Photon electroproduction with electron and positron beams

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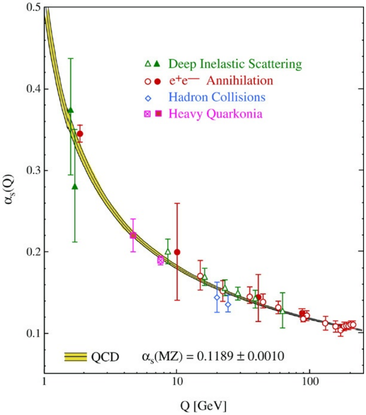
Tuesday 12^{th} 2017

The nucleon: a formidable lab to study the strong interaction

- The nucleon is a dynamical object made of quarks and gluons.
- This dynamics is ruled by the strong interaction.
- A perturbative approach from first principles to unravel this dynamics is impossible due to the large size of the strong coupling constant.



Although non-perturbative approaches (DSE, lattice QCD) starts making progress, the experimental approach remains more convenient to get complex information about this dynamics.

A set of distributions encoding the nucleon structure

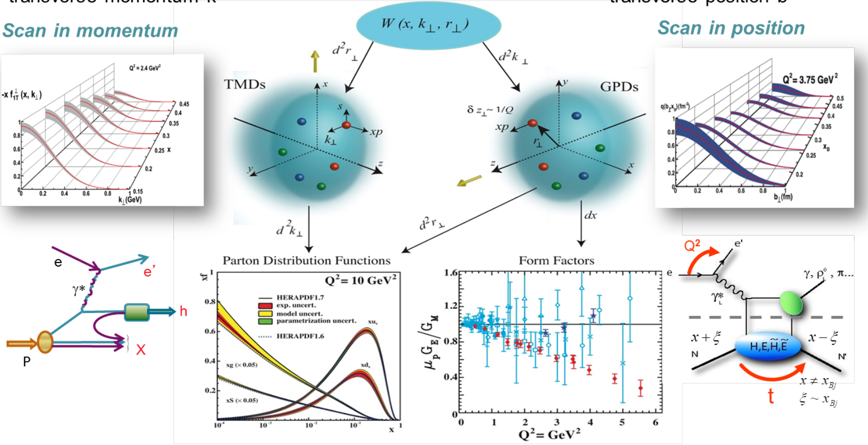
In the Infinite momentum frame, 5 coordinates for a parton in the nucleon.

TMDs: Fraction of longitudinal momentum x et transverse momentum k

GPDs: Fraction of longitudinal momentum x et transverse position b

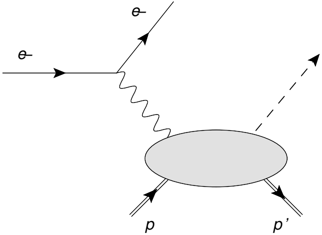
Scan in momentum

Scan in position



The deep exclusive processes

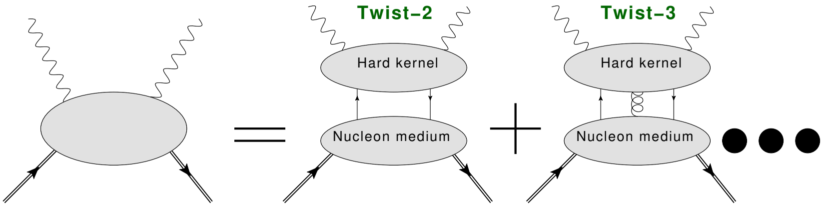
By measuring the cross section of deep exclusive processes, we get insights about the GPDs.

