

Probing the pion structure with RGA data

First measurement of the DVCS beam spin asymmetry in the Sullivan process

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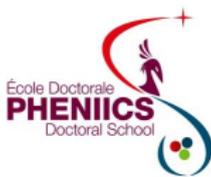


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Probing the pion structure

A unique hadron

The pion is the **lightest hadron**. It consists of a quark-antiquark bound state.

A theoretically clean system

- As a **spin-0** hadron, its structure is simpler than that of the proton.
- At leading twist, only **two GPDs** describes its partonic structure.

Experimentally constrained quantities

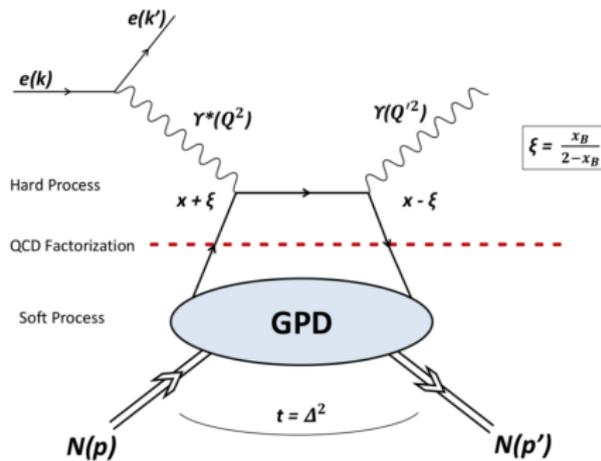
- Electromagnetic form factor (FF) from pion-electron scattering.
- Parton distribution functions (PDFs) from Drell–Yan measurements.

Our goal

- Access the pion Generalized Parton Distributions (GPDs) → 3D structure.

Deeply Virtual Compton Scattering (DVCS)

- Hard exclusive probe of hadron structure.
- Leading twist: **handbag** → photon hits a **single quark**.
- Gives access to **GPDs** via **CFFs**.



Compton Form Factor (CFF) at leading order:

$$\mathcal{H}(\xi, t, Q^2) = \sum_q e_q^2 \int_{-1}^1 dx \left(\frac{1}{x - \xi + i\epsilon} - \frac{1}{x + \xi - i\epsilon} \right) H^q(x, \xi, t)$$

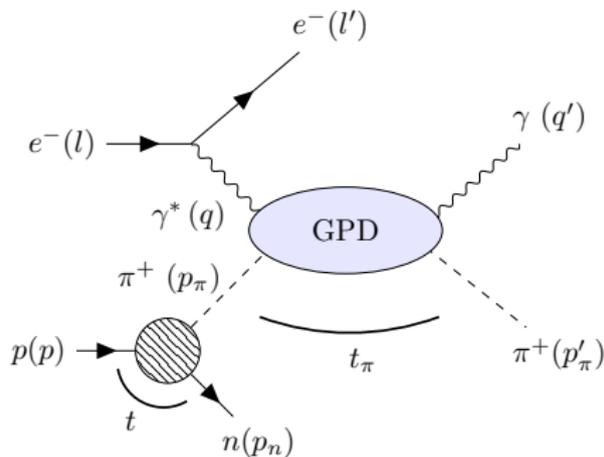
The Sullivan process

How to experimentally perform DVCS on the pion?

- No free pion targets.
- Pion-electron scattering: low luminosity and low momentum transfers.
- **Solution:** use the **Sullivan process** to access the pion structure [1].
- Successfully used in pion FF measurements at JLab energies [2].

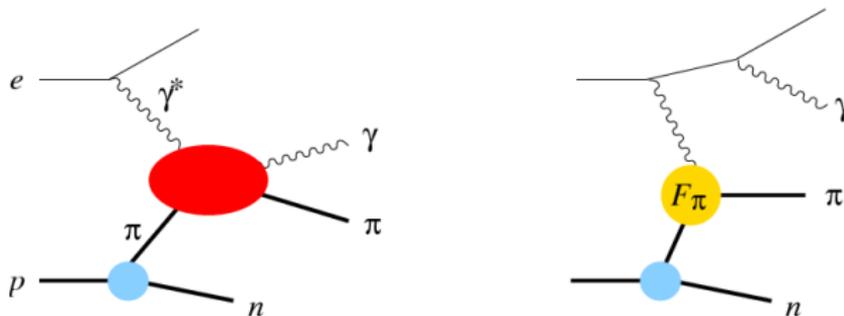
The Sullivan process

- Proton emits a nearly on-shell pion ($p \rightarrow \pi^+ n$).
- Virtual photon scatters off the pion \rightarrow **pion DVCS**.
- Mechanism valid near the **pion pole** (small $-t$).



Bethe-Heitler process and interference

Bethe-Heitler (BH) process : the final-state photon emitted by the incoming or scattered electron.



Cross section with helicity-dependent interference:

$$d\sigma = |T_{\text{BH}}|^2 + |T_{\text{DVCS}}|^2 + \mathcal{I}_{\text{unpol}} + \lambda_e \mathcal{I}_{\text{pol}}$$

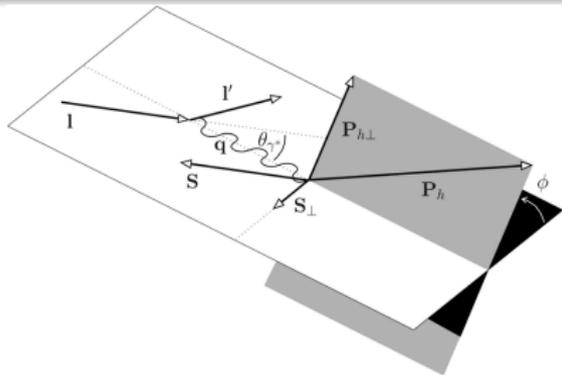
Beam Spin Asymmetry (BSA)

Beam-Spin Asymmetry (BSA)

Helicity-dependent observable from DVCS–BH interference:

$$A_{LU}(\phi) = \frac{1}{P_b} \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)} \propto \Im m(\mathcal{H}_\pi) \sin \phi$$

- Robust: cancels many systematics



Definition of ϕ_{Trento}

- Angle between lepton scattering plane and hadronic scattering plane.
- Measured in the $p_\pi + q$ rest frame.

