

Proton polarizabilities and polarizability radii

Nikos Sparveris

NREC 2026 Workshop

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Outline

Introduction to the VCS and GPs

Current progress

Spatial information & polarizability radii

Ongoing / upcoming experiments

Prospects & outlook

Proton Polarizabilities

Fundamental structure constants
(such as mass, size, shape, ...)

Response of the nucleon to external EM field

Sensitive to the full excitation spectrum

Accessed experimentally through Compton Scattering

RCS: static polarizabilities → net effect on the nucleon

PDG

150 Baryon Summary Table

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

p

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

Mass $m = 1.00727646681 \pm 0.00000000009$ u

Mass $m = 938.272046 \pm 0.000021$ MeV [a]

$|m_p - m_{\bar{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]

$|\frac{q_p}{m_p}|/(\frac{q_e}{m_e}) = 0.99999999991 \pm 0.00000000009$

$|q_p + q_{\bar{p}}|/e < 7 \times 10^{-10}$, CL = 90% [b]

$|q_p + q_e|/e < 1 \times 10^{-21}$ [c]

Magnetic moment $\mu = 2.792847356 \pm 0.000000023$ μ_N

$(\mu_p + \mu_{\bar{p}}) / \mu_p = (0 \pm 5) \times 10^{-6}$

Electric dipole moment $d < 0.54 \times 10^{-23}$ e cm

Electric polarizability $\alpha = (11.2 \pm 0.4) \times 10^{-4}$ fm³

Magnetic polarizability $\beta = (2.5 \pm 0.4) \times 10^{-4}$ fm³ (S = 1.2)

Charge radius, μp Lamb shift = 0.84087 ± 0.00039 fm [d]

Charge radius, $e p$ CODATA value = 0.8775 ± 0.0051 fm [d]

Magnetic radius = 0.777 ± 0.016 fm

Mean life $\tau > 2.1 \times 10^{29}$ years, CL = 90% [e] ($p \rightarrow$ invisible mode)

Mean life $\tau > 10^{31}$ to 10^{33} years [e] (mode dependent)

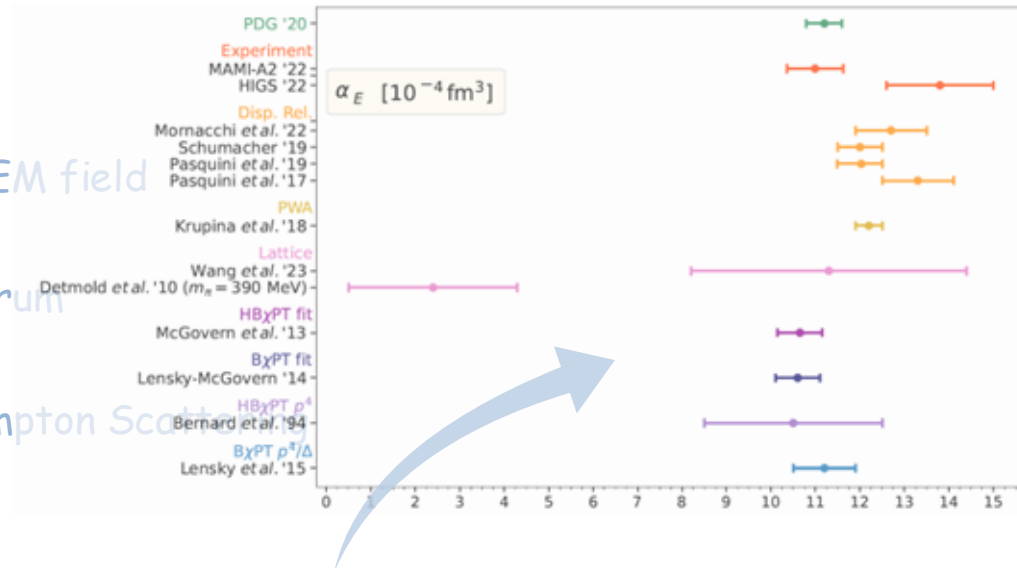
Proton Polarizabilities

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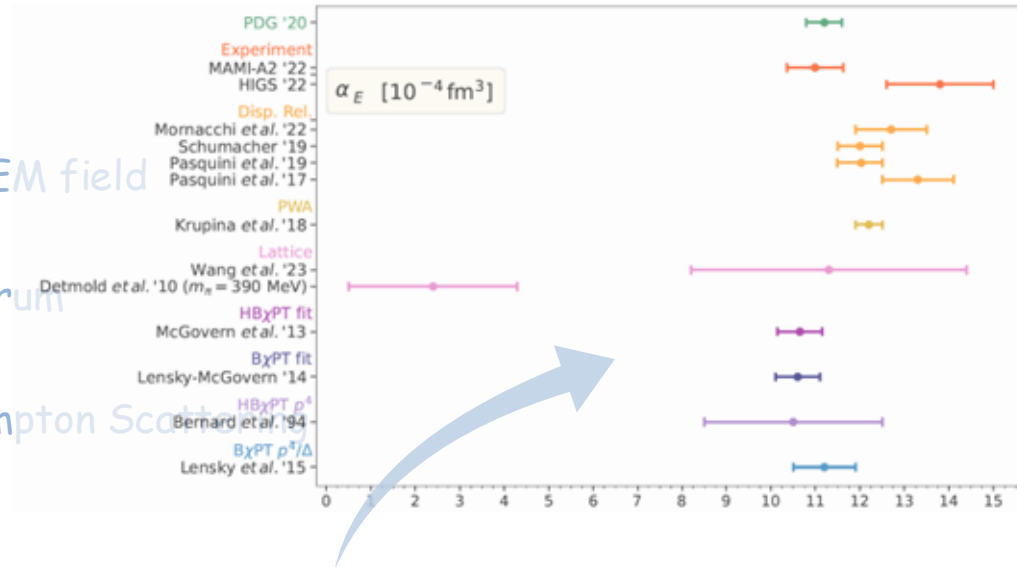
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Virtual Compton Scattering:

Virtuality of photon gives access to the GPs : $\alpha_E(Q^2)$ & $\beta_M(Q^2)$ + spin GPs

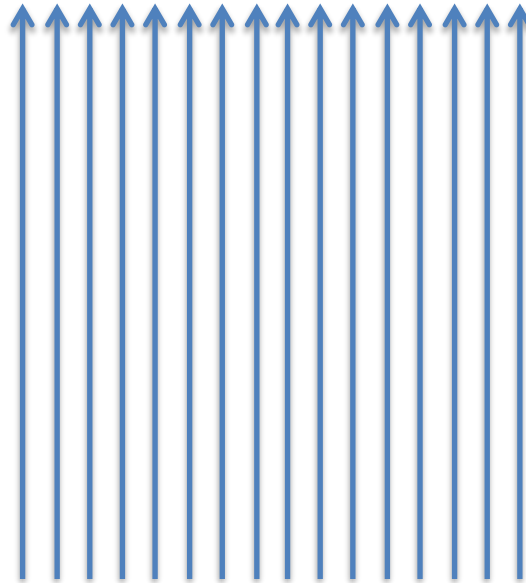
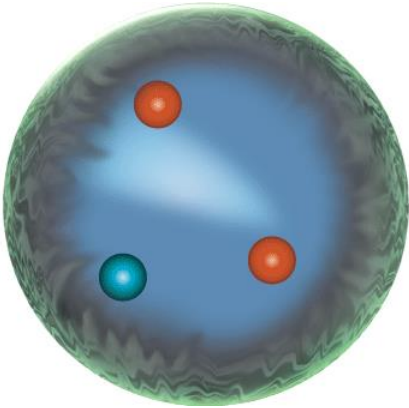
- \rightarrow spatial distribution of the polarization densities
- \rightarrow electric & magnetic polarizability radii

Fourier transform of densities of electric charges and magnetization of a nucleon deformed by an applied EM field

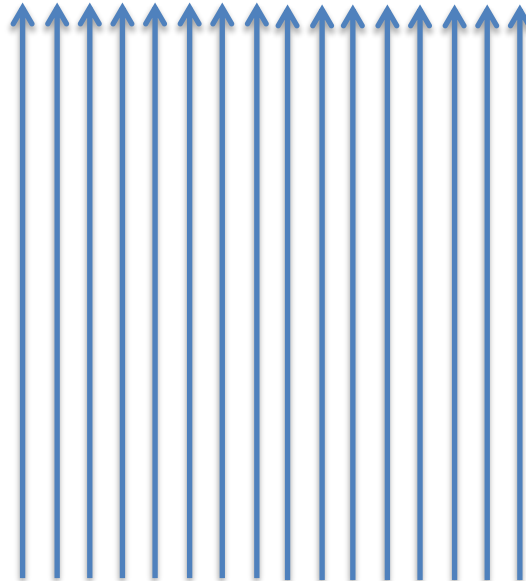
Scalar Polarizabilities

Response of internal structure to an applied EM field

Interaction of the EM field with the internal structure of the nucleon



\vec{E}

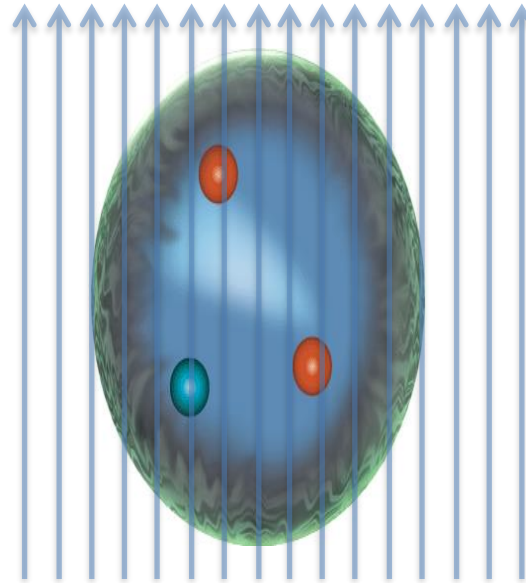
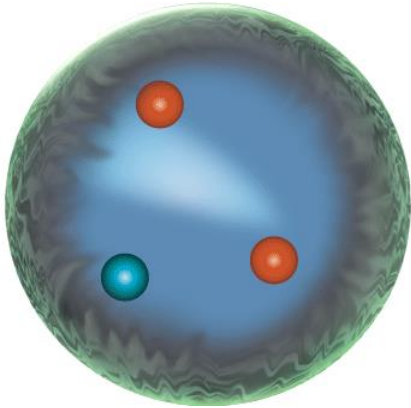


\vec{B}

Scalar Polarizabilities

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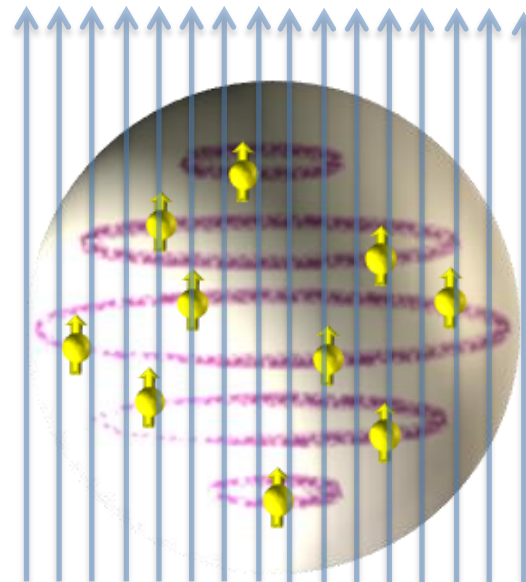


\vec{E}

“stretchability”

$$\vec{d}_{E \text{ induced}} \sim \alpha \vec{E}$$

External field deforms the charge distribution



\vec{B}

“alignability”

$$\vec{d}_{M \text{ induced}} \sim \beta \vec{B}$$

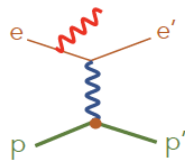
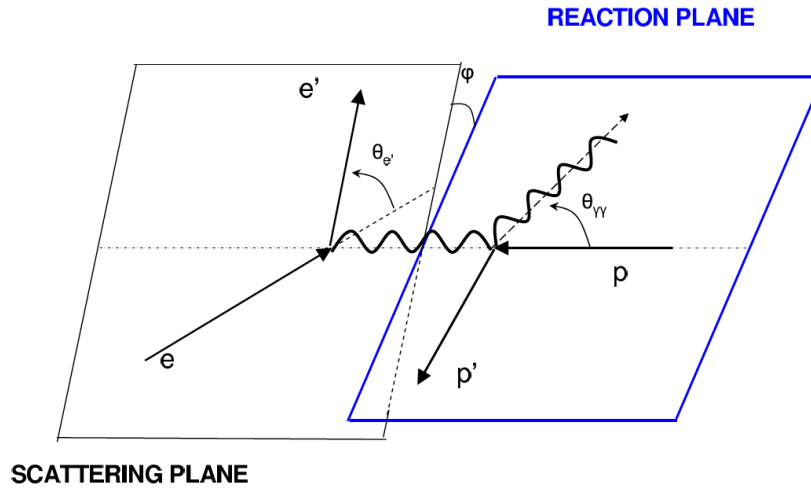
$$\beta_{\text{para}} > 0$$

$$\beta_{\text{diam}} < 0$$

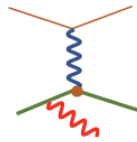
Paramagnetic: proton spin aligns with the external magnetic field

Diamagnetic: π -cloud induction produces field counter to the external perturbation

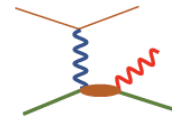
Virtual Compton Scattering



Bethe-Heitler



Born VCS



non-Born VCS

Elastic FFs

GPs

Virtual Compton Scattering

DR

valid below & above
Pion threshold

Dispersive integrals
for Non Born amplitudes

Spin GPs are fixed

Scalar GPs have
an unconstrained part

Fit to the experimental
cross sections at each Q^2

LEX

valid only below
Pion threshold

Response functions

$$d^5\sigma = d^5\sigma^{BH+Born} + q'_{cm} \cdot \phi \cdot \Psi_0 + \mathcal{O}(q'^2_{cm})$$

$$\Psi_0 = v_1 \cdot \left(P_{LL} - \frac{1}{\epsilon} P_{TT} \right) + v_2 \cdot P_{LT}$$

