# Phenomenology of Double DVCS

BY:
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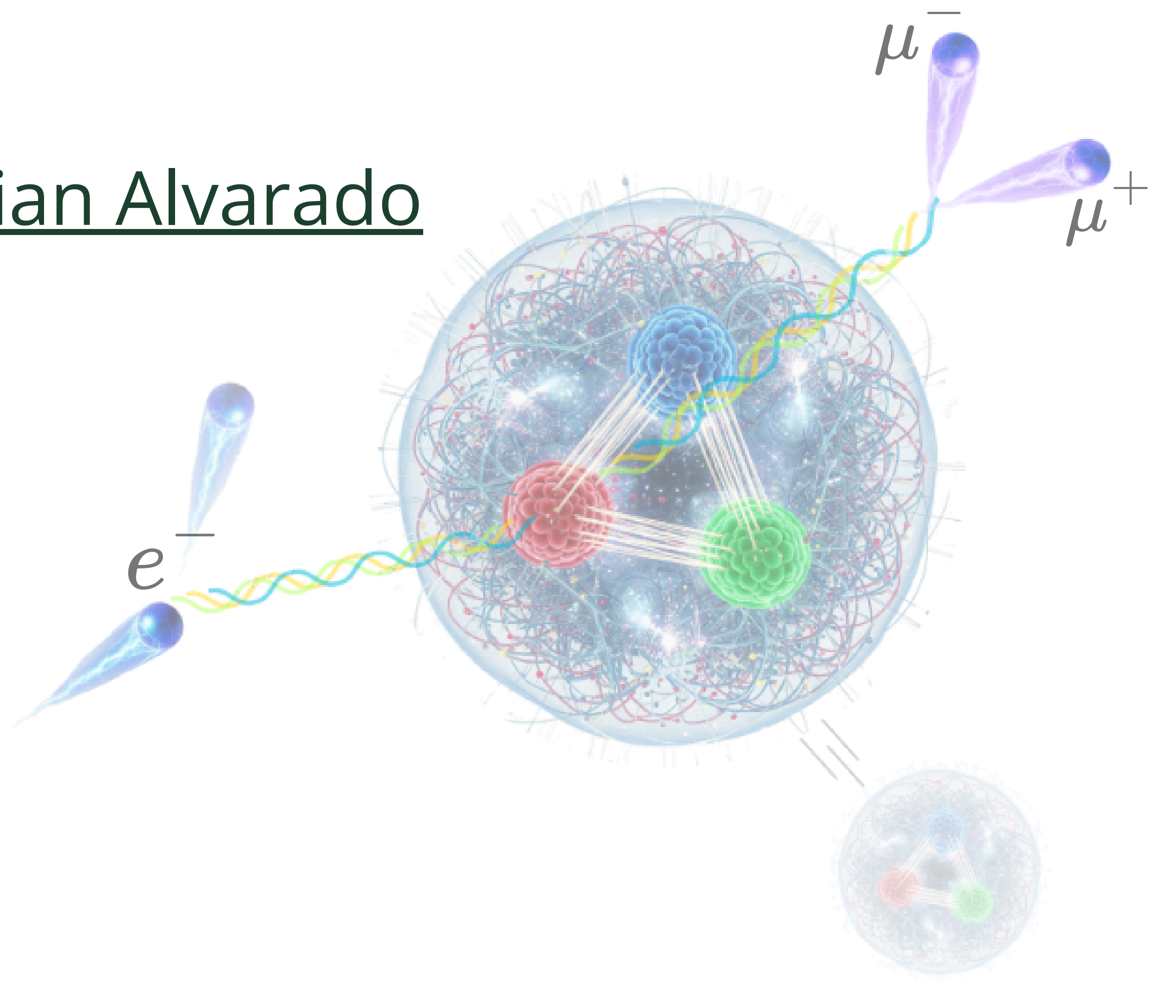
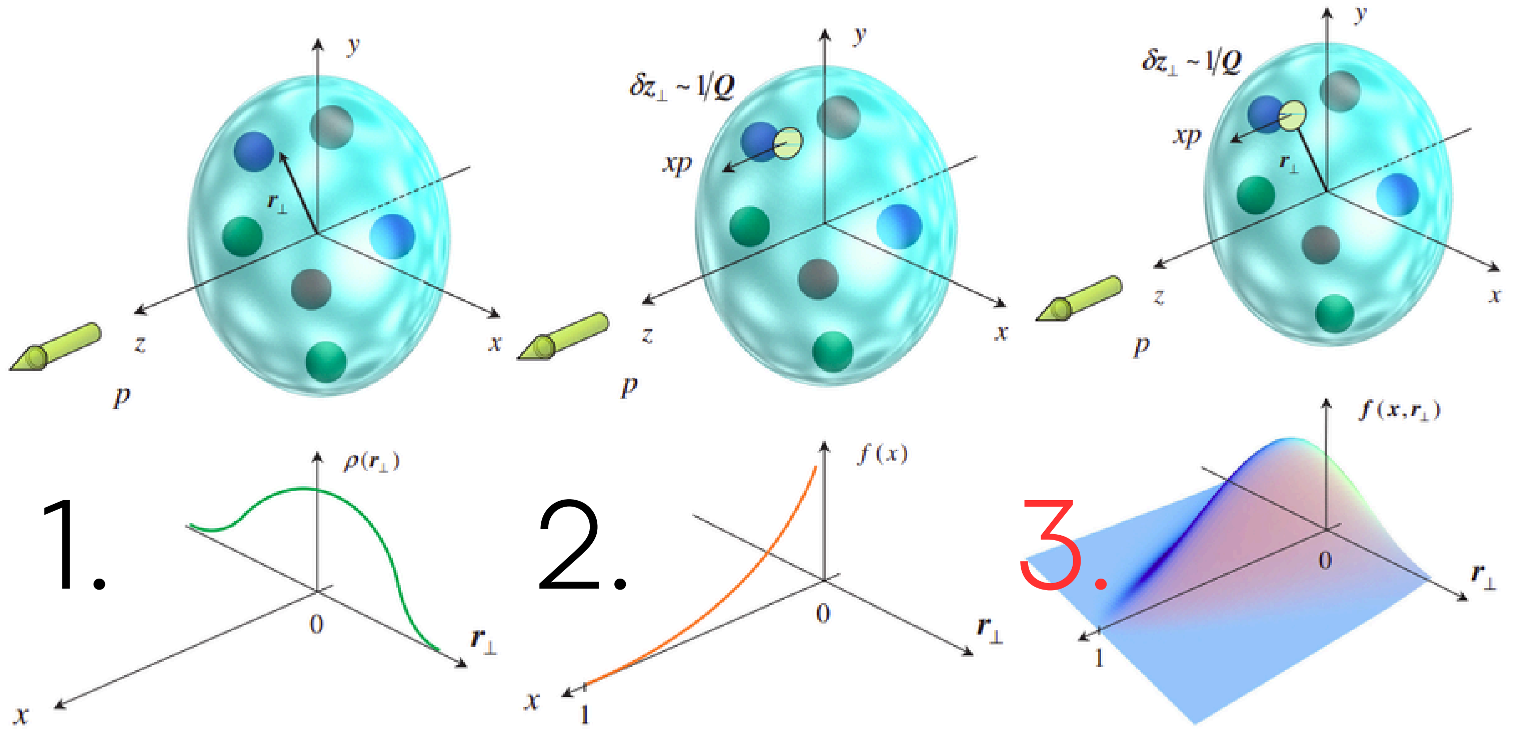



µCLAS12 Experiment workshop
09/03/2026

# Generalized Parton Distributions (GPDs)

At low energy QCD, we describe the nucleon structure in terms of structure functions including:

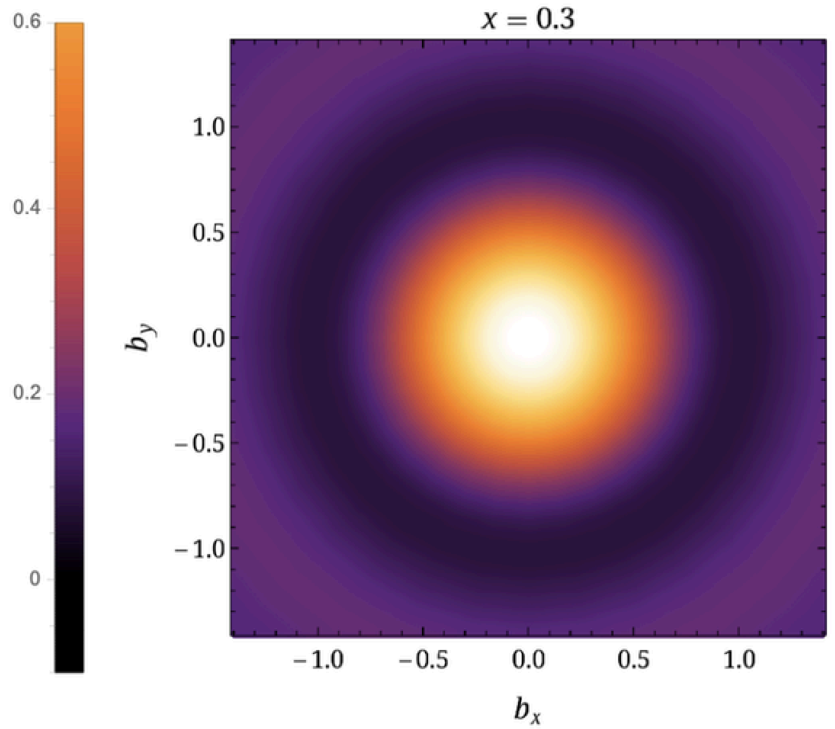
1. Form Factors describe transverse position of partons
2. Parton Distribution Functions describe longitudinal momentum distributions
3. Generalized Parton Distributions (GPDs) correlates transverse position and longitudinal momentum distributions




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.**

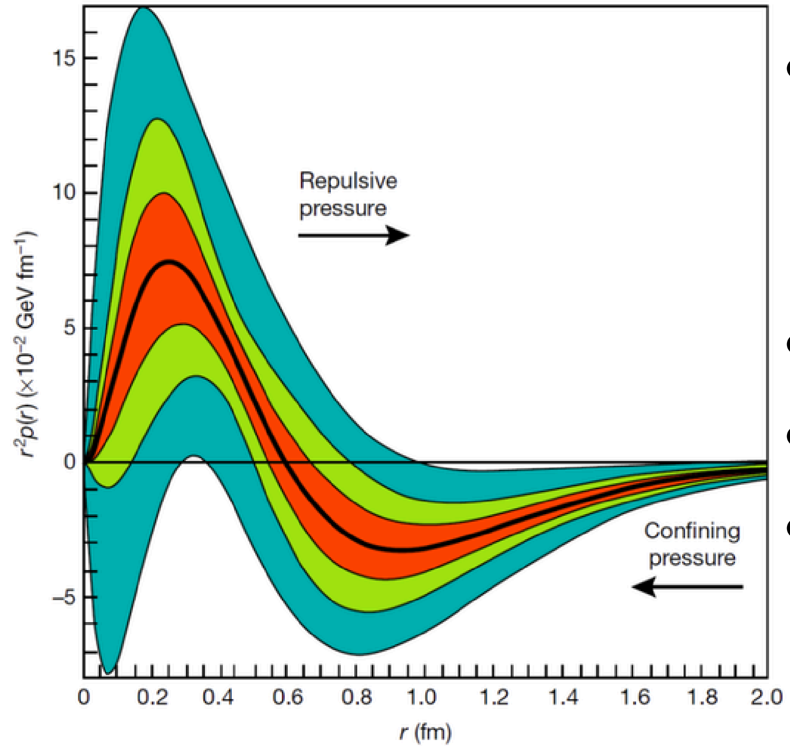
X. Ji, Phy.Rev.Lett.78,610(1997)

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

- Quark contribution is not the main contribution →Spin Crisis
- Quark's orbital angular momentum is accessed through GPDs
- Gluon contribution

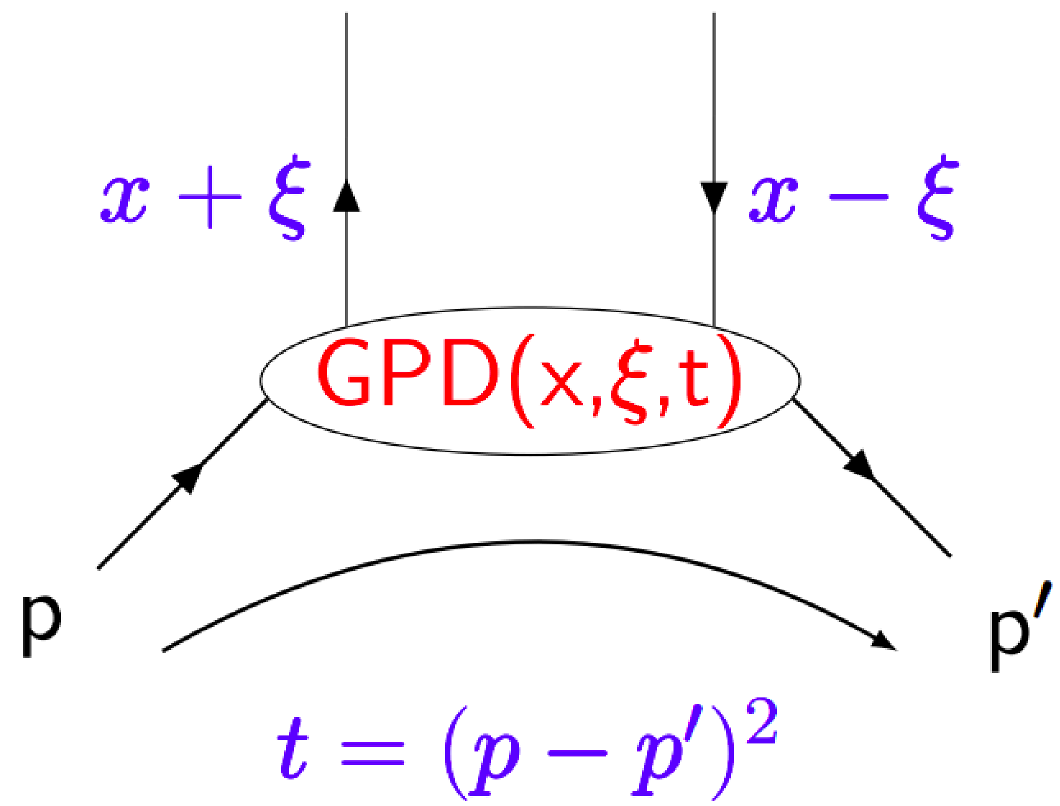
**Access to Gravitational Form Factors.**

