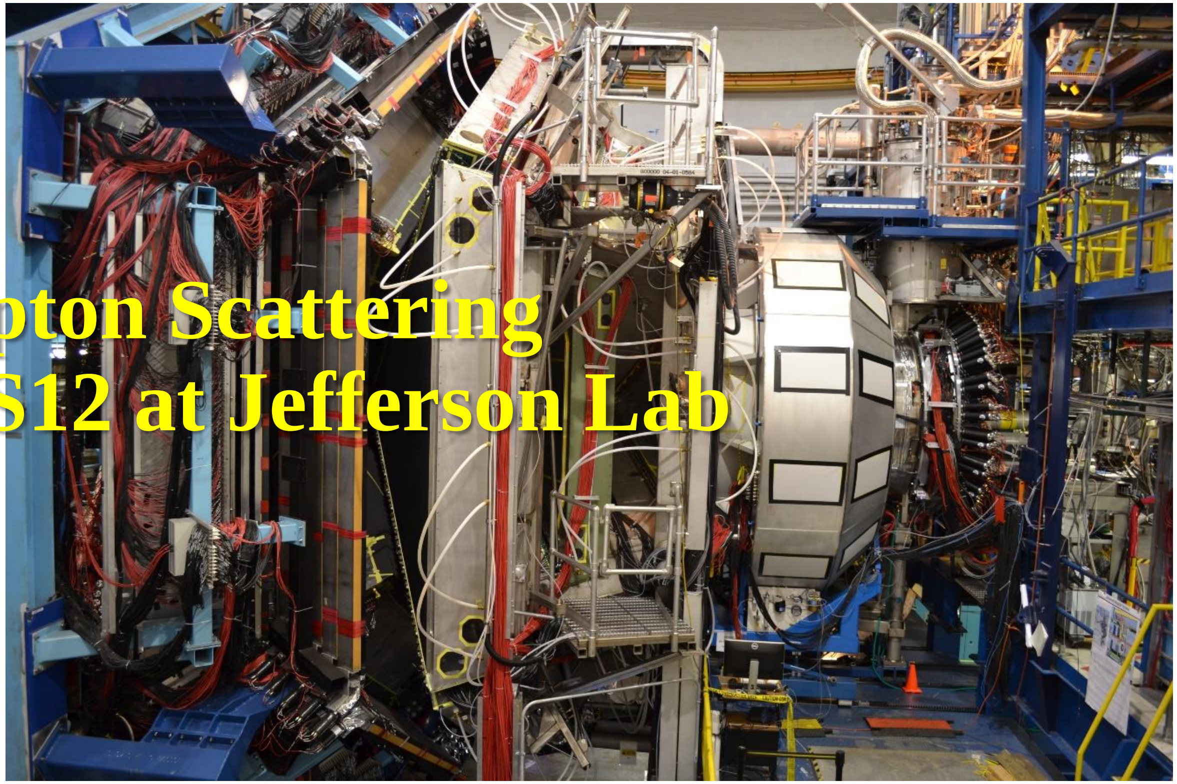


Deeply Virtual Compton Scattering on the neutron with CLAS12 at Jefferson Lab

Silvia Niccolai (IJCLab Orsay), for the CLAS Collaboration

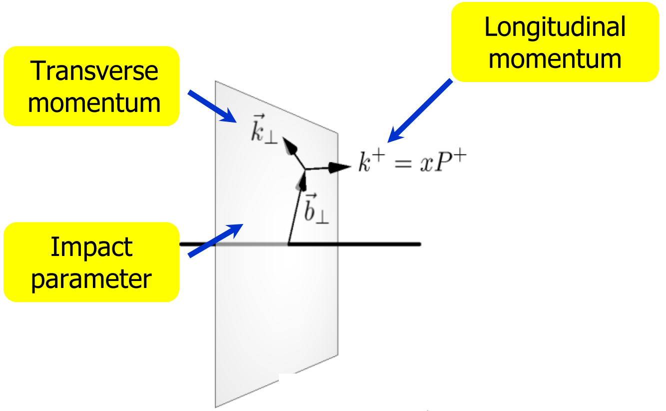
NSTAR 2024, York (UK), 17/6/2024

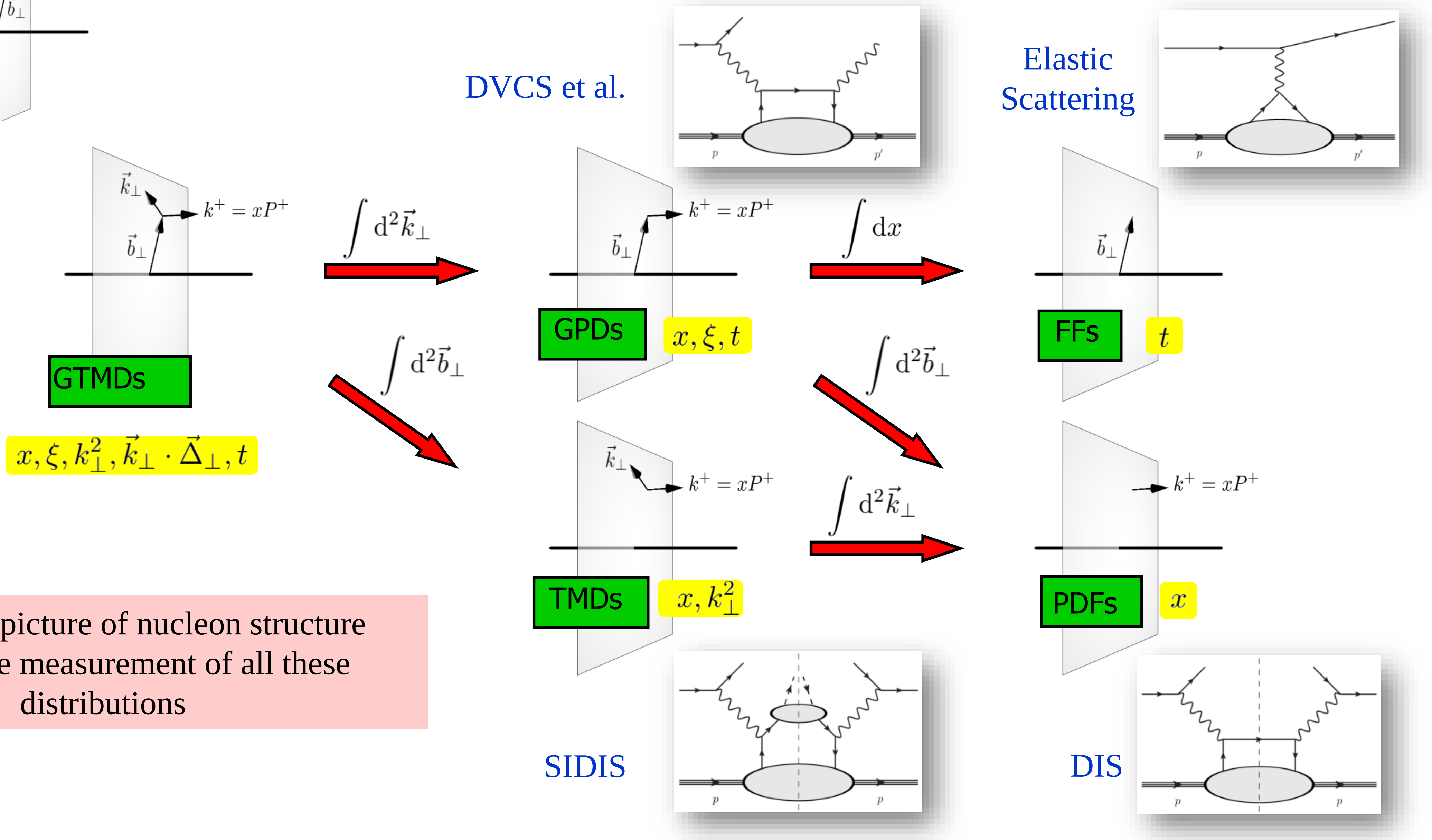
Analysis done by Adam Hobart (IJCLab)

CEBAF Large Acceptance Spectrometer

Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

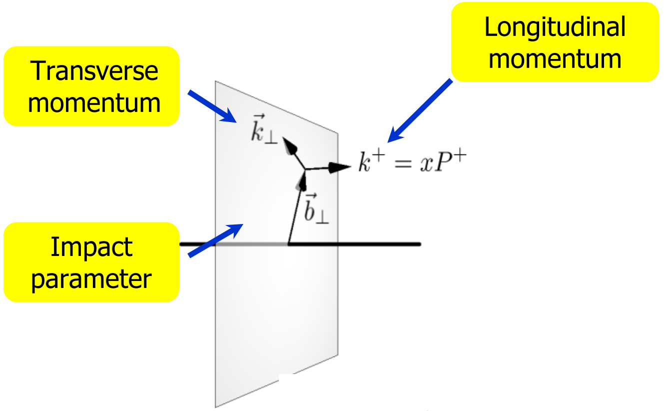
Multi-dimensional mapping of the nucleon

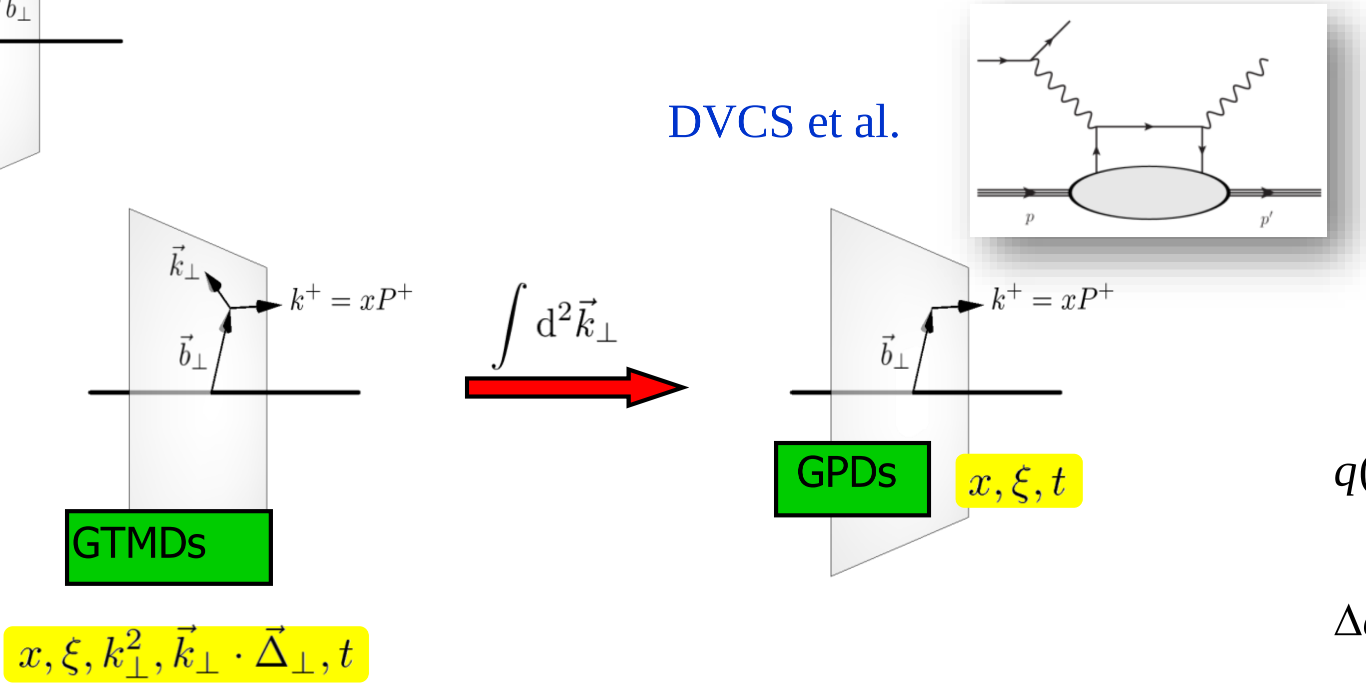




A complete picture of nucleon structure requires the measurement of all these distributions

