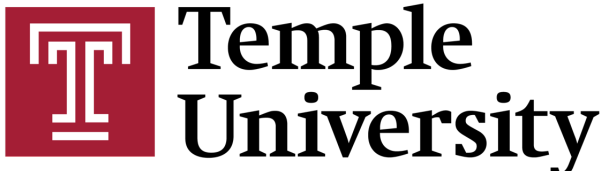
E12-23-001

Measurement of the Generalized Polarizabilities of the Proton in Virtual Compton Scattering

Sangbaek Lee

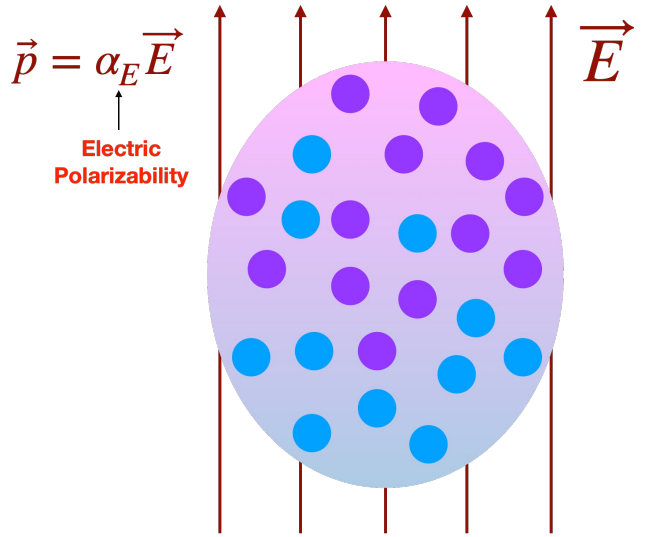
On behalf of VCS Collaboration

Hall C Winter Collaboration Meeting 2026, Virtual

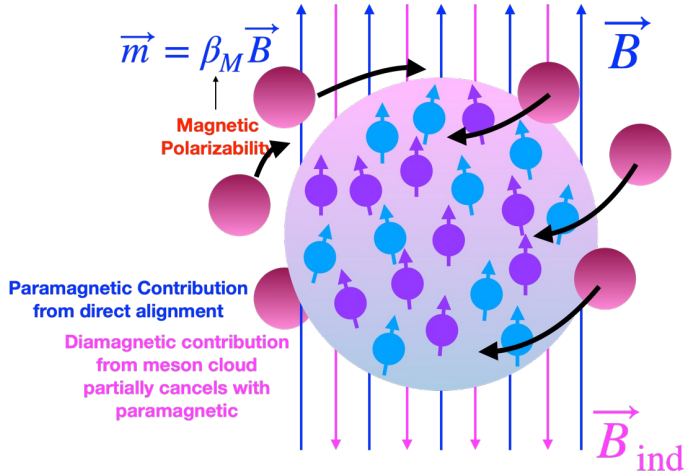


Electromagnetic (EM) Polarizabilities of Proton

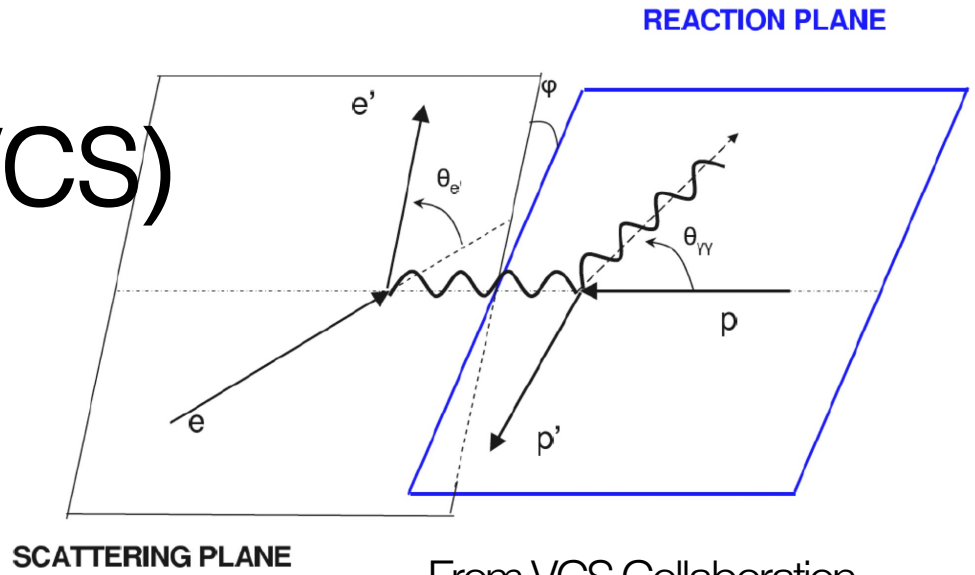
- Scalar EM Polarizability
  - Fundamental observables characterizing the proton's electromagnetic response
  - Defined as the ratio of the induced dipole moment to the applied local EM field
  - Different from intrinsic dipole moment



- Scalar EM Polarizabilities can be measured with Real Compton Scattering $\gamma p \rightarrow \gamma p$
  - The outgoing photon plays the role of the applied EM field.



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

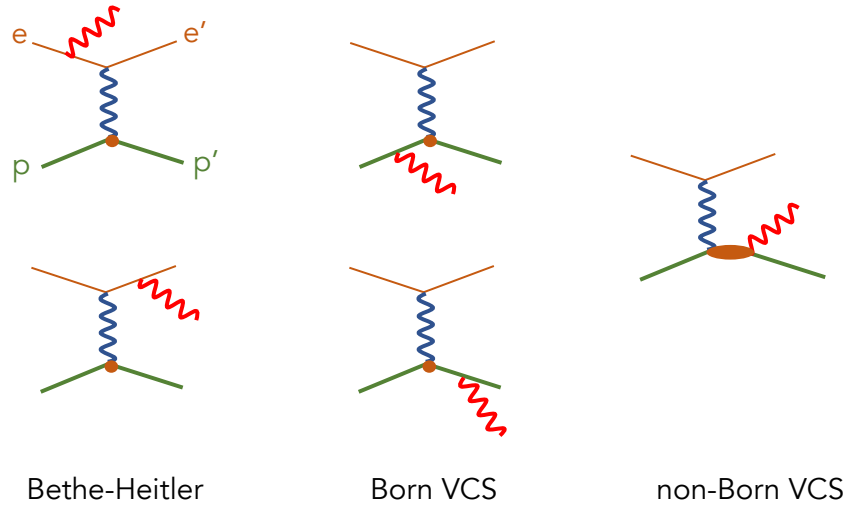


From VCS Collaboration, Proposal for E12-23-001, PAC 51

- GPs are accessed via Virtual Compton Scattering (VCS) $\gamma^* p \rightarrow \gamma p$ and extend the concept of the static EM polarizabilities to finite momentum transfer.

- GPs depend on Q^2, enabling spatial imaging of the proton's polarization densities.

- Scalar GPs reduce to the static EM polarizabilities in the RCS limit ($Q^2 \rightarrow 0$)



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

Static EM Polarizabilities and Scalar GPs

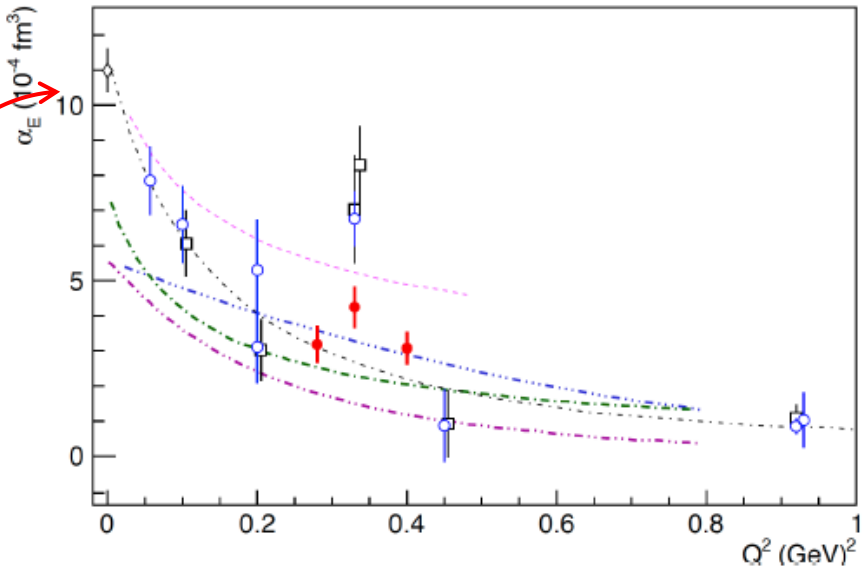
Listed in the PDG as a fundamental property:

