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DVCS on Polarized Nucleons with the CLAS12 experiment at Jefferson Lab

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A preliminary study for measuring the electro-production of photons off nucleons in the deeply inelastic regime is ongoing at Jefferson Lab using a nearly 12-GeV electron beam on longitudinally polarized proton and neutron targets. Beam-spin, target-spin, and double-spin asymmetries for $eN \to e'N'\gamma$ events will be extracted over wide kinematics in Q^2, x_{Bj}, t and Φ. In the framework of Generalized Parton Distributions (GPDs), they provide insight into the electric and axial charge distributions of valence quarks in protons and neutrons. Preliminary data is available for protons in hydrogen from an NH_3 target, and preliminary raw asymmetries are reported. Their comparison to previous measurements is used as a sanity check. It validates the available analysis tools that will be applied for the case of protons and neutrons in deuterium, for which data will be available in the near future. The neutron measurement is of particular interest since it will allow us to extract the flavor-dependence of the observables for the first time by comparison with the proton data.

25th International Spin Physics Symposium (SPIN 2023)
24-29 September 2023
Durham, NC, USA

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PoS(SPIN2023)247

1. Introduction

An intense research effort is focused on the extraction of observables giving access to Generalized Parton Distributions (GPDs) using the CLAS12 spectrometer [1] at Thomas Jefferson National Accelerator Facility (JLab). GPDs provide a three-dimensional picture of the partonic degrees of freedom of the nucleon in terms of longitudinal momentum, transverse spatial position, and their correlations. They are notably accessible in experiments measuring Deeply Virtual Compton Scattering (DVCS), the leading diagram of which is presented in Figure. 1.

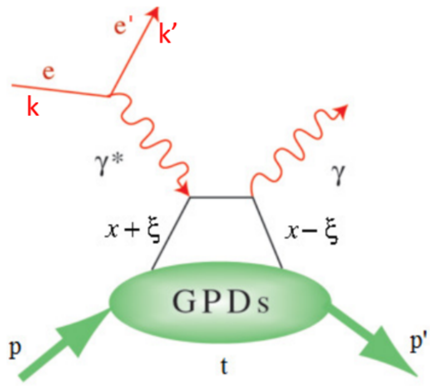


Figure 1: The DVCS process at leading order and leading twist. This diagram is based on QCD factorization. The incoming electron interacts via the exchange of a virtual photon with a single quark of the nucleon that then emits a real photon. This is a perturbative interaction, calculable in QED. The non-perturbative QCD processes describing the structure of the nucleon are encoded in GPDs. The diagram's "hard" and "soft" parts are factorized to compute the amplitude.

The structure of the nucleon is described by four quark GPDs for each quark flavor describing different combinations of the beam helicity and of the relative orientation of the quark and nucleon spins. Combining polarized electron beams and polarized nucleon targets in DVCS experiments and measuring single- and double-spin asymmetries gives an experimental path to the different GPDs.

A recent CLAS12 experiment, that ran between June 2022 and March 2023, uses polarized hydrogen and deuterium targets to measure DVCS on protons and neutrons with a polarized electron beam. Two new observables will be measured: the target-spin and double-spin asymmetries for polarized protons and neutrons in deuterium. They will give access to GPDs that have never been constrained before, particularly H for the neutron, completing the set of observables necessary to understand the structure of the proton and its spin decomposition. A crucial interest for this experiment is comparing protons and neutrons, allowing for flavor decomposition of GPDs. This experiment will also allow us to compare DVCS measurements for protons in hydrogen and deuterium to understand medium effects. Having good control of these effects is crucial since a free neutron target is not available.

This measurement is inscribed within Run Group C (RGC), the first polarized target experiment of the CLAS12 program. A 10.6 GeV polarized electron beam is scattered on longitudinally polarized protons and neutrons in solid NH_3 and ND_3 targets. The ammonia samples are dynamically polarized using the 5T field from the CLAS12 solenoid magnet and a cryostat system at 1K [2].

