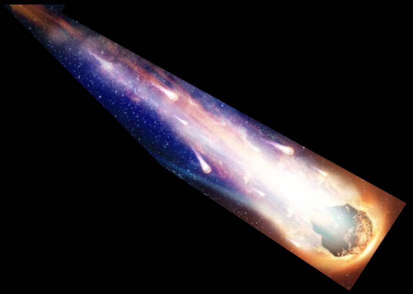


Exploring
the hadron structure at Jefferson Laboratory

Maxime Defurne et Francesco Bossù

Introduction

- Experimental program **proposed with CLAS12 in 2006**.

- Since then :
  - Various experimental measurements have been performed.
  - Tremendous progress in theoretical calculations (lattice QCD/Dyson Schwinger)
  - as well as in detector and electronics technologies (Micromegas Vertex Tracker, MAPS).

- To build a pertinent experimental program today, three questions must be asked:
  - **What is our final goal in hadron physics?**
  - **What are still the missing experimental observables ?**
  - **What are the strengths and weaknesses of our group ?**

- In association with our theory group, we propose three experiments :
  1) Sullivan DVCS : The first exploration of the pion 3D-structure.
  2) PoPEx : Possibly the first clean-access to the GPD E of the proton at Jefferson Lab .
  3) GluToNy : Gluon tomography in the proton with gamma polarimetry.

Sullivan DVCS : Studying the pion structure

- In 2015, at my PhD defense, I was asked what kind of experiment would I build if I had an infinite amout of money.
  My answer : An Electron-Pion collider (EPiC).

- What is the final goal of hadron physics ? « **To understand their quark/gluon structure** »
  => In other words, QCD must predict all experimental measurements.

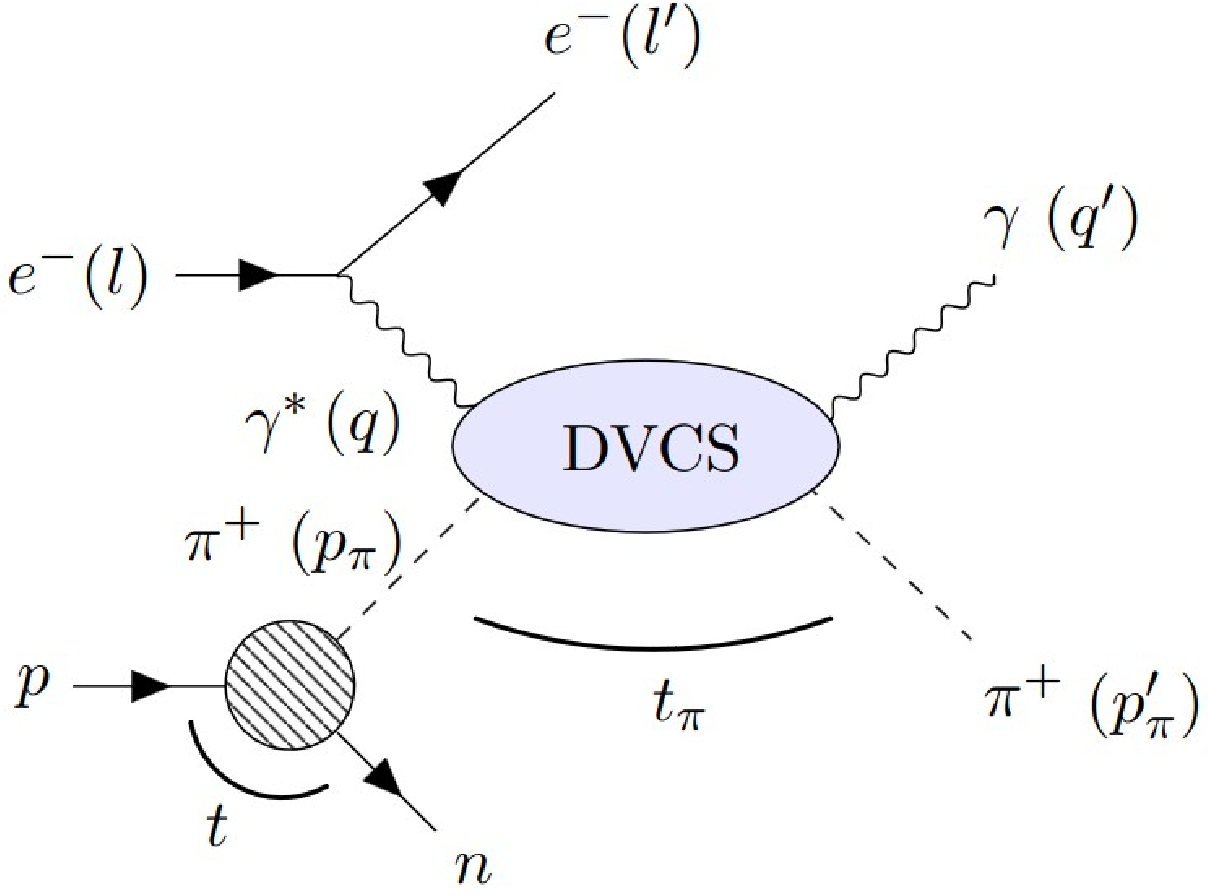
- **Pions** are the simplest hadron from a theory point-of-view :
  - There is **a single GPD** as it is a pseudo-scalar particle (4 for the proton).
  - Modelling meson structure is easier than baryon structure (2 vs 3 valence quarks).

- There is a **wealth of theory predictions** using various techniques and models (including DSE and lQCD).

- **Experimentally, pions are much more challenging** to study compared to the proton :
  - Drell-Yan process : Lepton pair production from particle/antiparticle annihilation in pion-proton collision.
  - Sullivan process : Lepton scattering off a pion-like structure in a nucleon.

- **Form Factors and Parton Distribution Functions** have already been studied through these two processes. **But GPDs never have !**

Sullivan DVCS : Process description



- There are three parts in the diagram :
  -**The leptonic part** in which the electron beam emits a virtual photon.

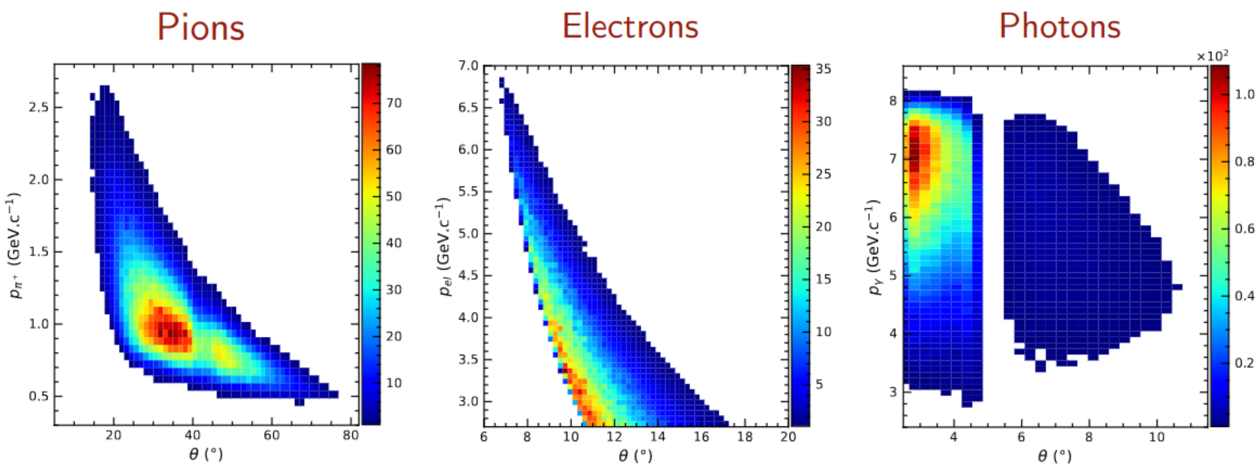
  -**The Sullivan part** in which the proton fluctuates in a pion/neutron state, the pion being virtual (t).

  -**The DVCS part** with the virtual photon and pion interacting to get a real pion and high energy photon in the final state.

- The squared momentum transfer between the pion states is noted t_π.

- The **mass of the neutron/pion** system in the final state will be required **> 1,5 GeV**.

