Generalized Polarizabilities from VCS Experiments

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Temple University

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Outline

Introduction to the VCS and GPs

Status

Results from recent experiments / Jlab & MAMI

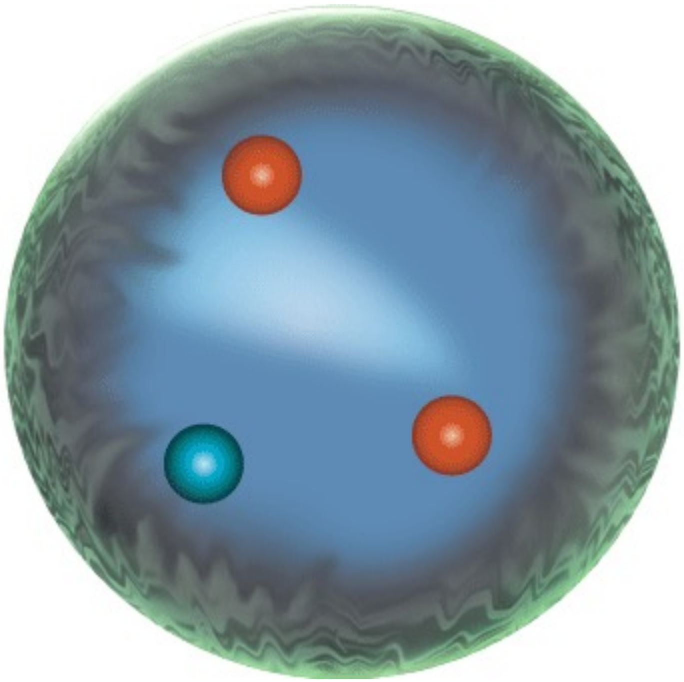
Spatial information & polarizability radii

Prospects

Proton

Despite being the only stable composite particle, several fundamental characteristics of the proton remain not fully understood, including its mass, spin, charge radius, and polarizabilities.

If we want to understand the characteristics of the proton as a building block of the universe… we need to understand the dynamics of the proton's constituents and how they contribute to those emergent characteristics.



Mass

Spin

Size

Shape

Polarizabilities

………….

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

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 ± 0.00039 fm [d]
Charge radius, ep 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)

Virtual Compton Scattering:

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

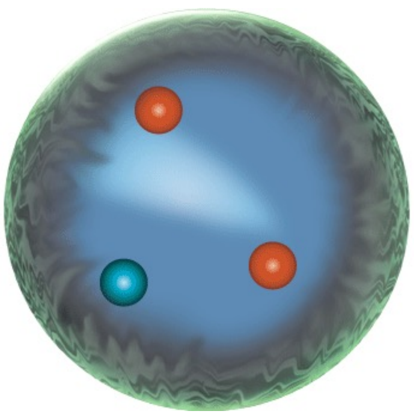
→ spatial distribution of the polarization densities
→ electric & magnetic polarizability radii

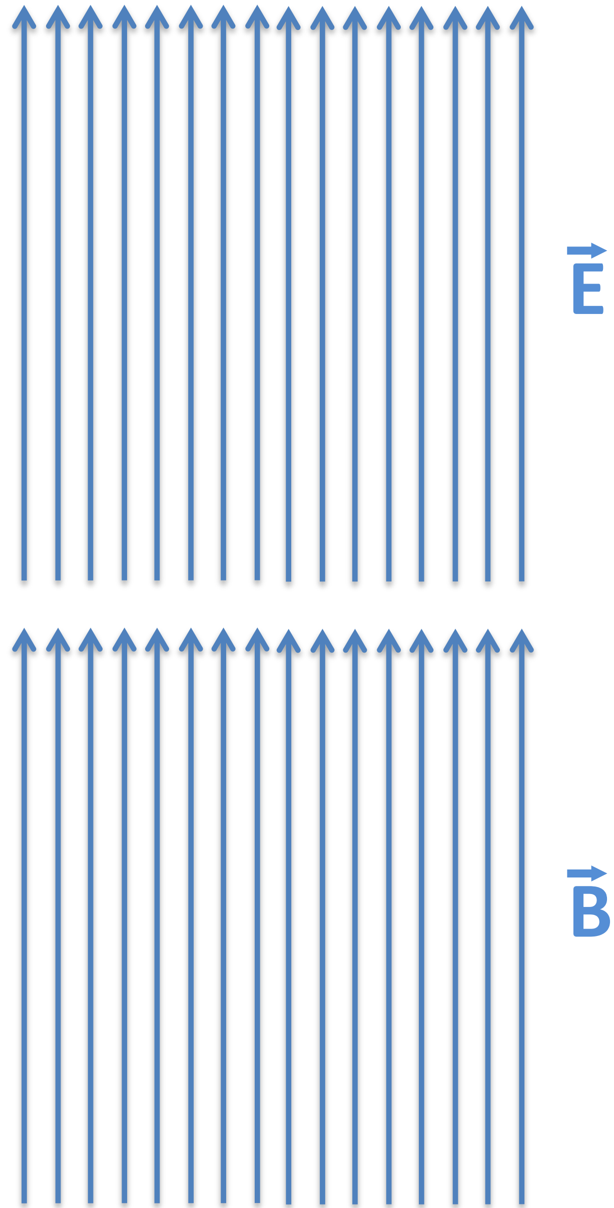
Fourier transform of densities of electric charges and
magnetization of a nucleon deformed by an applied EM field

Scalar Polarizablities

Response of internal structure to an applied EM field

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





Scalar Polarizablities

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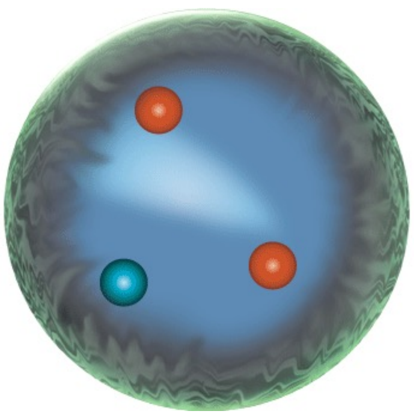
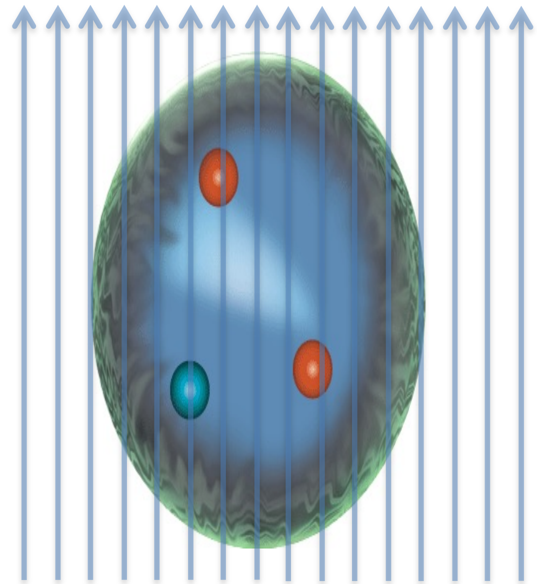


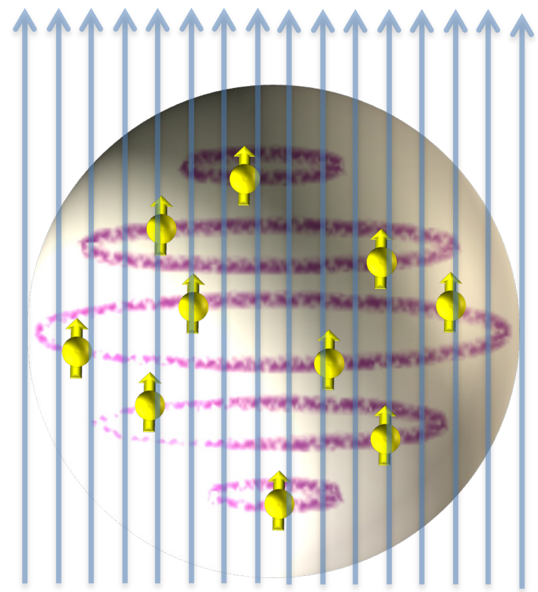


$\vec{E}$

"stretchability"

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

External field deforms the charge distribution



$\vec{B}$

"alignability"

