Deeply Virtual Compton Scattering on the neutron (and on the proton) from deuterium with CLAS12 at 11 GeV

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Light Cone 2021, Jejudo (South Korea)
12/1/2021
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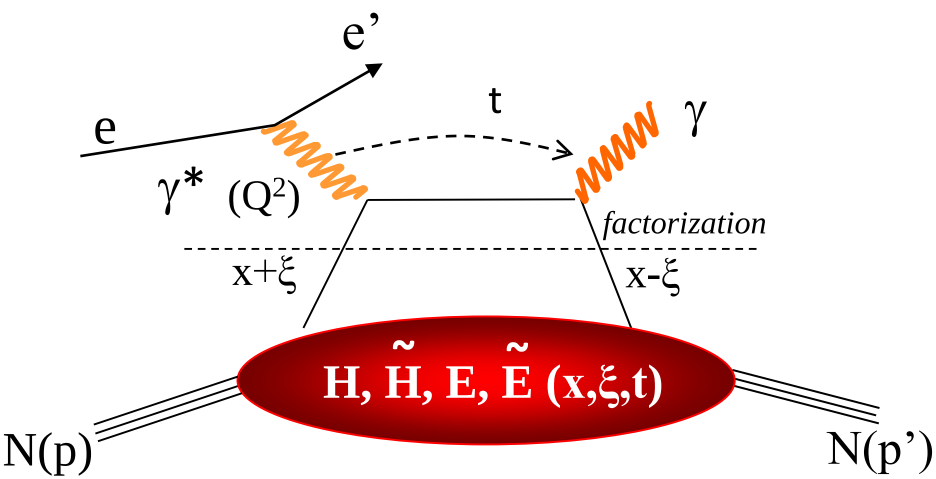
CEBAF Large Acceptance Spectrometer

IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

Deeply Virtual Compton Scattering and quark GPDs



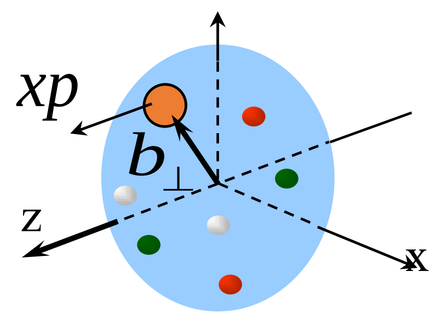
- $Q^2 = -(k-k')^2$
- $x_B = Q^2/2M\nu$ $n = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ long. mom. fract.
- $t = \Delta^2 = (p-p')^2$
- $x \cong x_B/(2-x_B)$

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)

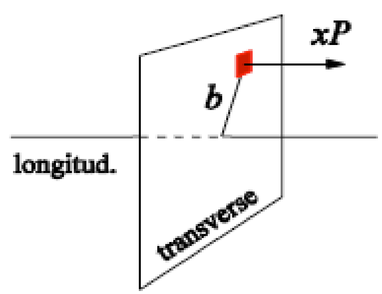


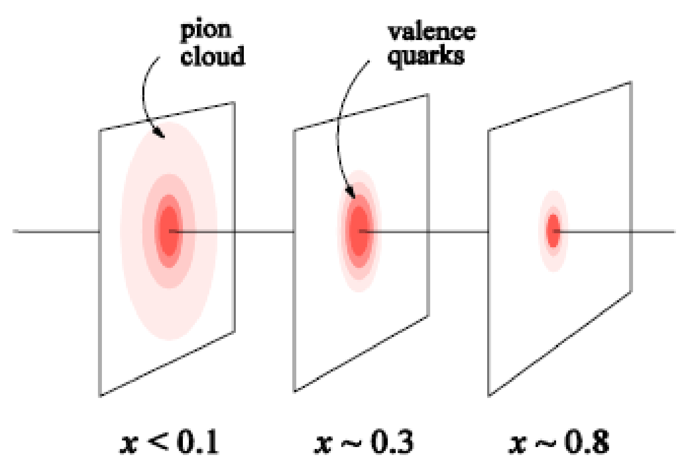
Nucleon tomography

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

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

M. Burkardt, PRD 62, 71503 (2000)





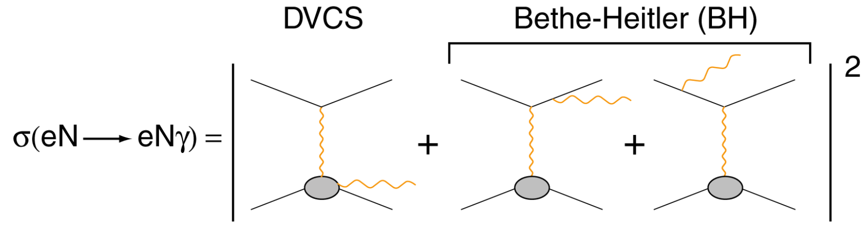
Accessing GPDs through DVCS

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

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

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

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



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

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

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:

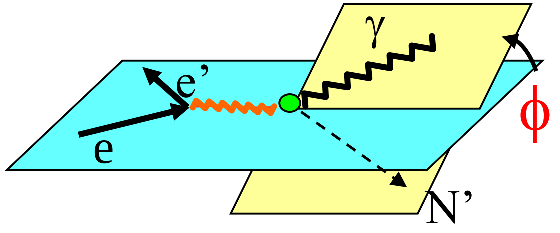
$\Delta\sigma_{UL} \sim \sin\phi\ Im\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E}) - \xi kF_2\tilde{\mathcal{E}}\}$ ⇒ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$, $Im\{\mathcal{H}_n, \mathcal{E}_n\}$

Polarized beam, longitudinal target:

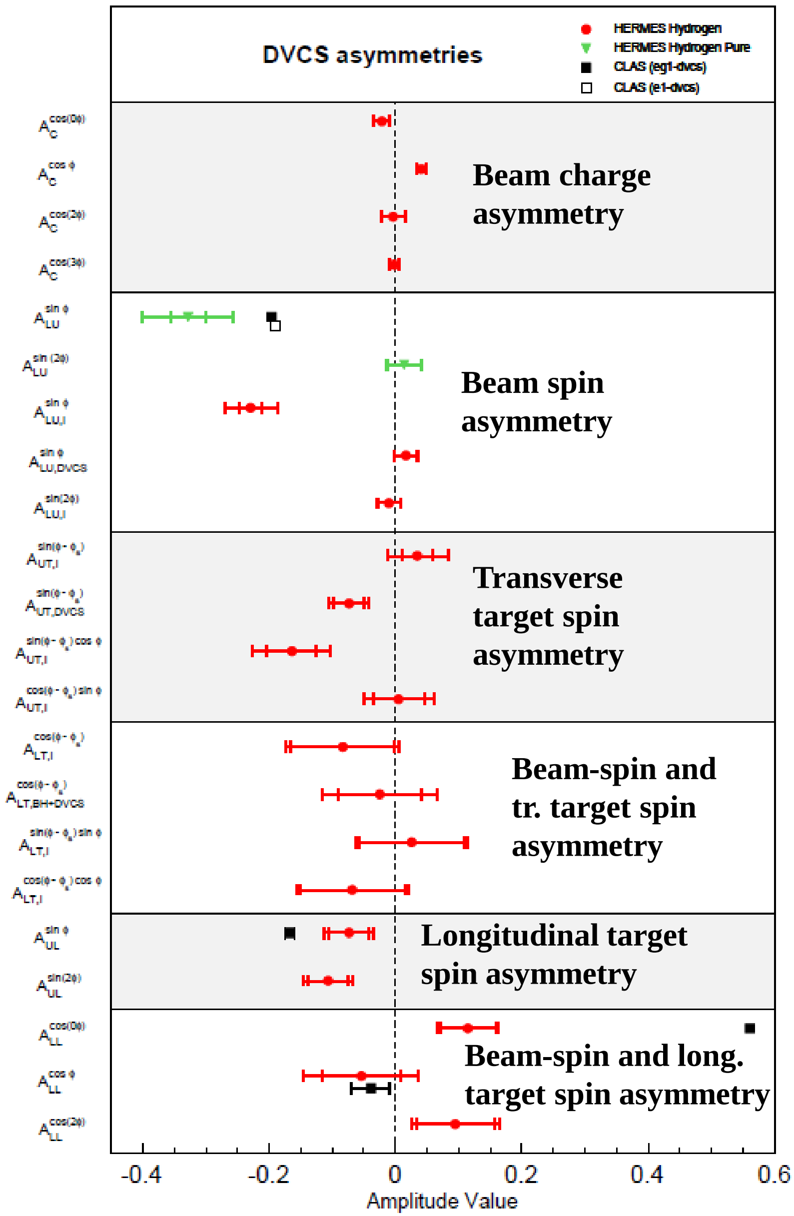
$\Delta\sigma_{LL} \sim (A+B\cos\phi)Re\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E}) + \ldots\}$ ⇒ $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$, $Re\{\mathcal{H}_n, \mathcal{E}_n\}$