Sullivan DVCS : CLAS12 Monte-Carlo simulation

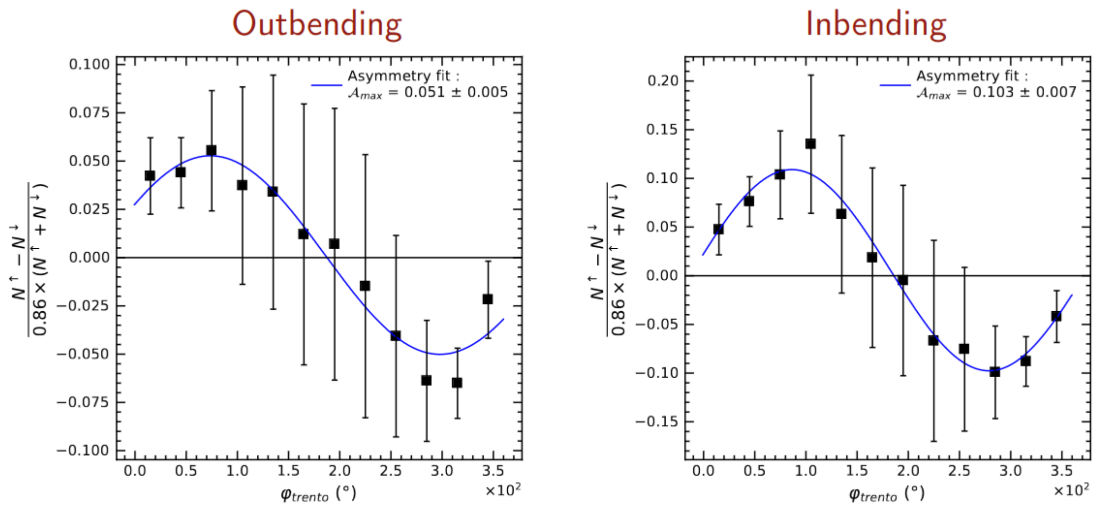


- **GPD model** developed by a theory collaboration **involving C. Mezrag and JM Chàvez** at LSN. (Phys.Rev.D105,094012)
- Amrath, Diehl et al performed feasibility studies for CLAS++ in 2008 (Eur.Phys.J.C58)
- Scientific impact of Sullivan DVCS first demonstrated for EIC and EiCC (PRL).

- Using CLAS12 Geant4 simulation, several tests were performed before looking in the data :
  - Resolution on the **missing mass of the neutron good enough**.

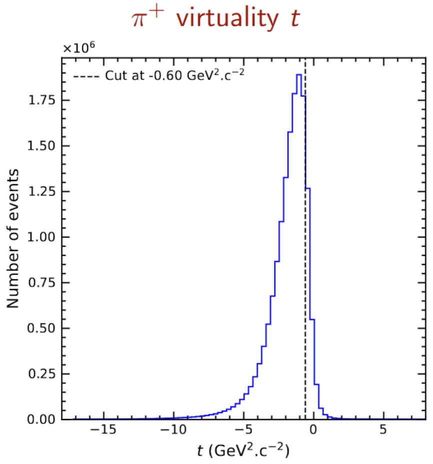
  - **Expected statistics high enough** to hope to see Sullivan DVCS in data.

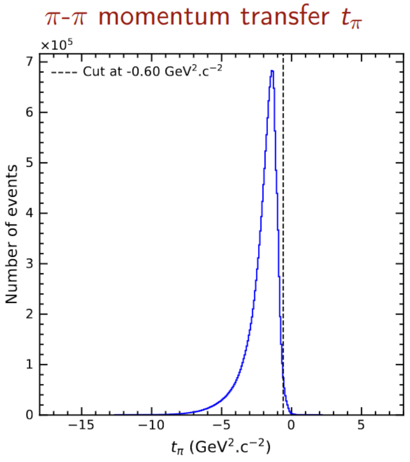
Courtesy T. Fauvet, Intern at LSN

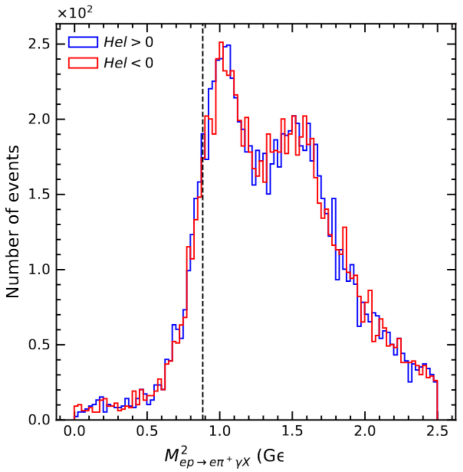


- Amplitude ~ 0.05
- Amplitude ~ 0.10

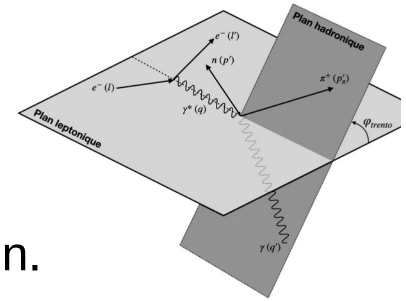
Sullivan DVCS : Data Analysis



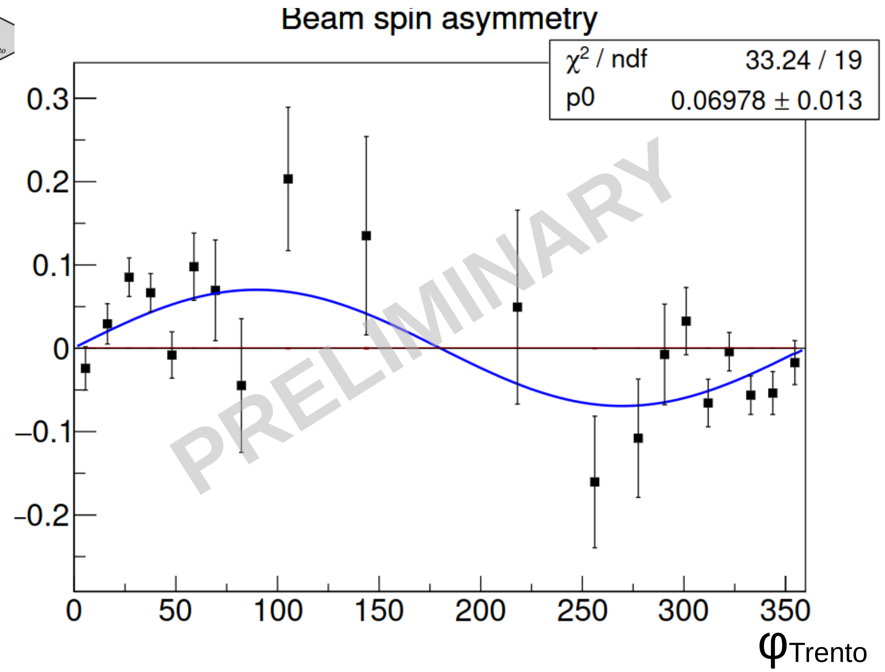




- **Kinematical cuts to ensure** proper interpretation of measurement with **Sullivan DVCS**.
- Clear signal seen on the neutron missing mass.
- Contamination subtraction adapted from pDVCS to Sullivan DVCS.



$$e + p \to e + n + \rho^+ \xrightarrow{Decay} e + n + \pi^+ + \pi^0$$



- Cut on neutron missing mass applied at 1,2 GeV².
- Missing momentum assigned to undetected neutron.
- **Non-zero beam-spin asymetry** measured and compatible with model predictions.

Courtesy T. Fauvet, Intern at LSN

Sullivan DVCS : Short/MidTerm perspectives

- **Experimental evidence of Sullivan DVCS** in the already-collected CLAS12 data.

- A **PhD position co-supervised by Glasgow and CEA-Saclay** to finish the data analysis and contribute to the second half of RGA (2026).

- This **PhD will complete the EIC study** with more realistic Monte-Carlo simulation.

- If the direction approves, a proposal will be submitted next year in 2025 to **be fully acknowledged as an official experiment** :
  -> As the yield depends much on the torus polarity, Sullivan DVCS needs PAC acknowledgement to be considered.

