Recent results on GPDs from CLAS12 at JLab

EIC-France and Heavy-Ion & Hadronic Physics Meeting

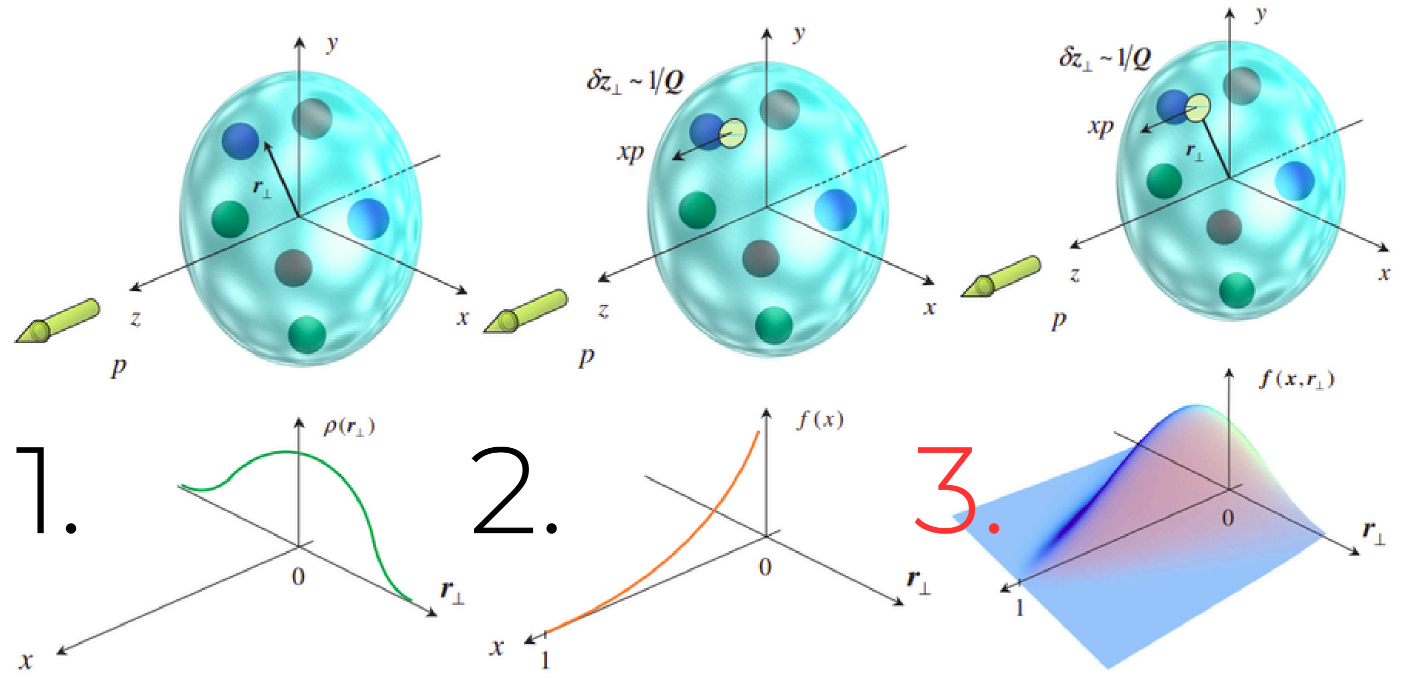
June 30th, 2026

Juan Sebastian Alvarado

GENERALIZED PARTON DISTRIBUTIONS (GPD)

Nucleon internal dynamics is described in terms of structure functions.
They are introduced to describe the partons'

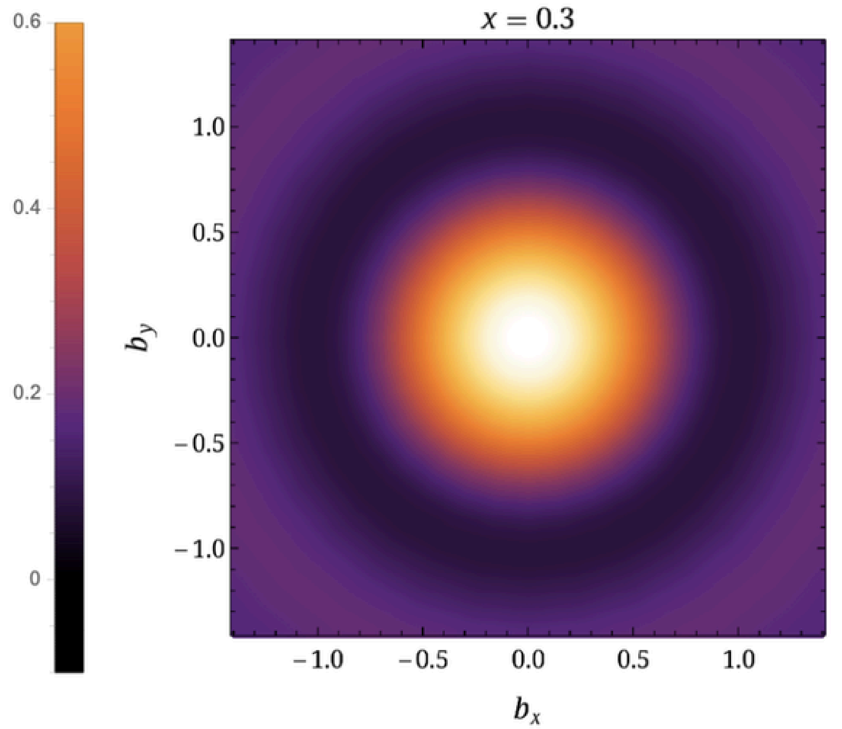
1. Transverse position distribution → FFs
2. Longitudinal momentum distribution → PDFs
3. Transverse position and longitudinal momentum → GPDs
4. Transverse position and transverse momentum → TMDs



GPDs encode information of the nucleon structure such as:

Nucleon Tomography

H.W. Lin, Phys. Rev. Lett. 127 (2021) 182001.



Contributions to the nucleon total spin.

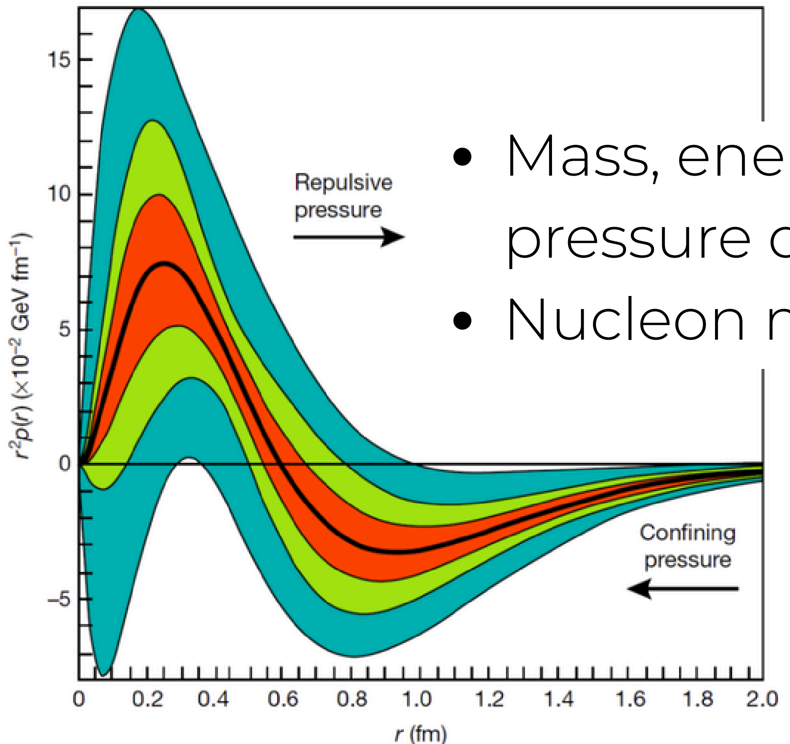
X. Ji, Phy.Rev.Lett.78,610(1997)

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

- Quark contribution
  - Not dominant →Spin Crisis
- Quark's orbital angular momentum
  - Accessed through GPDs
- Gluon contribution

Access to Gravitational Form Factors.

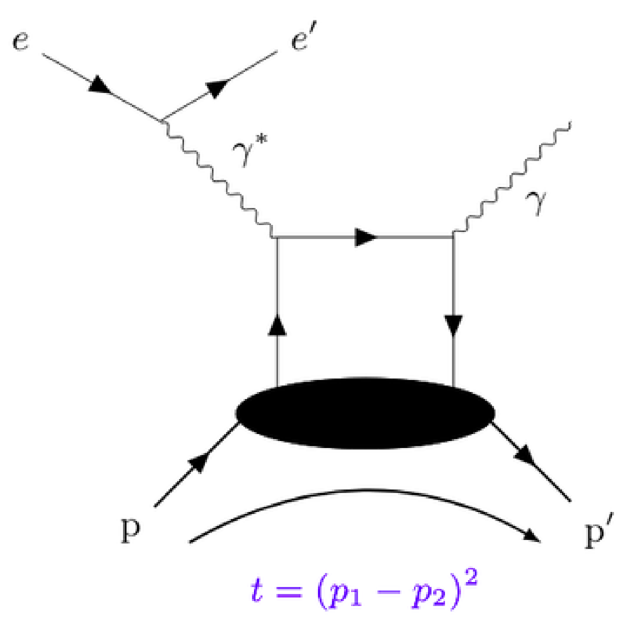
V. D. Burkert *et al*. Nature 557.7705 (2018): 396

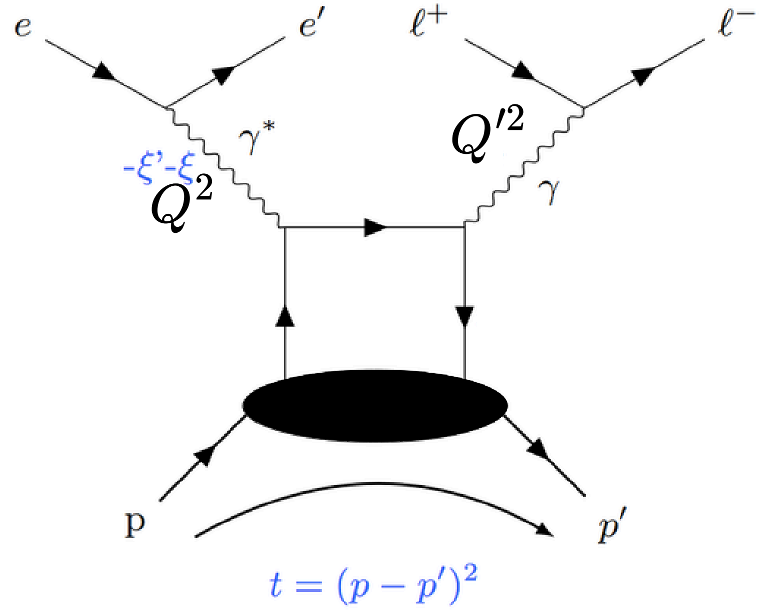


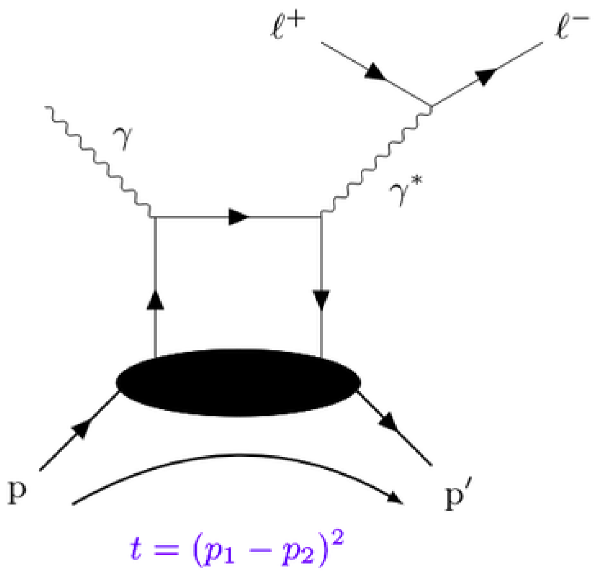
- Mass, energy, force, and pressure distributions
- Nucleon mass radius

DEEPLY VIRTUAL COMPTON SCATTERING (DVCS)

Golden channels to study GPDs are



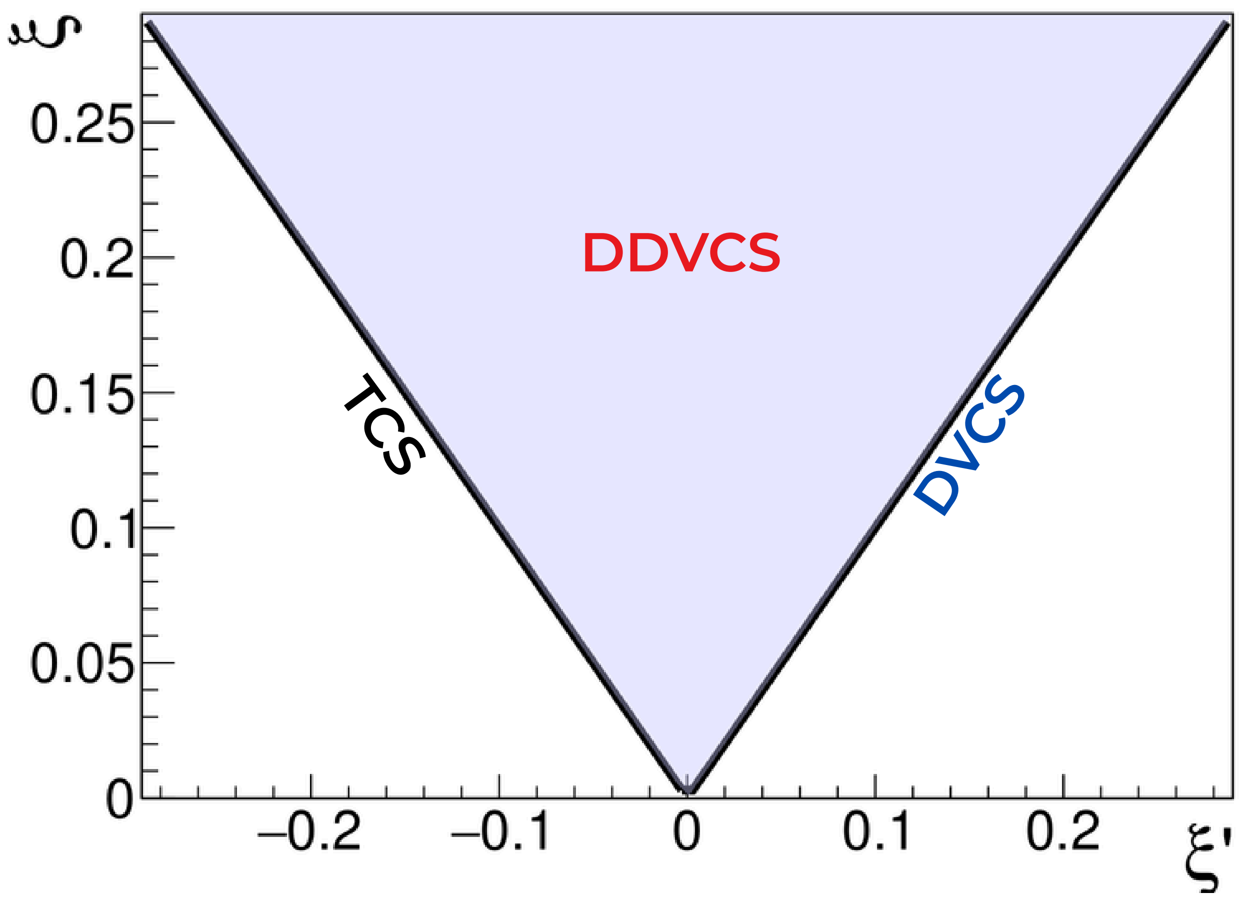




Deeply Virtual Compton Scattering (DVCS)

Double DVCS (DDVCS)

Timelike Compton Scattering (TCS)



They give access to the nucleon four chiral-even GPDs $F = H, E, \widetilde{H}, \widetilde{E}$

- GPDs enter the cross section through Compton Form Factors (CFF)

$$\mathcal{F}(\xi', \xi, t) = -\mathcal{P}\int_0^1 dx'\, F^+(x', \xi, t)\left[\frac{1}{x' - \xi'} \pm \frac{1}{x' + \xi'}\right] + i\pi F^+(\xi', \xi, t)$$

$$F^+(\xi', \xi, t) = F(\xi', \xi, t) \pm F(-\xi', \xi, t)$$

- Each reaction grants different access to GPDs:
  - DDVCS → |ξ'|<ξ
  - DVCS → ξ'=ξ
  - TCS → ξ'=-ξ

$$\xi = \frac{Q^2 + Q'^2}{\frac{2Q^2}{x_B} - Q^2 - Q'^2 + t}$$

$$\xi' = \frac{Q^2 - Q'^2 + t/2}{\frac{2Q^2}{x_B} - Q^2 - Q'^2 + t}$$

- DVCS has been the main source of experimental constraints on GPDs (CLAS, HERMES, etc.)
- First-time DDVCS measurements are foreseen at Jefferson Lab in the coming years
- The first TCS measurement was obtained with CLAS12

DEEPLY VIRTUAL COMPTON SCATTERING (DVCS)

Linear combinations of CFFs are extracted through beam- and target-spin asymmetries

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

Different sensitivity for a proton or neutron ($F_1 \sim 0$) target

Obs.	Proton	Neutron
A_{LU}	$\mathfrak{Im}[\mathcal{H}]$	$\mathfrak{Im}[\mathcal{E}]$
A_{UL}	$\mathfrak{Im}[\widetilde{\mathcal{H}}]$	$\mathfrak{Im}[\mathcal{H}]$
A_{LL}	$\mathfrak{Re}[\widetilde{\mathcal{H}}]$	$\mathfrak{Re}[\mathcal{H}]$
A_{UT}	$\mathfrak{Im}[\mathcal{E}]$	$\mathfrak{Im}[\mathcal{H}]$

Flavor separation of GPDs requires measurements on both nucleons

$$F_u(\xi,\xi,t) = \frac{9}{15}\left[4F_p(\xi,\xi,t) - F_n(\xi,\xi,t)\right]$$

$$F_d(\xi,\xi,t) = \frac{9}{15}\left[4F_n(\xi,\xi,t) - F_p(\xi,\xi,t)\right]$$

- Beam Spin Asymmetry

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

- Longitudinally polarized Target Spin Asymmetry

$$A_{UL} \propto \mathfrak{Im}\left[F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)\mathcal{H} - \xi\frac{t}{4M^2}F_2\widetilde{\mathcal{E}} + \mathcal{O}(\xi^2)\right]\sin\phi$$

- Double Spin Asymmetry (Longitudinally polarized Target)

$$A_{LL} \propto \mathfrak{Re}\left[F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)\mathcal{H} - \xi\frac{t}{4M^2}F_2\widetilde{\mathcal{E}} + \mathcal{O}(\xi^2)\right]\cos\phi$$

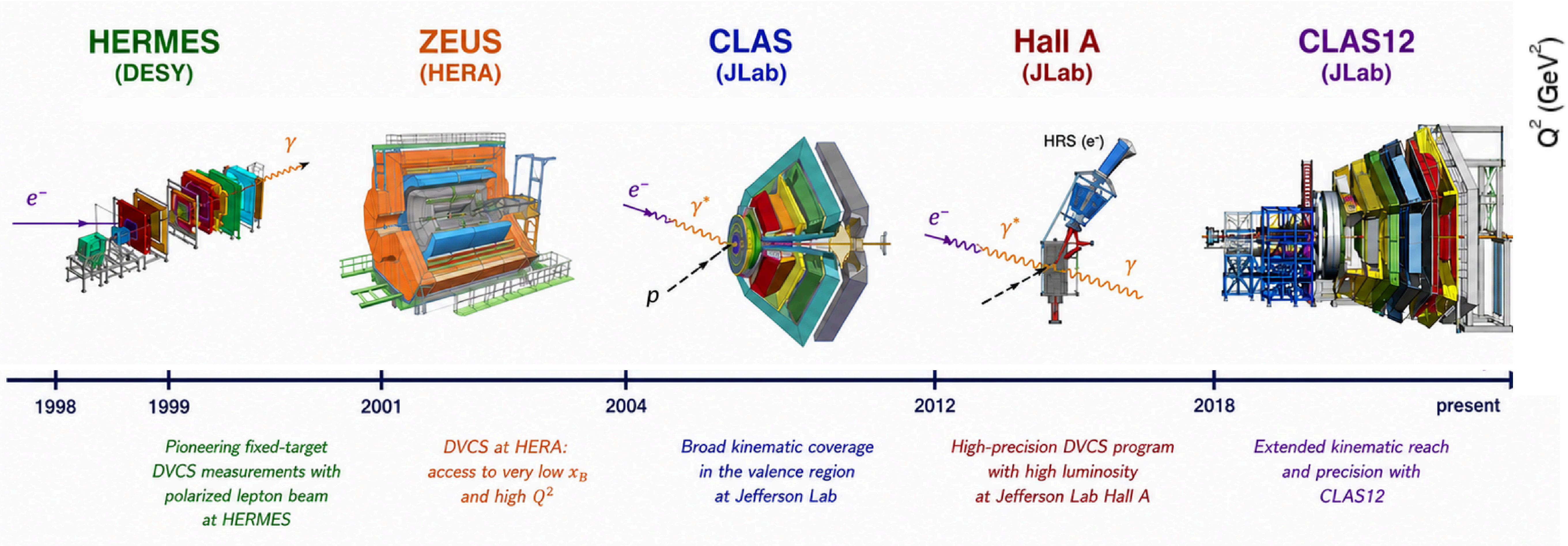
- Transversely polarized Target Spin Asymmetry

