GPD extraction from experimental data

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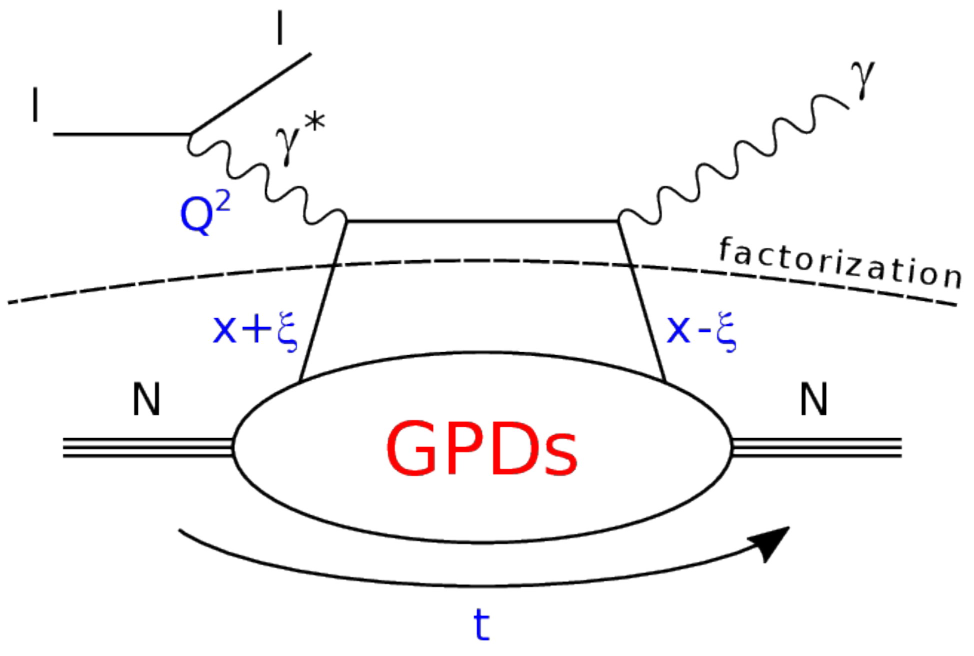
Polarisation measurements in ee, ep and pp and heavy-ions,
IJCLab, December 18th, 2020

Outline

- Introduction
- Experimental campaign
- Recent progress
- Summary

Deeply Virtual Compton Scattering (DVCS)



factorisation for |t|/Q² « 1

Chiral-even GPDs:
(helicity of parton conserved)

$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*for sum over parton helicities*
$\widetilde{H}^{q,g}(x,\xi,t)$	$\widetilde{E}^{q,g}(x,\xi,t)$	*for difference over parton helicities*
nucleon helicity conserved	*nucleon helicity changed*	

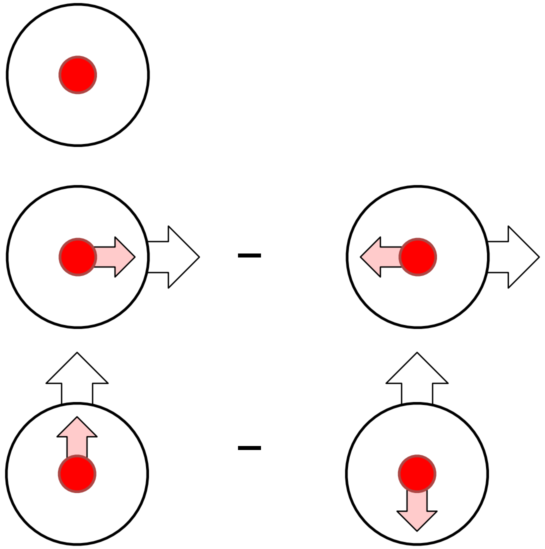
Introduction

- Reduction to PDFs:

$$H^q(x,0,0) \equiv q(x)$$

$$\widetilde{H}^q(x,0,0) \equiv \Delta q(x)$$

$$H_T^q(x,0,0) \equiv h_1(x)$$



no corresponding relations exist for other GPDs

- Reduction to Elastic Form Factors (EFFs):

$$\int_{-1}^{1} dx\, H^q(x,\xi,t) \equiv F_1^q(t) \qquad \int_{-1}^{1} dx\, E^q(x,\xi,t) \equiv F_2^q(t)$$

$$\int_{-1}^{1} dx\, \widetilde{H}^q(x,\xi,t) \equiv g_A^q(t) \qquad \int_{-1}^{1} dx\, \widetilde{E}^q(x,\xi,t) \equiv g_P^q(t)$$

Polynomiality - non-trivial consequence of Lorentz invariance:

$$\int_{-1}^{1} \mathrm{d}x\; x^n H^q(x,\xi,t) = h_0^{q,n}(t) + \xi^2 h_2^{q,n}(t) + \ldots + \mathrm{mod}(n,2)\xi^{n+1} h_{n+1}^{q,n}(t)$$

$$\int_{-1}^{1} \mathrm{d}x\; x^n \widetilde{H}^q(x,\xi,t) = \tilde{h}_0^{q,n}(t) + \xi^2 \tilde{h}_2^{q,n}(t) + \ldots + \mathrm{mod}(n+1,2)\xi^{n} \tilde{h}_{n}^{q,n}(t)$$

Positivity bounds - positivity of norm in Hilbert space, e.g.:

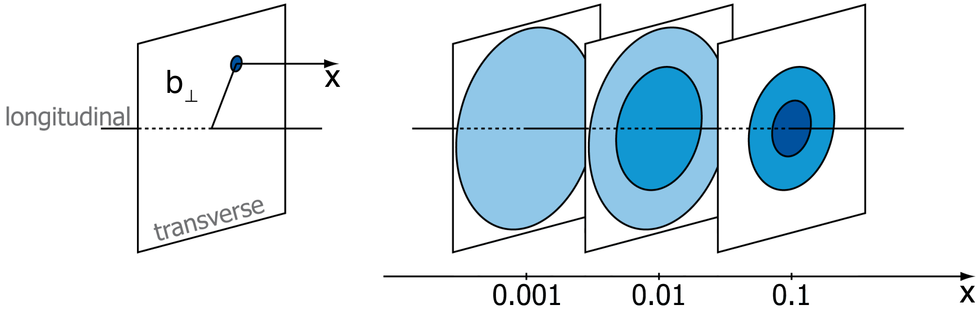
$$(1-\xi^2)\left(H^q - \frac{\xi^2}{1-\xi^2}E^q\right)^2 + \frac{t_0-t}{4m^2}\left(E^q\right)^2 \leq q\left(\frac{x+\xi}{1+\xi}\right) q\left(\frac{x-\xi}{1-\xi}\right)$$

strong constraint on GPD parameterisations!

