Recoil proton polarization in DVCS

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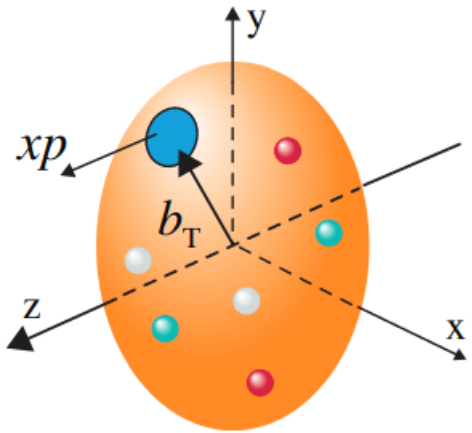
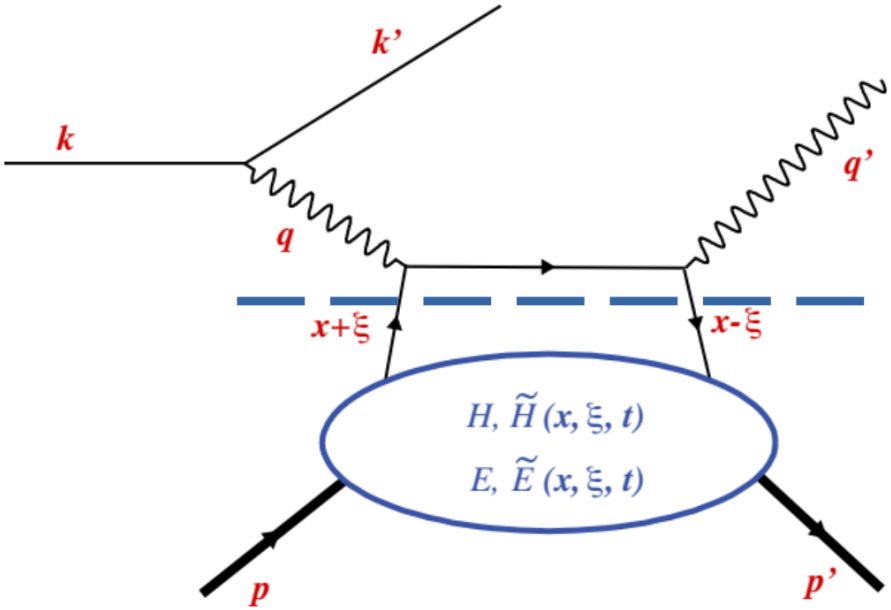
Proton structure and GPDs





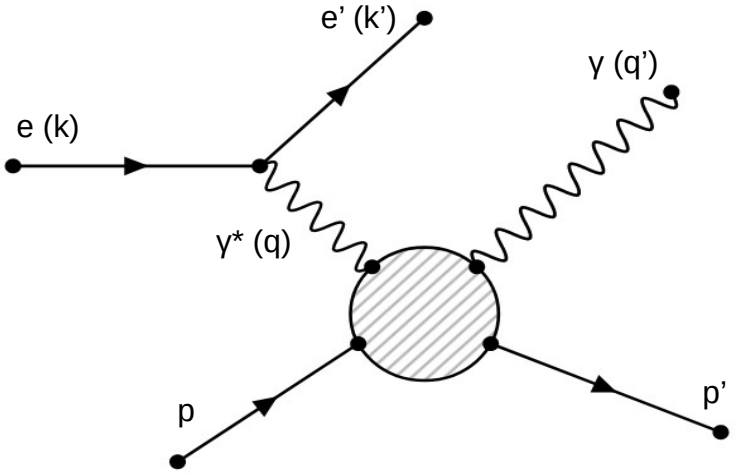
Generalized Parton Distributions (GPDs): nucleon structure in terms of longitudinal momentum & transverse position.

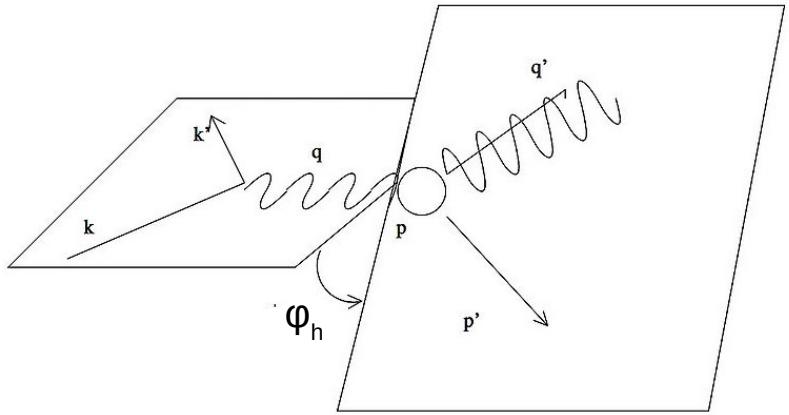
- Measured in exclusive processes like Deeply Virtual Compton Scattering (DVCS).