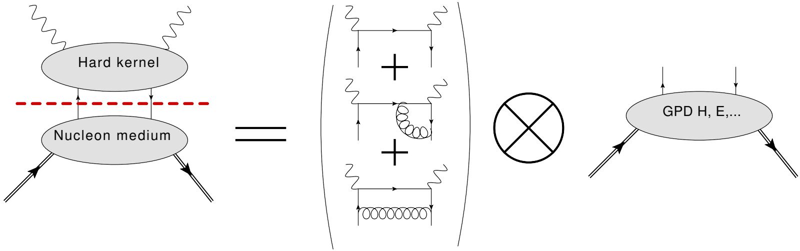


1. The electron interacts with the proton by exchanging a hard virtual photon.
2. The proton emits a particle (γ, π^0, ρ,...)

The link between these diagrams and the GPDs is guaranted by the factorization.

Factorization and GPDs





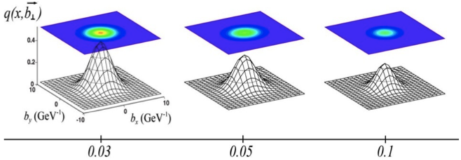
The amplitudes at twist-$(n+1)$ are suppressed by a factor $\frac{1}{Q}$ with respect to the twist-n amplitudes, with Q the virtuality of the photon.

The generalized parton distributions

At leading twist there are 8 GPDs for the proton:

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

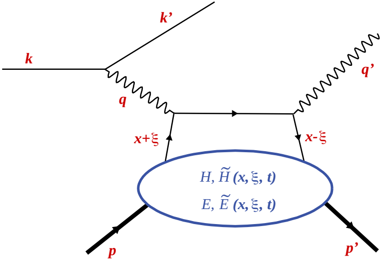
By Fourier transform of the GPD H, we obtain the distribution in the transverse plane of the partons as a function of their longitudinal momentum.



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

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

DVCS and GPDs



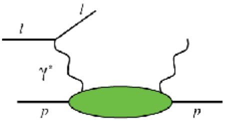
- $Q^2 = -q^2 = -(k - k')^2$.
- $x_B = \frac{Q^2}{2p \cdot q}$
- x longitudinal momentum fraction carried by the active quark.
- $\xi \sim \frac{x_B}{2 - x_B}$ the longitudinal momentum transfer.
- $t = (p - p')^2$ squared momentum transfer to the nucleon.

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

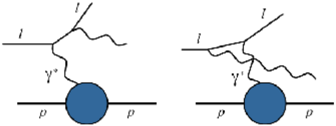
$$\mathcal{H}(\xi, t) = \int_{-1}^{1} H(x, \xi, t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) dx \; .$$

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 $\gamma^* p \to \gamma p$.

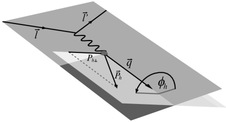


DVCS



Bethe-Heitler

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



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=ξ.

GPD hunter starter kit

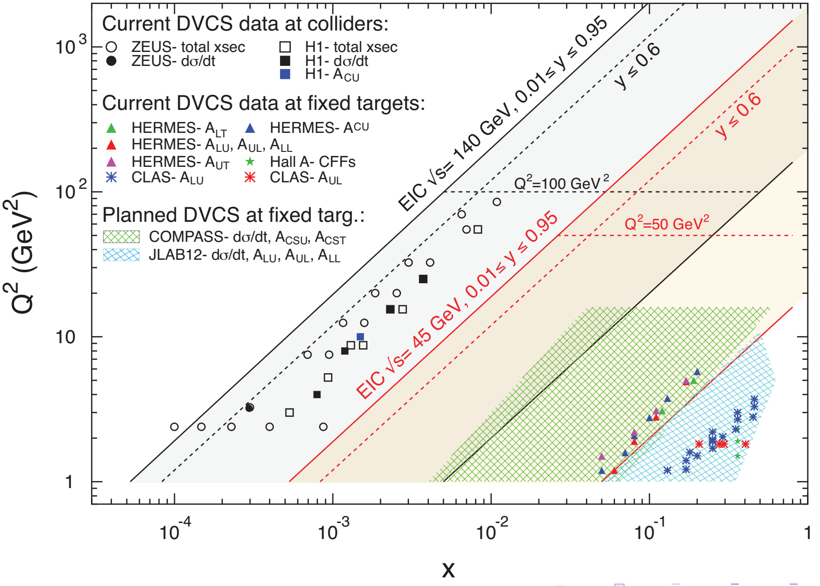
If we want to really get the GPDs, we need to:

- Different regions in the proton need to be probed for a complete picture/reconstruction... If possible with $Q^2 \gg M^2$
  $\rightarrow$ Need different facilities.

