Recoil proton polarization in DVCS

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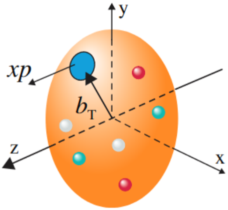
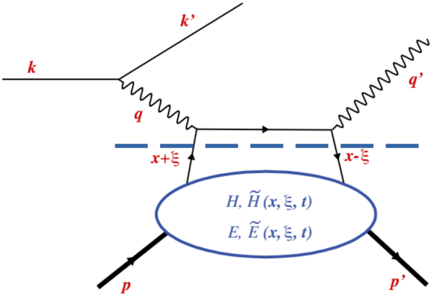
Proton structure and GPDs





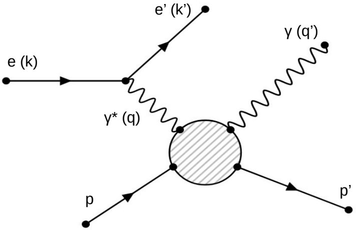
Generalized Parton Distributions (GPDs): nucleon structure in terms of longitudinal momentum & transverse position.

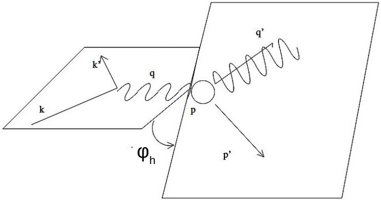
- Measured in exclusive processes like Deeply Virtual Compton Scattering (DVCS).

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

GPDs are accessible through **Compton Form Factors** (CFFs).

DVCS



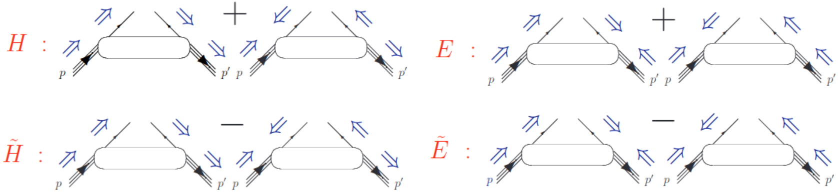


DVCS parameters

- 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.

GPD meanings



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

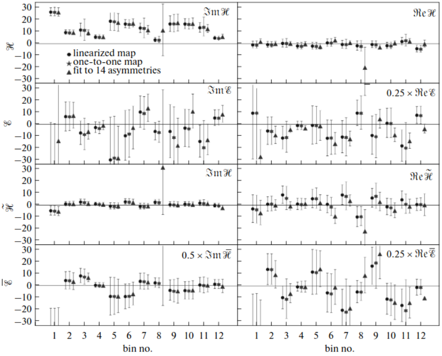
E describes the process when the proton changes helicity.

Can we introduce a new observable to determine E to higher precision?

Measuring CFFs

The common setup to measure CFFs

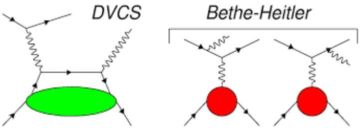
- $\mathcal{H}$: unpolarized target
- $\tilde{\mathcal{H}}$: longitudinally polarized target
- $\mathcal{E}$: transversely polarized target - challenge!
    - Gaseous transversely polarized target by HERMES (low luminosity).



- $\mathcal{E}$ is much less constrained than $\mathcal{H}$, $\tilde{\mathcal{H}}$.
- $\mathcal{E}$ can also be measured through DVCS on a deuterium target, but theoretical complications.
- Can we extract more info on $\mathcal{E}$ by measuring the **polarization** of the **recoil proton**?

Polarization

- Code by Pierre Guichon, 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.



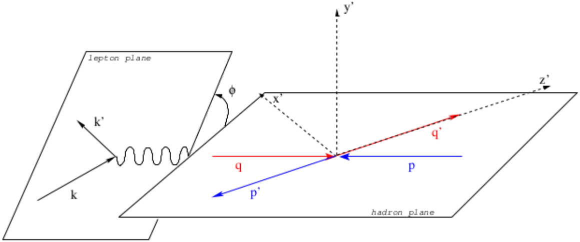
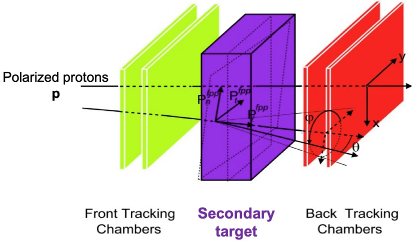


Figure 1: Rotated CM frame (x'y'z')

- P_y (normal to the hadronic plane) is sensitive to CFF $\mathcal{E}$.
- Additionally, P_x is sensitive to $\tilde{\mathcal{H}}$.

