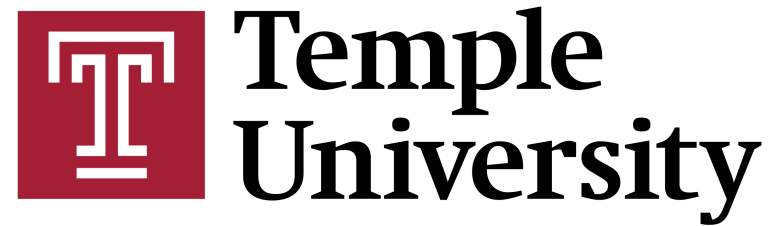


Recent and future measurements of Virtual Compton Scattering and Generalized Polarizabilities of Proton

Sangbaek Lee

On behalf of VCS-II Collaboration



October 22, 2026

MENU 2026—The 17th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

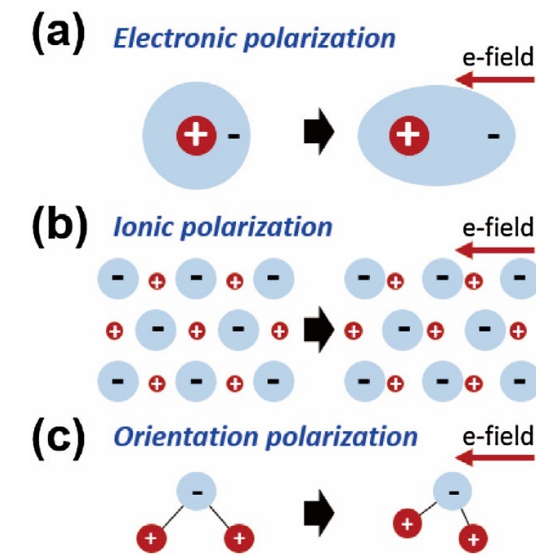
Electromagnetic Polarizabilities

- The electromagnetic polarizabilities are fundamental structure constants that characterize a system's deformation in external electromagnetic fields

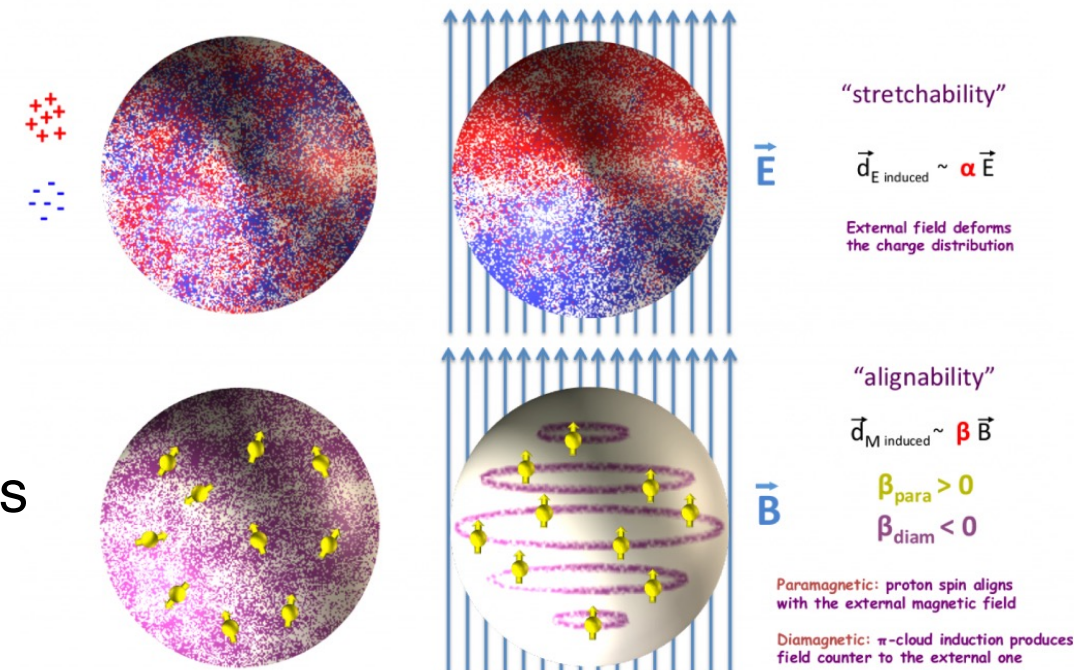
$$\vec{p} = \alpha_E \vec{E}_{ext}$$

$$\vec{\mu} = \beta_M \vec{B}_{ext}$$

- For a composite system such as a crystal, each component contributes to the polarizability, so the constants reflect the internal structure
- The EM polarizability of the proton probes the system's stretchability and alignability.



Material Science and Engineering R 114 (2017) 1–22



From Nikos Sparveris

Static EM Polarizabilities of the Proton

- Real Compton scattering (RCS) probes the proton EM polarizabilities
 - The incoming photon deforms the nucleons
 - The energy and angular distributions of the outgoing photon probes the induced current and magnetization densities.

- Sensitive to the full excitation spectrum

$$\alpha_{E1} = 2 \sum_{N^* \neq N} \frac{|\langle N^* | D_z | N \rangle|^2}{E_{N^*} - E_N}$$

- Important benchmark for EFTs and provides stringent tests of low-energy QCD
- The most recent measurements are from H γ S and MAMI in 2022
 - X. Li et al., PRL 128 (2022) 132502
 - E. Mornacchi et al. (A2), PRL 128, 132503 (2022)

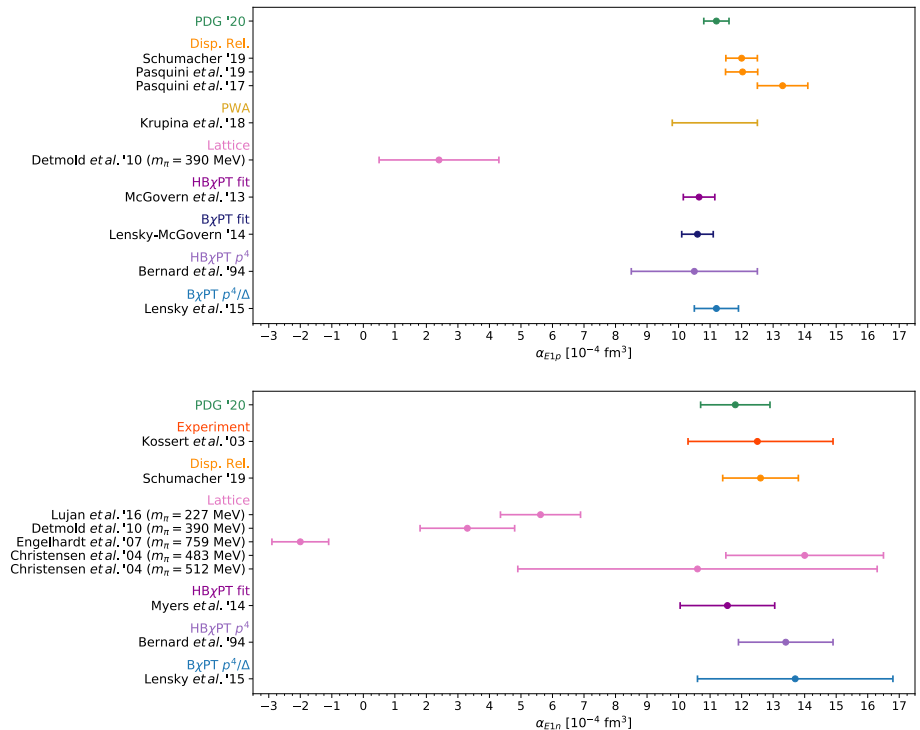
N BARYONS
 $(S = 0, I = 1/2)$
 $p, N^+ = uud; \quad n, N^0 = udd$

