The Proton Electromagnetic Generalized Polarizabilities

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16th European Research Conference on
Electromagnetic Interactions with Nucleons and Nuclei

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Temple University

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Outline

Introduction to the VCS and GPs

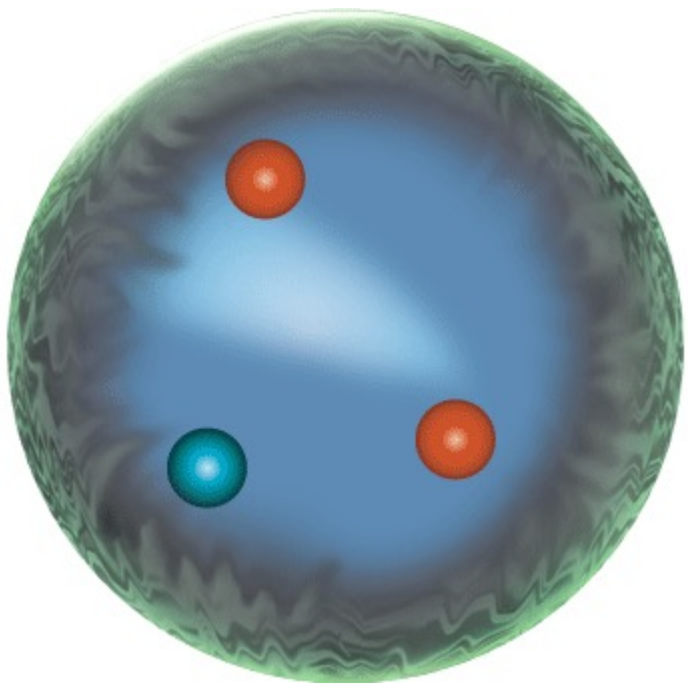
What have we learned so far

Upcoming experiments

Prospects & outlook

The broader goal: Explain how the proton emerges from the dynamics of the quark & gluon constituents

How can we accomplish it: Measure precisely the fundamental properties of the proton's bound state and understand their emergence within the framework of our fundamental theory



Mass

....

Spin

Polarizabilities

Size

Shape

Proton Polarizablities

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]
$|m_p - m_{\overline{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]
$|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p}) = 0.99999999991 \pm 0.00000000009$
$|q_p + q_{\overline{p}}|/e < 7 \times 10^{-10}$, CL = 90% [b]
$|q_p + q_e|/e < 1 \times 10^{-21}$ [c]
Magnetic moment $\mu = 2.792847356 \pm 0.000000023\ \mu_N$
$(\mu_p + \mu_{\overline{p}}) / \mu_p = (0 \pm 5) \times 10^{-6}$
Electric dipole moment $d < 0.54 \times 10^{-23}$ $e$cm
Electric polarizability $\alpha = (11.2 \pm 0.4) \times 10^{-4}$ fm^3
Magnetic polarizability $\beta = (2.5 \pm 0.4) \times 10^{-4}$ fm^3 (S = 1.2)
Charge radius, μp Lamb shift $= 0.84087 \pm 0.00039$ fm [d]
Charge radius, ep CODATA value $= 0.8775 \pm 0.0051$ fm [d]
Magnetic radius $= 0.777 \pm 0.016$ fm
Mean life $\tau > 2.1 \times 10^{29}$ years, CL = 90% [e] ($p \to$ invisible mode)
Mean life $\tau > 10^{31}$ to 10^{33} years [e] (mode dependent)

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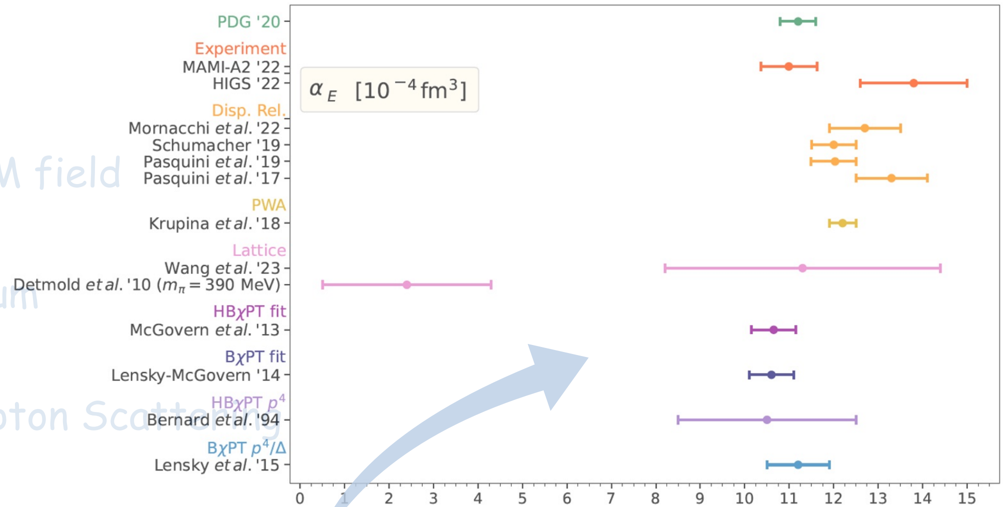

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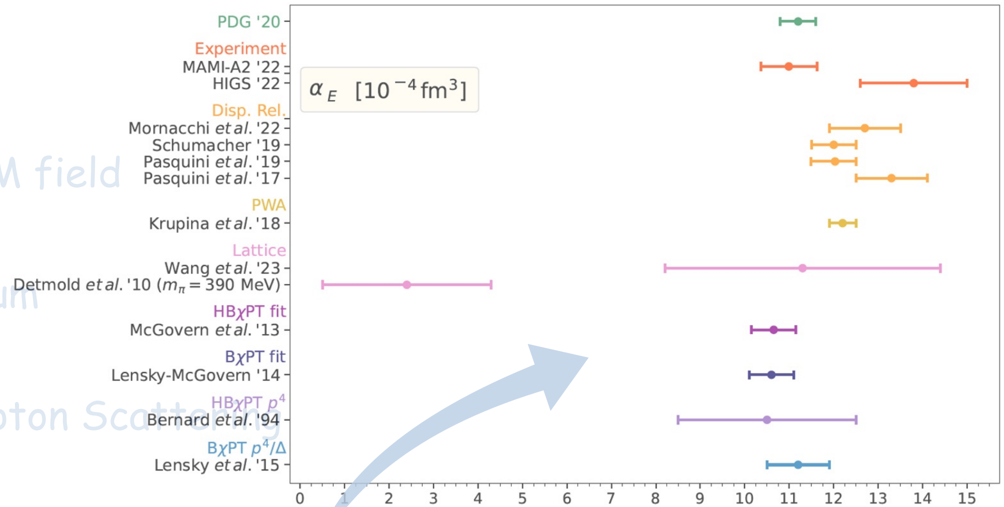


RCS: static polarizabilities → net effect on the nucleon

Virtual Compton Scattering:

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

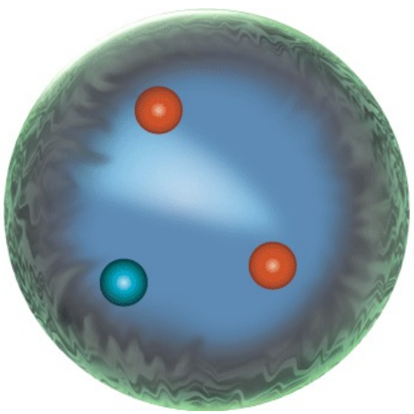
→ spatial distribution of the polarization densities
→ electric & magnetic polarizability radii

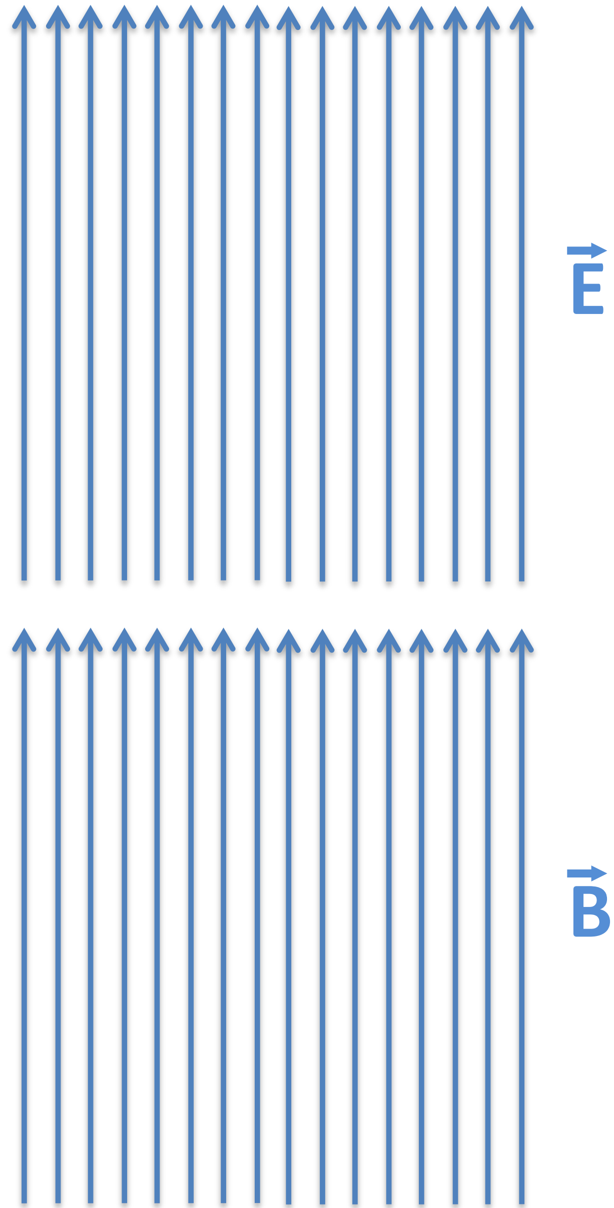
Fourier transform of densities of electric charges and magnetization of a nucleon deformed by an applied EM field

Scalar Polarizablities

Response of internal structure to an applied EM field

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





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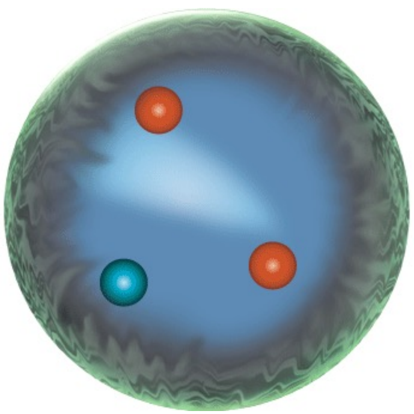
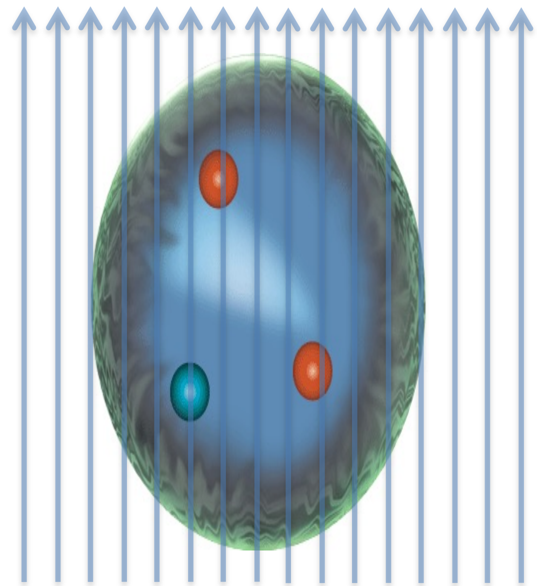


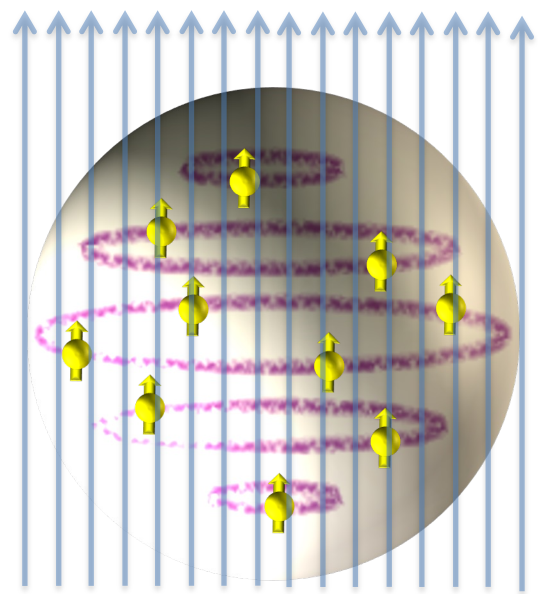


$\vec{E}$

"stretchability"

$\vec{d}_{E\ \mathrm{induced}} \sim \alpha\, \vec{E}$

External field deforms the charge distribution



$\vec{B}$

"alignability"