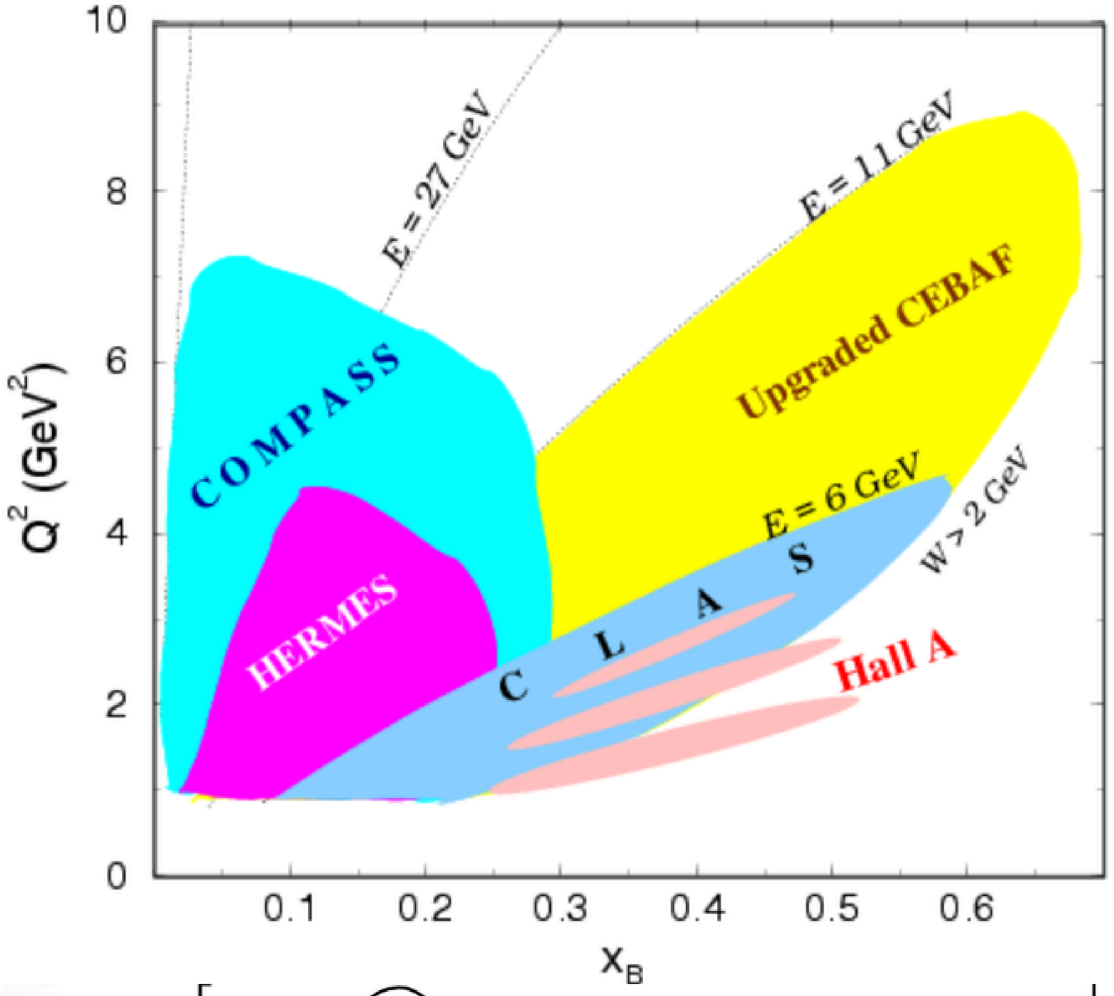
$$A_{UT} \propto \mathfrak{Im}\left[\frac{t}{4M^2}(F_2\mathcal{H} + F_1\mathcal{E}) + \mathcal{O}(\xi^2)\right]\cos\phi\sin(\Phi-\phi)$$

- These observables, as well as cross section, are covered by the CLAS12 DVCS program
- There are results already published, analyses in progress, and additional experiments planned

DEEPLY VIRTUAL COMPTON SCATTERING (DVCS)

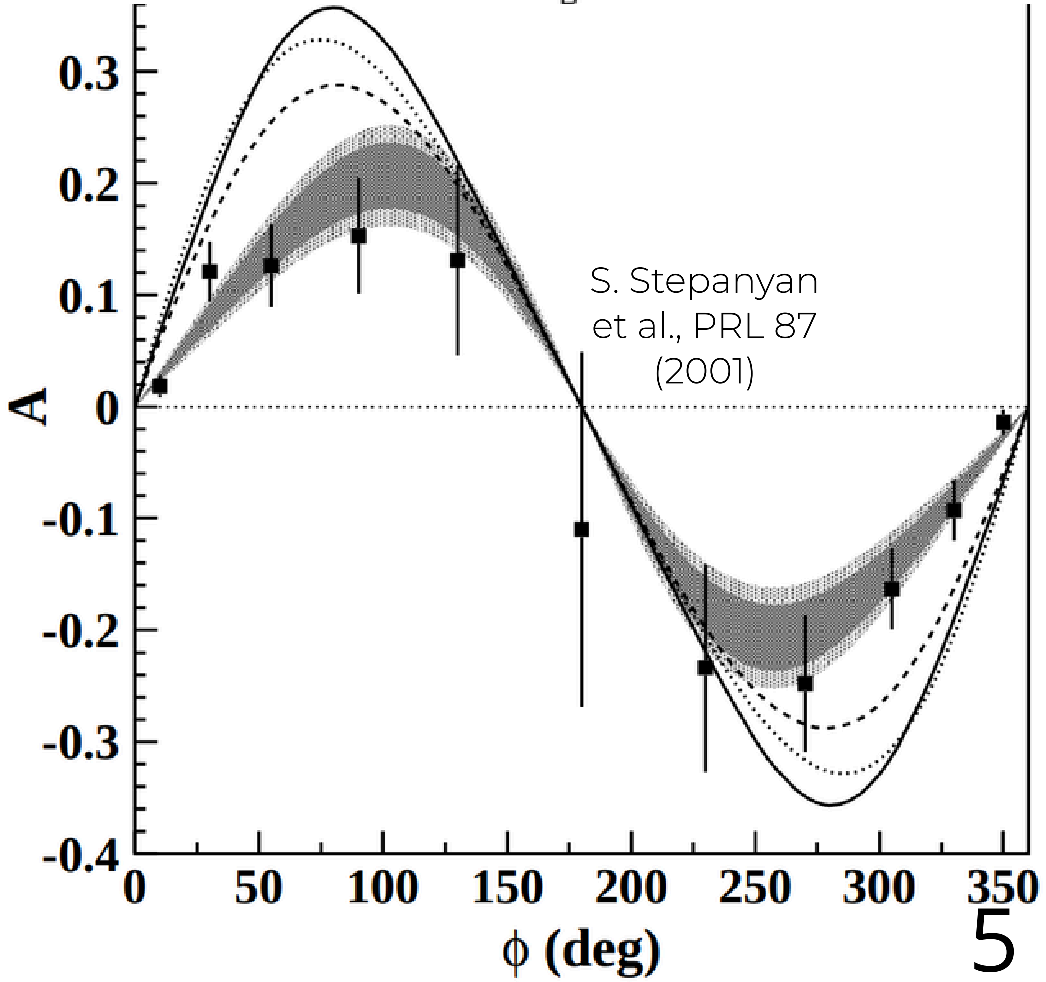
The DVCS reaction received a wolrdwide interest





- Cross section measurements:
  - H1, ZEUS
  - JLab Hall A, B (CLAS/CLAS12) and C
  - COMPASS
- Spin asymmetries
  - HERMES
  - CLAS/CLAS12

First observation of the BSA modulation with CLAS



Jefferson Lab

Status of GPD studies at Jefferson Lab

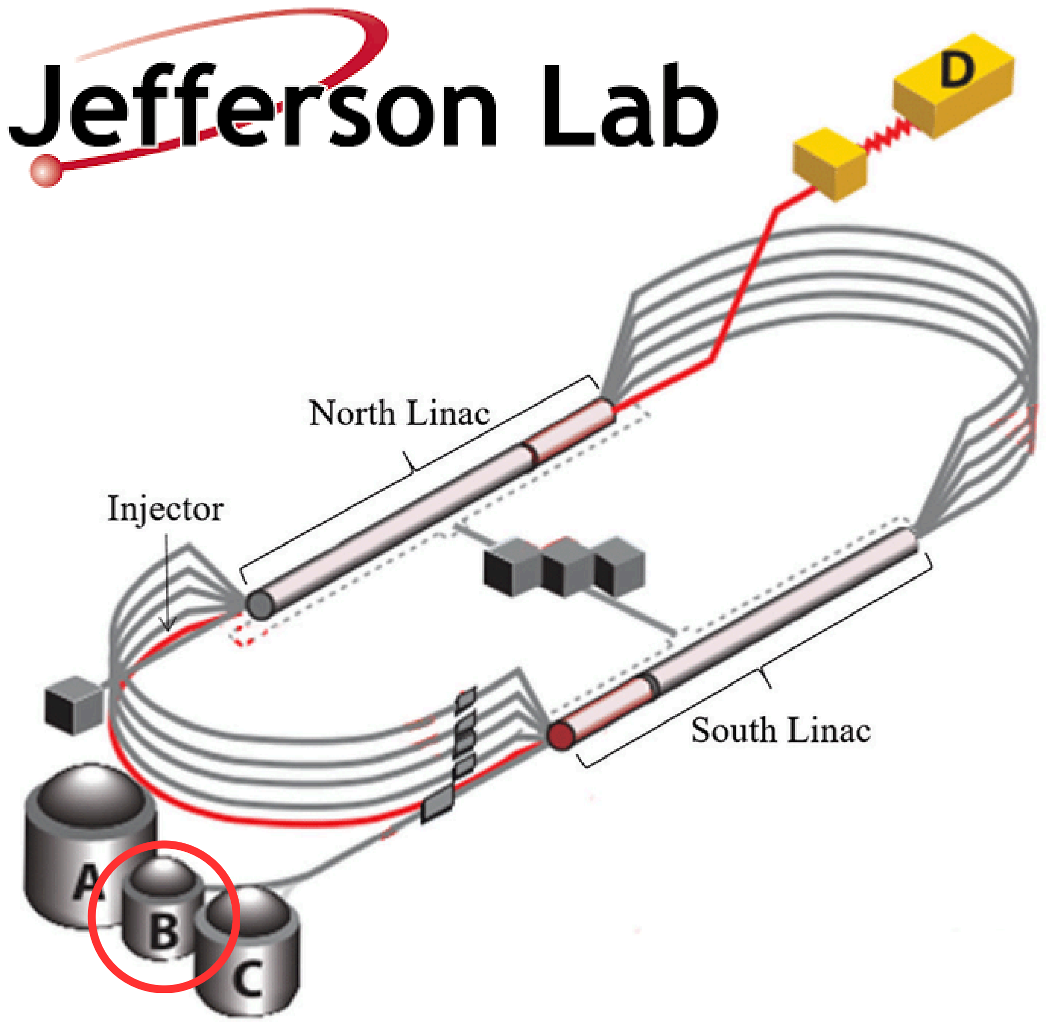
clas

CEBAF Large Acceptance Spectrometer

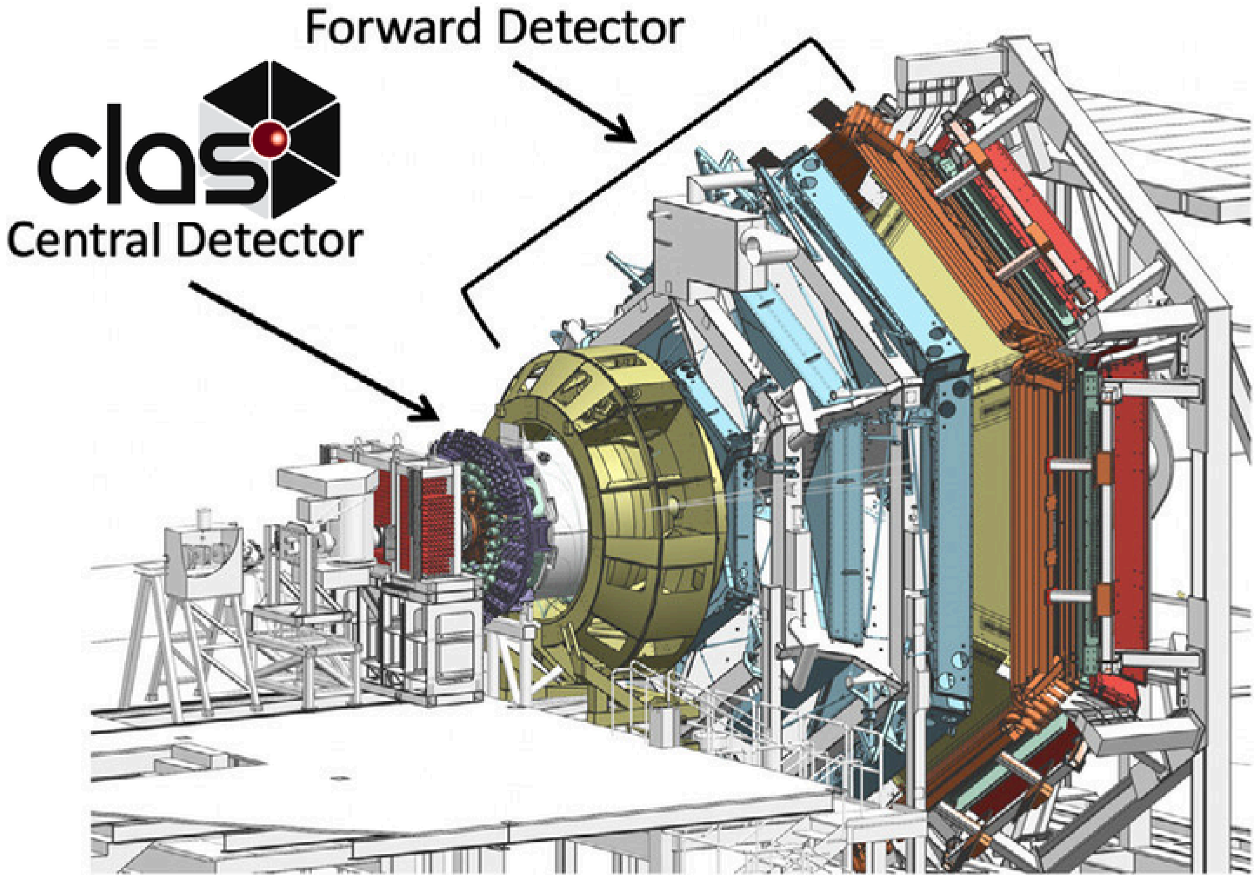
EXPERIMENTAL CONFIGURATION

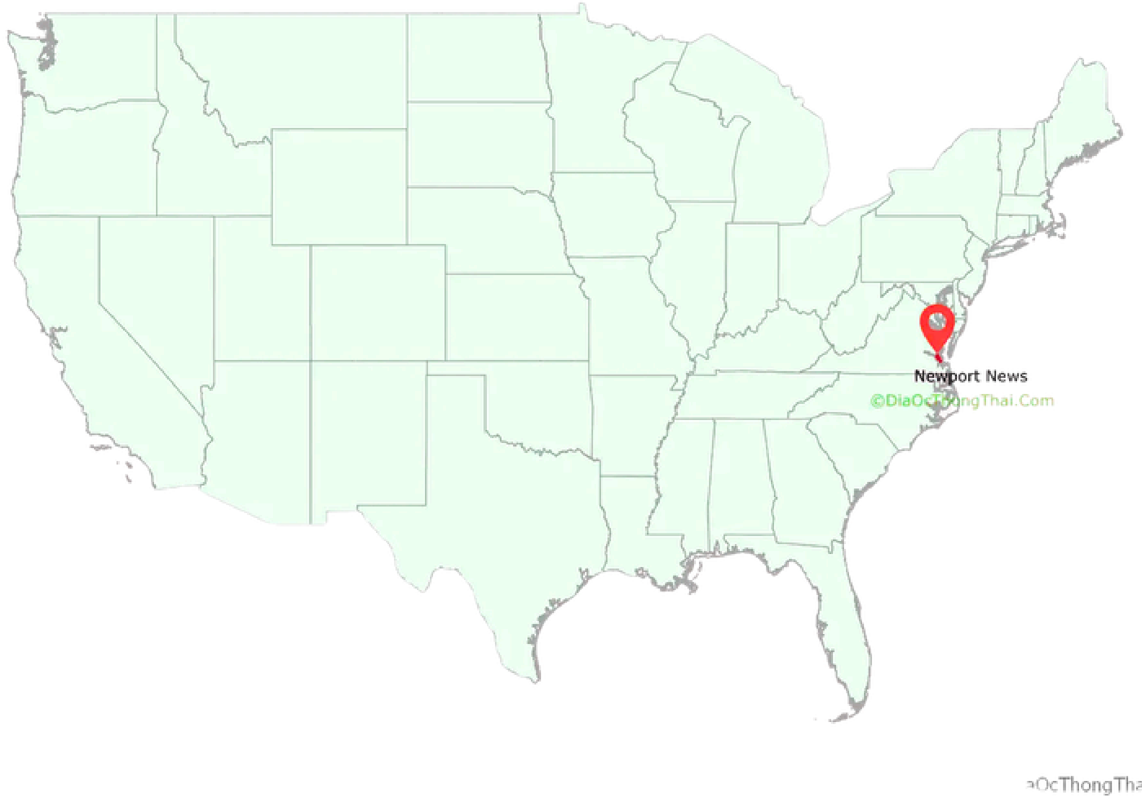
The Thomas Jefferson National Accelerator Facility **(JLab)** is a research facility run by the Department of Energy (DOE). Located in Newport News (Virginia).

The physics program relies on the **C**ontinuous **E**lectron **B**eam **A**ccelerator **F**acility (CEBAF), providing up to a 12 GeV **longitudinally polarized electron beam** to four experimental halls (A, B, C, and D).



