Completing the Picture: Final-State Polarization in Hadron Femtography

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July 21st 2026

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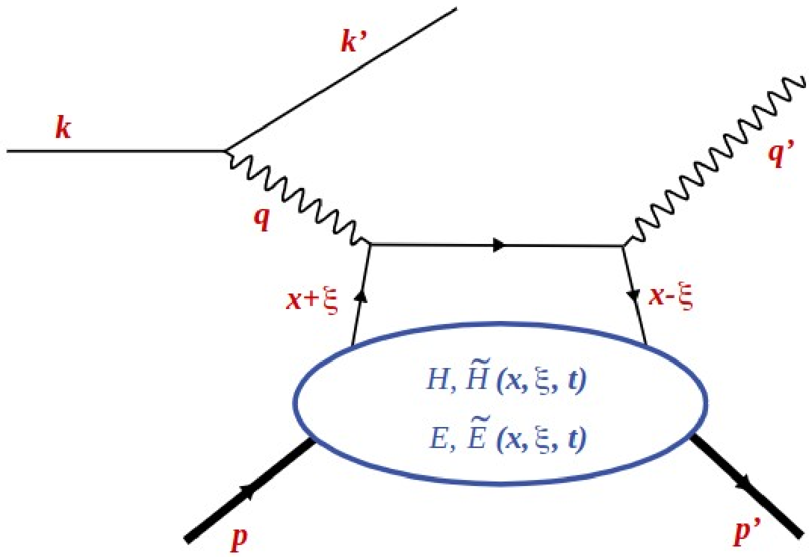
Deeply virtual Compton scattering at LT/LO



- $Q^2 = -q^2 = -(k-k')^2$.
- $x_B = \frac{Q^2}{2p \cdot q}$
- 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).

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

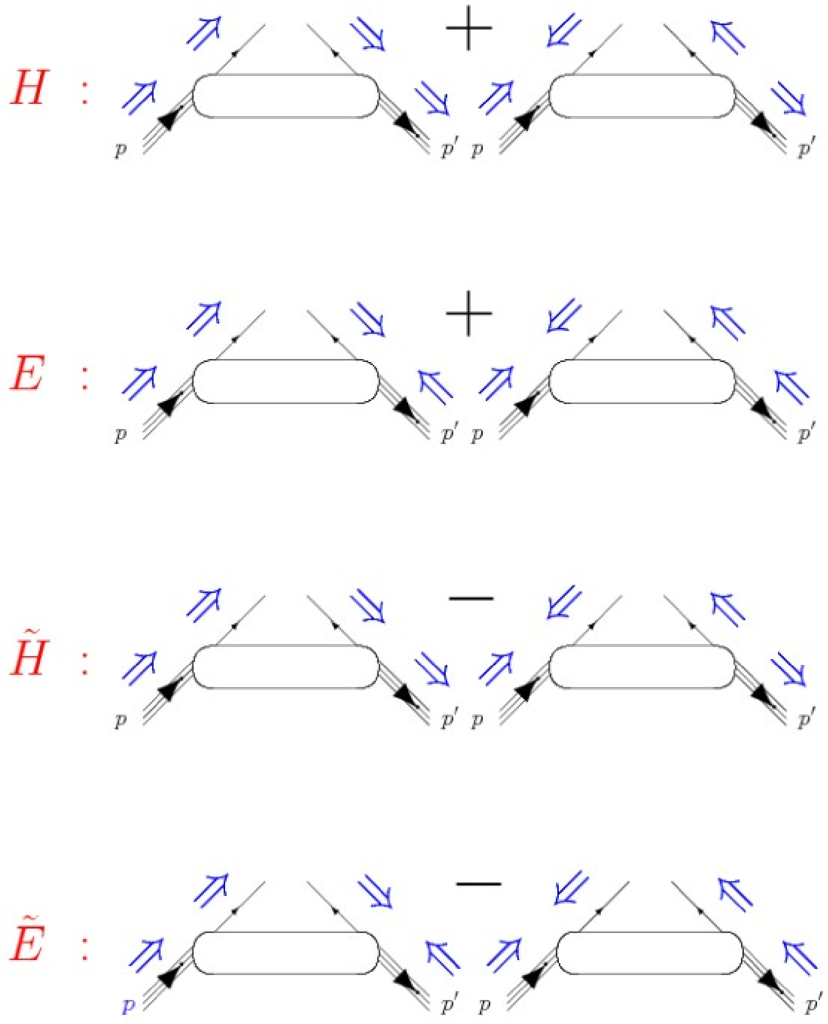
Generalized parton distributions for spin-1/2

At leading twist there are 8 GPDs per quark flavor/gluon (32 GPDs in total if g, u, d, s):

- 4 chiral-even GPDs: H, E, $\widetilde{H}$ and $\widetilde{E}$.
- 4 chiral-odd GPDs: H_T, E_T, $\widetilde{H}_T$ and $\widetilde{E}_T$.

The number of GPDs come from the different combinations of helicity/spin state.

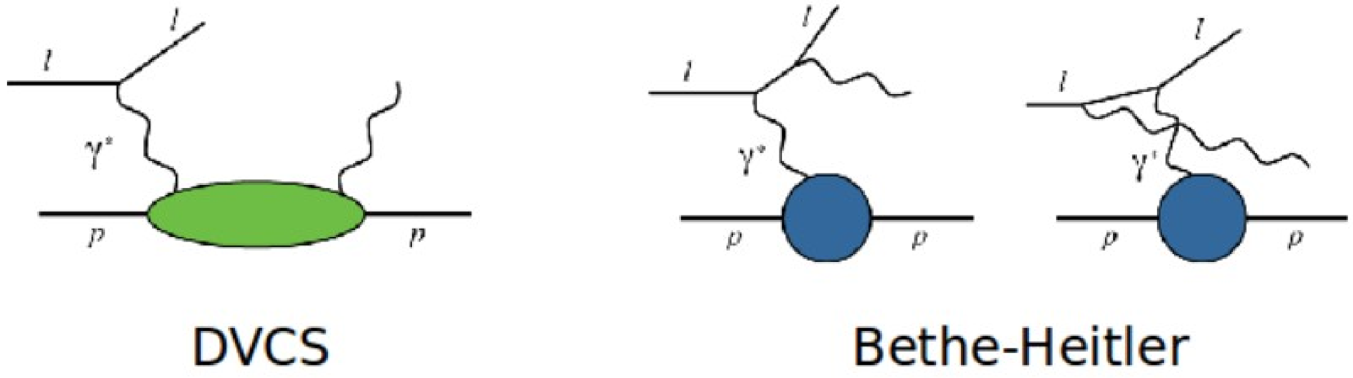
- The tilded GPDs are sensitive to the helicity of the active quarks.
- The E-GPDs describes processes with nucleon spin flip.
- The chiral-odd GPDs describe processes for which the active parton undergoes a helicity-flip.



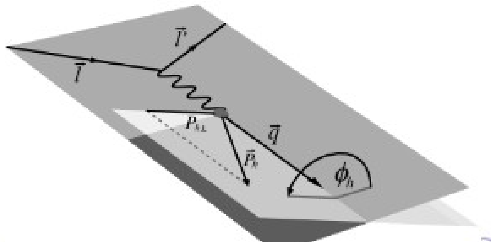
DVCS, Bethe-Heitler and their interference

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

On top of the interference between the polarizations of the virtual photon, you have the interference with the Bethe-Heilter process.



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



DVCS phenomenology at zeroth order

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

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

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

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

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

At leading-order, $Im\ \mathcal{H}(\xi,t) = \pi\left(H(-\xi,\xi,t) - H(\xi,\xi,t)\right)$.

At leading-order, photon electroproduction offers a direct access to GPDs... No need for ugly integrals!

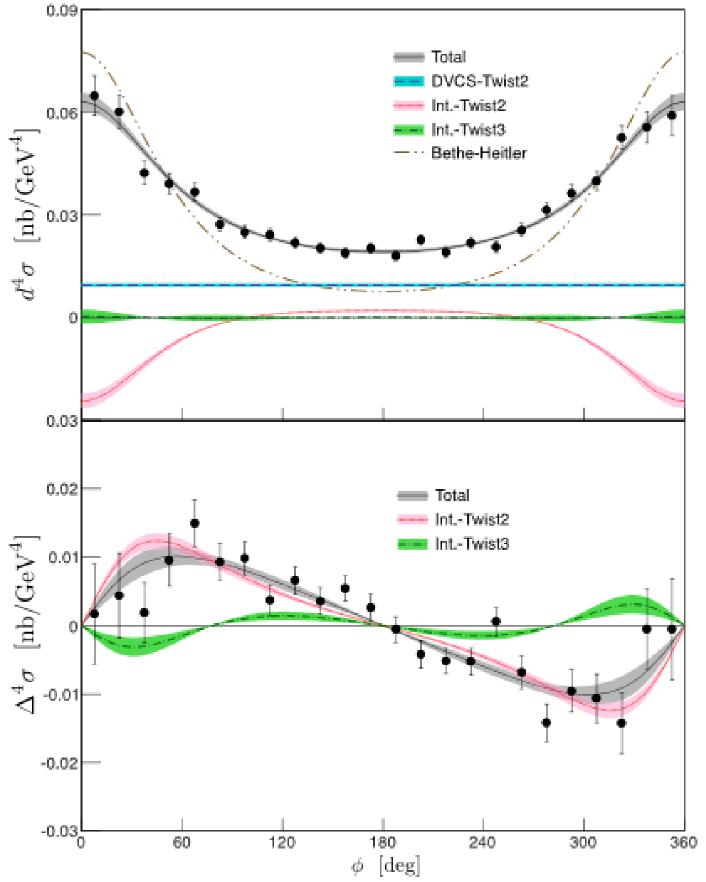


Figure: Unpolarized (top) and beam-helicity dependent cross sections at Q^2=2.3 GeV^2, x_B=0.36 and t=-0.3 GeV^2.

Proton DVCS : What can we know in the valence ?

- **There are 4 CFFs for quarks in the proton :**
  → **CFF H** : Constrained by measurements on **unpolarized protons** (Hall A/C – CLAS – CLAS12)
  Imaginary part +++ Real part ++

  → **CFF $\tilde{H}$** : Constrained by data collected on **longitudinally polarized protons** (CLAS – CLAS12).
  Imaginary part ++ Real part +

  → **CFF E** : Need data on **transversely polarized protons.**
  Imaginary part + Real part 0

  → CFF $\tilde{E}$: DVCS is **poorly sensitive** to this GPD.
  Imaginary part 0 Real part 0

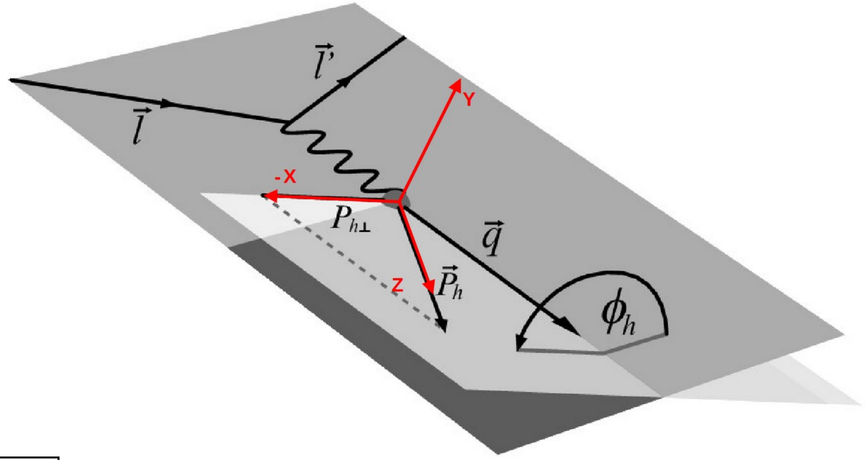
- Proposal with CLAS12 to take data with transversely polarized target scheduled for 2029/30-ish:
  → **Dedicated magnet is being designed**.
  → Will require **specific detector for proton detection**.