Introduction

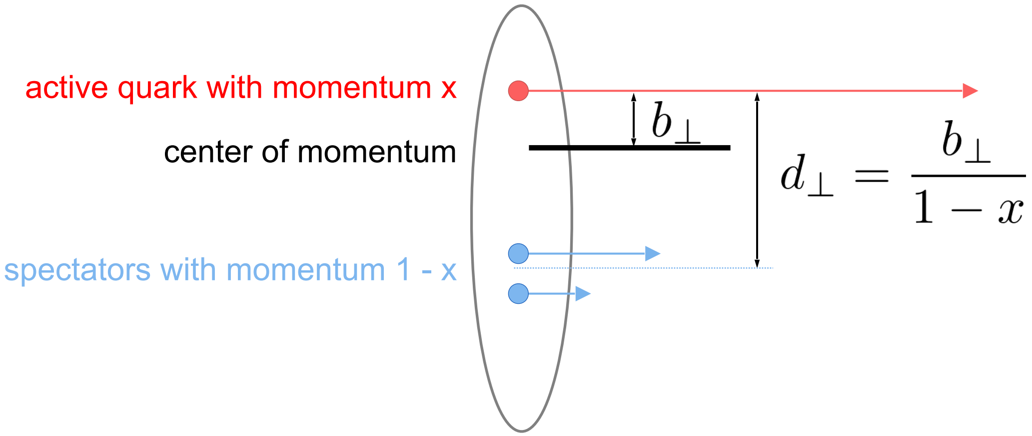
Nucleon tomography

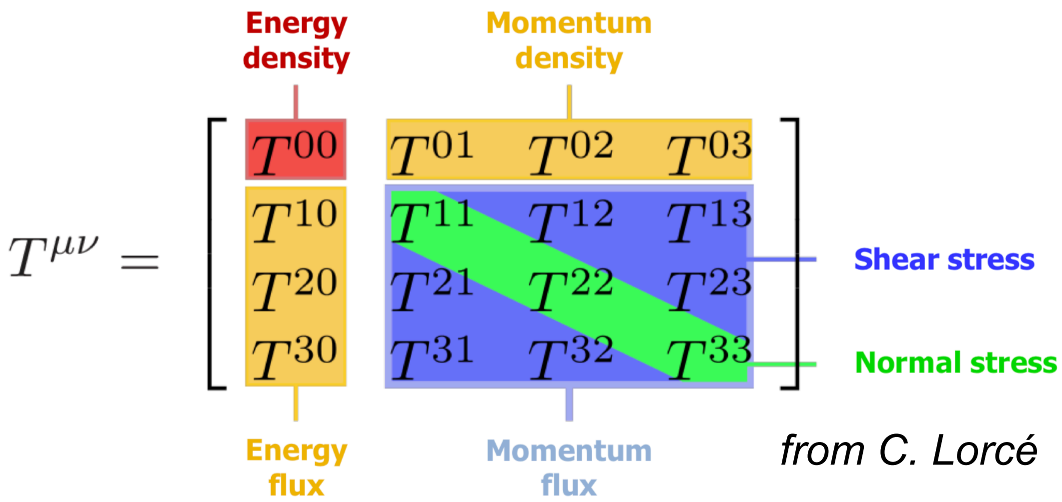
$$q(x, \mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}}{4\pi^2} e^{-i\mathbf{b}_\perp \cdot \mathbf{\Delta}} H^q(x, 0, t = -\mathbf{\Delta}^2)$$



Study of long. polarization with GPD $\widetilde{H}$
Study of distortion in transv. polarized nucleon with GPD E

Impact parameter $\mathbf{b}_\perp$ defined w.r.t. center of momentum, such as $\sum x\, \mathbf{b}_\perp = 0$





from C. Lorcé

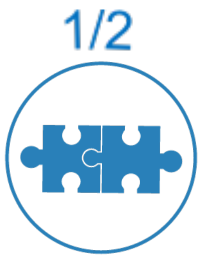
Energy momentum tensor in terms of form factors:

$$\langle p', s'|\widehat{T}^{\mu\nu}|p, s\rangle = \bar{u}(p', s')\Bigg[\frac{P^\mu P^\nu}{M} A(t) + \frac{\Delta^\mu \Delta^\nu - \eta^{\mu\nu}\Delta^2}{M} C(t) + M\eta^{\mu\nu}\bar{C}(t) + \frac{P^\mu i\sigma^{\nu\lambda}\Delta_\lambda}{4M}\left[A(t) + B(t) + D(t)\right] + \frac{P^\nu i\sigma^{\mu\lambda}\Delta_\lambda}{4M}\left[A(t) + B(t) - D(t)\right]\Bigg] u(p, s)$$

Introduction

Total angular momentum

$$A^q(0) + B^q(0) = \int_{-1}^{1} x \left[H^q(x, \xi, 0) + E^q(x, \xi, 0) \right] = 2J^q$$

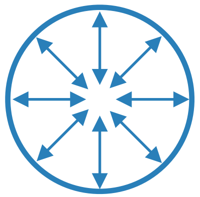


Ji’s sum rule

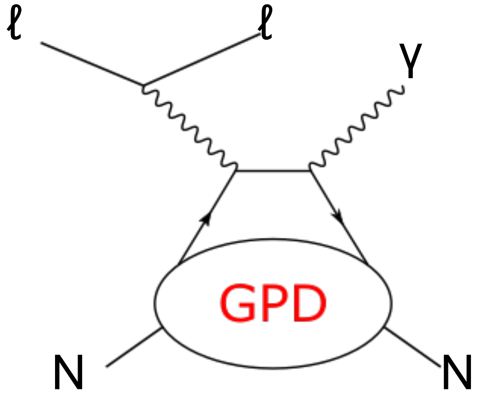
Introduction

"Mechanical" forces acting on quarks, e.g. pressure in nucleon center

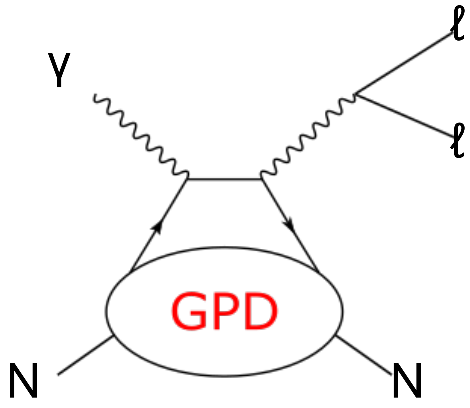
$$p(0) = \frac{1}{6\pi^2 M} \int_{-\infty}^{0} dt \sqrt{-t}\, t C(t)$$



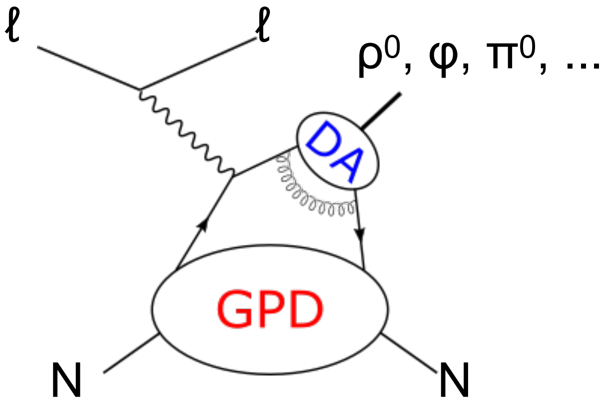
GPDs accessible in various production channels and observables
→ experimental filters



