E12-23-001

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

VCS2 Progress Report

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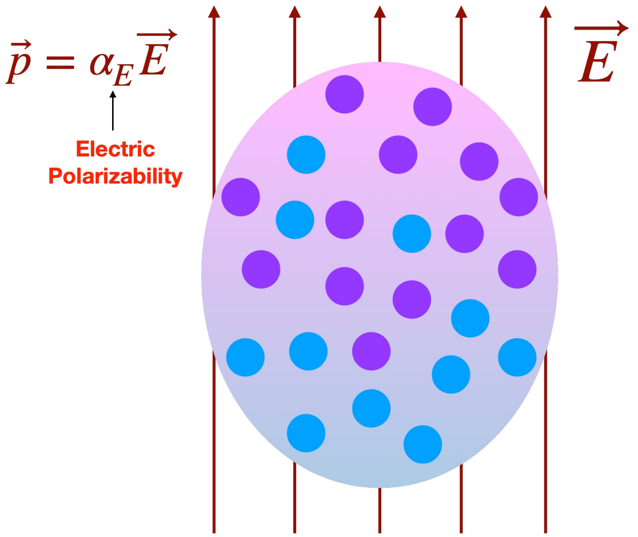
On behalf of VCS Collaboration

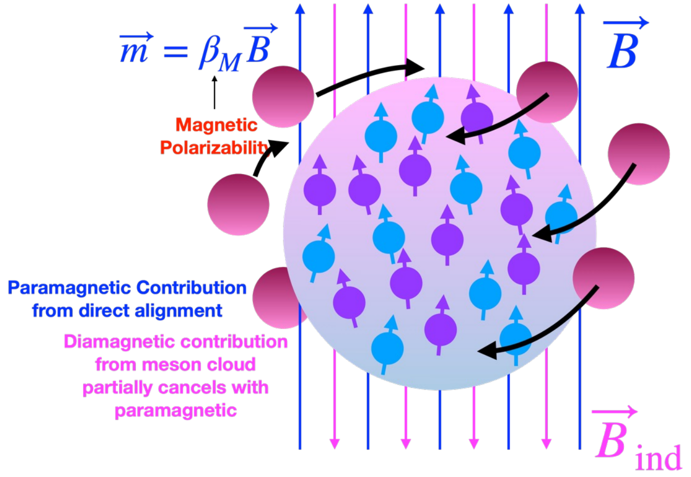
06/18/2026
Hall A/C Summer Collaboration Meeting 2026

Electromagnetic (EM) Polarizabilities of Proton

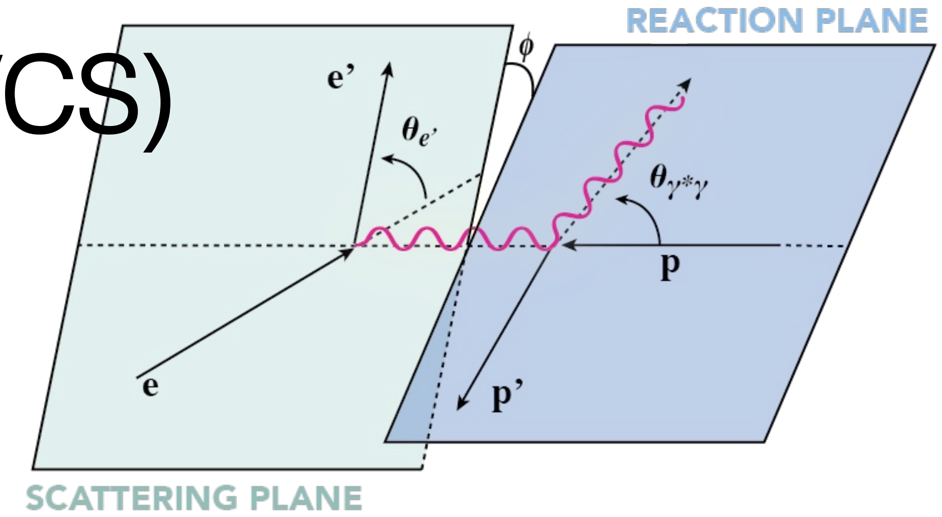
- Scalar EM Polarizability
  - Fundamental observables characterizing the proton's electromagnetic response
  - Defined as the ratio of the induced dipole moment to the applied local EM field
  - Different from intrinsic dipole moment



- 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.



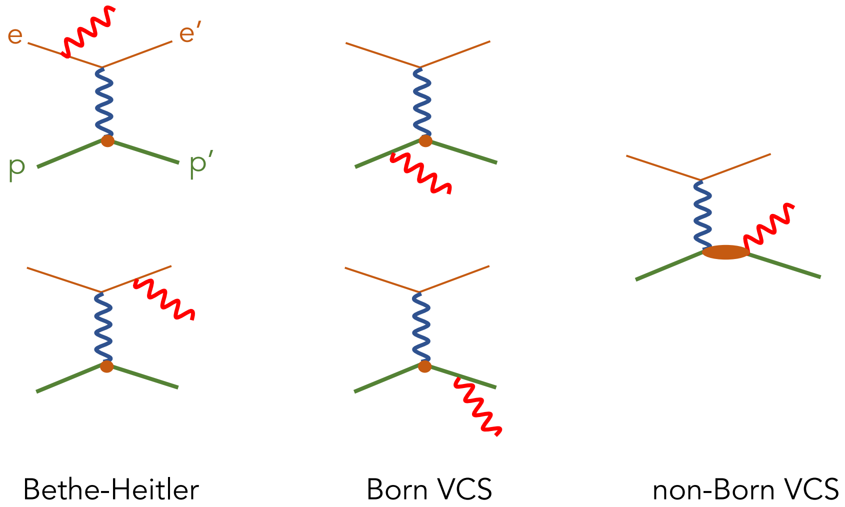
Generalized Polarizability (GP) and Virtual Compton Scattering (VCS)



- GPs are accessed via Virtual Compton Scattering (VCS) $\gamma^* p \to \gamma p$ 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 ($Q^2 \to 0$)



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:

