Recoil proton polarization in DVCS

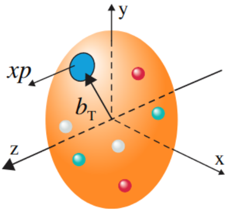
Assemblee General GDR QCD

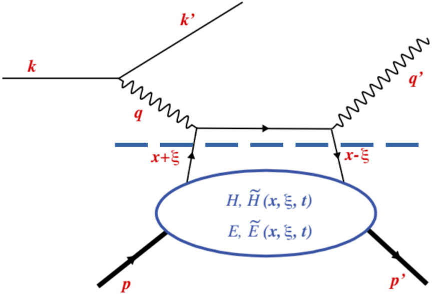
Olga Bessidskaia Bylund, Maxime Defurne, Pierre Guichon

CEA Saclay, IRFU, DPhN

24th of May 2022

Proton structure and GPDs





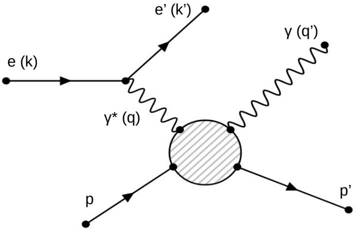
Generalized Parton Distributions (GPDs): nucleon structure in terms of longitudinal momentum & transverse position.

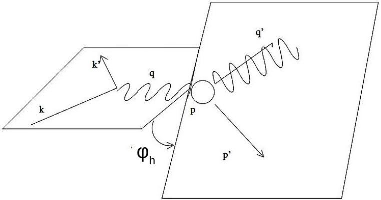
- Measured in exclusive processes like Deeply Virtual Compton Scattering (DVCS).

Factorization: splitting into perturbative hard part + non-perturbative soft part (GPDs).

GPDs are accessible through **Compton Form Factors** (CFFs): integrals over x - longitudinal momentum fraction of struck quark.

DVCS





DVCS parameters

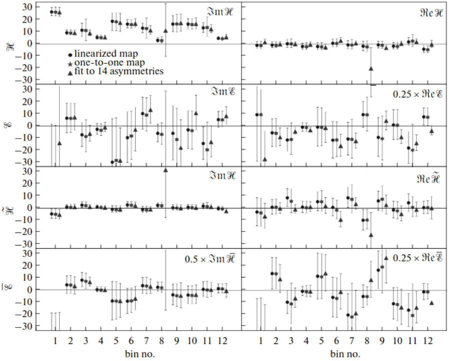
- E_k: beam energy.
- Q^2: virtuality of the photon, $Q^2 = -q^2 = -(k - k')^2$.
- $x_B = \frac{Q^2}{2p \cdot q}$.
- t: 4-momentum transfer to the proton, $t = (p' - p)^2$
- ϕ_h: angle between the leptonic and hadronic planes.

These parameters determine the kinematics of the scattered particles.

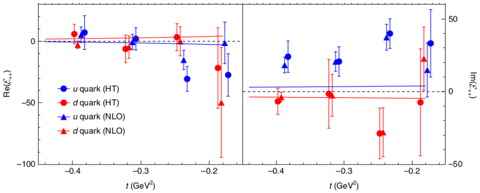
Measuring CFFs

Measurements outline

- $\mathcal{H}$: unpolarized target
- $\tilde{\mathcal{H}}$: longitudinally polarized target
- $\mathcal{E}$: transversely polarized target - challenge!
  - Gaseous transversely polarized target by HERMES (low luminosity).



Alternative: DVCS measurement on the neutron at Hall A, JLab

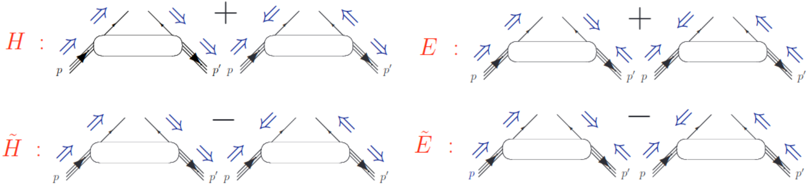


Uses a deuterium target.
Complications: FSI, bound state.