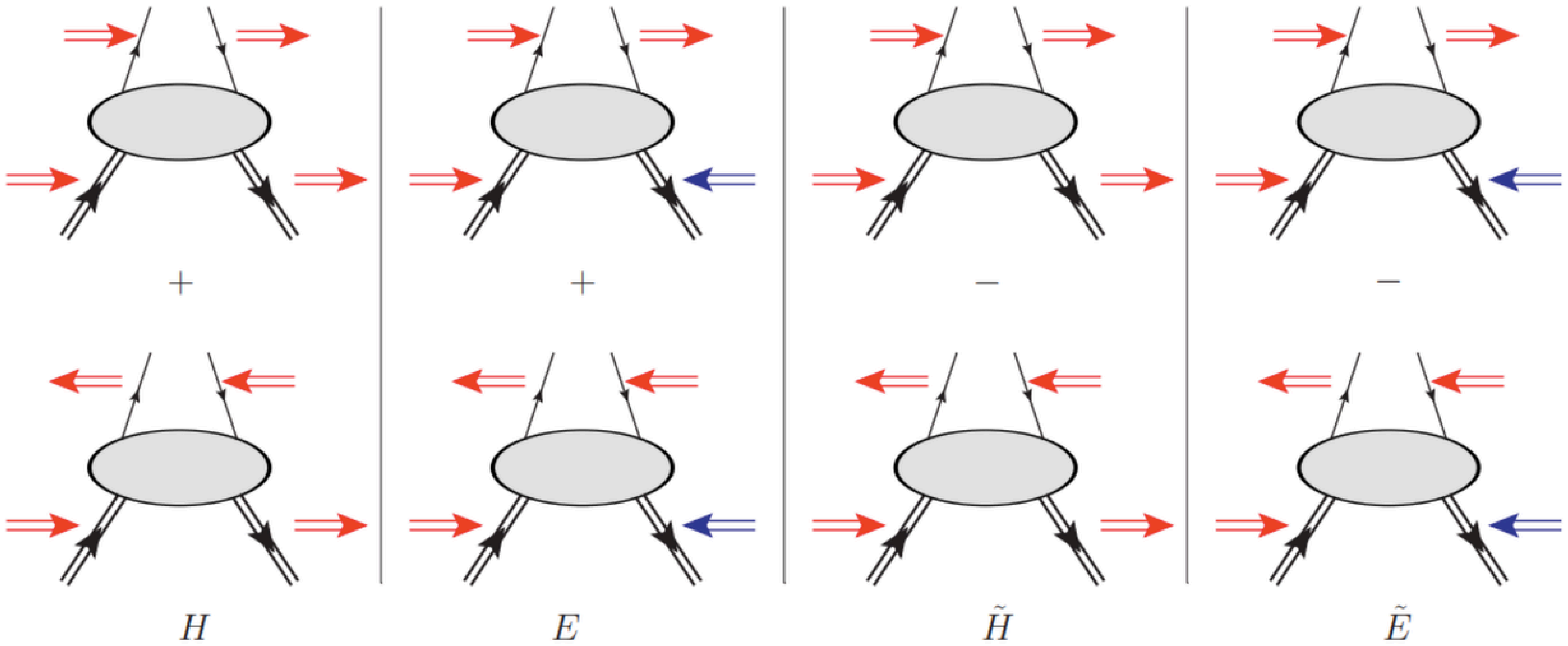
V. D. Burkert *et al*. Nature 557.7705 (2018): 396




- Mass/Energy distribution inside the nucleon
- Forces distribution.
- Nucleon mass radius
- Shear forces and pressure distribution

# Generalized Parton Distributions (GPDs)




- x average **momentum carried by the interacting parton**
- t is the nucleon **momentum transfer**
- ξ **skewness** variable

For a spin ½ particle, there are four chiral even GPDs

$$F = H, E, \widetilde{H}, \widetilde{E}(x,\xi,t)$$

Each represents a different parton helicity configuration

**GPDs enter the cross section of deep exclusive processes through Compton Form Factors (CFF)**

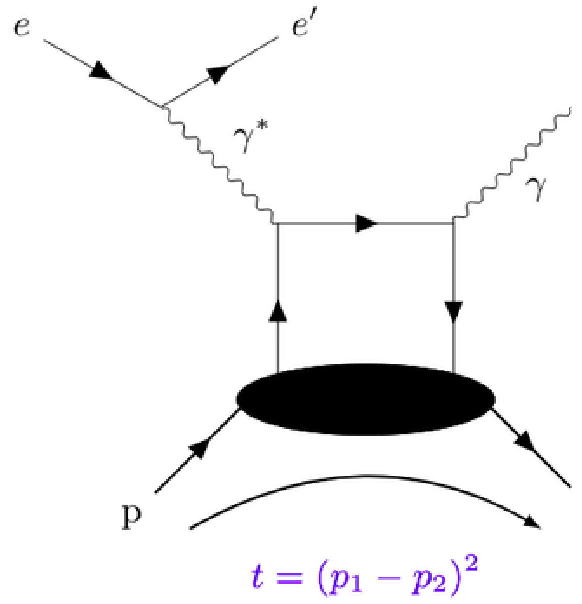
$$\mathcal{F}(x,\xi,t) = -\mathcal{P}\int_0^1 dx'\, F^+(x',\xi,t)\left[\frac{1}{x'-x} \pm \frac{1}{x'+x}\right] + i\pi F^+(x,\xi,t),$$

$$F^+(x,\xi,t) = F(x,\xi,t) \pm F(-x,\xi,t)$$

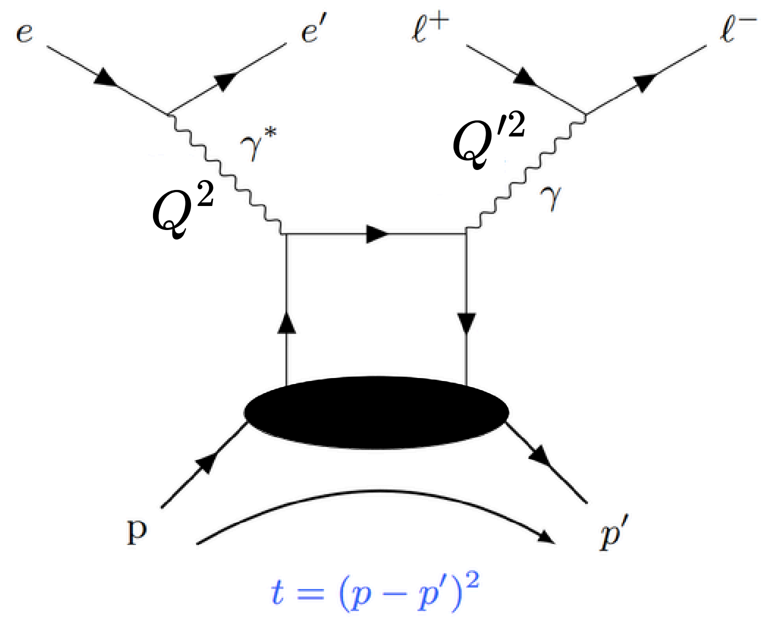
# The Double DVCS reaction

See Jakub's talk

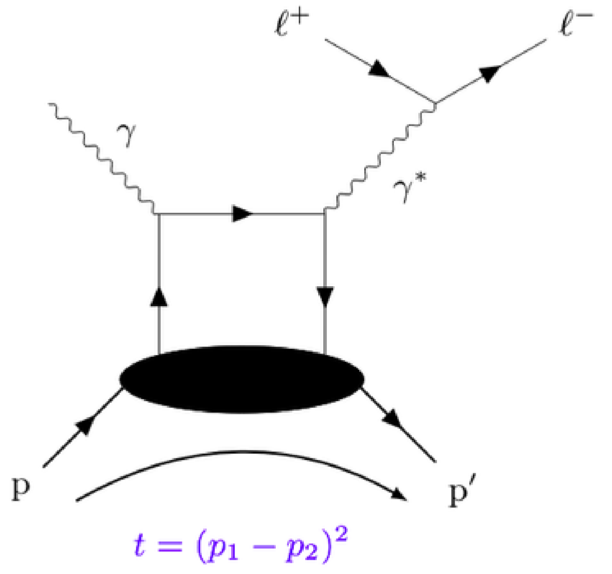
Golden channels to study GPDs are




Deeply Virtual Compton Scattering (DVCS)




Double DVCS (DDVCS)

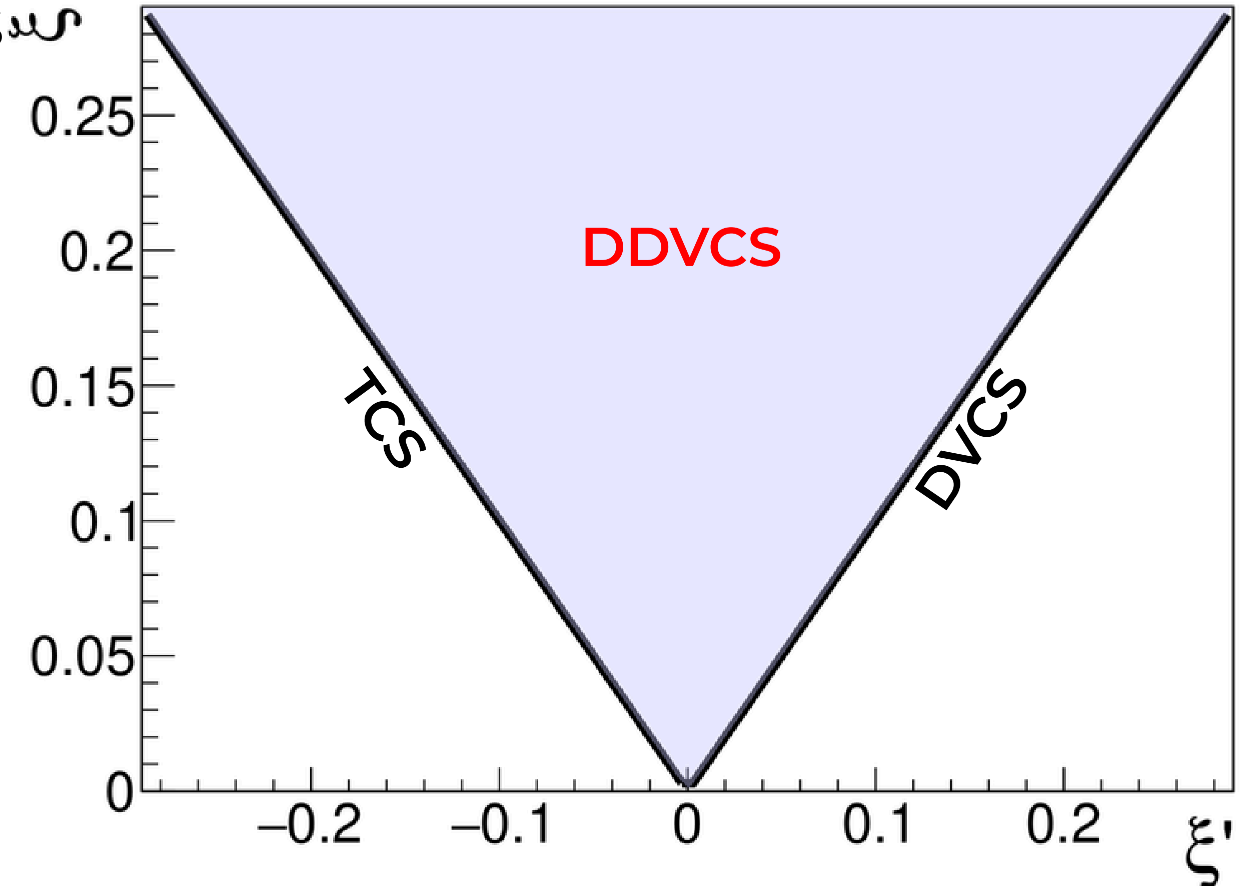



Timelike Compton Scattering (TCS)

- Double DVCS (DDVCS) accesses the **|ξ'|<ξ** region
- Generalizes DVCS and TCS
  - DVCS → **ξ'=ξ**
  - TCS → **ξ'=-ξ**