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

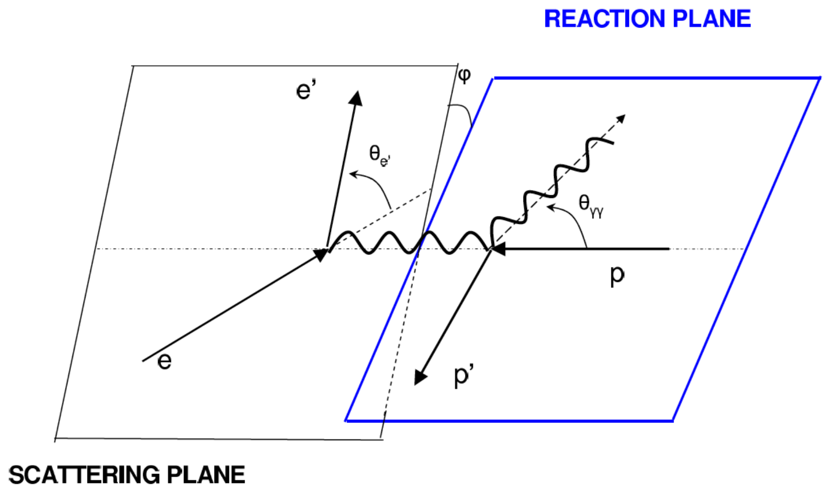
$\beta_{para} > 0$

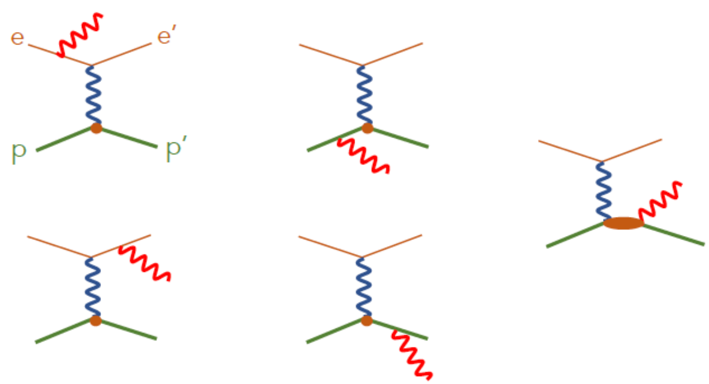
$\beta_{diam} < 0$

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

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

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

utilize DR

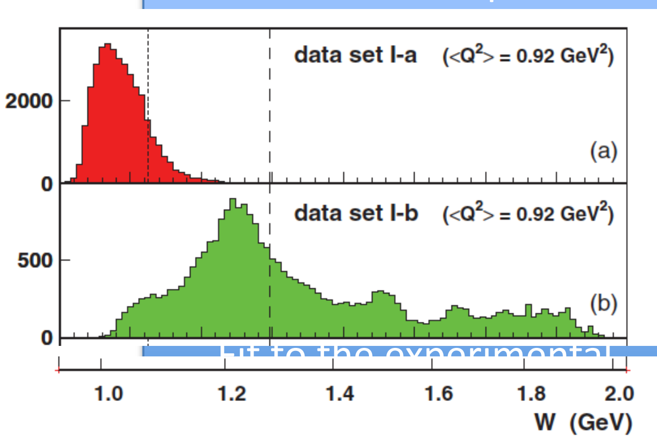
scalar GPs α_E and β_M

Virtual Compton Scattering

DR

valid below & above
Pion threshold

Dispersive integrals
for Non Born amplitudes



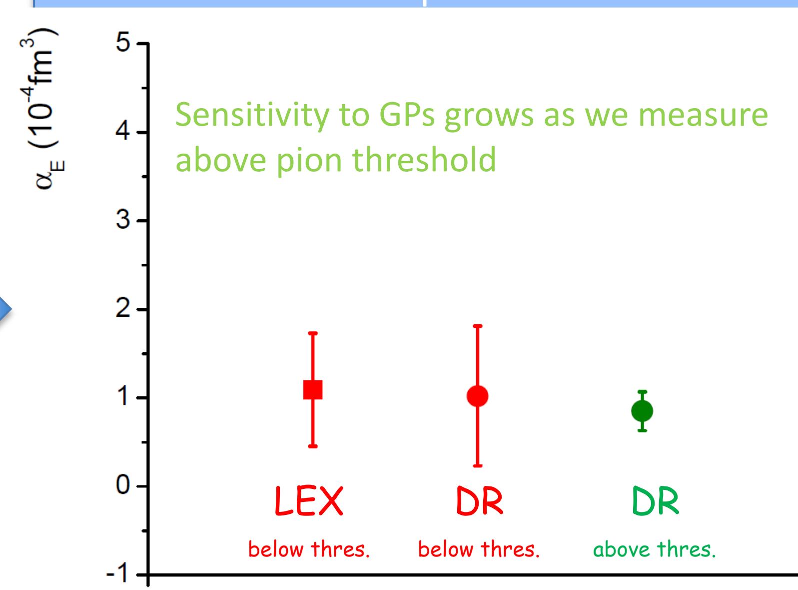
LEX

valid only below
Pion threshold

Response functions

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

P_{LT}



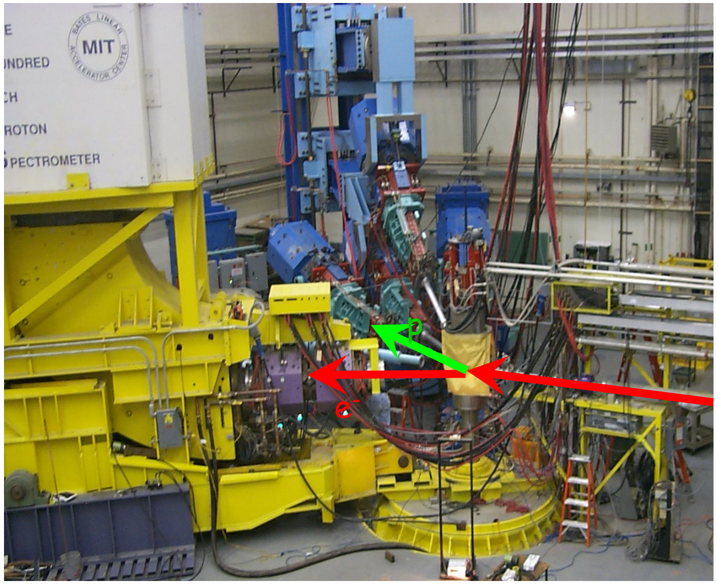
$P_{LT\ spin}]$

utilize DR

scalar GPs α_E and β_M

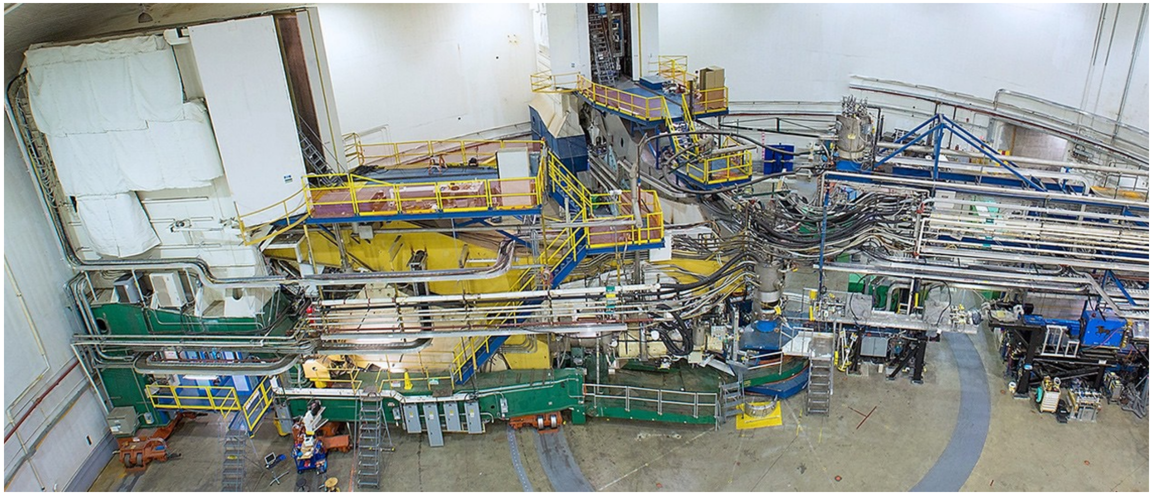
Early Experiments

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



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

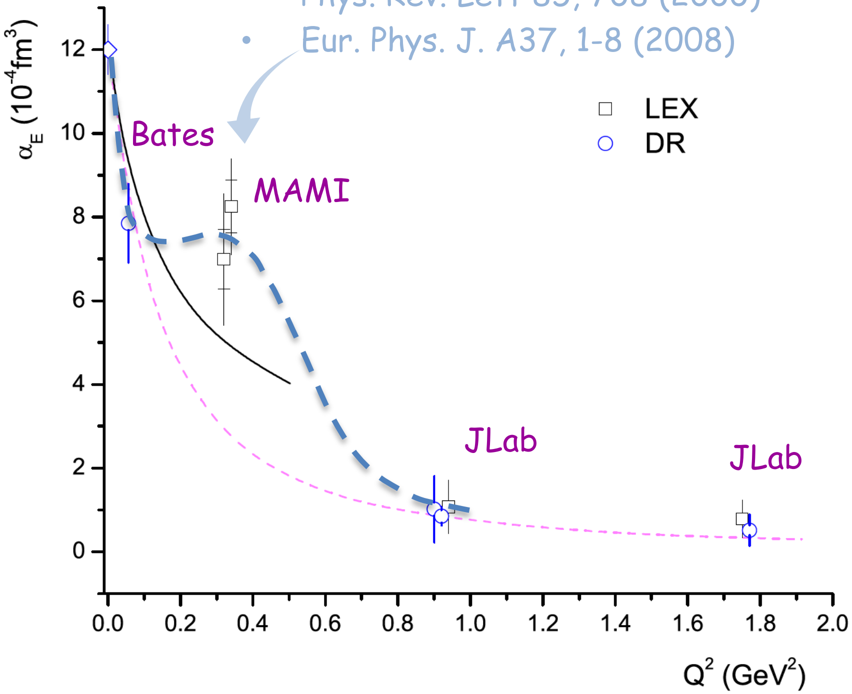
Jlab-Hall A @ Q^2=0.9 & 1.8 GeV^2

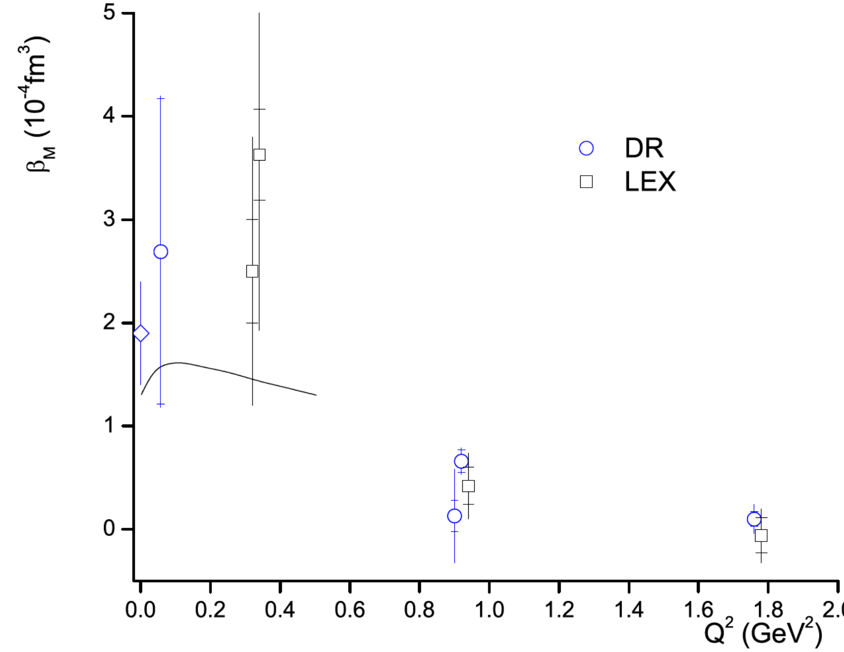


Early Experiments

Q^2 = 0.33 $(GeV/c)^2$ measured twice at MAMI:

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





$a_E \approx 10^{-3}\,V_N$ (stiffness / relativistic character)

Data: non-trivial Q^2 dependence of a_E (?)

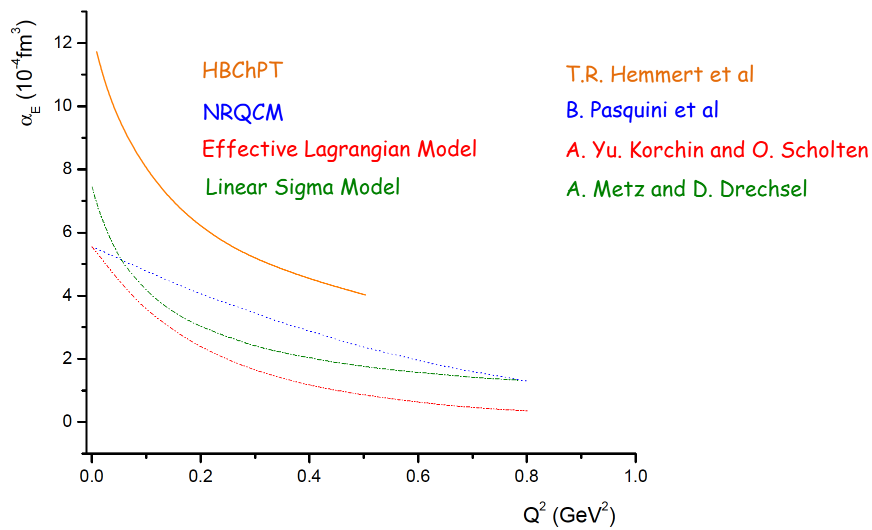
Theory: monotonic fall-off

β_M small ←→ cancellation of competing mechanisms

Large uncertainties

Higher precision measurements needed

➔ Quantify balance between dia/para-magnetism

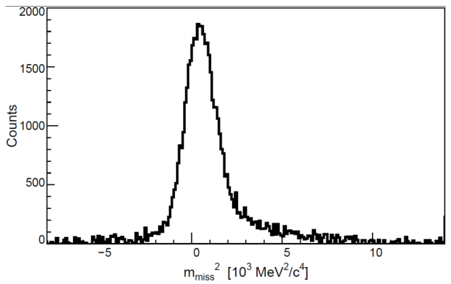


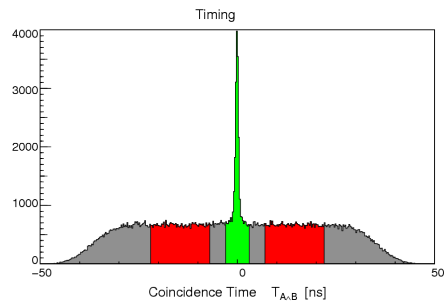
Recent Experiments

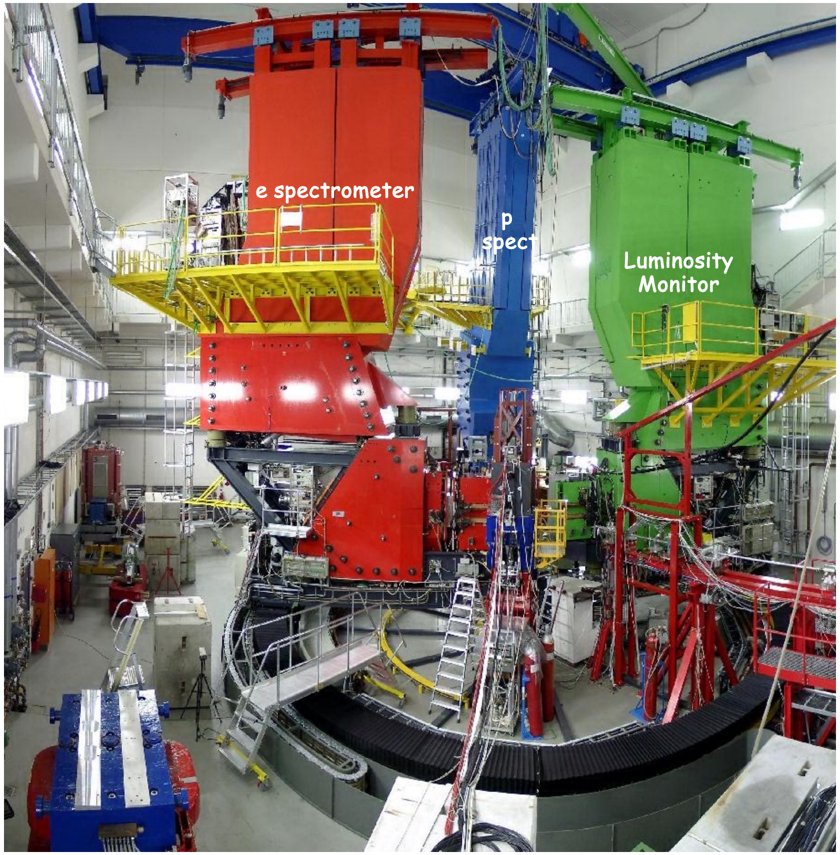
Recent Measurements: MAMI

MAMI	A1/1-09 (vcsq2)	below threshold
MAMI	A1/3-12 (vcsdelta)	above threshold

Both experiments utilized the A1 setup at MAMI







A1/1-09 @ MAMI

Several improvements were implemented compared to the early MAMI experiments.

e.g. 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 / phase space masking to keep these terms smaller than ~ 2%-3% level

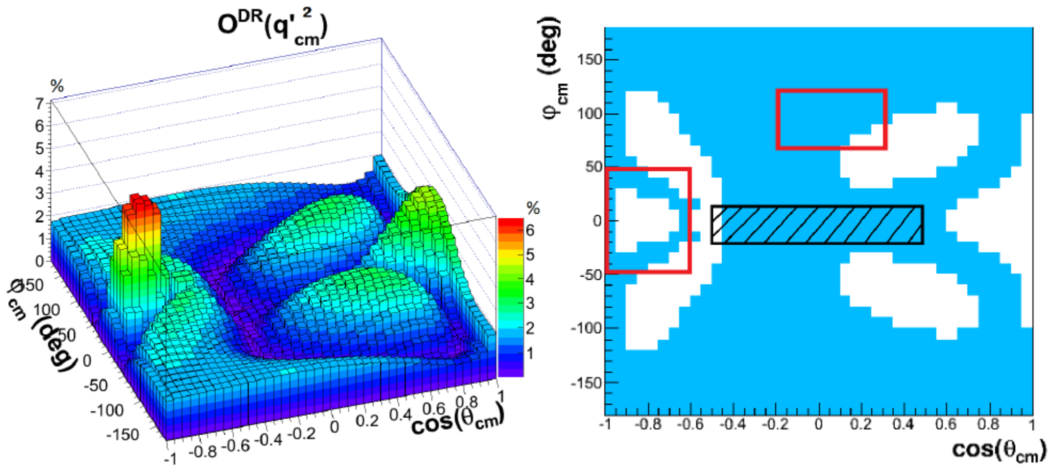
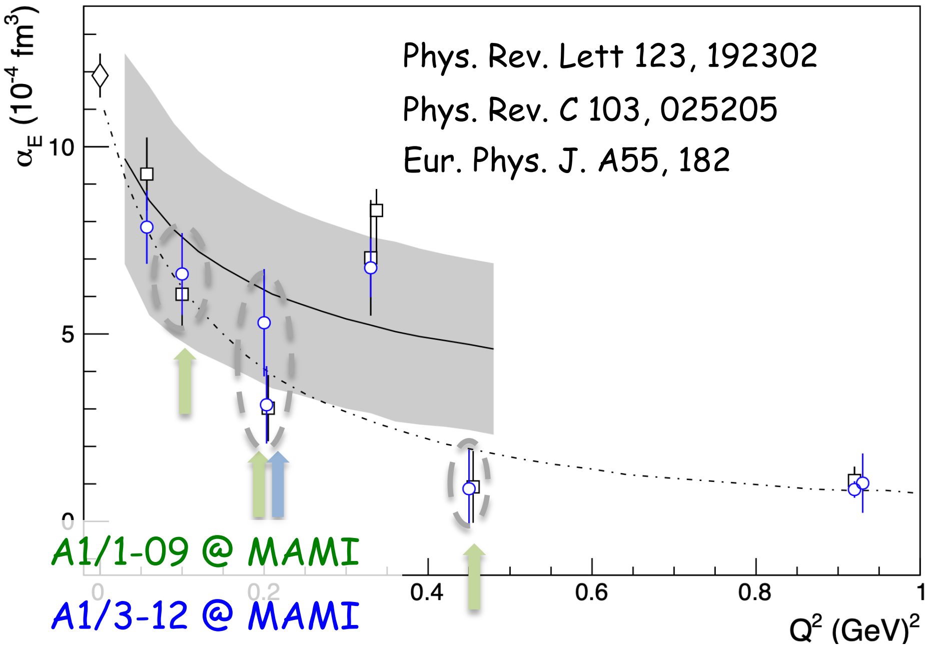
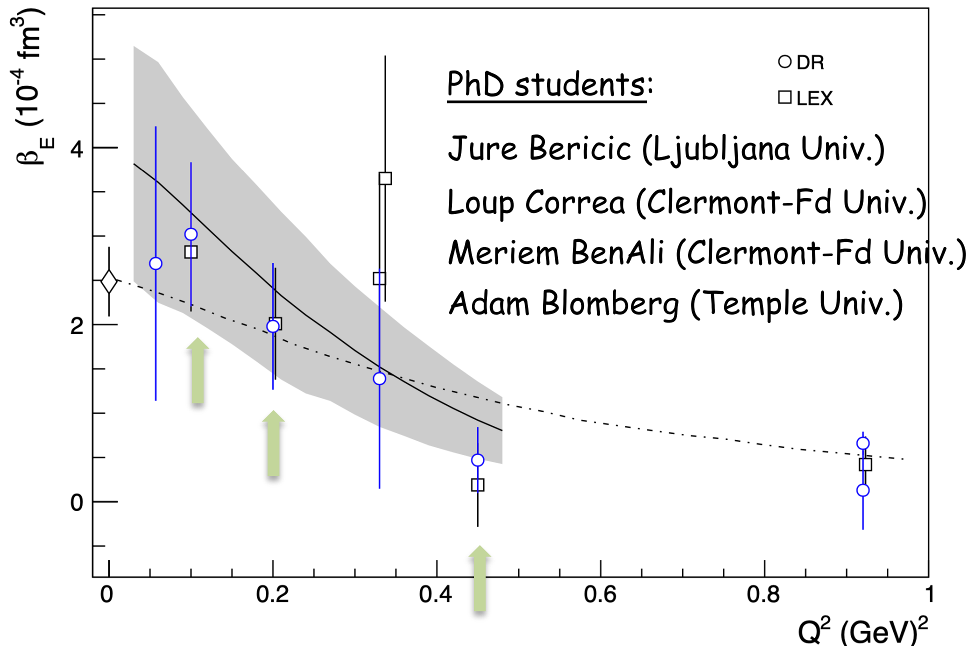


