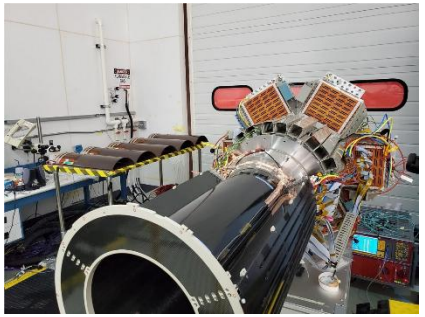
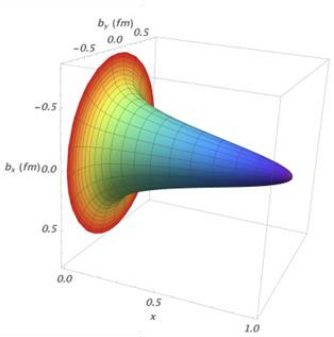
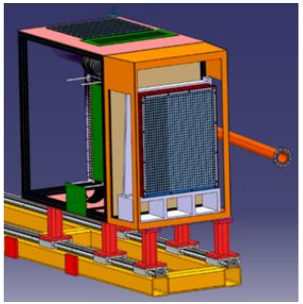
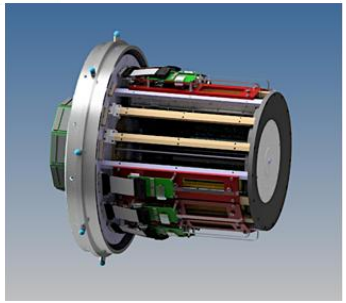
French activities at Jefferson Lab supported by PROBES





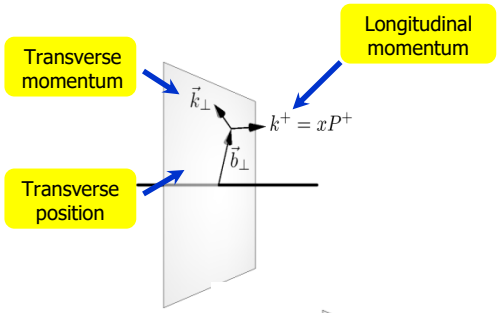


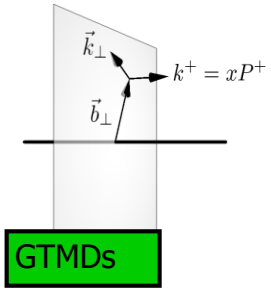


S. Niccolai, IJCLab (France)

PROBES Annual Meeting
Pisa (Italia) 28/11/2025

Multi-dimensional mapping of the nucleon



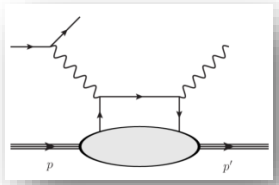


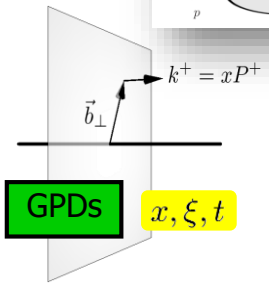
$x, \xi, k_\perp^2, \vec{k}_\perp \cdot \vec{\Delta}_\perp, t$

$\int \mathrm{d}^2\vec{k}_\perp$

$\int \mathrm{d}^2\vec{b}_\perp$

DVCS et al.



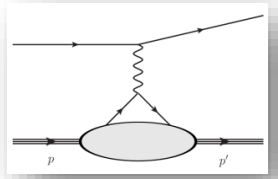


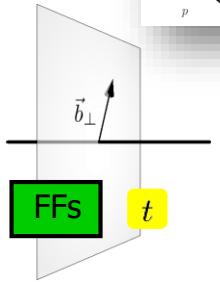
x, ξ, t

$\int \mathrm{d}x$

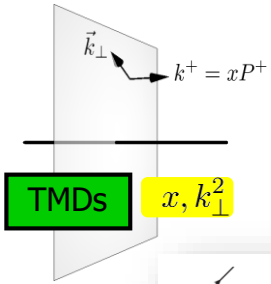
$\int \mathrm{d}^2\vec{b}_\perp$

Elastic Scattering



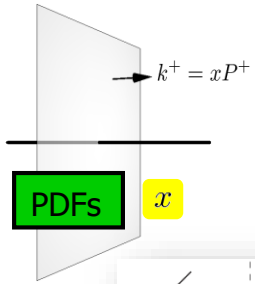


t



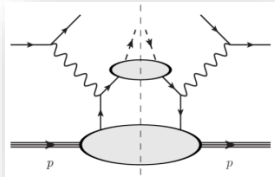
$x, k_\perp^2$

$\int \mathrm{d}^2\vec{k}_\perp$

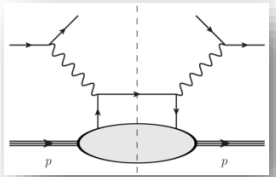


x

SIDIS

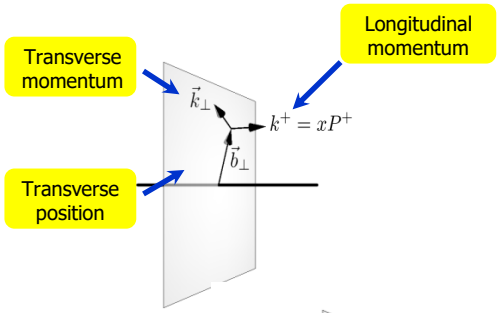


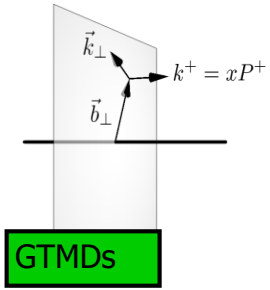
DIS



A complete picture of nucleon structure requires the measurement of all these distributions

Multi-dimensional mapping of the nucleon

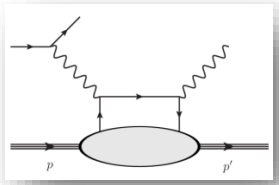


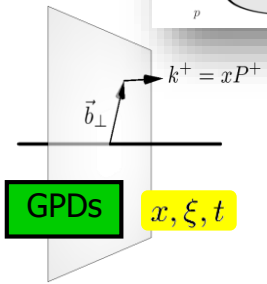


$x, \xi, k_\perp^2, \vec{k}_\perp \cdot \vec{\Delta}_\perp, t$

$\int \mathrm{d}^2\vec{k}_\perp$

DVCS et al.



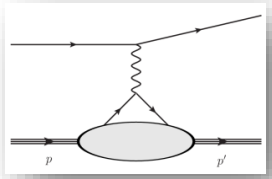


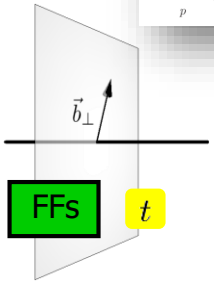
x, ξ, t

$\int \mathrm{d}x$

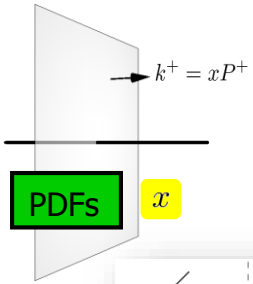
$\int \mathrm{d}^2\vec{b}_\perp$

Elastic Scattering



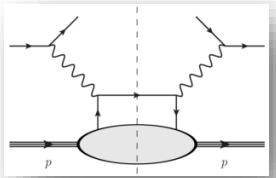


t



x

DIS



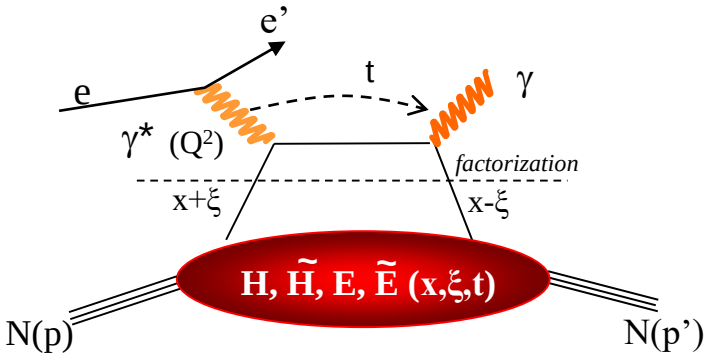
Generalized Parton Distributions:

✓fully correlated parton distributions in both **coordinate** and **longitudinal momentum** space

✓ linked to **FFs** and **PDFs**

✓**Accessible in exclusive reactions**

Deeply Virtual Compton Scattering and quark GPDs



eN→eNγ

- $Q^2 = -(k-k')^2$
- $x_B = Q^2/2M\nu$ $n=E_e-E_{e'}$
- $x+\xi$, $x-\xi$ long. mom. fract.
- $t = \Delta^2 = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$

At leading order QCD, twist 2, chiral-even (quark helicity is conserved), quark sector
→ **4 GPDs for each quark flavor**

Quark angular momentum (Ji's sum rule)

$$\frac{1}{2}\int_{-1}^{1} x dx (H(x,\xi,t=0)+E(x,\xi,t=0)) = J = \frac{1}{2}\Delta\Sigma + \Delta L$$

X. Ji, Phy.Rev.Lett.78,610(1997)

Nucleon spin: $\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + \Delta L}_{J} + \Delta G$

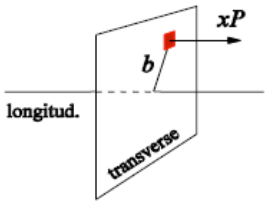
Intrinsic spin of the quarks $\Delta\Sigma \approx 30\%$
Intrinsic spin on the gluons $\Delta G \approx 20\%$
Orbital angular momentum of the quarks ΔL ?