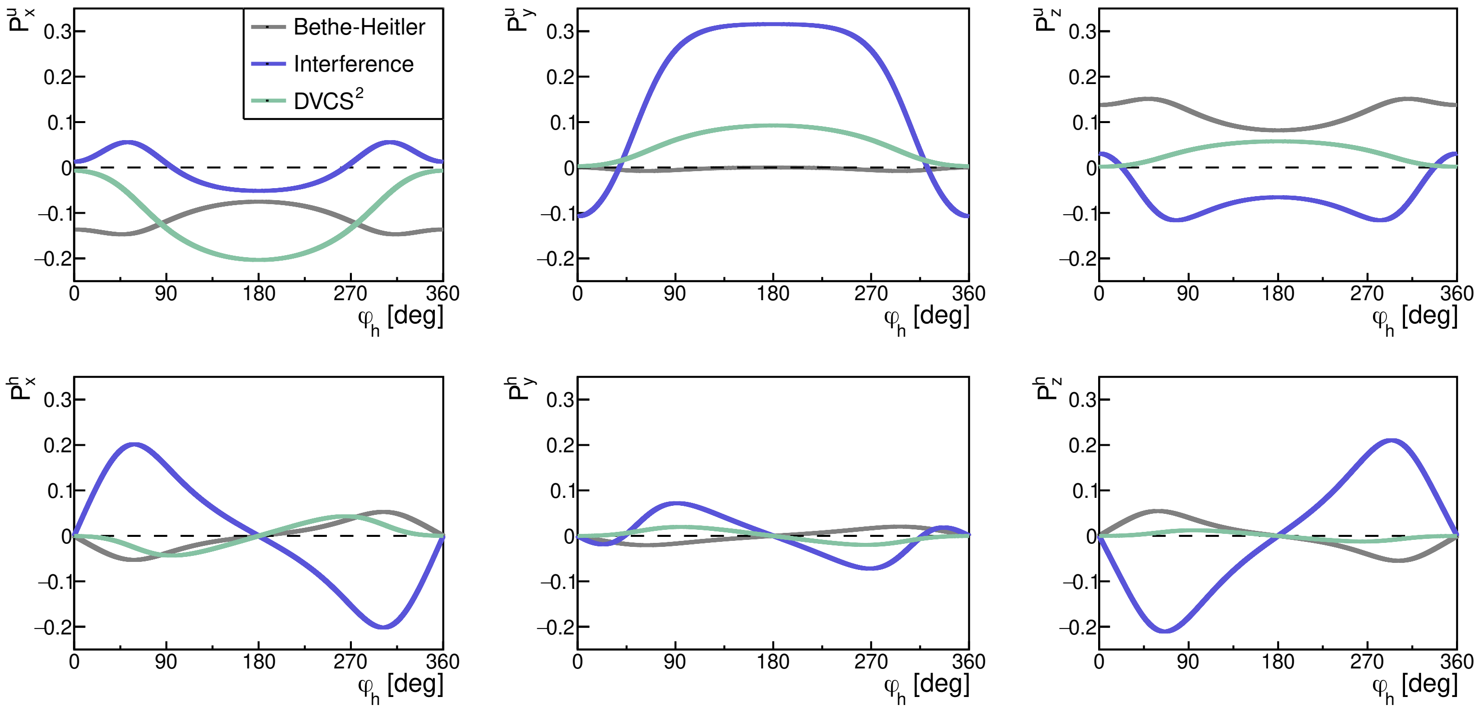
- **No gluon contribution ever included** and difficult to include as the problem is under-constrained

  => Need new experimental observables to constrain all helicity-amplitudes

PoPEx : A new experimental observable for DVCS

- **P. Guichon**, former theoretician at LSN, computed the recoil proton polarization as function of CFFs.
- Sensitivity studies initially performed with GK model.
- Similarly to elastic scattering, polarization transfer through Bethe-Heitler occurs only in-plane.





$$
\begin{aligned}
P^m_{x/z} &= h_e\left(P^u_{x/z} + h_e P^h_{x/z}\right)\,, \\
P^m_y &= P^u_y + h_e P^h_y\;.
\end{aligned}
$$

GPD-sensitivity study of the RP

- Sensitivity studies initially performed with GK model.

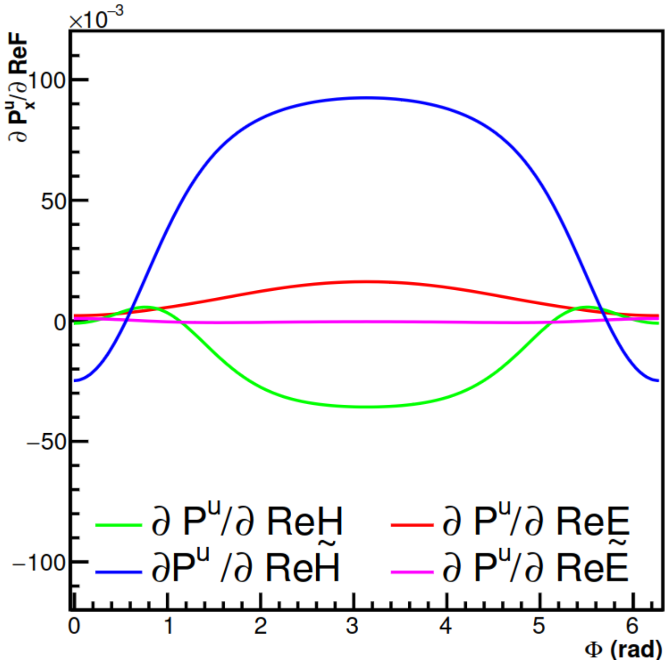
- Aiming at constraining E, a local measurement is needed at φ=3,14 rad.
  - **simultaneous access to ImE and ReH**.
  - ImH and Im$\tilde{H}$ constrained by collected JLab data.

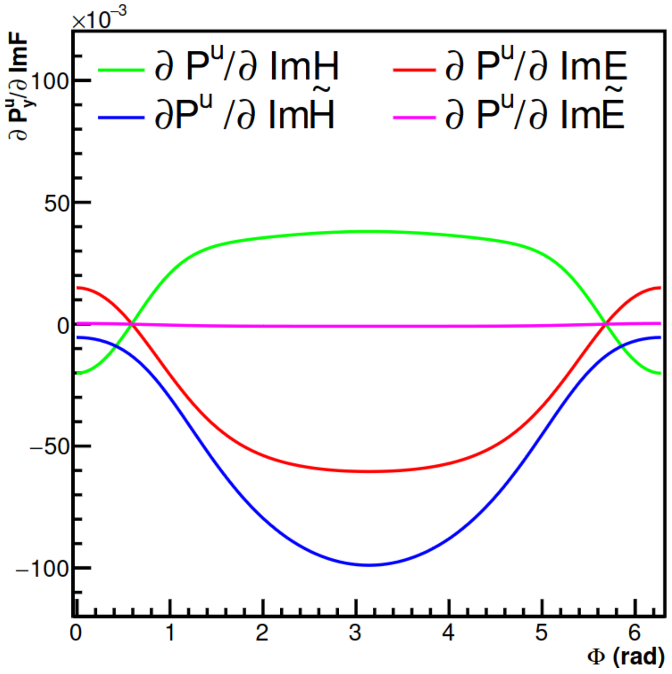
- At φ=1,5 rad, we may even constrain Re$\tilde{H}$ with ImE+ReH

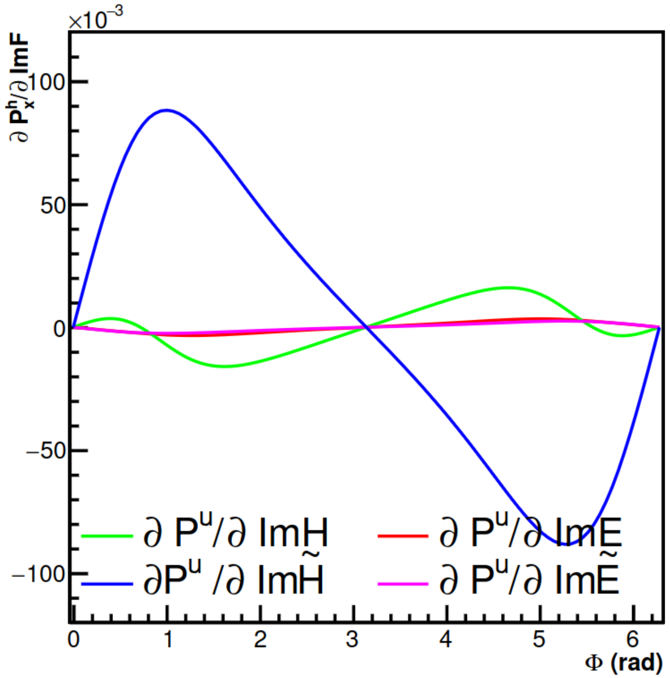
1) Need a longitudinally polarized beam!