The electron beam is rastered on the surface of the targets to reduce polarization losses. The DVCS measurement in RGC is performed using in particular the CLAS12 Forward Tracker, a low-angle detector where most of the DVCS photons are collected.

We report here on the preliminary extraction of DVCS asymmetries for protons in longitudinally polarized hydrogen. The available data is preliminary and has not been fully calibrated. All presented asymmetries are raw; they contain contamination from π^0 electro-production in particular. They are used as a sanity check for the analysis tools that will be applied to the deuterium data that will be available in the near future.

2. Target Polarization Extraction

2.1 Measuring the Polarization

Prior to discussing the DVCS measurement, the beam polarization P_b and target polarization P_t need to be evaluated since not all beam electrons or target nucleons are perfectly polarized. The beam polarization is monitored regularly with a Moller Polarimeter during the experiment. Beam polarizations above 80% are achieved in Hall B in JLab. A reliable method to extract the target polarization comes from data analysis of elastic events. The theoretical asymmetry for quasi-elastic events (A_{th}) is well determined for the proton since the ratio of its electric and magnetic form factors ($G = \frac{G_M}{G_E}$) has been measured precisely and is parametrized with good control [3]:

$$A_{th} = \frac{2\tau G[\frac{M}{E} + G(\tau\frac{M}{E} + (1+\tau)\tan(\frac{\theta}{2})^2)]}{1 + G^2\frac{\tau}{\epsilon}} \tag{1}$$

where E is the beam energy, M the proton mass, θ the polar angle of the scattered electron, $\tau = \frac{Q^2}{4M^2}$, $\epsilon = \frac{1}{1+2(1+\tau)tan(\theta/2)^2}$.

For a given polarized target, the idea is to extract $P = P_b \times P_t$ comparing A_{th} and the measured asymmetry $A_{meas} = \frac{N^+ - N^-}{N^+ + N^-}$ ($N^\pm$ is the number of events for $\pm$ electron helicities):

$$P = \frac{\sum_{i=0}^{N_{bins}} f_i A_{th,i}(N_i^+ - N_i^-)}{\sum_{i=0}^{N_{bins}} f_i^2 A_{th,i}^2 (N_i^+ + N_i^-)} \tag{2}$$

P is extracted using maximum likelihood estimation in N_{bins} Q^2 bins. f_i is the dilution factor in each Q^2 bin, that accounts for the proportion of unpolarized N background in the NH_3 target.

2.2 Event Selection

Elastic events are extracted from the exclusive measurement $ep \rightarrow ep$. Both the final proton and electron are detected, their momenta and angles are measured, and channel-selection cuts are applied using the following variables (Fig. 2):

- W^2, the square of the missing mass of X in the reaction $ep \rightarrow eX$.
- MM^2, the square of the missing mass of X in the reaction $ep \rightarrow epX$
- $\Delta\phi$, the coplanarity, defined as the difference between the azimuthal angles of the detected proton and electron

- $E_{beam}^{calc} = M(\frac{1}{tan(\theta_{e^-}/2)tan(\theta_p)} - 1)$, the beam energy estimated from the proton and electron polar angles.

