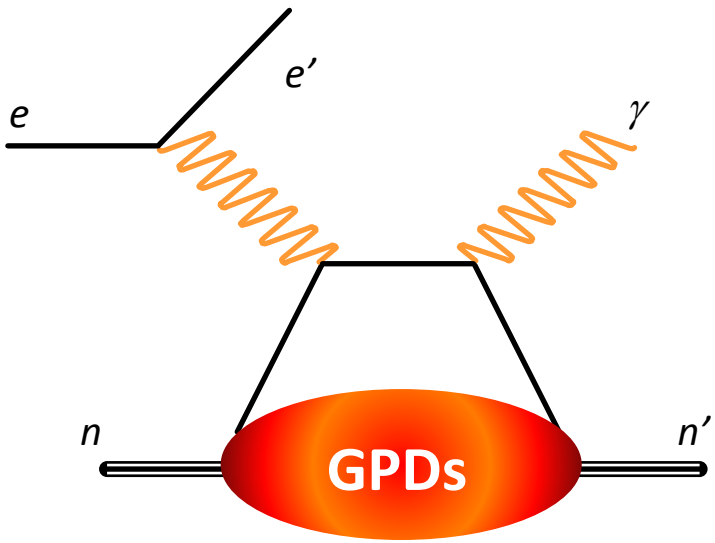
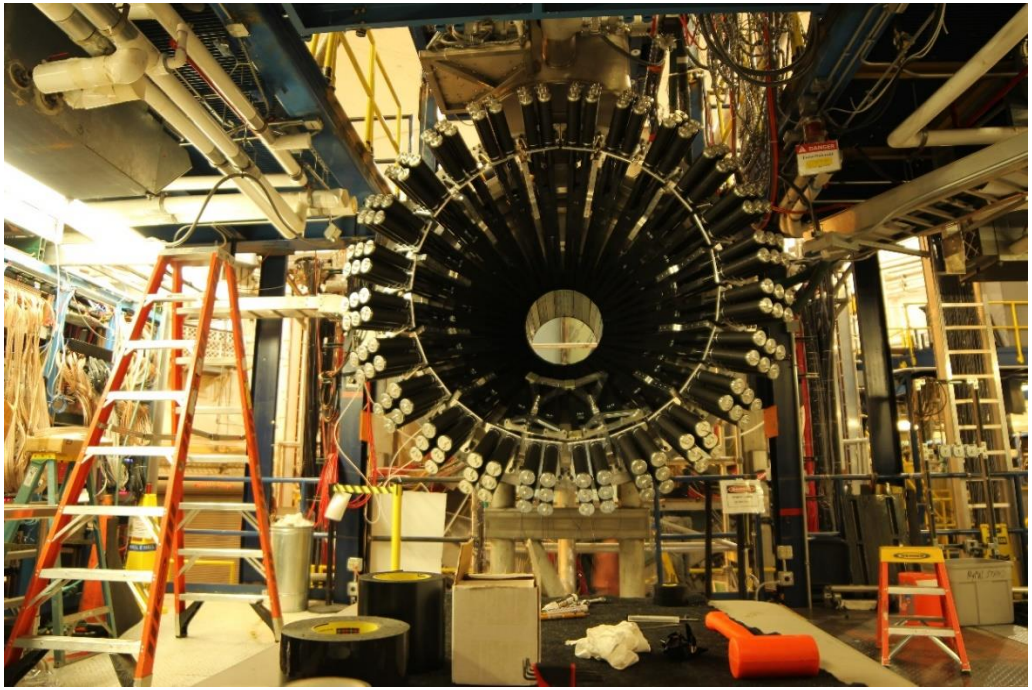
Deeply Virtual Compton Scattering on the neutron with CLAS12 at 11 GeV

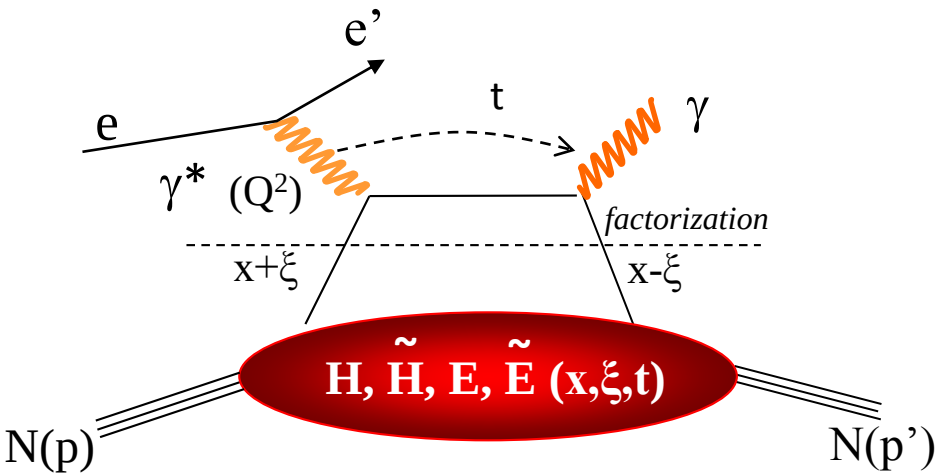




Silvia Niccolai (IPN Orsay), for the CLAS Collaboration

INPC 2019, Glasgow (UK) - August 1st, 2019

Deeply Virtual Compton Scattering and quark GPDs



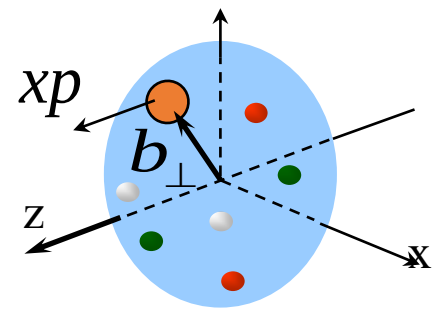
- $Q^2 = -(k-k')^2$
- $x_B = Q^2/2M\nu$ $n = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ long. mom. fract.
- $t = \Delta^2 = (p-p')^2$
- $x \cong x_B/(2-x_B)$

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)

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

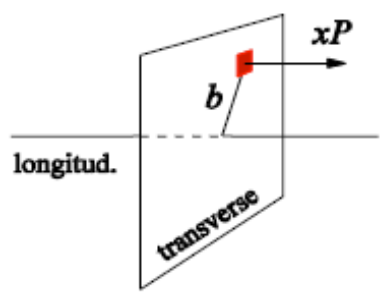
X. Ji, Phy.Rev.Lett.78,610(1997)

