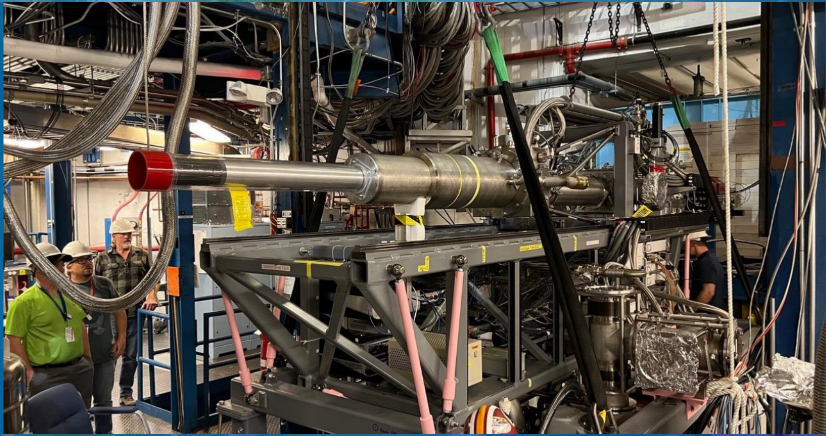
MARCH 14TH 2025

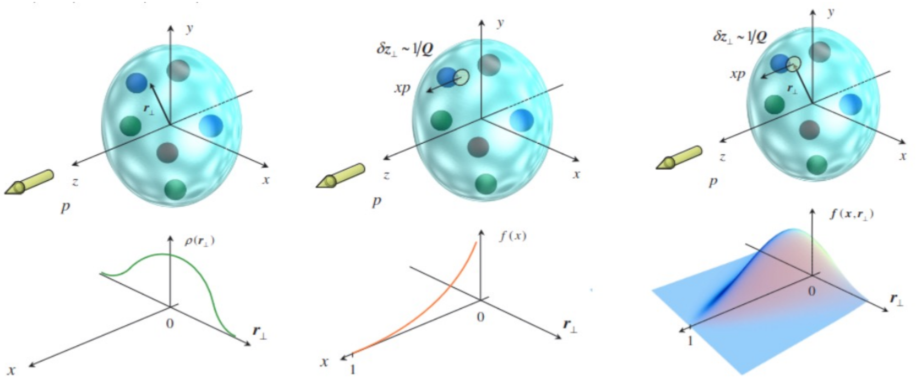
DVCS AT CLAS12 ON LONGITUDINALLY POLARIZED PROTONS AND NEUTRONS IN DEUTERIUM



NOÉMIE PILLEUX
Postdoctoral Appointee, Argonne National Laboratory
The work presented today was mostly conducted at IJCLab and Paris Saclay University

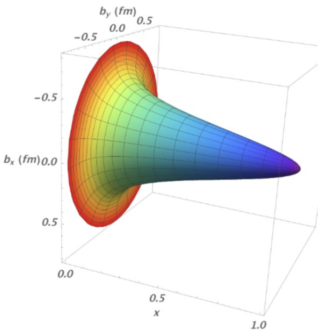
GENERALIZED PARTON DISTRIBUTIONS (GPDs)

- Generalized parton distributions: transverse position, longitudinal momentum, and their correlations.
- 3D imaging.
- Spin puzzle.
- Forces, pressures.

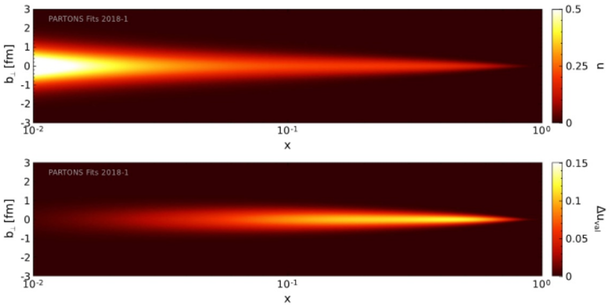


Belitsky, Radyushkin Physics Reports 2005

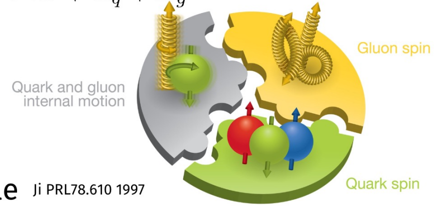
Dupré,Guidal,Vanderhaeghen PRD95 2017



Moutarde,Sznajder,Wagner EPJC 2018



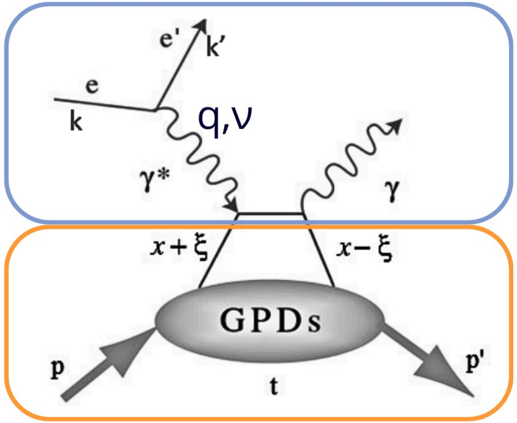
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



Ji’s sum rule Ji PRL78.610 1997

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

DEEPLY VIRTUAL COMPTON SCATTERING (DVCS)