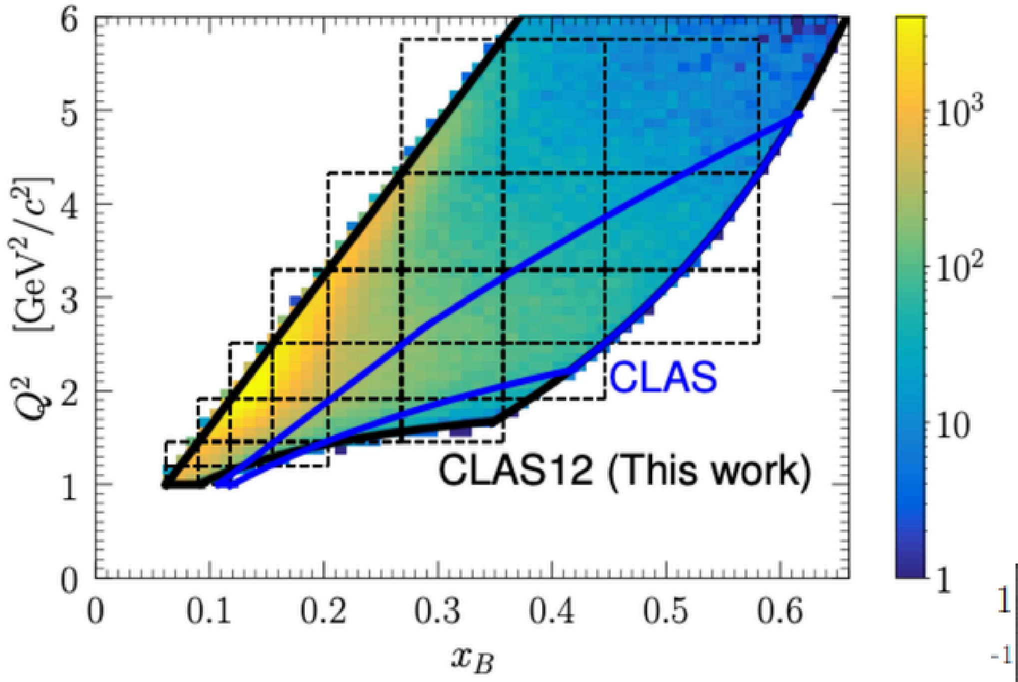
The **C**EBAF **L**arge **A**cceptance **S**pectrometer **(CLAS12)** located in Hall B enables DVCS measurements through active electron, photon, and proton detection

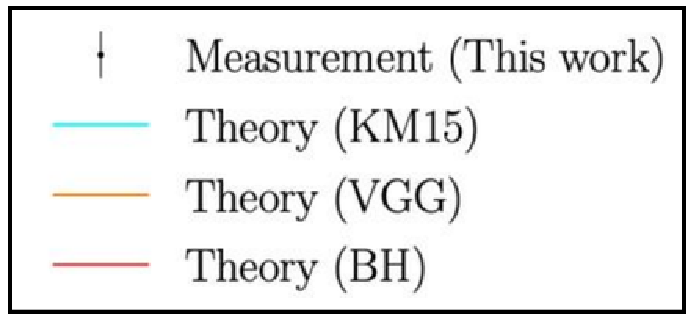


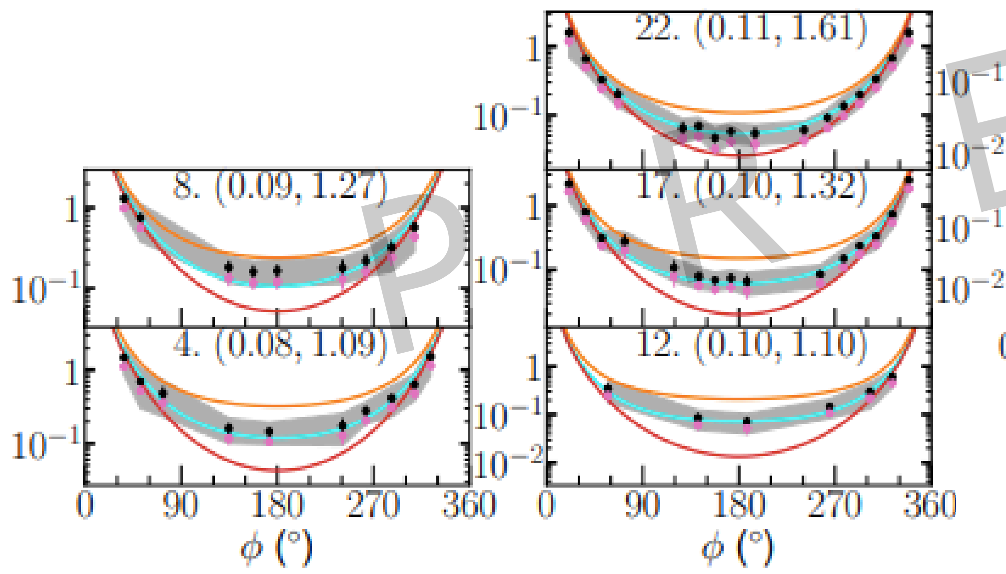
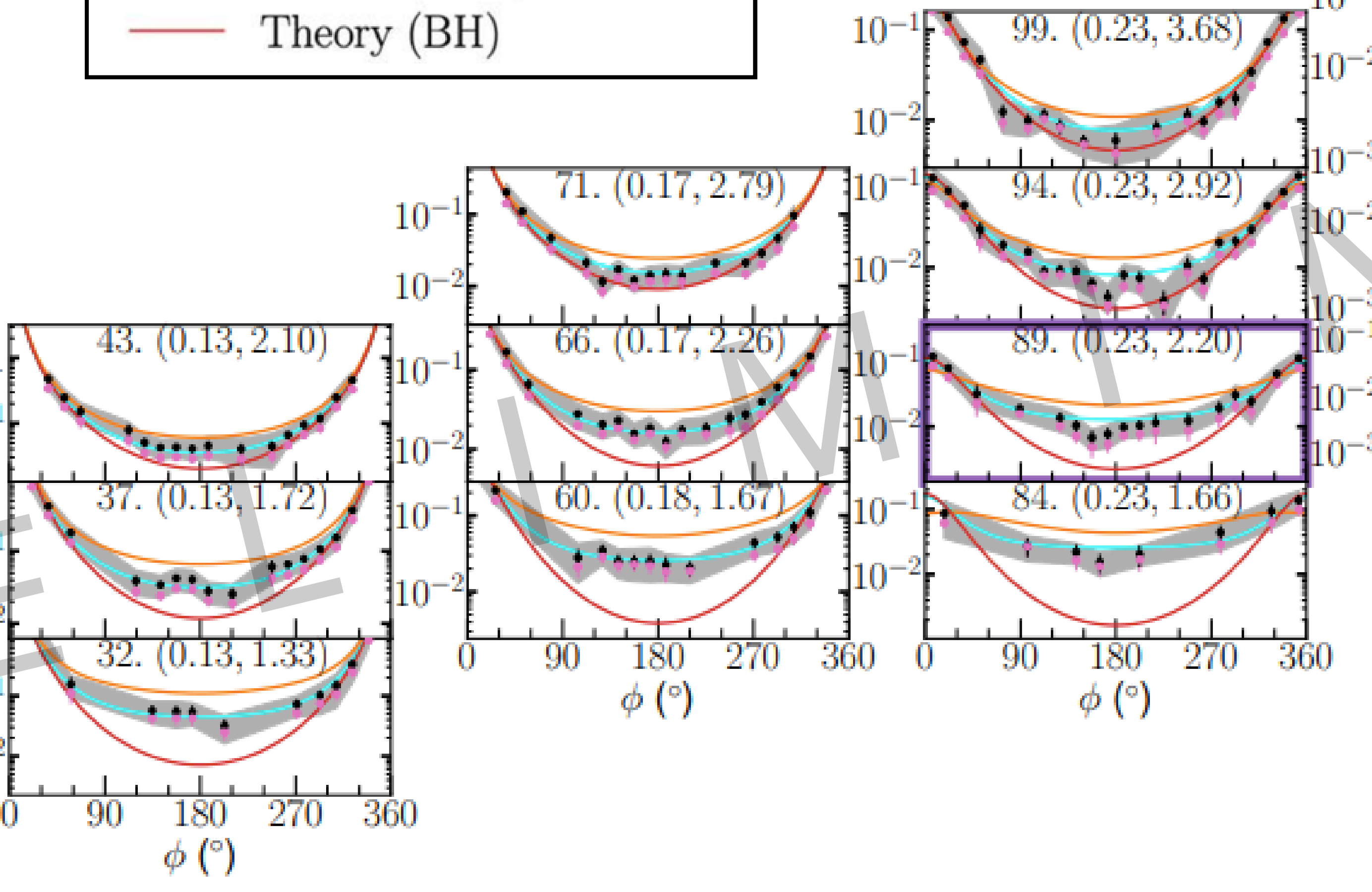


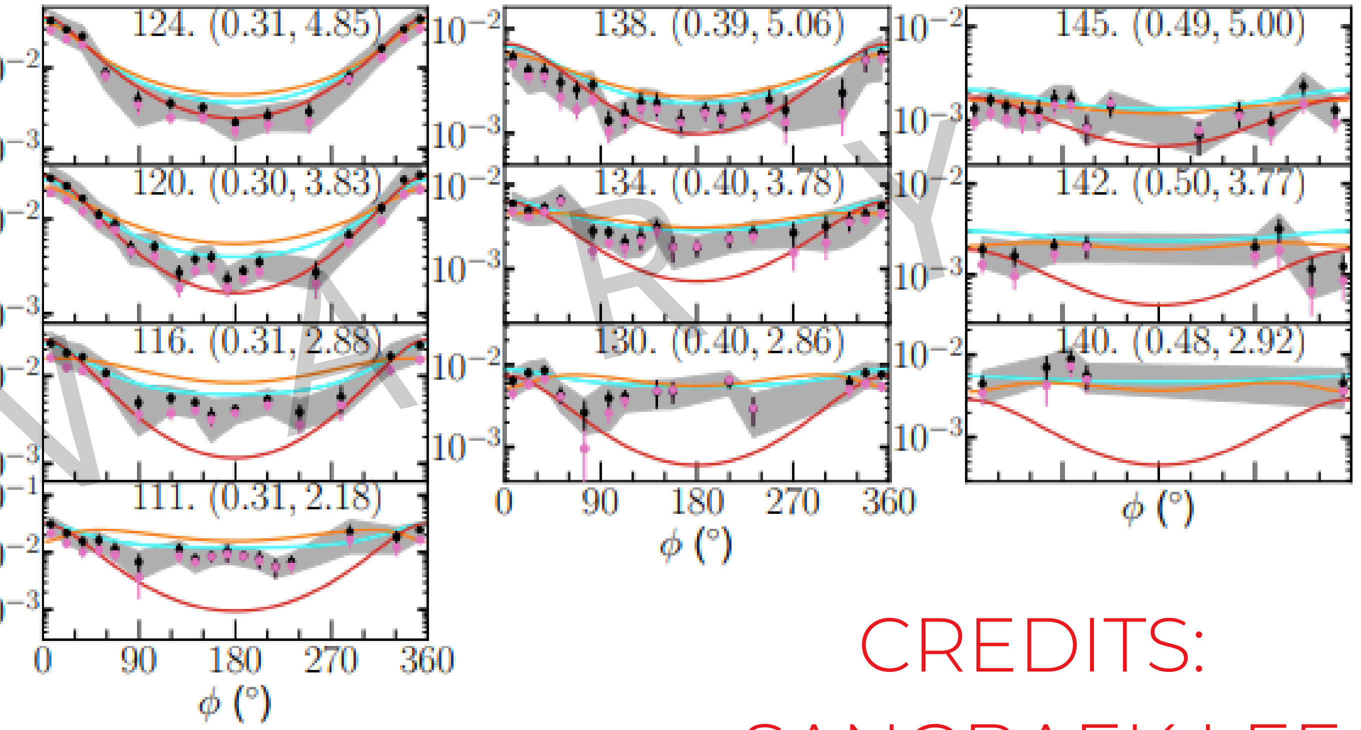
CROSS SECTION: UNPOLARIZED PROTON TARGET

$$\sigma_{UU} = \sigma_{\mathrm{BH}}(F_1(t), F_2(t)) + \sigma_{\mathrm{DVCS}}(\mathcal{F}(\xi, t)) + \sigma_{\mathrm{INT}}(\mathcal{F}(\xi, t))$$







CREDITS:
SANGBAEK LEE

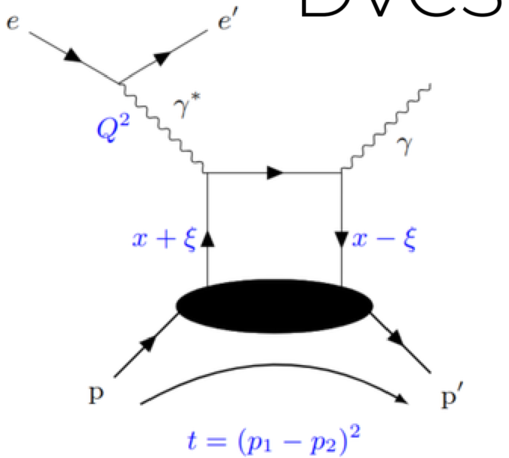
Fairly described by the KM15 model

Mainly sensitive to GPD H

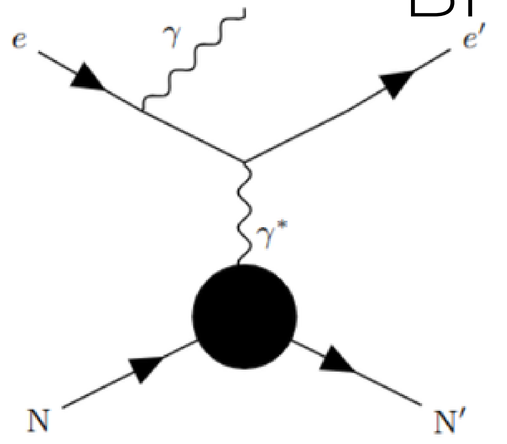
Significant contribution from GPD dynamics was observed

To be published soon

DVCS



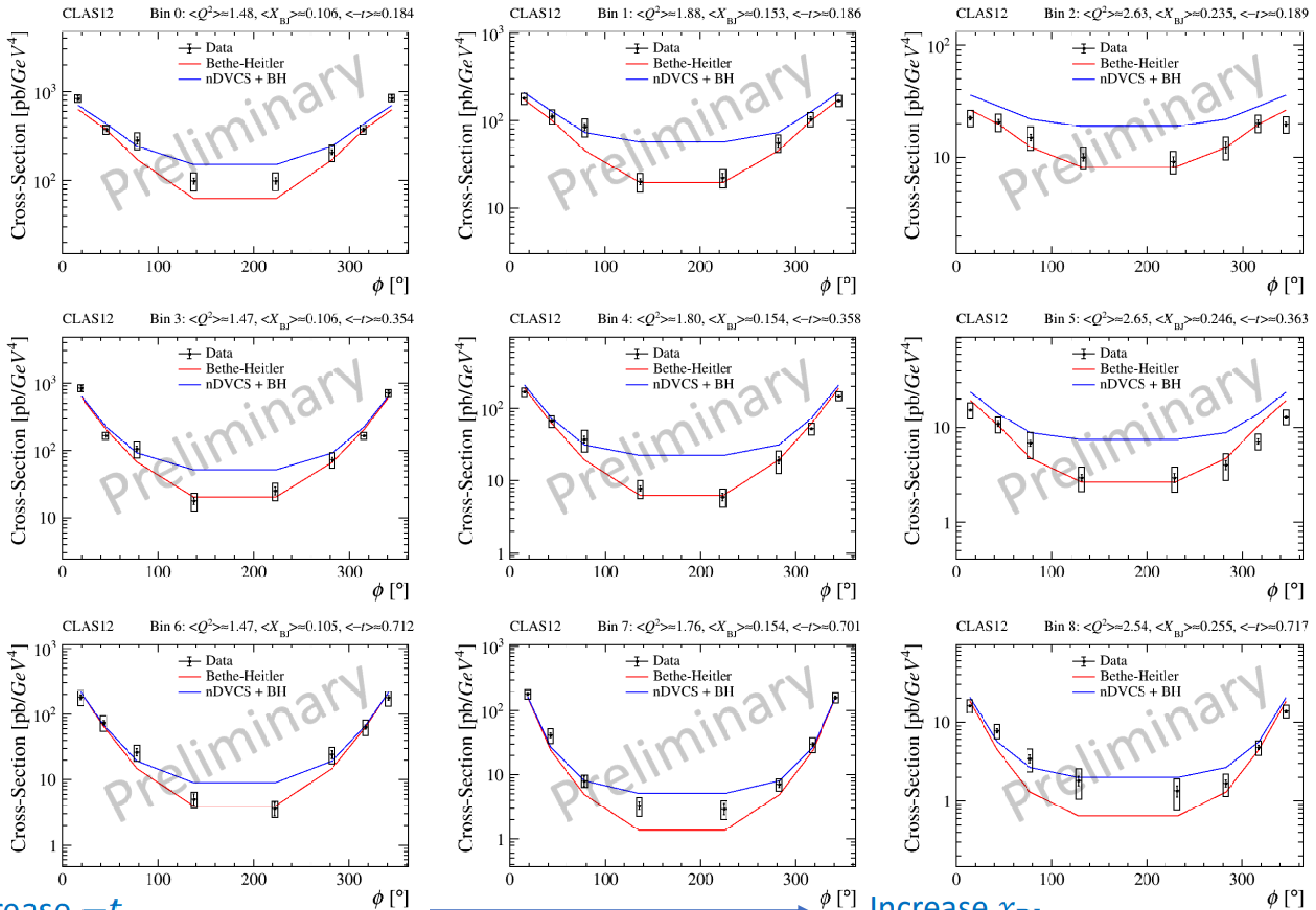
BH



CROSS SECTION: UNPOLARIZED NEUTRON TARGET

$$\sigma_{UU} = \sigma_{\mathrm{BH}}(F_1(t), F_2(t)) + \sigma_{\mathrm{DVCS}}(\mathcal{F}(\xi, t)) + \sigma_{\mathrm{INT}}(\mathcal{F}(\xi, t))$$

CREDITS:
LI XU



Increase $-t$

Increase x_{BJ}

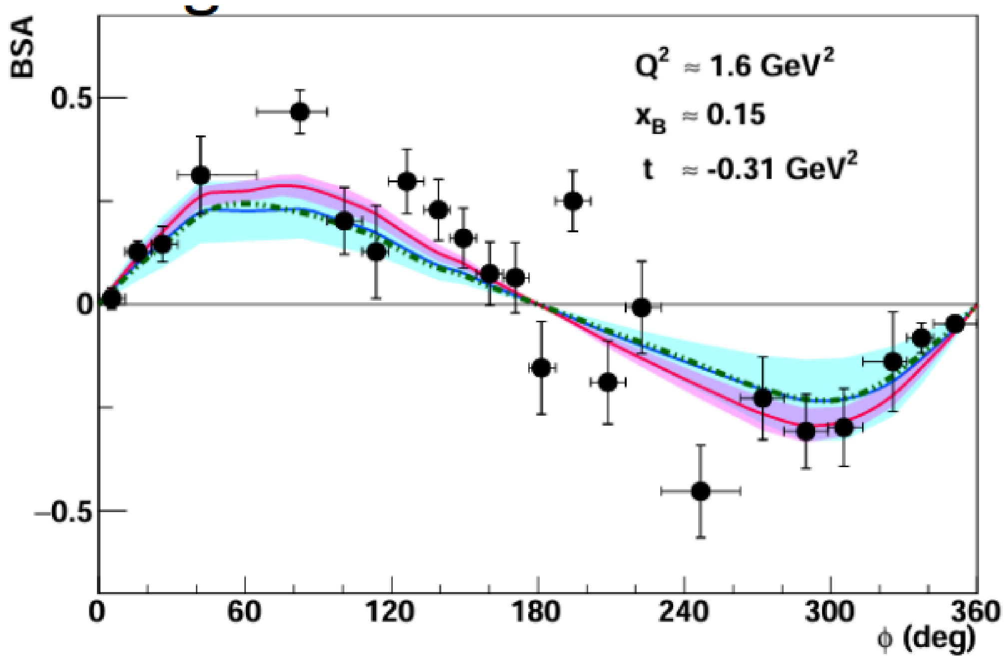
- **Sensitive to GPD E**
  - Together with H, provide constraints to the quark orbital momentum contribution to the nucleon spin
  - E models have been poorly constrained by existing data
- Predictions overshoot the data in the central region,
  - VGG parametrization of E is not optimal

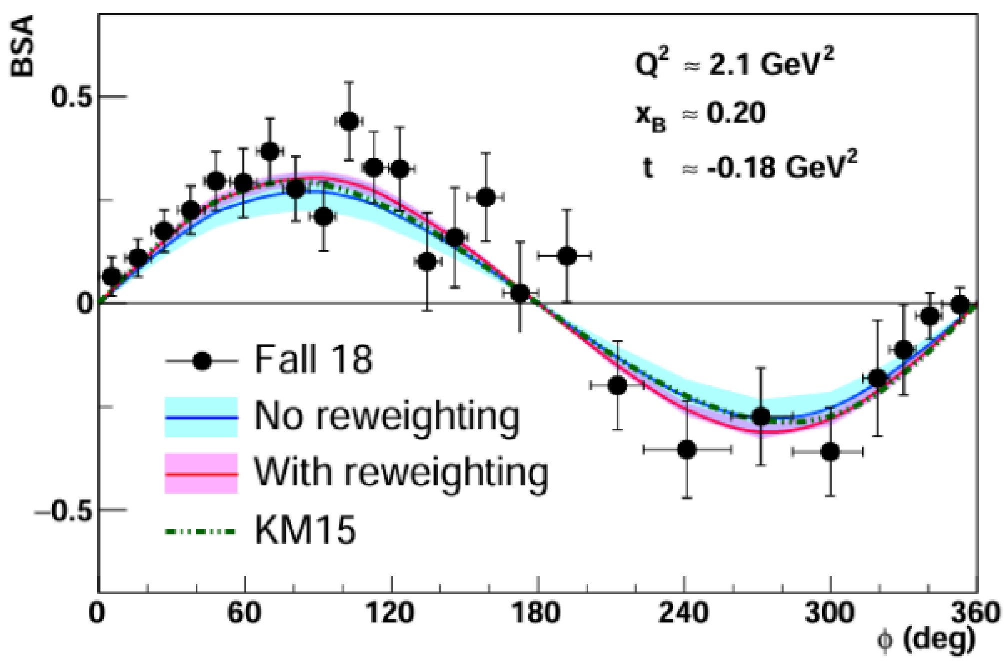
- **Error bars** → Statistical
- **Boxes** → Systematic
- **nDVCS+BH** → VGG model: J_u=0.3 and J_d=0.1

