PoPEx and GluToNγ: New observables for DVCS

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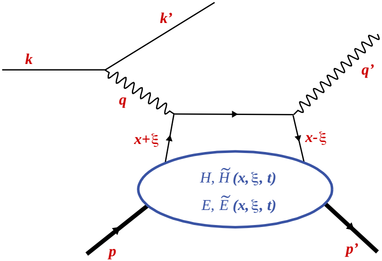
DVCS and GPDs



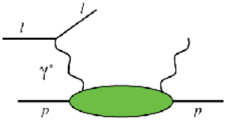
- $Q^2 = -q^2 = -(k - k')^2$.
- $x_B = \frac{Q^2}{2p \cdot q}$
- x longitudinal momentum fraction carried by the active quark.
- $\xi = \frac{x_B}{2 - x_B}$ the longitudinal momentum transfer.
- $t = (p - p')^2$ squared momentum transfer to the nucleon.

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

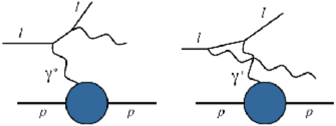
$$\mathcal{H}_{++}(\xi, t) = \int_{-1}^{1} H(x, \xi, t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) dx \,.$$

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

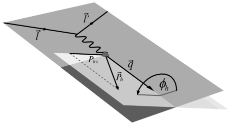


DVCS



Bethe-Heitler

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



Photon electroproduction and GPDs

The interference term allows to access the phase of the DVCS amplitude, *i.e* allows to isolate imaginary and real parts of CFFs.

$$c_{0,UU}^{DVCS} \sim 4(1-x_B)\left(\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*\right),$$

$$c_{1,UU}^{\mathcal{I}} \sim F_1\, Re\mathcal{H} + \xi(F_1+F_2)\, Re\widetilde{\mathcal{H}},$$

$$s_{1,LU}^{\mathcal{I}} \sim F_1\, Im\mathcal{H} + \xi(F_1+F_2)\, Im\widetilde{\mathcal{H}},$$

$$s_{1,UL}^{\mathcal{I}} \sim F_1\, Im\widetilde{\mathcal{H}} + \xi(F_1+F_2) Im\mathcal{H},$$

$$c_{1,UT}^{\mathcal{I}} \sim \frac{t}{4M^2}\left(-F_1\, Im\mathcal{E} + F_2 Im\mathcal{H}\right),$$

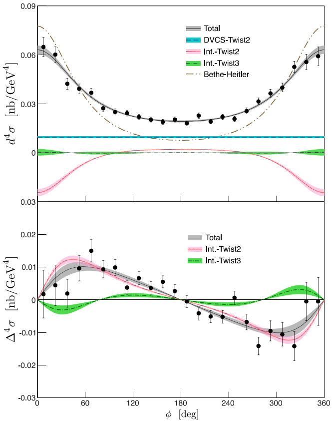


Figure: Unpolarized (top) and beam-helicity dependent cross sections at Q^2=2.3 GeV^2, x_B=0.36 and t=-0.3 GeV^2.

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.
And you need to detect the recoil proton, otherwise dilution factor is high.

LOI12-23-014: Why PoPEx?

PoPEx : Polarization of recoil Proton in Exclusive processes

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.

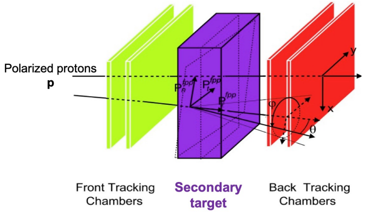
But not easy to start the study as the statistical significance of the measurement is a convolution of:

- 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.

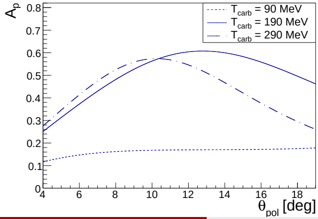
But first let's familiarize with the polarization and their connection with the CFFs.
All the following work is described in PRD 107, 014020(Bessidskaia-Bylund et al.).