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

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

DVCS





DVCS parameters

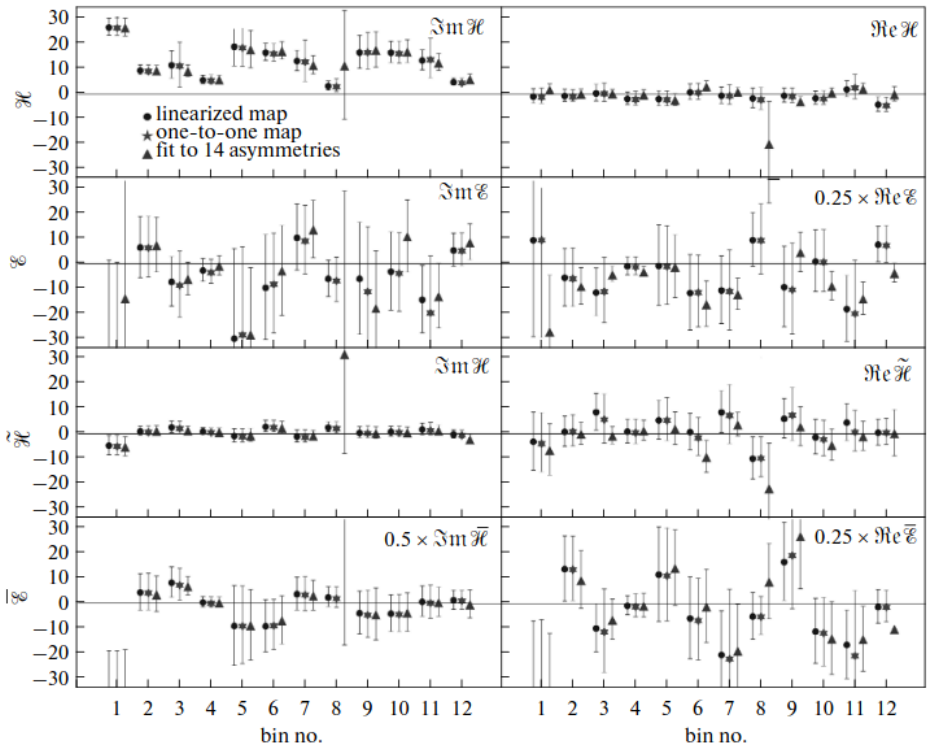
- E_k: beam energy.
- Q^2: virtuality of the photon, $Q^2 = -q^2 = -(k - k')^2$.
- $x_B = \frac{Q^2}{2p \cdot q}$.
- t: 4-momentum transfer to the proton, $t = (p' - p)^2$
- ϕ_h: angle between the leptonic and hadronic planes.

These parameters determine the kinematics of the scattered particles.

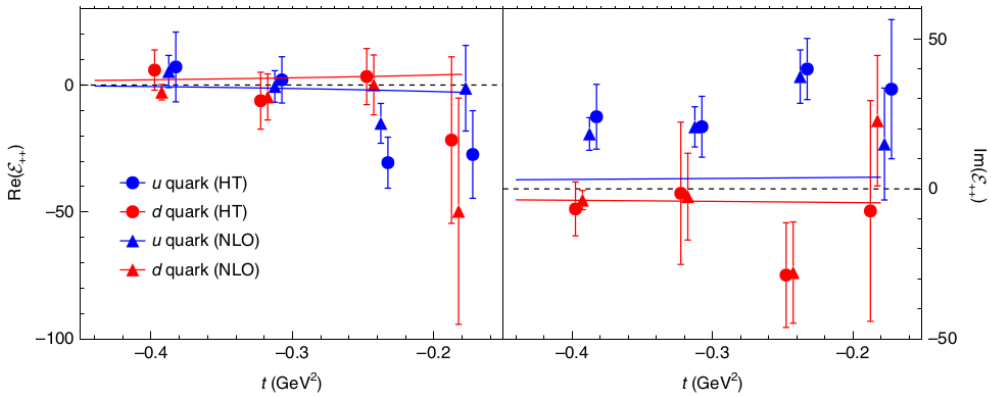
Measuring CFFs

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

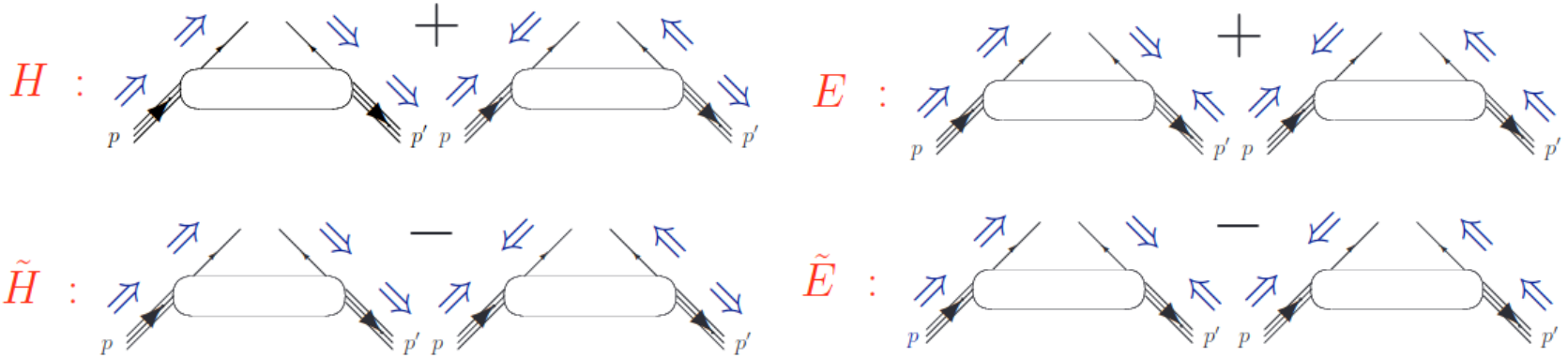


Uses a deuterium target.
Complications: FSI, bound state.

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?

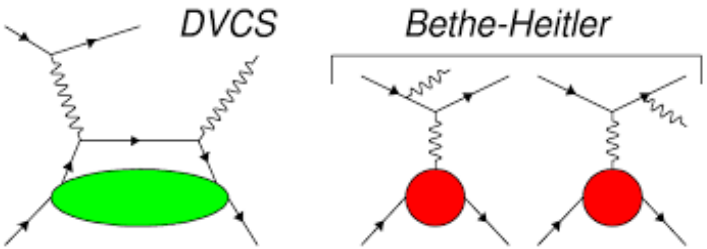


E describes the process when the proton changes helicity.

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 $\mathcal{E}$.