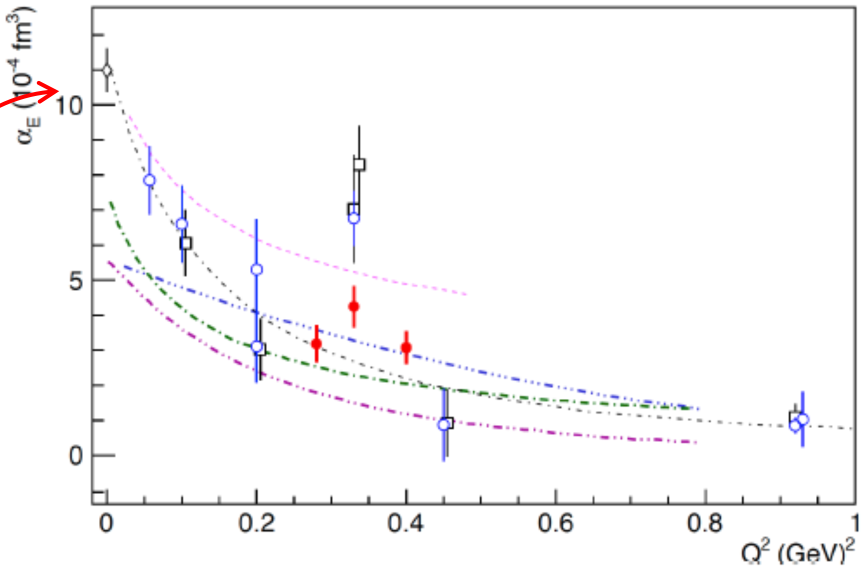
$$\alpha = (11.5 \pm 0.4) \times 10^{-4}\ \text{fm}^3$$
$$\beta = (2.31 \pm 0.29) \times 10^{-4}\ \text{fm}^3$$

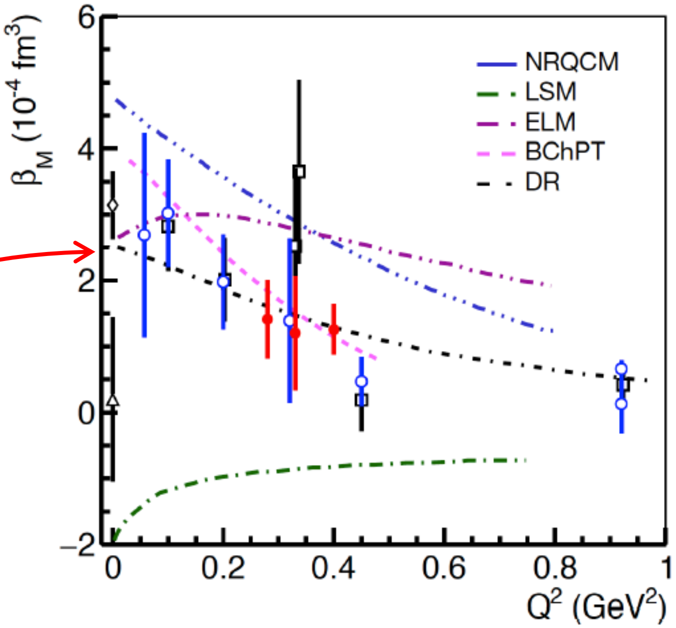
p $\quad I(J^P) = 1/2(1/2^+)$

Expand/Collapse A

p MASS (atomic mass units u)		1.007276466621 ±0.000000000053 u	⌄
p MASS (MeV)	[1]	938.27208816 ±0.00000029 MeV	⌄
$\lvert m_p - m_{\overline{p}}\rvert / m_p$	[2]	$< 7 \times 10^{-10}$ CL=90%	⌄
$\overline{p}/p$ CHARGE-TO-MASS RATIO, $\lvert\frac{q_{\overline{p}}}{m_{\overline{p}}}\rvert / (\frac{q_p}{m_p})$		1.000000000003 ±0.000000000016	⌄
$(\lvert\frac{q_{\overline{p}}}{m_{\overline{p}}}\rvert - \frac{q_p}{m_p}) / \frac{q_p}{m_p}$		$(0.3 \pm 1.6) \times 10^{-11}$	⌄
$\lvert q_p + q_{\overline{p}}\rvert / e$	[2]	$< 7 \times 10^{-10}$ CL=90%	⌄
$\lvert q_p + q_e\rvert / e$	[3]	$< 1 \times 10^{-21}$	⌄
p MAGNETIC MOMENT		2.7928473446 ±0.0000000008 μ_N	⌄
$\overline{p}$ MAGNETIC MOMENT		−2.792847344 ±0.000000004 μ_N	⌄
$(\mu_p + \mu_{\overline{p}}) / \mu_p$		$(2 \pm 4) \times 10^{-9}$	⌄
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





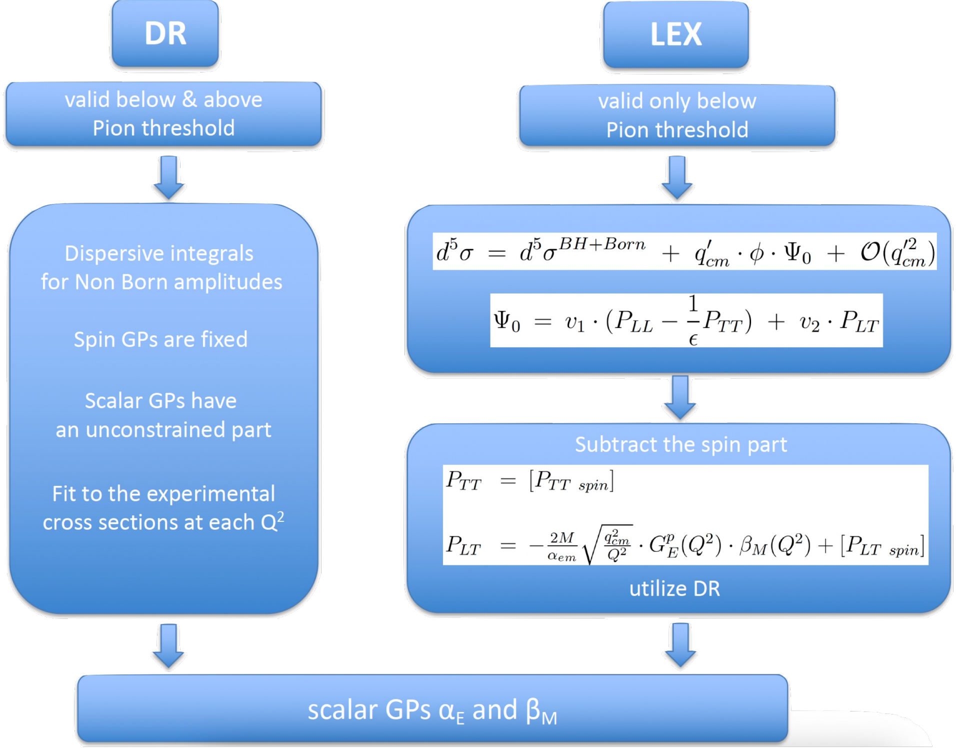
From VCS Collaboration, Proposal for E12-23-001, PAC 51