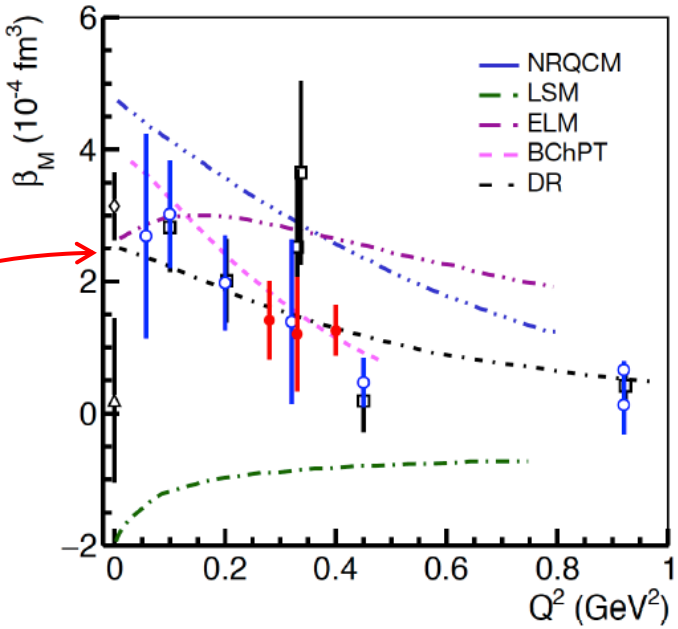
$$\alpha = (11.5 \pm 0.4) \times 10^{-4}\ \text{fm}^3$$
$$\beta = (2.31 \pm 0.29) \times 10^{-4}\ \text{fm}^3$$

p $I(J^P) = 1/2(1/2^+)$

Expand/Collapse A

p MASS (atomic mass units u)		$1.007276466621 \pm 0.000000000053$ u
p MASS (MeV)	[1]	$938.27208816 \pm 0.00000029$ MeV
$\lvert m_p - m_{\bar{p}} \rvert / m_p$	[2]	$< 7 \times 10^{-10}$ CL=90%
$\overline{p}/p$ CHARGE-TO-MASS RATIO, $\lvert \frac{q_{\bar{p}}}{m_{\bar{p}}} \rvert / (\frac{q_p}{m_p})$		$1.000000000003 \pm 0.000000000016$
$(\lvert \frac{q_{\bar{p}}}{m_{\bar{p}}} \rvert - \frac{q_p}{m_p}) / \frac{q_p}{m_p}$		$(0.3 \pm 1.6) \times 10^{-11}$
$\lvert q_p + q_{\bar{p}} \rvert / e$	[2]	$< 7 \times 10^{-10}$ CL=90%
$\lvert q_p + q_e \rvert / e$	[3]	$< 1 \times 10^{-21}$
p MAGNETIC MOMENT		$2.7928473446 \pm 0.0000000008\ \mu_N$
$\overline{p}$ MAGNETIC MOMENT		$-2.792847344 \pm 0.000000004\ \mu_N$
$(\mu_p + \mu_{\bar{p}}) / \mu_p$		$(2 \pm 4) \times 10^{-9}$
p ELECTRIC DIPOLE MOMENT		$< 2.1 \times 10^{-25}\ e$ cm
p ELECTRIC POLARIZABILITY α_p		0.00115 ± 0.00004 fm^3 (S = 1.1)
p MAGNETIC POLARIZABILITY β_p		$(2.31 \pm 0.29) \times 10^{-4}$ fm^3 (S = 1.1)





From PDG Live, Accessed 01/19/2026

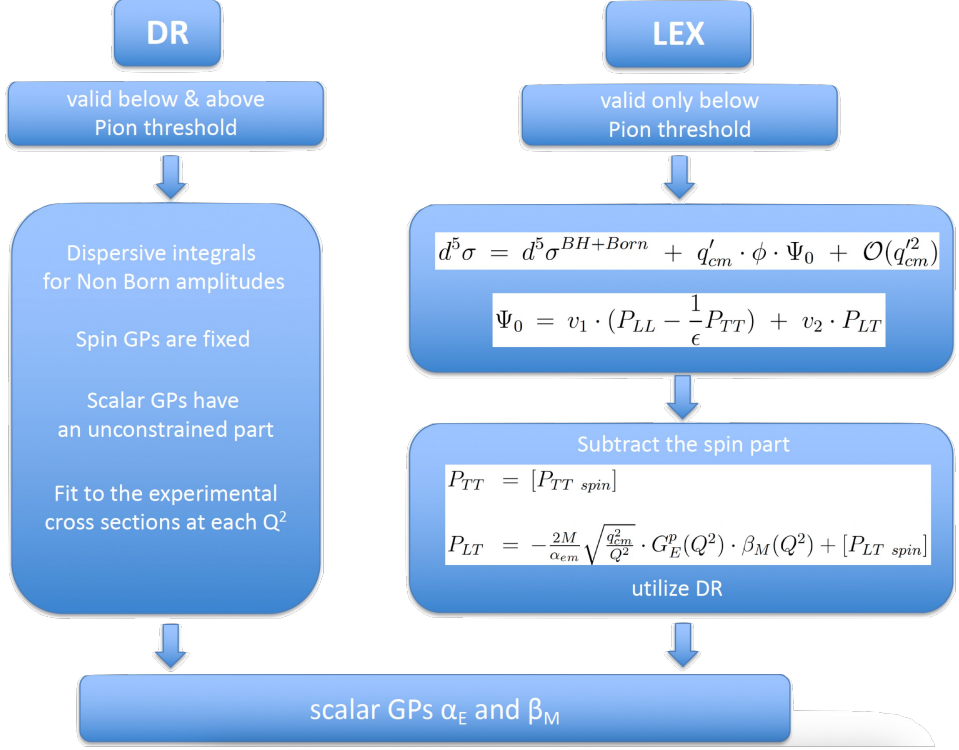
From VCS Collaboration, Proposal for E12-23-001, PAC 51

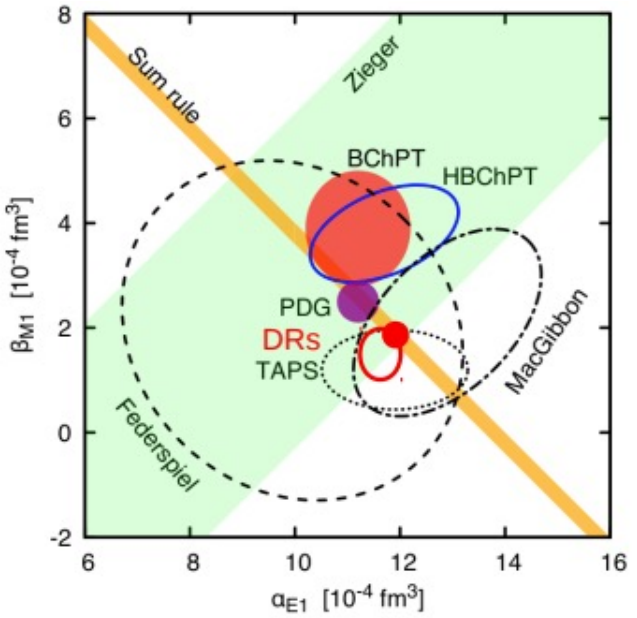
VCS Analysis Framework

- Traditionally, there are two methods to extract the polarizabilities:
  - The DR (dispersion relations) method:
    - Available above and below the pion production threshold
    - The scalar polarizabilities enter as free fit parameters.
  - The LEX (Low energy expansion) method
    - Valid only below the pion threshold

- The sensitivity of the VCS cross sections to the GPs increases with the photon energy, or W.
  - Motivates measurements above the pion threshold, up to *Δ* resonance

