DE LA RECHERCHE À L'INDUSTRIE



 $q(x, \overline{b_{\perp}})$

 b_v (GeV⁻¹)

 b_{r} (GeV⁻¹)

0.03

0.05

www.cea.fr

XIIIth Quark Confinement

and the Hadron Spectrum

0.1

Generalized Partons Distributions and Nucleon Tomography

F. Sabatié – CEA Saclay

□ Why nucleon imaging?

□ What are GPDs?

- □ How to access them?
- □ How to do imaging?
- A few recent experimental highlights from Jefferson Lab
- Software framework for proton imaging

□ Summary, Outlook

0.3

x

CEA-Saclay/DRF/Irfu SPhN F. Sabatié Confinement XIII, Maynooth 08/03/2018





Imaging has been **crucial** in the past for science as diverse as biology, medicine, chemistry, solid state physics and of course, **nuclear physics**.







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- Origin of mass
- Origin of spin







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Even though **the nucleon is the building block of all visible matter**, there is much we **do not understand about it** at a very basic level:

- Origin of mass
- Origin of spin

But also its:

- Size (proton radius puzzle)







- Partonic structure

And it has some consequences ... one recent example





On the importance of knowing one's beam/target before using it:

Data from pp and pA collisions at RHIC and LHC have shown that shape fluctuations of the proton at $x \sim 10^{-3}$ may potentially explain the observed puzzling collective behavior in small or very small systems











Generalized Parton Distributions





 $(x + \xi)$ and $(x - \xi)$: longitudinal momentum fractions of quarks

The structure of the nucleon can be described at leading-twist by

4 chiral-even Generalized Parton Distributions : $H, \widetilde{H}, E, \widetilde{E}(x, \xi, t; \mu_F^2)$ 4 chiral-odd $H_T, \widetilde{H}_T, E_T, \widetilde{E}_T(x, \xi, t; \mu_F^2)$

> They enter the $\gamma^* p \to (\gamma \text{ or } M) p$ amplitude as convolution integrals : no direct access

- > They are **universal** (DVCS, DVMP, TCS, ...)
- > Forward limit $(t=\xi=0)$ of H and \widetilde{H} : PDFs
- > First moment in x : Form Factors

> Second moment of (H+E) when $t \rightarrow 0\,$: total angular momentum



Impact parameter space Interpretation Burkardt, Diehl, ...



Deep Exclusive Scattering Parton distributions in both coordinate and momentum space





To sum it up:

GPDs encode the correlation of the longitudinal momentum and the transverse position of partons inside the nucleon

It gives insights on:

Spin structure, energy-momentum structure.

Even though it is quite complex, it provides:

Probabilistic interpretation of Fourier transform of GPD(x, $\xi = 0$, t) in the transverse plane.





Deeply Virtual Compton Scattering

- Theory is under control : up to $lpha_S^2$, twist-3, target mass corrections, etc.
- \square Sensitive to the quark combination : $\frac{4}{9}u + \frac{1}{9}d + \frac{1}{9}s$

Müller et al, Braun et al, ...

- Moutarde, Pire, At Jefferson Lab energies, *mostly* sensitive to valence quarks **FS**, Wagner, ...
- Actually sensitive to *gluon* GPDs at NLO or beyond (even at somewhat large x)
- ullet At LO, direct access the GPDs on the line $x=\xi$ through Beam Spin Asymmetries Diehl, Gousset, sensitive to the interference with known Bethe-Heitler process



Pire, Ralston, ...



Hard Meson Electroproduction

- □ Many channels available for flavor separation (ρ^0 , ρ^+ , π^0 , π^+ , ϕ , ...)
- \Box J/ Ψ and ϕ access gluon GPDs.
- Theory less under control : convolution with (unknown) meson WF,

potentially slow scaling, large power and NLO corrections



From data to 3D images, in a nutshell





In practice ... not so simple: incomplete measurement !



Adequate GPD model satisfying all known constraints

GPD fitting procedure on a lot of data

Extract $H(x, \xi, t, \mu_F^{ref})$ from experimental data.

Extrapolate to vanishing skewness $H(x, 0, t, \mu_F^{ref})$.

Extrapolate $H(x, 0, t, \mu_F^{ref})$ up to infinite *t*.

Compute 2D Fourier transform in transverse plane:

$$H(x, b_{\perp}) = \int_0^{+\infty} \frac{\mathrm{d}|\Delta_{\perp}|}{2\pi} |\Delta_{\perp}| J_0(|b_{\perp}||\Delta_{\perp}|) H(x, 0, -\Delta_{\perp}^2)$$

Propagate uncertainties.

Control extrapolations with an accuracy matching that of experimental data with **sound** GPD models.





