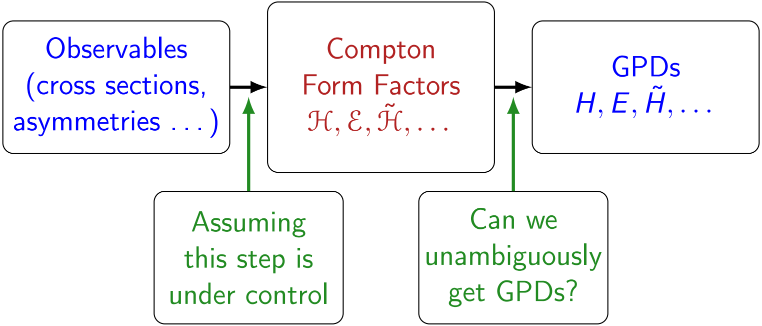

- It has been known for a long time that this is not the case at LO
  Due to dispersion relations, any GPD vanishing on $x = \pm\xi$ would not contribute to DVCS at LO (neglecting D-term contributions).
- Are QCD corrections improving the situation?

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

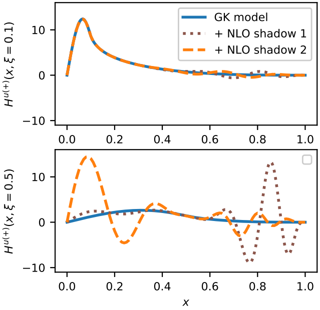
We define shadow GPD $H^{(n)}$ of order n such that when T is expanded in powers of α_s up to n one has:

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

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

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

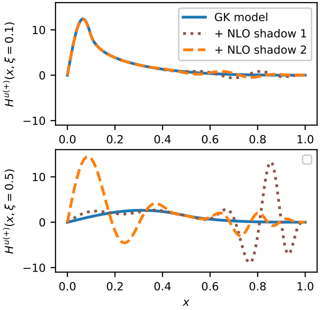
The DVCS deconvolution problem II

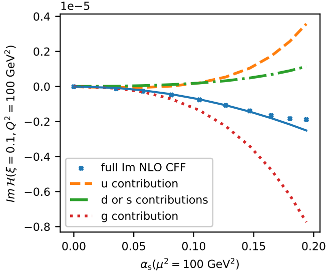


- NLO analysis of shadow GPDs:
  - Cancelling the line $x = \xi$ is necessary but **no longer** sufficient
  - Additional conditions brought by NLO corrections reduce the size of the "shadow space"...
  - ... but do not reduce it to 0 $\rightarrow$ NLO shadow GPDs

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

The DVCS deconvolution problem II





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

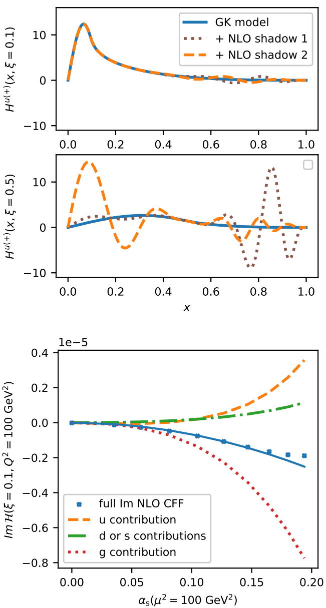
- Evolution
  - it was argued that evolution would solve this issue

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

  - but in practice it is not the case

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

The DVCS deconvolution problem II



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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
  - Positivity is going to play an important role

Improving the deconvolution problem

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

Deconvolution-proof results

CFF Zero crossing

- Quarks and gluons CFFs interfere destructively, *i.e.* there is a minus sign between their contributions at NLO.

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- So, for a given scale Q^2, reducing ξ one will strenghten the gluon contribution compared to the quark one, similarly to what happens with PDFs.
- At some point, the gluon might become so strong that the amplitude vanishes.

CFF Zero crossing

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- So, for a given scale Q^2, reducing ξ one will strenghten the gluon contribution compared to the quark one, similarly to what happens with PDFs.
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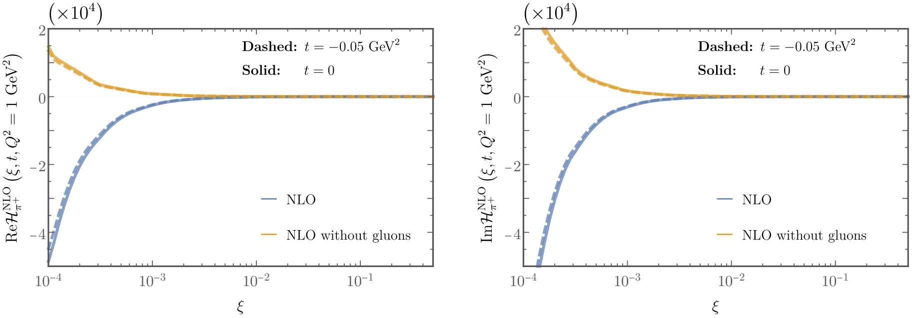
- This is maintained, and even slightly amplified at NNLO.