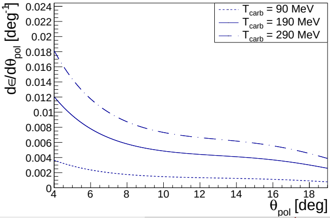
Proton Polarimetry

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



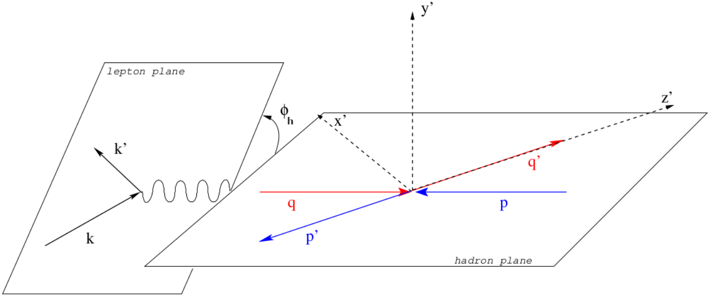
Two parameters must be considered, being the efficiency (the proton rescattering on a nucleus) and the analyzing power (strength of the spin-orbit coupling).





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.

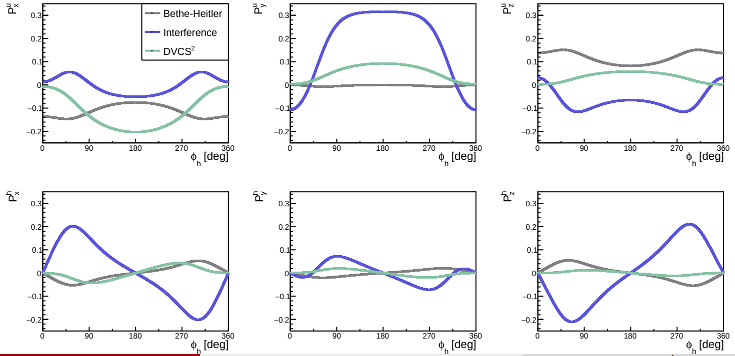
BH/DVCS/Interference decomposition

The polarization components can be written as:

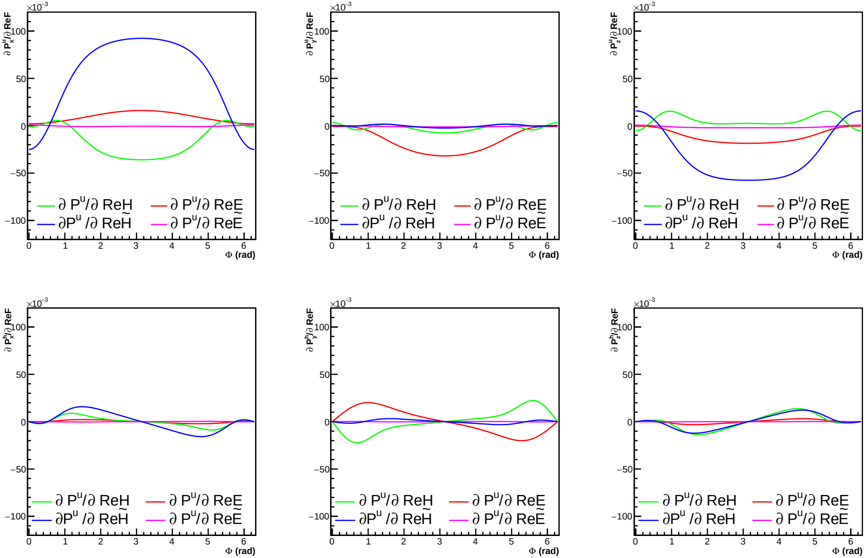
$$P_{x/y/z} = \frac{\mathcal{A}_{x/y/z}}{\sigma} = \frac{\mathcal{A}^{BH}_{x/y/z} + \mathcal{A}^{I}_{x/y/z} + \mathcal{A}^{DVCS}_{x/y/z}}{\sigma} \quad (1)$$