Multi-dimensional mapping of the nucleon





Nucleon tomography

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

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

Generalized Parton Distributions:

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

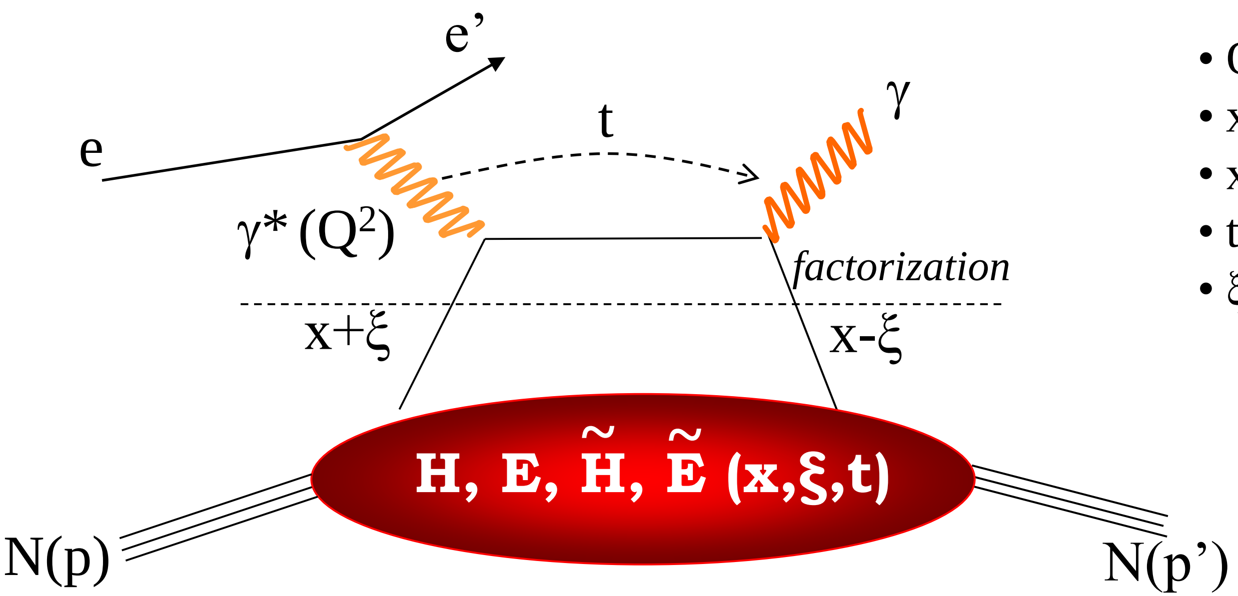
✓ linked to **FFs** and **PDFs**

✓**Accessible in exclusive reactions**

Quark angular momentum (Ji's sum rule)

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

Deeply Virtual Compton Scattering and GPDs



- $Q^2 = -(e-e')^2$
- $x_B = Q^2/2M\nu \quad \nu = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ longitudinal momentum fractions
- $t = \Delta^2 = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$

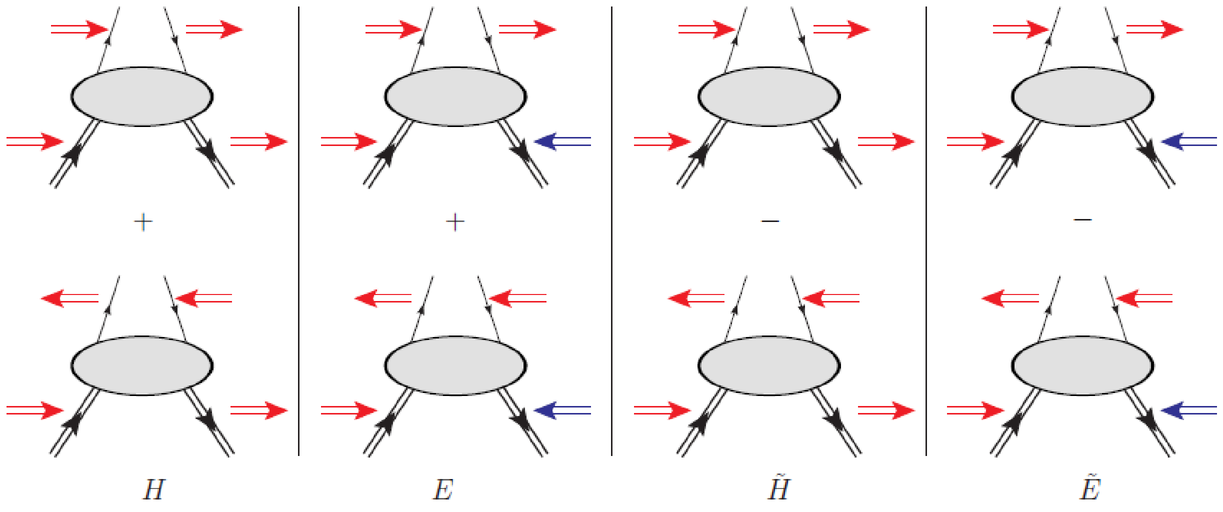
« **Handbag** » factorization, valid in the **Bjorken regime** (**high Q^2** and **ν**, fixed x_B), **$t \ll Q^2$**

*GPDs: Fourier transforms of **non-local**, **non-diagonal** QCD operators*

4 GPDs for each quark flavor
(leading-order, leading twist, quark-helicity conservation)

conserve nucleon spin

flip nucleon spin



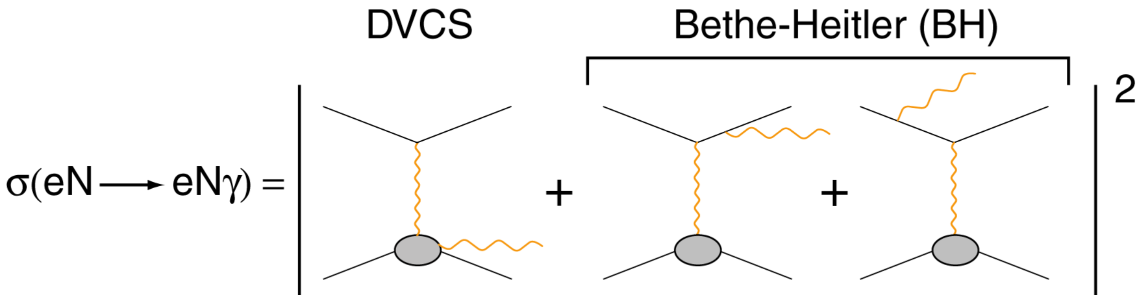
Vector **Tensor** **Axial-vector** **Ps.scalar**

Accessing GPDs through DVCS

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

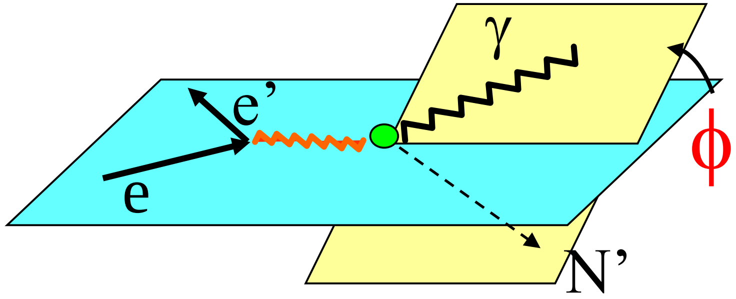
$$Re\mathcal{H}_q = e_q^2 P\int_0^{+1}\left(H^q(x,\xi,t) - H^q(-x,\xi,t)\right)\left[\frac{1}{\xi - x} + \frac{1}{\xi + x}\right]dx$$

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



$$\sigma \sim \left|T^{DVCS} + T^{BH}\right|^2$$

$$\Delta\sigma = \sigma^+ - \sigma^- \propto I\left(DVCS \cdot BH\right)$$



Proton Neutron

Polarized beam, unpolarized target:
$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\}$ ⇒ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$, $Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$

Unpolarized beam, longitudinal target:
$\Delta\sigma_{UL} \sim \sin\phi\,\mathrm{Im}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E}) - \xi kF_2\tilde{\mathcal{E}}\}$ ⇒ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$, $Im\{\mathcal{H}_n, \mathcal{E}_n\}$

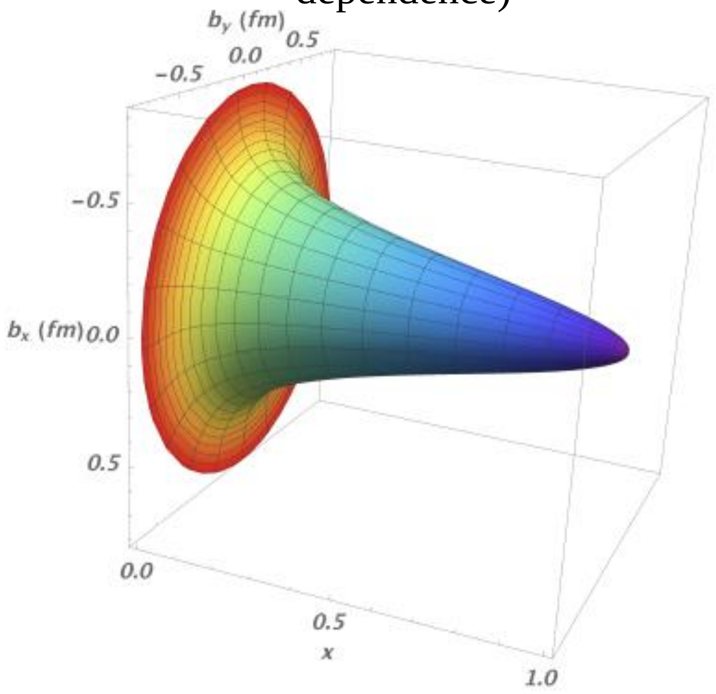
Polarized beam, longitudinal target:
$\Delta\sigma_{LL} \sim (A + B\cos\phi)\mathrm{Re}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E}) + \ldots\}$ ⇒ $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$, $Re\{\mathcal{H}_n, \mathcal{E}_n\}$

Unpolarized beam, transverse target:
$\Delta\sigma_{UT} \sim \cos\phi\sin(\phi_s - \phi)\mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}$ ⇒ $Im\{\mathcal{H}_p, \mathcal{E}_p\}$, $Im\{\mathcal{H}_n\}$

Unpolarized beam and target, different lepton charges:
$\Delta\sigma_C \sim \cos\phi\ \mathrm{Re}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\}$ ⇒ $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$, $Re\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$

What have we learned from the first generation of proton-DVCS results?