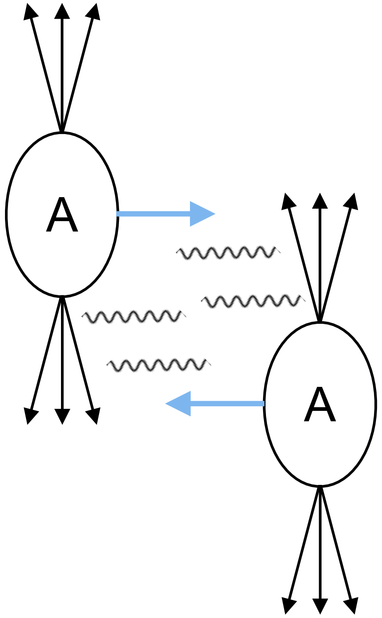
DVCS
Deeply Virtual Compton Scattering



TCS
Timelike Compton Scattering



HEMP
Hard Exclusive Meson Production



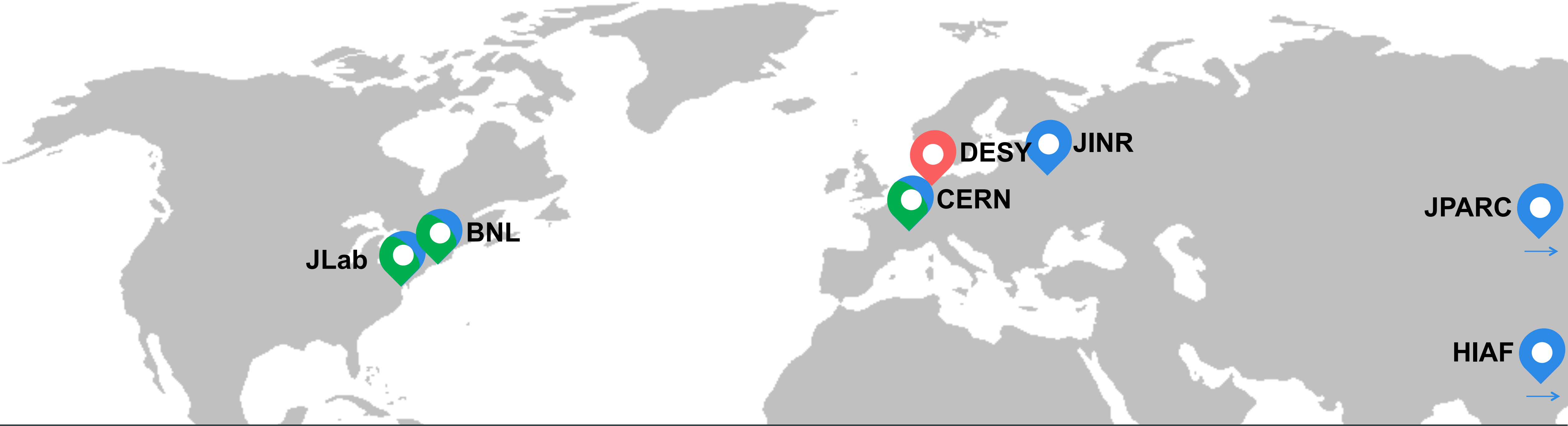
UPC
Ultra Peripheral Collisions

more production channels sensitive to GPDs exist!

GPDs studied in various laboratories
→ need to cover a broad kinematic range

experiments

closed **active** **planned**

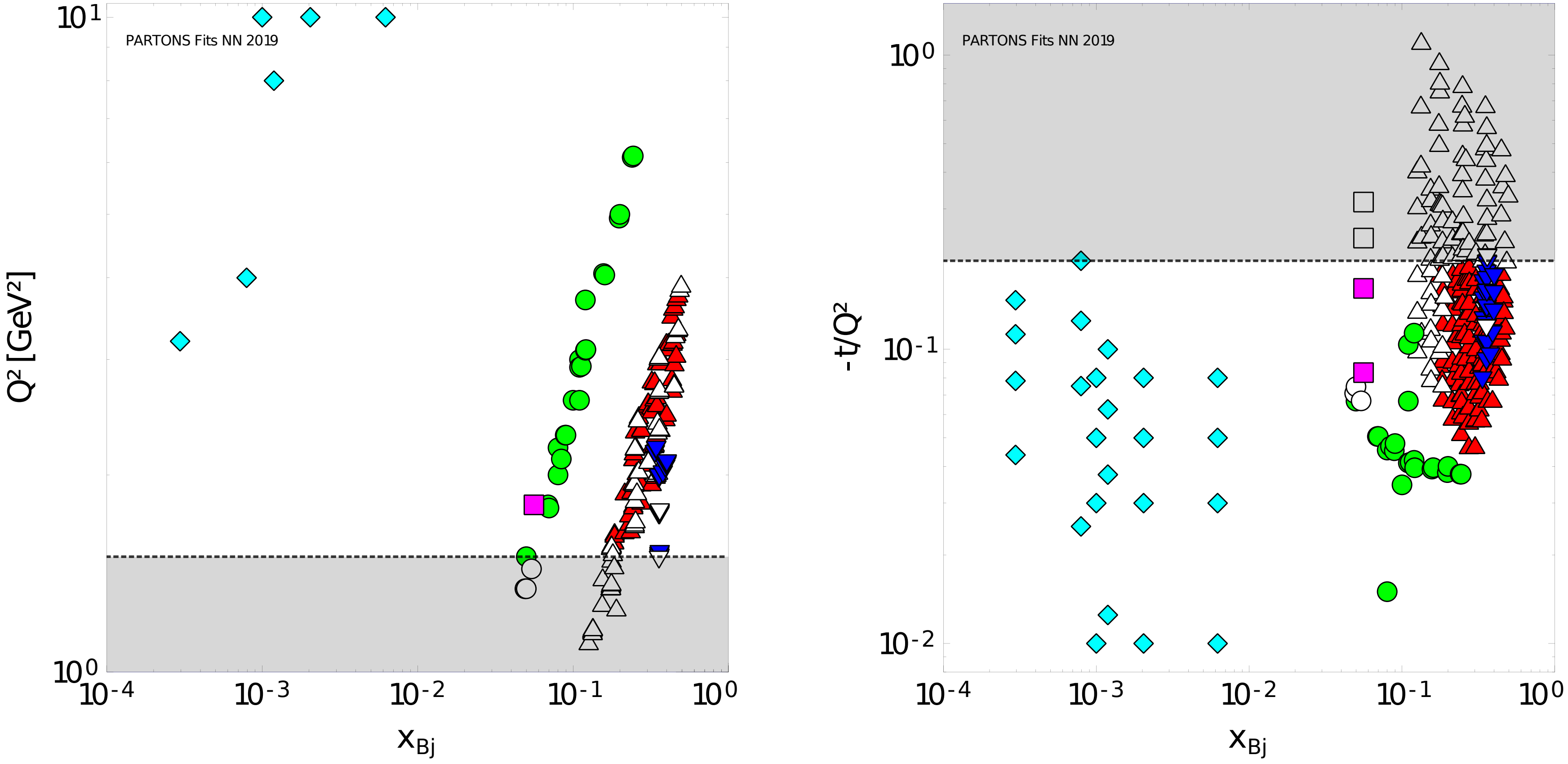


Kinematic cuts
used in our recent analyses:

$$Q^2 > 1.5\ \mathrm{GeV}^2$$

$$-t/Q^2 < 0.2$$

- HALL A
- CLAS
- HERMES
- COMPASS
- H1 and ZEUS

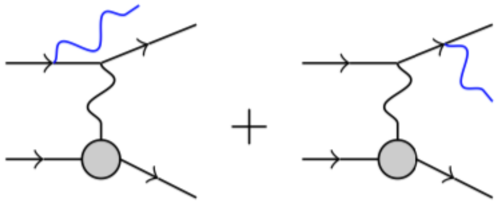


Compton Form Factors

Cross-section for single photon production $(l + N \rightarrow l + N + \gamma)$:

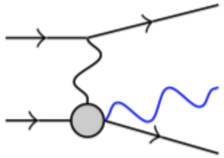
$$\sigma \propto |\mathscr{A}|^2 = |\mathscr{A}_{BH} + \mathscr{A}_{DVCS}|^2 = |\mathscr{A}_{BH}|^2 + |\mathscr{A}_{DVCS}|^2 + \mathscr{I}$$

Bethe-Heitler process



calculable within QED

DVCS



parametrised by CFFs

CFF - the most basic GPD-sensitive observables
- analogy with connection between structure functions and PDFs

- imaginary part

$$Im\mathcal{G}(\xi, t) \quad = \pi G^{(+)}(\xi, \xi, t) = \pi \sum_q e_q^2 G^{q(+)}(\xi, \xi, t)$$

$$G^{q(+)}(x, \xi, t) = G^q(x, \xi, t) \mp G^q(-x, \xi, t)$$

$$G^{q(+)}(\xi, \xi, t) = G^{q_{\mathrm{val}}}(\xi, \xi, t) + 2G^{q_{\mathrm{sea}}}(\xi, \xi, t)$$

"−" for $G \in \{H, E\}$
"+" for $G \in \{\widetilde{H}, \widetilde{E}\}$

- real part

$$Re\mathcal{G}(\xi, t) = \mathrm{P.V.} \int_0^1 G^{(+)}(x, \xi, t) \left(\frac{1}{\xi - x} \mp \frac{1}{\xi + x} \right) \mathrm{d}x$$

$$Re\mathcal{G}(\xi, t) = \mathrm{P.V.} \int_0^1 G^{(+)}(x, x, t) \left(\frac{1}{\xi - x} \mp \frac{1}{\xi + x} \right) \mathrm{d}x + C_G(t)$$

$$C_H(t) = -C_E(t) \qquad C_{\widetilde{H}}(t) = C_{\widetilde{E}}(t) = 0$$

connected to EMT FF

Subtraction Constant

Relation between subtraction constant and D-term:

$$C_G^q(t) = 2\int_{-1}^{1} \frac{D^q(z,t)}{1-z}\mathrm{d}z \equiv 4D^q(t)$$

where

$$z = \frac{x}{\xi}$$

Decomposition into Gegenbauer polynomials:

$$D^q(z,t) = (1-z^2)\sum_{i=0}^{\infty} d_i^q(t) C_{2i+1}^{3/2}(z)$$

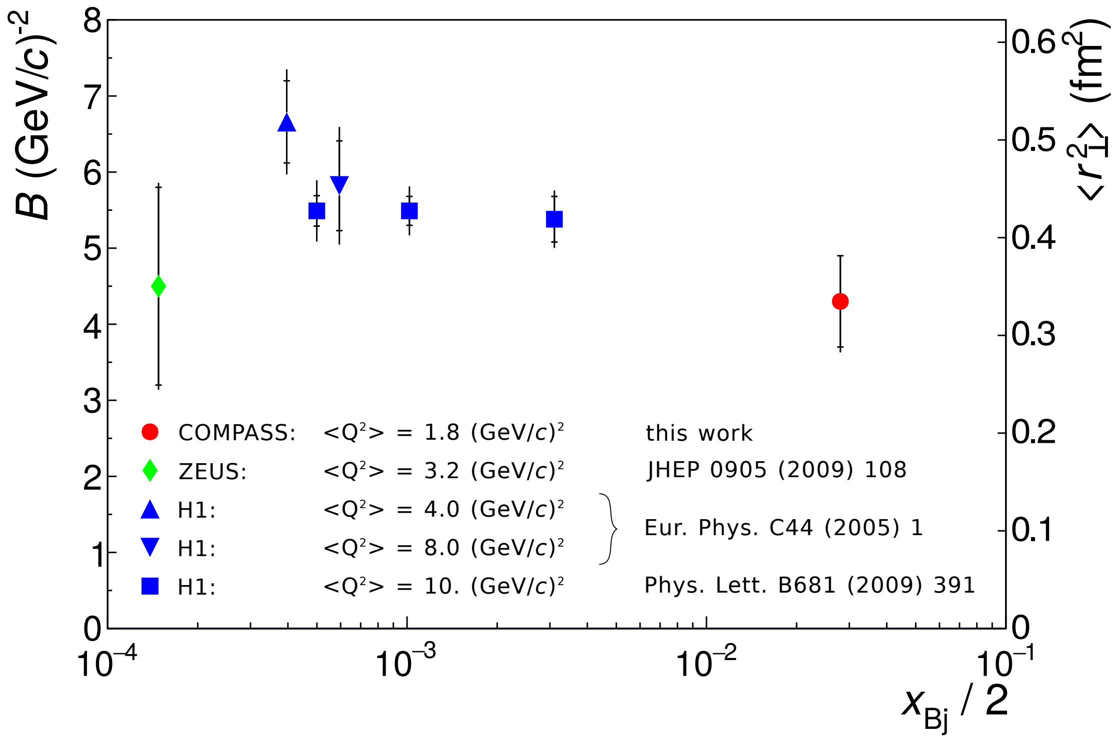
Connection to EMT FF:

$$D^q(t) = \sum_{\substack{i=1\\ \mathrm{odd}}}^{\infty} d_i^q(t)$$

$$d_1^q(t) = 5C^q(t)$$

- "Direct" measurement at low-x

COMPASS Collaboration, Phys. Lett. B793 (2019) 188



Slope of t-dependance:

$$\frac{d\sigma^{\gamma^* p \to \gamma p}}{dt} \propto e^{-Bt}$$

related to transverse extension of quarks:

$$\langle r_\perp^2(x_{\mathrm{Bj}}) \rangle \approx 2 \langle B(x_{\mathrm{Bj}}) \rangle$$

under following assumptions:

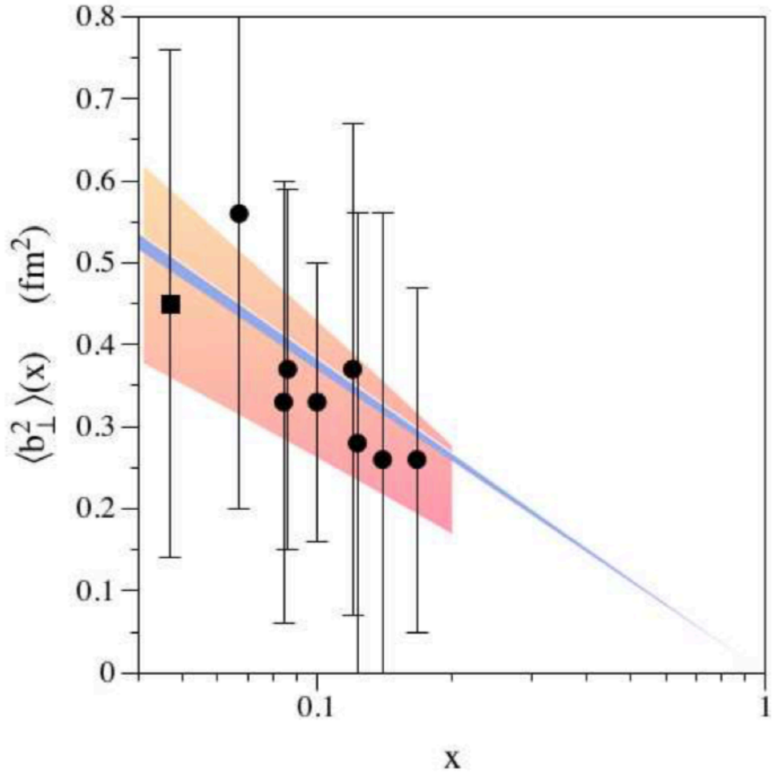
- dominance of CFF Im$\mathcal{H}$
- negligible "skewness effect"
  H(x, x, t) ~ H(x, 0, t)
- single-exponential dependence

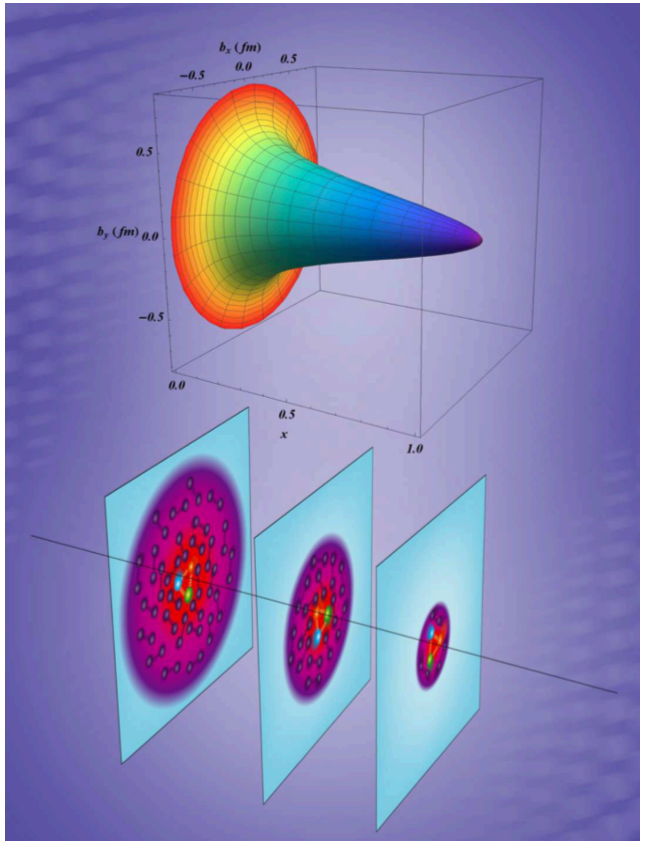
which are applicable at low-x

Nucleon tomography

- Local fits and de-skewness procedure at high-x

Dupre, Guidal, Vanderhaeghen, Phys. Rev. D95 (2017) no. 1, 011501
Dupré, Guidal, Niccolai, Vanderhaeghen, Eur. Phys. J. A53 (2017) no. 8, 171





The procedure:

1. Fit CFFs separately in each (x_B, t, Q^2) bin of data

2. Fit extracted ImH values with

$$Im\mathscr{H}(\xi, t, Q^2) = A(\xi)\ \exp(B(\xi)t)$$

$$A(\xi) = a_A \frac{1-\xi}{\xi}$$

$$B(\xi) = a_B \ln(1/\xi)$$

$$\xi \approx \frac{x_B}{2 - x_B}$$

- Global fits with skewness dependance encoded in Ansatz

H. Moutarde, PS, J. Wagner, Eur. Phys. J. C78 (2018) 11, 890

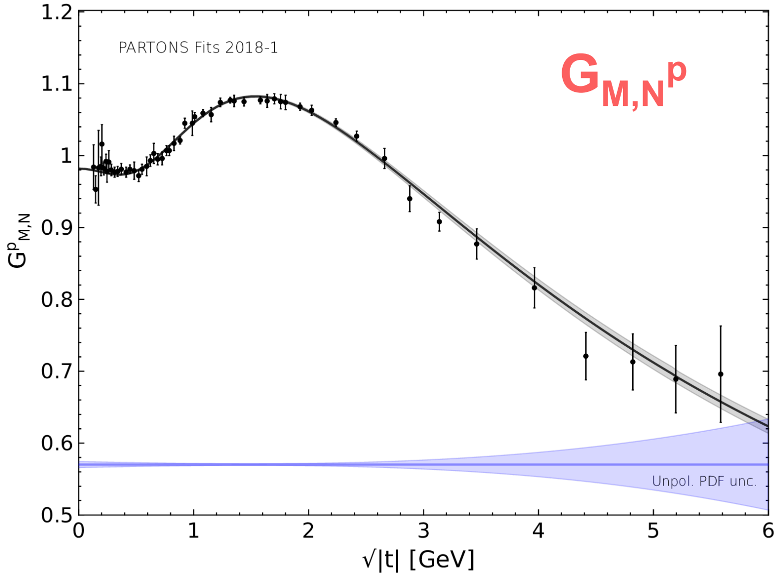
$$G^q(x,x,t) = G^q(x,0,t)\; g^q_G(x,x,t)$$