Polarized beam, polarized target (Longitudinal, Transverse) on proton

=> Separation of different GPDs

Deuterium (neutron) target => u, d flavor separation

Electroproduction of mesons => Strange quarks and gluons.



Q²-dependence to control higher-twists

□ Ideally, Timelike Compton Scattering and Double-DVCS

Beam energy variation for a complete separation of |DVCS|², Re[DVCS*BH]







HERMES

Lots of combinations (DVCS and DVMP) at $x_B \sim 0.1$ Poor control of the exclusivity (except for one data set with recoil detector) Low statistics

HERA (ZEUS + H1)

Unpolarized protons only Low statistics but very high Q^2 at low x_B





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JLab 6 GeV

DVCS and DVMP in the valence quark region Targets: H, D, 4He, Long. Pol. Protons (NH₃) High (Hall A) or Fair (Hall B) statistics Low Q²

Recent results:

- High statistics DVCS LH2 x-sec
- Energy-separation of DVCS x-sec
- First L/T separation of π^0 x-sec

COMPASS Short DVCS test run (2012) with proton target DVMP Low statistics in the sea-quark region



Accurate DVCS cross sections: Hall A 6 GeV



$x_B = 0.37, \quad Q^2 = 2.36 \text{ GeV}^2, \quad t = -0.32 \text{ GeV}^2$



Extraction of CFF and cross sections :

Fit of the the harmonic structure including kinematic dep., convoluted with MC acceptance to the data (parameters = a choice of CFFs)

$$d^4\sigma = \mathcal{T}_{\mathsf{BH}}^2 + \mathcal{T}_{\mathsf{BH}} \mathcal{R} e(\mathcal{T}_{\mathsf{DVCS}}) + \mathcal{T}_{\mathsf{DVCS}}^2$$

$$\begin{split} \mathcal{R}e(\mathcal{T}_{\text{DVCS}}) &\sim c_0^{\mathcal{I}} + c_1^{\mathcal{I}} \cos \phi + c_2^{\mathcal{I}} \cos 2\phi \\ \mathcal{T}_{\text{DVCS}}^2 &\sim c_0^{\text{DVCS}} + c_1^{\text{DVCS}} \cos \phi \end{split}$$

$$\Delta^{4}\sigma = \frac{d^{4}\overrightarrow{\sigma} - d^{4}\overleftarrow{\sigma}}{2} = \mathcal{I}m(\mathcal{T}_{\text{DVCS}})$$
$$\mathcal{I}m(\mathcal{T}_{\text{DVCS}}) \sim s_{1}^{\mathcal{I}}\sin\phi + s_{2}^{\mathcal{I}}\sin 2\phi$$



Accurate DVCS cross sections: Hall A 6 GeV





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Photon electroproduction cross section is given by:

$$\frac{d^{4}\sigma(\lambda,\pm e)}{dQ^{2}dx_{B}dtd\phi} = \frac{d^{2}\sigma_{0}}{dQ^{2}dx_{B}}\frac{2\pi}{e^{6}}\times\left[\left|\mathfrak{T}^{BH}\right|^{2}+\left|\mathfrak{T}^{DVCS}\right|^{2}\mp\mathfrak{I}\right]$$

 To separate all terms, having no positron beam, Measurement of cross sections at different beam energies.

E (GeV)	Q^2 (GeV ²)	х _В	W (GeV)
(3.355; 5.55)	1.5	0.36	1.9
(4.455; 5.55)	1.75	0.36	2
(4.455; 5.55)	2	0.36	2.1

• First phenomenological analysis including kinematical corrections $(t/Q^2 \text{ and } M^2/Q^2 \text{-terms})$ indicates necessity of having higher-twist or gluon contributions. Defurne, **F S** et al,

Nature Com. 8, 1408 (2017)



π^0 electroproduction cross section extraction: Hall A 6 GeV





Dominance of T cross section unexpected, may be explained by interplay with Twist3 DA

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GPD "extraction" from data and nucleon 3D imaging



Extraction of GPDs from data in order to provide3D nucleon imaging requires many steps, whichimaging requires many steps, whichhave been incorporated into the PARTONSBerthou, Moutarde, <u>F S</u> et al.framework, recently releasedBerthou, Moutarde, <u>F S</u> et al.EPJ C78 (2018) 6, 478