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

GPD(ξ',ξ,t) Phase Space



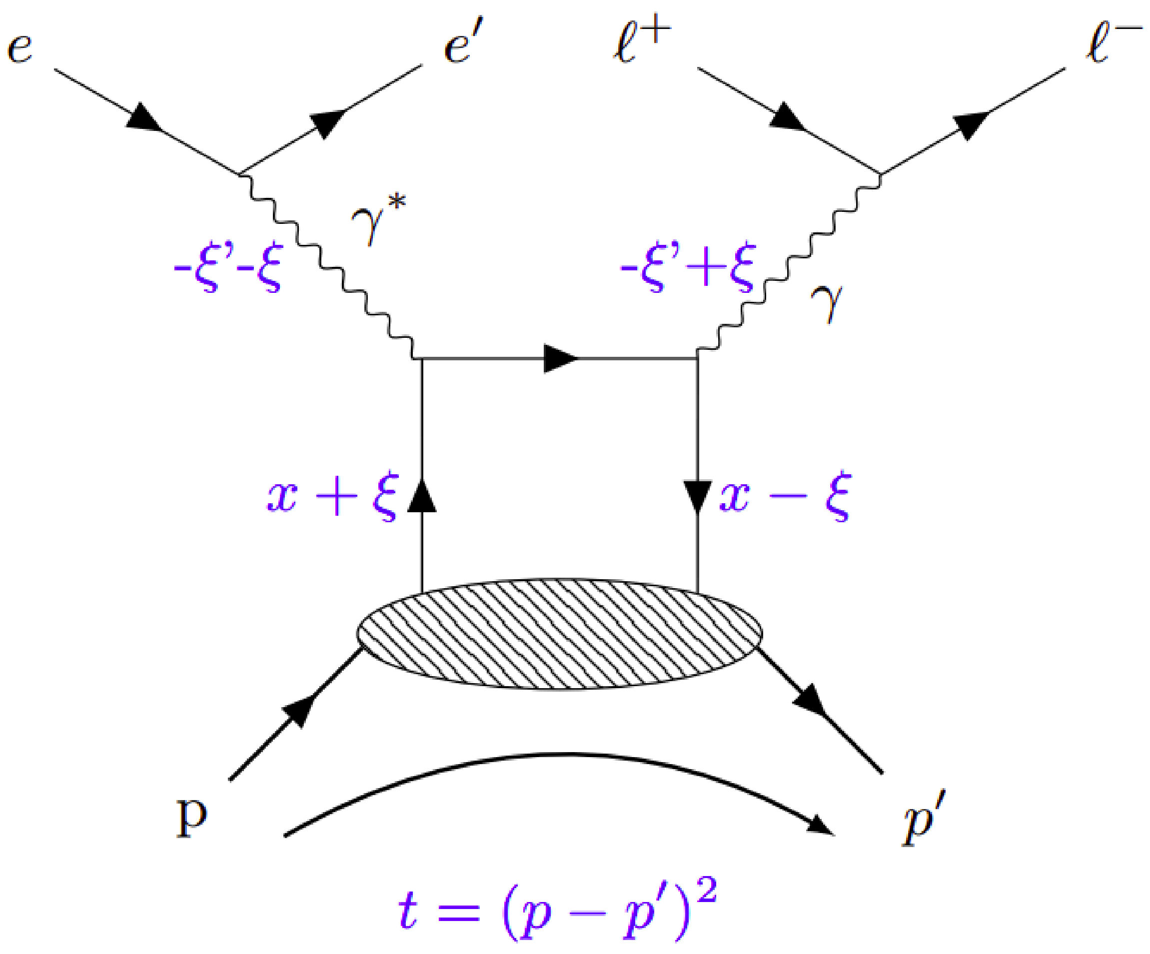

GPDs enter the cross section through Compton Form Factors (CFF)

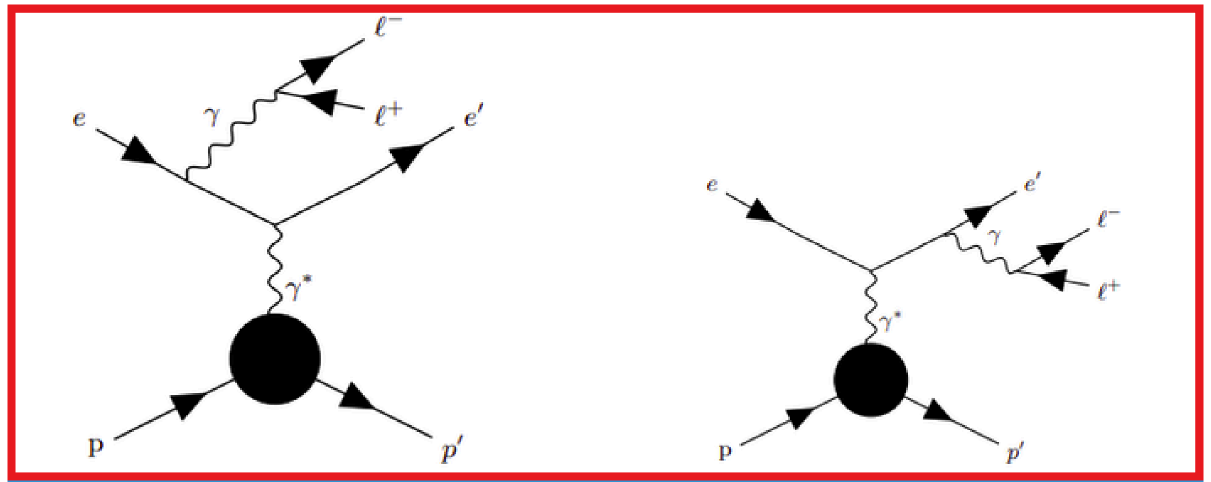
$$\mathcal{F}(\xi',\xi,t) = -\mathcal{P}\int_0^1 dx'\, F^+(x',\xi,t)\left[\frac{1}{x'-\xi'} \pm \frac{1}{x'+\xi'}\right] + i\pi F^+(\xi',\xi,t)$$

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

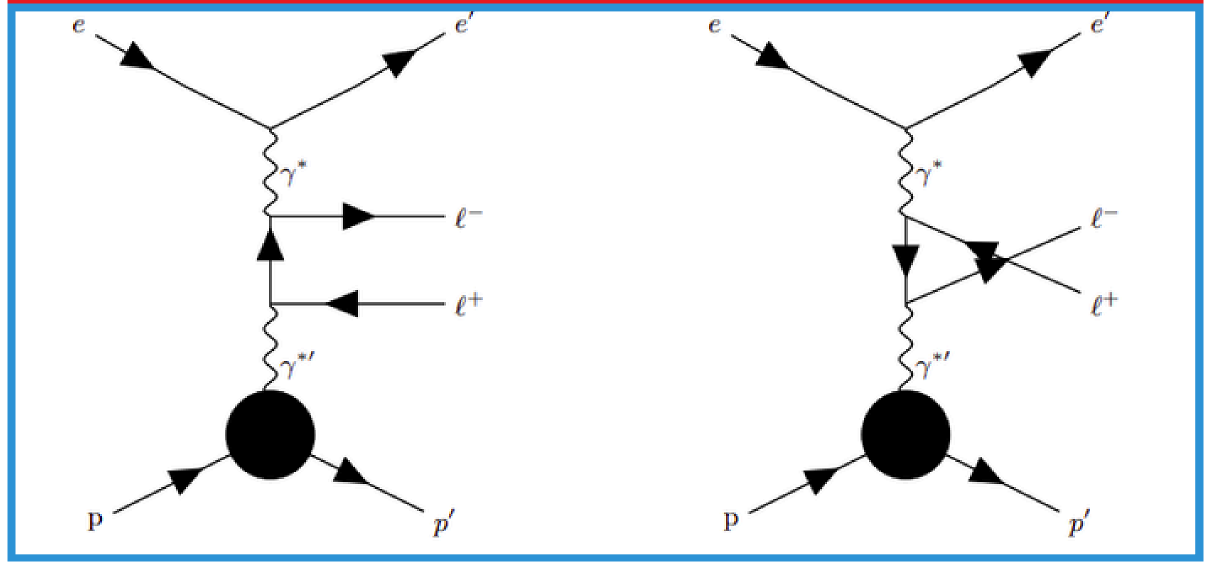
# The Double DVCS reaction

The DDVCS reaction interferes with the Bethe-Heithler (BH) process



DVCS-like BH = $BH_1$



TCS-like BH = $BH_2$

- Compared to DVCS, the DDVCS cross section is about 1000 smaller and it counts with two extra degrees of freedom

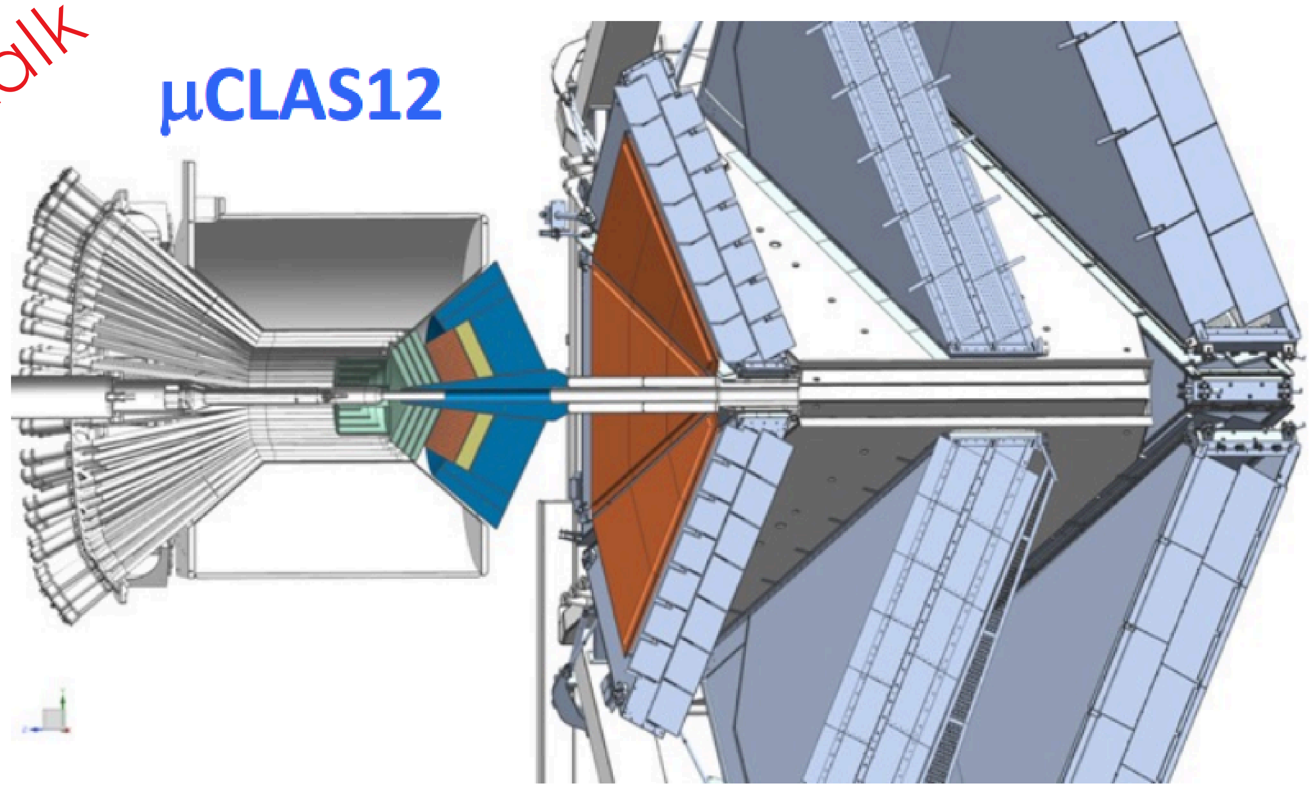
$$d^7\sigma \equiv \frac{d^7\sigma}{dx_B dQ^2 dQ'^2 dt d\phi d\Omega_\ell}$$