P

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

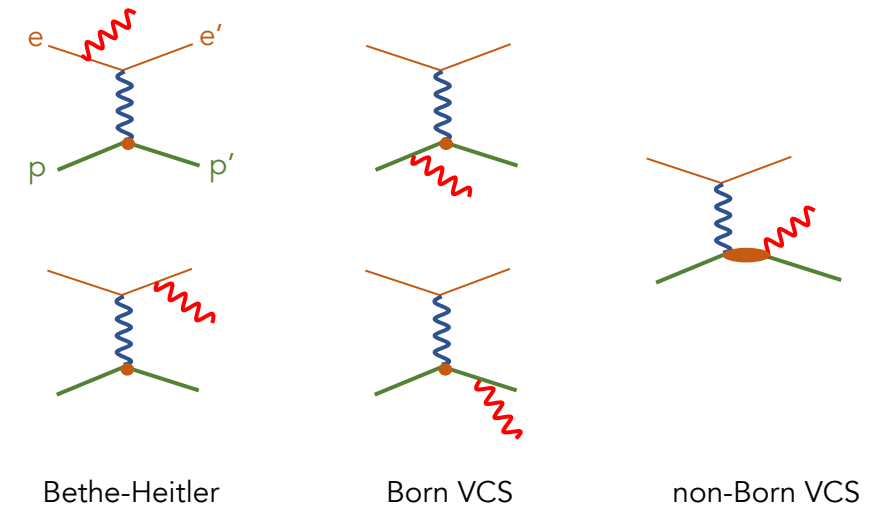
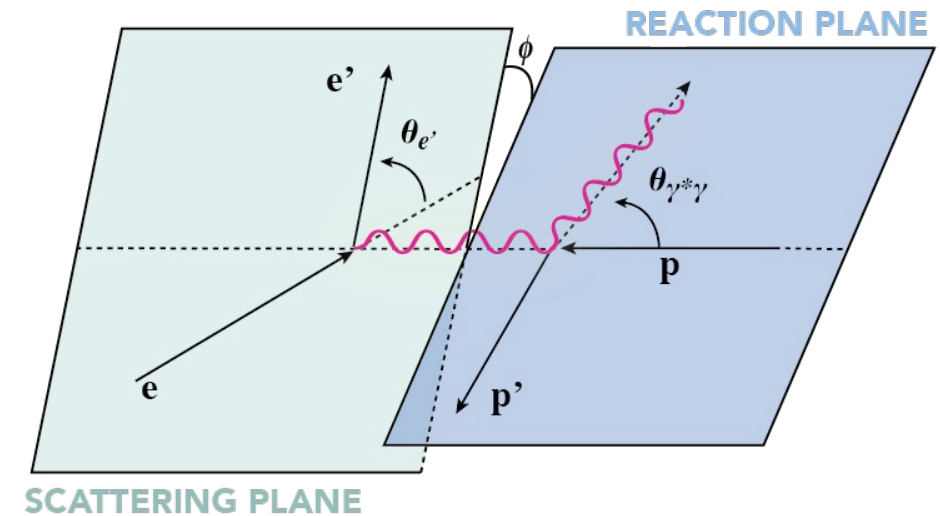
Mass $m = 1.0072764665789 \pm 0.00000000000083 \text{ u}$
 Mass $m = 938.27208943 \pm 0.000000029 \text{ MeV [a]}$
 $|m_p - m_{\bar{p}}|/m_p < 7 \times 10^{-10}, \text{ CL} = 90\% [b]$
 $|\frac{q_p}{m_p}|/(\frac{q_e}{m_p}) = 1.000000000003 \pm 0.000000000016$
 $|q_p + q_{\bar{p}}|/e < 7 \times 10^{-10}, \text{ CL} = 90\% [b]$
 $|q_p + q_e|/e < 1 \times 10^{-21} [c]$
 Magnetic moment $\mu = 2.7928473446 \pm 0.0000000008 \mu_N$
 $(\mu_p + \mu_{\bar{p}}) / \mu_p = (0.002 \pm 0.004) \times 10^{-6}$
 Electric dipole moment $d < 0.021 \times 10^{-23} \text{ ecm}$
 Electric polarizability $\alpha = (11.5 \pm 0.4) \times 10^{-4} \text{ fm}^3 \quad (S = 1.1)$
 Magnetic polarizability $\beta = (2.31 \pm 0.29) \times 10^{-4} \text{ fm}^3 \quad (S = 1.1)$

PDG (Assessed Oct. 2026)



Proton Generalized Polarizability (GP) and Virtual Compton Scattering (VCS)

- VCS gives access to the GPs as a function of photon virtuality Q^2 .
 - GPs provide spatially resolved information on the nucleon's response to external EM fields
- The outgoing real photon momentum q'_{cm} sets the scale of the EM perturbation.
 - Low-energy expansion (LEX) in q'_{cm} is model-independent t, and provides intuitive interpretation, and is valid up to π threshold.
 - The VCS cross section's sensitivity to GP grows with q'_{cm} or W
 - Using the dispersion relation (DR), one can extract the GP around the $\Delta(1232)$ resonance, where the polarizability effect is magnified.



R. Li et al. (VCS Collaboration),
Nature Vol 611, p. 265–270 (2022)

Early Experiments of the GPs

- Early GP measurements were performed at MAMI, JLab, and MIT-Bates. The LEX and DR analyses agree with each other.
- The electric GP shows a local enhancement at Q^2 of about 0.33 GeV^2 as indicated by two independent MAMI experiments
- Theoretical models predict a lower electric GP at higher Q^2 .
- The magnetic GP data have large uncertainties and are inconsistent among experiments.