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

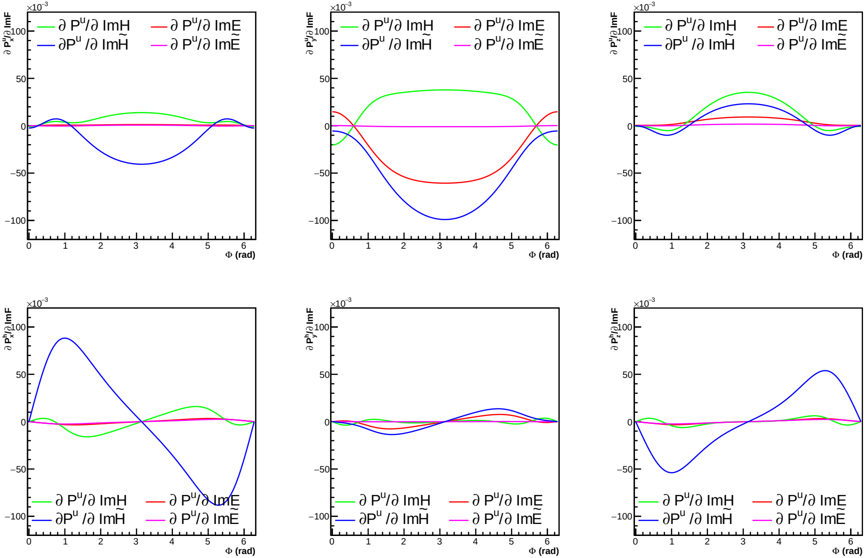
- $P^{DVCS}_{x/y/z} = \frac{\mathcal{A}^{DVCS}_{x/y/z}}{\sigma}$.
- $P_{x/z} = h_e \left(P^u_{x/z} + h_e P^h_{x/z}\right)$ and $P_y = P^u_y + h_e P^h_y$



Sensitivity studies - Re CFF



Sensitivity studies - Im CFF

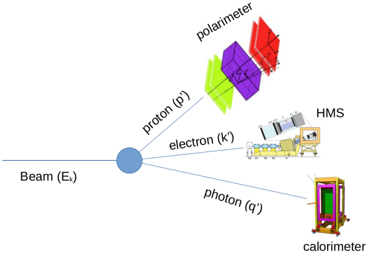


Kinematical study of the polarization

The study has been performed using GK model, with CFF computed within the PARTONS framework, and with Gepard.
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:

$$\mathcal{F} = F_p \times \sqrt{\frac{d\sigma}{dQ^2 dx_B dt d\phi}} \times \frac{\partial P_y^m}{\partial Im\mathcal{E}} \tag{2}$$

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

A local expression

We can look at normal expression of numerator in polarization and compare it with polarized target.

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

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

From Eur. Phys. J. C (2013) 73:2278 (Kroll et al.):

- P_x^u is similar to $A_{LL}^{cos\phi}$.
- P_x^h is similar to A_{UL}.
- P_y^u is similar to A_{UT}.

But here we do a single experiment instead of two for the polarized target.
=> Reduce systematics.