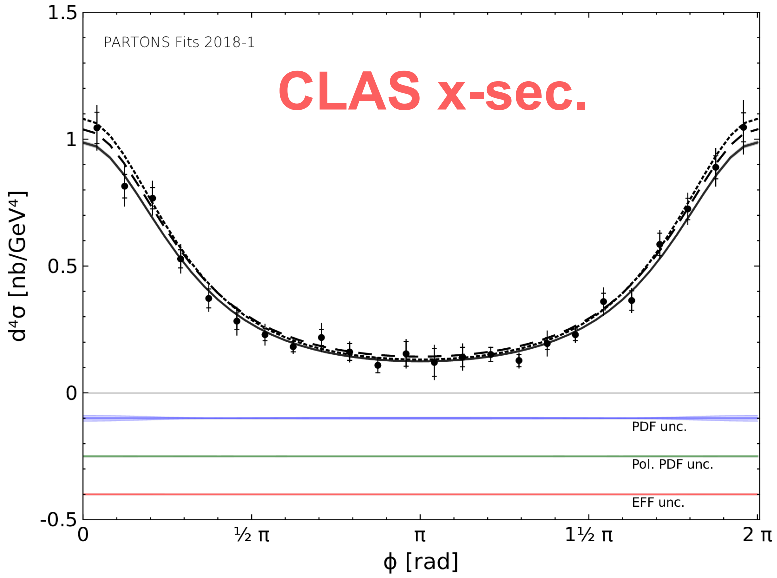
$$G^q(x,0,t) = \mathrm{pdf}^q_G(x)\;\; \exp(f^q_G(x)t)$$

$$g^q_G(x,x,t) = \frac{a^q_G}{(1-x^2)^2}\,(1+t(1-x)(b^q_G + c^q_G \log(1+x)))$$

$$f^q_G(x) = A^q_G \log(1/x) + B^q_G(1-x)^2 + C^q_G(1-x)x$$

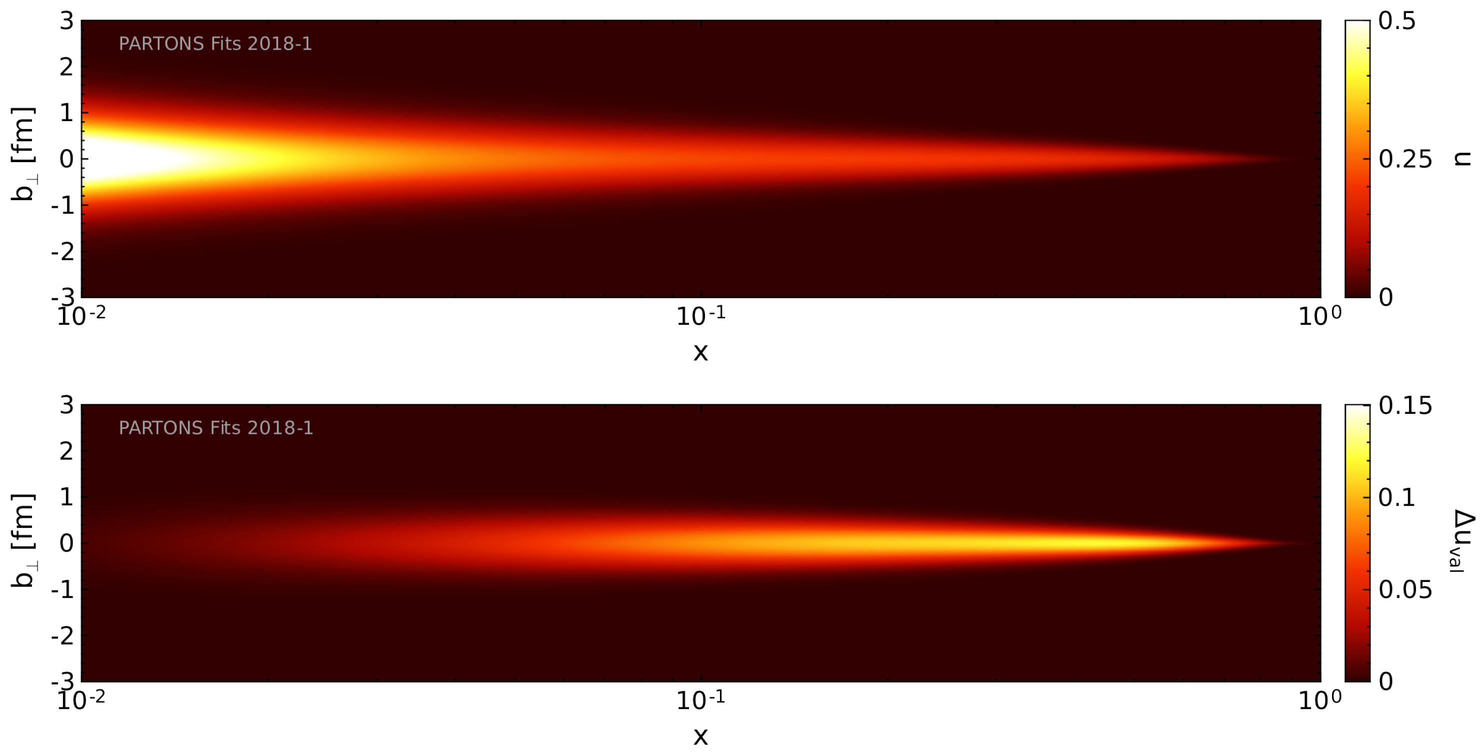
Allows for a global fit of both elastic FF and DVCS data