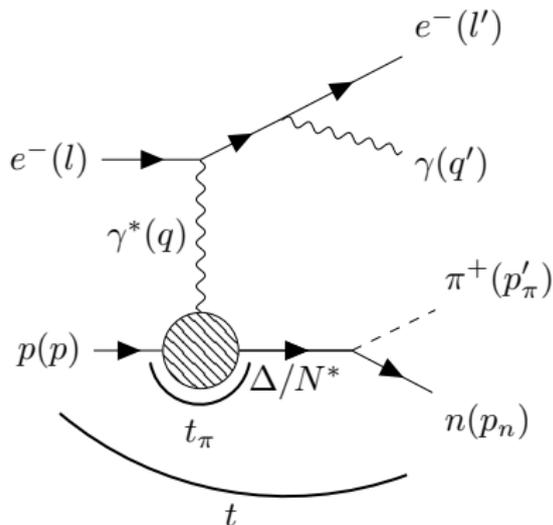
Nucleon resonance background

Resonance contribution

- Final state $e\gamma n\pi^+$ can arise from nucleon resonance:



- Events from DVCS and BH.



Impact on the analysis

- Irreducible background for the Sullivan process at JLab energies.
- Affects the interpretation in terms of pion GPDs.

RGA Data Sample

- Fall 2018 Outbending run.
- Path: /rg-a/production/recon/fall2018/torus+1/pass2/train/nSidis/.
- Integrated luminosity: $\mathcal{L}_{\text{int}} = 42.589 \text{ fb}^{-1}$ (charge measured with QADB).
- Beam polarization: $P_B \sim 86\%$.
- Main cuts applied:
 - $Q^2 > 1 \text{ GeV}^2$.
 - $W > 2 \text{ GeV}$.

Monte Carlo simulation

Pion DVCS

- DVCS model from A.V. Belitsky *et al.* [3], adapted to the Sullivan process using the pion flux factor from D. Amrath *et al.* [4].
- Pion GPD model from J. Chavez *et al.* [5], and for the BH process, the pion form factor parametrization from D. Amrath *et al.* [4].

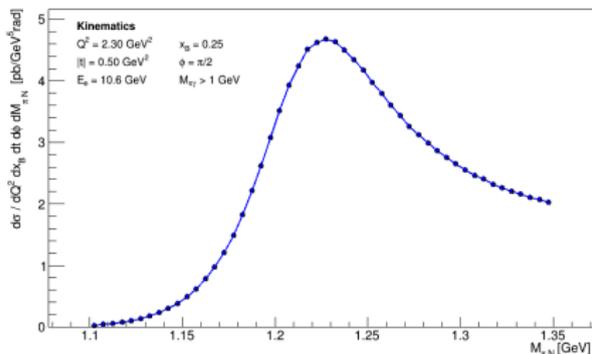
Nucleon resonance background

- BH process on Δ^+ .
- The cross section was derived and implemented starting from the amplitude given in K. Semenov and M. Vanderhaeghen [6], using FeynCalc (Mathematica) [7].

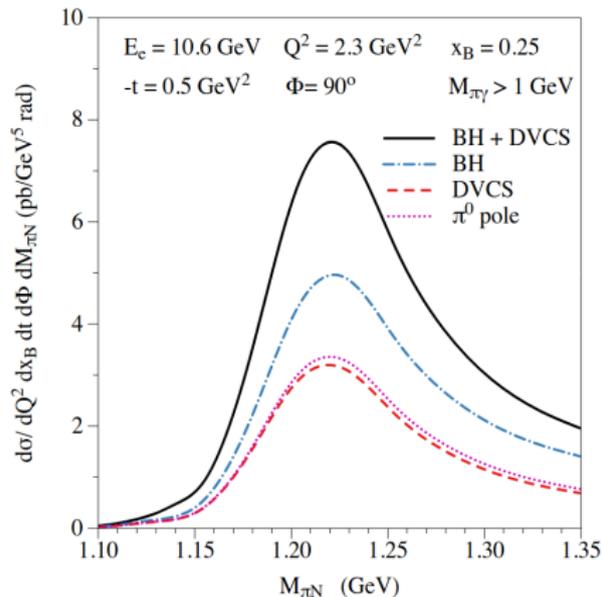
Event weighting

- Events weighted with : $w = \frac{\mathcal{L}_{\text{int}} \cdot d\sigma_{\text{tot}} \cdot d\Phi}{N_{\text{gen}}}$.

Check the BH implementation on the Δ^+ resonance



Dependence on the invariant mass $M_{\pi+n}$ of the $ep \rightarrow e\gamma\Delta^+ \rightarrow e\gamma n\pi^+$ cross section only for the BH process.



Dependence on the invariant mass $M_{\pi+n}$ of the $ep \rightarrow e\gamma\Delta^+ \rightarrow e\gamma n\pi^+$ cross section from [6].