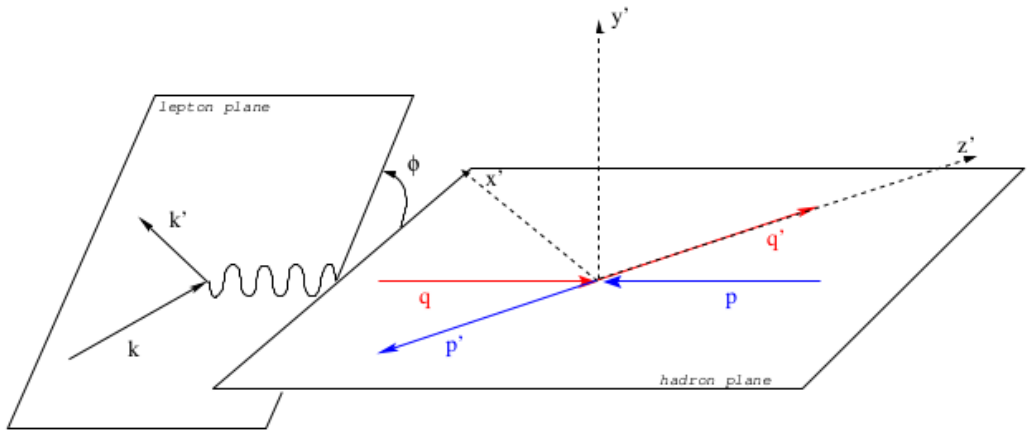
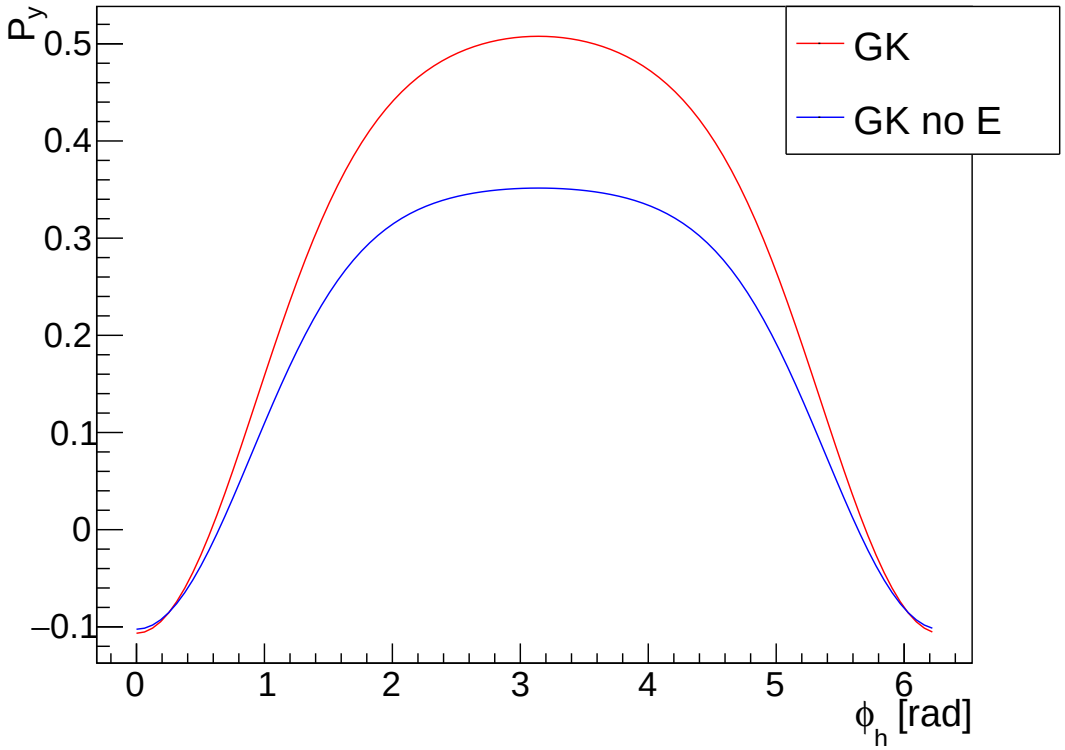


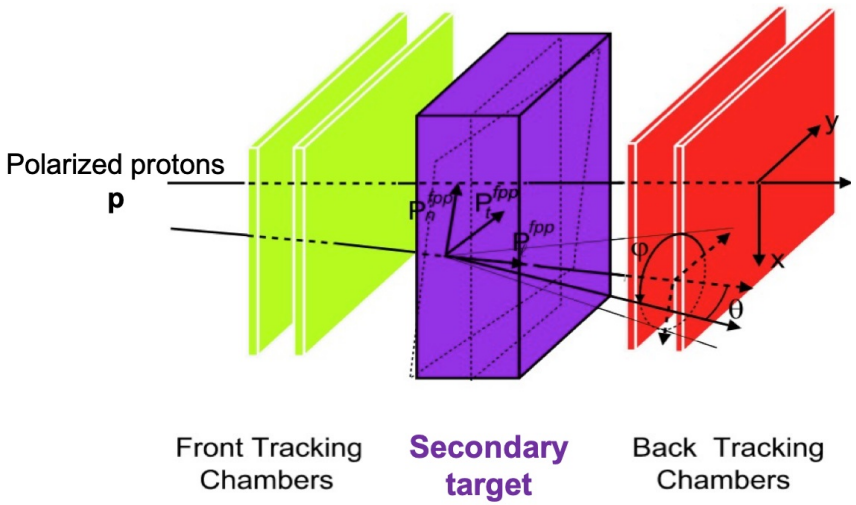
Figure 1: Rotated CM frame (x'y'z')

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 $\mathcal{E}$.

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.