- Jefferson Lab Hall A measurements demonstrate consistency between DR and LEX frameworks
  - PRL 93, 122001 (2004)
  - PRC 86, 015210 (2012)

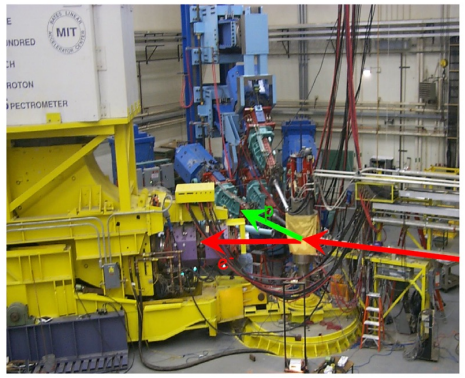




From B. Pasquini, M. Vanderhaeghen Ann. Rev. Nucl. Part. Sci. 68 (2018)

Early Experiments

MIT-Bates @ Q^2=0.06 GeV²



MAMI-A1 @ Q^2=0.33 GeV²

Jlab-Hall A @ Q^2=0.9 & 1.8 GeV²

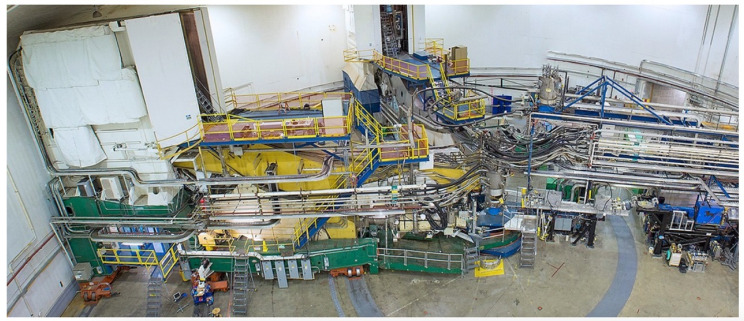
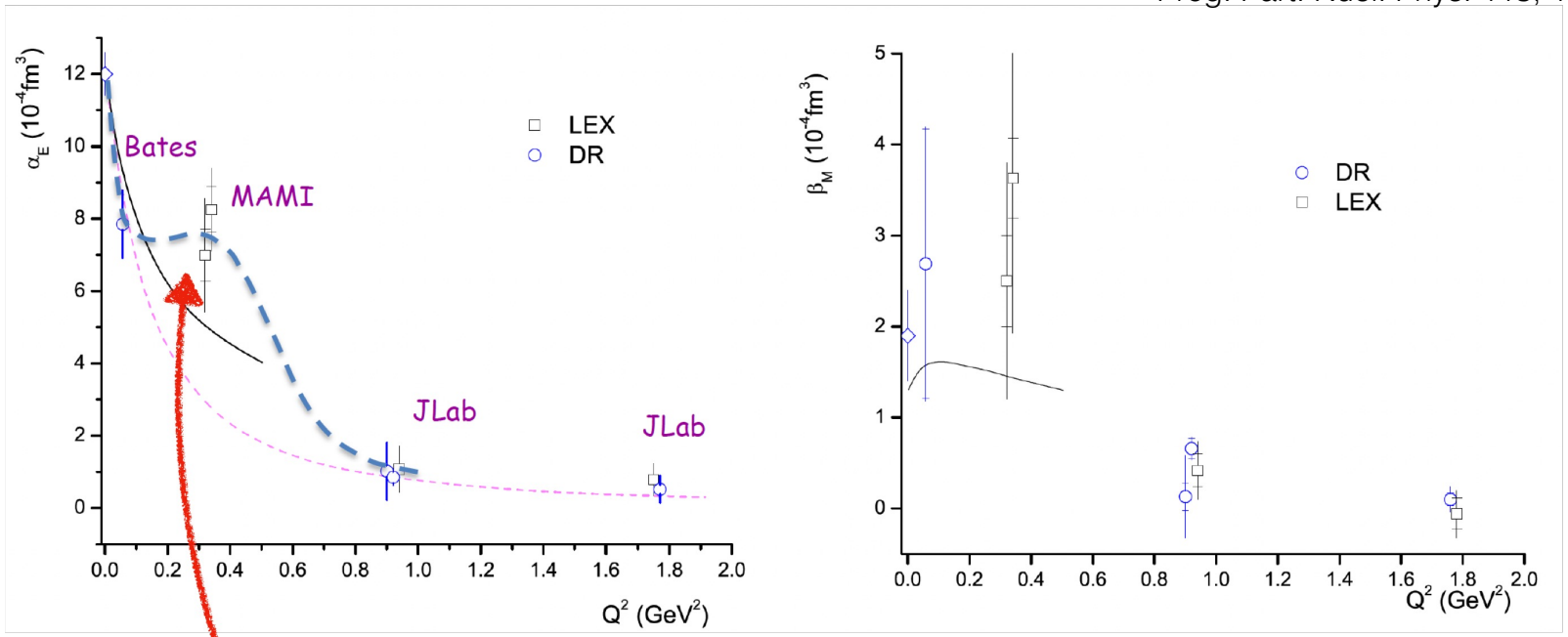


Table 2: Type of VCS experiments (in chronological order).

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

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



Initial investigations showed that the proton generally increases in stiffness as Q^2 increases.

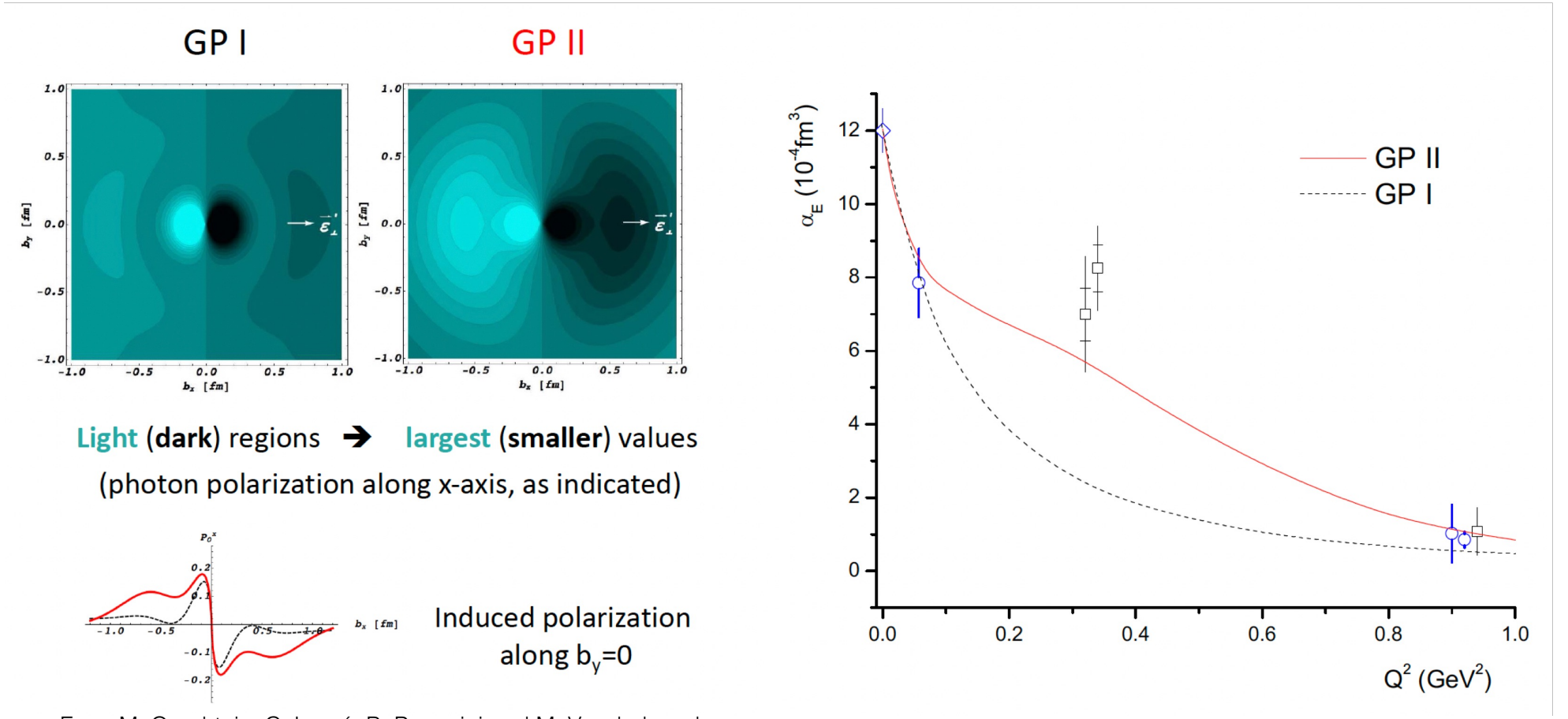
Early $Q^2 = 0.33$ GeV^2 measurement at MAMI seemed to buck the trend of a monatomic decrease. A second measurement at MAMI had similar results.