Subtract the spin part

$$P_{TT} = [P_{TT} \text{ spin}]$$

$$P_{LT} = -\frac{2M}{\alpha_{em}} \sqrt{\frac{q'^2_{cm}}{Q^2}} \cdot G_E^p(Q^2) \cdot \beta_M(Q^2) + [P_{LT} \text{ spin}]$$

utilize DR

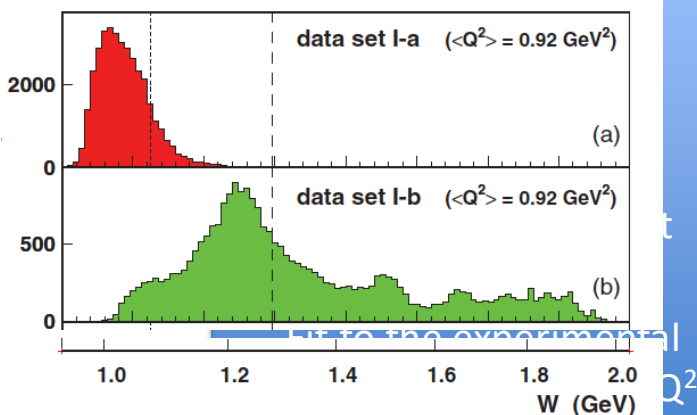
scalar GPs α_E and β_M

Virtual Compton Scattering

DR

valid below & above
Pion threshold

Dispersive integrals
for Non Born amplitudes

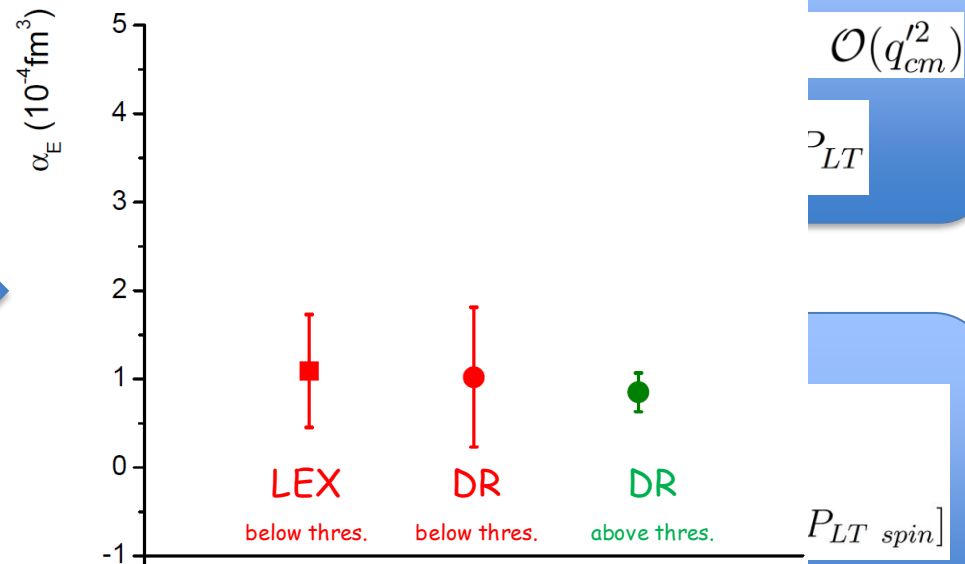


scalar GPs α_E and β_M

LEX

valid only below
Pion threshold

Response functions



utilize DR

Sensitivity to the GPs

Extracting the polarizability signal from the cross-section measurements is challenging, in particular when measuring below the pion threshold.

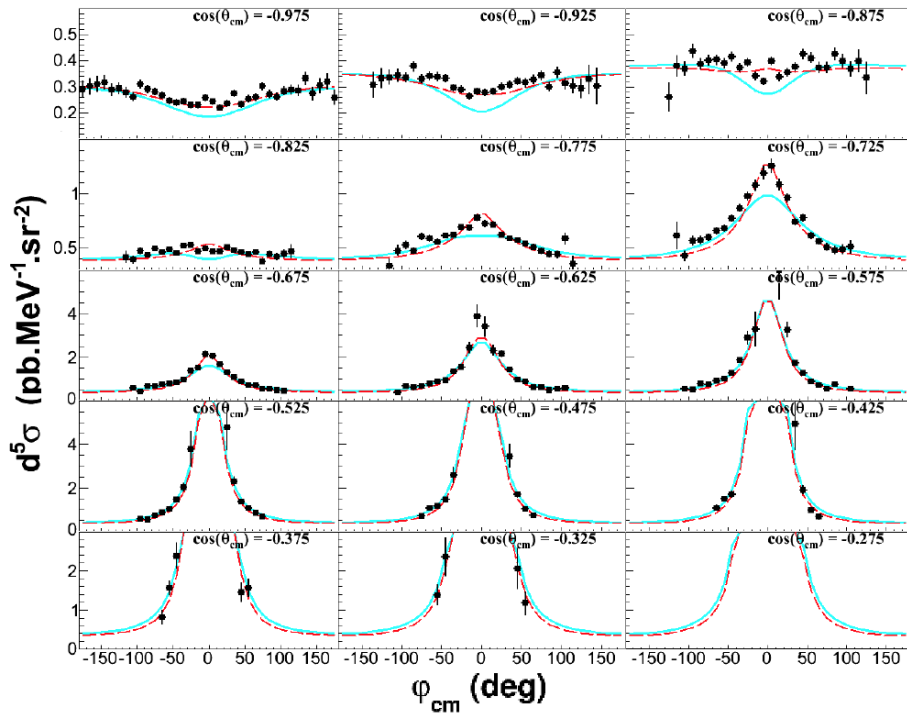


Figure 5.8: Setting INP: measured $ep \rightarrow ep\gamma$ cross section at fixed $q'_{cm} = 112.5 \text{ MeV}/c$ with respect to φ_{cm} for all the $\cos(\theta_{cm})$ -bins. The curves follow the convention of figure 5.6.

Figure from PhD thesis of L. Correa, Mainz / Cl. Ferrand

MAMI measurements

$$Q^2 = 0.1 (\text{GeV}/c)^2 - 0.45 (\text{GeV}/c)^2$$

BH+B ---

Polarizability effect ---

GP effect typically 5% - 15% of the cross section

Polarizability fits:

DR fit:

DR calculation includes full dependency in q'_{cm}

LEX fit:

truncated in q'_{cm} . Suppress contribution from higher order terms

Sensitivity to the GPs

For LEX the higher order terms have to be kept small / under control

$$d^5\sigma = d^5\sigma^{BH+Born} + q'_{cm} \cdot \phi \cdot \Psi_0 + \mathcal{O}(q'^2_{cm})$$

Refined analysis procedure in recent experiments / phase space masking to keep these terms smaller than $\sim 2\%-3\%$ level

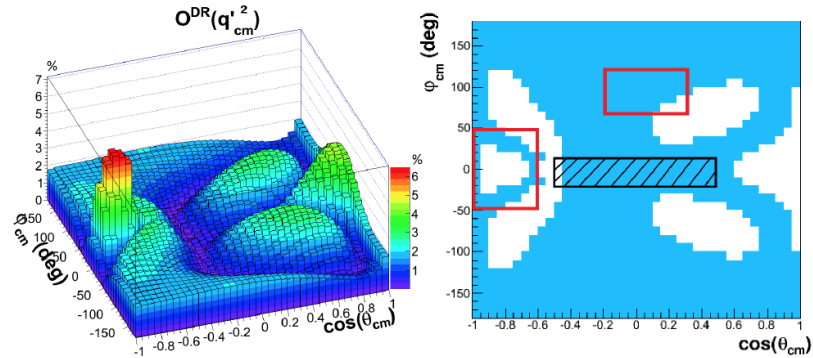
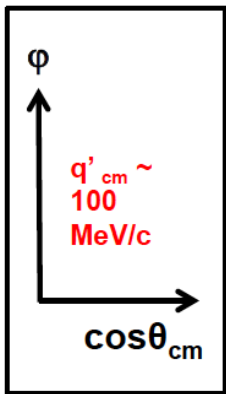
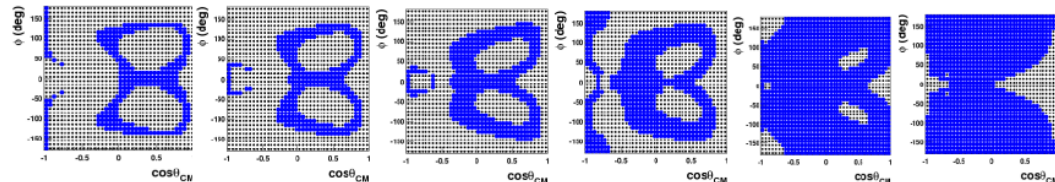


Figure 3.13: (Left) behavior of $\mathcal{O}^{DR}(q'^2_{cm})$ in the $(\cos(\theta_{cm}), \varphi_{cm})$ -plane at $q'_{cm} = 87.5 \text{ MeV}/c$ and (right) two-dimensional representation of the angular region where $\mathcal{O}^{DR}(q'^2_{cm}) < 2\%$ (blue), the red squares correspond to the two areas of interest to perform the GP extraction.

Blue bins = where the higher-order estimator is < 3% (LEX truncation « valid »)



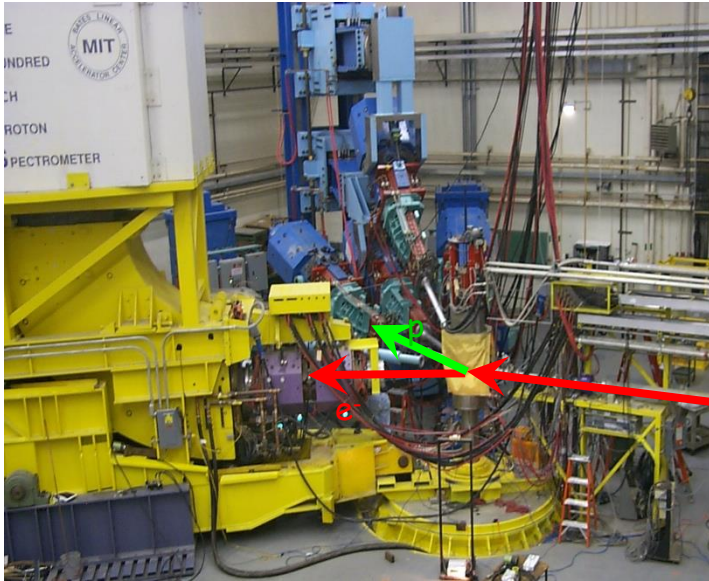
VCS expt : Bates MAMI MAMI MAMI MAMI JLab
 $Q^2 \text{ (GeV}^2\text{)} =$ **0.06** **0.10** **0.20** **0.33** **0.45** **0.92**



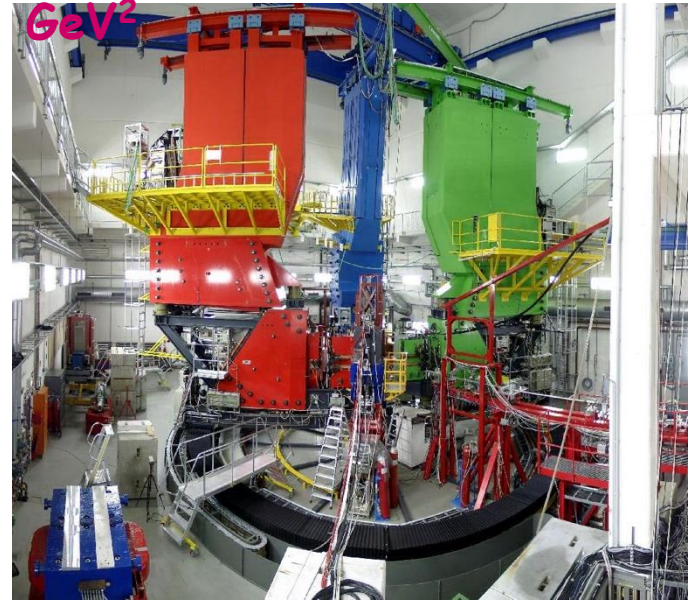
The effect is more prominent at low Q^2

VCS Experiments

MIT-Bates @ $Q^2=0.06 \text{ GeV}^2$



MAMI-A1 @ $Q^2=0.1 - 0.45 \text{ GeV}^2$



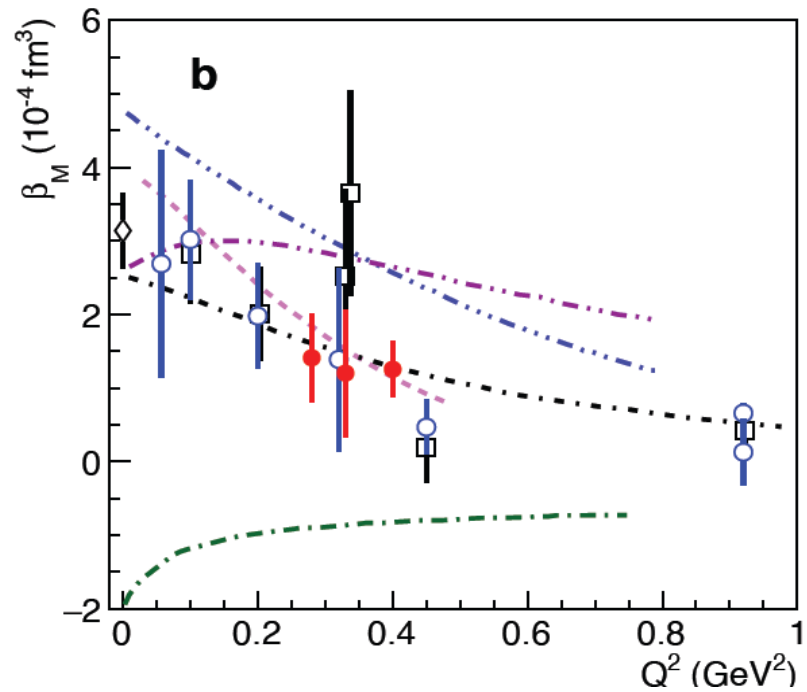
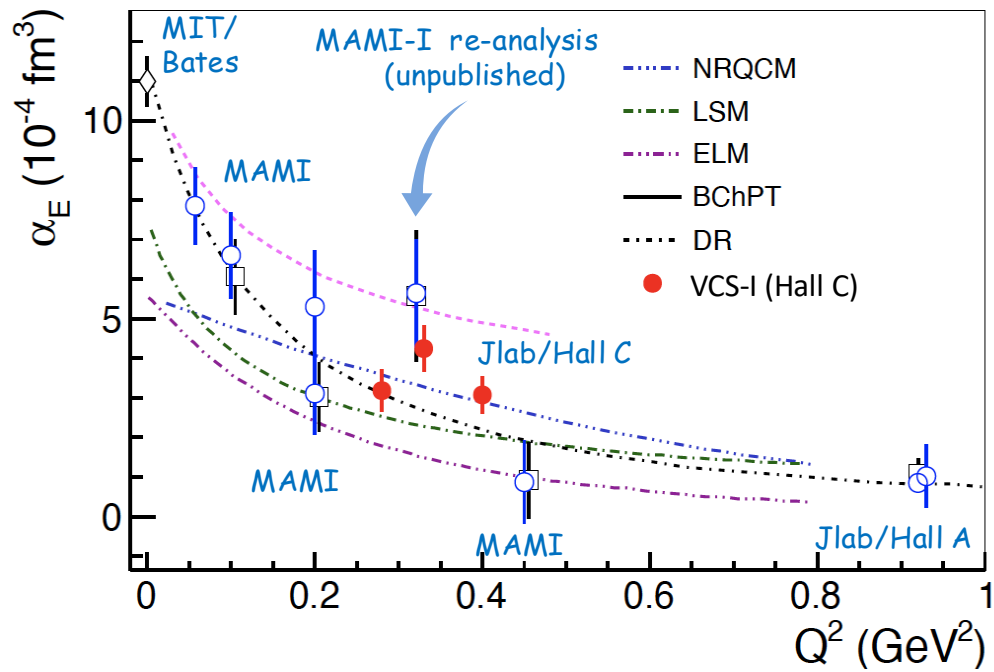
Jlab-Hall C @ $Q^2=0.05 - 0.5 \text{ GeV}^2$