2) Better than transversely polarized target

=> Measuring the cross section and RPP with a single experiment to access simultaneously 6 CFFs (unlike TP target)





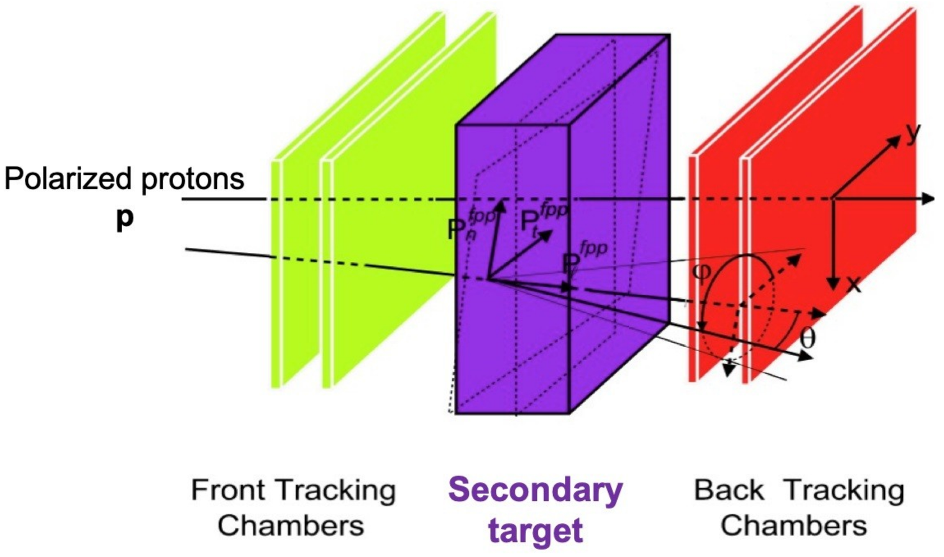


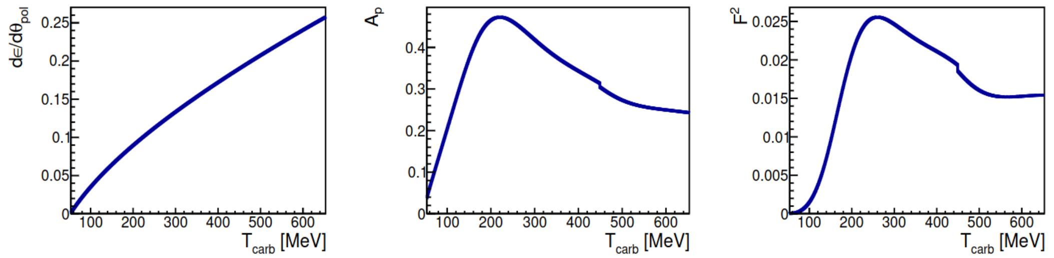
PoPEx : Basics of proton polarimetry

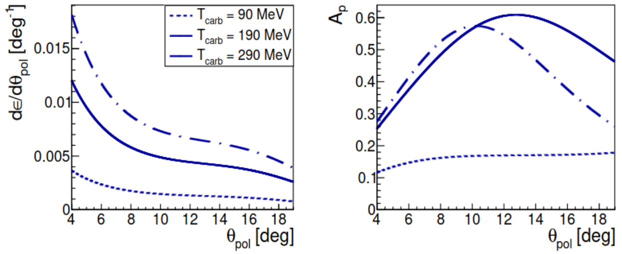
- **Proton polarization** obtained from harmonic analysis of **rescattering off a Carbon or Hydrogen nucleus**.

$$\frac{dN}{d\theta_{pol}} = N_0 \cdot \frac{d\epsilon}{d\theta_{pol}} \cdot (1 + A_p(P_y \cos\phi_{pol} - P_x \sin\phi_{pol}))$$

- Regular polarimeter consists of a **secondary target surrounded by trackers** :
  -A_p = **sensibility of the scattering process** to polarization.
  -ε = **Cross section** of p-Nucleus scattering







- **Non-trivial dependences of A_p and ε** with both proton momentum and rescattering angle.

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

- For the best measurement, **the Figure-of-Merit must be optimized**.

PoPEx : Scientific impact

- For PoPEx, we need :
  - a **local measurement**,
  - with a **high luminosity** (low XS + Polarimetry)

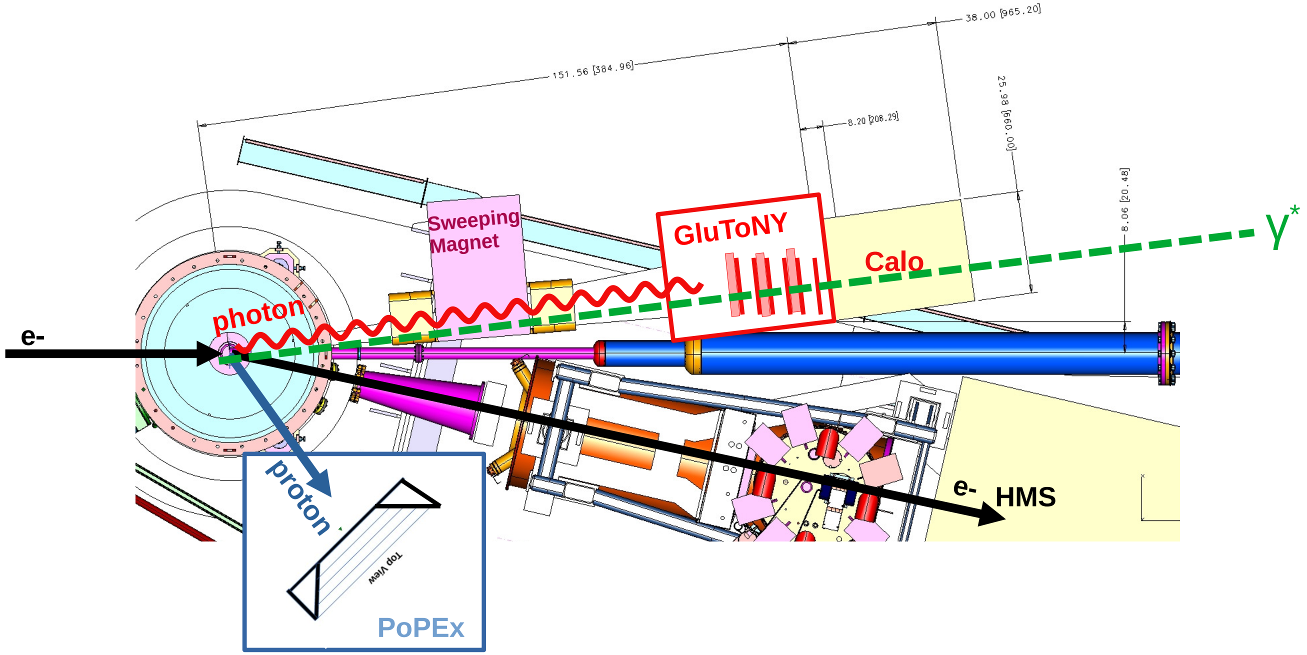
  => **Hall C DVCS setup is the only solution**.

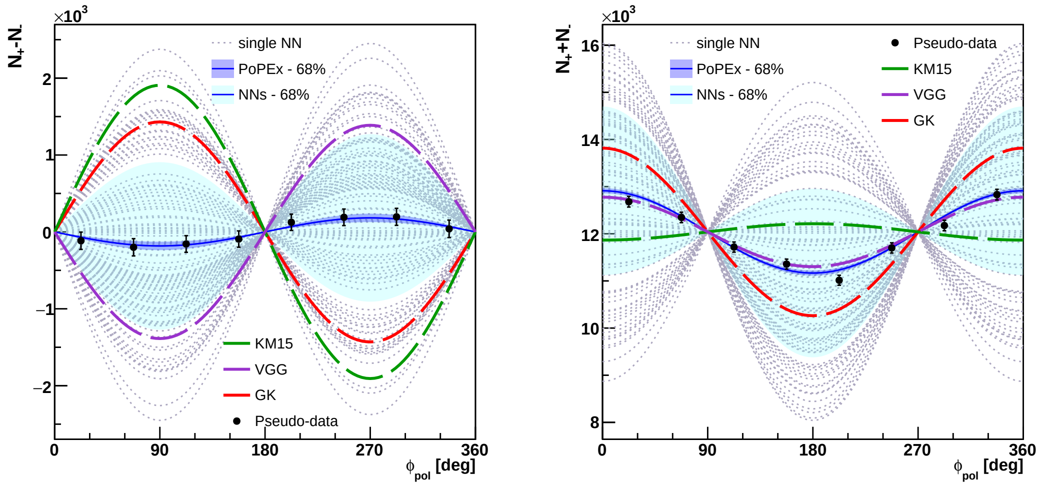
- First we need to find a kinematics to do a measurement :
  - Relatively high cross section,
  - High Figure-of-Merit for polarimeter,
  - High sensitivity to CFF E.

- **Assuming 3 weeks of beam time at 10 µA** :

  → Measurements of both Px and Py put **stringent constrains on models**.

  → Measurements would **still be relevant with only a tenth of a statistics**.