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

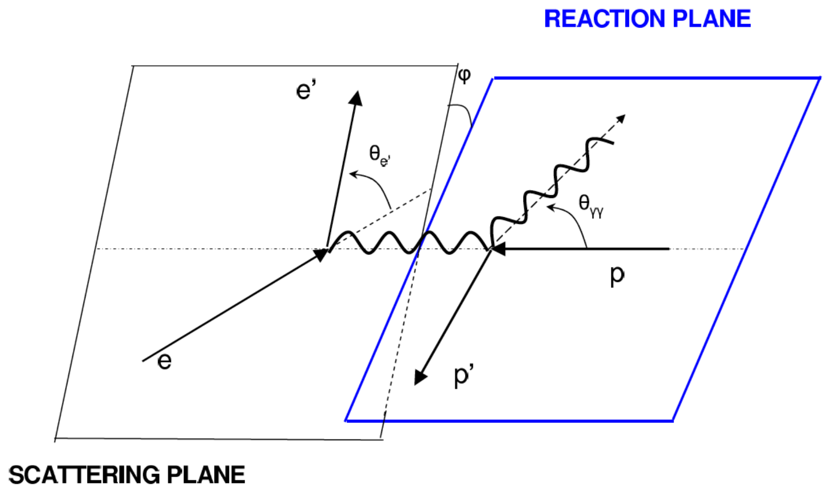
$\beta_{para} > 0$

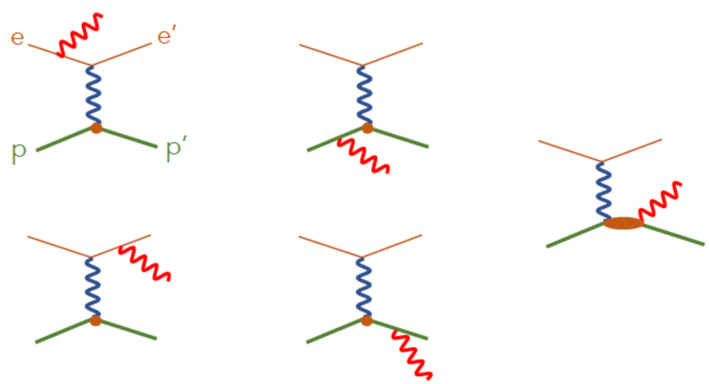
$\beta_{diam} < 0$

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

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

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

Subtract the spin part

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

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

utilize DR

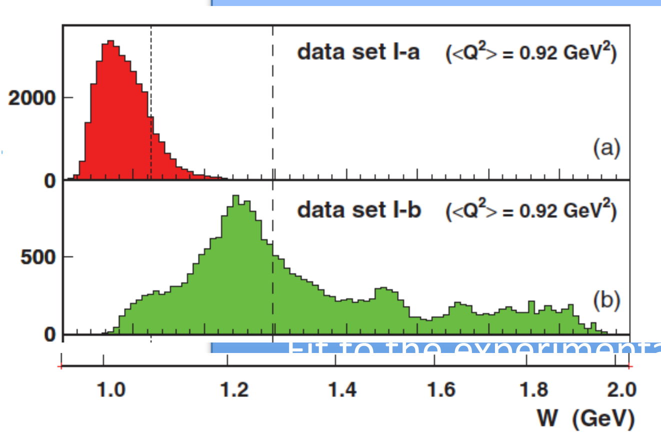
scalar GPs α_E and β_M

Virtual Compton Scattering

DR

valid below & above
Pion threshold

Dispersive integrals
for Non Born amplitudes



Fit to the experimental ... Q^2

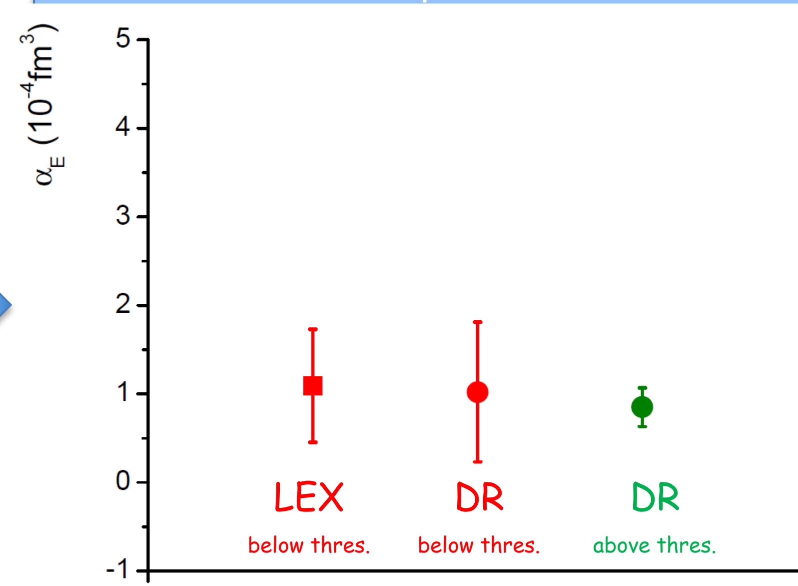
LEX

valid only below
Pion threshold

Response functions

$\mathcal{O}(q'^2_{cm})$

P_{LT}



$P_{LT\ spin}]$

utilize DR

scalar GPs α_E and β_M

Sensitivity to the GPs

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

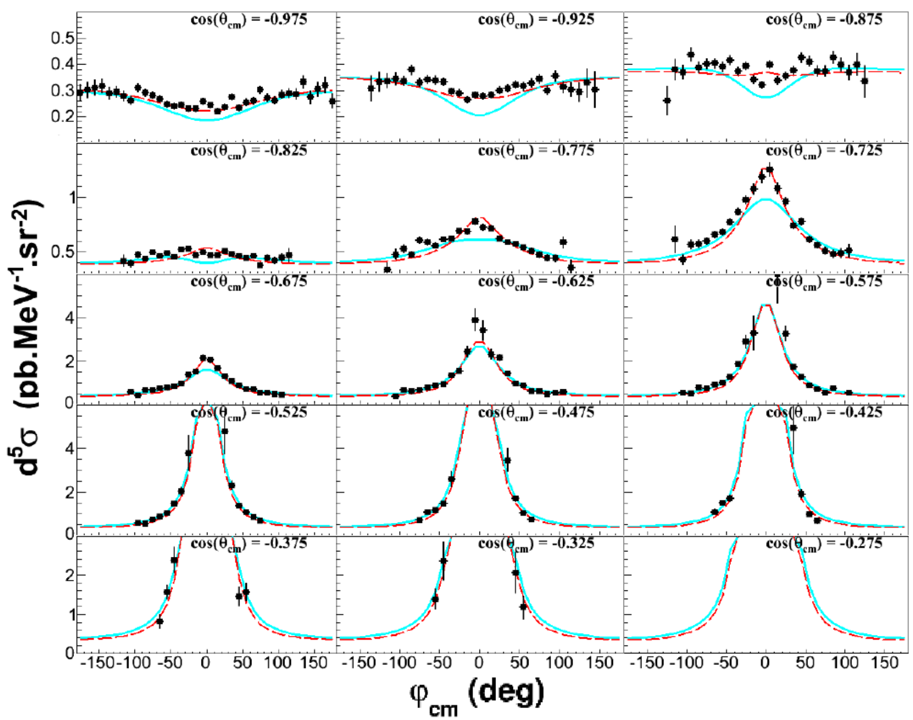


Figure 5.8: Setting INP: measured $ep \rightarrow ep\gamma$ cross section at fixed $q'_{cm} = 112.5\ MeV/c$ with respect to φ_{cm} for all the $cos(\theta_{cm})$-bins. The curves follow the convention of figure 5.6.

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

MAMI measurements

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

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 ~ 2%-3% level

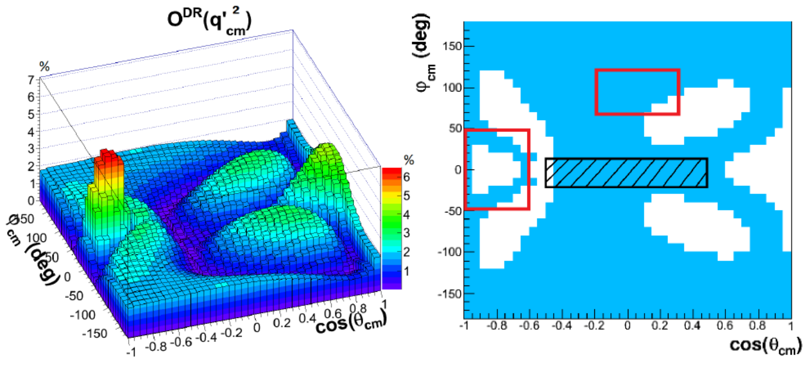
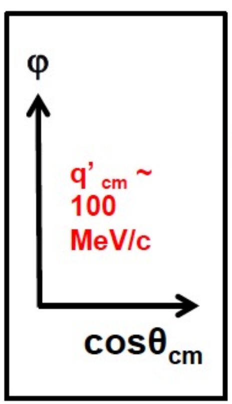
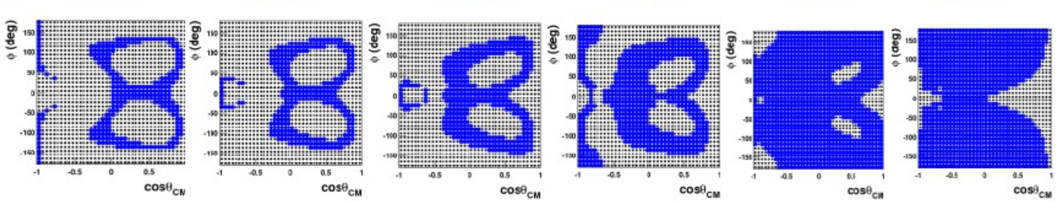


Figure 3.13: (Left) behavior of $\mathcal{O}^{DR}({q'_{cm}}^2)$ in the $(cos(\theta_{cm}),\varphi_{cm})$-plane at q'_{cm} = 87.5 MeV/c and (right) two-dimensional representation of the angular region where $\mathcal{O}^{DR}({q'_{cm}}^2) < 2\%$ (blue), the red squares correspond to the two areas of interest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

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



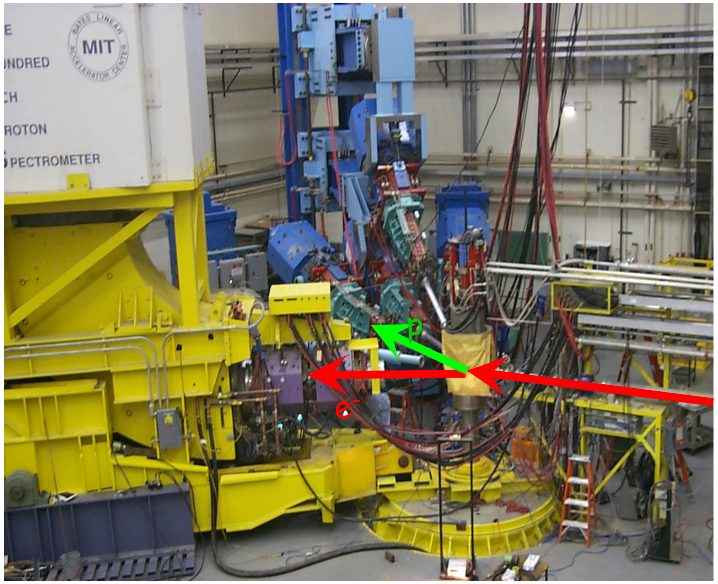
VCS expt :	Bates	MAMI	MAMI	MAMI	MAMI	JLab
Q2 (GeV2) =	0.06	0.10	0.20	0.33	0.45	0.92