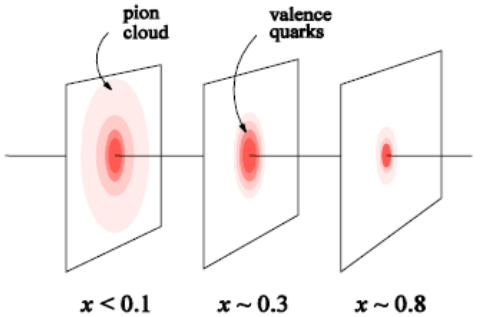
Nucleon tomography

$$q(x,b_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp b_\perp} H(x,0,-\Delta_\perp^2)$$

$$\Delta q(x,b_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp b_\perp} \tilde{H}(x,0,-\Delta_\perp^2)$$

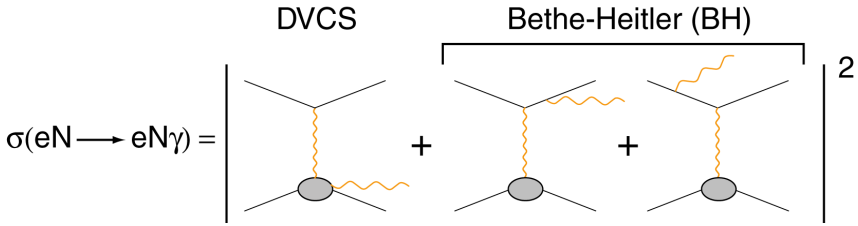
M. Burkardt, PRD 62, 71503 (2000)





Accessing GPDs through DVCS

$$T^{DVCS} \sim P\int_{-1}^{+1} \frac{GPDs(x,\xi,t)}{x \pm \xi} dx \pm i\pi GPDs(\pm\xi,\xi,t) + ..$$



Compton Form Factors (CFF)

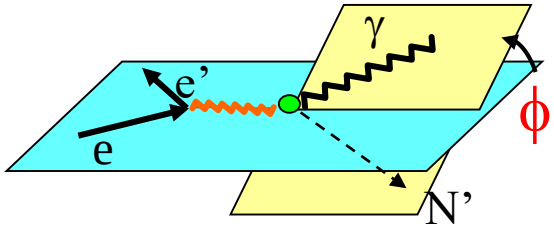
$$Re\mathcal{H}_q = e_q^2 P\int_0^{+1} \left(H^q(x,\xi,t) - H^q(-x,\xi,t)\right)\left[\frac{1}{\xi - x} + \frac{1}{\xi + x}\right] dx$$

$$Im\mathcal{H}_q = \pi e_q^2 \left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t)\right]$$

$$\sigma \sim |T^{DVCS} + T^{BH}|^2 \sim Re\ (CFF)$$
$$\Delta\sigma = \sigma^+ - \sigma^- \propto I(DVCS \cdot BH) \sim Im\ (CFF)$$

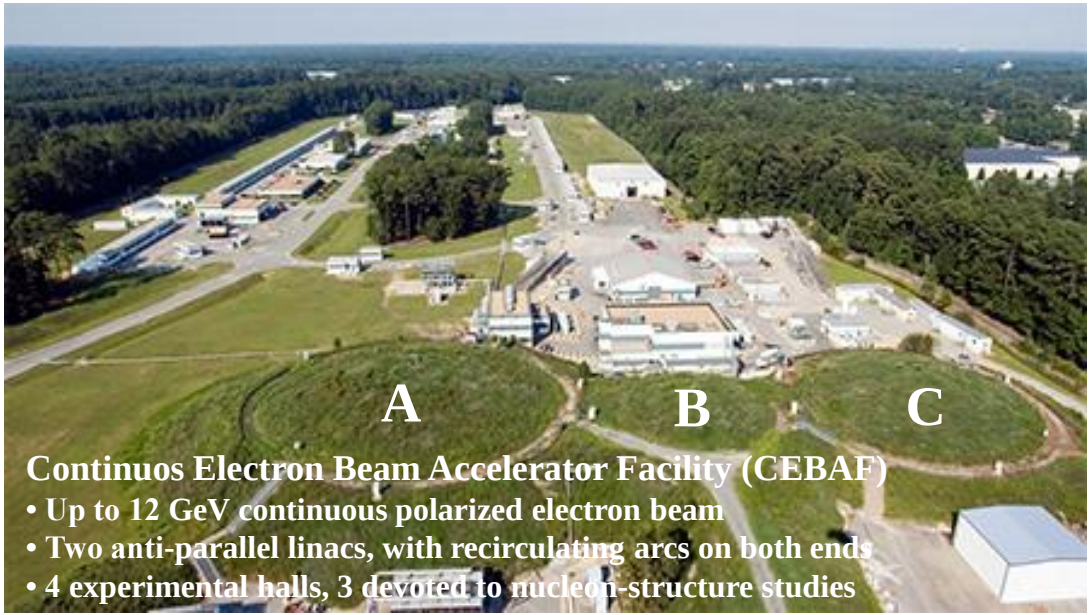
Different spin asymmetries for different targets → different CFFs

Observable	Proton	Neutron
$\Delta\sigma_{LU}$	$\Im\{\boldsymbol{H_p}, \tilde{H}_p, E_p\}$	$\Im\{H_n, \tilde{H}_n, \boldsymbol{E_n}\}$
$\Delta\sigma_{UL}$	$\Im\{\boldsymbol{H_p}, \boldsymbol{\tilde{H}_p}\}$	$\Im\{\boldsymbol{H_n}, E_n\}$
$\Delta\sigma_{LL}$	$\Re\{\boldsymbol{H_p}, \boldsymbol{\tilde{H}_p}\}$	$\Re\{\boldsymbol{H_n}, E_n\}$
$\Delta\sigma_{UT}$	$\Im\{\boldsymbol{H_p}, \boldsymbol{E_p}\}$	$\Im\{\boldsymbol{H_n}\}$



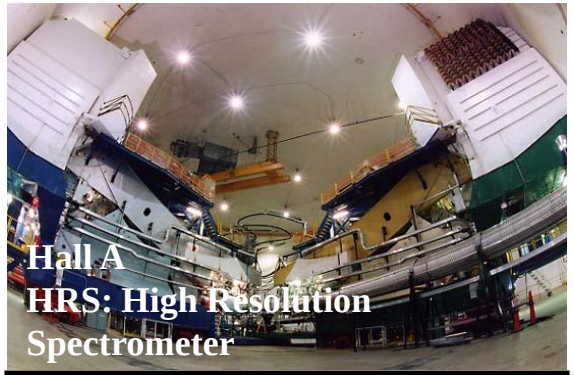
- **Different nucleon → different sensitivity to quark GPDs**
- **Proton + neutron DVCS → flavor separation of GPDs**

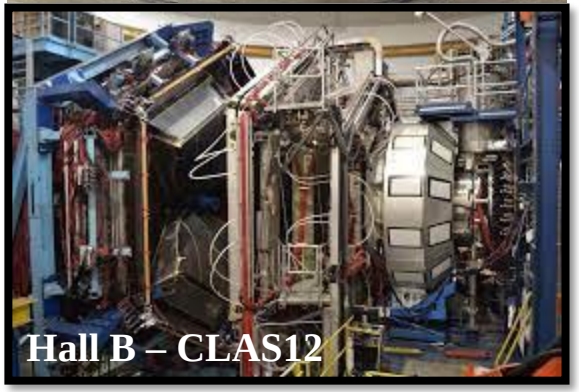
Jefferson Lab at 12 GeV



Continuos Electron Beam Accelerator Facility (CEBAF)

- **Up to 12 GeV continuous polarized electron beam**
- **Two anti-parallel linacs, with recirculating arcs on both ends**
- **4 experimental halls, 3 devoted to nucleon-structure studies**





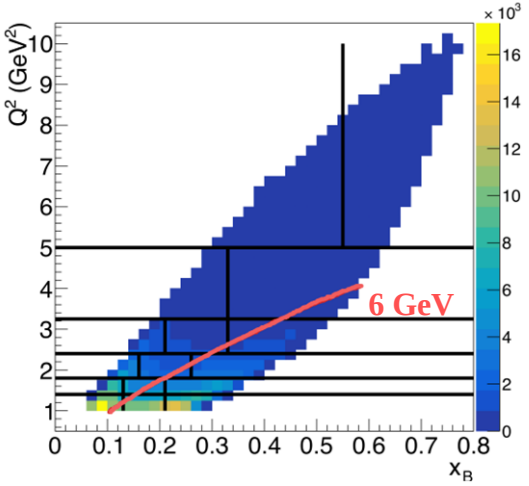
Complementarity of the setups in the Halls A/C and B

