Probing the pion structure with CLAS12

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

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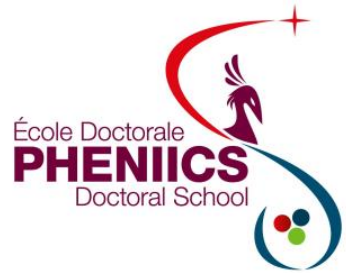


Table of contents

1. Motivation and theoretical framework
2. CLAS12 experiment
3. Preliminary results
4. Conclusion and Outlook

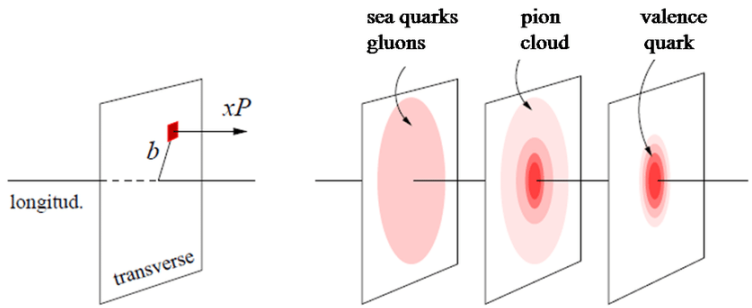
Probing the pion structure

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 $\quad \int dx\, H_\pi \rightarrow$ 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.

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

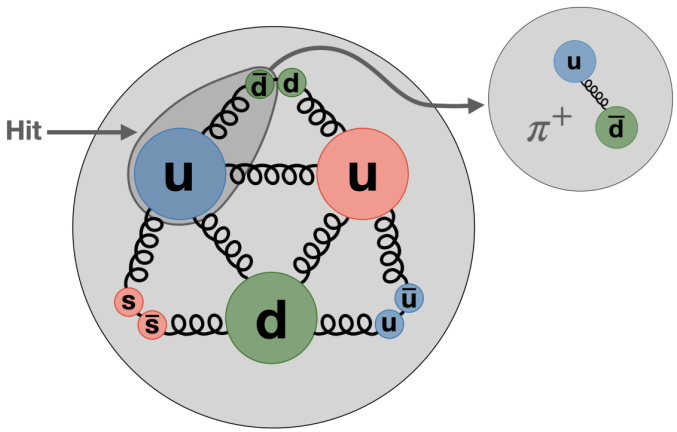
The Sullivan idea

How to experimentally perform DVCS on the pion?

- No free pion targets exist.
- π^+/e^- scattering: low luminosity and limited momentum transfers range.

Solution: the Sullivan process [1]

- The proton fluctuates into a virtual π^+ and a neutron: $p \to \pi^+ + n$.
- At low $t = (p - p_n)^2$, the virtual pion behaves as a quasi-real pion.
- DVCS on this virtual pion then gives access to the **pion GPDs**.



Using the virtual meson cloud of the proton as an effective pion target.

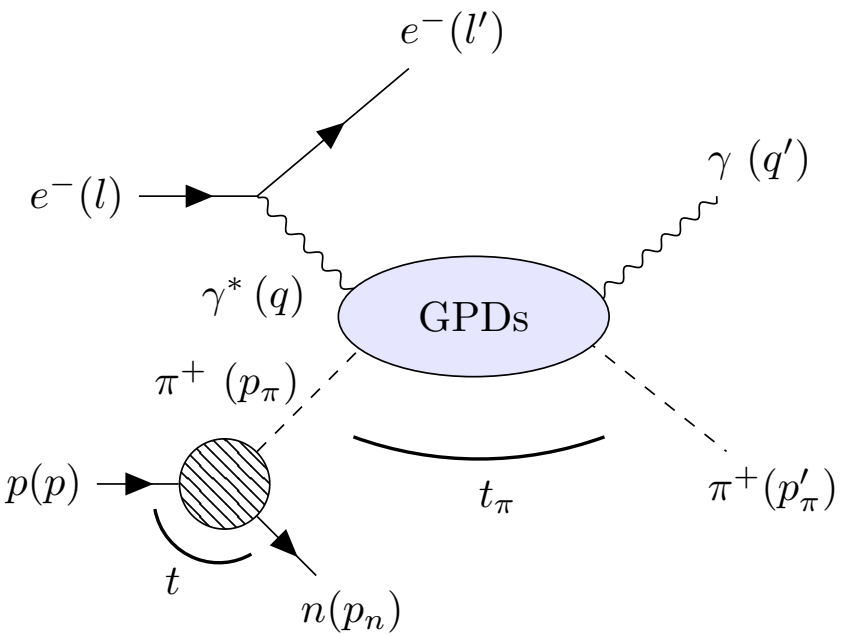
Experimental validation

- Already successfully exploited for FF measurements at JLab energies [2].

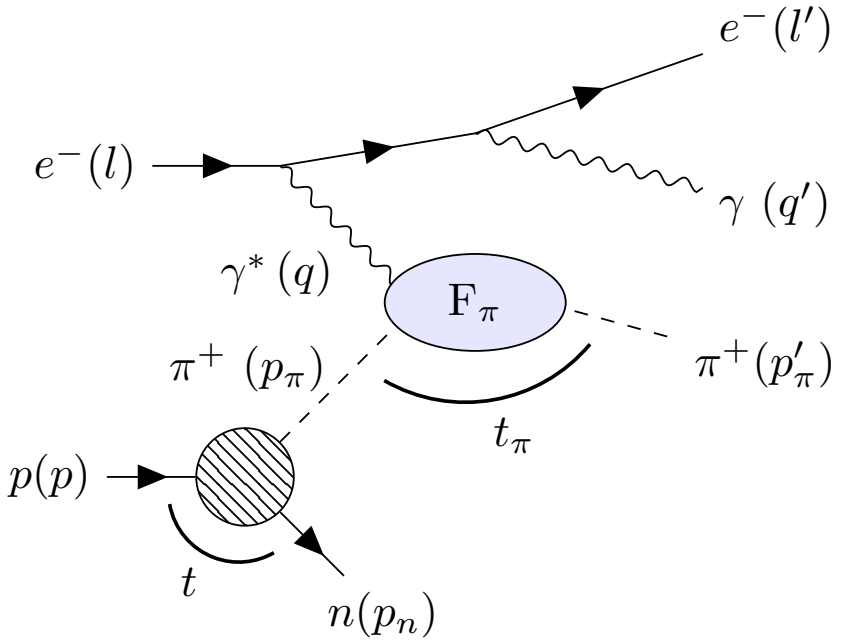
Sullivan DVCS to access pion GPDs

Cross section DVCS+BH $d\sigma = |T_{\mathrm{BH}}|^2 + |T_{\mathrm{DVCS}}|^2 + \mathcal{I}_{\mathrm{unpol}} + \lambda_e \mathcal{I}_{\mathrm{pol}}$ [3]

Sullivan DVCS



Sullivan BH



Compton Form Factor (CFF) at leading order:

$$\mathcal{H}_\pi(\xi, t, Q^2) = \sum_q e_q^2 \int_{-1}^{1} dx \underbrace{\left(\frac{1}{x - \xi + i\epsilon} - \frac{1}{x + \xi - i\epsilon} \right)}_{\text{hard scattering}} \underbrace{H_\pi^q(x, \xi, t)}_{\text{pion GPDs}}$$