- Disentangle the different GPD contributions
  $\rightarrow$ Plays with polarization of beam and targets for the different channels.
  $\rightarrow$ Switch to neutron also (change form factors)

- Separate the flavour contributions
  $\rightarrow$ Use DVMP data (Not in this talk).

What have we collected so far? (DVCS only)



What about JLab?

Since JLab began to collect data, DVCS has been studied to understand the valence region. During the 6 GeV era:

- Hall A: Unpolarized and beam helicity dependent cross sections (Rosenbluth separation).
- Hall B: Unpolarized, A_{UL}, A_{LU}, A_{LL}.

And during the 12 GeV era:

- Hall A: Unpolarized and beam helicity dependent cross sections (already collected... analysis in progress).
- Hall B: Unpolarized, BSA, A_{UL}, A_{LU}, A_{LL}.
- Hall C: Unpolarized and beam helicity dependent cross sections (Rosenbluth separation).

But only with electrons. What have we learnt?

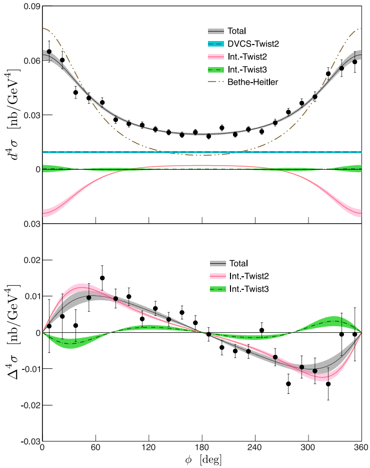
Disentangling everything with electrons... it is possible?

A core of assumptions at the beginning:

- $\left|\mathcal{T}^{DVCS}\right|^2$ very small.
- In the valence = only quarks.
- Q^2 large enough in front of M^2.

$$\frac{d^4\sigma(\lambda, \pm e)}{dQ^2 dx_B dt d\phi} \propto \left|\mathcal{T}^{BH}\right|^2 + \left|\mathcal{T}^{DVCS}\right|^2 \mp \mathcal{I} \ ,$$

With the ϕ-dependence and neglecting a "few" terms/CFFs:



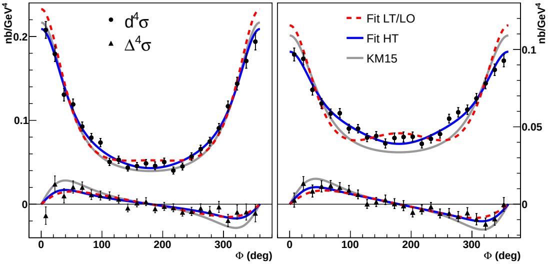
Trying to separate Interference/$DVCS^2$ with electron

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

The three terms have different energy dependence. The idea was to add the beam energy dependence as constrains to separate the interference and the DVCS^2 contributions.