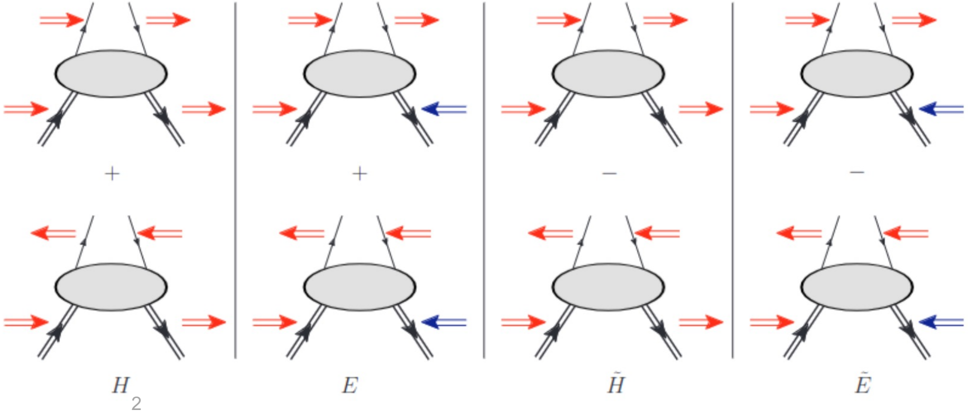


Hard scattering, perturbative.

Soft, non perturbative, parametrized by GPDs.

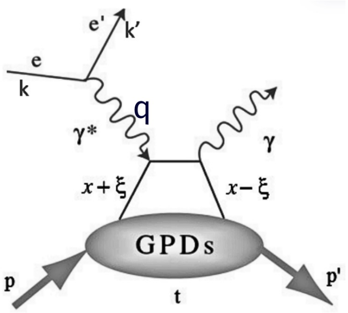
$Q^2 = -q^2 \qquad x_{Bj} = \frac{Q^2}{2M_N\nu} \qquad t = (p - p')^2 \qquad \xi \simeq \frac{x_{Bj}}{2 - x_{Bj}}$

- Four types of GPDs, depending on the quark and nucleon helicities.
- Quark helicities can be probed with polarized electron beams.
- Nucleon spin can be controlled in polarized targets experiments.



DVCS OBSERVABLES

- GPDs are accessed through Compton Form Factors (CFFs) in DVCS experiments.
- They are accessed in linear combinations with standard Form Factors in the interference between the DVCS and Bethe-Heitler (BH) processes.

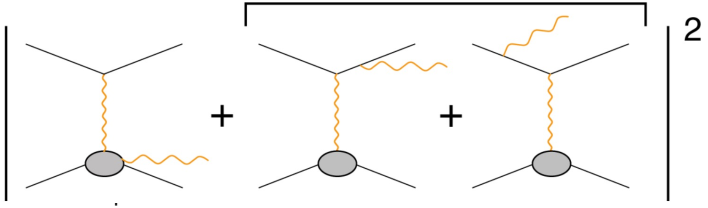


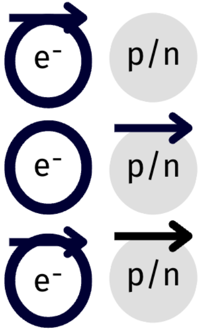
$$\Re e\mathcal{F} = \mathcal{P}\int_{-1}^{1} dx \left[\frac{1}{x-\xi} \mp \frac{1}{x+\xi}\right] F(x,\xi,t)$$

$$\Im m\mathcal{F}(\xi,t) = -\pi[F(\xi,\xi,t) \mp F(-\xi,\xi,t)]$$

DVCS Bethe-Heitler (BH)

σ(eN ⟶ eNγ) =

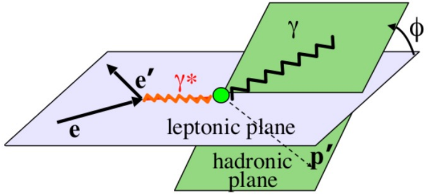




$$\Delta\sigma_{LU} \propto sin(\phi)\Im\left[F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - \xi\frac{t}{4M^2}F_2\mathcal{E}\right]$$

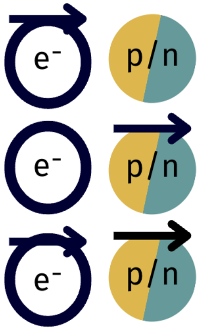
$$\Delta\sigma_{UL} \propto \sin(\phi)\Im\left[F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \frac{x_{bj}}{2}\mathcal{E}) - \xi(\frac{x_{bj}}{2}F_1 + \frac{t}{4M^2}F_2)\tilde{\mathcal{E}}\right]$$

$$\Delta\sigma_{LL} \propto (A+B\cos(\phi))\Re[F_1\tilde{\mathcal{H}}+\xi(F_1+F_2)(\mathcal{H}+\frac{x_{bj}}{2}\mathcal{E})-\xi(\frac{x_{bj}}{2}F_1+\frac{t}{4M^2}F_2)\tilde{\mathcal{E}}]$$



ACCESSING CFFs

- Accessing all CFFs:
  - Measuring observables involving polarized beams and polarized targets.
  - Experiments on protons or neutrons have different sensitivities.
- Comparing data on the proton and the neutron is essential to access the flavor dependence.
- No free neutron target: experiments with light nuclei, as deuterium.
- Nuclear environment effects are assessed comparing proton data in H and D.
- One of the main motivations for the Run Group C (RGC) experiment with the CLAS12 detector at Jefferson Laboratory using polarized NH_3 and ND_3 targets.