Figure 3.13: (Left) behavior of $\mathcal{O}^{DR}({q'_{cm}}^2)$ in the $(cos(\theta_{cm}),\varphi_{cm})$-plane at $q'_{cm} = 87.5\ MeV/c$ and (right) two-dimensional representation of the angular region where $\mathcal{O}^{DR}({q'_{cm}}^2) < 2\%$ (blue), the red squares correspond to the two areas of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

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

MAMI Results

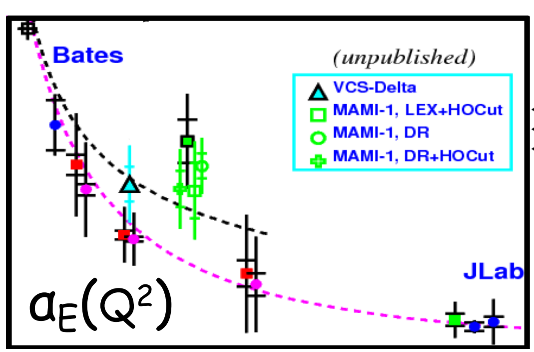




Revisiting the Q^2=0.33 GeV^2 data

Analysis revisited (unpublished):

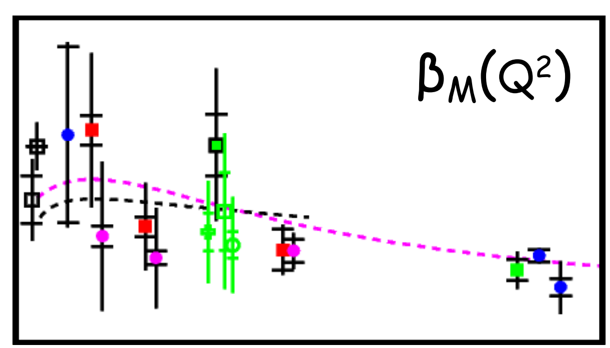
The α_E puzzle still holds



Re-fits at Q^2=0.33 GeV^2 (H.F.)

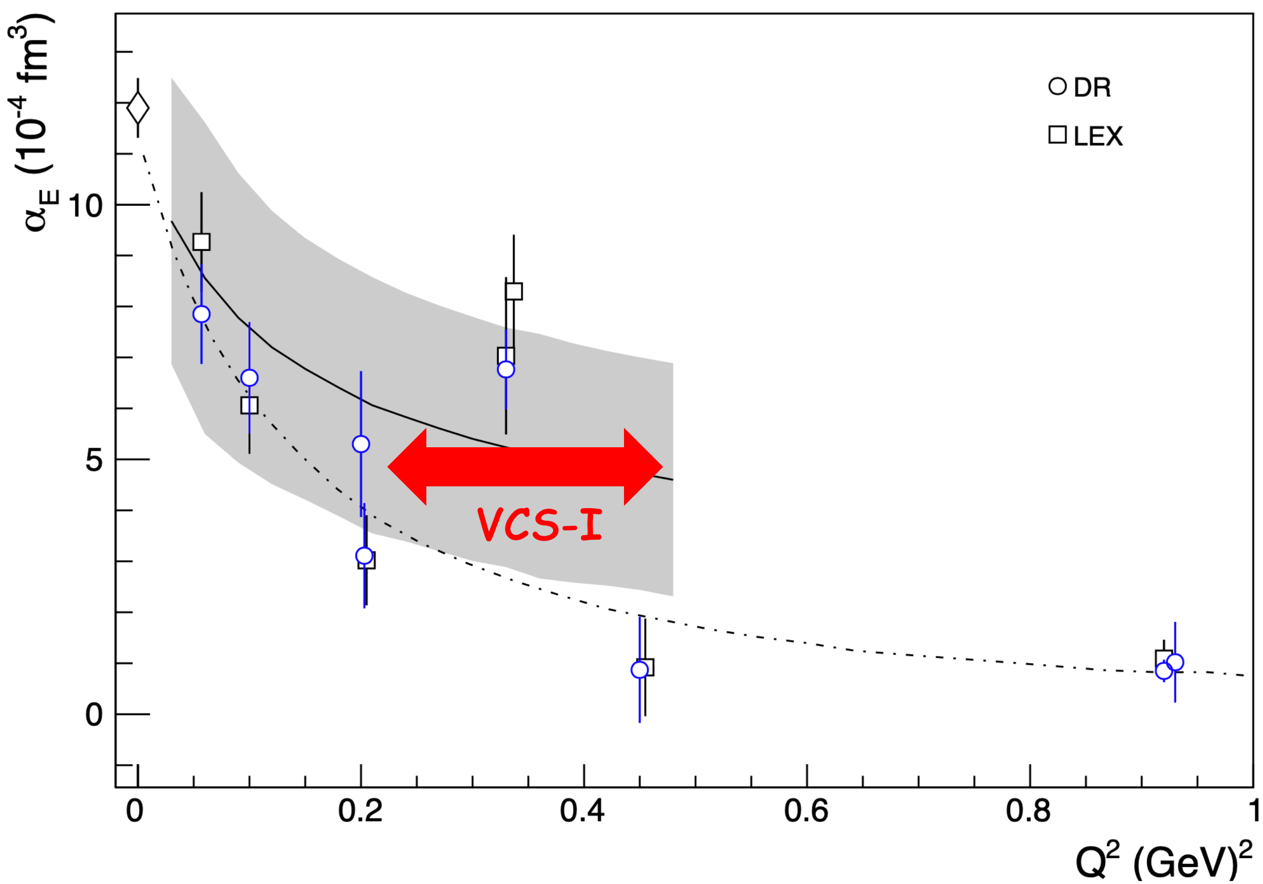
LEX and DR

Updated HO-cut

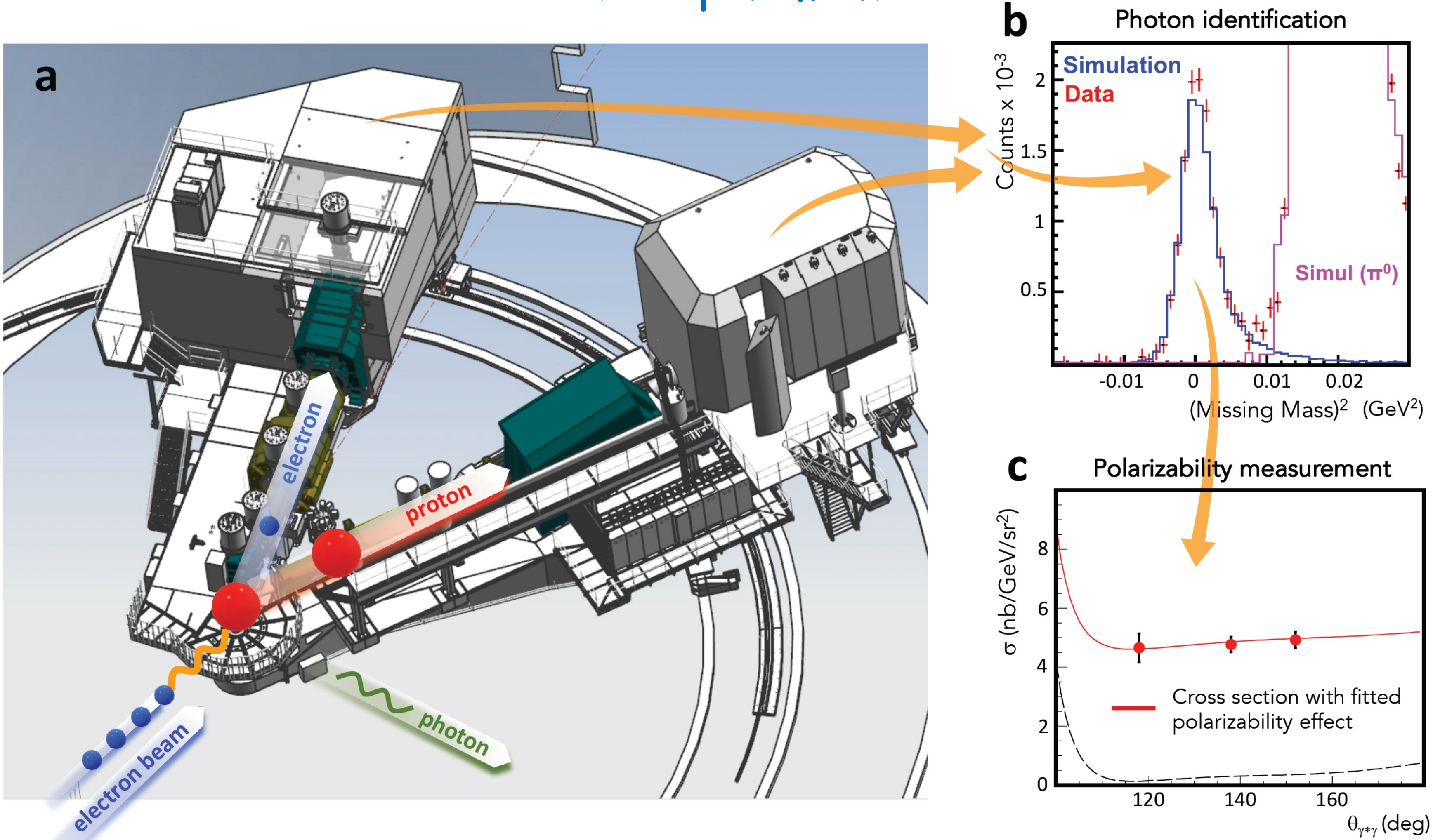


Jlab : VCS-I Experiment (E12-15-001) in Hall C

High precision measurements targeting
explicitly the kinematics of interest for α_E



The experiment



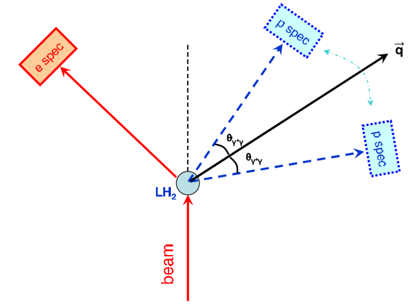
Hall C: SHMS, HMS
4.56 GeV
20 μA
Liquid hydrogen 10 cm

cross sections & azimuthal asymmetries

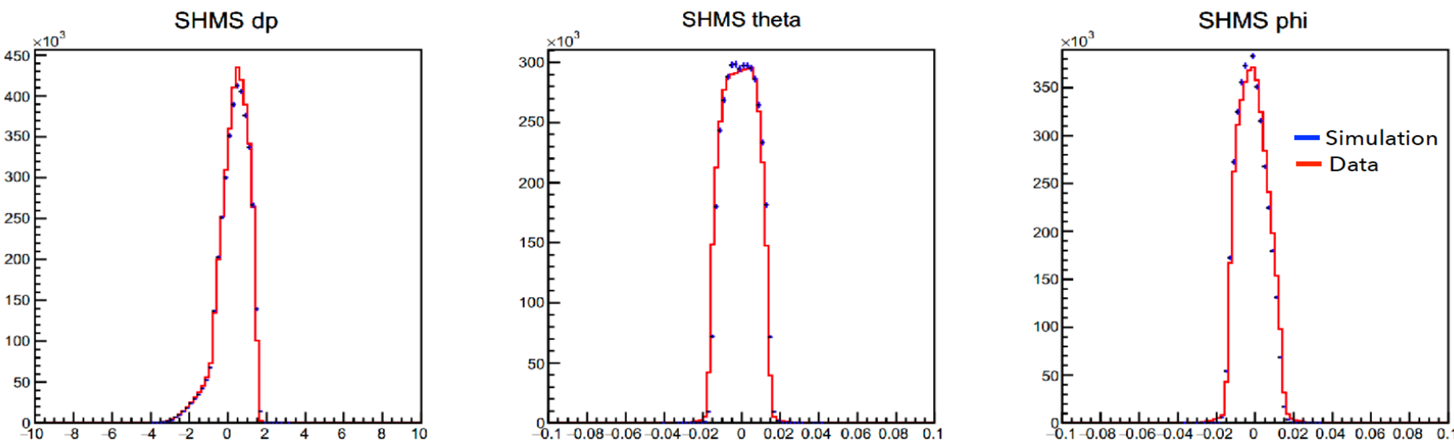
$$A_{(\phi_{\gamma*\gamma}=0,\pi)} = \frac{\sigma_{\phi_{\gamma*\gamma}=0} - \sigma_{\phi_{\gamma*\gamma}=180}}{\sigma_{\phi_{\gamma*\gamma}=0} + \sigma_{\phi_{\gamma*\gamma}=180}}$$