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.

Transverse polarization will induce a modulation:

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

- Polarization $\propto$ amplitude.
- At $\phi_h = 180°$: $P_x \to -P_x$, $P_y \to P_y$ when beam helicity switches.
  - Subtract over different beam helicity $\to P_x^m$ ($\tilde{\mathcal{H}}$).
  - Add all events $\to P_y$ ($\mathcal{E}$).
  - Two experiments in one.

Polarimeter performance

Efficiency

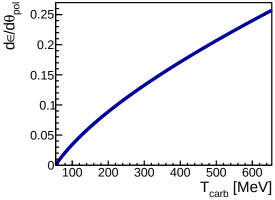
Probability to have a useful scattering in the analyzer, Bonin et al.

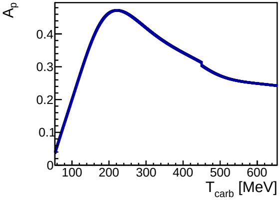
Analyzing power

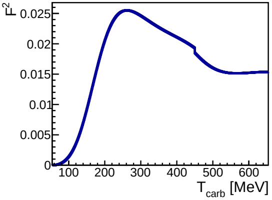
Sensitivity of the scattering to the polarization, McNaughton et al.

Figure of merit

$$F^2 = \int_{\theta_{min}}^{\theta_{max}} A_p(\theta)^2 \epsilon(\theta) \mathrm{d}\theta$$







The polarimeter performance depends on the proton momentum, scattering angle in the analyzer θ_{pol} and analyzer thickness (here 15 cm).

Experimental context

Challenges

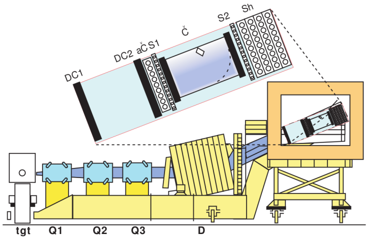
- DVCS has a low cross section compared to (semi-)inclusive processes.
- We need to rescatter the recoil proton, expecting a polarimeter efficiency of order 0.1.
- To achieve high statistics we need a high luminosity.

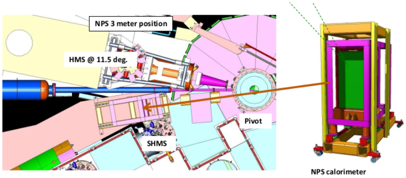
Candidate facility: Hall C at Jefferson Lab, using a **polarized electron beam** and an **unpolarized liquid hydrogen target**.

Example settings

- Target length: 15 cm.
- Beam current: 10 μA during 3 weeks of data taking.

Electron and photon detection





Electron detection: HMS

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

Photon detection: NPS 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.

Optimization

Procedure

- Consider different DVCS configurations (5 parameters fully determine the particle kinematics).
- Evaluate the CFFs using GK model and compute the differential cross section and polarization.
- Construct a figure of merit $\mathcal{F}'$ proportional to $\Delta P_y = P_y(\mathcal{E}) - P_y(0)$:
$$\mathcal{F}' = F \cdot \sqrt{N_{protons}} \cdot \Delta P_y \ .$$
- Take detector effects into account using Geant4 simulation.

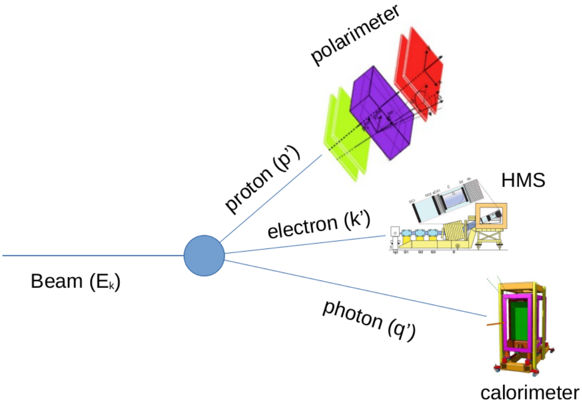
- Require isolation of all particles from each other (10° in general, 10.5° electron-beam, 30° proton-electron).
- Imposing constraint $|t|/Q^2 \leq 0.25$ for validity of leading twist.

