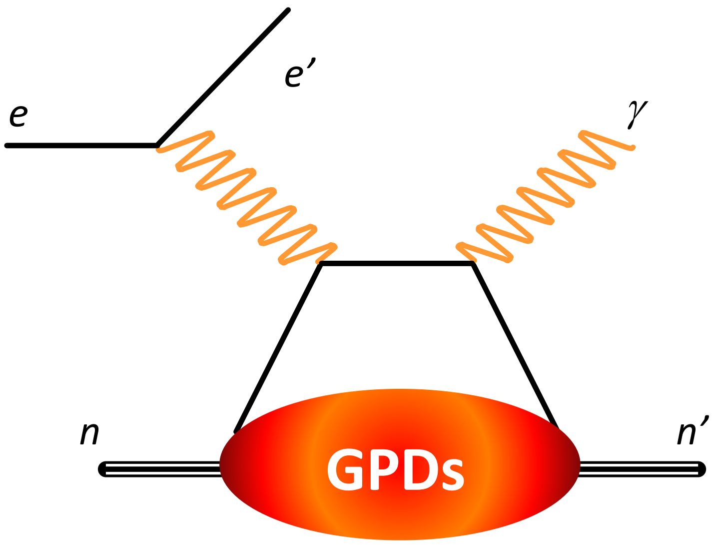
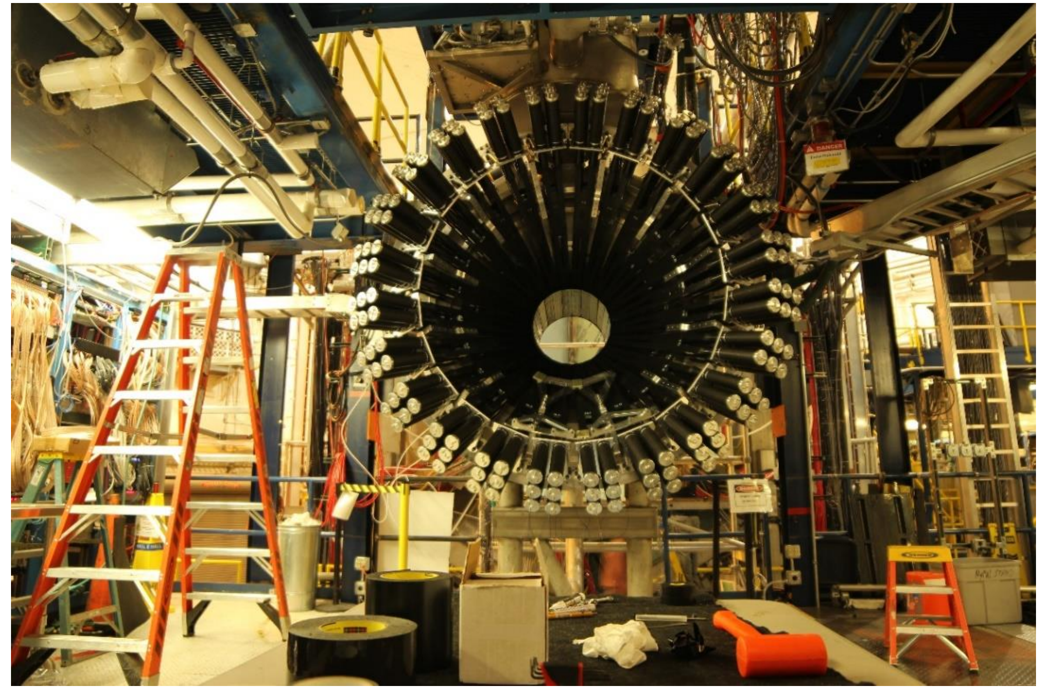
Deeply Virtual Compton Scattering on the neutron with CLAS12 at 11 GeV

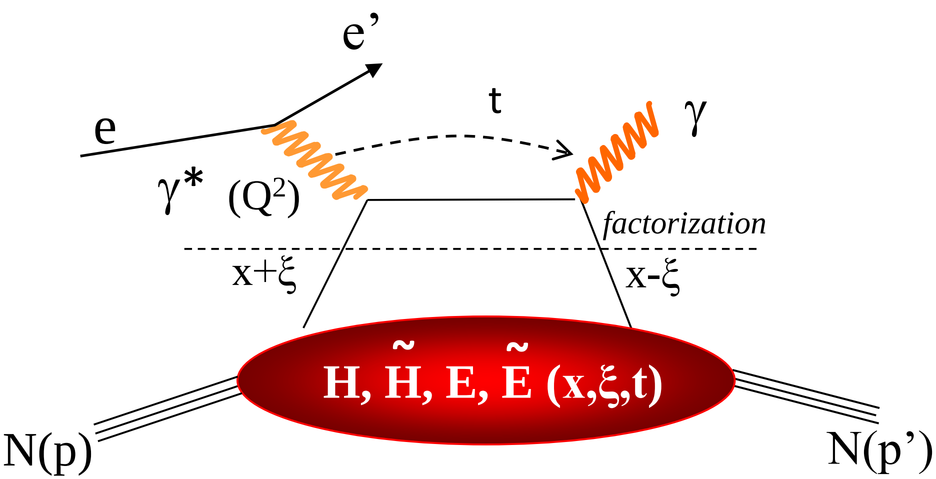




Silvia Niccolai (IJCLab Orsay),
for the CLAS Collaboration

JLab Users Group Meeting - June 23rd, 2020

Deeply Virtual Compton Scattering and quark GPDs



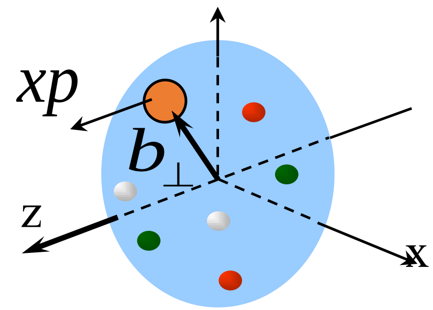
- $Q^2 = -(k-k')^2$
- $x_B = Q^2/2M\nu$ $n = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ long. mom. fract.
- $t = \Delta^2 = (p-p')^2$
- $x \cong x_B/(2-x_B)$

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)

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

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

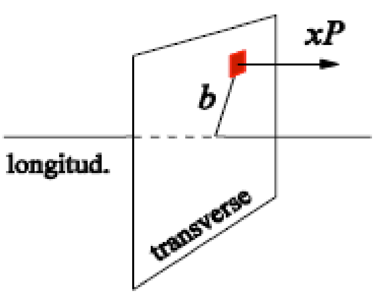


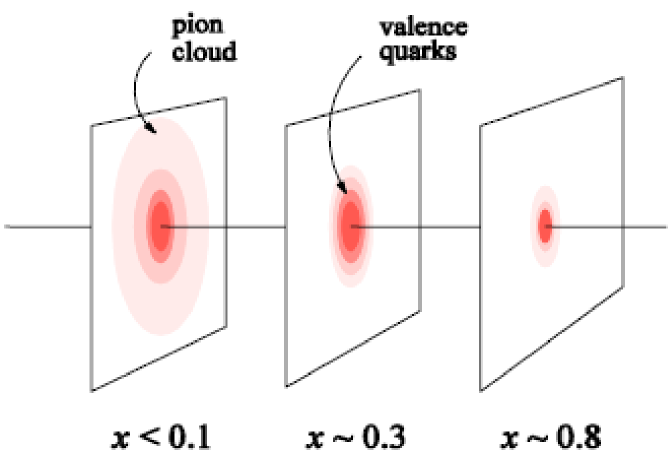
Nucleon tomography

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

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

M. Burkardt, PRD 62, 71503 (2000)





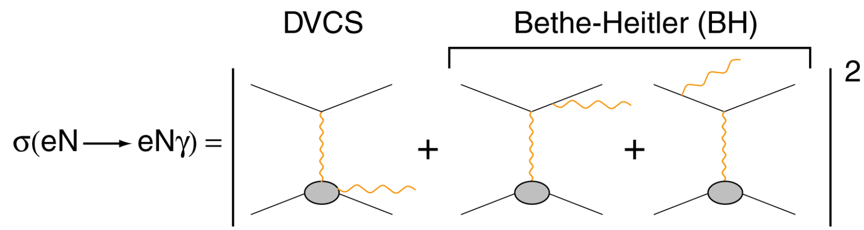
Accessing GPDs through DVCS

DVCS allows access to 4 complex GPDs-related quantities: **Compton Form Factors CFF(ξ,t)**