- Hall A/C: high luminosity → precision, small kinematic coverage, eγ topology
- Hall B (CLAS12): lower luminosity, large kinematic coverage, fully exclusive final state

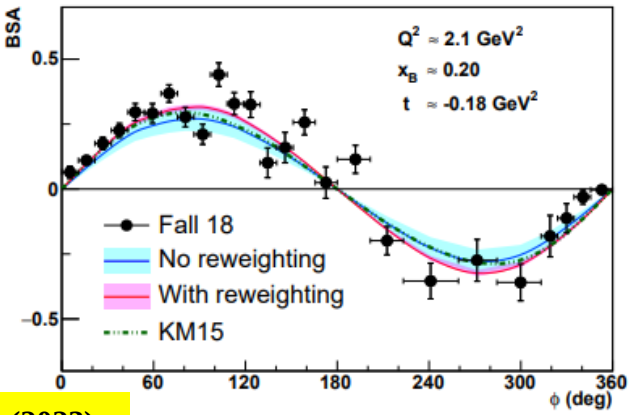
An extensive experimental program focused on DVCS and GPDs is underway

CLAS12: beam spin asymmetry for DVCS on the proton

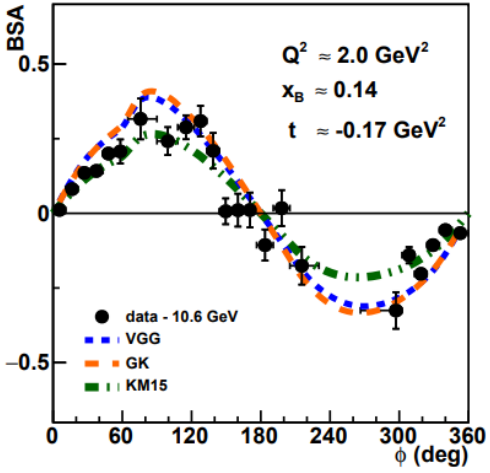
$\vec{e}p \rightarrow epγ$

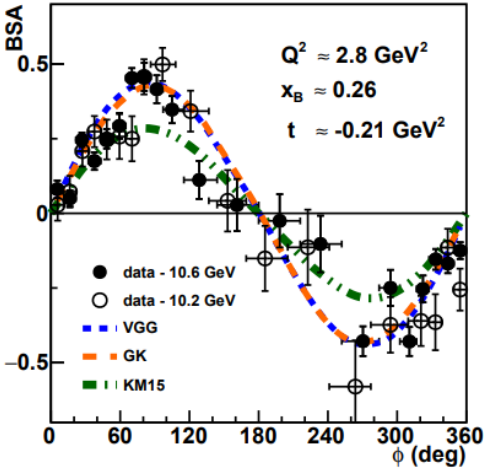


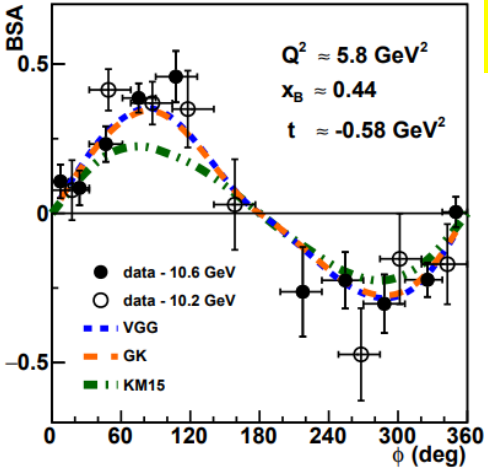
- Polarized beam (86%) with energy 10.6 GeV
- Unpolarized LH2 target
- 64 kinematical bins (Q^2, x_B, -t)
- Many **kinematics never covered before**
- In **previously measured kinematics**, the new data are in good agreement with existing data and **improve the precision of GPD fits**



G. Christiaens et al. (CLAS), Phys. Rev. Lett. 130 (2023)



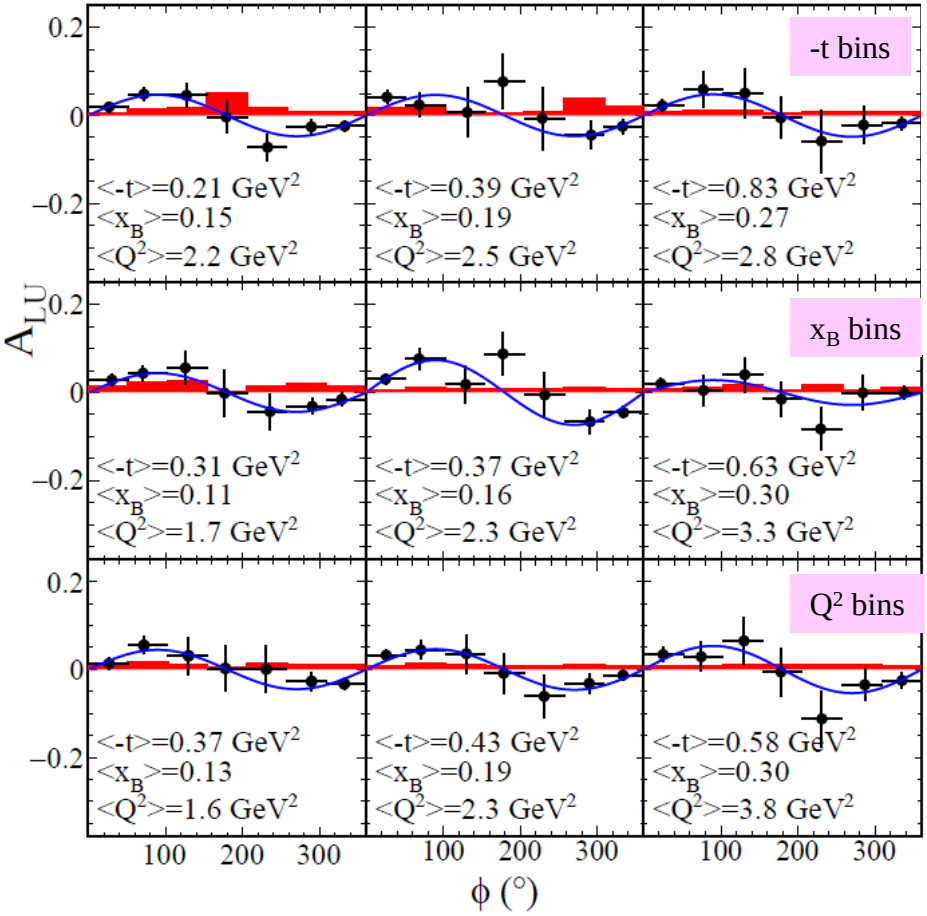


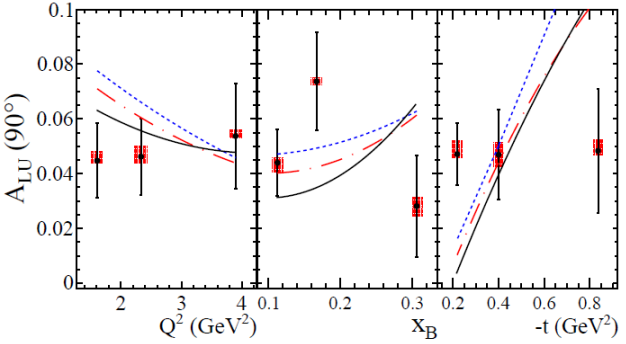


Examples of kinematics only accessible with ~10.6-GeV beam

First-time measurement of BSA for nDVCS with detection of the active neutron at CLAS12

$\vec{e}d \rightarrow en\gamma(p)$

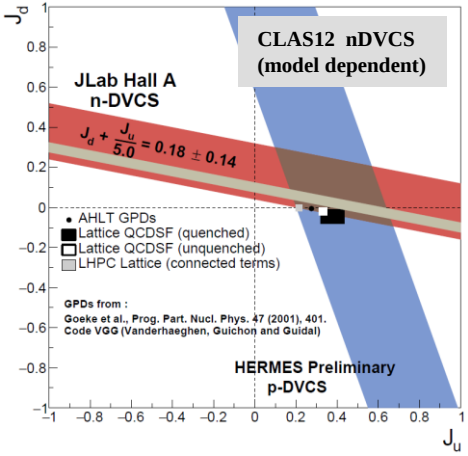




Ju = 0.35 Jd = 0.05
Ju = −0.2 Jd = 0.15
Ju = −0.45 Jd = 0.2
VGG model predictions giving the smallest χ^2