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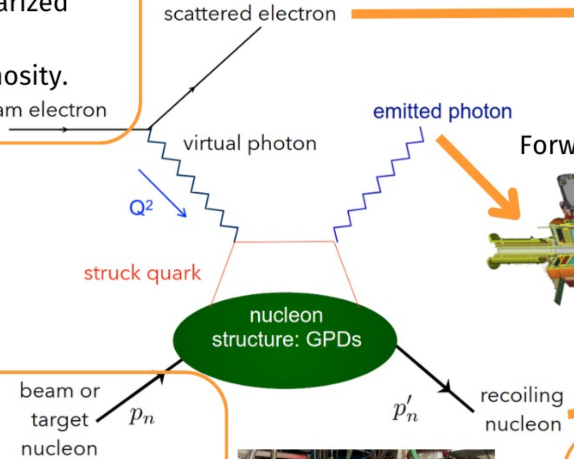
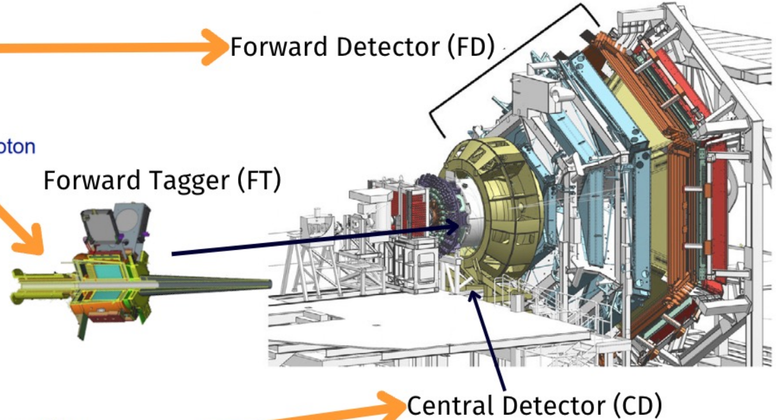
EXPERIMENTAL SETUP

DVCS MEASUREMENT WITH RGC

Polarized electron beam: CEBAF, JLab

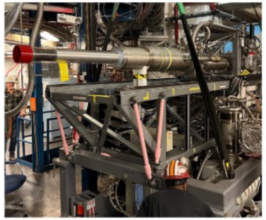
- highly polarized
- 10.5 GeV
- high luminosity.





Longitudinally polarized target: **Run Group C**

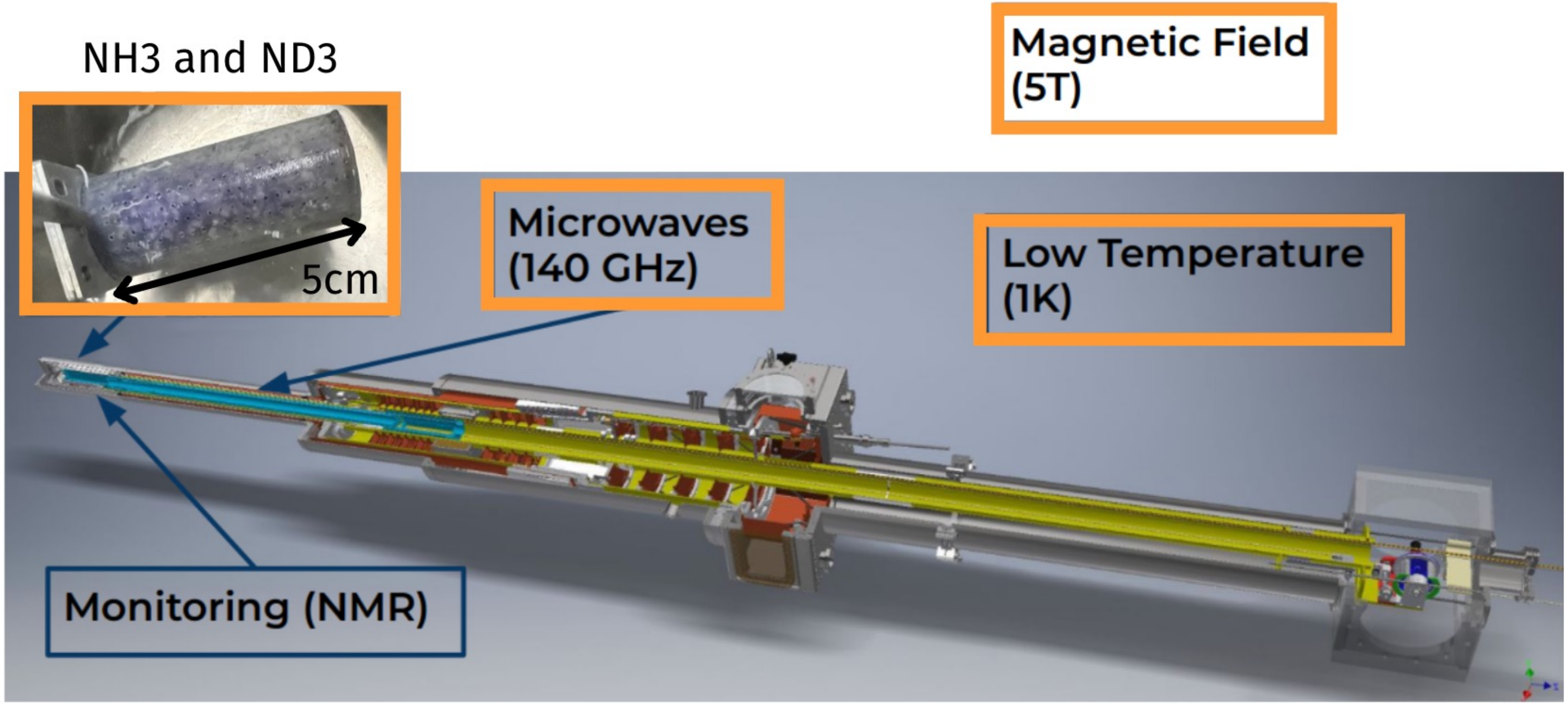
- New experiment with CLAS12!
- Ran between June 2022 and March 2023.
- 1/3 of the dataset available for analysis.
- Approved to run again