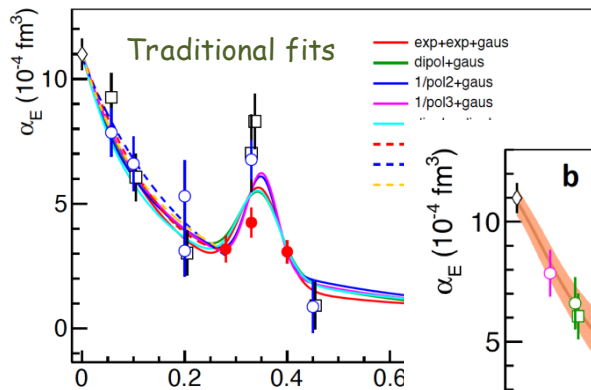
Jlab-Hall A @ $Q^2=0.9 \text{ \& } 1.8 \text{ GeV}^2$



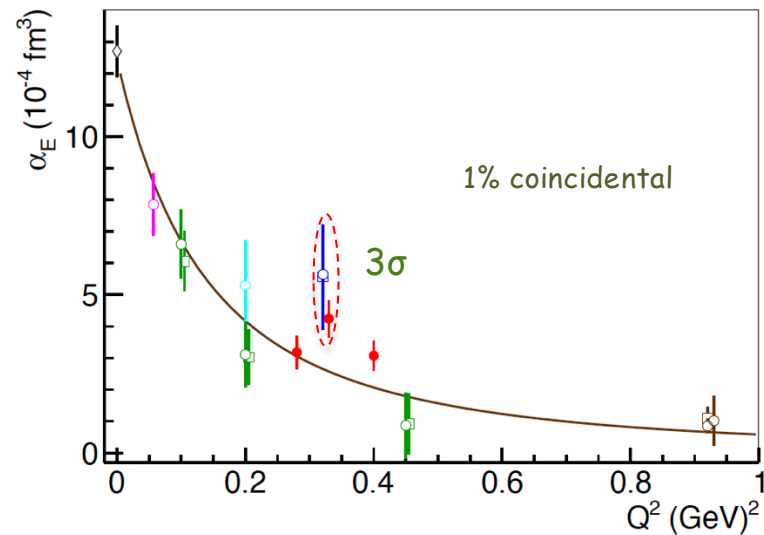
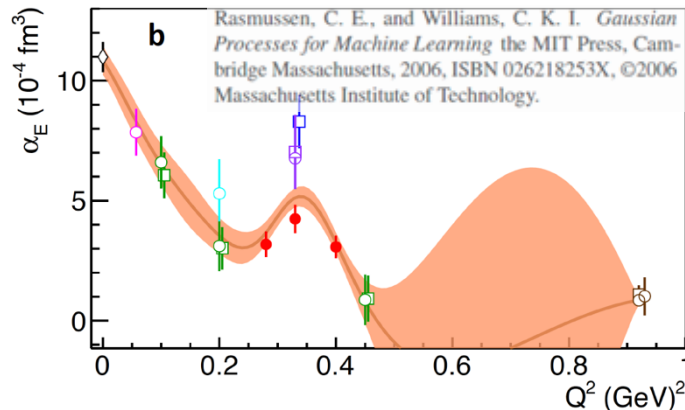
VCS Experiments



Electric GP



Data-driven techniques:
no underlying functional
form is assumed



Is the observed α_E structure coincidental or a true effect?

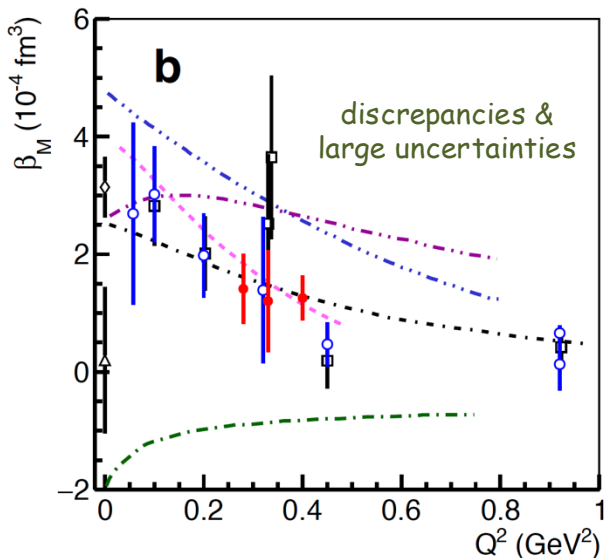
Yes: Measure the shape precisely \rightarrow input to theory

No: Can show it with additional measurements

Strong tension between world data (?)

Underestimated uncertainties?
Something not well understood? ...

Magnetic GP



Large uncertainties & discrepancies in the β_M

α_E and β_M with improved precision and consistent systematics across Q^2 will allow to disentangle para/dia-magnetism in the proton

Theory: BxPT

Generalized polarizabilities of the nucleon in baryon chiral perturbation theory

Vadim Lensky^{1,2,3,a}, Vladimir Pascalutsa¹, Marc Vanderhaeghen¹

¹ Institut für Kernphysik, Cluster of Excellence PRISMA, Johannes Gutenberg Universität Mainz, 55128 Mainz, Germany

² Institute for Theoretical and Experimental Physics, Moscow 117218, Russia

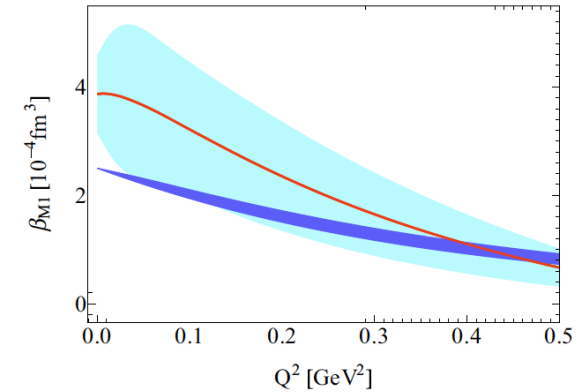
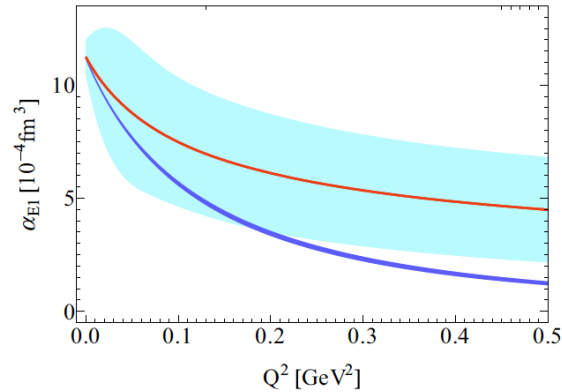
³ National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow 115409, Russia



BxPT calculation to NLO
in the δ -counting scheme



DR calculation
D. Drechsel, B. Pasquini, M. Vanderhaeghen,
Phys. Rep. 378,99 (2003)



Theory: Lattice QCD

Lattice QCD results for
the static polarizabilities

Lattice QCD calculations for
the GPs are challenging

		24D	32Dfine	PDG
Proton	$\alpha_E^{ii,N\pi}$	5.65(53)	6.5(1.2)	...
	$\alpha_E^{ii,es}$	-1.42(53)	-1.58(61)	...
	$\alpha_E^{ii,disc}$	1.4(1.2)	0.1(1.8)	...
	α_E^r	4.333(3)	4.333(3)	...
	α_E	10.0(1.3)	9.3(2.2)	11.2(4)

Spatial information & polarizability radii

Spatial dependence of induced polarizations

Nucleon form factor data → light-front quark charge densities

Formalism extended to the deformation of these quark densities when applying an external e.m. field:

GPs → spatial deformation of charge & magnetization densities under an applied e.m. field

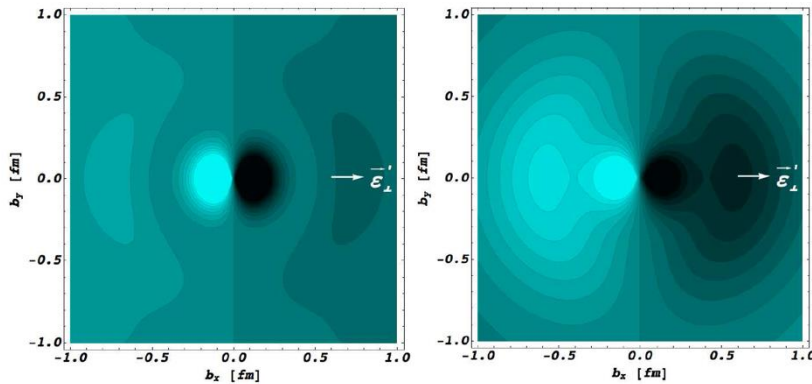
Induced polarization in a proton when submitted to an e.m. field

Phys. Rev. Lett. 104, 112001 (2010)

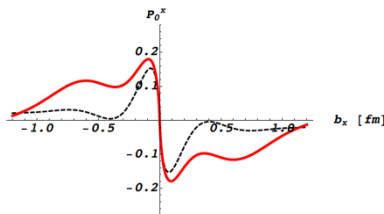
M. Gorchtein, C. Lorce, B. Pasquini, M. Vanderhaeghen

GP I

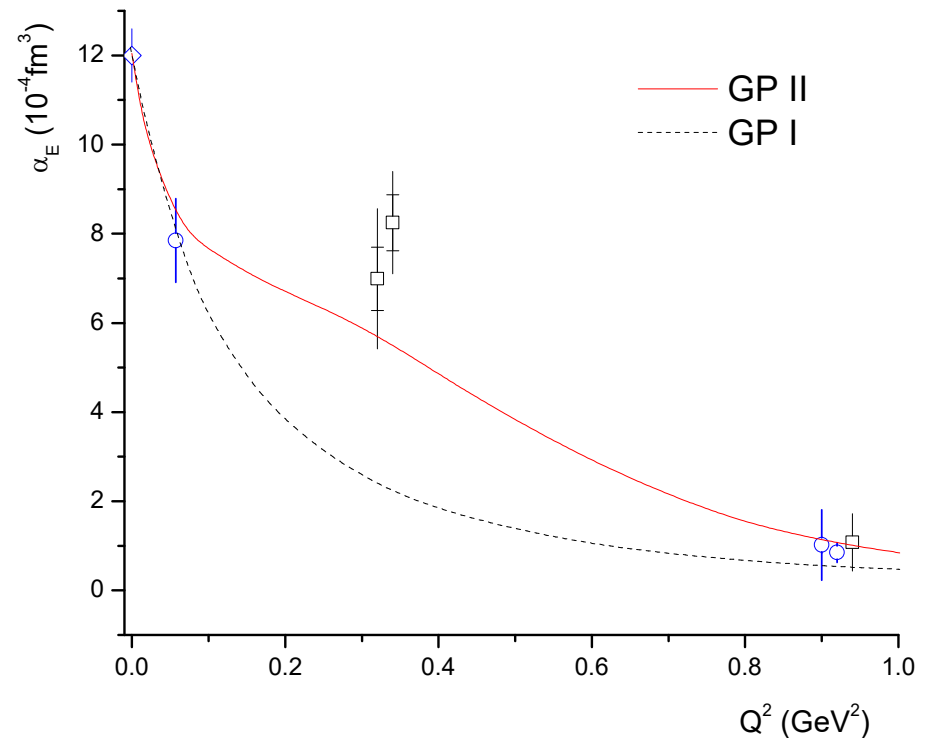
GP II



Light (dark) regions → largest (smaller) values
(photon polarization along x-axis, as indicated)



Induced polarization along $b_y=0$

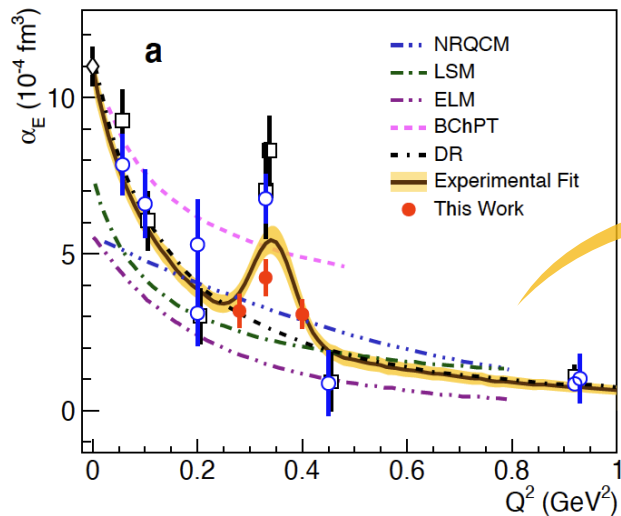


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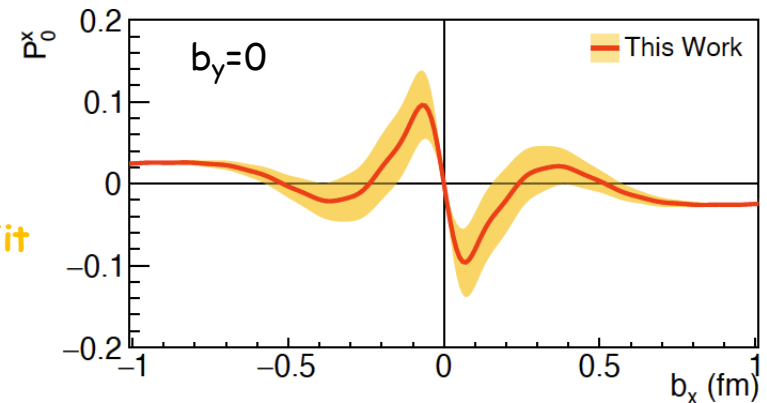
Formalism extended to the deformation of these quark densities when applying an external e.m. field:

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Experimental Fit

Induced polarization in a proton when submitted to an e.m. field



x-y defines the transverse plane with the z-axis being the direction of the fast-moving proton

Polarizability radii

$$\langle r_{\alpha_E}^2 \rangle = \frac{-6}{\alpha_E(0)} \cdot \frac{d}{dQ^2} \alpha_E(Q^2) \Big|_{Q^2=0}$$

$$\langle r_{\beta_M}^2 \rangle = \frac{-6}{\beta_M(0)} \cdot \frac{d}{dQ^2} \beta_M(Q^2) \Big|_{Q^2=0}$$

