Measurement of the Proton Generalized Polarizabilities with positron and polarized electron beams

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Positron Working Group Workshop

Jefferson Lab, March 2025

Temple University

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Outline

Introduction

Experimental results from unpolarized VCS measurements

Theoretical status, spatial information of proton & polarizability radii

Upcoming experiments in FY-2026 (VCS-II@JLab)

Prospects with positron & polarized electron beams (working progress)

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, $N^0 = udd$

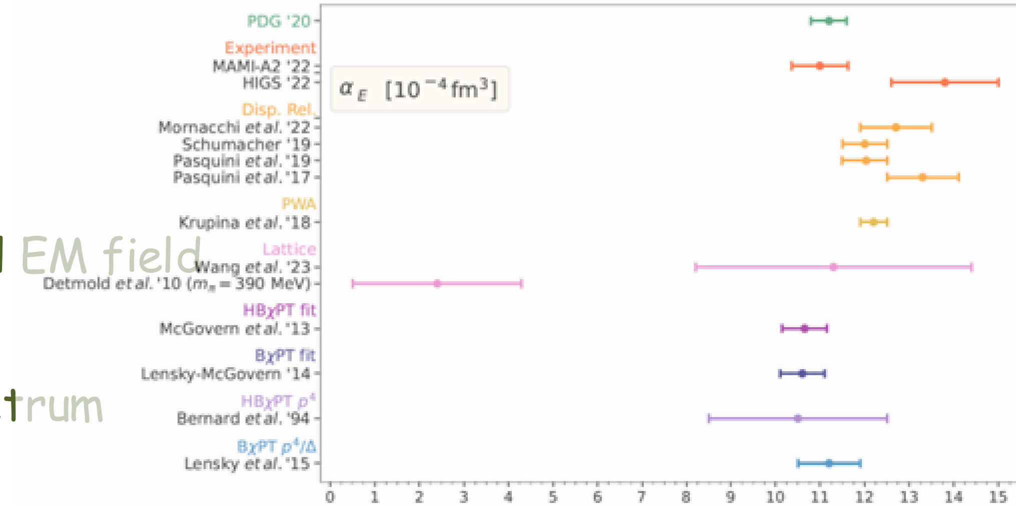
p

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

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

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

Proton Polarizablities

Fundamental structure constants
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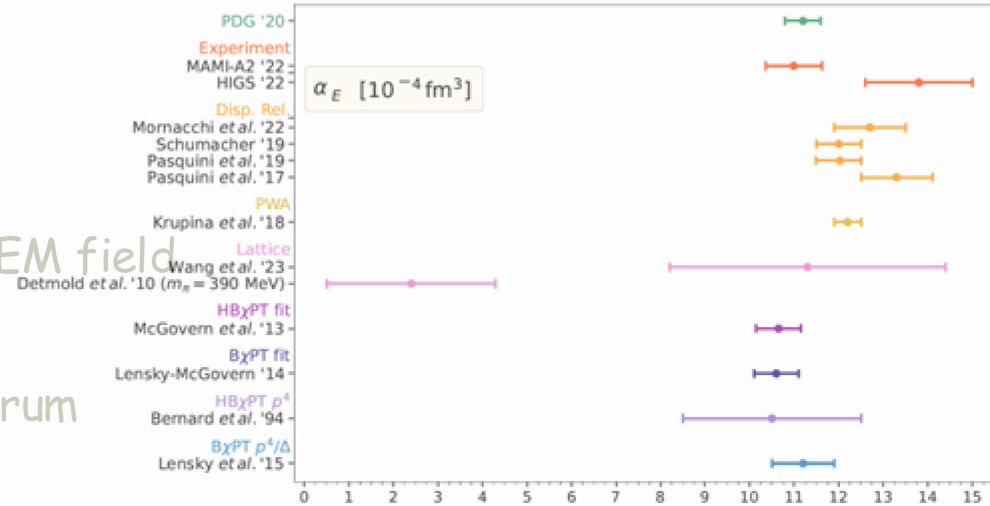


Response of the nucleon to external EM field

Sensitive to the full excitation spectrum

Accessed experimentally through Compton Scattering

RCS: static polarizabilities → net effect on the nucleon

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

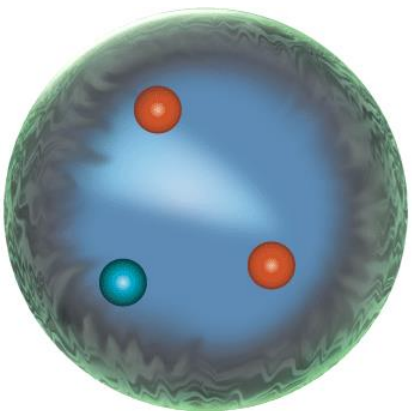
→ electric & magnetic polarizability radii