sensitivity to GPs

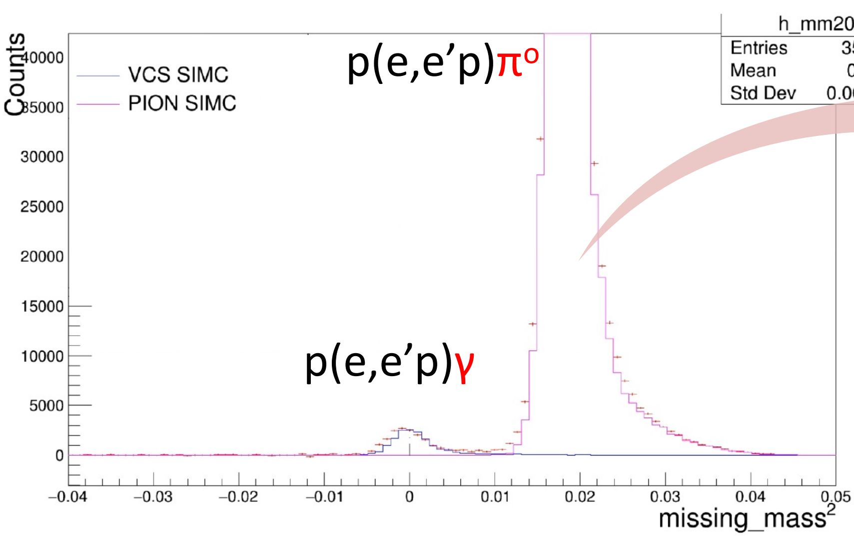
suppression of systematic asymmetries

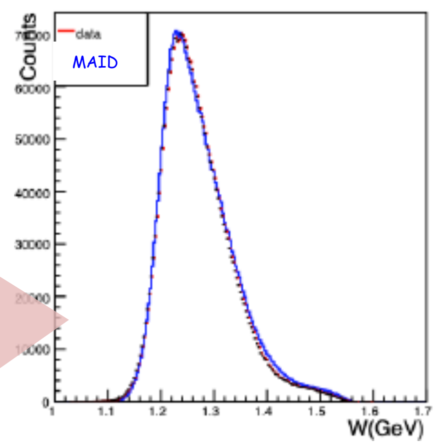


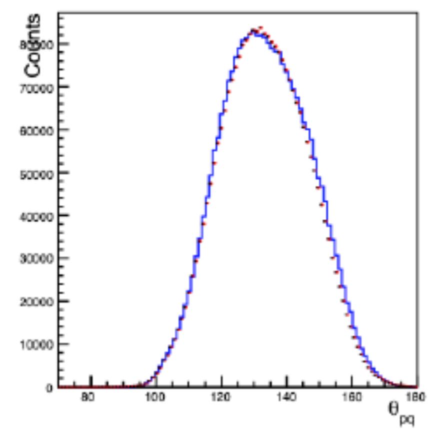
Elastic data

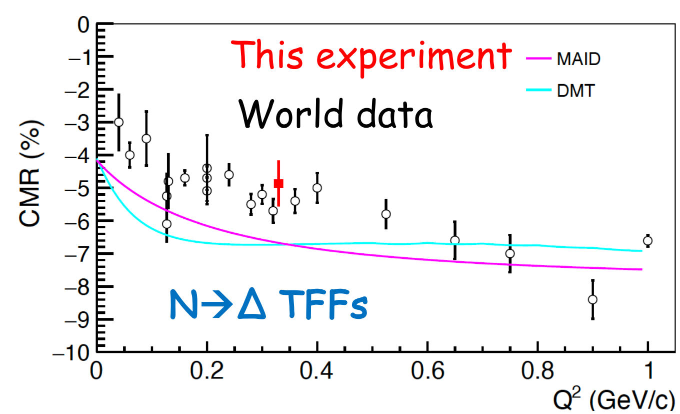


p(e,e'p)π^0



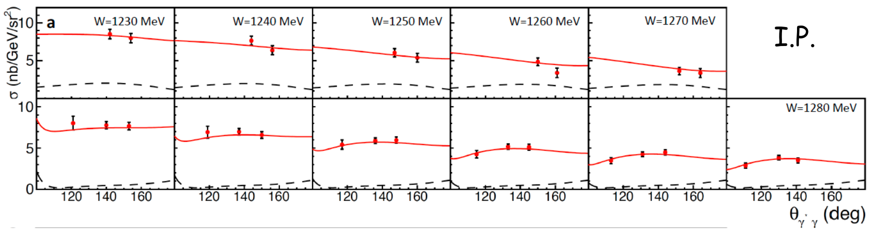




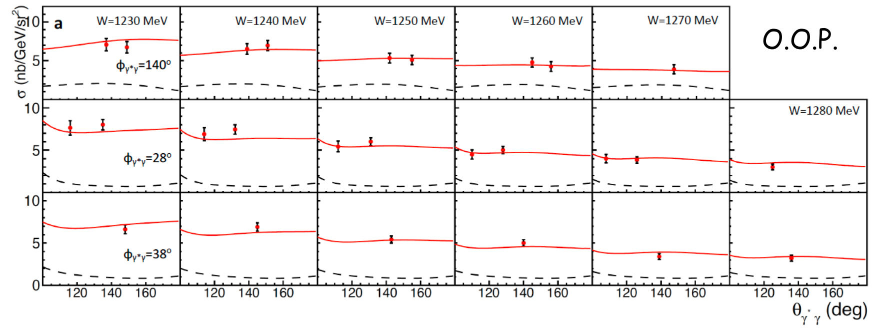


VCS-I results: cross sections

Q²=0.27 GeV²

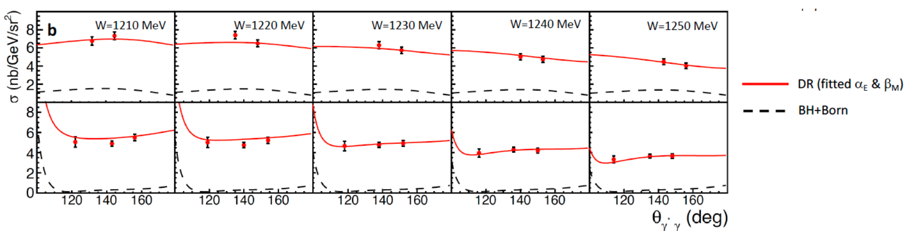


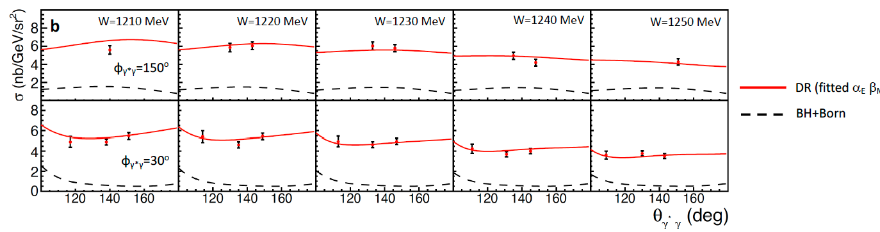
I.P.



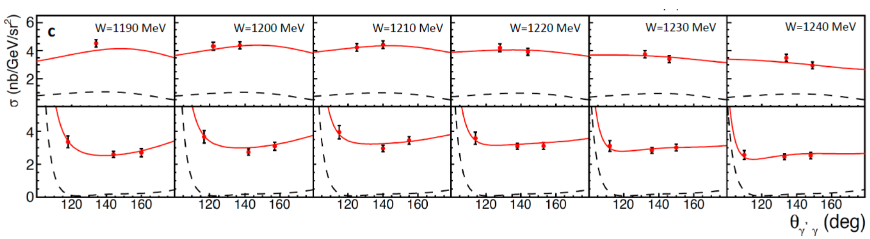
O.O.P.

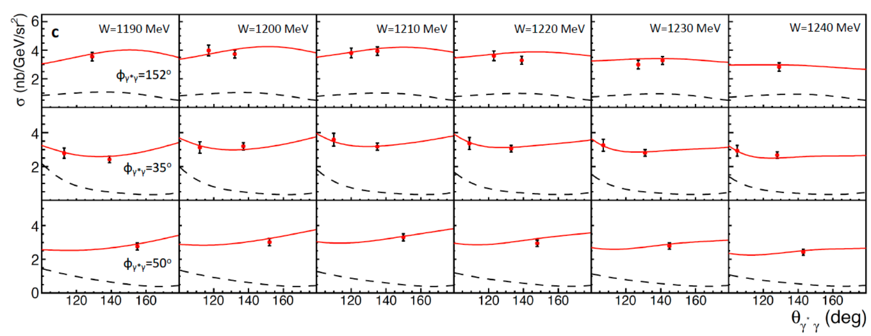
Q²=0.33 GeV²





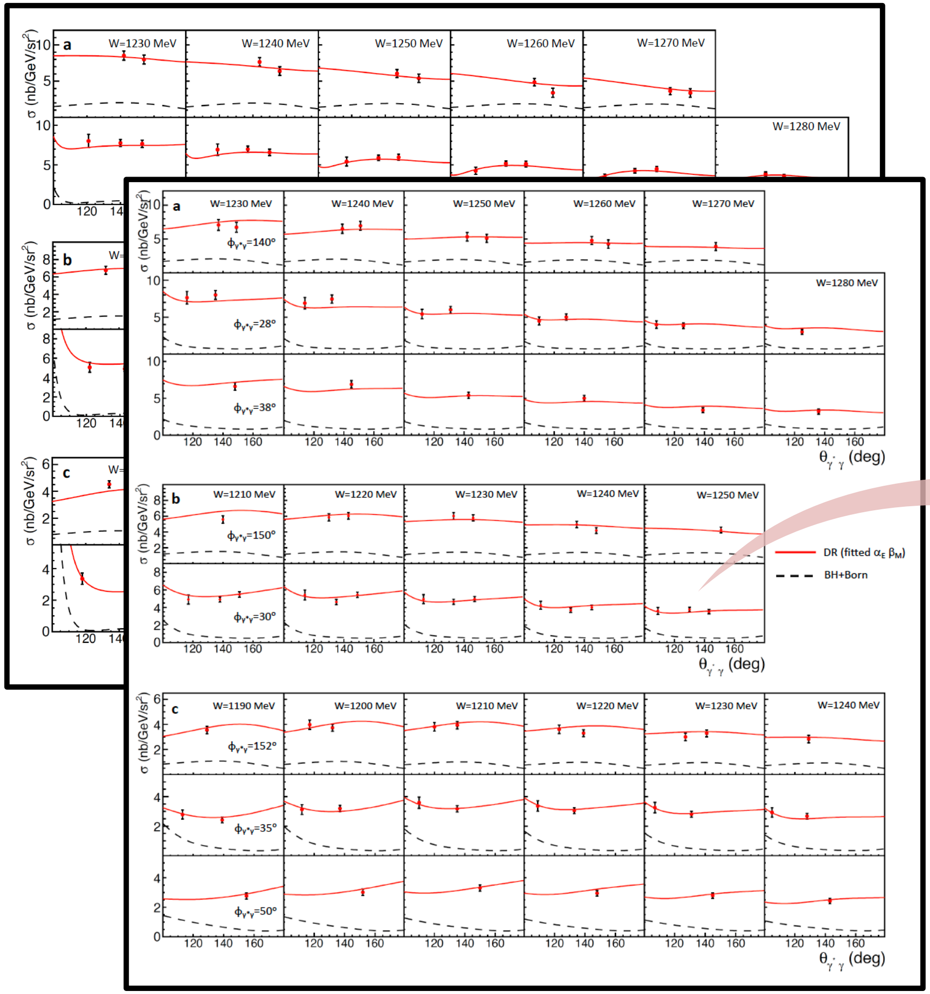
Q²=0.40 GeV²



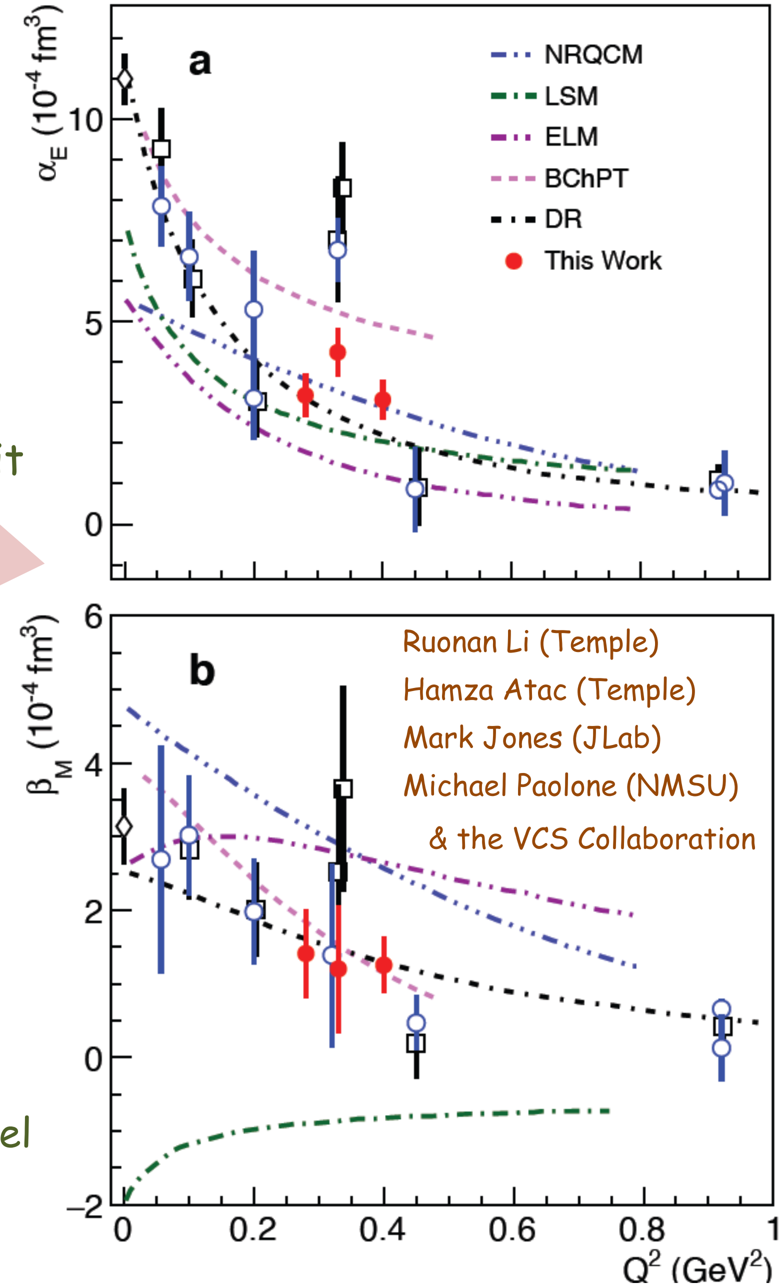


VCS-I results: GPs

Nature 611, 265 (2022)