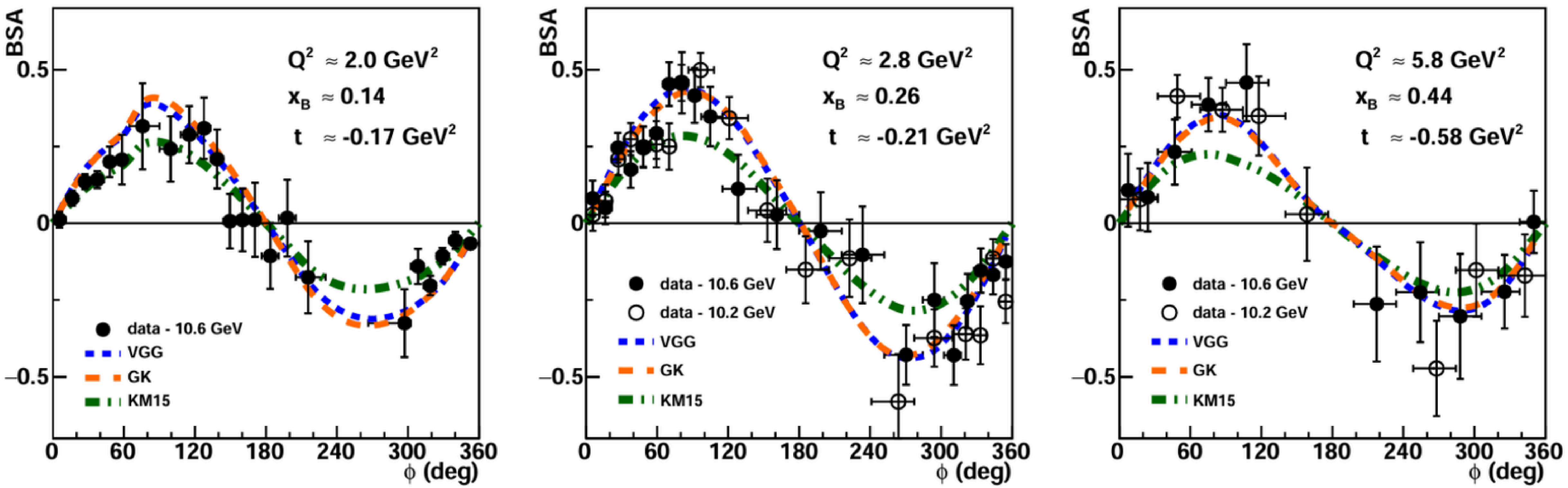
BEAM SPIN ASYMMETRY: PROTON TARGET

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

- CLAS12 BSA measurements of pDVCS have been published and made available in the Open database for GPD analyses (64 (Q^2, xB, t) bins)
  - Eur. Phys. J. C 85.8 (2025): 838 (https://opengpd.github.io/gpddatabase/)
  - Phys. Rev. Lett. 130 (21) 211902 (2023): Polarized beam, unpolarized LH2 target
- In addition to theoretical models, a series of ANNs were trained on the world dataset of DVCS measurements.
  - The ANN predictions, along with measurements, are in good agreement with the KM15 model





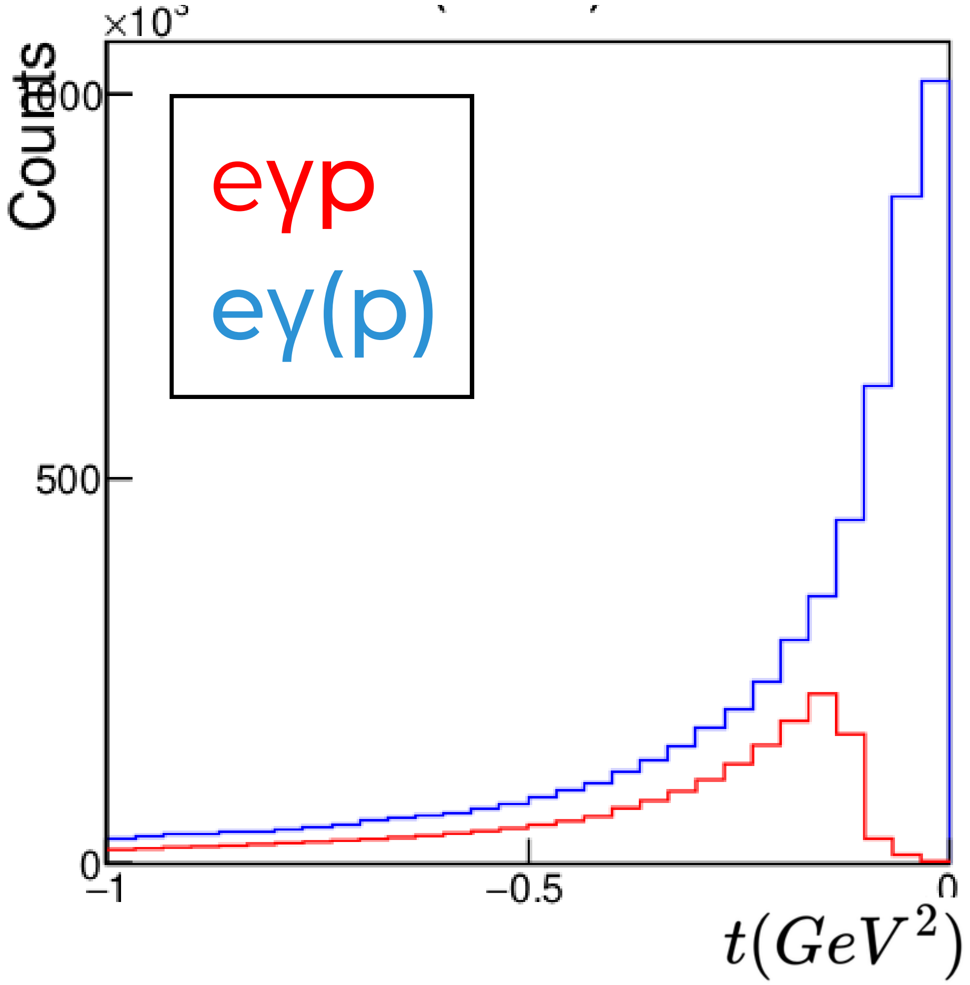


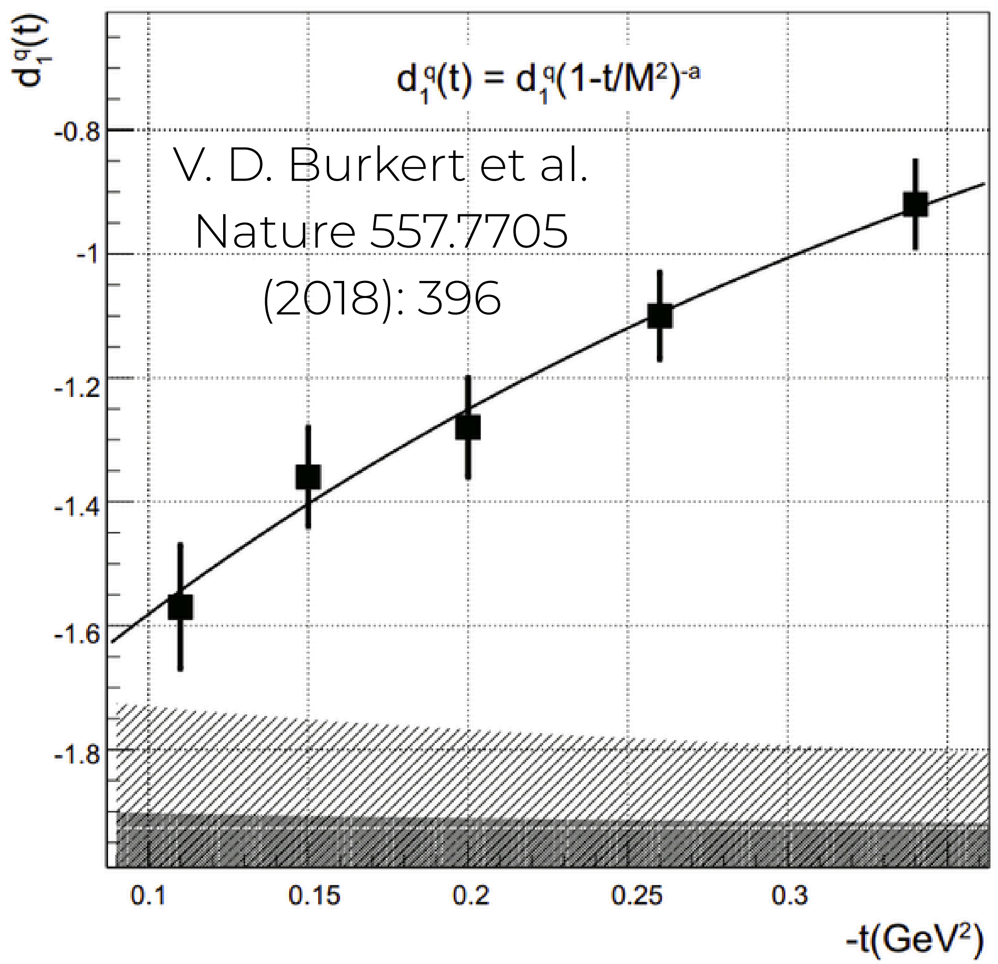
Access to a wide kinematic range

BEAM SPIN ASYMMETRY: PROTON TARGET

Nucleon information is accessed through CFFs values and slopes at t=0

- The largest uncertainty originates from extrapolating towards t=0
- CLAS12 acceptance sets a lower limit on |t|. Thus, we can unlock smaller |t|-values if we bypass proton detection
  - **This analysis was one of my main contributions during my PhD**





Contributions to the nucleon total spin.

X. Ji, Phy.Rev.Lett.78,610(1997)

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

Access to Gravitational Form Factors.

H. Dutrieux *et al.*, Eur. Phys. J. C 81 (2021) 4, 300

The D-term can be constrained through **cross-section (Re[CFFs] and BSA (Im[CFF] measurements**

$$D(t) = \mathfrak{Re}[\mathcal{H}(\xi,t)] - \frac{1}{\pi}\int_0^1 d\xi'\, \mathfrak{Im}[\mathcal{H}(\xi',t)]\left(\frac{1}{\xi-\xi'} - \frac{1}{\xi+\xi'}\right)$$

Therefore, we can **access the shear forces and pressure distribution** within the nucleon through $d_1(t)$

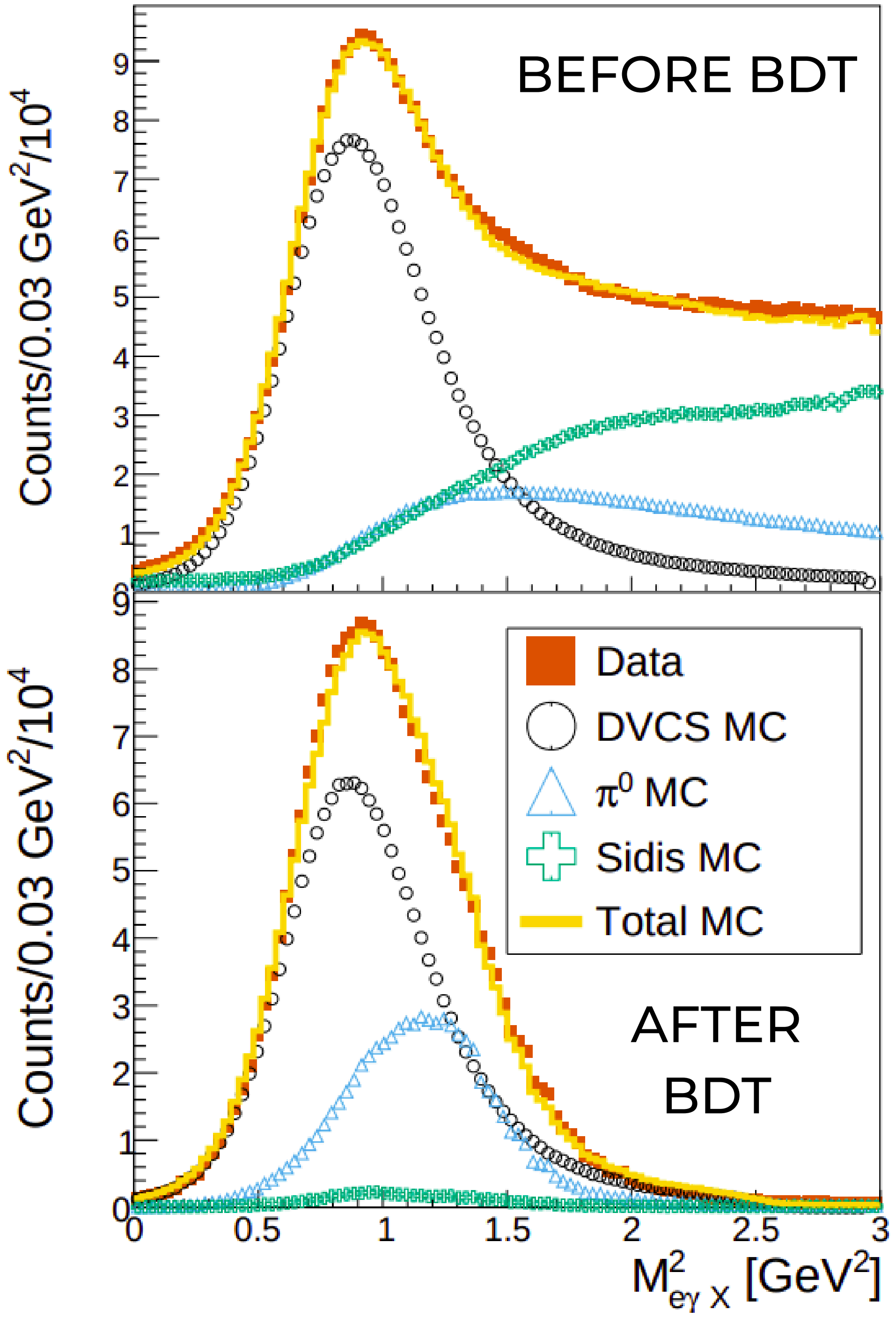
$$D(t) = \frac{1}{2}\int_{-1}^{1}\frac{dz}{1-z}(1-z^2)\left[d_1(t)C_1^{3/2}(z) + \cdots\right]$$

$$d_1(t) \equiv d_1(t=0)f_1(t)$$

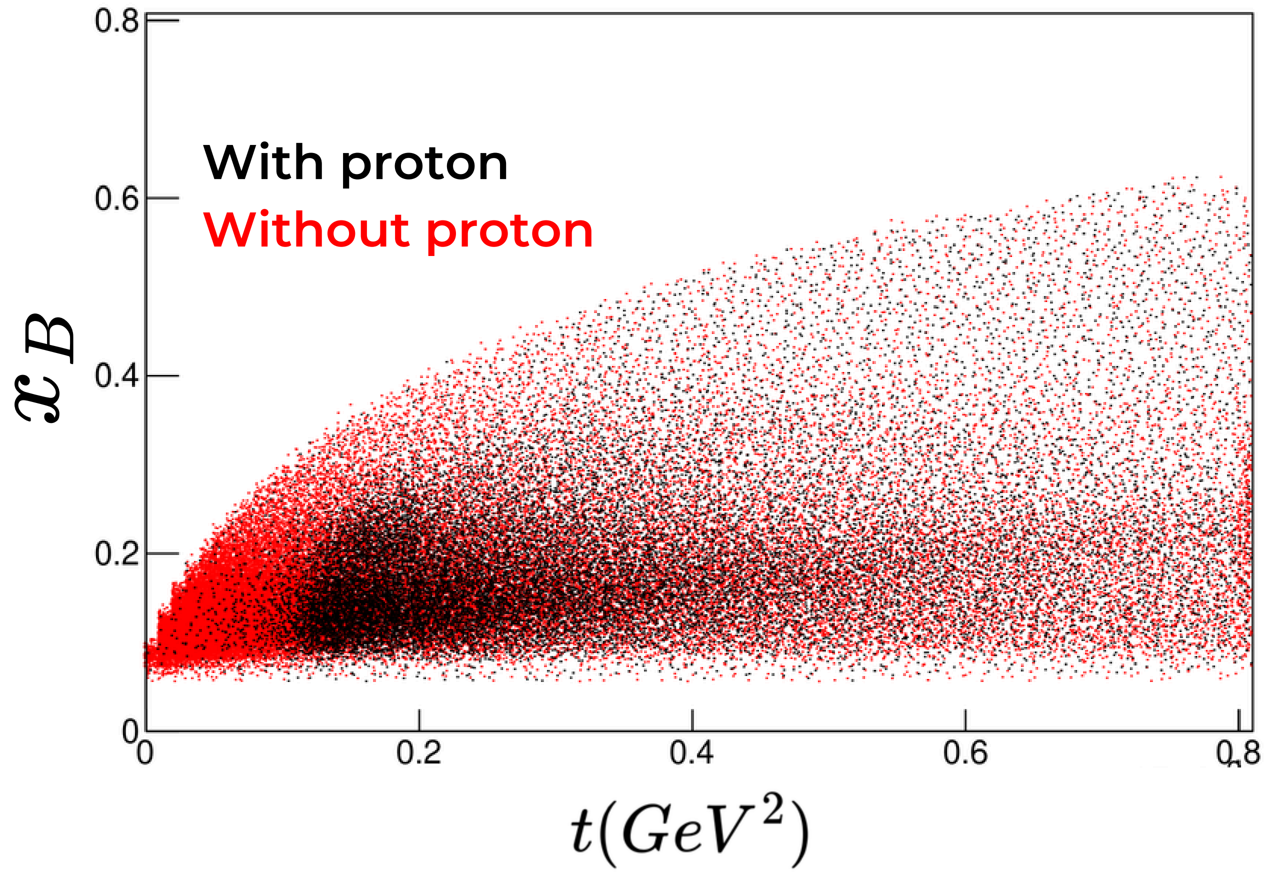
Extending measurements to the lowest possible |t| directly improves our knowledge of the nucleon.

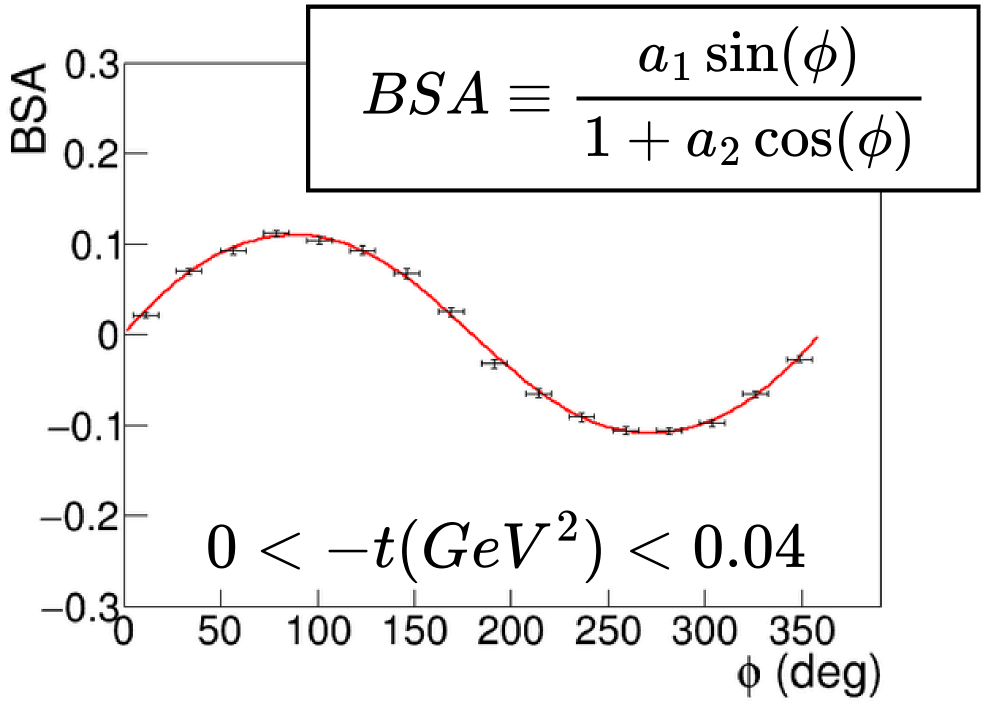
BEAM SPIN ASYMMETRY: PROTON TARGET, SMALL -t