Event Selection

Electron (FD)

- Exactly one scattered electron.
- PID cuts: $E_{\text{dep}}^{\text{PCAL}} > 0.06$ GeV, EM Calorimeter sampling fraction [8], $v_z \in [-11, 1]$ cm, $E_e > 2.0$ GeV.

π^+ (FD or CD)

- Exactly one π^+ with PID cuts: $\chi_{\text{PID}}^2 \in [-3, 3]$, $\Delta v_z \in [-20, 20]$ cm.

Photon (FD or FT)

- At least one photon.
- PID cuts: $\beta \in [0.9, 1.1]$, $\Delta\theta_{e\gamma} > 5^\circ$, $E_\gamma > 3.0$ GeV.

Neutron

Identified via missing mass reconstruction.

Fiducial Cuts

- Documented in: “*Fiducial cuts and PID refinements for RG-A pass 2 (Fa18 and Sp19)*” [8].

Momentum Corrections

- e^- and π^+ (FD) from Richard Capobianco [9].
- γ (FD) from Sebastian Alvarado [10].
- γ (FT) from Asli Acar [11] and Sebastian Alvarado [10].
- Missing momentum corrections for π^+ in the CD.

Monte Carlo Smearing

- e^- smearing applied using the formula from V. Klimenko [12].
- γ smearing applied such that the neutron missing mass width in data matches that of the Monte Carlo signal.

π^0 Background

π^0 Background Estimation Method

- Select reconstructed π^0 in data that can contaminate the signal with $ep \rightarrow e\pi^0\pi^+n$ final state.
- Each π^0 is decayed randomly $N_{\text{decay}} = 1000$ times and passed through GEMC.

Weighting Procedure

For each data π_i^0 :

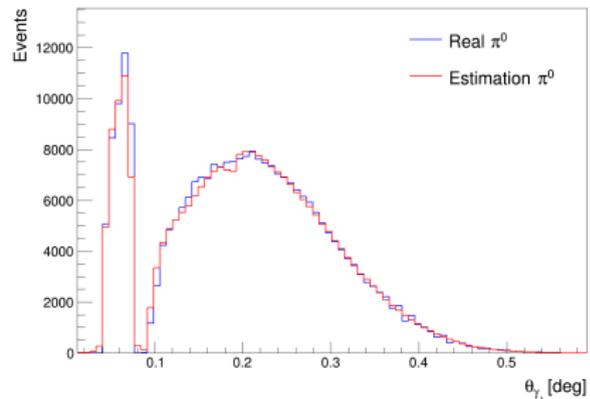
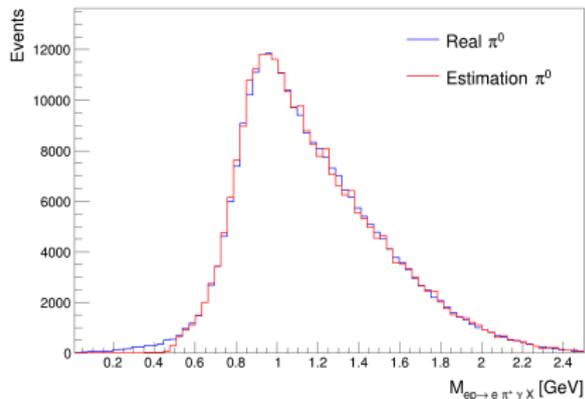
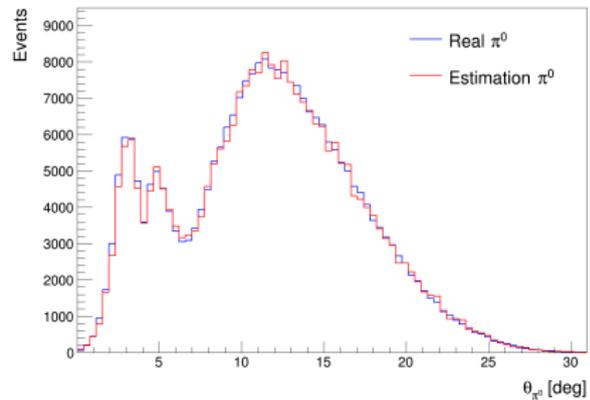
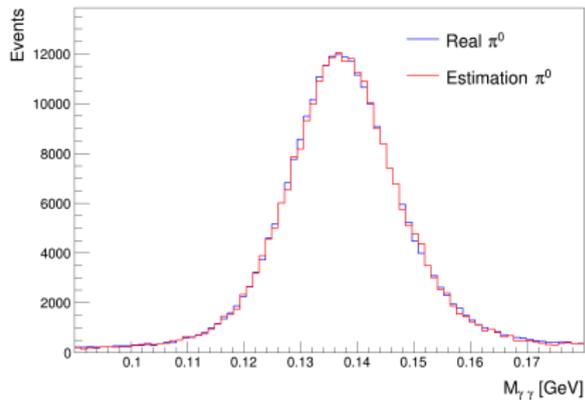
- $N_{\pi^0}^i$: reconstructed π^0 from this parent.
- Weight assigned to each fake DVCS event from the decay of π_i^0 :