- Regular opportunities with DVCS are available :
  - **Positron Sullivan DVCS** to access the Real Part of Compton Form Factors.
  - Ongoing discussion about **energy upgrade from which Sullivan DVCS would greatly benefit**.

Proton DVCS : What do 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 H̃** : 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 Ẽ : DVCS is **poorly sensitive** to this GPD.
  Imaginary part 0 Real part 0

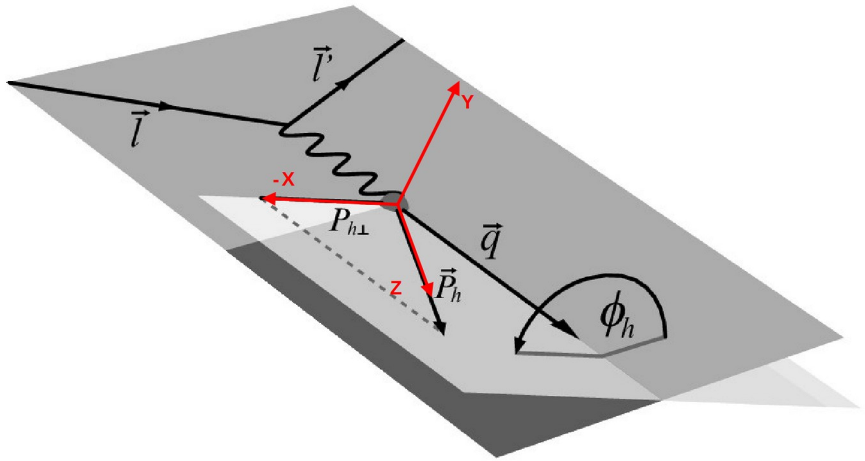
- Proposal with CLAS12 to take data with transversely polarized target scheduled for 2029-ish:
  → **Dedicated magnet is being designed**.
  → Will require **specific detector for proton detection**.

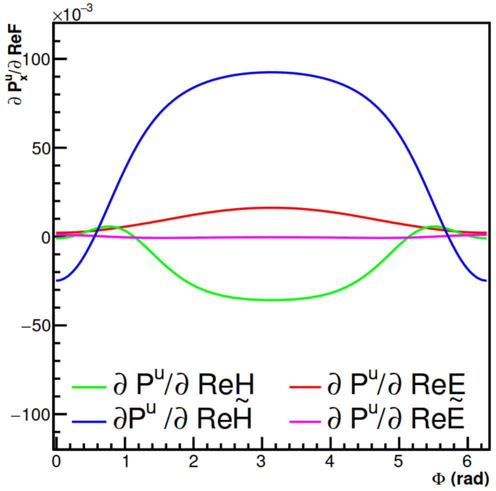
- **Since 2016**, been wondering about sensitivity of **recoil proton polarization (RPP) in DVCS** :
  - **No theoretical calculation** giving the links between CFFs and RPP.
  - **DVCS has a low cross section** : It will be a challenging experiments on many aspects.

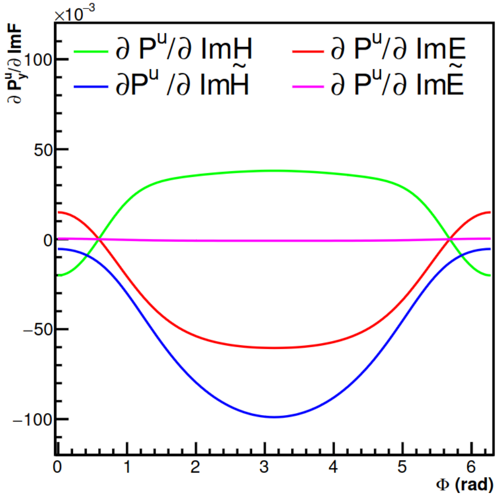
PoPEx : A new experimental observable for DVCS

With O. Bessidskaia-Bylund, Postdoc at LSN, funded with Bottom-Up CEA program

- **P. Guichon**, former theoretician at LSN, computed the recoil proton polarization as function of CFFs.
- Sensitivity studies initially performed with GK model.
- Aiming at constraining E, a local measurement is needed.
  - **simultaneous access to ImE and Re$\tilde{H}$**.
  - ImH and Im$\tilde{H}$ constrained by collected JLab data.







$$P^m_{x/z} = h_e \left(P^u_{x/z} + h_e P^h_{x/z} \right) ,$$

$$P^m_y = P^u_y + h_e P^h_y .$$

1) Need a longitudinally polarized beam!

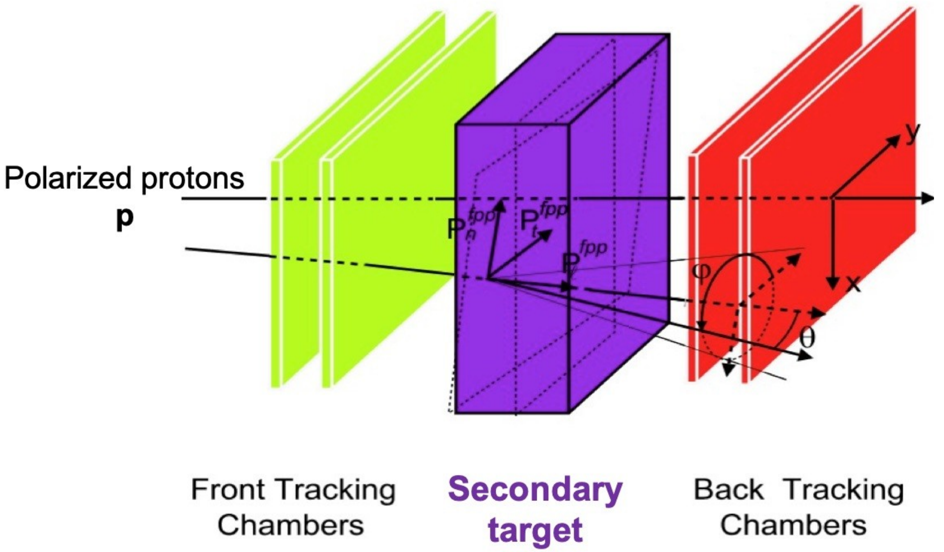
2) Need to avoid spin precession.

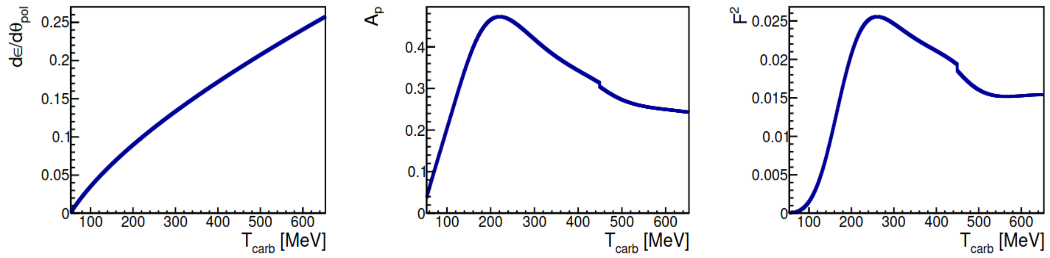
PoPEx : Basics of proton polarimetry

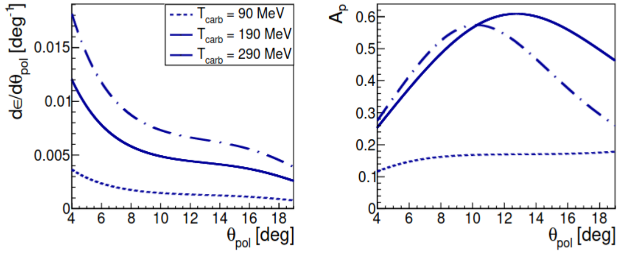
- **Proton polarization** obtained from harmonic analysis of **rescattering off a Carbon or Hydrogen nucleus**.

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

- 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.