**How do we study this 7-dimensional phase space?**

# How to approach the DDVCS reaction (1/2)

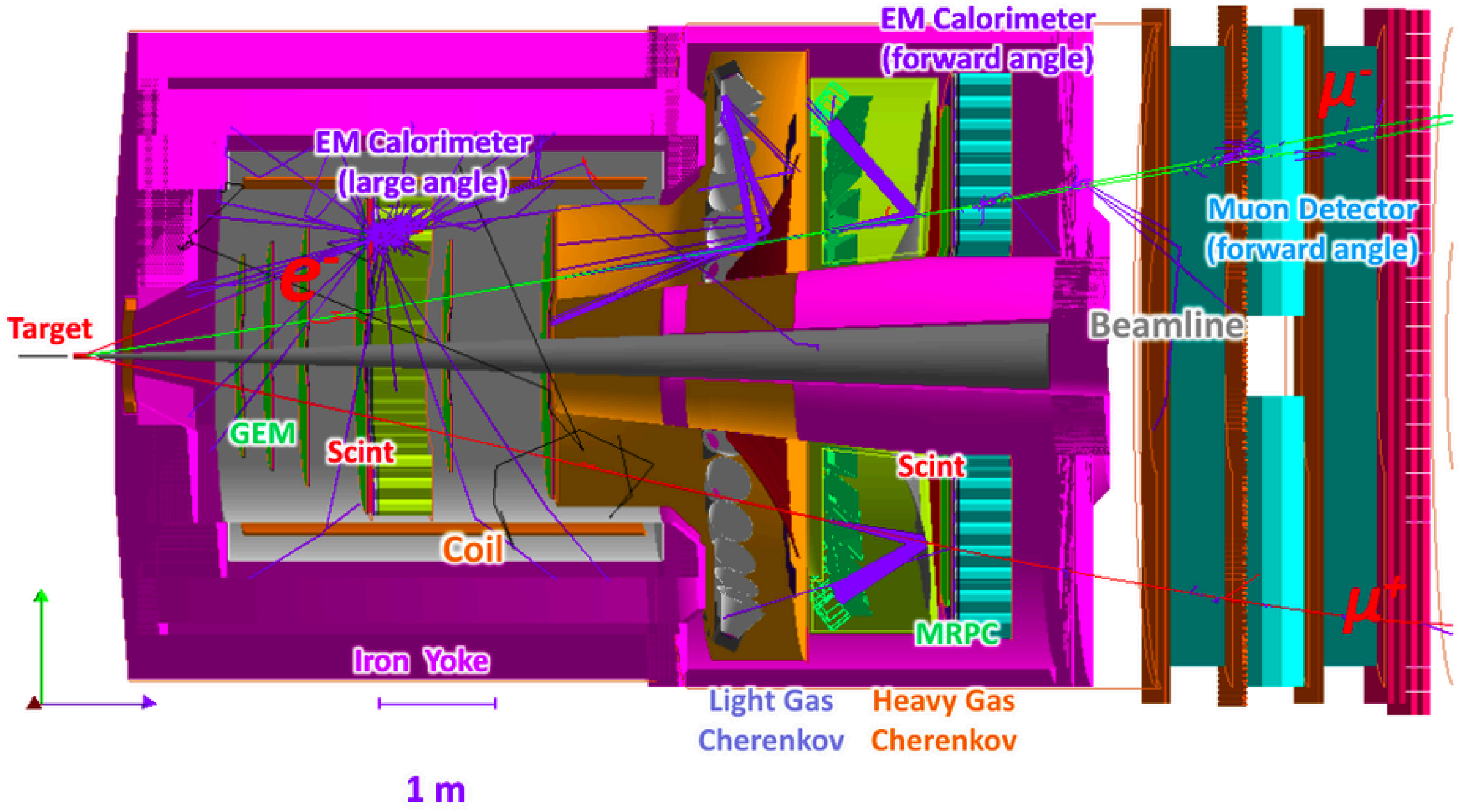
**Upgraded CLAS12 spectrometer at Hall B:**

See Pierre's talk




**SoLID spectrometer at Hall A**

See Alexandre's talk




Both spectrometers foresee:

- acceptance of charged particles from 7° to 35°
- muon detection capabilities
  - to ensure the identification of the scattered and decay leptons
- support for a luminosity of

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

# How to approach the DDVCS reaction (2/2)

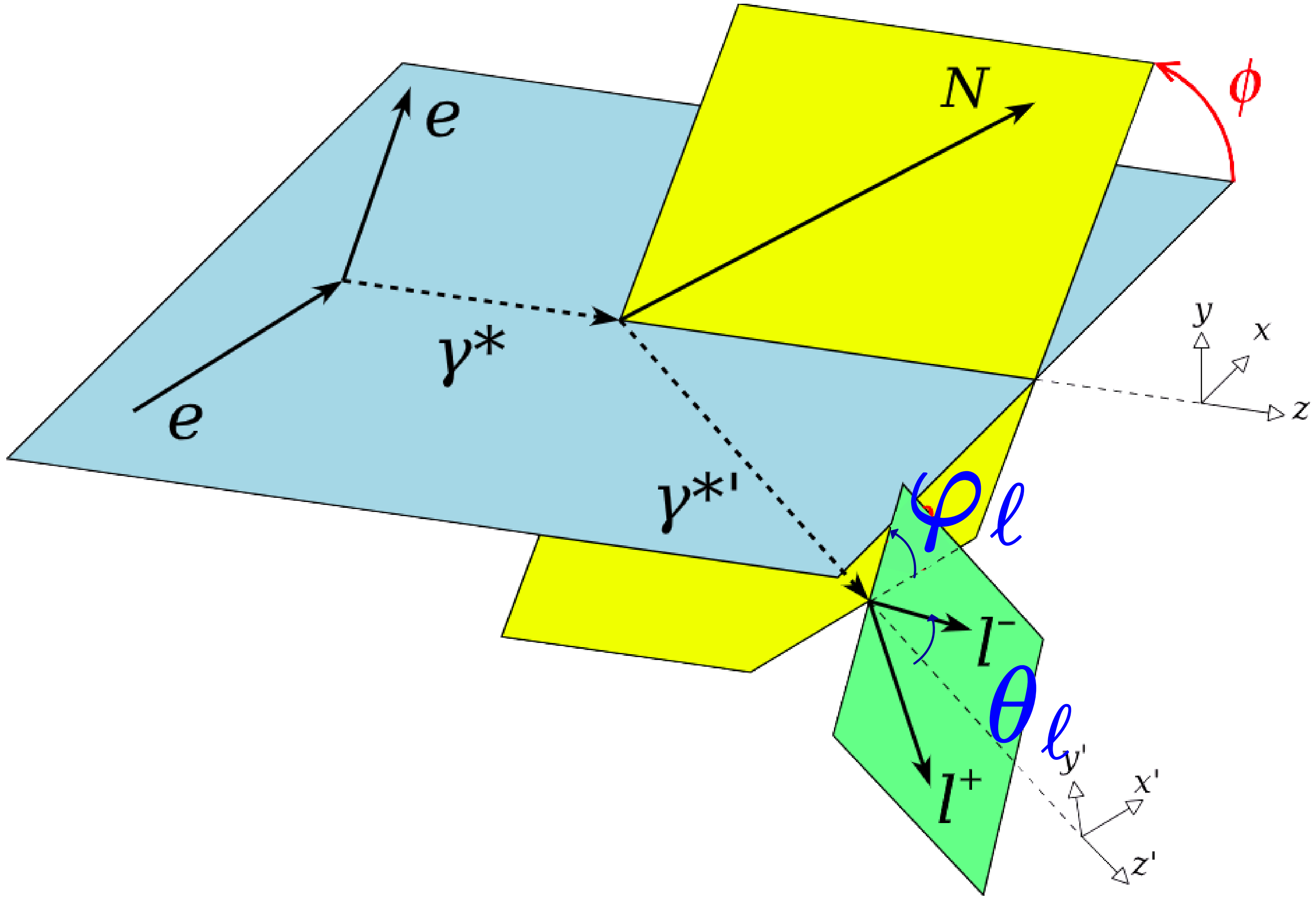
- We integrate two degrees of freedom to obtain measurable signals

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

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

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

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




We define a Beam-Spin Asymmetry (BSA) from the 5-fold differential cross section

$$\boxed{A_{LU}(\varphi_\ell)} \equiv \frac{d^5\Sigma^+ - d^5\Sigma^-}{d^5\Sigma^+ + d^5\Sigma^-} = \frac{d^5\Sigma_{\mathcal{I}_2}}{d^5\Sigma_{BH_1} + d^5\Sigma_{BH_2} + d^5\Sigma_{BH_{12}} + d^5\Sigma_{DDVCS} + d^5\Sigma_{\mathcal{I}_1} + d^5\Sigma_{\mathcal{I}_2}}$$

$$\boxed{A_{LU}(\phi)} \equiv \frac{d^5\sigma^+ - d^5\sigma^-}{d^5\sigma^+ + d^5\sigma^-} = \frac{d^5\sigma_{\mathcal{I}_1}}{d^5\sigma_{BH_1} + d^5\sigma_{BH_2} + d^5\sigma_{DDVCS} + d^5\sigma_{\mathcal{I}_1}}$$

- Isolate the DDVCS interference with $BH_1$ and $BH_2$
- <u>They produce different amplitudes</u>
- Both definitions access the same CFF combination

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

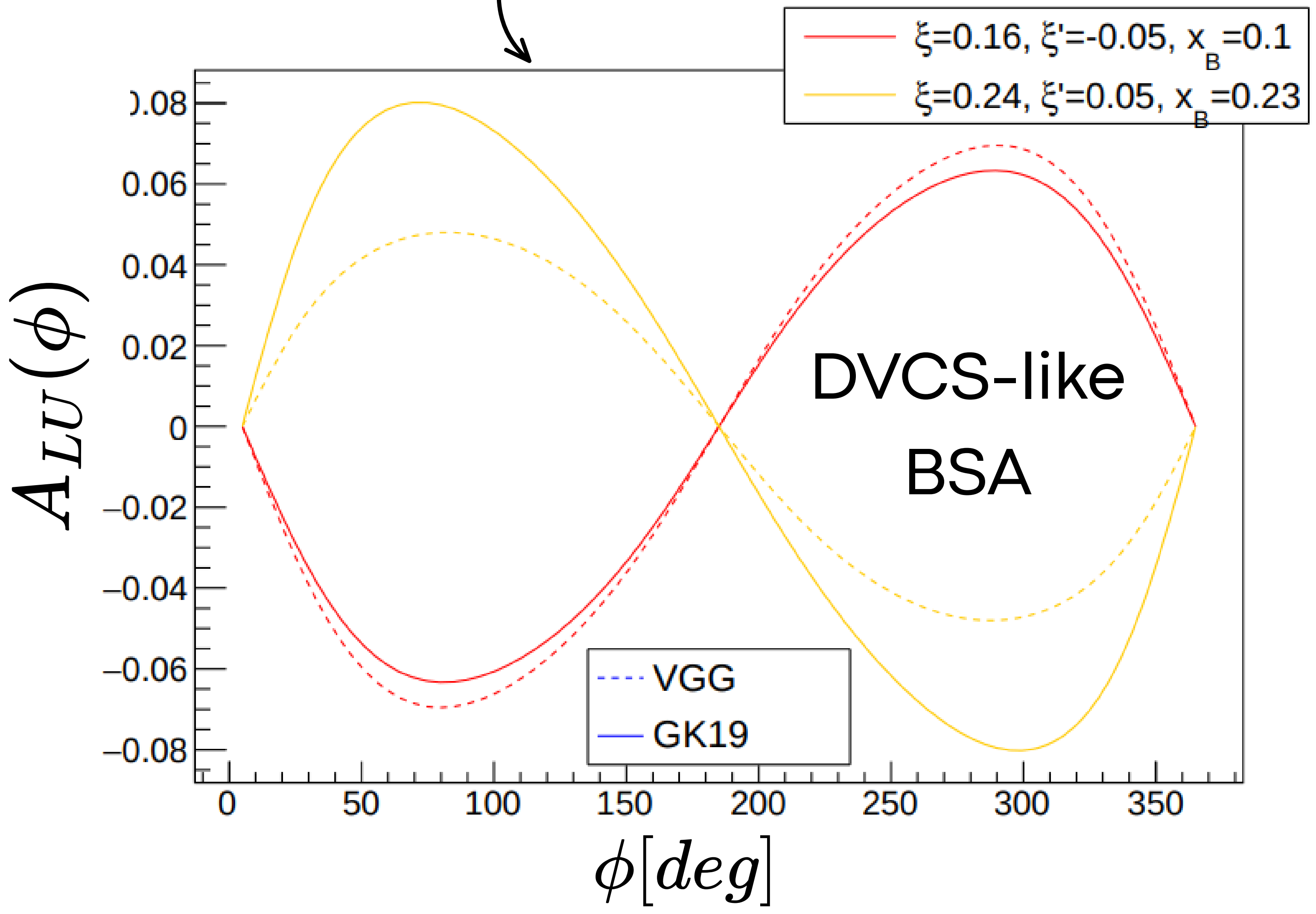
# Observable definition

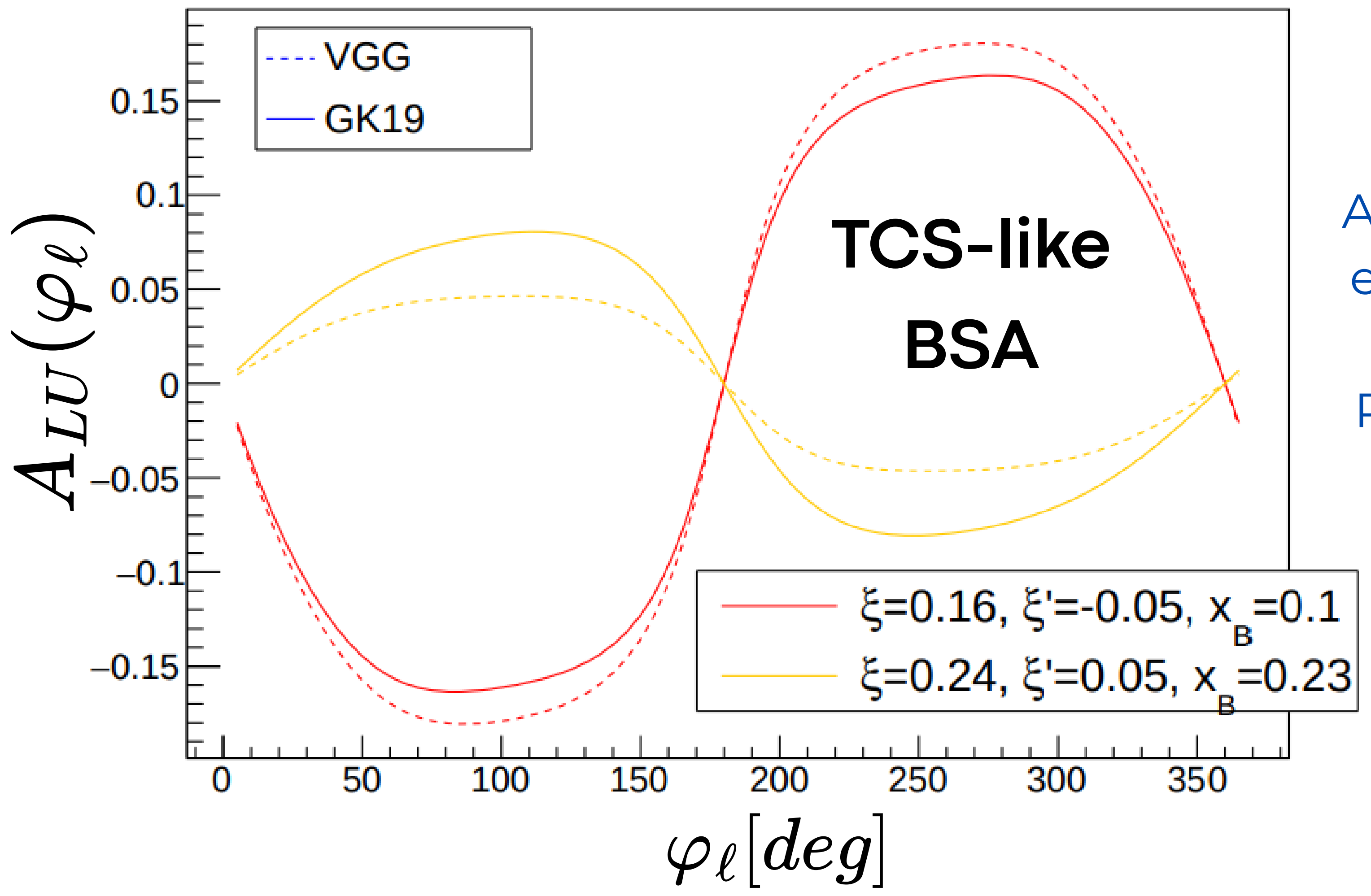
- We integrate two degrees of freedom to obtain measurable signals