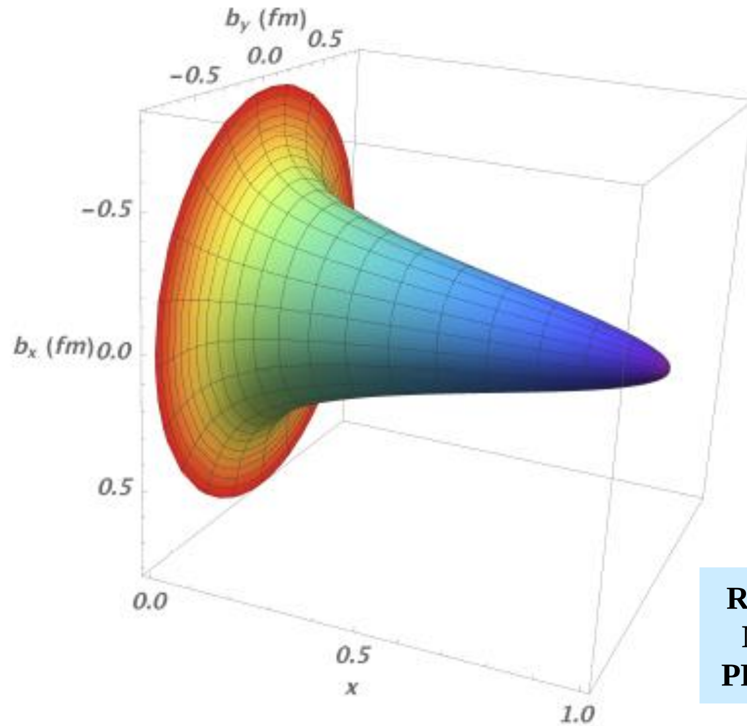
Unpolarized beam, transverse target:

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



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:

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

Neutron

Unpolarized beam, transversely polarized target:

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

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

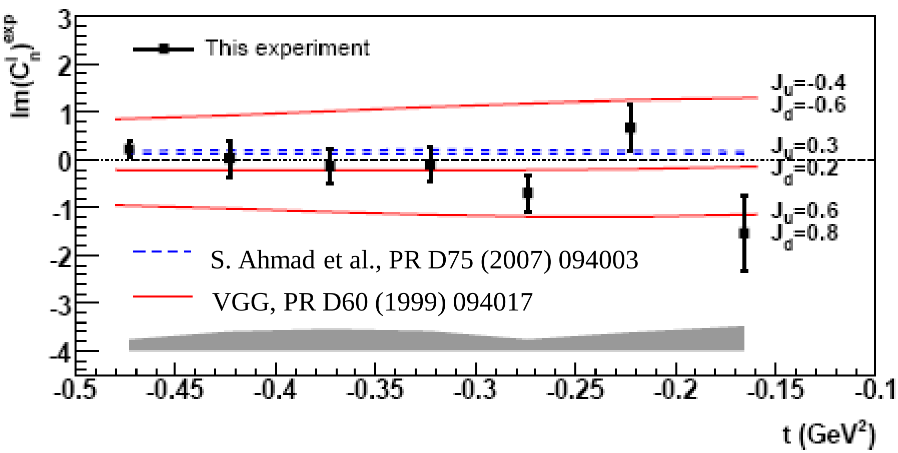
$\vec{e}d \to e\gamma(np)$

DVCS on the neutron in Hall A at 6 GeV

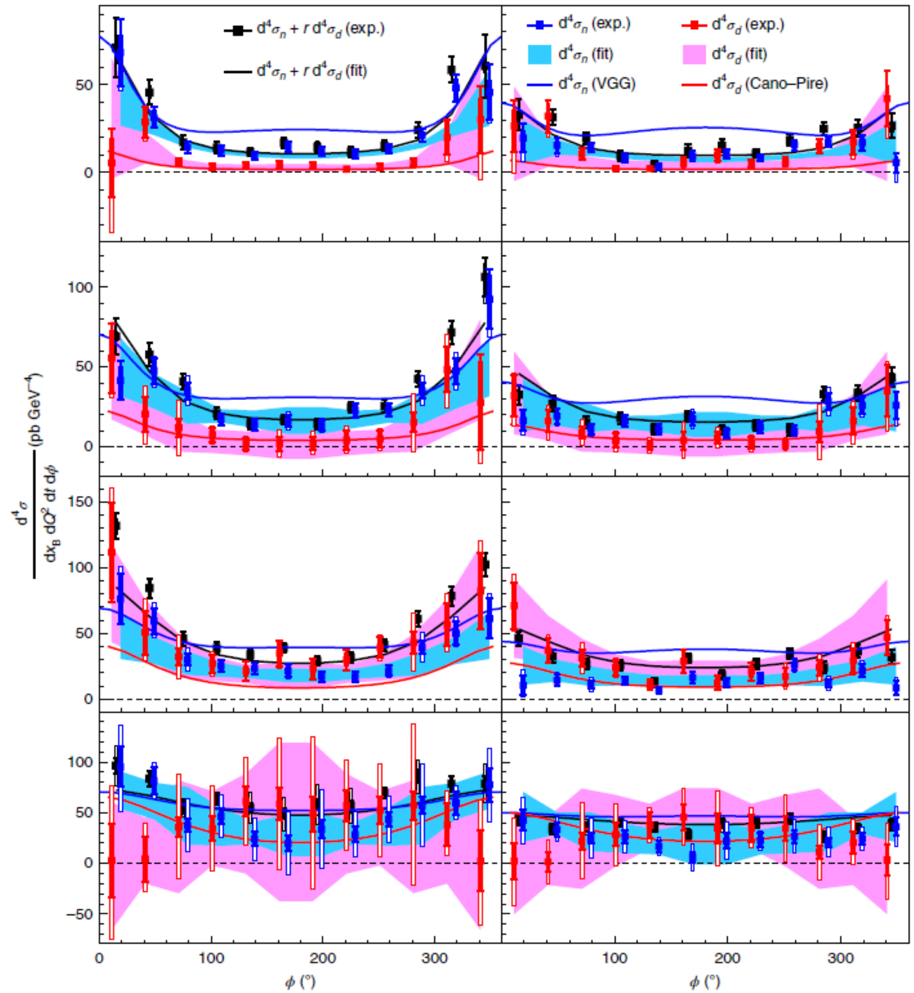
$$D(e,e'\gamma)X - H(e,e'\gamma)X = n(e,e'\gamma)n + d(e,e'\gamma)d + \ldots$$

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

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



Q^2=1.9 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)**

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

JLab PAC: **high-impact experiment**

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

The most sensitive observable to the GPD E

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

Fully exclusive final state:

CLAS12

+Forward Tagger

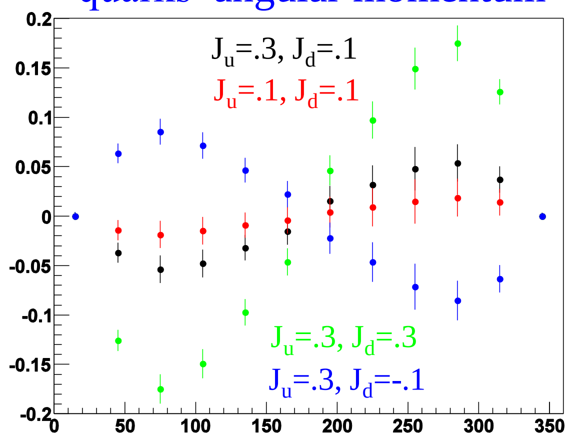
+Central Neutron Detector

Liquid deuterium target

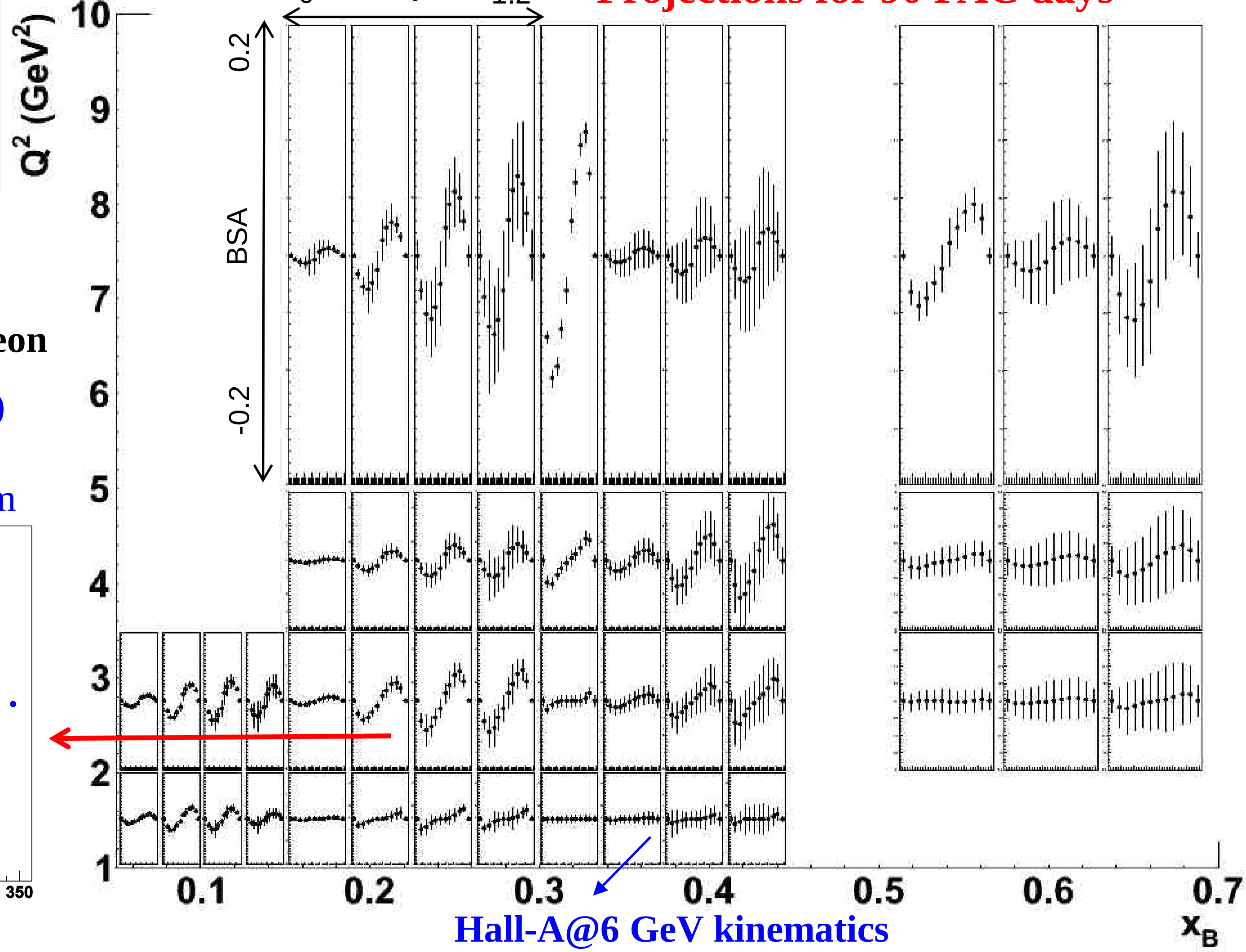
Beam polarization =85%

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

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

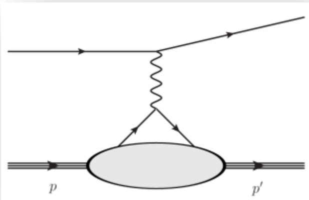


Projections for 90 PAC days



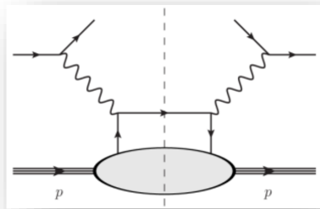
CLAS12 Run Group B

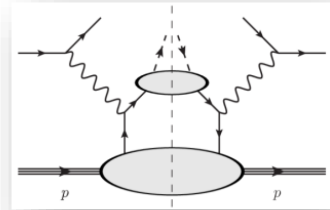
Electroproduction on deuterium with CLAS12



Elastic Scattering

DIS





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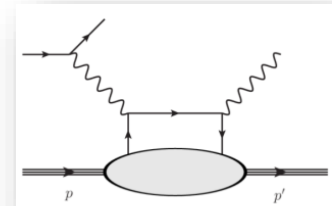
nDVCS



+ J/psi photoproduction
+ Short Range Correlations

2019 schedule:

February 6th - March 25th 2019 + December 3 –20 2019 + January 6 – 30 2020

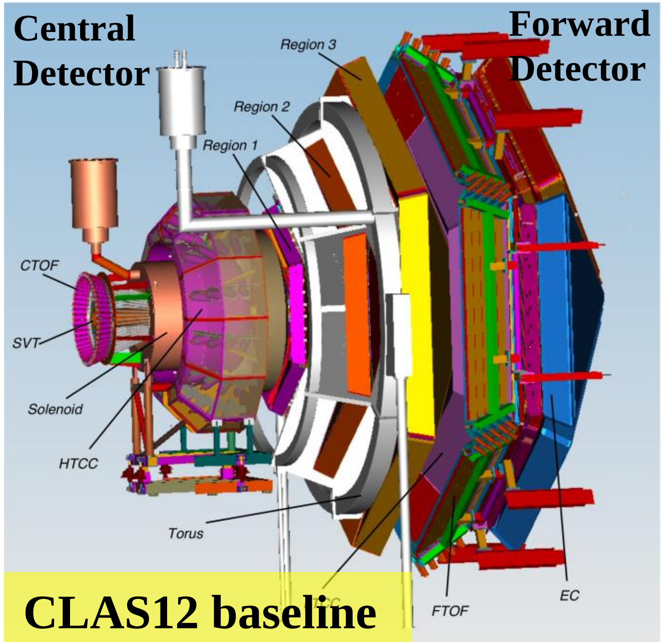
→ ~39 PAC days (~43% of the approved run time)

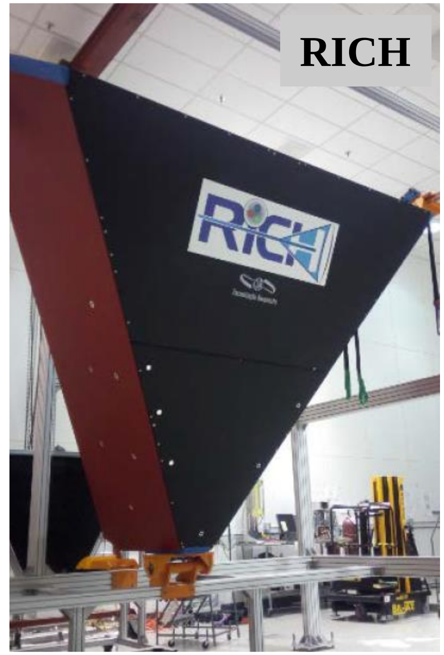
Run infos:

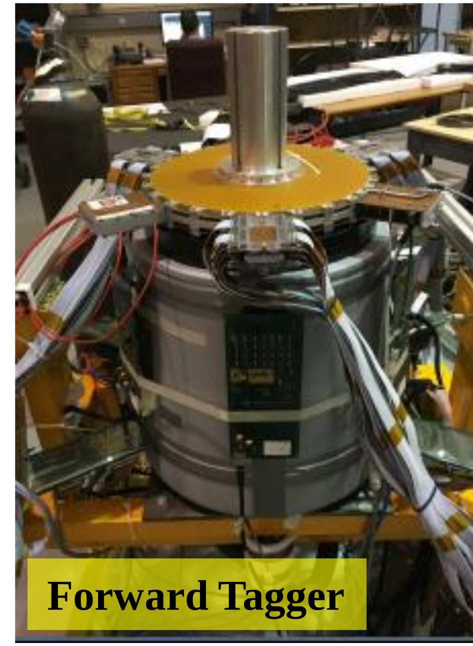
- 3 beam energies: 10.6 GeV, 10.2 GeV, 10.4 GeV
- Average beam polarization ~86% (22 Moeller runs)
- L = ~1.3 10^{35} $cm^{-2}s^{-1}$ per nucleon

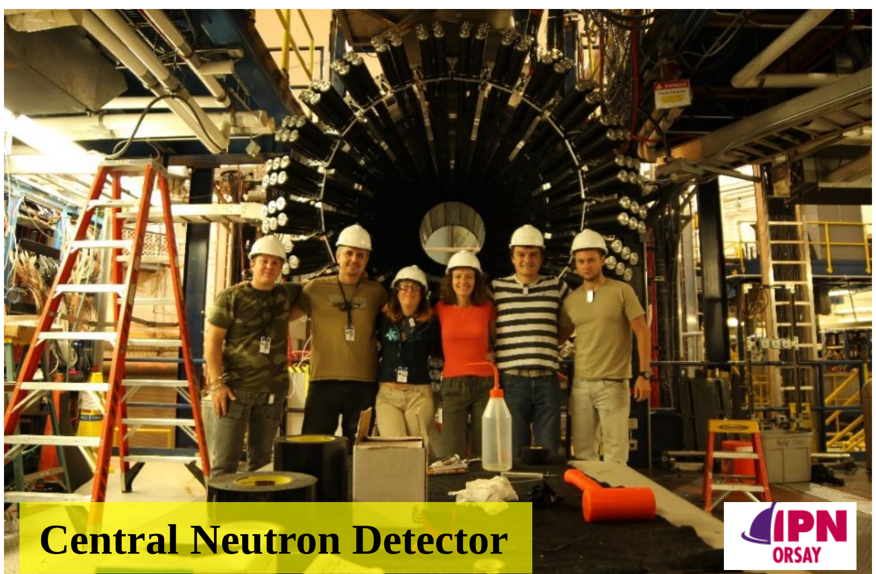
Jeopardy PAC (August 2020) awarded the remaining 51 days and maintained A-HI rating