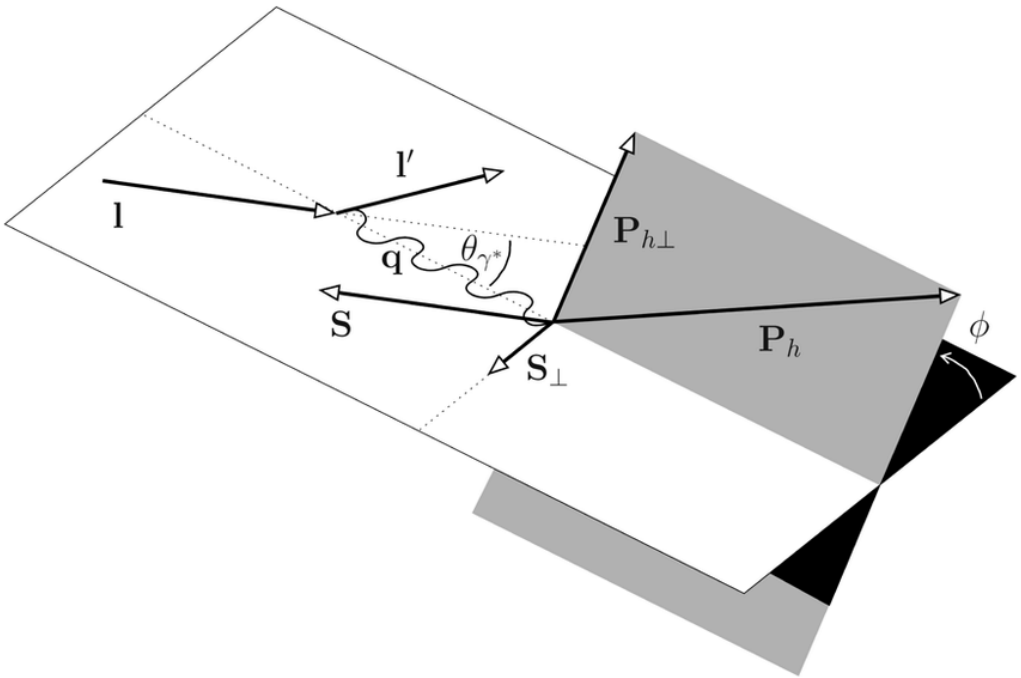
Observable

Beam-Spin Asymmetry (BSA)

Helicity-dependent observable from DVCS–BH interference:

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

- $P_b \approx 0.86$: effective beam polarization.



Definition of ϕ_{Trento}

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

Competing process: baryon resonance transition

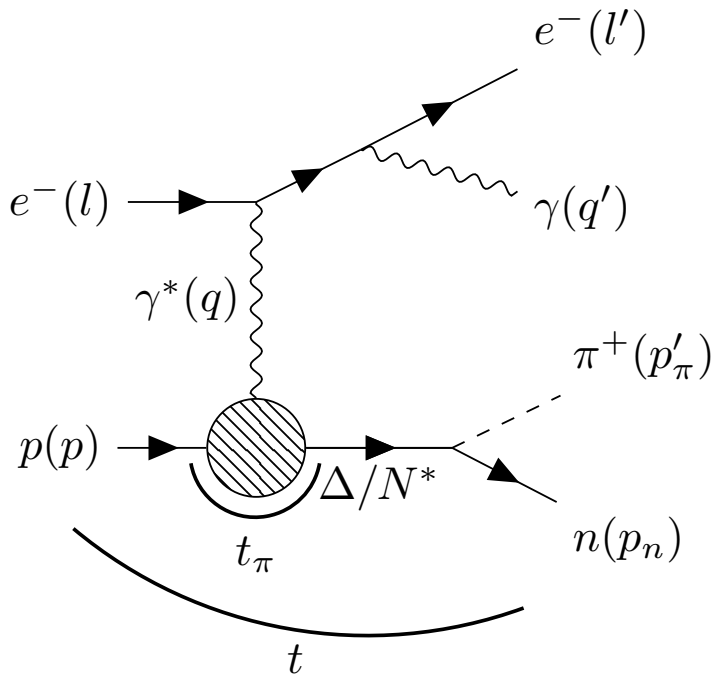
Resonance contribution

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

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

- Events from DVCS and BH.