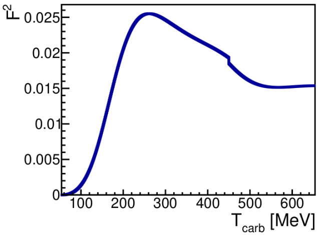
Optimization result

Maximizing $\mathcal{F}'$ gives:

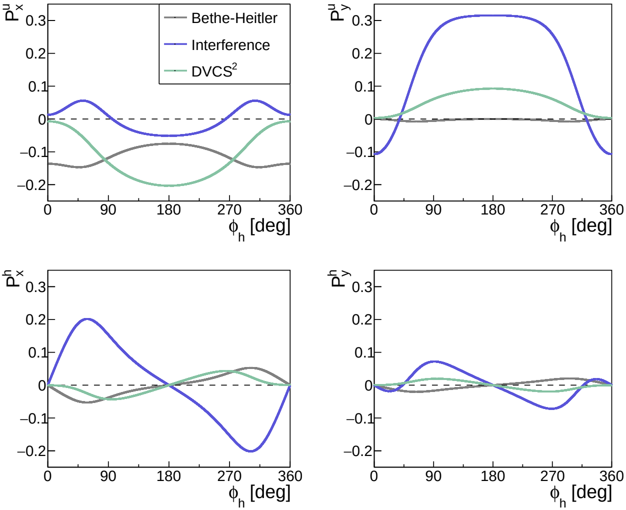
$$E_k = 10.6\,\mathrm{GeV},\; Q^2 = 1.8\,\mathrm{GeV}^2,\; x_B = 0.17,\; t = -0.45\,\mathrm{GeV}^2,\; \phi_h = 180^\circ$$

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





Decomposition as a function of ϕ_h

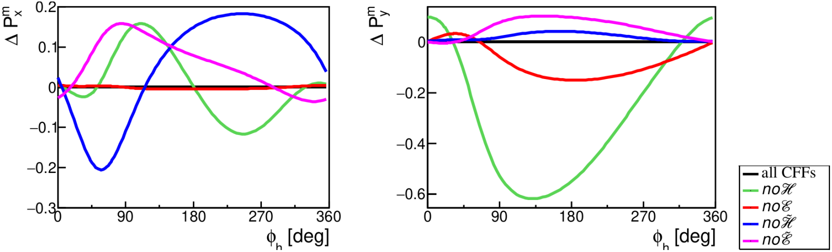


Beam helicity independent (P_i^u)

Beam helicity dependent (P_i^h)

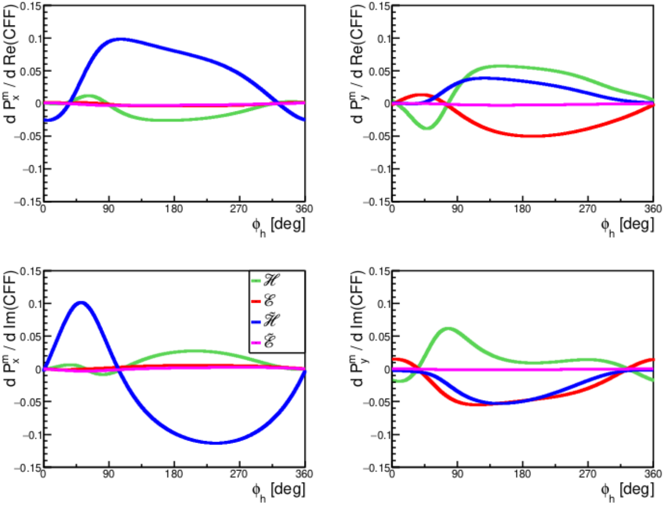
$$P_x = h_e(P_x^u + h_e P_x^h) \qquad P_y = P_y^u + h_e P_y^h$$

ϕ_h dependence



- Looking at the difference in polarization ΔP_i between the GK model and GK model with one coefficient set to 0.
- Non-trivial ϕ_h dependence.
- The polarization appears sensitive to all CFFs.
- The difference depends on the values of the CFFs in the GK model.

dP/dCFF derivatives, ϕ_h



Derivatives w.r.t. $\Re(CFF), \Im(CFF)$ removes the model dependence of the interference terms and reduces that of the (bilinear) DVCS^2 terms.