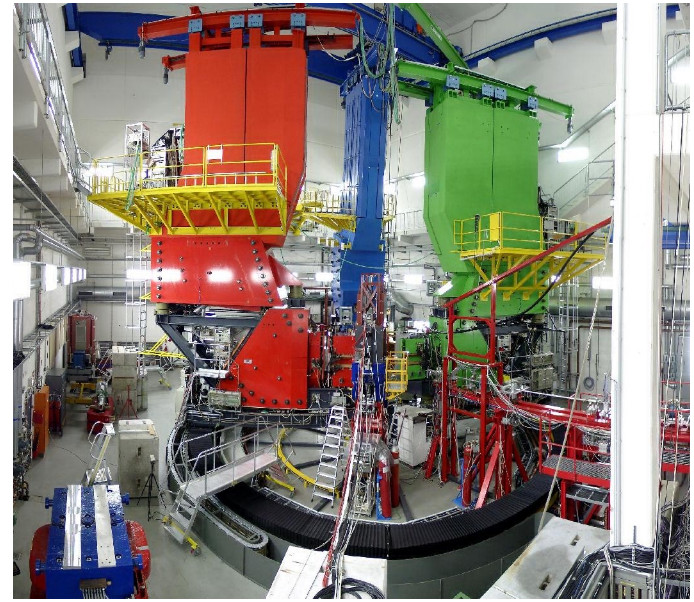
The effect is more prominent at low Q^2

VCS Experiments

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

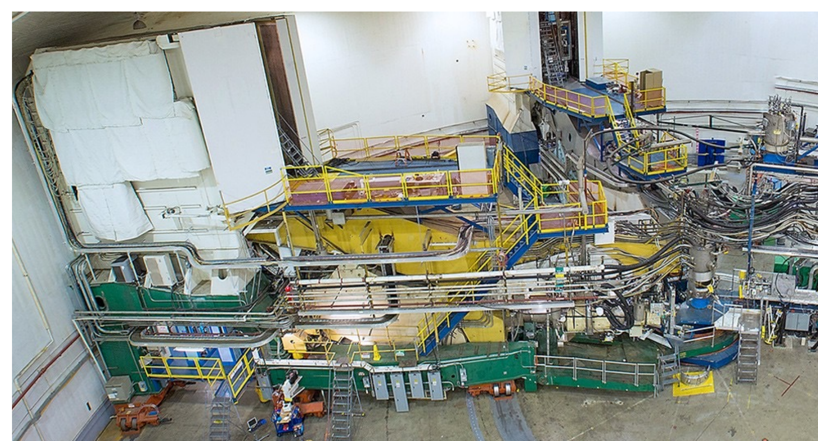


MAMI-A1 @ Q^2=0.1 -0.45 GeV^2

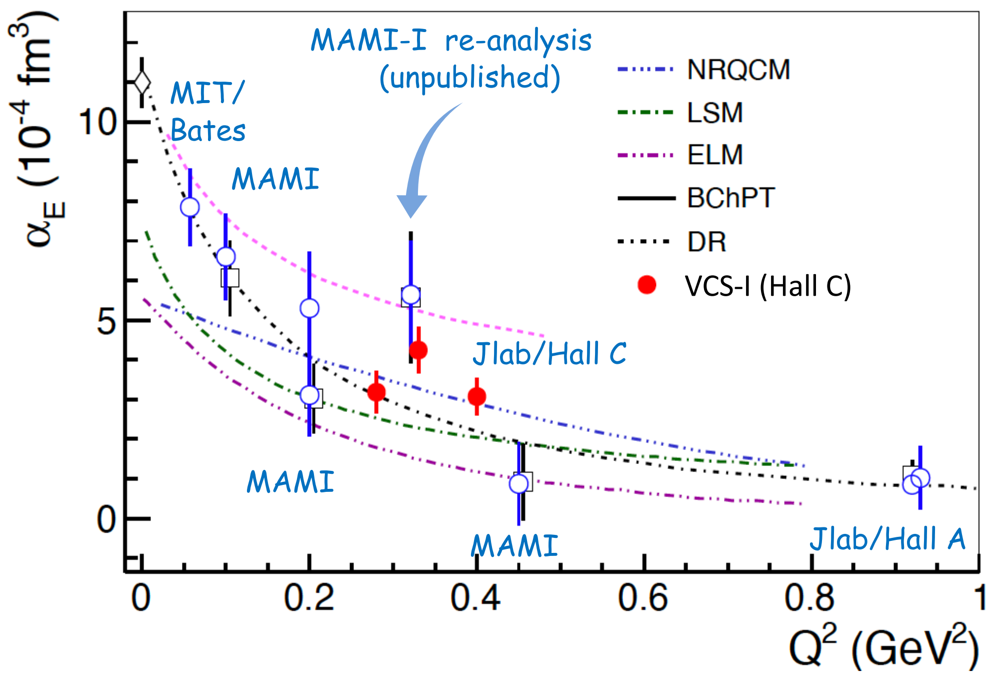


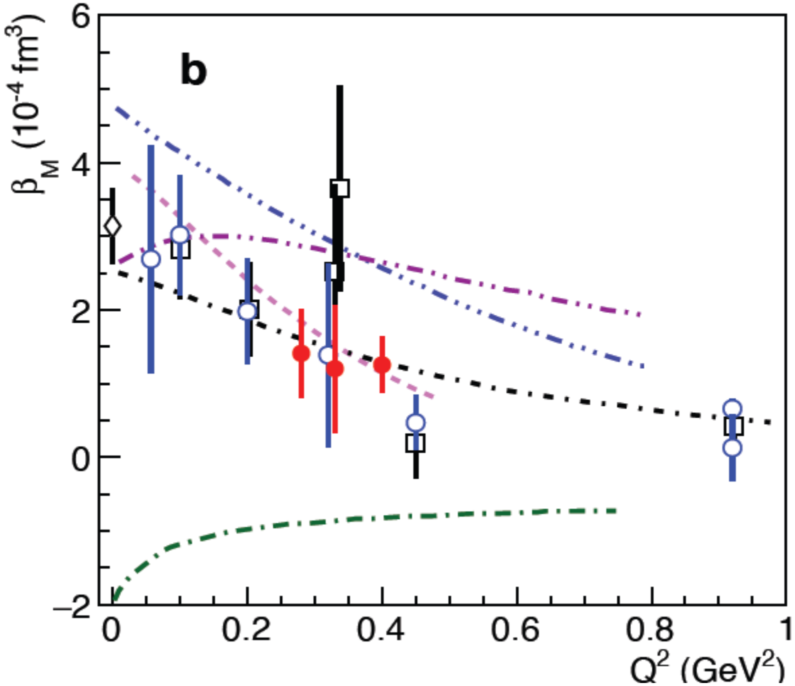
Jlab-Hall C @ Q^2=0.05 – 0.5 GeV^2

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

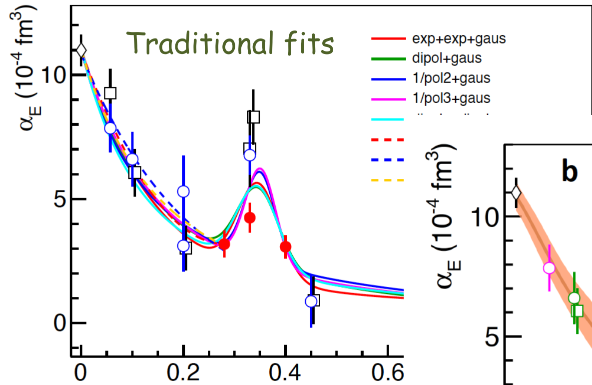


VCS Experiments

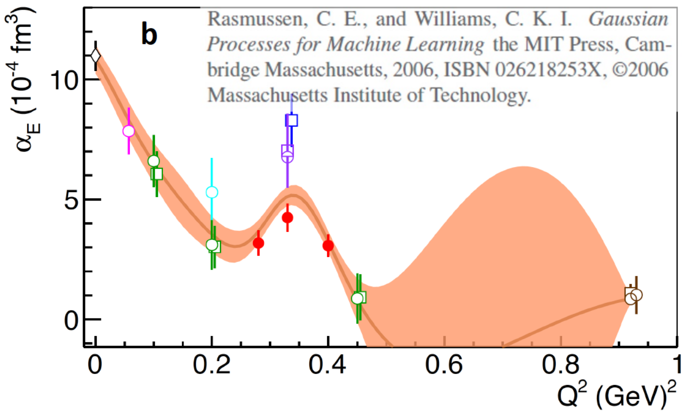


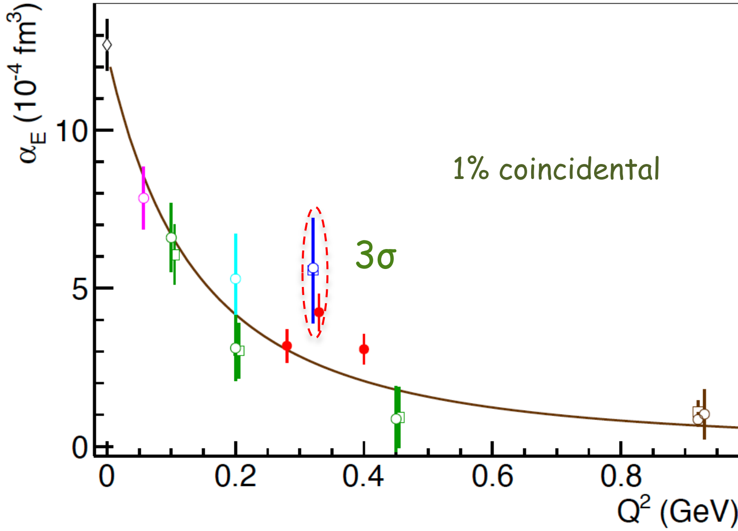


Electric GP



Data-driven techniques:
no underlying functional form is assumed





Is the observed α_E structure coincidental or not?

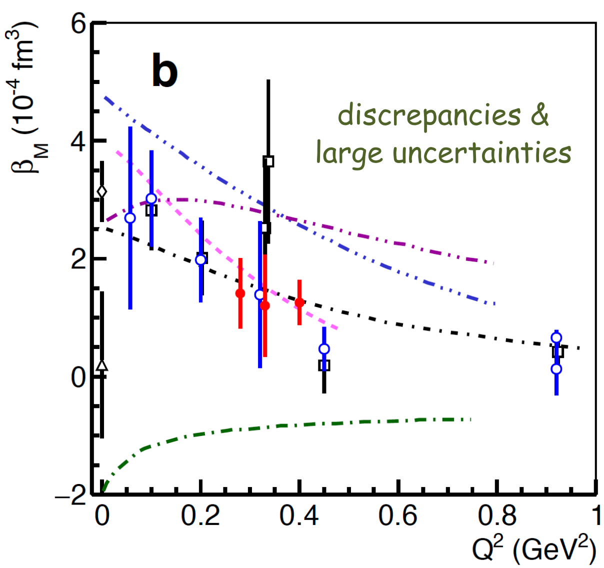
Yes: Measure the shape precisely → input to theory

No: Able to show it with more measurements

Strong tension between world data (?)

Underestimated uncertainties ?
Something not well understood ? …

Magnetic GP



Magnetic GP: Large uncertainties & discrepancies

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

Theory: BχPT

Eur. Phys. J. C (2017) 77:119
DOI 10.1140/epjc/s10052-017-4652-9

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Generalized polarizabilities of the nucleon in baryon chiral perturbation theory

Vadim Lensky[1,2,3,a], **Vladimir Pascalutsa**[1], **Marc Vanderhaeghen**[1]

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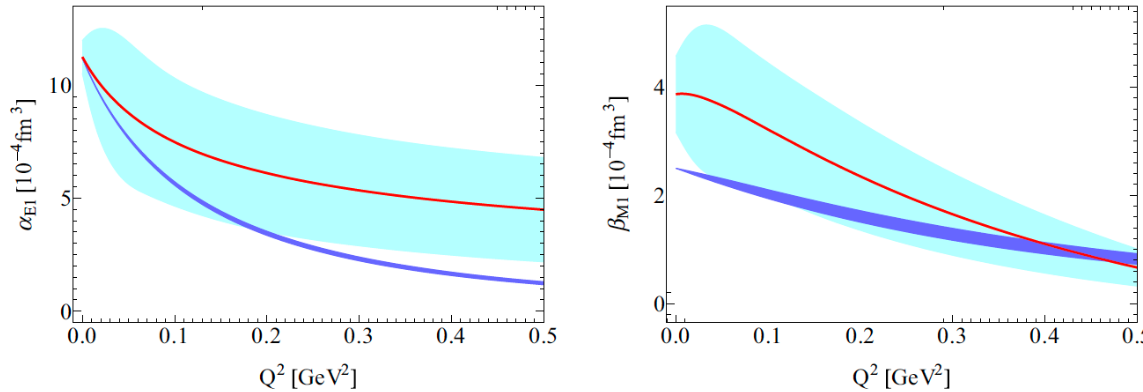
[2] Institute for Theoretical and Experimental Physics, Moscow 117218, Russia
[3] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow 115409, Russia

BχPT 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)	⋯
	$\alpha_E^{ii,\mathrm{disc}}$	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)

Wang X.et al. PRL 133, 141901 (2024)

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:

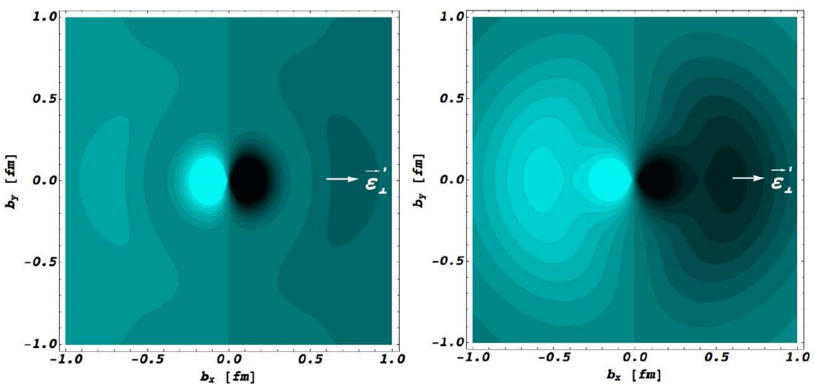
GPs ➔ spatial deformation of charge & magnetization densities under an applied e.m. field

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

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

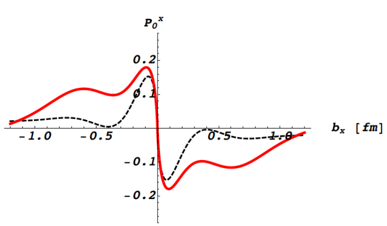
M. Gorchtein, C. Lorce, B. Pasquini, M. Vanderhaeghen

GP I GP II

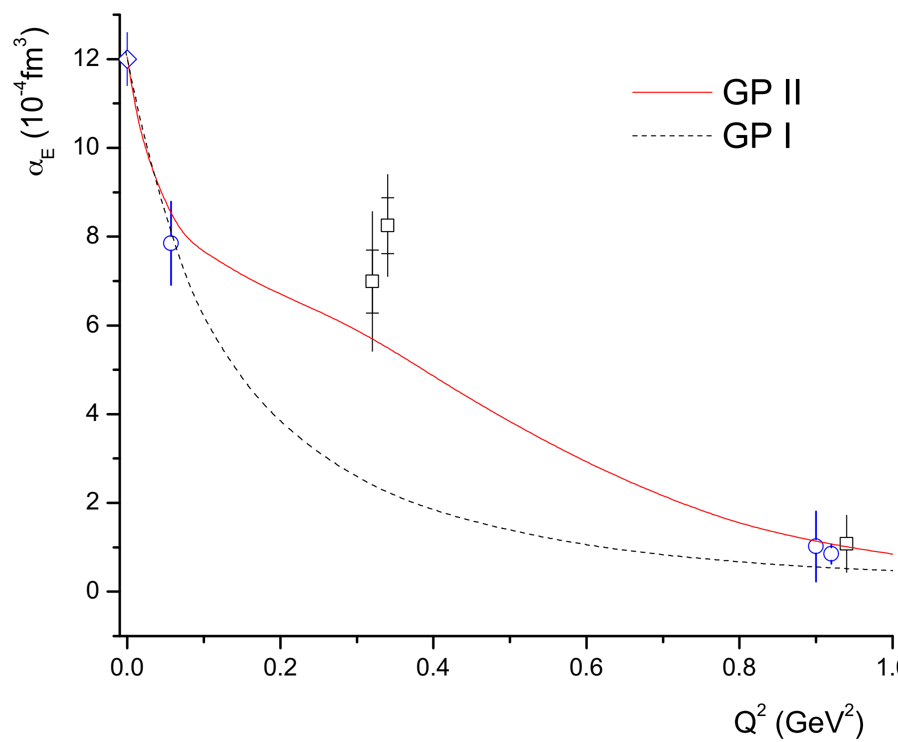


Light (**dark**) regions ➔ **largest** (**smaller**) values

(photon polarization along x-axis, as indicated)