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

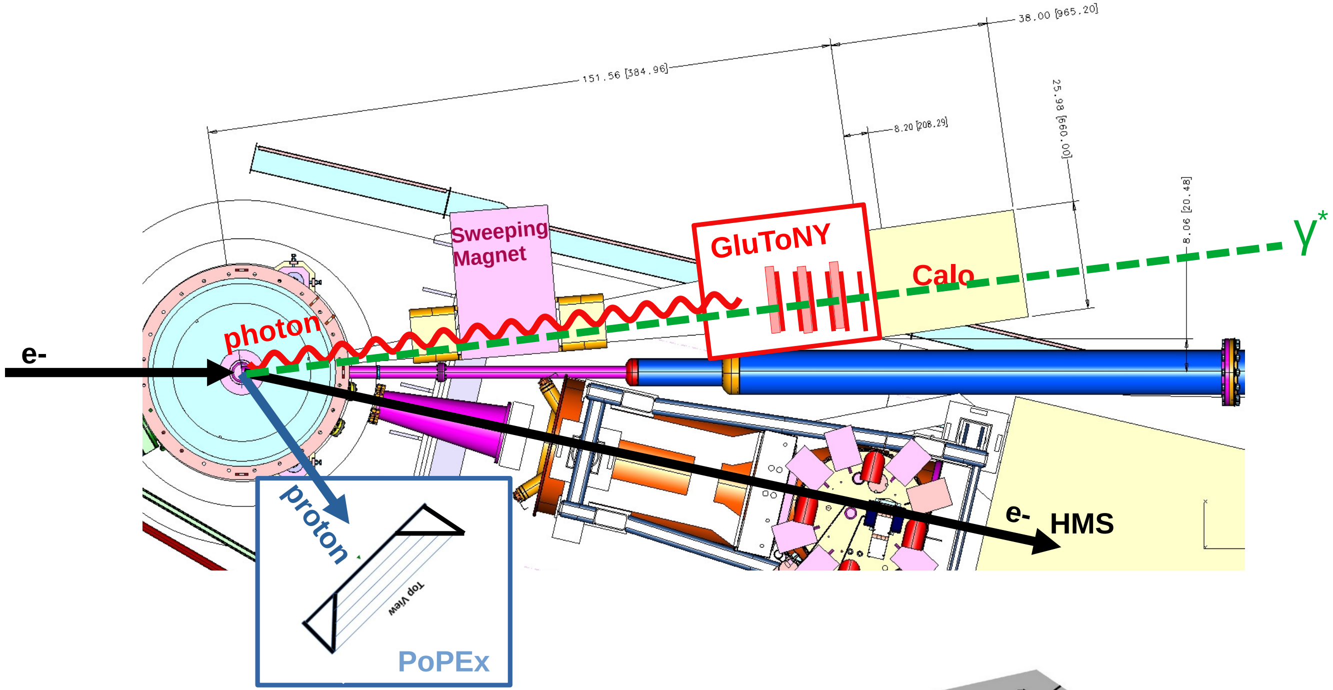
- For the best measurement, **the Figure-of-Merit must be optimized**.

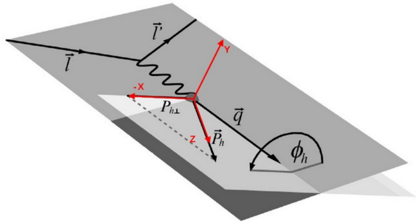
PoPEx : Experimental Hall C at JLab

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

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

- A PbWO4 calorimeter has been built and took data in Fall 23 and Spring 24
  - **Shifts to familiarize with Hall C**.





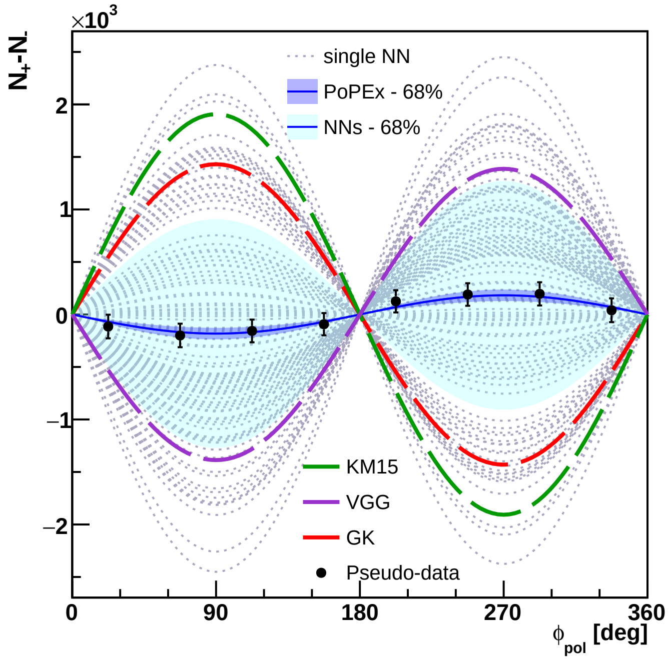
However we need to build a dedicated polarimeter:
- Need to find the space,
- Must sustain the high radiation environment,
- Must be able to find the DVCS proton (Good position and time resolution)

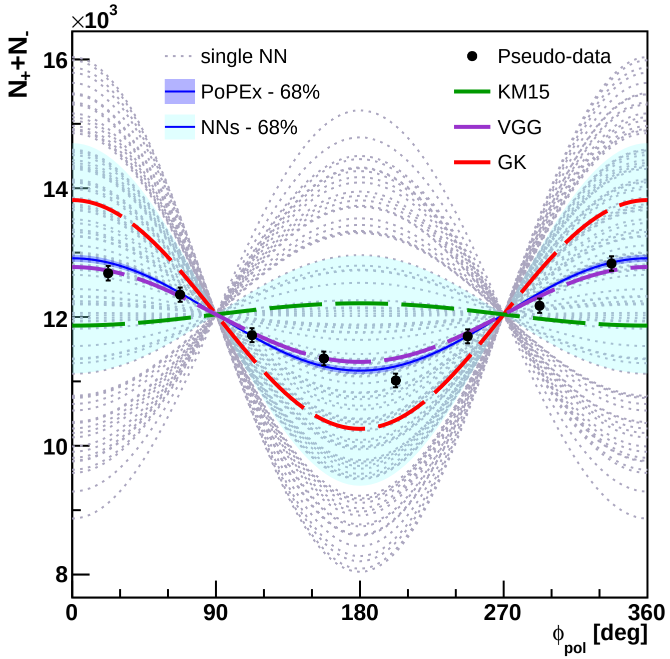
For next slide, the polarimeter is assumed ideal and is 1m^2 located at 1m from the target.

PoPEx : Scientific impact of a measurement

- 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.