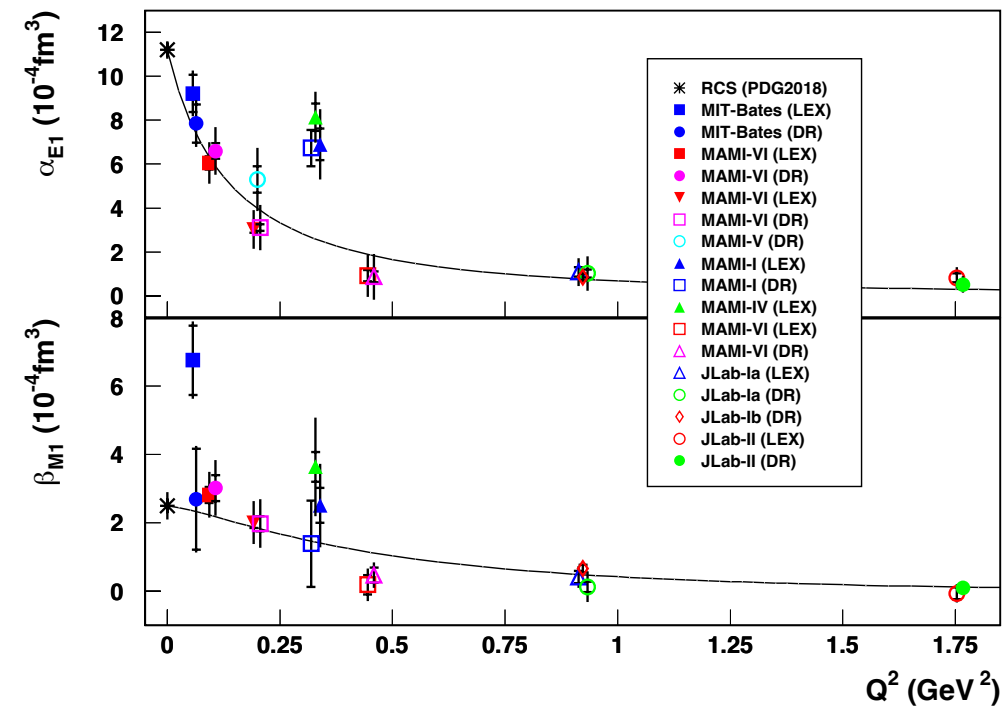


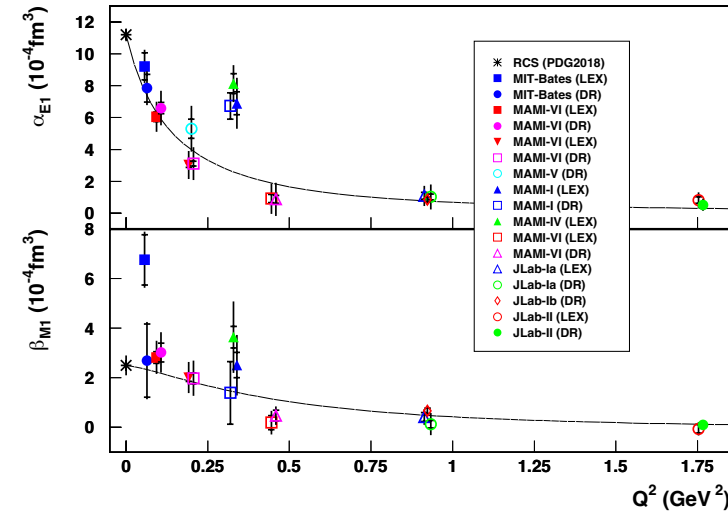
Table 2: Type of VCS experiments (in chronological order).

Laboratory	polarization	Q^2 (GeV^2)	c.m. energy W	ϵ	data taking
MAMI-I	unpolarized	0.33	$< \pi$ threshold	0.62	1995-1997
JLab	unpolarized	0.92, 1.76	up to 1.9 GeV	0.95, 0.88	1998
MIT-Bates	unpolarized	0.057	$< \pi$ threshold	0.90	2000
MAMI-II	$\vec{e}$	0.35	$\Delta(1232)$	0.48	2002-2004
MAMI-III	unpolarized	0.06	$\Delta(1232)$	0.78	2003
MAMI-IV	$\vec{e}$ and $\vec{p}'$	0.33	$< \pi$ threshold	0.645	2004-2006
MAMI-V	unpolarized	0.20	$\Delta(1232)$	0.77	2012
MAMI-VI	unpolarized	0.1, 0.2, 0.45	$< \pi$ threshold	0.91, 0.85, 0.63	2011-2015

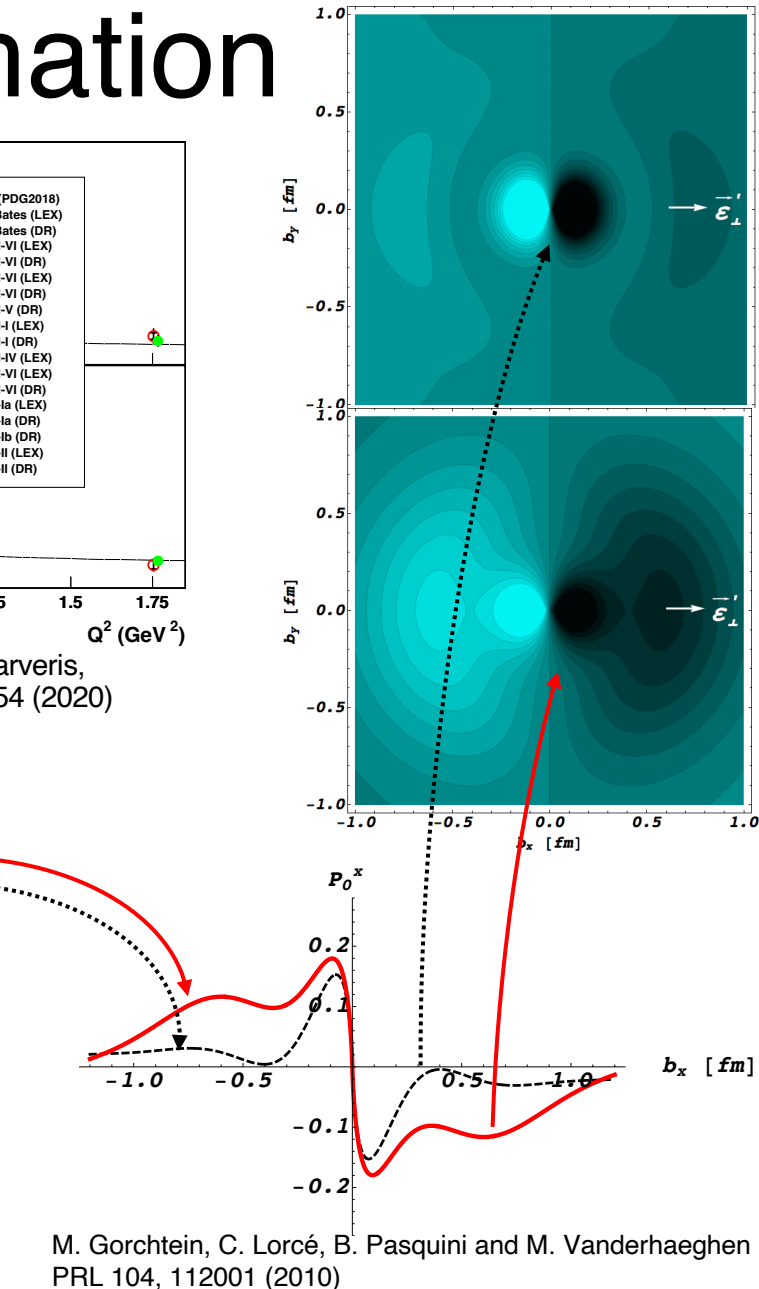
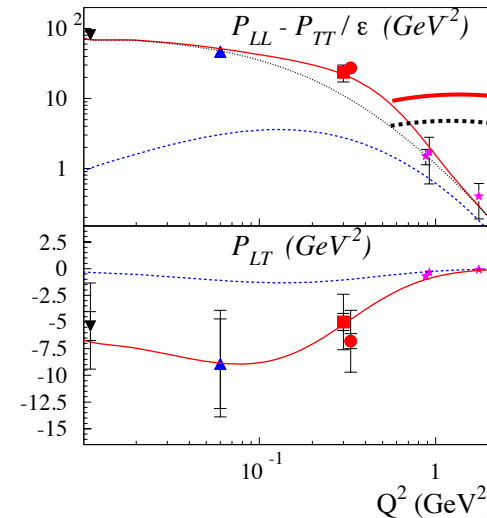
H. Fonvieille, B. Pasquini & N. Sparveris,
 Prog. Part. Nucl. Phys. 113, 103754 (2020)