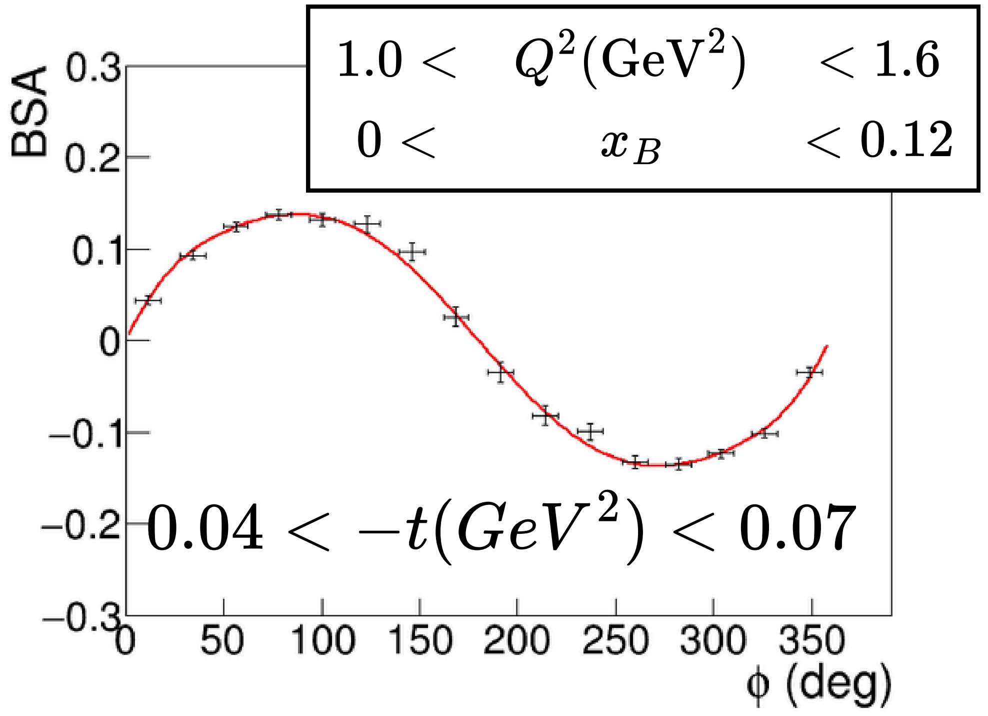
DVCS channel selection was improved with a Boosted Decision Tree Classifier



- An **analysis without requiring proton** detection allows:
  - Increase in statistics allowing **precise measurements**
  - **Access to small -t** values



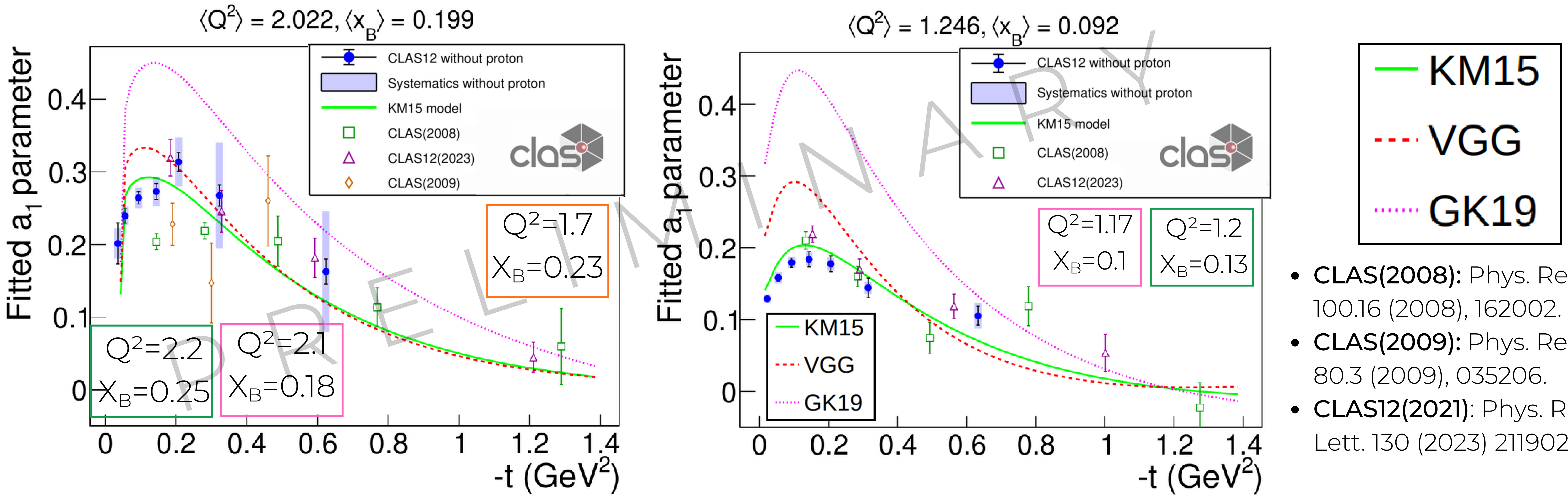




- The background channel is π^0 production
  - $ep \rightarrow ep\pi^0 \rightarrow ep\gamma(\gamma)$ (Exclusive)
  - $ep \rightarrow ep\pi^0 X \rightarrow ep\gamma(\gamma)X$ (SIDIS)
- The smaller the |t|, the better the interpretation of DVCS in terms of twist-2 GPDs

BEAM SPIN ASYMMETRY: PROTON TARGET, SMALL -t

$$A(\phi) \equiv \frac{a_1 \sin(\phi)}{1 + a_2 \cos(\phi)} \qquad a_1 \propto \mathfrak{Im}\left[\left(F_1\mathcal{H} - \frac{t}{4M^2}F_2\mathcal{E}\right) + \xi(F_1 + F_2)\widetilde{\mathcal{H}}\right]$$



- **CLAS(2008):** Phys. Rev. Lett. 100.16 (2008), 162002.
- **CLAS(2009):** Phys. Rev. C 80.3 (2009), 035206.
- **CLAS12(2021)**: Phys. Rev. Lett. 130 (2023) 211902.

- There is a general consistency picture among BSA measurements
- GK19 model (PARTONS) overestimates the asymmetry
- VGG and KM15 models give similar estimates for $-t>0.2$ GeV^2
- For small -t values, the KM15 predictions feature a better agreement with data
- To be published soon

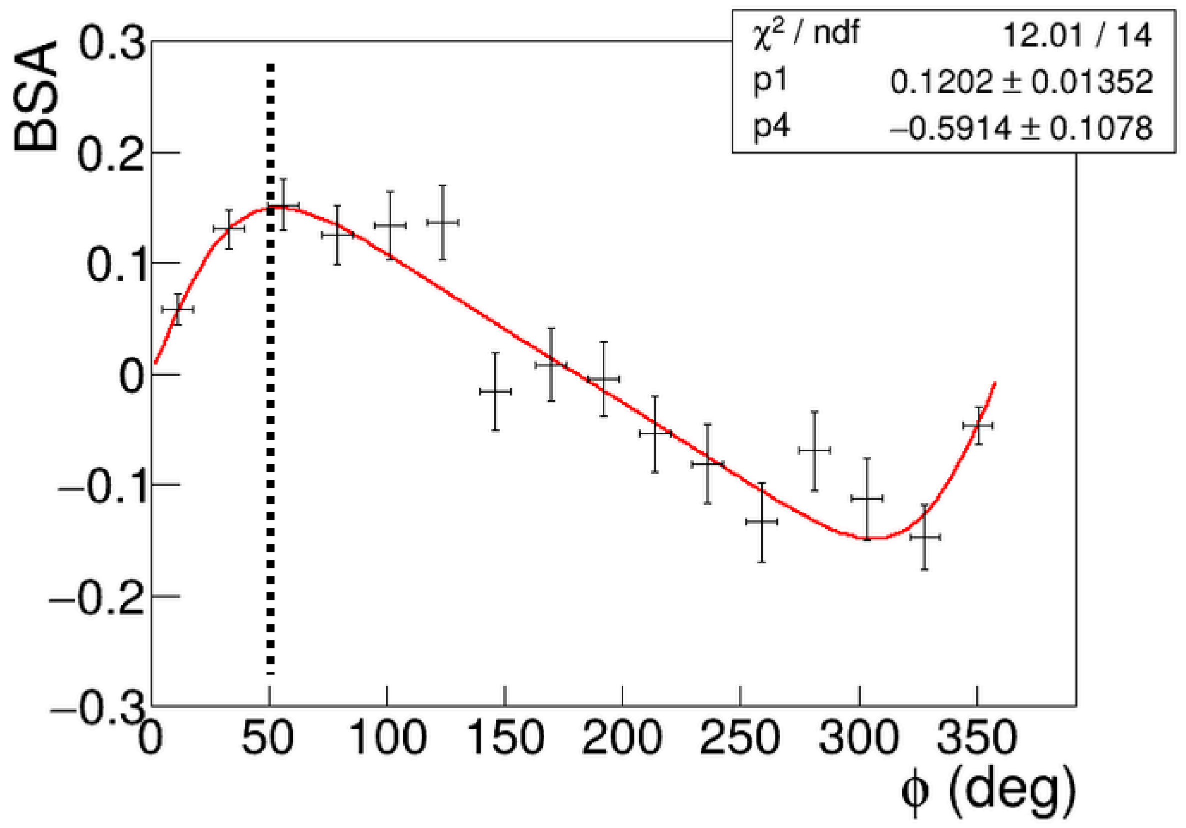
BEAM SPIN ASYMMETRY: PROTON TARGET, SMALL -t

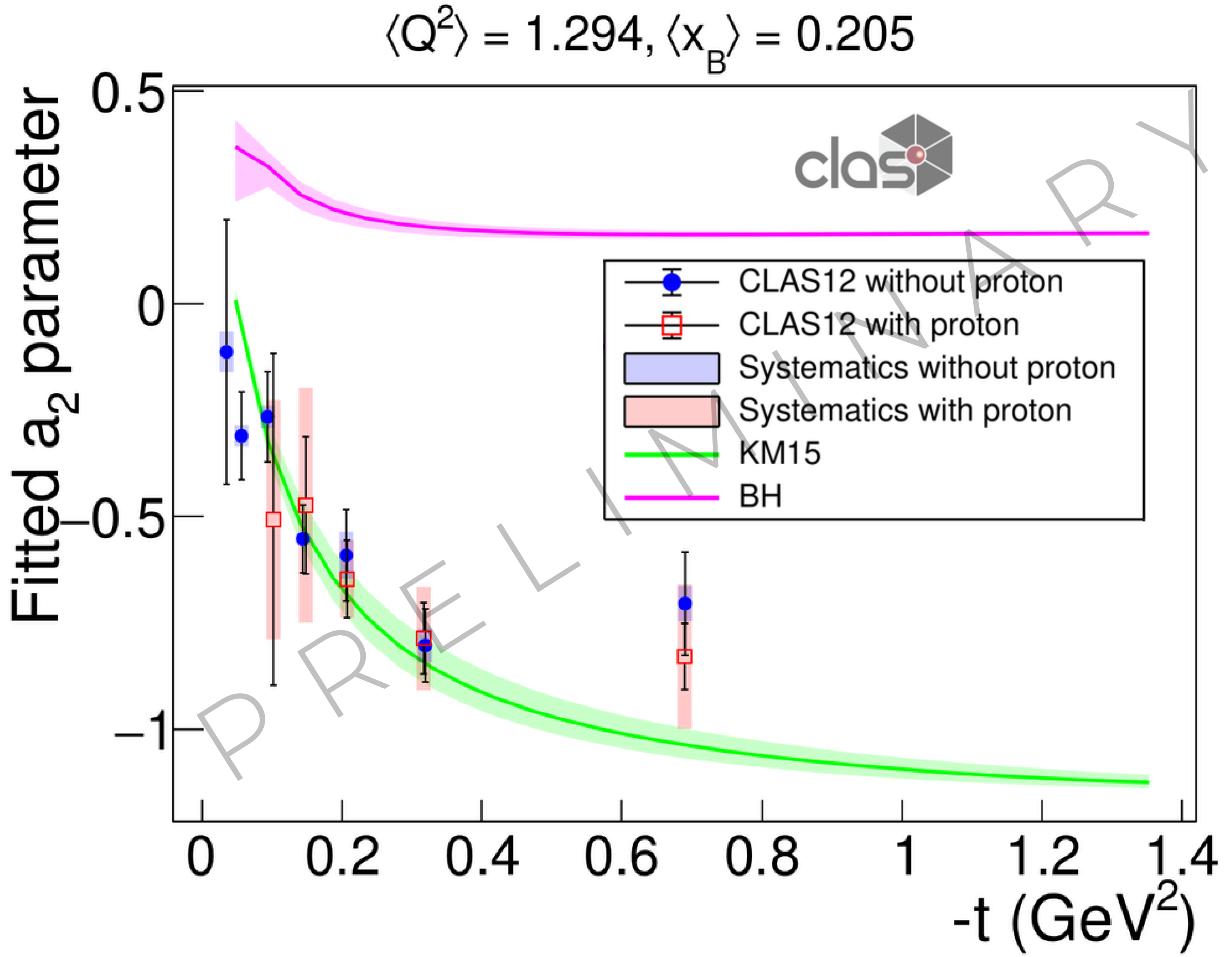
$$A(\phi) \equiv \frac{a_1 \sin(\phi)}{1 + a_2 \cos(\phi)} \qquad a_2 \equiv a_2(\Re e[CFFs])$$

Given the achieved precision on the BSA, constraints on the real part of CFFs can be retrieved

- It shows compatibility with the KM15 model
- It is not BH-dominated and given by:

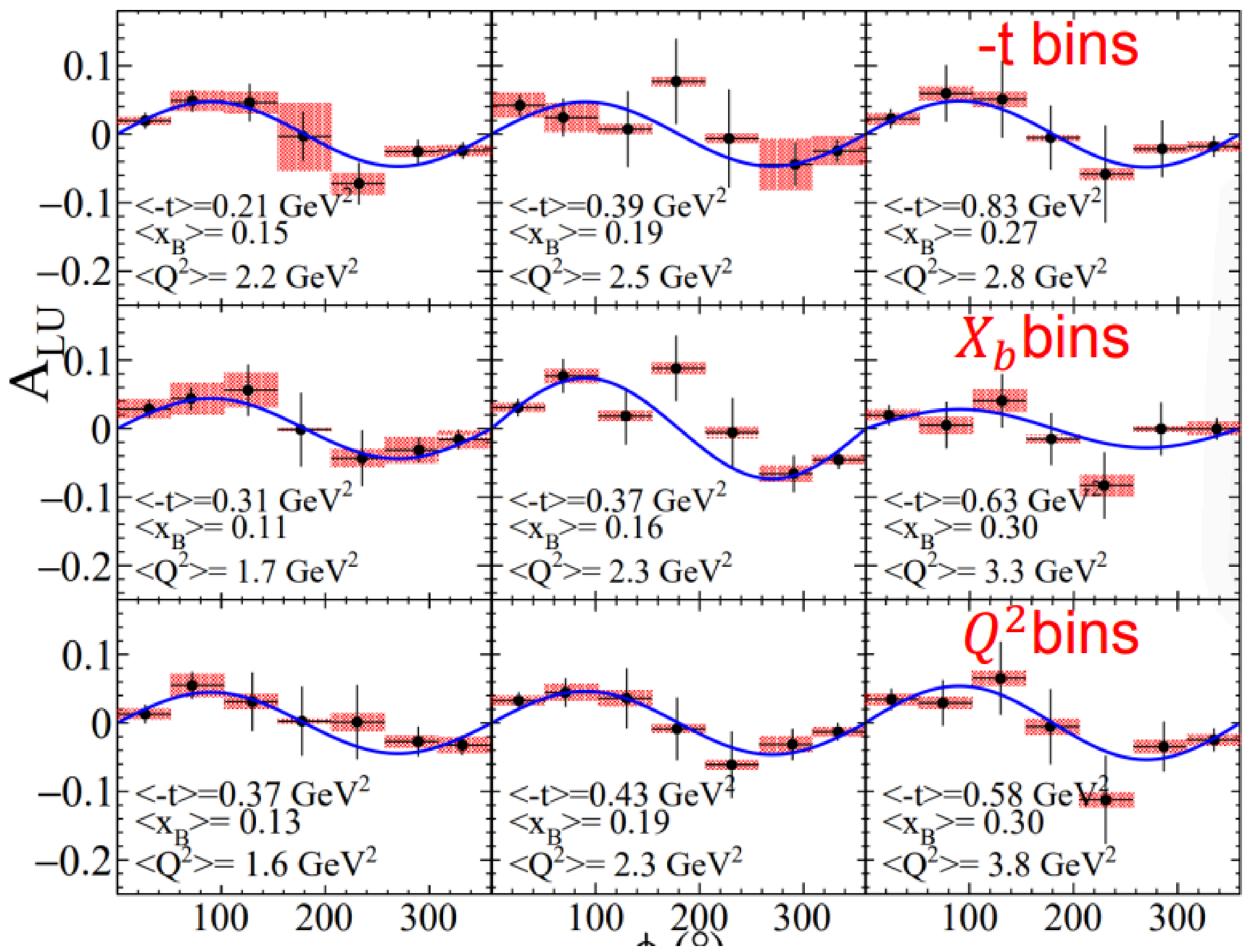
$$a_2 = \frac{2\int_0^{2\pi} d\phi \, \cos(\phi) \, \mathcal{P}_1\mathcal{P}_2(\phi) d^5\sigma_{UU}(\phi)}{\int_0^{2\pi} d\phi \, \mathcal{P}_1\mathcal{P}_2(\phi) d^5\sigma_{UU}(\phi)}$$





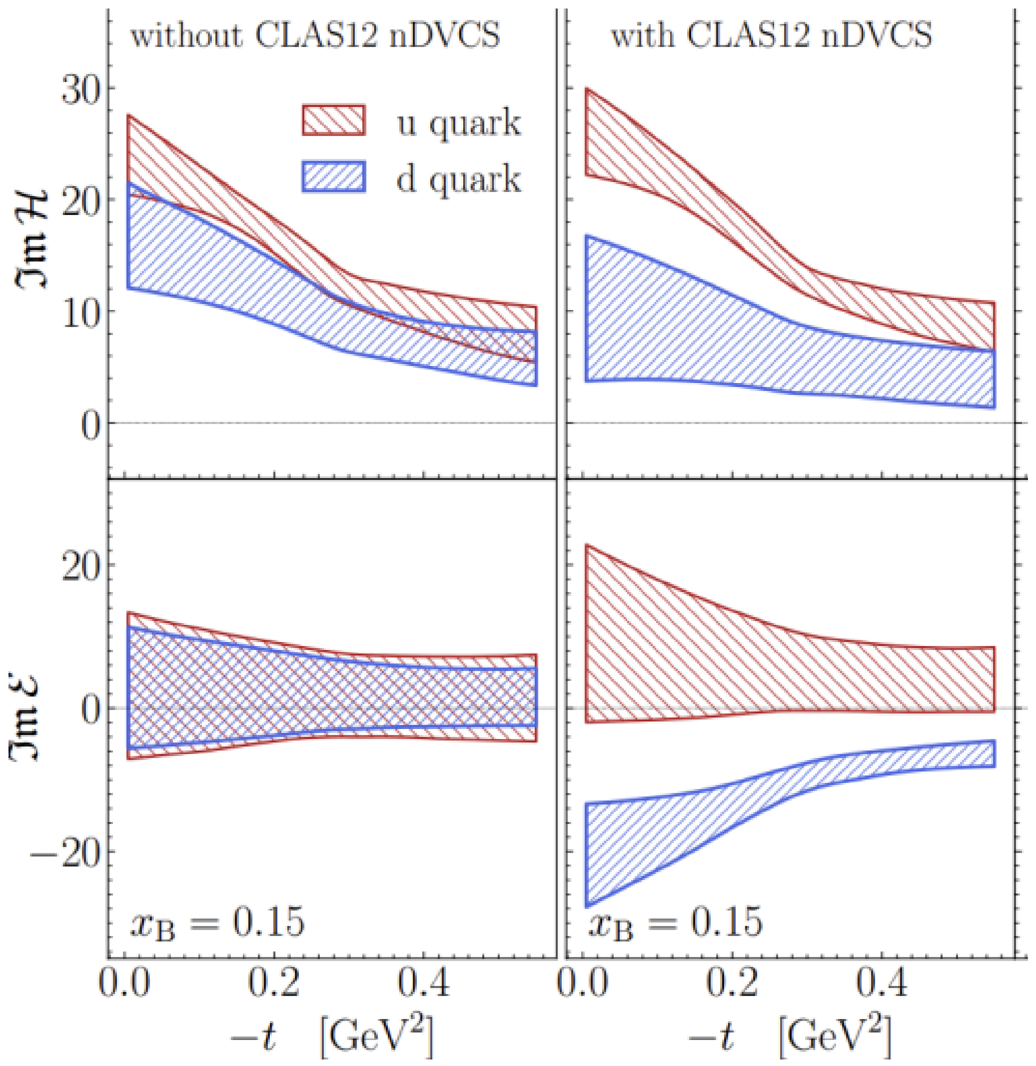
- The a_2 parameter shifts the position of the BSA maximum
- a_2 is not small compared to a_1
- For scarce statistics, a sinusoidal fit would provide misleading results
- To be published soon