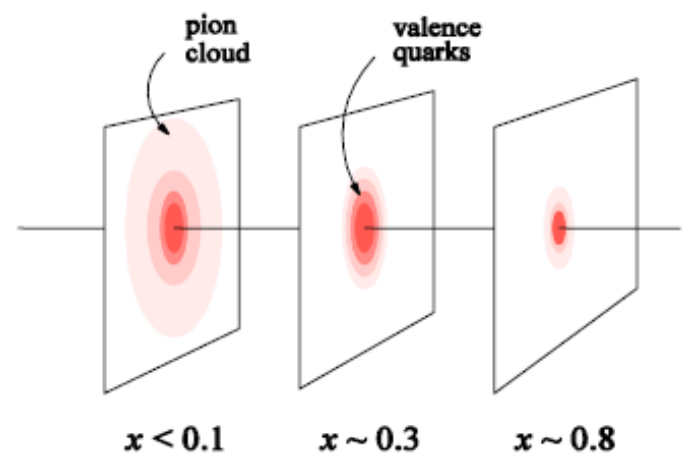


Nucleon tomography

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

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





M. Burkardt, PRD 62, 71503 (2000)

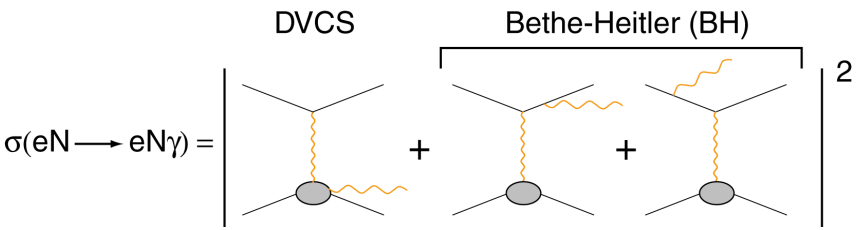
Accessing GPDs through DVCS

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

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

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

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



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

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

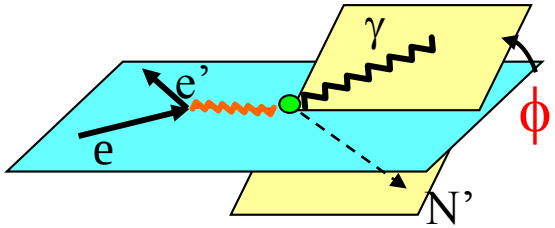
Proton Neutron

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

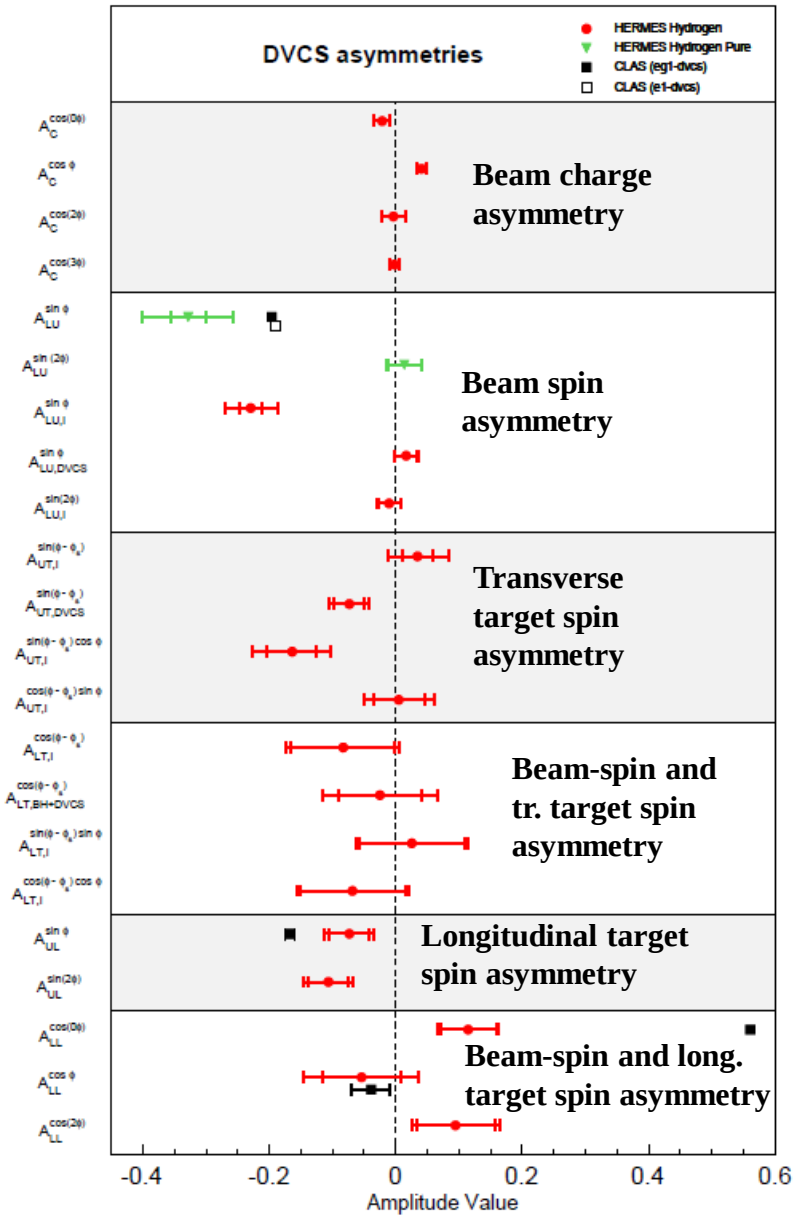
Unpolarized beam, longitudinal target:
$\Delta\sigma_{UL} \sim \sin\phi\,\mathrm{Im}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2\tilde{\mathcal{E}}\}$ ⇒ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$ $Im\{\mathcal{H}_n, \mathcal{E}_n\}$

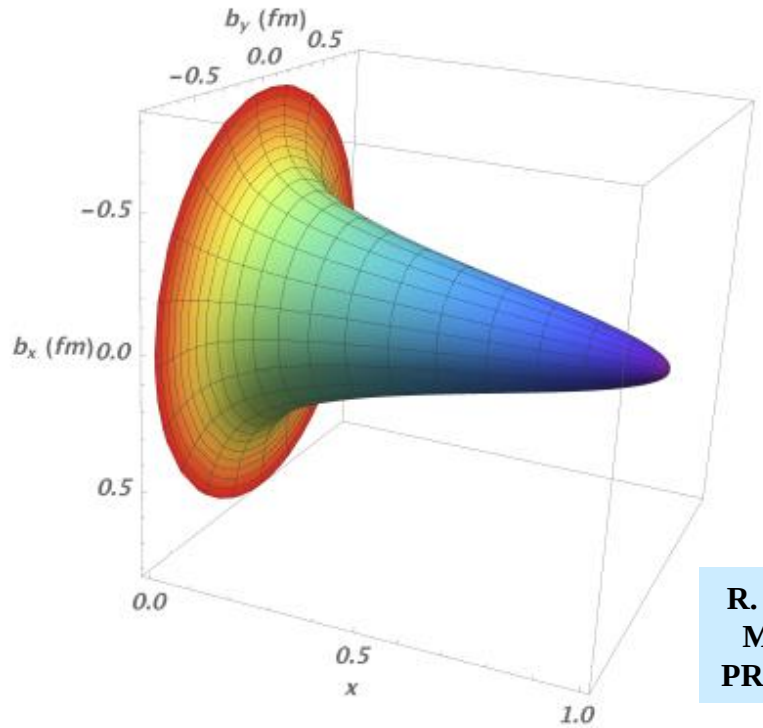
Polarized beam, longitudinal target:
$\Delta\sigma_{LL} \sim (A+B\cos\phi)\mathrm{Re}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) + \ldots\}$ ⇒ $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$ $Re\{\mathcal{H}_n, \mathcal{E}_n\}$

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



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

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

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:

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

Neutron

Unpolarized beam, transversely polarized target:

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

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

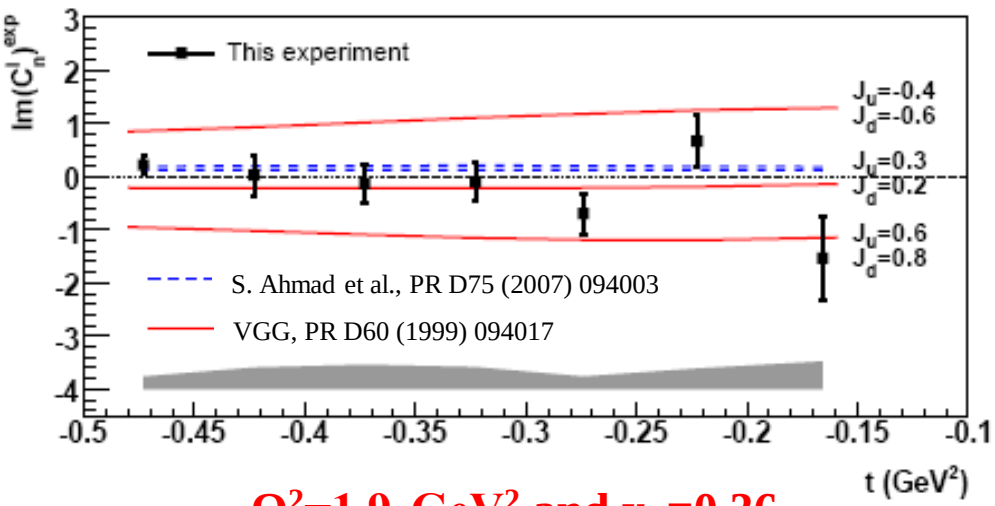
DVCS on the neutron in Hall A at 6 GeV

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

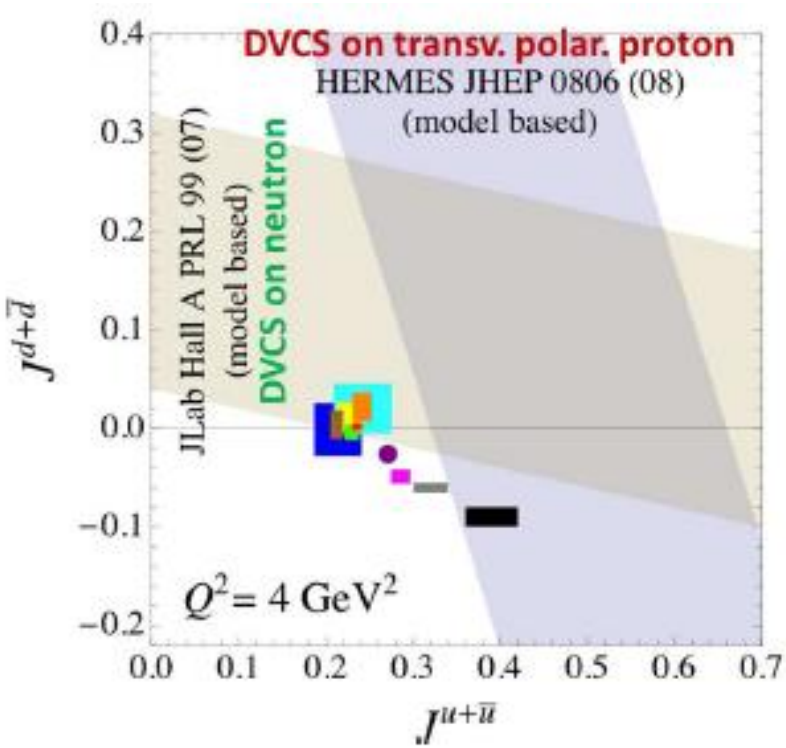
$$D(e,e'\gamma)X - H(e,e'\gamma)X = n(e,e'\gamma)n + d(e,e'\gamma)d + \ldots$$

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

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



Q^2=1.9 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

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

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
- Results recently submitted for publication

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

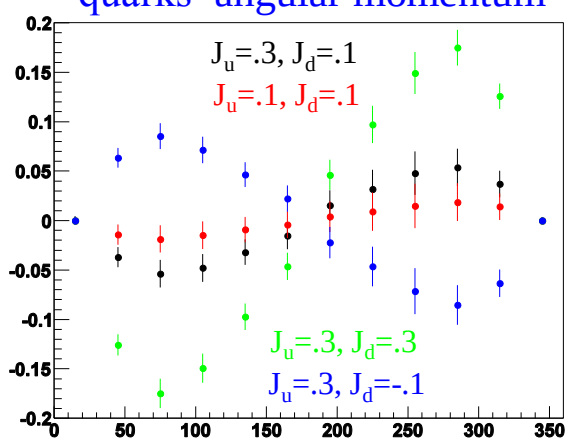
+Central Neutron Detector

Liquid deuterium target

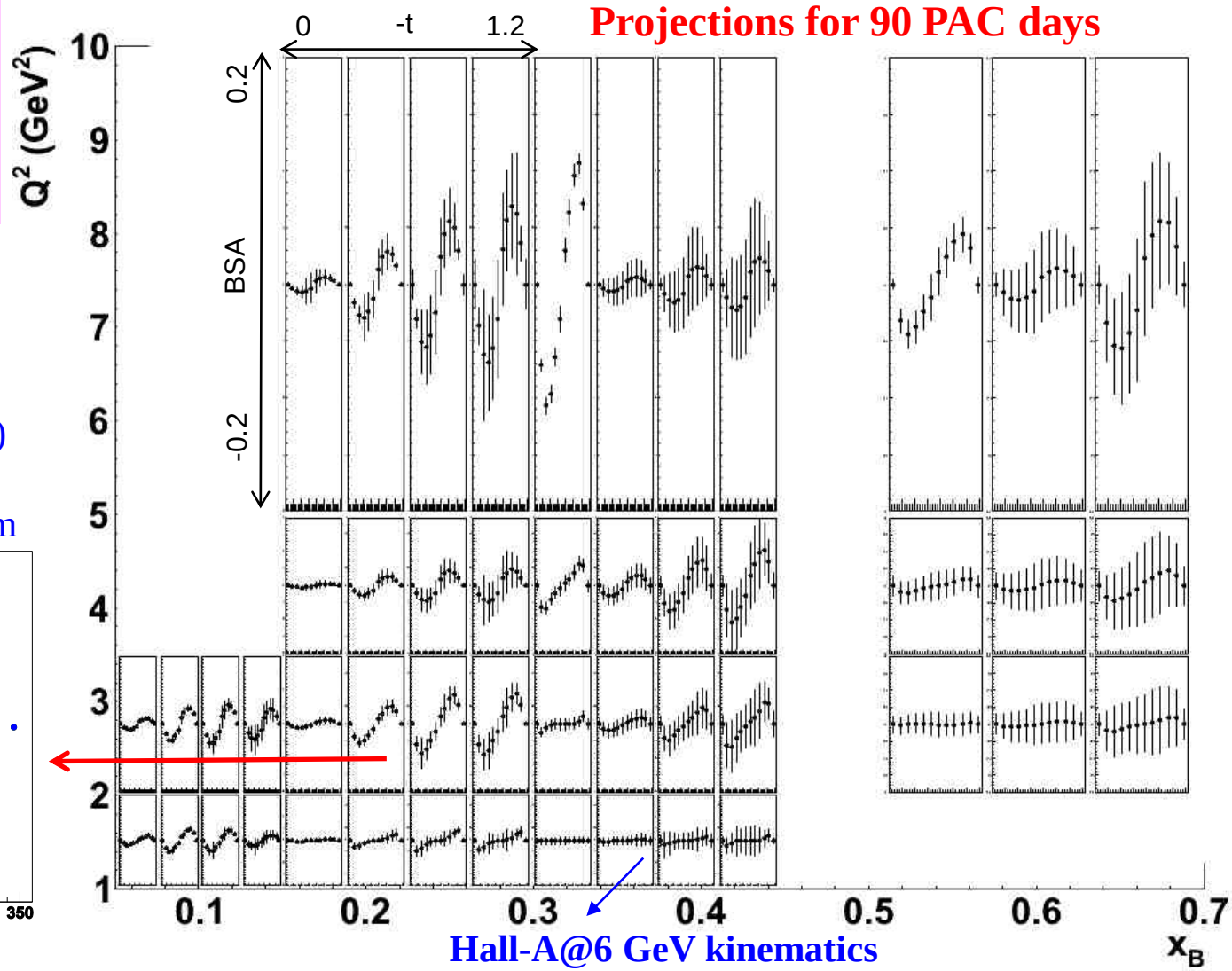
Beam polarization =85%

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

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



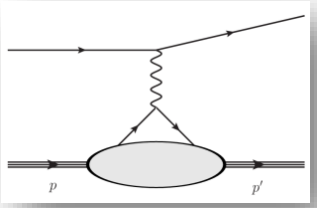
Projections for 90 PAC days



Hall-A@6 GeV kinematics

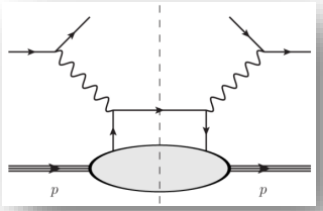
CLAS12 Run Group B

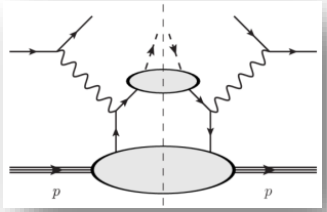
Electroproduction on deuterium with CLAS12