Experiment	Observable	Normalized CFF dependence
HERMES	$A_{\mathrm{C}}^{\cos 0\phi}$	$\mathrm{Re}\mathcal{H} + 0.06\mathrm{Re}\mathcal{E} + 0.24\mathrm{Re}\widetilde{\mathcal{H}}$
	$A_{\mathrm{C}}^{\cos \phi}$	$\mathrm{Re}\mathcal{H} + 0.05\mathrm{Re}\mathcal{E} + 0.15\mathrm{Re}\widetilde{\mathcal{H}}$
	$A_{\mathrm{LU,I}}^{\sin \phi}$	$\mathrm{Im}\mathcal{H} + 0.05\mathrm{Im}\mathcal{E} + 0.12\mathrm{Im}\widetilde{\mathcal{H}}$
	$A_{\mathrm{UL}}^{+,\sin \phi}$	$\mathrm{Im}\widetilde{\mathcal{H}} + 0.10\mathrm{Im}\mathcal{H} + 0.01\mathrm{Im}\mathcal{E}$
	$A_{\mathrm{UL}}^{+,\sin 2\phi}$	$\mathrm{Im}\widetilde{\mathcal{H}} - 0.97\mathrm{Im}\mathcal{H} + 0.49\mathrm{Im}\mathcal{E} - 0.03\mathrm{Im}\widetilde{\mathcal{E}}$
	$A_{\mathrm{LL}}^{+,\cos 0\phi}$	$1 + 0.05\mathrm{Re}\widetilde{\mathcal{H}} + 0.01\mathrm{Re}\mathcal{H}$
	$A_{\mathrm{LL}}^{+,\cos \phi}$	$1 + 0.79\mathrm{Re}\widetilde{\mathcal{H}} + 0.11\mathrm{Im}\mathcal{H}$
	$A_{\mathrm{UT,DVCS}}^{\sin(\phi-\phi_S)}$	$\mathrm{Im}\mathcal{H}\mathrm{Re}\mathcal{E} - \mathrm{Im}\mathcal{E}\mathrm{Re}\mathcal{H}$
	$A_{\mathrm{UT,I}}^{\sin(\phi-\phi_S)\cos\phi}$	$\mathrm{Im}\mathcal{H} - 0.56\mathrm{Im}\mathcal{E} - 0.12\mathrm{Im}\widetilde{\mathcal{H}}$
CLAS	$A_{\mathrm{LU}}^{-,\sin \phi}$	$\mathrm{Im}\mathcal{H} + 0.06\mathrm{Im}\mathcal{E} + 0.21\mathrm{Im}\widetilde{\mathcal{H}}$
	$A_{\mathrm{UL}}^{-,\sin \phi}$	$\mathrm{Im}\widetilde{\mathcal{H}} + 0.12\mathrm{Im}\mathcal{H} + 0.04\mathrm{Im}\mathcal{E}$
	$A_{\mathrm{UL}}^{-,\sin 2\phi}$	$\mathrm{Im}\widetilde{\mathcal{H}} - 0.79\mathrm{Im}\mathcal{H} + 0.30\mathrm{Im}\mathcal{E} - 0.05\mathrm{Im}\widetilde{\mathcal{E}}$

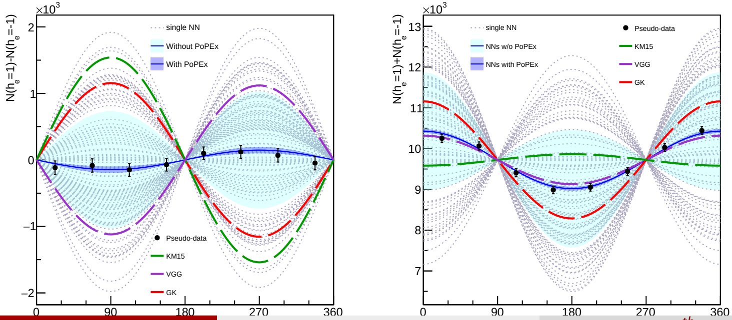
About the experiment

For the polarimeter,

- Approximately 1 sr $\Delta\theta=\pm20^\circ/\Delta\phi=\pm30^\circ$ at 1m, 15cm-thick Carbon analyzer,
- Weighting by efficiency and analyzing power for Figure **??**,
- no background or proton transport

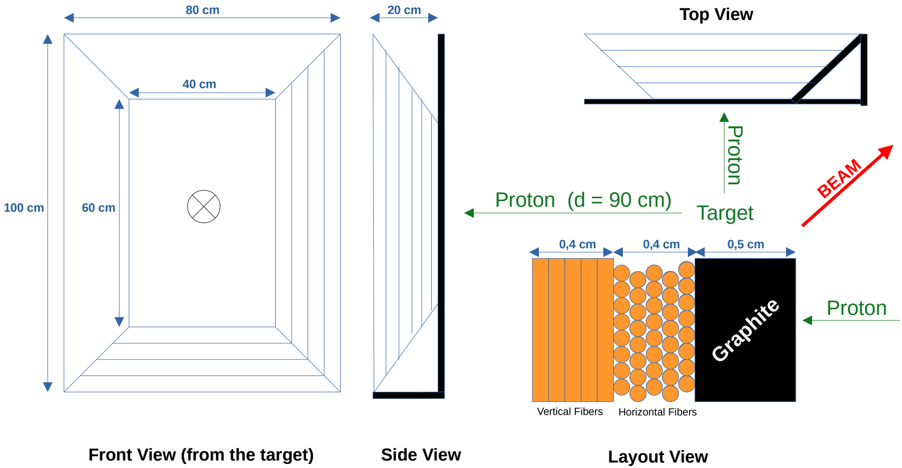
For the theory inputs:

- The GK, VGG (partons) and KM15 (gepard) are used for predictions.
- 100 ANNs from a global fit by the PARTONS collaboration. (valid as CLAS data were available at this kinematic point).



A Scintillating-Fiber polarimeter

No magnetic field to avoid spin precession: 1ns-time and 1mm-spatial resolution required to handle the background.



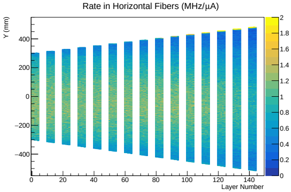
Detector rate and performances

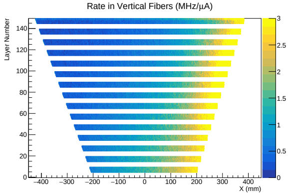
A few details about the simulation:

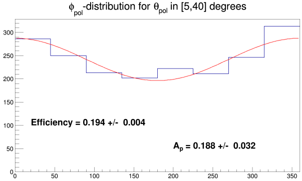
- Detailed description of the geometry in NPS Geant4 simulation.
- Specific classes for polarized proton event-by-event scattering.
- Number of photo-electron computed with Energy deposit.

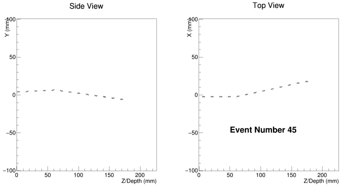
The rates are reaching 3 MHz/μA for vertical fibers at most. It is high but time resolution and DVCS kinematics will dramatically help to find the proton.

The analyzing power is found to be 0.2 with a 20%-efficiency, so equivalent Figure-of-merit than in PRD.









What is next for PoPEx?

A few steps are required on the simulation side to finalize a proposal

- Finalize the design of the polarimeter: Adding 5mm of air between each 3-layer will increase the lever-arm measure small angle scattering and improve analyzing power.
- Write a resilient pattern recognition/tracking code: Beam current will be limited by detector rate and tracking efficiency.
  N.B: Electron/Photon will allow to determine 4-momentum of proton (position and time).

In parallel, a careful check must be performed wrt to radiation hardness of SiPM, fibers and expected rate: Test run with scintillating fibers in Hall C maybe next year.

More possible physics cases:

- Neutral pion electroproduction for free! Have contacted Peter Kroll to compute recoil proton polarization.
- Neutron DVCS? Replacing Graphite with CH2 or scintillator. Need to check analyzing power.
- Any exclusive processes...
- Proton polarization of remnant proton in SIDIS?

If you are interested to join the effort, do not hesitate to contact me.

LOI12-23-003: Why GluToNγ?

GluToNγ: Gluon Tomography of Nucleons by γ-polarimetry.

You can write:

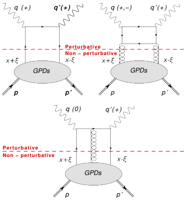
$$|\mathcal{A}_{DVCS}|^2 = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cos(2\phi) + \sqrt{\epsilon(1-\epsilon)}\sigma_{TL}\cos(\phi) \quad (5)$$

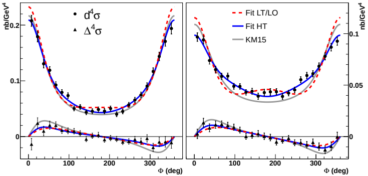
The helicity-conserved amplitude is the LT/LO amplitude but:

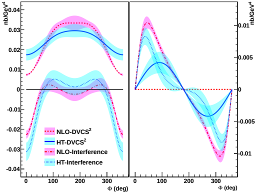
- Failure to fit DVCS data with only LT/LO (Hall A 6GeV/12GeV) with kinematical corrections (BMNP-formalism).
- Need to include either HT or NLO gluon linearity GPD contribution.