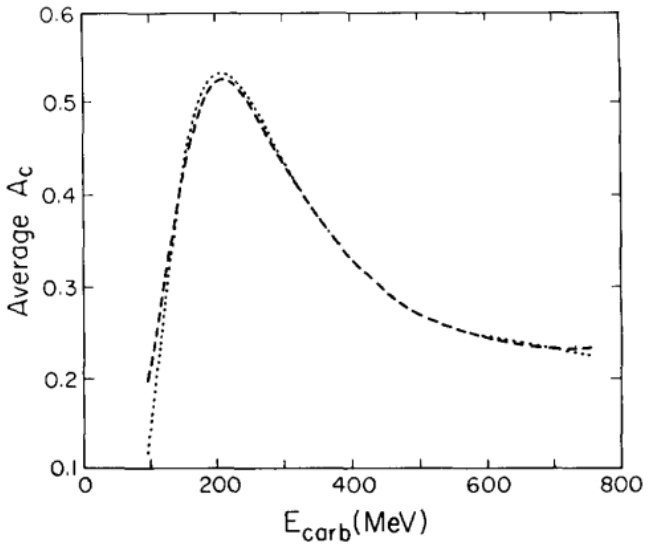
Polarimeter performance

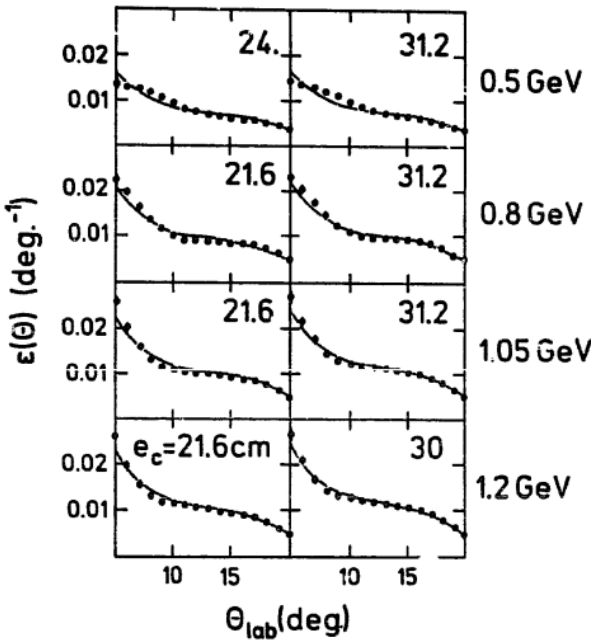
Analyzing power

- $A_p(\theta_{pol}, p')$: 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.





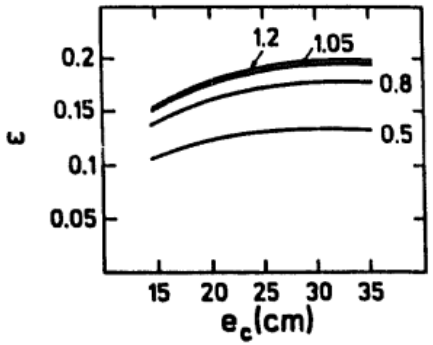


Figure of merit to characterise a polarimeter: $F^2 = \int_{\theta_{min}}^{\theta_{max}} A_p(\theta)^2 \epsilon(\theta) \mathrm{d}\theta$

Experimental context

Challenges

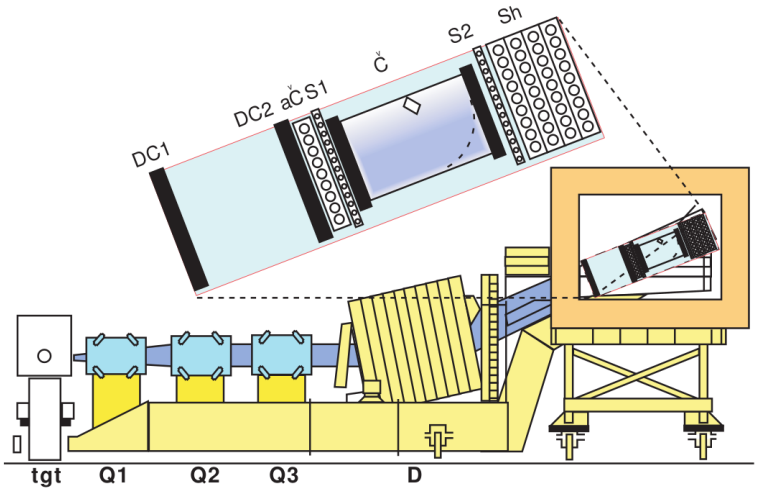
- DVCS has a low cross section compared to (semi-)inclusive processes.
- We need to rescatter the recoil proton, expecting a polarimeter efficiency of order 0.1.
- To achieve high statistics we need a high luminosity.

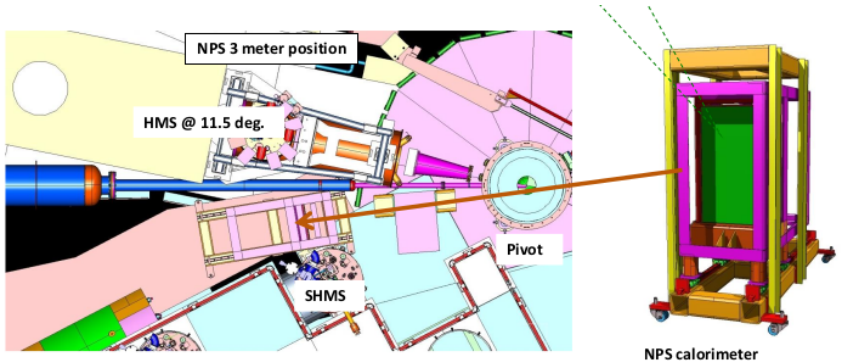
Candidate facility: Hall C at Jefferson Lab, using an **unpolarized electron beam** and an **unpolarized liquid hydrogen target**.

Example settings

- Target length: 15 cm.
- Beam current: 10 μA during 18 days 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 Eq. for 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.