Induced polarization along b_y=0



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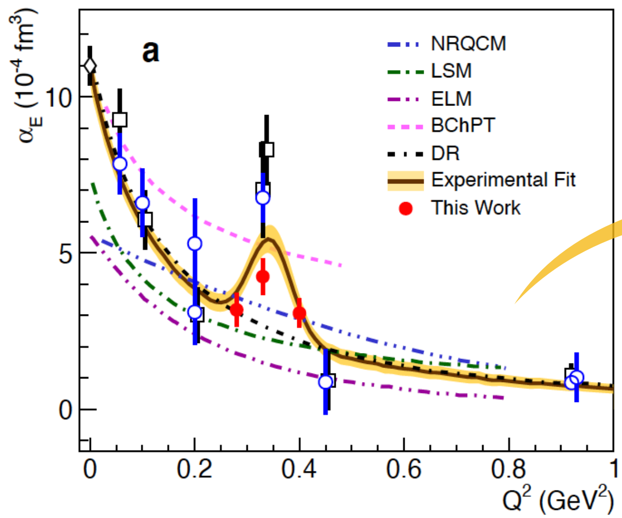
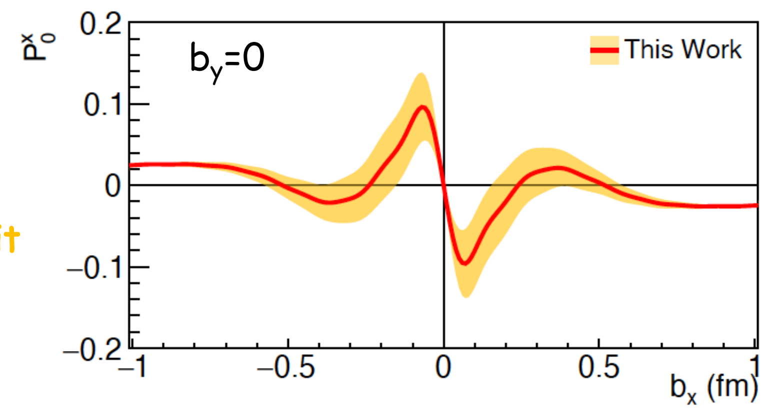


Experimental Fit

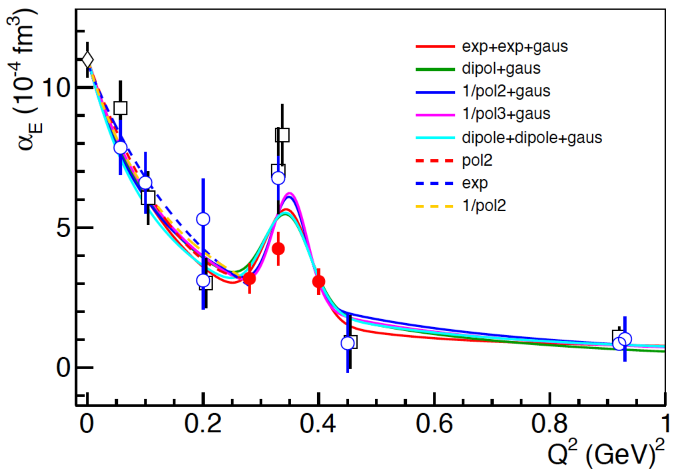


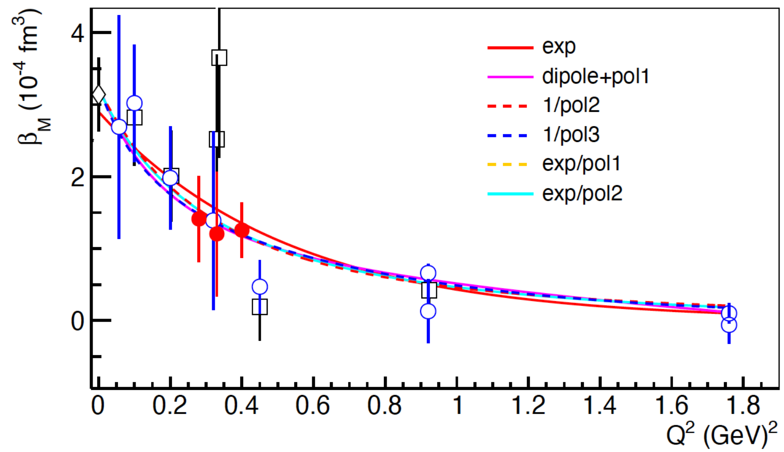
x-y defines the transverse plane with the z-axis being the direction of the fast-moving proton

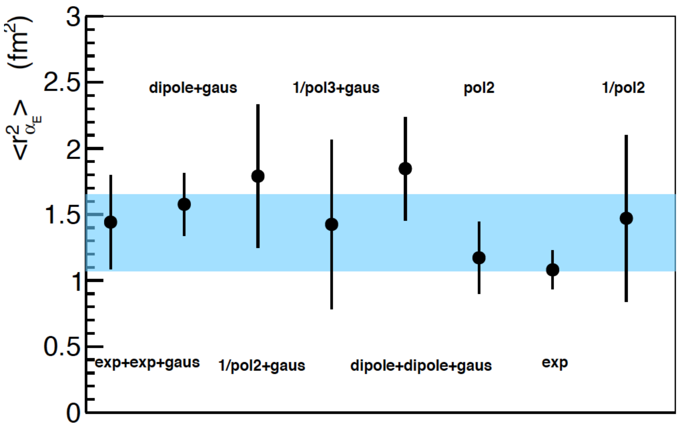
Polarizability radii

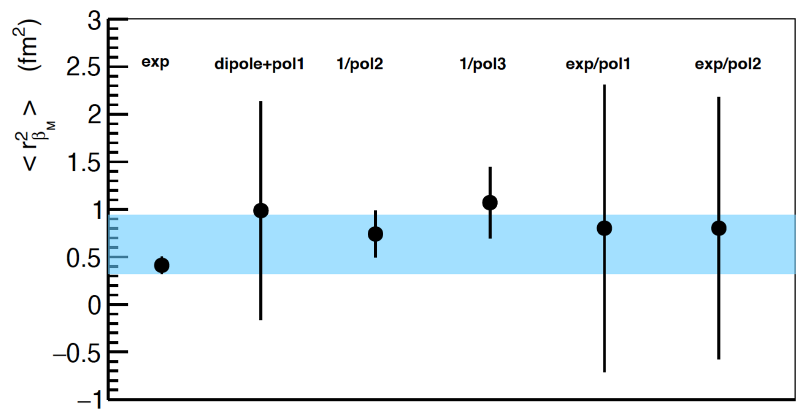
$$\langle r^2_{\alpha_E} \rangle = \frac{-6}{\alpha_E(0)} \cdot \frac{d}{dQ^2} \alpha_E(Q^2) \Big|_{Q^2=0}$$

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





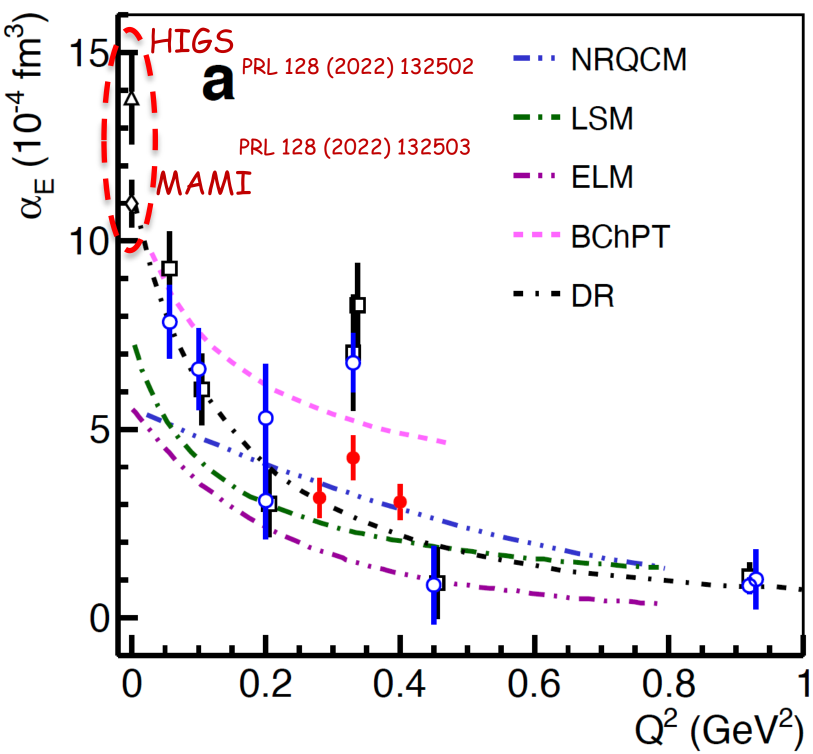


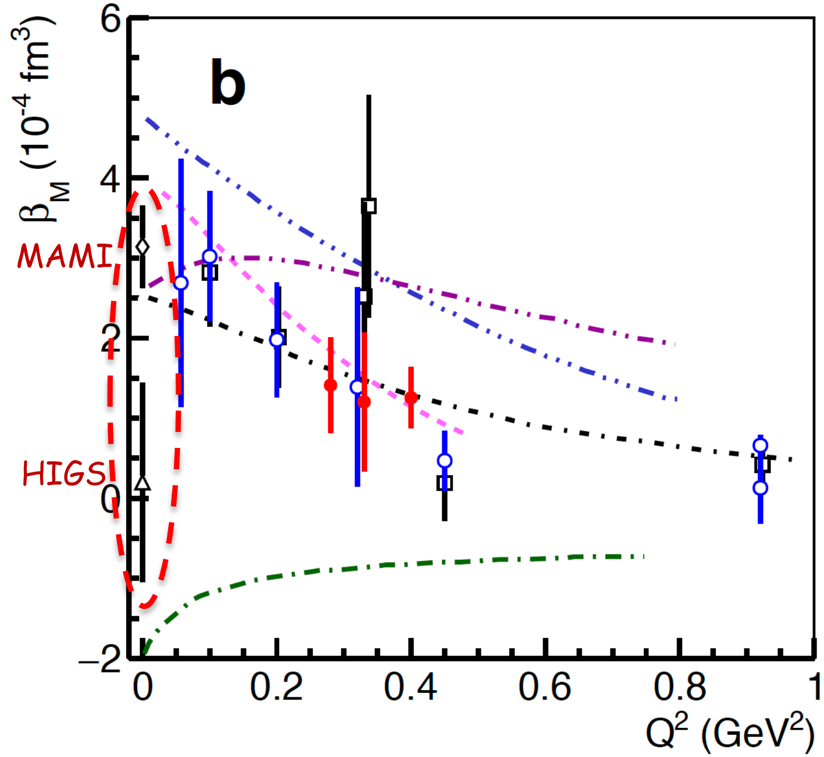


$$\langle r^2_{\alpha_E} \rangle = 1.36 \pm 0.29 \text{ fm}^2$$

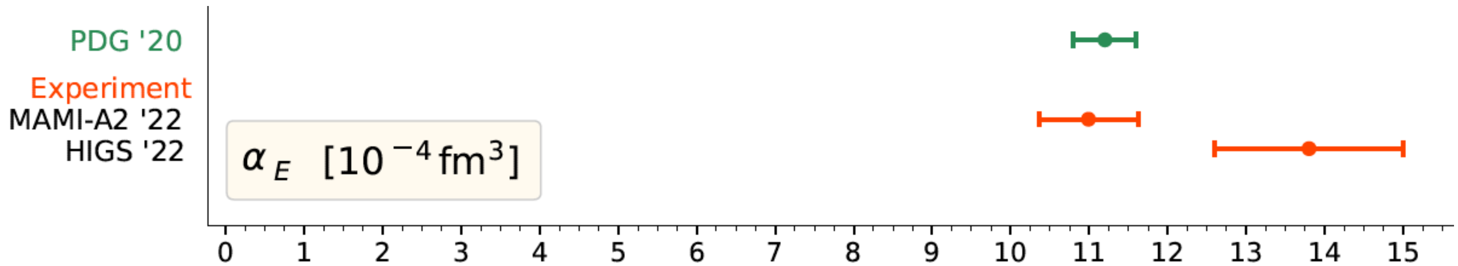
$$\langle r^2_{\beta_M} \rangle = 0.63 \pm 0.31 \text{ fm}^2$$