$$w_i = \frac{1}{N_{\pi^0}^i}$$

Current Status

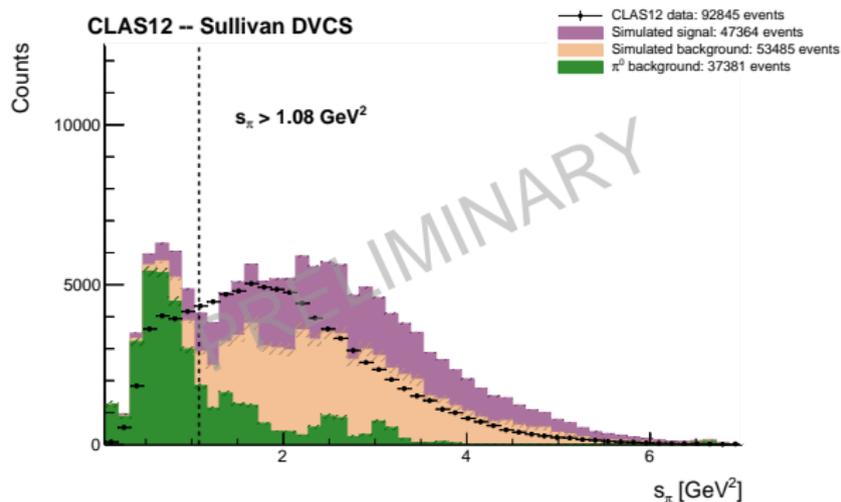
Only 16.75% of the available π^0 sample has been processed. All weights are therefore multiplied by a factor 5.97.

Validation of the π^0 background estimation method



Cut on the pion-photon invariant mass s_π

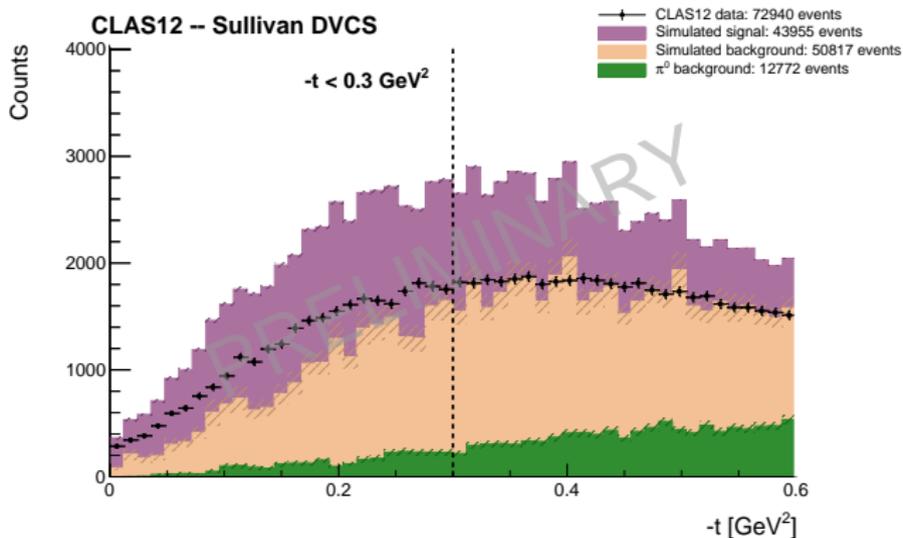
All MC and π^0 contributions are stacked on top of each other in the histogram.



We apply the cut $s_\pi > 1.08 \text{ GeV}^2$ to remove the ρ^+ production background, with $s_\pi = (p_\pi + q)^2$.

Spectrum of the pion-photon invariant mass s_π .

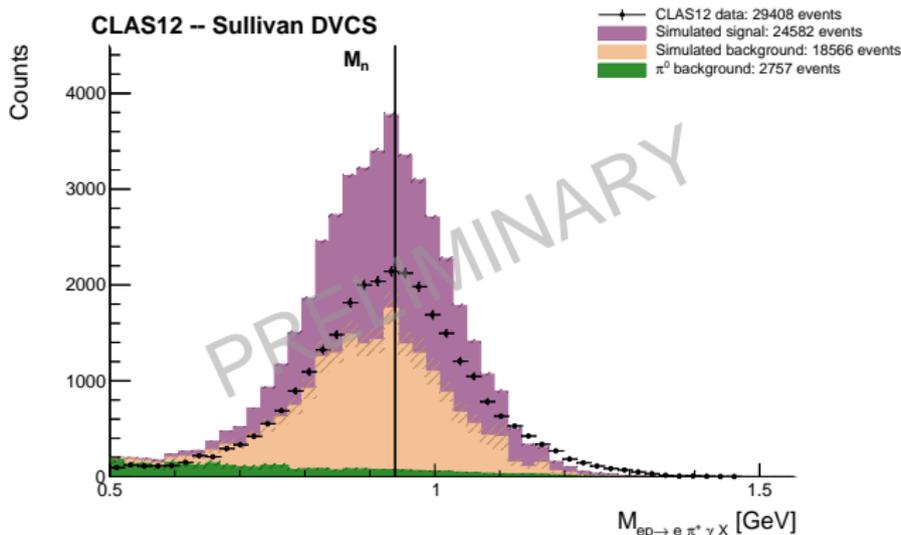
Cut on the pion virtuality $-t$



Spectrum of the pion virtuality $-t$ after the cut on s_π .

We apply the cut $-t < 0.3 \text{ GeV}^2$ to ensure a nearly on-shell pion, with $t = (p - p_n)^2$.