Imaging the charge density deformation

- GPs can be transformed to charge density deformation with respect to the direction of induced polarization in the light-front frame
- The MAMI results have a sizeable impact on the induced polarization mapping
- Independent measurements are needed to confirm the local enhancement



H. Fonvielle, B. Pasquini & N. Sparveris, Prog. Part. Nucl. Phys. 113, 103754 (2020)

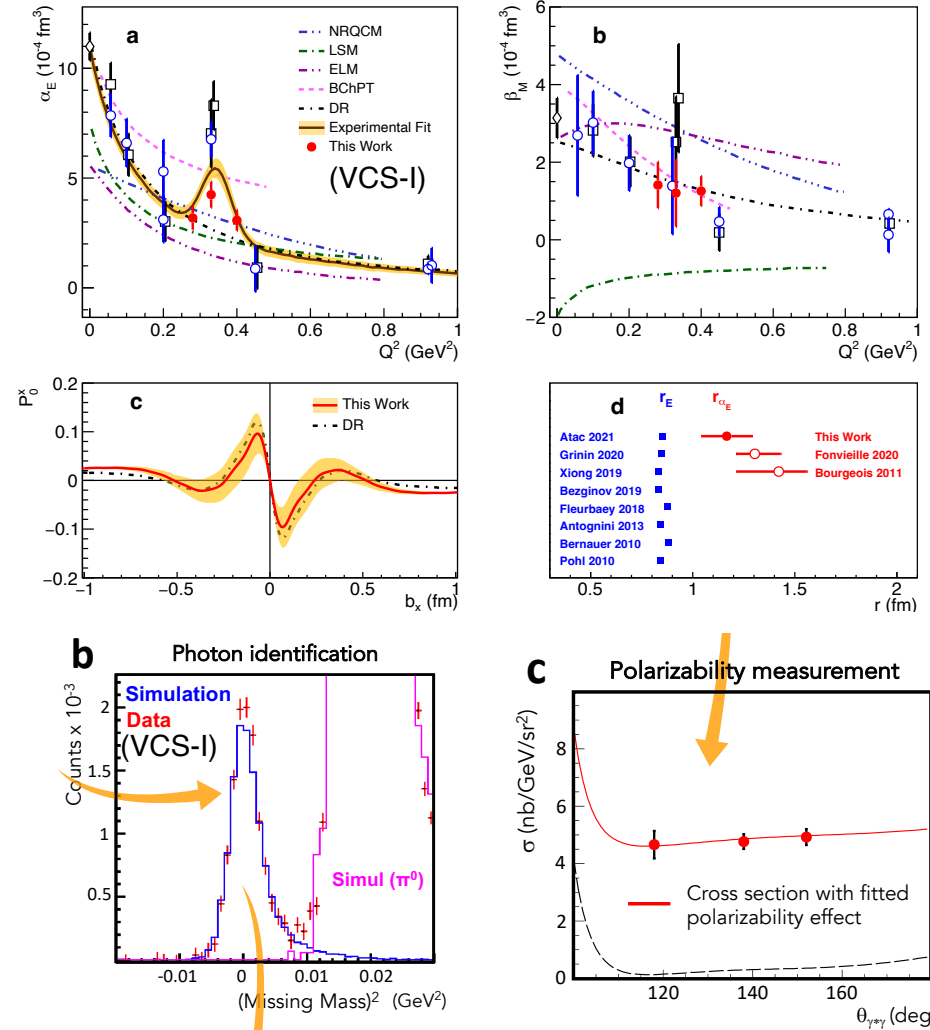


M. Gorchtein, C. Lorcé, B. Pasquini and M. Vanderhaeghen PRL 104, 112001 (2010)

VCS Experiment (E12-15-001)

- The VCS Experiment at Hall C, Jefferson Lab ran for about 16 days in 2019 with the 4.6 GeV electron beam and 10 cm LH2 target
 - The result is consistent with the local enhancement of the proton electric GP (although with a smaller magnitude compared to the earlier measurements), but cannot exclude the structure is coincidental
 - The Q^2 dependence of the magnetic GP needs data over a wider range
 - The VCS experiment demonstrated that the systematics of the Hall C measurement are under control
- A high-precision measurement over a broader kinematic range is needed for a quantitative understanding.

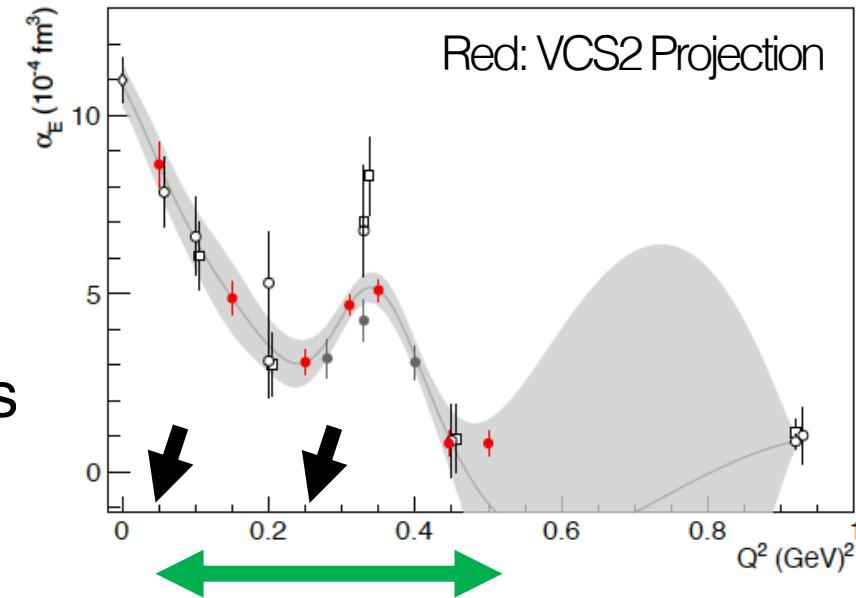
→ VCS-II Experiment



R. Li et al. (VCS Collaboration),
Nature Vol 611, p. 265–270 (2022)

VCS-II Experiment (E12-23-001)