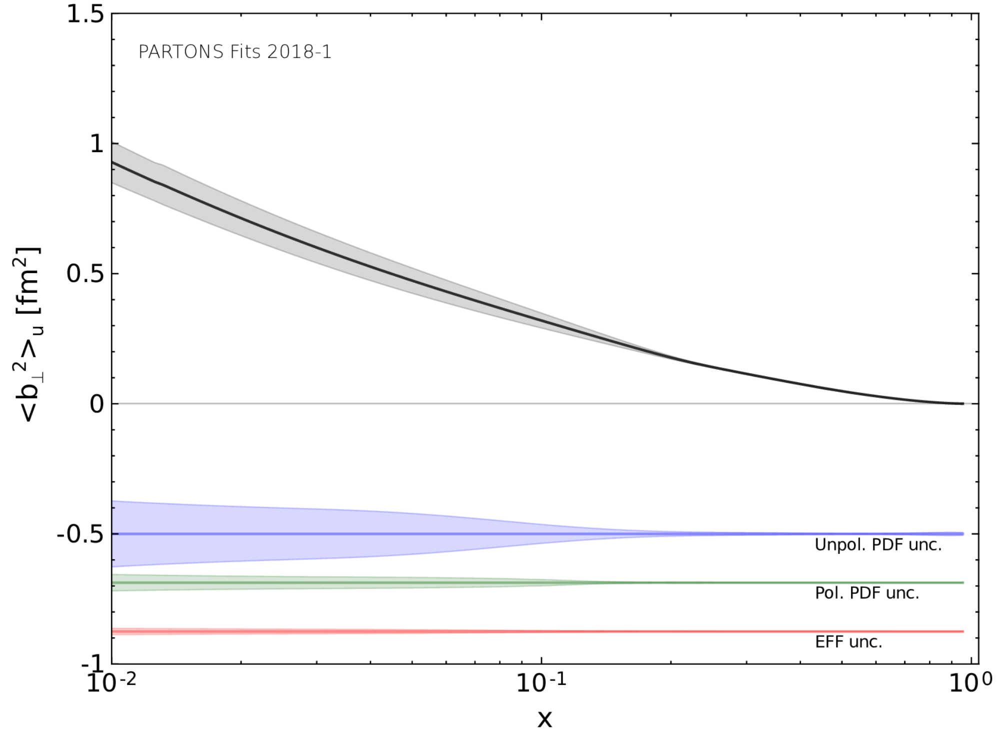




- Global fits with skewness dependance encoded in Ansatz

H. Moutarde, PS, J. Wagner, Eur. Phys. J. C78 (2018) 11, 890





$$Q^2 = 2\ \mathrm{GeV}^2$$

Ji's sum rule - TOAM

No recent progress here :-(

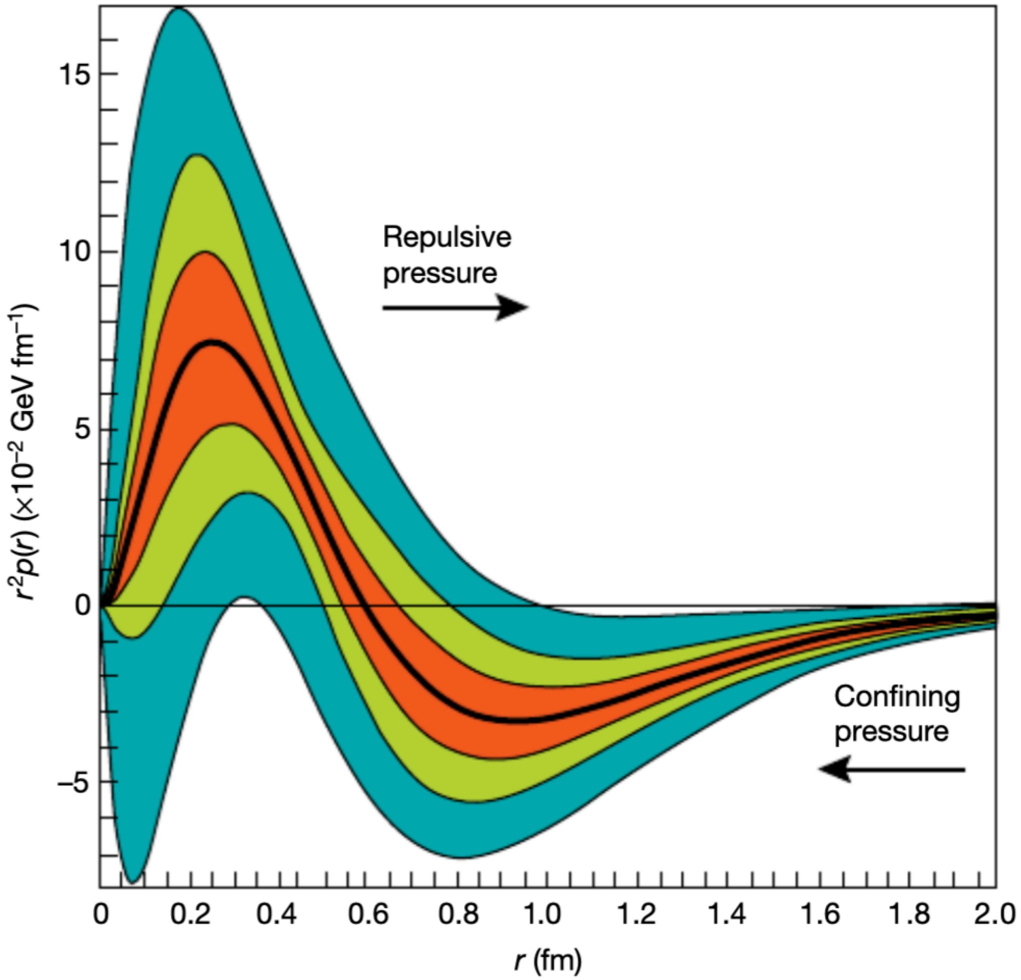
Need for more neutron data or data taken with transversely polarized targets

Need for modern GPD models to access H/E(x, const ξ, t=0) from exclusive data

Elastic data provide important constraints on GPDs E (however, only for valance contribution), see for instance Eur. Phys. J. C73 (2013) no. 4, 2397

Subtraction constant

V.D. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557 (2018) no. 7705, 396



The procedure:

1. Extract subtraction constant using KM model and CLAS data

2. Fit extracted values with

$$d_1(t) = d_1(0)\left(1 - \frac{t}{M^2}\right)^{-\alpha}$$

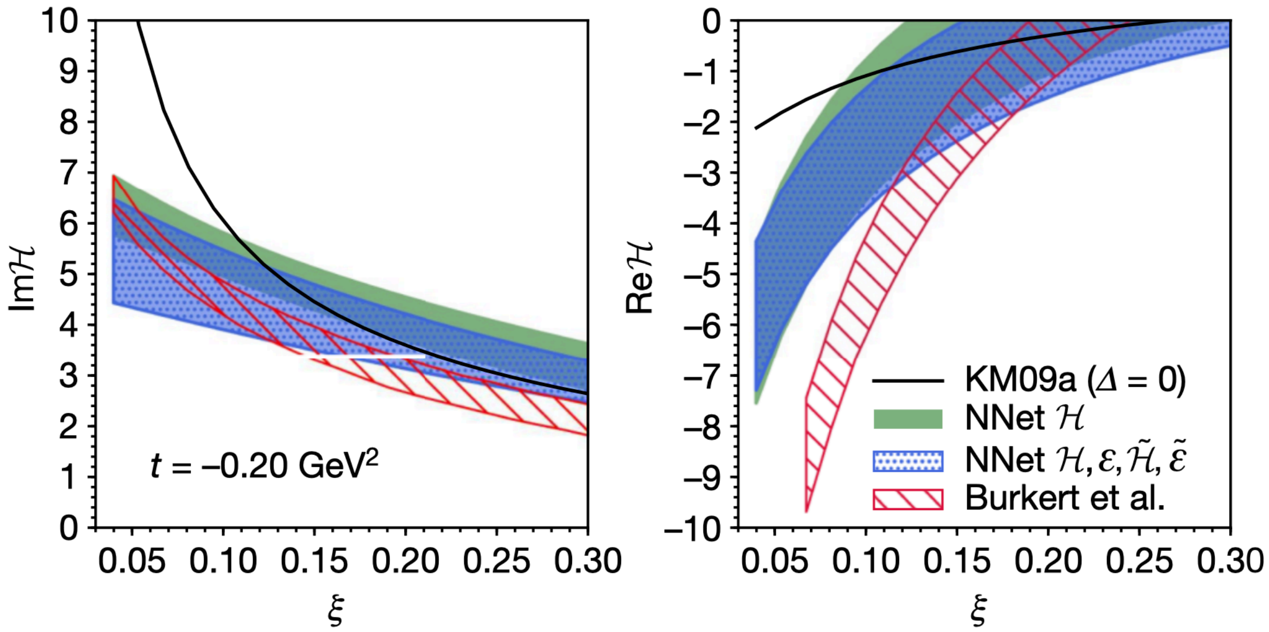
without JLab 6 GeV data

with JLab 6 GeV data

with JLab 12 GeV data (projected)