BH on baryon resonance

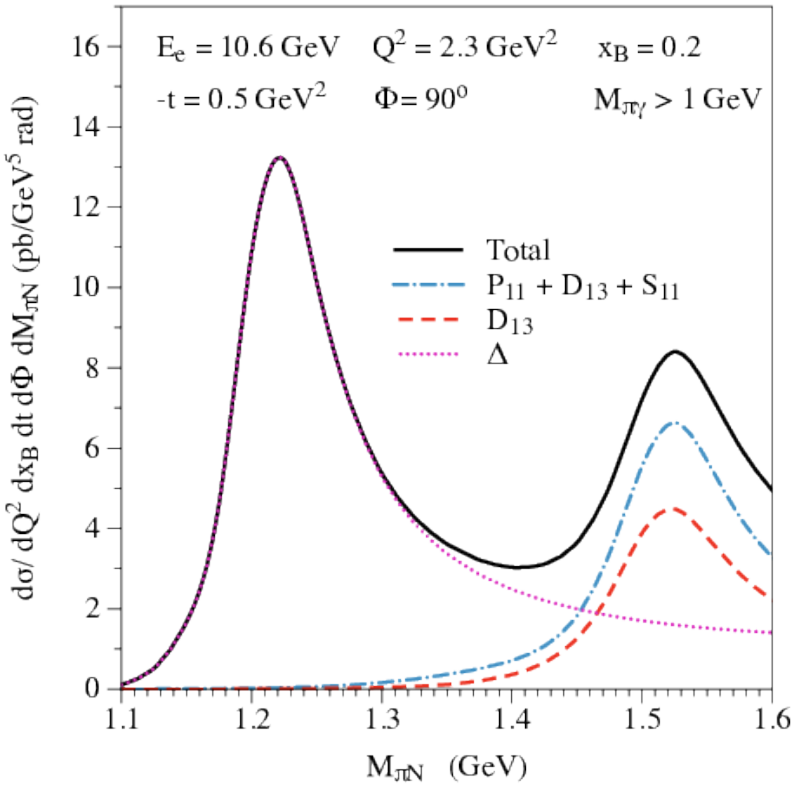


Impact on the analysis

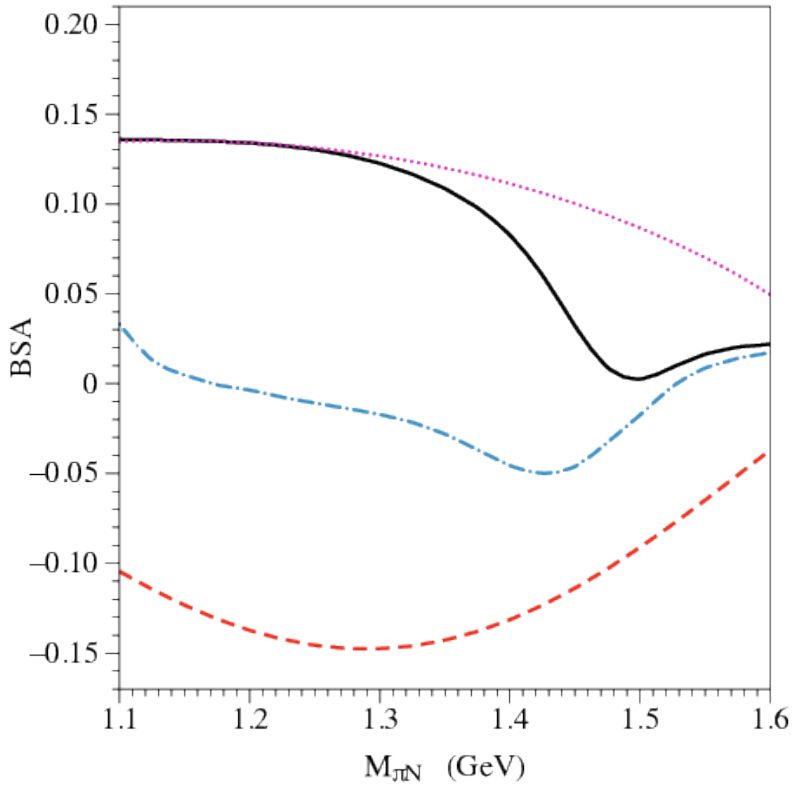
- Irreducible background for the Sullivan process at JLab energies.
- Affects the interpretation in terms of pion GPDs.

BSA predictions for baryon resonance transition

Cross section



Beam-Spin Asymmetry



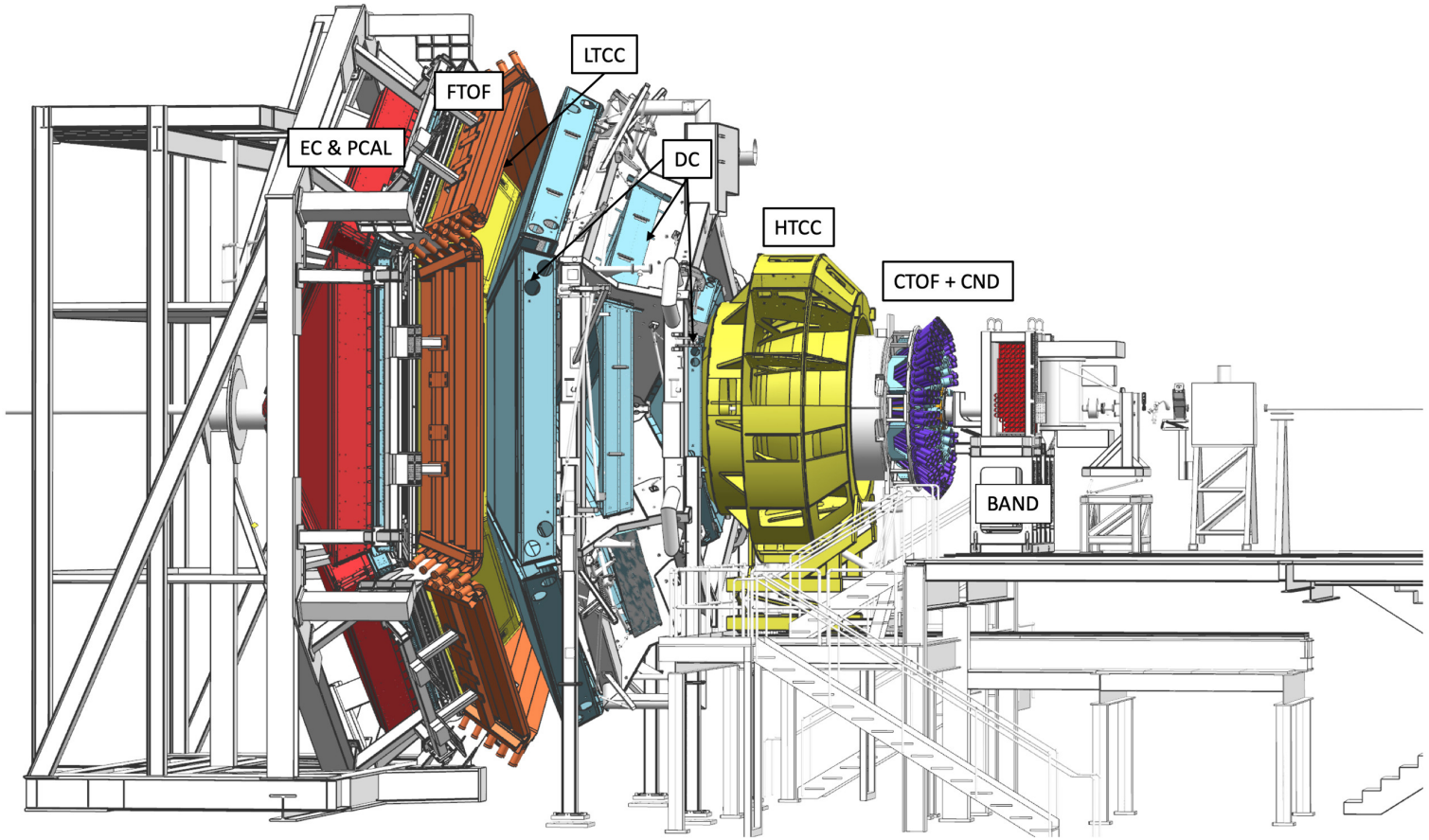
Predictions from Semenov-Tian-Shansky and Vanderhaeghen [4]

- Resonance contributions: $\Delta^+(1232)$, $N^*(1440)$, $N^*(1520)$, $N^*(1535)$.
- Non-zero BSA amplitudes $A_{LU}^{\sin\phi}$ predicted for these resonances.

$\Longrightarrow$ Estimation of these contributions is crucial to extract the pion GPDs from the data.