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

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

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



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

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

Proton Neutron

Polarized beam, unpolarized target:

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

Unpolarized beam, longitudinal target:

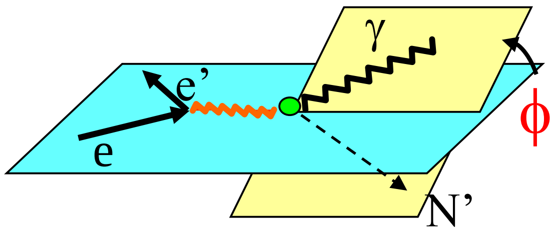
$\Delta\sigma_{UL} \sim \sin\phi\ Im\{F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E}) - \xi kF_2\tilde{\mathcal{E}}\}$ ⇒ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$, $Im\{\mathcal{H}_n, \mathcal{E}_n\}$

Polarized beam, longitudinal target:

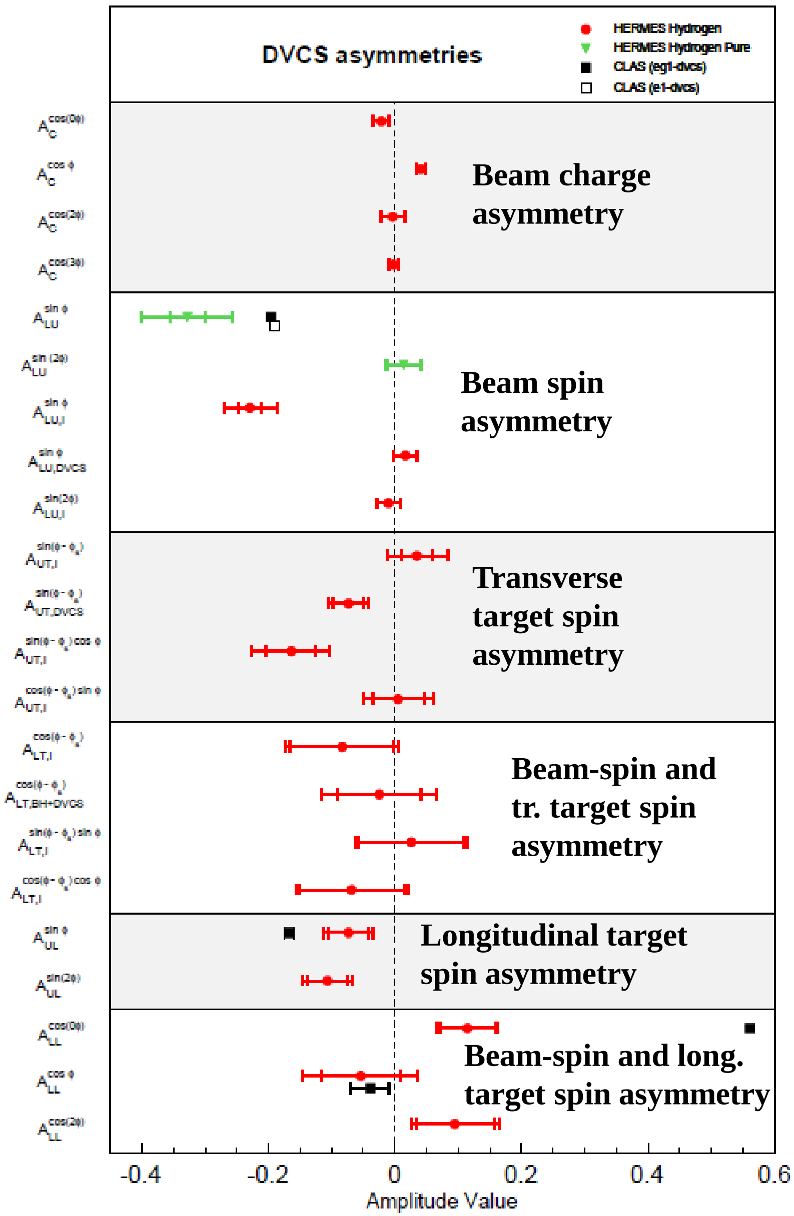
$\Delta\sigma_{LL} \sim (A+B\cos\phi)Re\{F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E})+\ldots\}$ ⇒ $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$, $Re\{\mathcal{H}_n, \mathcal{E}_n\}$

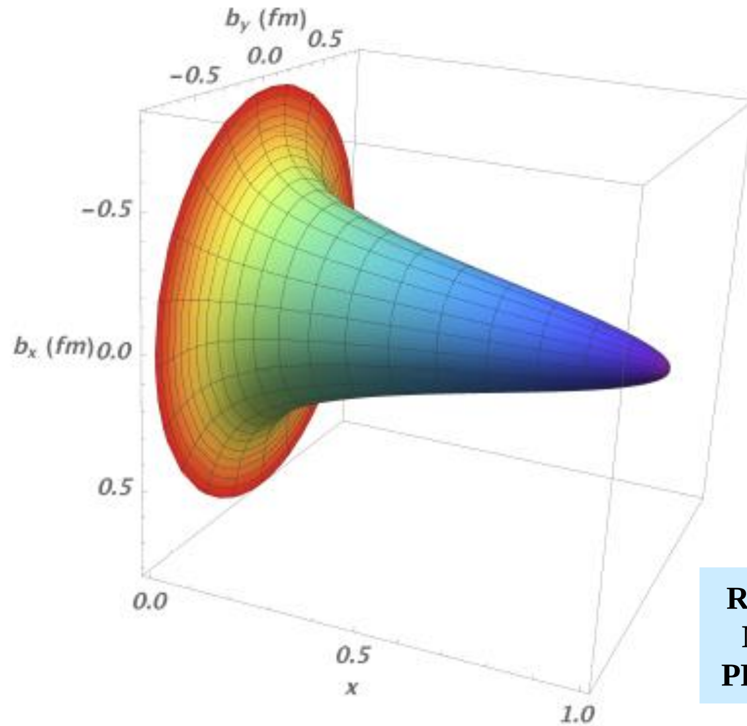
Unpolarized beam, transverse target:

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



Summary of proton-DVCS spin observables and tomography





R. Dupré, M. Guidal, M.Vanderhaeghen, PRD95, 011501 (2017)

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 flavor separation of GPDs

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

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

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:

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

Unpolarized beam, transversely polarized target:

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

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

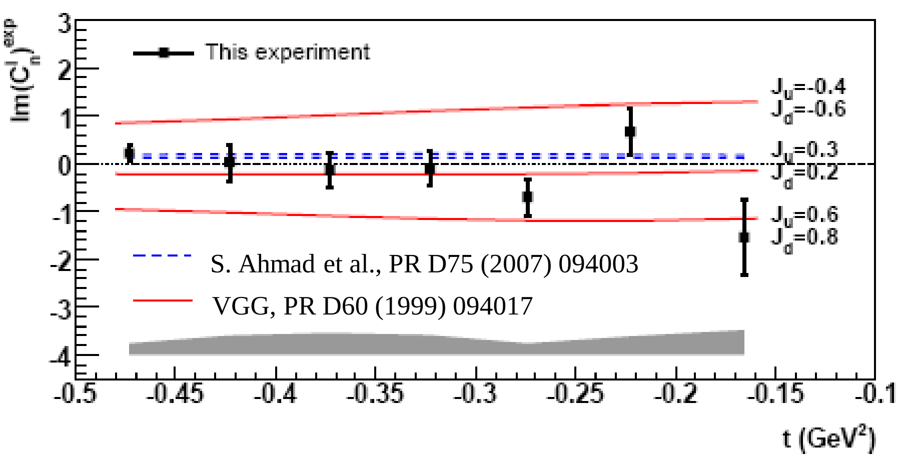
$\vec{e}d \rightarrow e\gamma(np)$

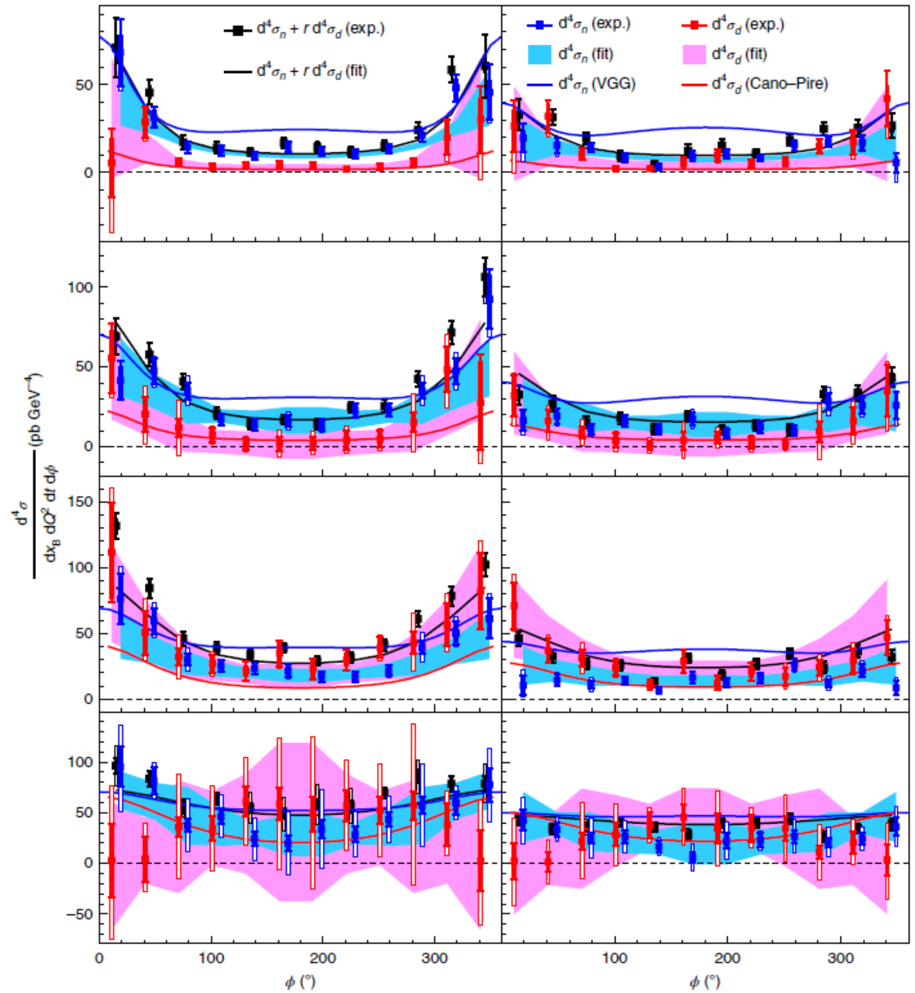
DVCS on the neutron in Hall A at 6 GeV

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

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

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





Q^2=1.9 GeV² and x_B=0.36

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

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

NEW! 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)**

E12-11-003: nDVCS on the neutron with CLAS12 at 11 GeV

JLab PAC: **high-impact experiment**

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

The most sensitive observable to the GPD E

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

Fully exclusive final state:

CLAS12

+Forward Tagger

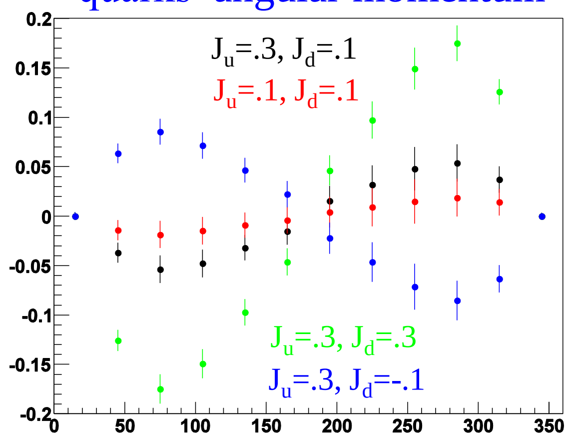
+Central Neutron Detector

Liquid deuterium target

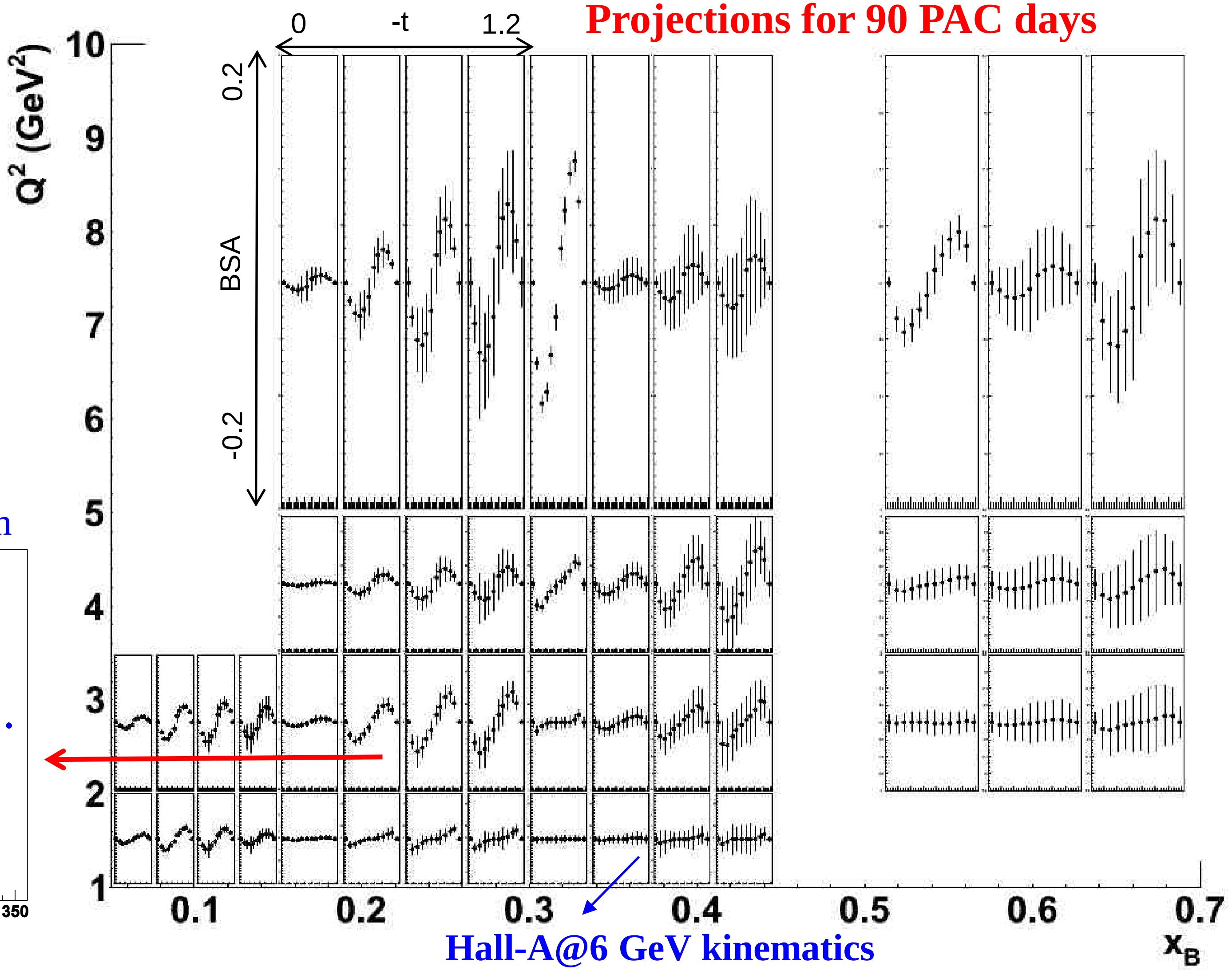
Beam polarization =85%

L = 10^{35} cm^{-2}s^{-1}/nucleon

Model predictions (VGG) for different values of quarks' angular momentum

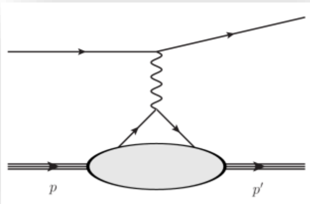


Projections for 90 PAC days



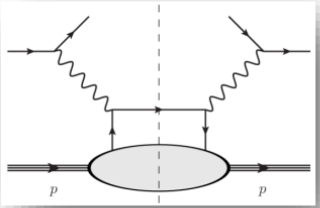
CLAS12 Run Group B

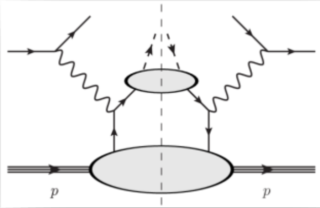
Electroproduction on deuterium with CLAS12