Phys. Rev. Lett 85, 708 (2000)

Eur. Phys. J. A37, 1-8 (2008)

Spatial Dependence of Induced Polarizations

- In the same vein of transforming nucleon form-factor data to quark charge density on the light-cone:
  - Generalized polarizabilities can be transformed to density deformation with respect to the direction of induced polarization.

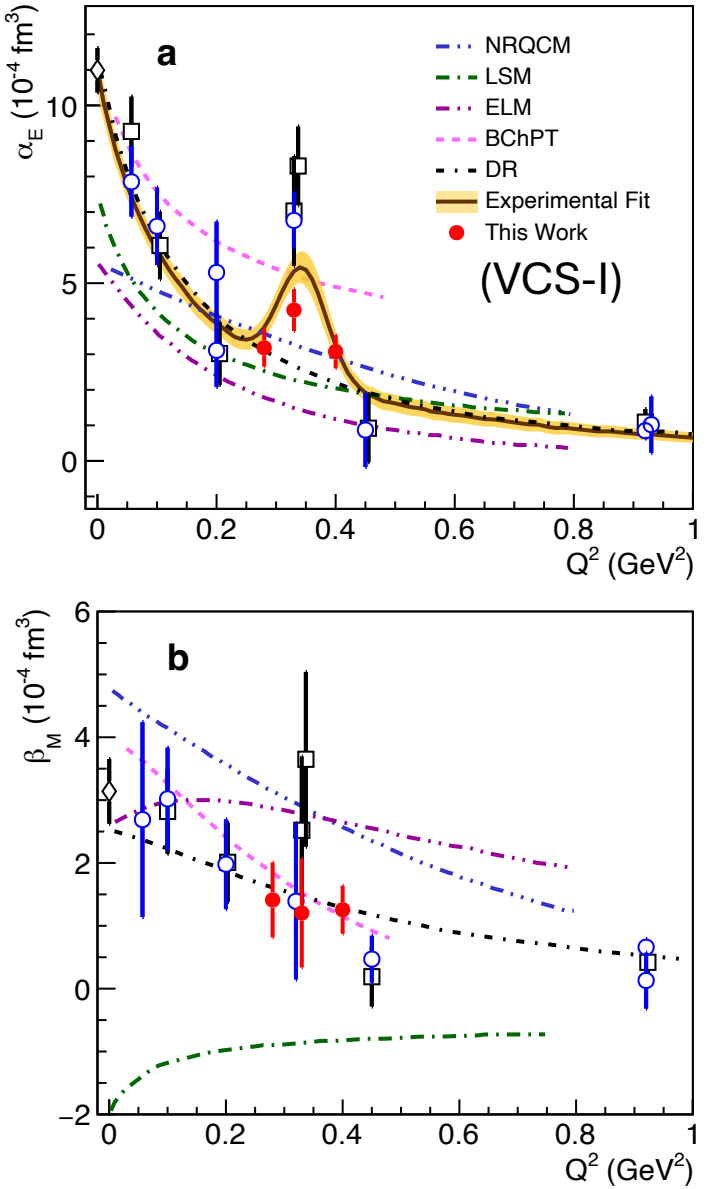


From M. Gorchtein, C. Lorcé, B. Pasquini and M. Vanderhaeghen
PRL 104, 112001 (2010)

World Data of GPs

- Early **MAMI measurements** revealed an unexpected local enhancement near Q^2=0.33 GeV^2
- The Hall C E12-15-001 (VCS-I) experiment confirmed the structure at Q^2~0.33 GeV^2 (red dots)
- Theoretical calculations predict a monotonic decrease of electric GP $\alpha_E(Q^2)$ with increasing Q^2
- World data for the magnetic GP $\beta_M(Q^2)$ show large uncertainties and inconsistences
- A high-precision measurement over a broader kinematic range is needed for a quantitative understanding.

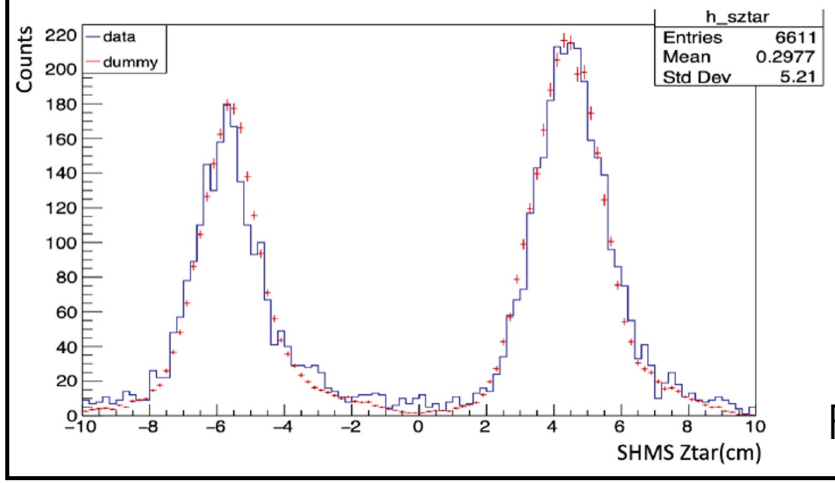
  → VCS-II Experiment



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

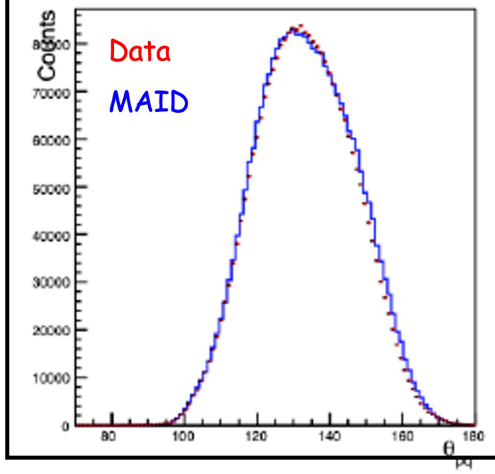
Overview of VCS-I Analysis

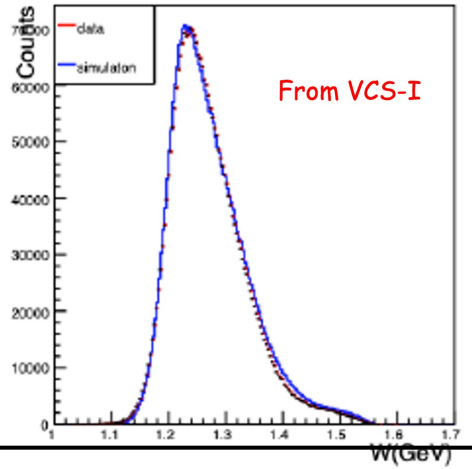
Dummy Subtraction



From R. Li, PhD Thesis (2022)

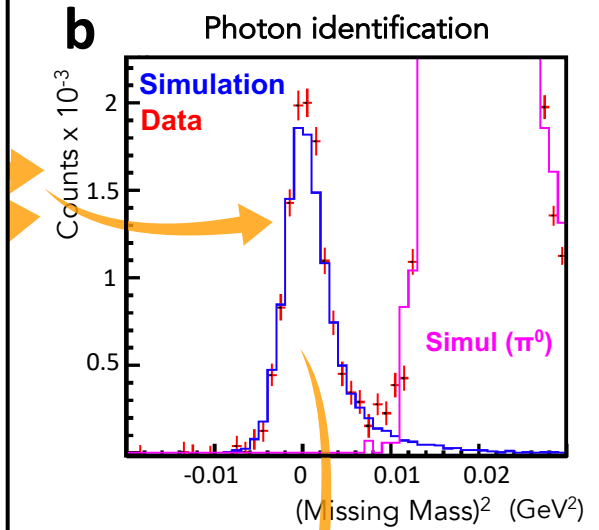
$p(e,e'p)\pi^0$ Background Characterization and Subtraction