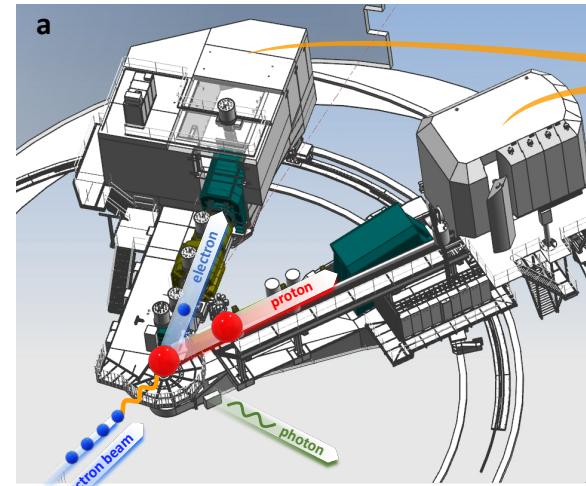
- A high-precision VCS program covering Q^2 from 0.05 to 0.5 GeV^2 will provide the Q^2 dependence of the GPs needed to reconstruct the spatial distribution of the induced polarization in the proton
- The VCS-II Phase1 for two Q^2 settings (black arrows) was successfully completed in spring 2026
 - 0.05 GeV^2 : 1.4 GeV beam energy
 - 0.25 GeV^2 : 2.1 GeV beam energy
- Each Q^2 setting consists of several recoil proton kinematics settings to measure the cross section and its azimuthal dependence



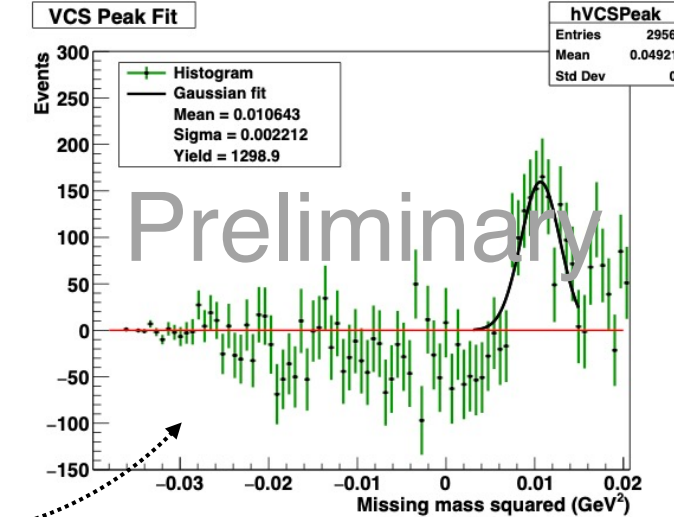
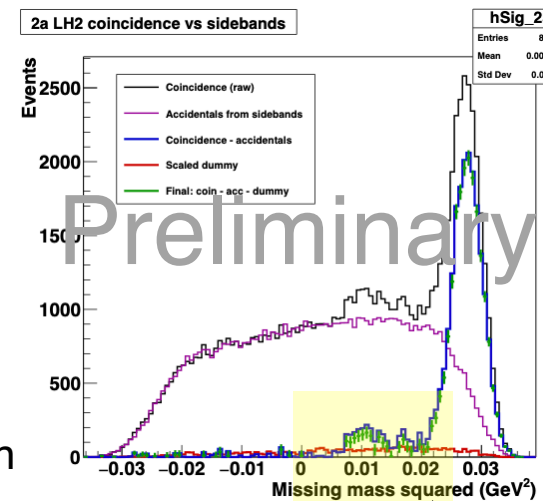
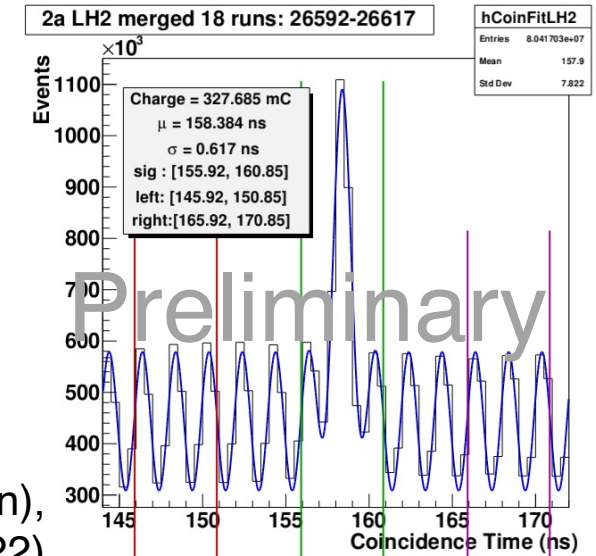
From VCS Collaboration,
Proposal for E12-23-001, PAC 51

VCS-II Production Runs

- Data were collected with a 10 cm LH2 target (and a dummy Al foil) for VCS-II
 - 4 cm LH2 target and a dummy target for N-Delta
- The trigger was a coincidence of e' and p'
 - The timing was tuned to each proton velocity (time of flight).
- The clear separation of π^0 and photon peaks allowed online yield monitoring to optimize the measurement time while ensuring sufficient statistics for analysis
- A minor shift of π^0 and photon peaks indicates the need for an energy loss correction
- Calibration and analysis efforts are underway.
 - The preliminary plots on the right are before the calibration



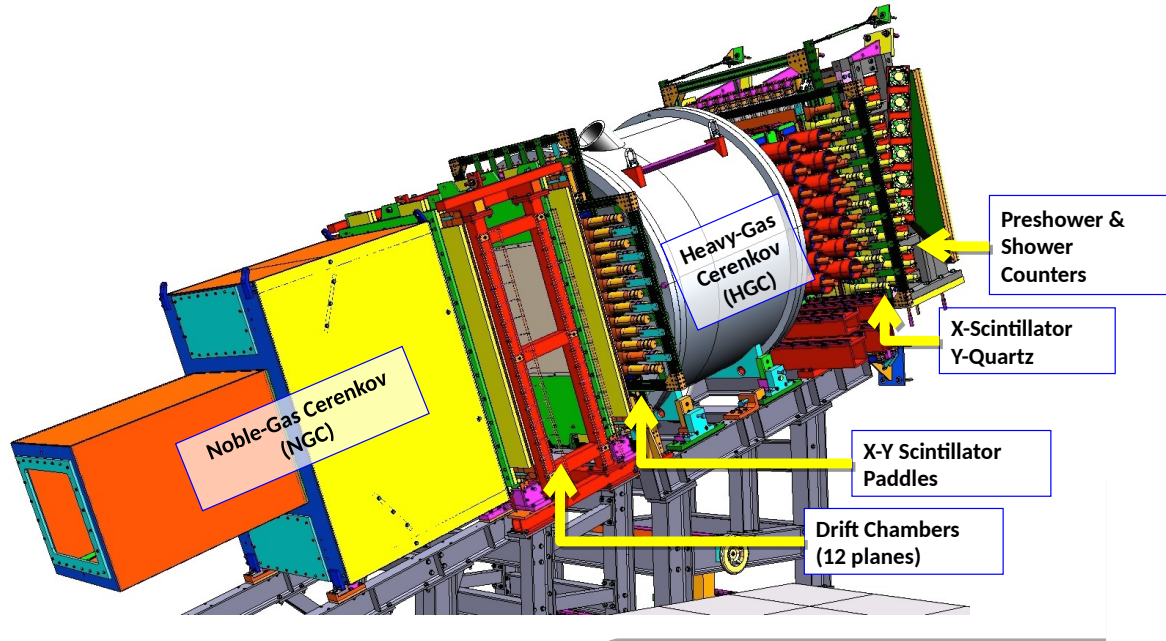
R. Li et al. (VCS Collaboration),
Nature Vol 611, p. 265–270 (2022)