Elastic Scattering

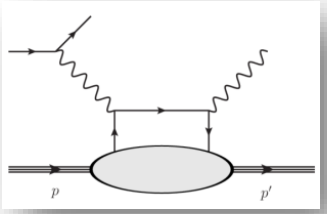
DIS





SIDIS

nDVCS



+ J/psi photoproduction
+ Short Range Correlations

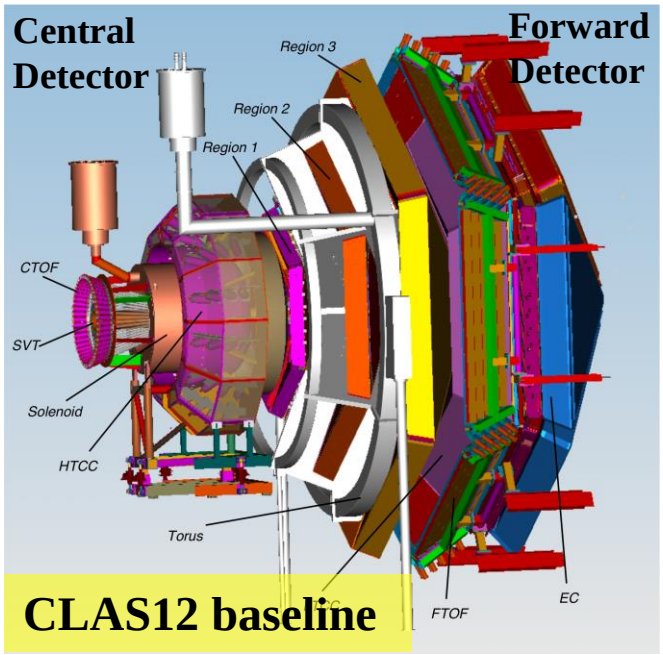
2019 schedule: first part of RG B in Febuary 6th - March 25th 2019, second part in November 1st – December 19th
→ ~44.5 PAC days (~1/2 of approved run time)

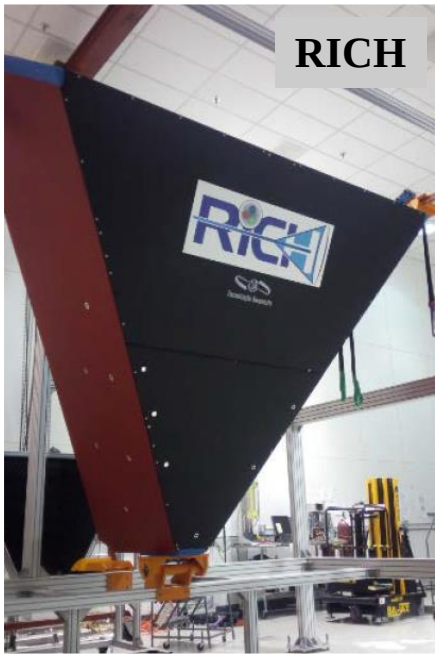
Statistics for the spring run:

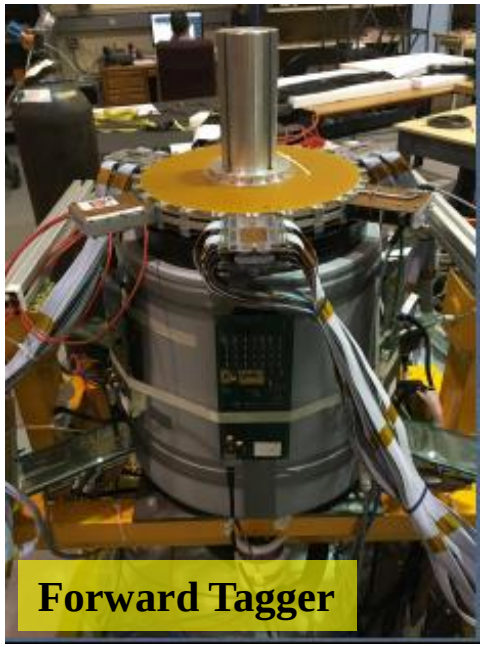
- 237 « good » production runs + various ancillary runs
- « Production » beam current: 50 nA
- ~9.7 B triggers at **10.6 GeV**, 11.7 B triggers at **10.2 GeV**
- Average beam polarization ~86% (22 Moeller runs)
- ~25% of the approved beam time

- ✓ First round of preliminary calibrations done
- ✓ Reconstruction ongoing

CLAS12 Run group B: experimental setup







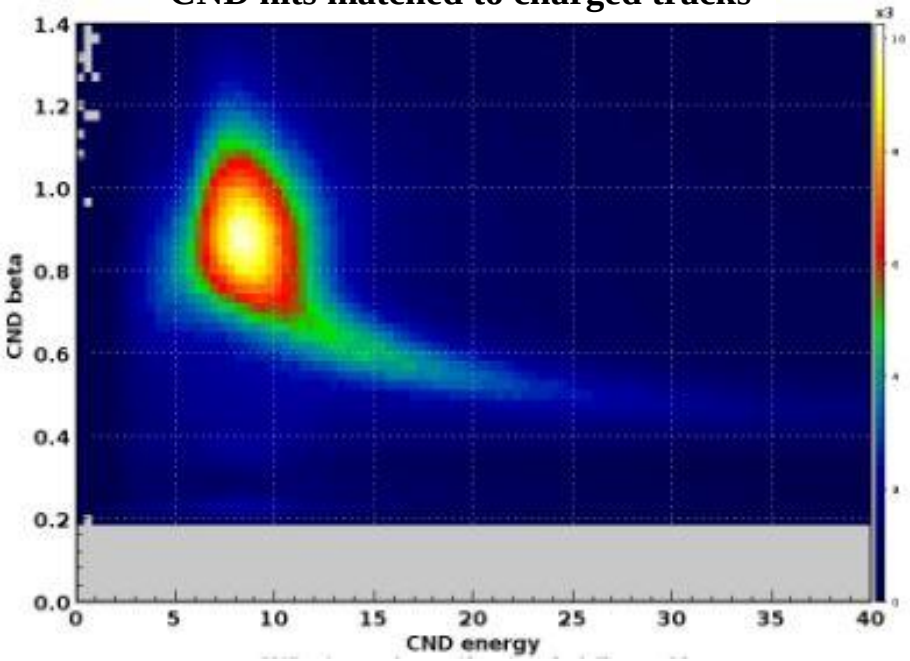
CND: characteristics and performances with RGB data

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 ✓
- momentum resolution $\delta p/p < 10\%$ ✓
- neutron detection efficiency ~10% ✓

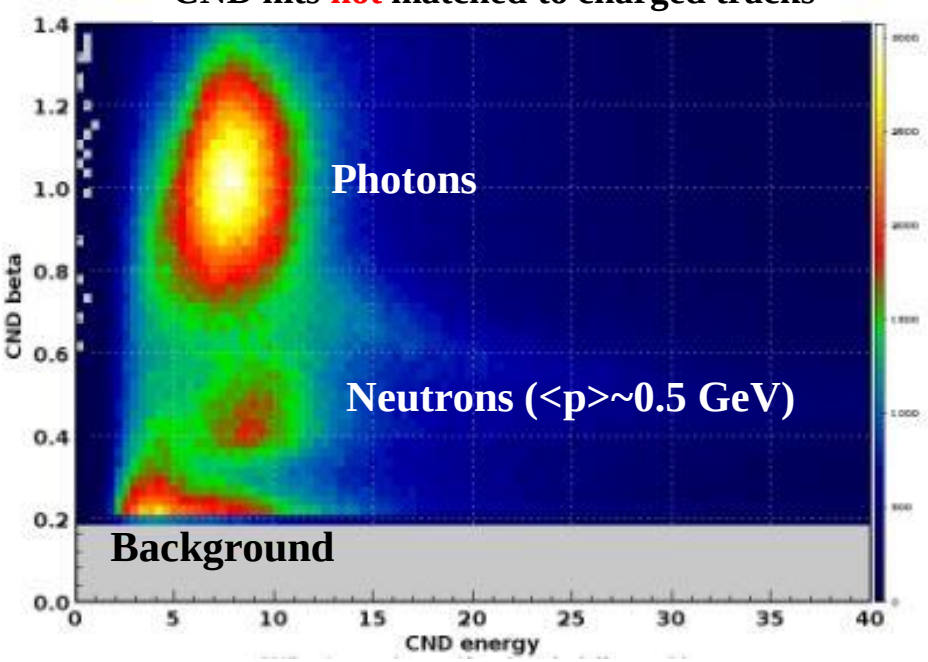
CND design: scintillator barrel - 3 radial layers, 48 bars per layer **coupled two-by-two** downstream by a **"u-turn" lightguide,** 144 long light guides with **PMTs** upstream