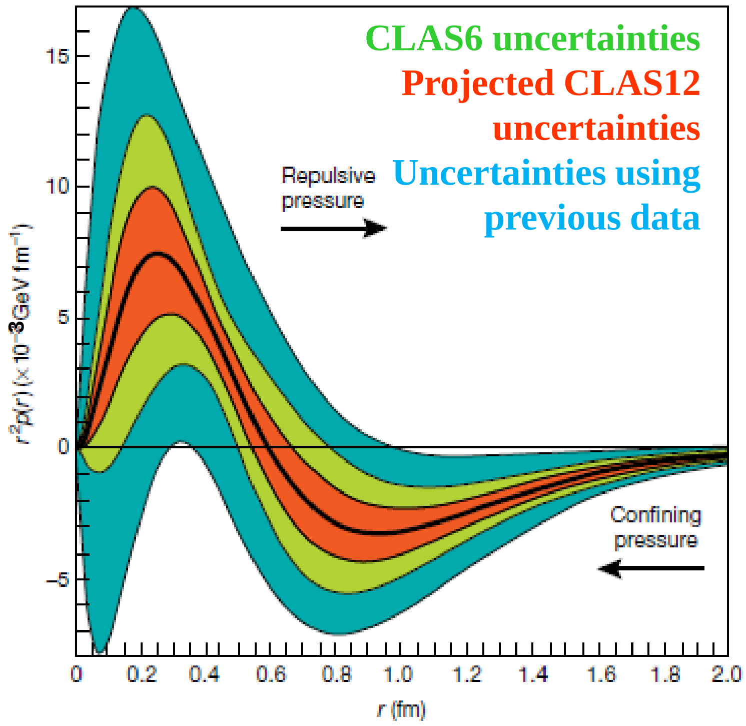
Proton tomography from *local fits* to HERMES, CLAS, and Hall-A data (**Im$\mathcal{H}$** + **model dependent** assumptions for x dependence)



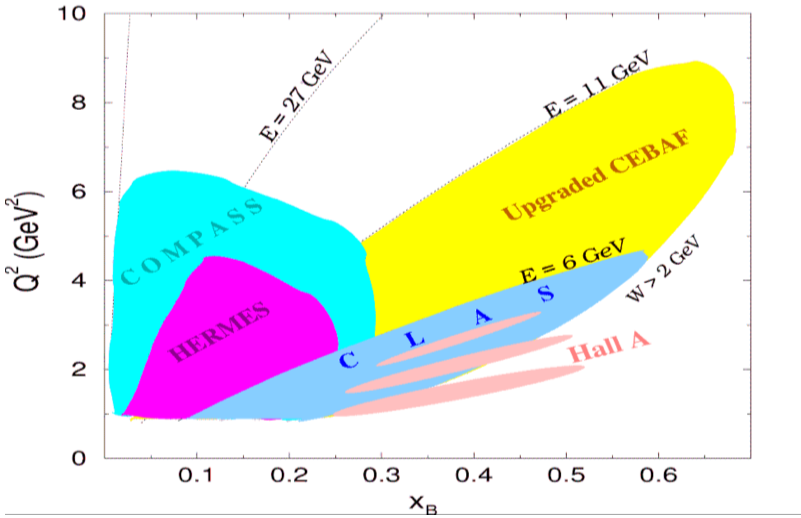
High-momentum quarks (valence) are at the core of the nucleon, low-momentum quarks (sea) spread to its periphery

R. Dupré, M. Guidal, M.Vanderhaeghen, PRD95 (2017)

From **$\mathcal{H}$-only fit** of DVCS BSA and cross section from CLAS@6 GeV **(model dependent): an insight in the pressure distribution in the proton**



V. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396-399 (2018)



An extensive experimental program is underway for proton DVCS at JLab@12 GeV

Observable (target)	12-GeV experiments
$\Delta\sigma_{beam}$(p)	Hall A, CLAS12,Hall C
BSA(p)	CLAS12
TSA(p)	CLAS12
DSA(p)	CLAS12
tTSA(p)	CLAS12

Interest of DVCS on the neutron

A combined analysis of DVCS observables for proton and neutron targets
is necessary for the flavor separation of GPDs

$$(H,E)_u(\xi,\xi,t) = {}^{9}\!/_{15}\left[4(H,E)_p(\xi,\xi,t) - (H,E)_n(\xi,\xi,t)\right]$$

$$(H,E)_d(\xi,\xi,t) = {}^{9}\!/_{15}\left[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)\right]$$

Moreover, the beam-spin asymmetry for nDVCS is the most sensitive observable to the GPD E
→ Ji's sum rule for Quarks Angular Momentum

Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi \,\mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E}\}d\phi \quad \Longrightarrow \quad \mathrm{Im}\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \mathcal{E}_n\}$$

Unpolarized beam, transversely polarized target:

$$\Delta\sigma_{UT} \sim \cos\phi \,\mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \dots\}d\phi \quad \Longrightarrow \quad \mathrm{Im}\{\mathcal{H}_p, \mathcal{E}_p\}$$

Neutron
Proton

The BSA for nDVCS:

- is complementary to the TSA for pDVCS on transverse target, aiming at *E*
- depends strongly on the kinematics → wide coverage needed
- is smaller than for pDVCS → more beam time needed to achieve reasonable statistics

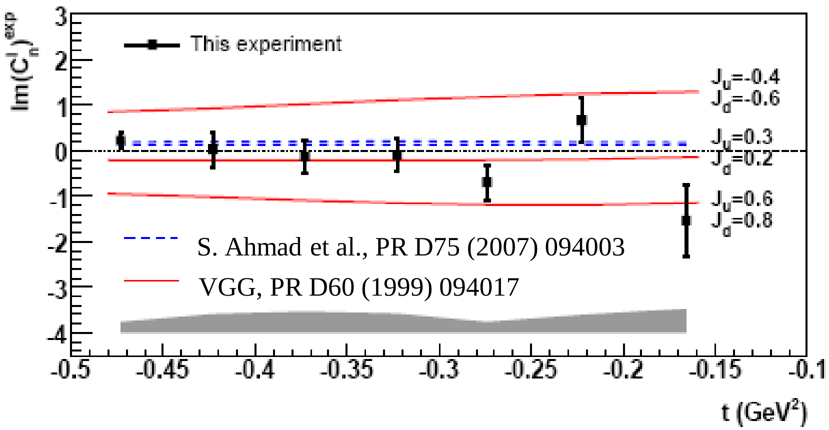
DVCS on the neutron in Hall A at 6 GeV

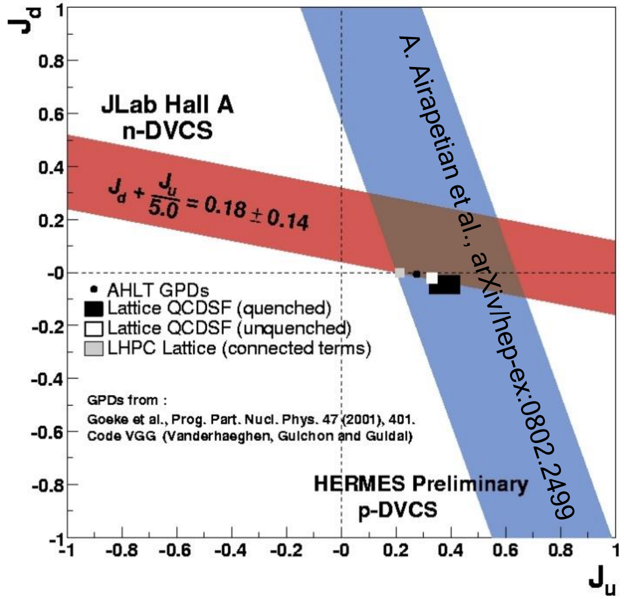
$\vec{e}d \rightarrow e\gamma(np)$

$$D(e,e'\gamma)X - H(e,e'\gamma)X = n(e,e'\gamma)n + d(e,e'\gamma)d + \dots$$

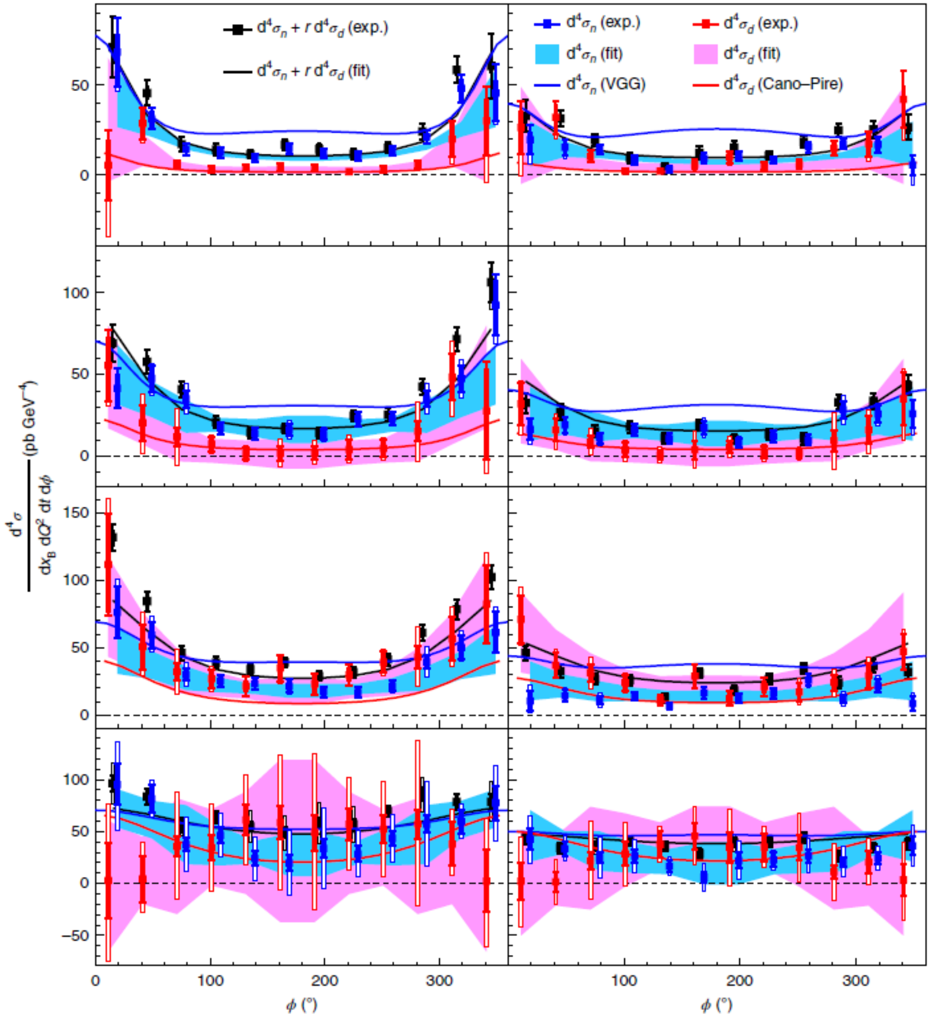
$$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E}\}$$

