

Probing the pion structure with CLAS12

Measurement of the DVCS beam spin asymmetry in the $e\gamma\pi^+$ final state, targeting the Sullivan-process region

Elouan Ferrand

CEA Saclay

September 10, 2026



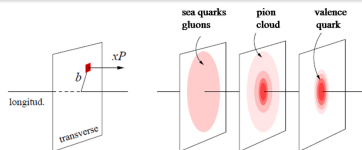
Probing the pion structure

Why the pion?

- **Lightest hadron:** quark-antiquark bound state.
- Goldstone boson of chiral symmetry breaking.
- **Spin-0:** only **two GPDs** at leading twist $\rightarrow$ simpler than the proton.
- FF and PDFs known, but **3D structure remains unexplored.**

Generalised Parton Distributions (GPDs)

- Generalise PDFs *and* FFs in a single object.
- $H_\pi(x, 0, 0) \rightarrow$ PDFs $\int dx H_\pi \rightarrow$ FF
- Full $H_\pi(x, \xi, t)$: **3D tomography** of the pion.
- Encode the **mechanical properties** (pressure, energy density) via the gravitational FF.



Our goal

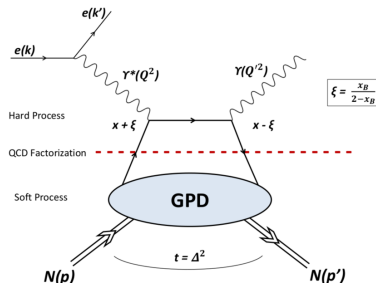
Access the **pion GPDs** via **Deeply Virtual Compton Scattering (DVCS)**: the most direct hard exclusive process to probe the partonic structure in 3D.

$$e\pi^+ \rightarrow e\gamma\pi^+$$

Accessing pion GPDs: DVCS and the Sullivan process

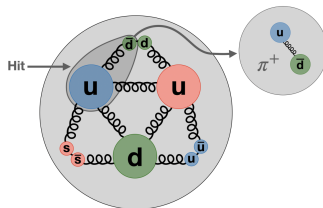
Deeply Virtual Compton Scattering

- Hard exclusive: $eX \rightarrow e\gamma X$.
- Large $Q^2 \Rightarrow$ collinear factorisation:
 $\mathcal{A} = C_{\text{hard}} \otimes H_{\pi}(x, \xi, t)$.



The Sullivan process

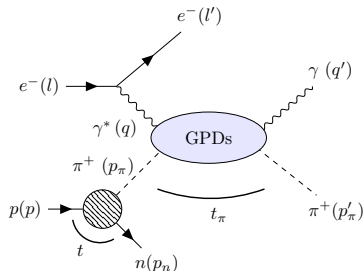
- No free π^+ target $\rightarrow$ use $p \rightarrow \pi^+ + n$ fluctuation.
- Small $|t|$: virtual π^+ is quasi-real.
- Validated for F_{π} at JLab [1].



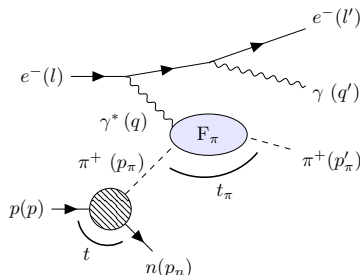
Virtual meson cloud as an effective pion target.

Sullivan DVCS: cross section

Sullivan DVCS



Sullivan Bethe–Heitler



Sullivan cross section: $d\sigma = |T_{\text{BH}}|^2 + |T_{\text{DVCS}}|^2 + \mathcal{I}_{\text{unpol}} + \lambda_e \mathcal{I}_{\text{pol}}$ [2]

The beam spin asymmetry (BSA): $A_{LU}(\phi) = \frac{1}{P_b} \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$

$\Rightarrow$ Direct access to the pion GPDs at the points $x = \pm\xi$ (LO and leading twist).