Exclusive detection of the final state with CLAS12

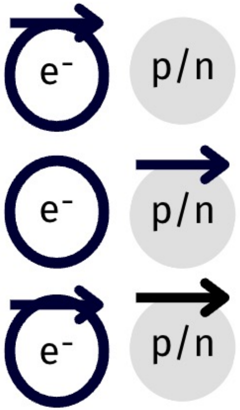
- Scattered electrons in the FD
- Nucleons in the CD
- Addition of a low-angle detector, FT

THE RGC POLARIZED TARGET



V. Lagerquist and the JLab Target Group

EXPERIMENTAL DETERMINATION OF THE DVCS ASYMMETRIES



$$A_{LU} = \frac{P_t^-(N^{++} - N^{-+}) + P_t^+(N^{+-} - N^{--})}{P_b \times (P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))}$$

$$A_{UL} = \frac{N^{++} + N^{-+} - N^{+-} - N^{--}}{D_f \times (P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))}$$

$$A_{LL} = \frac{N^{++} + N^{--} - N^{+-} - N^{-+}}{P_b \times D_f \times (P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))}$$

$$N^{b,t}$$

- Fraction of polarized electrons: **beam polarization** P_b, measured using Moller scattering during the experiment (~83%).
- Fraction of polarized nucleons in D: **target polarization** P_t assessed with the analysis of the elastic reaction.
- Fraction of D in the ND_3 target: **dilution factor** D_f assessed using data on a carbon target (similar nuclear environment to nitrogen).

TARGET POLARIZATION MEASUREMENT

MEASURING THE TARGET POLARIZATION WITH THE ELASTIC REACTION

- Elastic (ep → e'p') double spin asymmetry.

$$A_{th} = \frac{2\tau G[\frac{M_p}{E_b} + G(\tau \frac{M_p}{E_b} + (1+\tau)\tan(\frac{\theta}{2})^2)]}{1 + G^2 \frac{\tau}{\epsilon}} \qquad G = \frac{G_M}{G_E}$$

- Product of the beam and target polarizations. $P_b P_t = \frac{A_{meas}}{A_{th}}$

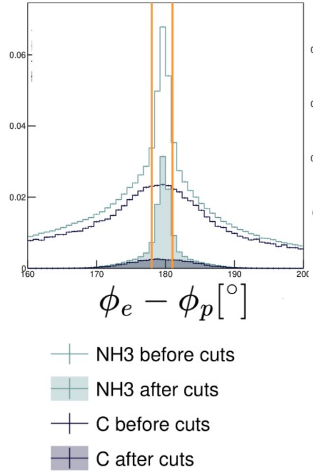
- It is measured for each orientation of the target polarization, integrating over the whole experiment to have enough statistics.

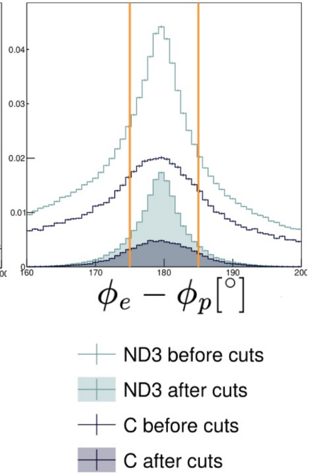
dilution factor yields with positive/negative beam helicity

$$P_b P_t = \frac{\sum_{i=0}^{N_{bins}} f_i A_{th,i} (N_i^+ - N_i^-)}{\sum_{i=0}^{N_{bins}} f_i^2 A_{th,i}^2 (N_i^+ + N_i^-)} \qquad f = \frac{N_D}{N_{ND_3}}$$

ANALYSIS AND RESULTS

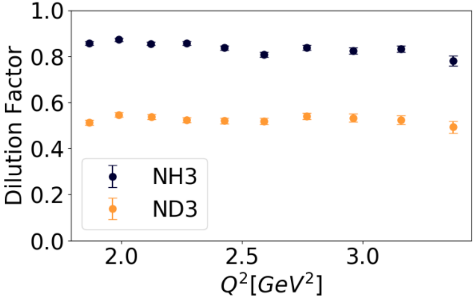
- Elastic events are selected from (e'p') final states, using four-momentum conservation to build exclusivity variables.
- Data on NH_3/ND_3 is compared to data on C to measure the dilution factor.
- Fermi motion is a challenge for measurements in ND_3!
- Good (or very good) target polarization performances.
- Another challenge for deuterium data are lower polarizations.





$$D_f = 1 - \frac{cN_C}{N_{ND_3}}$$

$$c = \frac{7}{6} \frac{l_{ND_3}\rho_{ND_3}Q_{ND_3}}{l_C \rho_C Q_C}$$



Preliminary

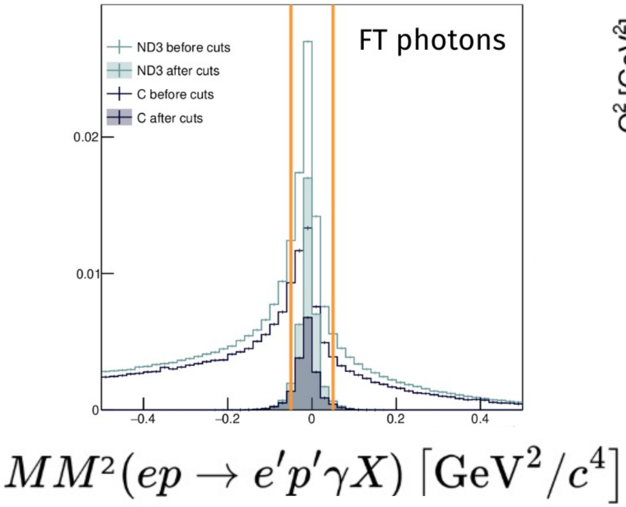
Target	$P_b P_t$
NH3+	0.71±0.03
NH3-	-0.66±0.03
ND3+	0.20±0.03
ND3-	-0.14±0.04

