Recoil Proton Polarization in DVCS

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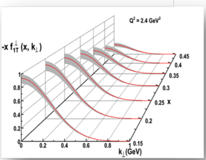
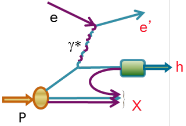
A set of distributions encoding the nucleon structure

TMDs: Fraction of longitudinal momentum x et transverse momentum k

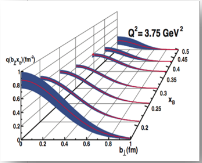
Scan in momentum

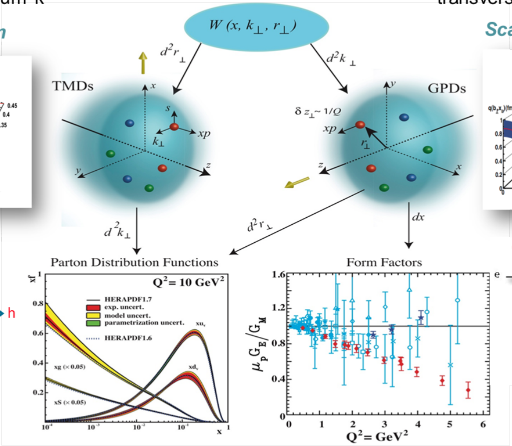


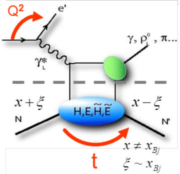


GPDs: Fraction of longitudinal momentum x et transverse position b

Scan in position

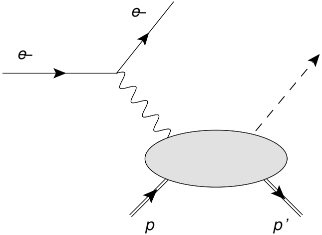






The deep exclusive processes

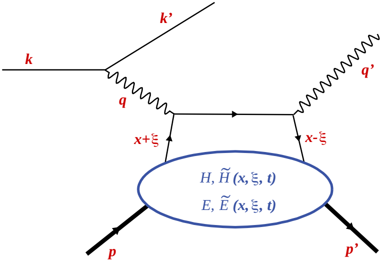
By measuring the cross section of deep exclusive processes, we get insights about the GPDs.



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.

DVCS and GPDs



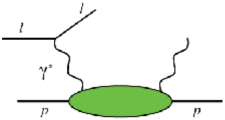
- $Q^2 = -q^2 = -(k-k')^2$.
- $x_B = \frac{Q^2}{2p \cdot q}$
- x longitudinal momentum fraction carried by the active quark.
- $\xi = \frac{x_B}{2-x_B}$ the longitudinal momentum transfer.
- $t = (p-p')^2$ squared momentum transfer to the nucleon.

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

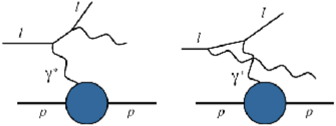
$$\mathcal{H}_{++}(\xi, t) = \int_{-1}^{1} H(x, \xi, t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) dx \ .$$

Photon electroproduction

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

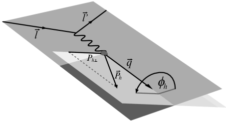


DVCS



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.

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

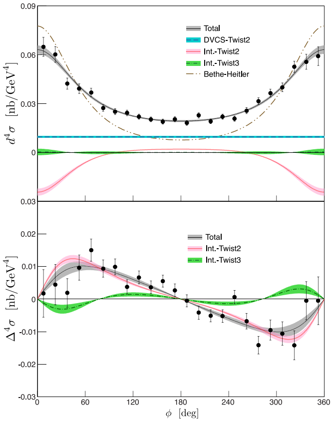


Figure: Unpolarized (top) and beam-helicity dependent cross sections at Q^2=2.3 GeV^2, x_B=0.36 and t=-0.3 GeV^2.

What do we know about CFF?

Considering only quarks, there are 4 CFFs involved in the DVCS amplitude:
$\mathcal{H}$, $\mathcal{E}$, $\widetilde{\mathcal{H}}$, $\widetilde{\mathcal{E}}$

- $\mathcal{H}$: Both real and impaginary parts Very well constrained by measurements on unpolarized target with the polarized beam.
- $\widetilde{\mathcal{H}}$: Imaginary part accessible with longitudinally polarized target (CLAS and CLAS12) but the real part not constrained.
- $\mathcal{E}$: Imaginary part accessible with transversely polarized target (none at JLab), and neutron target (FSI? Nuclear effects? Low detection efficiency). Real part not constrained as well.
- $\widetilde{\mathcal{E}}$: DVCS is poorly sensitive to $\widetilde{\mathcal{E}}$.