M. Vanderhaeghen, P.A.M. Guichon, and M. Guidal, PRD 60, 094017 (1999)

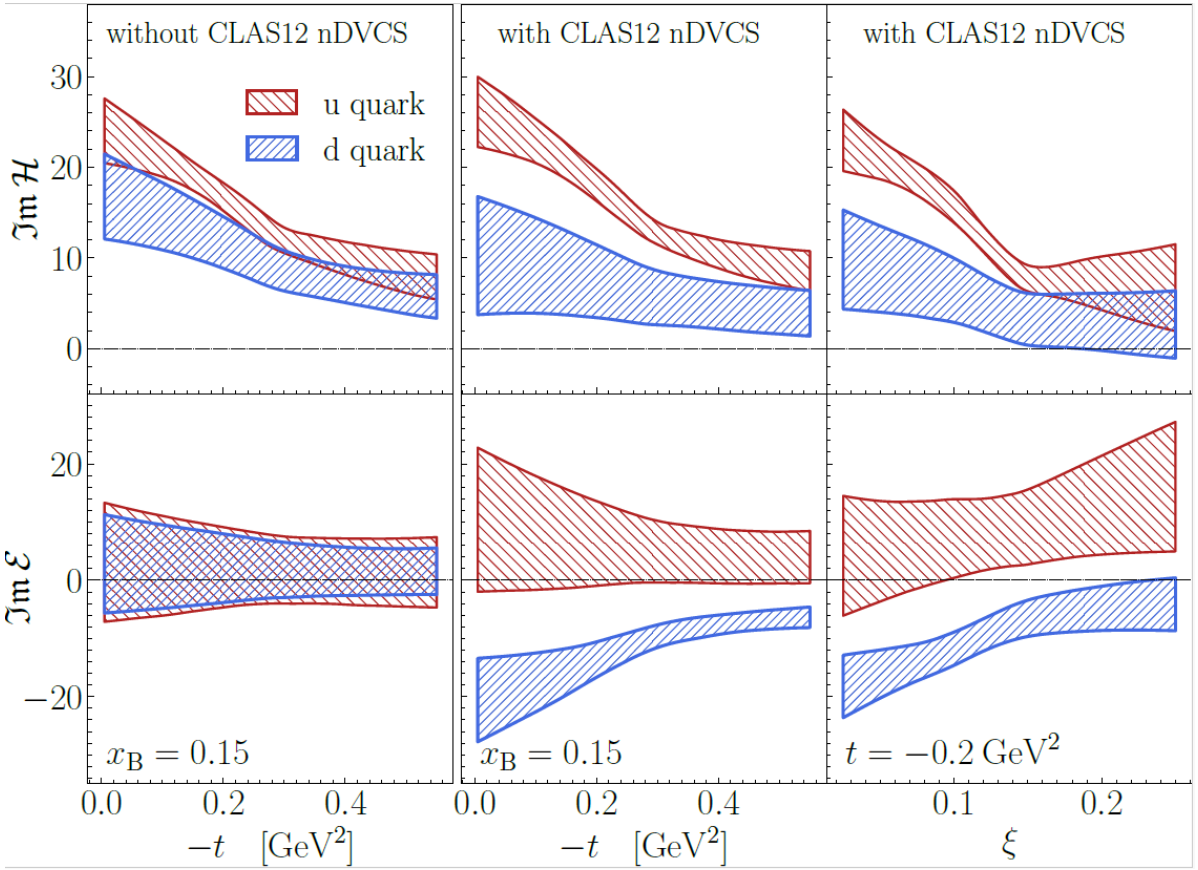
A. Hobart, S.N. et al (CLAS), PRL 133 (2024)



Flavor separation of CFFs using the CLAS12 p,n DVCS data

- **Global fits of CFF** using **neural networks** (**K. Kumericki et al., JHEP 07, 073531 (2011); M. Cuic, K. Kumericki, et al., Phys. Rev. Lett. 533 125, 232005 (2020)**).
- Data used: CLAS6 and HERMES pDVCS observables, CLAS12 pDVCS BSA and nDVCS BSA
- Same extraction method applied to nDVCS Hall-A data, only separation for Im$\mathcal{H}$

The CLAS12 nDVCS data allow the quark-flavor separation of both Im$\mathcal{H}$ and Im$\mathcal{E}$

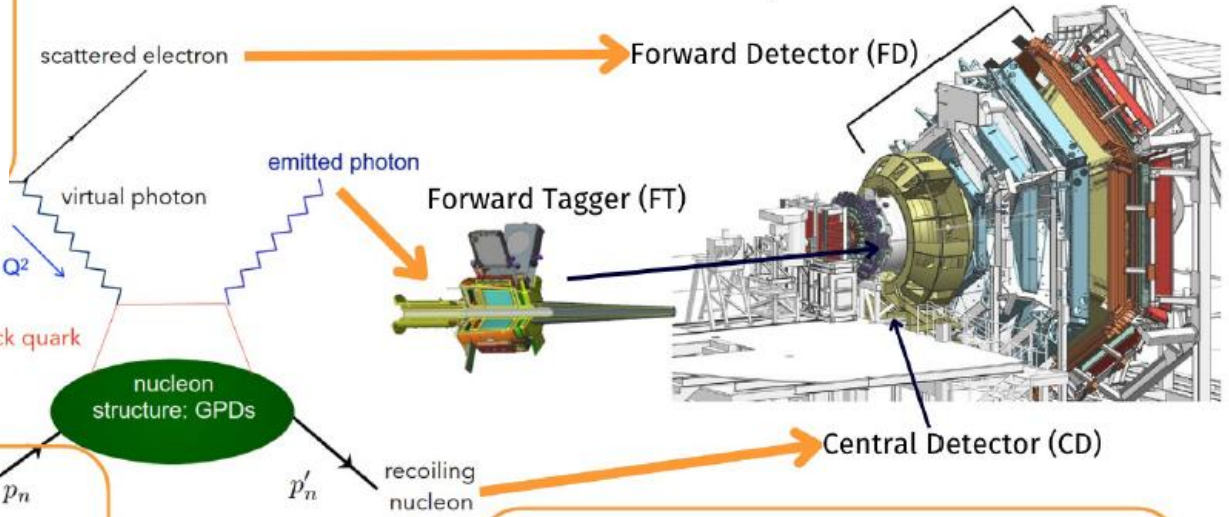


https://physicsworld.com/a/inner-workings-of-the-neutron-illuminated-by-jefferson-lab-experiment/

DVCS with longitudinally polarized NH3 and ND3 targets at CLAS12

CEBAF polarized electron beam

- **Polarization ~84%**
- **Energy 10.5 GeV**



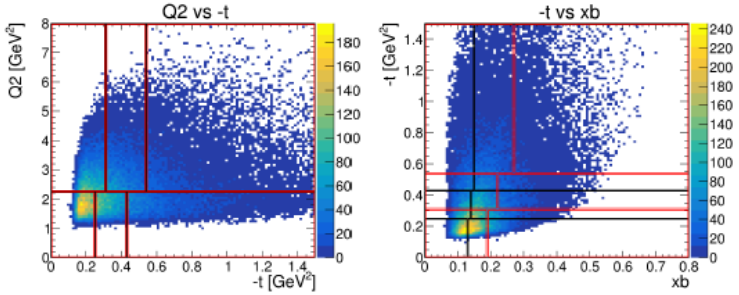
Run Group C experiment at CLAS12

- **Longitudinally polarized target**
- **Ran between June 2022 and March 2023**
- **Approved to run again (~2027) ~ to get 40% more data**

Exclusive final-state detection with CLAS12

- **Scattered electrons in the FD**
- **Nucleons in the CD**
- **Photons in the FD and in the FT**

pDVCS on longitudinally polarized NH3 target: results (TSA)