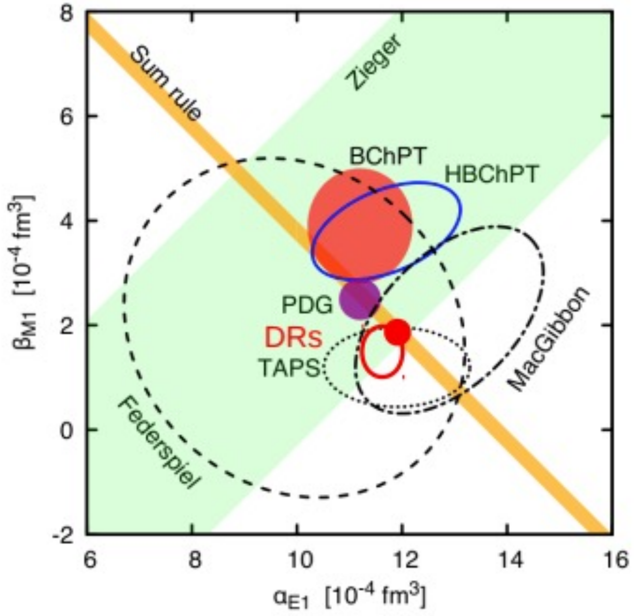
VCS Analysis Framework

- 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)

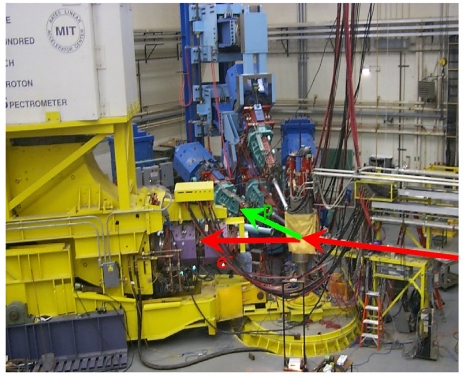
Early Experiments

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

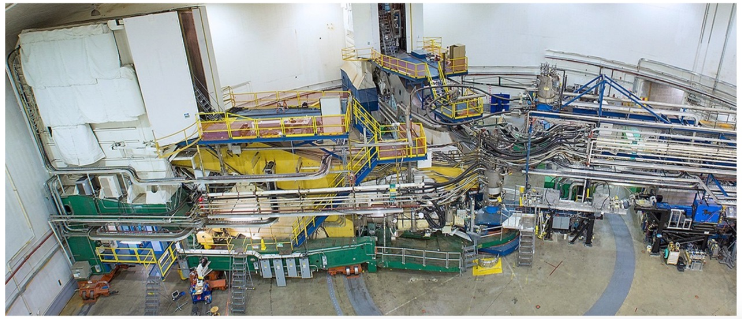
From H. Fonvieille, B. Pasquini & N. Sparveris, Prog. Part. Nucl. Phys. 113, 103754 (2020)

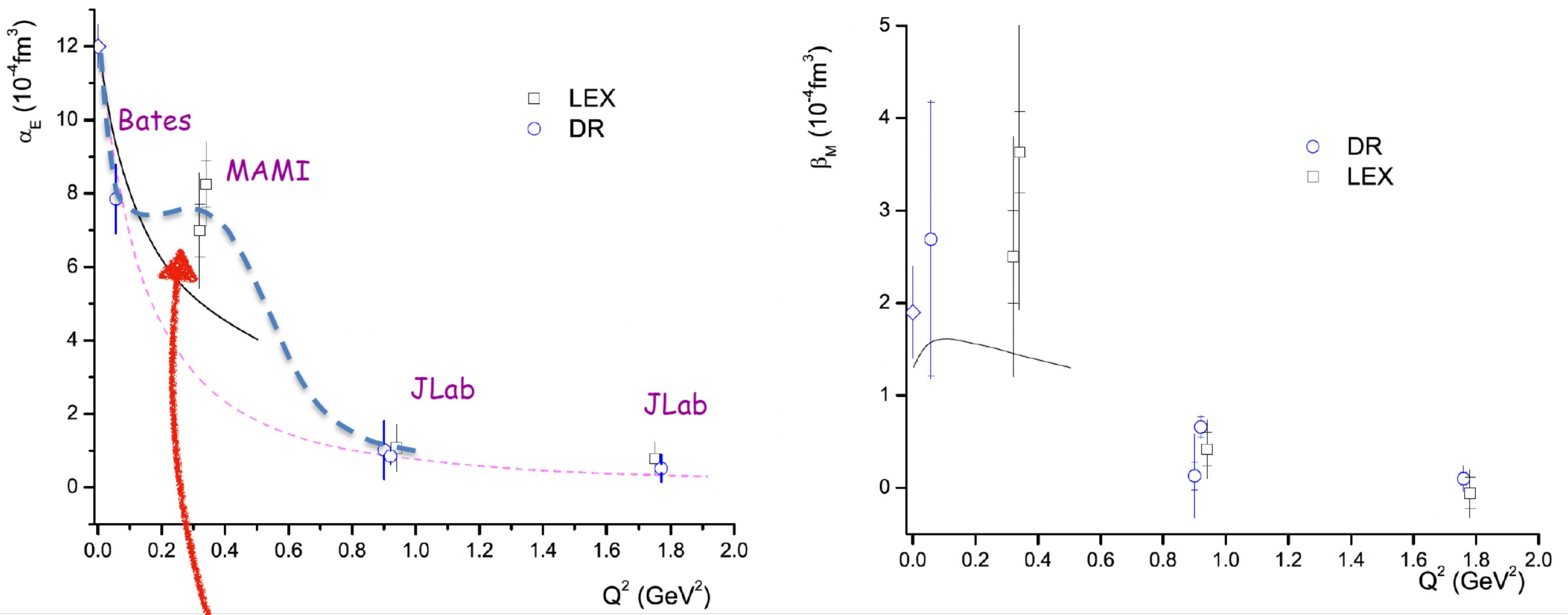
MIT-Bates @ Q^2=0.06 GeV^2



MAMI-A1 @ Q^2=0.33 GeV^2

Jlab-Hall A @ Q^2=0.9 & 1.8 GeV^2





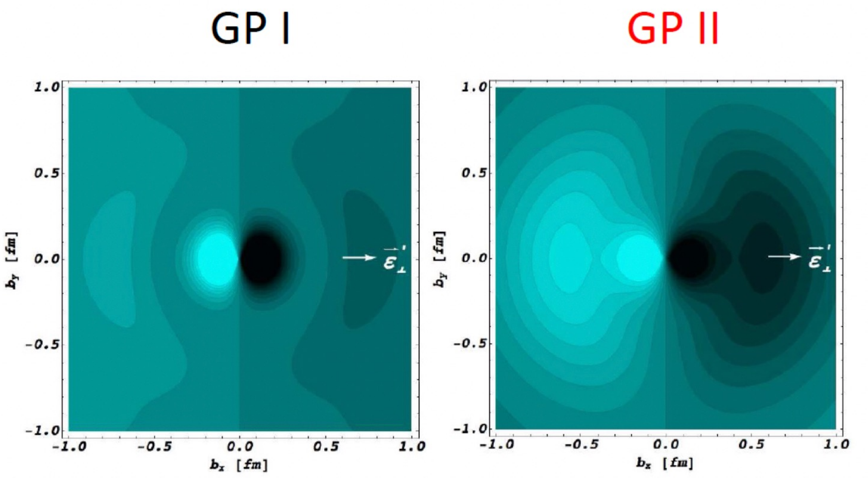
Initial investigations showed that the proton generally increases in stiffness as Q^2 increases.