Static Polarizabilities



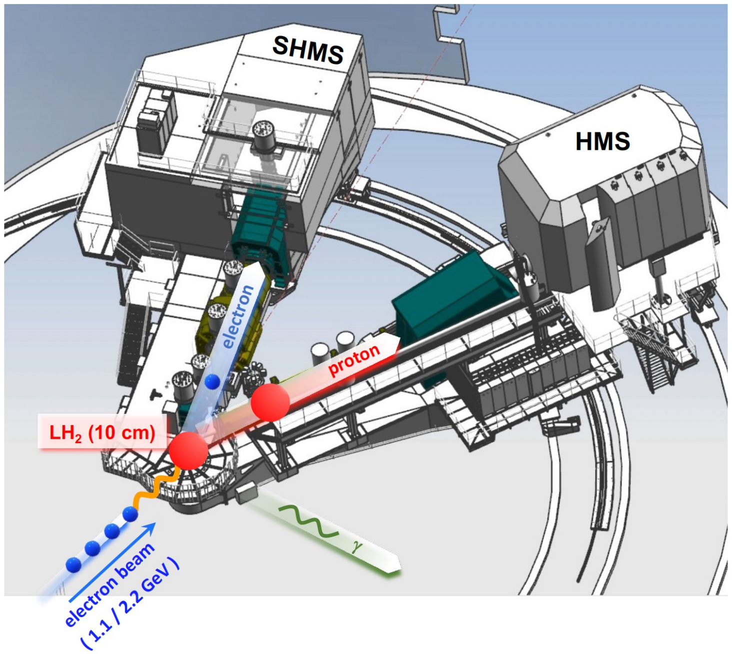


Recent measurements exhibit tension → affects the pol. radius extraction



Upcoming Experiments

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



Follow up to 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

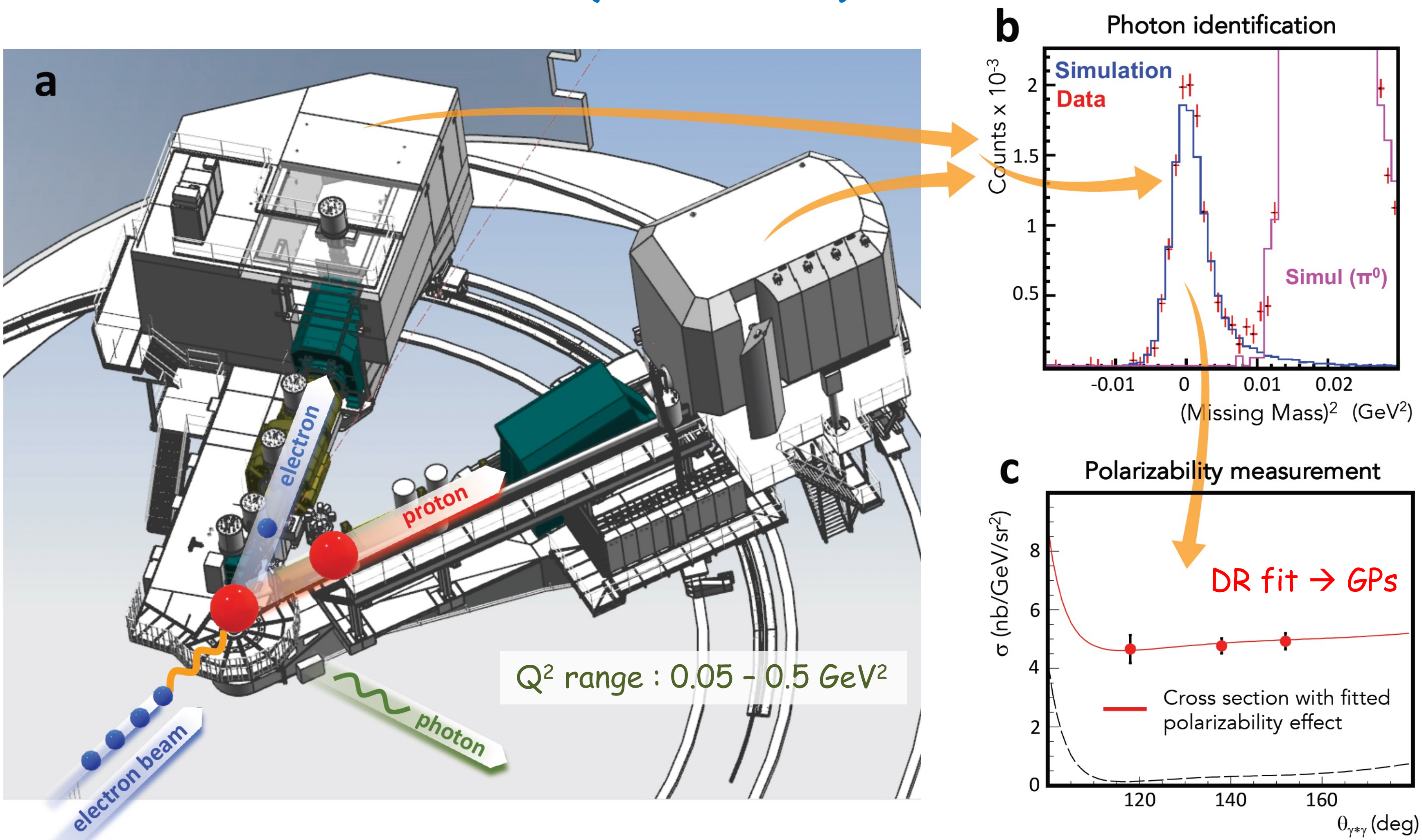
Production (E_o = 1.4 GeV) :	6 days
Production (E_o = 2.1 GeV) :	53 days
Studies (optics/dummy/calibrations) :	3 days

Experiment was approved by PAC 51

Scheduled to acquire data in 2026

Total: 62 days @ 100% efficiency

VCS-II (E12-23-001)



Hall C: SHMS, HMS

E_{beam} = 1.4 & 2.1 GeV

I = 75 μA

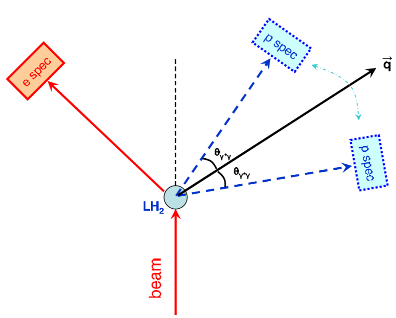
LH2 10 cm

cross sections & azimuthal asymmetries

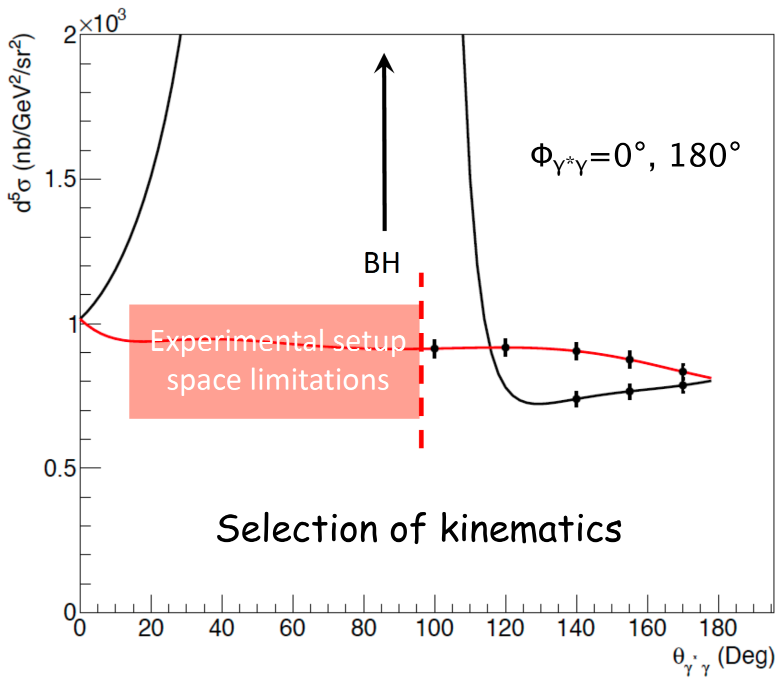
$$A_{(\phi_{\gamma^*\gamma}=0,\pi)} = \frac{\sigma_{\phi_{\gamma^*\gamma}=0} - \sigma_{\phi_{\gamma^*\gamma}=180}}{\sigma_{\phi_{\gamma^*\gamma}=0} + \sigma_{\phi_{\gamma^*\gamma}=180}}$$

Asymmetries help with the sensitivity to GPs

& suppression of systematic uncertainties



Projected cross section measurements



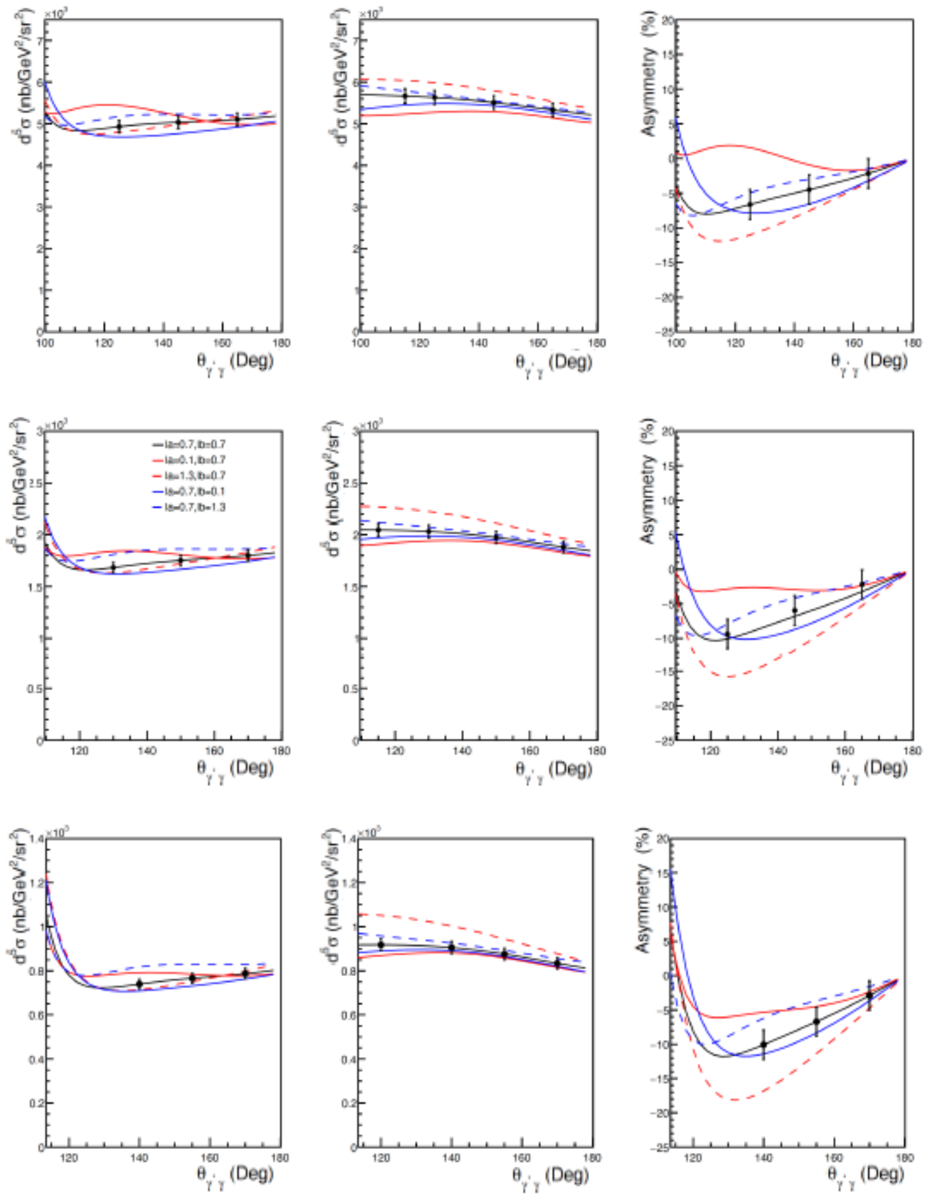
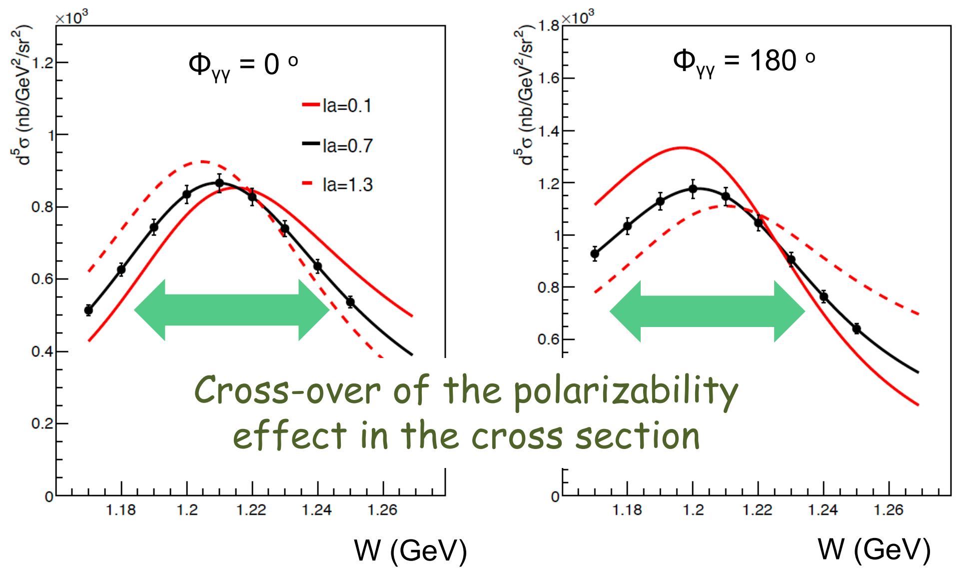


FIG. From left to right: cross sections at $\phi_{\gamma^*\gamma} = 0°$ (left) and 180° (center) and asymmetries (right). Top panels correspond to $Q^2 = 0.15\ (GeV/c)^2$, middle panels to $Q^2 = 0.25\ (GeV/c)^2$ and bottom panels to $Q^2 = 0.35\ (GeV/c)^2$.