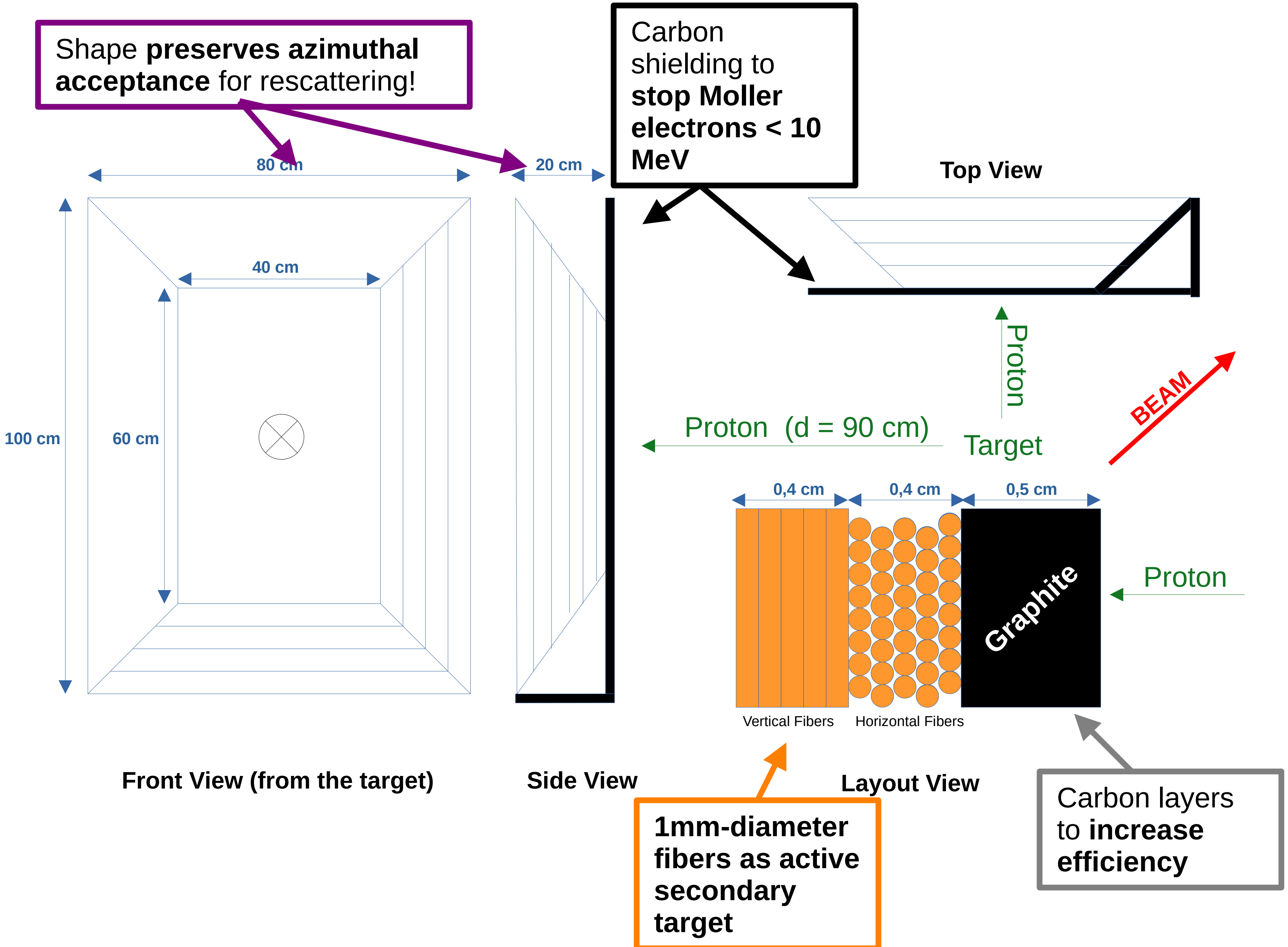


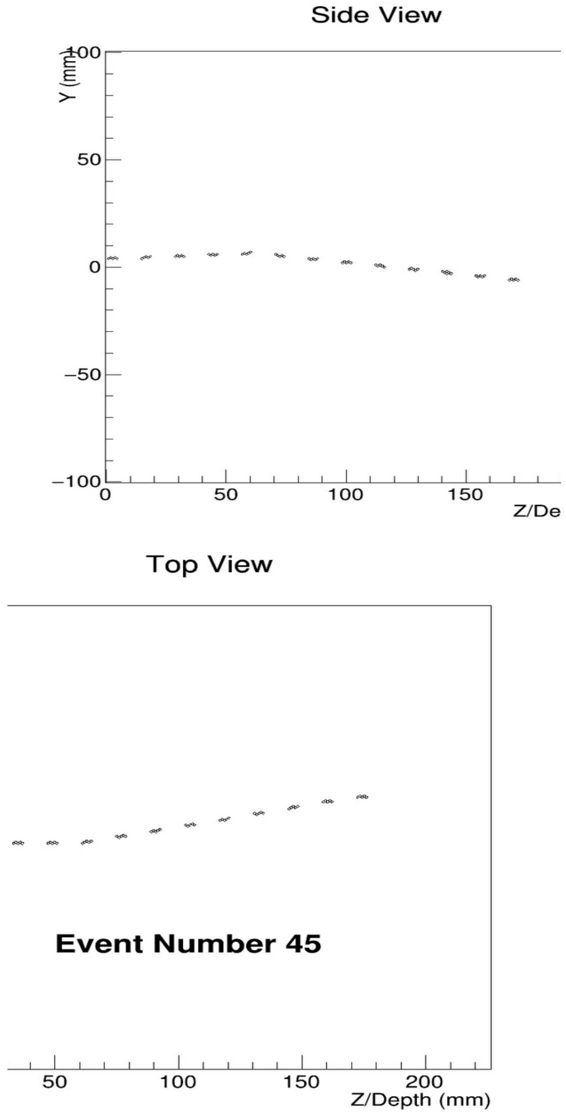
E_b = 10,6 GeV
Q^2 = 1,8 GeV²
x_b = 0,17
t = -0,45 GeV²
φ_{Trento} = 180°

Published in Phys. Rev D107, 014020

PoPEx : A first design

Glasgow University provided a **specific class for polarized pN-scattering**.





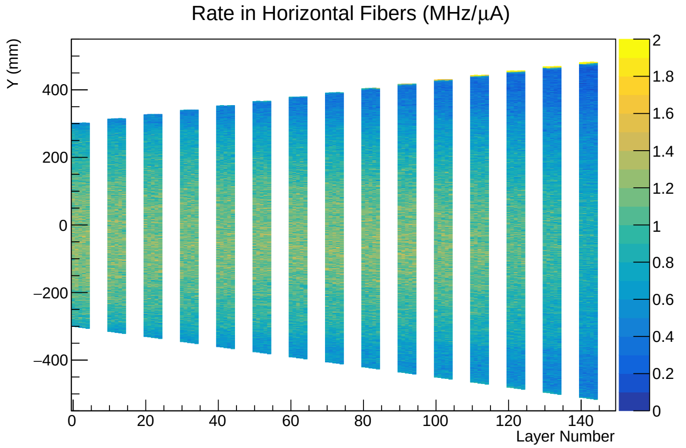
PoPEx : Performance and rates

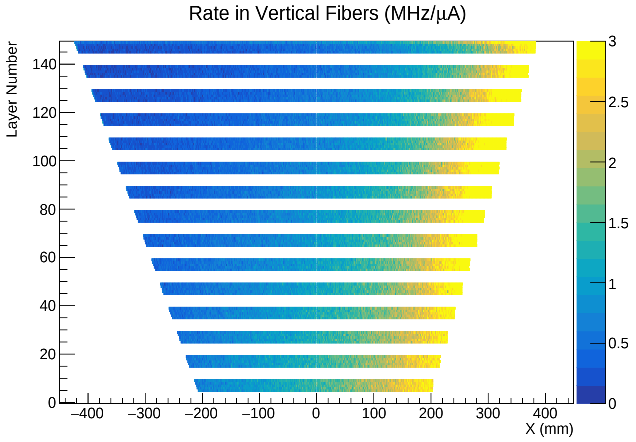
- Design has been implemented in the Hall C DVCS Geant4 simulation.
  → Rates were estimated at **3MHz/µA** for vertical fibers closest to the beam.

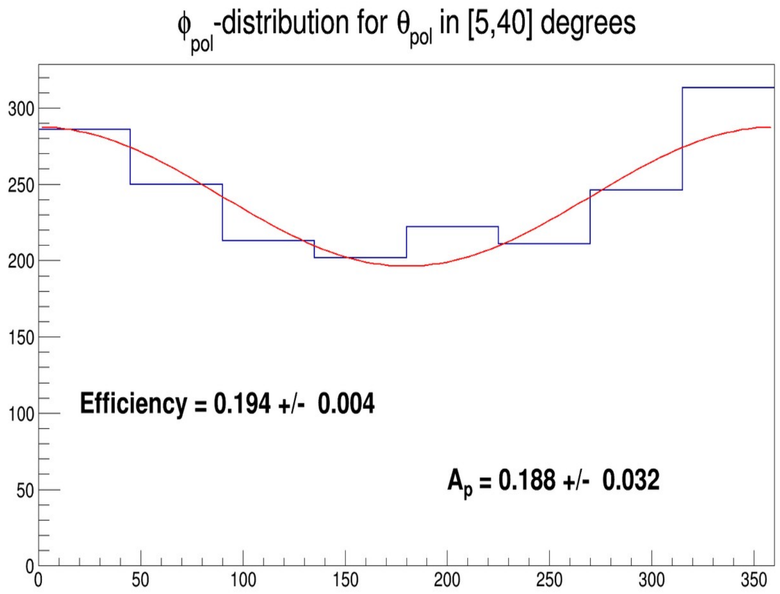
- Assuming a **1ns**-time resolution, hottest fibers will be fired **13 %** of the time within the proton window at **7 µA**.
  → Proton direction will help sorting hits and finding the proton.

- With a preliminary tracking, Figure-of-merit is found compatible with initial prediction.

- Reduce cost by :
  - Moving away the polarimeter and use 3mm fibers multiplexed on electronic channel.
  - Writing optimized Tracking/Analysis code for further optimization.
  => Must validate SciFi rates to optimize further







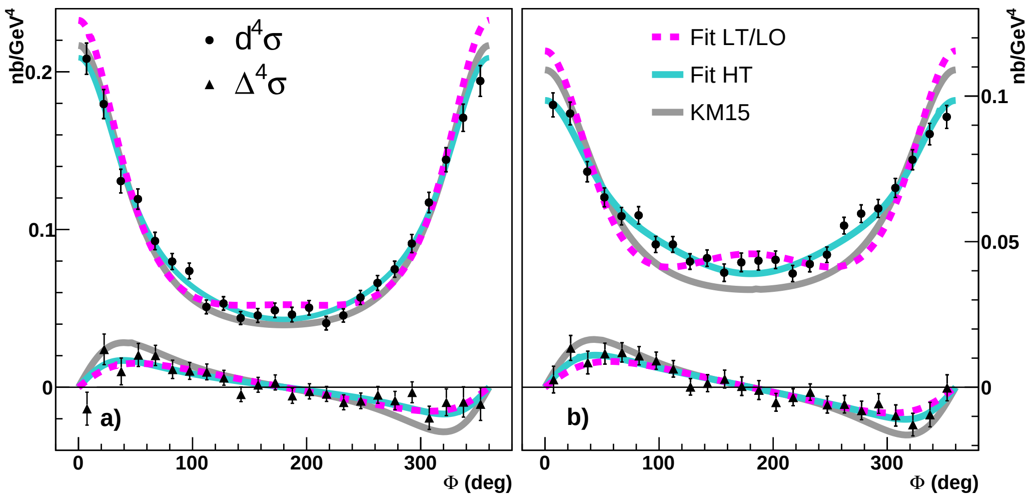
PoPEx : Perspectives

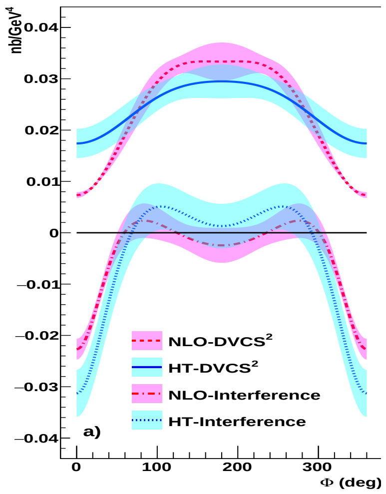
- Possibility to develop the physics case:
  → Neutral pion for instance is measured along with DVCS. But missing the predictions (Simonetta?)
  → Can we do neutrons ? Test of Sullivan interpretation in charged pion electroproduction?
  → Deuterium target studies
  → Easier with u-channel processes ? (Polarimeter could be further and smaller)

- Collaboration between Orsay and University of Glasgow to do SciFi rates : Grant obtained for material!
  → Kuraray and Luxium (former Saint-Gobain) 2mm SciFi acquired.
  → Jlab loaned maPMT (Thank you Alex and Bogdan)
  → Need to purchase SiPM for radiation hardness study
  → « Just » need to find students, postdocs and/or technicians to help.