Back to basics

Connection to the total orbital angular momentum of the quarks through Ji's sum rule: $J^q = \frac{1}{2} \int \mathrm{d}x \, x \, [H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0)]$

Can we introduce a new observable to measure $\mathcal{E}$ to higher precision?

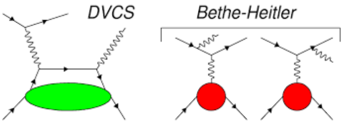


E describes the process when the proton changes helicity.

Can we extract more information on CFF $\mathcal{E}$ by measuring the **polarization** of the **recoil proton**?

Polarization

- Code by Pierre Guichon at leading order, leading twist, using the exact mathematical expressions.
- The polarization $\vec{P} = (P_x, P_y, P_z)$ is computed for the DVCS+Bethe-Heitler process, including their interference.
- P_y (normal to the hadronic plane) is particularly sensitive to CFF $\mathcal{E}$.



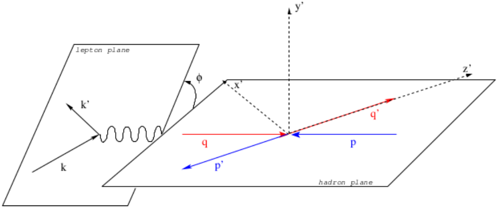
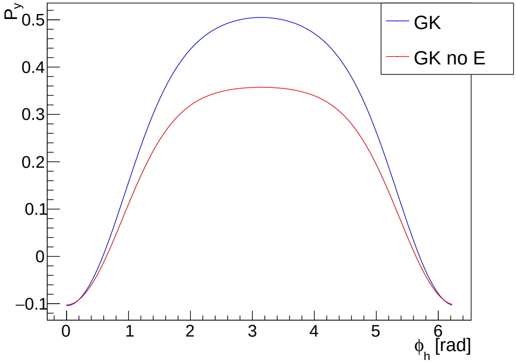


Figure 1: Rotated CM frame (x'y'z')

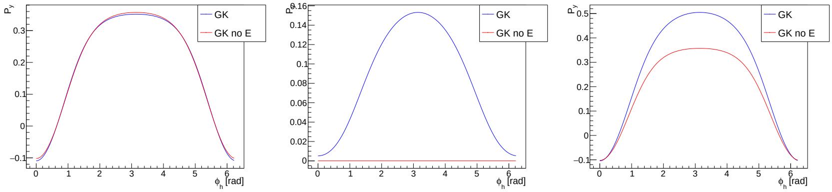
Polarization ϕ_h-dependence



- P_y is sensitive to $\mathcal{E}$ for the Goloshokov-Kroll (GK) model.
- P_x and P_z are not sensitive to $\mathcal{E}$.
- For $\phi_h = \pi$ there is a large difference in P_y when switching off $\mathcal{E}$.

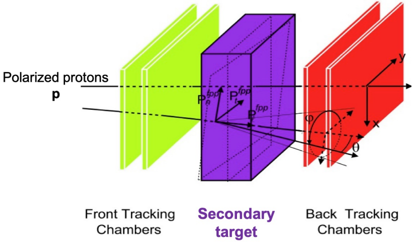
Polarization contributions

BH-DVCS interference DVCS Total



- The total magnitude of P_y comes largely from the interference with Bethe-Heitler.
- The sensitivity of P_y to $\mathcal{E}$ comes from DVCS.

Proton polarimeter



- Rescatter the proton with θ_{pol}, ϕ_{pol} inside a carbon analyzer.
- A set of trackers before and after the analyzer detect the incoming and outgoing protons.

A polarization perpendicular to the proton momentum will result in an asymmetry in ϕ_{pol}:

$$N(\theta_{pol}, \phi_{pol}) = N_0[1 + A_p(\theta_{pol})(P_y \sin\phi_{pol} - P_x \cos\phi_{pol})]$$

- The P_x dependence cancels out at $\phi_h = \pi$ for an unpolarized beam.
- P_y can be extracted by fitting the distribution.