CLAS12 detector overview

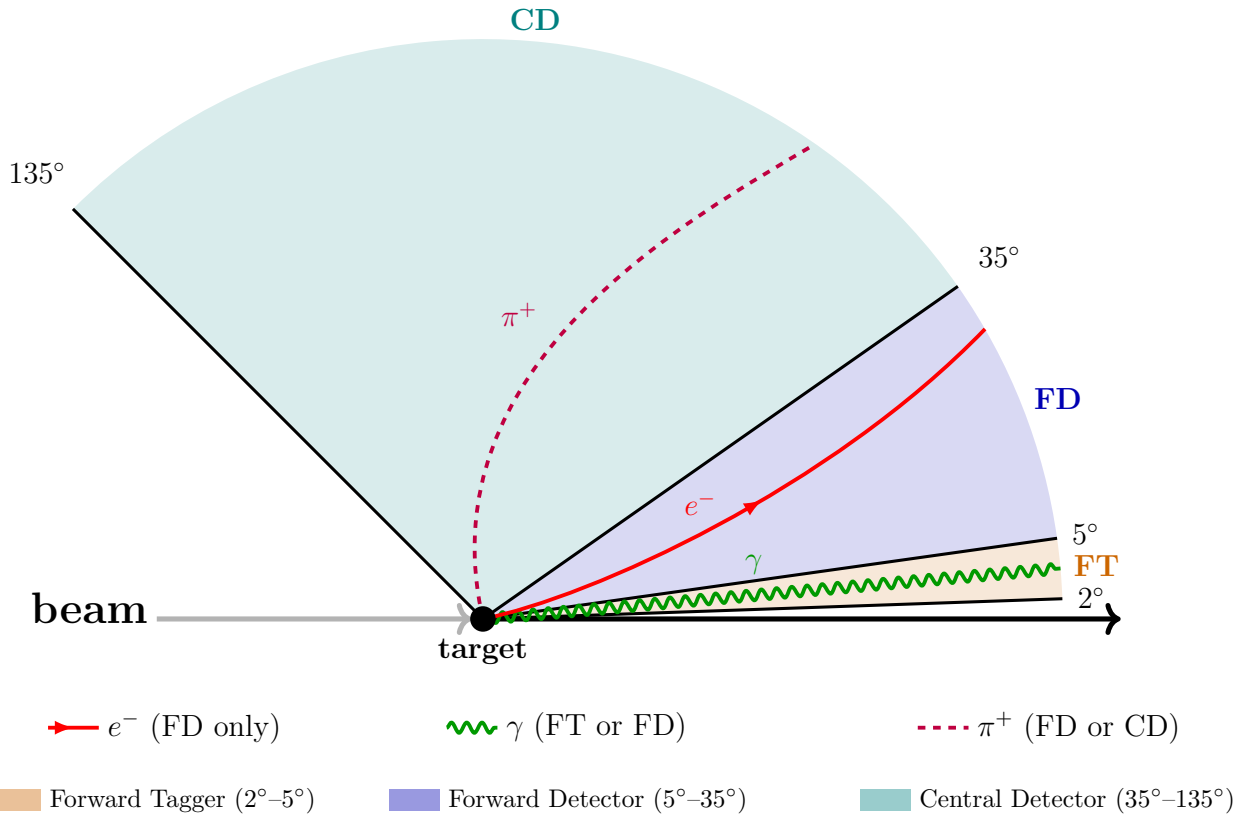
- Located at Jefferson Lab (JLab) in Newport News, Virginia, USA.
- CEBAF: 10.6 GeV polarized electron beam on a fixed target.
- CLAS12: large acceptance spectrometer in Hall B.



Sullivan DVCS event topology in CLAS12

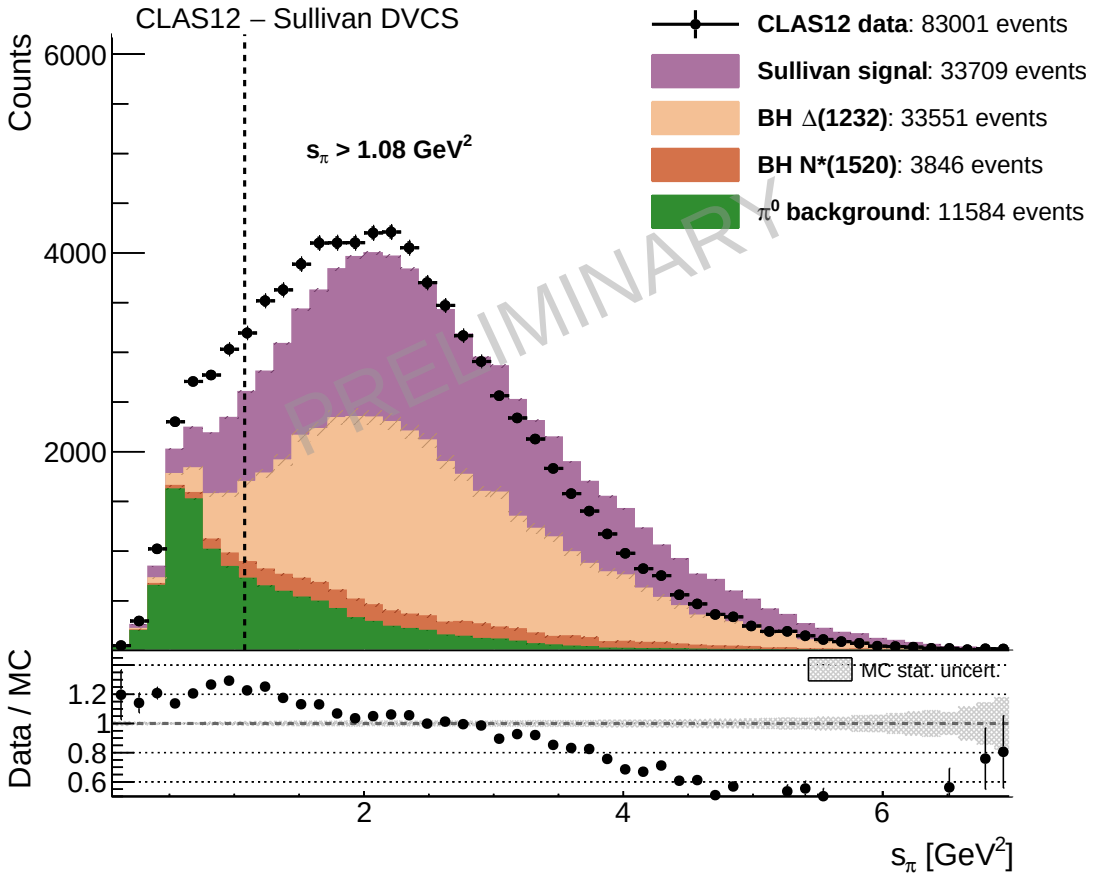
- **Forward Tagger (FT)**: tracking and calorimetry at small angles (2°–5°).
- **Forward Detector (FD)**: tracking, calorimetry, time-of-flight, and PID at intermediate angles (5°–35°).
- **Central Detector (CD)**: tracking and time-of-flight at large angles (35°–135°).