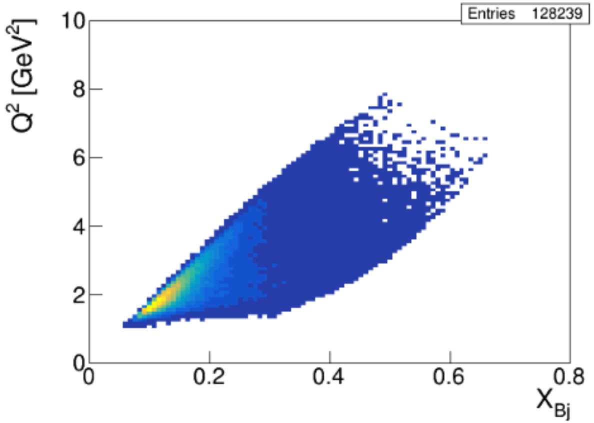
P_b = 82.6 ± 2.0%

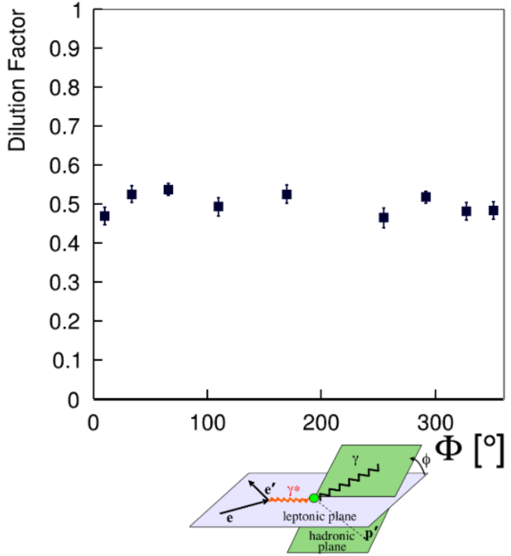
DVCS IN ND_3

pDVCS ANALYSIS

- Selecting (e'p'ɣ) final states, building exclusivity variables.
- Comparison between ND_3 and C data to measure the dilution factor.



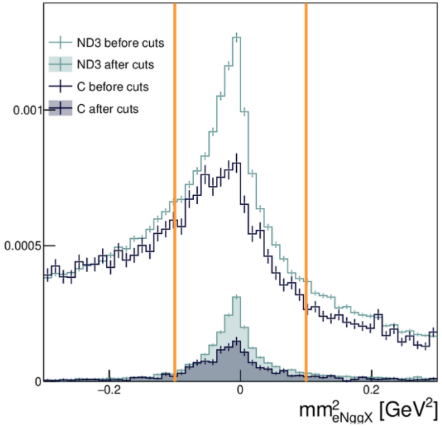


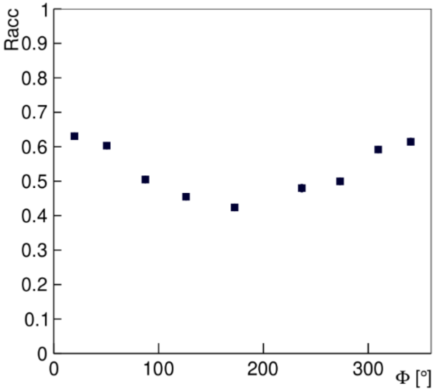


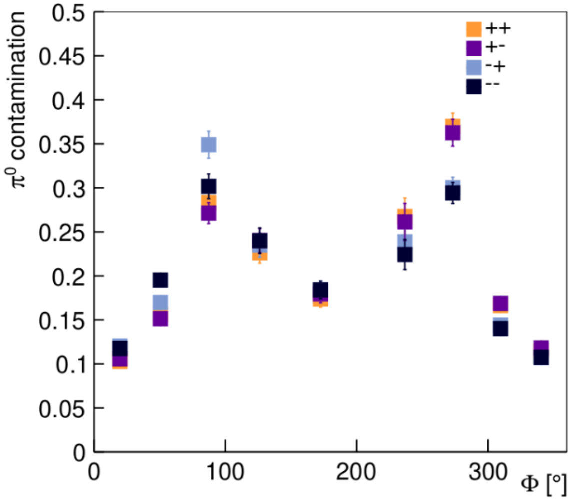
NEUTRAL PION BACKGROUND

- Important source of background: electroproduction of neutral pions.
- Contamination is assessed with MC simulations:
  - Measuring the production of neutral pion events in RGC
  - Estimating the fraction of events passing the DVCS selection.