VCS-II Projected Measurements

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

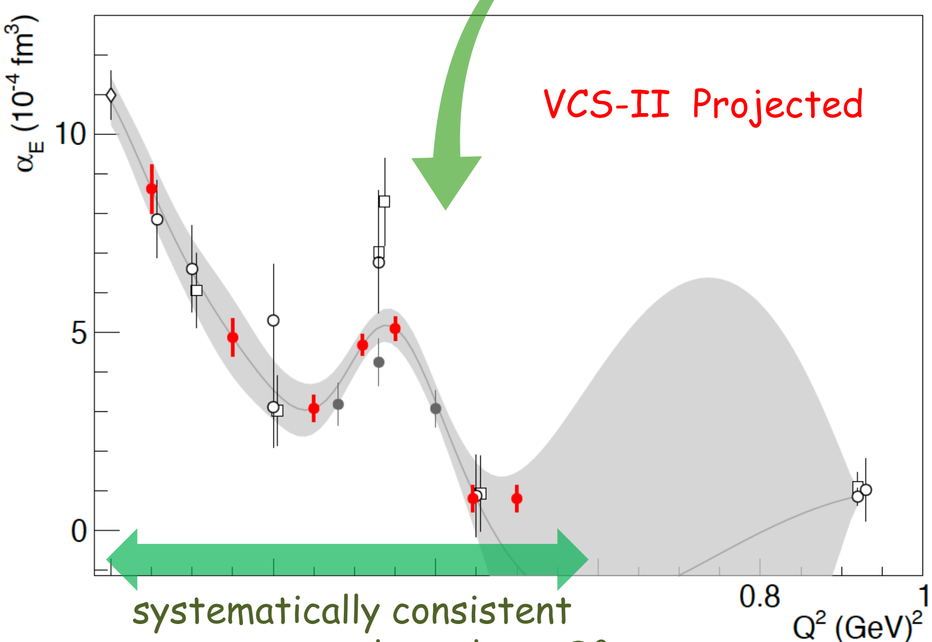


Cross-over of the polarizability
effect in the cross section

Decouples polarizability extraction
from normalization

VCS-II Projected Measurements

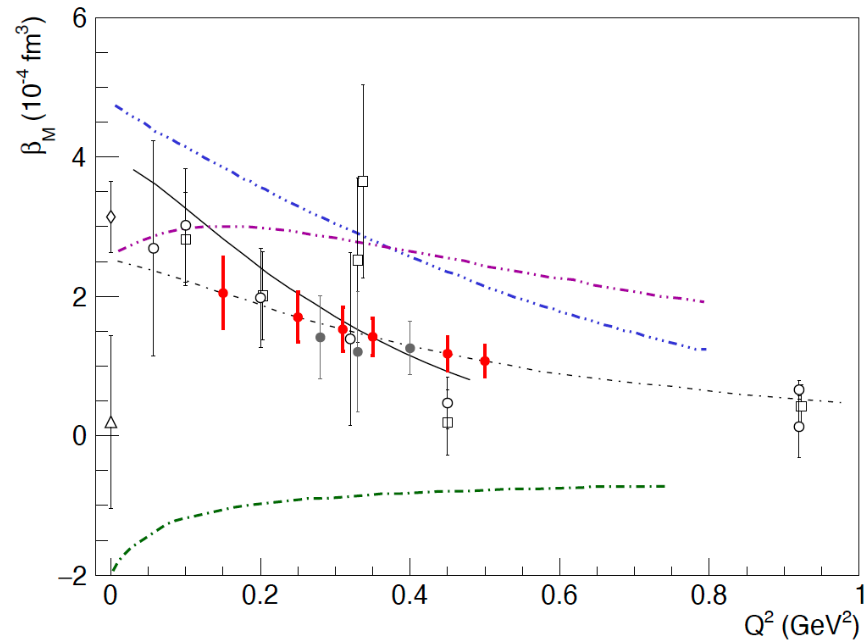
High precision measurements combined with a fine mapping in Q^2



systematically consistent measurements throughout Q^2

Improve upon β_M :

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



First phase of data-taking in spring 2026

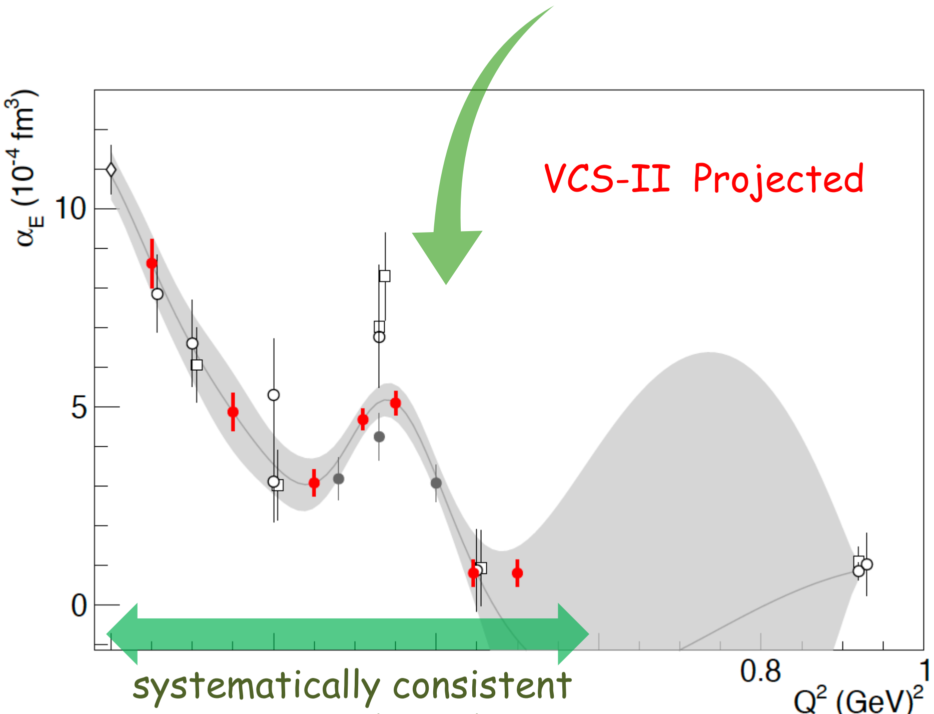
2 months of beam-time February to April

Second phase of data-taking in 2027

Preliminary results ~ 2028

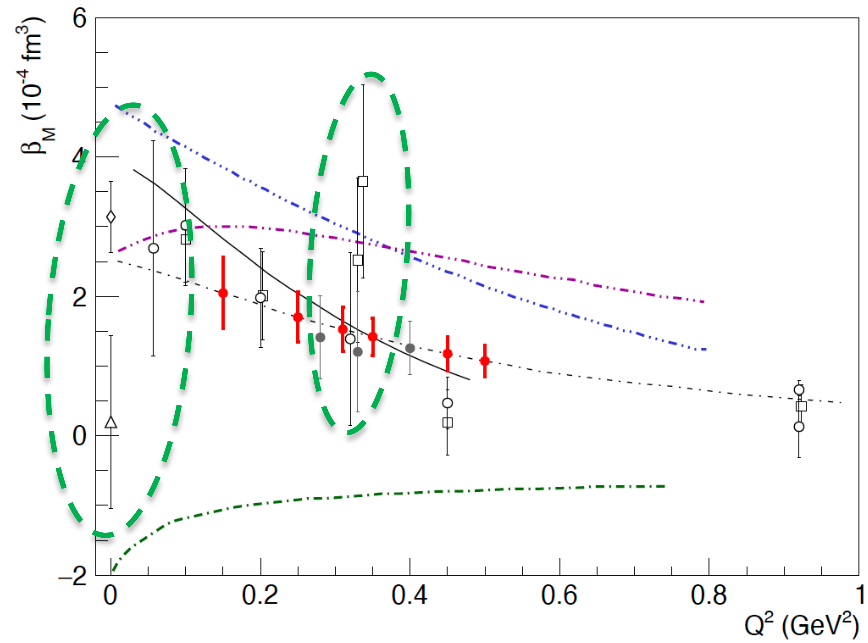
VCS-II Projected Measurements

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



systematically consistent
measurements throughout 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 February to April

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 <u>independent path</u> to access experimentally the GPs

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

Virtual Compton scattering at low energies with a positron beam

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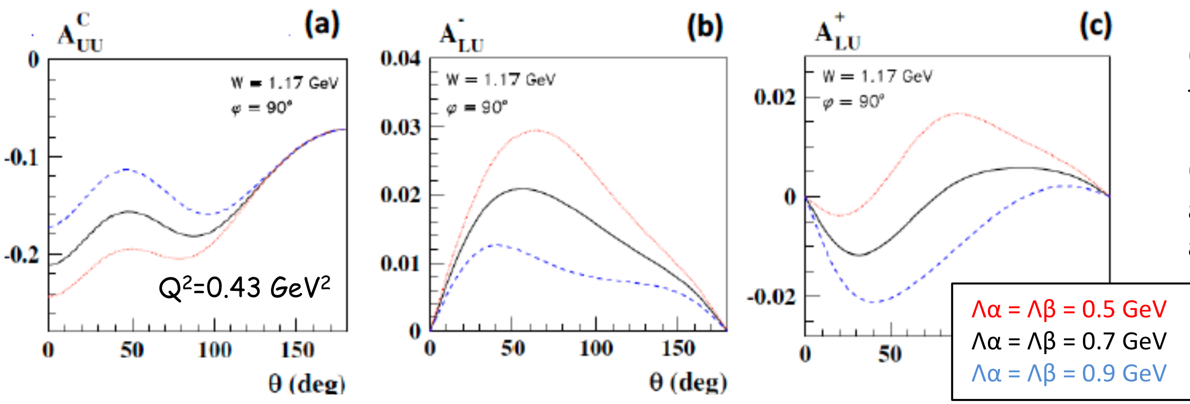
[1]Dipartimento di Fisica, Università degli Studi di Pavia, 27100 Pavia, Italy
[2]Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, 27100 Pavia, Italy
[3]Institut für Kernphysik and PRISMA+ Cluster of Excellence, Johannes Gutenberg Universität, D-55099 Mainz, Germany



(a): The beam-charge asymmetry as a function of the photon scattering angle at Q2 = 0.43 GeV 2.

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

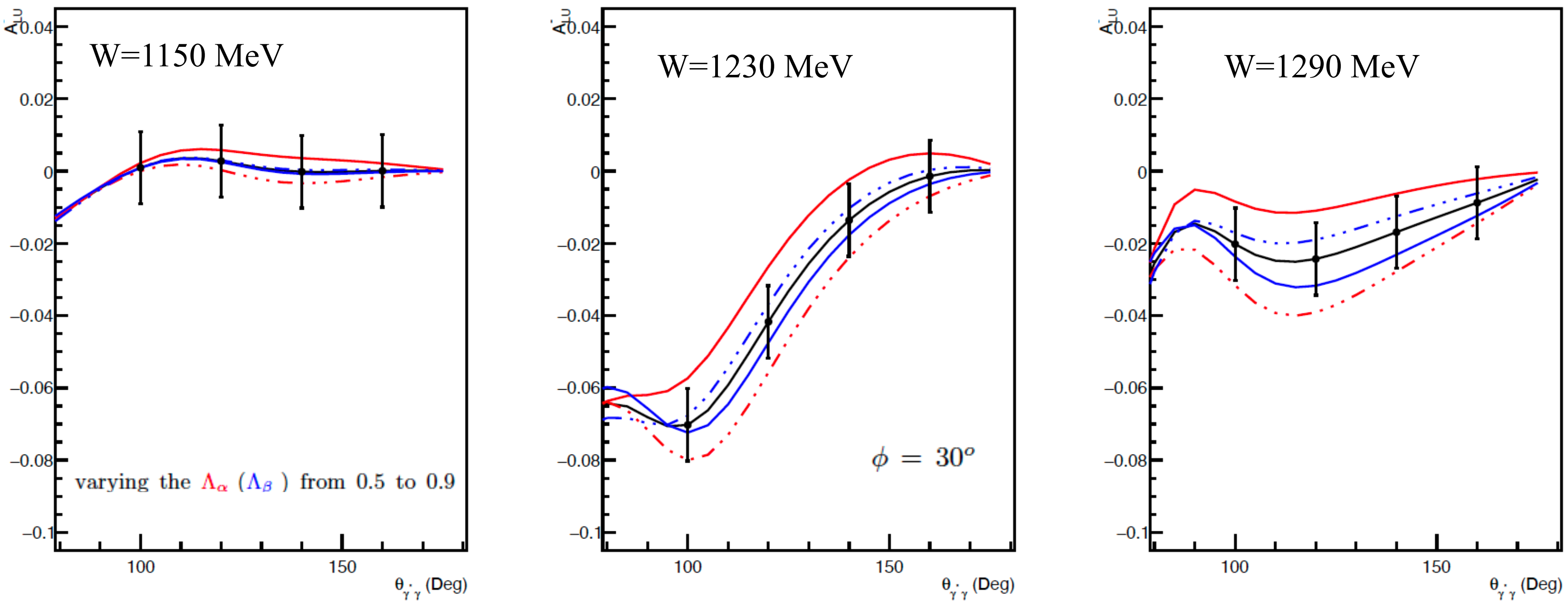
Unpolarized beam charge asymmetry (BCA) : $$A^C_{UU} = \frac{(d\sigma^+_+ + d\sigma^+_-) - (d\sigma^-_+ + d\sigma^-_-)}{d\sigma^+_+ + d\sigma^+_- + d\sigma^-_+ + d\sigma^-_-}$$