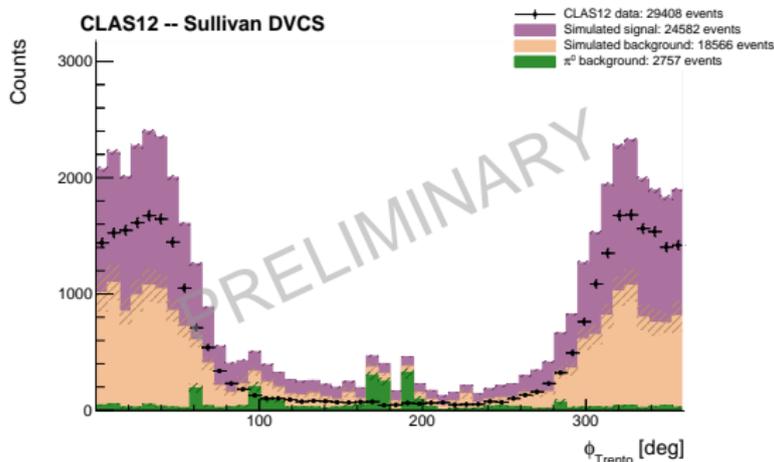
Neutron missing mass



Distribution of the missing mass $M_{ep \rightarrow e \gamma \pi^+ X}$ after the cuts on s_π and $-t$.

$$\text{Neutron missing mass calculated as } M_X^2 = (p + l - l' - q' - p'_\pi)^2.$$

Azimuthal angle ϕ



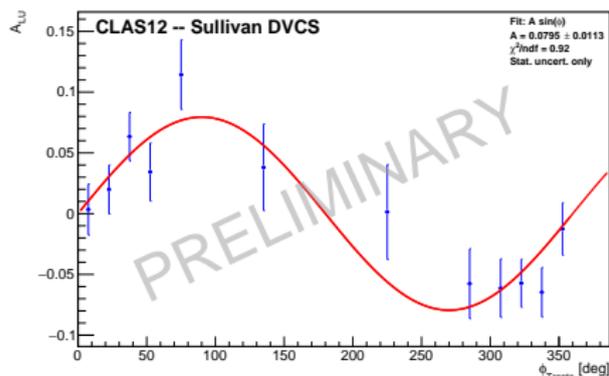
Distribution of the azimuthal angle ϕ .

- The ϕ_{Trento} distribution is driven by the BH process.
- BH dominates the cross section in this kinematic regime.
- Most events cluster around $\phi = 0^\circ$ and $\phi = 360^\circ$, where the BH amplitude is maximal.

Extraction of $A_{LU}^{\sin\phi}$

$$A_{LU}(\phi) = \frac{1}{P_B} \cdot \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$

- $N^+(\phi)$ and $N^-(\phi)$ are the number of events for positive and negative electron helicities, respectively.
- P_B is the effective beam polarization, $\sim 86\%$.



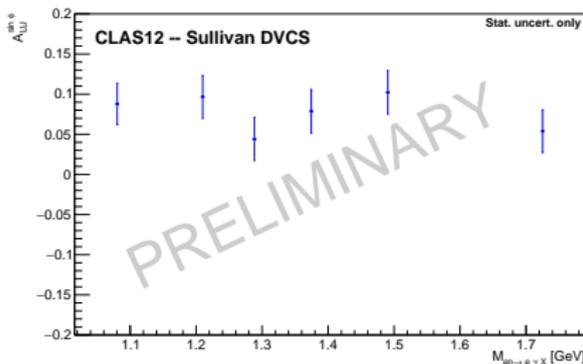
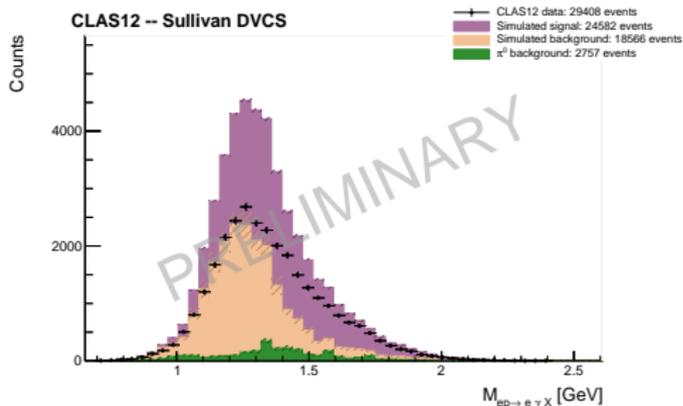
Beam-spin asymmetry extracted from the data and fitted with $A\sin(\phi)$.

Unbinned fit

- Perform an **unbinned maximum likelihood fit** to extract $A_{LU}^{\sin\phi}$ directly from the events.
- Avoids potential binning effects.
- Results are consistent with the binned method.

Invariant mass of the $\pi^+ n$ system

- Our signal falls within the pion-neutron invariant-mass range characteristic of nucleon resonances.



Distribution of the invariant mass of the pion-neutron system $M_{\pi^+ n}$.

Evolution of the amplitude $A_{LU}^{\sin \phi}$ as a function of the invariant mass $M_{\pi^+ n}$.

No significant variation of the beam-spin asymmetry amplitude $A_{LU}^{\sin \phi}$ is observed across the invariant mass spectrum.

Analysis Timeline

Short term (1–2 weeks)

- BH implementation on $N^*(1520)$.
- Completion of π^0 background subtraction.

1 month

- π^+ (CD) momentum corrections.
- Improved photon smearing: match neutron missing mass width in data vs. full MC.
- Finding an efficiency factor to apply to the MC events to match the data yield.

April / May 2026

- Remaining baryonic resonances: $N^*(1440)$ and $N^*(1535)$.

October 2026

- Submission of the analysis note.

October 2027

- PhD thesis defense.

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Main cuts applied to the data

Virtuality of the photon Q^2

- $Q^2 > 1 \text{ GeV}^2$ with $Q^2 = -(l - l')^2$ to ensure the hard scattering regime.

Inelasticity W^2

- $W^2 > 4 \text{ GeV}^2$ with $W^2 = (p + l - l')^2$ to guarantee the deeply inelastic regime of the reaction.