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

$e^- p \to e^- p\gamma$ with two beam energies



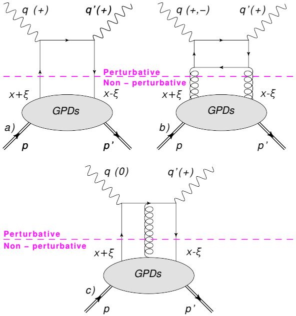


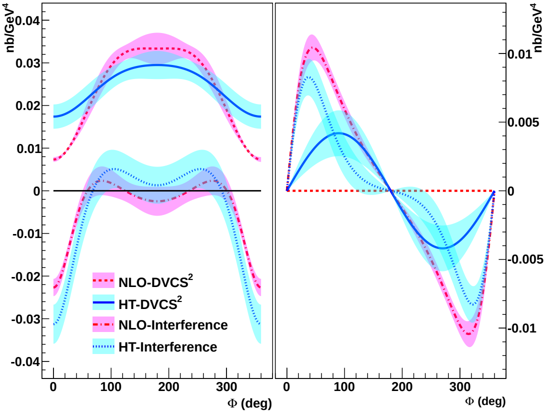
Figure: Q^2=1.75 GeV^2, -t=0.3 GeV^2.
E=4.445 GeV (left) and E=5.55 GeV (right)

- LT/LO: Only using leading-twist CFFs, the ones we want in the end (a).
- HT: Taking into account some CFFs from qqg correlations (c).
- NLO: Taking into account some CFFs from gluon GPDs (b).

Equally good fit between the HT and NLO scenario. M. Defurne *et al.*, Hall A collaboration, arXiv:1703.0944 (Accepted in Nat. Commun.)

Separation of DVCS and interference but still under some assumptions

Still a separation which is assumption-dependent:



NB: In the HT scenario, the beam helicity dependent cross section is not a pure interference term, as it is usually assumed in most phenomenological analyses.

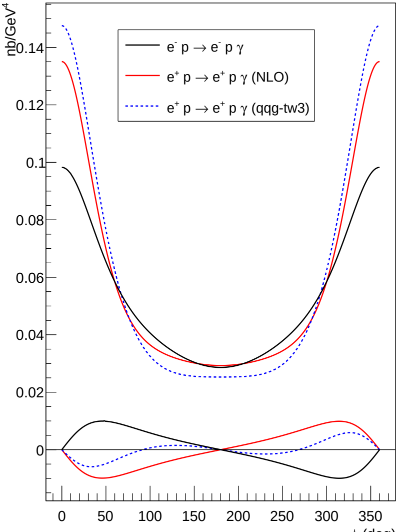
The perfect separation with positrons

What if, instead of changing the beam energy, we used unpolarized positrons:

Nothing more simple and reliable to separate the interference from the DVCS contribution, in a pure experimental way.

$$\frac{d^4\sigma(\lambda, \pm e)}{dQ^2 dx_B dt d\phi} \propto \left|\mathcal{T}^{BH}\right|^2 + \left|\mathcal{T}^{DVCS}\right|^2 \mp \mathcal{I} ,$$

RED/BLUE-BLACK=2$\mathcal{I}$



What should we measure with positrons?

- There is no need to start a high statistical accuracy DVCS program with positrons. Just specific points to challenge assumptions.
- These specific points must be determined once 12-GeV data has been collected.
  $\rightarrow$ Increase the beam energy will decrease BH contributions at some Q^2, x_B (Rosenbluth/quasi-pure DVCS).
- In cooperation with phenomenologists.
- Need also to choose a point where BH/ Interference /DVCS are all about 30%.
  (If no BH or $DVCS^2$, no sensitive difference between e^-/e^+ since no interference.)
- Polarized measurements with CLAS12 (Beam-spin asymetries).
  Unpolarized measurements in Hall A/C with higher intensity positron beam.

Conclusion

- Using positrons, you separate in the cleanest way Interference and $DVCS^2$ contribution.

- A lot of data has been collected with electrons at JLab during 6 GeV era, and will be collected at 12 GeV. But, so far, GPD/CFF extraction highly dependent on numerous assumptions.
  $\rightarrow$ Total return on investment made with electrons, with well-chosen positron points.

- Straightforward conclusion once DVCS^2 is measured
  (Flat DVCS^2: LT/LO, $\cos\phi$ = Twist-3, $\cos 2\phi$ = gluon so NLO)

Thank you!