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

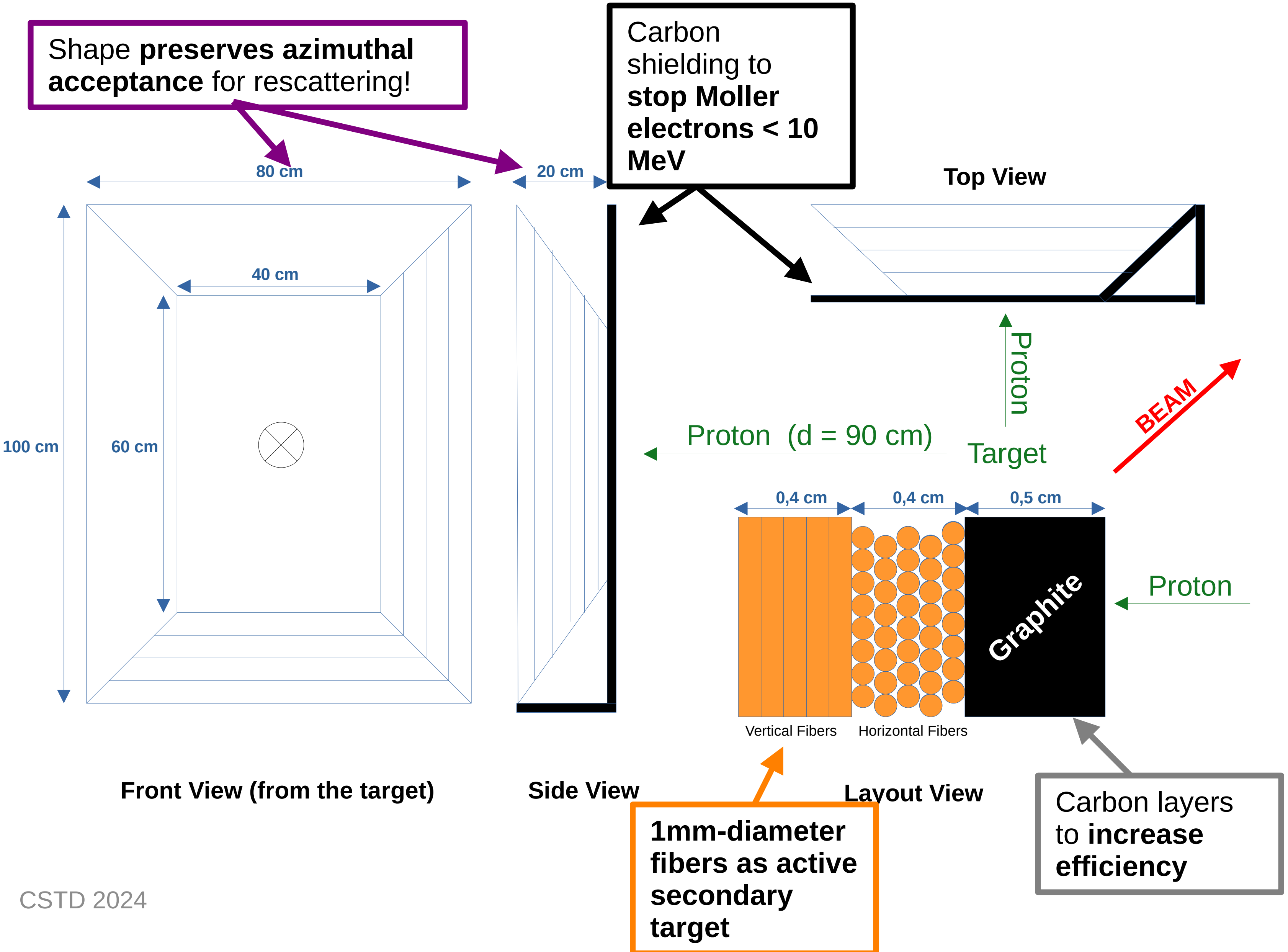


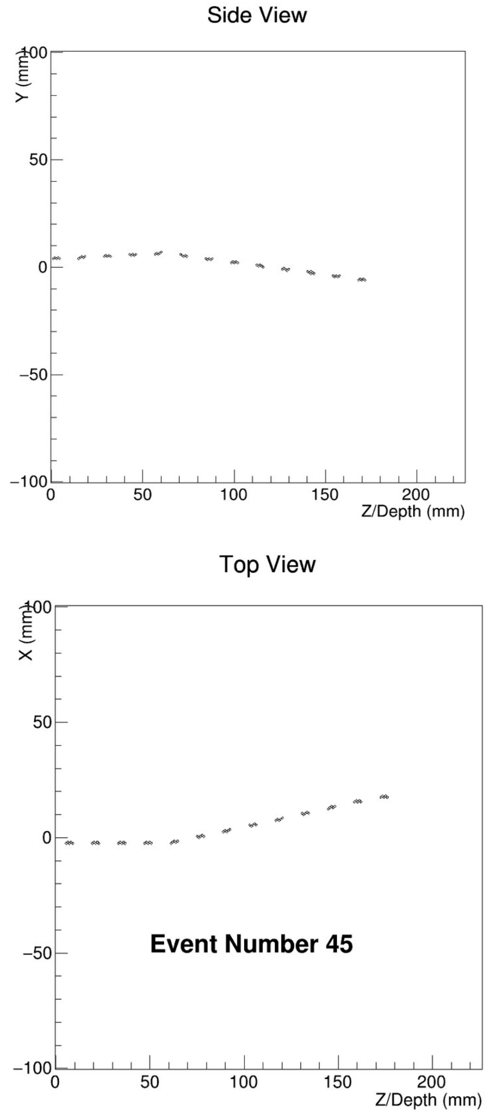


Published in Phys. Rev D107, 014020

- Using the Hall C DVCS Geant4 simulation and **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**.

PoPEx : A first design





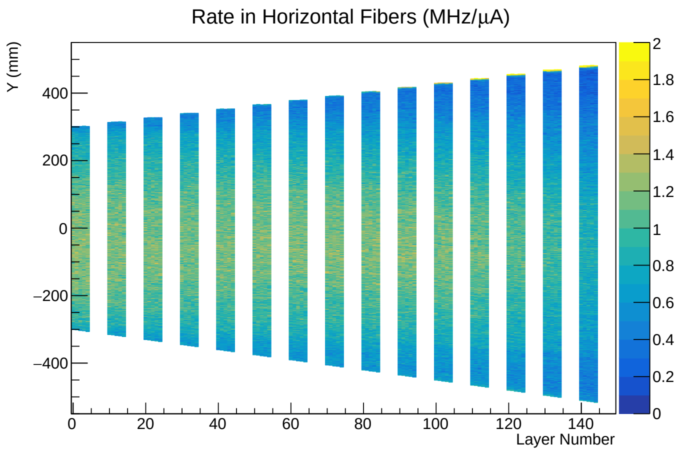
PoPEx : Performance and rates

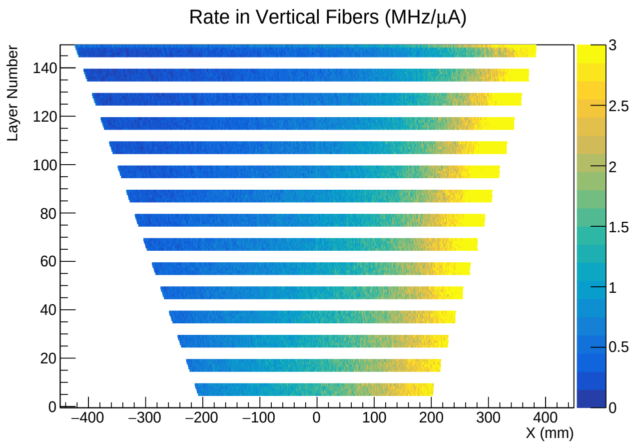
- Design has been implemented in the Hall C DVCS Geant4 simulation.
  → Rates were estimated at **3MHz/µA** for vertical fibers closest to the beam.

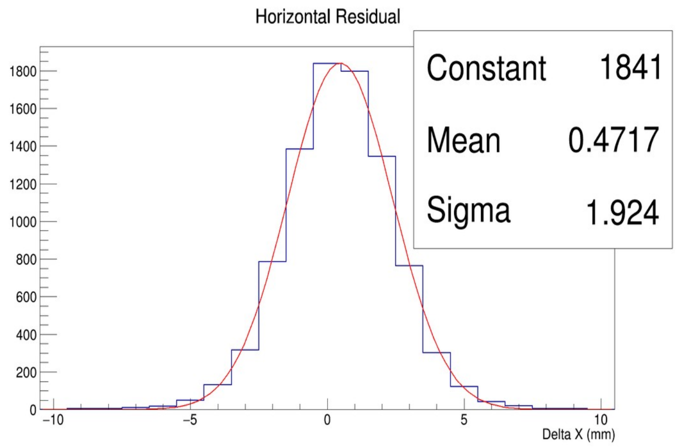
- Assuming a **1ns**-time resolution, hottest fibers will be fired **13 %** of the time within the proton window at **7 µA**.
  → Proton direction will help sorting hits and finding the proton.

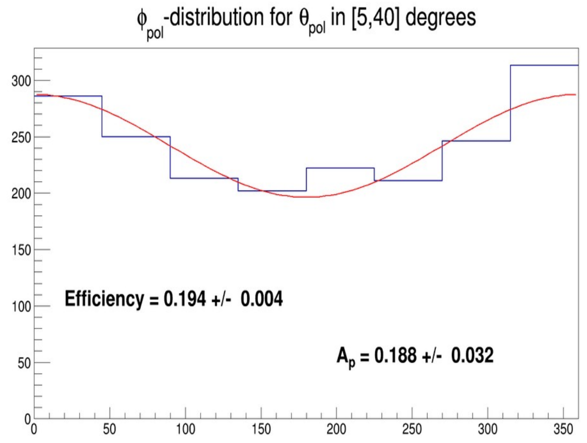
- Glasgow University provided a **specific class for polarized pN-scattering**.