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

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

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




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

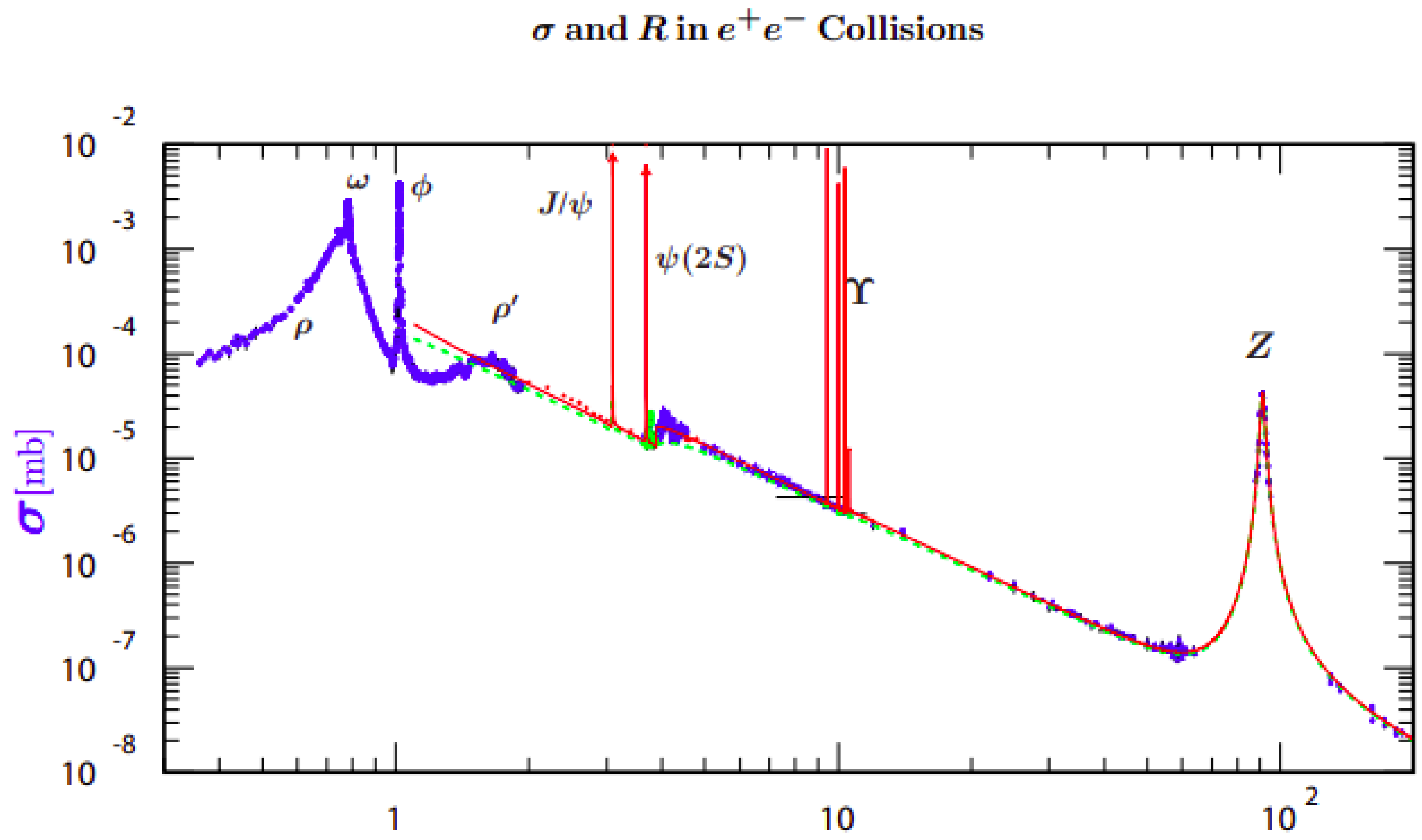
- A TCS-like BSA produces larger asymmetries in the ξ'<0 region

# Observable definition

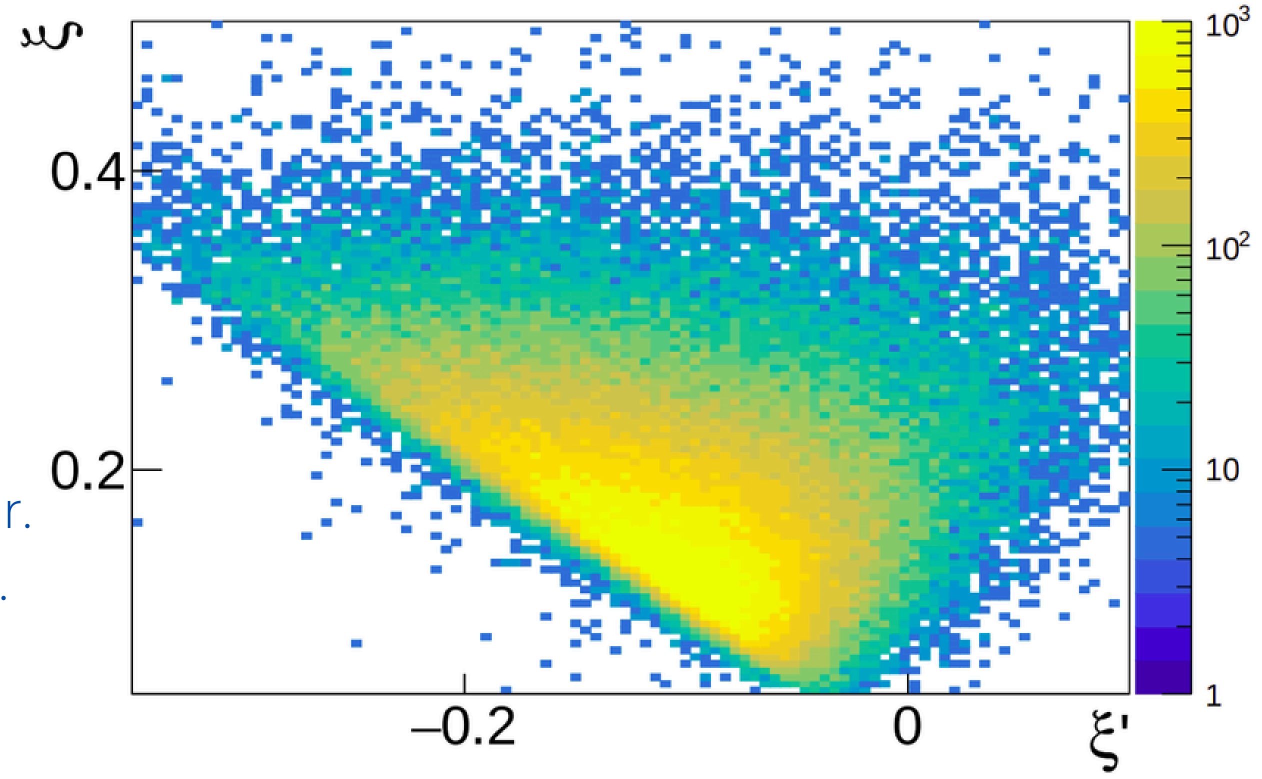
## Why be careful with the observable definition?

The di-lepton final state might come from a vector meson resonance

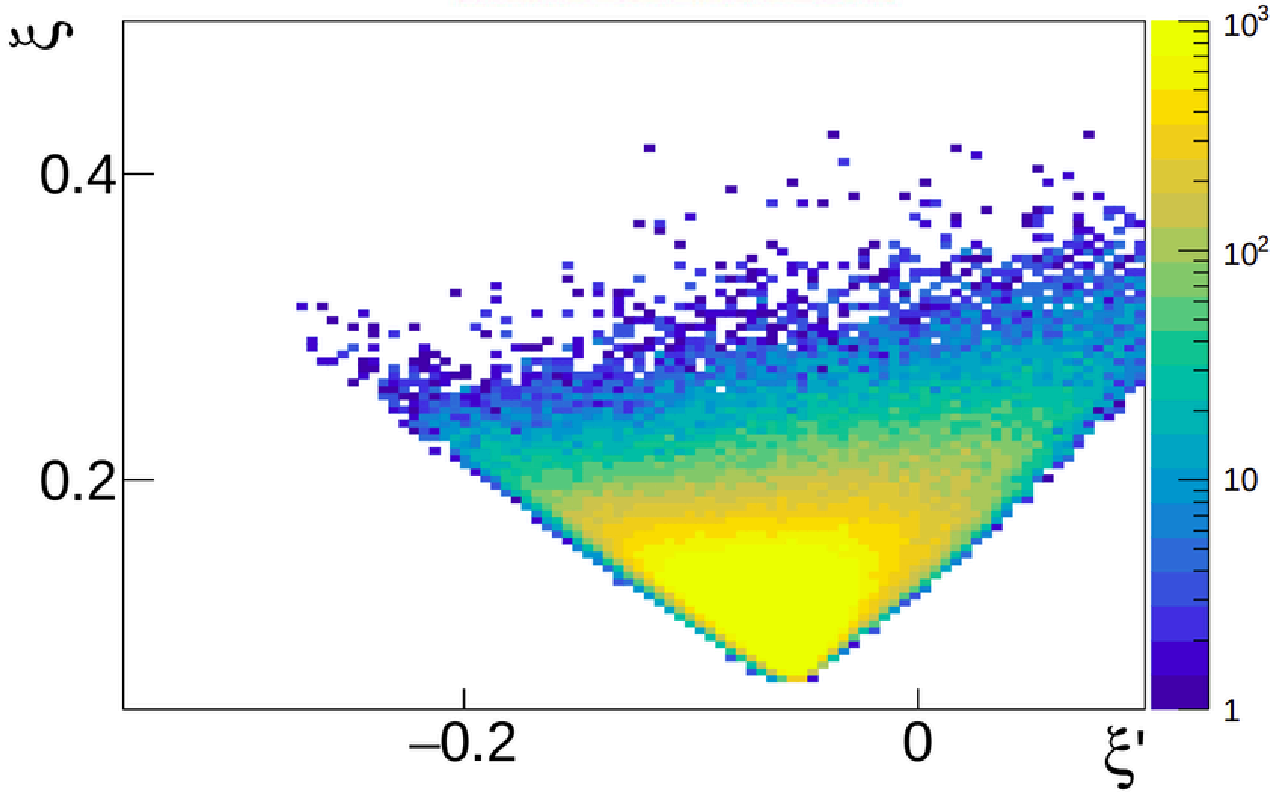
- We restrict ourselves to **Q' > 1.2 GeV** to exclude them
  - It imposes a **ξ'**<0 -dominated window for DDVCS
    - TCS-like BSA yields larger amplitudes