GluToNγ : Gluon Tomography by γ-polarimetry

- **2015** : Fit of DVCS data indicates that there might be **contributions from higher-twist or NLO contributions.**

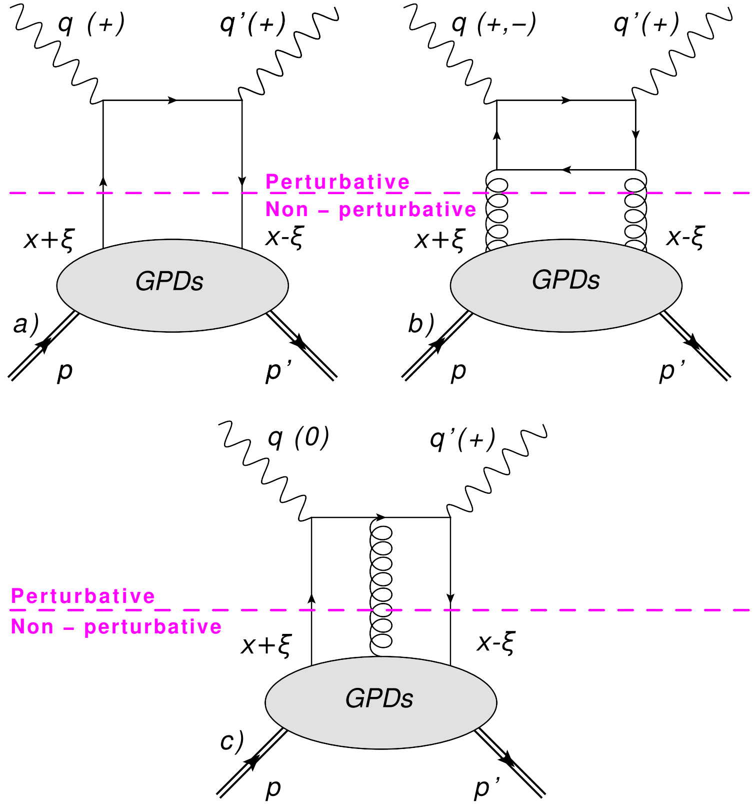




- Their contribution is tightly linked to the γ-helicity amplitudes.

- Therefore let's take a look at the photon polarization at Leading-twist.
  => Higher-twist could be isolated with Rosenbluth separation.

- Two kinds of Gluon GPDs :
  → **Chiral-even GPDs** : Do not flip the photon helicity to be added to quarks.
  → **Chiral-odd GPDs** : Solely flipping the photon helicity (independent term).
  Intrinsic Glue binding the proton !

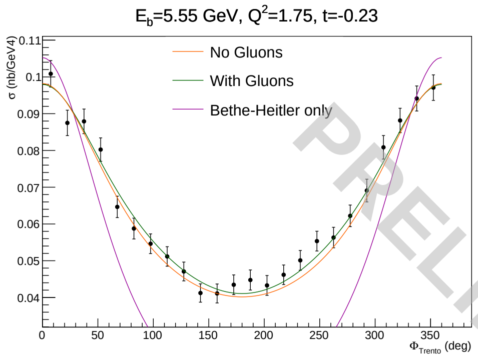


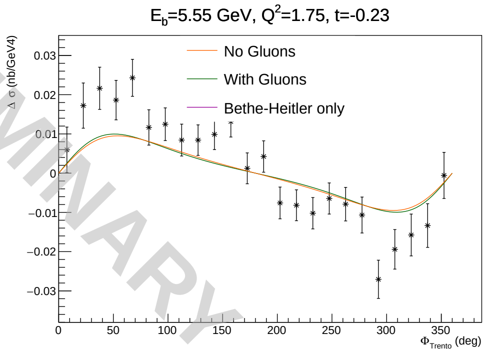
GluToNγ : A first look at theoretical predictions

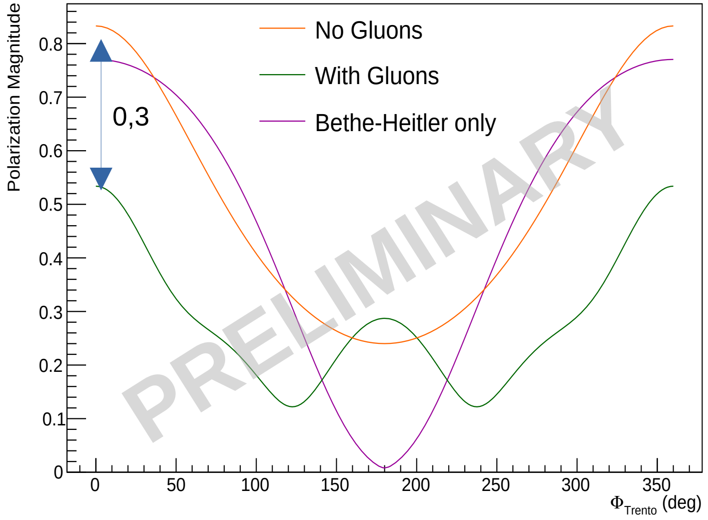
- **P. Guichon**, former theoretician at LSN, computed the fraction of linear polarization and its direction, with H_T^g and E_T^g

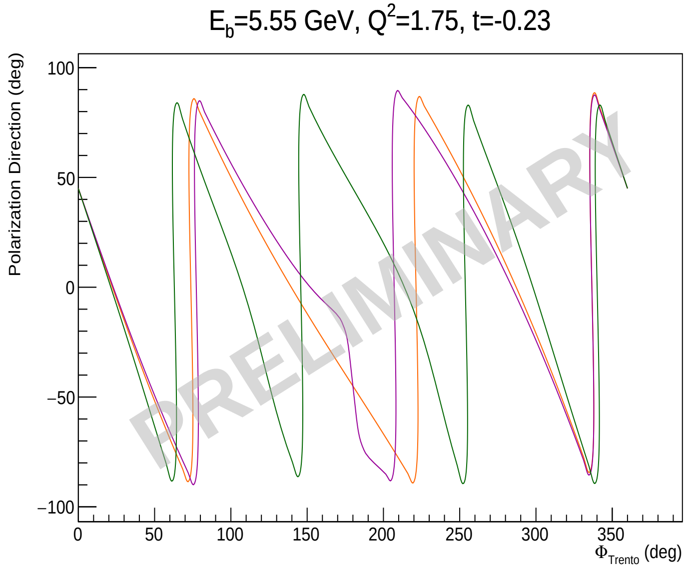
- No model for gluon linearity GPDs => **UNKNOWN !!**

- First try to **fit Hall A data** with various combination of CFFs and **then compute associated polarization**.









- Same XS but :
  → **Different Magnitude**
  → **Different direction**

- φ_{Trento} = 0 degree seems the best angle for measurement. (High XS)

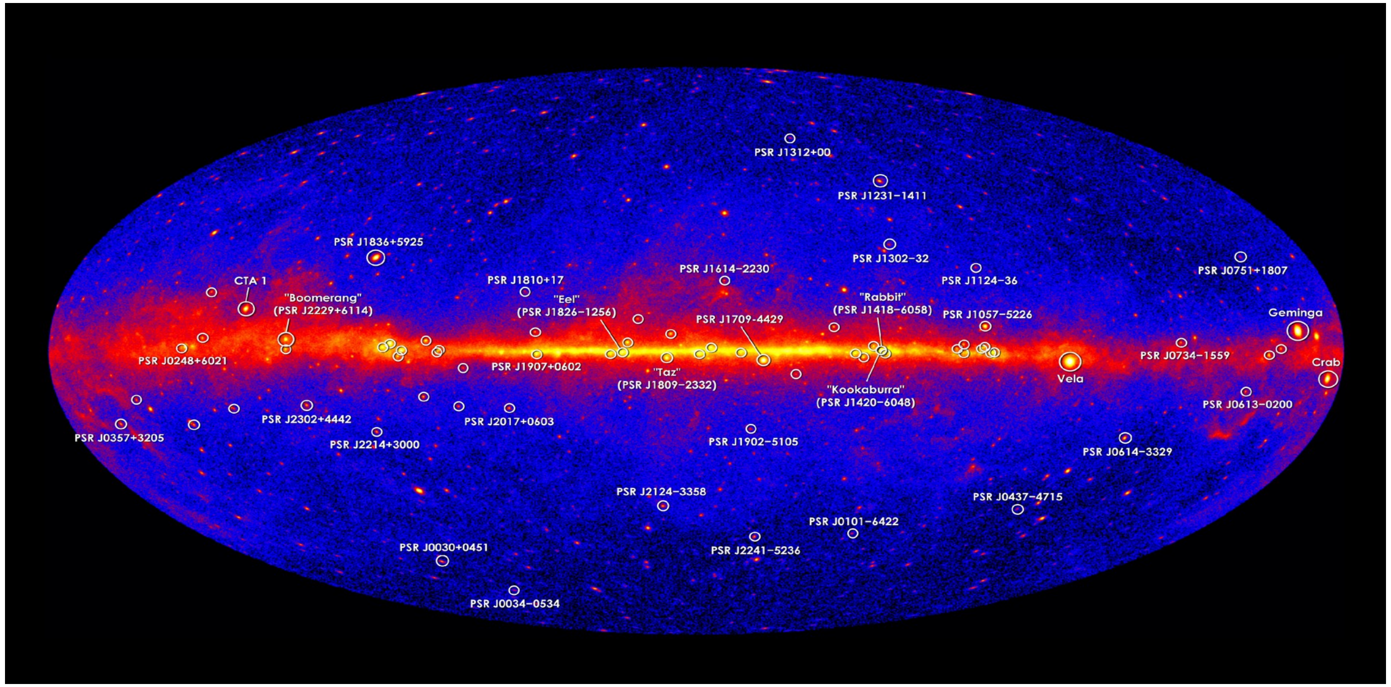
GluToNγ : Physics cases for multi-GeV γ-polarimeter

- Many astrophysical sources emit multi-GeV γ-rays :
  - Heavy Mass Binaries (Top left)
  - Active galactic nuclei (Top right)
  - Gamma-ray bursts (Bottom left)
  - Pulsars (Bottom right + 5-yr FermiLAT Sky map)

  => Issue for polarimetry : Low luminosity

- Axion searches

- Study of vacuum birefrengence



GluToNY : Designing a multi-GeV γ-polarimeter

- **Photon polarization** obtained from harmonic analysis of **pair conversion** (tiny opening angle < 1mrad).

$$N_{ee}(\phi_{ee}) = N_\gamma \epsilon \left(1 + P_\gamma A_{ee} A_{MS} \cos(2(\phi_{ee} - \phi_\gamma))\right)$$

With following parameters:
-A_{ee} = Sensibility of pair conversion (0,14).
-ε = Conversion rate.
-A_{MS} = Multiple scattering (MS)/resolution effect.