$$eN \rightarrow e'N'\pi^0 \rightarrow e'N'\gamma(\gamma)$$

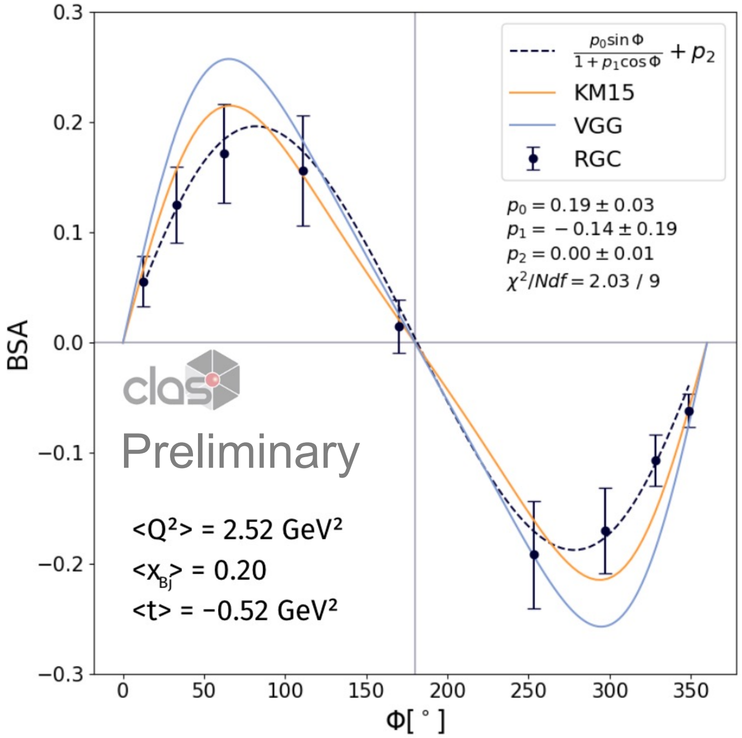






$$n = n_{raw} - n_{eN\pi^0} \frac{N_{1\gamma}^{MC}}{N_{2\gamma}^{MC}}.$$

BEAM SPIN ASYMMETRY FOR pDVCS IN ND_3



$$A_{LU}(\phi) \simeq \frac{s^I_{1,unp}\sin(\phi)}{c^{BH}_{0,unp} + \left(c^{BH}_{1,unp} + c^I_{1,unp}\right)\cos(\phi)}$$

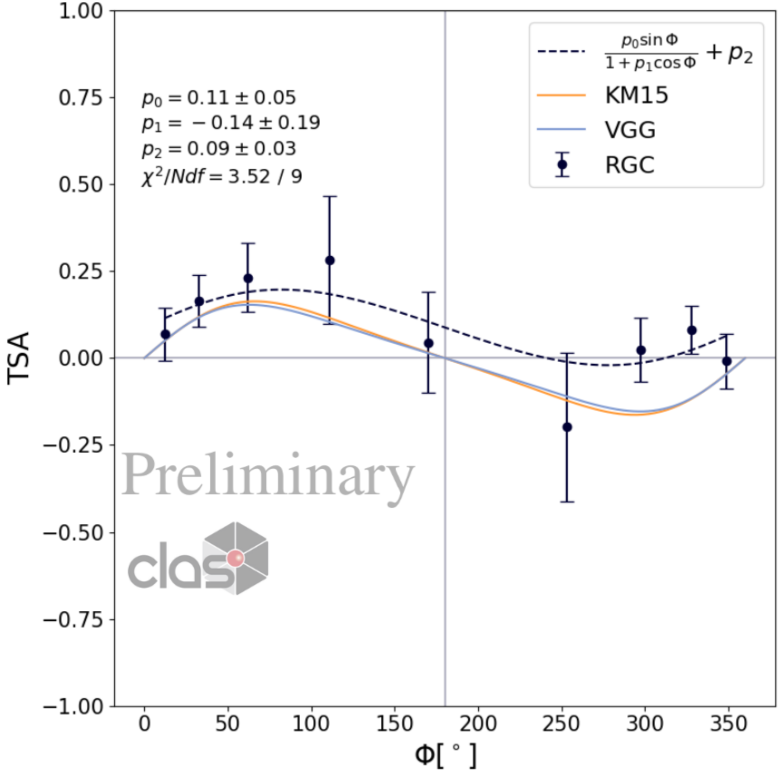
$$\text{with } s_{1,unp} \propto \Im\text{m}\left[F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - \xi\frac{t}{4M^2}F_2\mathcal{E}\right]$$

- VGG model and KM15 fit for free protons.
- BSA does not account for the N background.

$$A_{LU} = \frac{P_t^-(N^{++} - N^{-+}) + P_t^+(N^{+-} - N^{--})}{P_b \times (P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))}$$

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

TARGET SPIN ASYMMETRY FOR pDVCS IN D

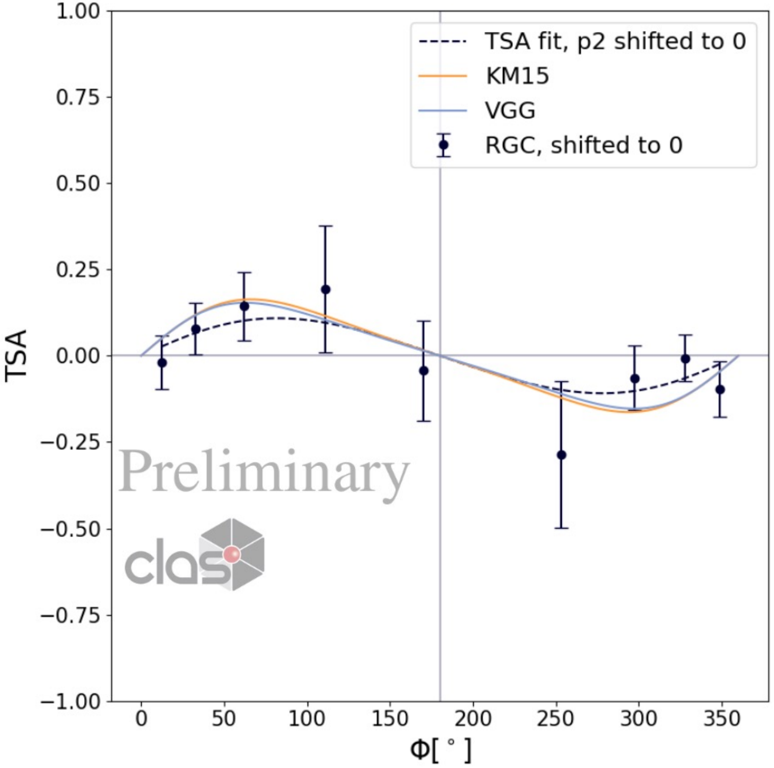


$$A_{UL}(\phi) \simeq \frac{s^I_{1,LP}\sin(\phi)}{c^{BH}_{0,unp} + \left(c^{BH}_{1,unp} + c^I_{1,unp}\right)\cos(\phi)}$$

$$\text{with } s_{1,LP} \propto \mathfrak{Im}\left[F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)\left(\mathcal{H} + \frac{x_{bj}}{2}\mathcal{E}\right) - \xi\left(\frac{x_{bj}}{2}F_1 + \frac{t}{4M^2}F_2\right)\tilde{\mathcal{E}}\right]$$

- Constant shift to the TSA?
- Under investigation:
  - Normalization of the yields?
  - Acceptance effects?
  - Target density?