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









PoPEx : Towards a proposal (part I)

- A first experimental setup has been **fully caracterized with Monte-Carlo simulation.**
- As the measurement and its scientific impact are validated, a **Letter-of-Intent was submitted to JLab Program Advisory Committee last year**.

Issues: The TAC theory report points out two issues:

- It is recommended to revisit the theory of QED radiative corrections in DVCS, which may need to be adjusted for the recoil polarization measurement. → Afasanev is sure it is as small as for elastic scattering
- Other physics processes need to be considered for calibration of the recoil polarimeter, such as *ep* elastic scattering or exclusive pion production in kinematics with large known recoil polarization. → Need to finalize polarimeter design

Summary: The proposed method of using recoil nucleon polarization for DVCS and the π^0 electroproduction is well motivated. Next steps are laid out, including the finalization of the polarimeter design and the development of a Machine Learning tracking algorithm.
The PAC recommends the proponents to proceed to a proposal taking into account the issues raised above.

- Why only a LoI ?
  → Could not determine the maximal beam current (Tracking efficiency),
  → Need to **validate SciFi rates and radiation hardness of setup**,
  → The proposed design, **not aimed at being final, is expensive (~ 4 Million Euros / 105 000 channels)**.

PoPEx : Towards a proposal (part II)

- **Priority 1 : Reduce the cost**
  → Move away the polarimeter by a factor 2 and use 3mm-diameter fibers (**105 000 → 12 000 kSciFi**)
  Maximal rate expected per fiber ~ **1,5 MHz/µA (6,3 %)**
  → Multiplexing of SciFi on one electronic channel (**12 000 → 6 000 channels**)

- **Priority 1 : Check simulation rates and test SiPM/SciFi hardness**
  → Beam test is being prepared in collaboration with Hall C and NPS collaborators (Mark Jones letter),
  → **48 kEuros** = 15 kEuros from DPhN + 33 kEuros from P2I
  (unsuccessful in 2023, **accepted in 2024 thanks to submitted LoI**) ,
  → Still need to design small prototype,
  → Do beam test analysis for early 2025.

- **Priority 2 : Write Tracking/Analysis code**
  → Adapt simulation code
  → Maximal beam current will be determined by SciFi occupancies.
  → Use Electron/Photon information + Machine-Learning ?

Priority 0:
Need to hire a postdoc.

- Once done, **proposal ready to be submitted in 2025 for LoI expiration ?**
  → M. Defurne (0,3 FTE), A. Francisco (0,1 FTE from 2025)
  → F. Jeanneau at Dedip (0,1 FTE)

PoPEx : Timeline and Human resources

- 2024 : Studies to finalize proposal (0,3 DPhN + 0,05 DPhN + 0,1 Dedip)
- **2025 (+1 ?) : Proposal submitted (0,4 DPhN + 0,1 Dedip)**
- **2026 (+1-3 ?): Grant obtained to fund the detector** (0,7 DPhN + 2 * 0,25 Dedip + 2 * 0,25 Technicians)
  → Additional staff at 0,3 for DPhN or increasing share of A. Francisco
- 2028 **(+3 ?)**: Detector caracterization (0,7 DPhN + 2 * 0,25 Dedip + 1 * 0,25 Technicians)
- 2030 **(+3 ?)** : Data taking (0,7 DPhN + 1 PhD DPhN + 1 PostDoc DPhN)
- Although JLab is hoping to run until 2042, it is more careful to consider that JLab may stop 2 years after EIC finally starts (2033-2035)
  => **Not much margin if pessimistic scenario**.
- Other measurements possible with PoPEx :
  → π^0 electroproduction, π^- electroproduction off neutron,
  → epMX SIDIS measurements,
  → Neutron polarimetry ? (DVCS on deuterium and changing Carbon by CH2)

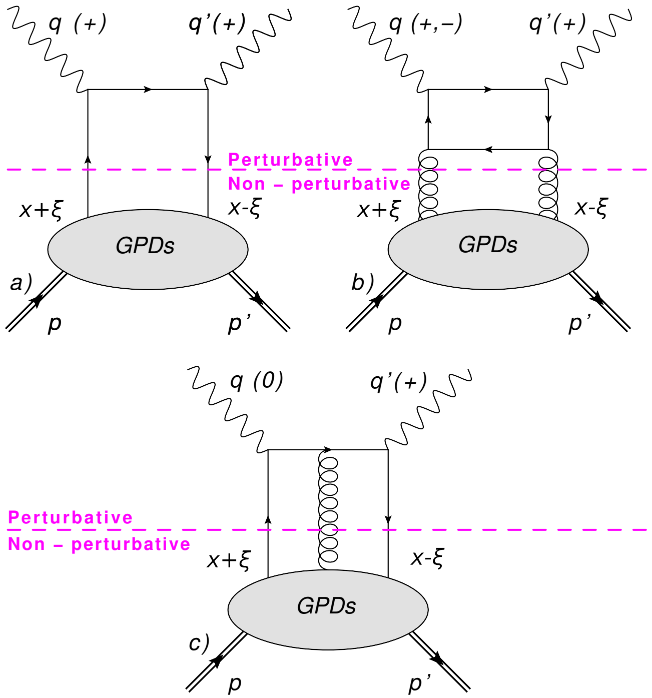
GluToNγ : Gluon Tomography by γ-polarimetry

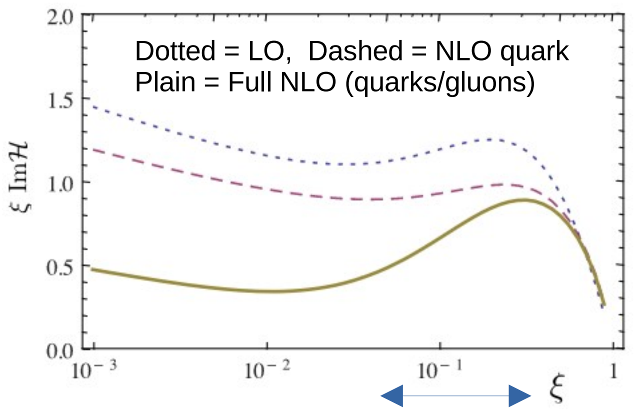
- **2015** : Fit of DVCS data indicates that there might be **contributions from higher-twist or NLO contributions.**

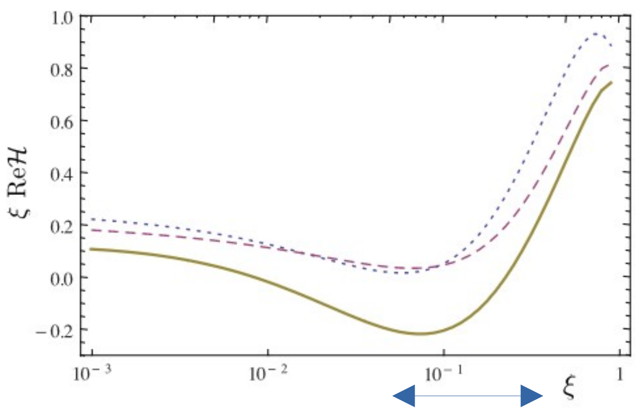
- Their contribution is tightly linked to the γ-helicity amplitudes.

- 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 !