Local expression

While the full expression is super lengthy, we have derived a local one, showing the kinematical coefficients.

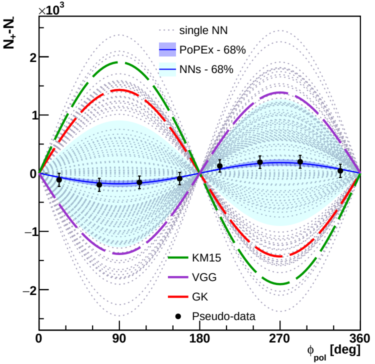
At E_k=10.6 GeV, Q^2=1.8 GeV^2, x_B=0.17, t=−0.45 GeV^2, ϕ_h=180°:

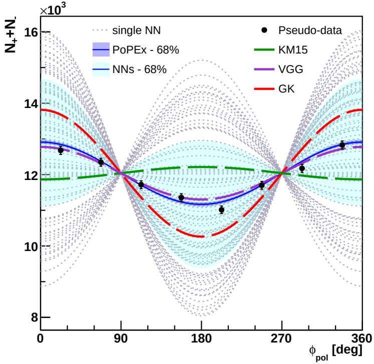
$$\mathcal{M}(x) = -20.42 + 19.06\ \mathrm{Re}\tilde{\mathcal{H}} + 7.15\ \mathrm{Re}\mathcal{H} - 1.04\ \mathrm{Re}\mathcal{E} - 0.56\ \mathrm{Re}\tilde{\mathcal{E}} \\ -2.93\left(\mathcal{H}\tilde{\mathcal{H}}^* + \mathcal{H}^*\tilde{\mathcal{H}}\right) + 0.16\left(\mathcal{E}\tilde{\mathcal{H}}^* + \mathcal{E}^*\tilde{\mathcal{H}}\right) \\ +0.04\left(\mathcal{H}\tilde{\mathcal{E}}^* + \mathcal{H}^*\tilde{\mathcal{E}}\right) + 0.03\left(\mathcal{E}\tilde{\mathcal{E}}^* + \mathcal{E}^*\tilde{\mathcal{E}}\right) \quad (1)$$

$$\mathcal{M}(y) = 15.50\ \mathrm{Im}\mathcal{H} - 10.05\ \mathrm{Im}\mathcal{E} + 3.44\ \mathrm{Im}\tilde{\mathcal{H}} - 0.44\ \mathrm{Im}\tilde{\mathcal{E}} \\ +1.51\ \mathrm{Im}\left(\mathcal{E}\mathcal{H}^* - \mathcal{E}^*\mathcal{H}\right) + 0.14\ \mathrm{Im}\left(\tilde{\mathcal{E}}\tilde{\mathcal{H}}^* - \tilde{\mathcal{E}}^*\tilde{\mathcal{H}}\right) \quad (2)$$

$P^i = \mathcal{M}(i)/\mathcal{M}(0)$.

Fitting the polarization





Toy simulation of the polarimeter

- We assume a $\pm 20^\circ \times \pm 30^\circ$ $(\theta_{p'} \times \phi_{p'})$ polarimeter and simulate.
- Extract P_x, P_y from the difference, sum over beam helicity.
- Statistical precision excludes $\sim 90\%$ of the NN replicas from the PARTONS team and discriminate betwen GPD models.

Optimizing wrt derivatives pre-simulation

Target	E_k	Q^2	x_B	t	$dP_y/dCFF$	dxs [pb/..]	F'
$\Re(E)$	10.6	1.9	0.19	-0.47	0.061	2.7	1.45
$\Im(E)$	8.8	1.9	0.15	-0.47	0.045	5.5	1.53
$\Im(E)$	10.6	2.2	0.17	-0.55	0.067	1.9	1.46
Ref ($\Re$)	10.6	1.8	0.17	-0.45	0.050	3.8	1.33
Ref ($\Im$)	"	"	"	"	0.049	"	1.31