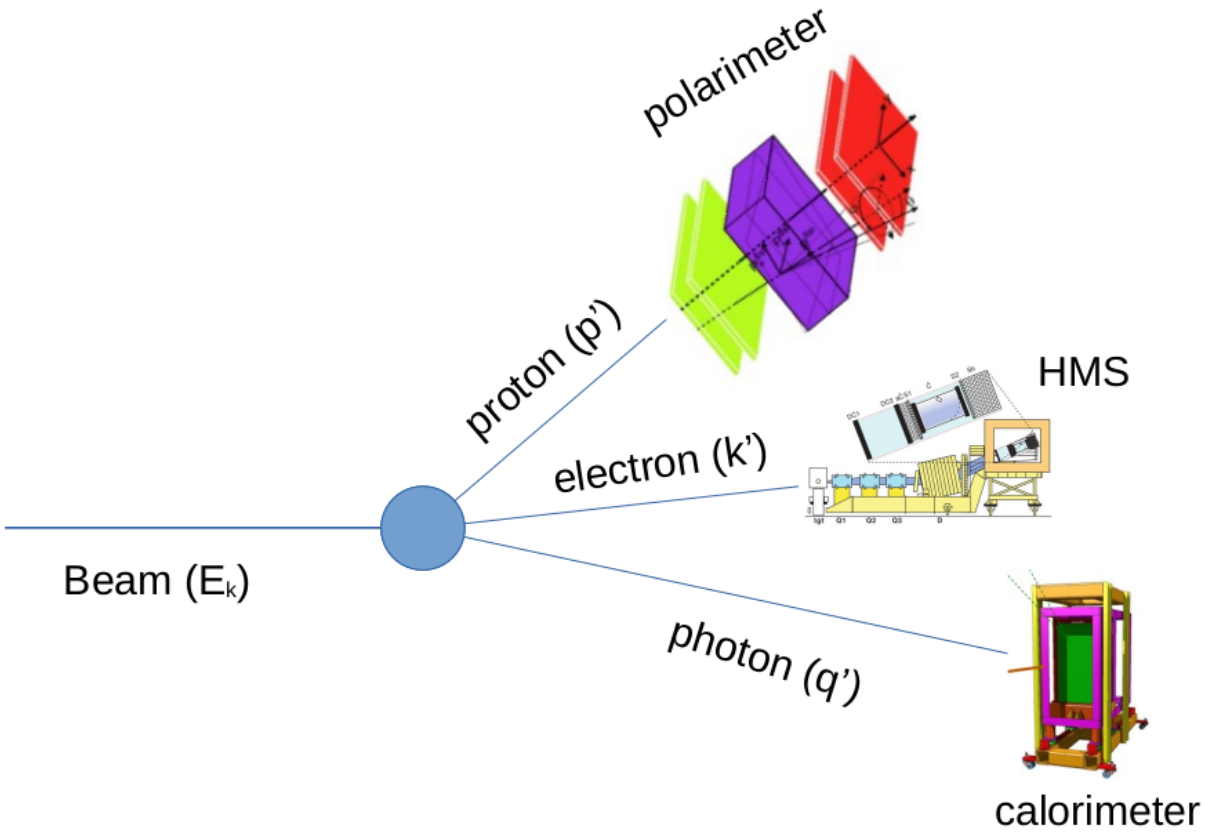
- Require: $|\theta_{k'}| > 10.5^\circ$, $\theta_{q'}, \theta_{p'} > 10^\circ$, $\Delta\theta_{i,j} > 10^\circ$ (isolation).

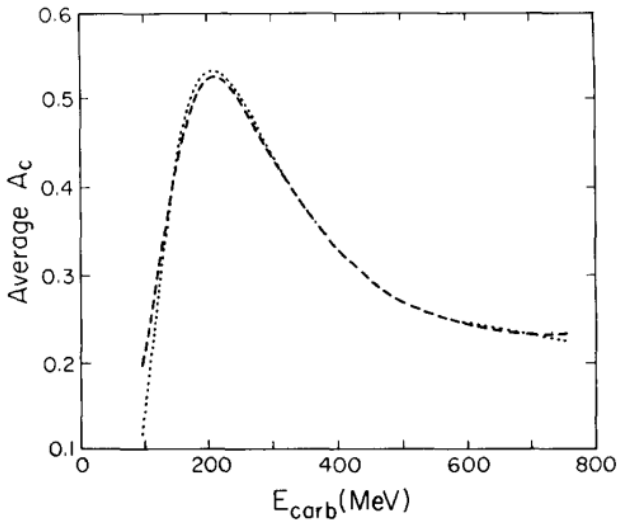
Optimization result

Maximizing $\mathcal{F}'$ gives:

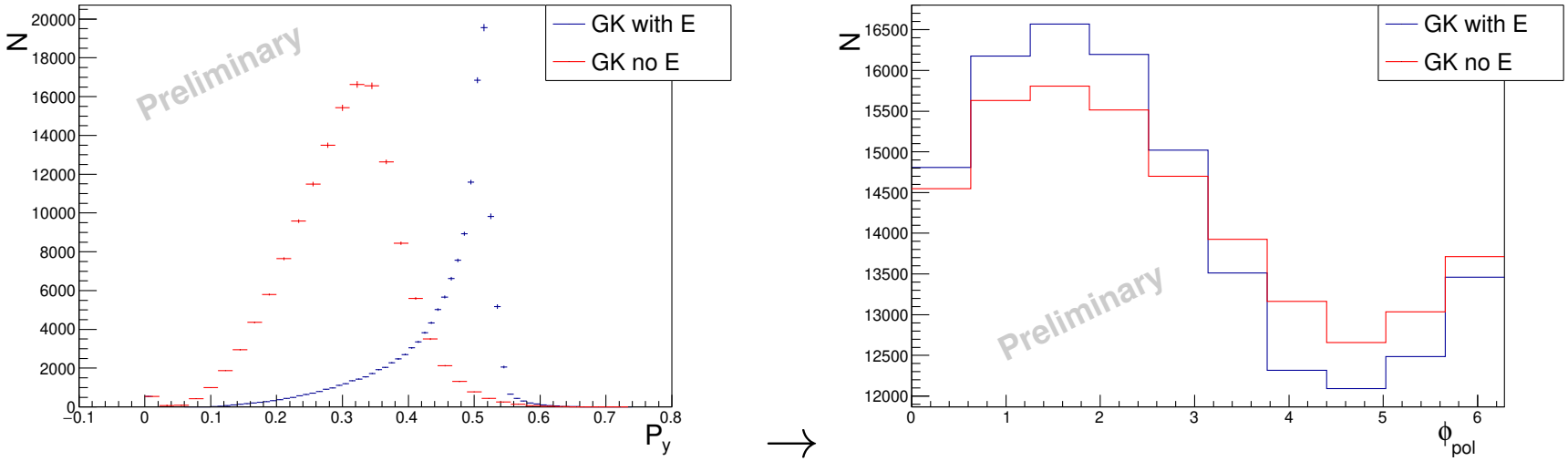
$$E_k = 10.6\,\mathrm{GeV},\ Q^2 = 1.8\,\mathrm{GeV}^2,\ x_B = 0.17,\ t = -0.45\,\mathrm{GeV}^2,\ \phi_h = \pi$$

electron $\lvert k' \rvert$	$\theta_{k'}$	photon $\lvert q' \rvert$	$\theta_{q'}$	proton $\lvert p' \rvert$	E_{carb}	$\theta_{p'}$
4.96 GeV/c	10.6°	5.40 GeV/c	-15.1°	0.71 GeV/c	0.19 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, 18 days of data-taking, $10\mu A$.
- **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.