A non-trivial background: baryon resonance transitions

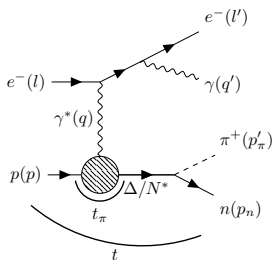
Resonance contribution

- The final state $e\gamma n\pi^+$ can also arise from:

$$ep \rightarrow e\gamma \Delta/N^* \rightarrow e\gamma n\pi^+$$

- Both DVCS and BH topologies contribute.
- **Irreducible** at JLab energies: cannot be removed by kinematics alone.

Bethe-Heitler off the Δ/N^*

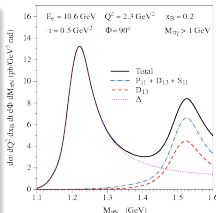


Impact on the analysis

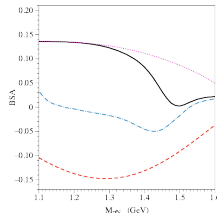
- Contaminates the Sullivan signal.
- Non-zero BSA: can bias the extraction of pion GPDs.

⇒ Estimating these contributions is **crucial** to extract pion GPDs.

Cross section



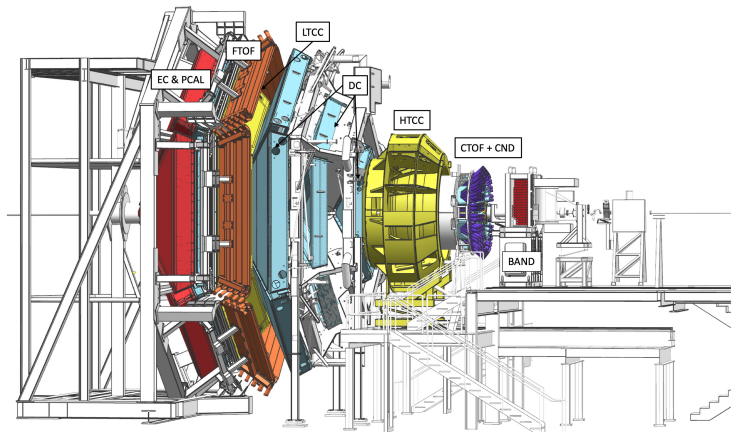
BSA



Semenov-Tian-Shansky & Vanderhaeghen [3]

CLAS12 detector overview

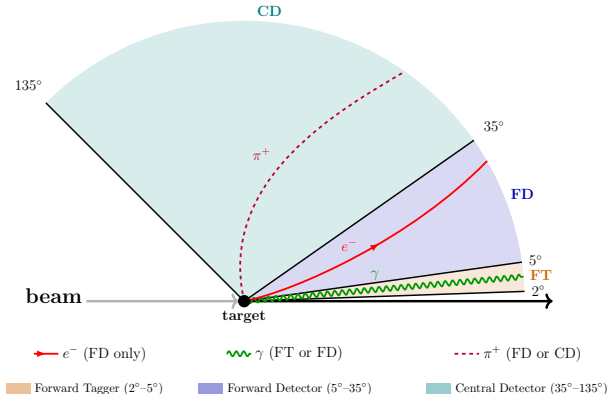
- Located at Jefferson Lab (JLab) in Newport News, Virginia, USA.
- CEBAF: 10.6 GeV polarized electron beam on a fixed target.
- CLAS12: large acceptance spectrometer in Hall B.