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



Cut on the pion-photon invariant mass s_π

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

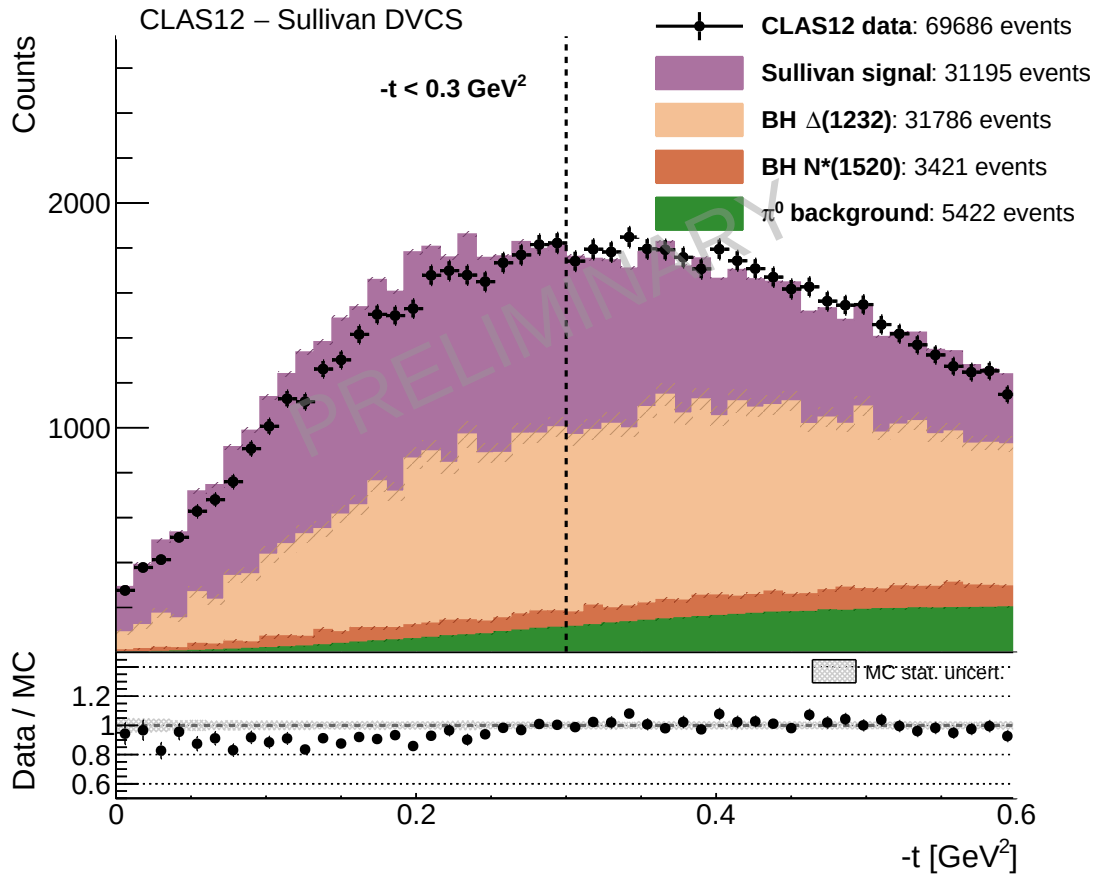


Spectrum of the pion-photon invariant mass s_π.

- **Purple:** MC events from the Sullivan signal.
- **Brown:** MC events from the BH on $\Delta^+(1232)$.
- **Orange:** MC events from the BH on $N^*(1520)$.
- **Green:** π^0 background.

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

Cut on the pion virtuality $-t$

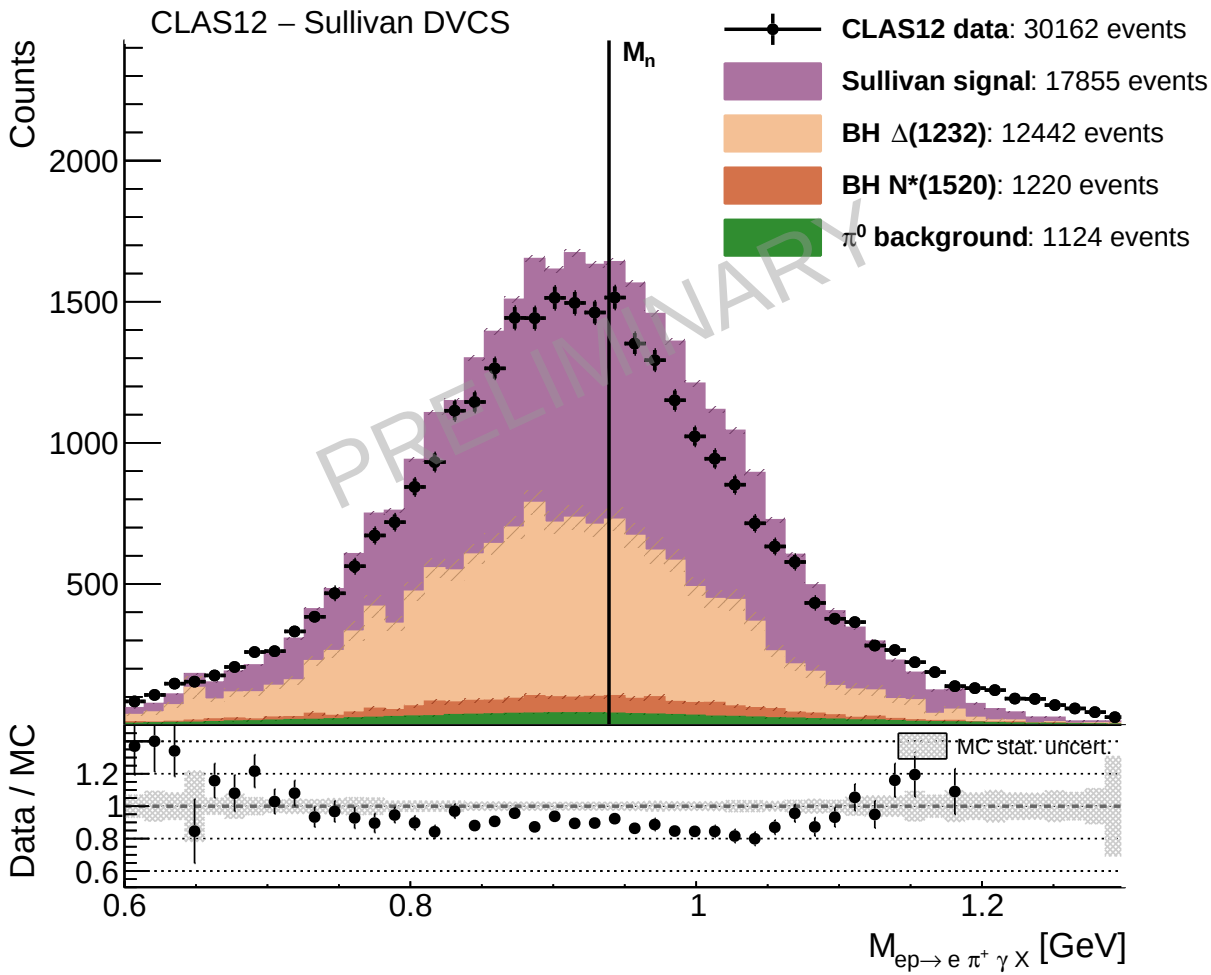


- $-t = -(p - p_n)^2$.
- $-t < 0.3\ \mathrm{GeV}^2$.
- Region where:
  - Sullivan process is expected to dominate,
  - interpretation in terms of pion GPDs is valid.

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

Neutron missing mass

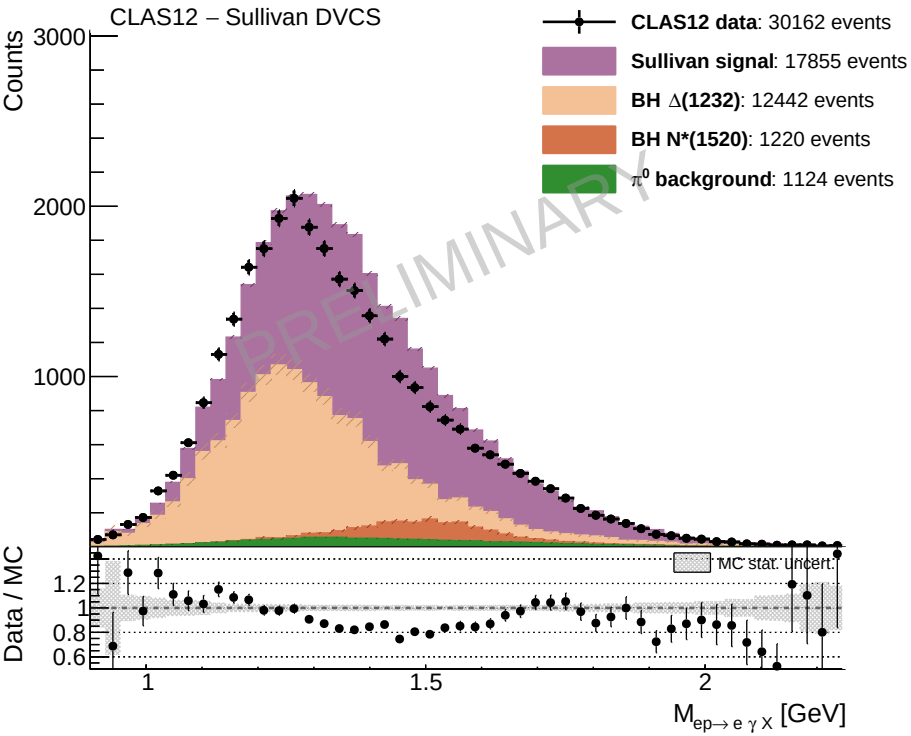
Neutron missing mass calculated as $M_X = \sqrt{(p + l - l' - q' - p'_\pi)^2}$.