A full description of DVCS at NLO needs to account for both, regular and linearity gluon GPDs.

Gluon linearity GPDs do not mix with quark GPDs by evolution: Intrinsic gluon content of proton!







Measuring the photon polarization

At DVCS photon energy, the polarization is measured with pair conversion.

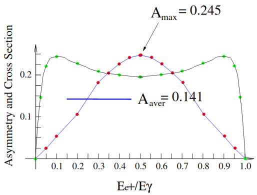
$$\frac{d\Gamma}{d\phi} \propto (1 + A_c A_{eff} P \cos[2(\phi - \phi_0)]) \;, \qquad (6)$$

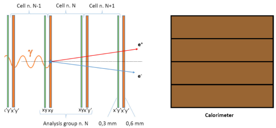
with A_c the analyzing power of the conversion process, P the linear polarization, ϕ_0 the direction of polarization, and A_{eff} the analyzing power of the polarimeter.

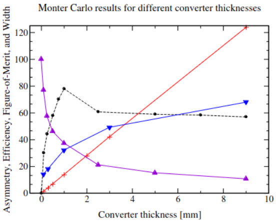
Like for proton polarimeter, the figure-of-merit $F = A_c^2 A_{eff}^2 \eta$ with η the conversion rate.
It is important to optimize F with the converter thickness:

- Thicker means larger η,
- but thicker means more multiple scattering blurring ϕ-measurement as $\theta_{+-} = \frac{1.6\ MeV}{E_\gamma}$

Eingorn et al., Journal of Astronomical Telescopes, Instruments, and Systems 4, 1 (2018)







Main idea of the experiment

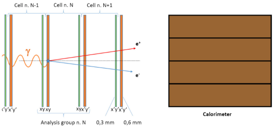
The experiment would run in Hall C:

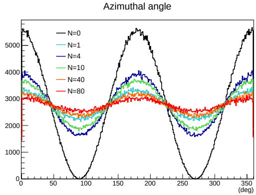
- The electron is detected in HMS or SBS (large acceptance).
- The photon is detected in NPS equiped with a "pre-shower" made of many layers of Pixel silicon detectors (MAPS).
- The sweeping magnet is used to run at high beam current.
- No need to detect the recoil proton.

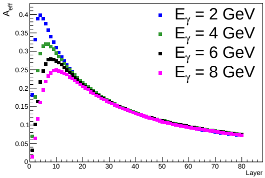
Multi-parameter optimization must be performed:

- Distance between MAPS.
- MAPS thickness and numbers.
- Additional converter: Coton-candy like converter? Density? Geometry? Thickness?

With higher beam current, larger electron acceptance and similar conversion efficiency, similar to proton polarimeter.







Conclusion

Regarding the GluToNγ-experiment, here are the perspectives:

- Pierre Guichon finished the calculation of the photon polarization. Final checks are being performed.
- Like the proton, careful study of sensitivity will have to be performed (more complicated though!).
- Two measurements: The polarization magnitude and its direction.
- In parallel, the design of the polarimeter will be finalized with Geant4.

PoPEx and GluToNγ are two experiments that requires high luminosity and can only be performed at Jefferson Lab. It does not require any beam energy upgrade... quite the contrary.

Twenty years ago, these experiments would not have been possible. But the progress in detector technology and DAQ are making these measurements nowadays possible!

Acknowledgement

I want to thank the NPS collaboration for providing a lot of Monte-Carlo codes to start these studies and their support to submit these LoI.

I want to thank Hall C staff (M. Jones, B. Wojtsekhowski and A. Camsonne) for the current and future help to turn these ideas into proposals within the next two years.