Early MAMI data deviates from the monotonic decreasing trend.
A second measurement at MAMI had similar results.

Phys. Rev. Lett 85, 708 (2000)
Eur. Phys. J. A37, 1-8 (2008)

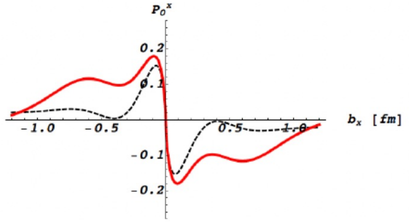
Spatial Dependence of Induced Polarizations

- 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.

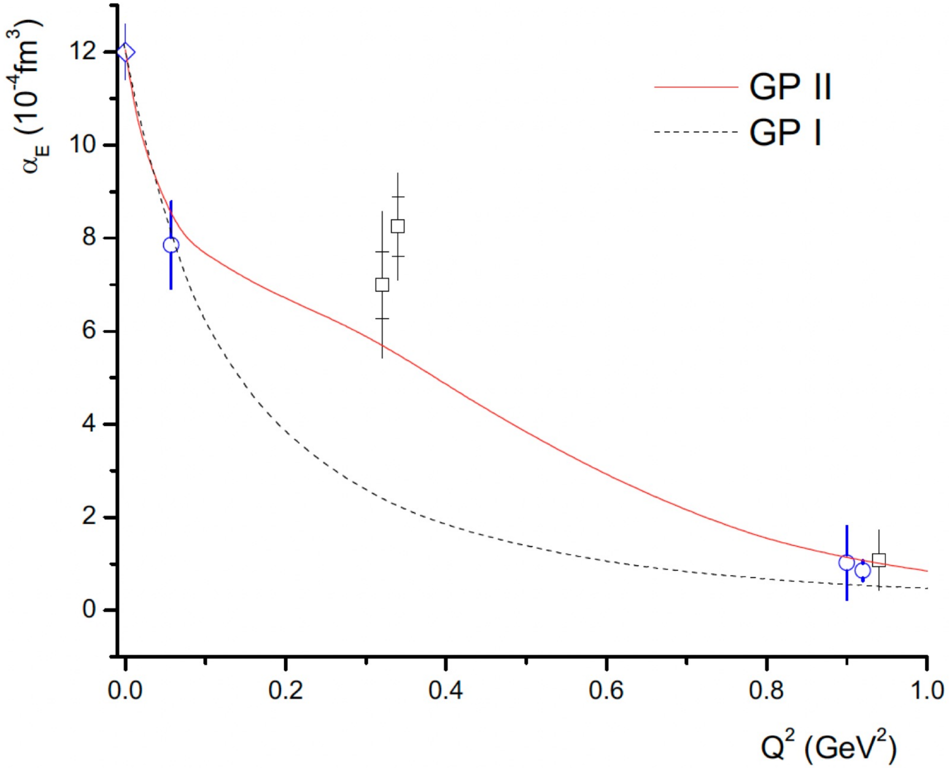


Light (**dark**) regions ➔ **largest** (**smaller**) values

(photon polarization along x-axis, as indicated)



Induced polarization along b_y=0

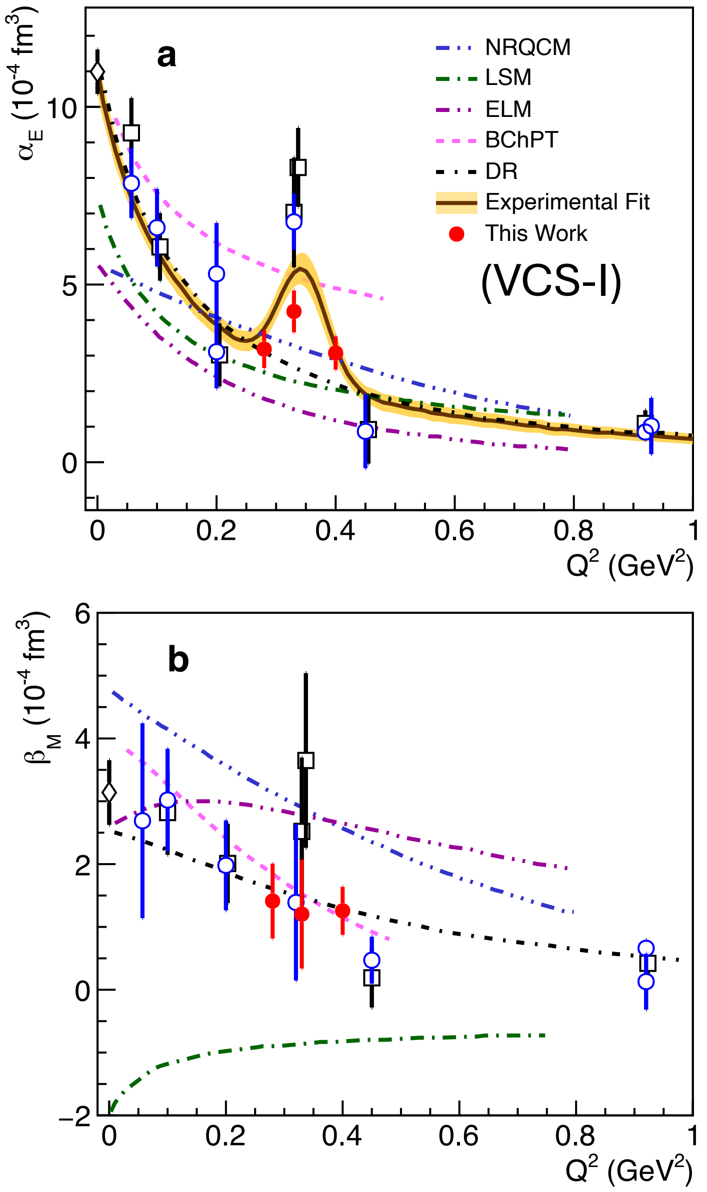


From M. Gorchtein, C. Lorcé, B. Pasquini and M. Vanderhaeghen
PRL 104, 112001 (2010)

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.