CLAS12 Run group B: experimental setup









CND: performances with CLAS12 data

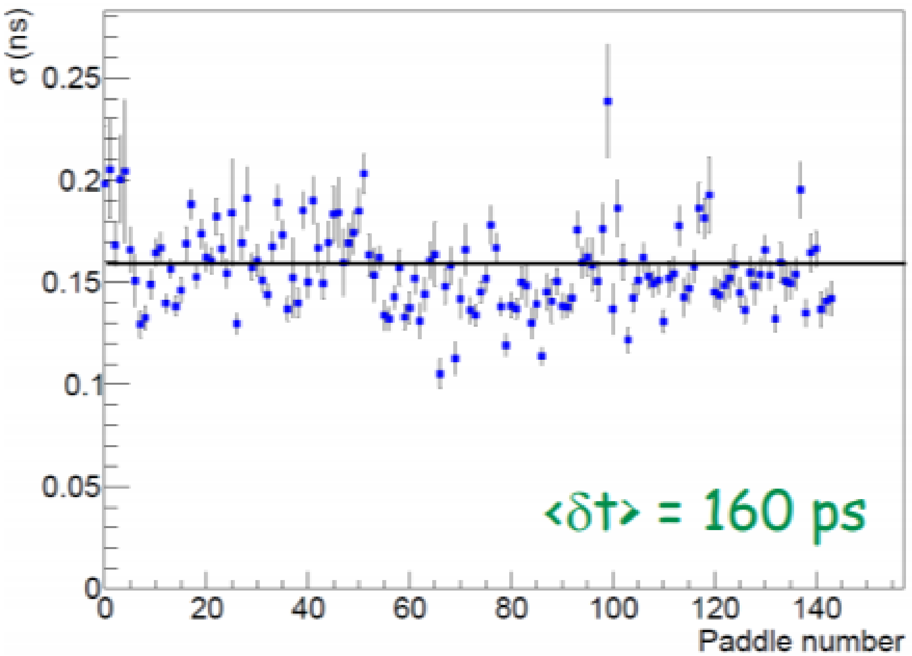
Purpose: detect the **recoiling neutron in nDVCS**
Requirements/performances**:**
- good neutron/photon separation for $0.2<p_n<1$ GeV/c
→ ~150 ps time resolution ✓ (~160 ps)
- momentum resolution δp/p < 10% ✓
- neutron detection efficiency ~10% ✓

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

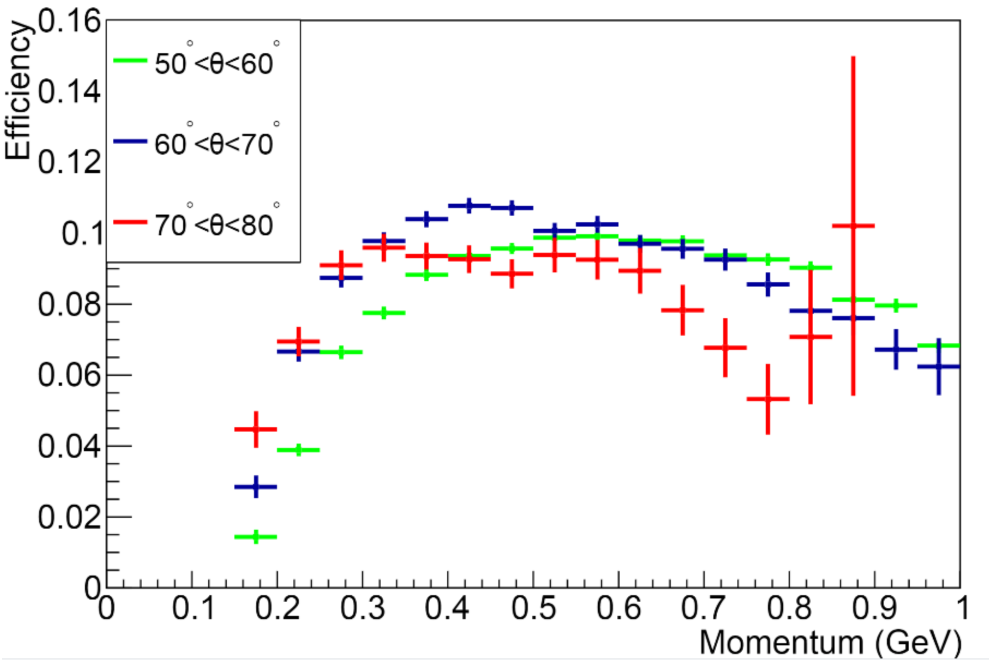
S.N. *et al*., NIM A 904, 81 (2018)

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

Timing resolution per paddle (RGB data)

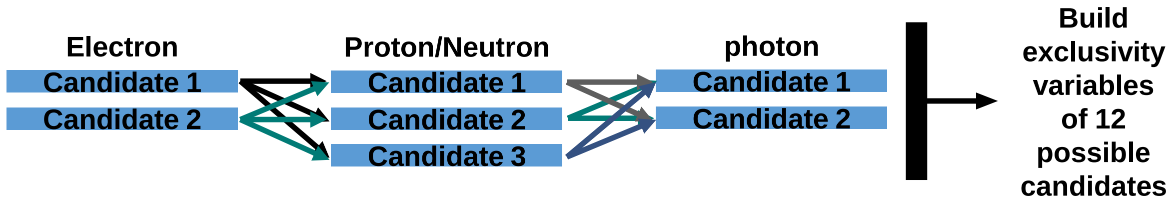


Neutron efficiency from ep→e'nπ⁺ (RGA data)



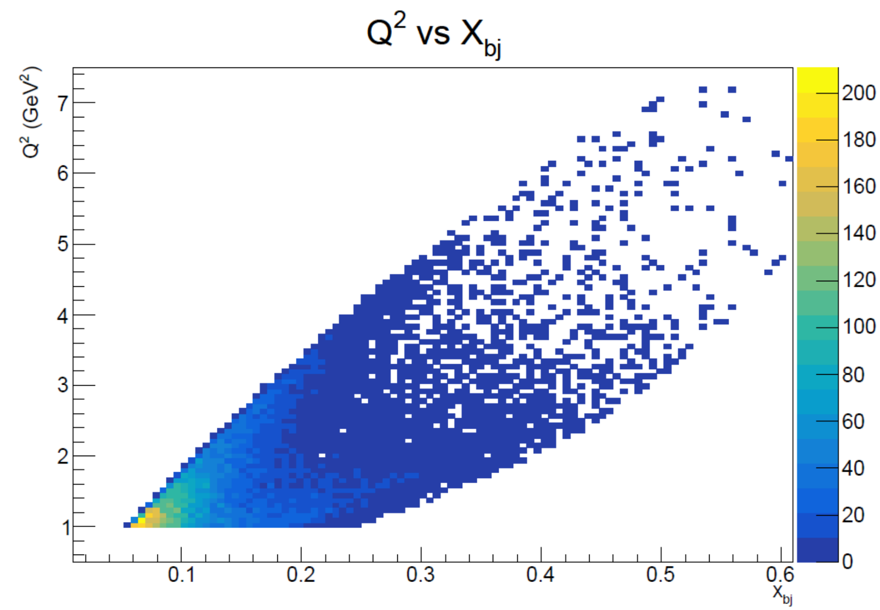
Channel selection for nDVCS (and pDVCS)

- Construct all the possible combinations of final state particles: $ed \rightarrow e'N\gamma(N_{spec})$ (N:nucleon)
  - Final states 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