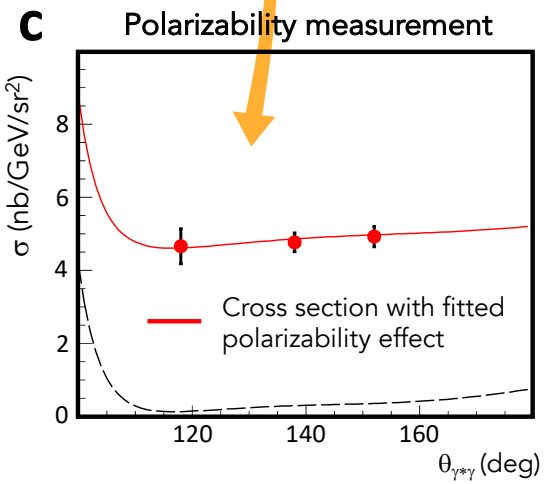




From VCS Collaboration, Proposal for E12-23-001, PAC 51

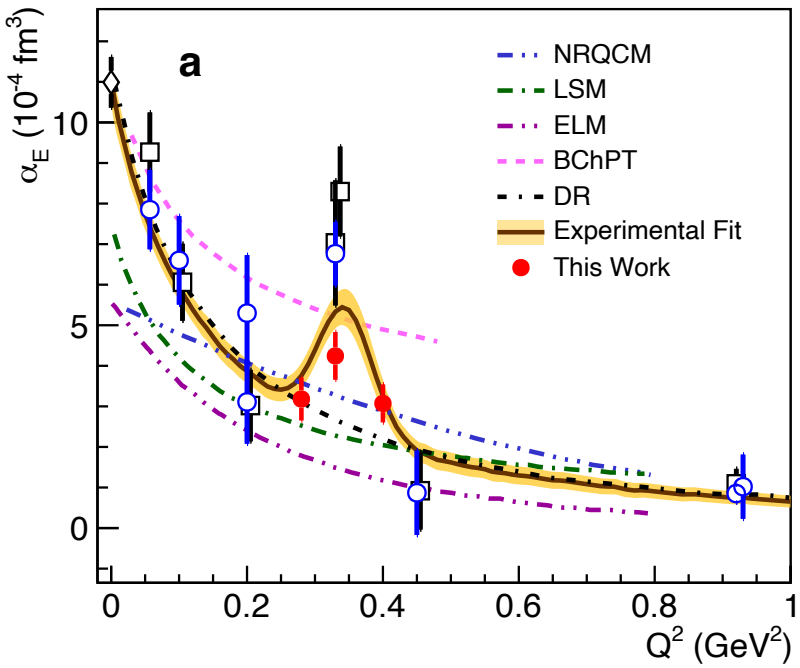
Cross Section Extraction

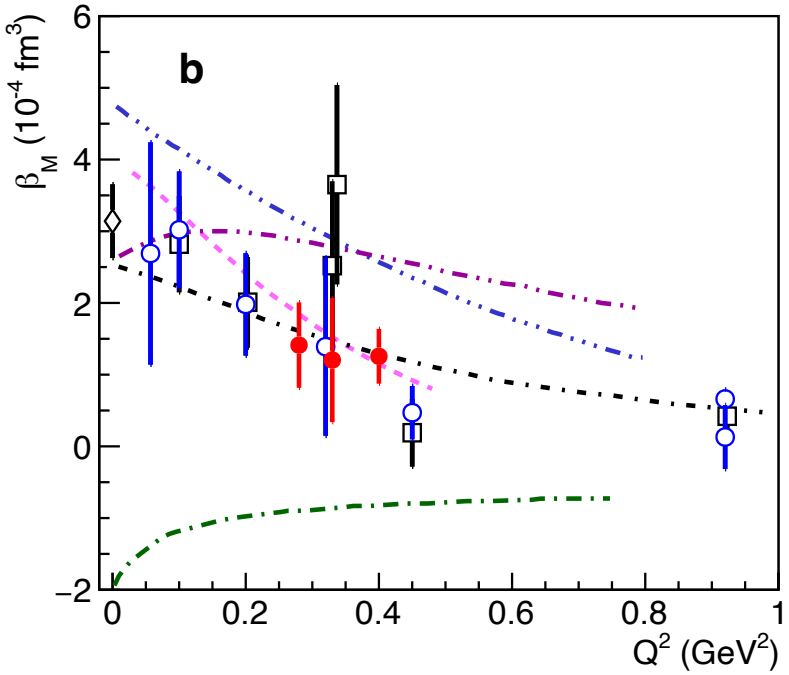


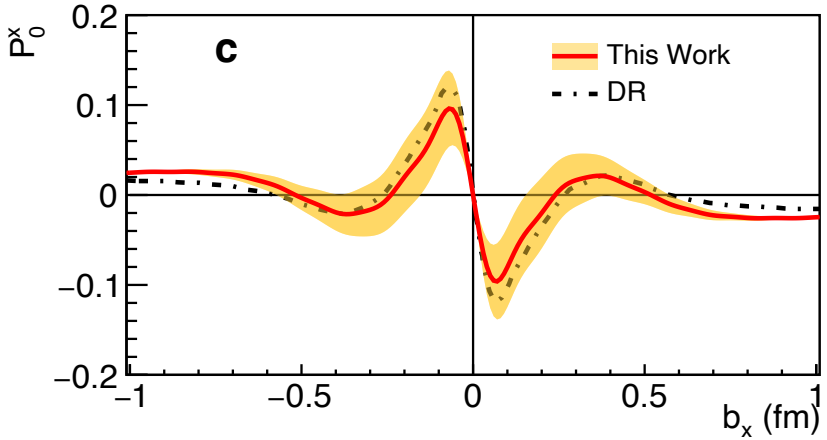


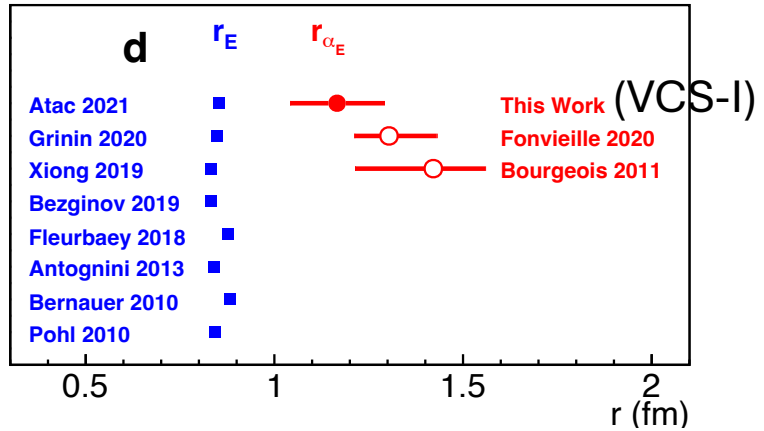
From R. Li *et al.* (VCS Collaboration), Nature Vol 611, p. 265–270 (2022)