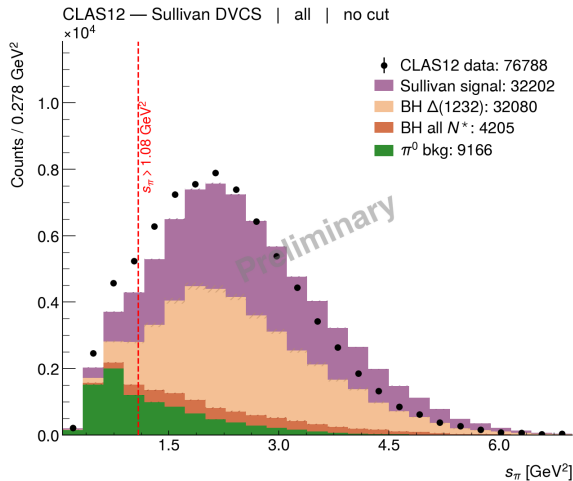
Sullivan DVCS event topology in CLAS12

- **Forward Tagger (FT):** tracking and calorimetry at small angles (2° – 5°).
- **Forward Detector (FD):** tracking, calorimetry, time-of-flight, and PID at intermediate angles (5° – 35°).
- **Central Detector (CD):** tracking and time-of-flight at large angles (35° – 135°).

- **Final state:**
 $e' n \gamma \pi^+$.
- **Detected:**
 e', γ, π^+ .
- **Neutron:**
missing mass.



Cut on the pion-photon invariant mass s_π

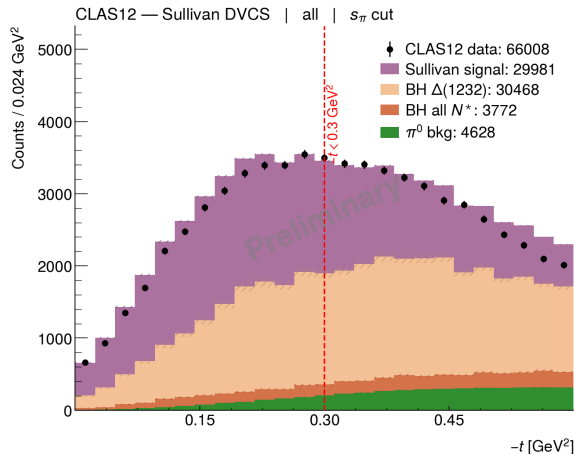


- **Purple:** MC events from the Sullivan signal.
- **Brown:** MC events from the BH on $\Delta^+(1232)$.
- **Orange:** MC events from the BH on all N^* .
- **Green:** π^0 background.

- $s_\pi = (p_\pi + q')^2$.
- $s_\pi > 1.08 \text{ GeV}^2$.
- Removes ρ^+ .

Spectrum of the pion-photon invariant mass s_π .

Cut on the pion virtuality $-t$



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

- $-t < 0.3 \text{ GeV}^2$.

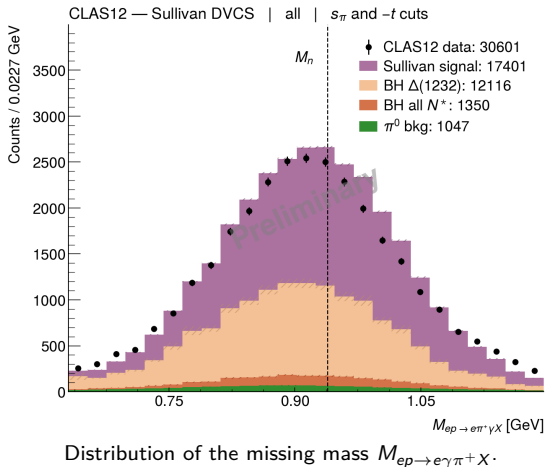
- Region where:

- Sullivan process is expected to dominate,
- interpretation in terms of pion GPDs is valid.

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

Exclusivity check: neutron missing mass

- Missing mass computed as: $M_X = \sqrt{(p + l - l' - q' - p'_\pi)^2}$.