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

CND hits matched to charged tracks



CND hits not matched to charged tracks



First glance at nDVCS from RGB spring data

- **Very preliminary calibrations and reconstruction**
  - 11 full runs, at both beam energies (10.6 and 10.2 GeV)
  - ~5% of the spring run statistics (1.25% of the approved beam time)

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

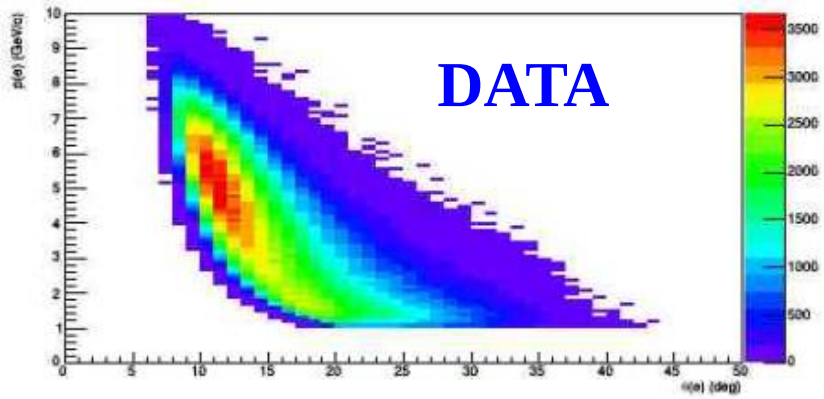
$\vec{e}d \rightarrow e\gamma n(p)$

- **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
  - The neutron having momentum closest to the average expected momentum for nDVCS (~0.6 GeV) is taken

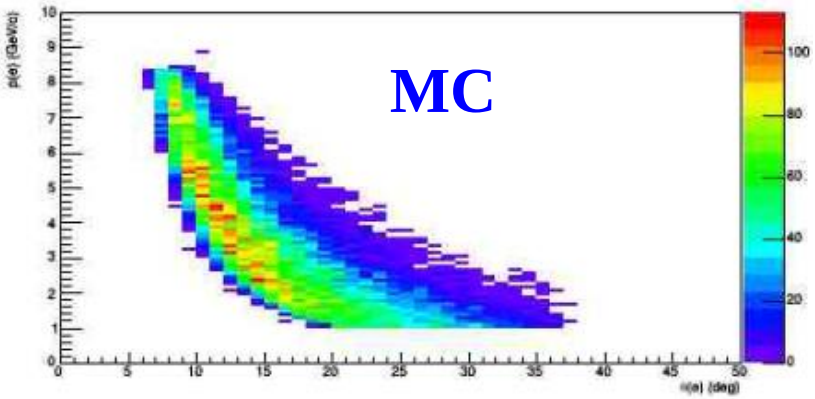
- **nDVCS simulation** on deuteron (GPD based generator)
  - Same event selection as for the data
  - Helps determine optimal detection topology and exclusivity cuts

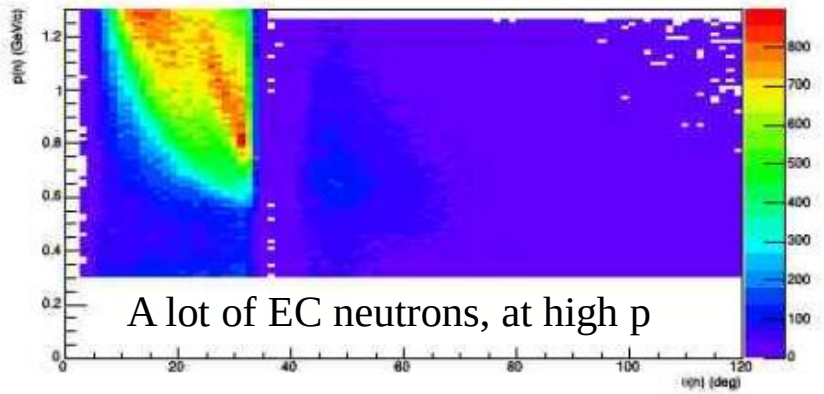
Kinematics (θ vs p): electron, neutrons, photons

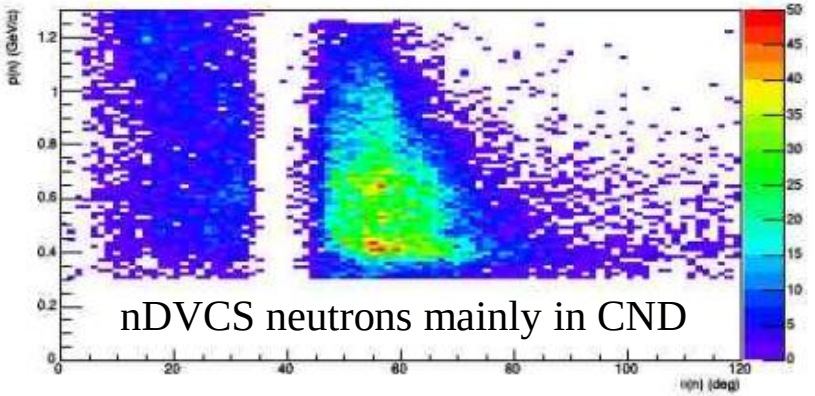


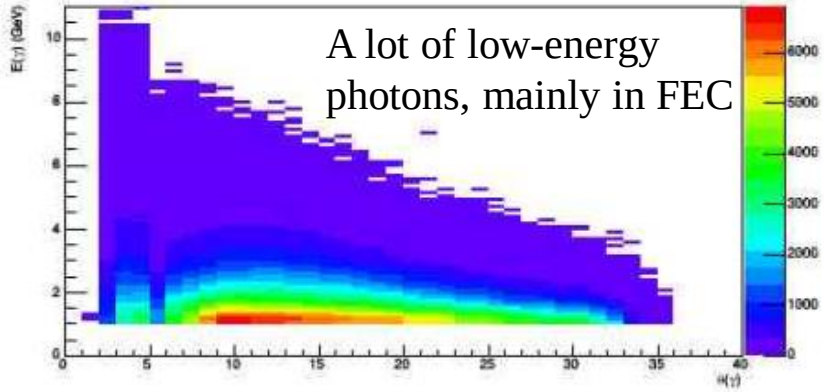
Base cuts:

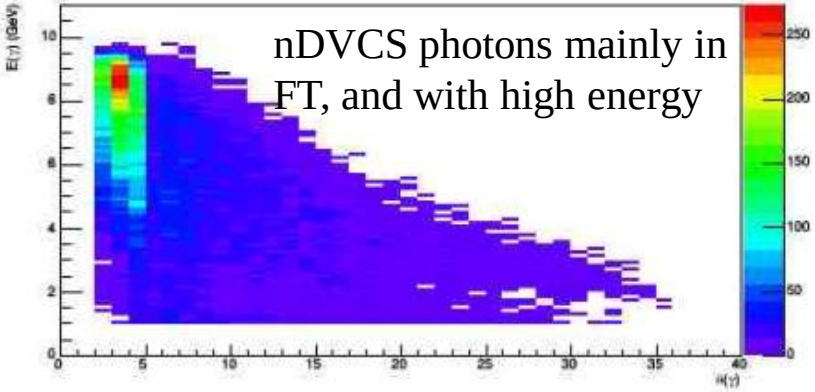
- Q^2>1 GeV^2
- θ(e)>5°
- p(e)>1 GeV
- vz(e) cut
- p_n>0.3 GeV
- No other charged particles detected