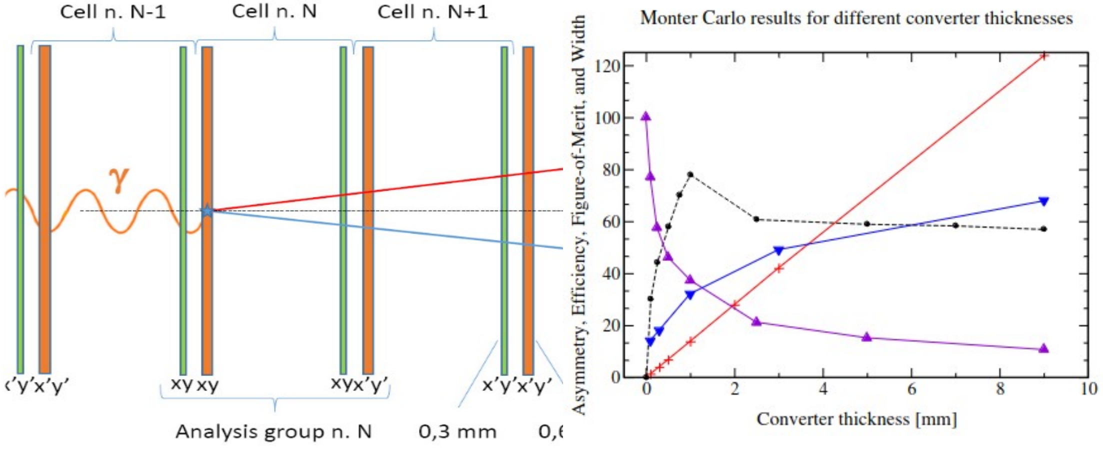
- Need to **optimise the Figure-of-Merit**

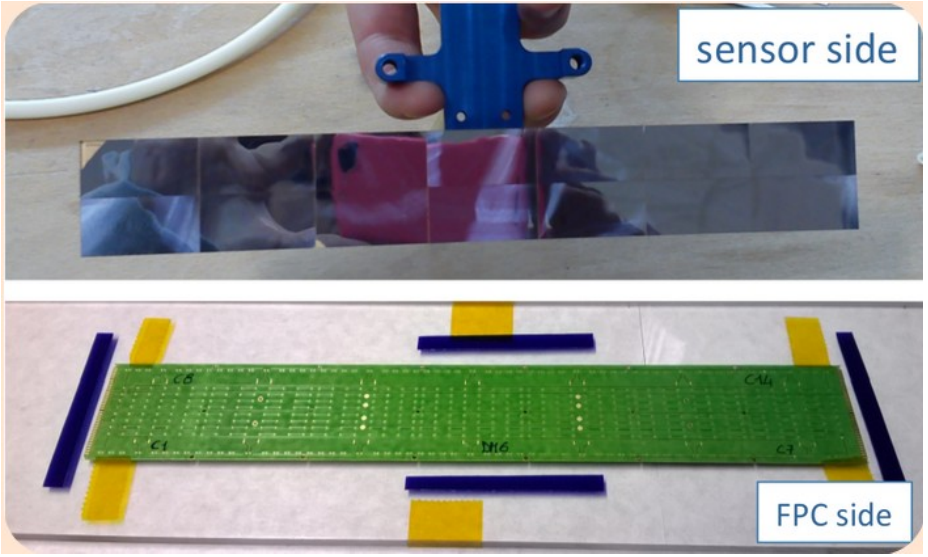
$$FoM = \epsilon \times A^2_{MS}$$

- Revisit with **Pixel Silicon technology**
ALPIDE : 25 x 27 μm^2

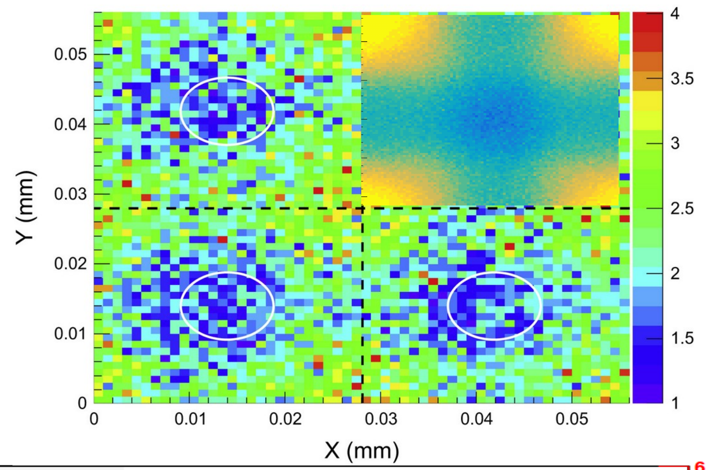
- **How to design a γ-polarimeter :**
1) Faithful simulation of detector
2) Write a super-reconstruction code
3) Optimize all parameters to optimize the FoM

Einghorn, Wojtsekhowski et al, JATIS, Vol 4, Issue 1, 011006

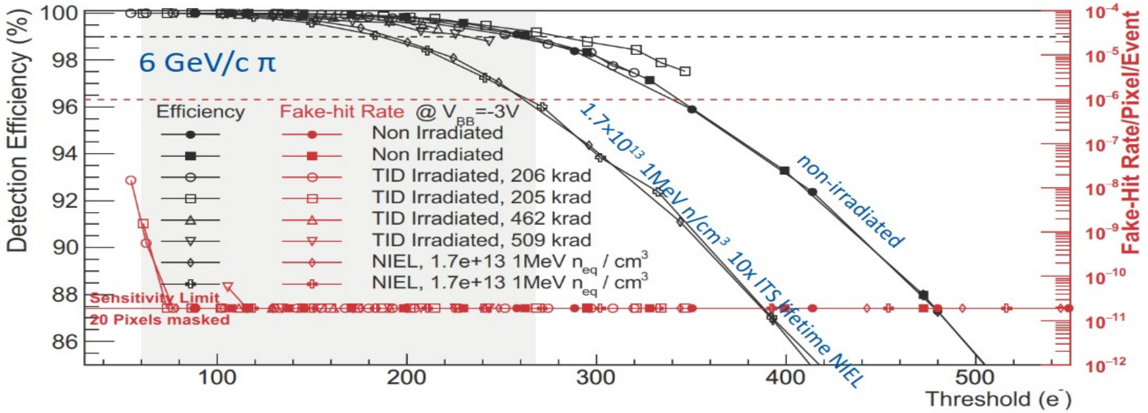


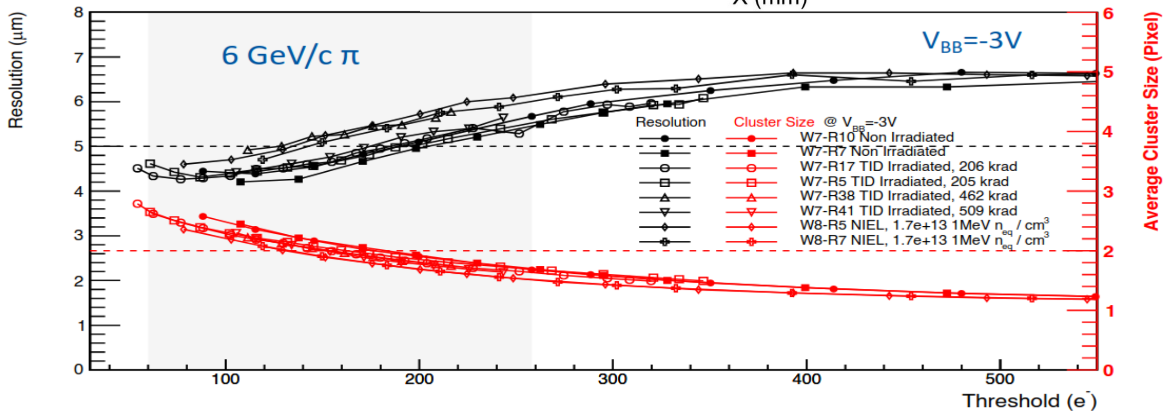


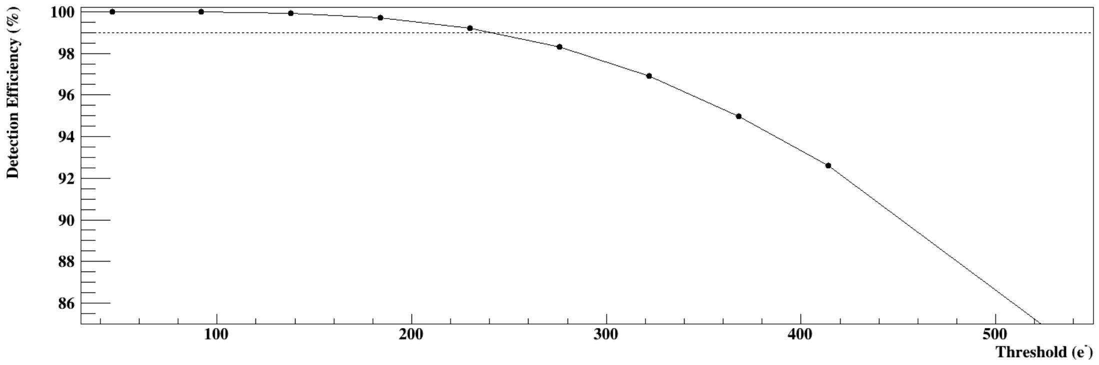
GluToNY : MAPS simulation - singles

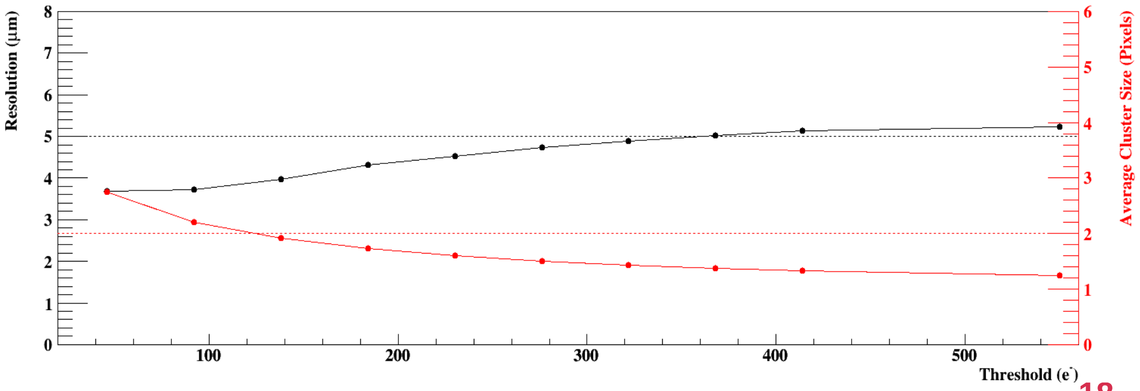


- MAPS simulation includes :
  - Energy deposit in the silicon depth
  - Electric field map in silicon depth
  - Transverse diffusion
  - Carrier mobility