M. Mazouz et al., PRL 99 (2007) 242501





Q^2=1.9 GeV^2 and x_B=0.36



- **E03-106: First-time measurement of $\Delta\sigma_{LU}$ for nDVCS, model-dependent extraction of J_u, J_d**

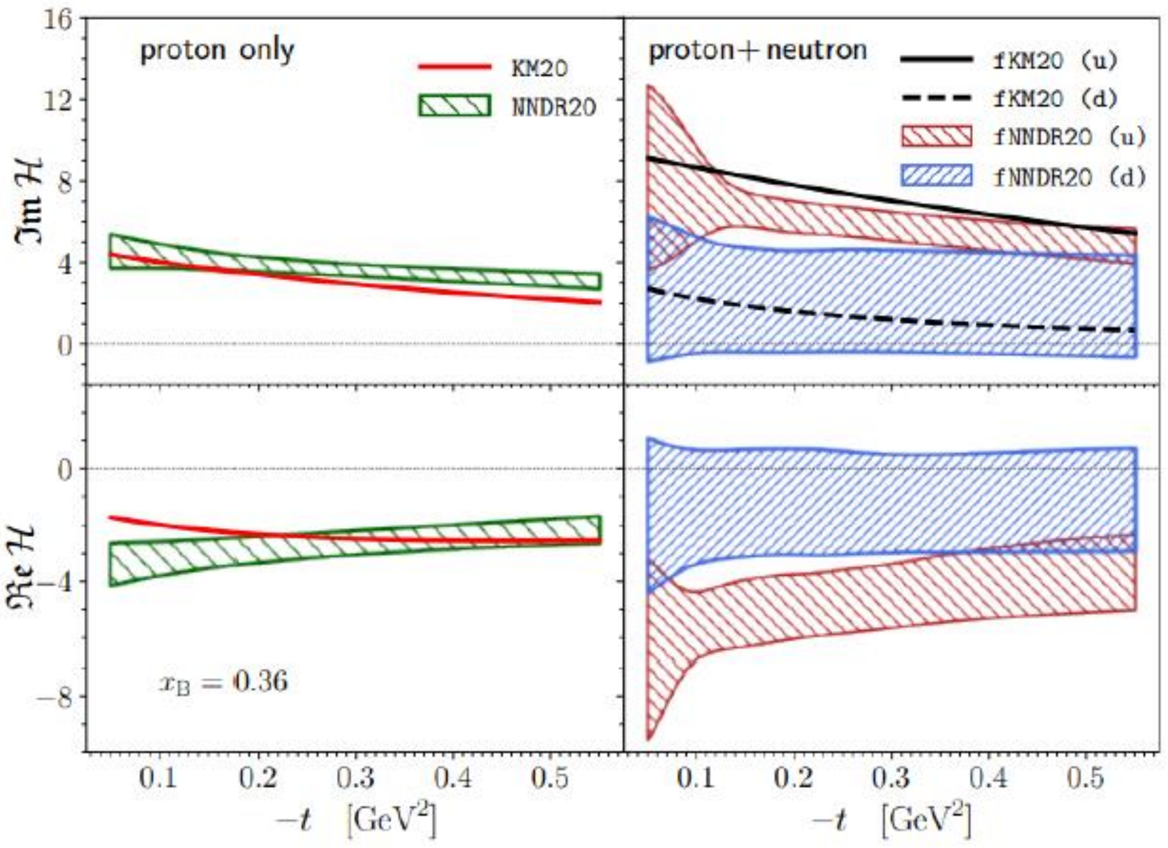
$$\frac{1}{2}\int_{-1}^{1} x\,dx\,(H(x,\xi,t=0) + E(x,\xi,t=0)) = J$$

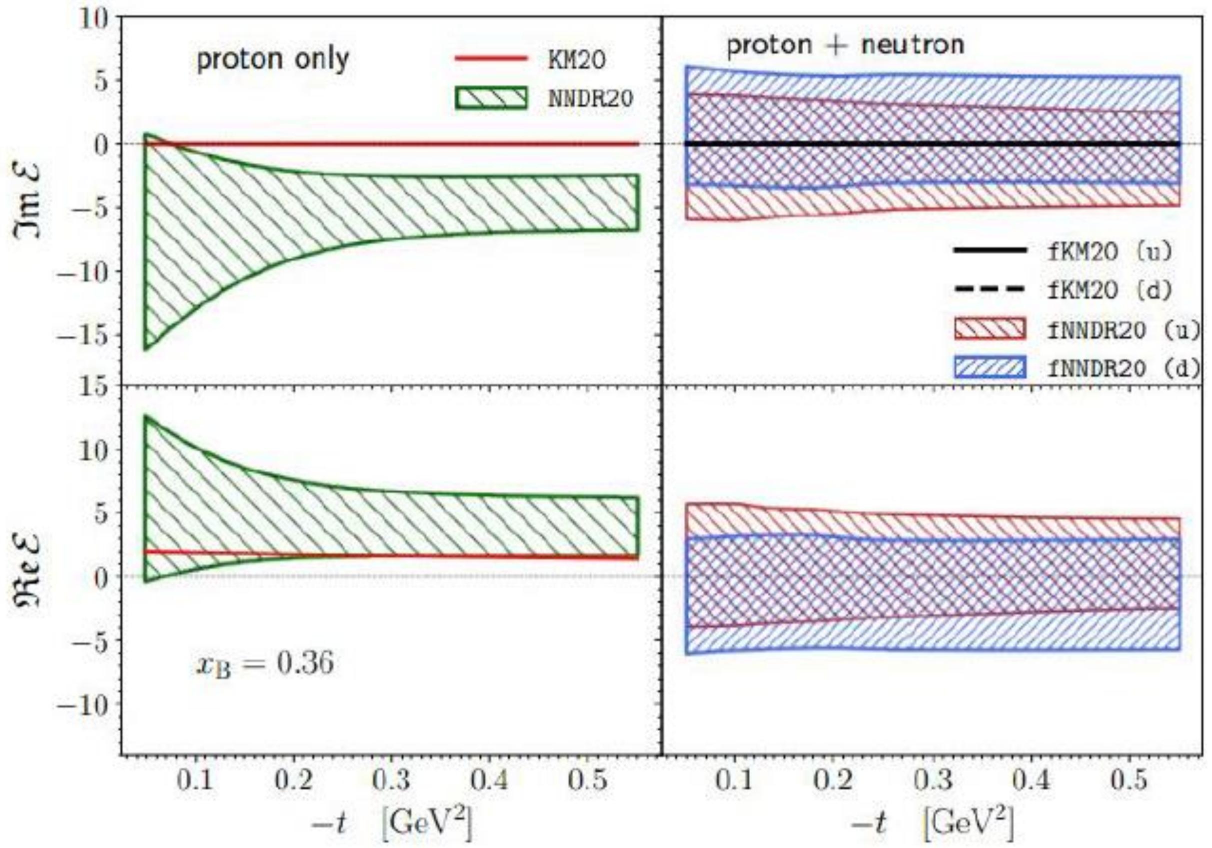
Hall-A experiment E08-025 (2010)

- Beam-energy « Rosenbluth » separation of nDVCS CS using an LD2 target and two different beam energies
- First observation of non-zero nDVCS CS
- **M. Benali et al., Nature 16 (2020)**

Extraction of CFFs and flavor separation using 6-GeV JLab data

M. Čuić, K. Kumericki et al. Phys. Rev. Lett.125.232005 (2020) and Arxiv 2007.00029 (2020)





- Proton- and neutron-DVCS data from JLab (CLAS6 and Hall A)
- Up and down contributions to the CFFs of H are separated
- The CFFs of E are not separated, a significant sign ambiguity remains

CLAS12 Run Group B at Jefferson Lab

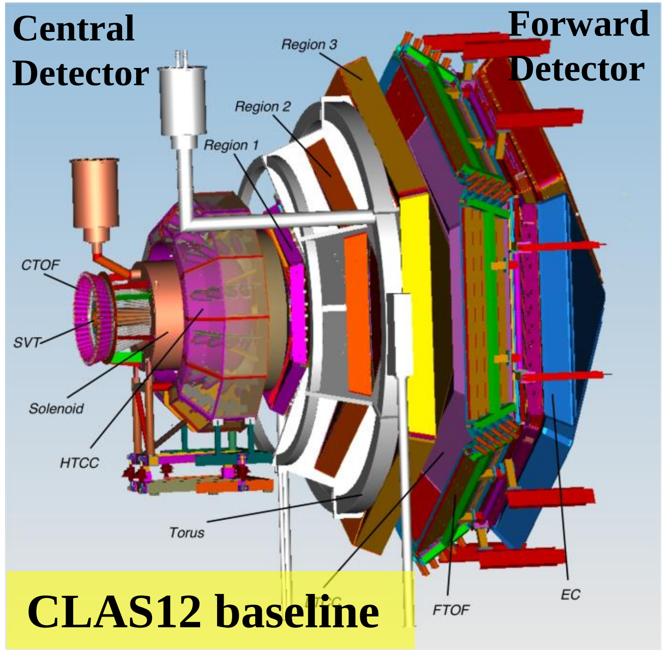
Electroproduction on deuterium with CLAS12

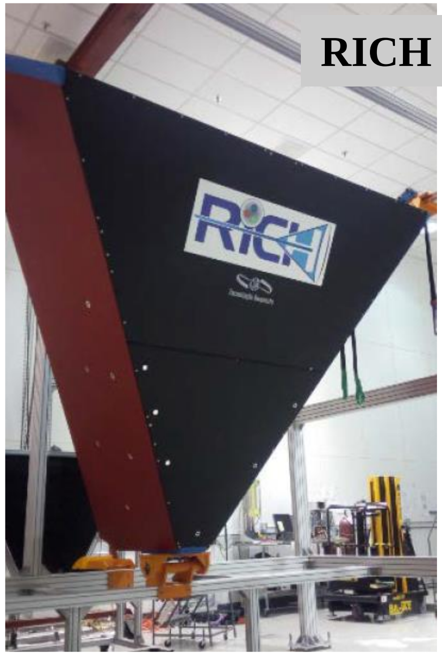
Run infos:

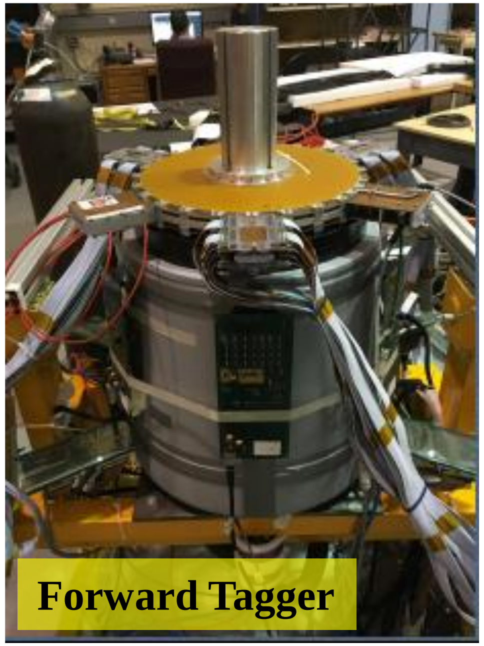
- Feb. 6th – Mar. 25th 2019 + Dec. 3 –20 2019 + Jan. 6 – 30 2020 → ~39 PAC days (~43% of the approved run time)
- 3 beam energies: 10.6, 10.2, 10.4 GeV
- Average beam polarization ~86%
- Liquid deuterium target, 5 cm long
- L = ~1.3 10^{35} $cm^{-2}s^{-1}$ per nucleon

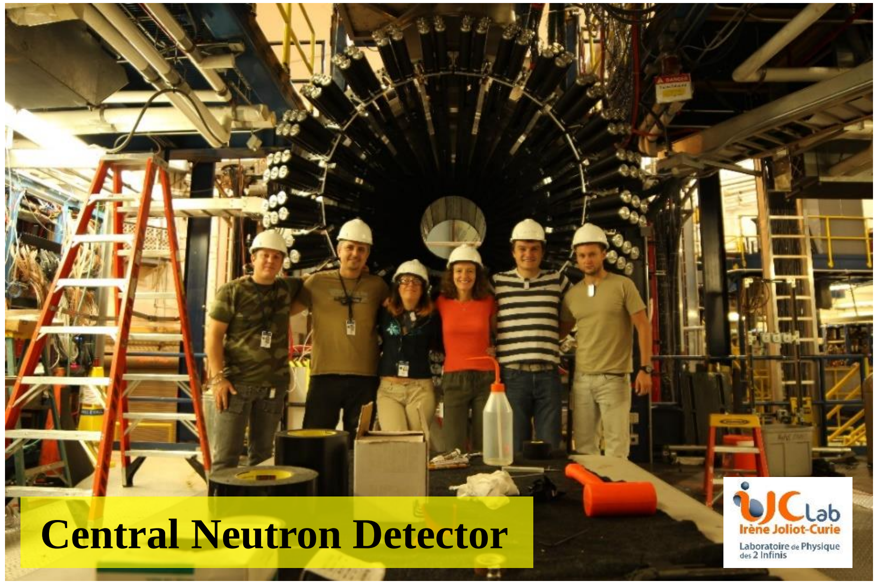
Physics goals:

- Form factors
- DIS
- SIDIS
- DVCS
- J/psi photoproduction
- Short-Range Correlations









Central Neutron Detector: performances with CLAS12 data

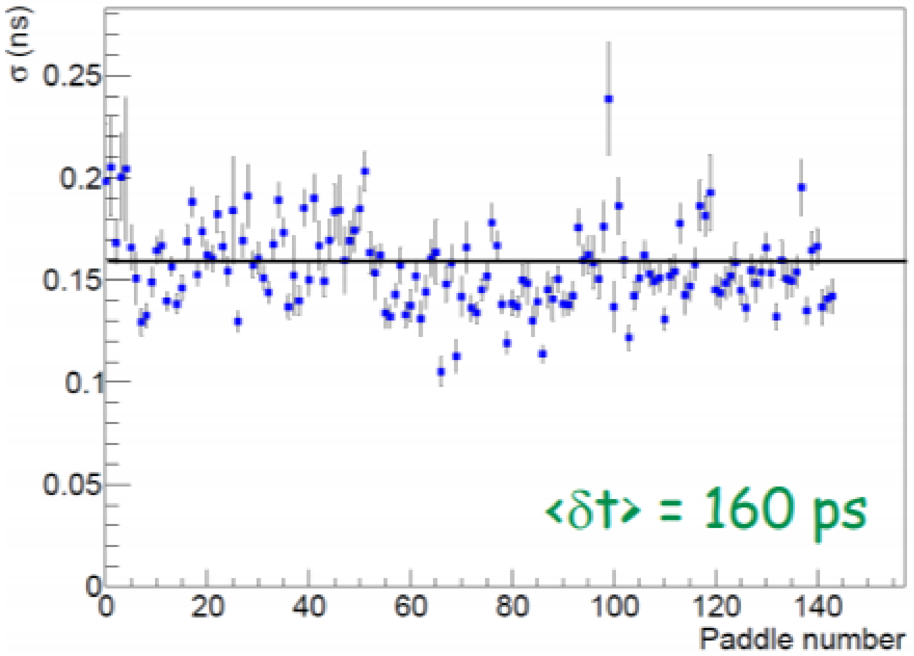
Purpose: detect the **recoiling neutron in nDVCS**
Requirements/performances**:**
- good neutron/photon separation for $0.2<p_n<1$ GeV/c
  → ~150 ps time resolution ✓ (~160 ps)
- momentum resolution $\delta p/p < 10\%$ ✓
- neutron detection efficiency ~10% ✓

CND design: **scintillator barrel** - 3 radial layers, 48 bars per layer **coupled two-by-two** downstream by a **"u-turn" lightguide,** 144 long light guides with **PMTs** upstream

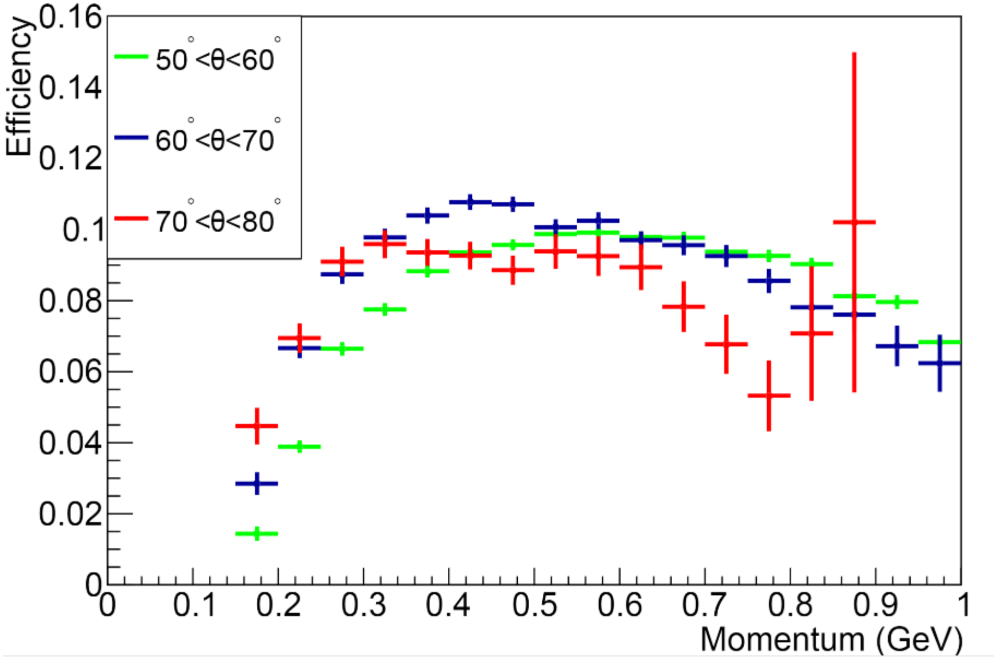
S.N. *et al*., NIM A 904, 81 (2018)

P. Chatagnon et al., NIM A 959 (2020) 163441

Timing resolution per paddle (RGB data)

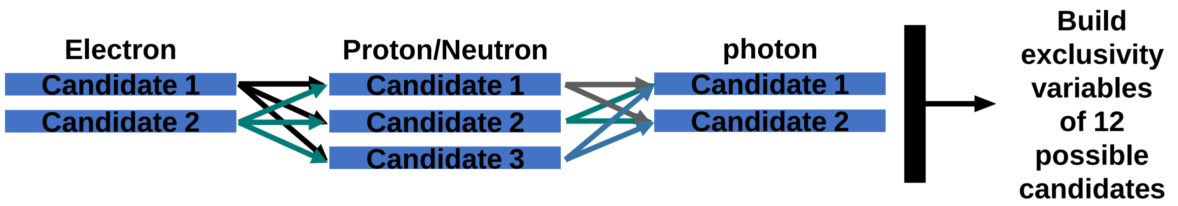


Neutron efficiency from $ep\to e'n\pi^+$ (RGA data)



Channel selection for nDVCS

- Select events with **at least one electron, one neutron, one photon**
- Final state reconstructed using **CLAS12 PID + a dedicated proton veto**, based on Machine Learning, for neutron selection optimization
  - Best candidate in event is selected based on best exclusivity criteria (a multi-dimensional χ^2 with all exclusivity variables)



- **Fiducial cuts** included for: electrons in PCAL and DC, photons in PCAL and protons in DC
- The nDVCS final state is selected using:
  - **Missing masses**: $ed \rightarrow en\gamma X$, $en \rightarrow en\gamma X$, $en \rightarrow enX$
  - **Missing momentum** (spectator proton) in $ed \rightarrow en\gamma X$
  - **$\Delta\phi$, Δt**: Difference between two ways of calculating ϕ and t
  - **$\theta(\gamma,X)$:** Cone angle between measured and reconstructed photon
- Cuts informed by **Monte Carlo simulations**:
  - GPD-based event generator for DVCS/π^0 on deuterium
    - DVCS amplitude calculated according to the BMK formalism
    - Fermi-motion distribution evaluated according to Paris potential

	Proton	Electron	Photon	Neutron
Momentum (GeV)	0.3	1	2	0.35

Q2>1 GeV2 W>2 GeV2

$\theta(e,\gamma) > 5^{\circ}$ Remove radiative photons

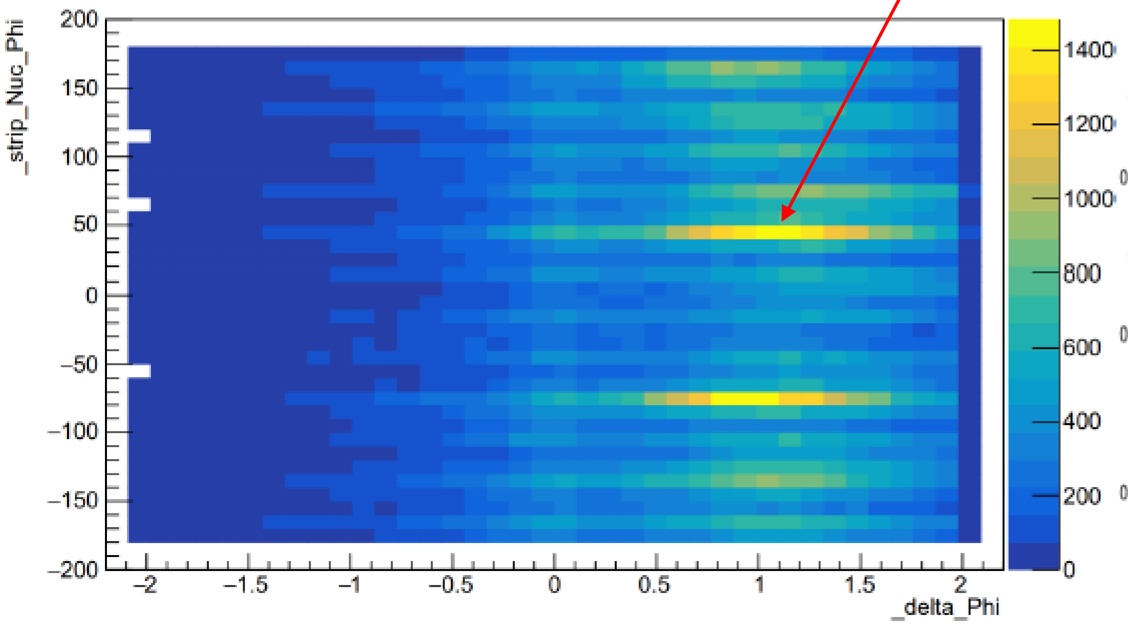
Proton contamination removal from CND neutrons