DR fit



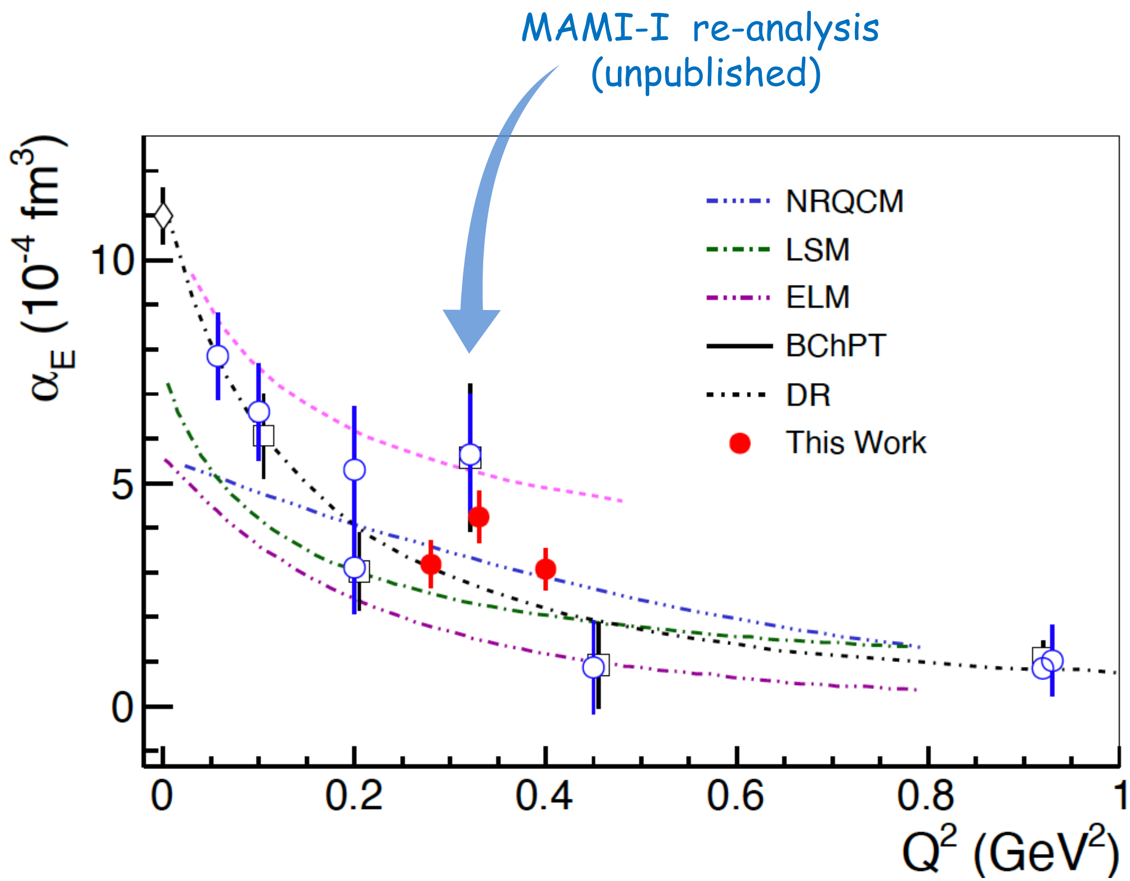
Ruonan Li (Temple)
Hamza Atac (Temple)
Mark Jones (JLab)
Michael Paolone (NMSU)
& the VCS Collaboration

Experimental cross sections are compared to the DR model predictions for all possible values for the GPs

→ $\alpha_E(Q^2)$ and $\beta_M(Q^2)$ are fitted by a χ^2 minimization

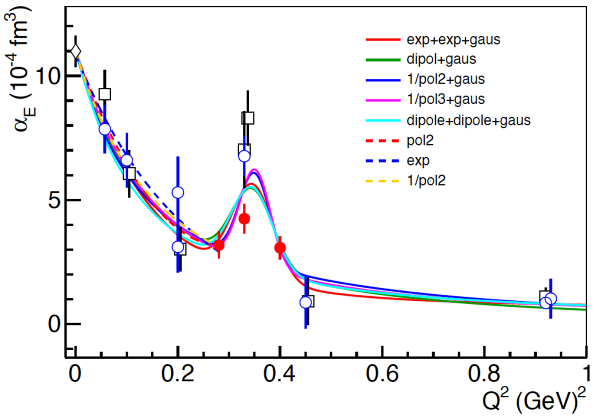
Electric GP

Is there a non-trivial structure vs Q^2 ?



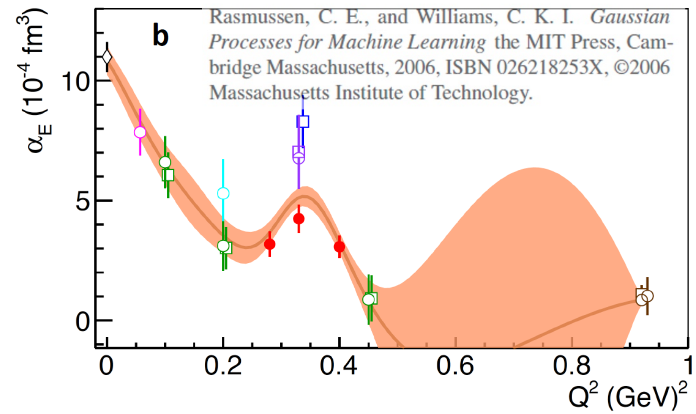
Electric GP

Traditional fits

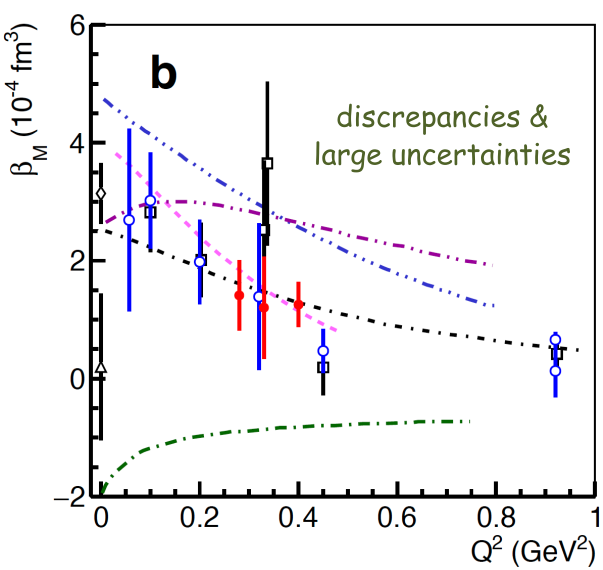


Data-driven techniques:

no underlying functional form is assumed



Magnetic GP



Is the observed α_E structure coincidental or not?

If true: Measure the shape precisely → input to theory

If not: We are able to show it with more measurements

Strong tension between world data (?)

Something we do not yet understand well?
Underestimated uncertainties? …

Magnetic GP: Large uncertainties & discrepancies

Precision and consistent systematics are needed to disentangle para/dia-magnetism in the proton

Spatial information & polarizability radii

Spatial dependence of induced polarizations

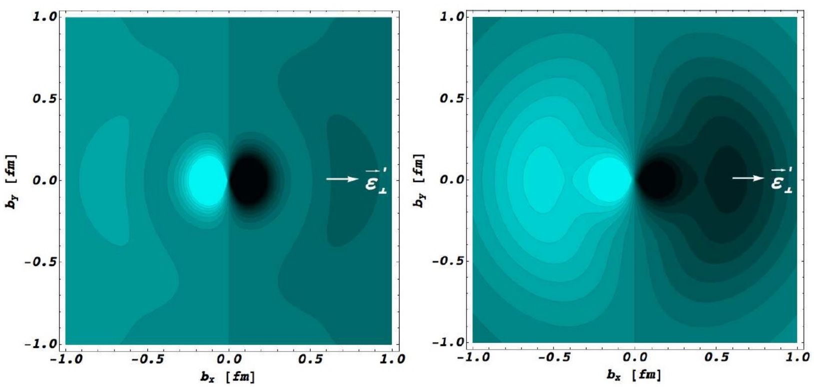
Nucleon form factor data ➔ light-front quark charge densities

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

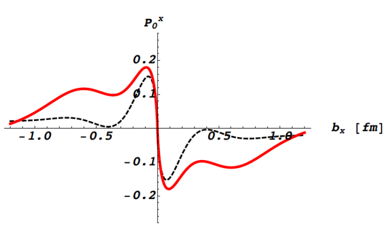
Induced polarization in a proton when submitted to an e.m. field

GP I   GP II



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

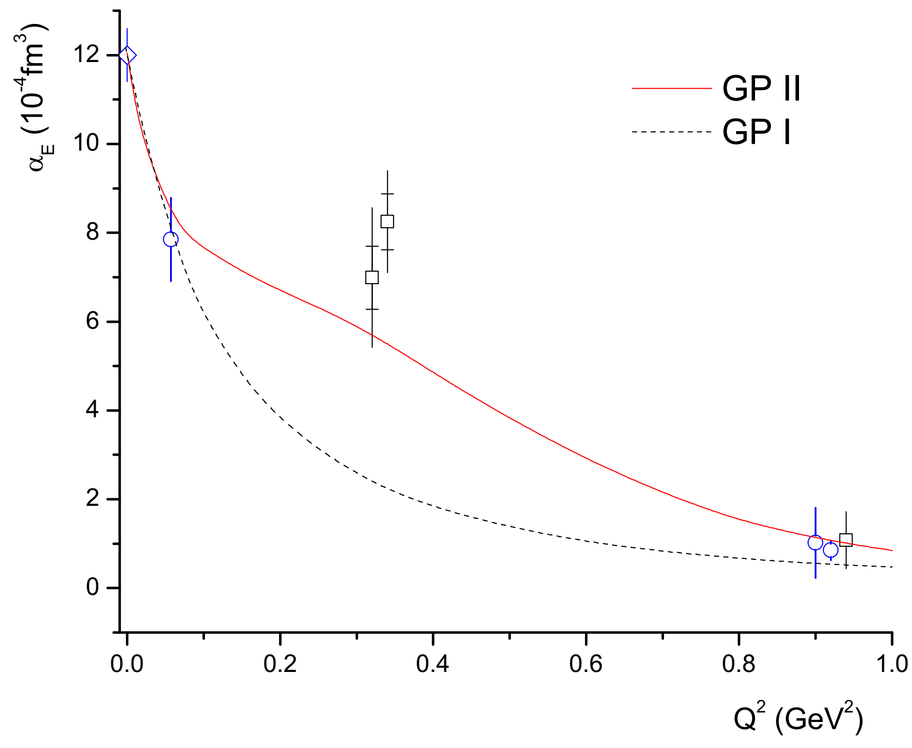
(photon polarization along x-axis, as indicated)



Induced polarization along b_y=0

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

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



Spatial dependence of induced polarizations

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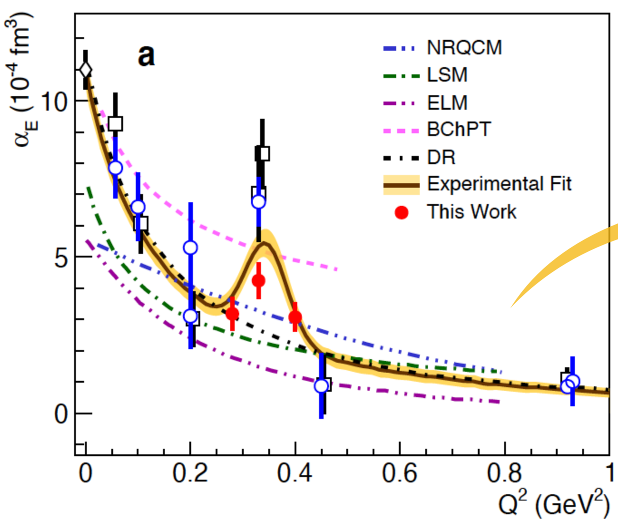
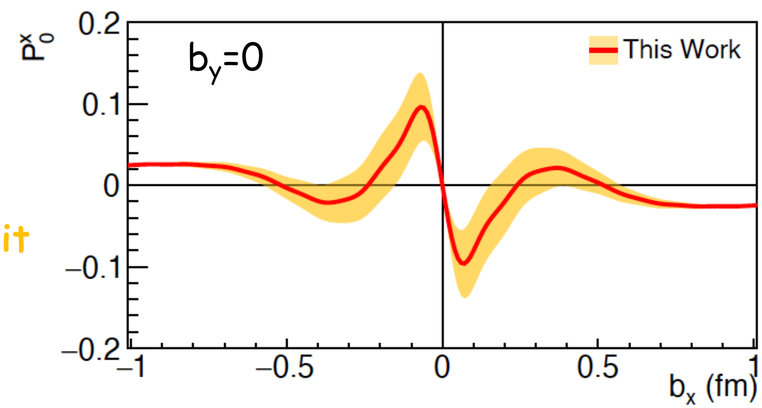