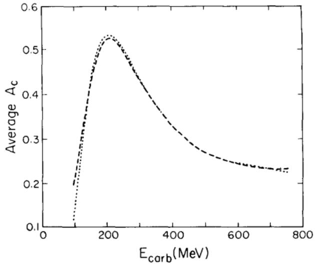
Polarimeter performance

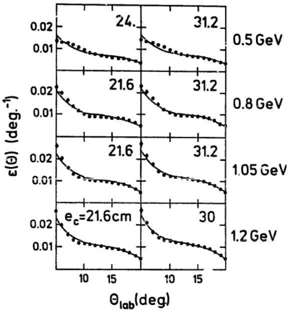
Analyzing power

- $A_p(\theta_{pol}, p')$: sensitivity of the scattering to the polarization.
- McNaughton's low-energy parametrization.

Efficiency

- $\epsilon(\theta_{pol}, p', e_c)$: probability to have a useful scattering in the analyzer. Bonin et al.





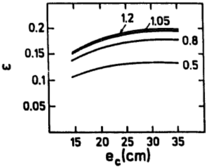


Figure of merit to characterise a polarimeter: $F^2 = \int_{\theta_{min}}^{\theta_{max}} A_p(\theta)^2 \epsilon(\theta) \mathrm{d}\theta$

Experimental context

Challenges

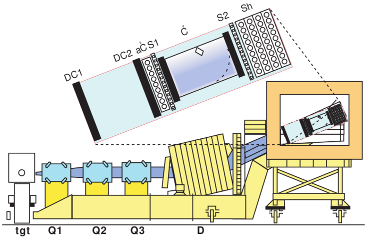
- DVCS has a low cross section compared to (semi-)inclusive processes.
- We need to rescatter the recoil proton, expecting a polarimeter efficiency of order 0.1.
- To achieve high statistics we need a high luminosity.

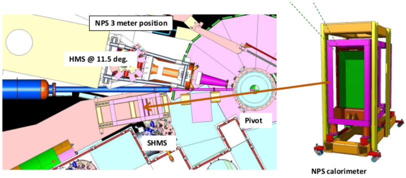
Candidate facility: Hall C at Jefferson Lab, using an **unpolarized electron beam** and an **unpolarized liquid hydrogen target**.

Example settings

- Target length: 15 cm.
- Beam current: 20 μA during 3 weeks of data taking.
- This gives an integrated luminosity $L = 7.2 \cdot 10^7$ pb^{-1}.

Electron and photon detection





Electron detection: HMS

- Focusing spectrometer.
- Scattering angle range 10.5-80°.
- Angular acceptance: ± 1.8° in-plane, ±4.9° out-of-plane.
- Momentum acceptance ±10%.

Photon detection: calorimeter

- Angular acceptance: ±5.3° horizontally, ±6.7° vertically.
- 30x36 $PbWO_4$ crystals. Position resolution: 2-3 mm.
- Sweeping magnet reduces low energy electron background.

Input

- The protons will be created from DVCS events.
- The event kinematics (momenta, angles) are determined by the DVCS parameters (E_k, Q^2, x_B, ϕ_h).
- The polarization depends on the CFFs - model dependence.

Model	P_y
GK	0.50
GK no E	0.36
VGG	0.24
KM15	0.15

- GK model: considerable sensitivity of P_y to $\mathcal{E}$. Used for optimization.
- We aim to discriminate between: GK, GK no E, VGG and KM15.

Optimization

Procedure

- Generate a grid in Q^2, x_B and t, setting $\phi_h = \pi$, $E_k = 10.6\,\mathrm{GeV}$.
- Compute the particle kinematics, the CFFs, the differential cross section and polarization.
- Construct a figure of merit $\mathcal{F}'$ proportional to $\Delta P_y = P_y(\mathcal{E}) - P_y(0)$.
- $\mathcal{F}'$ is inspired by accuracy of polarimeter $\delta_P \propto \frac{1}{F\sqrt{N_{inc}}}$, with $\delta P \to \Delta P_y$, $N_{inc} \to$ differential cross section:
$$\mathcal{F}' = F \cdot \sqrt{\mathrm{d}\sigma} \cdot \Delta P_y \,.$$
- Refine after Geant4 simulation, taking into account detector acceptance - larger lepton momenta preferred.