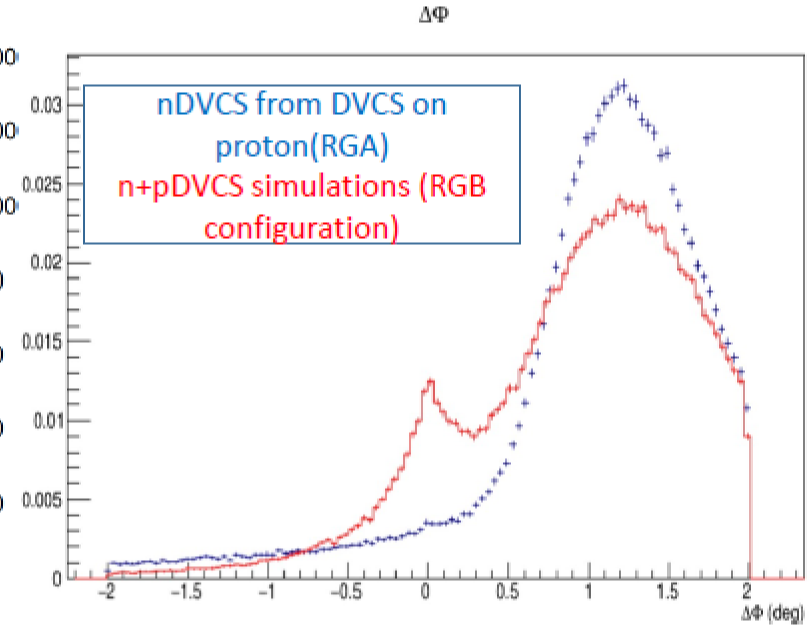
- Tracking in the CVT is not 100% efficient: in the dead regions of the Central Vertex Tracker protons can be identified as neutrons
- Protons roughly account for **more than 40% contamination** in the signal sample

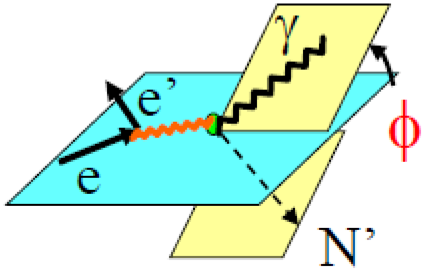
Approach based on Machine Learning & Multi-Variate Algorithms:

- Reconstruct nDVCS from DVCS experiment on proton (RG-A) requiring neutron PID: selected neutrons are misidentified protons
- Use this sample to determine the characteristics of fake neutrons in low and high level reconstructed variables
- Based on those characteristics, subtract the fake neutrons contamination from nDVCS
- « Signal » sample in the training of the ML: $ep \rightarrow en\pi^+$ events from RG-A