BEAM SPIN ASYMMETRY: NEUTRON TARGET



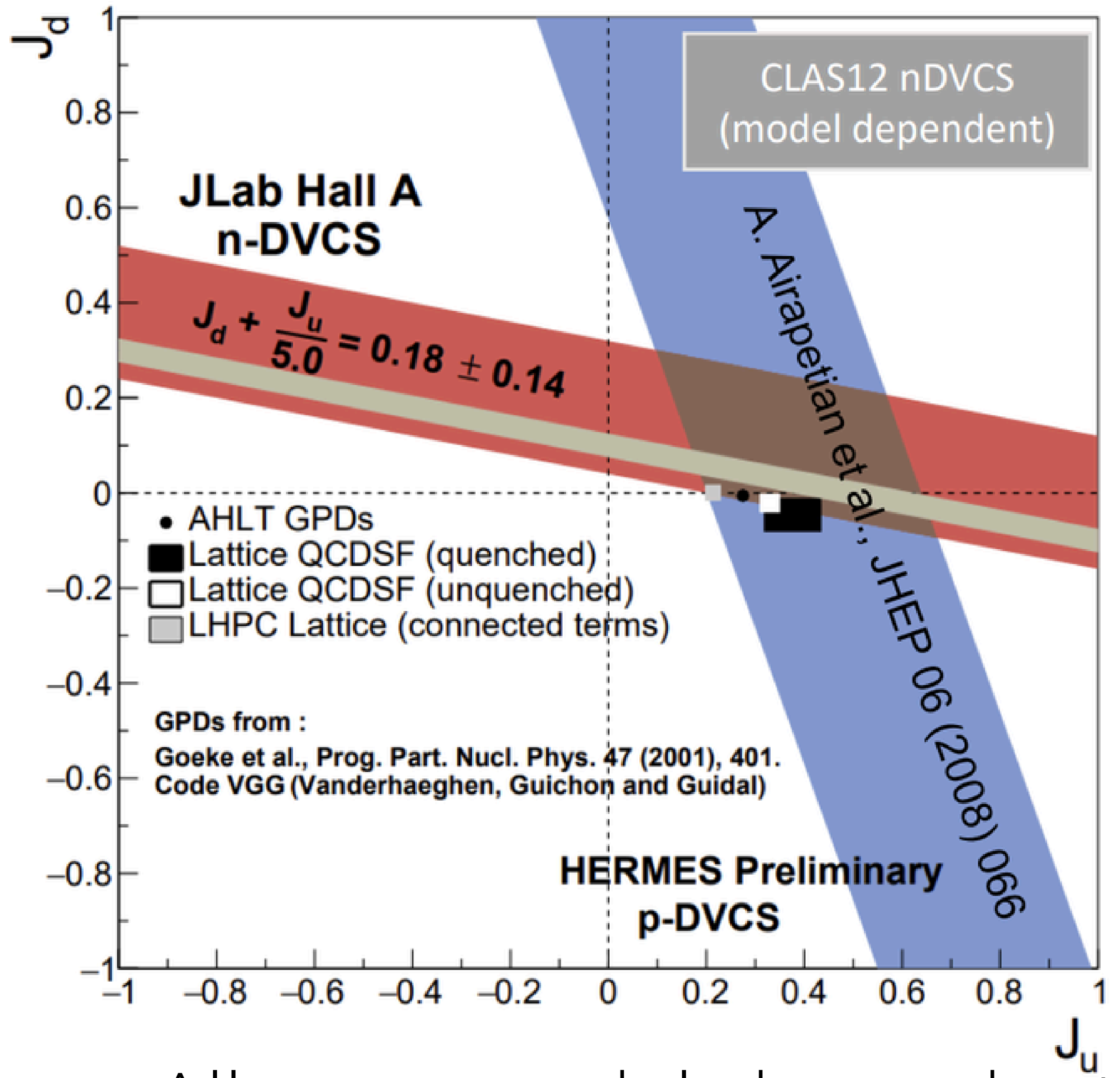
First-time measurement of nDVCS with detection of the active neutron

Phys. Rev. Lett. 133.21 (2024): 211903.



CLAS12 nDVCS data allowed a **clear quark-flavor separation** on Im[H] and Im[E]

JHEP 07, 073531 (2011); Phys. Rev. Lett. 533 125, 232005 (2020)).



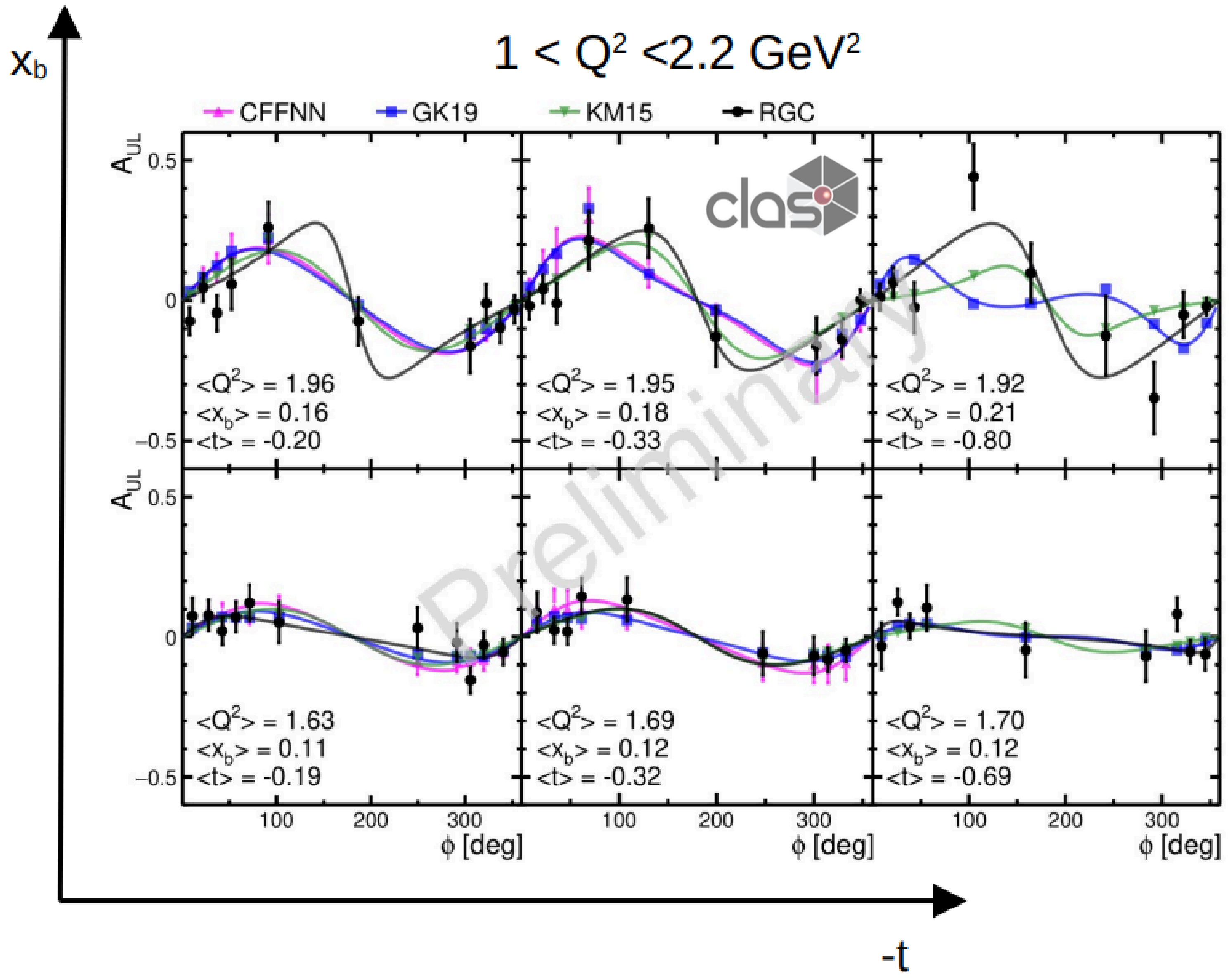
- Allows a model-dependent extraction of quarks' orbital momentum
- Compatible with limits set by the pioneering Hall A measurement and Lattice QCD predictions

LONGITUDINALLY POLARIZED PROTON TARGET

Asymmetries on the proton in NH_3

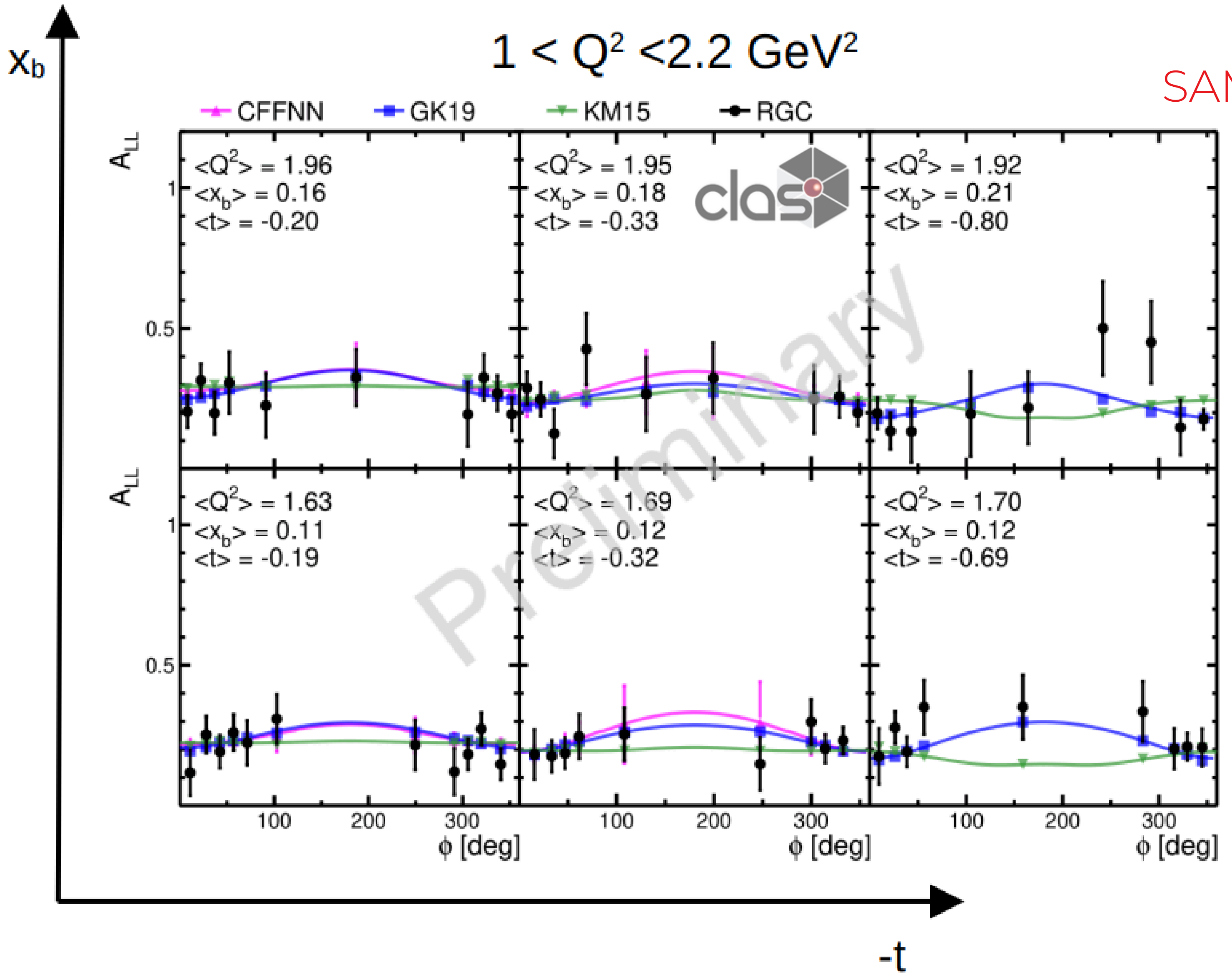
Target Spin Asymmetry

$$A_{UL} \propto \Im\mathfrak{m}\left[F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)\mathcal{H} - \xi\frac{t}{4M^2}F_2\widetilde{\mathcal{E}} + \mathcal{O}(\xi^2)\right]\sin\phi$$



Double Spin Asymmetry

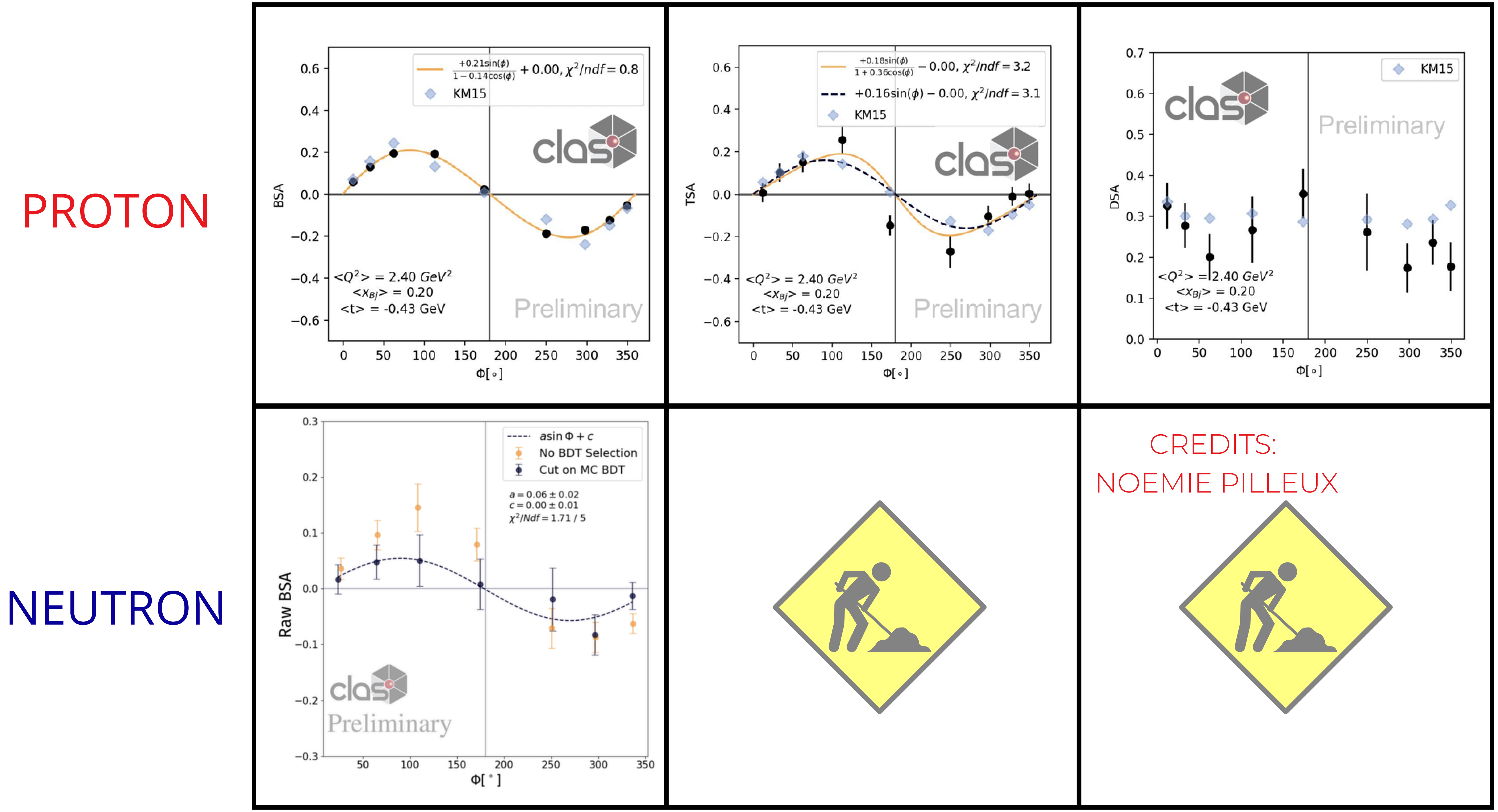
$$A_{LL} \propto \Re\mathfrak{e}\left[F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)\mathcal{H} - \xi\frac{t}{4M^2}F_2\widetilde{\mathcal{E}} + \mathcal{O}(\xi^2)\right]\cos\phi$$



CREDITS:
SAMY POLCHER

- Preliminary measurements are consistent with model predictions
- High impact expected on the extraction of the proton $\tilde{H}$

LONGITUDINALLY POLARIZED ND_3 TARGET



- Integrated asymmetries show compatibility with KM15 model predictions
- Work is underway towards nDVCS measurements
- High impact expected on
  - H and $\tilde{H}$ extractions
  - Quark-flavor separation

PHYSICS PROGRAM

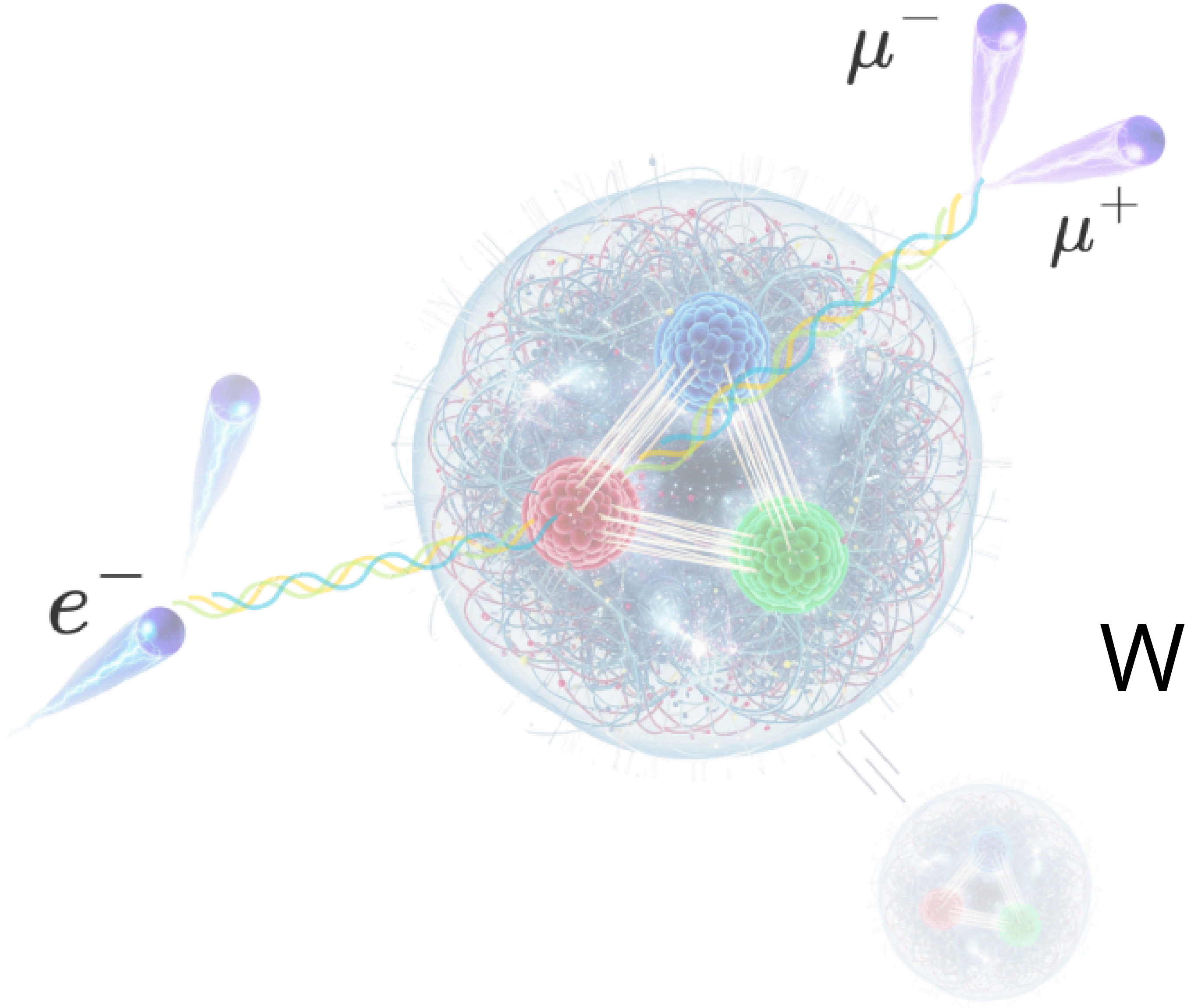
Today we focused on DVCS results, but GPD studies extend further

- **Published results:**
  - pDVCS BSA: Phys. Rev. Lett. 130 (21) 211902 (2023)
  - nDVCS BSA: Phys. Rev. Lett. 133, 211903 (2024)
  - TCS Phys. Rev. Lett. 127, 262501 (2021)
  - DVπ^0P BSA: Phys. Lett. B 849 (2024) 138459 (Chiral-odd GPDs)
  - J/ψ production off proton: Phys.Rev.C 113 (2026) 6, 065203 (gluon GPDs)

- **Results to be published soon:**
  - pDVCS cross section (S. Lee)
  - pDVCS BSA from deuterium (M. Hoballah)
  - pDVCS BSA at small -t (J. S. Alvarado)
  - J/ψ production from deuterium (R. Tyson) (gluon GPDs)

- **Ongoing analyzes**
  - pDVCS cross section at small -t (J. S. Alvarado)
  - nDVCS cross section (L. Xu)
  - Longitudinal target: BSA TSA (proton) and BSA (neutron) ND3 (N. Pilleux)
  - Longitudinal target: BSA TSA DSA (proton) NH3 (S. Polcher)
  - π^0 cross section (I. Korover) (Chiral-odd GPDs)
  - Φ electroproduction off proton (M. Ronayette)
  - Φ electroproduction cross section (B. Singh)
  - Sullivan DVCS: BSA (E. Ferrand) (Pion GPDs)
  - DVCS at multiple beam energies (Yijie Wang)
  - $\pi^+\pi^-$ BSA (T. Hayward)
  - etc.