Elastic Scattering

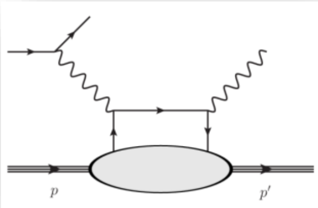
DIS





SIDIS

nDVCS



+ J/psi photoproduction
+ Short Range Correlations

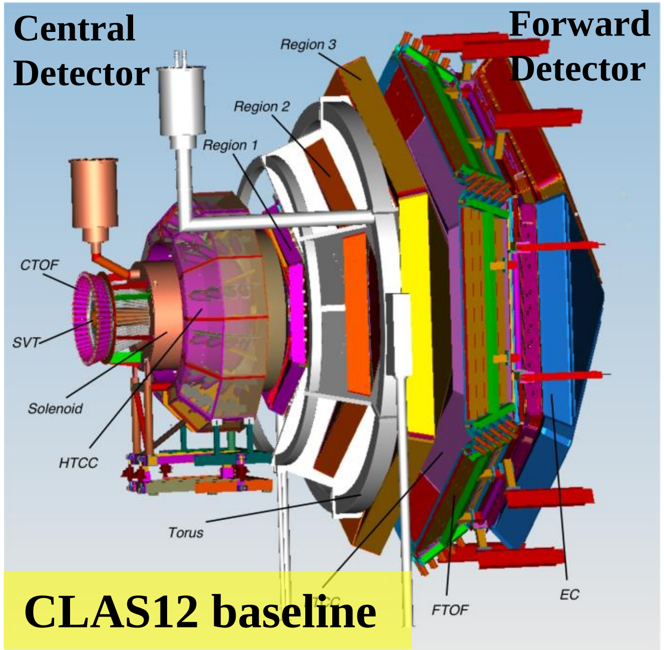
2019 schedule:
Febuary 6th - March 25th 2019 + December 3 –20 2019 + January 6 – 30 2020
→ ~39 PAC days (~43% of approved run time)

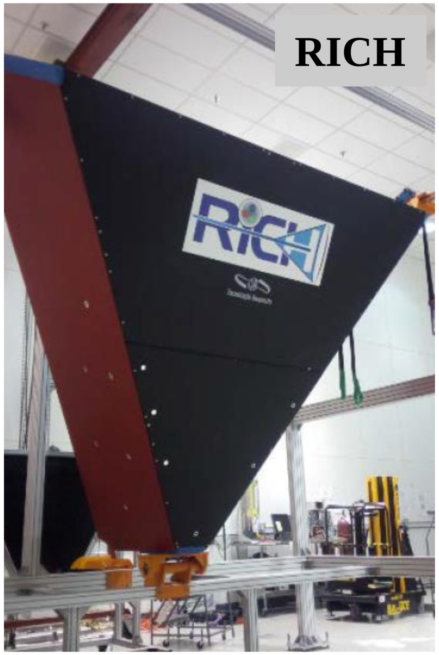
Statistics:

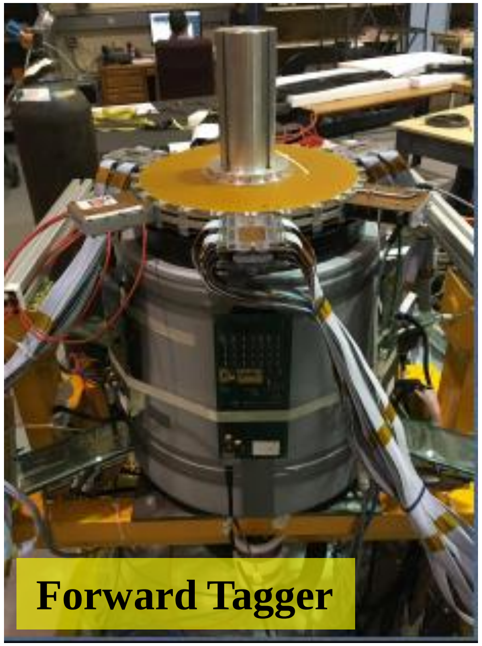
- 43.3 B triggers collected:
  - ➢ 10.6 GeV (9.7 B)
  - ➢ 10.2 GeV (11.7 B)
  - ➢ 10.4 GeV (21.9 B – 9 B are outbending)
- Average beam polarization ~86% (22 Moeller runs)

Jeopardy proposal just submitted to PAC
(51 days requested)