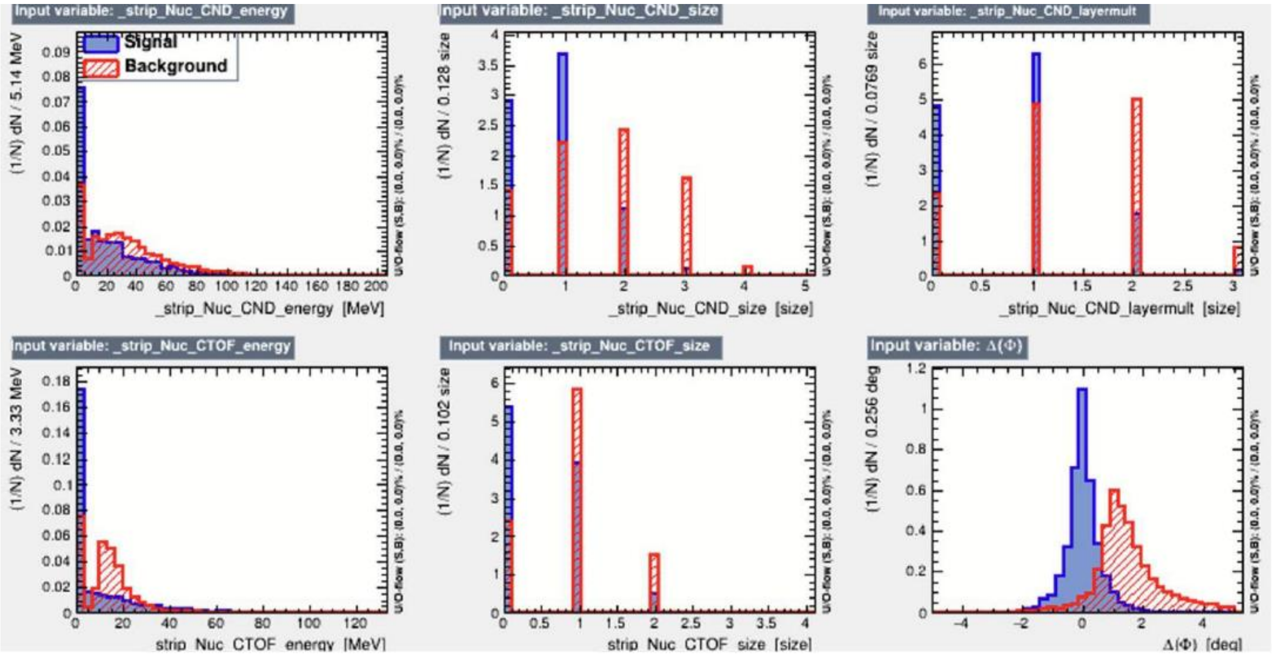
Low-efficiency regions of the CVT

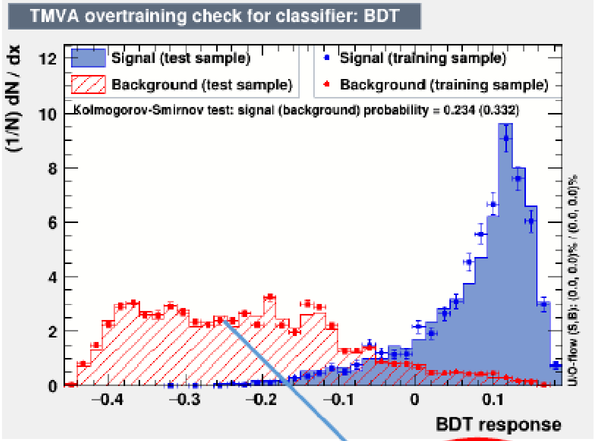


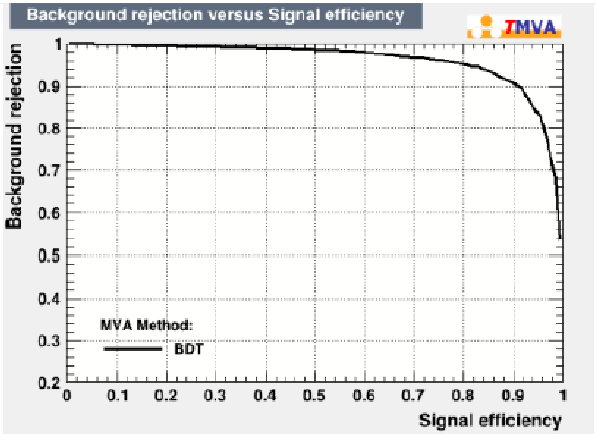


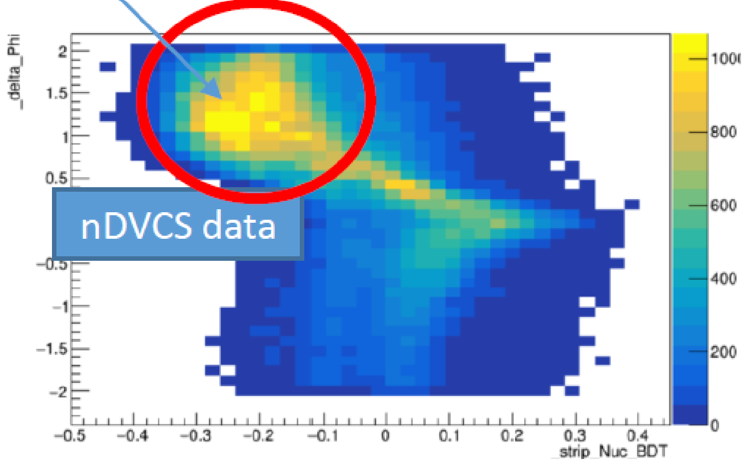


Proton contamination removal from CND neutrons

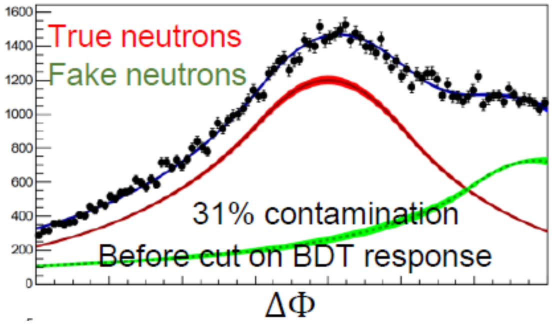


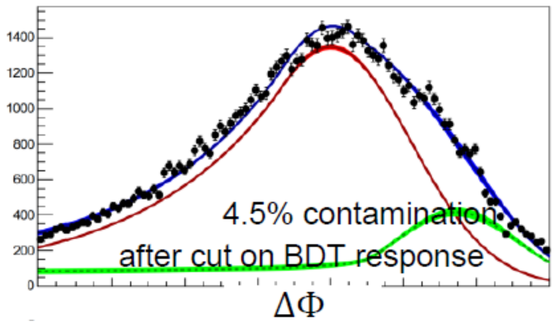




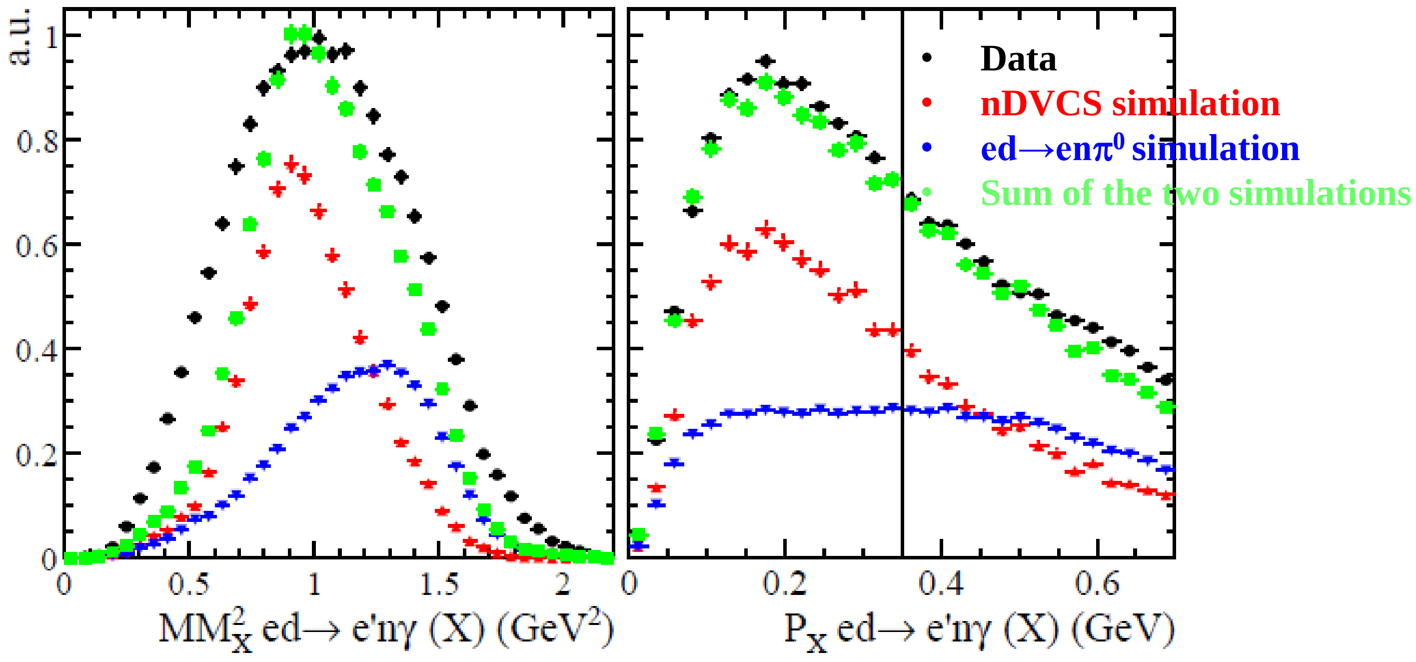


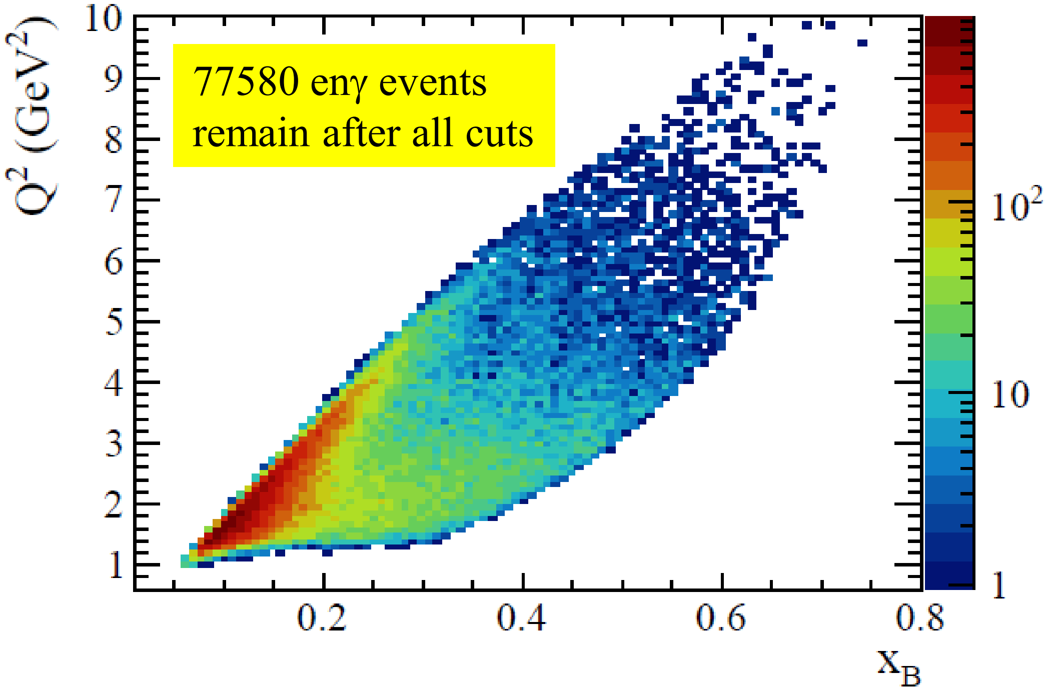
- Using detector variables (CTOF and CND) and one exclusivity variable ($\Delta\phi$)
- Directly trained on data
- Better optimization of signal to background ratio than straight cuts
- Few percent irreducible contamination corrected for in the final BSA





Selected nDVCS events sample and background subtraction





- Subtraction of the π^0 background from **simulation** and reconstructed exclusive π^0 events from **data**
  - Estimate the ratio R of partially reconstructed enπ^0 (1 photon) decay to fully reconstructed enπ^0 events in simulation
  - Multiply this ratio by the number of **reconstructed enπ^0 in data** to get the number of enπ^0 (1 photon) in data
  - Subtract this number from DVCS reconstructed decays in data **per each kinematical bin** and **beam helicity**

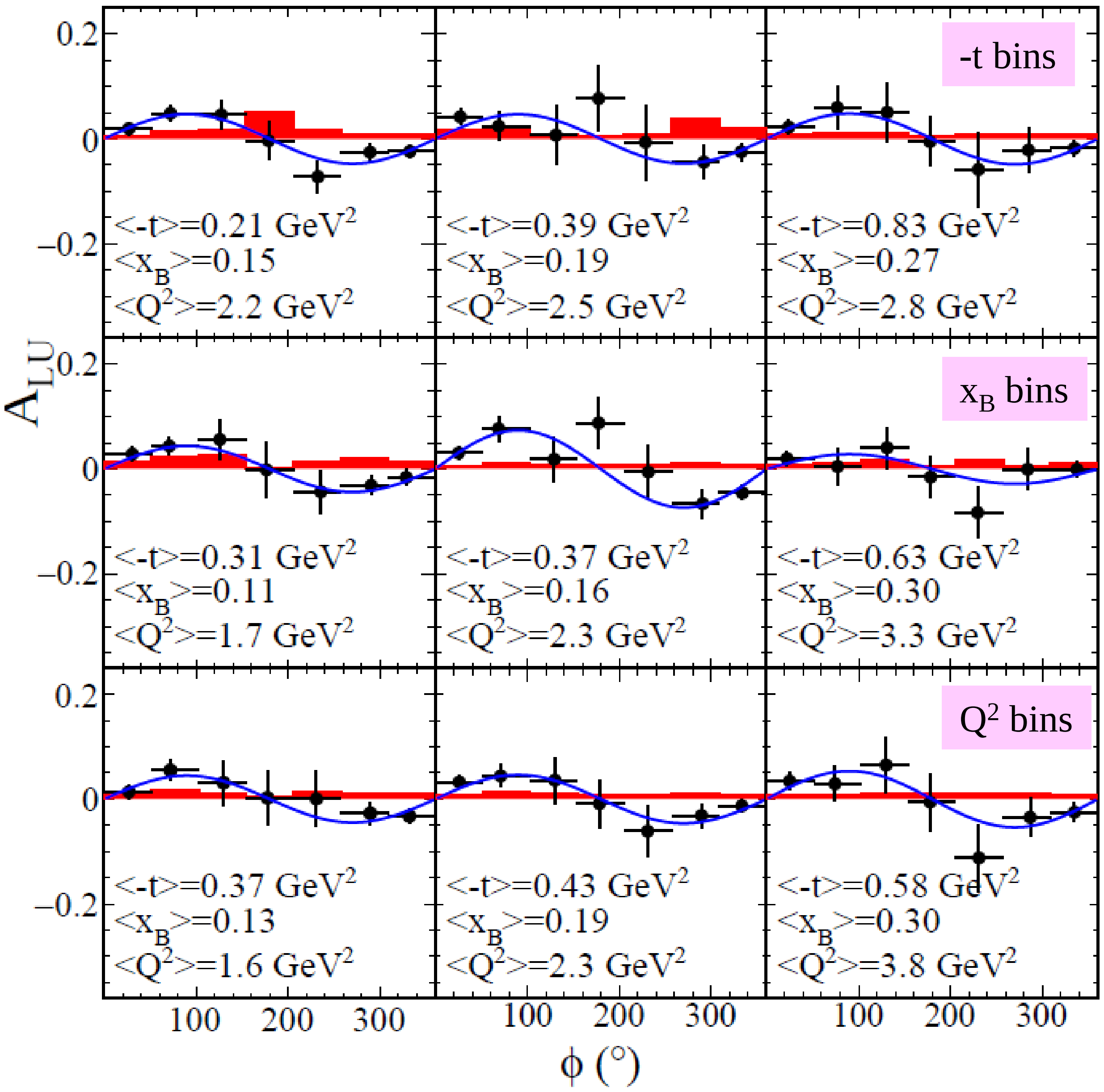
$$R = \frac{N(eN\pi^0_{1\gamma})}{N(eN\pi^0)}$$