Polarizability radii

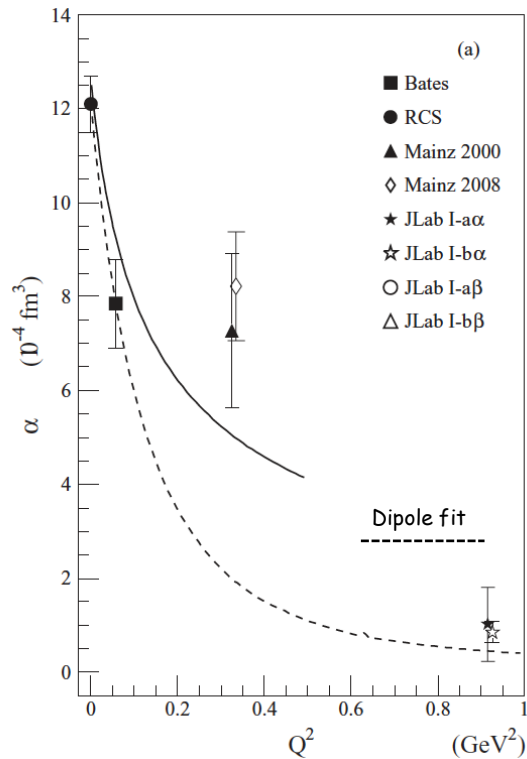
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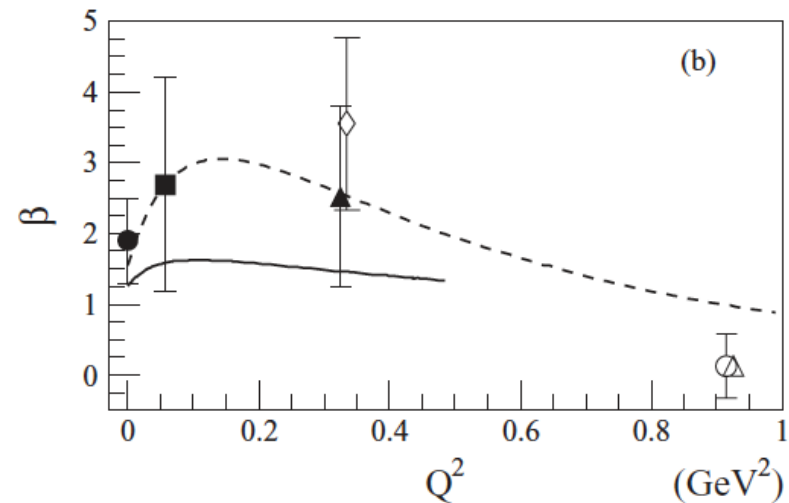
First extraction made possible with the MIT-Bates measurement ($Q^2=0.06 \text{ GeV}^2$)

PRL **97**, 212001 (2006)

PHYSICAL REVIEW C **84**, 035206 (2011)



$$\langle r_{\alpha}^2 \rangle = 2.16 \pm 0.31 \text{ fm}^2$$

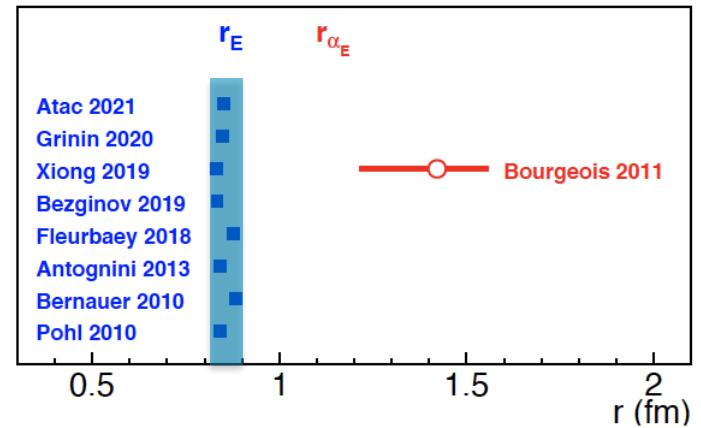
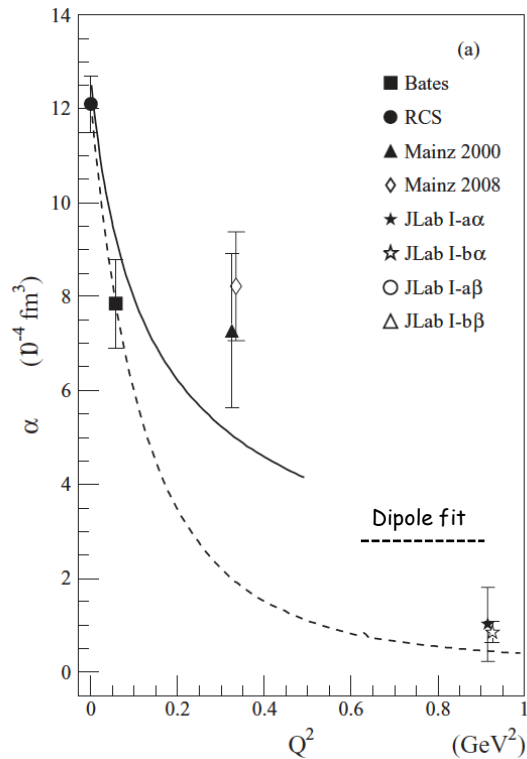


$$\frac{\langle r_{\beta}^2 \rangle}{-4.67^{+5.36}_{-13.04}}$$

Polarizability radii

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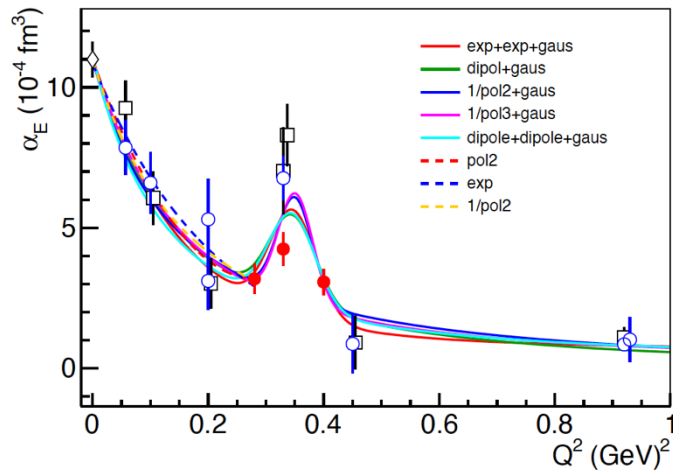
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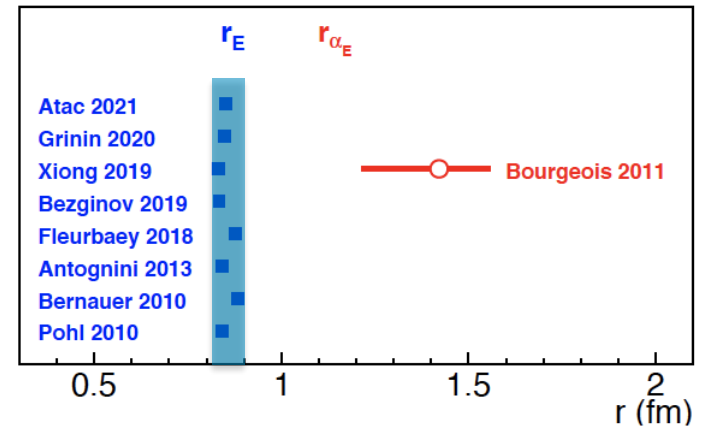
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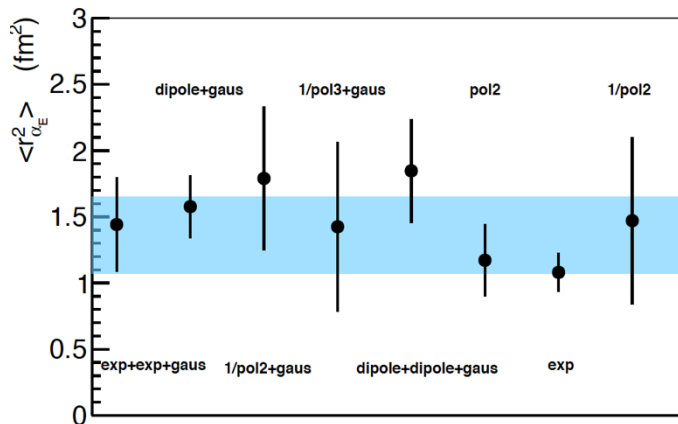
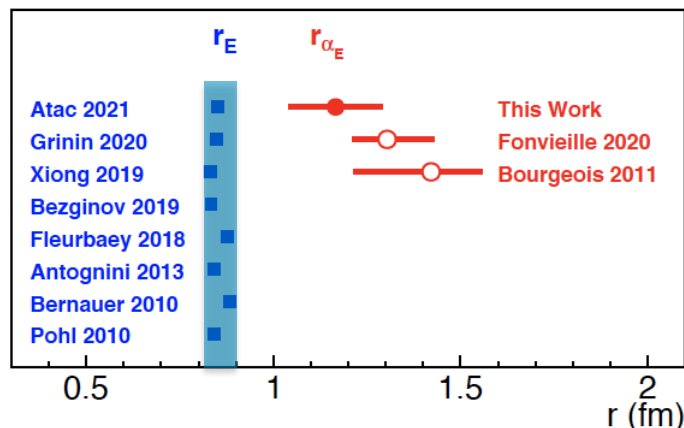
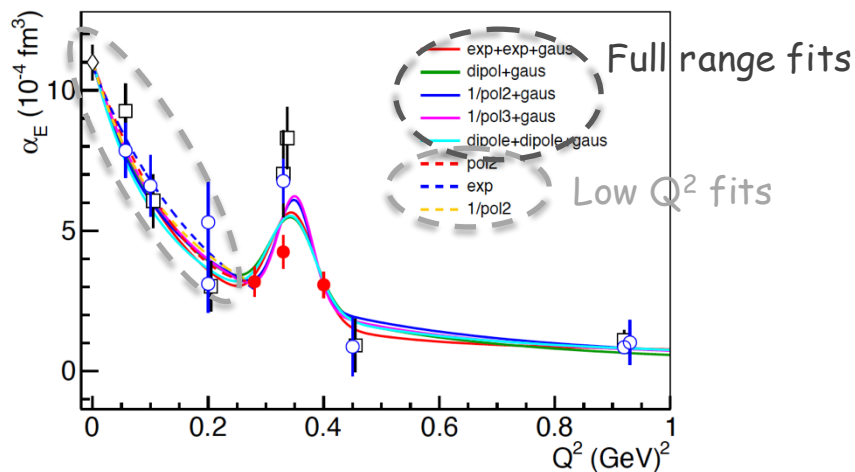
Since then: more data and more comprehensive treatment of the radius extraction



Polarizability radii

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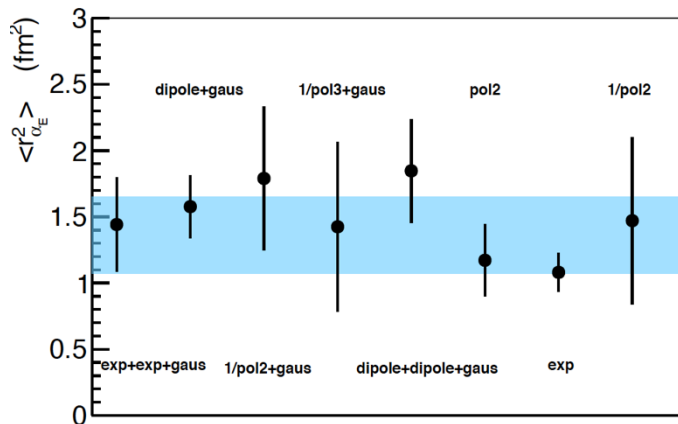
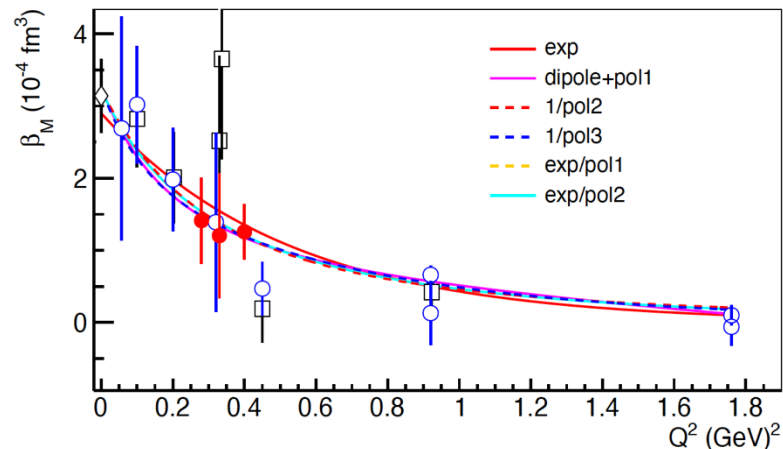
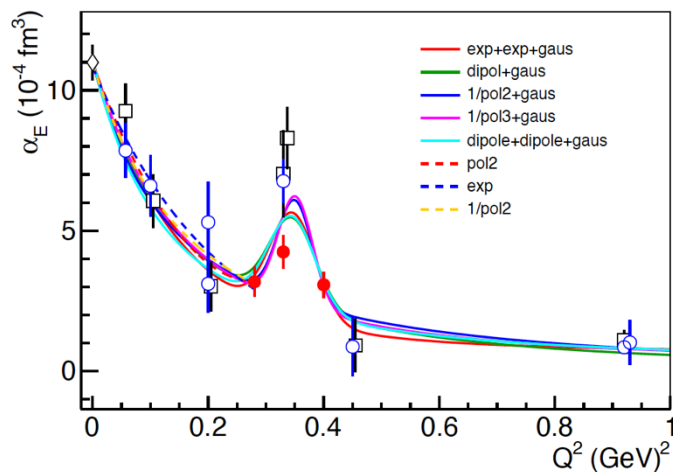