V. Braun *et al.*, JHEP 09 (2020) 117

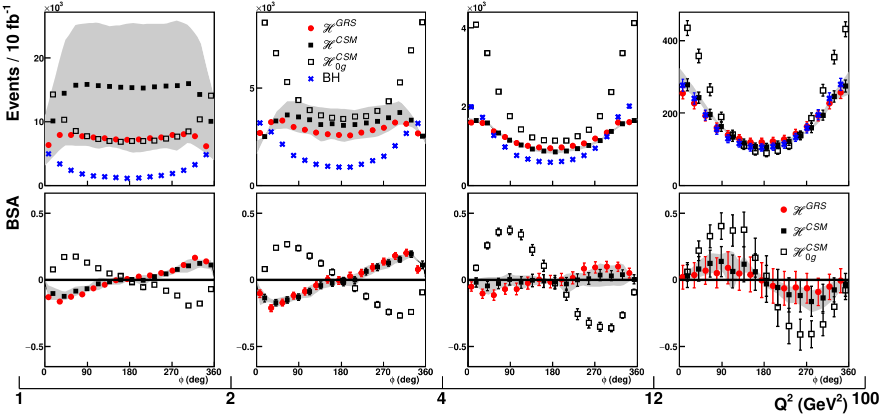
Example on a Pion model



J.-M. Morgado CHavez *et al.*, Phys.Rev.D 105 (2022) 9, 094012

- In such a model, the sign change is clear at the level of the amplitude
- No experimental guidance on the pion, so reality may be different

Impact on observables



J.-M. Morgado CHavez *et al.*, Phys.Rev.Lett. 128 (2022) 20, 202501

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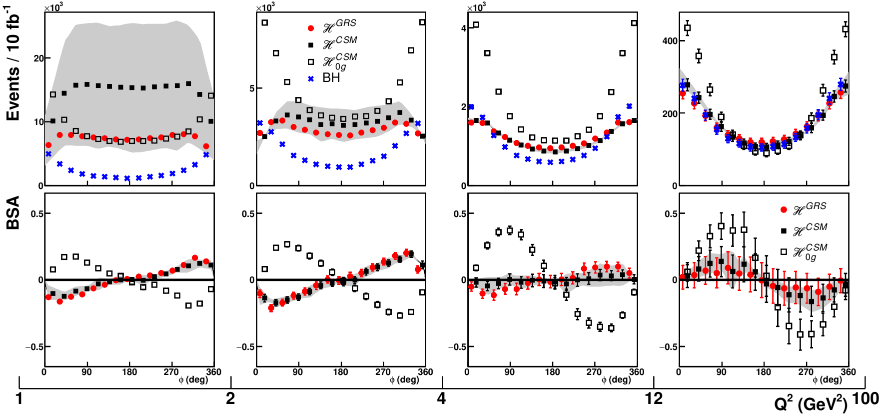

J.-M. Morgado CHavez *et al.*, Phys.Rev.Lett. 128 (2022) 20, 202501

The beam spin asymetry is directly sensitive to the relative strength of quarks and gluons

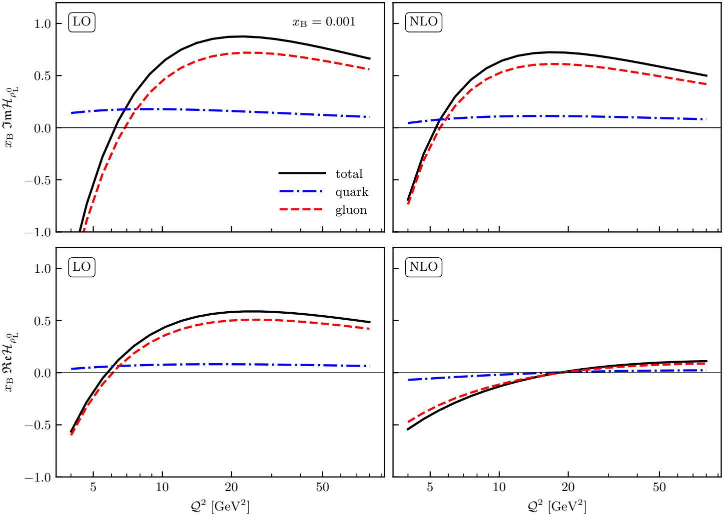

figure from M. Cuic *et al.*, JHEP 12 (2023) 192

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

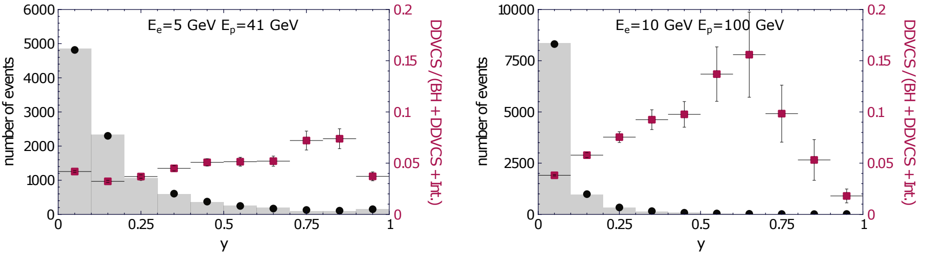
- EIC data promise to be interesting, even independently of the deconvolution problem !