CLAS12 Run group B: experimental setup







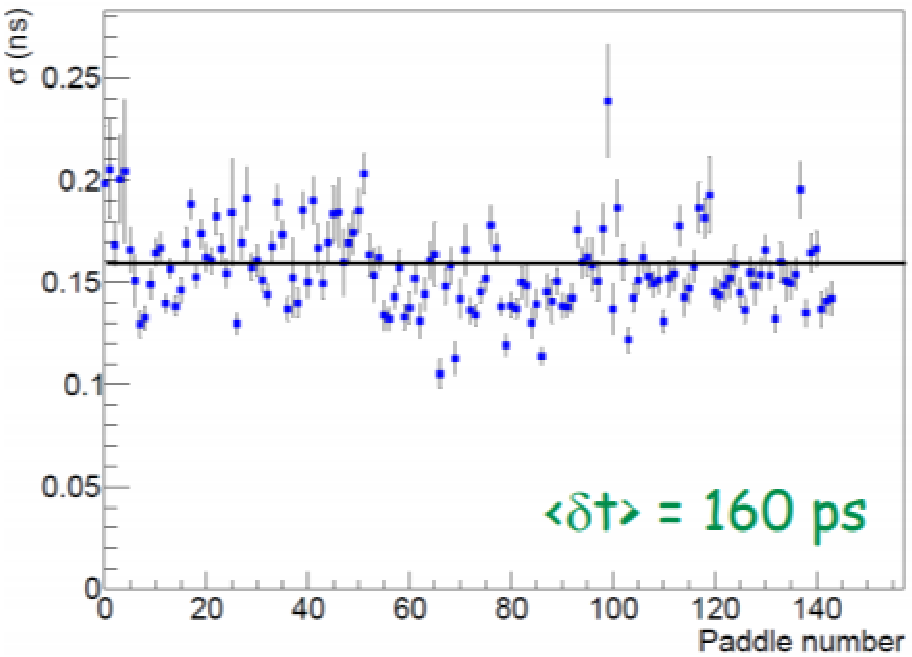
CND: performances with CLAS12 data

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

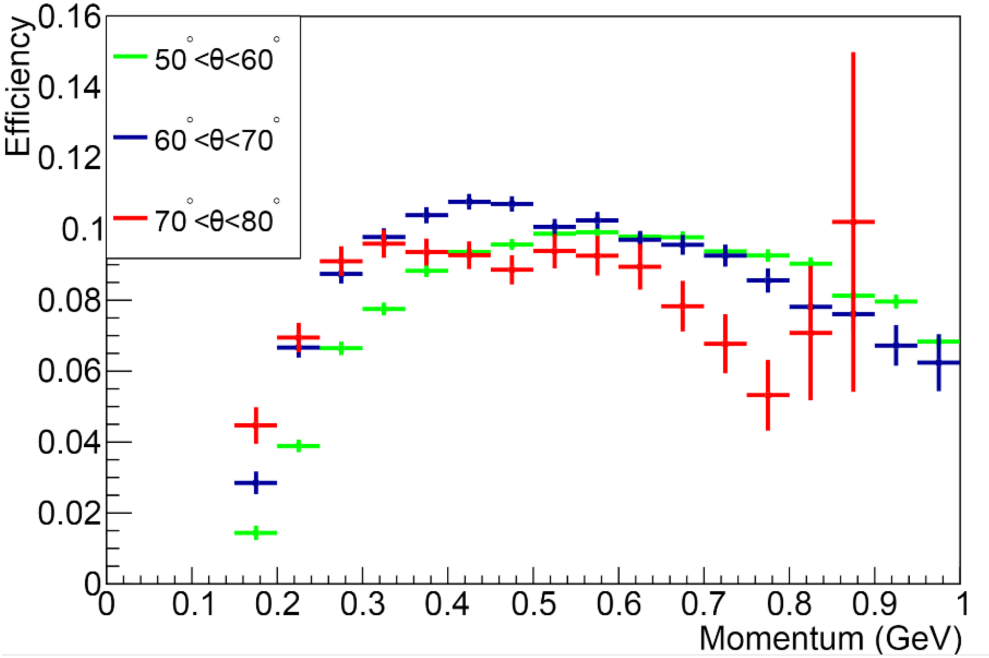
CND design: scintillator barrel - 3 radial layers, 48 bars per layer **coupled two-by-two** downstream by a **"u-turn" lightguide,** 144 long light guides with **PMTs** upstream

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

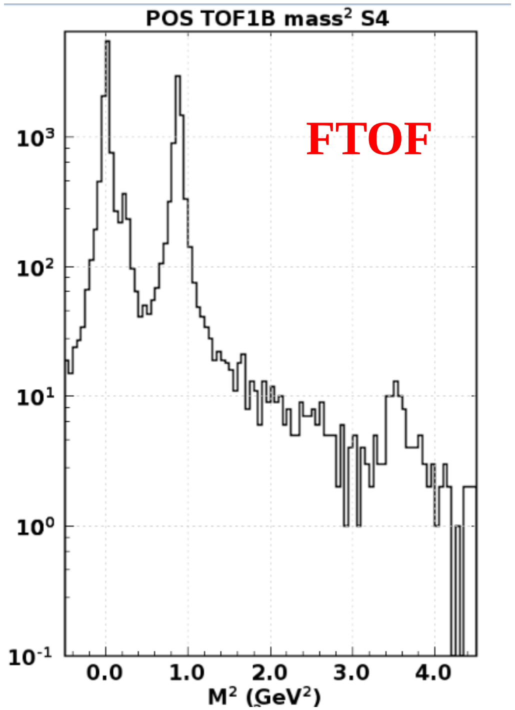
Timing resolution per paddle (RGB data)

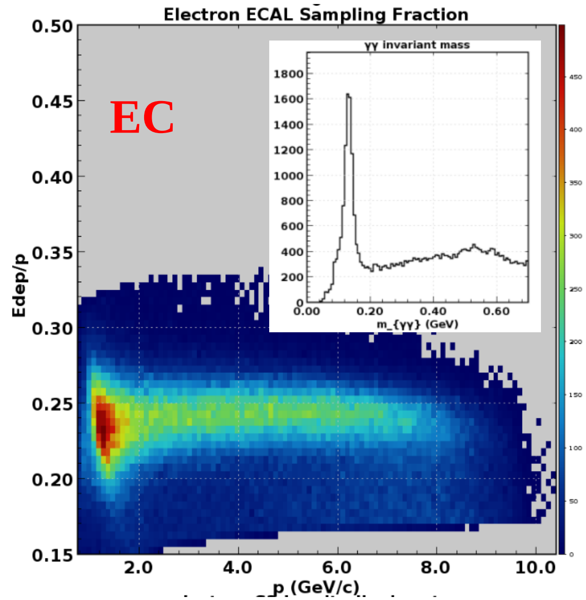


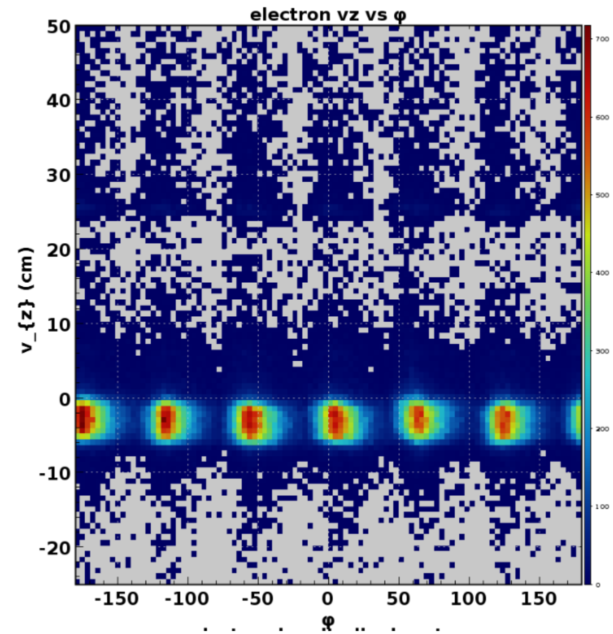
Neutron efficiency from $ep \rightarrow e'n\pi^+$ (RGA data)

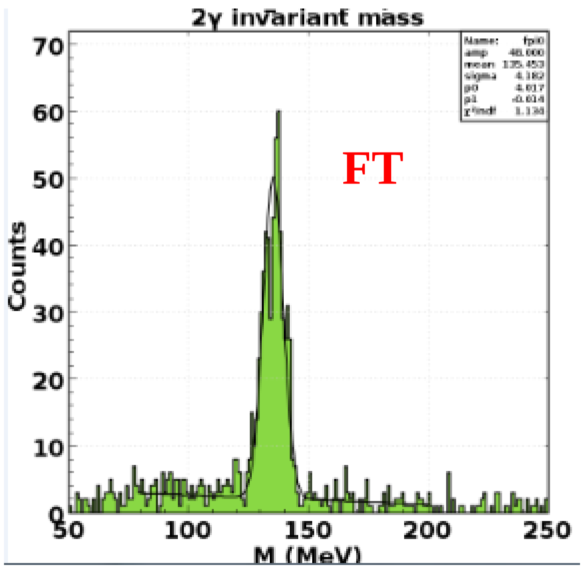


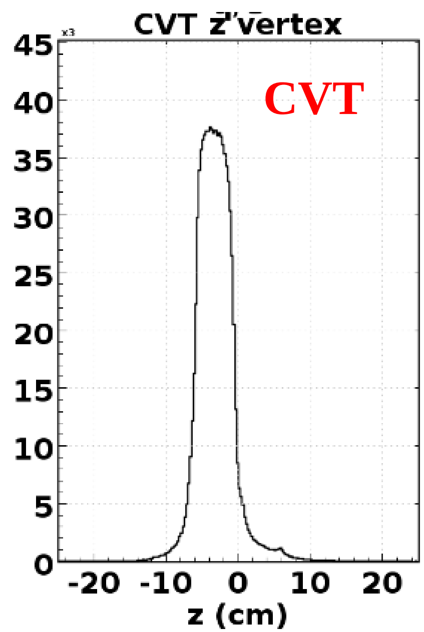
Data quality of RGB data

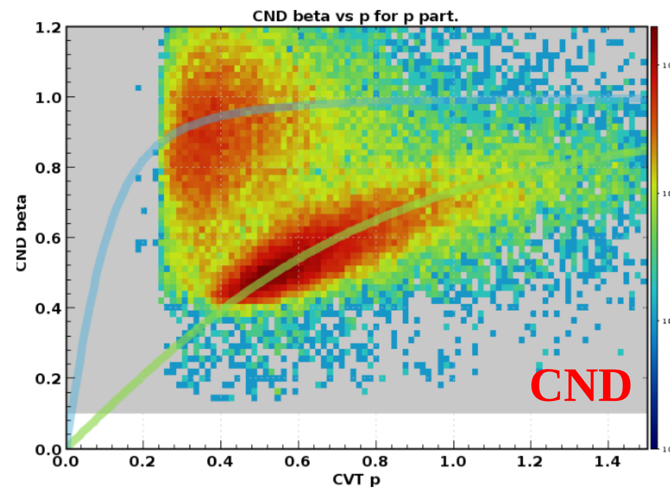












10 files of winter run 11324

First glance at nDVCS from RGB spring data

- **Preliminary calibrations and reconstruction (« DNP cooking »)**
  - 33 runs, at two beam energies (10.6 and 10.2 GeV)
  - ~20% of the spring run statistics (~8% of the 2019 data, ~3% of the originally approved beamtime)