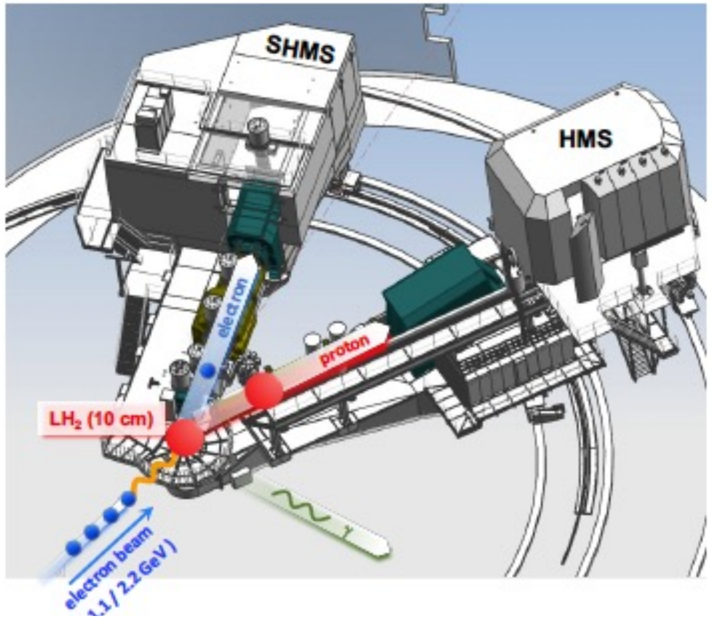
  → VCS2 Experiment

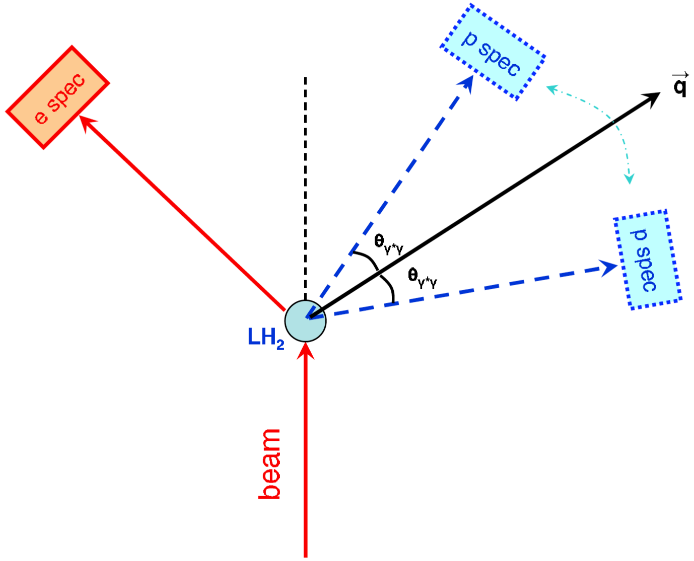


From R. Li *et al.* (VCS Collaboration), Nature Vol 611, p. 265–270 (2022)

VCS2 Phase 1 Overview

- 05/02/2026–06/01/2026: 76 shifts and 21 cancelled shifts
- The standard 10-cm liquid hydrogen target was used.
- The scattered electron was detected with the SHMS and the recoil proton was detected with the HMS.
    - Production a settings: Q^2 = 0.05 GeV^2, 1.4 GeV beam, up to 15 uA
      SHMS central values:10.5 deg, 1.05 GeV/c
      HMS central values:14–56 deg, 0.48–0.60 GeV/c
    - Production c settings: Q^2 = 0.25 GeV^2, 2.1 GeV beam, up to 60 uA
      SHMS central values: 5.5 deg, 1.64 GeV/c
      HMS central values: 20–55 deg, 0.70–0.83 GeV/c
    - Calibration runs include single arm with various targets mainly studying the target boiling effect
- Primary observables
    - Absolute cross sections
    - In-plane azimuthal asymmetries
- One DAQ (coincidence) was used