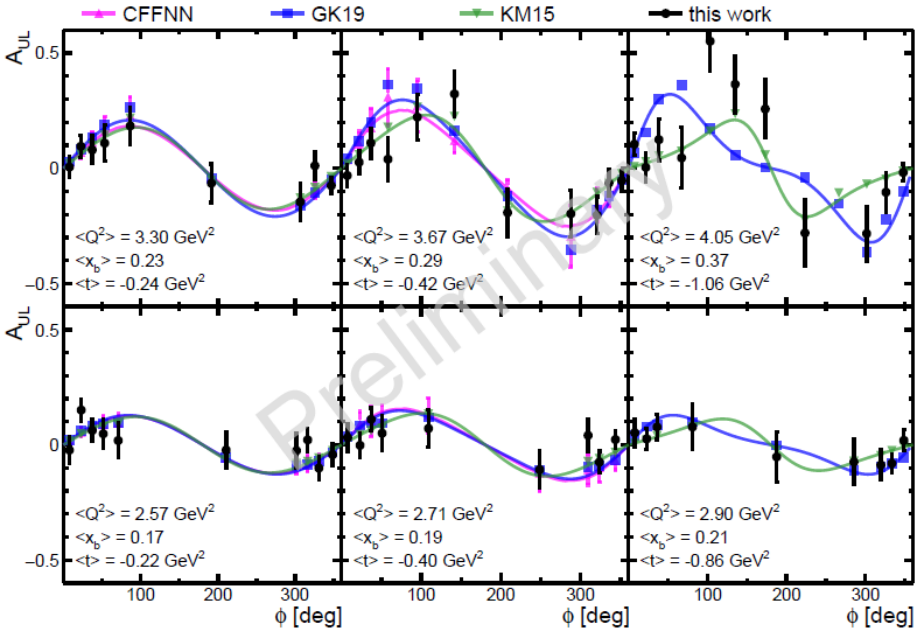
Work by S. Polcher

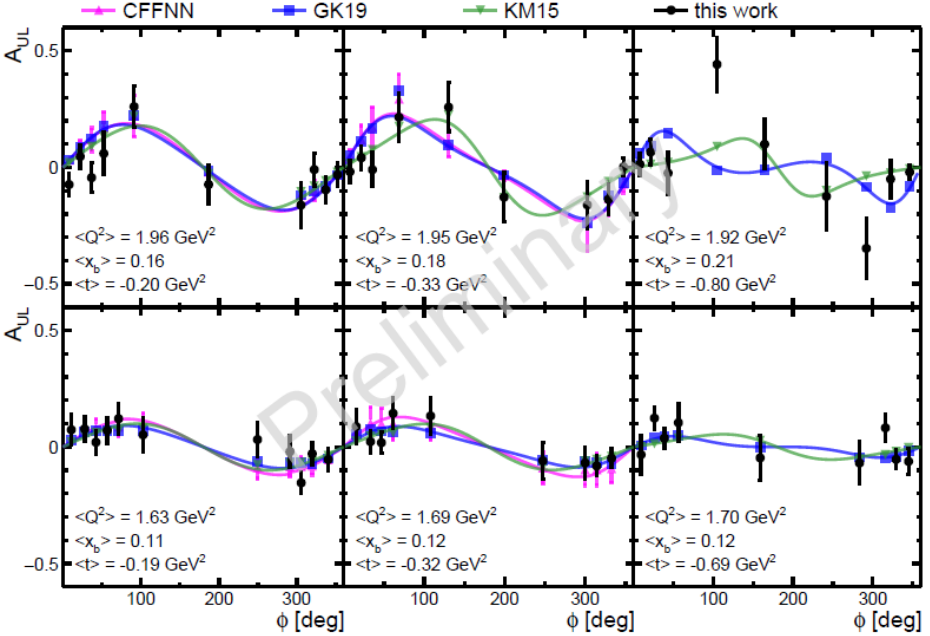
cea

$\vec{e}\vec{p} \to epγ$

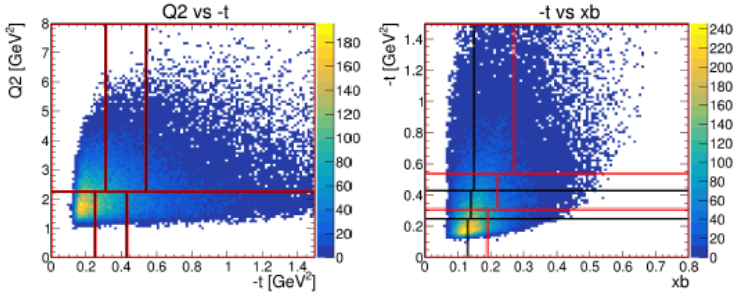
~30% of the collected data

$$\Delta\sigma_{UL} \sim \sin\phi\ \mathbf{Im}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi k F_2\,\tilde{\mathcal{E}} + \ldots\}$$





pDVCS on longitudinally polarized NH3 target: results (DSA)

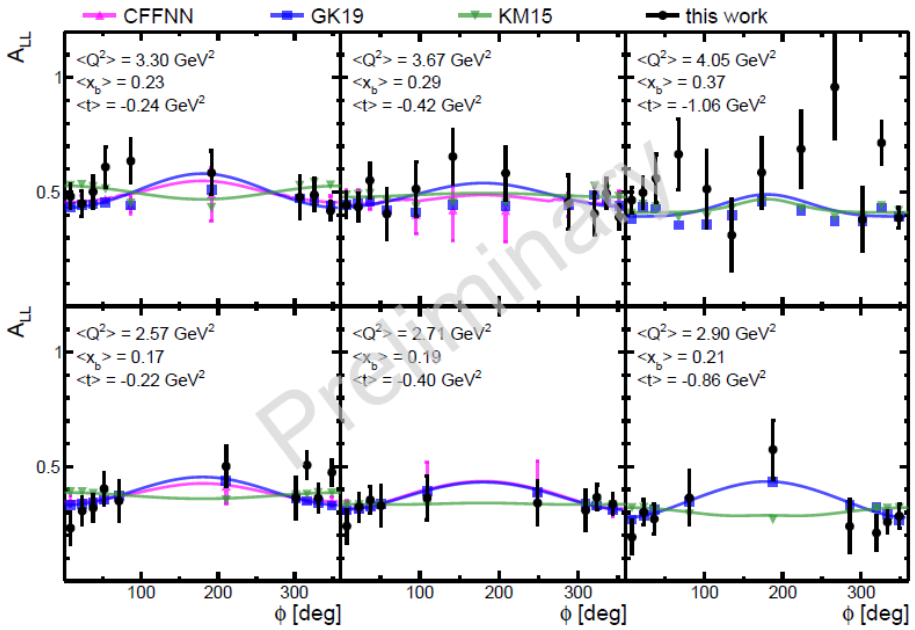


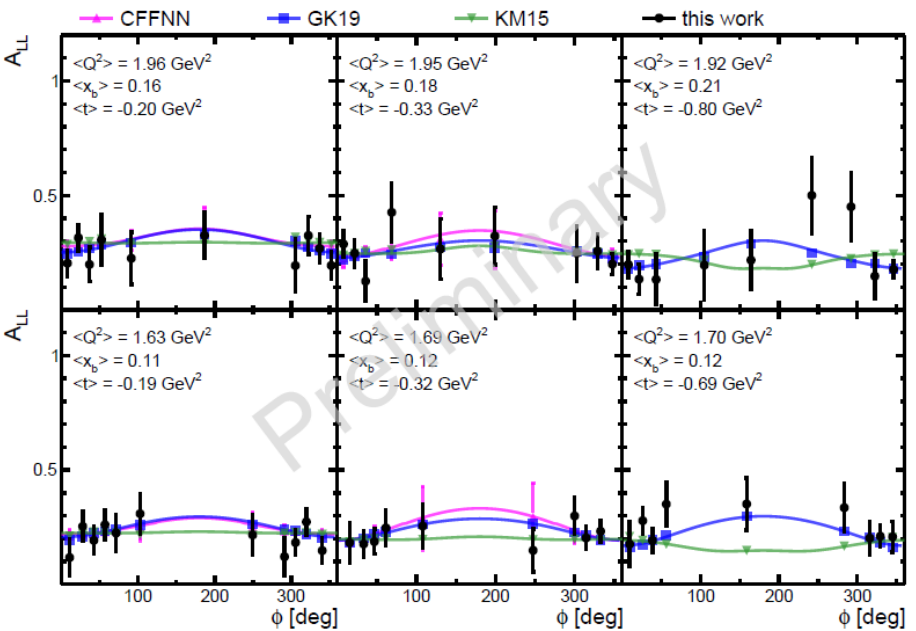
Work by S. Polcher

~30% of the collected data

$\vec{e}\vec{p} \to ep\gamma$

$$\Delta\sigma_{LL} \sim (A+B\cos\phi)\ \mathbf{Re}\{F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H}+x_B/2\mathcal{E})-\xi kF_2\,\tilde{\mathcal{E}}+\ldots\}$$