Experimental Fit



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

Polarizability radii

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

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

Polarizability radii

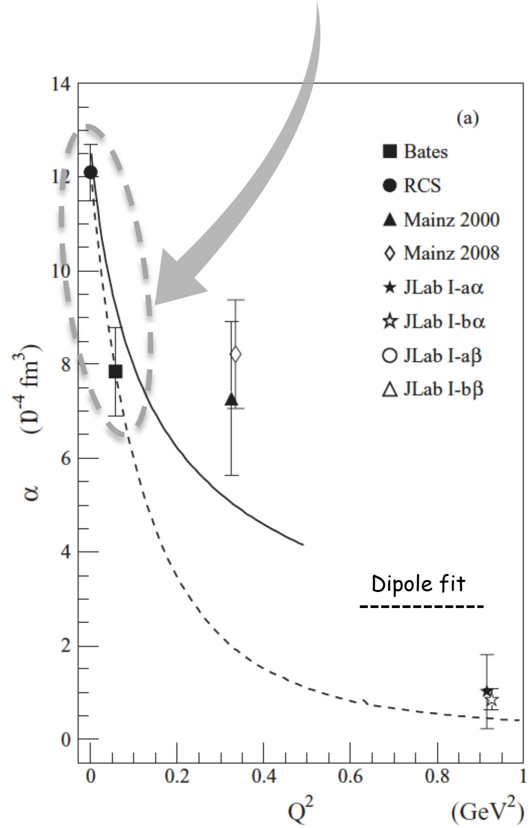
$$\langle r^2_{\alpha_E} \rangle = \frac{-6}{\alpha_E(0)} \cdot \frac{d}{dQ^2}\alpha_E(Q^2)\bigg|_{Q^2=0}$$

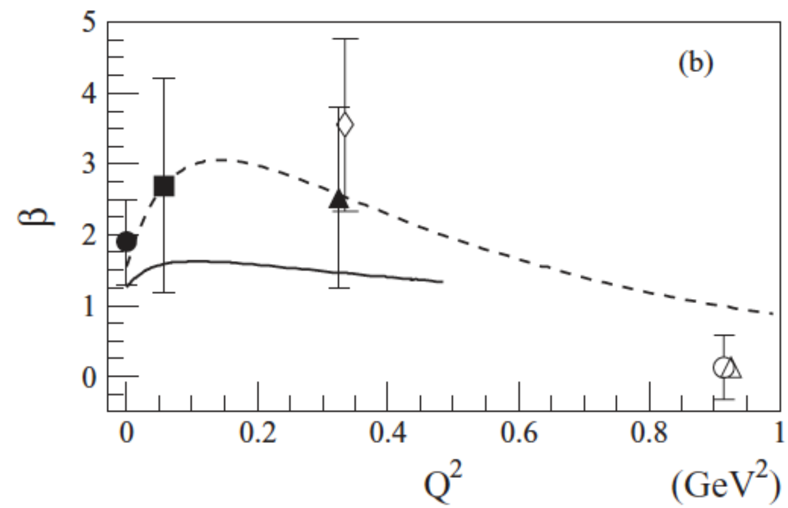
$$\langle r^2_{\beta_M} \rangle = \frac{-6}{\beta_M(0)} \cdot \frac{d}{dQ^2}\beta_M(Q^2)\bigg|_{Q^2=0}$$

First extraction made possible with the MIT-Bates measurement (Q^2=0.06 GeV^2)

PRL **97,** 212001 (2006)

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





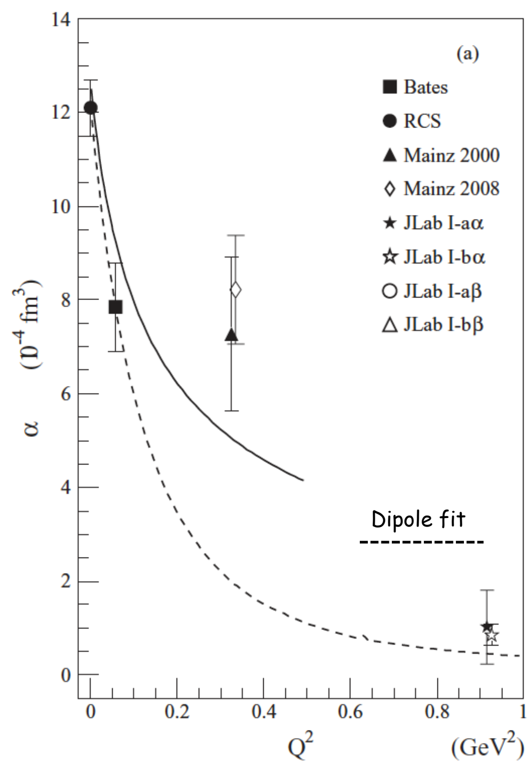
$$\langle r^2_\alpha \rangle = 2.16 \pm 0.31 \text{ fm}^2$$

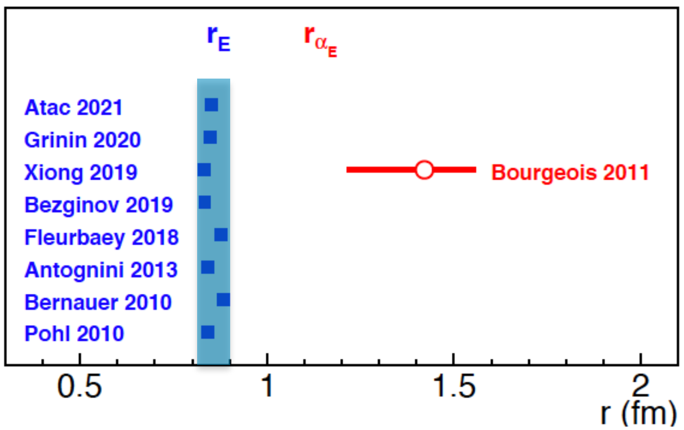
$\langle r^2_\beta \rangle$
$-4.67^{+5.36}_{-13.04}$

Polarizability radii

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

First extraction made possible with the MIT-Bates measurement (Q^2=0.06 GeV^2)





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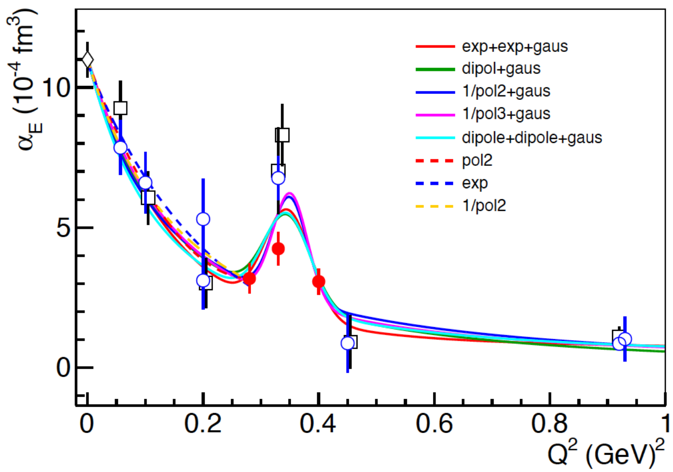
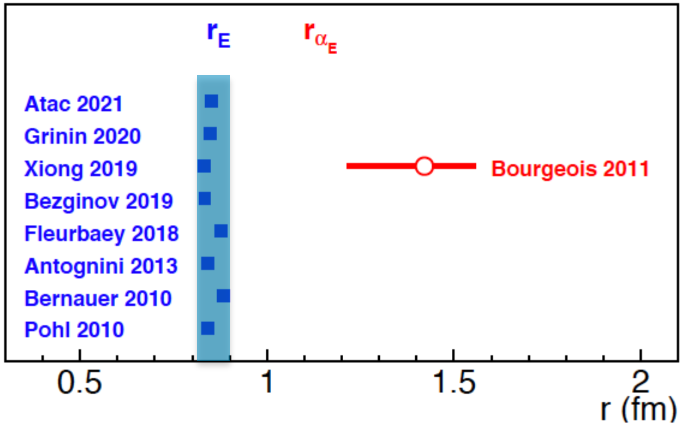


Since then: more data and more comprehensive treatment of the radius extraction



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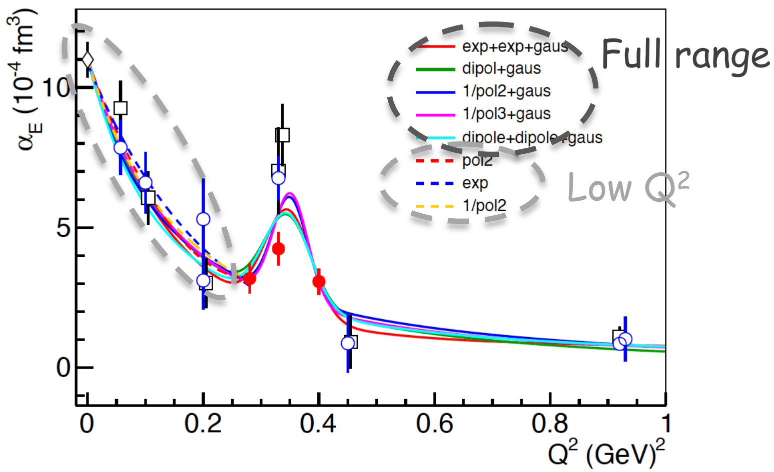

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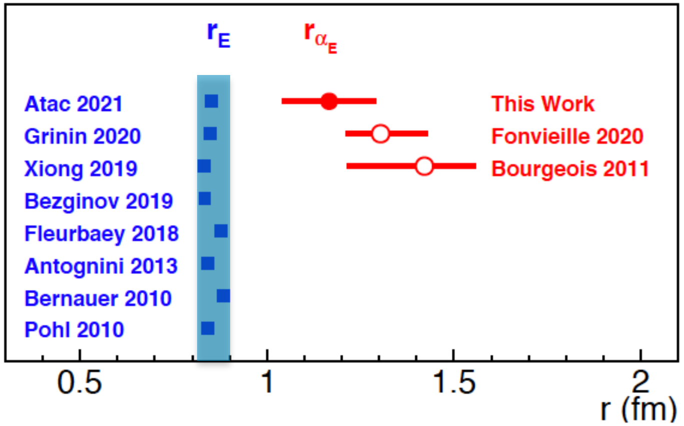
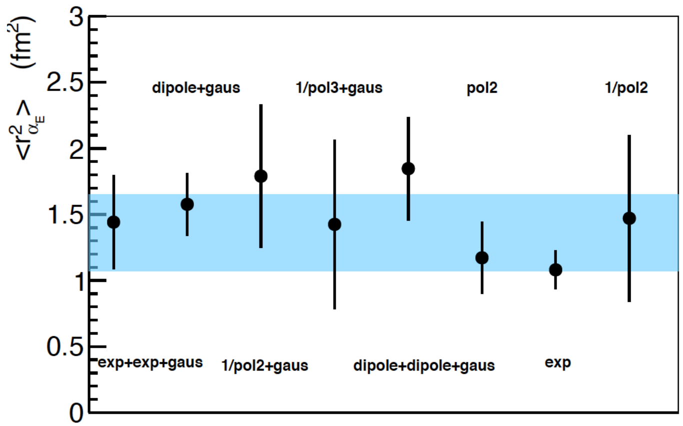


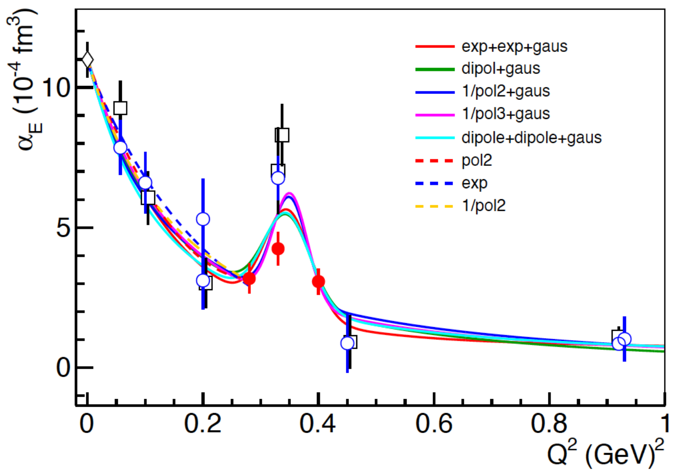


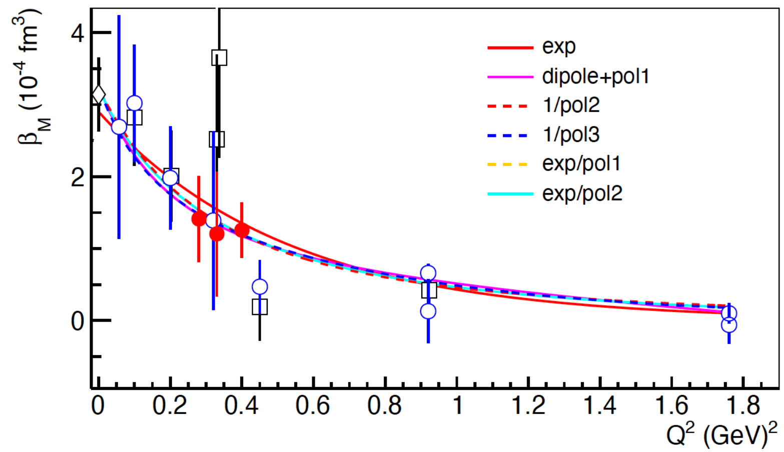
$$\langle r^2_{\alpha_E} \rangle = 1.36 \pm 0.29 \text{ fm}^2$$

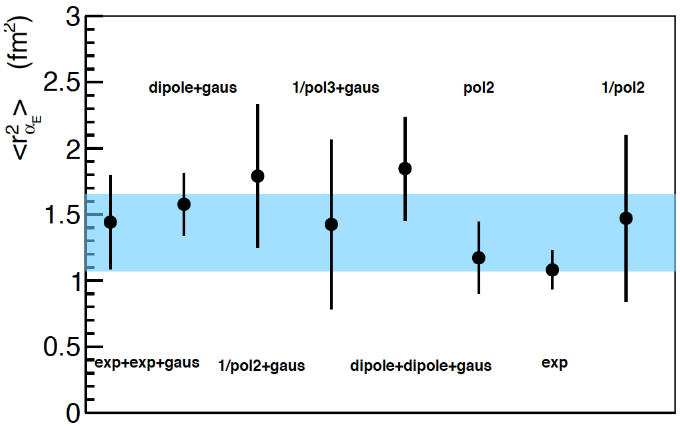
Polarizability radii

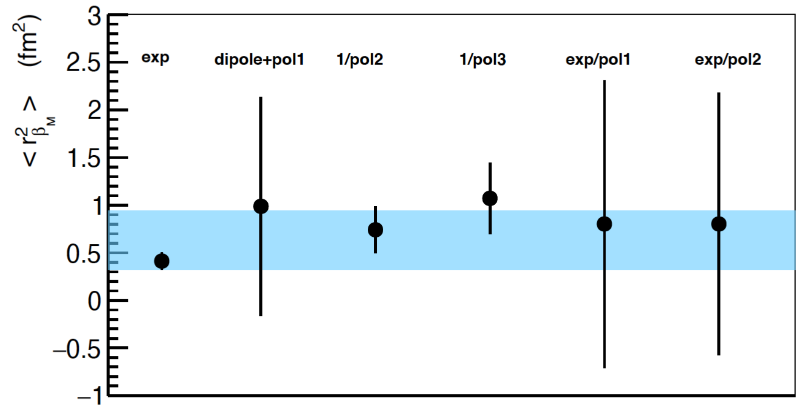
$$\langle r^2_{\alpha_E} \rangle = \frac{-6}{\alpha_E(0)} \cdot \frac{d}{dQ^2} \alpha_E(Q^2) \Big|_{Q^2=0}$$