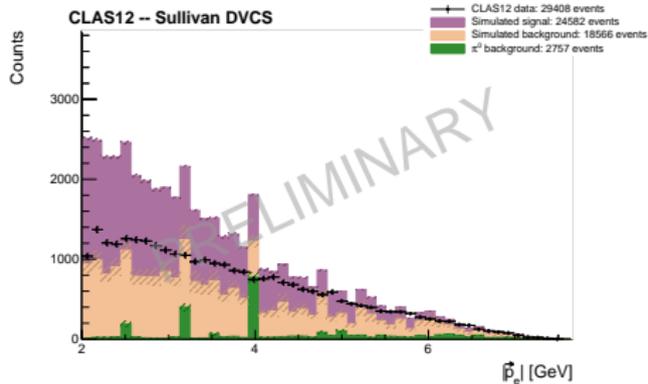
Momentum transfer to the recoil pion t_π

- $-t_\pi < 0.55 \text{ GeV}^2$ with $t_\pi = (p_\pi - p'_\pi)^2 = (p - p_n - p'_\pi)^2$ to select the dominant (leading-twist) contribution.

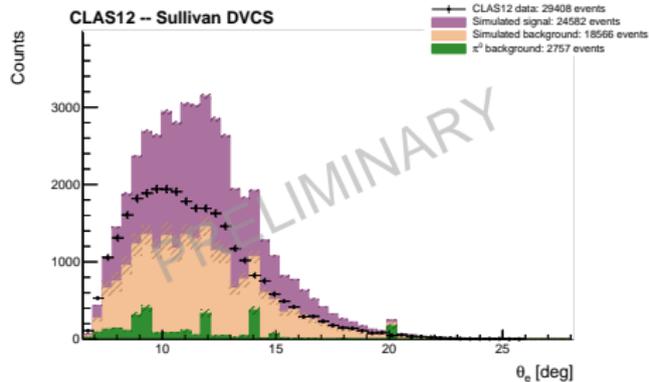
Neutron missing mass $M_{ep \rightarrow e\gamma\pi^+X}$

- $M_{ep \rightarrow e\gamma\pi^+X} \in [0.5, 2.0] \text{ GeV}$, the missing mass of the $ep \rightarrow e\gamma\pi^+X$ system, to select events consistent with a neutron in the final state.

Electron kinematics



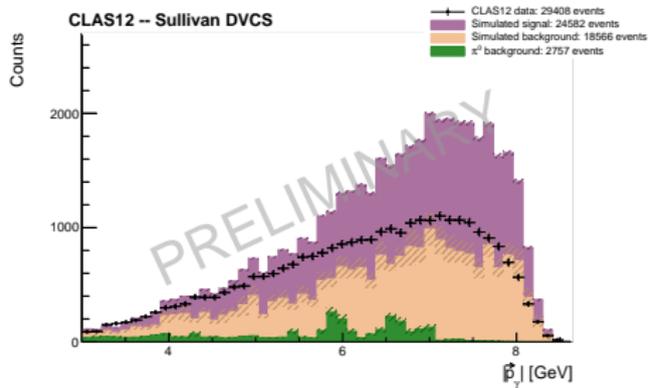
Momentum distribution of the scattered electron.



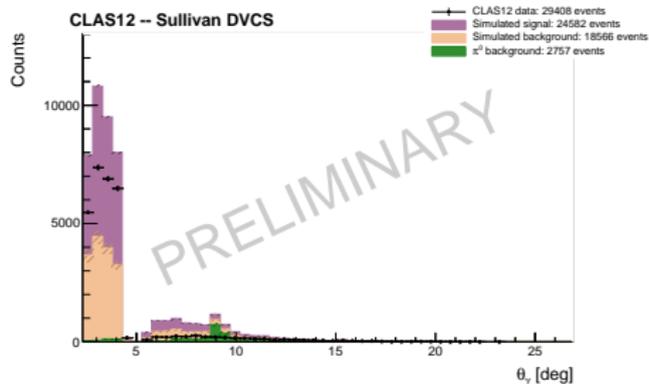
Polar angle distribution of the scattered electron.

All electrons are detected in the FD.

Photon kinematics

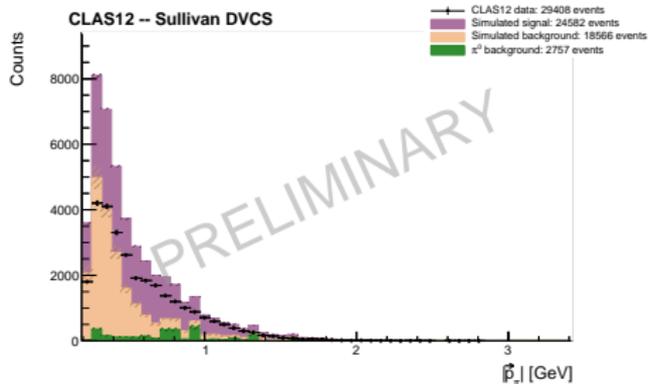


Momentum distribution of the photon.

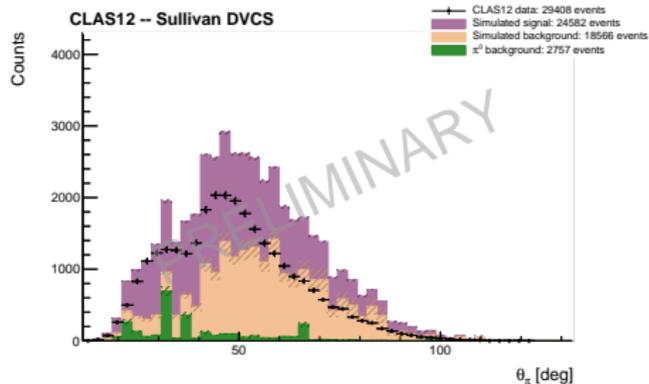


Polar angle distribution of the photon.