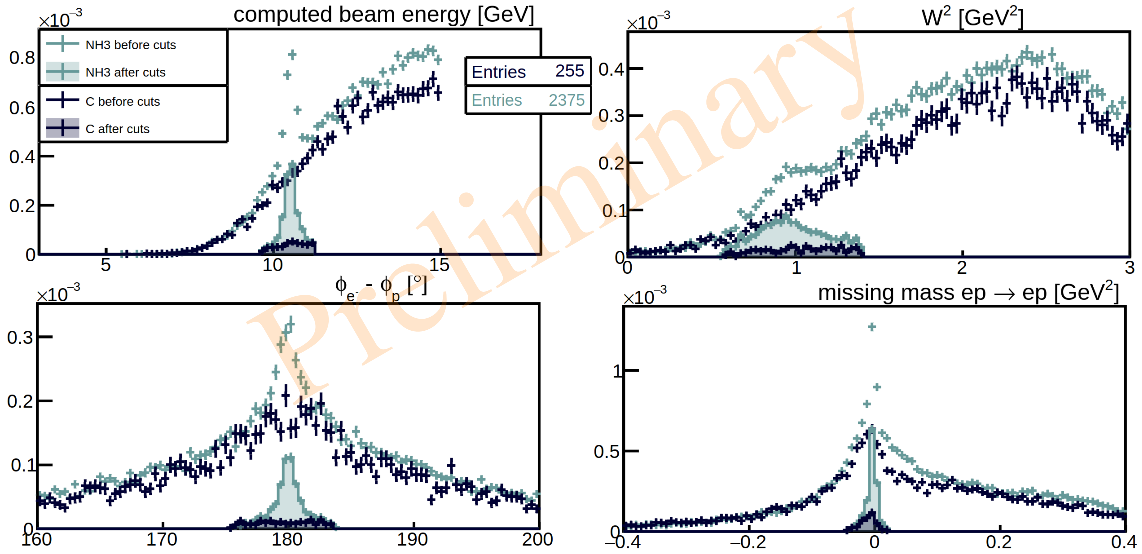


Figure 2: Elastic exclusivity variables for NH_3 (in green) and C (in black) data. The comparison before (simple points) and after (filled distribution) cuts highlights the selection of the H peak above the N background, whose distributions are similar to the C data.

After these selection cuts, the dilution factor is estimated from the remaining yields of NH_3 and C data in bins of Q^2 as:

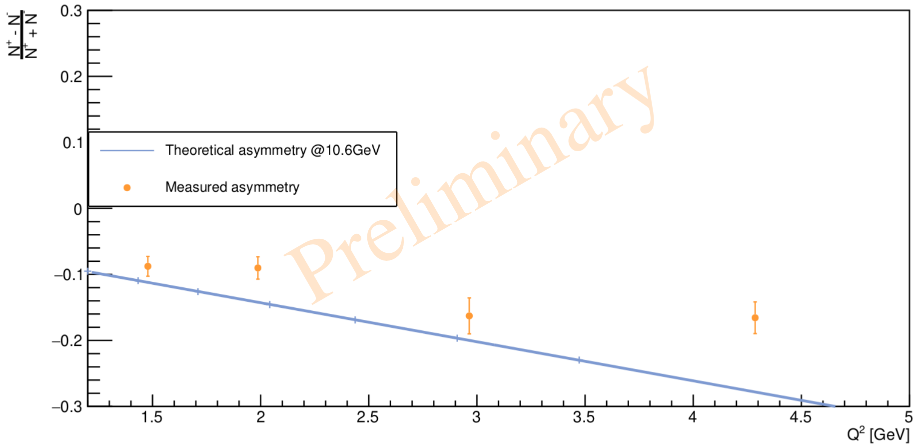
$$f_i = 1 - \frac{C_i}{NH_{3i}} \tag{3}$$

2.3 Results

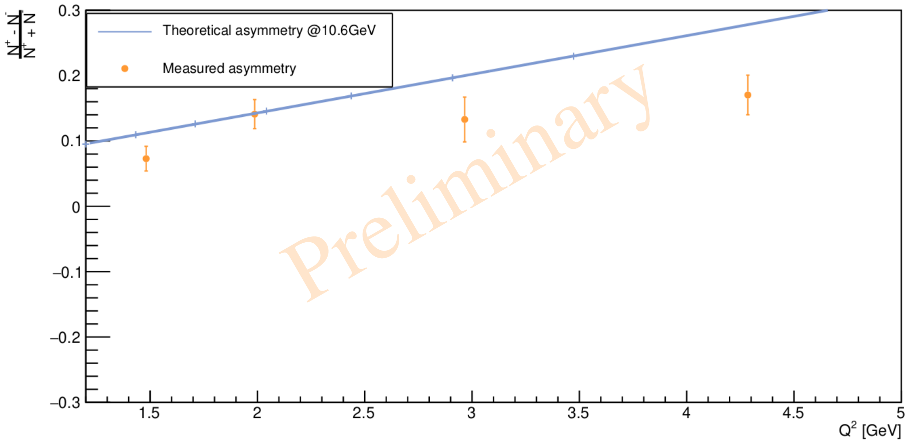
This procedure was derived for two sets of data: one with positively polarized NH3 and one with negatively polarized NH3. They represent around 5% of the total RGC dataset. Measurements are presented in Fig. 3. The extracted values are:

- Positively polarized NH3: $P_b \times P_t = 0.692 \pm 0.085$
- Negatively polarized NH3: $P_b \times P_t = -0.664 \pm 0.056$

P_t can be evaluated using the Möller measurement for $P_b = 83.534\% \pm 1.440\%$.



(a) Negatively polarized NH_3



(b) Positively polarized NH_3

Figure 3: Elastic double spin asymmetry and target polarization.

3. DVCS analysis

3.1 Event Selection

Events with at least one proton, one electron, and one photon are selected. Only events for which the GPD formalism can be applied are selected: $Q^2 >= 1$ GeV^2 and $W >= 2$ GeV^2. Selection cuts are applied using the following quantities (Fig. 4):

- $MM^2_{ep\gamma}$, the square of the missing mass of X in the reaction $ep \to ep\gamma X$
- $MM^2_{eX\gamma}$, the square of the missing mass of X in the reaction $ep \to eX\gamma$.
- MM^2_{epX}, the square of the missing mass of X in the reaction $ep \to epX$.
- Δt, the difference between two ways of computing the momentum transfer t between the initial and final state protons.

- $\Delta\Phi$, the difference between two ways of computing the angle Φ between the leptonic and hadronic planes.

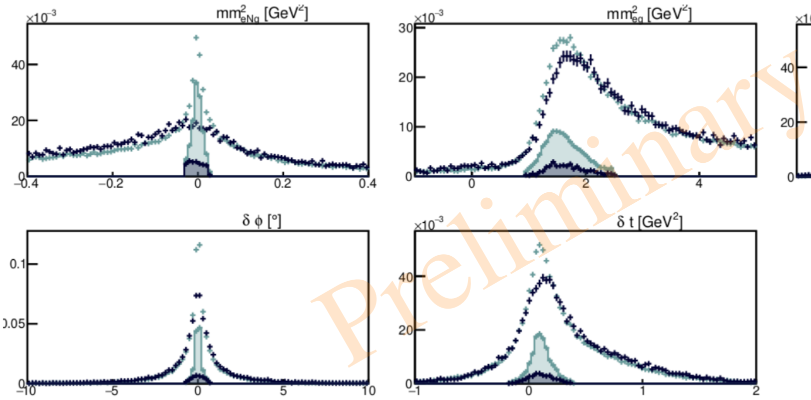


Figure 4: DVCS exclusivity variables for NH_3 (in green) and C (in black) data. The comparison before (simple points) and after (filled distribution) cuts highlights the selection of the H peak above the N background.

The phase-space covered by the selected DVCS events is presented in Fig. 5 and is ($1 < Q^2 < 10$ (GeV/c)^2), ($0.05 < x_{Bj} < 0.7$), ($0.08 < -t < 2$ (GeV/c)^2), ($0 < \Phi < 360°$).