Reconstruction of the final state and exclusive selection



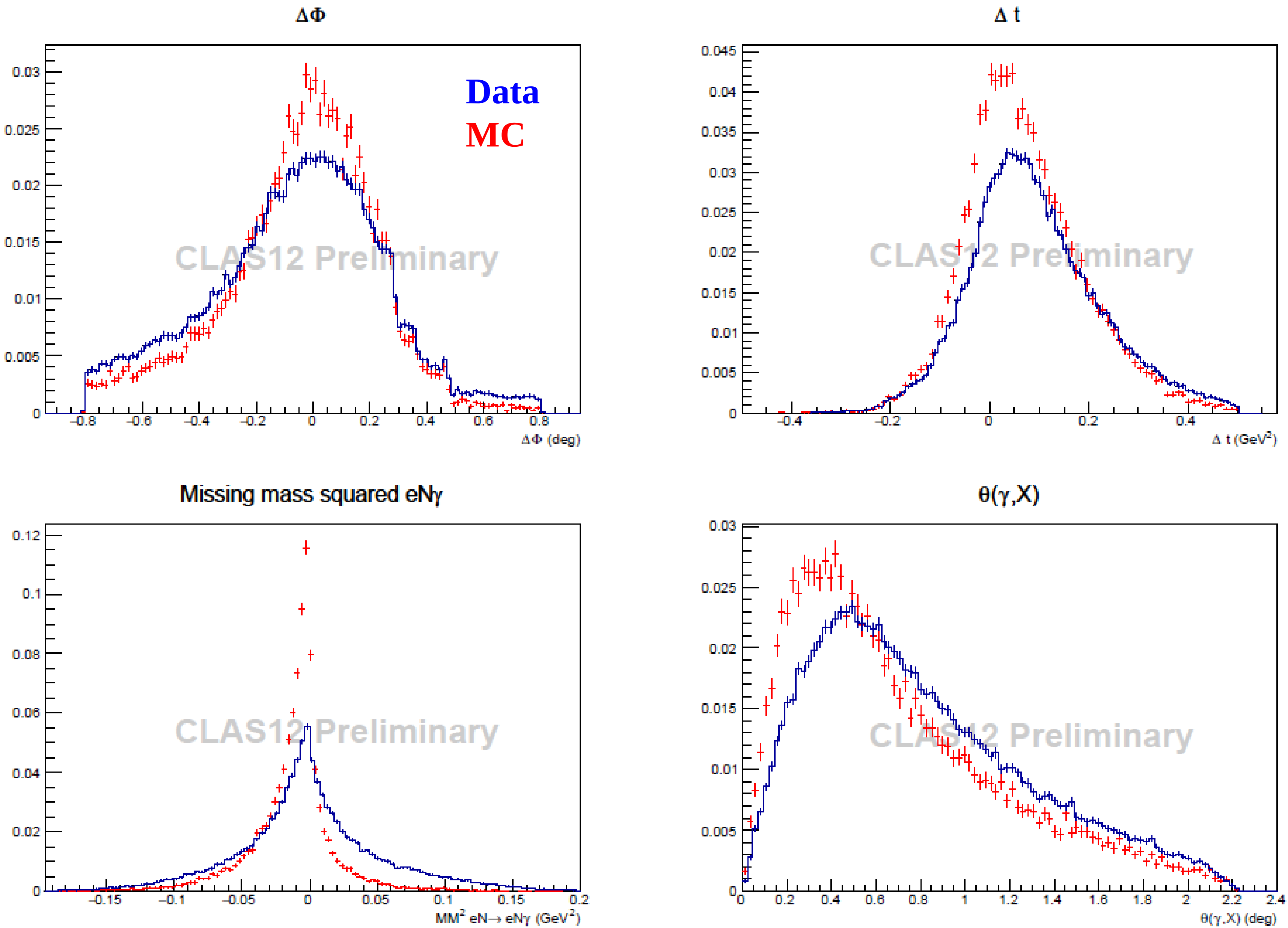
- The nDVCS (pDVCS) final state is selected : using
  - Missing masses:
    - e d → e N γ X
    - e N → e N γ X
    - e N → e N X
  - Missing momentum (spectator nucleon)
    - e d → e N γ X
  - ΔΦ, Δt, θ(γ,X)
    - Difference between two ways of calculating Φ and t
    - Cone angle between measured and reconstructed photon
- The optimization of the exclusivity cut is performed on the sum of the squares of ΔΦ, Δt, θ(γ,X) and missing mass e N → e N X
- Cuts informed by Monte Carlo simulations:
  - GPD-based event generator for DVCS/pi0 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

Exclusivity variables for nDVCS: data/MC comparison

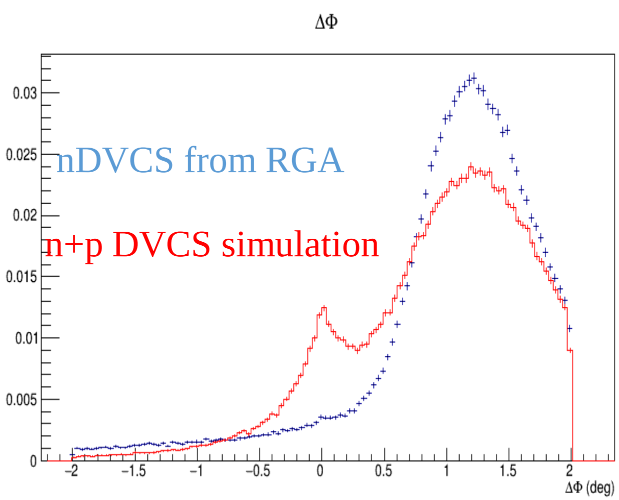


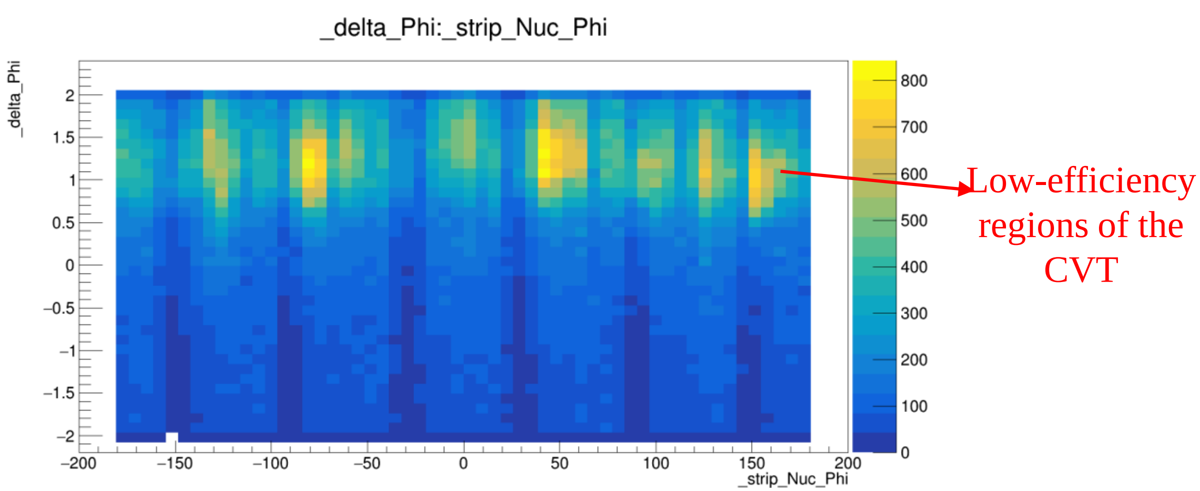
Proton contamination removal from CND neutrons

- Tracking in the CVT is not 100% efficient
- In the dead regions of the CVT protons have no associated track and thus can be identified as neutrons
- Protons roughly account for more than 20% contamination in the signal sample

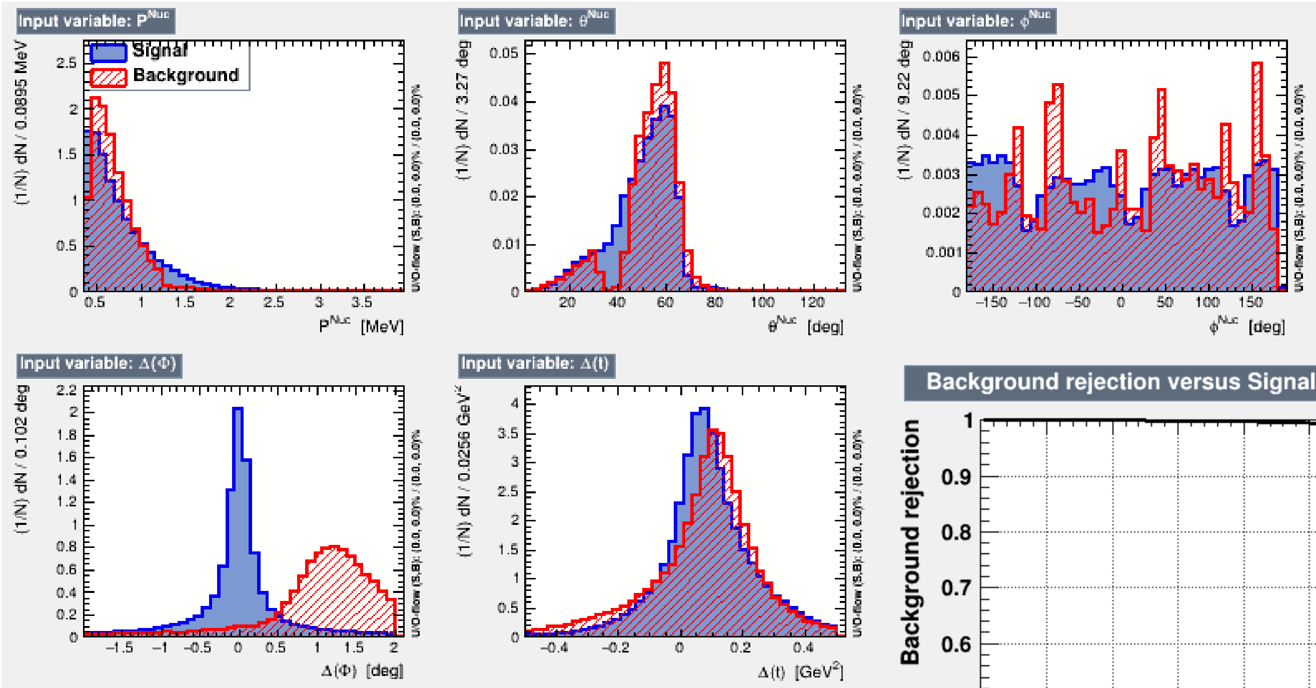
Current approach, based on Machine Learning & Multi-Variate Algorithms:

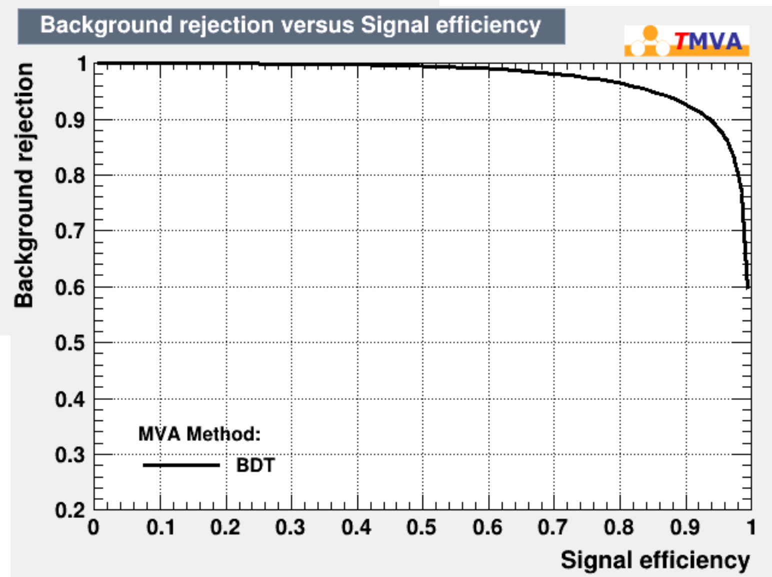
- Reconstruct nDVCS from proton-data (RG-A) requiring neutron PID
    - Most of those neutrons are actually misidentified protons
- Use this sample to determine the characteristics of *fake neutrons* in high-level reconstructed variables
- Based on those characteristics try and subtract contamination from nDVCS in RGB
- And for signal….use protons from RGA!