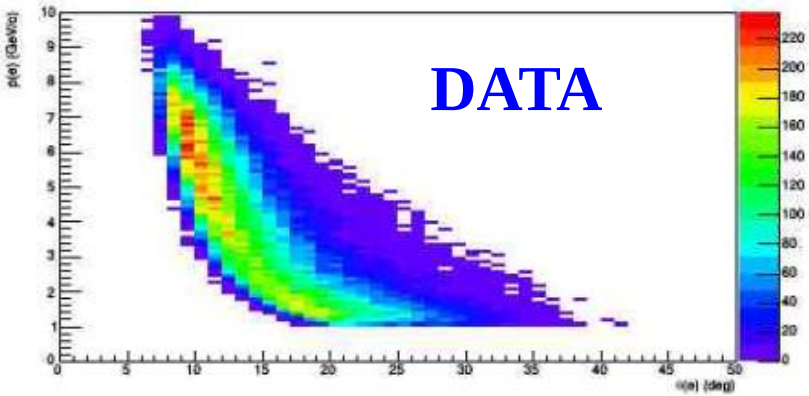






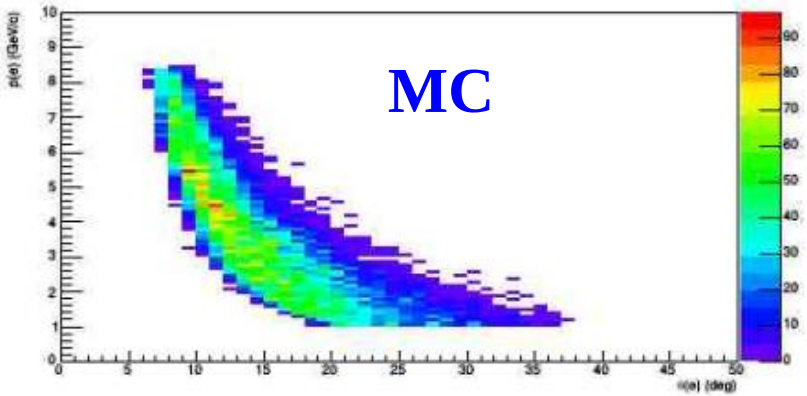


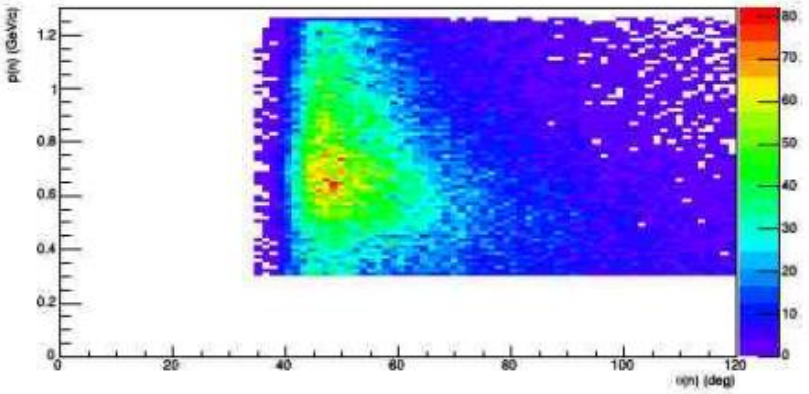
Kinematics (θ vs p): electron, neutrons, photons

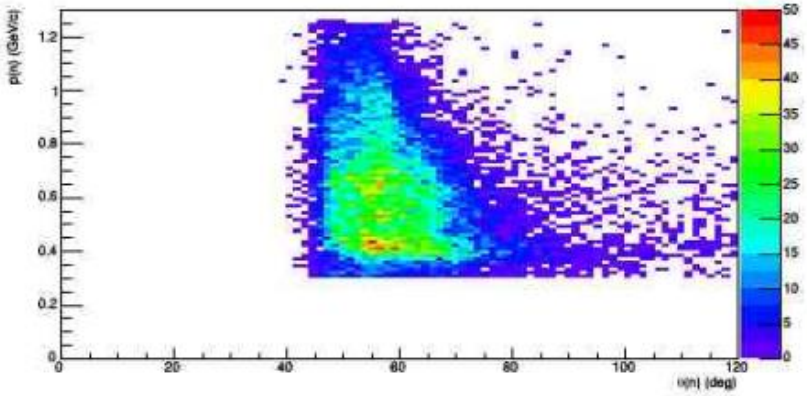


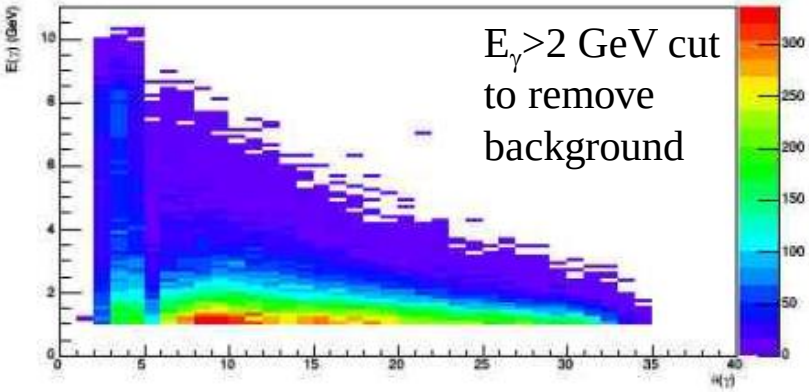
Base cuts:

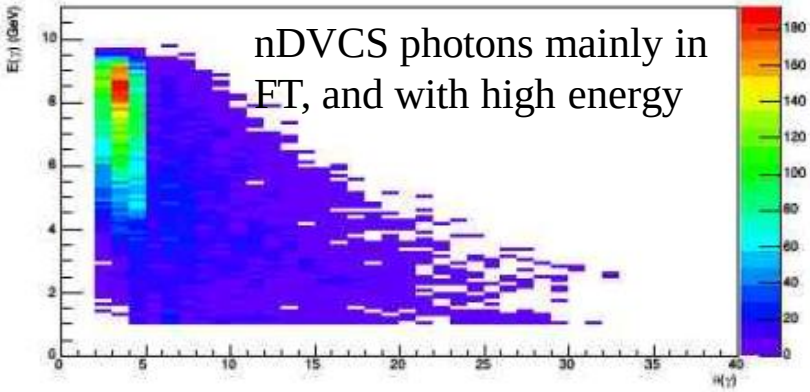
- Q^2>1 GeV^2
- θ(e)>5°
- p(e)>1 GeV
- vz(e) cut
- p_n>0.3 GeV
- No other charged particles detected
- **Neutrons in CND**