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





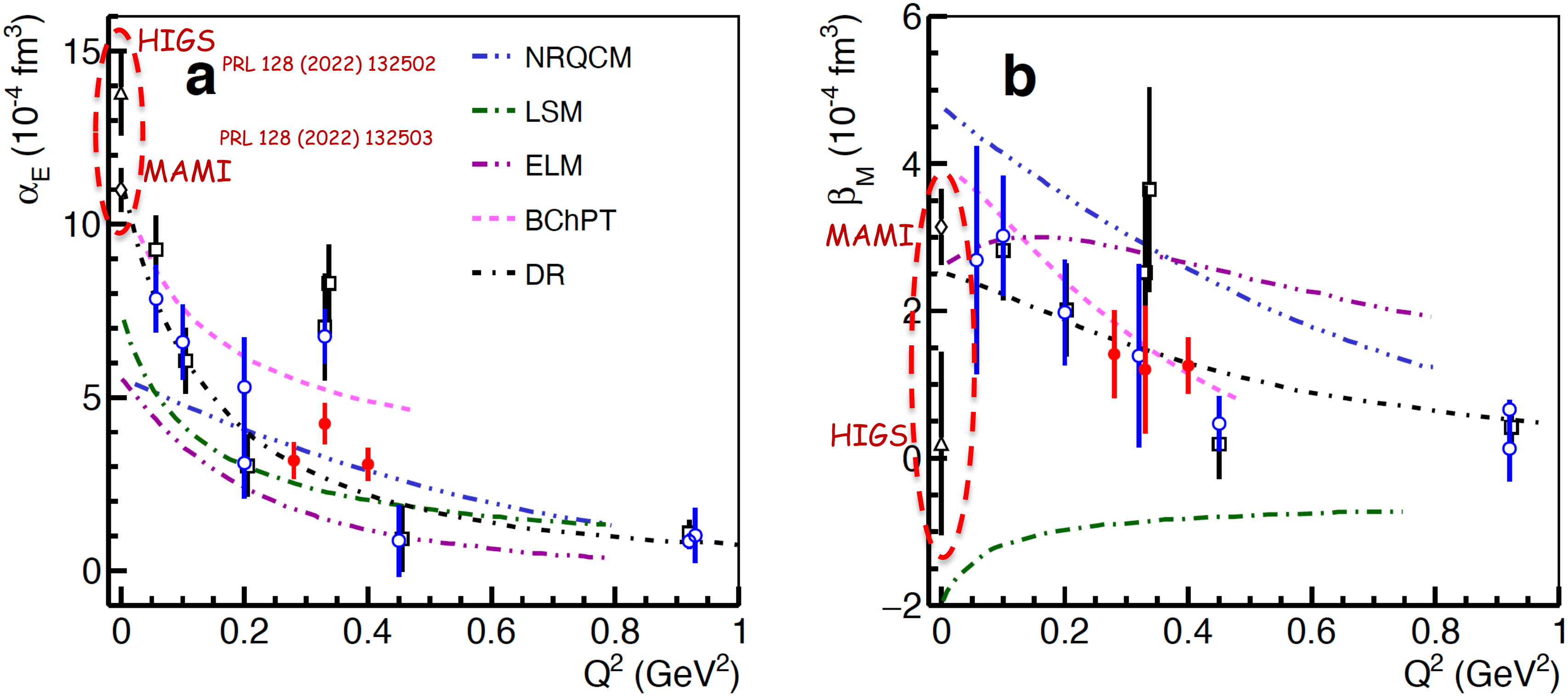




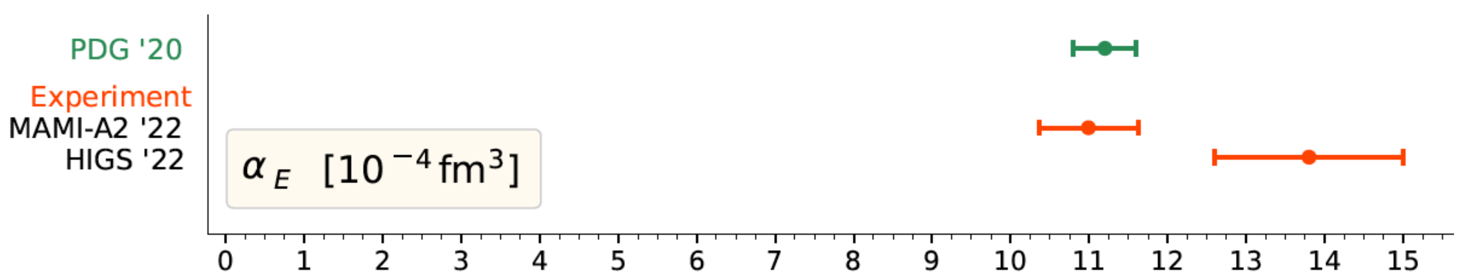
$$\langle r^2_{\alpha_E} \rangle = 1.36 \pm 0.29 \text{ fm}^2$$

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

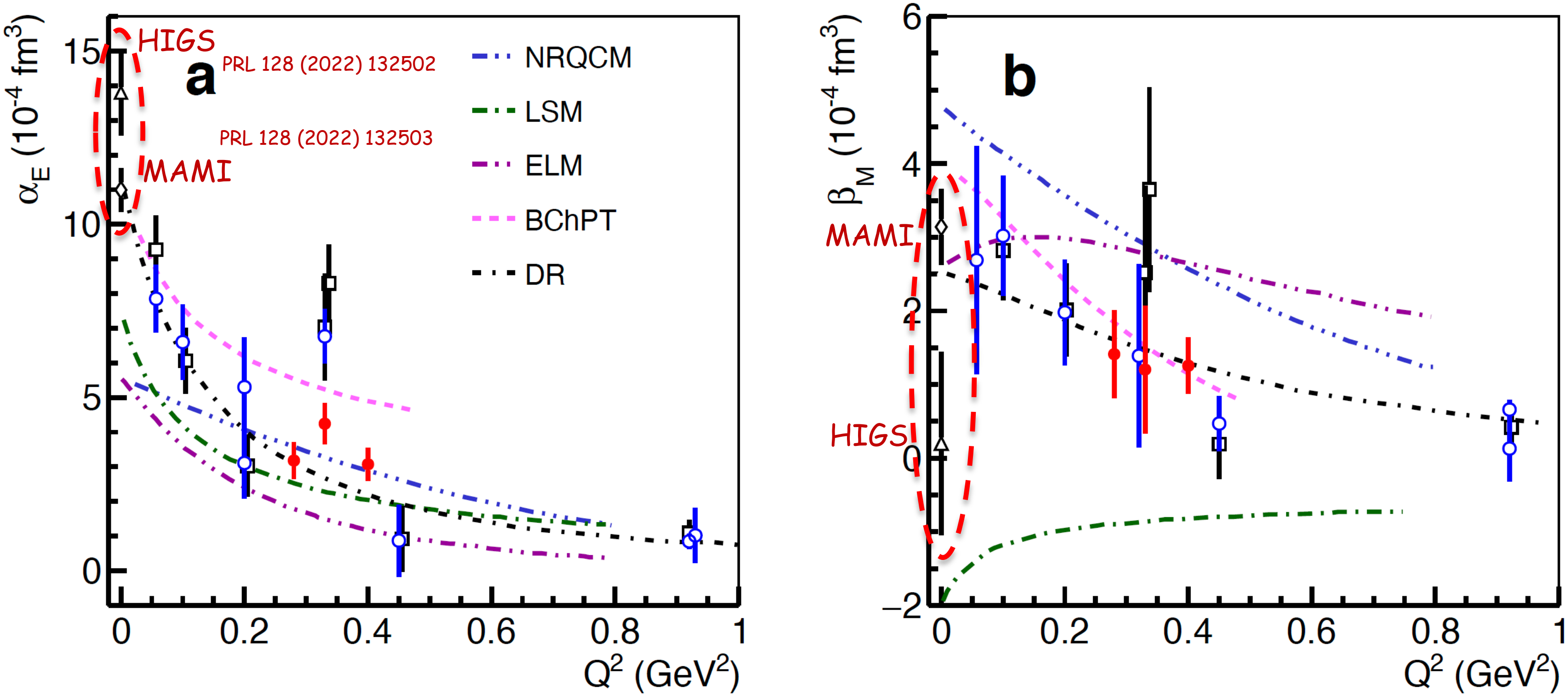
Static Polarizabilities



Recent measurements exhibit tension → affects the pol. radius extraction

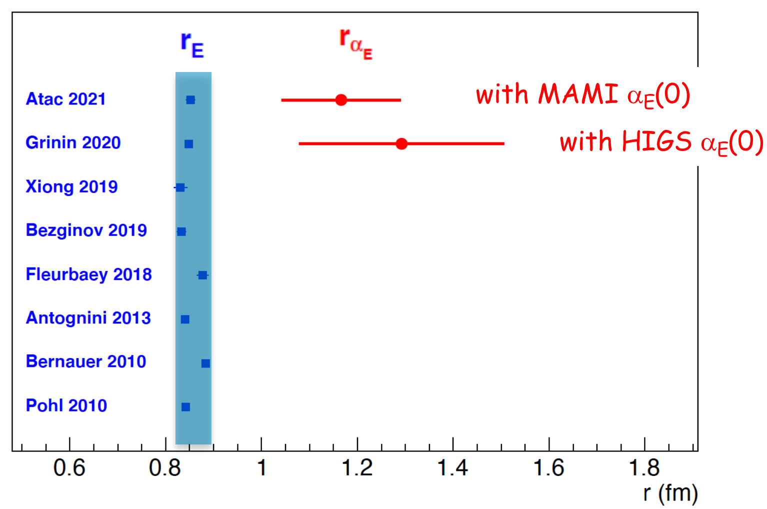


Polarizability radii - Static Polarizabilities



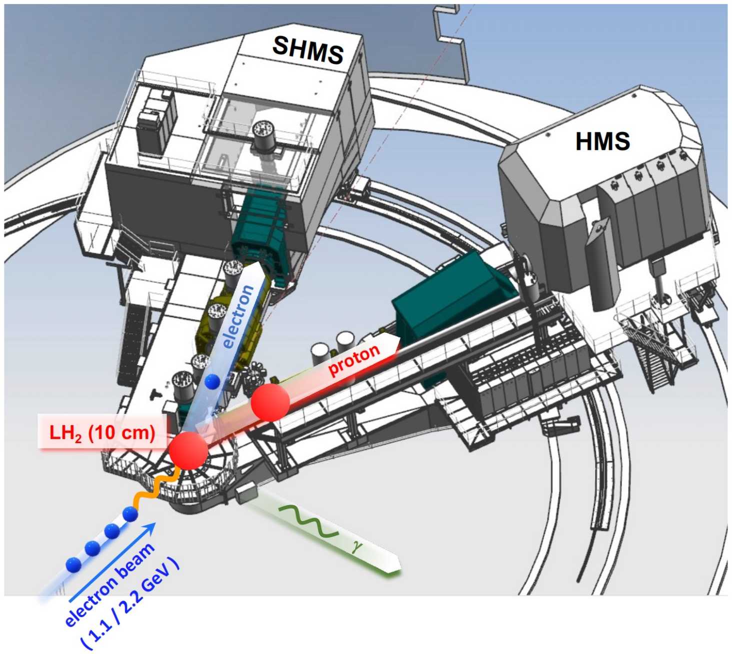
$$\langle r^2_{\alpha_E} \rangle = 1.36 \pm 0.29 \; fm^2$$

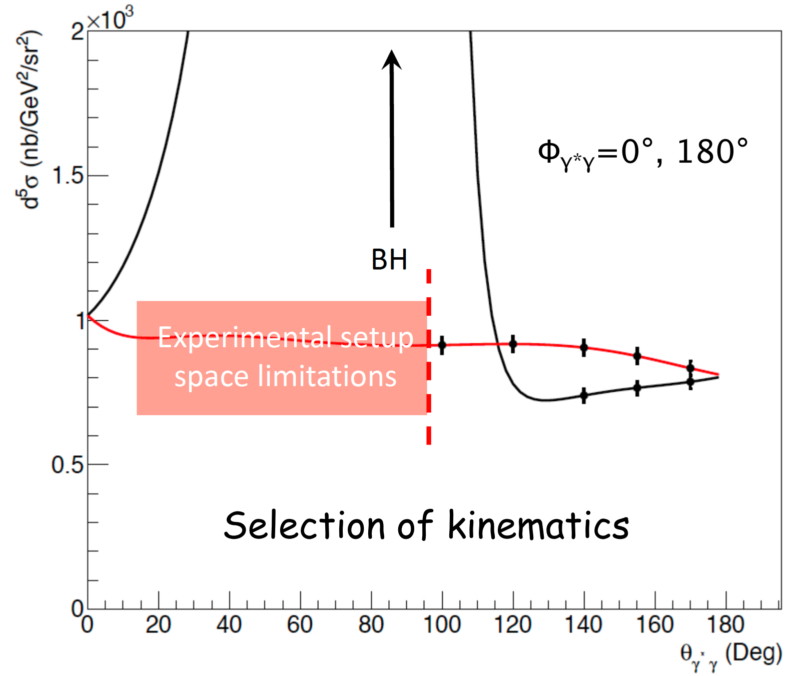
$$\langle r^2_{\alpha_E} \rangle = 1.67 \pm 0.50 \; fm^2$$



Moving Forward

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





Extend Q^2 range & targeted measurements to fully exploit the sensitivity to the EM GPs

