Accessing experimentally the generalized parton distributions

M. Defurne

CEA Saclay - IRFU/DPhN

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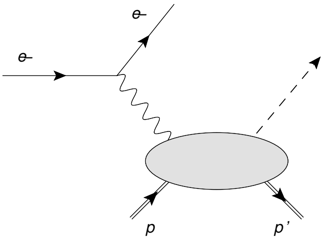
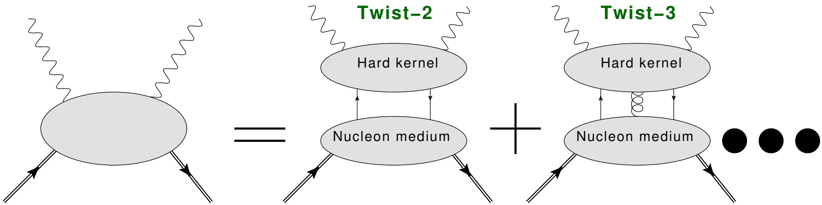
By measuring the cross section of deep exclusive processes, we get insights about the GPDs.

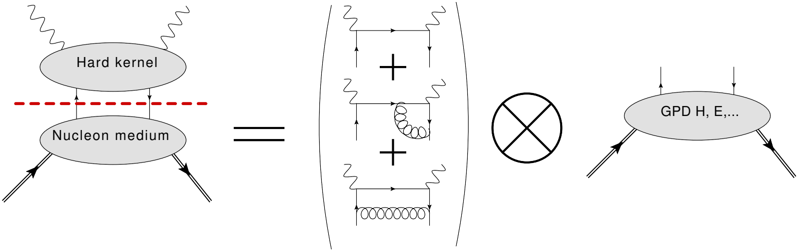


1. The electron interacts with the proton by exchanging a hard virtual photon with transverse and longitudinal polarization.
2. The proton emits a particle (γ, π^0, ρ,...)

The link between these diagrams and the GPDs is guaranted by the factorization (Proven for DVCS for all polarization, only longitudinal for DVMP).

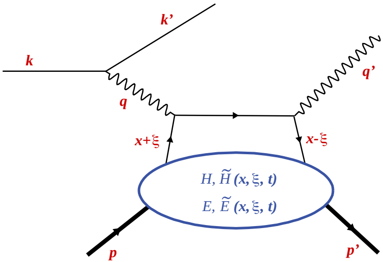
Factorization and GPDs





The amplitudes at twist-$(n+1)$ are suppressed by a factor $\frac{1}{Q}$ with respect to the twist-n amplitudes, with Q the virtuality of the photon.

DVCS and GPDs



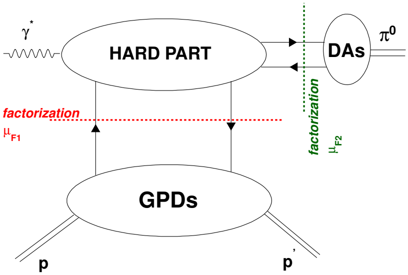
- $Q^2 = -q^2 = -(k-k')^2$.
- $x_B = \frac{Q^2}{2p \cdot q}$
- x longitudinal momentum fraction carried by the active quark.
- $\xi = \frac{x_B}{2-x_B}$ the longitudinal momentum transfer.
- $t = (p-p')^2$ squared momentum transfer to the nucleon.

The GPDs enter the DVCS amplitude through a complex integral. This integral is called a *Compton form factor* (CFF).

$$\mathcal{H}_{++}(\xi,t) = \int_{-1}^{1} H(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right) dx \,.$$

DVMP and GPDs: just a few words about it

In DVMP, there is an additional non-perturbative structure: the meson. The factorization have only be proven for longitudinally polarized photons.



The amplitude is given by the product of two twist-expansions:
There is a coupling between the GPDs and the DAs.

$$\mathcal{M} = GPDs(x, \xi, t, \mu_{F1}) \otimes HARD(x/\xi, z, \mu_{F1}, \mu_{F2}) \otimes DA(z, \mu_{F2})$$

But we can play with DAs to perform flavour separation or privilieged access to specific GPDs.

The generalized parton distributions and the nucleon

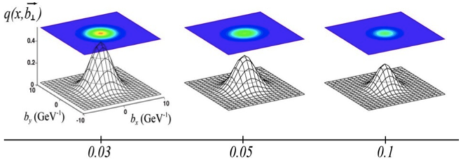
At leading twist there are 8 GPDs:

- 4 chiral-even GPDs: H, E, $\widetilde{H}$ and $\widetilde{E}$.
- 4 chiral-odd GPDs: H_T, E_T, $\widetilde{H}_T$ and $\widetilde{E}_T$.