- Final state: **enγ** reconstructed using CLAS12 PID
  - no refined PID, no fiducial cuts, no corrections

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

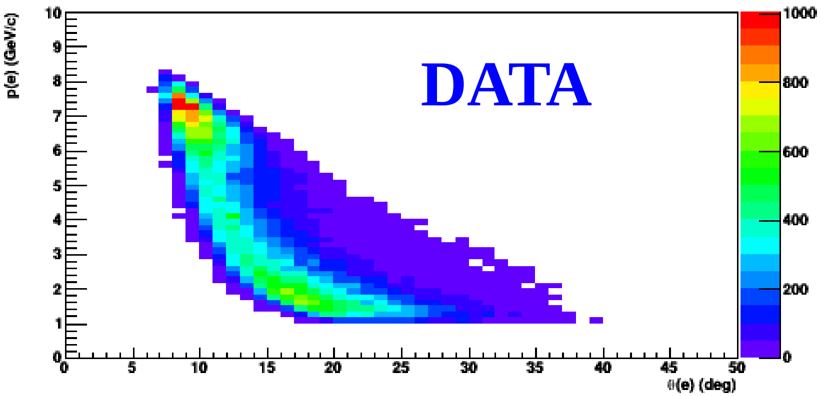
- **Photons** are reconstructed in FT and FEC
  - Minimum energy 1 GeV
  - The highest-energy photon of the event is chosen

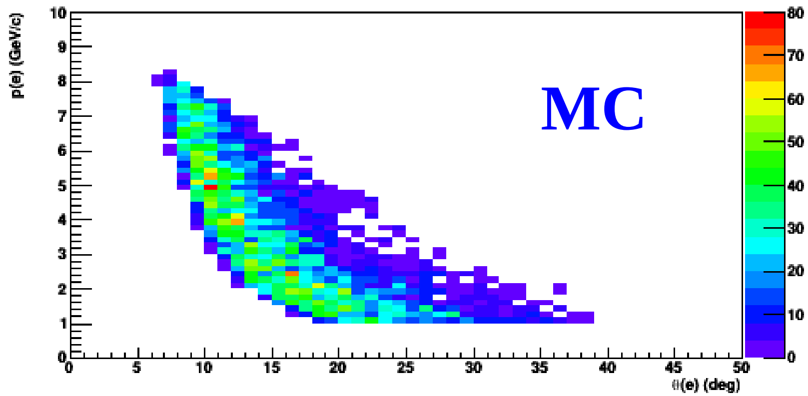
- **Neutrons** are reconstructed in CND and FEC

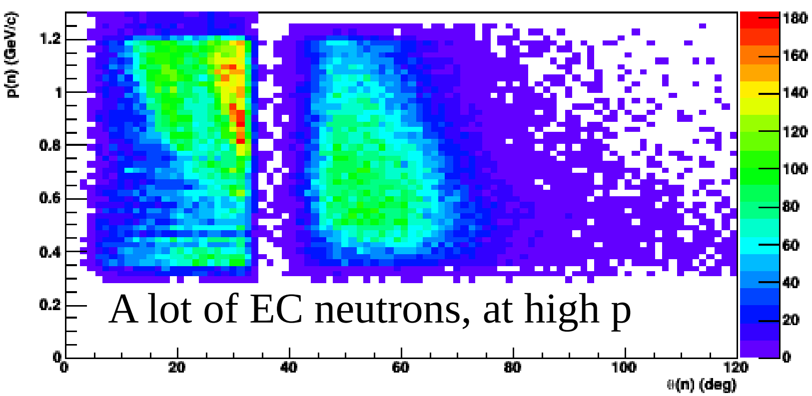
- **nDVCS simulation** on deuteron (GPD based generator)
  - Same event selection as for the data
  - Helps determine optimal detection topology and exclusivity cuts

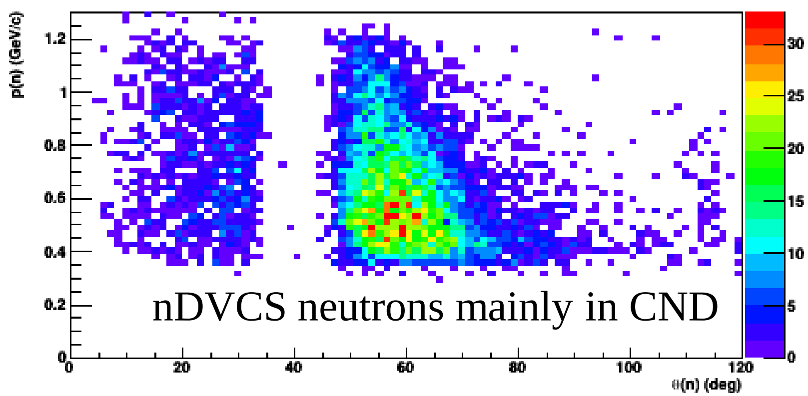
Disclaimer: since the DNP cooking
- ➢ all calibrations for the spring run were completed
- ➢ « Pass1-review » passed
- ➢ Reconstruction of the whole spring dataset ongoing
- ➢ ***New results will be available soon***

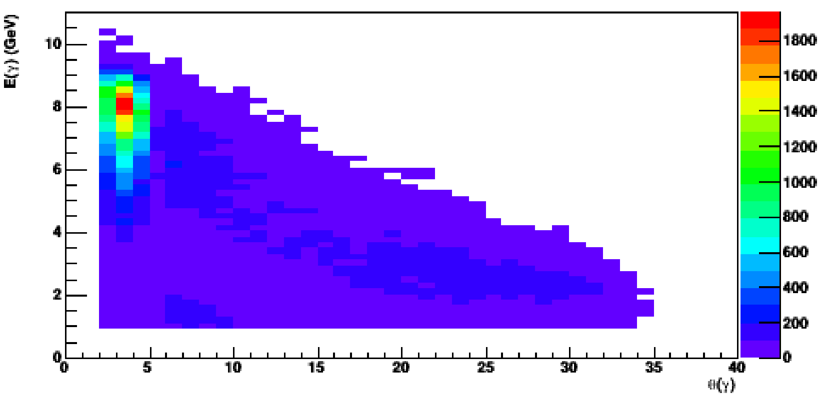
Kinematics (θ vs p): electron, neutrons, photons

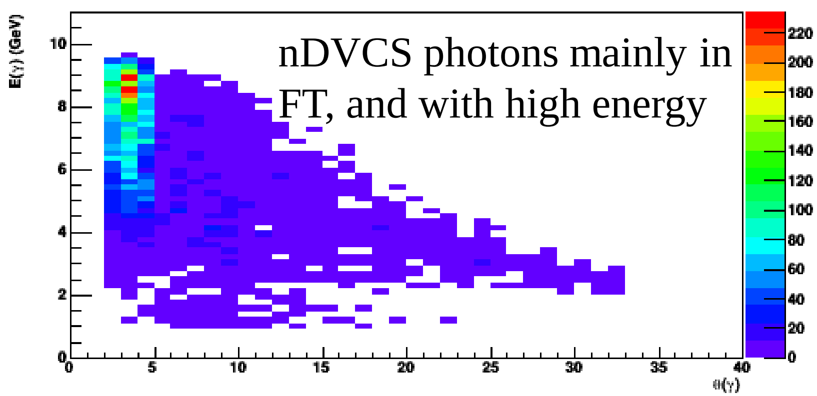












Base cuts:

- Q^2>1 GeV^2
- θ(e)>5°
- p(e)>1 GeV
- vz(e) cut
- p_n>0.3 GeV

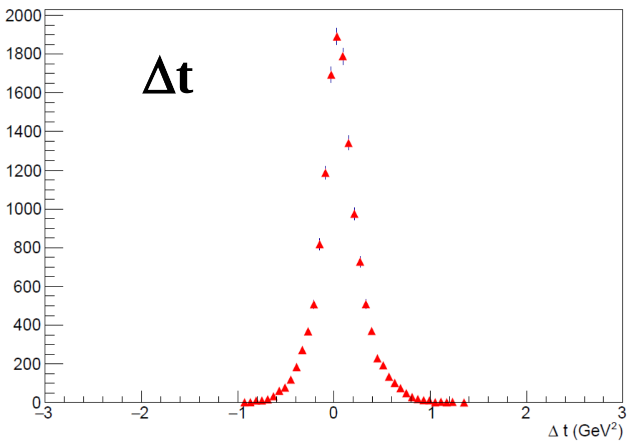
nDVCS: preliminary raw BSA

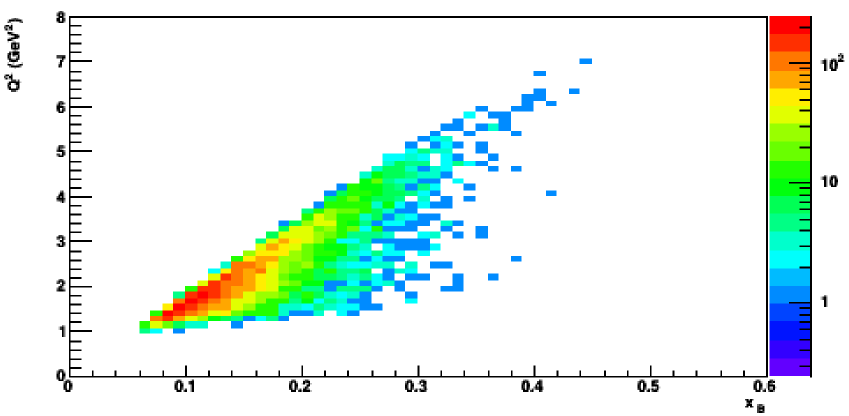
ed→enγ(p)

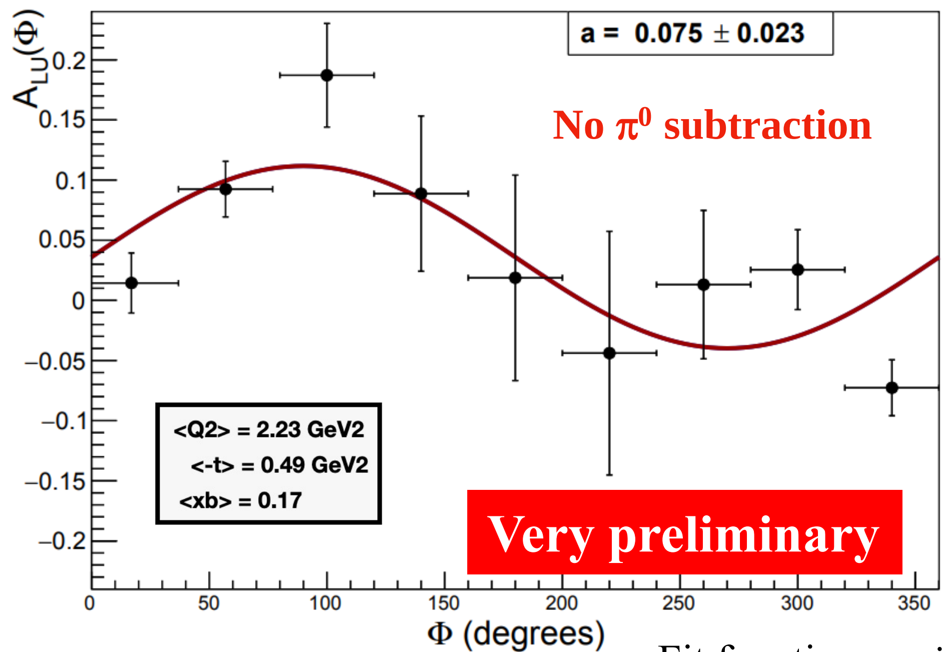
- The chosen combination in each event is the one satisfying at best the exclusivity criteria:

M_X, p_X, E_X (ed→enγX), Δt, Δϕ, $\theta_{\gamma X}$

- 10300 identified nDVCS candidates







Fit function: $a \sin\Phi$

- Raw BSA integrated over all kinematics and detection topologies
- Work ongoing on π^0 subtraction and fiducial cuts
- Work in progress on **a charged particle veto** based on CND and CTOF information: remove proton contamination, due to CVT inefficiencies, from neutron sample

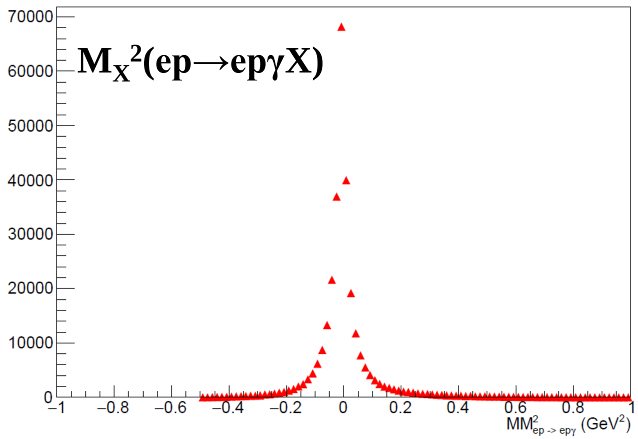
K. Price, A. Hobart (Orsay)

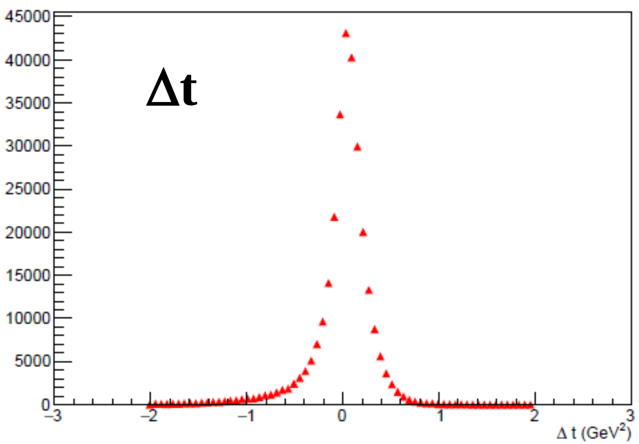
Sanity check (and more): pDVCS on deuterium

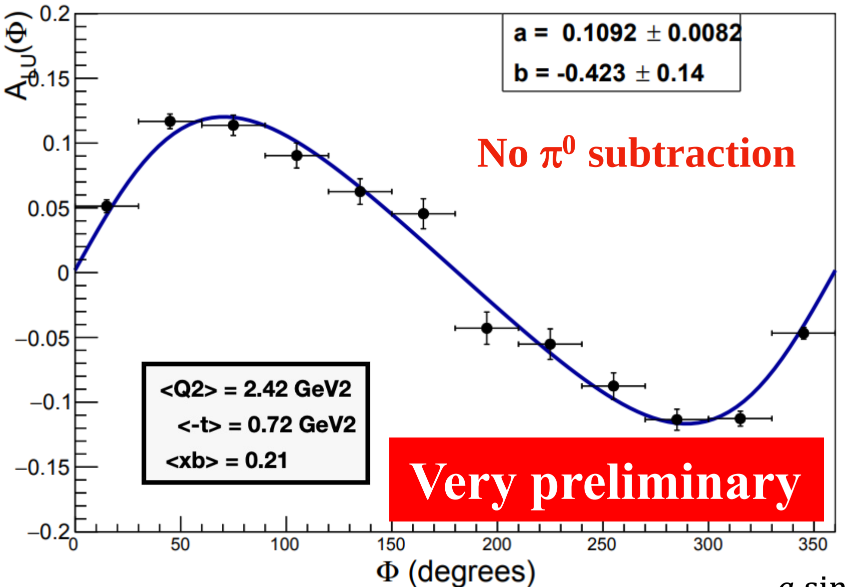
ed→epγ(n)