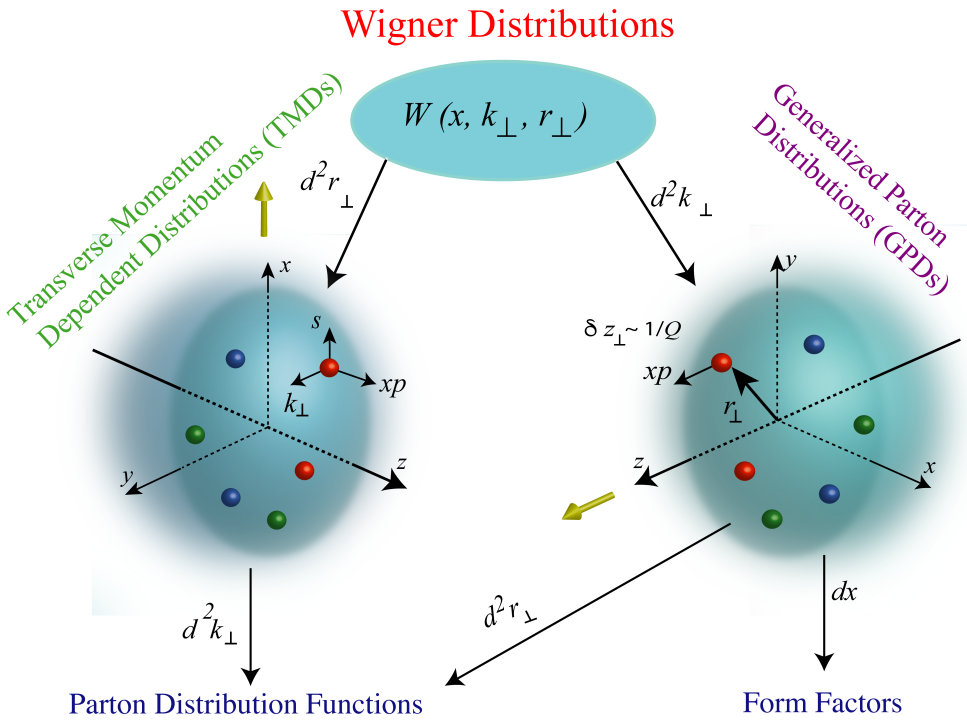
Plan to upload on arXiv shortly

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.

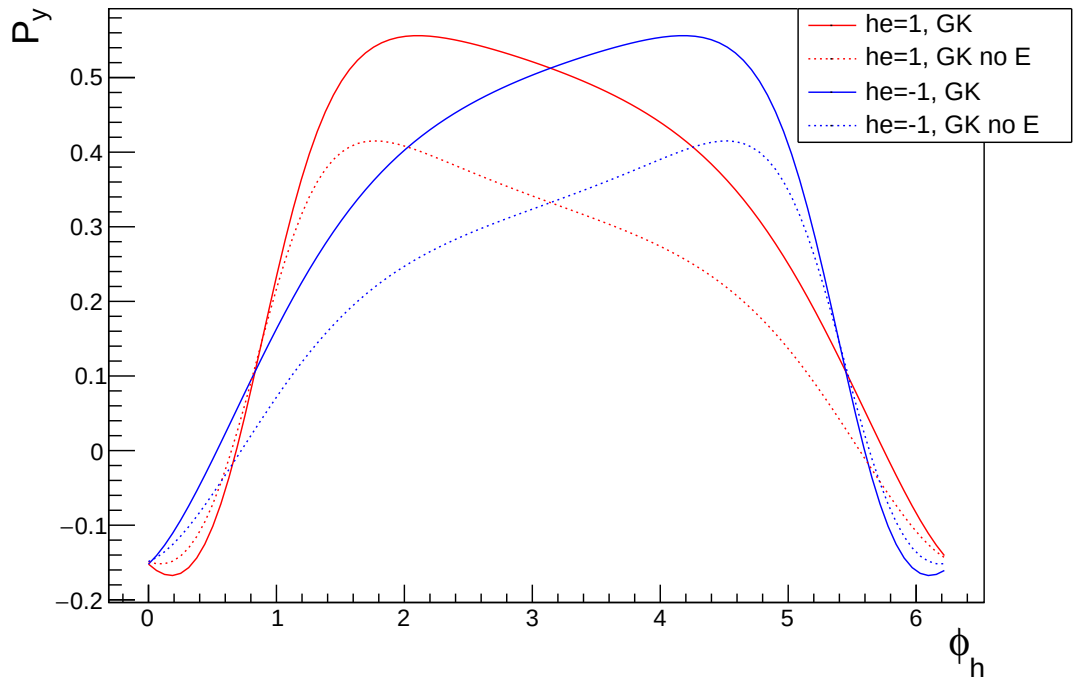
DVCS on neutron

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



- 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 $\mathcal{E}$.

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

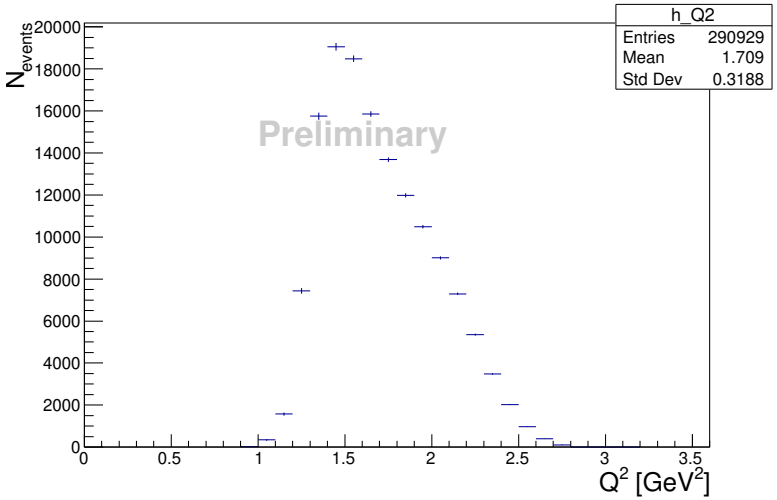
Model	$\mathcal{H}$	$\mathcal{E}$	$\tilde{\mathcal{H}}$	$\tilde{\mathcal{E}}$	P_y
ANN	$-1.8^{\pm 1.3} + 3.4^{\pm 1.7}$i	$-4^{\pm 7} + 0^{\pm 9}$i	$0.4^{\pm 1.4} + 1.2\text{i}^{\pm 1.8}$	$-25^{\pm 65} + 3^{\pm 59}$ i	0.45