Highlights of VCS-I Measurement







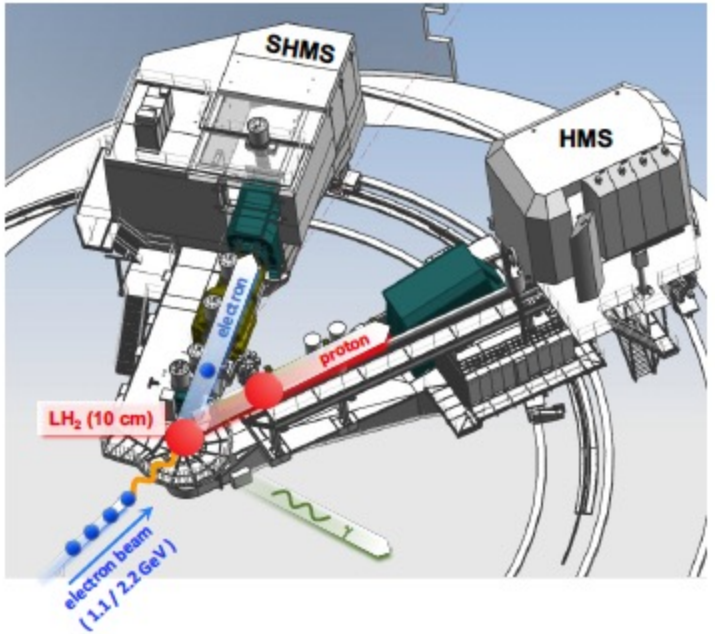


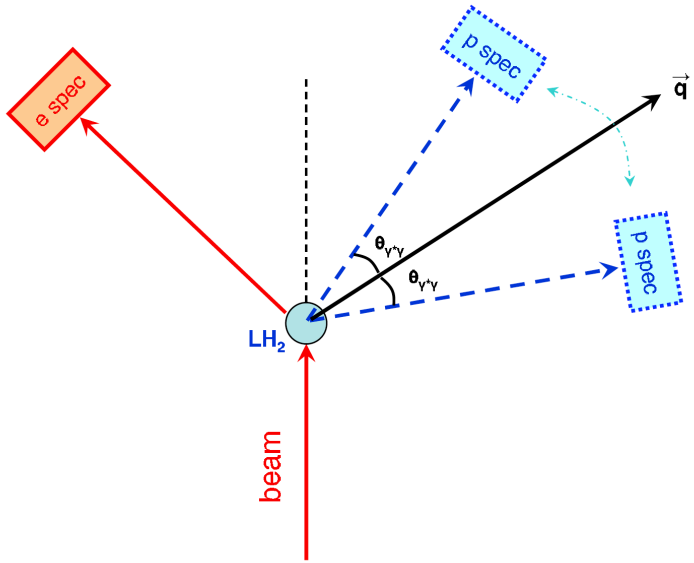
From R. Li *et al.* (VCS Collaboration), Nature Vol 611, p. 265–270 (2022)

Planned VCS-II Experiment

- An expanded **Hall C VCS measurement (VCS-II)** will be carried out in **2026–2027**

- A high-precision VCS program covering Q^2 from 0.05 to 0.5 GeV^2 will provide critical data to map the **spatial distribution of polarization densities** in the proton

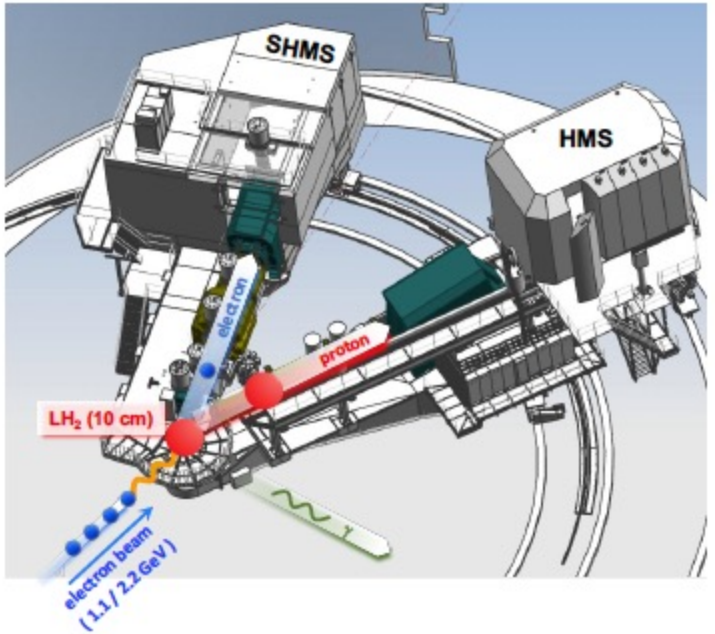


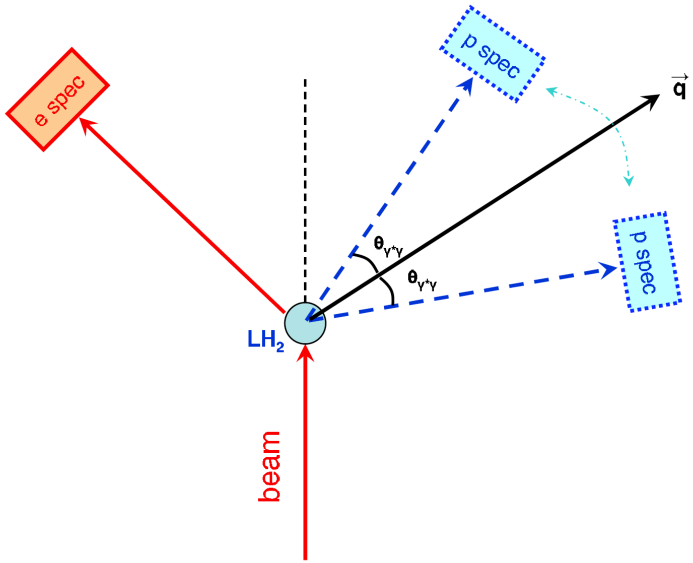


From VCS Collaboration, Proposal for E12-23-001, PAC 51

VCS-II Experimental Setup

- The standard 10-cm liquid hydrogen target will be used.
- The scattered electron will be detected with the SHMS and the recoil proton with the HMS, at the following angular setting.
  - SHMS: 10.5—11.8°
  - HMS: 13.6—56.3°
- Primary observables
  - Absolute cross sections
  - In-plane azimuthal asymmetries
- DAQ will employ a coincidence trigger