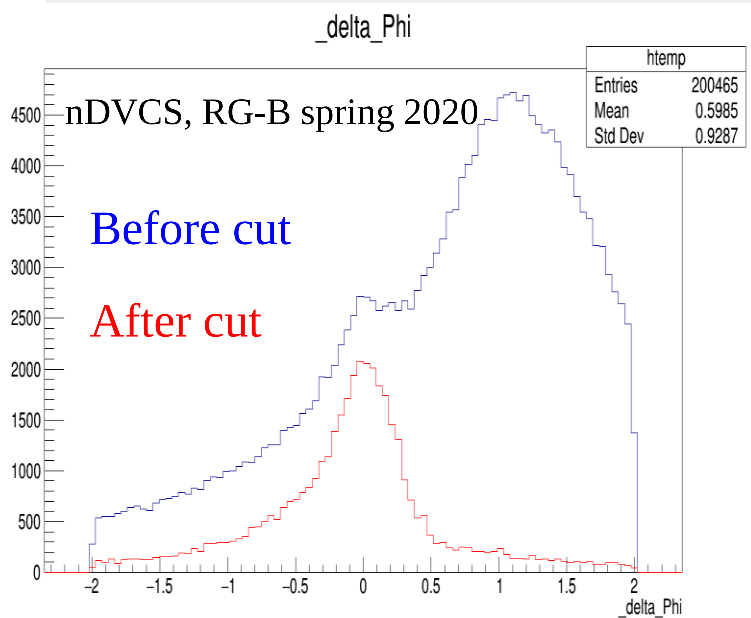




Training variables and signal efficiency vs. background rejection

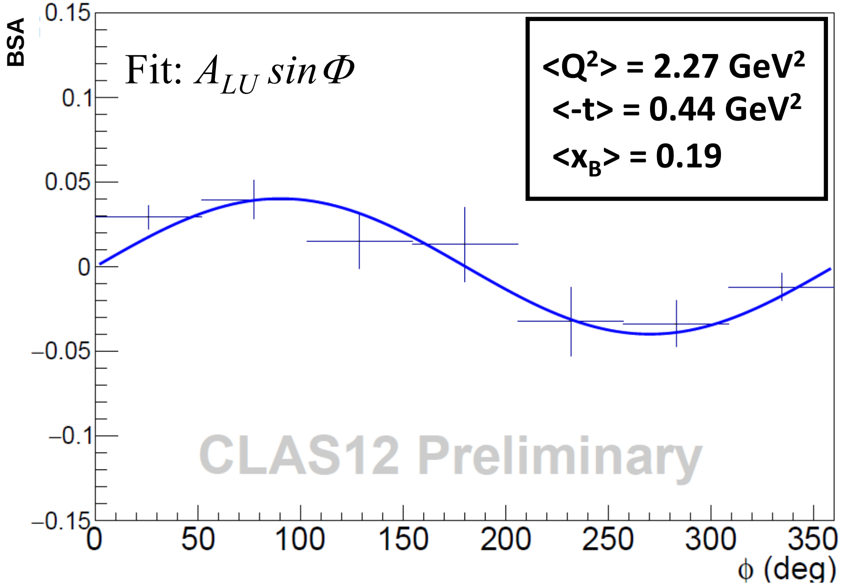




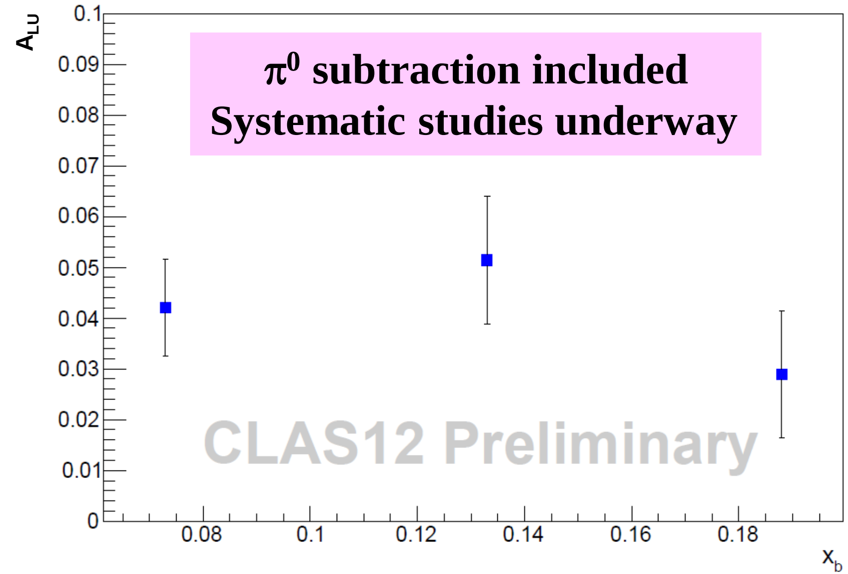


nDVCS: preliminary BSA

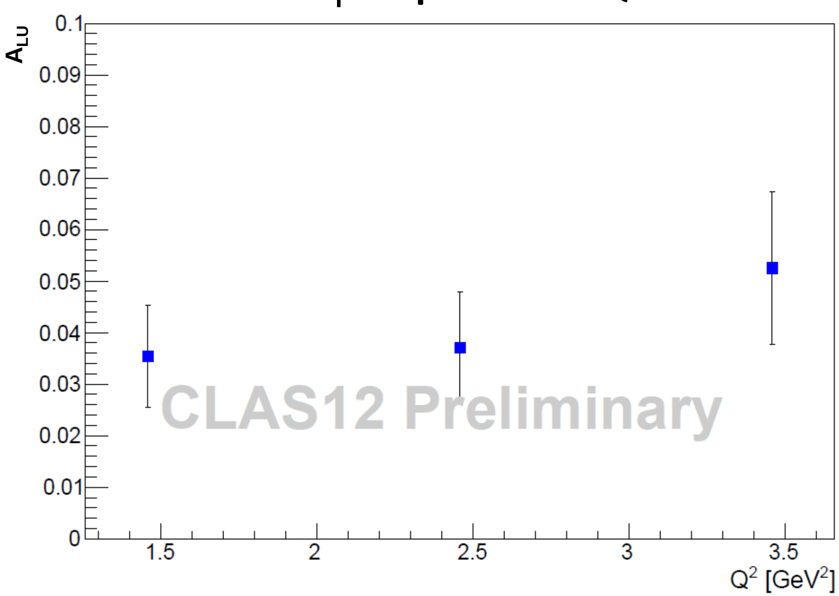
$\vec{e}d \to en\gamma(p)$



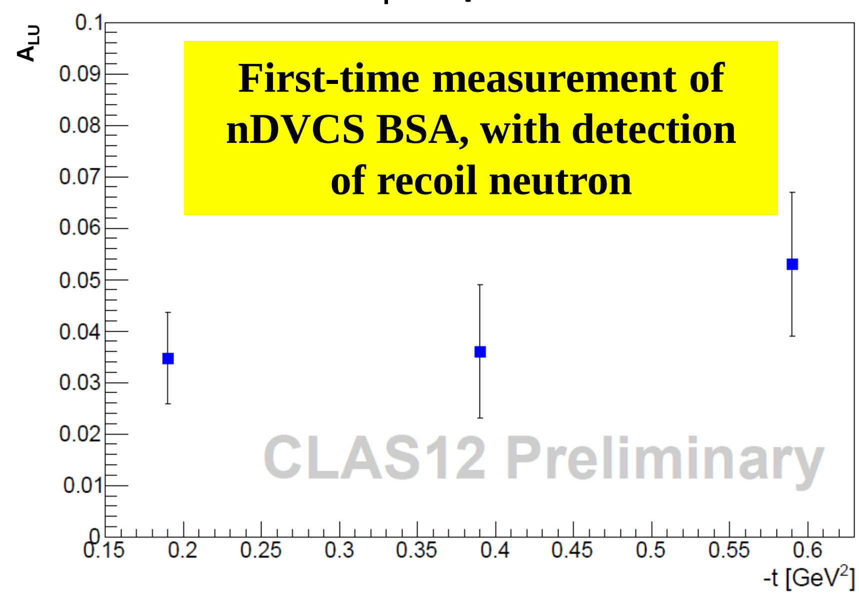
sinϕ amplitude vs x_B



sinϕ amplitude vs Q^2



sinϕ amplitude vs -t

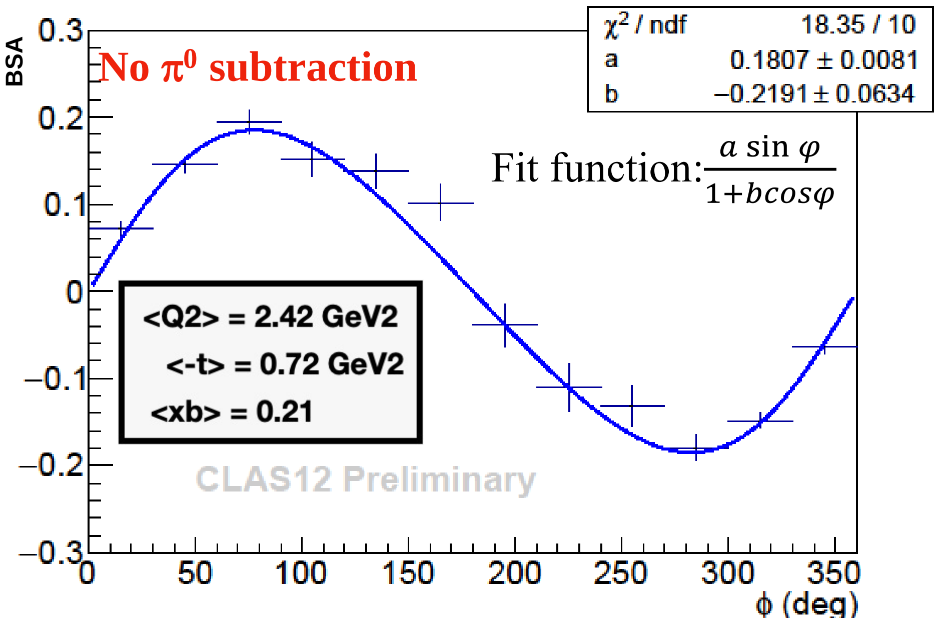


Sanity check (and more): pDVCS on deuterium

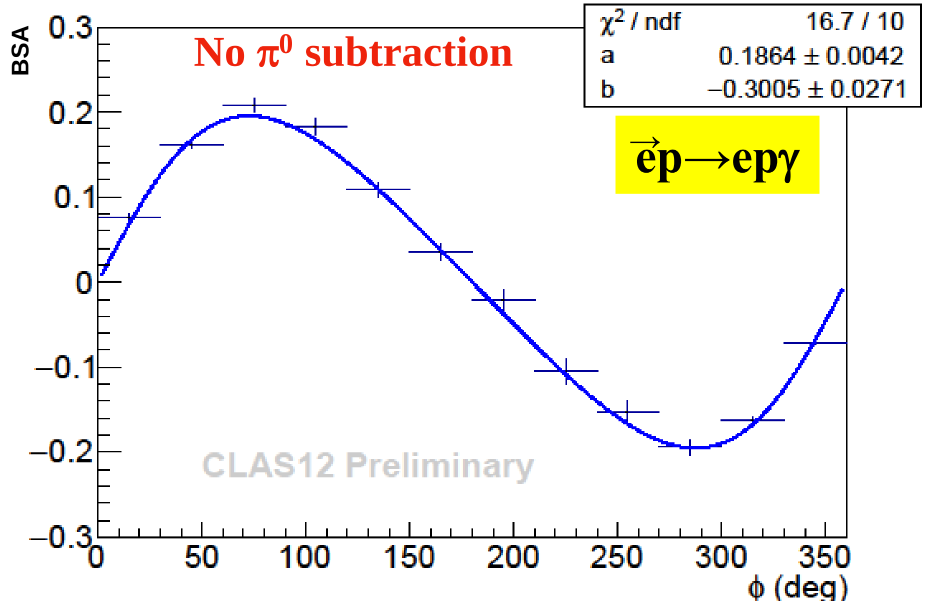
$\vec{e}d \rightarrow ep\gamma(n)$

Interest of pDVCS on deuterium:

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



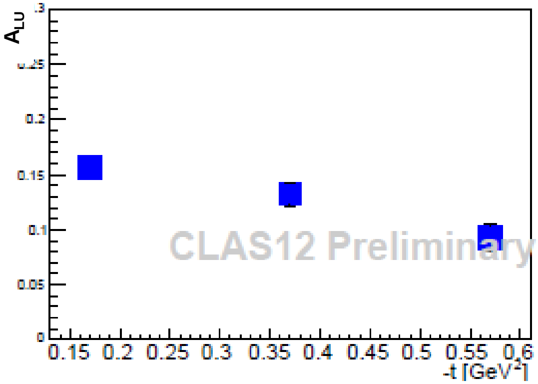
Fit function: $\frac{a \sin\varphi}{1+b\cos\varphi}$

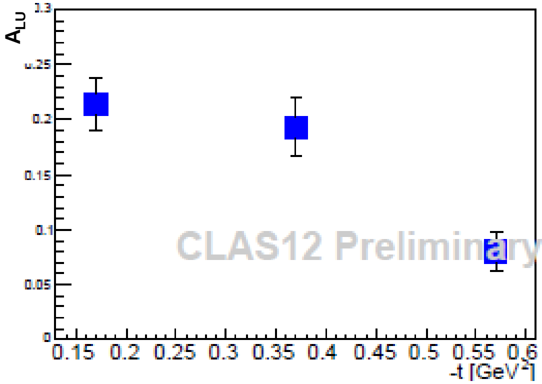


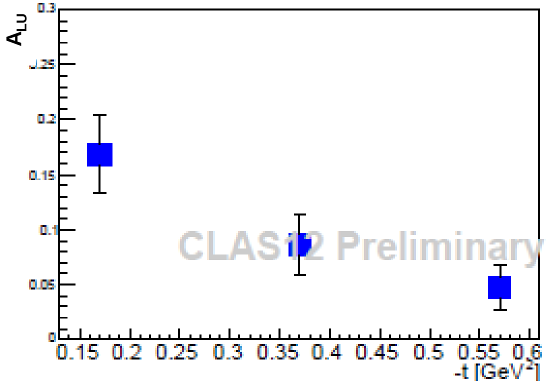
$\vec{e}p \rightarrow ep\gamma$

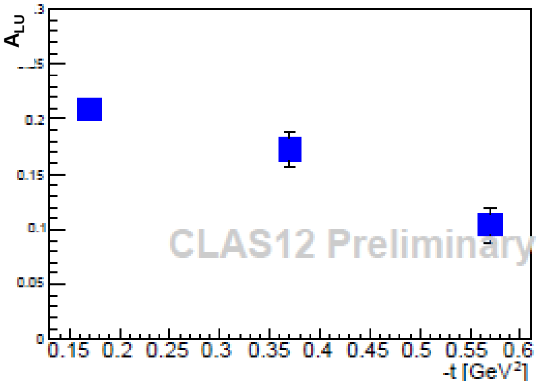
- Raw BSA integrated over all kinematics and detection topologies
- **Compatible with raw BSA from pDVCS in RGA, no evidence of medium effects at this stage**