Using the GPDs, we can determine the total angular momentum of quarks in the nucleon.

$$\int_{-1}^{1} x \left[H^f(x, \xi, 0) + E^f(x, \xi, 0) \right] dx = J^f \qquad \forall \xi \, .$$

By Fourier transform of the GPD H at ξ=0 (need extrapolation), we obtain the distribution in the transverse plane of the partons as a function of their longitudinal momentum.

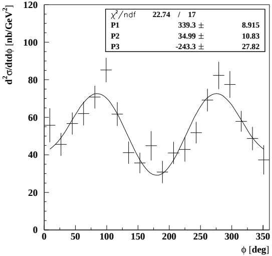


DES cross sections

The cross section of deep exclusive processes can be written under a common form:

$$\frac{d^4\sigma}{dtd\phi dQ^2 dx_B} = \frac{1}{2\pi}\Gamma_{\gamma^*}(Q^2, x_B, E_e)\Big[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}cos(2\phi)\Big],$$

For pseudo-scalar meson, the longitudinal response is the leading-twist one and the transverse one is higher-twist. For DVCS, it is the opposite.



Striking evidence of higher-twist contributions which has triggered theoretical effort (Liuti-Goldstein, Kroll-Goloskokov).

At LT-LO, DVCS^2 is flat. So what about DVCS?

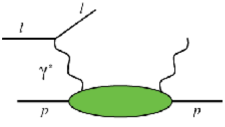
I. Bedlinskiy *et al.* (CLAS collaboration), PhysRevC.90.025205 (2014)

Photon electroproduction and GPDs (PART I)

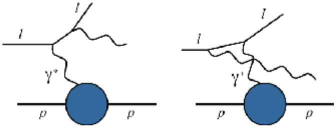
We use leptons beam to generate the γ^* in the initial state... not without consequences.

Indeed, experimentally we measure the cross section of the process $ep \to ep\gamma$ and not strictly $\gamma^* p \to \gamma p$.

Second level of interference with Bethe-Heitler making complicated the straightforward conclusion

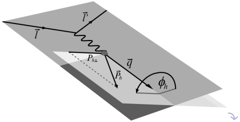


DVCS



Bethe-Heitler

$$\frac{d^4\sigma(\lambda, \pm e)}{dQ^2 dx_B dt d\phi} = \frac{d^2\sigma_0}{dQ^2 dx_B} \frac{2\pi}{e^6} \times \left[\left| \mathcal{T}^{BH} \right|^2 + \left| \mathcal{T}^{DVCS} \right|^2 \mp \mathcal{I} \right] ,$$



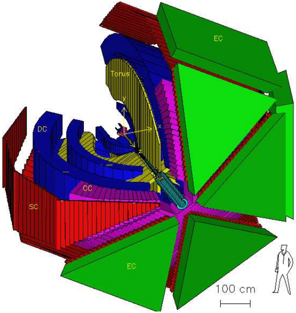
Photon electroproduction and GPDs (PART II)

The interference term allows to access the phase of the DVCS amplitude, *i.e* allows to isolate imaginary and real parts of CFFs.
A few examples of harmonic coefficients and their sensitivity to CFFs:

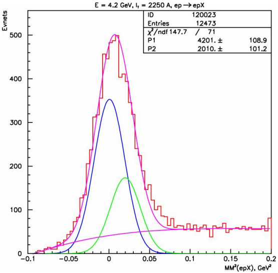
$$
\begin{aligned}
c_{0,UU}^{DVCS} &\propto 4(1-x_B)\left(\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*\right) + \cdots \qquad (1)\\
c_{1,UU}^{\mathcal{I}} &\propto F_1 \, Re\mathcal{H} + \xi(F_1+F_2) \, Re\widetilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \, Re\mathcal{E} \, , \\
s_{1,LU}^{\mathcal{I}} &\propto F_1 \, Im\mathcal{H} + \xi(F_1+F_2) \, Im\widetilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \, Im\mathcal{E} \, , \\
s_{1,UL}^{\mathcal{I}} &\propto F_1 \, \widetilde{\mathcal{H}} + \xi(F_1+F_2) \left(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\right) - \xi\left(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2\right) \widetilde{\mathcal{E}} \, ,
\end{aligned}
$$

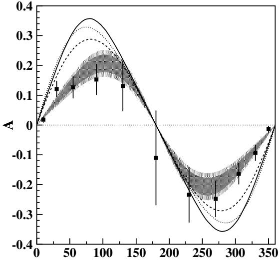
At leading-order, the imaginary part of CFFs gives access to the GPD value on the diagonal $x=\xi$.