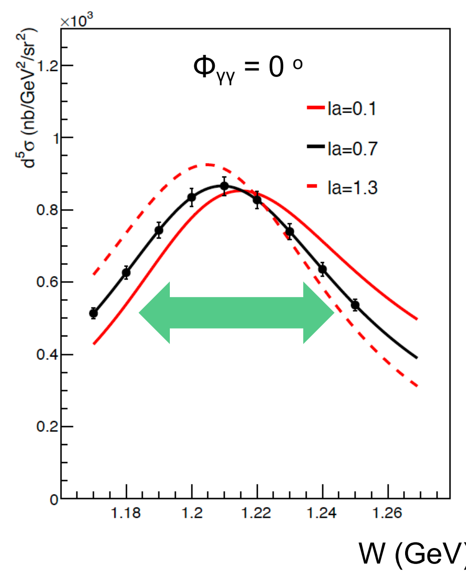
APPROVED PAC 51

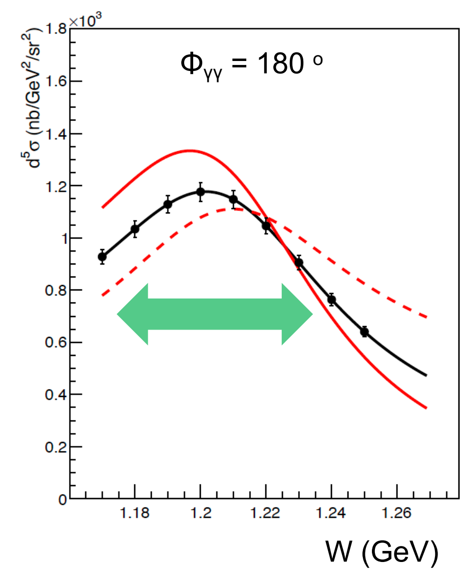
Production (E_0 = 1.1 GeV) : 6 days

Production (E_0 = 2.2 GeV) : 53 days

Studies (optics/dummy/calibrations) : 3 days

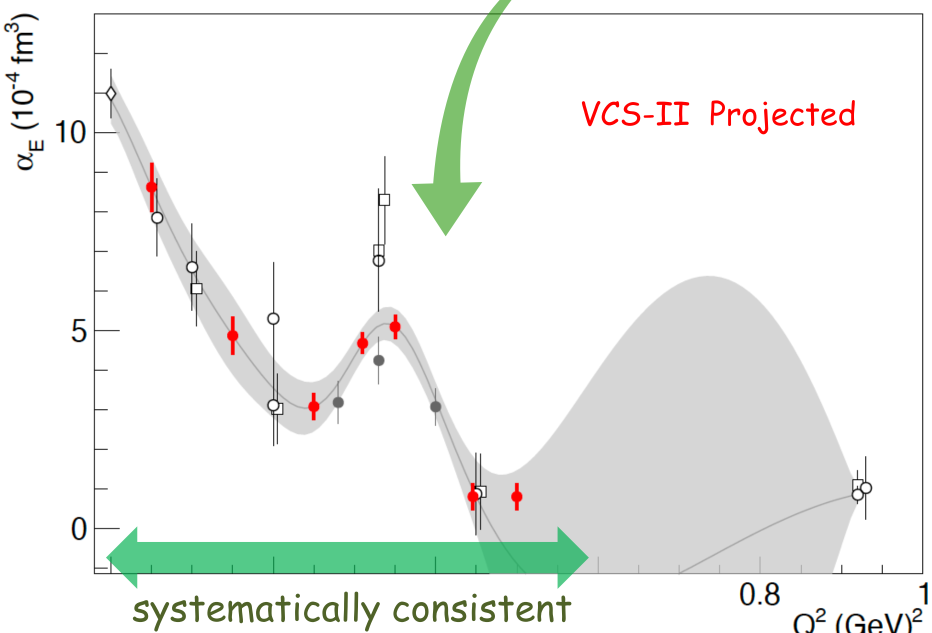
Total: 62 days





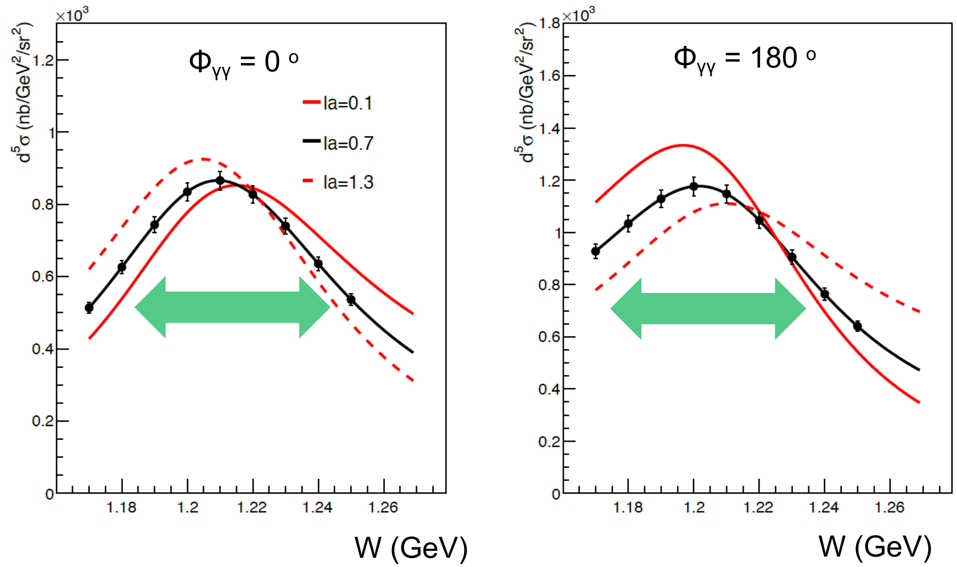
VCS-II Projected Measurements

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



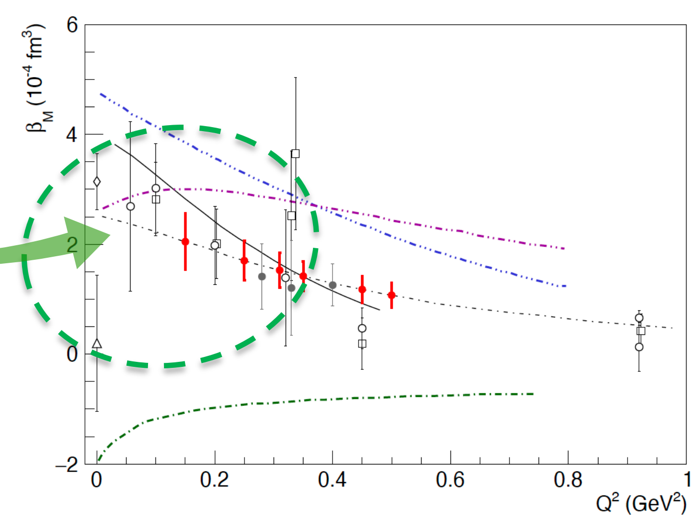
systematically consistent
measurements throughout Q^2

Targeted measurements to fully
exploit the sensitivity to the GPs



Improve upon β_M :

Pin down the competing
para/dia-magnetic contributions
in the nucleon



Can we measure with a different method ?

Yes: positrons and/or beam spin asymmetries

Positrons allow for an independent path to access experimentally the GPs

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Virtual Compton scattering at low energies with a positron beam

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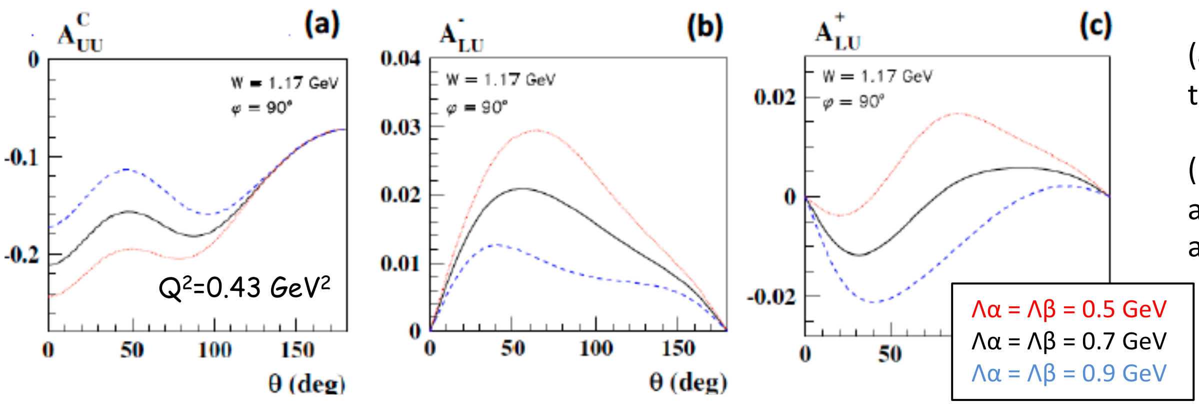
[1]Dipartimento di Fisica, Università degli Studi di Pavia, 27100 Pavia, Italy
[2]Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, 27100 Pavia, Italy
[3]Institut für Kernphysik and PRISMA+ Cluster of Excellence, Johannes Gutenberg Universität, D-55099 Mainz, Germany



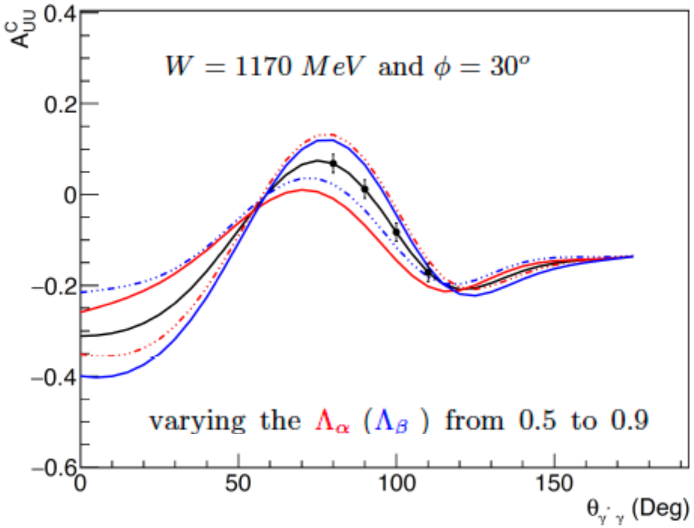
(a): The beam-charge asymmetry as a function of the photon scattering angle at Q2 = 0.43 GeV 2.

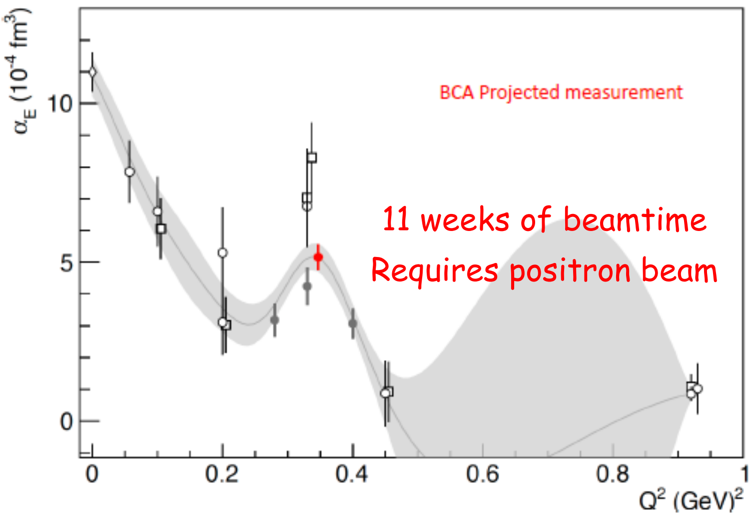
(b) & (c): The electron and positron beam-spin asymmetry as a function of the photon scattering angle for out-of-plane kinematics.

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

BCA (electrons & positrons)





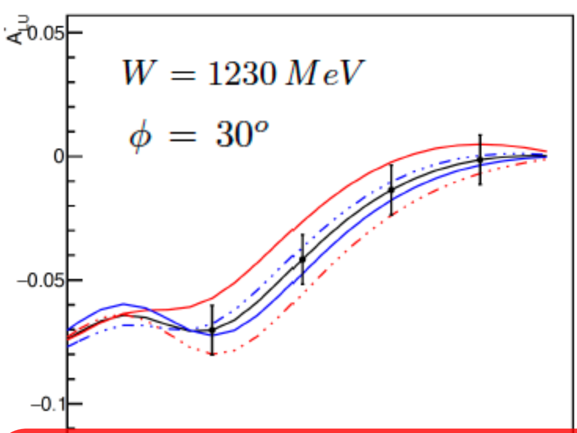
Hall C (SHMS / HMS)

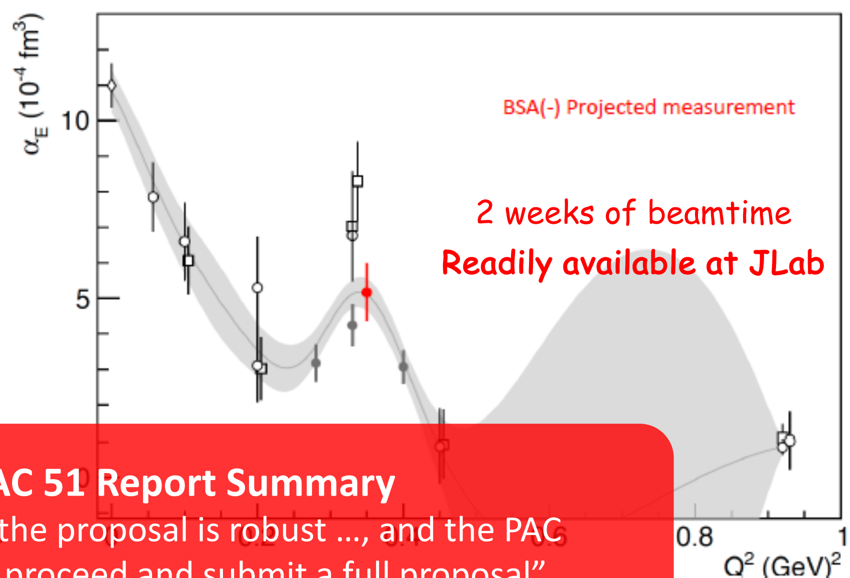
e^- : ~ 1 week @ 50 μA

and

e^+ : ~ 10 weeks @ 5 μA

BSA (electrons or positrons)





e^- (pol. 85% @ 70 μA)

~ 2 weeks of beamtime

or

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

~ 3 orders of magnitude more beamtime

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

JLab: leading the efforts of the VCS program, past/ present / future

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

Future experimental goals

Improve β_M

Identify the shape of the α_E structure (if it exists)
pin it down with precision - important input for the theory

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

Thank you!