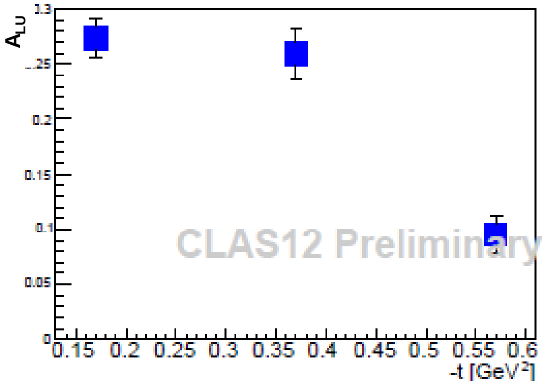
4D sinϕ amplitude of BSA for pDVCS

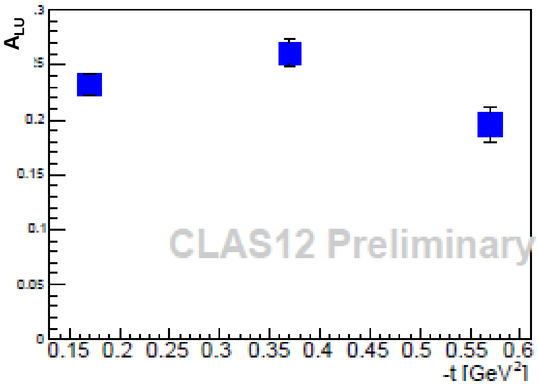












First-time measurement of incoherent pDVCS on a deuterium target

What's next: nDVCS on longitudinally polarized target

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

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

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

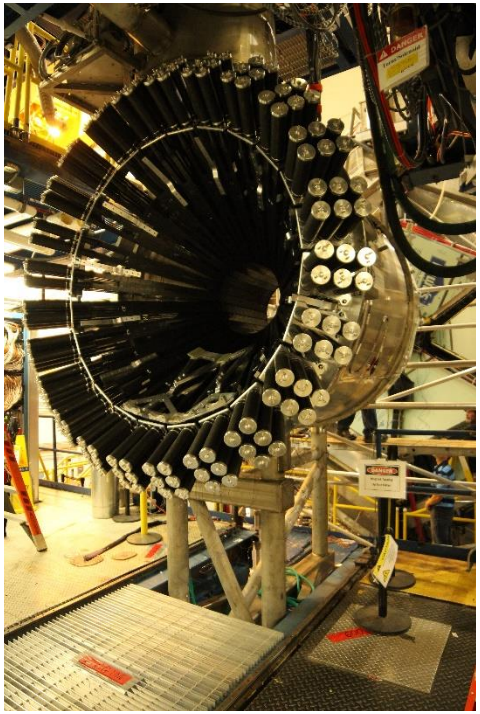
→ 3 observables (including BSA), constraints on real and imaginary CFFs of various neutron GPDs

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

CLAS12 + Longitudinally polarized target + CND

Run time = 40 days
$P_t = 0.4$; $P_b = 0.85$

Scheduled for June 2022-Febuary 2023



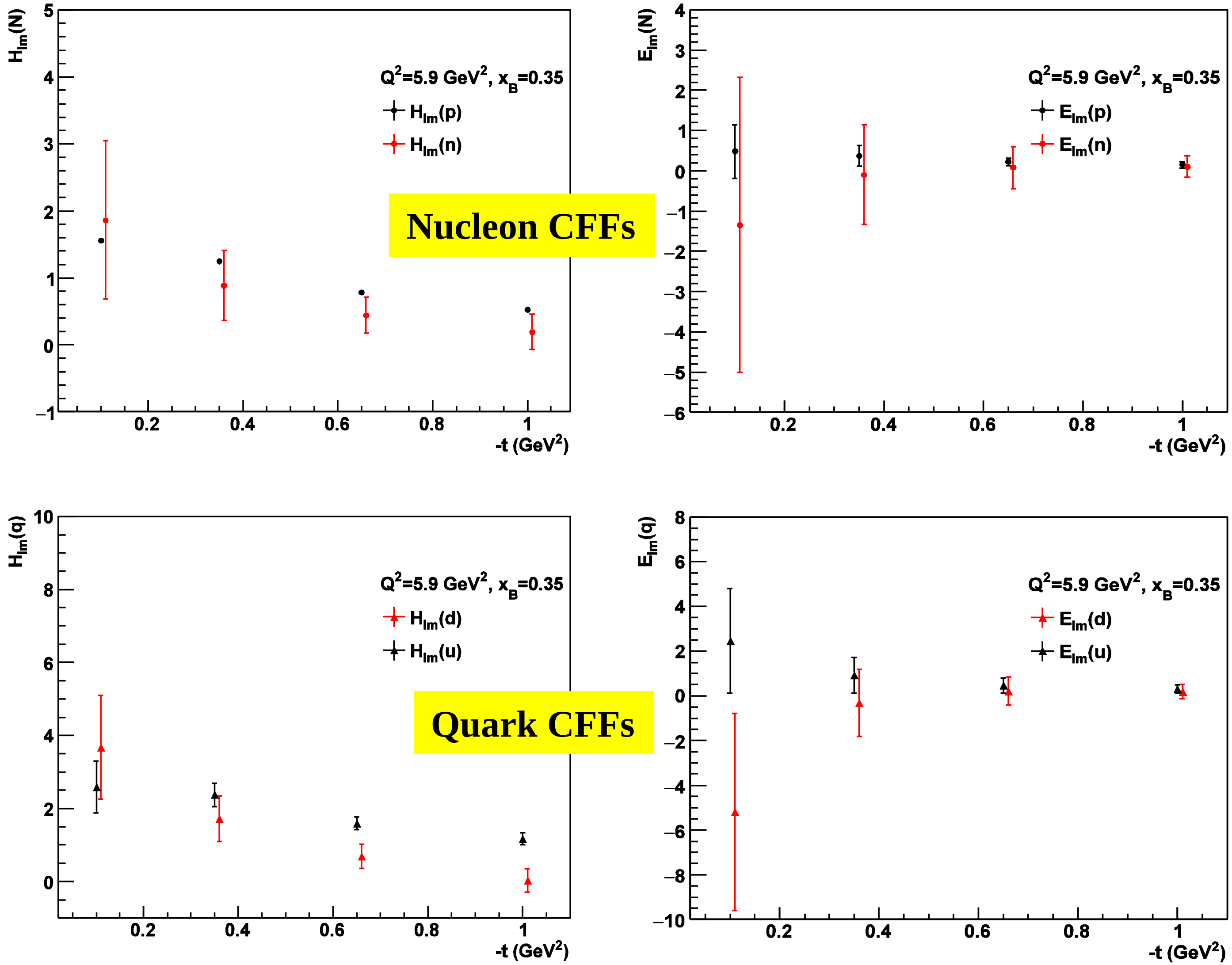
CLAS12: projections for flavor separation

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

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

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

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

- The **beam-spin asymmetry for nDVCS** is a precious tool to constrain the GPD E and perform quark-flavor separation of GPDs
- The pioneering **Hall-A experiments 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** is performing according to specifications
- A preliminary analysis of the data shows that **the nDVCS channel can be extracted,** with a small but clear **BSA signal**
- Systematics studies and selection optimization are underway, publication in spring 2022
- A first-time measurement of **BSA for incoherent pDVCS** on deuterium is also in progress

- Another nDVCS experiment on **polarized deuterium target** will be carried out in the second half of 2022 with CLAS12
- The second half of RG-B will likely run with **double luminosity** following CLAS12 upgrade
- 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 **quark-flavor separation of CFFs**
- **A Transversely polarized pDVCS experiment is foreseen for ~2025 with CLAS12**
- The **Ji's sum rule** is the ultimate, ambitious goal of this program

A little final advertisement: the CLAS12 TCS paper was just accepted by PRL ☺
https://arxiv.org/abs/2108.11746
A lot of exciting new results on GPDs are coming from CLAS12!