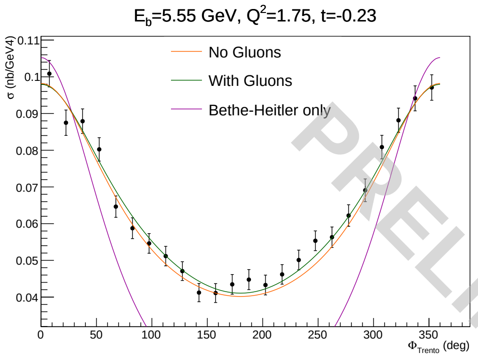
=> Study of DVCS at NLO with gluon chiral-even GPDs: Significant effect!
(Moutarde et al., PRD, 87, 054029)

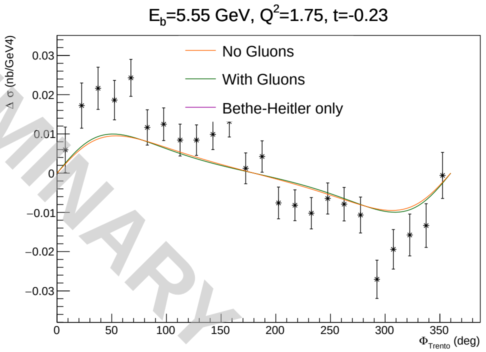
GluToNγ : A first look at theoretical predictions

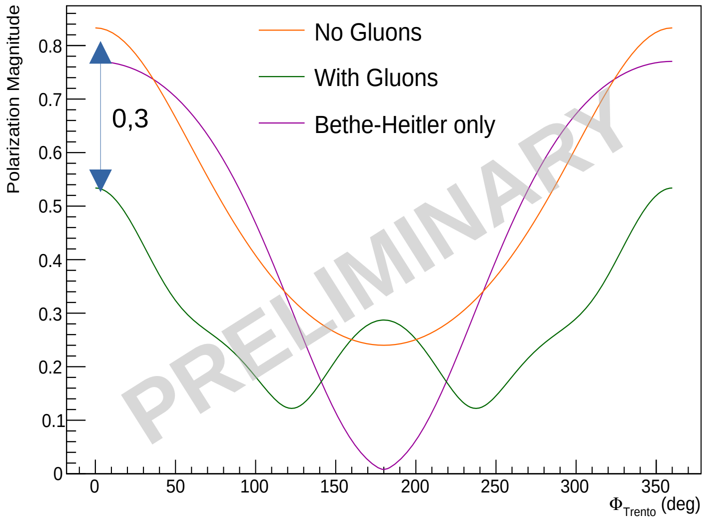
- **P. Guichon**, former theoretician at LSN, computed the fraction of linear polarization and its direction, with H_T^g and E_T^g

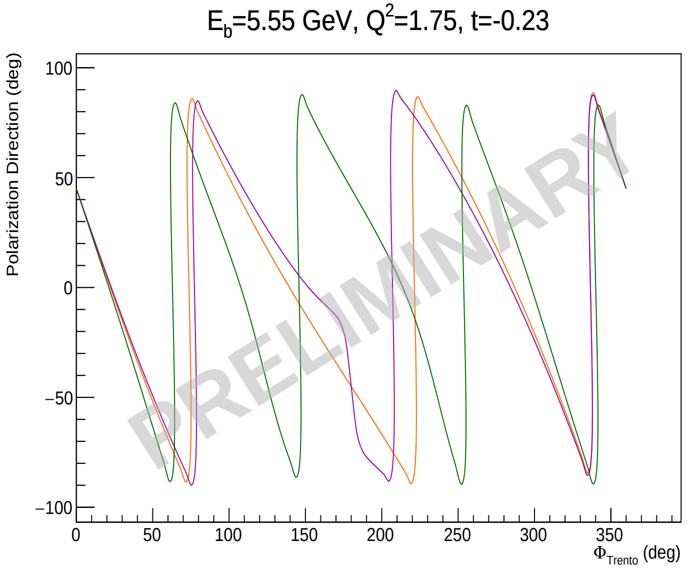
- No model for gluon linearity GPDs => **UNKNOWN !!**

- 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)

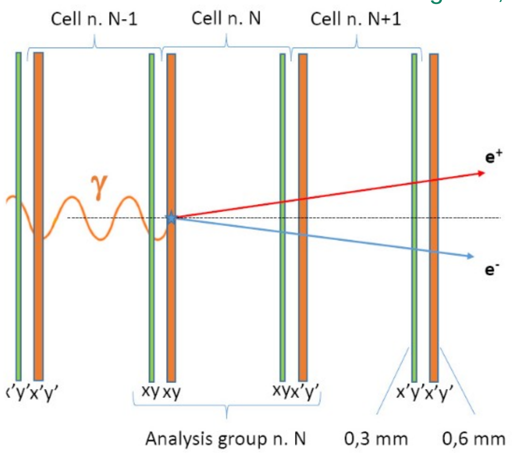
GluToNY : Designing a pair polarimeter for DVCS

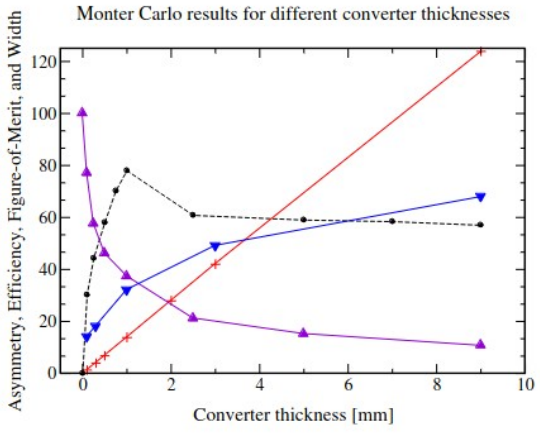
- **Photon polarization** obtained from harmonic analysis of **pair conversion**.

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

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

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



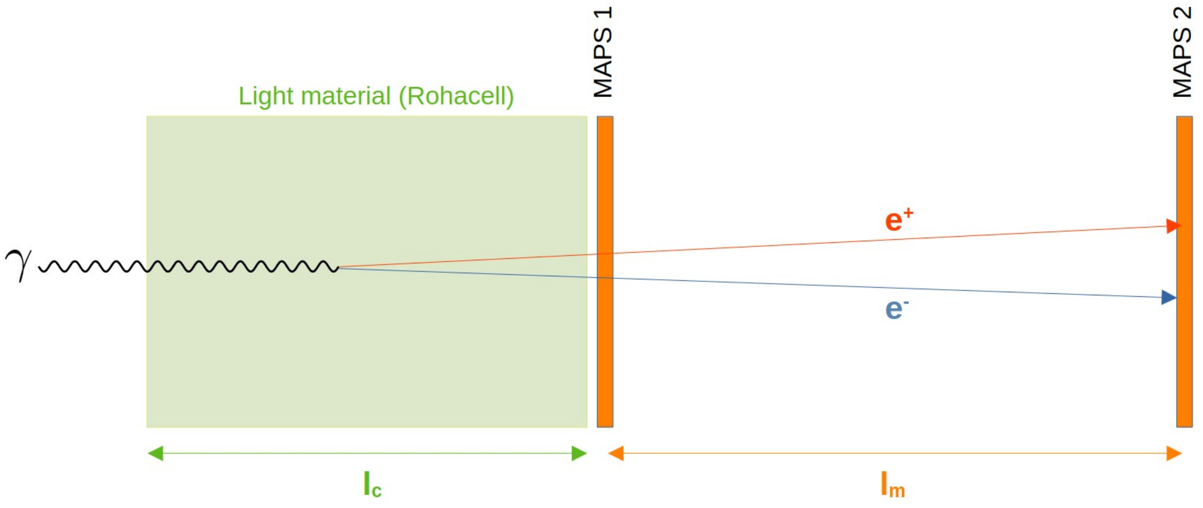


- Need to **optimise the Figure-of-Merit**

$$FoM = \epsilon \times A_{MS}^2$$

- Revisit with **Pixel Silicon technology**

- **Vary converter parameters to dilute MS :**
  - Density (Uniform, Linear, Quadratic profile)
  - Length



GluToNγ : What is next ?

- **Geant 4 simulation and tracking algorithm are ready** :
  → Arthur Muhulet (current intern) will work on the optimization of the polarimeter design.

- Once the design is optimized, it will be added to the Hall C DVCS simulation to estimate beam time :
  → **Much easier than PoPEx as the polarimeter is attached to NPS**,
  → Sweeping magnet will dramatically reduce the background,
  → **Polarization sensitivity large where cross section is large**,
  → Detector can be several meters away from target to cover similar acceptance as PoPEx.

- **A few Alpide are available** and could be used to validate Monte-Carlo simulation results at a γ-facility.

- Regarding the polarization study, a few checks need to be run to understand why the cross sections cannot be fitted.
  + Need to develop the formulas for all DVCS helicity amplitudes with finite-t/target-mass corrections.

- **Two unsuccessful grant applications** for 1-year PostDoctoral position.
  Submitted a grant application for « Emerging action » in collaboration with Astrophysics department.