μCLAS
CEBAF Large Acceptance Spectrometer




SoLIDμ
SOLENOIDAL LARGE INTENSITY DEVICE

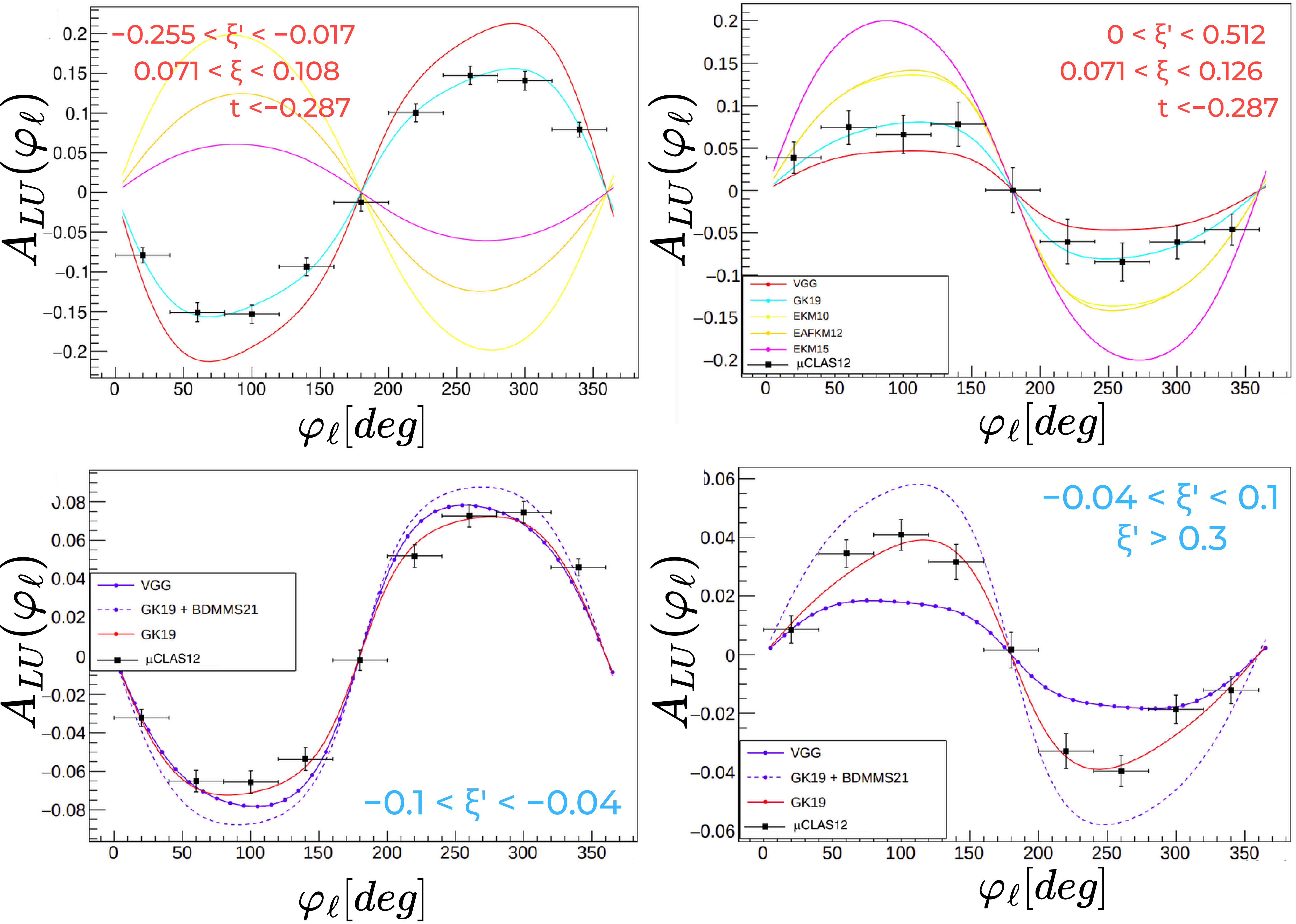



EpIC

Events generated with EpIC

E. C. Aschenauer et al. Eur. Phys. J C 82.9 (2022): 819.

# BSA projections

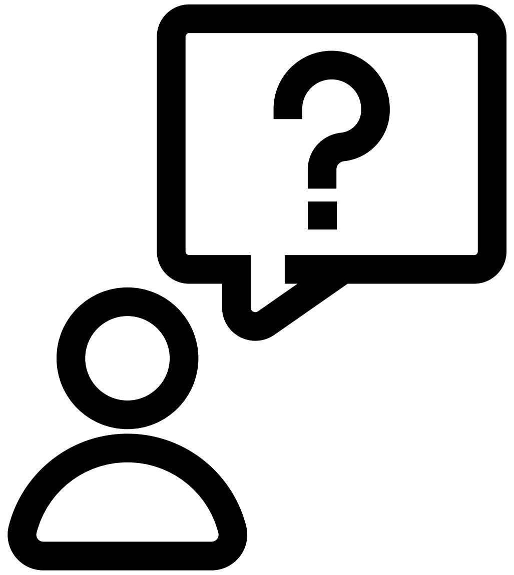



**The DDVCS program will provide**

- 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 >$10^{38}$ $cm^{-2}s^{-1}$



Can we extend measurements beyond BSA?

# The muon charge asymmetry

Inspired by the Forward-Backward asymmetry in TCS, we define an angular asymmetry for DDVCS

It accesses the **real part of CFFs** encoded in the DDVCS*$BH_2$ interference amplitude

It is diluted with a BH contribution

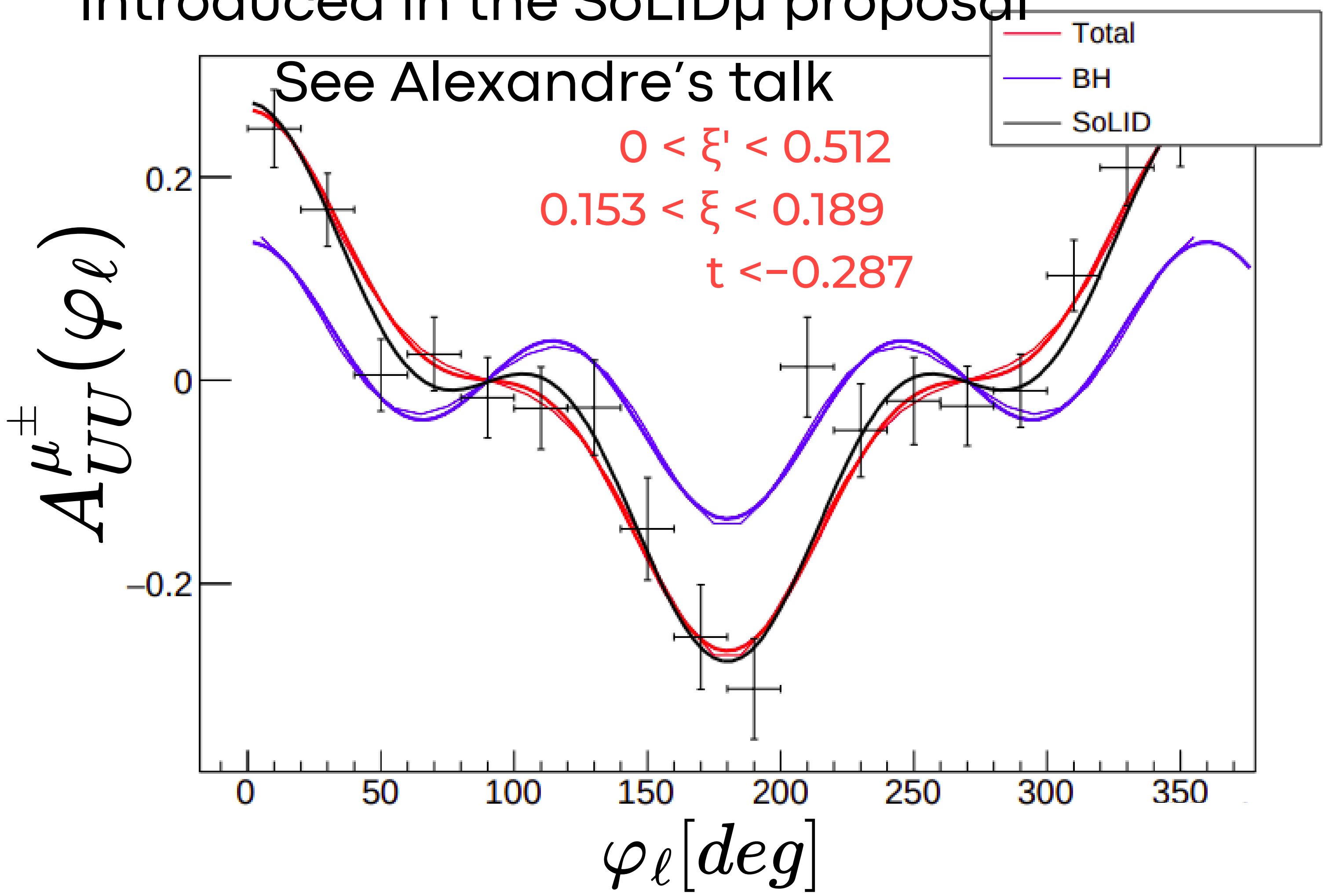
$$A^{\mu^\pm}_{UU}(\varphi_\mu) = \frac{d^5\Sigma_{UU}(\varphi_{\mu^-}) - d^5\Sigma_{UU}(\varphi_{\mu^+})}{d^5\Sigma_{UU}(\varphi_{\mu^-}) + d^5\Sigma_{UU}(\varphi_{\mu^+})}$$

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

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

Introduced in the SoLIDμ proposal

See Alexandre's talk




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

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

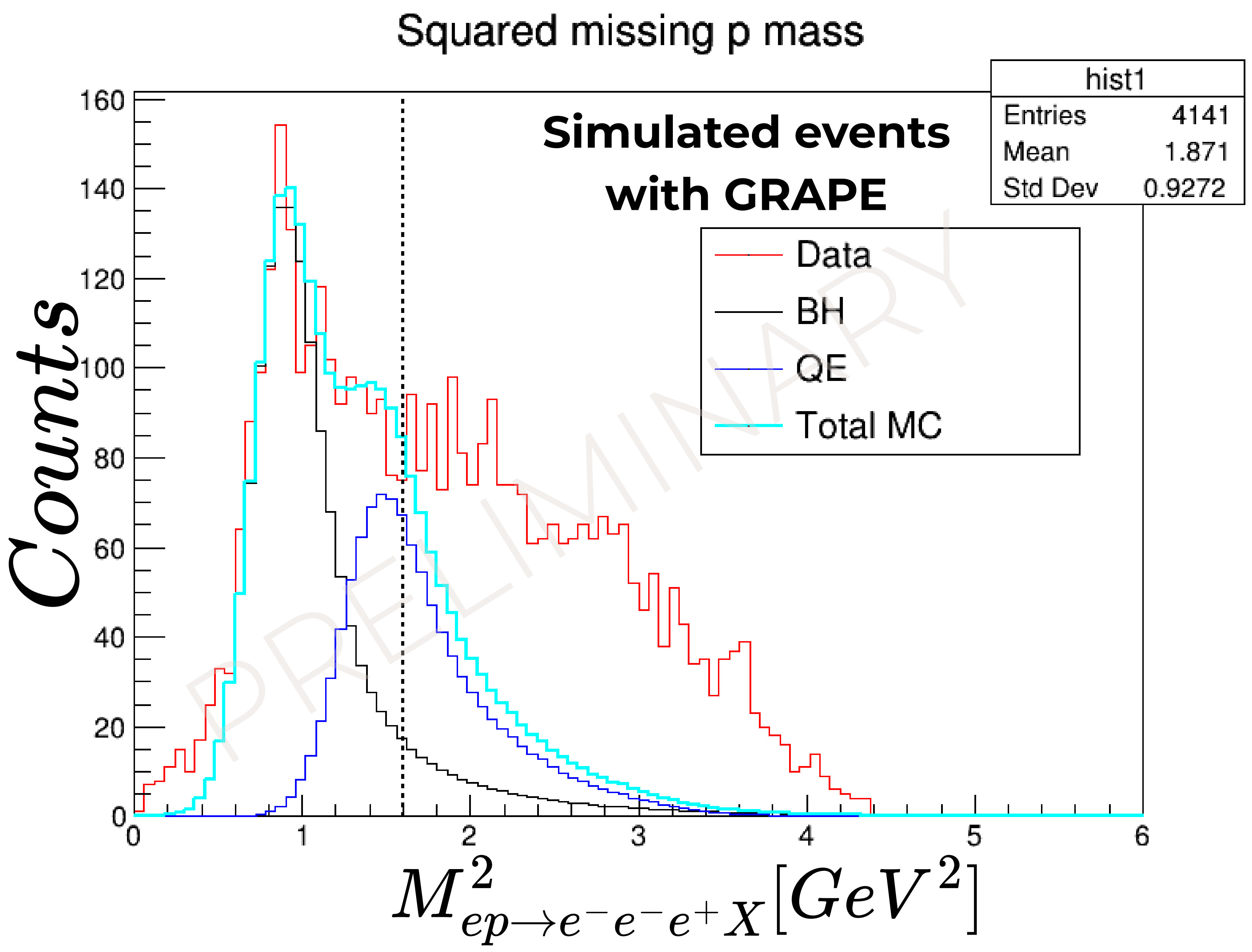
It accesses the same CFF combination of a Beam Charge Asymmetry