Lepton beam spin asymmetry (BSA) : $$A^e_{LU} = \frac{d\sigma^e_+ - d\sigma^e_-}{d\sigma^e_+ + d\sigma^e_-}$$

BSA (electrons or positrons)

Lepton beam spin asymmetry (BSA) : $A^e_{LU} = \frac{d\sigma^e_+ - d\sigma^e_-}{d\sigma^e_+ + d\sigma^e_-}$

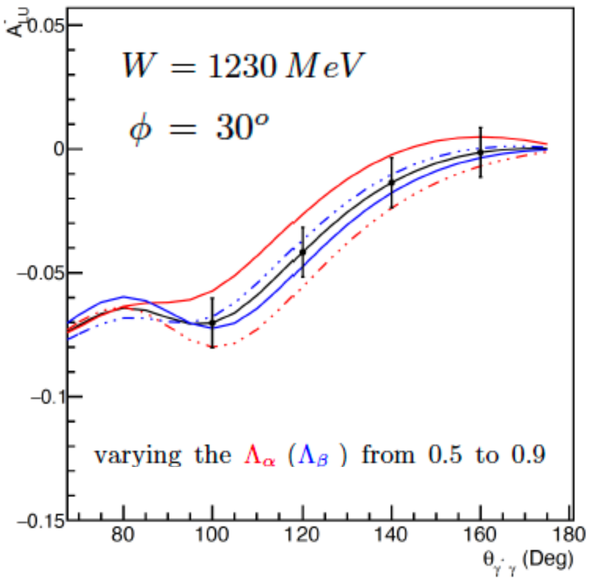
electrons

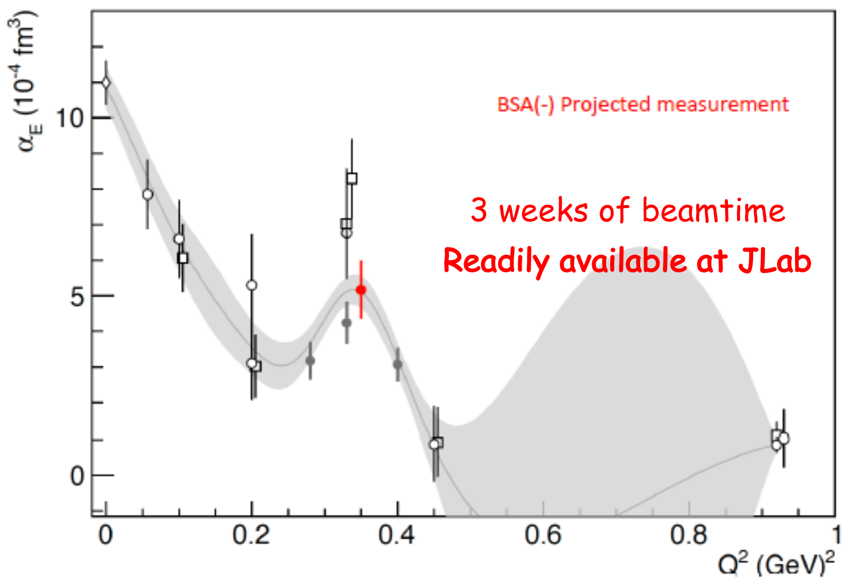


Projected measurements with SHMS / HMS

BSA (electrons or positrons)

Lepton beam spin asymmetry (BSA) : $A^e_{LU} = \frac{d\sigma^e_+ - d\sigma^e_-}{d\sigma^e_+ + d\sigma^e_-}$



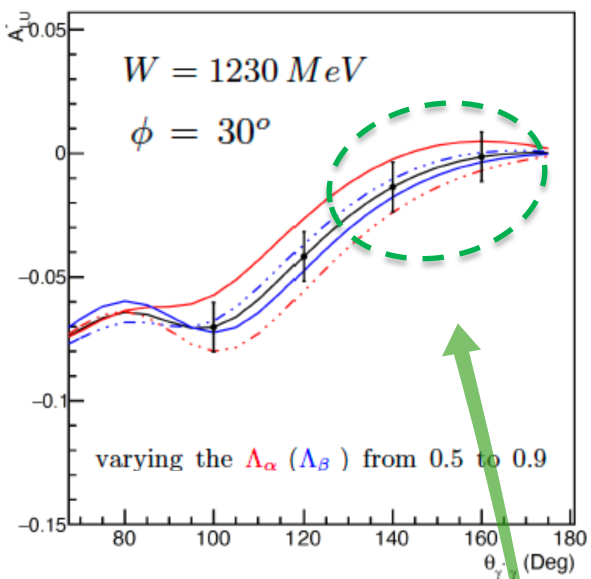


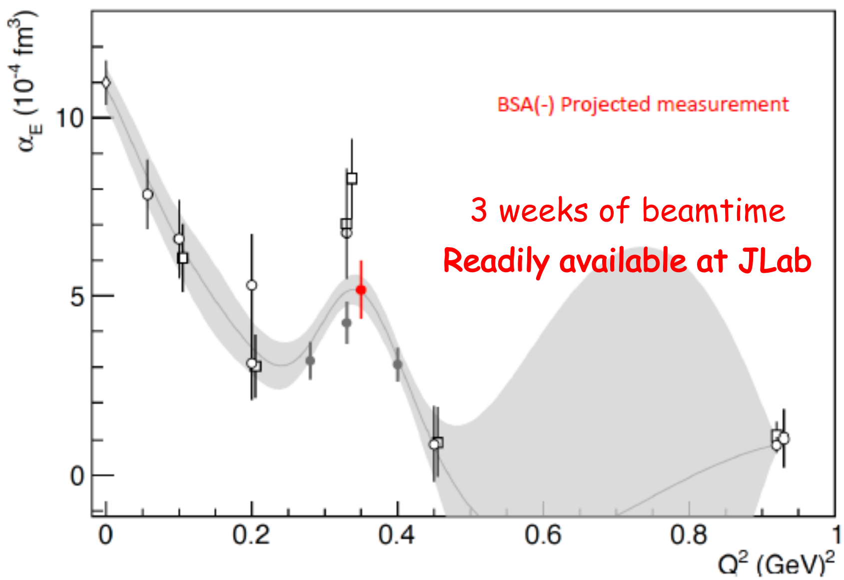
e^- (pol. 85% @ 70 μA)

~ 3 weeks of beamtime

BSA (electrons or positrons)

Lepton beam spin asymmetry (BSA) : $A^e_{LU} = \dfrac{d\sigma^e_+ - d\sigma^e_-}{d\sigma^e_+ + d\sigma^e_-}$





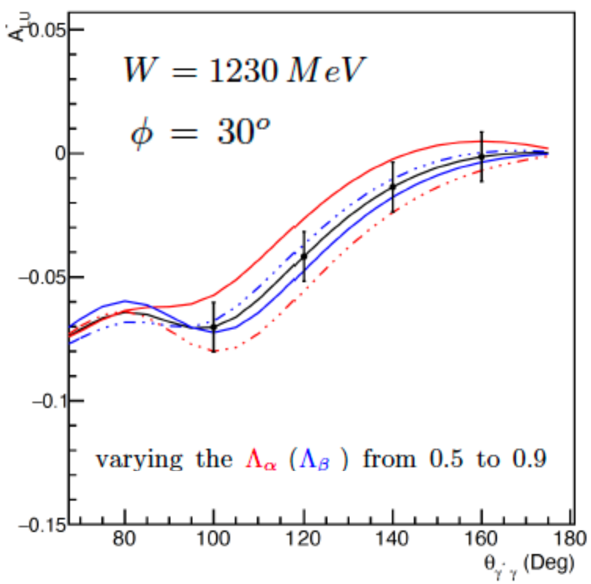
e^- (pol. 85% @ 70 μA)

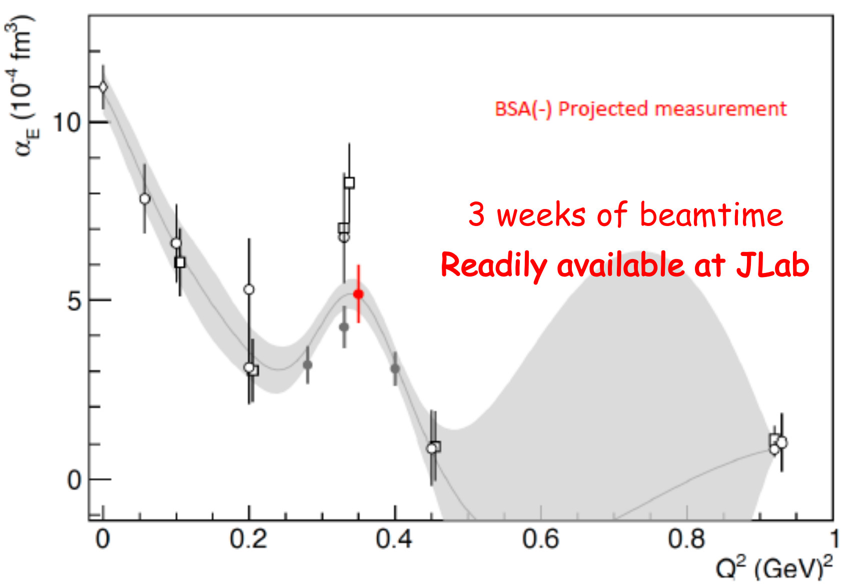
~ 3 weeks of beamtime

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) : $A^e_{LU} = \frac{d\sigma^e_+ - d\sigma^e_-}{d\sigma^e_+ + d\sigma^e_-}$





e^- (pol. 85% @ 70 μA)

~ 3 weeks of beamtime

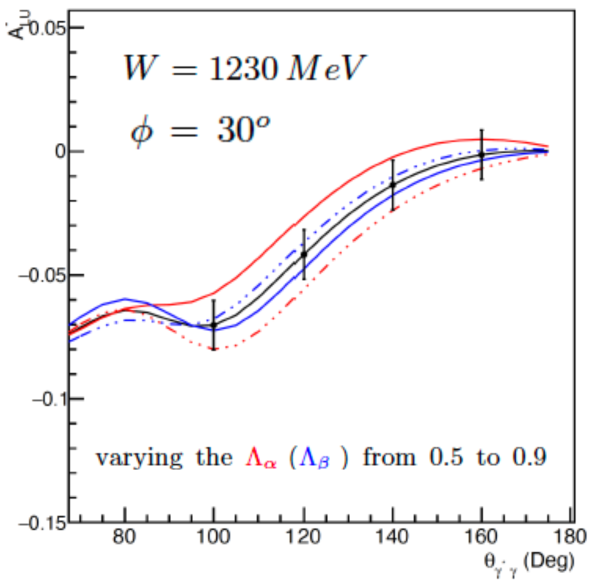
or

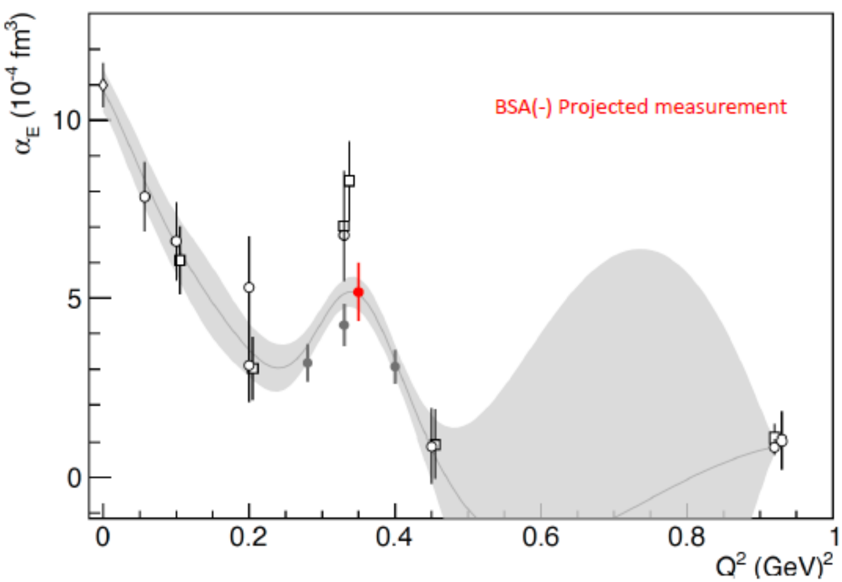
e^+ (pol. 60% @ 50 nA)

~ 3 orders of magnitude more beamtime

BSA (electrons or positrons)

Lepton beam spin asymmetry (BSA) : $A^e_{LU} = \frac{d\sigma^e_+ - d\sigma^e_-}{d\sigma^e_+ + d\sigma^e_-}$





PR12-25-008

"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

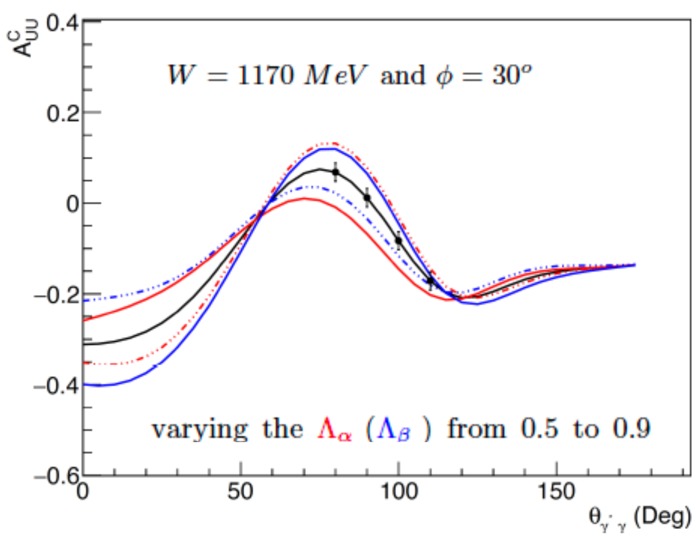
Can collect 20% of the data parasitically during VCS-II