Not a complete list



What comes next?

μCLAS

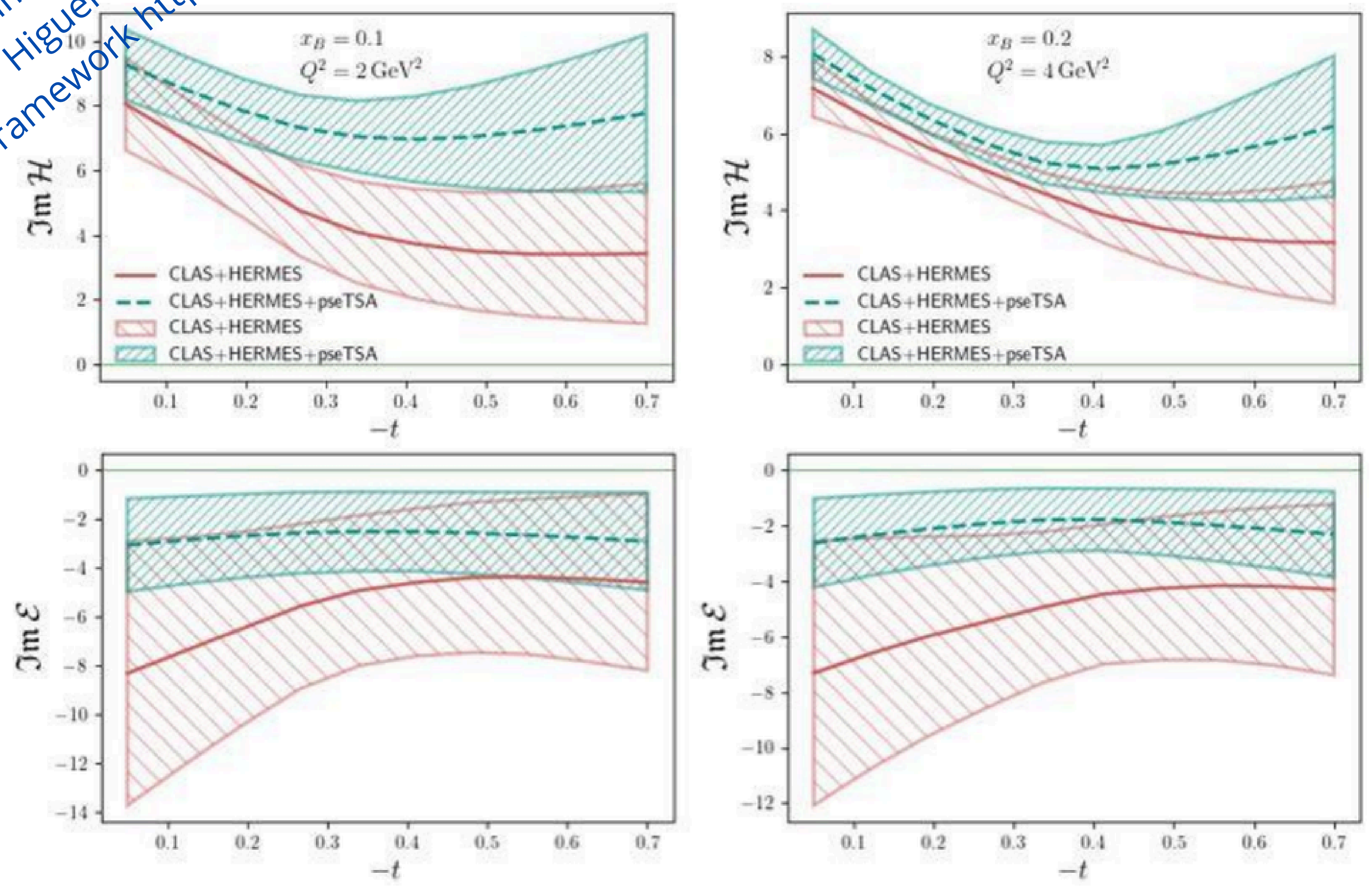
CEBAF Large Acceptance Spectrometer

1. Transversely polarized proton target

$$A_{UT} \propto \mathfrak{Im}\left[\frac{t}{4M^2}(F_2\mathcal{H} + F_1\mathcal{E}) + \mathcal{O}(\xi^2)\right] \cos\phi \sin(\Phi - \phi)$$

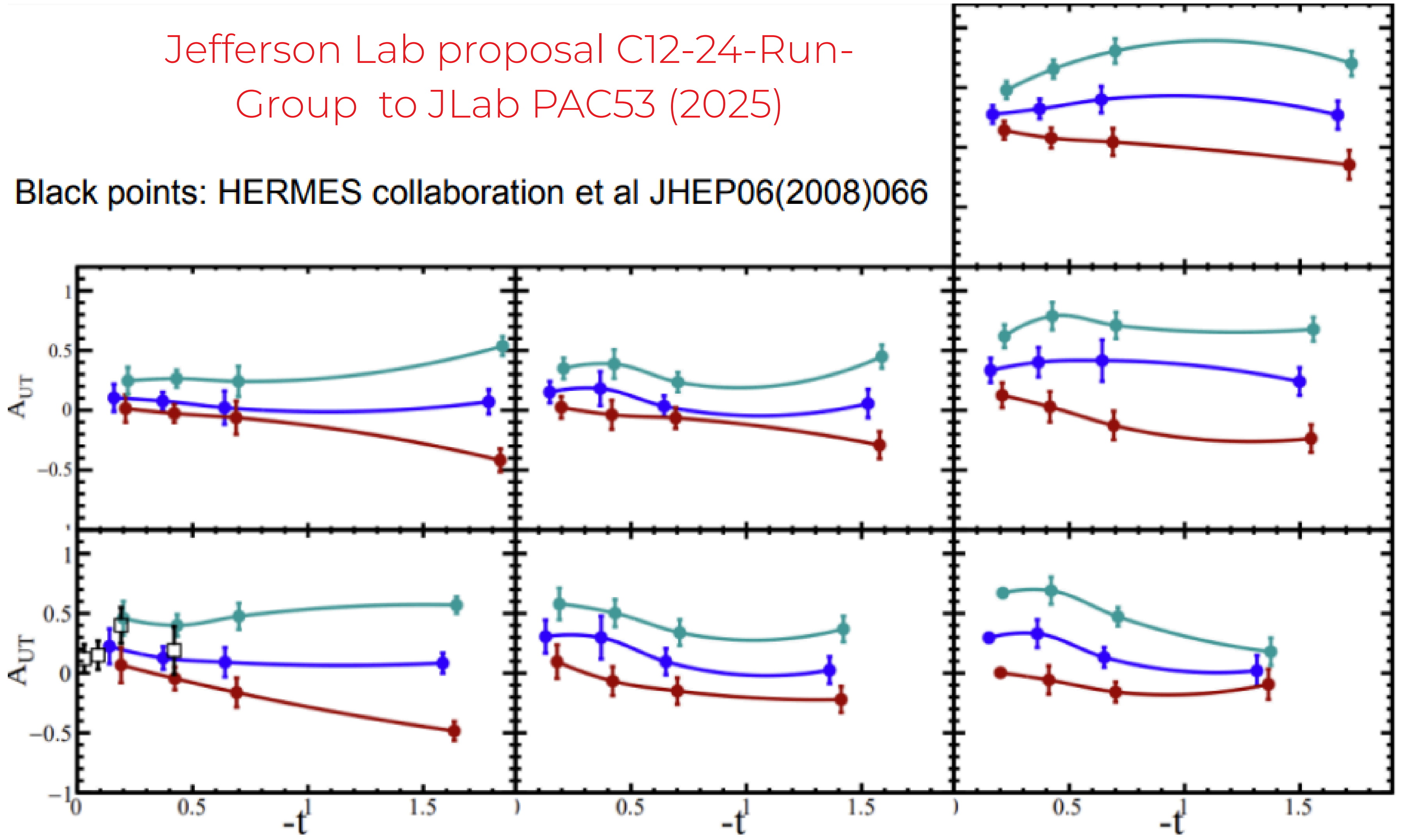
Preliminary analysis by Melany Higuera with the GEPARD framework https://gepard.phy.hr/

Transversely polarized proton target experiments grant access to GPD E



Jefferson Lab proposal C12-24-Run-Group to JLab PAC53 (2025)

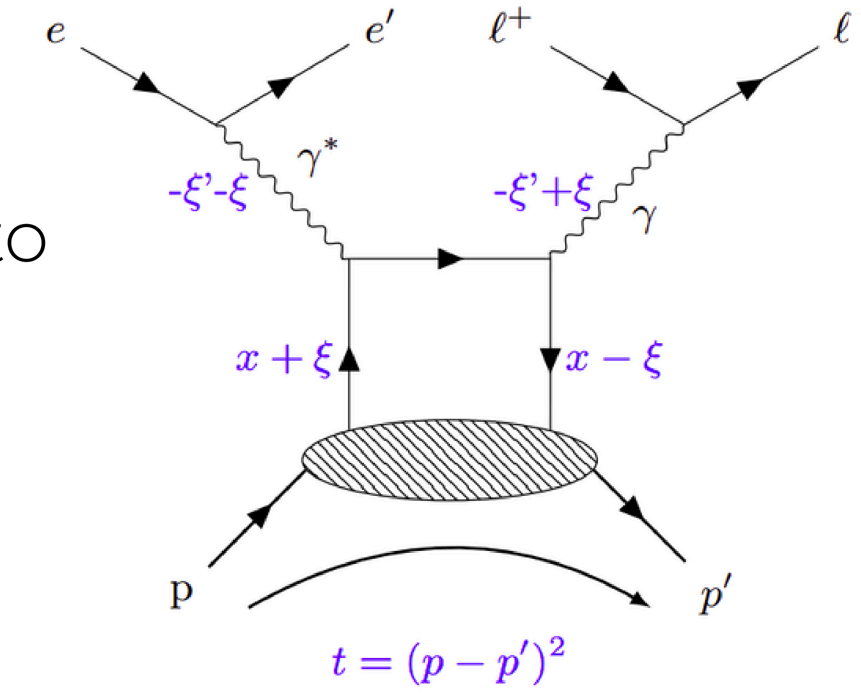
Black points: HERMES collaboration et al JHEP06(2008)066



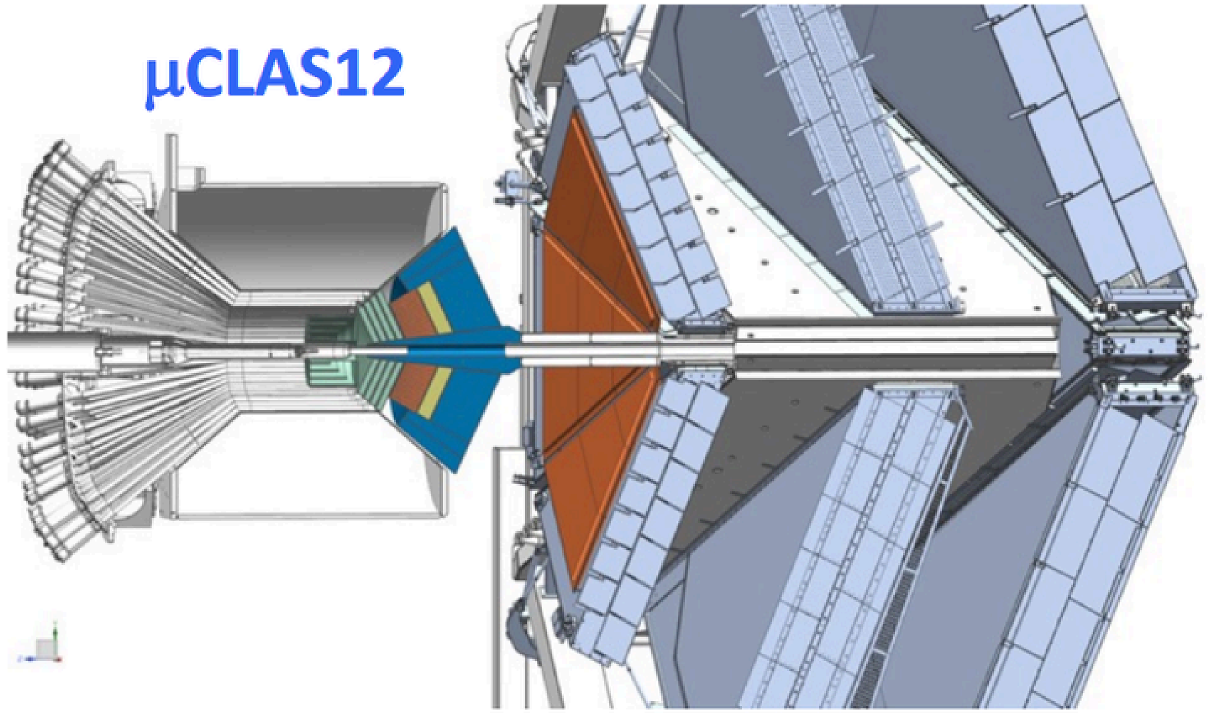
- Currently, E is poorly constrained by experimental data
- The experiment proposal was approved by the JLab Program Advisory Committee
  - Foreseen to run in ~2030
- High impact on the extraction of Im[E] is expected

2. The Double DVCS reaction

Compared to DVCS, the DDVCS cross-section
- is about 1000 times smaller
- has two extra degrees of freedom
- requires the muon-decay channel to distinghish the scattered electron



Upgraded CLAS12 spectrometer at Hall B

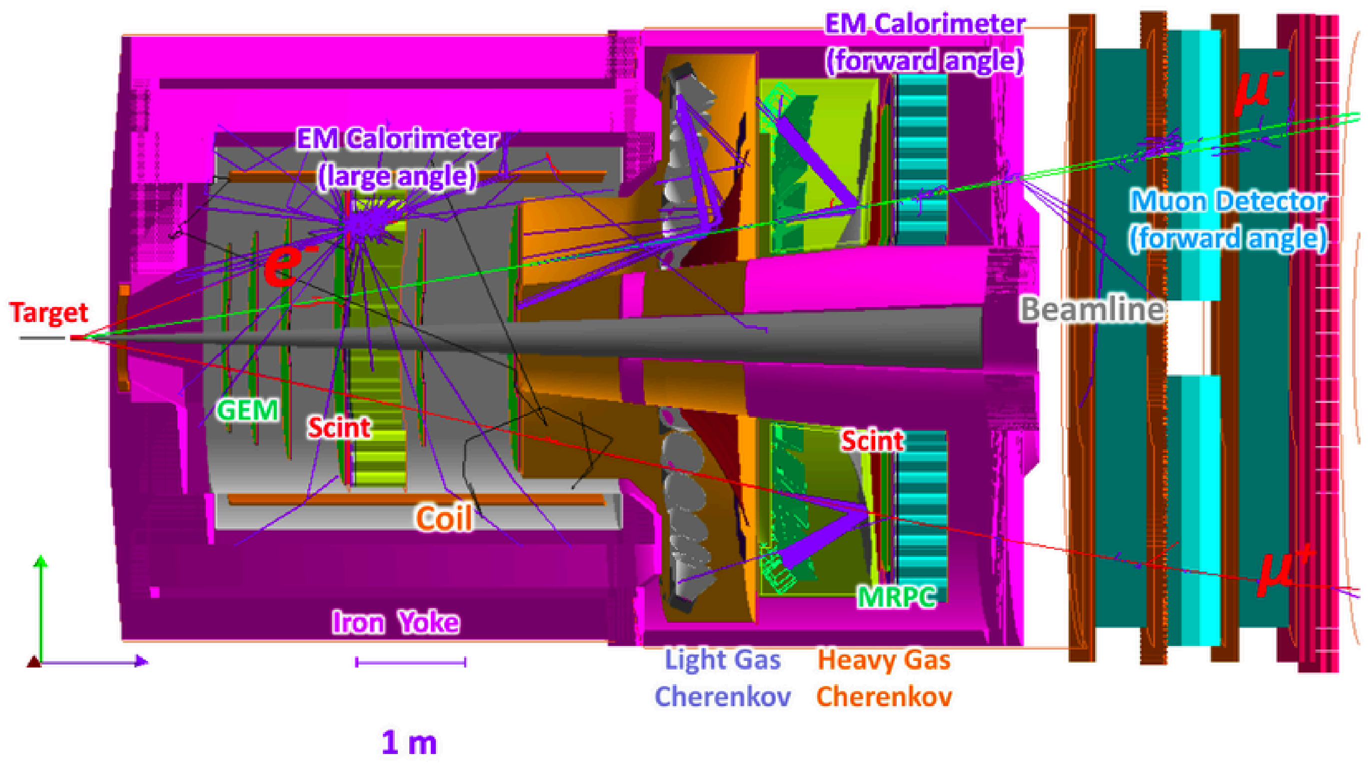


- DDVCS detection will rely on the μCLAS12 (Hall B) and SoLIDμ (Hall A) spectrometers
  - Both foresee **muon detection** capabilities and

$$\mathcal{L} = 10^{37}\text{cm}^{-2}\text{s}^{-1}$$

Studying the feasibility of this reaction at JLab was another contribution during my PhD