They complement each other

# The ~~muon~~ electron charge asymmetry

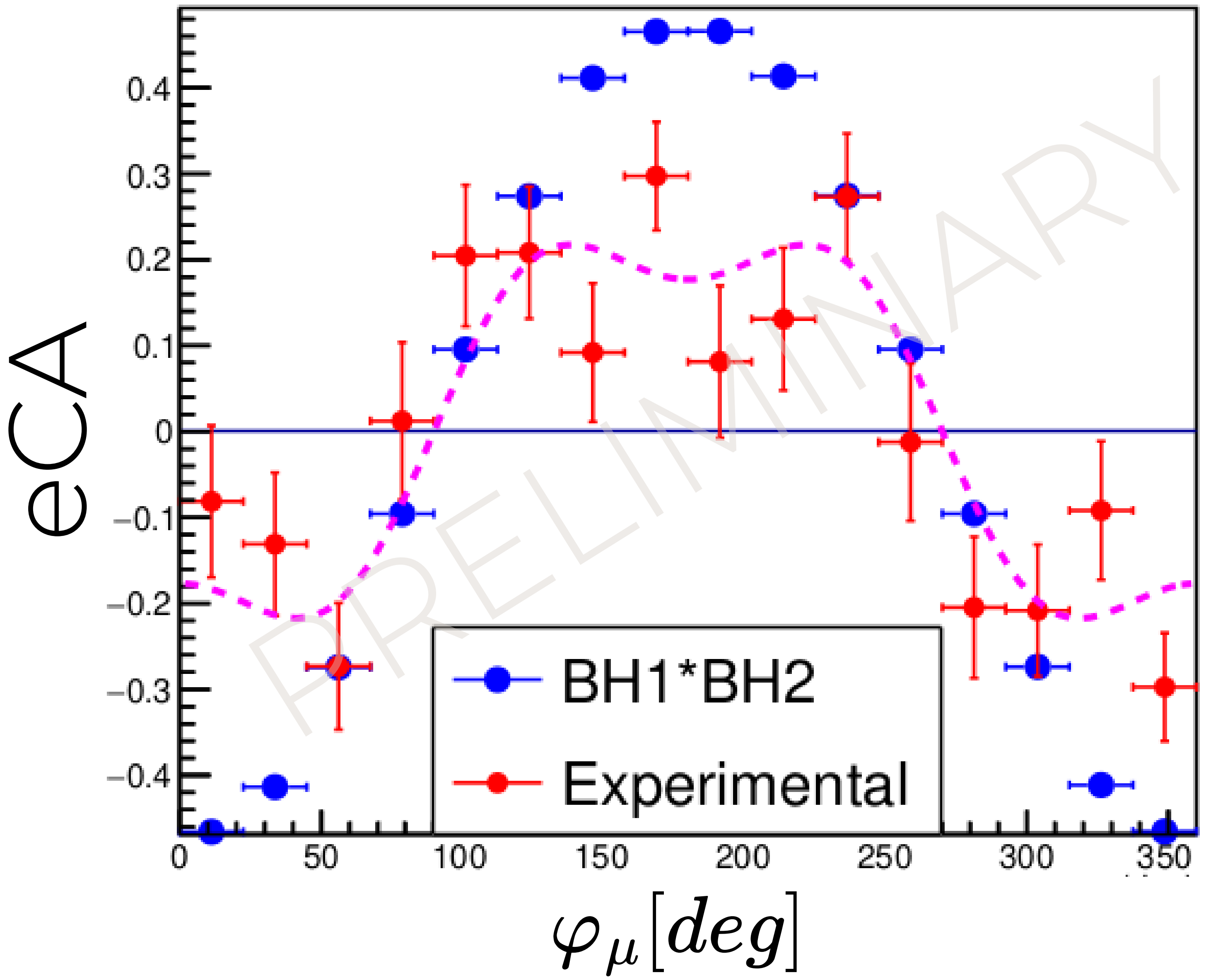
**Let us test this observable with experimental data in the $e^+e^-$ channel**

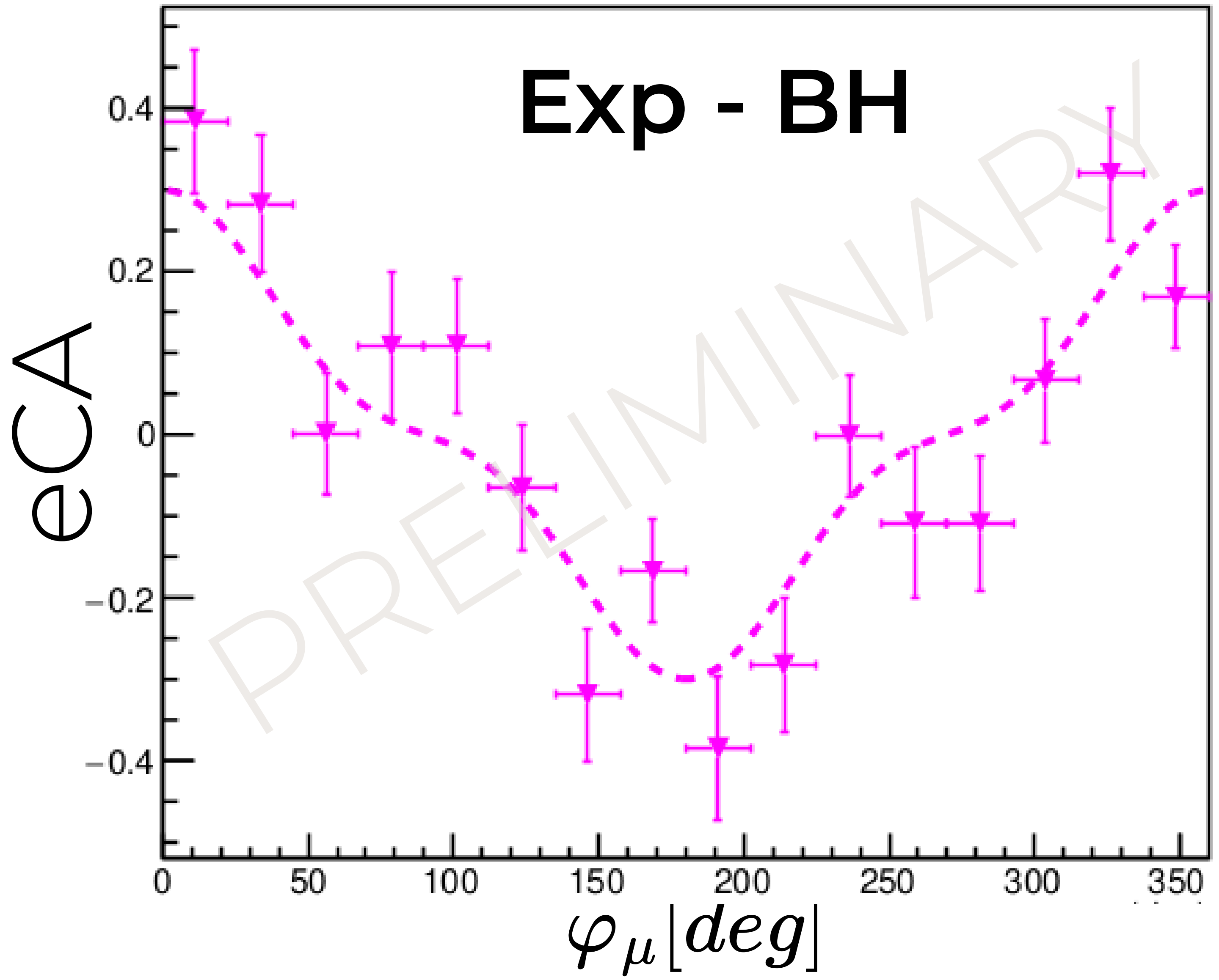
- Using data from the **RG-A fall2018-inbending** dataset, we select events with
  - Two electrons
  - One positron
  - Missing mass of the $ep \to e^-e^-e^+ X$ reaction near the proton mass
- BH and QE missing proton mass distributions reproduce the experimental data up to $M_P^2 = 1.6$ GeV²
  - $M_P^2 > 1.6$ GeV² receives DIS contributions
- A cut on $M_P^2 < 1.0$ GeV² would provide an almost clean DDVCS sample
  - **1K events**



# The ~~muon~~ electron charge asymmetry

Large amplitudes are not only expected from model predictions

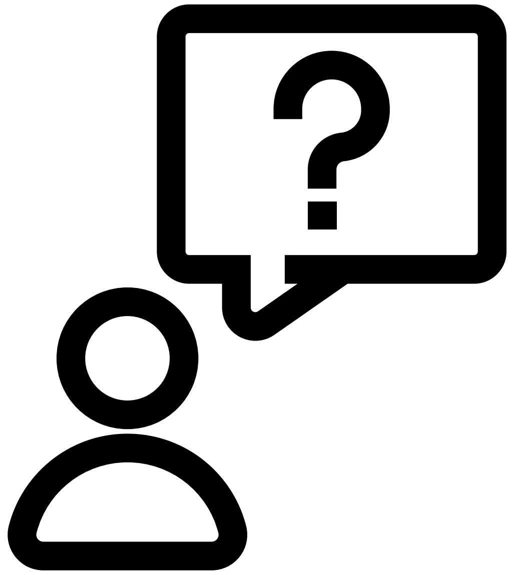



A single preliminary measurement can be recovered from the $e^+e^-$ channel @ CLAS12

Fall2018-inbending data

- Scattered electron in FT
- decay electron in FD

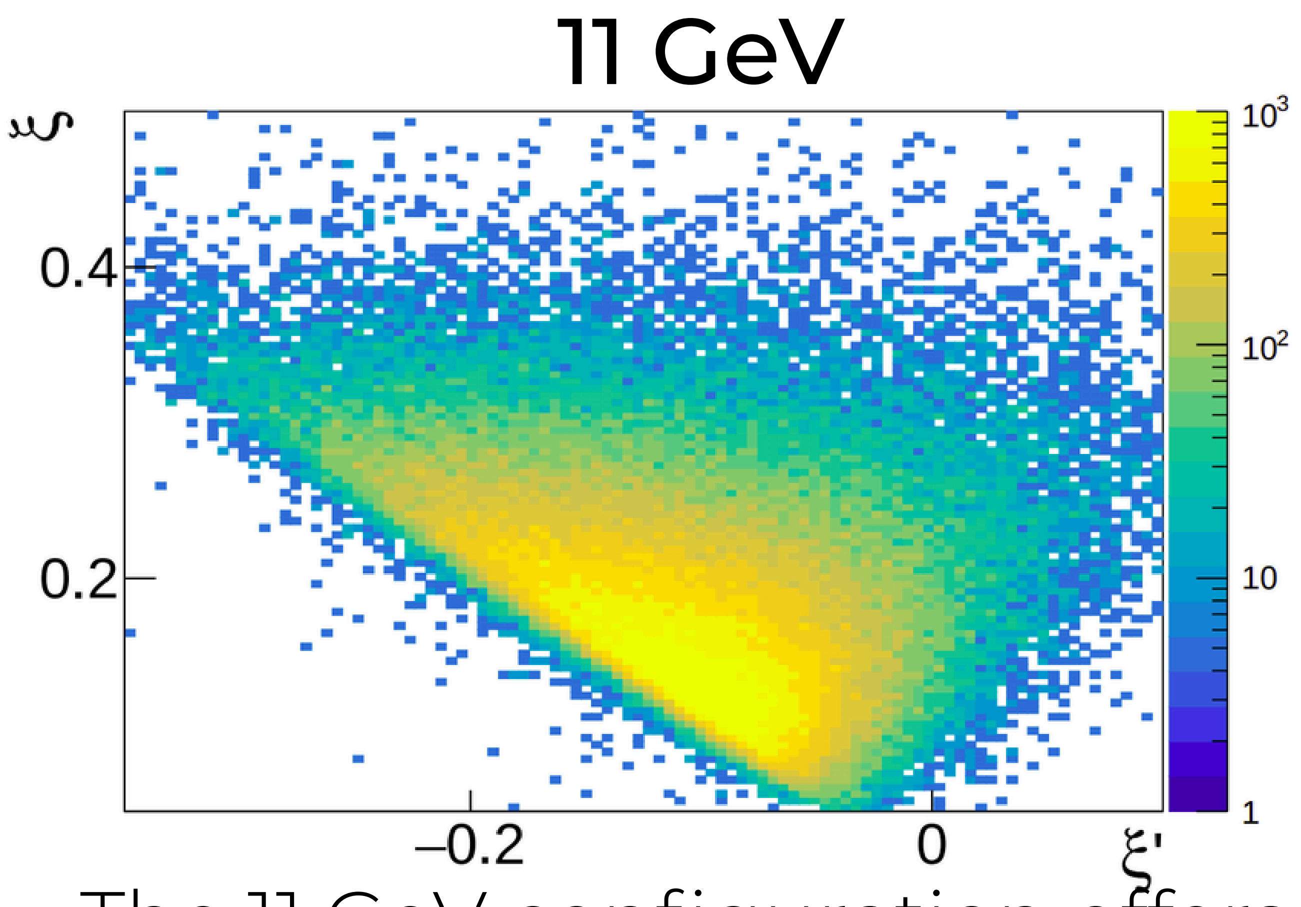


What about exploring the ξ'>ξ region with DVCS-like observables?