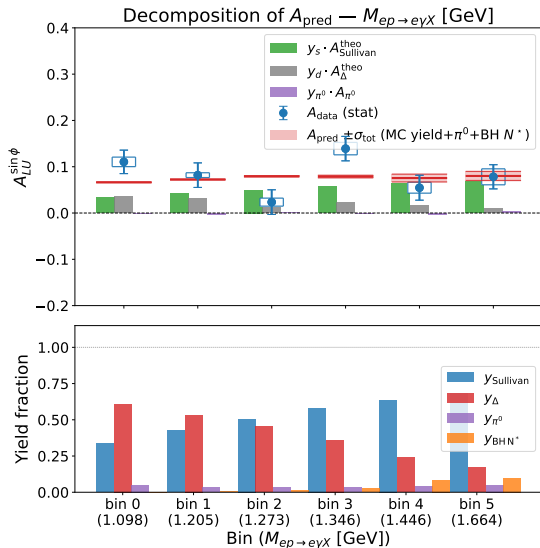
Predicted BSA — construction of A_{pred}

$$A_{LU,i}^{\sin\phi, \text{pred}} = y_{\text{Sull},i} A_{\text{Sull},i}^{\text{theo}} + y_{\Delta,i} A_{\Delta,i}^{\text{theo}} + y_{\pi^0,i} A_{\pi^0,i}^{\text{fit}} + y_{N^*,i} A_{N^*}$$

Term-by-term description

- $y_{c,i} = W_{c,i} / \sum_{c'} W_{c',i}$: yield fraction of channel c from MC weights.
- **Sullivan signal**: pion GPD model of Chavez et al. [4].
- **Δ background**: large- N_c GPD model [3, 5] ($h_M \approx E^u - E^d$), computed on a discrete $(Q^2, t_\pi, M_{\pi N})$ grid by Sangyeong Son and Kirill M. Semenov-Tian-Shansky.
- **π^0 background**: BSA extraction from π^0 estimation.
- **N^* background**: no calculation available $\rightarrow$ enters only as $A_{N^*} = \pm 0.1$ uncertainty.

Predicted BSA — decomposition by contribution

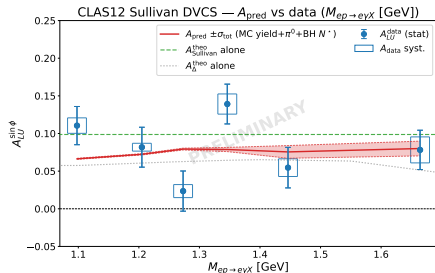
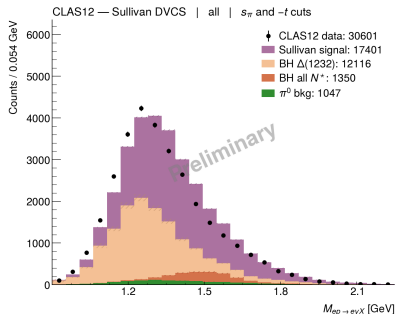


- The predicted band (red) is built from the statistical uncertainty of the π^0 BSA extraction, the statistical uncertainty of the Monte Carlo simulations, and the ± 0.1 assumption on A_{N^*} .

- Sullivan yield y_{Sullivan} increases with $M_{ep \rightarrow e\gamma X}$, as the Δ region is left behind — the prediction becomes increasingly dominated by the Sullivan contribution.
- y_{π^0} and y_{N^*} remain $\lesssim 0.1$ across all bins $\rightarrow$ sub-dominant corrections.
- The predicted band (red) is narrow: the dominant uncertainty comes from the $N^* \pm 0.1$ assumption.

Baryon resonance background

- Signal lies in the $\pi^+ n$ invariant mass region characteristic of baryon resonances.

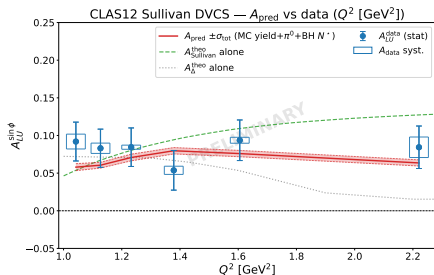


Amplitude $A_{LU}^{\sin \phi}$ vs. invariant mass $M_{\pi^+ n}$.