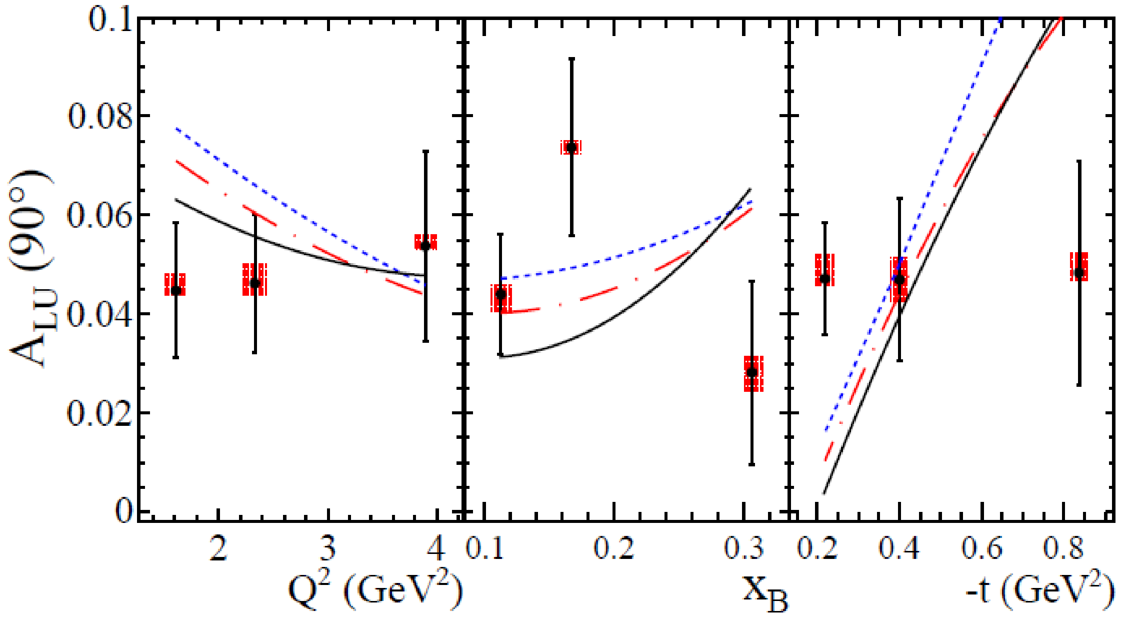
$$N(eN\pi^0_{1\gamma}) = R * N(eN\pi^0)$$

$$N(DVCS) = N(DVCS_{recon}) - N(eN\pi^0_{1\gamma})$$

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

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





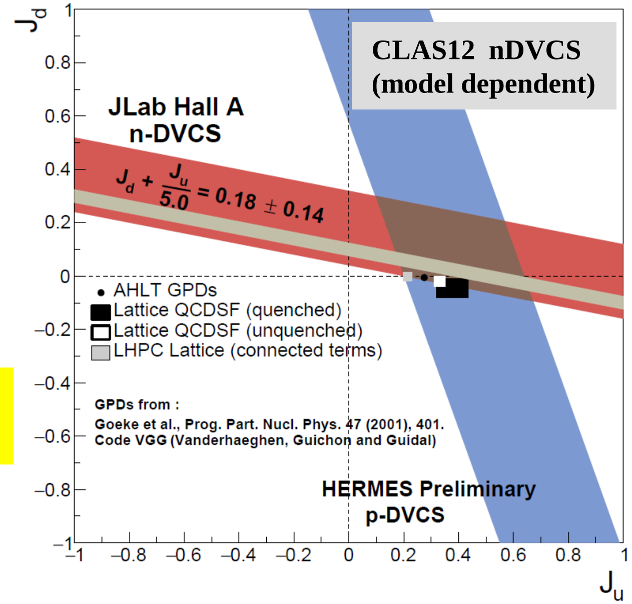
$J_u = 0.35$ $J_d = 0.05$

$J_u = -0.2$ $J_d = 0.15$

$J_u = -0.45$ $J_d = 0.2$

VGG model predictions giving the smallest χ^2

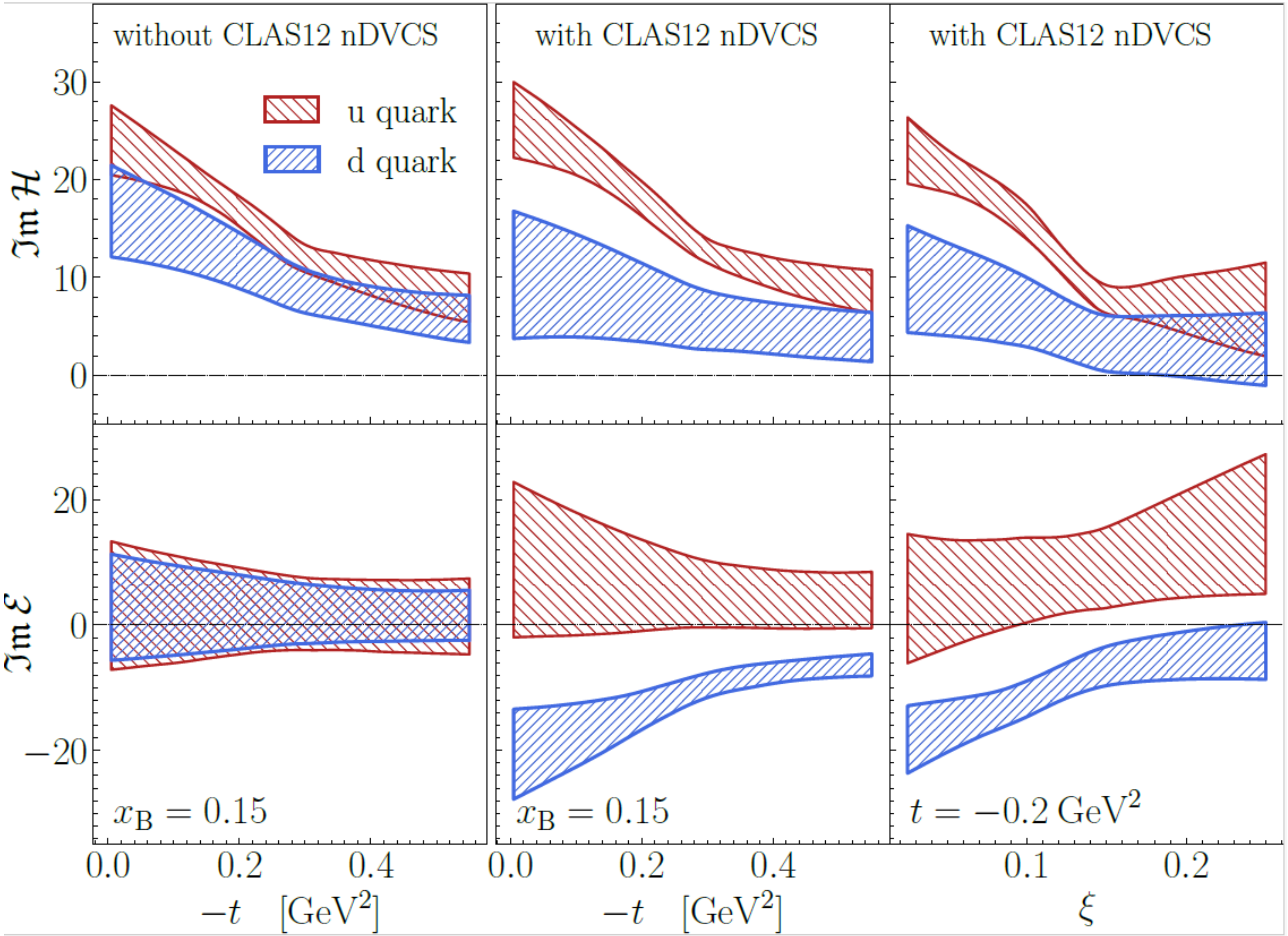
M. Vanderhaeghen, P.A.M. Guichon, and M. Guidal, PRD 60, 094017 (1999)



Flavor separation of CFFs with Hall A pDVCS and 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$\mathcal{E}$



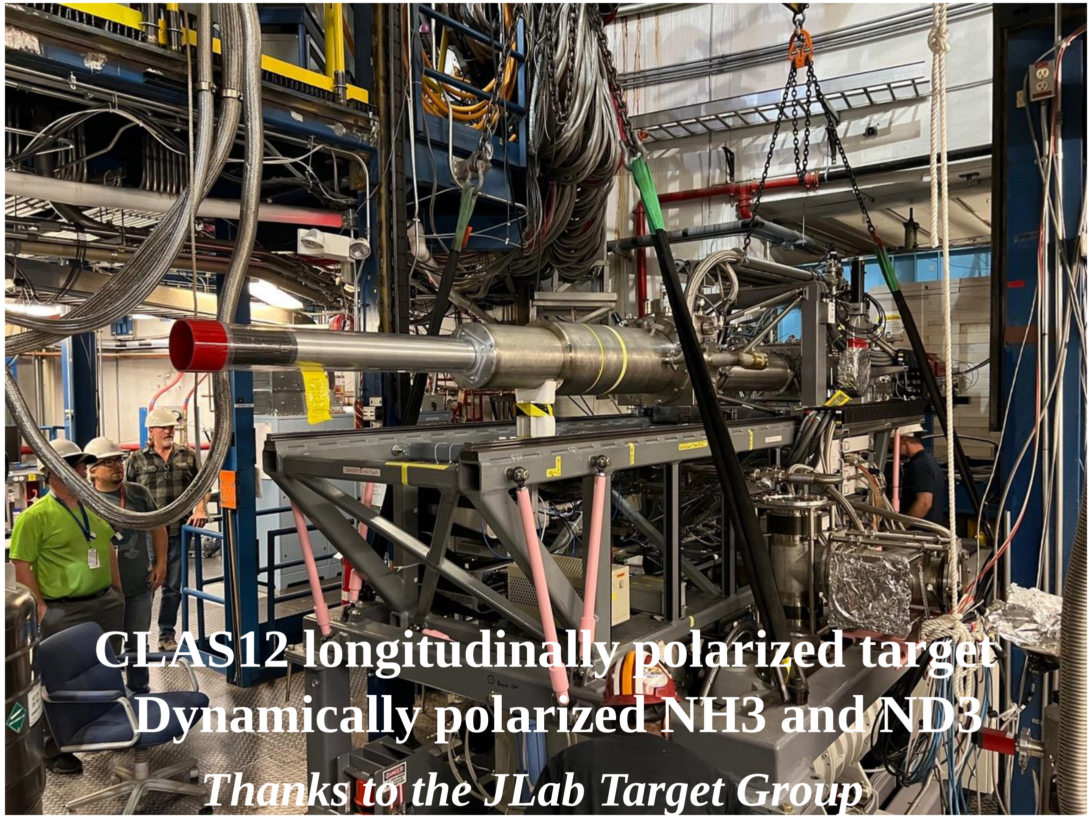
Recently run with CLAS12: DVCS (p, n) on longitudinally polarized target

First-time measurement of longitidunal target-spin asymmetry and double (beam-target) spin asymmetry for nDVCS

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

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

→ 3 observables (including BSA), constraints on real and imaginary CFFs of various **neutron GPDs**



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

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

CLAS12 + Longitudinally polarized target + CND

Ran from June 2022 to March 2023

Ultimate goals: flavor separation of CFFs & Ji's sum rule

See Noémie Pilleux's talk

Summary and outlook

- The **beam-spin asymmetry for nDVCS** is a precious tool to constrain the GPD E and for quark-flavor separation of GPDs
- **CLAS12** measured the **BSA for nDVCS with detected neutron for the first time**
- The first **~43%** of the experiment ran in 2019-2020 at JLab
- The **Central Neutron Detector** performed according to specifications
- A small but clear **BSA was extracted**
- Comparison with a model allows to put **model-dependent constraints on J_d**
- The data, together with the proton DVCS data, allow the **quark-flavor separation of ImH and ImE**
- An article is **ready for submission to PRL**
- A first-time measurement of **BSA for incoherent pDVCS** on deuterium is in progress

➢ Another nDVCS experiment on **polarized deuterium target** was carried out in 2022-2023 with CLAS12

➢ The second half of Run Group B will run with **double luminosity** following the CLAS12 high-lumi upgrade

➢ **A transversely polarized target pDVCS experiment** is foreseen for ~2028 with CLAS12

➢ The combination of all neutron and proton DVCS data will allow **quark-flavor separation of all CFFs** in the valence regime

➢ The **Ji's sum rule** is the ultimate, ambitious goal of this program

First Measurement of Deeply Virtual Compton Scattering on the Neutron with Detection of the Active Neutron

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