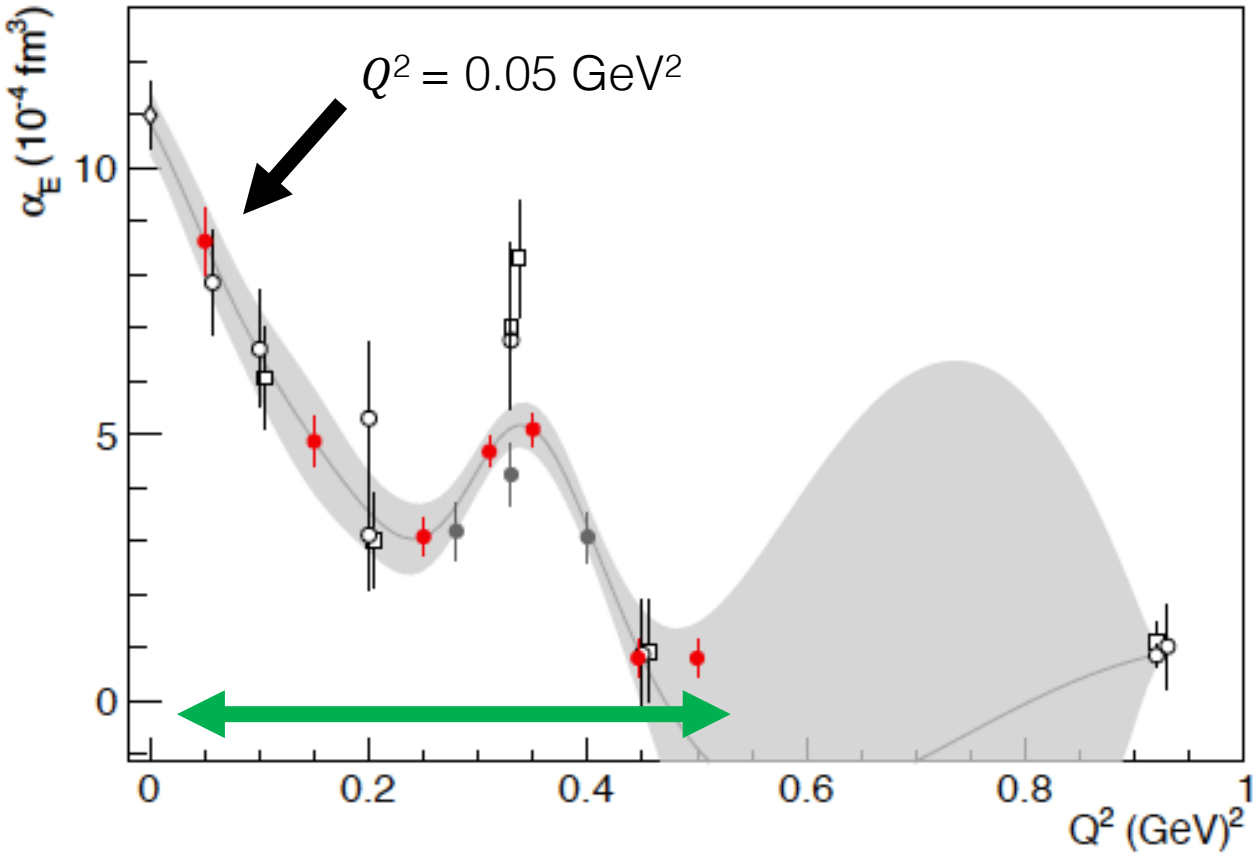




From VCS Collaboration, Proposal for E12-23-001, PAC 51

VCS-II Run Plan

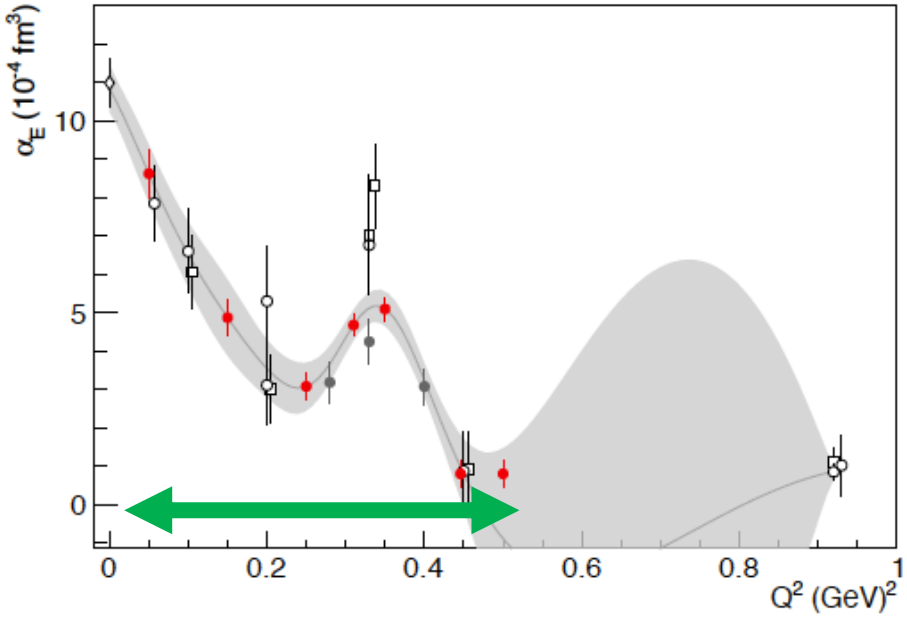
- Red data points indicate **VCS-II projected measurements**
- The program was approved for **59 PAC days of production** and **3 PAC days of calibration**
- A total of **30 calendar days** is scheduled for the upcoming run period this year.
  - This corresponds to **two kinematic settings**
  - The lowest Q^2 setting (0.05 GeV^2) will be measured first with the same beam energy (~1.4 GeV) as the N-Δ experiment.

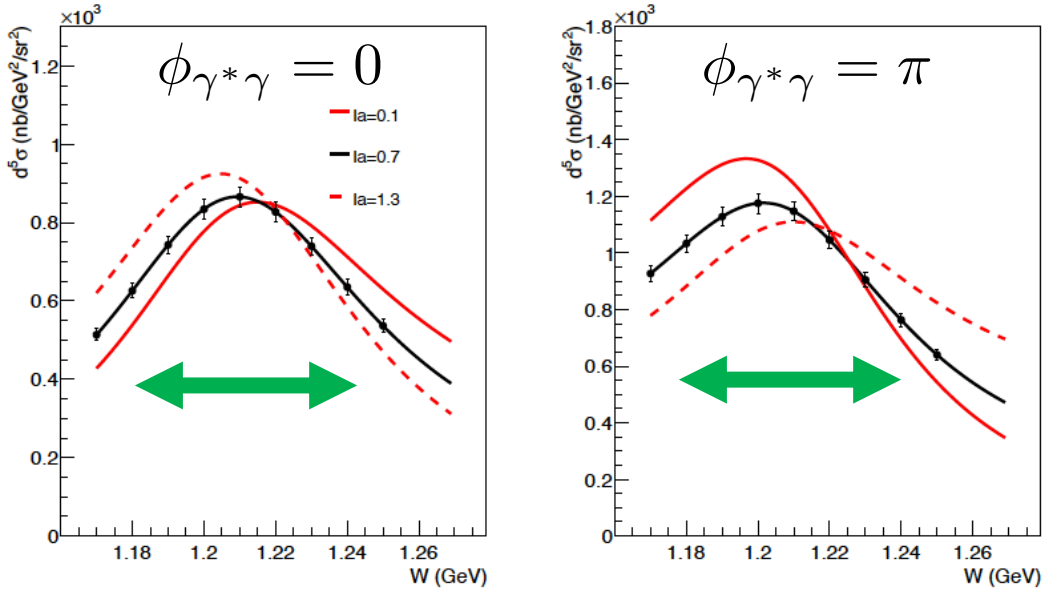


From VCS Collaboration, Proposal for E12-23-001, PAC 51

VCS-II Run Plan (Cont'd)

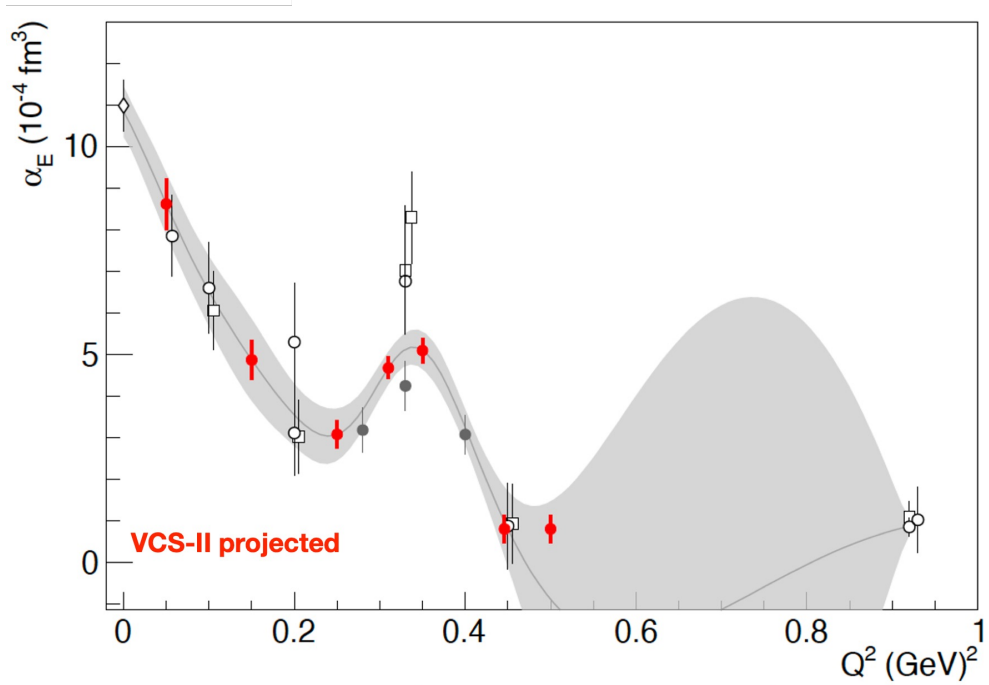
- Remaining kinematic points will be measured using ~2.1 GeV beam
- One additional kinematic setting will be measured **this year**, with the remaining setting scheduled for **next year**
- Measurement at W = 1.19 GeV will enable a study of the W-dependence of cross section.