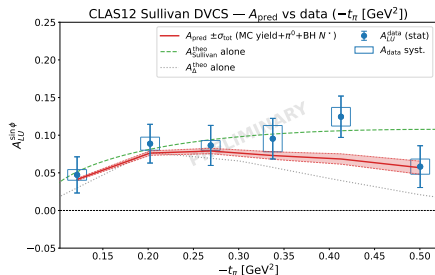
Invariant mass of the pion-neutron system.

There are still some discrepancies between the predicted BSA and the measured one in the Δ region, this needs to be investigated further by improving the Δ model (including the DVCS and interference contributions in the yield and testing other GPDs models).

Results for $A_{LU}^{\sin\phi}$



Amplitude $A_{LU}^{\sin\phi}$ vs. photon virtuality Q^2 .



Amplitude $A_{LU}^{\sin\phi}$ vs. $-t_{\pi}$.

The predicted BSA, although only indicative given the model limitations, is found to be of the same sign and same order of magnitude as the measured BSA.

Summary and outlook

Summary

- **First measurement** of $A_{LU}^{\sin\phi}$ for $ep \rightarrow e\gamma\pi^+$ in Sullivan region at CLAS12.
- Comparison of results with predictions as a function of Q^2 , $-t_\pi$, and $M_{\pi n}$.

Next steps

- Improve the Δ model by including the DVCS and interference contributions in the yield and testing other GPDs models.
- Study the N^* contribution to the BSA.
- Simulate the signal and the resonance background for EIC predictions (see below).

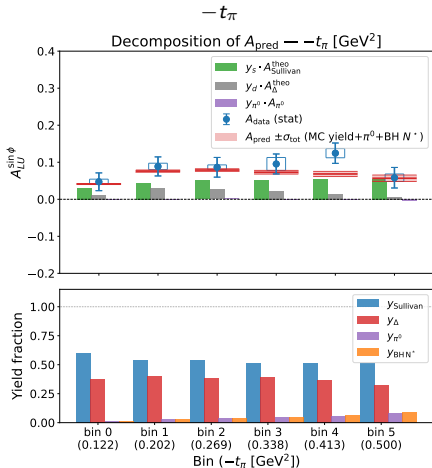
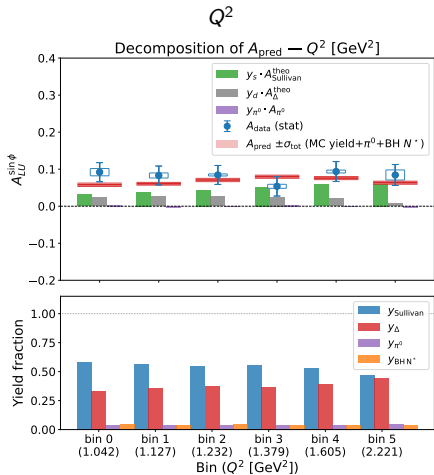
Long-term outlook: the EIC

- The future **Electron-Ion Collider (EIC)** will reach kinematics well **beyond the resonance region**, providing a clean Sullivan window with negligible resonance contamination.
- This will enable a model-independent extraction of the **pion GPDs** [6].