- Need to contact theoreticians to **check possibilities with γ-polarimetry at EIC (or VCS/RCS formulas)!**

Jefferson Lab : Perspective

- Two opportunities are worth being considered at Jefferson Lab :

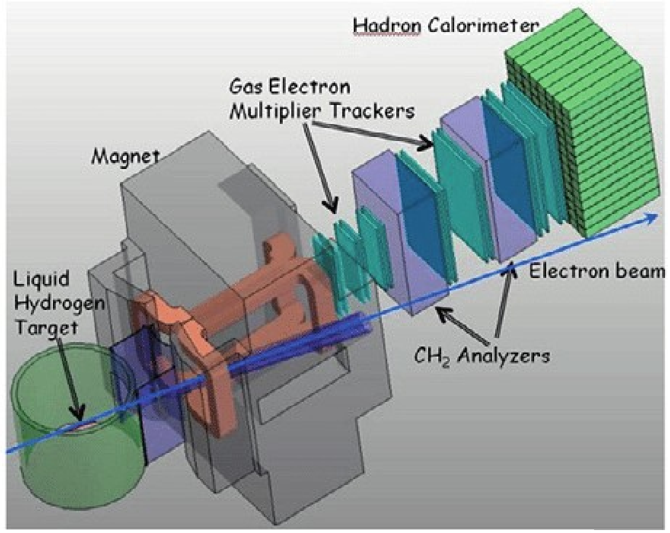
  → **Super Big Bite Spectrometer** may move to Hall C permanently

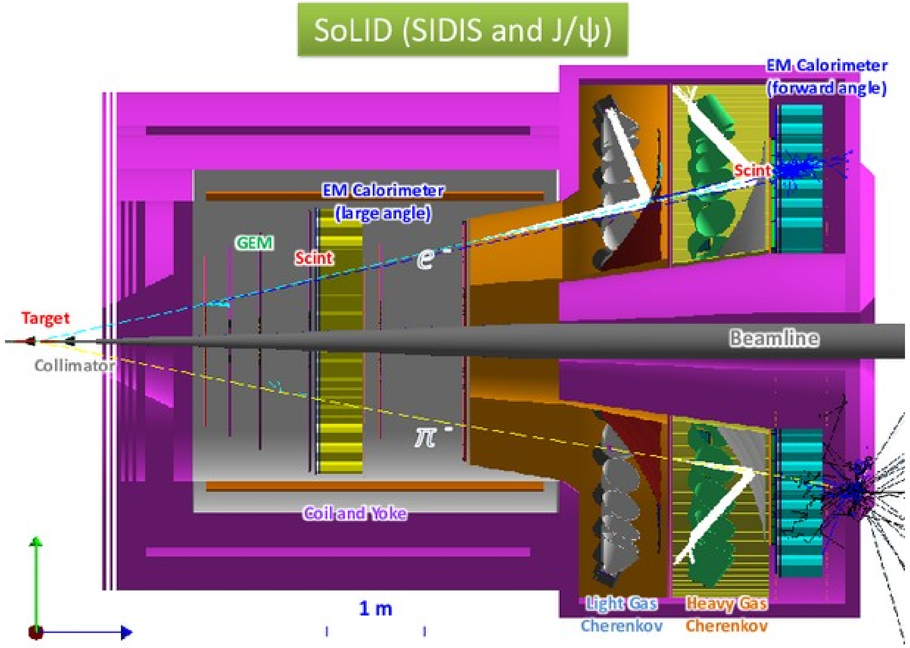
  Medium solid angle (70 msr) with modular detector package
  Resolution on momentum 0,5 %
  Still able to run at high beam current.

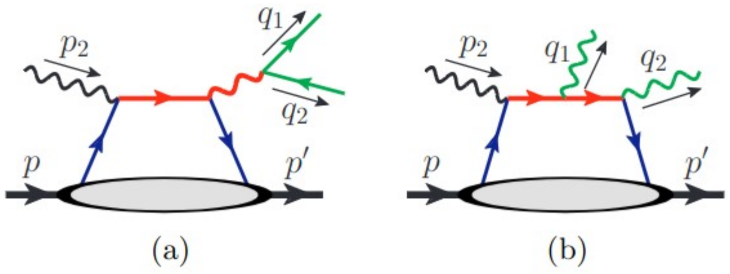
  Does it make Hall C a better place than CLAS12 for exclusive processes ?

  → **SoLID** in Hall A

  Large acceptance and able to run at **80 µA**
  Not official yet !
  What could we do with such a device ?
  2→3 processes give a clean access to GPD







Summary

- An ambitious experimental program : **the Next Generation of Nucleon Tomography experiments**.

- The **facility already exists** : JLab at 12 GeV with CLAS12 and Hall C.

- **Sullivan DVCS : Studying the simplest hadron to challenge QCD predictions with experimental data.**
  → With a PhD student co-supervised with Glasgow University, it will run from 2024-2027.
  → A nice bridge to EIC

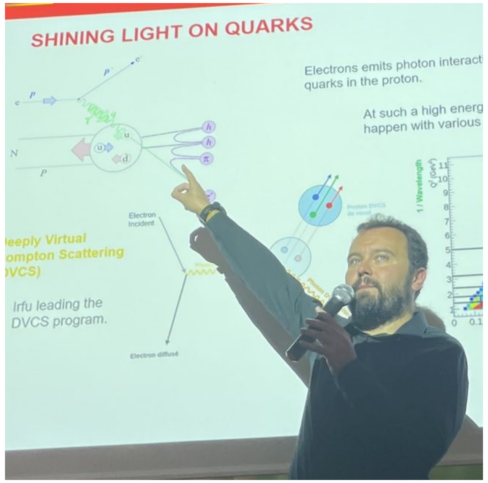
- **PoPEx : Accessing simultaneously E and H by measuring the recoil proton polarization in DVCS.**
  → Need to finalize design of a proton polarimeter.
  → However it is definitely a very promising alternative to the never-achieved TP-target.
  → For grant application, it may be considered redundant with EIC and old-school polarimetry.

- **GluToNγ : Probing the gluon core of proton with γ-polarimetry**
  → Need to finalize the design of the photon polarimeter
  → Establish minimum beam time required for a statistically significant measurement.
  → For grant application : Nice synergy with Astrophysics and a brand new observable for many processes.

- These experiments, relying on high luminosity, **may extend JLab operations.**

LSN staff working on JLab activities

Maxime Defurne



- CLAS12 :
  - Sullivan DVCS
  - Spare BMT
  - WG chair
- Hall C :
  - PoPEx P.I.
  - GluToNγ P.I.
- EIC :
  - Sullivan DVCS

Francesco Bossù

- EIC :
  - Micromegas P.I.
- CLAS12 :
  - LPT DVCS analysis
  - Spare BMT
  - Lambda Polarization

Audrey Francisco

- sPhenix :
  - Micromegas P.I.
  - π^0 asymmetry
- EIC :
  - Micromegas
- Hall C (2025) :
  - PoPEx
  - GluToNγ

Pierre Chatagnon

- Mainly CLAS12 (2025) :
  - TCS
  - J/ψ-photoproduction
- EIC (2025)

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Finally, we are very grateful to the referee for their fruitful comments and supportive feedback on our 40-pages long report.

Question 1

- Could maybe the same experimental setup be used to measure also pion electromagnetic or transition form-factors ?

  → In theory : Yes we can use the same setup

  → Pragmatically it would be complicated :
  Extraction of Electromagnetic or transition FF would require to separate the Longitudinal and transverse term in the deep virtual meson production cross section.

  Currently the systematics associated to normalization are large with CLAS12 and it would represent a significant amount of work to reduce it in order to perform L/T separation.

  For pion EFF, Hall C did several measurements : It gets more statistics and much smaller systematics.

Question 2

- Finally, it is claimed that SoLID might make CLAS12 obsolete. Is this a general statement or will the proposed experiments, if approved, prolong the relevance of CLAS12 ?

→ Currently CLAS12 is currently the perfect experimental setup for :
- Polarized target experiments.
- More than « 3-required-particle final state » processes.
  (DVCS is 2 but phi-/rho-electroproduction and Sullivan DVCS is 3)

But CLAS12 is currently limited to 75nA (may reach 300nA in a midterm future)

→ SoLID would run 50-80 µA with a full forward acceptance :
- Consequently more than « 3-required-particle final state » processes will be easier/faster to study.

→ Therefore CLAS12 may be restricted to low beam current experiments.