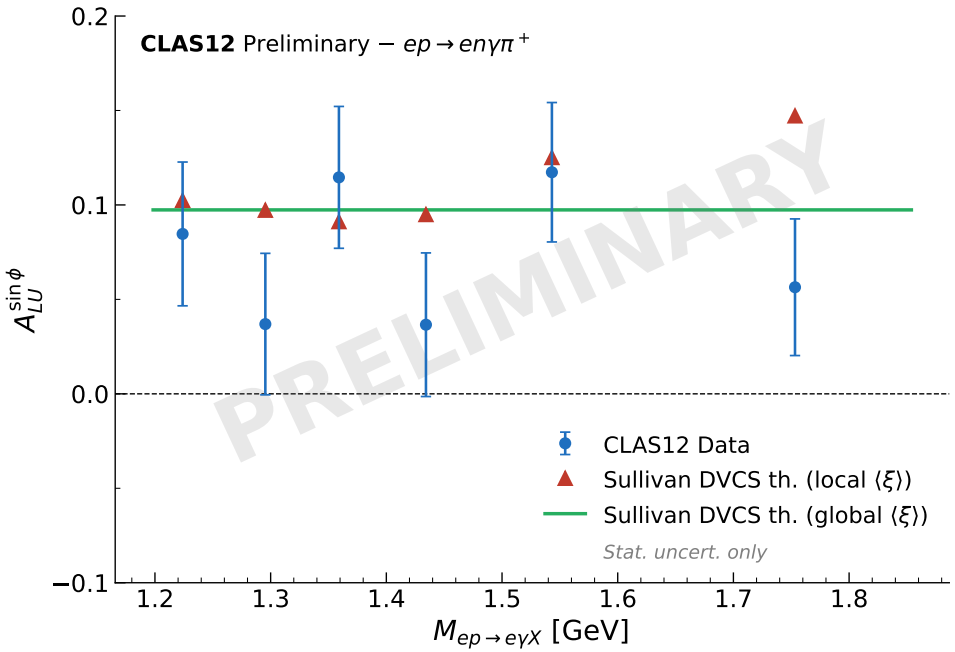
Distribution of the missing mass $M_{ep\to e\gamma\pi^+X}$ after the cuts on s_π and $-t$.

Baryon resonance background

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



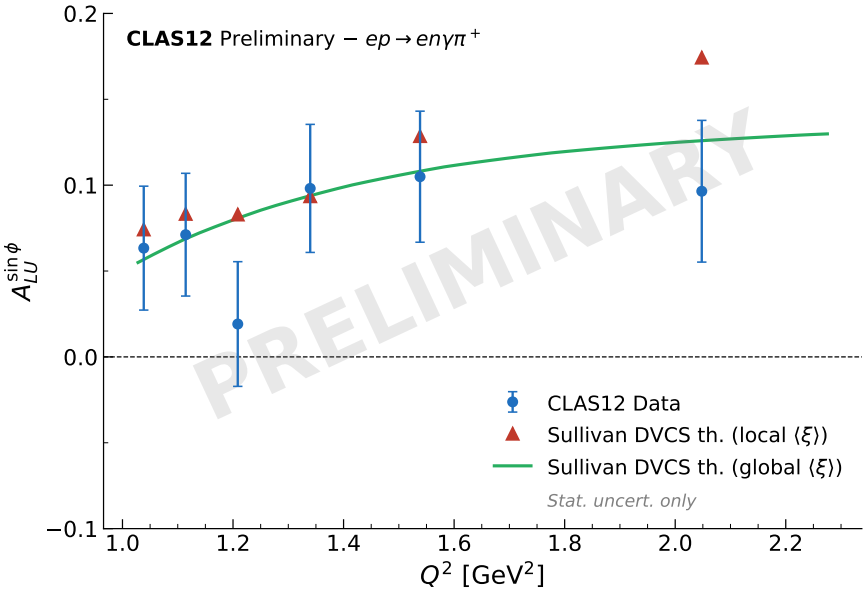
Distribution of the invariant mass of the pion-neutron system $M_{\pi^+ n}$.



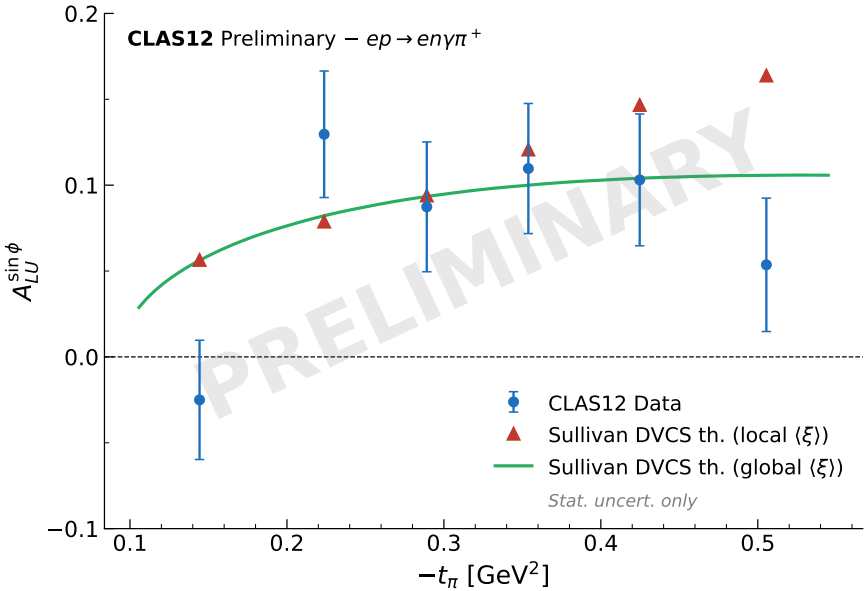
Evolution of the amplitude $A_{LU}^{\sin\phi}$ as a function of the invariant mass $M_{\pi^+ n}$.

- The contribution from the baryon resonances is significant and must be properly estimated to extract the pion GPDs.