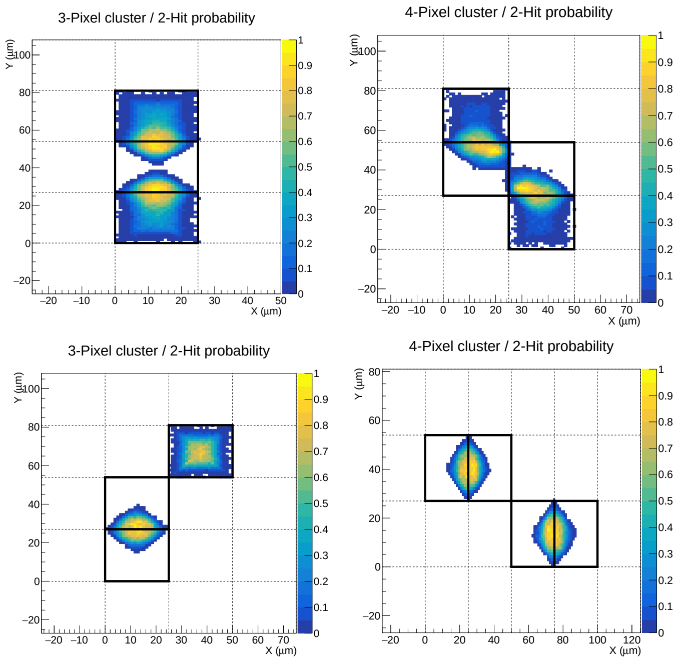


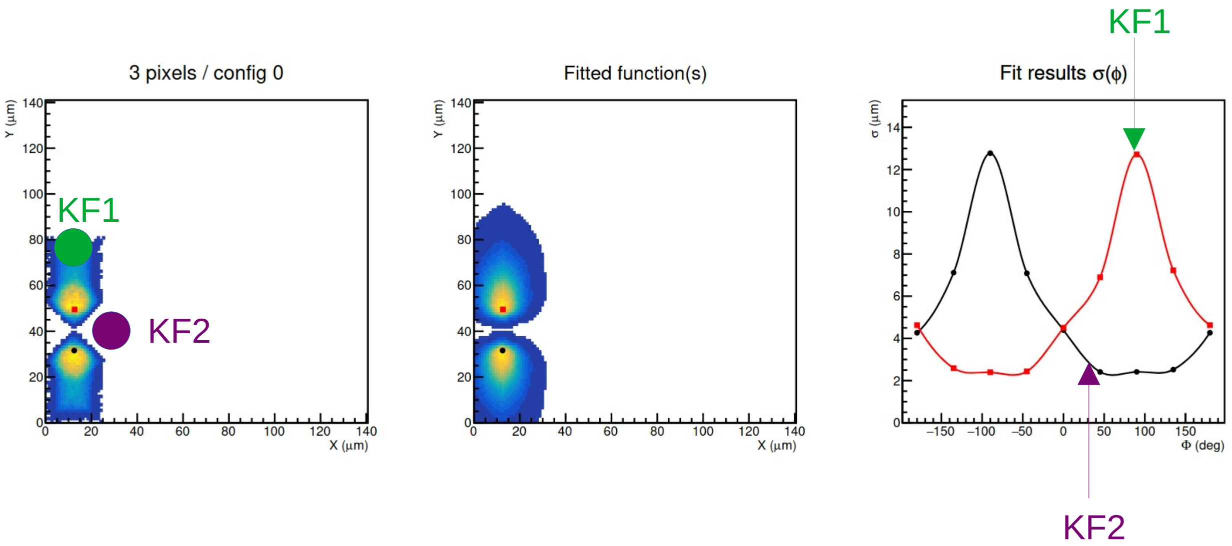
GluToNY : Two-close-particle pattern study

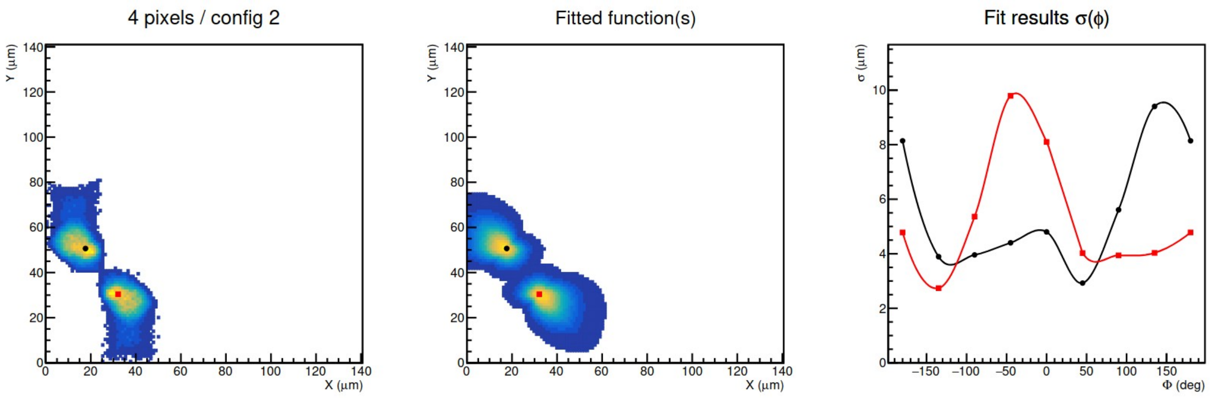
- Knowing that two particles created a cluster is a huge information.
- In Kalman filter, uncertainties are assumed to be gaussian.

$$
\begin{aligned}
f(x,y) &= \mathbf{C} \times \exp\left(-\frac{\sqrt{(x-\mathbf{x_0})^2 + (y-\mathbf{y_0})^2}}{2\boldsymbol{\sigma}^2(\phi)}\right) \\
\phi &= \operatorname{atan}\,(y - \mathbf{y_0}, x - \mathbf{x_0})
\end{aligned}
$$

- KF-Predictions are matched with closest measurements
- Uncertainty of measurements set with position of the predictions

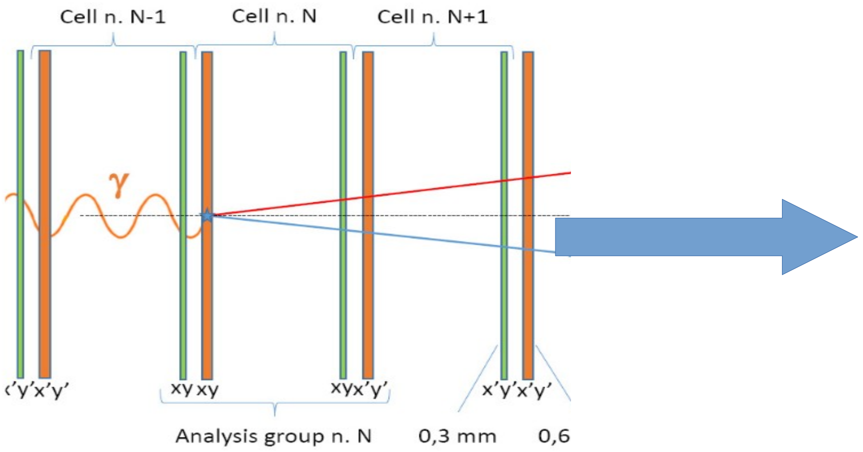


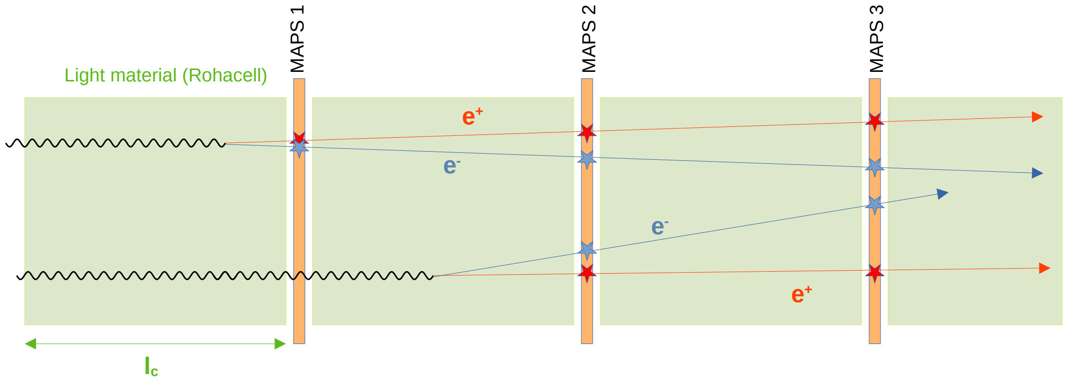


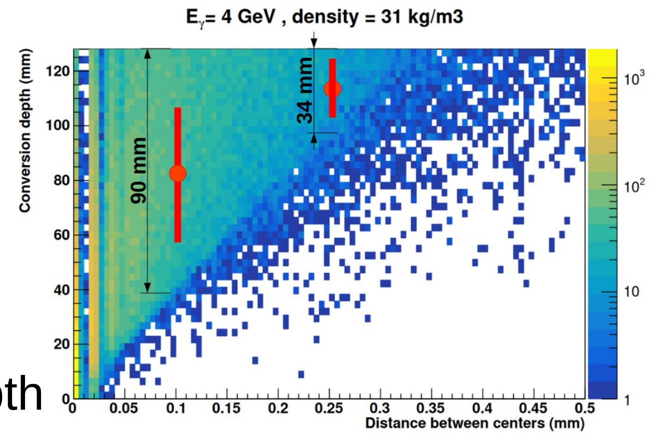


GluToNY : Azimuthal angle reconstruction

- In Einghorn’s design, detector and converter are together.
  => Here we suggest to separate converter and detector.