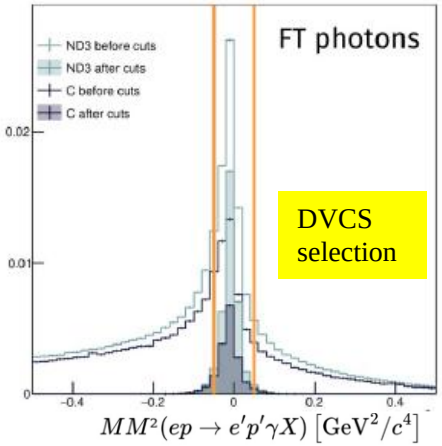


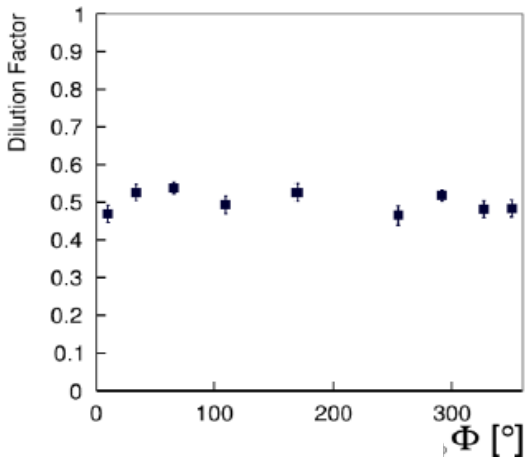


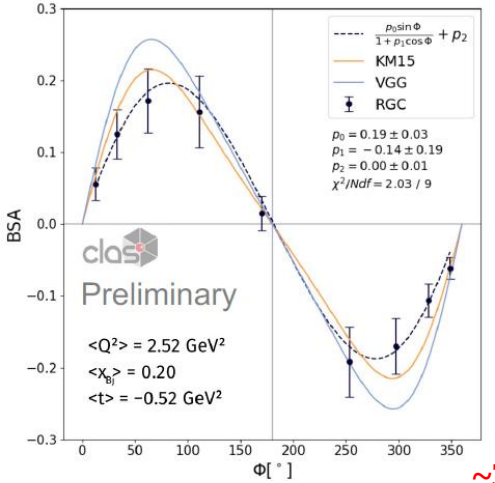
Work by N. Pilleux

pDVCS on longitudinally polarized ND3 target

$\vec{e}\vec{d} \rightarrow ep\gamma(n)$



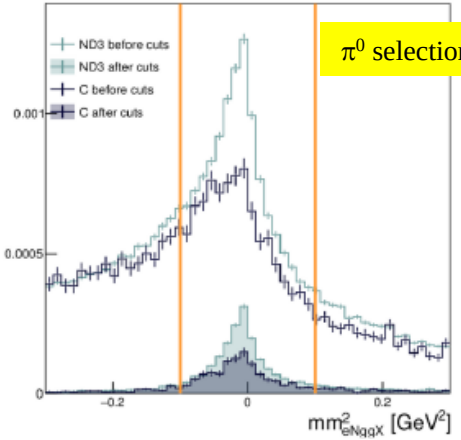


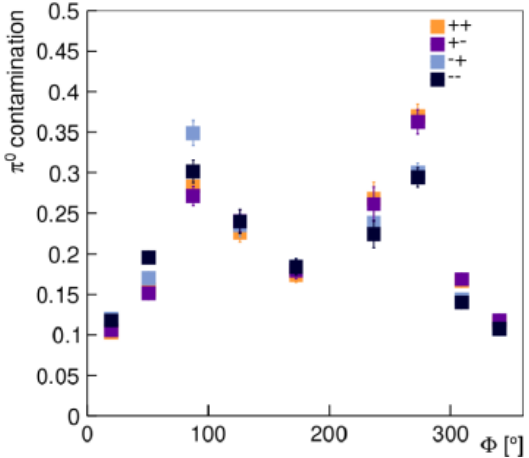


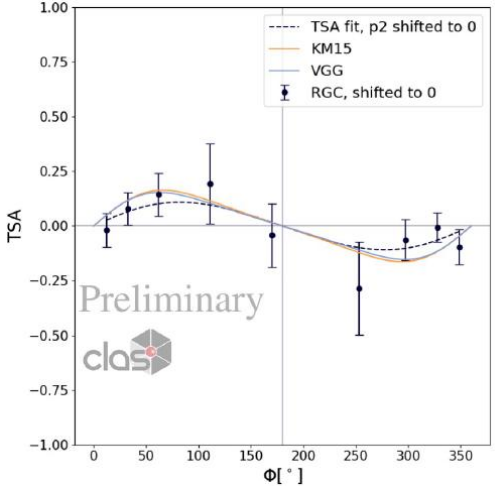
BSA does not account for the N background

- Dilution factor is 50%: contribution from bound protons in N must be considered

~30% of the collected data







Very preliminary **TSA**

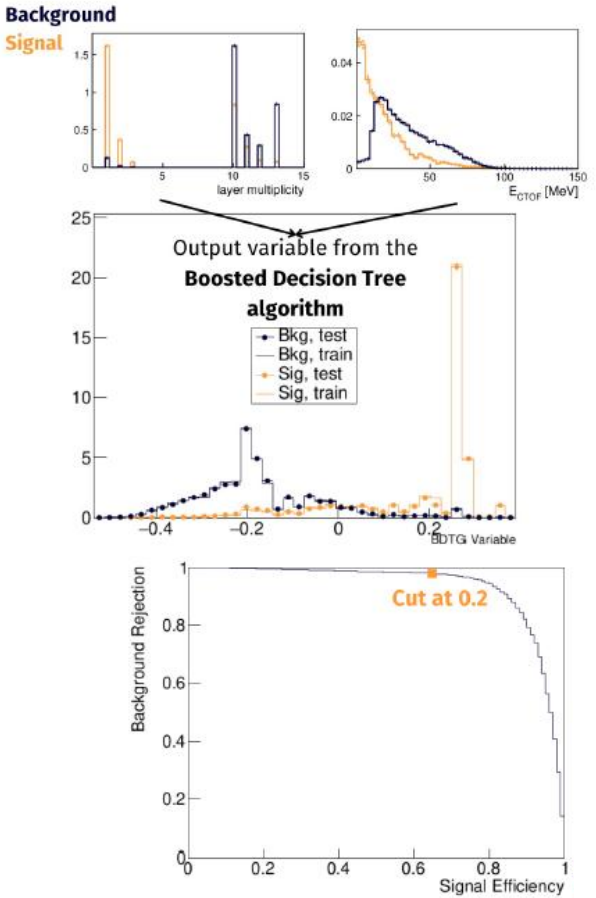
- Shift under study
- Fairly good agreement with models for free proton

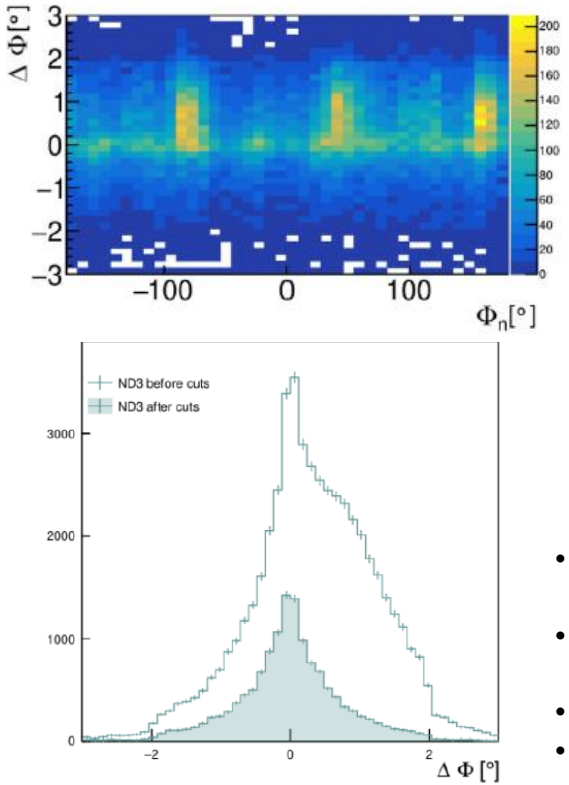
Work by N. Pilleux

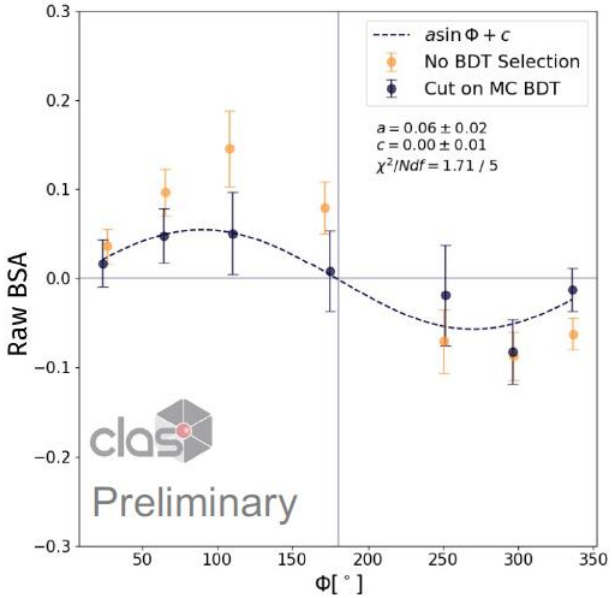
nDVCS on longitudinally polarized ND3 target

$\vec{e}\vec{d}\rightarrow en\gamma(p)$

Contamination from **protons misidentified as neutrons** – suppressed using **ML**





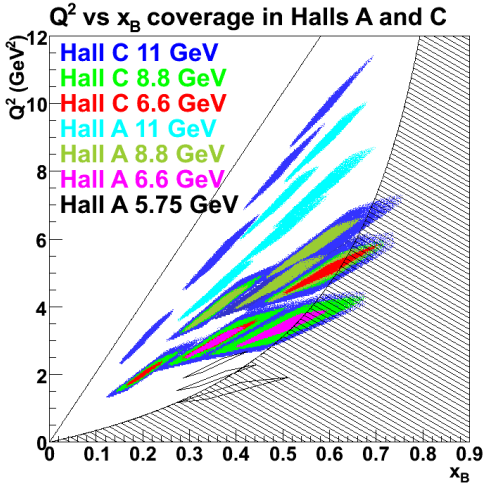


- **Expected shape** for the **raw BSA** (π^0 background not subtracted)
- **Agreement with nDVCS BSA** on unpolarized deuterium, Hobart et al. (CLAS), PRL 133 (2024)
- Insufficient statistics for TSA and DSA for now
- The remainder of the dataset needs to be analyzed