$$\langle r_{\alpha_E}^2 \rangle = 1.36 \pm 0.29 \text{ fm}^2$$

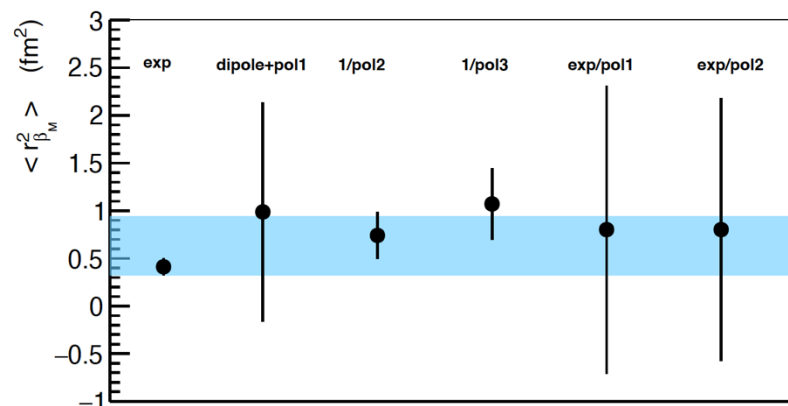
Polarizability radii

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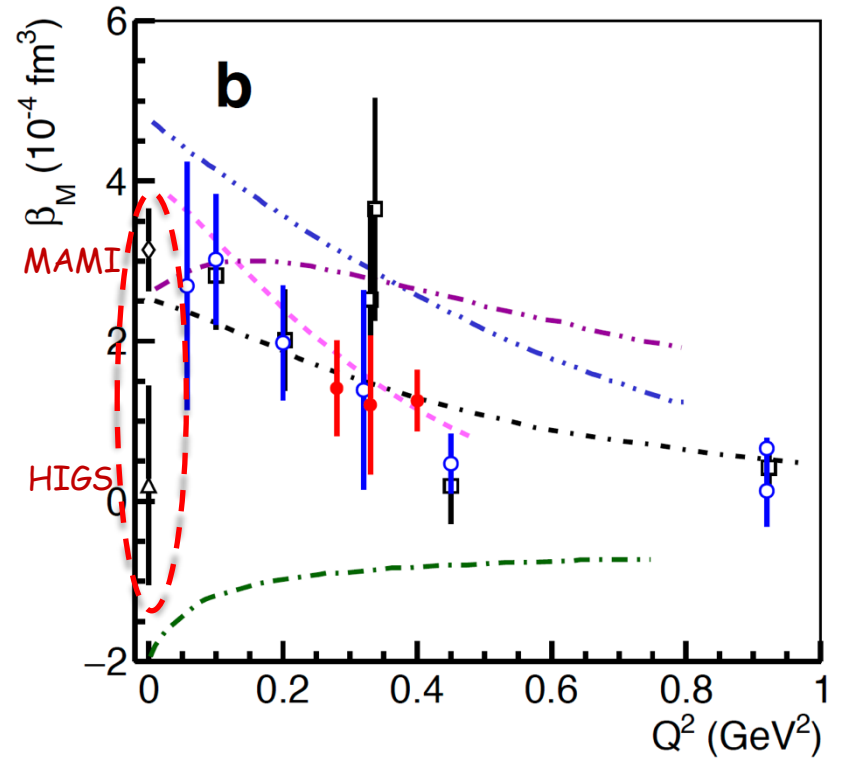
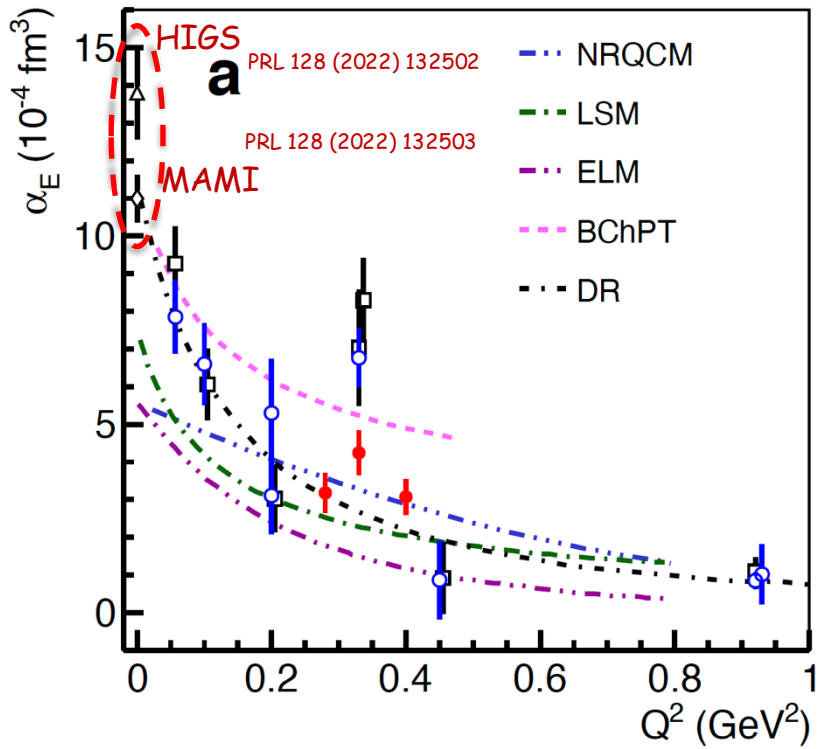


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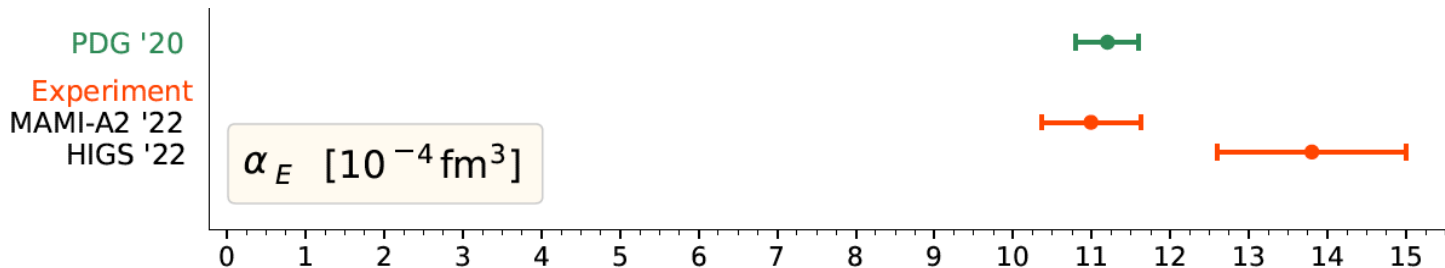


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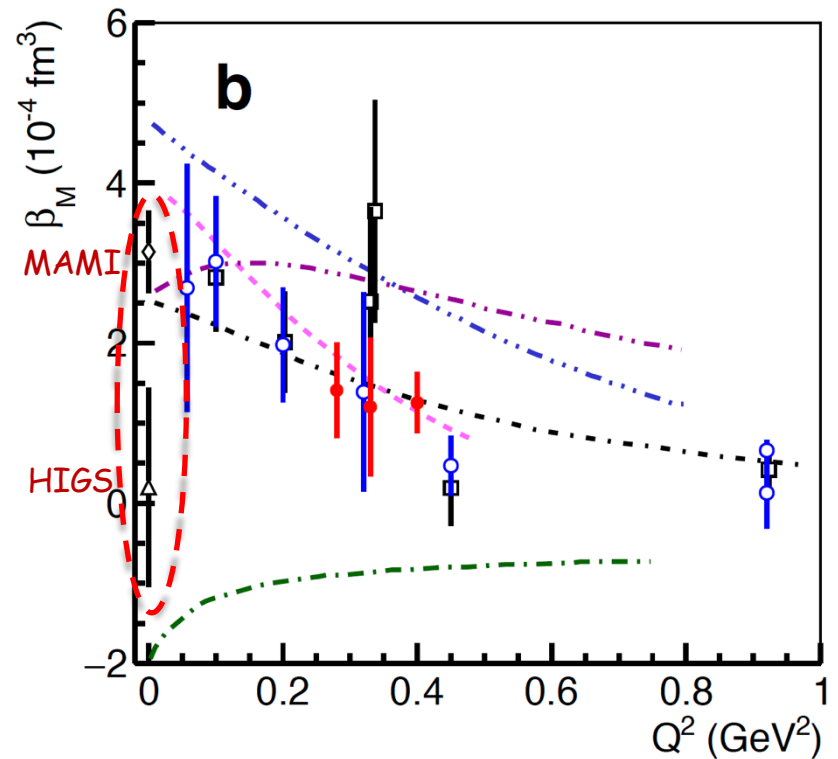
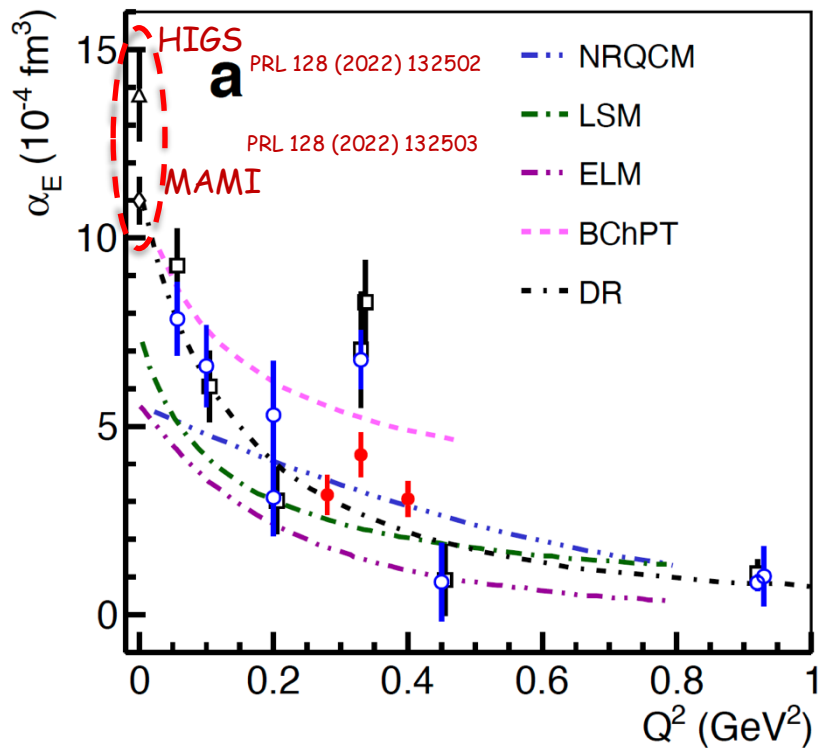
Static Polarizabilities



Recent measurements exhibit tension \rightarrow affects the pol. radius extraction

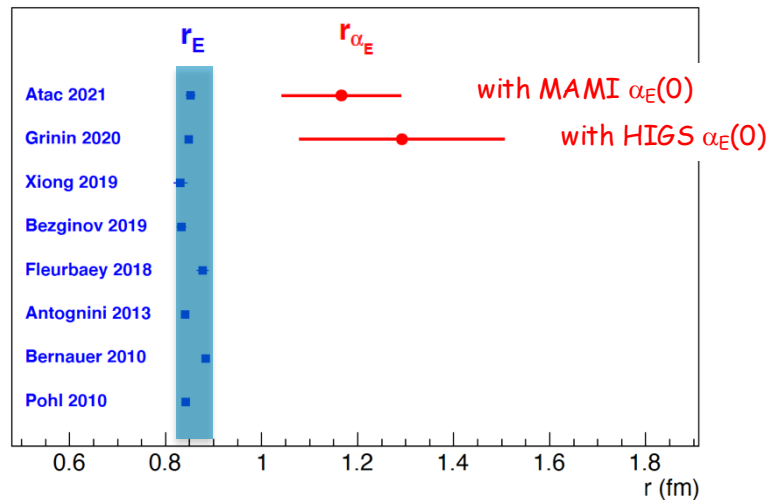


Polarizability radii - Static Polarizabilities



$$\langle r_{\alpha_E}^2 \rangle = 1.36 \pm 0.29 \text{ fm}^2$$

$$\langle r_{\alpha_E}^2 \rangle = 1.67 \pm 0.50 \text{ fm}^2$$

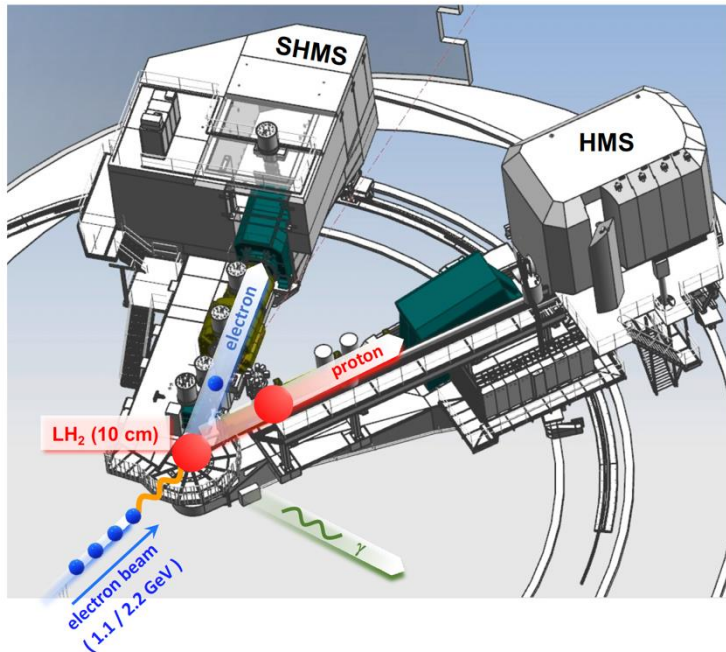


$$\langle r_{\beta_M}^2 \rangle = 0.63 \pm 0.31 \text{ fm}^2$$

$$\langle r_{\beta_M}^2 \rangle = 0.20 \pm 0.36 \text{ fm}^2$$

Prospects & Outlook

VCS-II (E12-23-001) @ JLab



Follow up of the VCS-I experiment

Extend Q^2 range of the Hall C measurements and provide a fine mapping in Q^2

Improve precision of measurements, both in terms of statistics and systematics (i.e. targeted series of measurements to control systematics, uniformity of systematics across the full data set)

Will fully exploit the sensitivity of the Hall-C setup to the EM GPs and will provide measurements of unprecedented precision