TARGET SPIN ASYMMETRY FOR pDVCS IN D



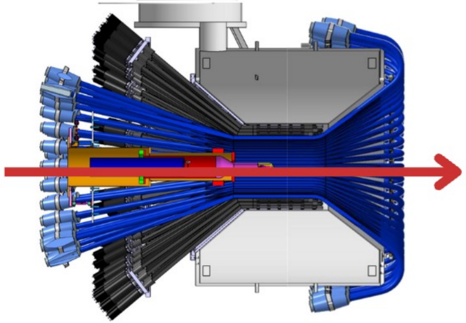
$$A_{UL}(\phi) \simeq \frac{s^{I}_{1,LP}\sin(\phi)}{c^{BH}_{0,unp} + \left(c^{BH}_{1,unp} + c^{I}_{1,unp}\right)\cos(\phi)}$$

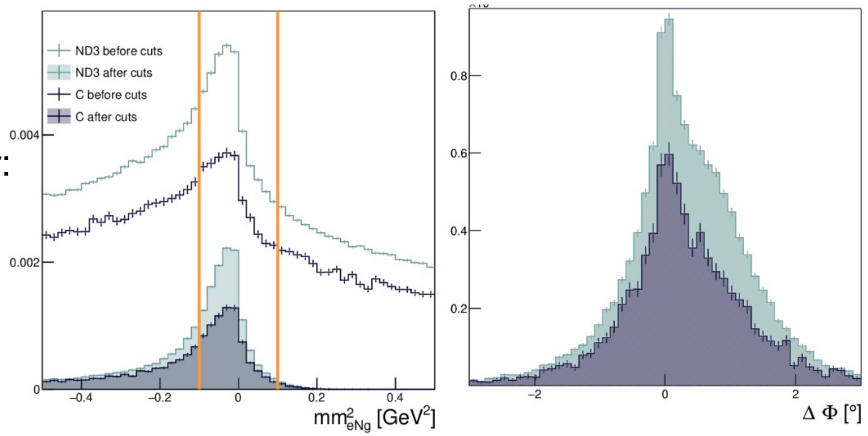
$$\text{with } s_{1,LP} \propto \Im\mathfrak{m}\left[F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)\left(\mathcal{H} + \frac{x_{bj}}{2}\mathcal{E}\right) - \xi\left(\frac{x_{bj}}{2}F_1 + \frac{t}{4M^2}F_2\right)\tilde{\mathcal{E}}\right]$$

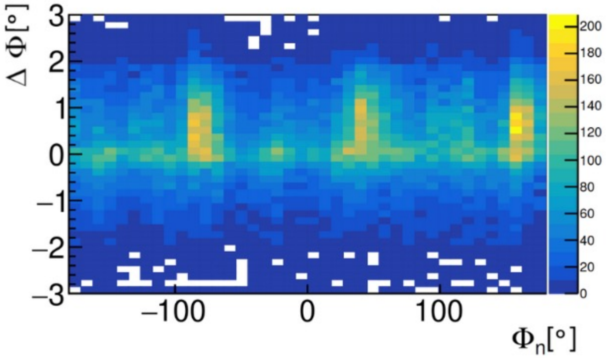
- Constant shift to the TSA?
- Under investigation:
  - Normalization of the yields?
  - Acceptance effects?
  - Target density?

NEUTRON DVCS

- RGC nDVCS events en → e’n’γ
- Proton and neutron detection in the central detector:
  - Tracking system (CVT) around the target.
  - Four layers of scintillators: CTOF and CND.



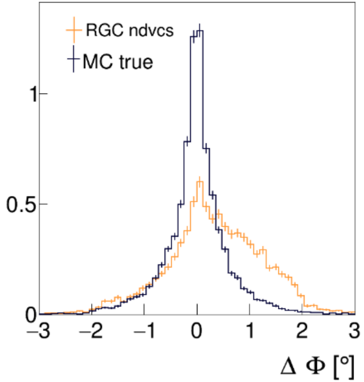


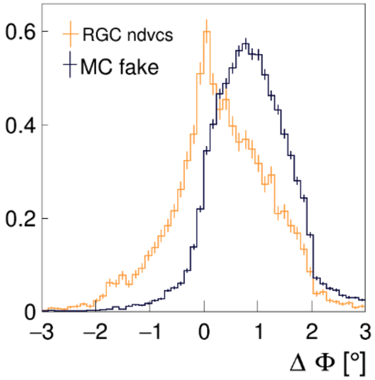


- CD neutrons = hits in CTOF/CND not associated with tracks.
- If a proton track is missed, it is assigned a neutron PID.
- It is assigned a straight track; its momentum is not well reconstructed: can be seen in exclusivity variable distributions!