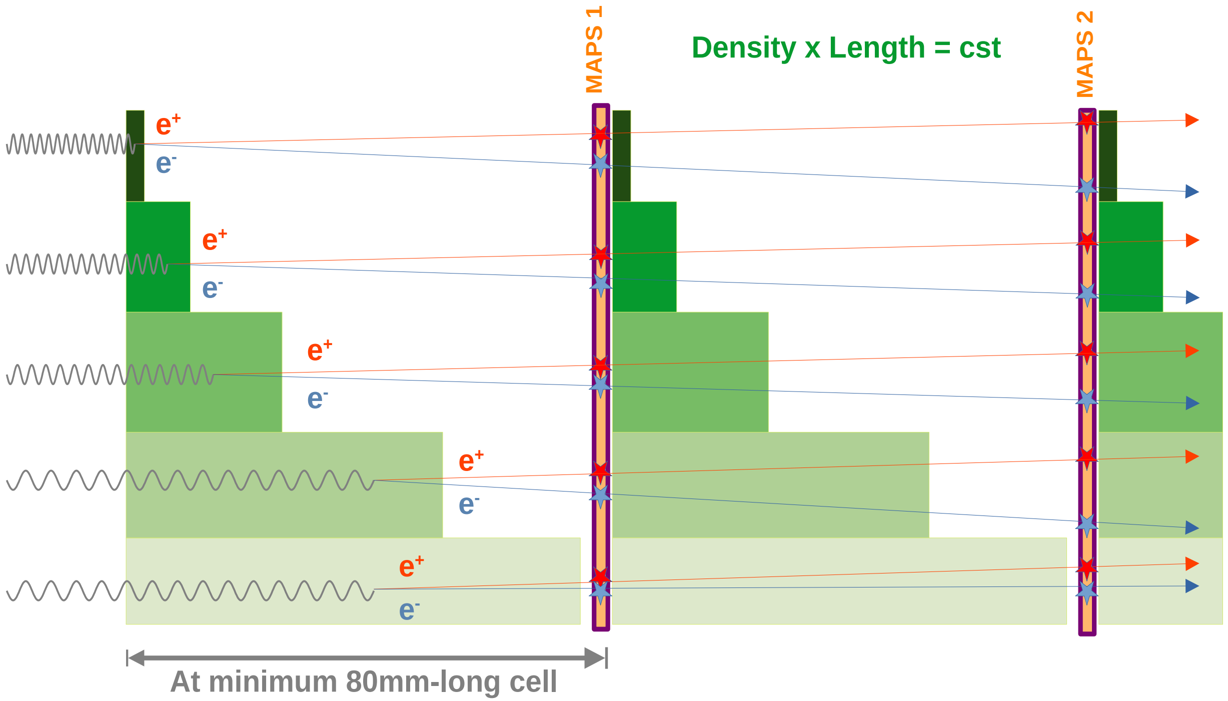


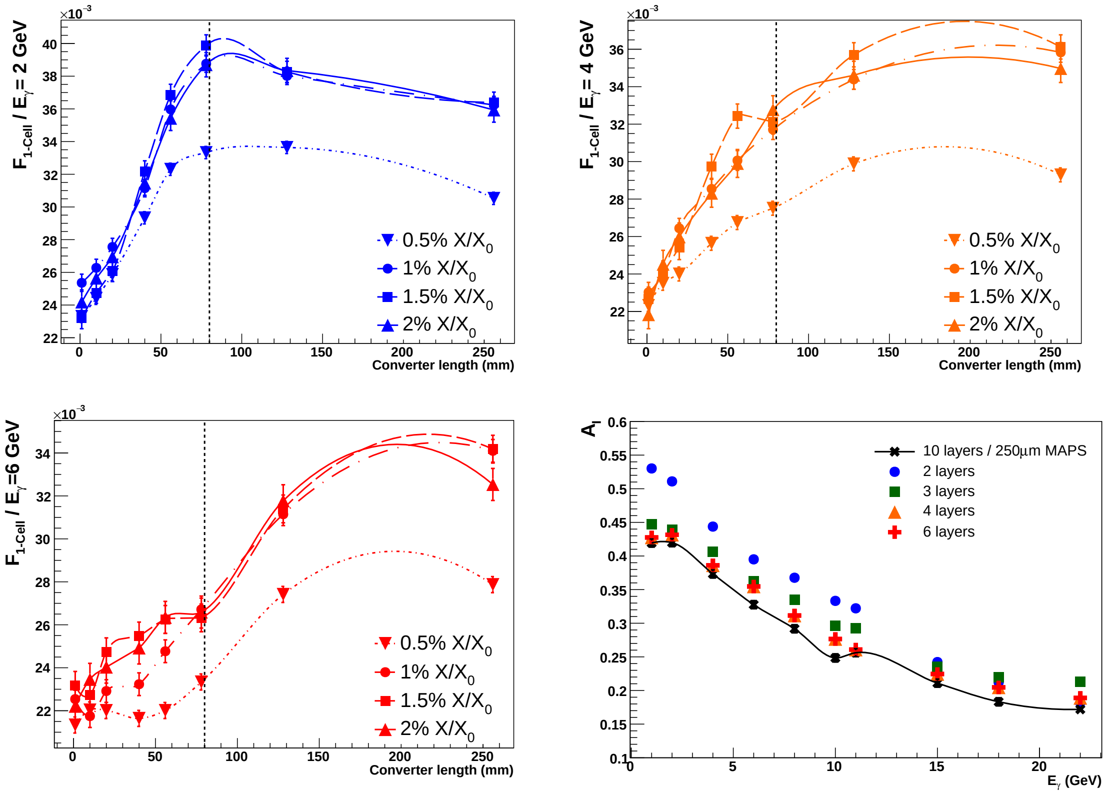
- The vertex is known in Einghorn by having the conversion in the detector.

- To recover this knowledge, a measurement is added in the Kalman Filter :
  → Projection of one lepton’s position in the Rohacell for the tracking of the other.

- The distance between the two hits in the first plane constrains the conversion depth

GluToNY : Optimization of the design





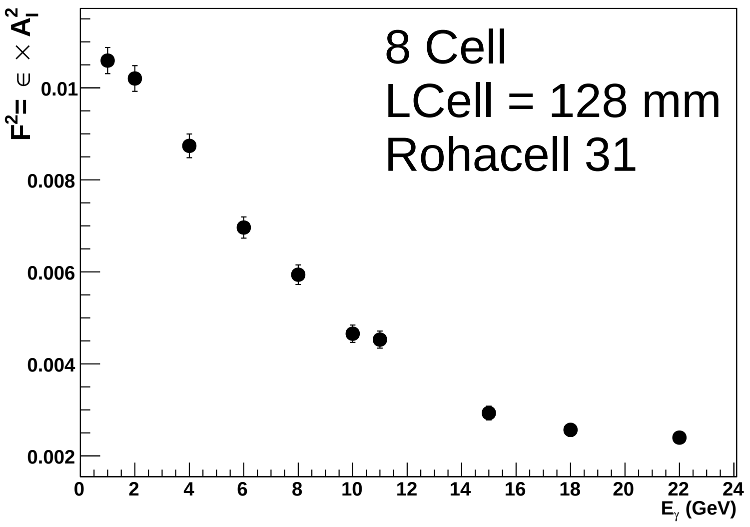
- Scan of Density/Length to optimize FoM
  → Need to know space/energy spectrum
  → Smallest RadLength is preferred.

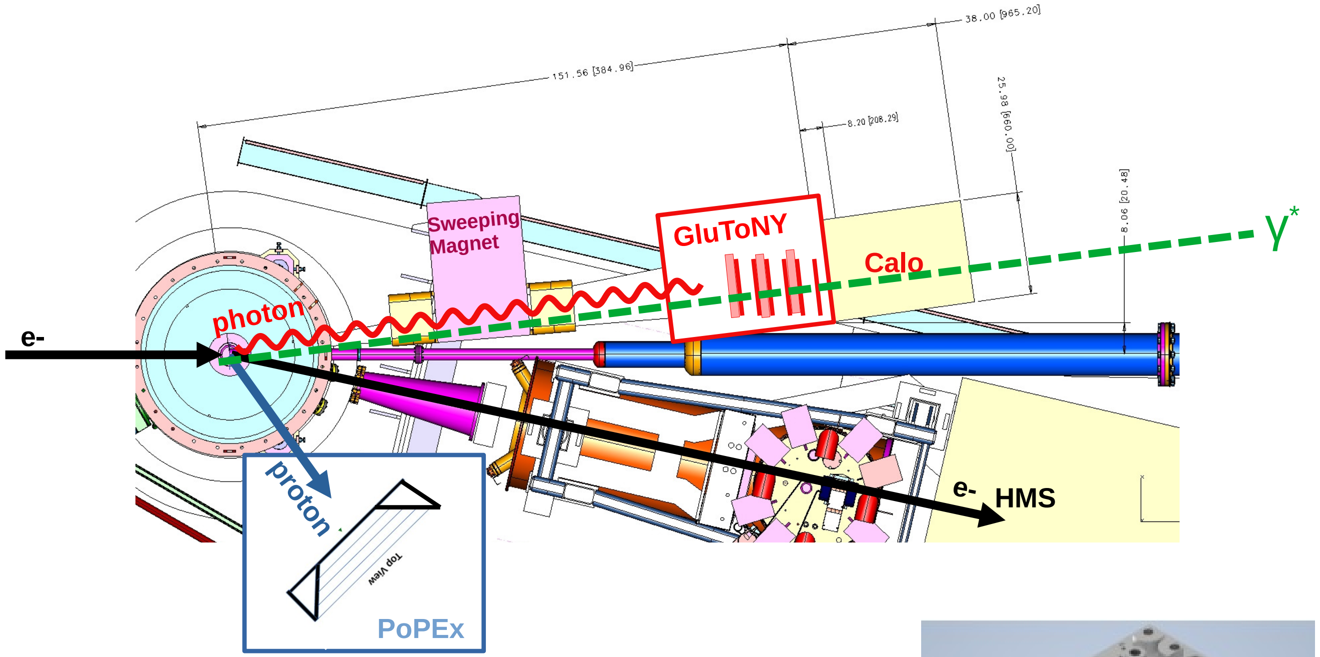
- Study of AI against number of MAPS layer :
  => Only two appears to be enough

$$\epsilon = 1 - \exp\left(-\frac{7}{9}\frac{X}{X0} \times (N_{Cell} - 1)\right)$$

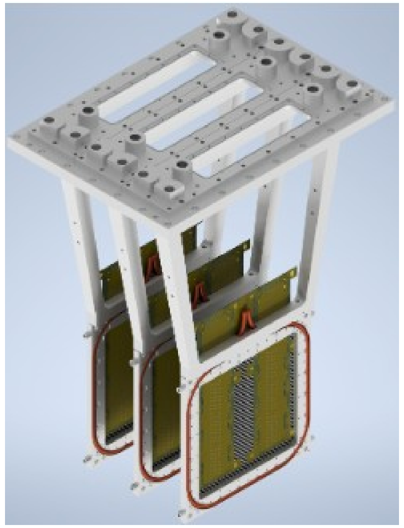
GluToNY : Conclusion

- **First** multi-GeV γ-polarimeter for experimental measurements fully characterized





- As the photon is forward, the polarimeter much smaller than PoPEx polarimeter.
- Approximately about 1 000 000 DVCS events are necessary for a 0,1-measurement.
- Next step would be to validate the Monte-Carlo simulation with beam tests :
  - Bronze/Silver ALPIDE sensors available
  - Mechanical structure, cooling, thin PCB designed for proton radius at AMBER



Let’s capitalize on this with an ERC

→ Where this comes from?

1) 4 years ago, CEA asked me to define a new ERC-scale research program → PoPEx & GluToNY

2) Encouraged along the way by GPD theorists, phenomenologists, experimentalists and polarimetry experts

3) Validated by a successful PoPEx beam test grant and a Royal Society fellowship supported by UofG – many thanks!

4) And by my wife, who kept pushing me this far… to Scotland.

5) Existing re-usable detectors and studies

The physics case is now sharp enough, and hard enough, to be ERC-competitive.

→ Why now?

1) Funding news is bad everywhere, and it is hitting major projects — EIC and LHCb included

2) ERC money is European, curiosity-driven, and relatively insulated from those cuts

3)JLab and EIC physics overlap far more than our funding lines suggest:
The same detector R&D, the same observables, largely the same people

What’s in this for you ?

An ERC is a few M€ over 5–6 years — a game-changer for PoPEx, GluToNY and the theory work they need. Built smartly, it can also feed EIC subsystem R&D.

To my US colleagues — this is not a European-only conversation:
→ On a Synergy, one PI may be based outside the EU. That means you (for the moment, UofG?+HI?+Barcelona?+?).
→ On a Consolidator, the budget sits in Europe, but postdocs, students, test campaigns and hardware can be shared.

What I'm asking for:
→ Point me to what I'm missing — I have no global view of hardware activities across EIC.
→ Pixel silicon/SciFi testing, NLO fitting? Tell me, and let's see what we can attach as a realistic side project — detector or theory.
→ 20 minutes and your honest opinion. Tell me where this proposal is weak. A "this won't fly" now is worth more than a rejection in 2028 with a 3-year ban for resubmission.

With many thanks to the organizers for the invitation to this workshop.