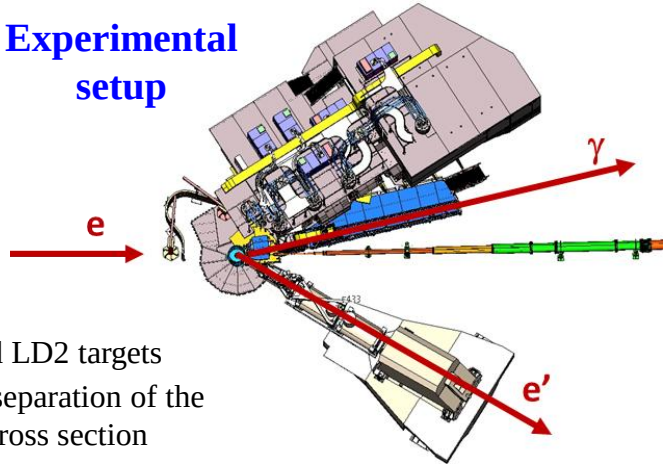
~30% of the collected data

NPS experiment in Hall C

$\vec{e}p \rightarrow e\gamma(p)$

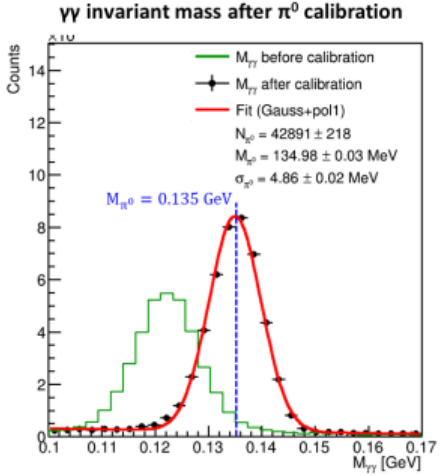


Experimental setup



- LH2 and LD2 targets
- Energy separation of the DVCS cross section
- Low x_B coverage

Energy calibration of the NPS calorimeter



NPS –Neutral Particle Spectrometer

Mechanical design and construction of the calorimeter support structure at IJCLab

NIM paper on the performances of NPS submitted

Intrinsic Energy and Time Resolution of the Jefferson Lab Hall C Neutral Particle Spectrometer

W. Hamdi [a], J. Crafts[b], H. Huang[c], Z. Huang[d], M. Kerver[e], M. Mathison[f], C. Ploen[e], A. Singh[b], T. Song[g], Y. Zhang[h], D. Adhikari[i], A. Ahmed[ae], H. Albataineh[j], K. Aniol[k], J. Arrington[l], A. Asaturyan[m], C. Ayerbe Gayoso[e], P. Bosted[n], E. Brash[n],

- Energy resolution 1.25% (at 4-7 GeV)
- Time resolution <100 ps (>1 GeV)

Thesis ongoing at IJClab: preliminairy results in one year

A Low Energy Recoil Tracker (ALERT) for CLAS12

Physics program exploring nucleaireffects on PDFs and GPDs :

- Coherent and incoherent DVCS on nuclei
- Partonic structure on nuclei
- « tagged EMC effect »

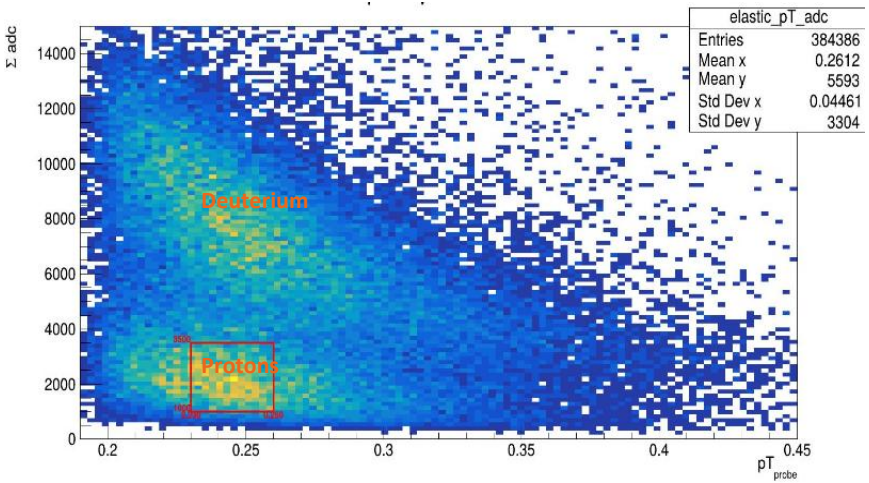
Design: Compact drift chamber (IJCLab) + Scintillators (ANL)

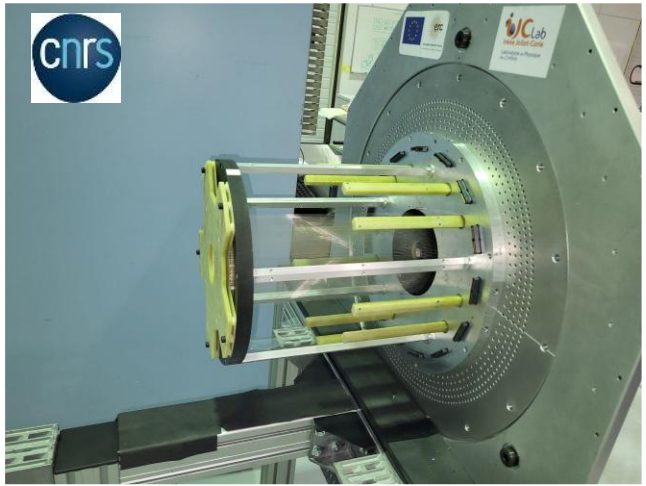
- R&D and design at IJCLab, detector and mechanics
- Partnership with ANL and other US institutions

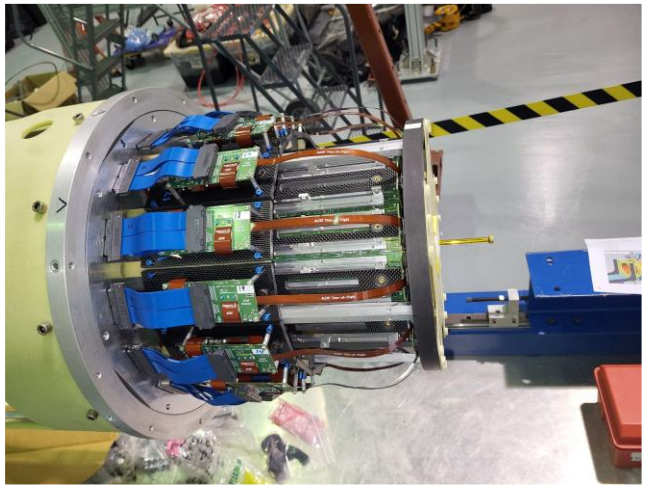
2024: construction of the drift chamber and delivery to JLab

2025: ALERT experiment atJLlab:

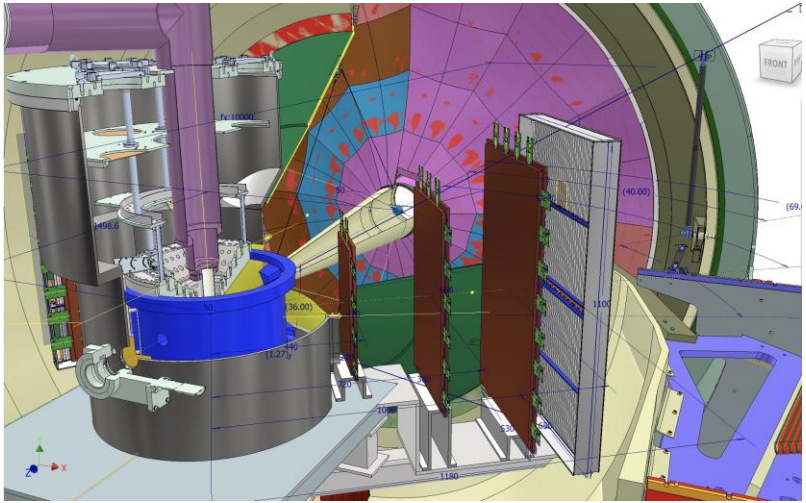
- Commissioning between end 2024 and early 2025
- Data taking April-September 2025
- ALERT data show good quality even before calibration