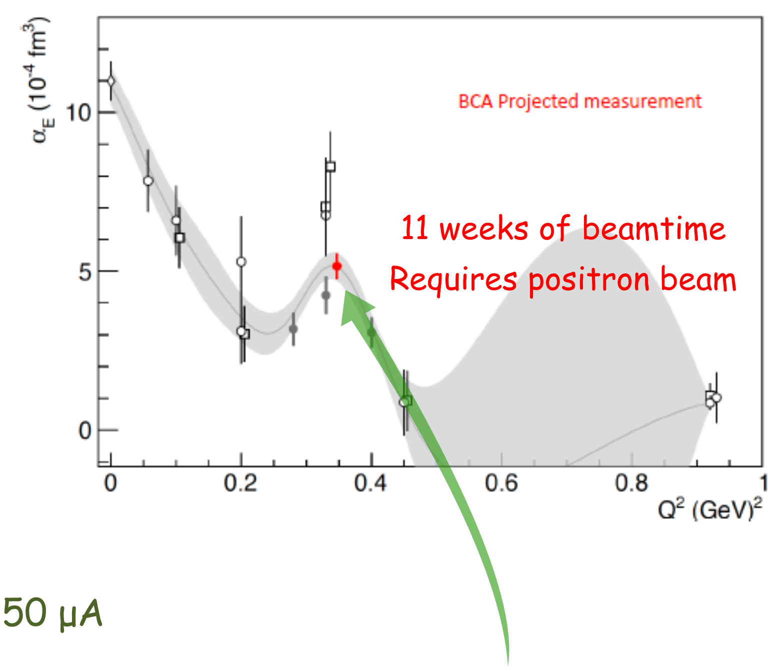
e^- (pol. 85% @ 70 μA)

~ 3 weeks of beamtime

BCA (electrons & positrons)

Unpolarized beam charge asymmetry (BCA) : $A^C_{UU} = \frac{(d\sigma^+_+ + d\sigma^+_-) - (d\sigma^-_+ + d\sigma^-_-)}{d\sigma^+_+ + d\sigma^+_- + d\sigma^-_+ + d\sigma^-_-}$





Hall C (SHMS / HMS)

- e^- : ~ 1 week @ 50 μA
- and
- e^+ : ~ 10 weeks @ ~ μA

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 $\alpha_E(Q^2)$ (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

Future experimental goals

Improve β_M → paramagnetism / diamagnetism in the proton

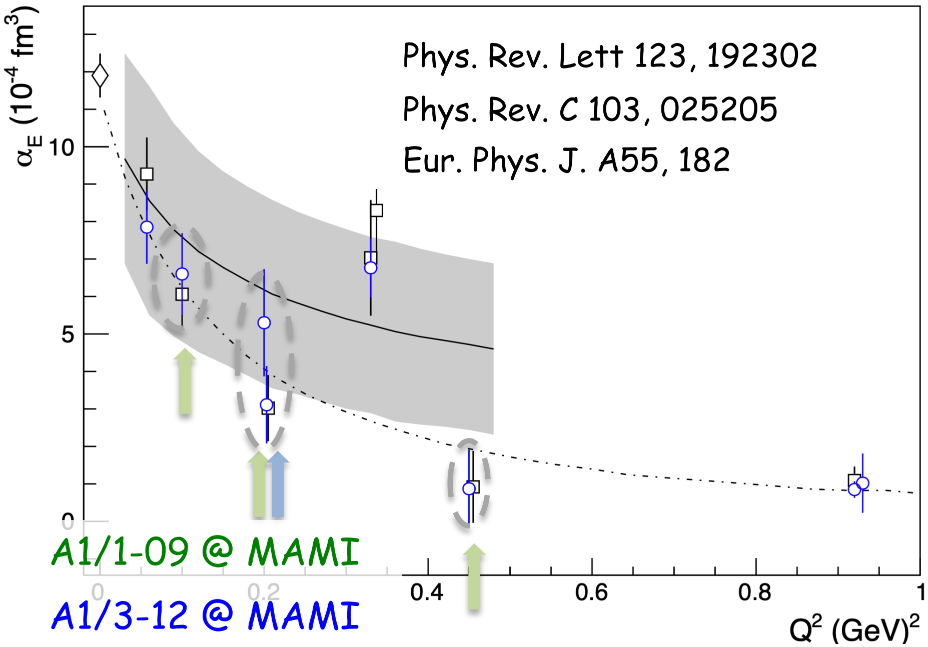
Identify the shape of the α_E structure (if it exists ?)
Important input for the theory

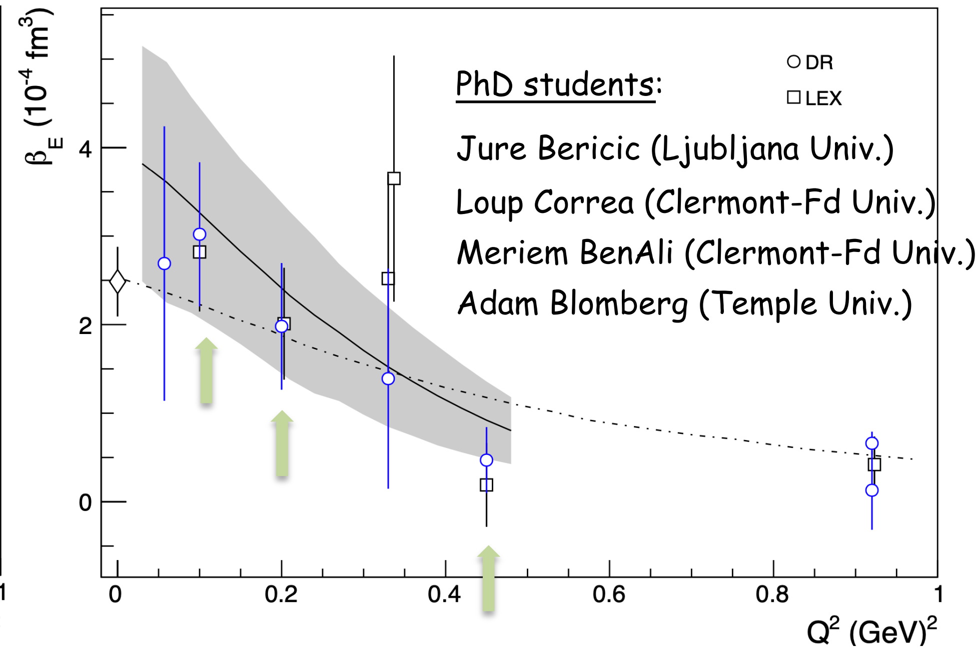
Conduct an independent cross-check
Measure via a different channel (BS asymmetries & positrons)

Thank you!

More

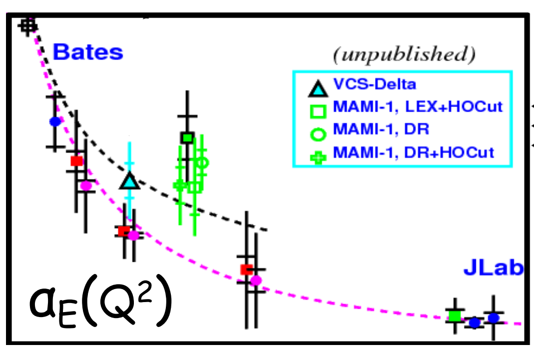
MAMI Results





Revisiting the Q²=0.33 GeV² data

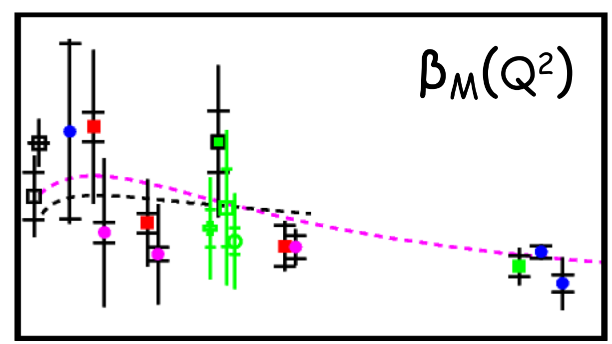
Analysis revisited (unpublished):



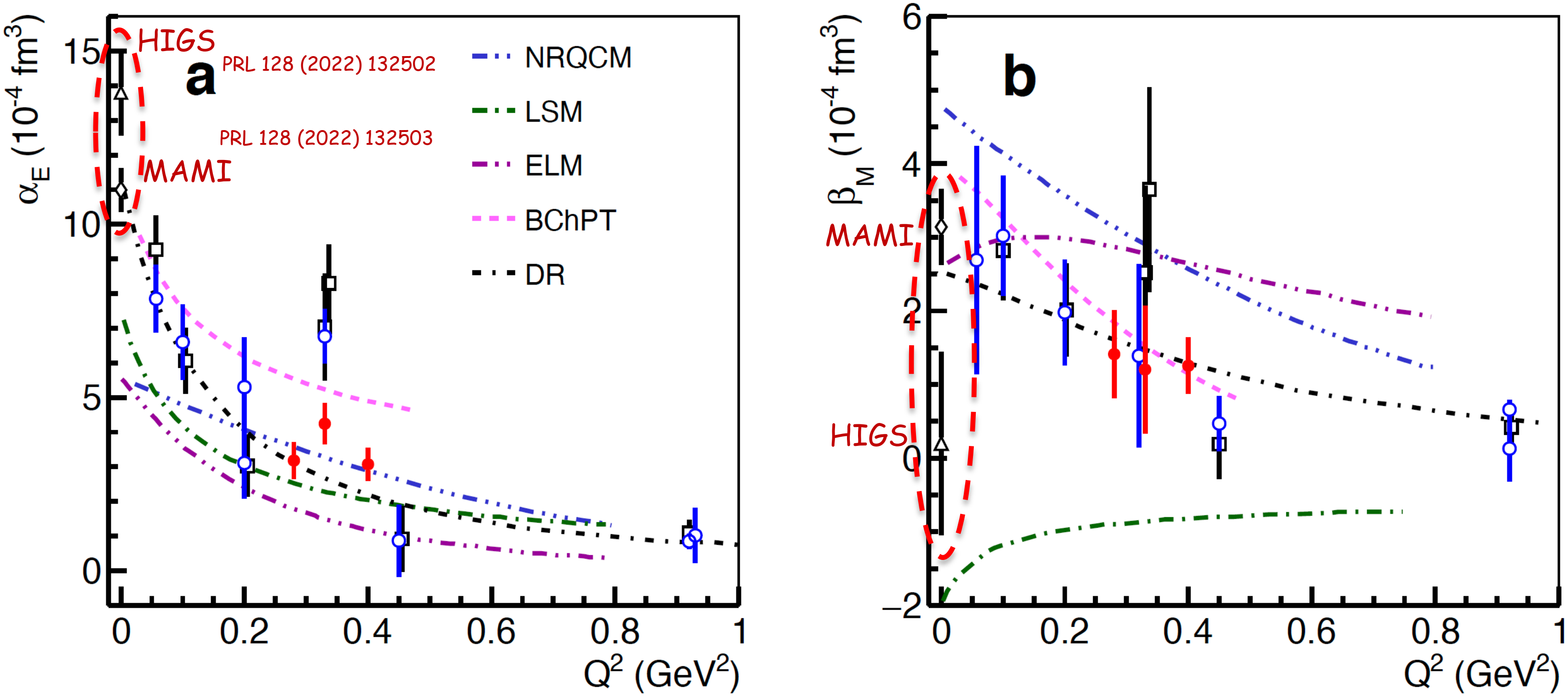
Re-fits at Q²=0.33 GeV² (H.F.)

LEX and DR

Updated HO-cut

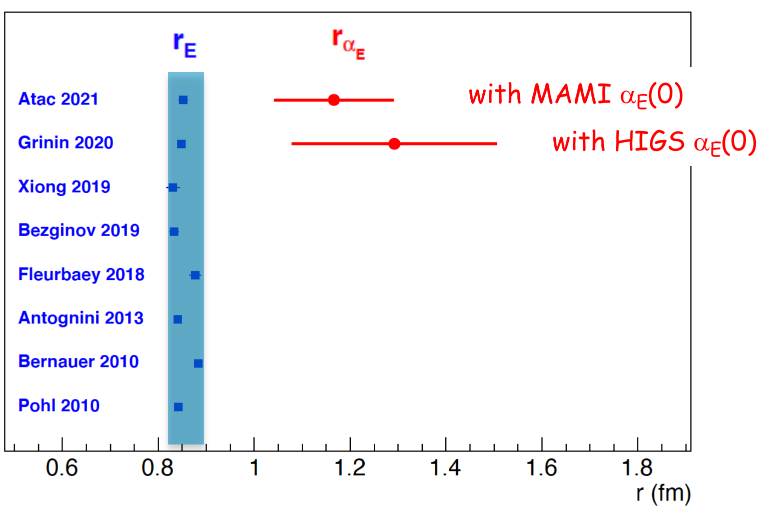


Polarizability radii - Static Polarizabilities



$$\langle r^2_{\alpha_E} \rangle = 1.36 \pm 0.29 \; fm^2$$

$$\langle r^2_{\alpha_E} \rangle = 1.67 \pm 0.50 \; fm^2$$



$$\langle r^2_{\beta_M} \rangle = 0.63 \pm 0.31 \; fm^2$$

$$\langle r^2_{\beta_M} \rangle = 0.20 \pm 0.36 \; fm^2$$