Preliminary results for $A_{LU}^{\sin\phi}$



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



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

- The total amplitude can be expressed as a weighted sum of the individual contributions:

$$A_{LU,\,\text{Total}}^{\sin\phi} = \sum_i w_i\, A_{LU,i}^{\sin\phi} \quad \Longrightarrow \quad A_{LU,\,\text{Sulli}}^{\sin\phi} = \frac{1}{w_{\text{Sulli}}} \left(A_{LU,\,\text{Total}}^{\sin\phi,\,\text{data}} - \sum_{i \neq \text{Sulli}} w_i\, A_{LU,i}^{\sin\phi} \right)$$

where i runs over the different contributions and w_i are the corresponding yield fractions.

$\Downarrow$

Predictions of $A_{LU}^{\sin\phi}$ for each resonance contribution are required to isolate the pion GPD signal.

Conclusion and Outlook

Summary

- **First measurement** of $A_{LU}^{\sin\phi}$ for $ep \to en\gamma\pi^+$ in Sullivan region at CLAS12.
- Comparison of results with Sullivan DVCS predictions [5] as a function of Q^2, and $-t_\pi$.
- Baryon resonance contributions (for the Δ) are non-negligible and must be **disentangled** before extracting pion GPDs.

Next steps

- Obtain $A_{LU}^{\sin\phi}$ predictions for each resonant channel.
- Evaluate systematic uncertainties.
- $\Rightarrow$ Extract **pion GPDs** via the yield decomposition: $A_{LU}^{\text{tot}} = \sum_i w_i \, A_{LU,i}^{\sin\phi}$

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].

Bibliography I

[1] J. D. Sullivan. "One-Pion Exchange and Deep-Inelastic Electron-Nucleon Scattering". In: *Phys. Rev. D* 5 (7 Apr. 1972), pp. 1732–1737. DOI: 10.1103/PhysRevD.5.1732. URL: https://link.aps.org/doi/10.1103/PhysRevD.5.1732.

[2] G. M. Huber et al. "Charged pion form-factor between Q**2 = 0.60-GeV**2 and 2.45-GeV**2. II. Determination of, and results for, the pion form-factor". In: *Physical Review C* 78.4 (Oct. 2008). ISSN: 1089-490X. DOI: 10.1103/physrevc.78.045203. URL: http://dx.doi.org/10.1103/PhysRevC.78.045203.

[3] Daniela Amrath, Markus Diehl, and Jean-Philippe Lansberg. "Deeply virtual Compton scattering on a virtual pion target". In: *Eur. Phys. J. C* 58 (2008), pp. 179–192. DOI: 10.1140/epjc/s10052-008-0769-1. arXiv: 0807.4474 [hep-ph].

Bibliography II

[4] Kirill M. Semenov-Tian-Shansky and Marc Vanderhaeghen. *Deeply-virtual Compton process $e^- N \to e^- \gamma \pi N$ to study nucleon to resonance transitions*. 2023. arXiv: 2303.00119 [hep-ph]. URL: https://arxiv.org/abs/2303.00119.

[5] José Manuel Morgado Chávez et al. "Pion generalized parton distributions: A path toward phenomenology". In: *Phys. Rev. D* 105 (9 May 2022), p. 094012. DOI: 10.1103/PhysRevD.105.094012. URL: https://link.aps.org/doi/10.1103/PhysRevD.105.094012.

[6] José Manuel Morgado Chávez et al. "Accessing the Pion 3D Structure at US and China Electron-Ion Colliders". In: *Phys. Rev. Lett.* 128.20 (2022), p. 202501. DOI: 10.1103/PhysRevLett.128.202501. arXiv: 2110.09462 [hep-ph].

Main cuts applied to the data

Virtuality of the photon Q^2

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

Inelasticity W^2

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

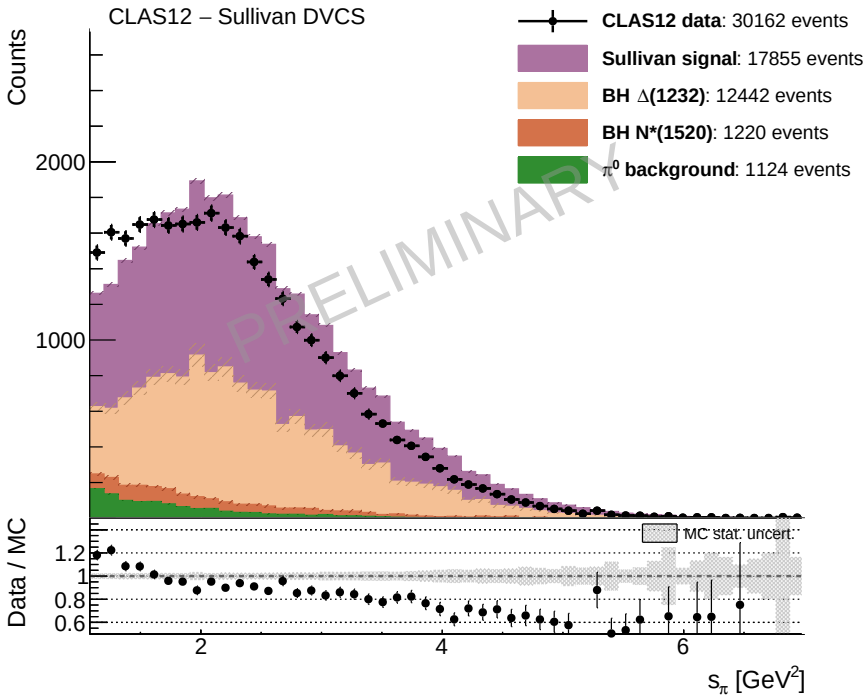
Momentum transfer to the recoil pion t_π

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

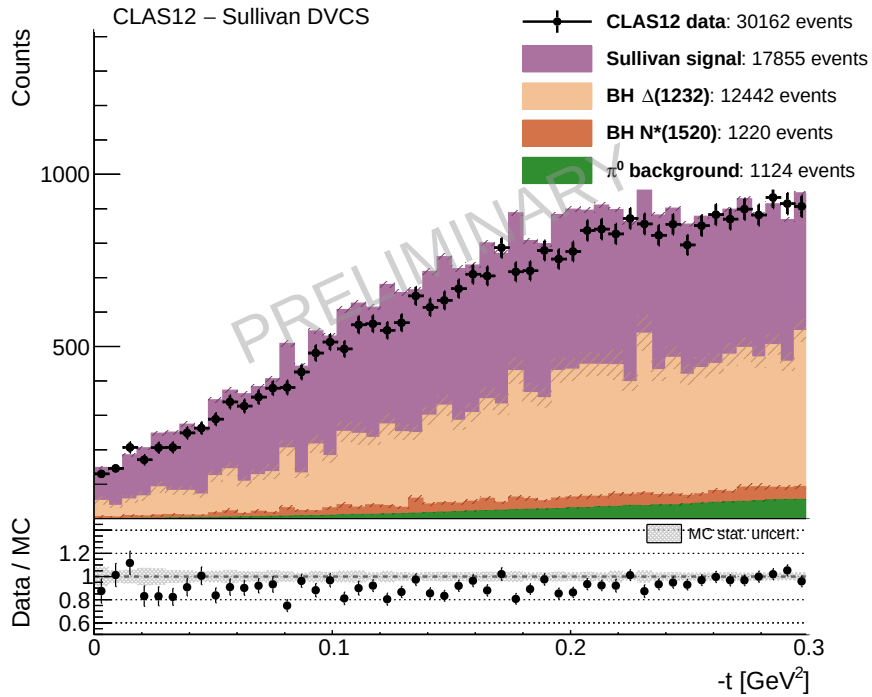
Neutron missing mass $M_{ep\to e\gamma\pi^+X}$

- $M_{ep\to e\gamma\pi^+X} \in [0.6, 1.3]\ \mathrm{GeV}$, the missing mass of the $ep \to e\gamma\pi^+X$ system, to select events consistent with a neutron in the final state.