Building and maintaining a high polarization is not a trivial task.
Using a polarized target implies a dramatic limitation on the luminosity.

Why considering the recoil proton polarization

The latter can be expected to be as sensitive to CFF than observable using a polarized target, as being a 'mirror' observable.
We can already think about some experimental advantages:

- No luminosity limitation using an unpolarized target.
- Trackers are quite easy to build and are not that expensive.

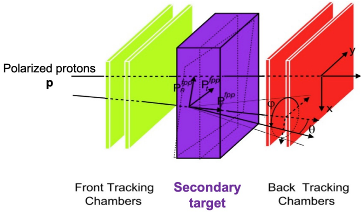
But not easy to start the study as the statistical significance of the measurement is a convolution of:

- the DVCS cross section driving the number of incident protons and their momentum,
- the polarimeter FoM depending on the proton momentum and carbon thickness,
- the sensitivity of the polarization to the CFFs.

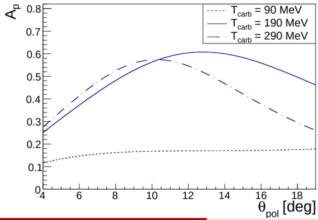
But first let's familiarize with the polarization and their connection with the CFFs.
All the following work is described in https://arxiv.org/abs/2209.04313 and has been accepted in PRD.

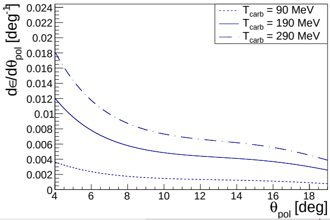
Proton Polarimetry

The polarization of the proton is measured by having it rescattered on a nucleus. An azimuthal distribution will result from the spin-orbit coupling.



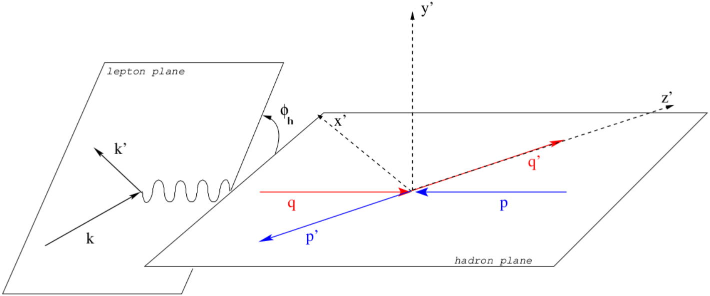
Two parameters must be considered, being the efficiency (the proton rescattering on a nucleus) and the analyzing power (strength of the spin-orbit coupling).





Theoretical computations

The recoil proton polarization has been computed by Pierre Guichon using Mathematica. His code returns the polarization components defined as follows in the $\gamma^* p$ com-frame:



A polarimeter measures the polarization transverse to the proton momentum in the lab frame. So we apply a last set of boosts and rotations to get the measured components in the lab:

- P_y^m is orthogonal to the hadronic plane.
- P_z^m is defined by the direction of the recoil proton in the lab.
- P_x^m such as X/Y/Z is a right-handed system.

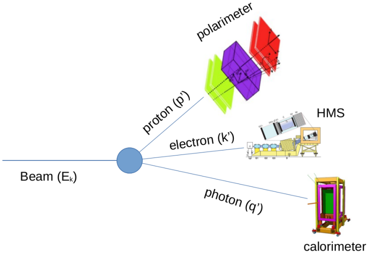
Kinematical study of the polarization

The study is performed using GK model, with CFF computed within the PARTONS framework.

As the phase space is vast, we will show plots around a kinematic point of interest. This setting was determined by maximizing a figure of merit:

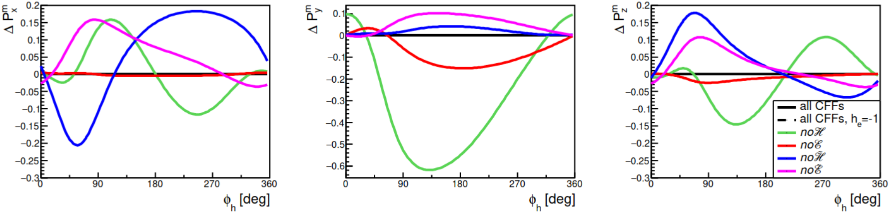
$$\mathcal{F} = F_p \times \sqrt{\frac{d\sigma}{dQ^2 dx_B dt d\phi}} \times \left(P_y^m(\mathcal{E}_{GK}) - P_y^m(\mathcal{E}=0)\right) \quad (1)$$

where F_p is the FoM of the polarimeter. Particles emitted above 10° with the beam, and more than 10° between the particles.