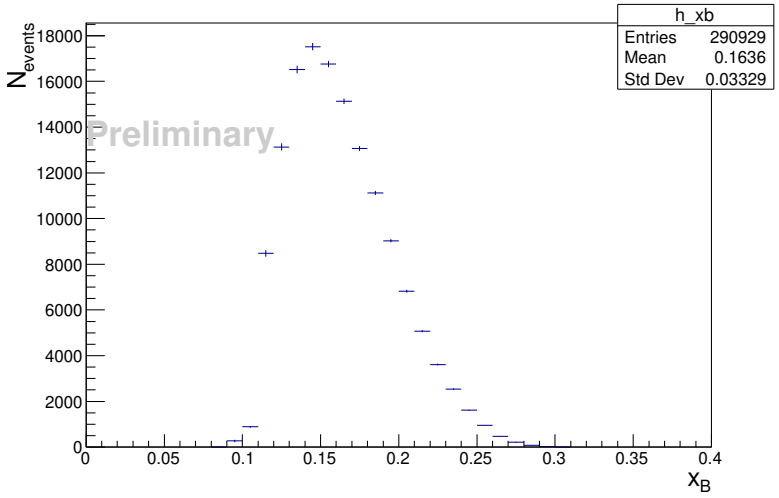
Variations

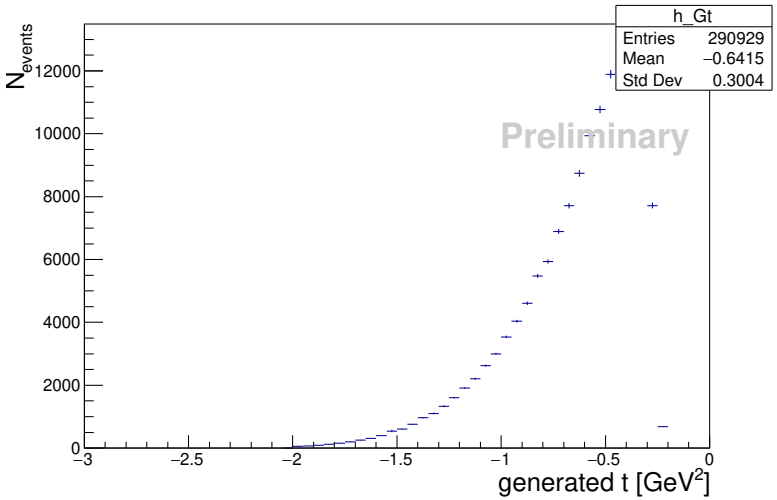
- Larger $|t| \rightarrow$ larger ΔP_y, smaller $\mathrm{d}\sigma$.
- Larger $Q^2 \rightarrow$ smaller ΔP_y, smaller $\mathrm{d}\sigma$.
- Larger $x_B \rightarrow$ smaller $\mathrm{d}\sigma$.
- Large $|\mathrm{k}'|$ (small Q^2/x_B) $\rightarrow$ larger acceptance.

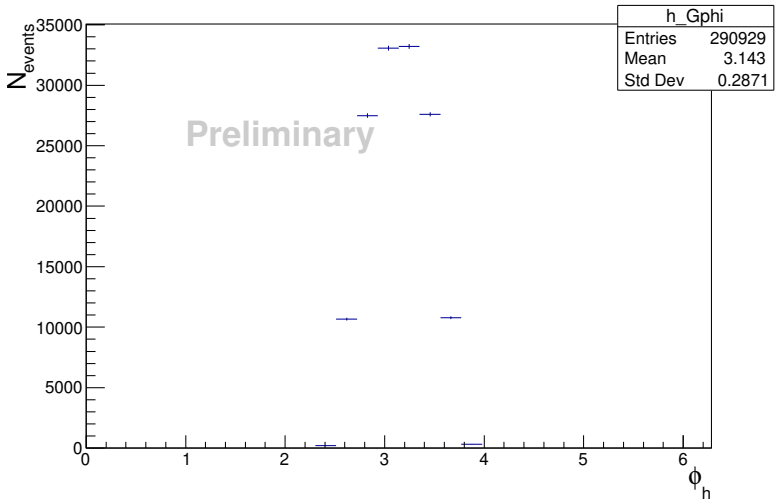
Also require $|t|/Q^2 \leq 0.25$.