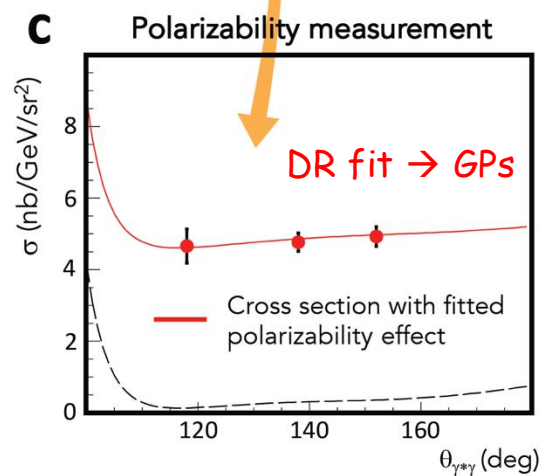
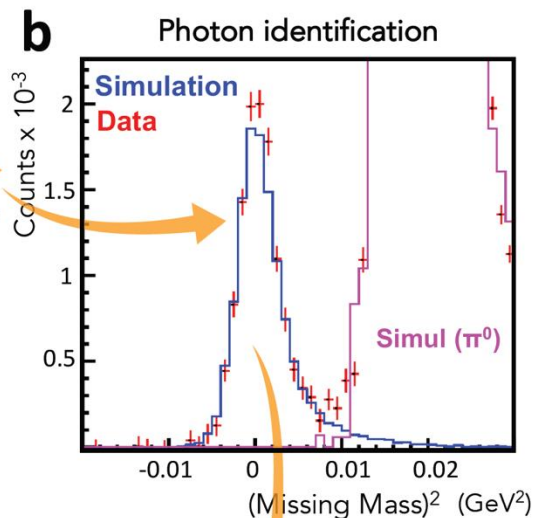
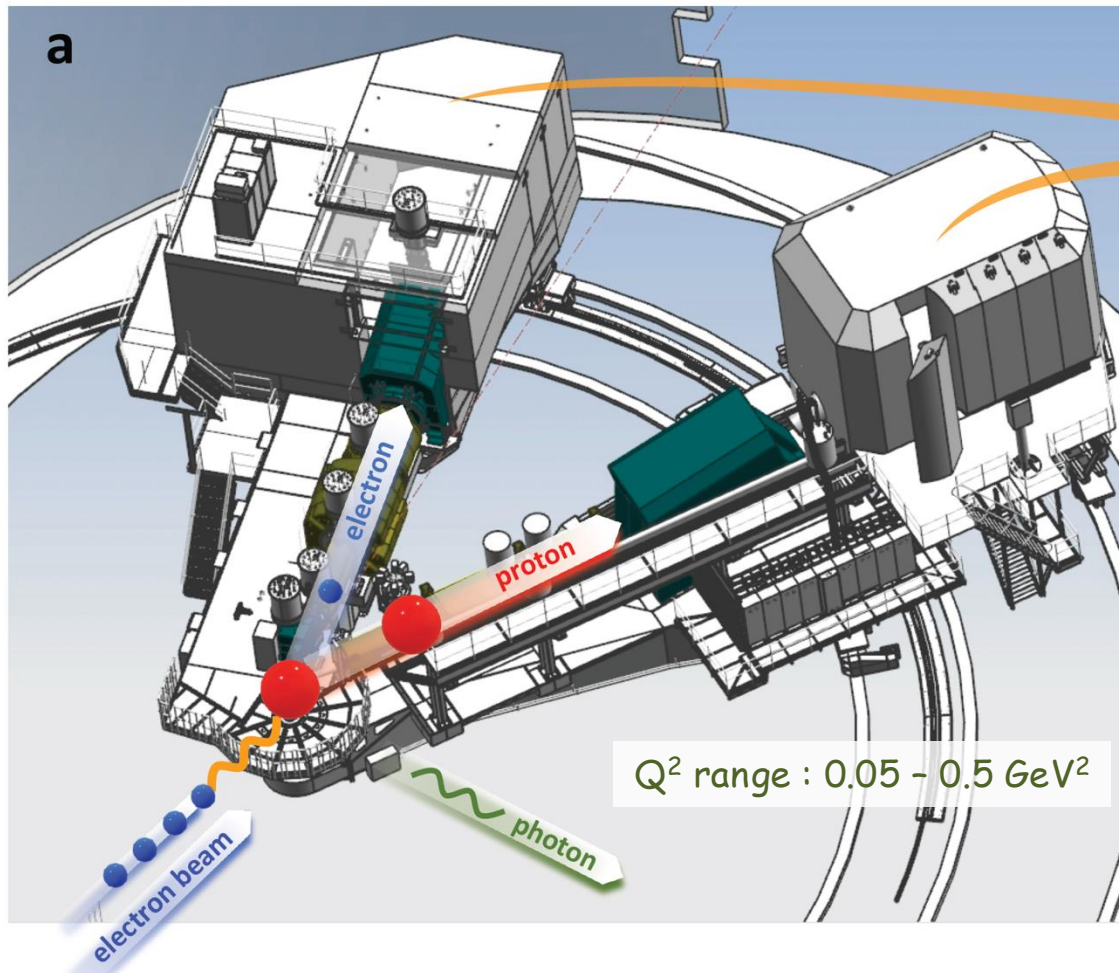
Experiment was approved by PAC 51

Scheduled to acquire data in 2026 & 2027

Production ($E_0 = 1.4 \text{ GeV}$) :	6 days
Production ($E_0 = 2.1 \text{ GeV}$) :	53 days
Studies (optics/dummy/calibrations) :	3 days

Total: 62 days @ 100% efficiency

VCS-II (E12-23-001)

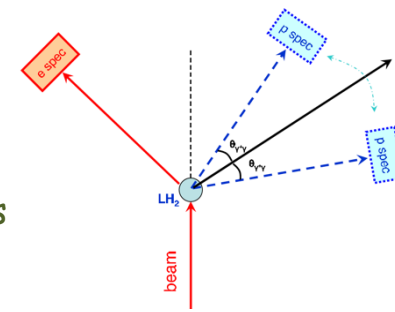


Hall C: SHMS, HMS
 $E_{\text{beam}} = 1.4 \text{ \& } 2.1 \text{ GeV}$
 $I = 75 \mu\text{A}$
 LH2 10 cm

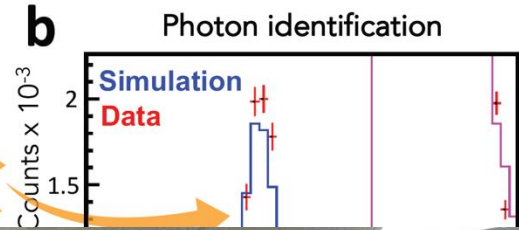
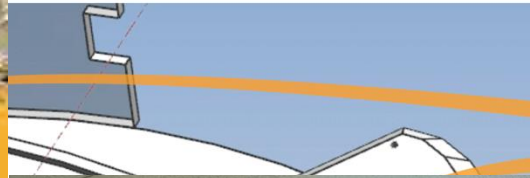
cross sections & azimuthal asymmetries

$$A_{(\phi_{\gamma^*\gamma}=0,\pi)} = \frac{\sigma_{\phi_{\gamma^*\gamma}=0} - \sigma_{\phi_{\gamma^*\gamma}=180}}{\sigma_{\phi_{\gamma^*\gamma}=0} + \sigma_{\phi_{\gamma^*\gamma}=180}}$$

Asymmetries help with the sensitivity to GPs
 & suppression of systematic uncertainties



VCS-II (E12-23-001)



- ★ First beam on March 27th
- ★ System checkout, optics & calibrations
- ★ Production (phase I): April & May 2026
- ★ Production (phase II): FY 2027 ~ 6 weeks

Projected cross section measurements

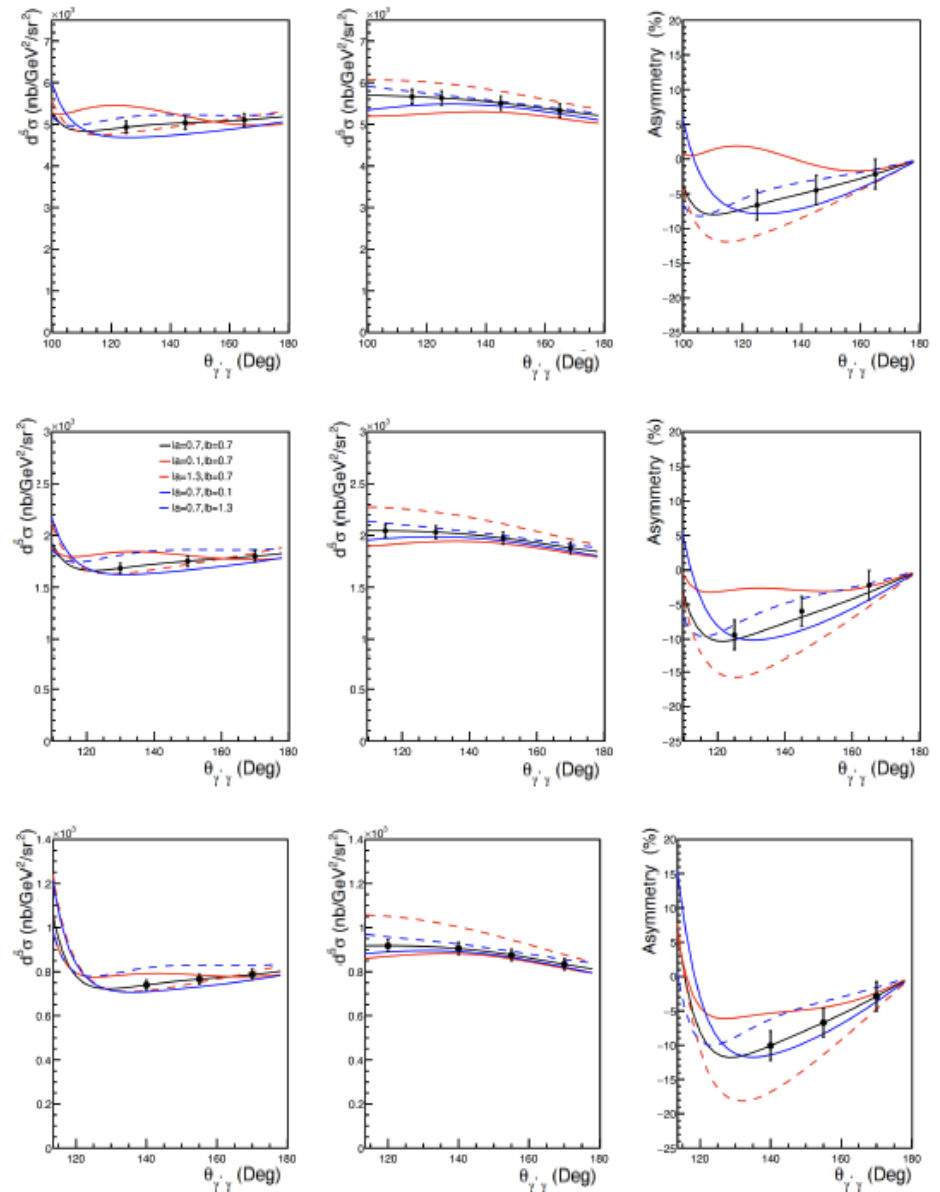
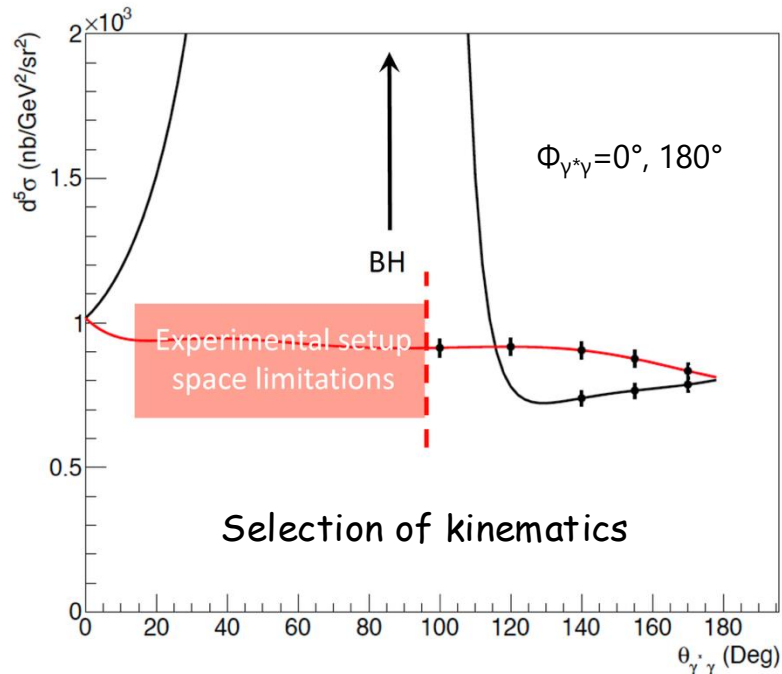
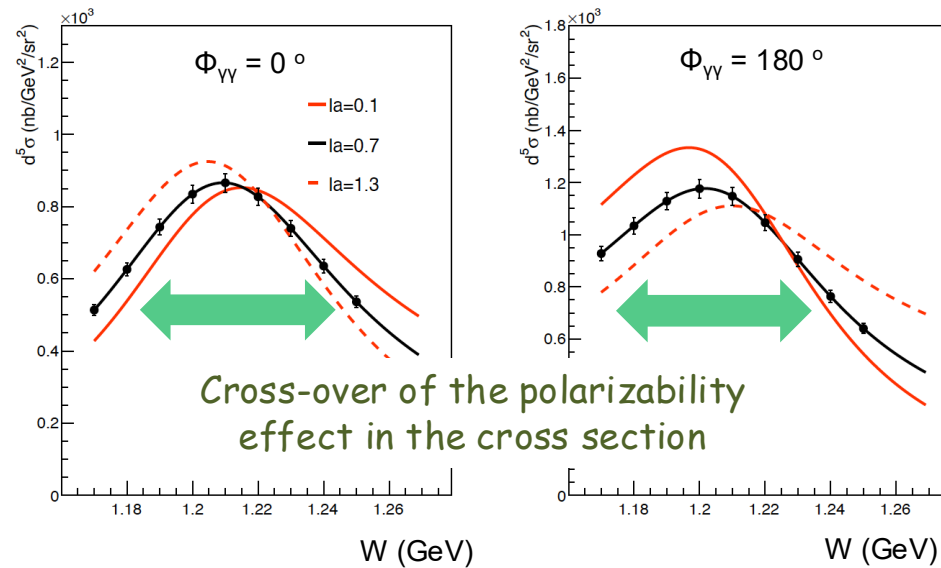


FIG. From left to right: cross sections at $\Phi_{\gamma^*\gamma} = 0^\circ$ (left) and 180° (center) and asymmetries (right). Top panels correspond to $Q^2 = 0.15$ (GeV/c)², middle panels to $Q^2 = 0.25$ (GeV/c)² and bottom panels to $Q^2 = 0.35$ (GeV/c)².