The adventure starts in Hall B with CLAS in 1999



CLAS=Cebaf Large acceptance spectrometer.
Very large beam-spin asymmetries measured, arising from the interference between DVCS and BH.
→ Straightforward conclusion: Access to the GPDs at JLab!

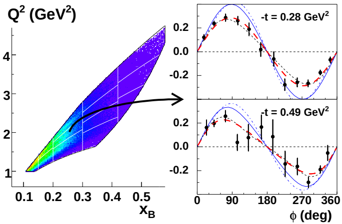


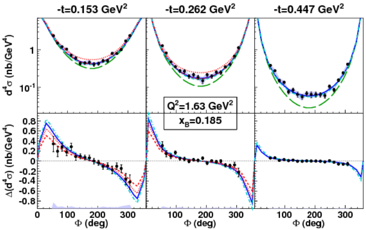


S. Stepanyan *et al.*, CLAS collaboration, Phys.Rev.Lett. 87 (2001) no.21, 182002

The CLAS collaboration has a impressive DVCS data set. First came:

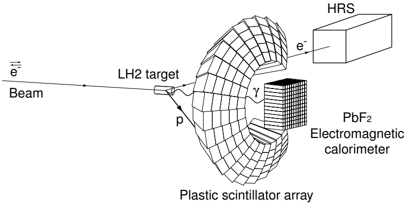
- Beam-spin asymmetries (A_{LU}).
  F-X. Girod *et al.*, Phys. Rev. Lett. 100, 162002
- Target-spin asymmetries (A_{UL}).
  E. Seder *et al.*, Phys.Rev.Lett. 114 (2015) no.3, 032001
- Double-spin asymmetries (A_{LL}).
  S. Pisano *et al.*, Phys.Rev. D91 (2015) no.5, 052014
- With unpolarized cross sections (V-shape of Bethe-Heitler) (2015).

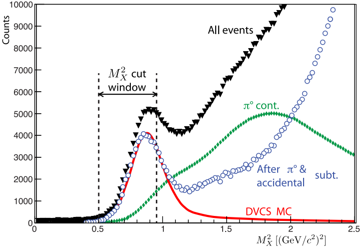


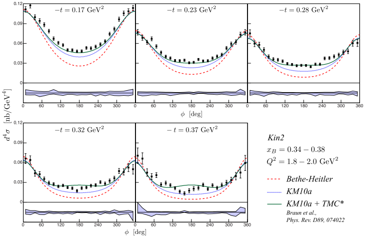


H.S. Jo *et al.*, Phys.Rev.Lett. 115 (2015) no.21, 212003

2004: Dedicated DVCS experiment in Hall A for high statistical unpolarized cross sections







- Beam-helicity dependent and independent cross section
- Large DVCS^2 contribution!
- Kinematical power corrections seems to explain the gap.

M. Defurne *et al.*, Hall A collaboration, Phys.Rev. C92 (2015) no.5, 055202

how to disentangle the interference and DVCS contributions with electrons only?

The ϕ-dependence is not enough to disentangle the contributions. Using the beam energy dependence, we can add constrains on the model (separation of DVCS and interference contribution)

Setting	E (GeV)	Q^2 (GeV^2)	x_B	W (GeV)
2004-Kin1	5.7572	1.5	0.36	1.9
2004-Kin2	5.7572	1.9	0.36	2.06
2004-Kin3	5.7572	2.3	0.36	2.23

Setting	E (GeV)	Q^2 (GeV^2)	x_B	W (GeV)
2010-Kin1	(3.355 ; 5.55)	1.5	0.36	1.9
2010-Kin2	(4.455 ; 5.55)	1.75	0.36	2
2010-Kin3	(4.455 ; 5.55)	2	0.36	2.1