Distributions



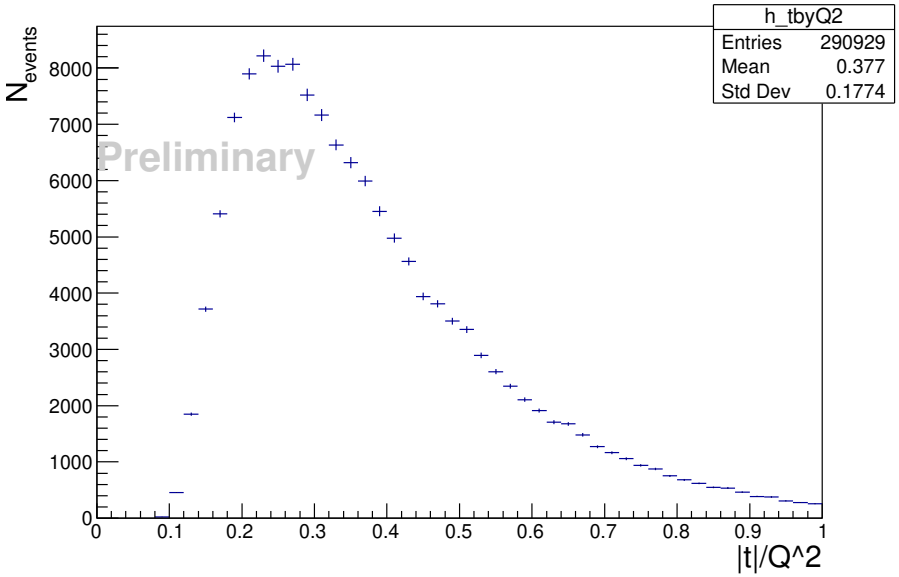


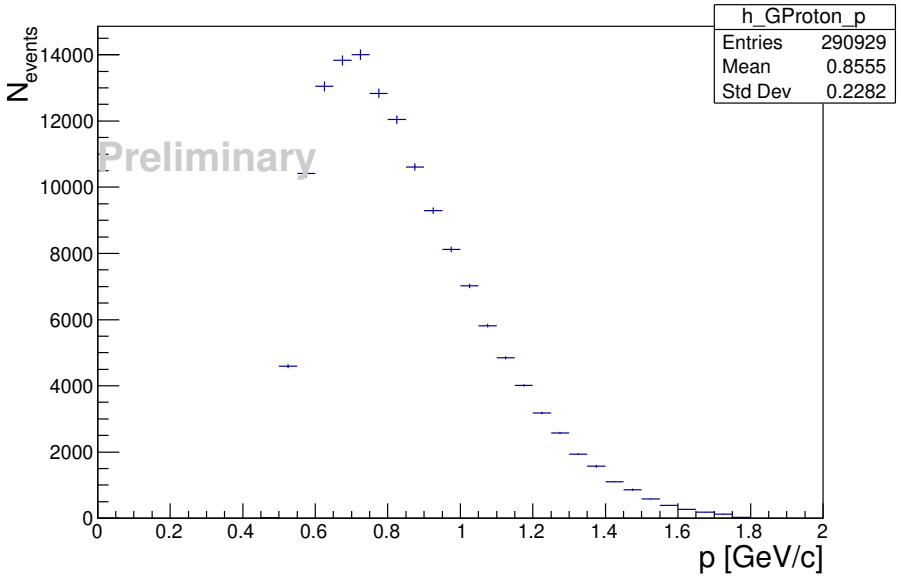




Imposing $\theta_{p'} = \theta_{p'}^{target} \pm 20°$, $\phi_{p'} = \phi_{p'}^{target} \pm 30°$ gives these distributions, with Q^2, x_B, ϕ_h centered near the target values (1.8, 0.17, π).

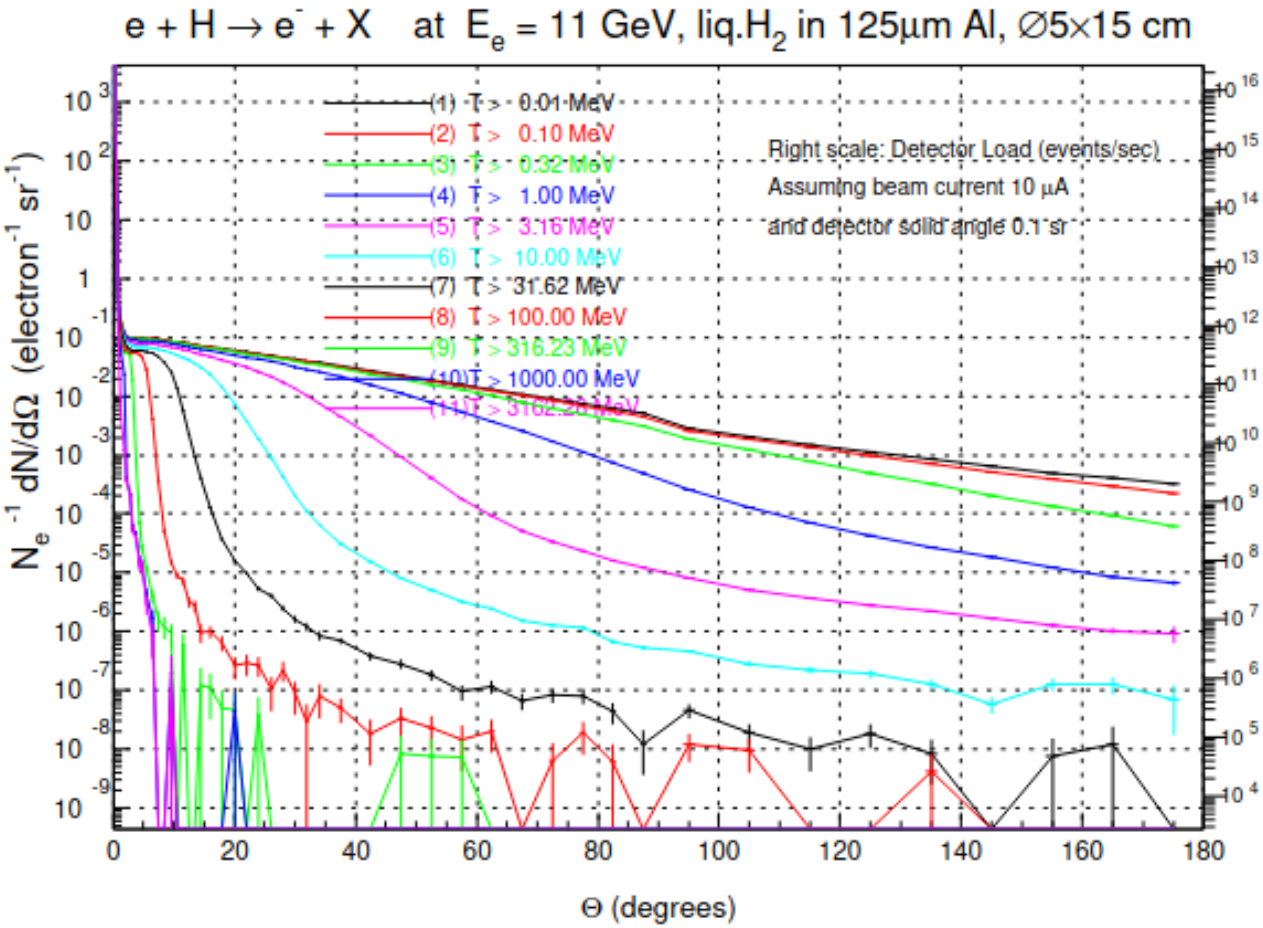
Distributions (2)





$|t|/Q^2$ 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_{evts}^{obs}	ΔP_y^{obs}	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: $\theta_{p'} \pm 20°$, $\phi_{p'} \pm 30°$ + requirement of non-zero reconstructed scattered lepton p_x.

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