F' $= d\sigma \cdot (dP_y/dCFF)^2 \cdot$ FoM$_{pol} \cdot 100$

Optimizing wrt derivatives pre-simulation

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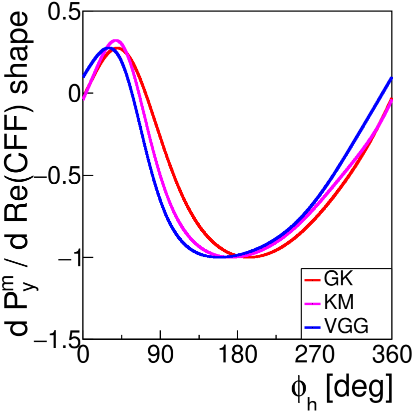
Ref ($\Im$)	"	"	"	"	0.049	"	1.31

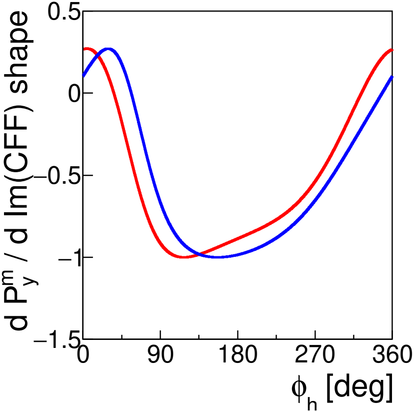
F' $= d\sigma \cdot (dP_y/dCFF)^2 \cdot$ FoM$_{pol} \cdot 100$

DVCS parameters	$p'_e,\ \theta'_e$	$p'_\gamma,\ \theta'_\gamma$	p'_p, θ'_p
10.6,1.9,0.19,-0.47	5.27, 10.6	5.08, -16.6	0.730, 41
8.8,1.9,0.15,-0.47	2.05, 18.7	6.50, -10.8	0.730, 50
10.6,2.2,0.17,-0.55	3.70, 13.6	6.60, -12.6	0.797, 46
10.6,1.8,0.17,-0.45	4.96, 10.6	5.40, -15.1	0.712, 44

Note: The HMS has a higher acceptance at higher electron momentum.

Derivative for different input models





The value at 180° is near the highest absolute value of the derivatives for the VGG and KM models too.

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 sr polarimeter, 3 weeks of data-taking, $10\mu A$.
- **Good discrimination** between the GK, VGG and KM15 models in the statistical analysis. Potential to exclude many NN replicas.
- A starting point for a proposal has been identified.
- Robustness checks:
  - The optimization result does not change by much when optimizing w.r.t. derivatives rather than $P_y - P_y(E = 0)$ in GK.
  - For VGG and GK models, $\phi_h = 180^\circ$ is also a good choice.

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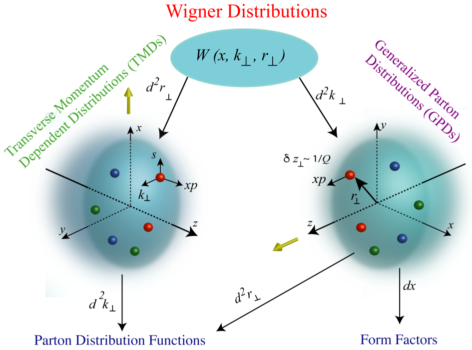
Outlook

- Consider the **background** and how to reduce it.
- Develop a polarimeter design and determine polarimeter dimensions.
  - The Super Big-bite Spectrometer will be moved to Hall C. Can the GEM detectors run without magnetic field at 44 degrees 1.5-2m away from the target?
  - Another possibility: scintillating fibers active polarimeter.
- Prepare a proposal for Hall C.

Backup

GPDs and proton structure



GPDs

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

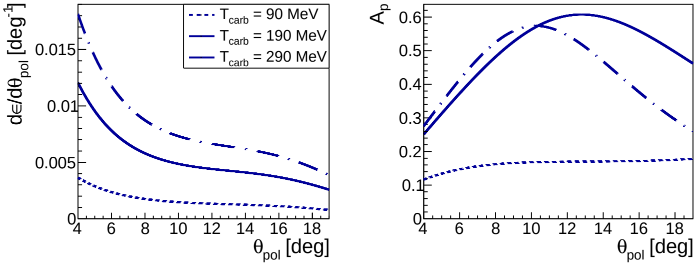
DVCS on the neutron

From helicity-dependent cross-section difference:

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

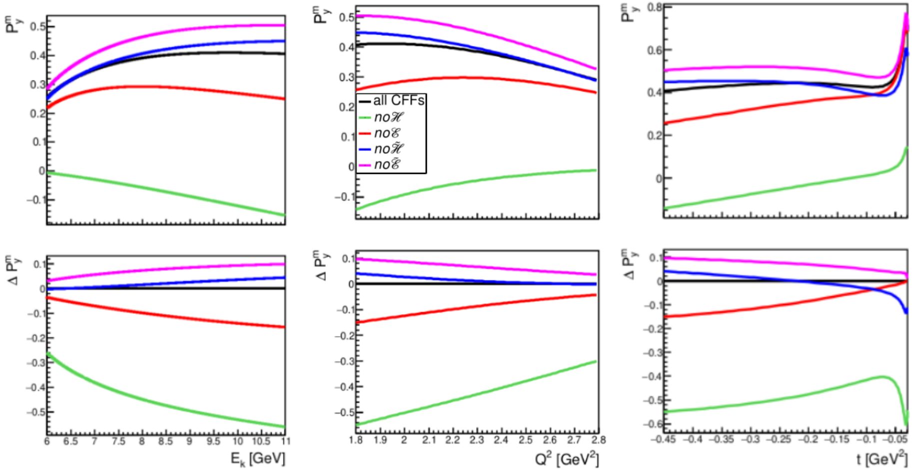
- Dominated by $\mathcal{H}$, $\tilde{\mathcal{H}}$ for a proton.
- In neutron:
  - F_1 is small.
  - Cancellation between u, d polarized distibutions in $\tilde{\mathcal{H}}$.

Polarimeter properties in our region of interest



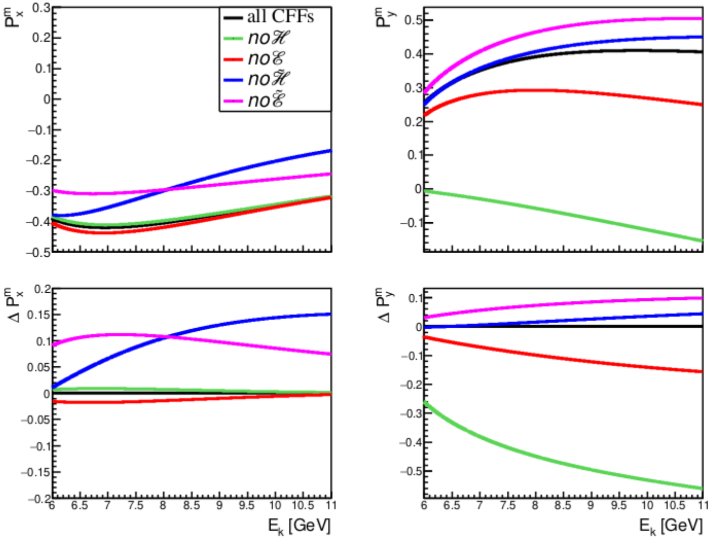
- The efficiency increases with proton energy.
- The analyzing power peaks around a kinetic energy of ∼200 MeV.

Variations around the proposed kinematics

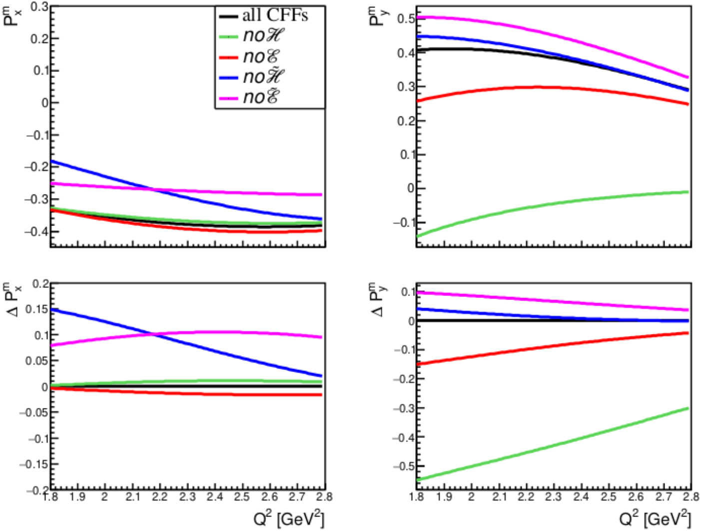


The figure of merit favours high beam energy E_k, low photon virtuality Q^2 and high momentum transfer to the proton $|t|$.
Imposing constraint $|t|/Q^2 \leq 0.25$ for validity of leading twist.