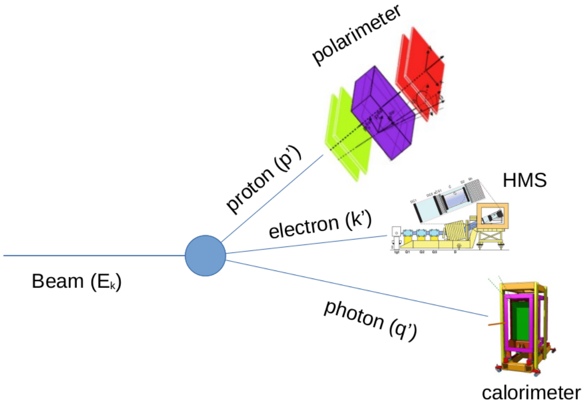
- Require: $|\theta_{k'}| > 10.5^\circ$, $\theta_{q'}, \theta_{p'} > 10^\circ$, $\Delta\theta_{i,j} > 10^\circ$ (isolation).

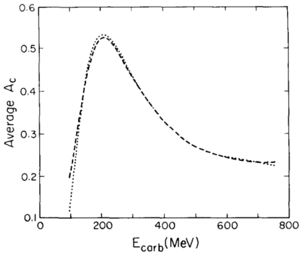
Optimization result

Maximizing $\mathcal{F}'$ gives:

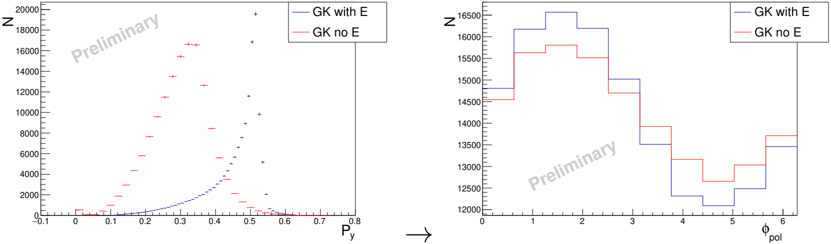
$$E_k = 10.6\,\mathrm{GeV},\; Q^2 = 1.8\,\mathrm{GeV}^2,\; x_B = 0.17,\; t = -0.45\,\mathrm{GeV}^2,\; \phi_h = \pi$$

electron $\lvert k' \rvert$	$\theta_{k'}$	photon $\lvert q' \rvert$	$\theta_{q'}$	proton $\lvert p' \rvert$	E_{carb}	$\theta_{p'}$
$4.96\,\mathrm{GeV}/c$	10.6°	$5.40\,\mathrm{GeV}/c$	-15.1°	$0.71\,\mathrm{GeV}/c$	$0.19\,\mathrm{GeV}/c$	44°





Fitting the polarization



Toy simulation of the polarimeter

- We assume a 1 str polarimeter to detect the recoil proton.
- This gives 3.6M events. Assign θ_{pol}, ϕ_{pol}.
- Knowing A_p, P_y can then be extracted (back) from ϕ_{pol}.

Fit results

$P_y(GK) = 0.475 \pm 0.011$ (cf weighted average: 0.463)
$P_y(\mathcal{E} = 0) = 0.316 \pm 0.011$ (cf weighted average: 0.304).

Conclusions

Summary

- We have explored a new way of measuring $\mathcal{E}$ - by looking at the **polarization** of the **recoil proton** in DVCS.
- P_y is highly sensitive to $\mathcal{E}$ and to different models.
- **Very high statistics** for 1 str polarimeter, 3 weeks data-taking, $20\mu A$.
- **Good discrimination** between the baseline and null hypothesis and between GK, VGG and KM15 in the statistical analysis.
- A starting point for a proposal has been identified.

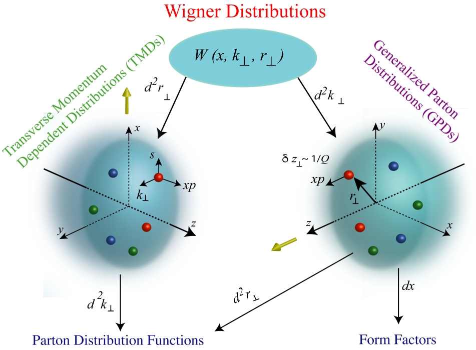
Plan to upload on arXiv shortly

Perspectives

- Develop a polarimeter design.
- Determine polarimeter dimensions.
- Consider the **background** and how to reduce it.