VCS-II Projected Measurements

Targeted measurements to fully exploit the sensitivity to the GPs and to constrain systematic effects

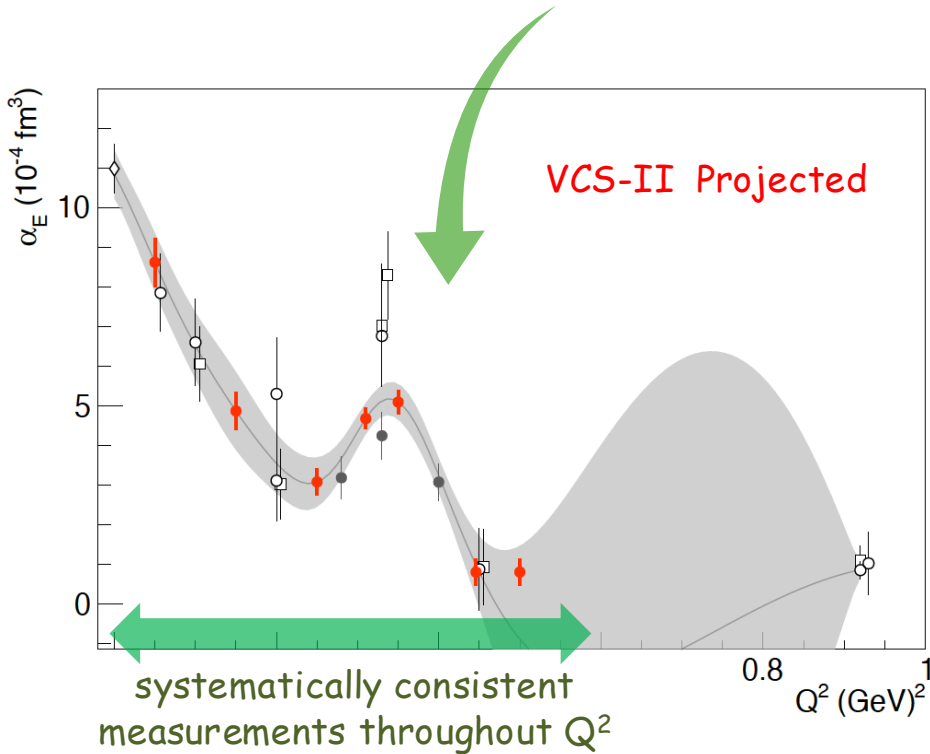


Cross-over of the polarizability effect in the cross section

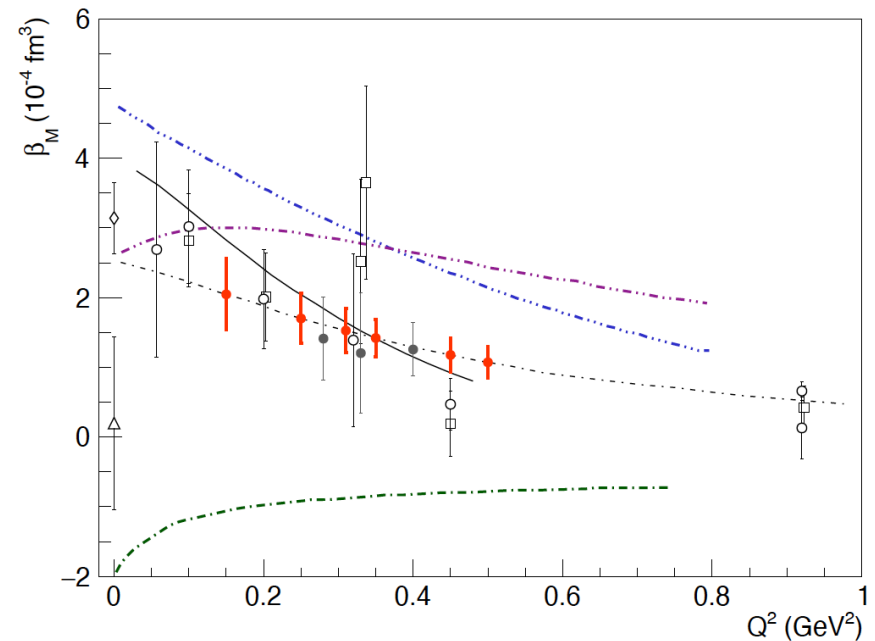
Decouples polarizability extraction from normalization

VCS-II Projected Measurements

High precision measurements
combined with a fine mapping in Q^2



Improve upon β_M :
Disentangle the competing para/dia-
magnetic contributions in the nucleon



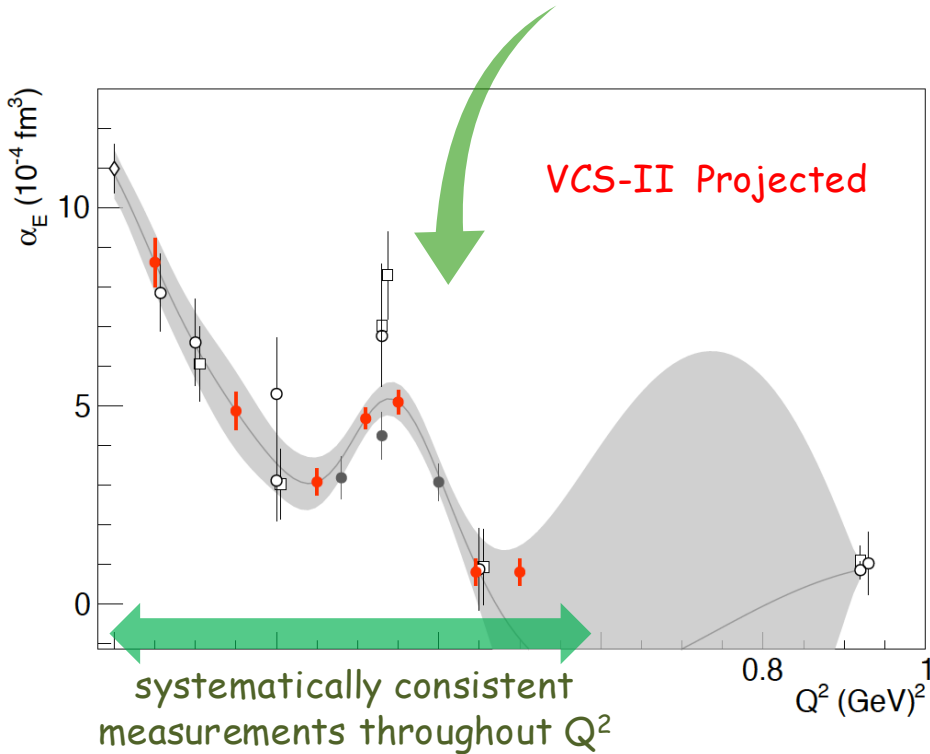
First phase of data-taking in spring 2026
2 months of beam-time April and May

Second phase of data-taking in 2027

Preliminary results ~ 2028

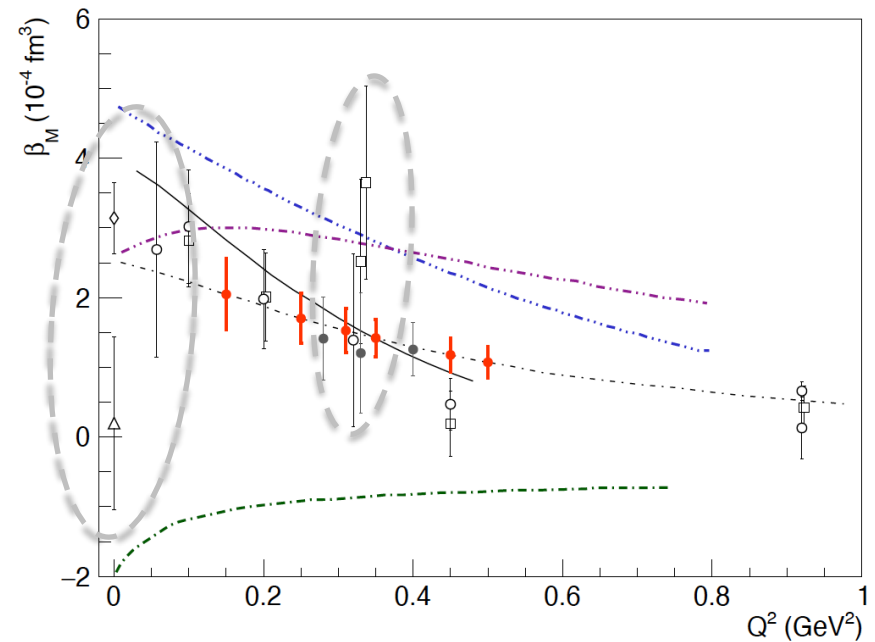
VCS-II Projected Measurements

High precision measurements
combined with a fine mapping in Q^2



Improve upon β_M :

Disentangle the competing para/dia-
magnetic contributions in the nucleon



First phase of data-taking in spring 2026

2 months of beam-time April and May

Second phase of data-taking in 2027

Preliminary results ~ 2028

Can we measure the GPs with a different experimental method ?

Yes: positrons and/or beam spin asymmetries

allow for an independent path to access experimentally the GPs

Eur. Phys. J. A 57 (2021) 11, 316

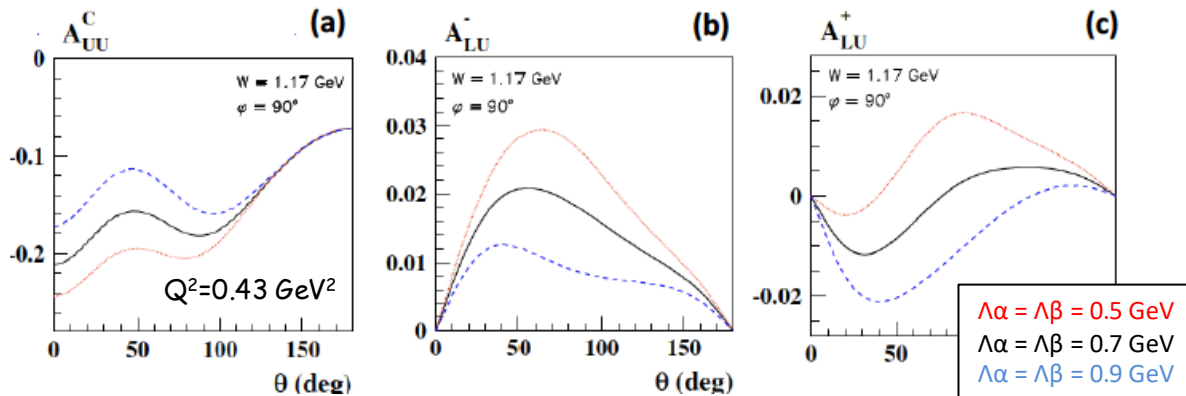
Virtual Compton scattering at low energies with a positron beam

Barbara Pasquini^{a,1,2}, Marc Vanderhaeghen^{b,3}

¹Dipartimento di Fisica, Università degli Studi di Pavia, 27100 Pavia, Italy

²Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, 27100 Pavia, Italy

³Institut für Kernphysik and PRISMA⁺ Cluster of Excellence, Johannes Gutenberg Universität, D-55099 Mainz, Germany



(a): The beam-charge asymmetry as a function of the photon scattering angle at $Q^2 = 0.43 \text{ GeV}^2$.

(b) & (c): The electron and positron beam-spin asymmetry as a function of the photon scattering angle for out-of-plane kinematics.

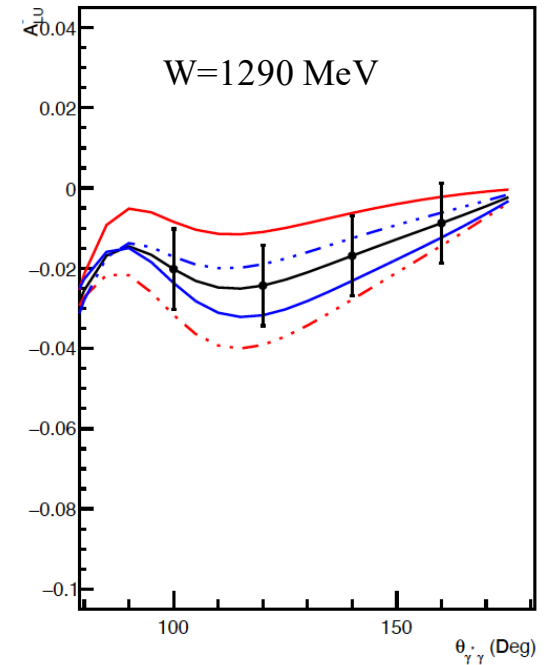
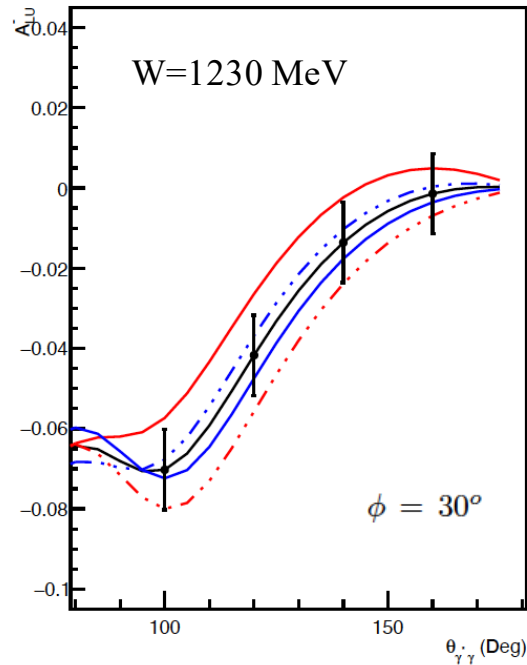
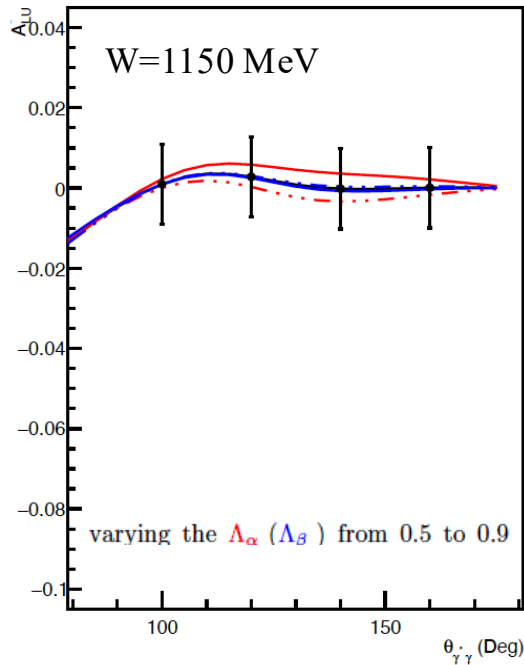
Unpolarized beam charge asymmetry (BCA):
$$A_{UU}^C = \frac{(d\sigma_+^+ + d\sigma_-^+) - (d\sigma_+^- + d\sigma_-^-)}{d\sigma_+^+ + d\sigma_-^+ + d\sigma_+^- + d\sigma_-^-}$$

Lepton beam spin asymmetry (BSA):
$$A_{LU}^e = \frac{d\sigma_+^e - d\sigma_-^e}{d\sigma_+^e + d\sigma_-^e}$$

BSA (electrons or positrons)

Lepton beam spin asymmetry (BSA) :
$$A_{LU}^e = \frac{d\sigma_+^e - d\sigma_-^e}{d\sigma_+^e + d\sigma_-^e}$$

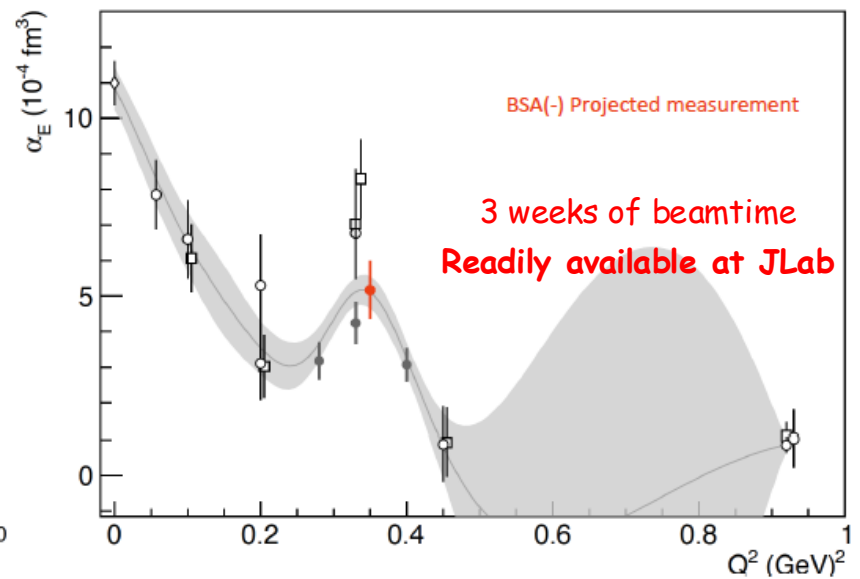
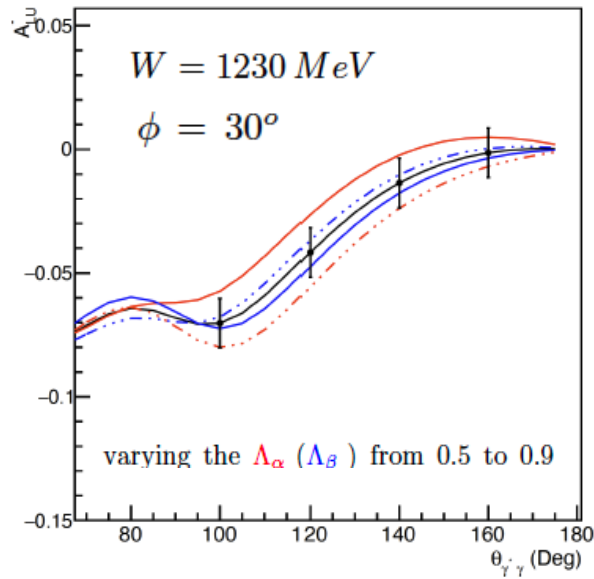
electrons