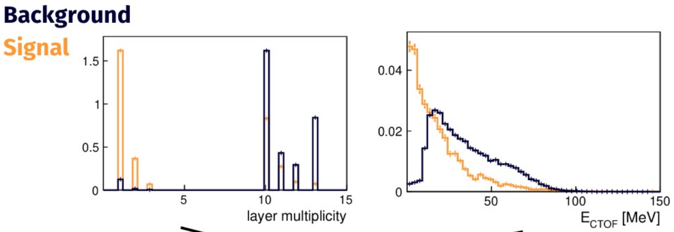
FAKE NEUTRON BACKGROUND

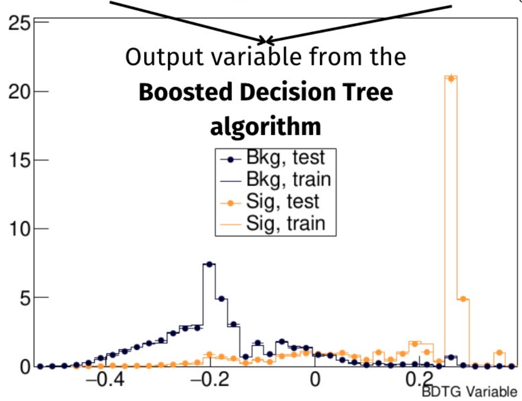
- Background studied using MC simulations.
  - True neutron sample, from generated nDVCS.
  - Fake neutron sample from generated pDVCS.

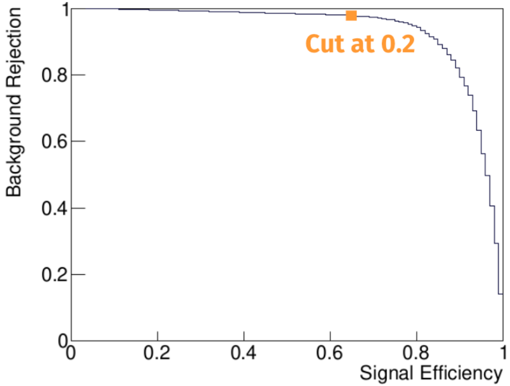




- Goal: PID improvement at detector-level.
  - Machine Learning approach.
  - MC Simulations used to train classifier algorithms.
  - Procedure derived with CLAS12 data on a proton target as well.

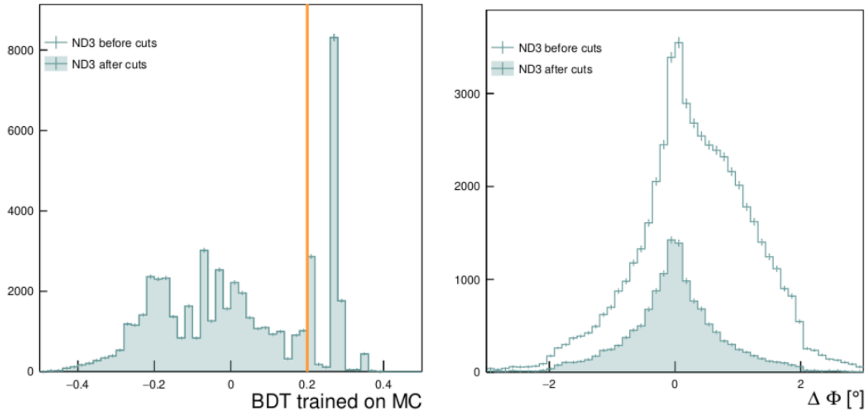


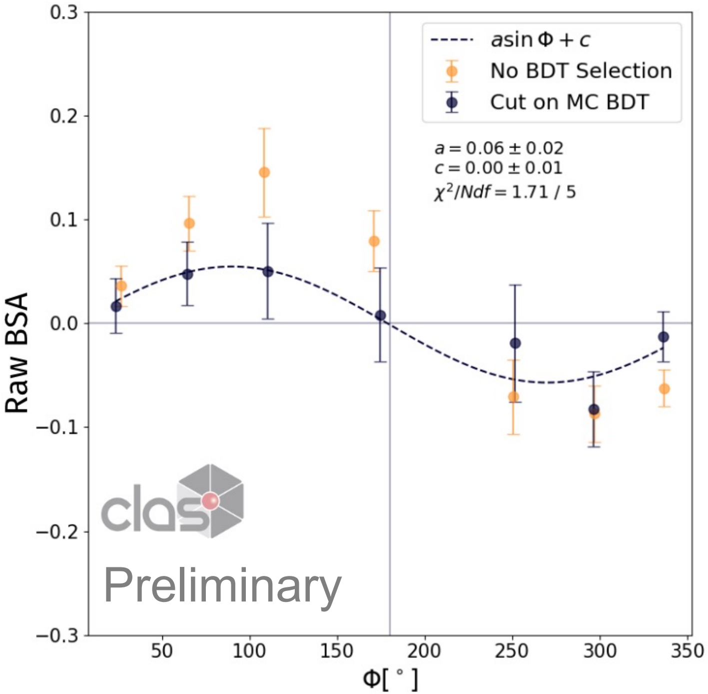




NEUTRON BSA IN ND_3

- Applying this method to the neutron sample reduces the fake neutron background.





- Expected shape for the raw BSA (π^0 background not subtracted).
- Agreement with nDVCS BSA on unpolarized deuterium [Hobart, Niccolai, arXiv:2406.15539 (2024)]
- Insufficient statistics for TSA and DSA for now.
- The remainder of the dataset will be available very soon!

OUTLOOK

- The **first polarized target experiment with the CLAS12 detector** has been conducted with a rich program around the study of the structure of nucleons.
- **DVCS with longitudinally polarized neutrons** will give access to new observables related to poorly-known **CFFs and their flavor dependence**.
- Specific tools have been implemented to deal with a **molecular, polarized target**.
- **Preliminary results for proton DVCS and the neutron BSA** are encouraging!
- The extraction of the TSA and DSA for the neutron will need the full dataset and refinement of the analysis techniques.
- More results to come with the other two thirds of the dataset available very soon.

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