E= 10.6 GeV, h_e=1, Q^2= 1.8 GeV^2, x_B=0.17, t=-0.45 GeV^2 and ϕ_h=180°.

E= 10.6 GeV, Q^2= 1.8 GeV^2, x_B=0.17, t=-0.45 GeV^2



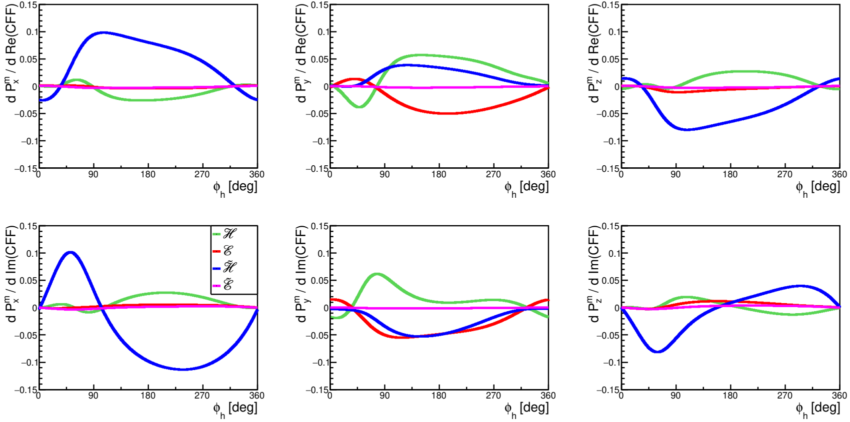
Quite complex ϕ_h-dependence, with beam helicity dependence to be considered.

- At small ϕ around 0 and 360 degrees, very small sensitivity to GPDs.
- For $\mathcal{E}$(red curve), only P_y seems sensitive.
- Surprising sensitivity to $\widetilde{\mathcal{E}}$(magenta curve).
- P_x and P_z sensitive to $\widetilde{\mathcal{H}}$.

However, all plots shown are CFF-model dependent as setting the CFF to 0 depends on its initial value.

A less-biased quantity: the first-order derivative

With the first-order derivative, the bias is reduced to the initial value of the CFFs and allows to have a better idea about the kinematical sensitivity of the polarization to CFF.



- No $\widetilde{\mathcal{E}}$-sensitivity... Previously it was an artefact of GK-model.
- P_x very sensitive to $\widetilde{\mathcal{H}}$, P_y equally to $\mathcal{H}$,$\widetilde{\mathcal{H}}$and $\mathcal{E}$.

A local expression

The polarization components can be written as:

$$P_{x/y/z} = \frac{\mathcal{A}_{x/y/z}}{\sigma} = \frac{\mathcal{A}^{BH}_{x/y/z} + \mathcal{A}^{I}_{x/y/z} + \mathcal{A}^{DVCS}_{x/y/z}}{\sigma} \tag{2}$$

where σ is the unpolarized cross section. The $\mathcal{A}_{x/y/z}$ are linear and bilinear in CFFs.

$$\begin{aligned}\mathcal{A}_x = & -20.42 + 19.06\ \mathrm{Re}\tilde{\mathcal{H}} + 7.15\ \mathrm{Re}\mathcal{H} - 1.04\ \mathrm{Re}\mathcal{E} - 0.56\ \mathrm{Re}\tilde{\mathcal{E}} \\ & -2.93\left(\mathcal{H}\tilde{\mathcal{H}}^* + \mathcal{H}^*\tilde{\mathcal{H}}\right) + 0.16\left(\mathcal{E}\tilde{\mathcal{H}}^* + \mathcal{E}^*\tilde{\mathcal{H}}\right) \\ & +0.04\left(\mathcal{H}\tilde{\mathcal{E}}^* + \mathcal{H}^*\tilde{\mathcal{E}}\right) + 0.03\left(\mathcal{E}\tilde{\mathcal{E}}^* + \mathcal{E}^*\tilde{\mathcal{E}}\right)\end{aligned} \tag{3}$$