PARtonic Tomography Of Nucleon Software



Recently, a fit was performed using the newly released framework

Cez

Cea

Brand new: DVCS global fit using PARTONS



Moutarde et al. arXiv:1807.07620

2600 data points used in this recent PARTONS fit

No.	Collab.	Year	Ref.	Observable	
1	HERMES	2001	[13]	A_{LU}^+	
2		2006	[114]	$A_C^{\cos i\phi}$	i = 1
3		2008	[115]	$A_C^{\cos i\phi}$	i = 0, 1
				$A_{UT, \text{DVCS}}^{\sin(\phi - \phi_S) \cos i\phi}$	i = 0
				$A_{UT,\mathrm{I}}^{\sin(\phi-\phi_S)\cos i\phi}$	i = 0, 1
				$A_{UT,I}^{\cos(\phi-\phi_S)\sin i\phi}$	i = 1
4		2009	[116]	$A_{LU,I}^{\sin i\phi}$	i = 1, 2
			1 1	$A_{LU,\text{DVCS}}^{\sin i\phi}$	i = 1
				$A_C^{\cos i\phi}$	i = 0, 1, 2, 3
5		2010	[117]	$A_{UL}^{+,\sin i\phi}$	i = 1, 2, 3
				$A_{LL}^{+,\cos i\phi}$	i = 0, 1, 2
6		2011	[118]	$A_{LT, \text{DVCS}}^{\cos(\phi - \phi_S)\cos i\phi}$	i = 0, 1
				$A_{LT, \text{DVCS}}^{\sin(\phi - \phi_S) \sin i\phi}$	i = 1
				$A_{LT,I}^{\cos(\phi-\phi_S)\cos i\phi}$	i = 0, 1, 2
				$A_{LT,I}^{\sin(\phi-\phi_S)\sin i\phi}$	i = 1, 2
$\overline{7}$		2012	[119]	$A_{LU,I}^{\sin i\phi}$	i = 1, 2
			T T	$A_{LU,DVCS}^{\sin i\phi}$	i = 1
				$A_C^{\cos i\phi}$	i = 0, 1, 2, 3
8	CLAS	2001	[14]	$A_{LU}^{-,\sin i\phi}$	i = 1, 2
9		2006	[120]	$A_{UL}^{-,\sin i\phi}$	i = 1, 2
10		2008	[121]	A_{LU}^-	
11		2009	[122]	A_{LU}^-	
12		2015	[123]	$A_{LU}^-, A_{UL}^-, A_{LL}^-$	
13		2015	[124]	$d^4\sigma^{UU}$	
14	Hall A	2015	[112]	$\Delta d^4 \sigma^{LU}$	
15		2017	[113]	$\Delta d^4 \sigma_{LU}^{-1}$	
16	COMPASS	2018	[55]	b	



Position and polarisation of u quarks in the proton







COMPASS

Unpolarized H (runs 2016-2017) (muon) charge/spin cross-sections



JLab 12 GeV (Hall A+C, CLAS12) H, D, Longitudinally polarized H ³H, He Transversely polarized H?

Huge DVCS+DVMP data set to be expected







Since February 2018, production data at 10.6 GeV with CLAS12 on LH2 target

Second part of the run will start August 22nd

Spokespersons: <u>**F S**</u> et al.



- 119 PAC days.
- 50 nA on 5-cm LH₂.
- Polarization: 85%.
- Goal: 1-2% BSA for DVCS



CQZ





Committee on Assessment of U.S.-Based Electron-Ion Collider Science

The National Academies of Sciences, Engineering, and Medicine was asked by the U.S. Department of Energy to assess the scientific justification for building an Electron-Ion Collider (EIC) facility. The unanimous conclusion of the Committee is that an EIC, as envisioned in this report, would be...

... a unique facility in the world that would answer science questions that are compelling, fundamental, and timely, and help maintain U.S. scientific leadership in nuclear physics.

NAS Committee Review released July 24th 2018



The National Academies of SCIENCES • ENGINEERING • MEDICINE





Bottom Line

The committee unanimously finds that the science that can be addressed by an EIC is compelling, fundamental, and timely.

The unanimous conclusion of the Committee is that an EIC, as envisioned in this report, would be a unique facility in the world that would boost the U.S. STEM workforce and help maintain U.S. scientific leadership in nuclear physics.

The project is strongly supported by the nuclear physics community.

The technological benefits of meeting the accelerator challenges are enormous, both for basic science and for applied areas that use accelerators, including material science and medicine.

NAS Committee Review released July 24th 2018

> The National Academies of SCIENCES • ENGINEERING • MEDICINE





- □ Imaging the proton is crucial to understand the building block of ordinary matter
- Generalized Partons Distributions (and TMDs) are the right tools for this job
- □ They can be accessed with **Deep Exclusive Scattering processes** such as DVCS, DVMP
- Already a nice collection of data from HERA (H1, ZEUS, HERMES), JLab and COMPASS. I specifically showed exciting new results from JLab.



Exciting times for GPD physics !

- New high quality data upcoming from Jefferson Lab 12 GeV and COMPASS
- □ PARTONS software framework released and producing interesting results already
- EIC will be a game changer: It will image the proton from low to high-x, from valence quark to gluon regions. Positive NAS review just came out, should except CD-0 soon.