- [1] Henk Blok et al. “Charged pion form factor between $Q^2=0.60$ and 2.45 GeV^2 . I. Measurements of the cross section for the $^1\text{H}(e, e'\pi^+)n$ reaction”. In: *Physical Review. C, Nuclear Physics* 78 (Oct. 2008). ISSN: ISSN PRVCAN. DOI: 10.1103/PhysRevC.78.045202. URL: <https://www.osti.gov/biblio/956094>.
- [2] D. Amrath, M. Diehl, and J.-P. Lansberg. “Deeply virtual Compton scattering on a virtual pion target”. In: *Eur.Phys.J.* C58 (2008), pp. 179–192. DOI: 10.1140/epjc/s10052-008-0769-1. arXiv: 0807.4474 [hep-ph].
- [3] Kirill M. Semenov-Tian-Shansky and Marc Vanderhaeghen. “Deeply-virtual Compton process $e^-N \rightarrow e^-\gamma\pi N$ to study nucleon to resonance transitions”. In: (2023). arXiv: 2303.00119 [hep-ph]. URL: <https://arxiv.org/abs/2303.00119>.

- [4] José Manuel Morgado Chavez et al. “Pion GPDs: A path toward phenomenology”. In: *arXiv:2110.06052* (Oct. 2021). arXiv: 2110.06052 [hep-ph].
- [5] Vladimir Pascalutsa, Marc Vanderhaeghen, and Shin Nan Yang. “Electromagnetic excitation of the $\Delta(1232)$ -resonance”. In: *Physics Reports* 437.5-6 (Jan. 2007), pp. 125–232. ISSN: 0370-1573. DOI: 10.1016/j.physrep.2006.09.006. URL: <http://dx.doi.org/10.1016/j.physrep.2006.09.006>.
- [6] J. M. Morgado Chávez et al. “Accessing the pion 3D structure at US and China Electron-Ion Colliders”. In: *arXiv:2110.09462* (Oct. 2021). arXiv: 2110.09462 [hep-ph].

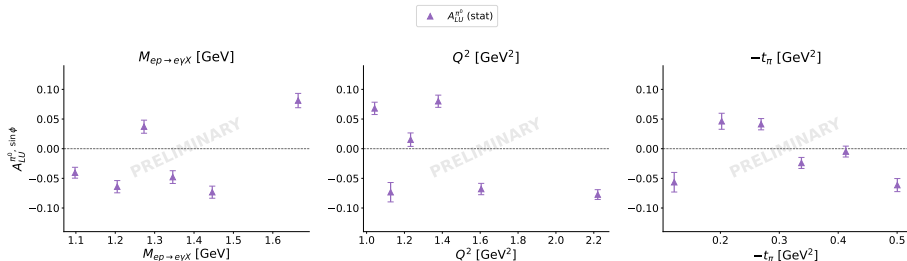
Predicted BSA — decomposition by contribution bis



Predicted BSA — π^0 contribution

The π^0 background BSA is extracted via a weighted maximum likelihood fit, identical to the data method. The log-likelihood is: $\mathcal{L}(A) = -2 \sum_i w_i \ln(1 + h_i P A \sin \phi_i)$ where w_i are the π^0 contamination weights. The statistical uncertainty uses the sandwich estimator: $\sigma(A) = \sqrt{\sum w_i^2 g_i^2 / \sum w_i g_i^2}$ with $g_i = h_i P \sin \phi_i / f_i$, which reduces to the standard Fisher error for uniform weights.

CLAS12 Sullivan DVCS — π^0 BSA



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.

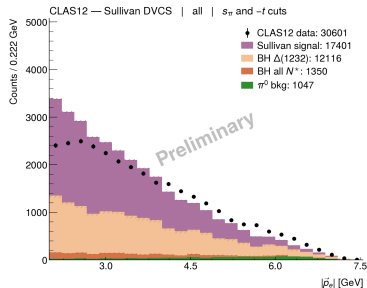
Momentum transfer to the recoil pion t_π

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

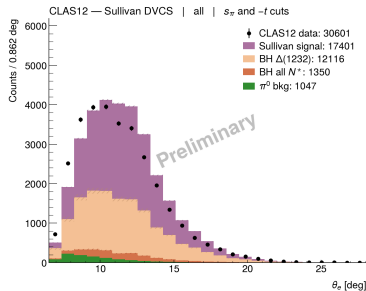
Neutron missing mass $M_{ep \rightarrow e\gamma\pi^+X}$