Backup

GPDs and proton structure



GPDs

- GPDs and TMDs can both be obtained from Wigner distributions.

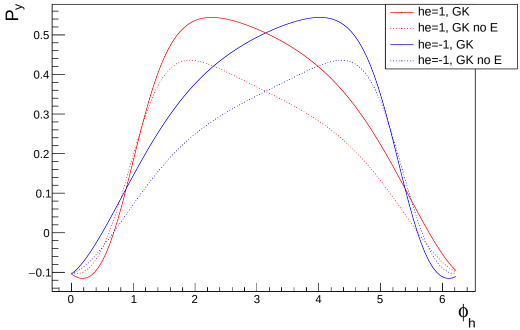
DVCS on neutron

From helicity-dependent cross-section difference:

$$[\mathcal{C}_n^I]^{exp} \simeq [\mathcal{C}_n^I] = F_1\mathcal{H} + \xi(F_1 + F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$

- Dominated by $\mathcal{H}$, $\tilde{\mathcal{H}}$ for a proton.
- In neutron:
  - F_1 is small.
  - Cancellation between u, d polarized distibutions in $\tilde{\mathcal{H}}$.

Polarization ϕ_h-dependence with a polarized beam



- P_y is sensitive to switching $\mathcal{E}$ on or off for the GK model.
- P_x and P_z are not sensitive to $\mathcal{E}$.
- For $\phi_h = \pi$ there is a large difference in P_y when switching off $\mathcal{E}$.

Luminosity

$\mathcal{L} = \Phi \cdot \rho \cdot L$

Beam

- 20 μA electron beam
- 1A $= 6.24 \cdot 10^{18}$ electrons/s
- $\rightarrow \Phi = 12 \cdot 10^{13}/\text{s}$

Target

- 0.15 m LH2 target.
- Density:
  - Density: 71 kg$/m^3$
  - Molar mass: 2.016 g / mol $= 3.35 \cdot 10^{27}$ kg/particle
  - $\rightarrow \rho = 2.1 \cdot 10^{28}/m^3$

$\mathcal{L} = 4.0 \cdot 10^{41}/\text{s}/m^2$.
$t = 9.1 \cdot 10^5\text{s} = 3$ weeks of data-taking
$L = \mathcal{L} \cdot t = 7.2 \cdot 10^{47}/m^2 = 7.2 \cdot 10^7 \mathrm{pb}^{-1}$ (conversion factor $10^{-(28+12)}$)

CFF inputs

Model	$\mathcal{H}$	$\mathcal{E}$	$\tilde{\mathcal{H}}$	P_y
GK	-1.1 + 5.41i	-2.4 - 0.4i	0.7 + 1.8i	0.50
GK no $\mathcal{E}$	-1.1 + 5.41i	0	0.7 + 1.8i	0.36
VGG	-2.5 + 5.0i	-1.1 + 1.6i	0.5 + 1.5i	0.24
KM15	-2.9 + 3.2i	1.6	0.5 + 1.5i	0.15

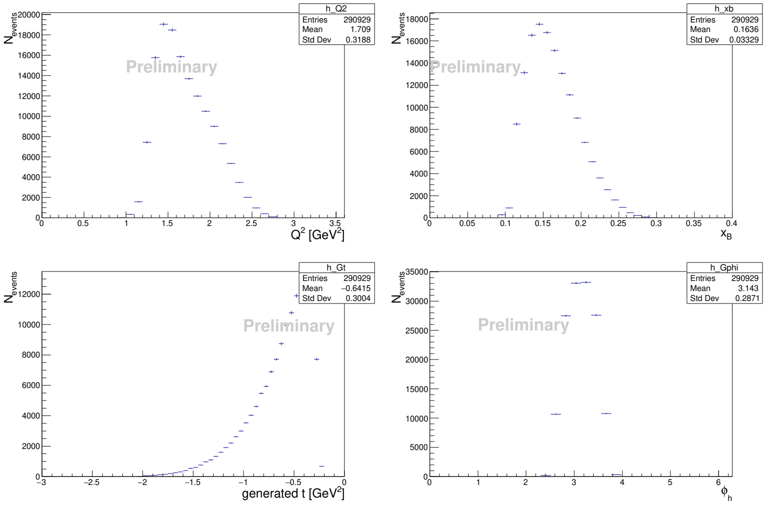
Model	$\mathcal{H}$	$\mathcal{E}$	$\tilde{\mathcal{H}}$	$\tilde{\mathcal{E}}$	P_y
ANN	$-1.8^{\pm 1.3} + 3.4^{\pm 1.7}i$	$-4^{\pm 7} + 0^{\pm 9}i$	$0.4^{\pm 1.4} + 1.2i^{\pm 1.8}$	$-25^{\pm 65} + 3^{\pm 59}\, i$	0.45