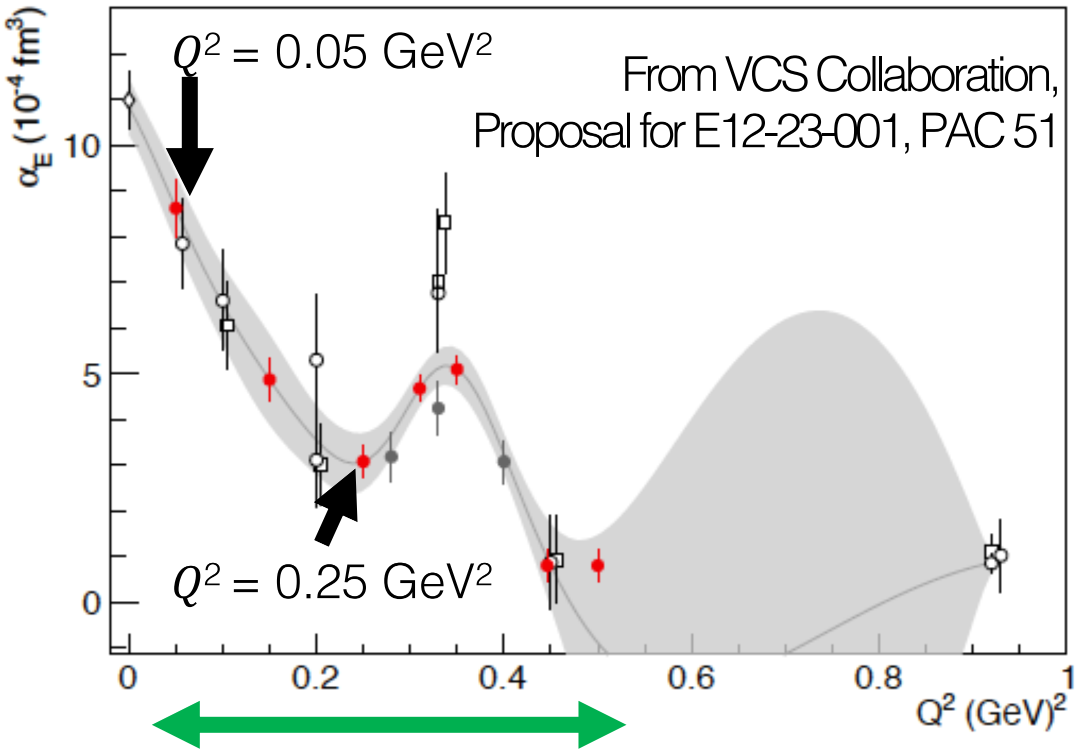


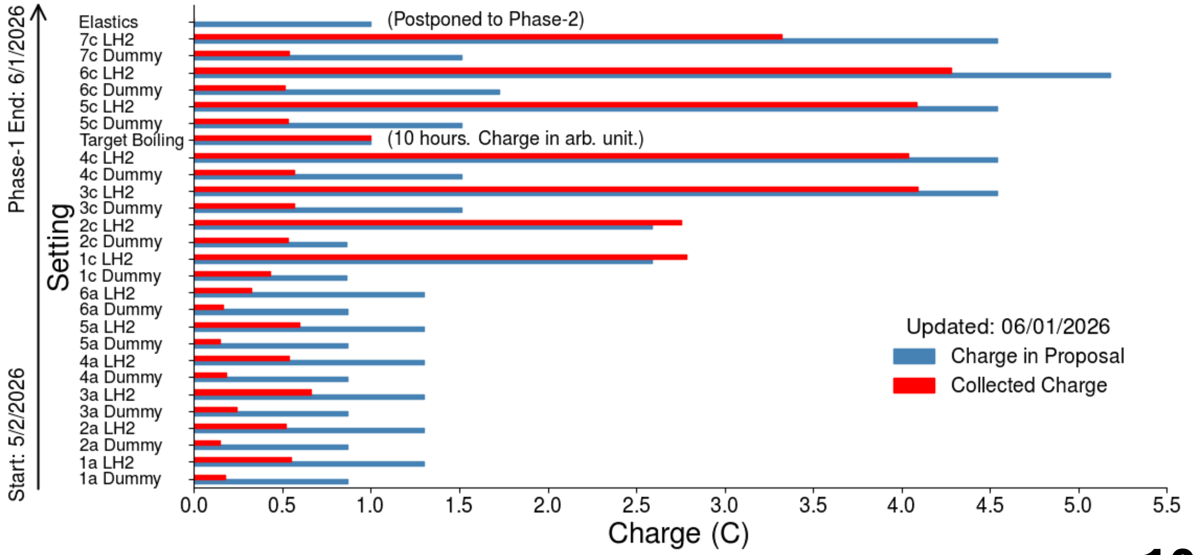


From VCS Collaboration,
Proposal for E12-23-001, PAC 51

VCS2 Phase 1 Status

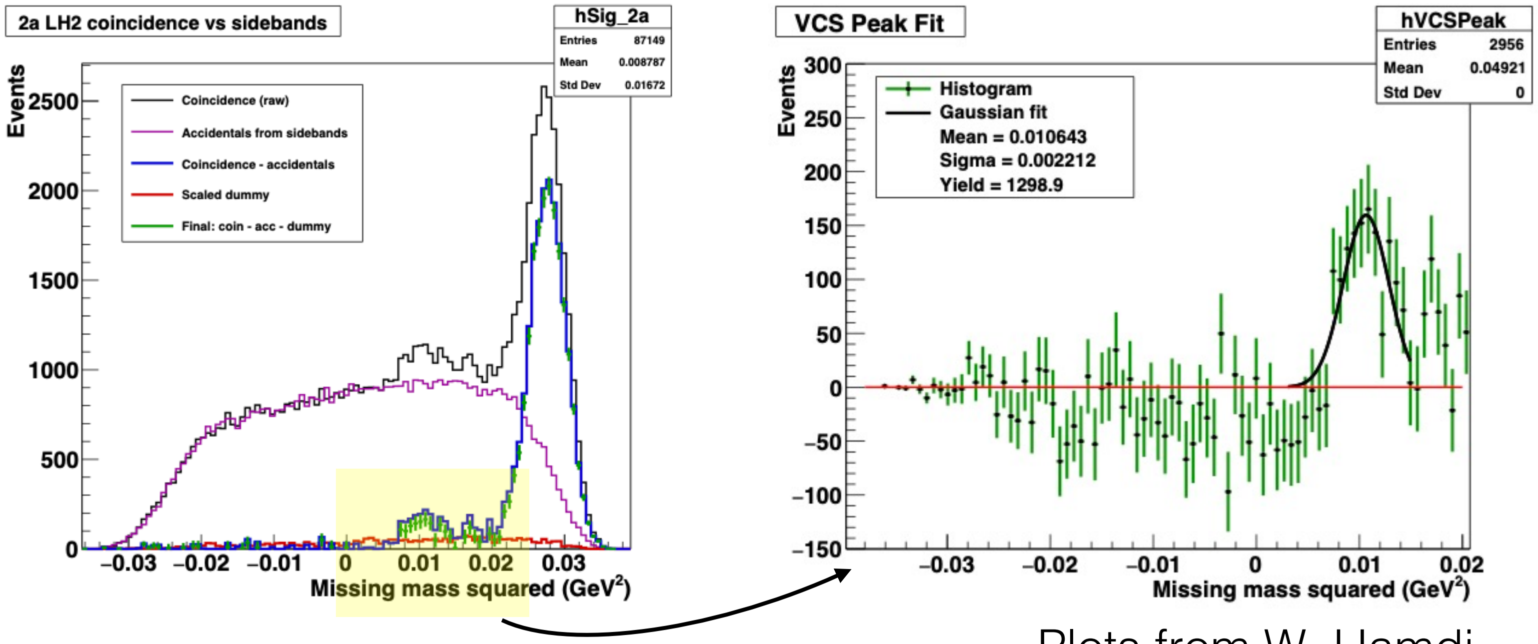
- Red data points indicate VCS2 projected measurements
- The program was approved for 59 PAC days of production and 3 PAC days of calibration
- We have completed two Q^2 settings, which corresponds to 17 PAC days, as well as one PAC day of calibration.



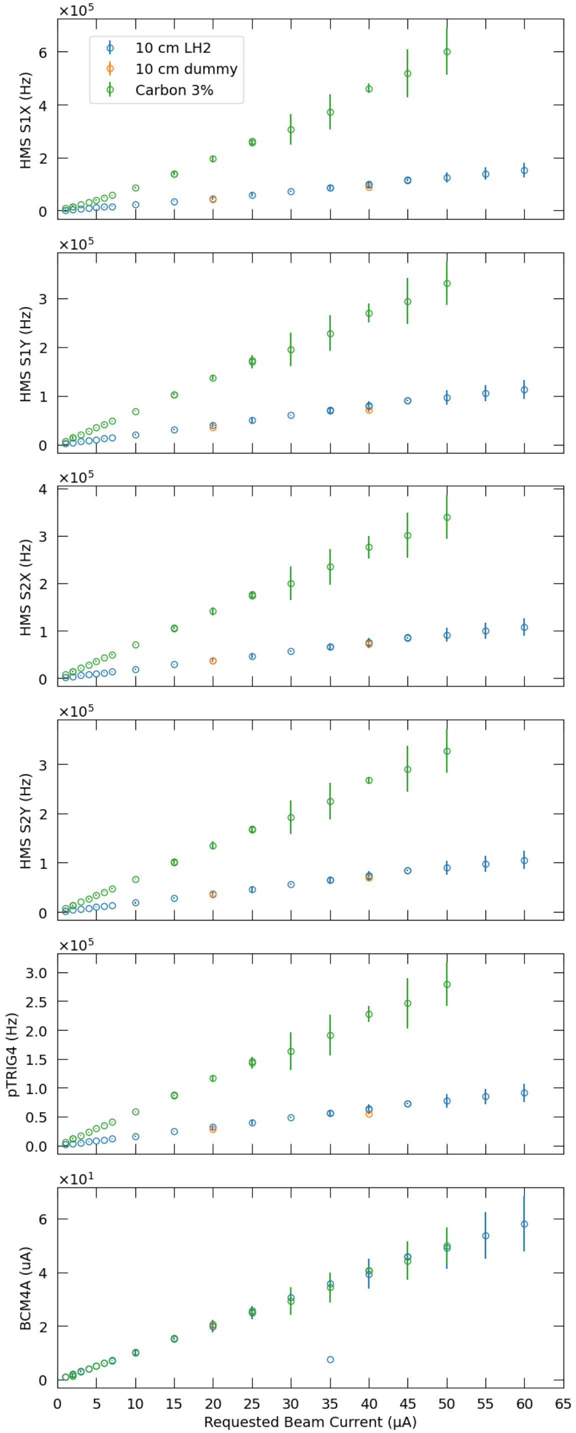


VCS2 Phase 1 Analysis Update

- Online analysis was conducted simultaneously with the measurements. Good statistics were ensured for each setting.
- VCS Collaboration is performing careful calibrations to enable more robust analyses.