- $M_{ep \rightarrow e\gamma\pi^+X} \in [0.9, 2.25] \text{ GeV}$, 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

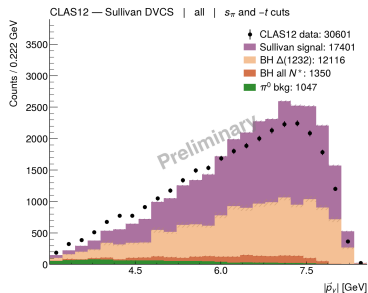


Momentum distribution of the scattered electron.

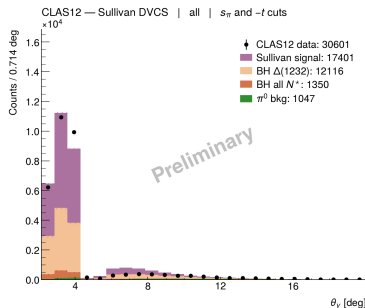


Polar angle distribution of the scattered electron.

Photon kinematics

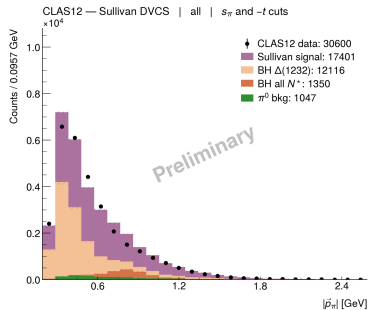


Momentum distribution of the photon.

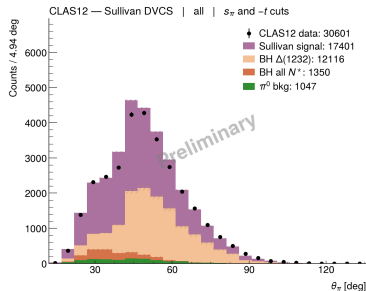


Polar angle distribution of the photon.

Pion kinematics

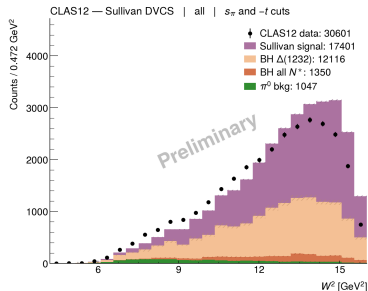


Momentum distribution of the pion.

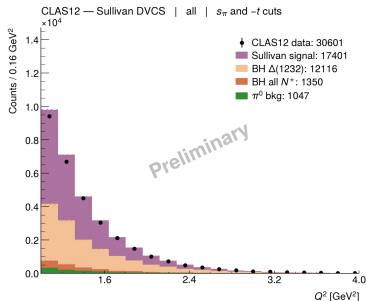


Polar angle distribution of the pion.

DIS kinematic variables

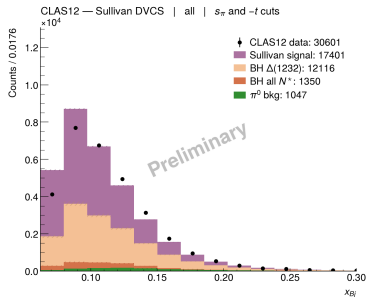


Distribution of W^2 .

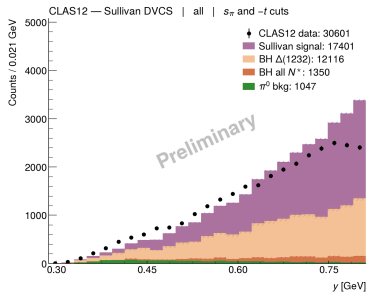


Distribution of Q^2 .