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

VCS-II Primary Experiment Goals

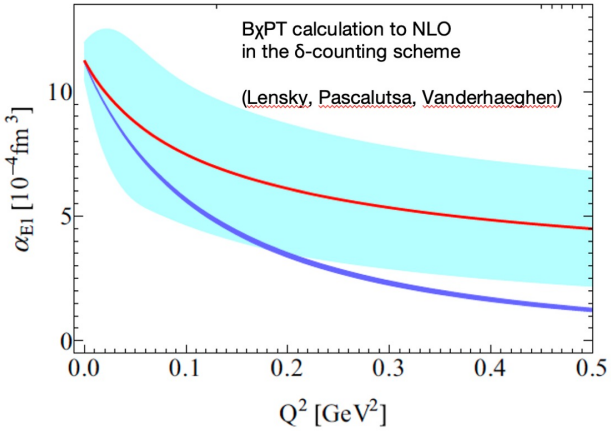


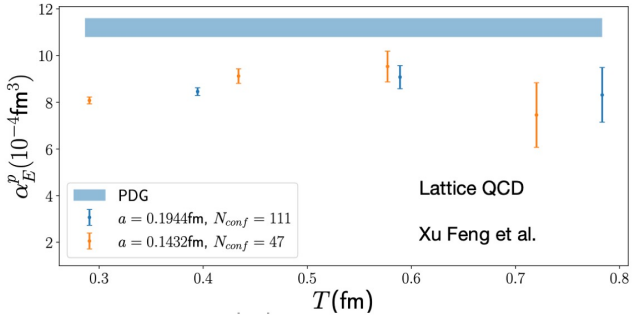
High precision benchmark data

χPT

LQCD

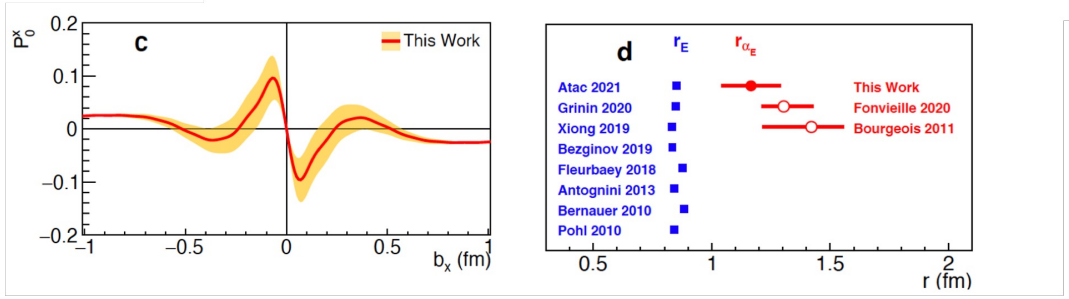
theoretical models

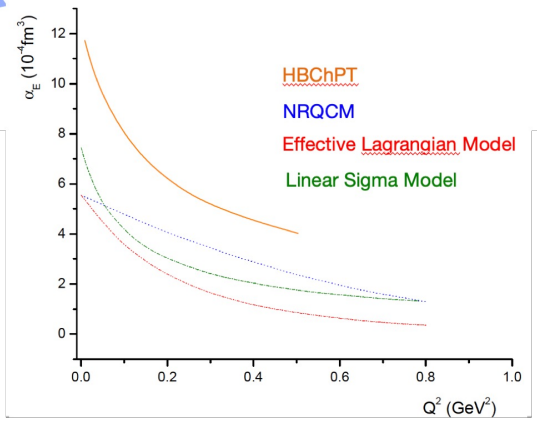




Induced polarization in the proton

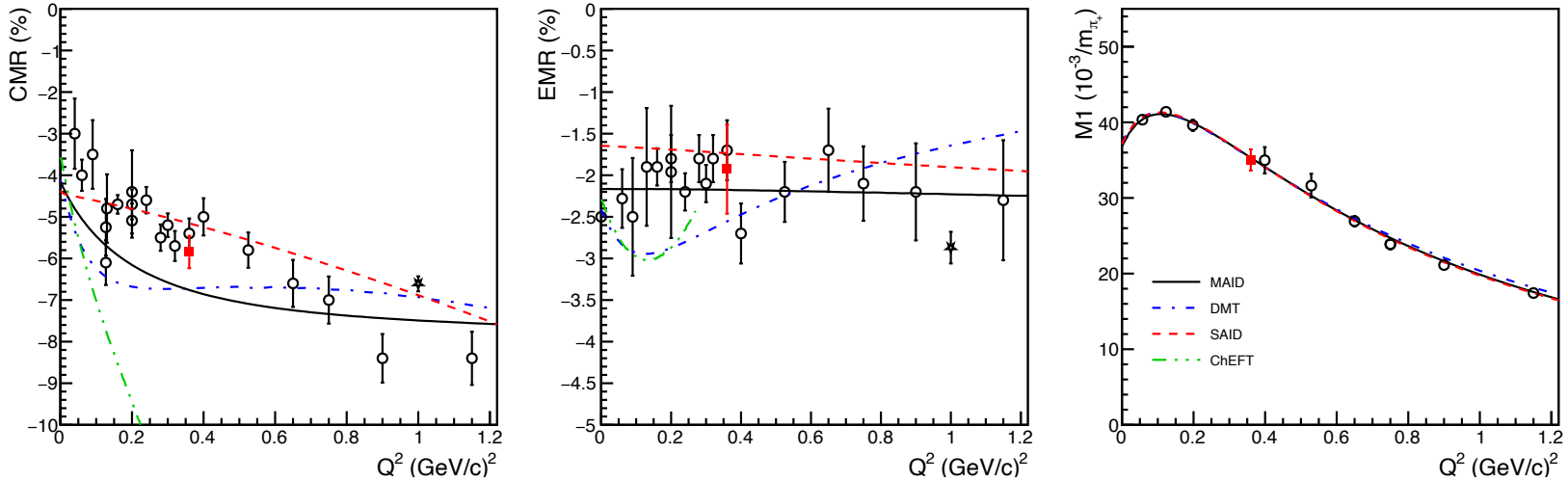
Polarizability radii
$\langle r_{\alpha E} \rangle$, $\langle r_{\beta M} \rangle$





Synergy with N-Delta (E12-22-001) Measurement

- Smooth transition from the N-Δ experiment to the lowest Q^2 VCS setting
  - The same beam energy (~1.4 GeV)
- Background and normalization will be cross-checked using the N-Δ data
- VCS measurements provide complementary dataset to N-Δ data for the Transition Form Factor Study.
  - Ex) Recent TFF publication using VCS-I data
- Both collaborations work closely, sharing expertise and experience



From R. Li *et al.* (VCS Collaboration), EPJ A Vol 60, 168 (2024)

VCS-II Current Beam Schedule

- Currently, N-Δ and VCS-II experiments are scheduled for 3/18 to 5/10 this year.
  - 3/18–4/10 for N-Δ
  - 4/11–5/10 for VCS-II
- We are inviting the Hall C collaborators to these two exciting experiments.
- Shift Requirements
  - **5 shifts** are required for authorship on the papers related to the **N-Δ experiment**.
  - **10 shifts** are required for authorship on the papers related to the **VCS-II experiment**.
  - **12 shifts** are required for authorship on all the papers from **both the VCS-II and N-Δ experiments**.
- Please note that the VCS-II experiment (E12-23-001) will collect data in two phases the first in Spring 2026 and the second one in FY27 (TBD).
  - Shifts taken during the second phase (FY27) will count toward the total shift requirement
  - 10 shifts for participation in the VCS experiment alone, or 12 shifts for those participating in both VCS-II and N-Δ.
  - https://misportal.jlab.org/mis/apps/physics/shiftSchedule/index.cfm?experimentRunId=HALLC-NDELTA-VCS
- Being RC is equivalent to 10.5 shifts.
  - Please email me at sangbaek.lee@temple.edu, or talk with Mark Jones.

Conclusion

- VCS-II will provide **precision measurements of GPs** over an expanded kinematic range, probing **fundamental proton properties**
  - Improve precision (X 2) of world-data combined with a fine mapping in Q^2 of the scalar GPs
  - Insight to the response of proton constituents to an external EM field, deformation of the proton densities, interplay of para/dia-magnetism in the proton, polarizability radii, …
  - Understand the dynamical signature of α_E or the tension in the world-data
  - Precise benchmark data for χPT & LQCD calculations

- The VCS collaboration is experienced and prepared for the VCS-II experiment.

- Please sign up for the shifts and RCs.
  - JLab Shift schedule
  - https://misportal.jlab.org/mis/apps/physics/shiftSchedule/index.cfm?experimentRunId=HALLC-NDELTA-VCS