SoLID spectrometer at Hall A

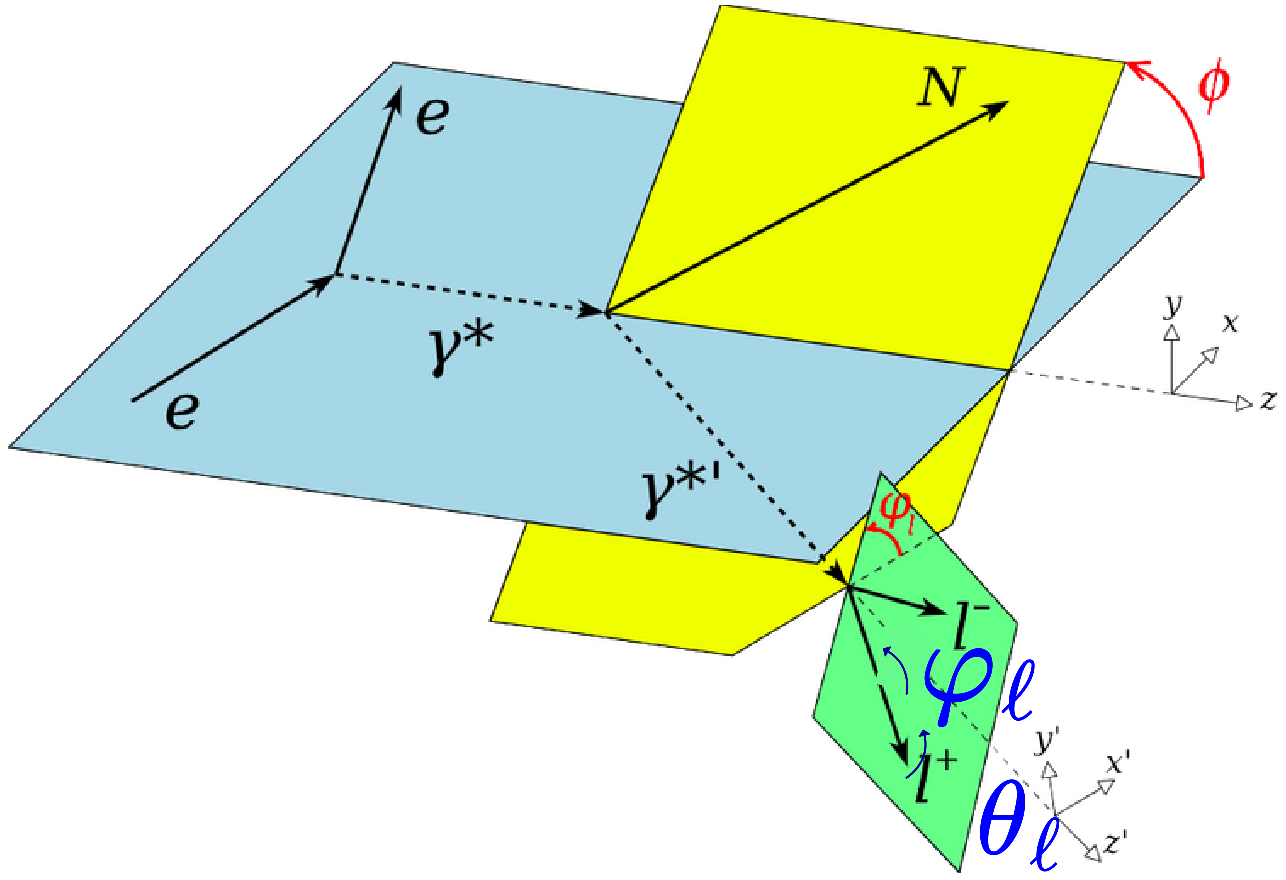


2. The Double DVCS reaction

We integrate two degrees of freedom to obtain measurable signals

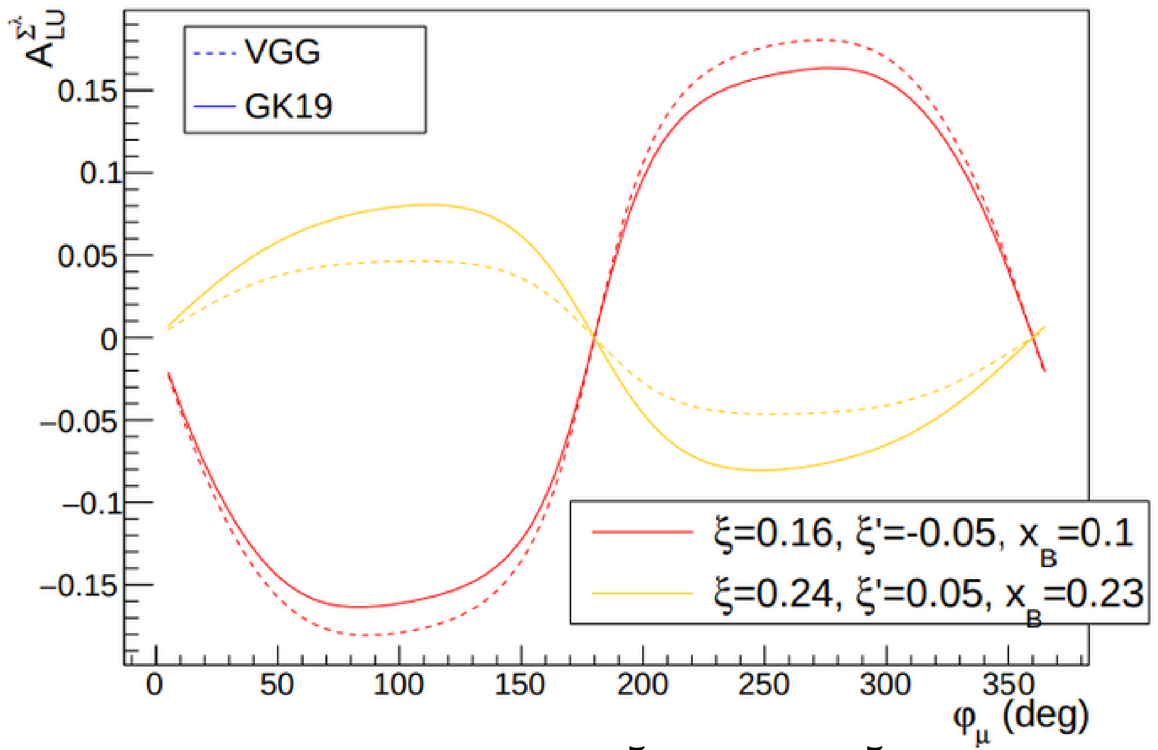
$$d^5\Sigma^\lambda(\varphi_\mu) \equiv \frac{d^5\sigma^\lambda(\varphi_\mu)}{dx_B\, dy\, dt\, dQ'^2\, d\varphi_\mu} = \int_0^{2\pi} d\phi \int_{\pi/2-\theta_0}^{\pi/2+\theta_0} d\theta_\mu \sin(\theta_\mu) \frac{d^7\sigma^\lambda(\phi,\theta_\mu,\phi_\mu)}{dx_B\, dy\, dt\, d\phi\, dQ'^2\, d\Omega_\mu}$$

θ_l and φ_l are the muon decay angles in the $\mu^+\mu^-$ center-of-mass frame



A. Cammsonne et al., Jefferson Lab proposal PR12-25-010 to PAC53 (2025)

We define a BSA from the 5-fold cross section

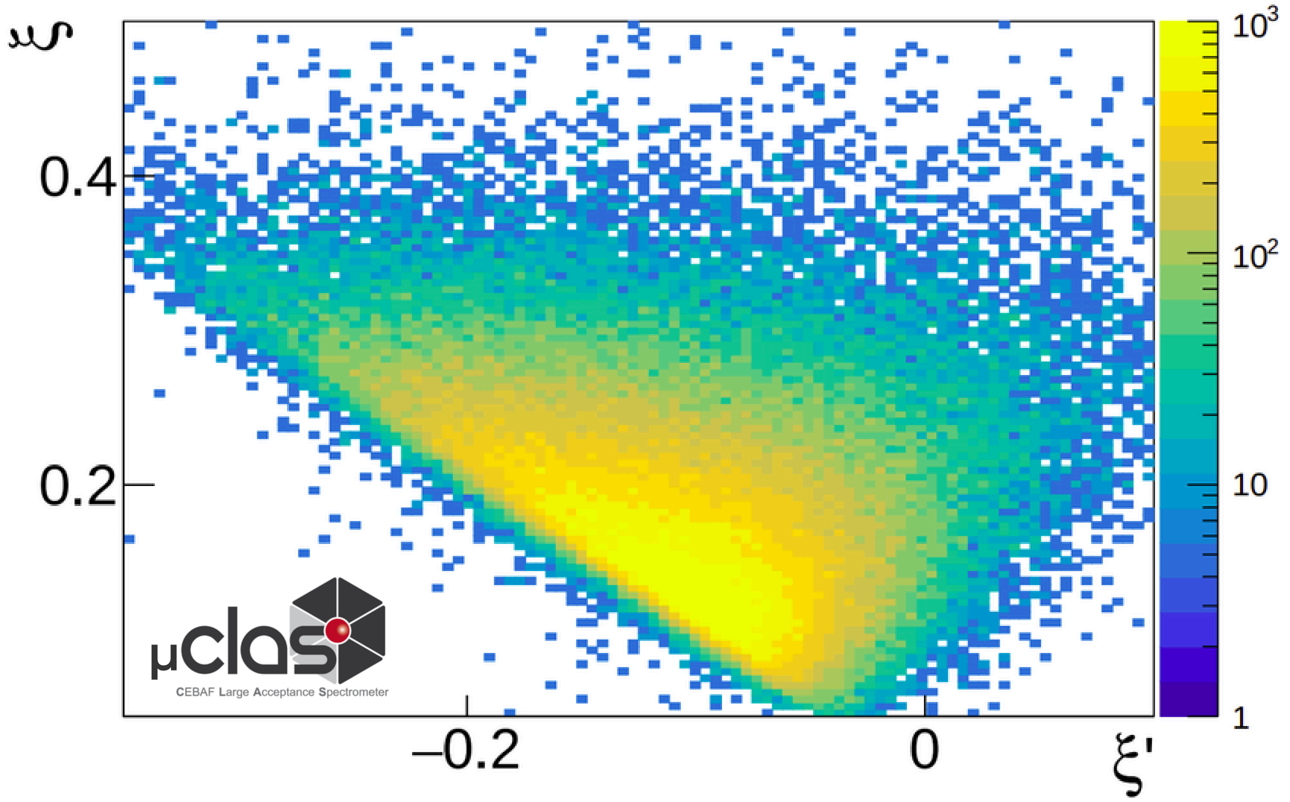


$$A_{LU}(\varphi_\ell) \equiv \frac{d^5\Sigma^+ - d^5\Sigma^-}{d^5\Sigma^+ + d^5\Sigma^-}$$

$$A_{LU} \propto \mathfrak{Im}[F_1\mathcal{H} - kF_2\mathcal{E} + \xi'(F_1+F_2)\widetilde{\mathcal{H}}]$$

J.S. Alvarado et al. Phys. Rev. C 111, 065205 (2025)

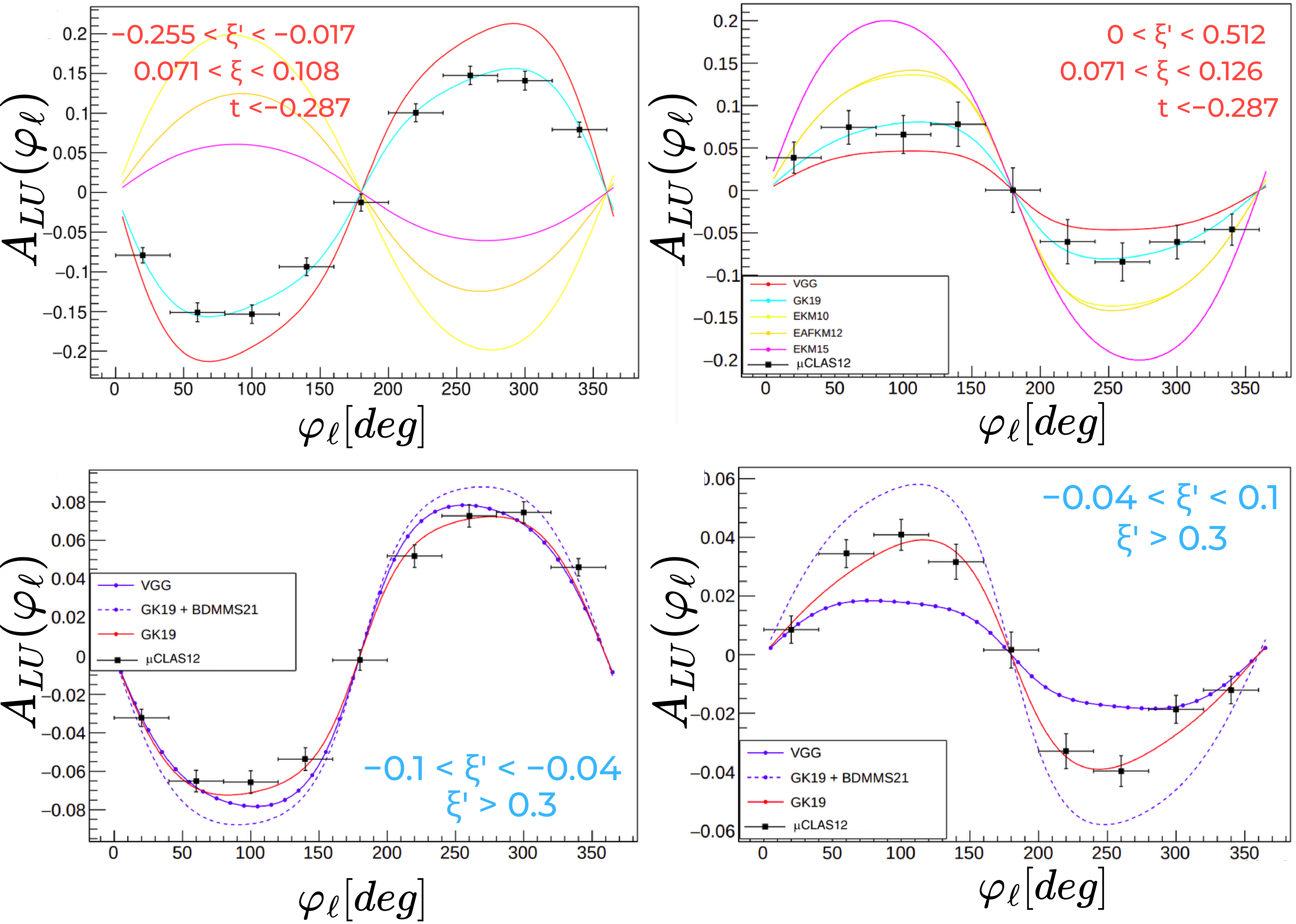
µCLAS12 phase space coverage



This definition leads to large asymmetries in the ξ'<0 region

S. Stepanyan et al., Jefferson Lab proposal PR12-25-001 to PAC53 (2025)

2. The Double DVCS reaction: BSA projections



The DDVCS program will provide

- The first-time observation of the BSA sign change
- Shadow GPD sensitive measurements
  - GPDs of null CFF in the DVCS limit

In particular,

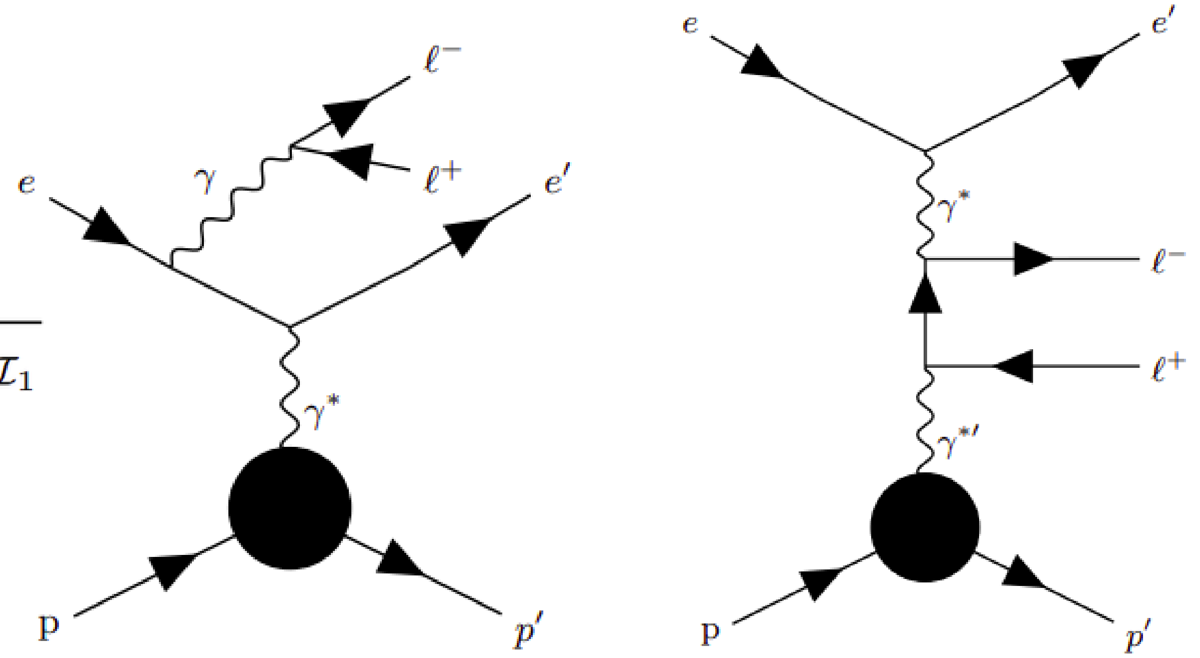
- Data will provide 4D exploratory measurements
  - Enables meaningful CFF extraction
- opens the door for a full 5D exploration at L >10^{38} $cm^{-2}s^{-1}$

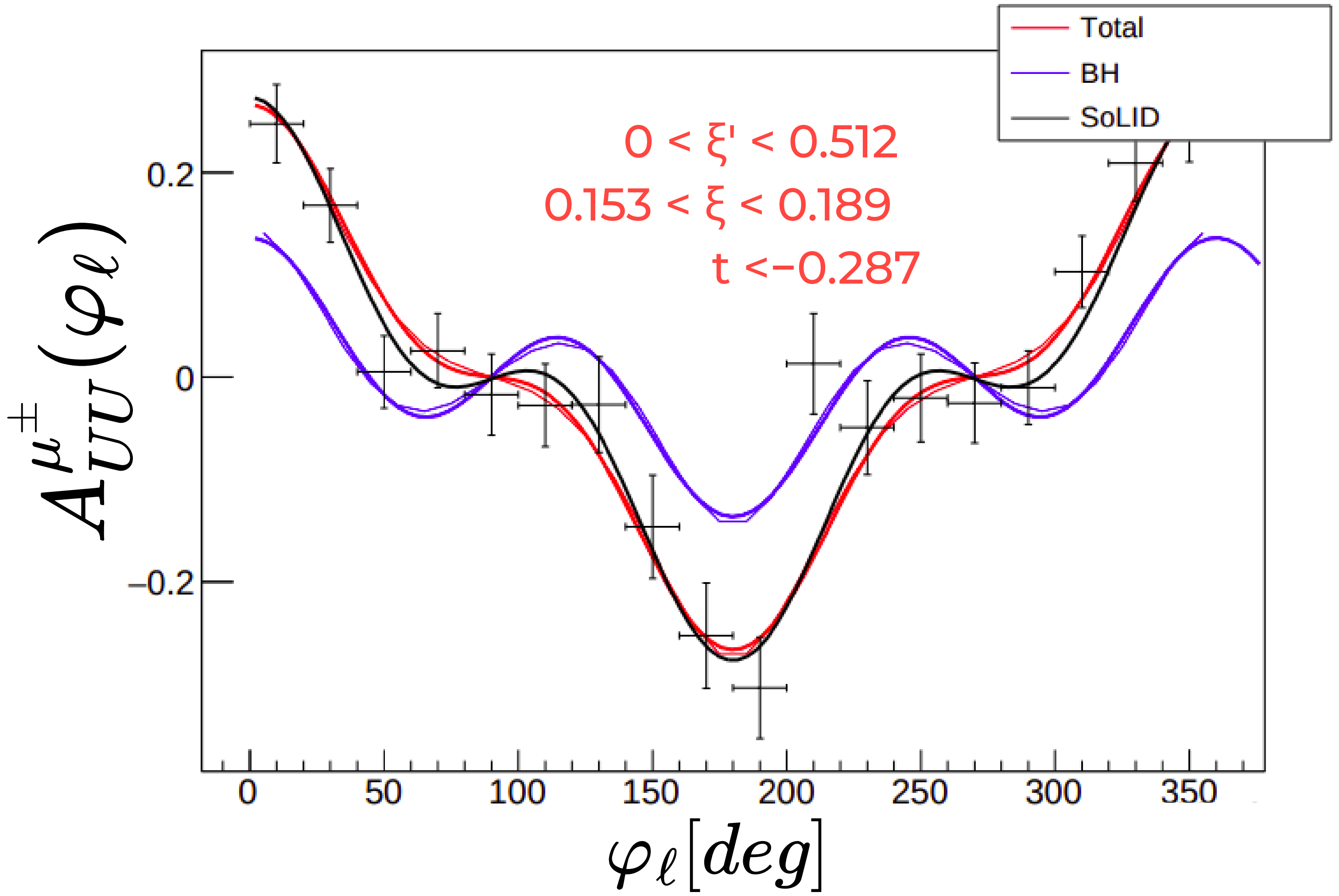
2. The Double DVCS reaction: μ-Charge asymmetry

I studied an angular asymmetry that accesses the **real part of CFFs,** but it is **diluted with a Bethe-Heitler contribution**

$$A_{UU}^{\mu^\pm}(\varphi_\mu) = \frac{d^5\Sigma_{UU}(\varphi_{\mu^-}) - d^5\Sigma_{UU}(\varphi_{\mu^+})}{d^5\Sigma_{UU}(\varphi_{\mu^-}) + d^5\Sigma_{UU}(\varphi_{\mu^+})} \qquad A_{UU}^{\mu^\pm}(\varphi_\mu) = \frac{d^5\Sigma_{BH_{12}} + d^5\Sigma_{\mathcal{I}_2}}{d^5\Sigma_{BH_1} + d^5\Sigma_{BH_2} + d^5\Sigma_{DDVCS} + d^5\Sigma_{\mathcal{I}_1}}$$

$$d^5\Sigma_{\mathcal{I}_2} \propto \mathfrak{Re}\left[\frac{\xi'}{\xi}\left(F_1\mathcal{H} - \frac{t}{4M_N^2}F_2\mathcal{E}\right) + \xi(F_1+F_2)\tilde{\mathcal{H}}\right]$$





A. Cammsonne et al., Jefferson Lab proposal PR12-25-010 to PAC53 (2025)

- At LO and leading twist, it features cos(φ$_l$) and cos(3φ$_l$) harmonics
- Model predictions point to large amplitudes

It accesses the same CFF combination of a Beam Charge Asymmetry

Control of systematic errors of e$^+$/e$^-$ beam configurations

Dominance of BH contribution

They complement each other

A publication is being prepared

SUMMARY

Obs.	Proton	Neutron
A_{LU}	✔ 90%	✔
A_{UL}	🚧	🚧
A_{LL}	🚧	🚧
A_{UT}	🕒	
σ_{UU}	90%	🚧

- BSA measurements have been published
  - Proton measurements at small -t will be published soon
- Ongoing TSA and DSA analyses
- Proton cross-section results will be published soon
  - Ongoing neutron cross-section analysis
- Transverse target measurements are planned for the coming years

- In addition, first-time DDVCS measurements will be performed with the upgraded CLAS12 detector, allowing unique off-diagonal access to GPDs
- The coming Transverse-Target experiment will provide unique constraints on the so weakly constrained E^p

SUMMARY

- Neutron cross-section measurements have been published.
  - pDVCS measurements will be published soon
- BSA measurements with proton and neutron targets are available.
  - It provides major constraints on H^p and E^n and has improved our knowledge of quark GPDs.
  - BSA analysis without proton detection enables small -t measurements and boosts statistics.
    - High impact expected on the extraction of the D-term
    - Results to be published soon.
  - Fits to the proton-BSA
    - Results show a general agreement with the KM15 model predictions
    - Strong constraints on the imaginary part of CFFs are foreseen.
      - Constraints on the real part are also expected.
    - Consistent picture with the measurements of previous experiments
- Longitudinally polarized target measurements will provide unique constraints on $\tilde{H}^p$ and H^n

THANKS