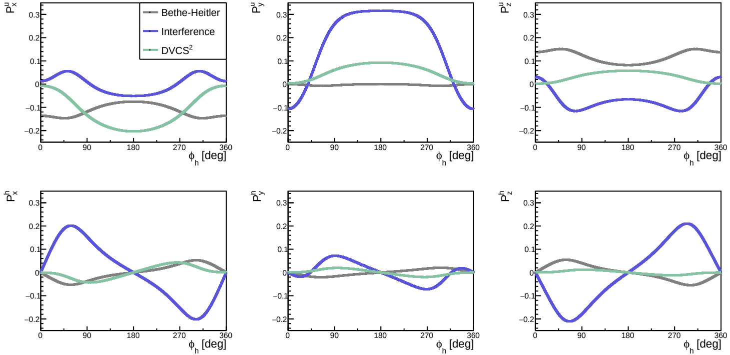
$$\begin{aligned}\mathcal{A}_y = & \ 15.50\ \mathrm{Im}\mathcal{H} - 10.05\ \mathrm{Im}\mathcal{E} + 3.44\ \mathrm{Im}\tilde{\mathcal{H}} - 0.44\ \mathrm{Im}\tilde{\mathcal{E}} \\ & +1.51\ \mathrm{Im}\left(\mathcal{E}\mathcal{H}^* - \mathcal{E}^*\mathcal{H}\right) + 0.14\ \mathrm{Im}\left(\tilde{\mathcal{E}}\tilde{\mathcal{H}}^* - \tilde{\mathcal{E}}^*\tilde{\mathcal{H}}\right)\end{aligned} \tag{4}$$

$$\tag{5}$$

BH/DVCS/Interference decomposition

We define:

- $P^{DVCS}_{x/y/z} = \frac{\mathcal{A}^{DVCS}_{x/y/z}}{\sigma}$.
- $P_{x/z} = h_e \left(P^u_{x/z} + h_e P^h_{x/z} \right)$ and $P_y = P^u_y + h_e P^h_y$



P_y almost pure GPD signal.

About the experiment

Now that there is an interest to measure the polarization of the proton, let's run a simulation.

- Using the NPS simulation package,
- Beam current = 10μA,
- Beam time = 3 weeks,
- P_e=0.85,

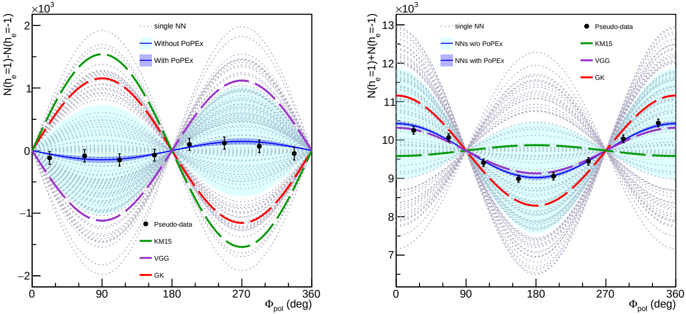
For the polarimeter,

- Approximately 1 sr $\Delta\theta$=$\pm$20°/$\Delta\phi$=$\pm$30° at 1m,
- 15cm-thick Carbon analyzer,
- Weighting by efficiency and analyzing power for Figure **??**,
- no background or proton transport

For the theory inputs:

- The GK, VGG and KM15 are used for predictions.
- 100 ANNs from a global fit of DVCS data by the PARTONS collaboration are used as well to assess the statistical significance of a measurement. (valid as CLAS data were available at this kinematic point).

Expected results



There are margins to still have a useful measurements:

- Reduce beam time,
- Reduce the beam current,
- Reduce polarimeter size or increase polarimeter distance to the target.

There is more to learn:

- π^0-measurement for free!! (Not exactly as the measurement must be done to study DVCS).

What is next?

Physics case is rock-solid.
Statistical significance is expected.
$\rightarrow$ **Let's turn this idea into a proposal.**

1. redo the kinematics search with first-order derivative instead of ΔP_y.
2. estimate the background rate...
3. ... and capabilities of both polarimeter ideas:
   - A standard polarimeter consisting of one/two carbon blocks and tracking stations.
   - An active analyzer with a block of scintillating fibers.

At first, we would like to avoid using a sweeping magnet because of the spin precession.
With this single experiment, all three CFFs ($\mathcal{H}$,$\widetilde{\mathcal{H}}$,$\mathcal{E}$) would be measured all at once.

If you have any comment/suggestion or idea, please contact me.