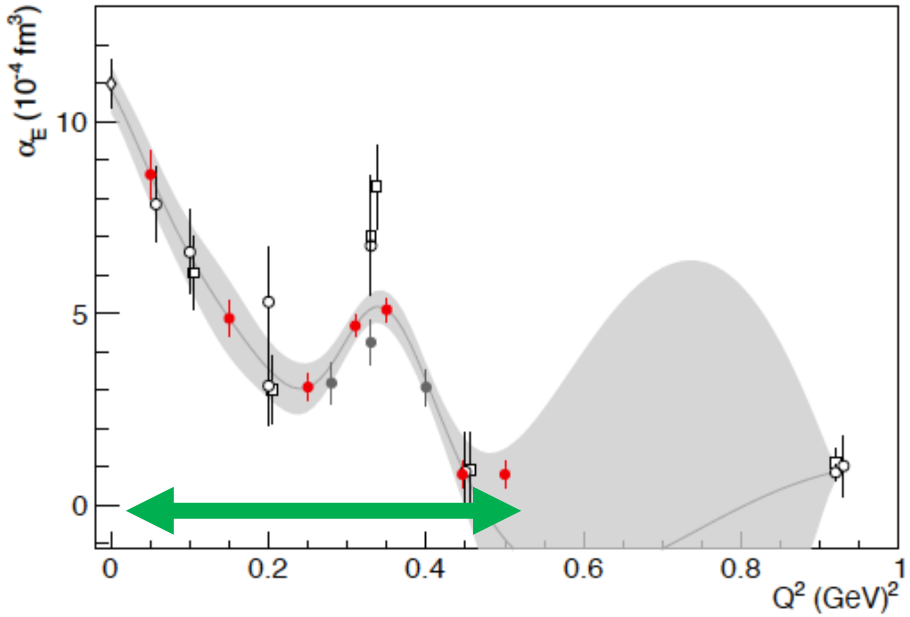
Plots from W. Hamdi

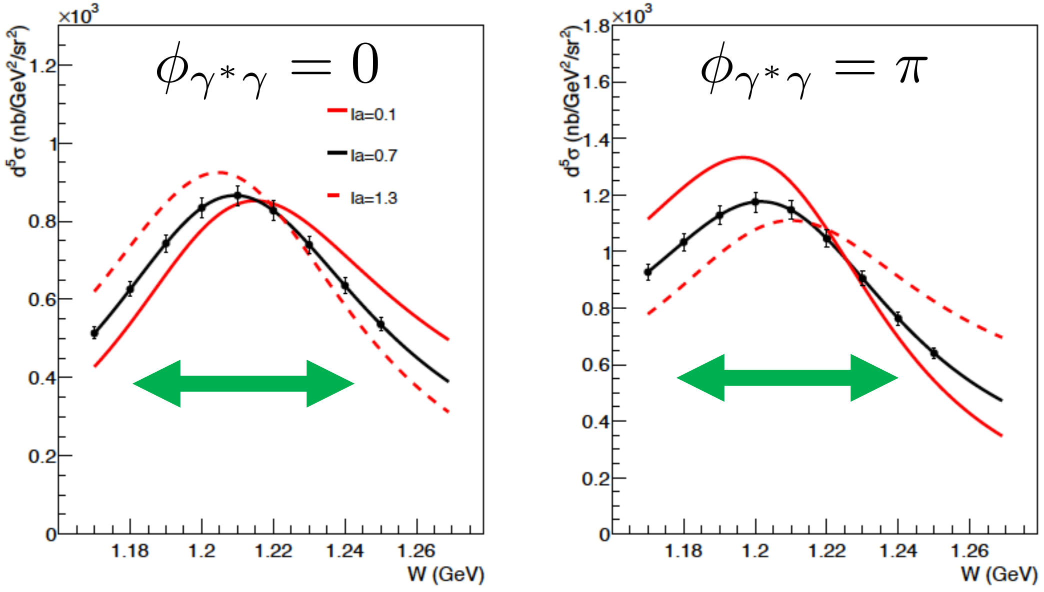


VCS2 Phase 2

- We expect to perform VCS-II Phase 2 in FY2027 to collect data for the remaining kinematic points and hydrogen elastics, in order to study trigger efficiency.

- Measurement at W = 1.19 GeV will enable a study of the W-dependence of cross section.