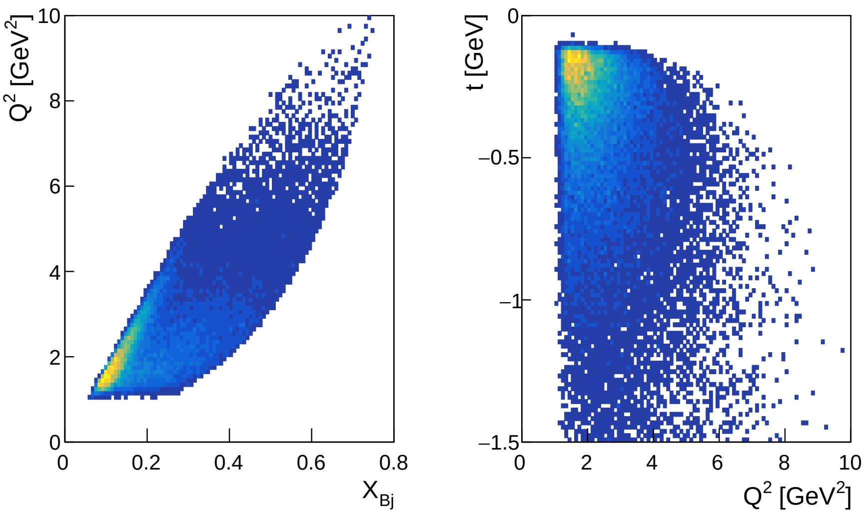


Figure 5: $Q^2 - x_{Bj}$ and $t - Q^2$ coverage for the DVCS events. The high-Q^2 region is particularly well-covered thanks to the 10.6 GeV beam of the CEBAF accelerator.

3.2 Asymmetries

Three kinds of asymmetries are reported in this document, as defined in equations (4) to (6). For each number of selected events N, the first sign in the superscript is the beam helicity (b), and the second sign corresponds to the target polarization (t). All N^{bt} yields are normalized by the charge that was recorded by the Faraday cups: $N^{bt} = \frac{\text{yield}(b,t)}{\text{accumulated charge}(b,t)}$.

- Beam-spin asymmetry (BSA)

$$A_{LU} = \frac{P_t^-(N^{++} - N^{-+}) + P_t^+(N^{+-} - N^{--})}{P_b \times (P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))} \tag{4}$$

- Target-spin asymmetry (TSA)

$$A_{UL} = \frac{N^{++} + N^{-+} - N^{+-} - N^{--}}{Df \times (P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))} \tag{5}$$

- Double-spin asymmetry (DSA)

$$A_{LL} = \frac{N^{++} + N^{--} - N^{+-} - N^{-+}}{P_b \times Df \times (P_t^-(N^{++} + N^{-+}) + P_t^+(N^{+-} + N^{--}))} \tag{6}$$

As with the elastic analysis, the dilution factor D_f is computed as the fraction of polarized events comparing NH_3 and C data similarly to Eq. (3). It is presented in Fig. 6.