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

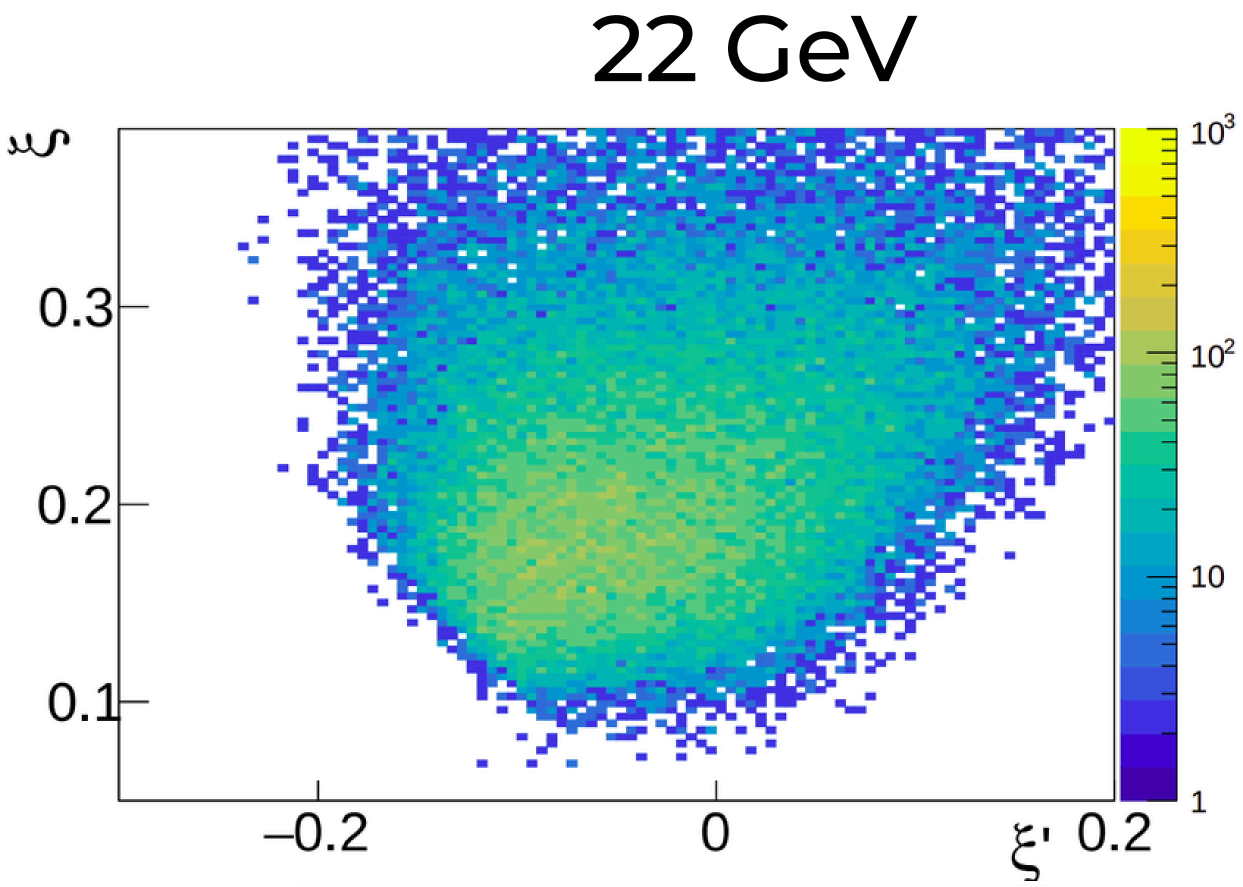
$$d^5\sigma^\lambda(\phi) \equiv \frac{d^5\sigma^\lambda(\phi)}{dx_B\, dy\, dt\, dQ'^2\, d\phi} = \int_0^{2\pi} d\varphi_\mu \int_{\pi/2-\theta_0}^{\pi/2+\theta_0} d\theta_\mu \sin(\theta_\mu)\, \frac{d^7\sigma^\lambda(\phi,\theta_\mu,\phi_\mu)}{dx_B\, dy\, dt\, d\phi\, dQ'^2\, d\Omega_\mu}$$

# DDVCS SIMULATIONS

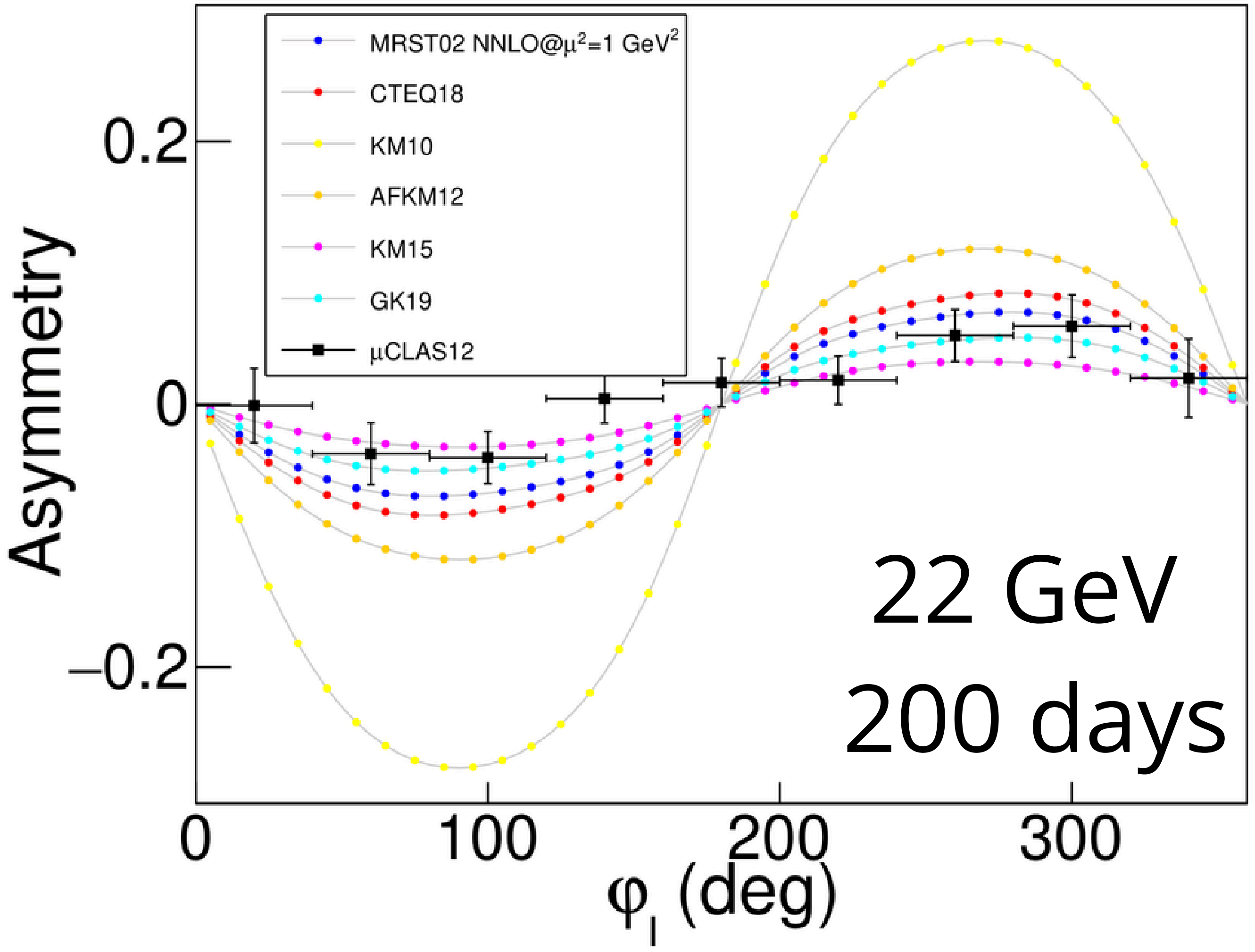


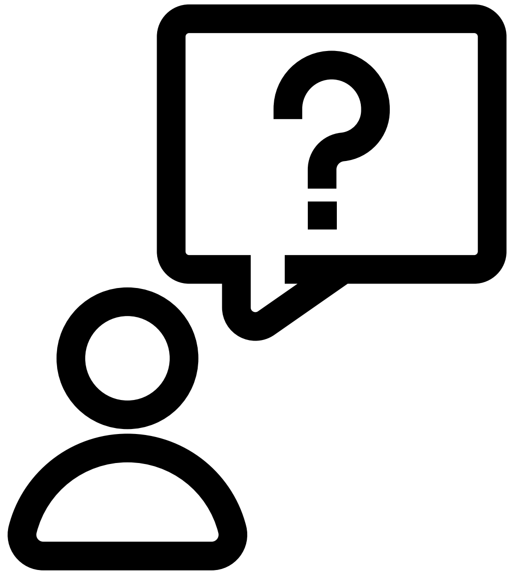

CEBAF Large Acceptance Spectrometer

J. S. Alvarado, M. Hoballah, and E. Voutier, Phys. Rev. C, 111 (2025), 065205.



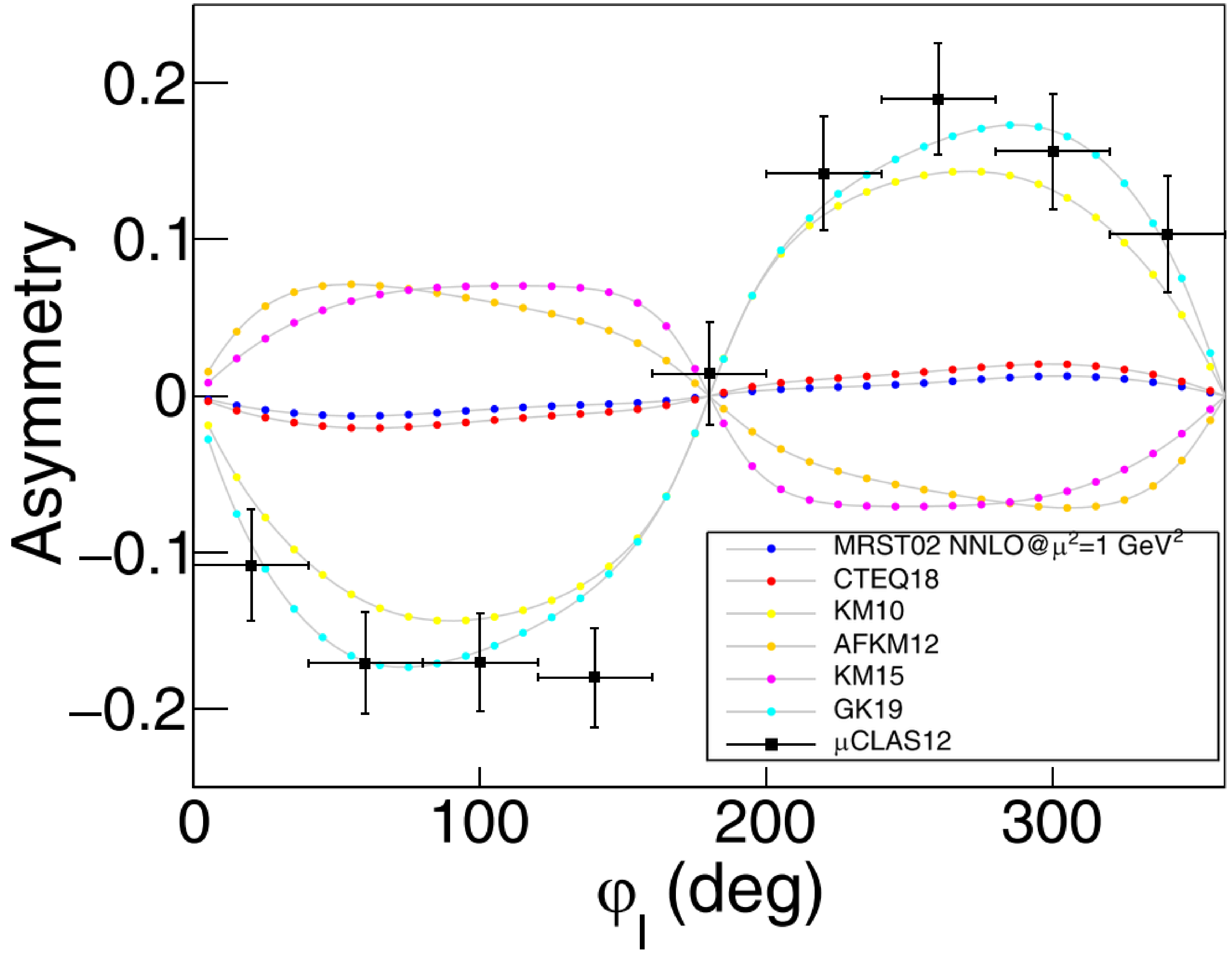

- The 11 GeV configuration offers limited access to the ξ'>0 region
- Further coverage is granted by the 22 GeV configuration
  - As $Q^2_{MAX} = \sqrt{(2ME_{Beam})}$, there is more coverage of $Q^2 > Q'^2$ kinematics
  - DVCS-like observables might play a major role
  - Exploration of the DVCS-like region might be possible





What about target-polarized observables?

# TSA PROJECTIONS




$$\xi' < -0.069 \text{ and } \xi < 0.107$$

$$A_{UL} \propto \sin(\phi)\Im\left(F_1\tilde{\mathcal{H}} + \xi'(F_1+F_2)\left(\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}\right) - \xi\left(\frac{\xi}{1+\xi}F_1 + kF_2\right)\tilde{\mathcal{E}}\right)$$

J. S. Alvarado, M. Hoballah, and E. Voutier, Phys. Rev. C, 111 (2025), 065205.

200 days might as well allow the observation of longitudinally-polarized Target Spin Asymmetries (TSA)

- Projections built on top of GK19 model predictions
  - Error bars are scaled accordingly to 3/17 dilution factor ($NH_3$ target)
  - Error from target polarization $P_t$ =0.8 ± 0.02 is included
- Strong model sensitivity

- For a proton target:
  - $\tilde{H}$ dominance
  - Measurements at small ξ' kinematics would provide clean access to $\tilde{H}$
- For a neutron target ($F_1$ ~0)
  - H dominance
  - Sensitivity to $\tilde{E}$ at small ξ' kinematics

# SUMMARY

- The DDVCS program will provide unprecedented access to GPDs.
  - Contrary to DVCS and TCS, DDVCS enables off-diagonal access to GPDs.
- Major insights are foreseen through measurements of the BSA
  - BSA sign-change when transitioning between the positive and negative $\xi'$ regions
  - Sensitivity to shadow GPD contributions
- Phase space coverage privileges the $\xi'<0$ region
  - TCS-like observables feature an enhanced sensitivity
  - The real part of CFFs is accessible through the $\mu$CA
- Projected statistics point to a 3D exploration of the DDVCS reaction.

# OUTLOOK

- This experiment is just the beginning, as it joins the motivation for
  - A further luminosity upgrade to perform a 5-dimensional analysis
  - An energy upgrade towards a 22 GeV beam
  - The development of target-polarized experiments
  - The development of neutron-DDVCS experiments to achieve off-diagonal quark-flavor separation of GPDs.

# THANKS