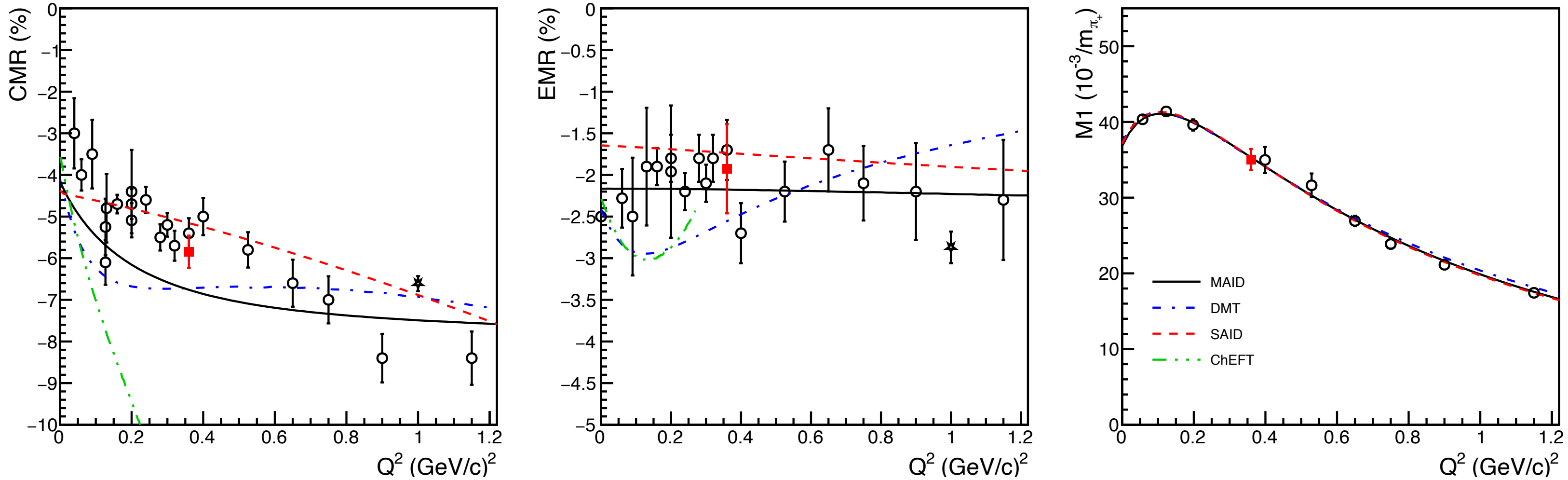




From VCS Collaboration,
Proposal for E12-23-001, PAC 51

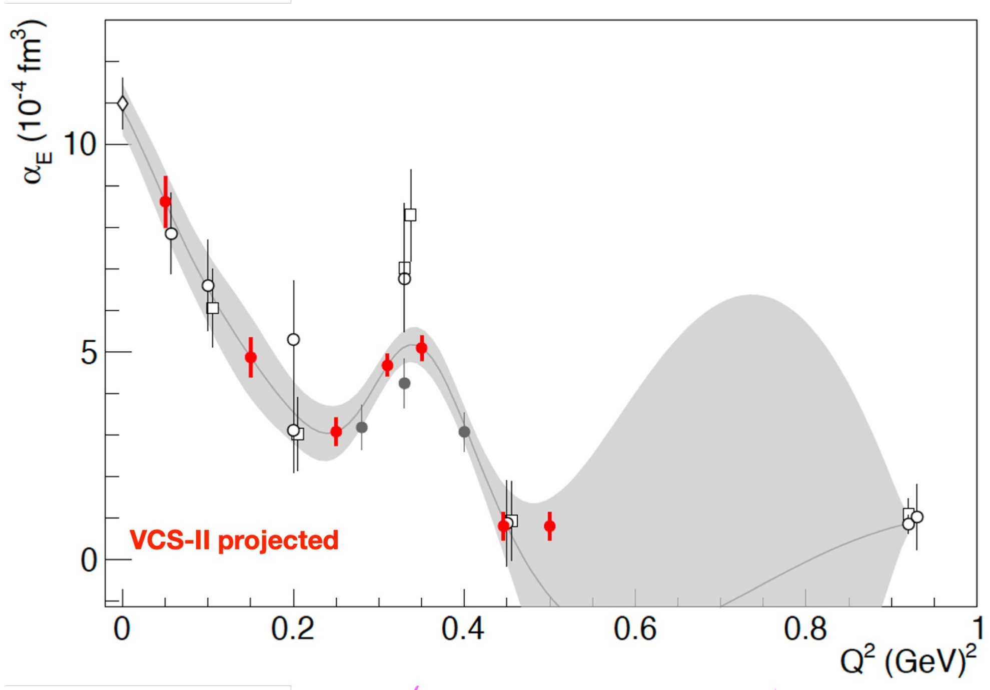
Synergy with N-Delta (E12-22-001) Measurement

- Calibration, background and normalization studies 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



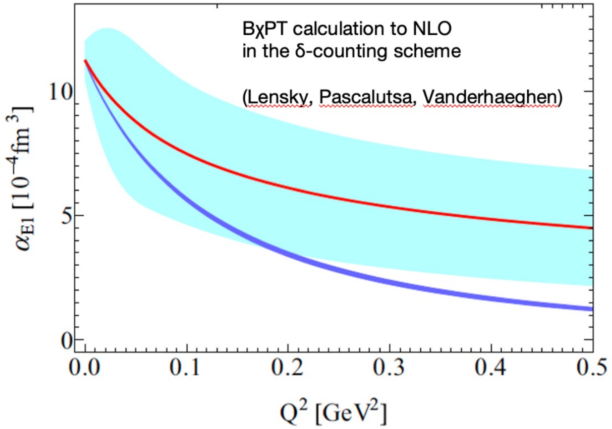
From R. Li *et al.* (VCS Collaboration), EPJ A Vol 60, 168 (2024)

VCS-II Primary Experiment Goals

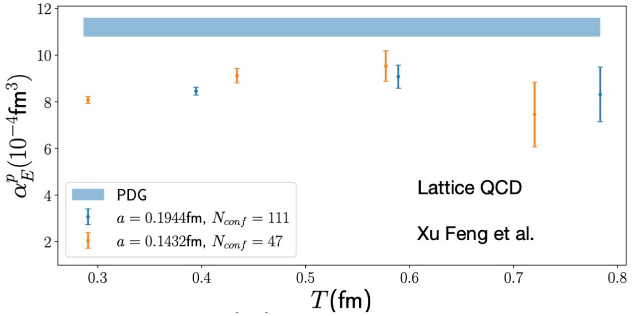


High precision benchmark data

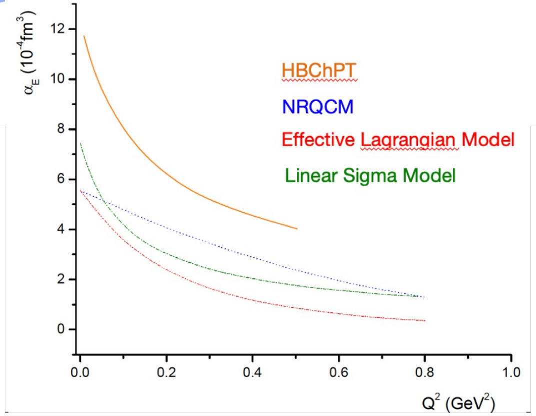
χPT



LQCD

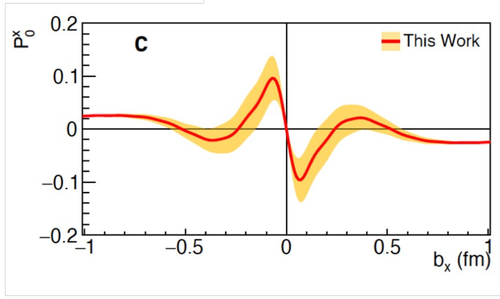


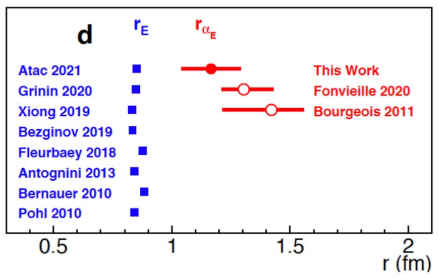
theoretical models



Induced polarization in the proton

Polarizability radii
<$r_{\alpha E}$> , <$r_{\beta M}$>





Conclusion

- We have successfully completed VCS2 Phase 1, thanks to huge support of everyone, who participated in the experiment.
- We have achieved our target statistics. Calibrations and offline analysis of VCS2 Phase 1 dataset are ongoing.
- VCS2 Phase 2 is expected to happen next year. Please stay tuned for the experiment schedule.
- Full VCS2 dataset will enable **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