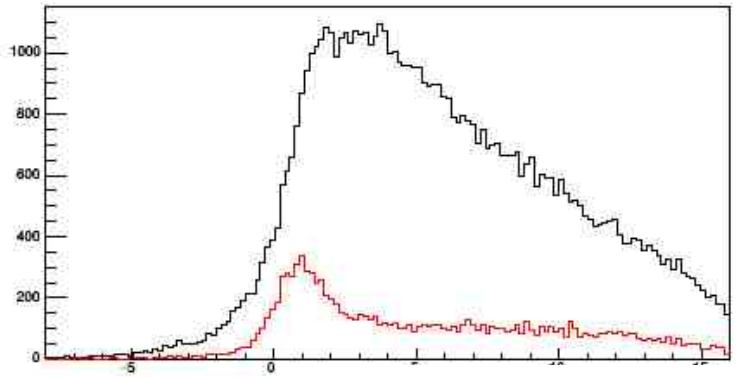




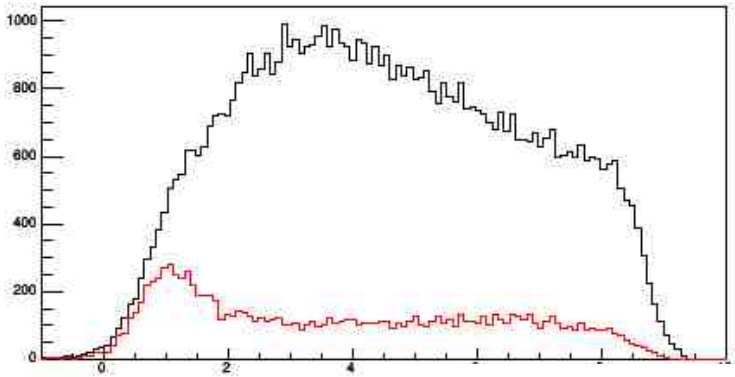




Exclusivity variables

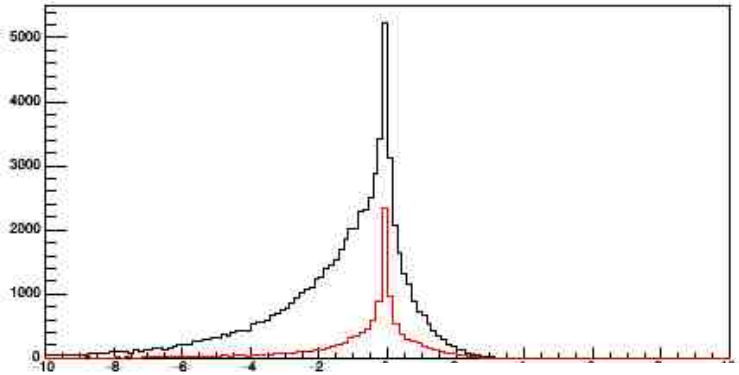


M(X)^2 (ed→e'nγX) (GeV^2)

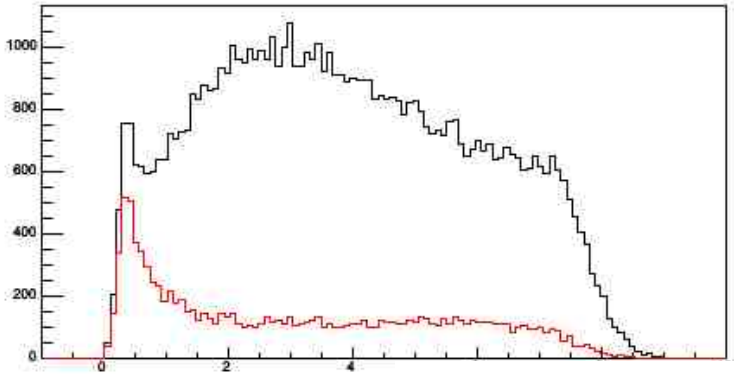


E(x) (ed→e'nγX) (GeV)

Base cuts + E_γ>2 GeV



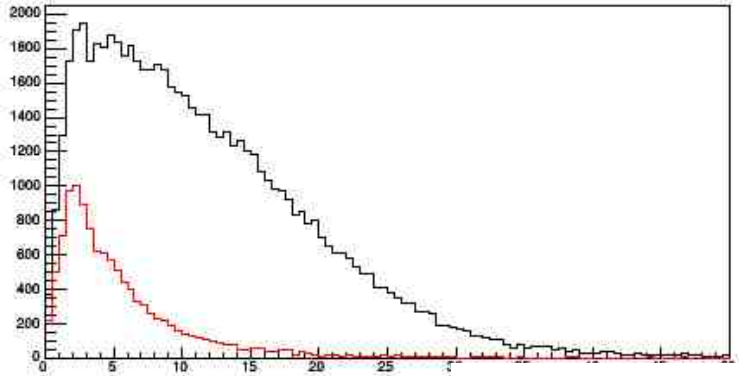
M(X)^2 (en→e'n'γX) (GeV^2)



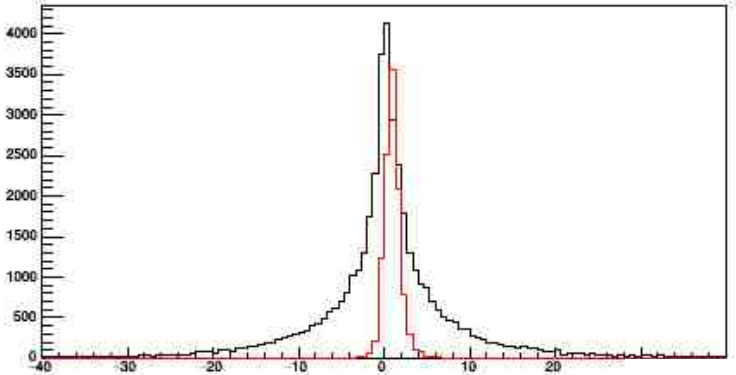
p(x) (ed→e'nγX) (GeV)

enγ events with CND neutron

enγ events with CND neutron, FT photon



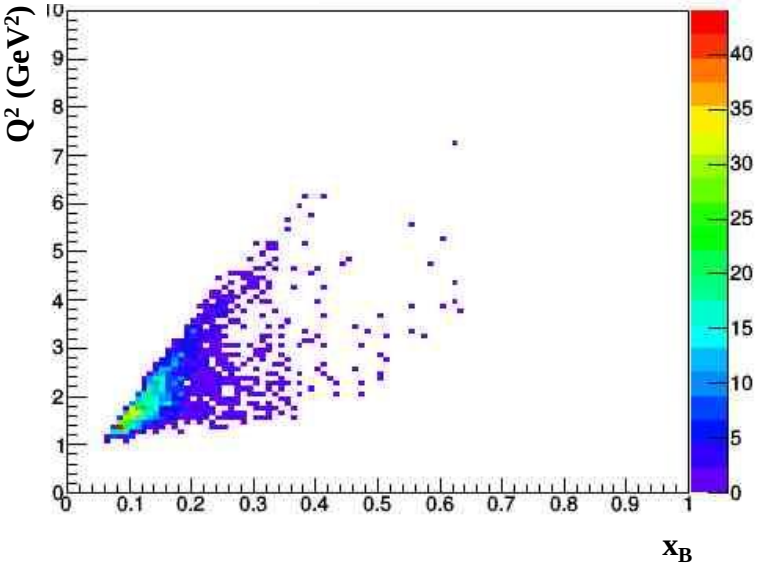
Cone angle θγX (°)

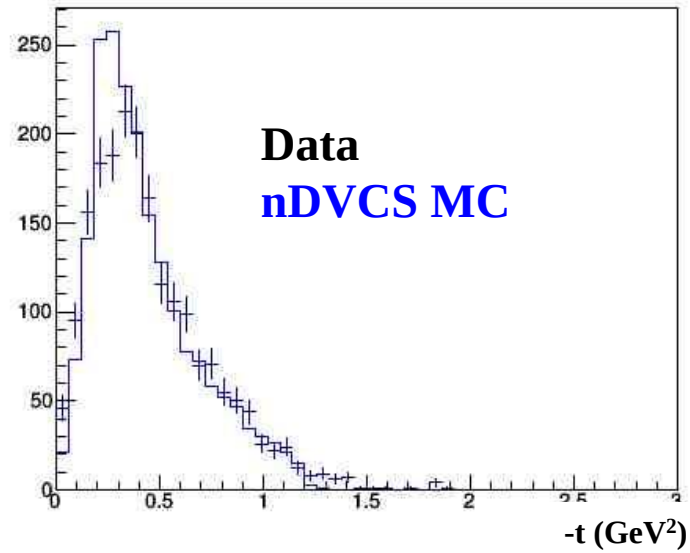


Δϕ (°)