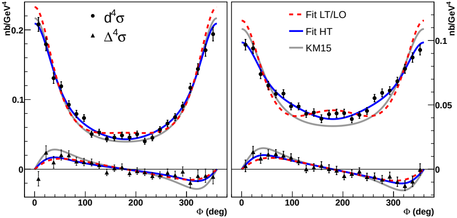
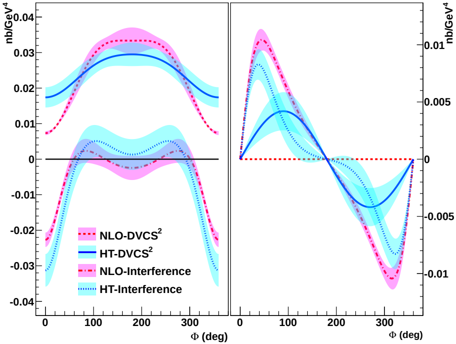


Figure: Q^2=1.75 GeV^2, -t=0.3 GeV^2. E=4.445 GeV (left) and E=5.55 GeV (right)



→ First data set at fixed kinematics but mutiple beam-energy.
→ First phenomenological analysis including kinematical power corrections.

- NLO: Gluon transversity GPDs (Non-zero σ_{TT}).
- HT: Non-zero σ_L and σ_{TL}.

M. Defurne *et al.*, Hall A collaboration, arXiv:1703.0944

6 GeV era: To summarize...

The data can be interpreted by model at leading-twist and leading-order.
But it is not proof that no higher-twist or gluonic contributions

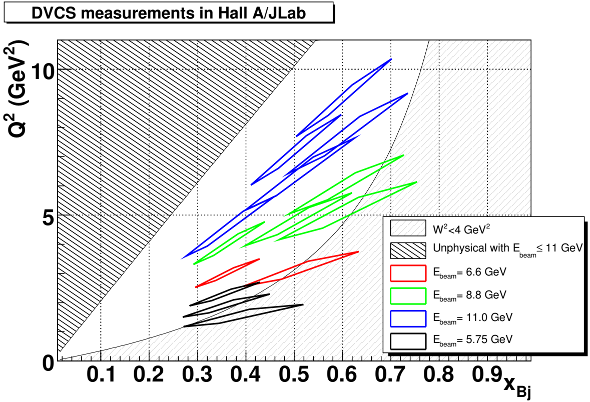
High statistics data sets seem to constrain more and more the data. Taking into account in a simple way the kinematical corrections,it seems that LT/LO approximation does not hold.

How to test the validity of leading-twist/leading-order assumption?

mid-term Future: Jefferson Lab 12 GeV program

Since 2014, it has started to take data in Hall A. DVCS experiment until late 2016 and extends the kinematical coverage of previous experiments to high x_B at higher Q^2.

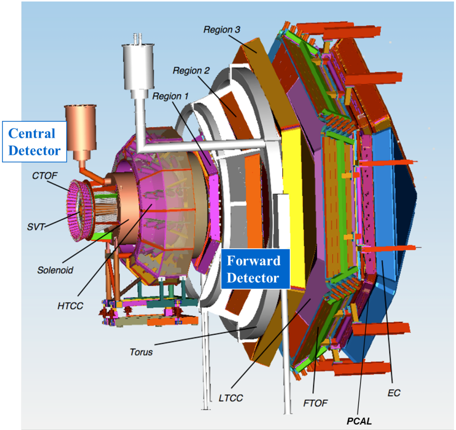
In Hall C, HMS upgraded to Super-HMS, Rosenbluth separation of DVCS and π^0 electroproduction.



It is an exciting time in Hall B since CLAS12 will be fully assemble this summer to receive beam this Fall.

A complete GPD program will be covered:

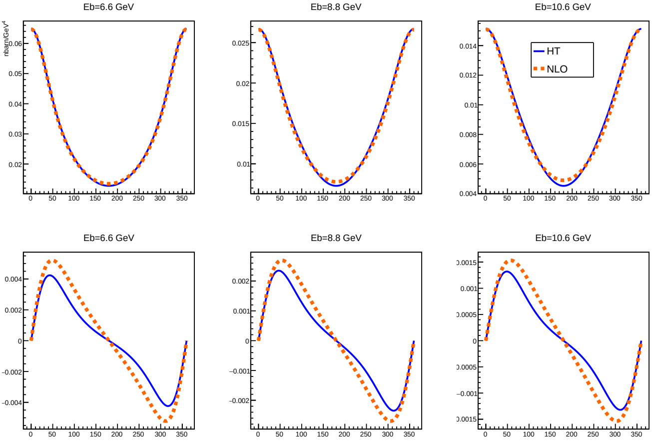
- longituinally polarized electron beam at multiple energy (6.6, 8.8, 11 GeV),
- proton and neutron target,
- unpolarized, longitudinally polarized, transversely polarized (HD-ice),
- to study DVCS and DVMP (π, ϕ, η).