Variations: beam energy

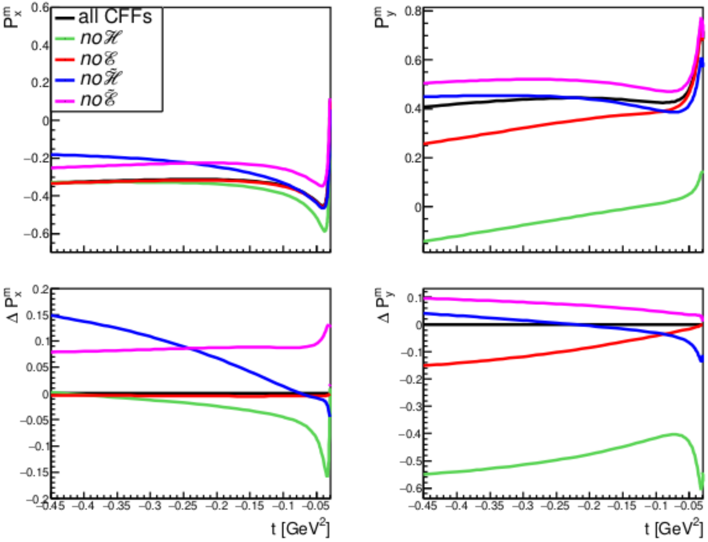


A high beam energy is preferred.



A low photon virtuality is favoured.

Variations: momentum transfer to the proton t



A high $|t|$ is favoured, but we also impose $|t|/Q^2 \leq 0.25$.

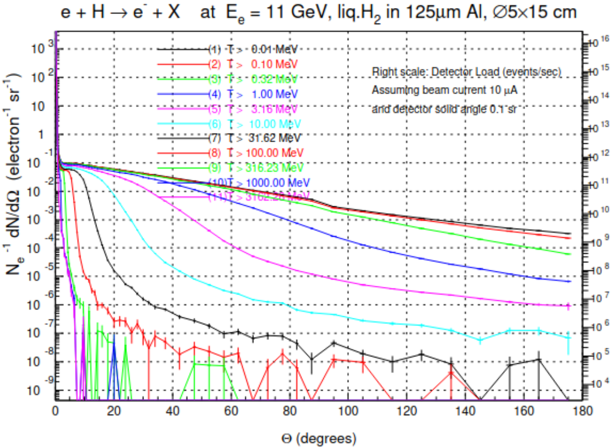
CFF inputs

Model	$\mathcal{H}$	$\mathcal{E}$	$\tilde{\mathcal{H}}$	$\tilde{\mathcal{E}}$	P_x^m	P_y^m
GK	-1.1 +5.4i	-2.4 -0.4i	0.7 +1.8i	38 +19i	-0.33	0.41
VGG	-2.2 +4.8i	-1.0 +1.5i	0.5 +1.4i	51 +0i	0.32	0.17
KM15	-2.9 +3.2i	1.6 +0i	0.5 +1.5i	124 +0i	-0.44	-0.04
ANN	$-1.6^{\pm 2.6}+3.3^{\pm 3.3}$i	$-4.1^{\pm 9.2}+0^{\pm 18}$i	$0.6^{\pm 3.0}+1.1^{\pm 2.5}$i	$-25^{\pm 265}+4^{\pm 72}$	$0.04^{\pm 0.25}$	$0.20^{\pm 0.41}$

Variations

- Larger $|t| \to$ larger ΔP_y, smaller $\mathrm{d}\sigma$.
- Larger $Q^2 \to$ smaller ΔP_y, smaller $\mathrm{d}\sigma$.
- Larger $x_B \to$ smaller $\mathrm{d}\sigma$.
- Large $|\mathrm{k}'|$ (small Q^2/x_B) $\to$ larger acceptance.
- Small E_k or large Q^2 - the angle between the electron and the proton decreases.

Accidental background



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