Variations

- Larger $|t| \rightarrow$ larger ΔP_y, smaller $\mathrm{d}\sigma$.
- Larger $Q^2 \rightarrow$ smaller ΔP_y, smaller $\mathrm{d}\sigma$.
- Larger $x_B \rightarrow$ smaller $\mathrm{d}\sigma$.
- Large $|\mathrm{k}'|$ (small Q^2/x_B) $\rightarrow$ larger acceptance.

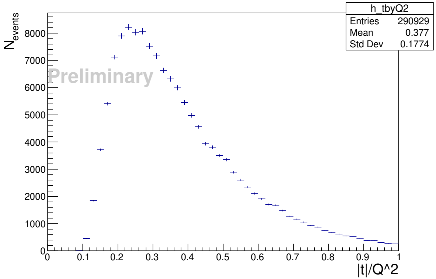
Also require $|t|/Q^2 \leq 0.25$.

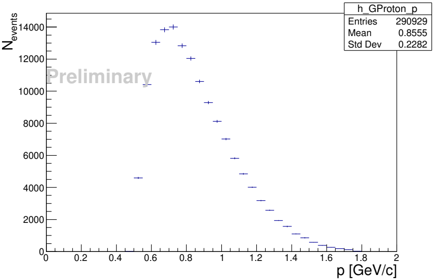
Distributions



Imposing $\theta_{p'} = \theta_{p'}^{target} \pm 20^\circ$, $\phi_{p'} = \phi_{p'}^{target} \pm 30^\circ$ gives these distributions, with Q^2, x_B, ϕ_h centered near the target values (1.8, 0.17, π).

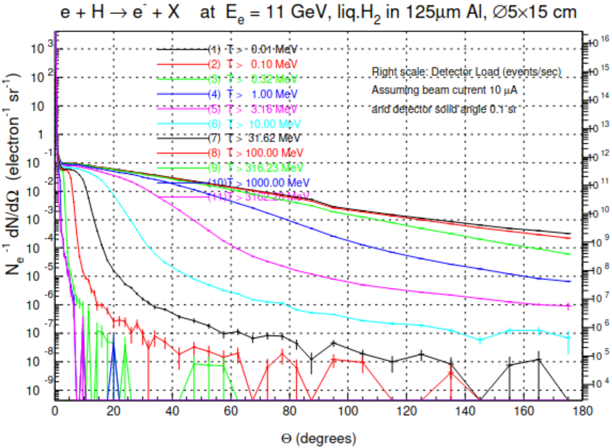
Distributions (2)





$|t|/Q^2$ and scattered proton momentum

Accidental background



- The background of accidental electrons is largest at small angles from the beam.

Refining the optimization

Q^2, x_B, t	$\mathcal{F}'$	N^{obs}_{evts}	ΔP^{obs}_y	Fitted δ_P
1.6,0.12,-0.40	0.057	0.5M	0.13	0.031
1.7,0.14,-0.42	0.049	1.6M	0.15	0.017
1.7,0.15,-0.42	0.046	2.6M	0.16	0.013
1.8,0.17,-0.45	0.039	3.6M	0.16	0.011
1.9,0.19,-0.47	0.032	4.1M	0.14	0.010

Selection: $\theta_{p'} \pm 20^\circ$, $\phi_{p'} \pm 30^\circ$ + requirement of non-zero reconstructed scattered lepton p_x.

Increasing x_B, decreasing Q^2/x_B or increasing θ^{min}_{calo} and recomputing $\mathcal{F}'$ post-simulation until it reaches the peak gives the same optimal configuration.