Pion kinematics

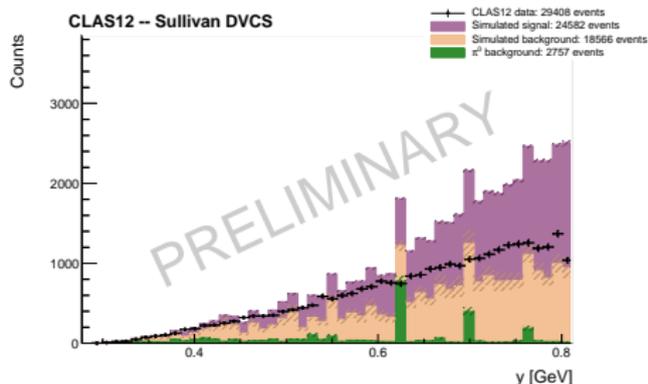
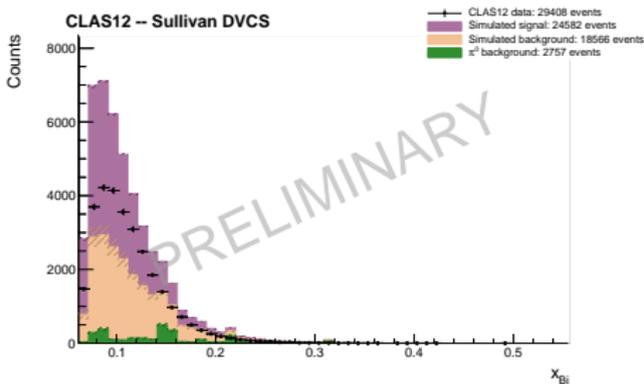
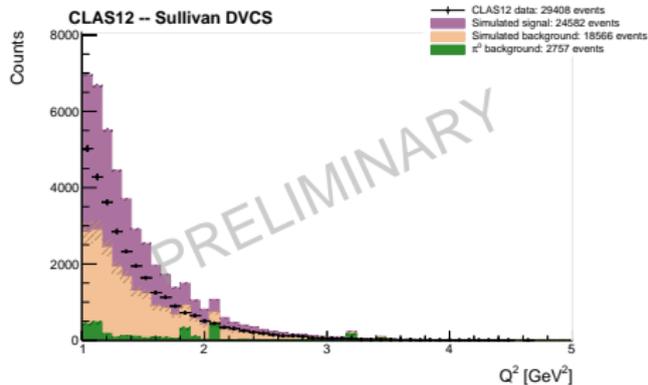
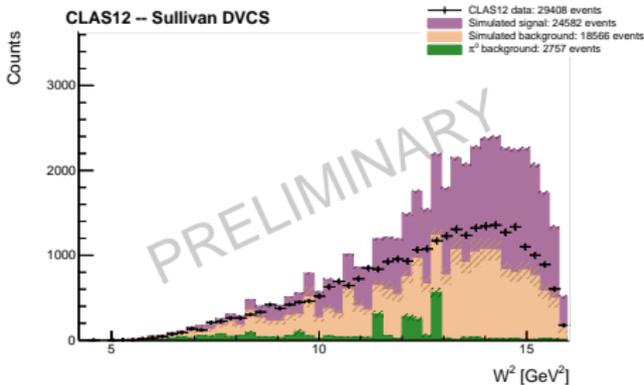


Momentum distribution of the pion.



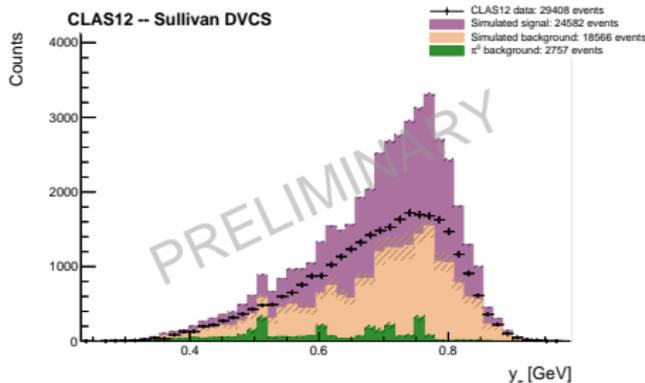
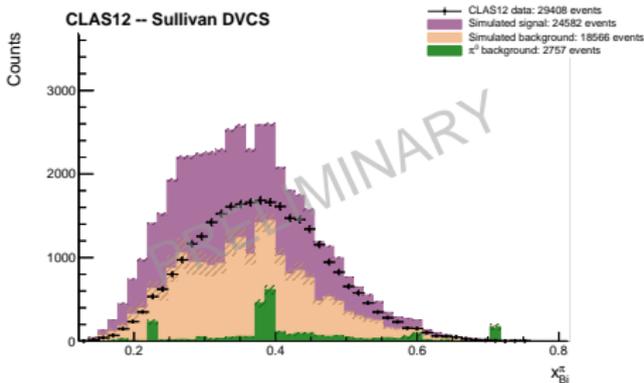
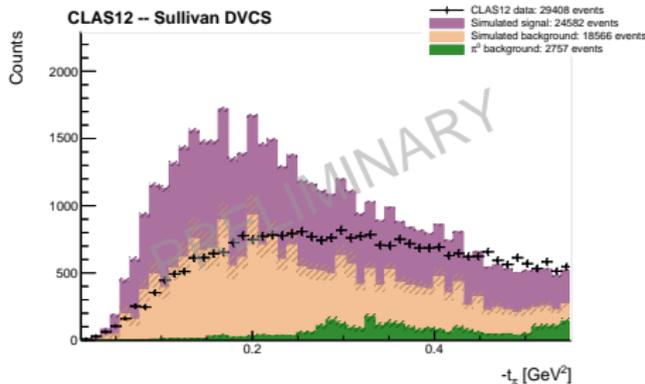
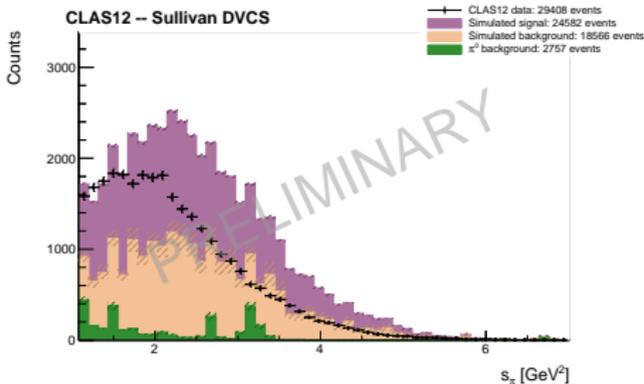
Polar angle distribution of the pion.