Kinematic distributions after s_π and $-t$ selection cuts

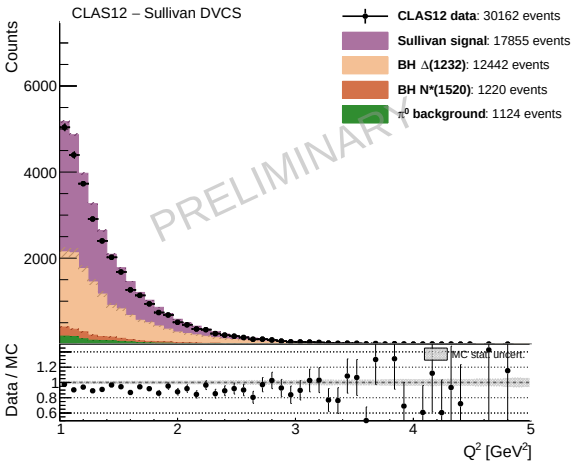


Distribution of s_π.



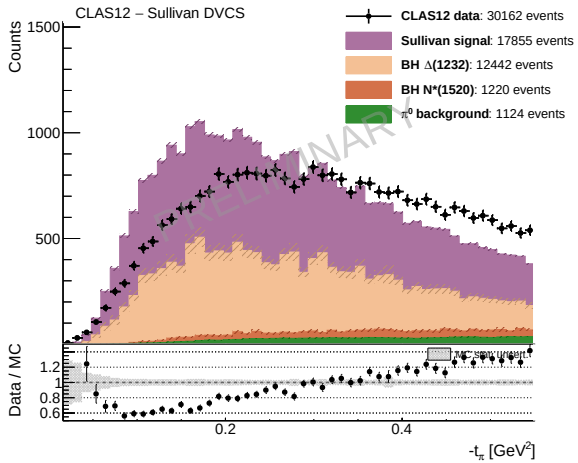
Distribution of $-t$.

Overview of the reconstructed kinematic variables



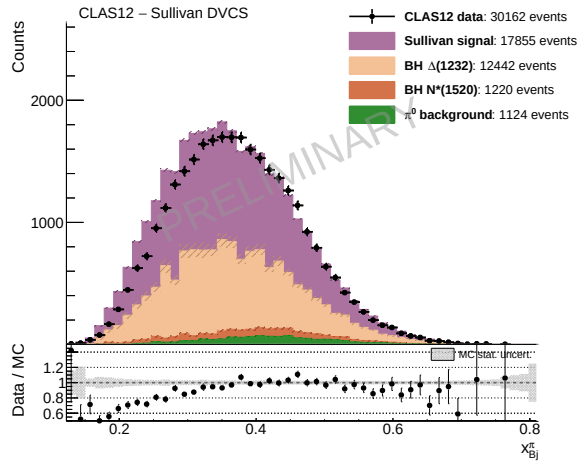
Distribution of Q^2.

$\langle Q^2 \rangle = 1.43$ GeV^2



Distribution of $-t_\pi$.

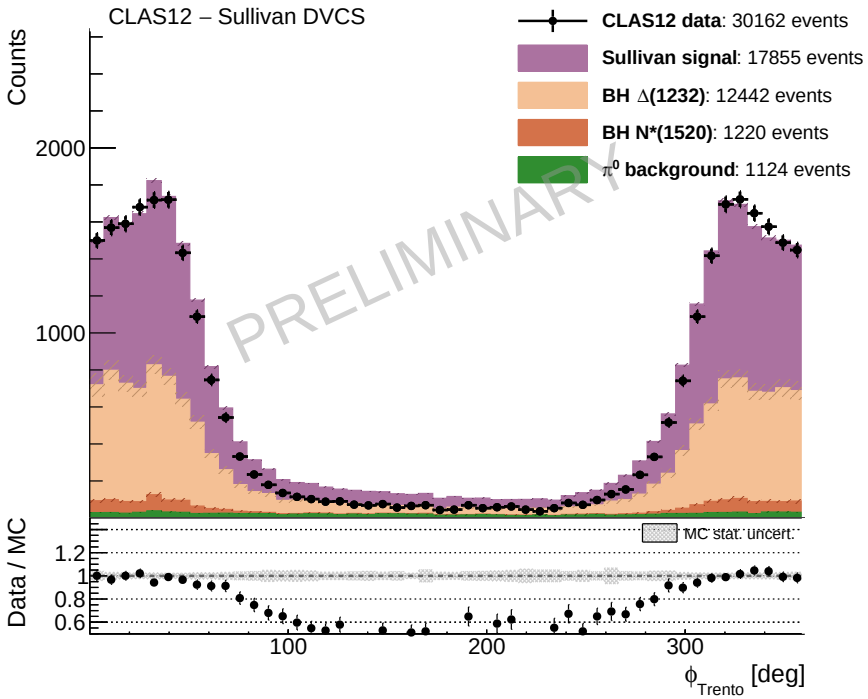
$\langle -t_\pi \rangle = 0.311$ GeV^2



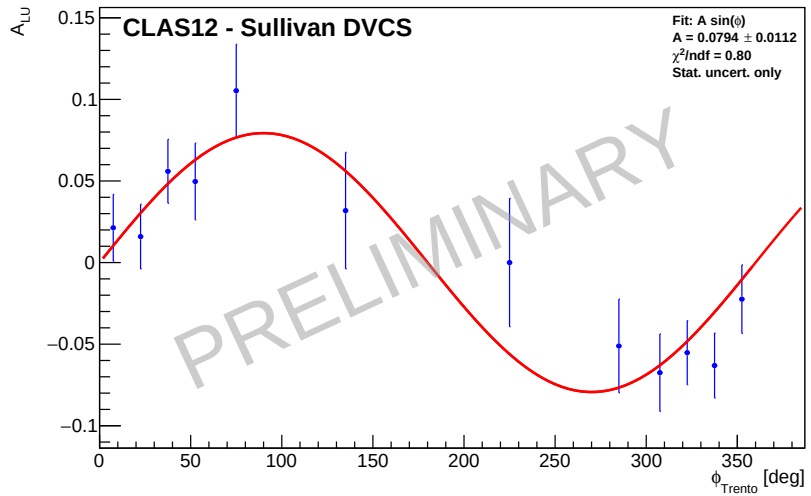
Distribution of x^π_{Bj}.

$\langle x^\pi_{Bj} \rangle = 0.373$

Trento azimuthal angle ϕ and BSA as a function of ϕ



Distribution of ϕ_{Trento}



$A_{LU}^{\sin\phi}$ fit with $f(\phi) = A \times \sin\phi$.

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:

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

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

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

Demonstration of the event probability density function

Analytic expression for the asymmetry

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

Normalized by the beam polarization P_B:

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

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

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

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