Projected measurements with SHMS / HMS

BSA (electrons or positrons)

Lepton beam spin asymmetry (BSA) :
$$A_{LU}^e = \frac{d\sigma_+^e - d\sigma_-^e}{d\sigma_+^e + d\sigma_-^e}$$

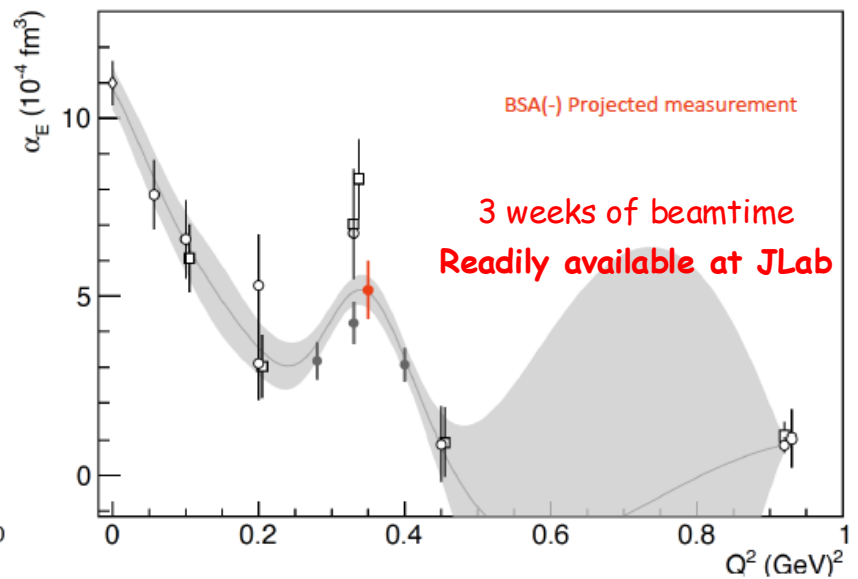
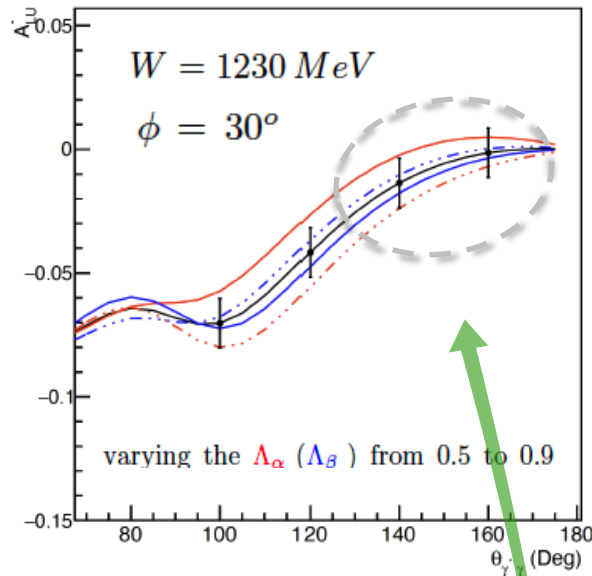


e^- (pol. 85% @ 70 μA)

~ 3 weeks of beamtime

BSA (electrons or positrons)

Lepton beam spin asymmetry (BSA) :
$$A_{LU}^e = \frac{d\sigma_+^e - d\sigma_-^e}{d\sigma_+^e + d\sigma_-^e}$$

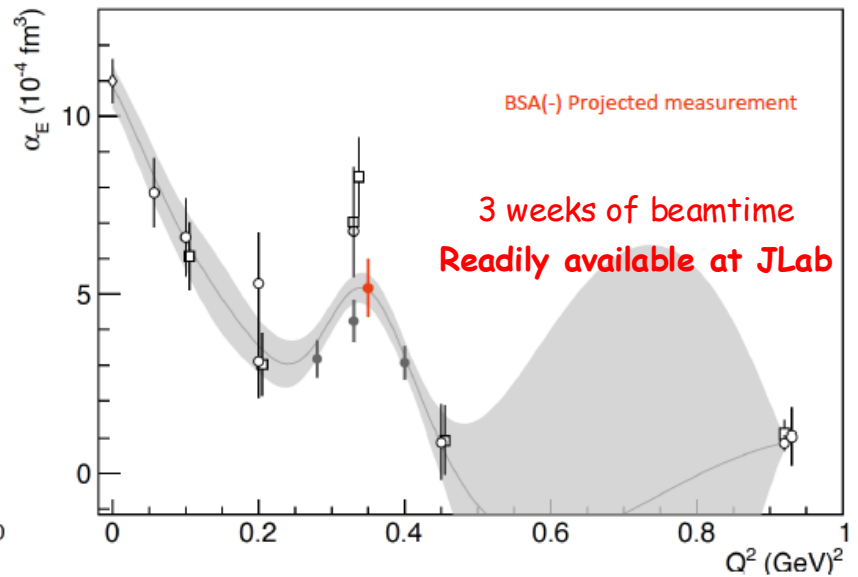
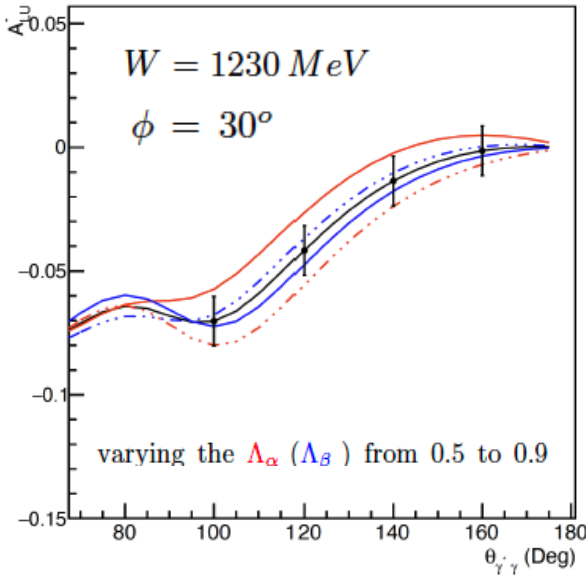


e^- (pol. 85% @ 70 μA)
 ~ 3 weeks of beamtime

Can take advantage of the VCS-II beam-time (2026-2027)
 for part of the overlapping kinematics
 provided that the beam is polarized

BSA (electrons or positrons)

Lepton beam spin asymmetry (BSA) :
$$A_{LU}^e = \frac{d\sigma_+^e - d\sigma_-^e}{d\sigma_+^e + d\sigma_-^e}$$



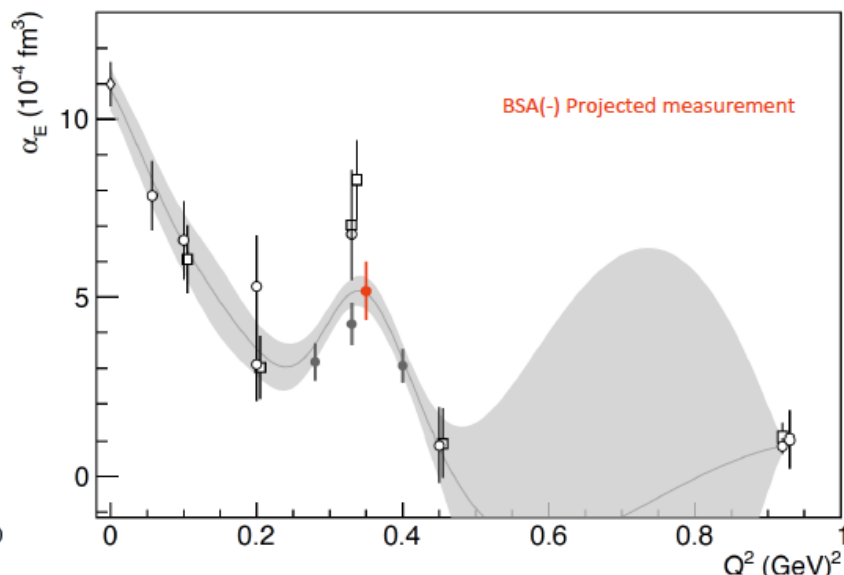
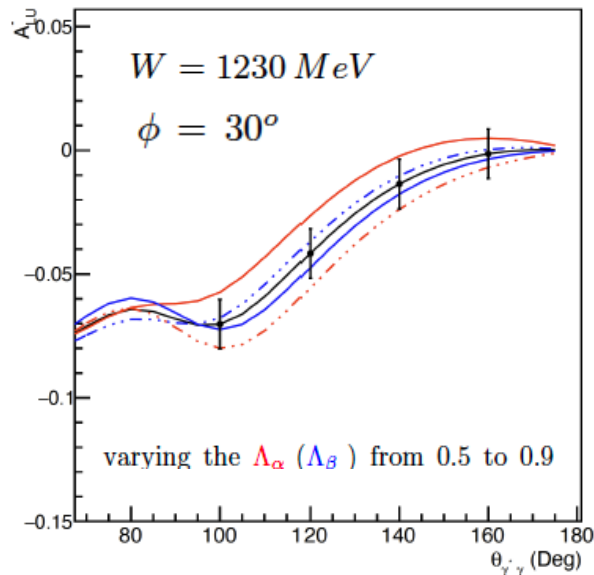
e^- (pol. 85% @ 70 μA)
 ~ 3 weeks of beamtime

or

~~e^+ (pol. 60% @ 50 nA)
 ~ 3 orders of magnitude
 more beamtime~~

BSA (electrons or positrons)

Lepton beam spin asymmetry (BSA):
$$A_{LU}^e = \frac{d\sigma_+^e - d\sigma_-^e}{d\sigma_+^e + d\sigma_-^e}$$



E12-25-008

"First Measurement of the Proton GPs with a Polarized electron beam in VCS"

Experiment was approved by the JLab PAC 53

"new measurement to provide an independent cross-check of the unpolarized VCS experiments, in particular, in a Q^2 region where electric polarizability data has revealed a significant enhancement"

To be scheduled

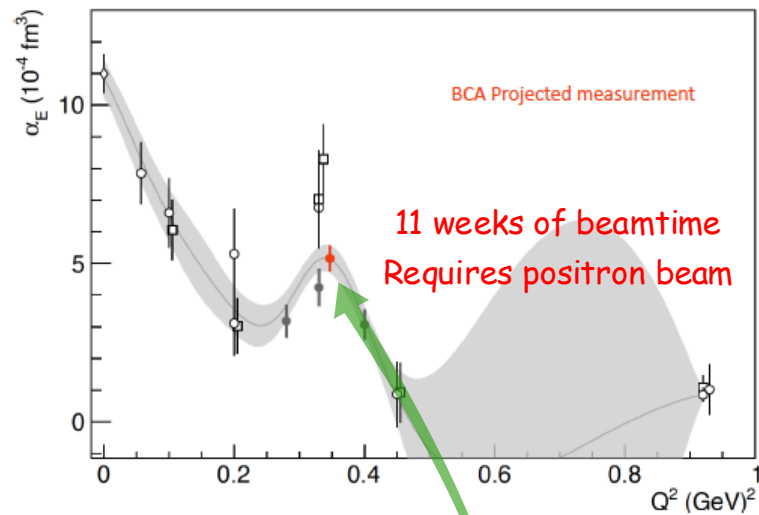
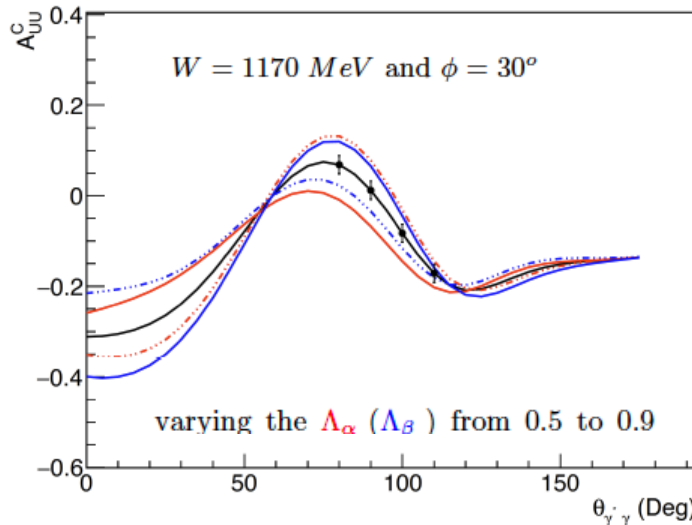
* can collect fraction of the data parasitically during VCS-II

e^- (pol. 85% @ 70 μA)

~ 3 weeks of beamtime

BCA (electrons & positrons)

Unpolarized beam charge asymmetry (BCA): $A_{UU}^C = \frac{(d\sigma_+^+ + d\sigma_-^+) - (d\sigma_+^- + d\sigma_-^-)}{d\sigma_+^+ + d\sigma_-^+ + d\sigma_+^- + d\sigma_-^-}$



Hall C (SHMS / HMS) $\left\{ \begin{array}{l} e^- : \sim 1 \text{ week @ } 50 \mu\text{A} \\ \text{and} \\ e^+ : \sim 10 \text{ weeks @ } \sim \mu\text{A} \end{array} \right.$

BCA measurements offer superb precision!!

LOI 23-12-001 : PAC 51 Report Summary

“The physics case presented in the proposal is robust ..., and the PAC encourages the proponents to proceed and submit a full proposal”

Summary

A vibrant experimental program is ongoing focusing on the study of fundamental proton properties

Insight to spatial deformation of the nucleon densities under an applied EM field, interplay of para/dia-magnetism in the proton, polarizability radii, ...

Electric GP: { possibility for a non-trivial (non-monotonic) behavior in $a_E(Q^2)$
(albeit with a smaller magnitude than originally suggested)
or
at minimum: strong tension between world data

Experiment is ahead of theory

Stringent constraints to theoretical predictions

High precision benchmark data for upcoming LQCD calculations

Updated theory calculations are needed and encouraged

Upcoming experimental goals

Improve β_M : paramagnetism / diamagnetism in the proton

Identify the shape of the a_E structure (if true?) : input for the theory

Determine the polarizability radii with higher precision

Conduct an independent cross-check

Measure via a different channel (BS asymmetries & positrons)

Thank you!