Taming the deconvolution problem

Double DVCS and the deconvolution problem

- DDVCS : $ep \to ep\mu^+\mu^-$
- Main difference : $\mathcal{H}(\rho, \xi, t, Q^2)$
  $\Rightarrow$ this additional kinematic variable give a new level-arm to improve the ill-posed charatere of the deconvolution problem
- However, measuring it requires both a high-luminosity, and an excellent ability to detect the final muon pair
- Can it be seen at EIC ?

DDVCS at EIC



figures from K. Deja *et al.*, Phys.Rev.D 107 (2023) 9, 094035

- Measuring DDVCS observable may be possible at EIC (2.6/2.1 fb^{-1} necessary for 10^4 events)
- However, no detector acceptance nor efficiency was taken into account here
- Deeper studies are needed to assess the feasibility of measuring DDVCS at EIC

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

A word about evolution

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$$\Gamma(\mu^2, \mu_0^2) = 1 + \alpha_s(\mu^2) K^{(0)} \ln\left(\frac{\mu^2}{\mu_0^2}\right) + \mathcal{O}(\alpha_s^2)$$

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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).

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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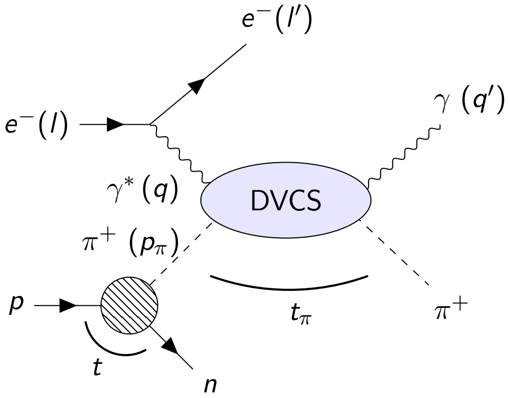
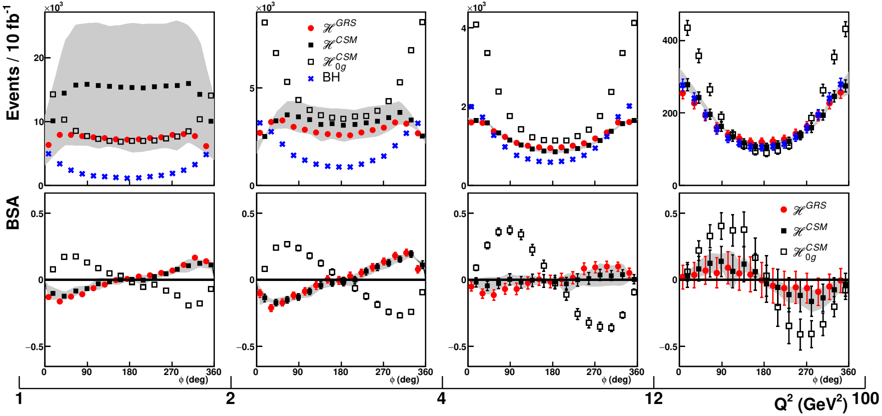


- $e^- p \to e^- \gamma \pi^+ n$
- kinematical cuts to avoid N^* resonances
- Already used to extract pion EFF at JLab
- Considered for pion structure function at EIC and EicC

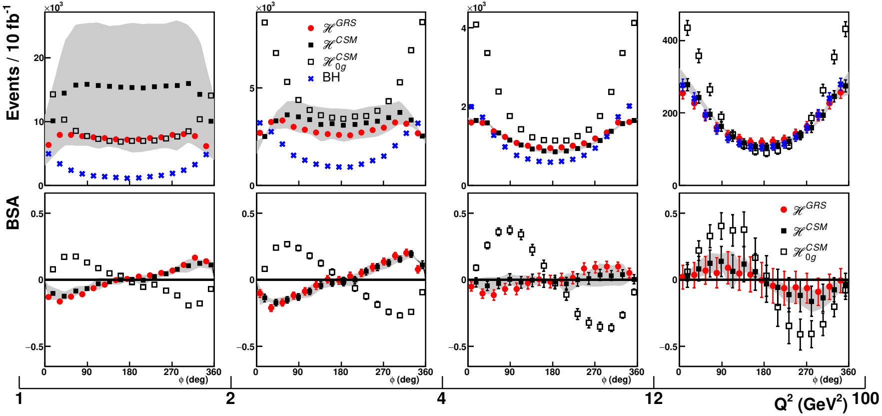
EIC Yellow report, Nucl.Phys.A 1026 (2022) 122447
EicC white paper, Front.Phys.(Beijing) 16 (2021) 6, 64701

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