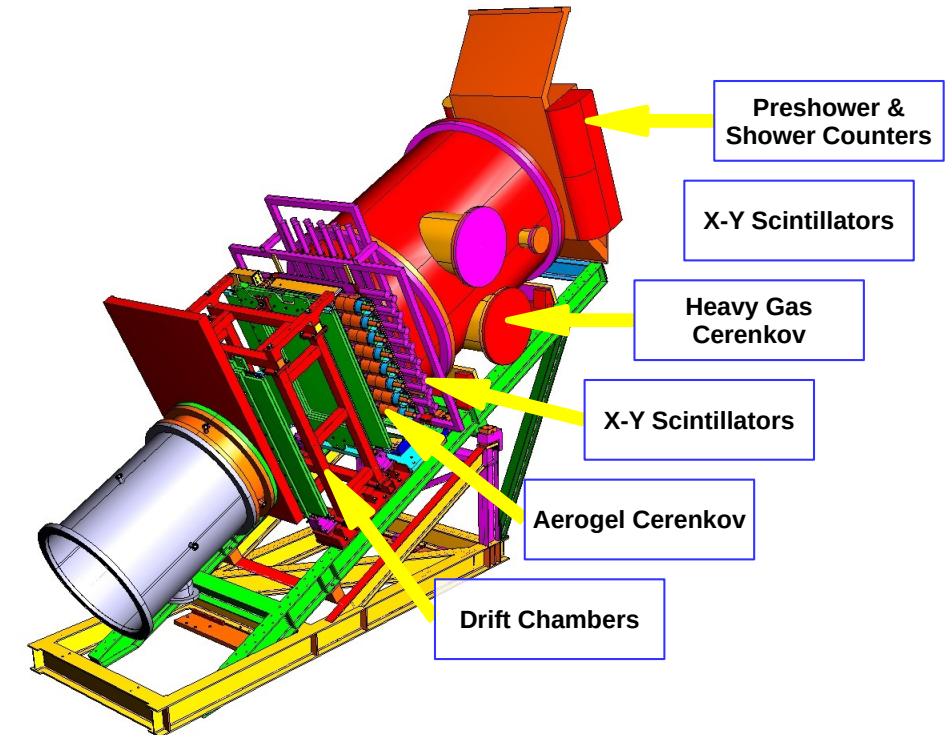
Plots by W. Hamdi Jefferson Lab

Jefferson Lab Hall C SHMS and HMS

SHMS



HMS

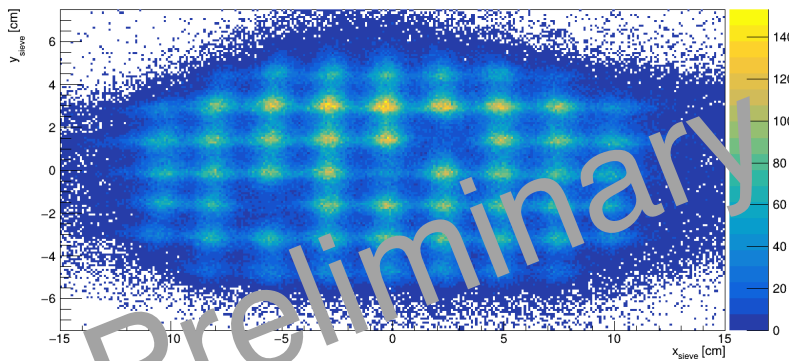


S. Ali et al (Jefferson Lab Hall C), NIM A 1083 (2026) 171070

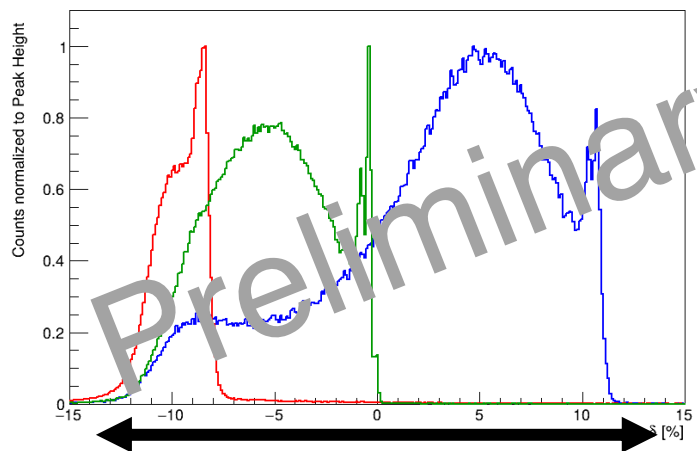
- VCS2 experiment uses the (fairly) standard Hall C spectrometer setup.
 - No SHMS NGC for Phase 1, No aerogels are needed
 - The first low beam run (1.4 GeV/ 2.1 GeV) after 12 GeV upgrade
 - low central momentum setting (electron: 1–1.6 GeV/c, proton: 0.5–1.0 GeV/c)
- ➔ Calibration!

VCS-II Calibration Runs

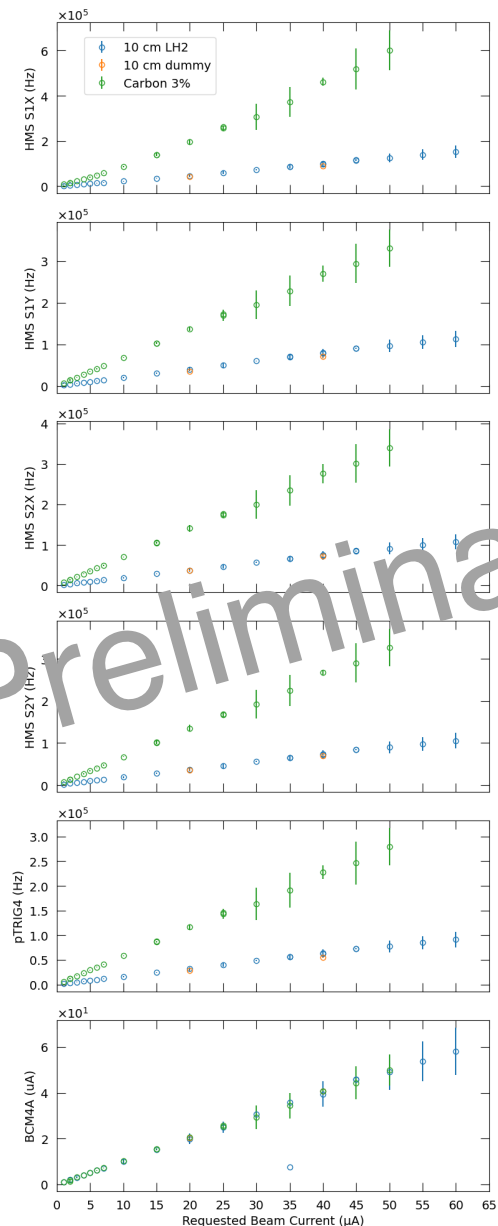
- Dedicated calibration data were collected for the following systematic study
 - Single-arm optics calibration
 - Single arms with a sieve slit and a carbon target
 - Delta scan with the carbon target
 - Trigger efficiency: Elastic scattering $p(e, e')p$, $p(e, e'p)$
 - Normalization: beam current monitor calibration with various beam currents



HMS optics run at 1.0 GeV/c
The sieve slit geometry is documented on the Hall C wiki.