DIS kinematic variables



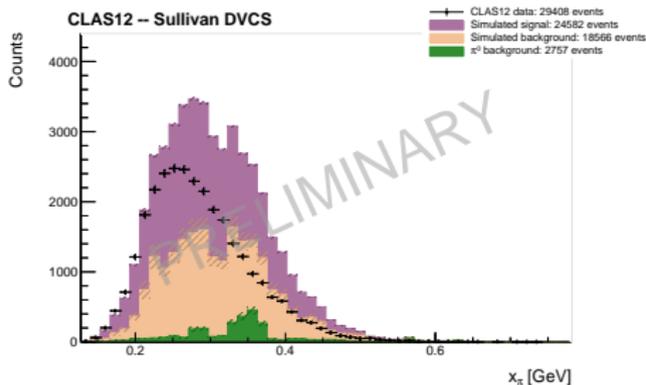
Distribution of kinematic variables W^2 , Q^2 , x_{Bj} , and y .

DVCS kinematic variables



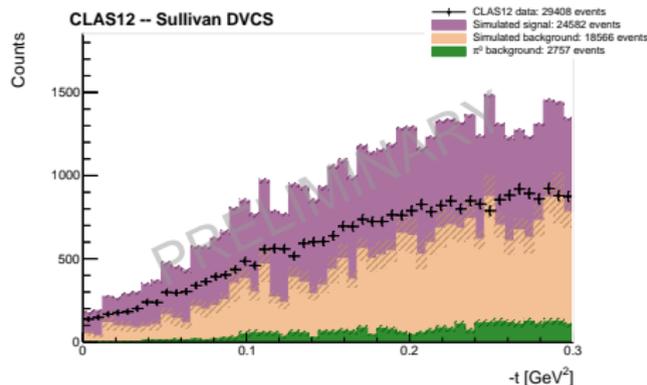
Distribution of kinematic variables s_π , t_π , x_{Bj}^π , and y_π .

Variables relative to the emission of the virtual pion



Distribution of the variable x_{π} .

- $x_{\pi} = \frac{p_{\pi} \cdot l}{p \cdot l}$



Distribution of the variable $-t$.

- $-t = -(p - p_n)^2$

Unbinned extraction of $A_{LU}^{\sin \phi}$ — Method

- Due to limited statistics and a non-uniform event distribution in ϕ , a binned extraction of A_{LU} can introduce statistical fluctuations and bin-width-dependent biases.
- To avoid this, an unbinned maximum likelihood fit is performed.

Event probability density function

$$f(h_i, \phi_i; A) = 1 + h_i P_B A \sin \phi_i$$

where $h_i = \pm 1$ is the beam helicity and P_B the effective beam polarization.

Log-likelihood function

$$\ln \mathcal{L}(A) = \sum_{i=1}^N \ln f(h_i, \phi_i; A)$$

The best-fit amplitude A_{fit} minimizes:

$$\chi^2 = -2 \ln \mathcal{L}(A)$$

Demonstration of the event probability density function

Event probability density function

For each event i with helicity $h_i = \pm 1$, the event probability is:

$$f(\phi_i, h_i; A) = 1 + h_i P_B A \sin \phi_i$$

Definition of asymmetry

The beam-spin asymmetry is defined as:

$$\mathcal{A}_{\text{LU}}(\phi) = \frac{\text{Prob}(h = +1|\phi) - \text{Prob}(h = -1|\phi)}{\text{Prob}(h = +1|\phi) + \text{Prob}(h = -1|\phi)}$$

Conditional probabilities from $f(\phi_i, h_i; A)$

$$\text{Prob}(h = \pm 1|\phi) = \frac{1 \pm P_B A \sin \phi}{2}$$

Demonstration of the event probability density function

Analytic expression for the asymmetry

$$\mathcal{A}_{LU}(\phi) = \frac{(1 + P_B A \sin \phi) - (1 - P_B A \sin \phi)}{(1 + P_B A \sin \phi) + (1 - P_B A \sin \phi)} = P_B A \sin \phi$$

Normalized by the beam polarization P_B :

$$\mathcal{A}_{LU}(\phi) = A \sin \phi$$

Uncertainty on $A_{LU}^{\sin \phi}$

The statistical uncertainty is obtained from the curvature of the log-likelihood at its minimum:

$$\sigma_A = \left(\frac{\partial^2(-\ln \mathcal{L})}{\partial A^2} \Big|_{A=A_{\text{fit}}} \right)^{-1/2}$$