DIS kinematic variables

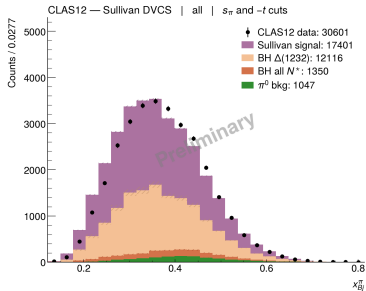


Distribution of x_{Bj} .

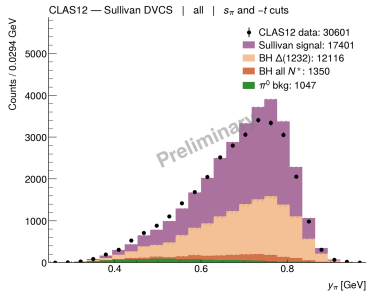


Distribution of y .

DVCS kinematic variables

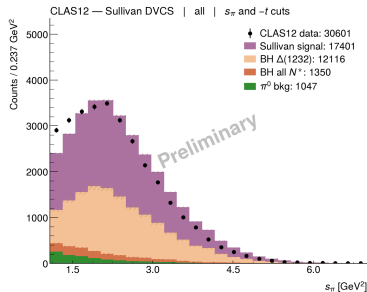


Distribution of x_B^π .

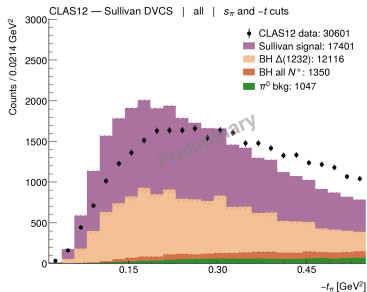


Distribution of y_π .

DVCS kinematic variables

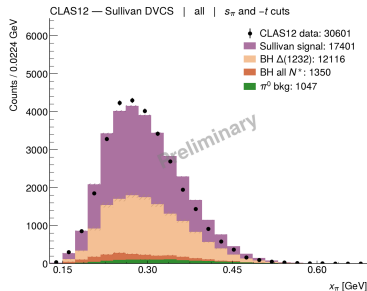


Distribution of s_π .

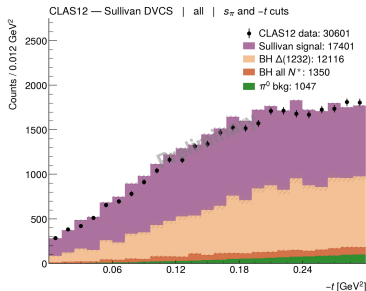


Distribution of $-t_\pi$.

Variables relative to the virtual pion emission

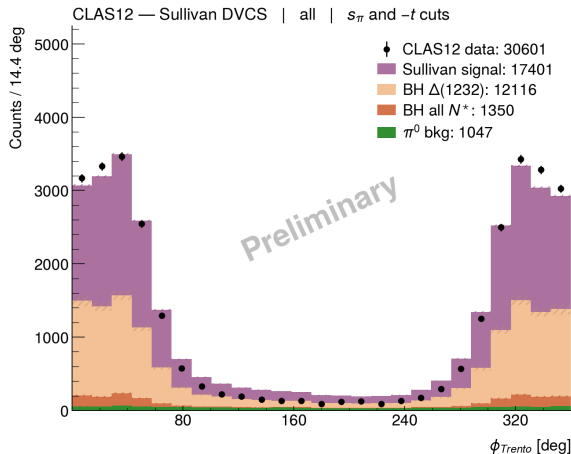


Distribution of x_π .



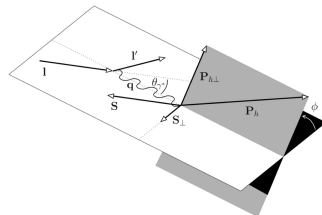
Distribution of $-t$.

Azimuthal angle ϕ



Distribution of the azimuthal angle ϕ .

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



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

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

Normalized by the beam polarization P_B :

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

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

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

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

Method: 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 :

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