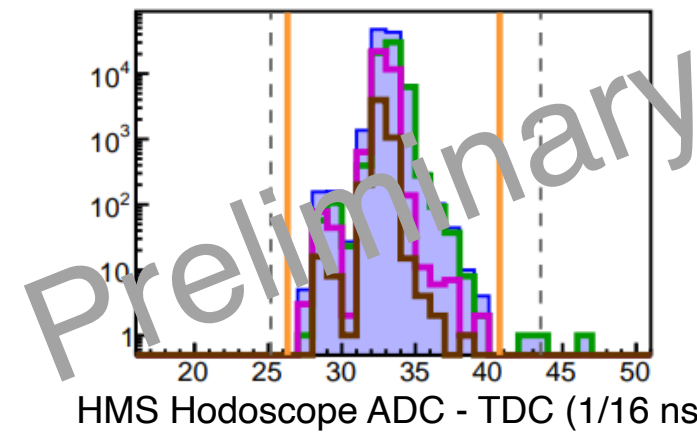
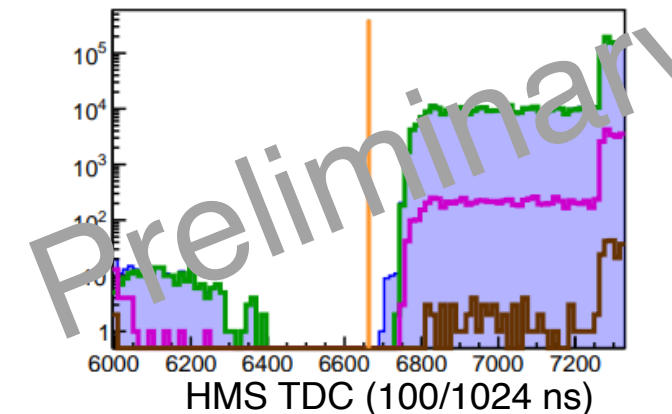
HMS Delta (dp/p) scan range
The carbon elastic peaks and the inelastic region



Scaler rates (hodoscope, trigger, and BCM) vs requested beam current

VCS-II Calibration and Analysis Status

- The calibration and analysis steps that affect downstream procedures were completed in summer 2026.
 1. Run condition database management
 2. TDC and ADC reference time
 3. Detector time window
 4. Hodoscope timing calibration
 - timewalk correction
 - cable time correction
 - plane-to-plane time offsets
- Members of the N-Delta and VCS2 collaborations, including Temple, NMSU, and Jefferson Lab, contributed to the calibration
- Other detector calibrations will proceed in parallel in fall 2026



Wrapping up the hodoscope time window cuts (#42)

Sangbaek authored on Aug 28

Commits on Aug 24, 2026

Add hodoscope timing cuts for run 26369 (#41)

psmith313 authored on Aug 24

Add hodoscope timing window cuts for run#27064 (#40)

suman0725 authored on Aug 24

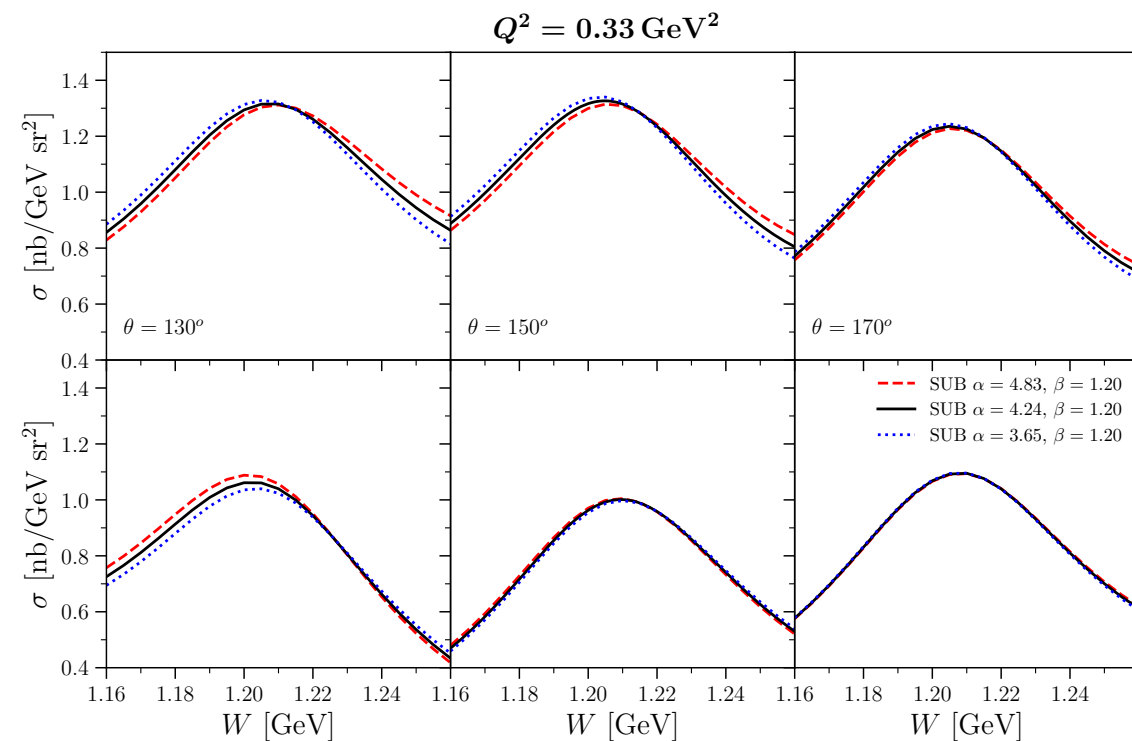
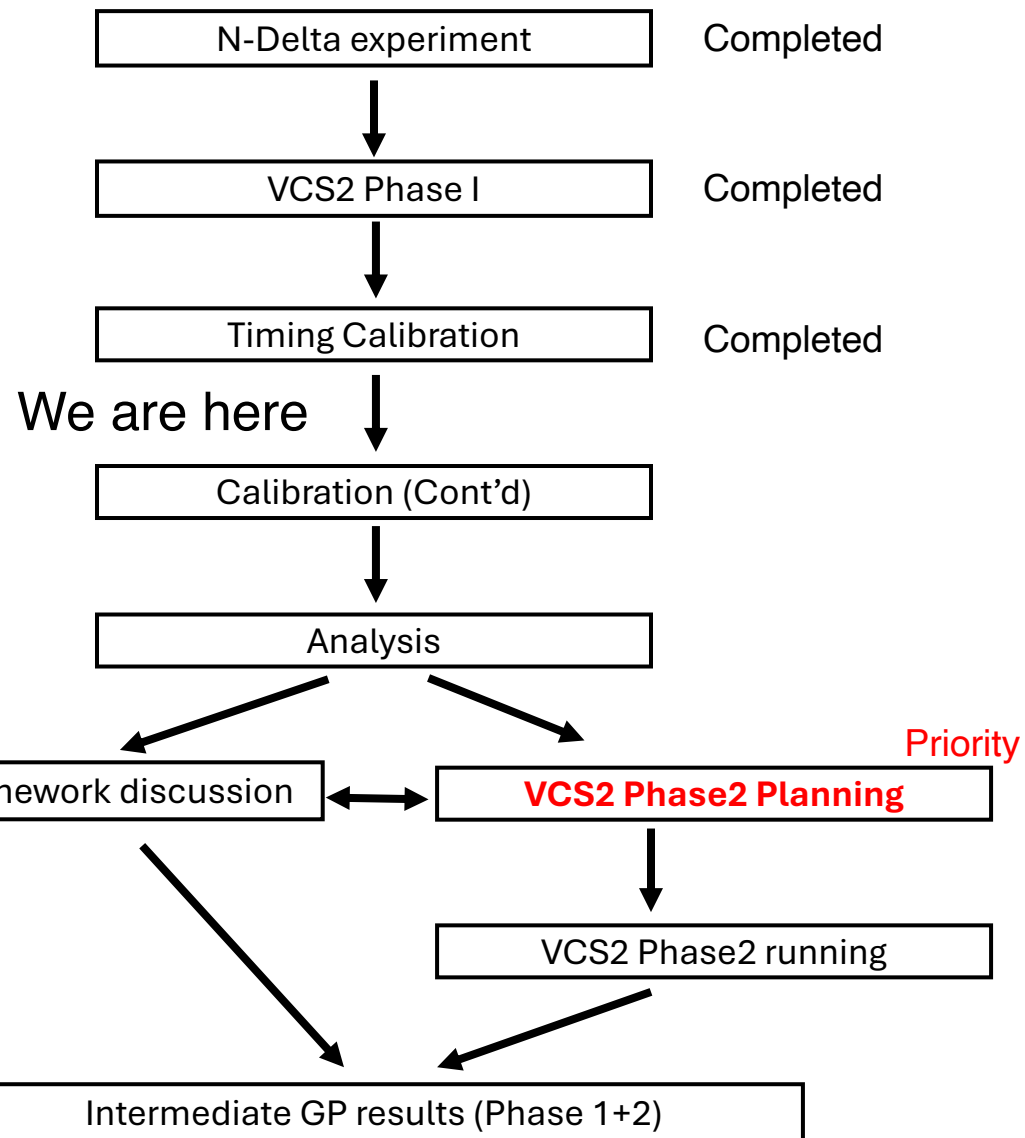
Add hodoscope timing-window calibration for run 26382 (#39)