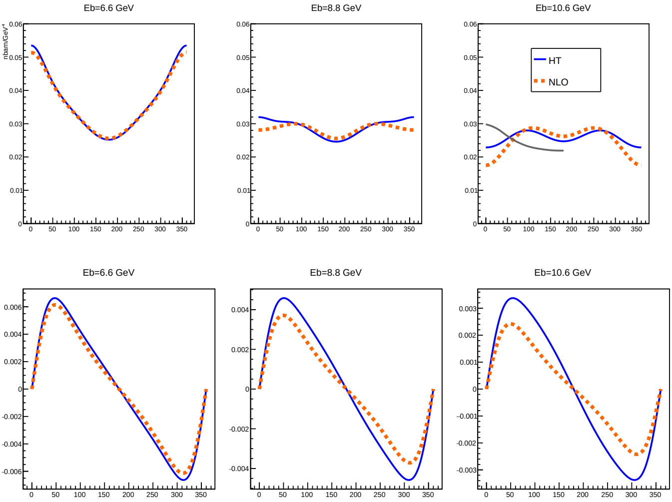
Better than Christmas for the GPD business!

Data has been collected at 6.6 (Q^2=3.2), 8.8 (Q^2=3.6) and 10.6 GeV (Q^2=4.2) in Hall A, still at xB=0.36.

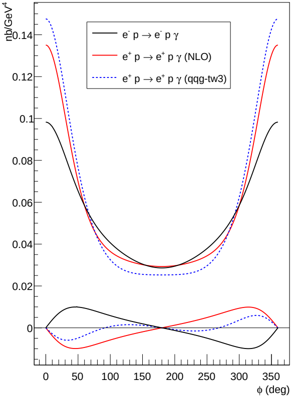
Assuming Q^2-independence (I would have tried to do something better but lack of time), we can expect this:



If we stay at Q^2=2, but use higher beam energy



Decreasing Bethe-Heitler might reveal $DVCS^2$ but limits Q^2
(Gray line is LT-LO shape- KM15).



Positrons and electrons are assumption-free/cleanest way to separate DVCS/interference. Studying the phi-dependence of the DVCS contribution is the most straightforward way to know the order of the different contributions (twist-3, NLO).

With 1 μA of unpolarized positrons, we could directly answer the questions between NLO and HT.

Essential to our community: Theory and phenomenology

Many channels, many observables provided by different facilites and each of them holds a specific piece of the puzzle.
Need to work hand-by-hand with phenomenologists and theorists .

We will need to develop global analysis tools in order to:

- combine all data and thus strongly constrain fits or models.
- test systematically the impact of diverse assumptions:
  - LO, NLO, NNLO,...
  - the numbers of flavours,
  - the numbers of GPDs,

These tools are missing. F-X and I are spending quite a lot of time to debate about "what is a good GPD measurement?" but cannot conclude before data collection will start.

GPD Computing made simple.

Differential studies: physical models and numerical methods.

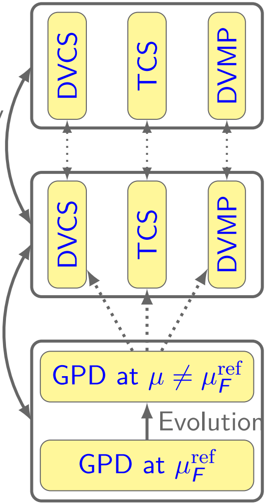
Phenomenology of Generalized Parton Distributions

PARTONS Project

Full processes
Experimental data and phenomenology

Small distance
Computation of amplitudes

Large distance
First principles and fundamental parameters



- Many observables.
- Kinematic reach.

- Perturbative approximations.
- Physical models.
- Fits.
- Numerical methods.
- Accuracy and speed.

H. Moutarde | Recent results | 2 / 4

Conclusion

- So far a lot of data have been collected for DVCS, but high statistical data set startputting LT-LO models and fits under pressure.
- The future data at 12 GeV, with an unprecedented statistical precision, will add even more constrains.
- But a good measurement is not only made of high statistics... Need to measure at well-chosen points (But what definition of well chosen point?).
- Multichannel analysis should be our goal to constrain and fit all at once the GPDs. But DVMP is much less theoretically under control than DVCS.

It is a great time to join the GPD adventure.