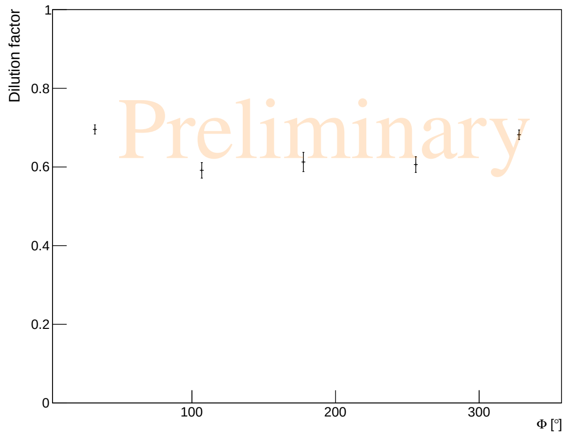
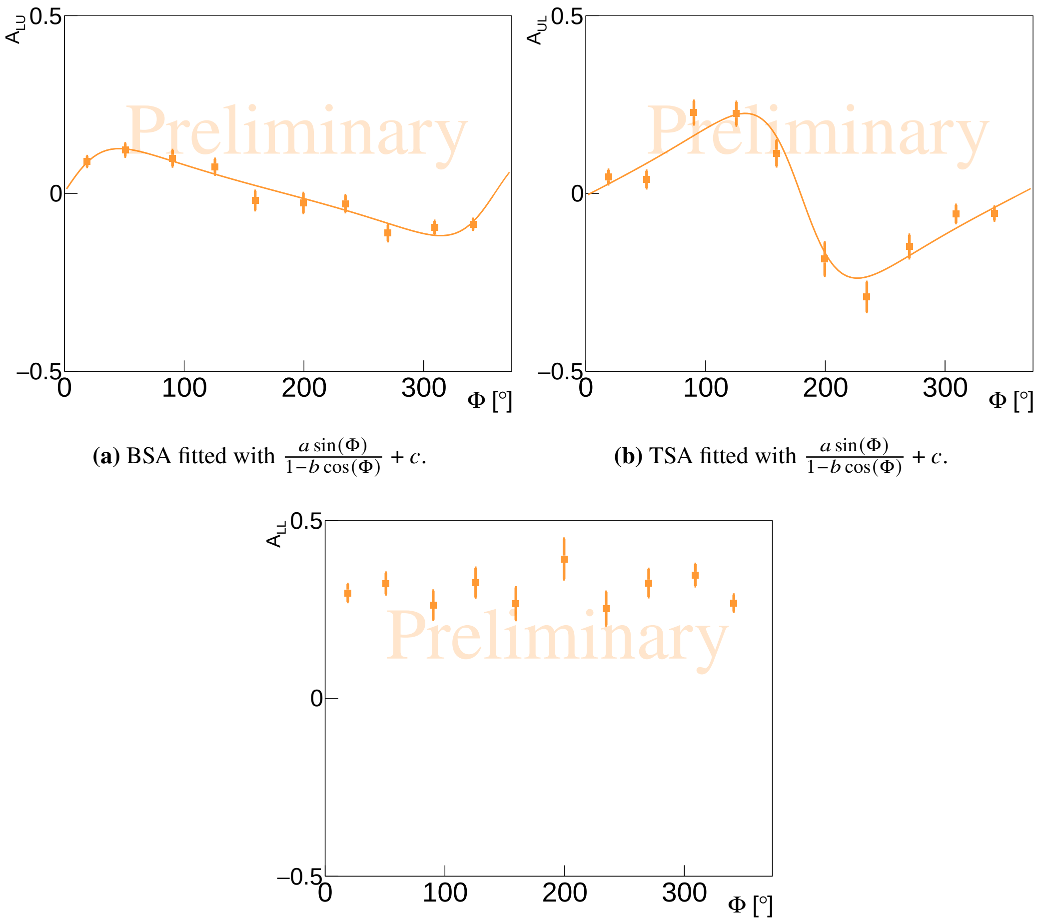


Figure 6: Dilution factor for the pDVCS events.

The asymmetries are computed in Φ bins and presented in Fig. 7. The amplitudes must be read cautiously since these asymmetries are integrated over a vast range of kinematics and are still contaminated by π_0 production. The BSA, in particular, is lower than previous measurements for DVCS [4] since the N background is not accounted for. However, all asymmetries show the expected signs and shapes as sinusoidal functions of ϕ. The t-dependence of the amplitude of the asymmetries agrees with previous measurements and model predictions: the BSA amplitude increases significantly at large $-t$, and remains stable for the TSA and DSA.



(a) BSA fitted with $\frac{a\sin(\Phi)}{1-b\cos(\Phi)}+c$.

(b) TSA fitted with $\frac{a\sin(\Phi)}{1-b\cos(\Phi)}+c$.

(c) DSA

Figure 7: Preliminary raw asymmetries for pDVCS in NH_3.