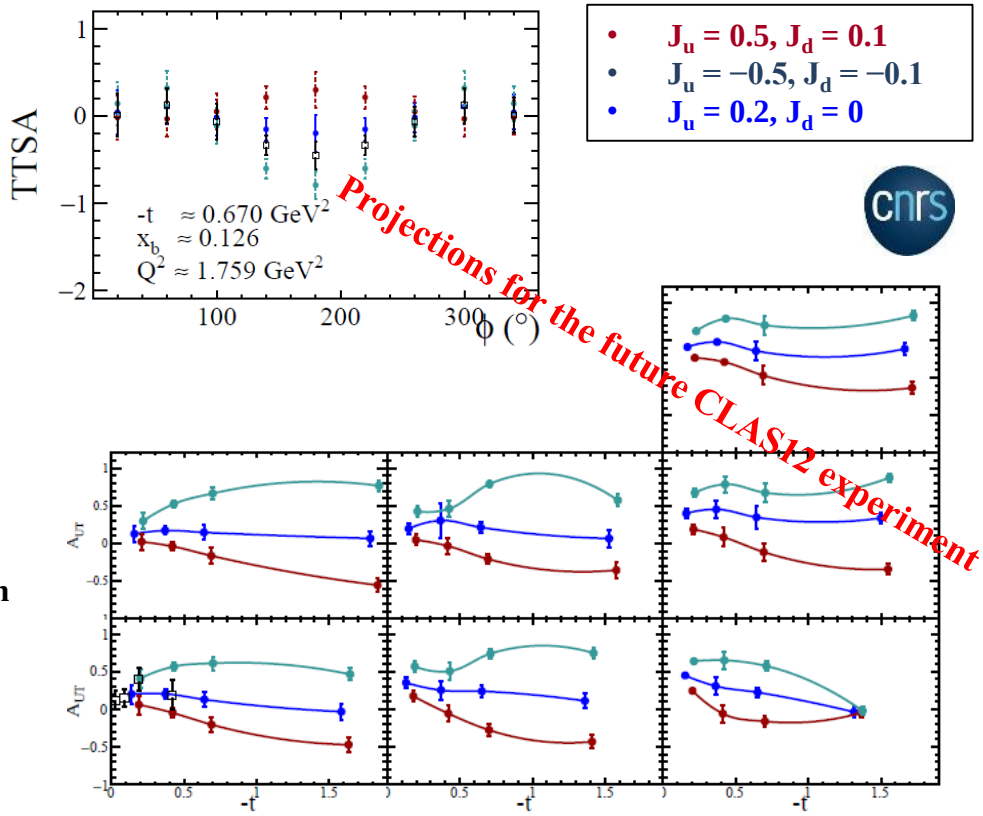




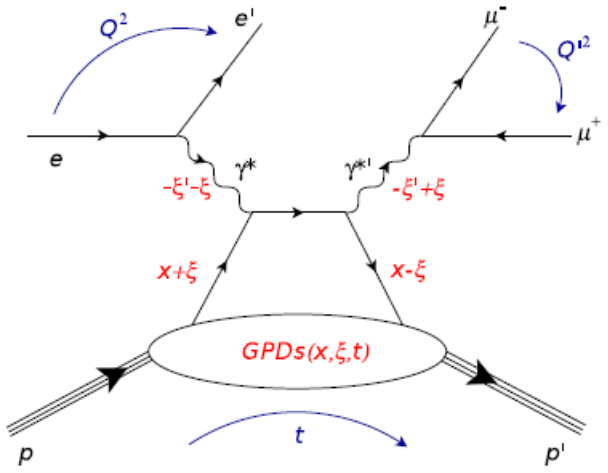
Experiments approved this year: 1) pDVCS with transversely polarized target at CLAS12



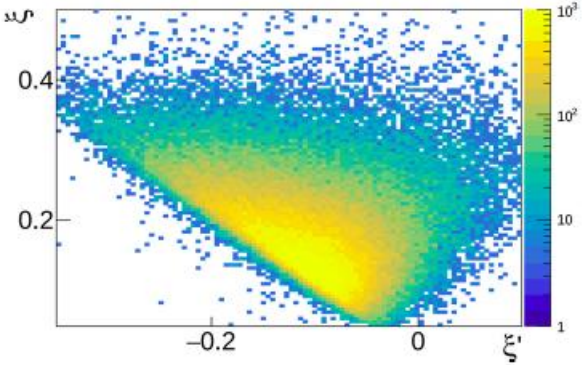
- Measuring pDVCS with a transversally polarized target is **vital to access the GPD E of the proton → quark's angular momentum**
- **Strong contribution** of CNRS team to the proposal
- Experiment **approved** by the latest PAC of JLab
- A new magnet is being designed
- A **recoil detector** to compensate the loss of acceptance due to the new magnet is being developed, in collaboration with INFN and Duke
- Experiment foreseen for ~2030

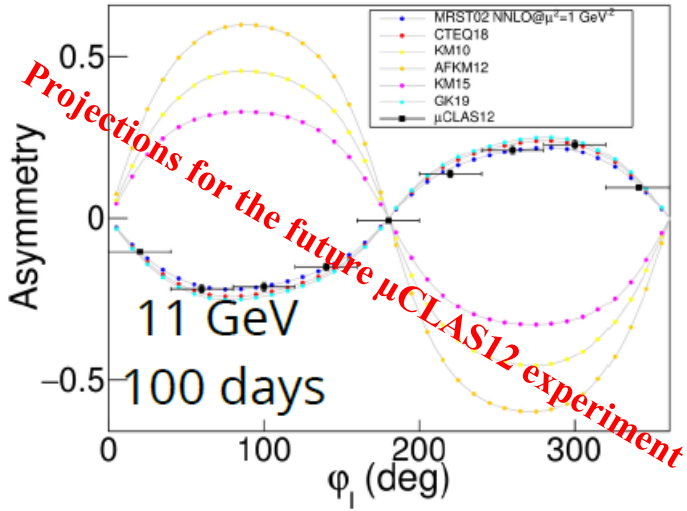


Experiments approved this year: 2) Double DVCS with μCLAS12



J.S. Alvarado, M. Hoballah, E. Voutier, PRC 111 6, 065205 (2025)





Thanks to the final photon virtuality, Q'², **DDVCS** gives a unique access access to GPDs at **$x \neq \pm\xi$**, which is necessary to model them

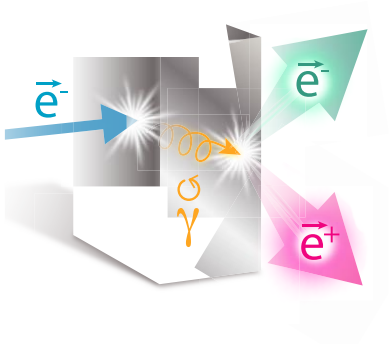
$$\mathcal{H}_{\mathrm{DDVCS}}(\xi',\xi,t) = \int_{-1}^{1} dx H(x,\xi,t)\left(\frac{1}{\xi'-x-i\epsilon} - \frac{1}{\xi'+x-i\epsilon}\right)$$
$$\mathrm{Im}\,\mathcal{H}_{\mathrm{DDVCS}}(\xi',\xi,t) \propto H(\xi',\xi,t) - H(-\xi',\xi,t)$$

Experimental challenges:

- Small cross section (300 times less than DVCS)
- Detection of muons

Conditionally approved experiments (PAC53): μCLAS12 and μSoLID
For μCLAS12: $ep \rightarrow e'p'\mu^+\mu^-$ $L \sim 10^{37}$ cm^{-2}s^{-1}
New tracker, calorimeter, shielding

Ce$^+$BAF : polarized positron beam for CEBAF@JLab



JLab PAC51/52/53 (2023-2025) **approved the three pillars of an experimental program** with **polarized positrons beam at JLab** via 7 experiment proposals covering these fields:

- Multi-photons exchange machanisms;
- GPDs (2 proposals from our team);
- Tests of the Standard Model.

471 days of approved beam time, with high scientific rating.

PhD of S. Habet, UPS, IJCLab/JLab (defended on 4/12/23)

Activities	Fiscal Year																		
	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Moller (MIE, 413.3B, CD-2/3)																			
SoLID (LRP, Rec 4)																			
Positron Source (R&D)																			
CEBAF Upgrade preCDR/preplan																			
Positron Project (potential)																			
Transport e+																			
22 GeV Development (R&D)																			
22 GeV Project (potential)																			
EIC Project (V4.2, CD-1, CD-3A)																			
CEBAF Up																			

- The **validation of the technologies** (polarises electrons source, production target, etc.) will be carried out during the next two years.
- The project advances towards the preparation of a **pre-CDR.**

Conclusions

The CNRS and CEA teams are very active in the study of nucleon structure at JLab, mainly via measurements of DVCS to access Generalized Parton Distributions.

The secondments at JLab of the CNRS and CEA teams supported by PROBES were very fruitful and contributed to several crucial aspects of our research:

- Completion of data analyses: publication of BSA for pDVCS, nDVCS
- Maintenance of existing detectors (MicroMegas, CND)
- Completion of detector projects: NPS, ALERT
- Data takings: Run Group C, NPS, ALERT
- Progress in ongoing analyses: longitudinal p-nDVCS asymmetries, nDVCS cross section, TMDs in nuclei, …
- Preparation of future experiments: transverse pDVCS, Double-DVCS, positron beam