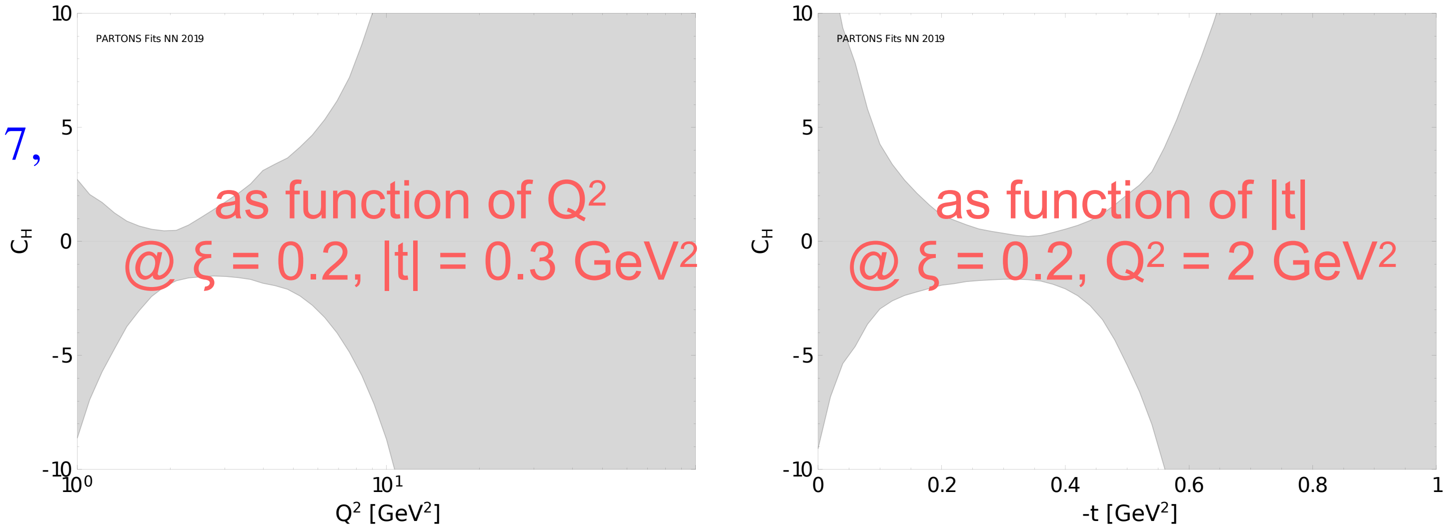
Subtraction constant

K. Kumerički, Nature 570 (2019) no.7759, E1



Result: C(t) = 0.78 ± 1.5
almost no t-dependence

H. Moutarde, PS, J. Wagner, Eur. Phys. J. C79 (2019) no. 7, 614



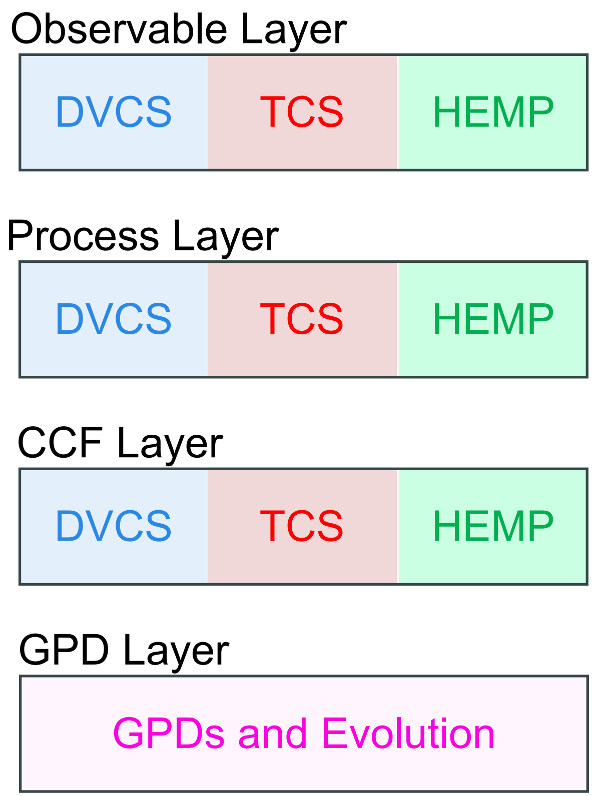
Generalised Parton Distributions

- novel way to describe partonic structure of nucleon
- allows to study (highlights):
  - $\rightarrow$ nucleon tomography
  - $\rightarrow$ total angular momentum of partons
  - $\rightarrow$ “mechanical” properties of parton distributions

- need for more data, better description of exclusive processes, extraction methods

PARTONS project

- PARTONS - platform to study GPDs
- Come with number of available physics developments implemented
- Addition of new developments as easy as possible
- To support effort of GPD community
- Can be used by both theorists and experimentalists



PARTONS project

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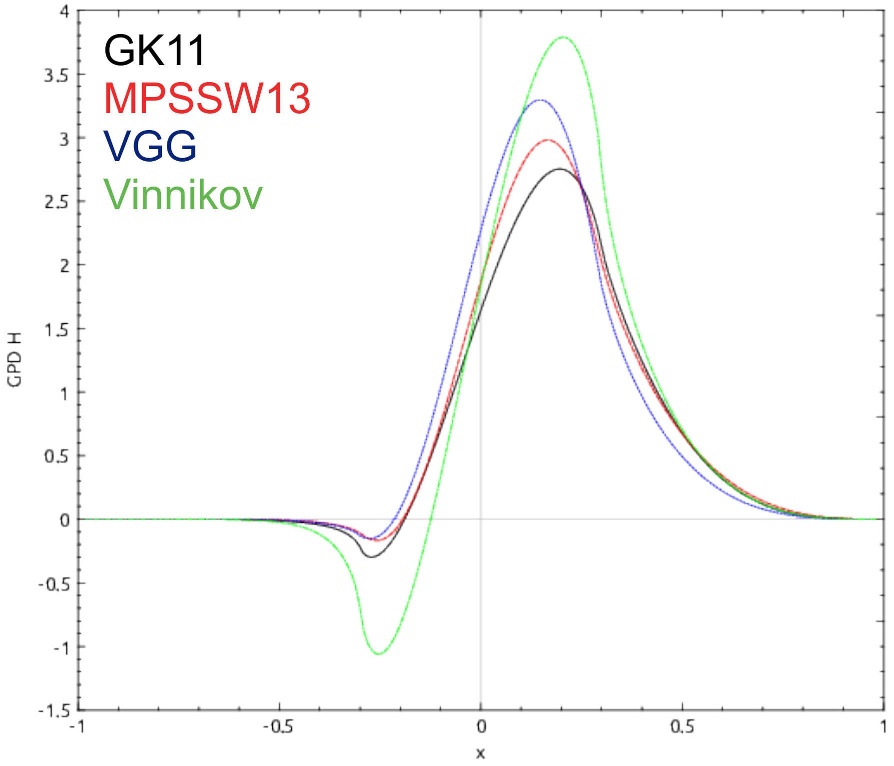
H^u @ xi = 0.2, t = -0.1 GeV^2, μ_F^2 = 2 GeV^2



More information

PARTONS is open source project distributed under following licenses (per subproject):

- elementary-utils: Apache
- numa, partons and partons-example: GPL

To download and for tutorials, useful information, reference documentation see:

http://partons.cea.fr

For detail description of architecture see:

Eur. Phys. J. C78 (2018) 6, 478

Compile PARTONS from scratch
or use provided Virtual Machine / Docker image