4. Conclusions

The analysis for the first CLAS12 polarized-target experiment is ongoing. Single-beam, single-target, and double-spin asymmetries for DVCS on polarized protons and neutrons will be measured over a large phase space (in particular up to $Q^2 = 10(\text{GeV/c})^2$) at the same kinematics. Preliminary, raw asymmetries have been extracted for protons in a hydrogen target, demonstrating the readiness of the analysis tools to be applied to the data with protons and neutrons in deuterium, which will soon be available. The target polarization can be extracted by analysis of (quasi)-elastic events. Events on Hydrogen can be isolated from the unpolarized nitrogen background, from the molecular NH_3 and ND_3 targets, and the remaining contamination can be evaluated with sufficient precision by comparison to carbon data. The extracted raw asymmetries show the expected behavior in their Φ and t-dependencies.

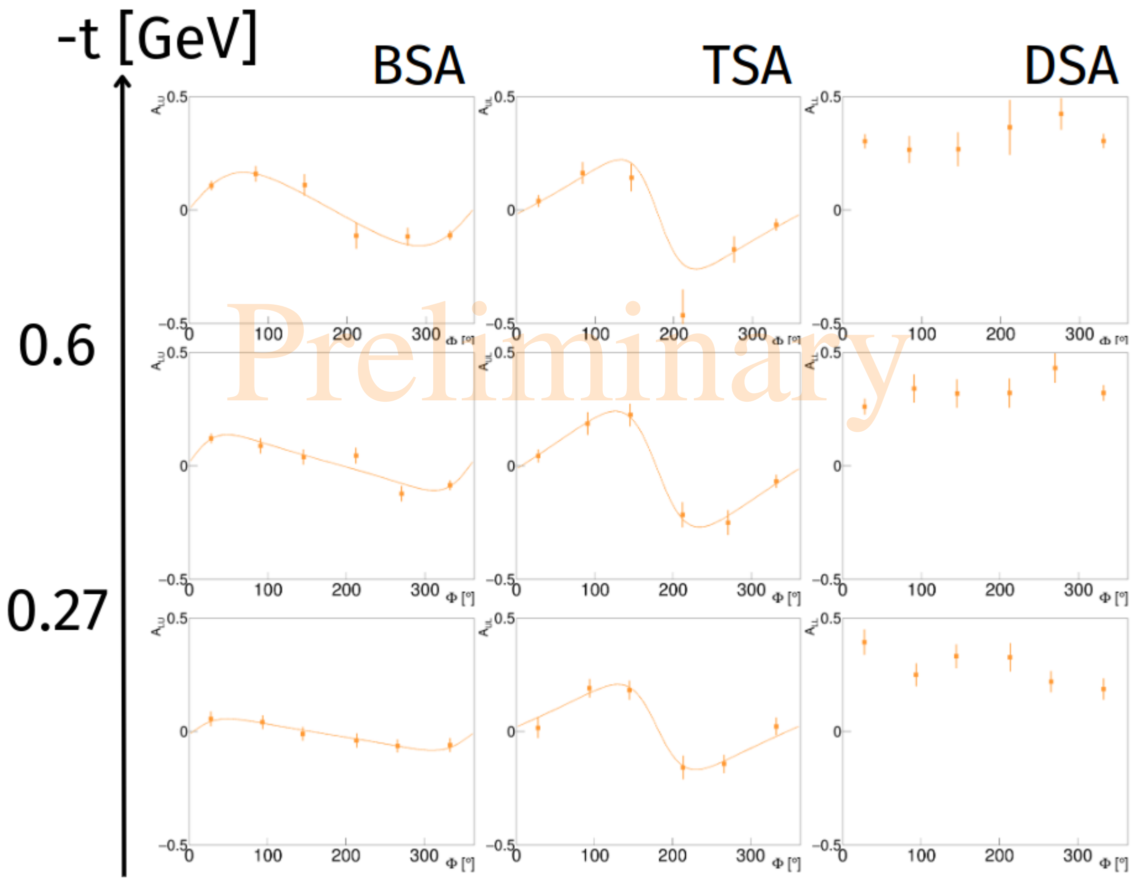


Figure 8: Preliminary raw asymmetries for pDVCS in H in bins of $-t$.

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