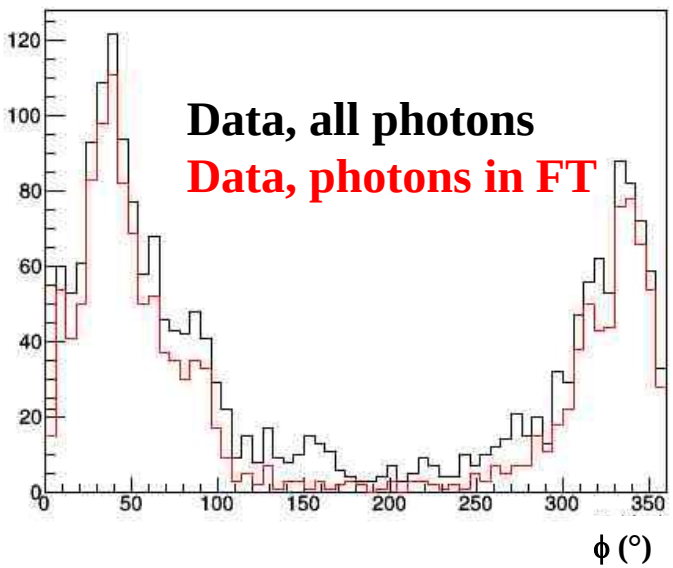
enγ yield vs ϕ, after exclusivity cuts

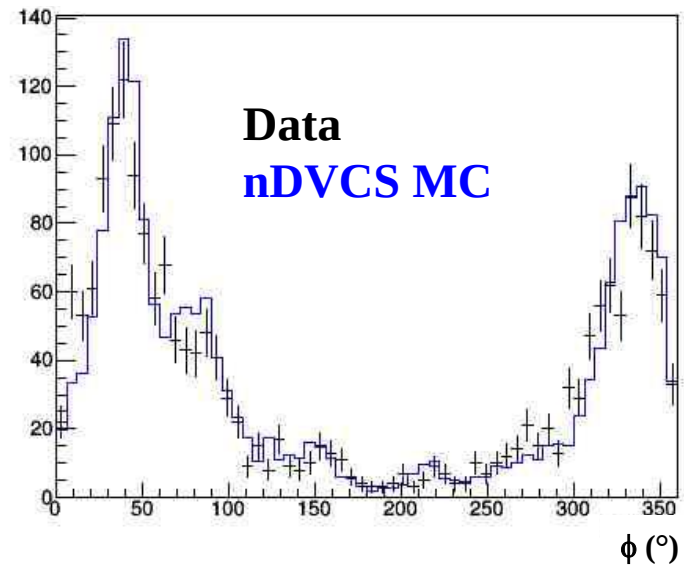
Very preliminary





Very preliminary
exclusivity cuts:
$0<M(X)^2<2$ GeV^2
$0<E(X)<2$ GeV
$0<p(X)<1$ GeV
$-2°<\Delta\phi<2°$
$-1<\Delta t<1$ GeV^2





To-do list:

- Refine calibrations
- Reconstruct all data
- Refine exclusivity cuts
- Study other topologies (FD…)
- Beam-helicity asymmetry
- π^0 background subtraction
- ....

Future experiment: nDVCS, target-spin asymmetry

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

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

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

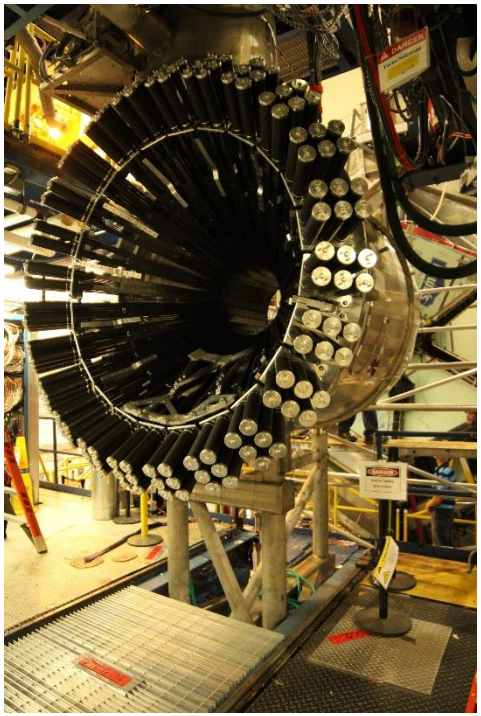
→ 3 observables (including BSA), constraints on real and imaginary CFFs of various neutron GPDs

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

CLAS12 + Longitudinally polarized target + CND

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

Will run in 2021



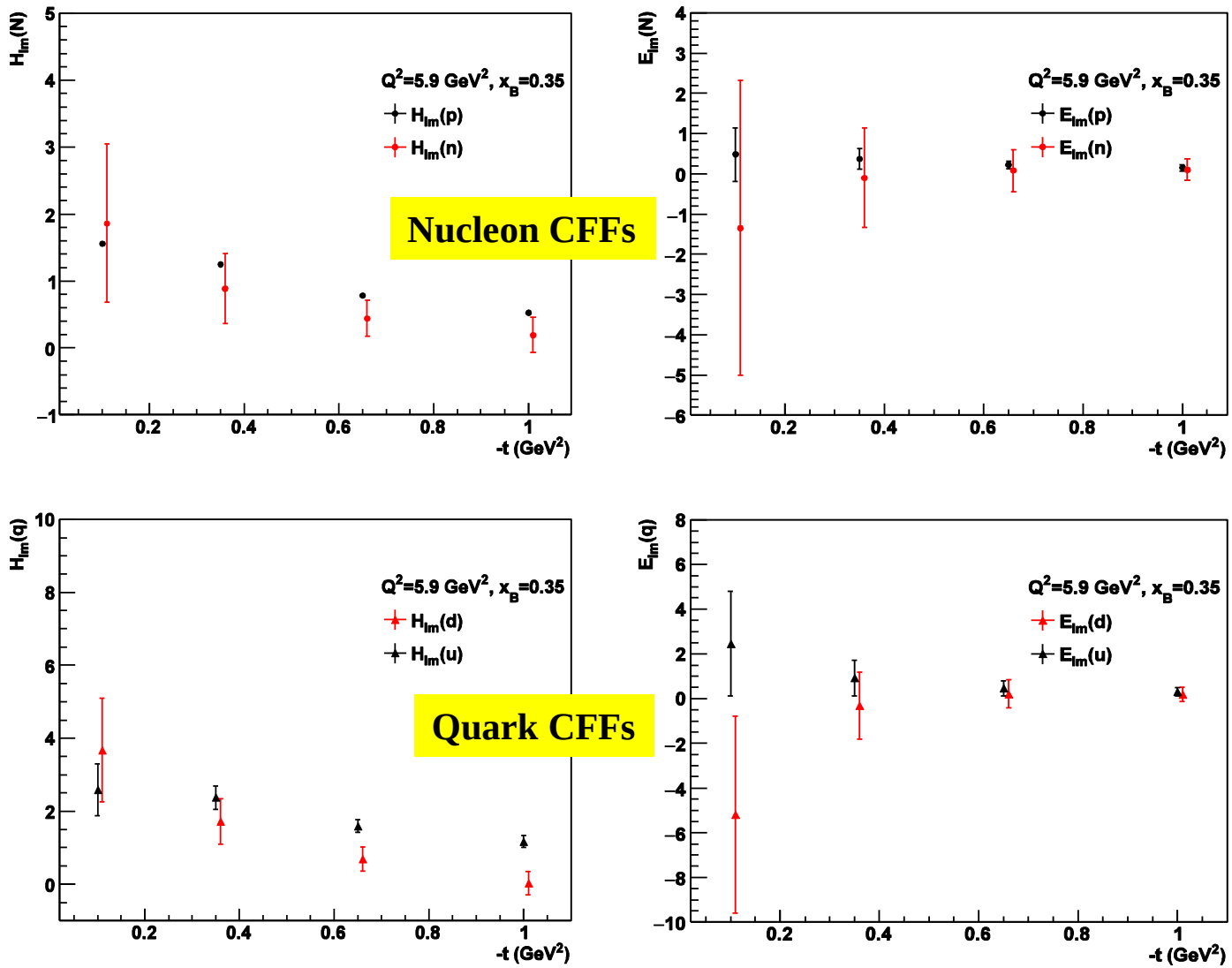
CLAS12: projections for flavor separation

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

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

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

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 **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 but the kinematics were unfavorable (~zero asymmetry signal)
- The **CLAS12** experiment E12-11-003 is perfectly suited to measure **BSA for nDVCS over a vast phase space**
- The first ~25% 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**
- The first half of E12-11-003 will be completed in the fall/winter of 2019
- Another nDVCS experiment on **polarized deuterium target** will be carried out in 2021 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