- Final state selection: at least 1 electron, 1 proton, 1 photon (EB PID + kinematic cuts)
- The chosen combination in each event is the one satisfying at best the exclusivity criteria:

M_X, p_X, E_X (ep→epγX), Δt, Δϕ, $\theta_{\gamma X}$







Fit function: $\frac{a \sin \varphi}{1+b\cos\varphi}$

- 320453 identified pDVCS candidates
- Raw BSA integrated over all kinematics and detection topologies
- **Compatible with raw BSA from pDVCS in RGA**
- **nDVCS and pDVCS yields scale as expected (CS, efficiency)**
- Work on π^0 subtraction underway

Interest of pDVCS on deuterium:

- In itself: nuclear medium effects on proton structure
- To evaluate FSI for nDVCS, comparing to free pDVCS

A. Hobart (Orsay)

Future experiment: nDVCS, target-spin asymmetry

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

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

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

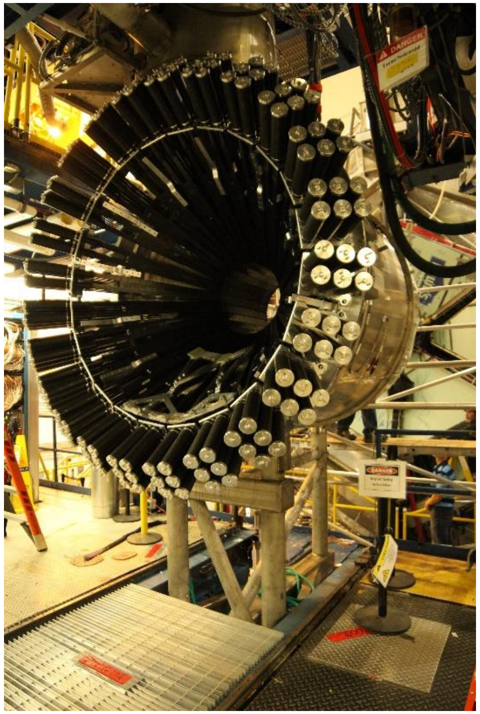
→ 3 observables (including BSA), constraints on real and imaginary CFFs of various neutron GPDs

$eND_3 \rightarrow e(p)n\gamma$

CLAS12 + Longitudinally polarized target + CND

$L = 3/20\cdot10^{35}cm^{-2}s^{-1}$
Run time = 40 days
$P_t = 0.4$; $P_b = 0.85$

Foreseen for 2022



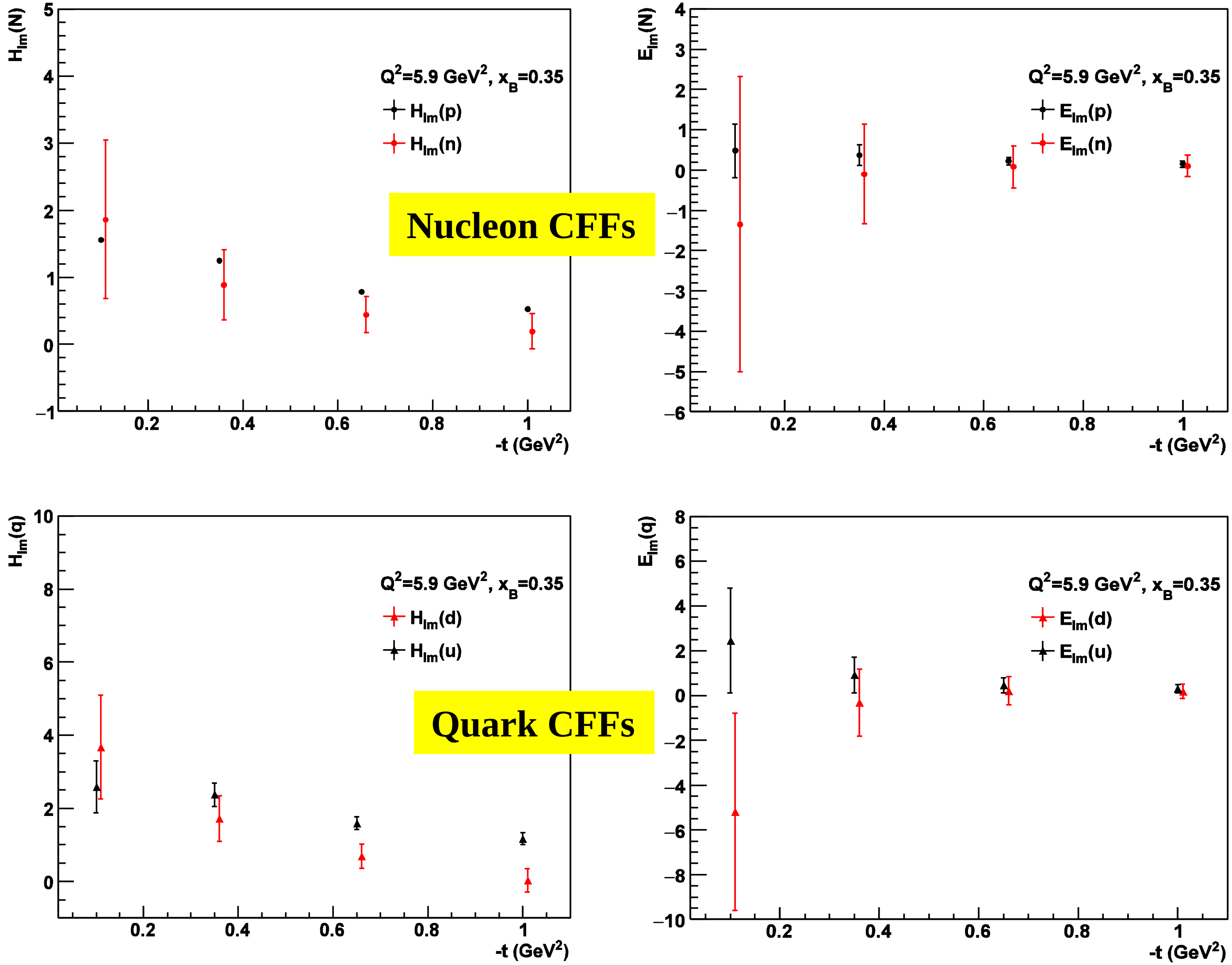
CLAS12: projections for flavor separation

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

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

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

Fits done to all the **projected observables** for **pDVCS** (BSA, lTSA, lDSA, tTSA, CS, DCS) and **nDVCS** (BSA,lTSA, lDSA) of the CLAS12 program



Summary and outlook

- Now that a first tomographic image of the proton was delivered extracting CFFs from pDVCS, it is time to think about **GPD flavor separation** and **Ji's sum rule**
- The **beam-spin asymmetry for nDVCS** is a precious tool for this task
- The pioneering **Hall-A experiment at 6 GeV** showed the importance of this channel
- The **CLAS12** experiment E12-11-003 measures the **BSA for nDVCS with detected neutron, over a vast phase space**
- The first ~43% of the experiment ran in the spring of 2019 at JLab
- The **Central Neutron Detector**, built for this experiment, is performing according to specifications
- A first exploratory analysis of a small fraction of the data shows that **the nDVCS channel can be extracted,** with a promising **raw BSA signal**
- The 2019 data are currently being processed

- ➢ Another nDVCS experiment on **polarized deuterium target** will be carried out in 2022 with CLAS12
- ➢ The two experiments will be combined to extract **neutron CFFs** (in particular Im$\mathcal{H}$ and Im$\mathcal{E}$)
- ➢ The combination of neutron and proton CFFs will allow **flavor separation**
- ➢ The **Ji's sum rule** is the ultimate, ambitious goal of this program