cp-95 and Chathuri Kekuluthotuwage Don authored on Aug 24

Add hodoscope timing window calibration for run 26549 (#38)

nanayakkarahareendra-bot and Thareendra Nanayakkara authored on Aug 24

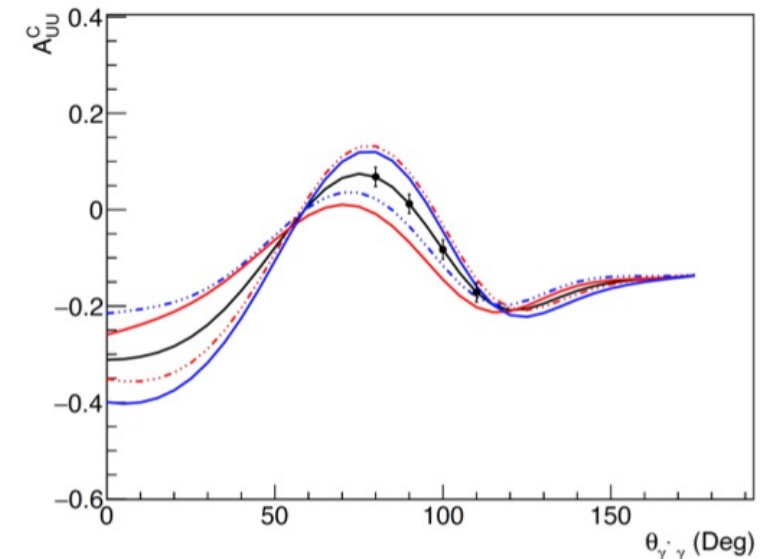
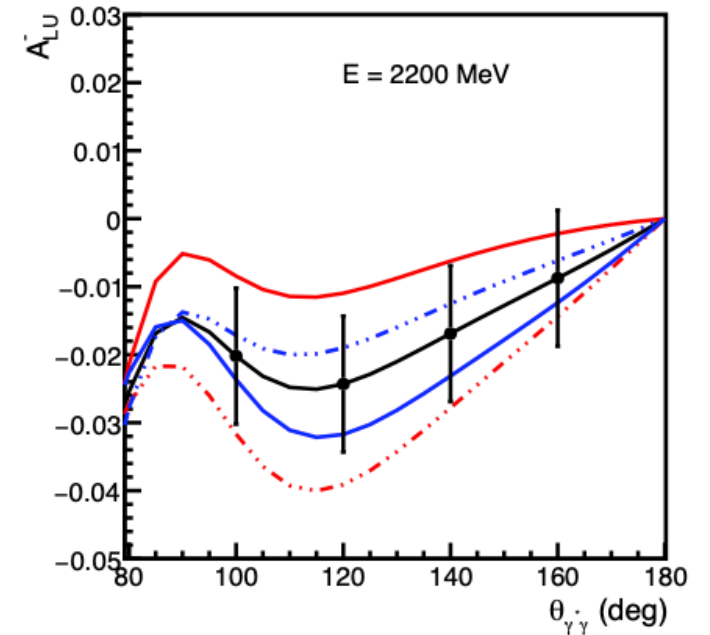
VCS-II Path Forward



I. Danilkin et al., PRD 114, 054035 (2026)

Future VCS experiments: VCS-III

- The VCS-III experiment (E12-25-008), which is the first measurement of the VCS beam-spin asymmetry (BSA), has been approved by the JLab PAC.
- This first measurement will provide new method to measure the GPs
- More theory details: I. Danilkin et al., PRD 114, 054035 (2026)
- The beam-charge asymmetry (BCA) is also sensitive to GPs. The BCA possibility and projection were also discussed in the same proposal.
- More theory details: B. Pasquini and M. Vanderhaeghen, EPJ A 57 (2021) 11, 316



From E12-25-008 Proposal

Summary

- The VCS-II experiment will provide measurements of unprecedented precision for the electric and the magnetic GPs and for the polarizability density in the proton and it will address the open question in regard to the observed electric polarizability structure at intermediate Q^2 .
- The VCS-II Experiment Phase1 were successfully completed at Hall C, Jefferson Lab. The calibration and analysis of the datasets are underway. The next phase of VCS-II Experiment will be performed next year.
- Future experiments with alternative techniques will provide independent cross-check for the GP measurement.