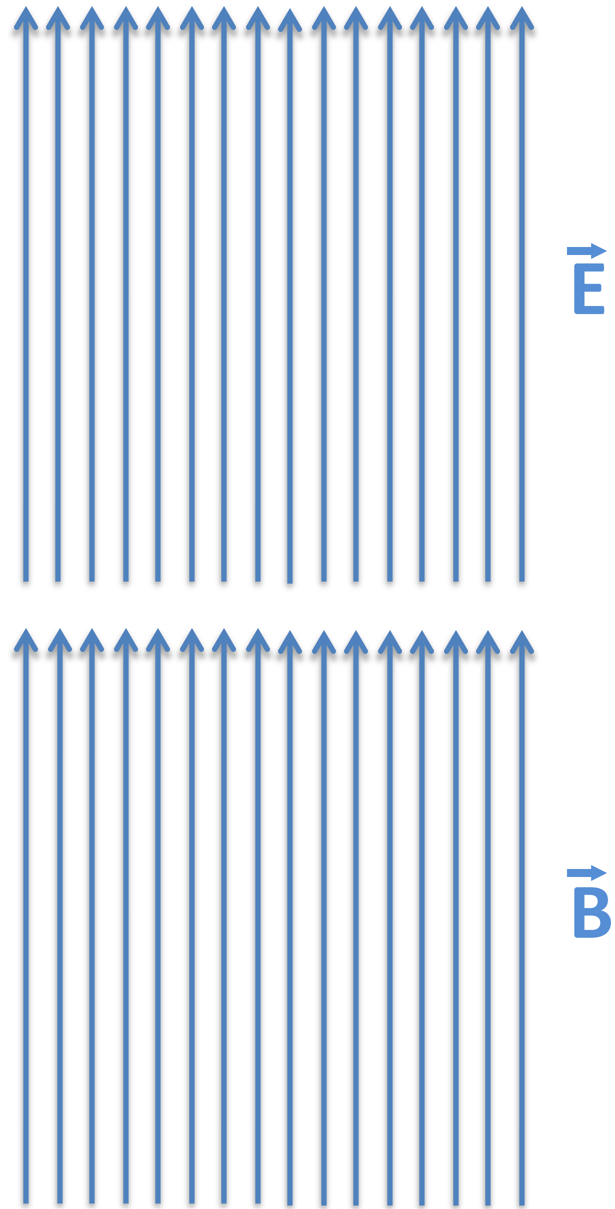
Fourier transform of densities of electric charges and magnetization of a nucleon deformed by an applied EM field

Scalar Polarizablities

Response of internal structure to an applied EM field

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

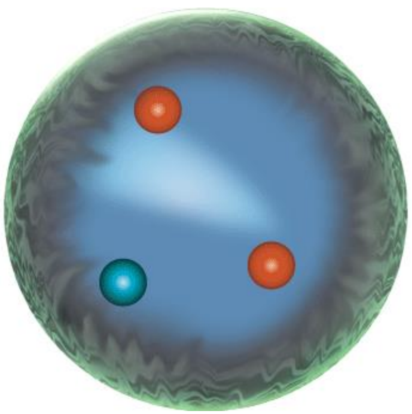


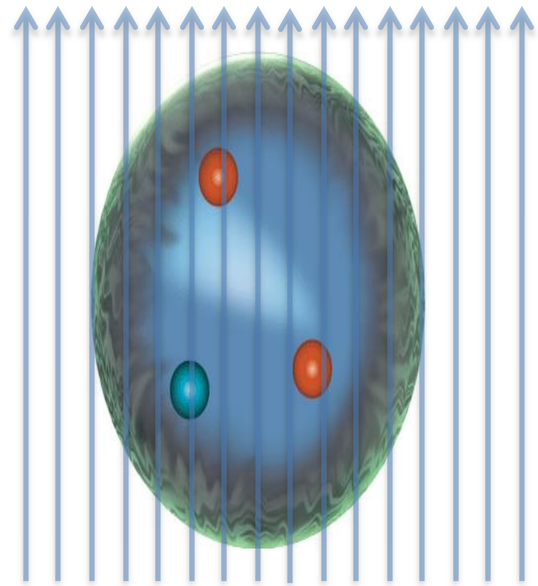


Scalar Polarizablities

Response of internal structure to an applied EM field

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



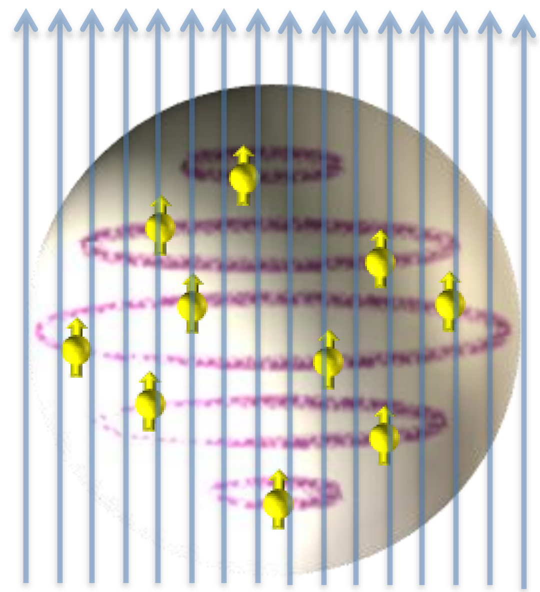


$\vec{E}$

"stretchability"

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

External field deforms the charge distribution



$\vec{B}$

"alignability"

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

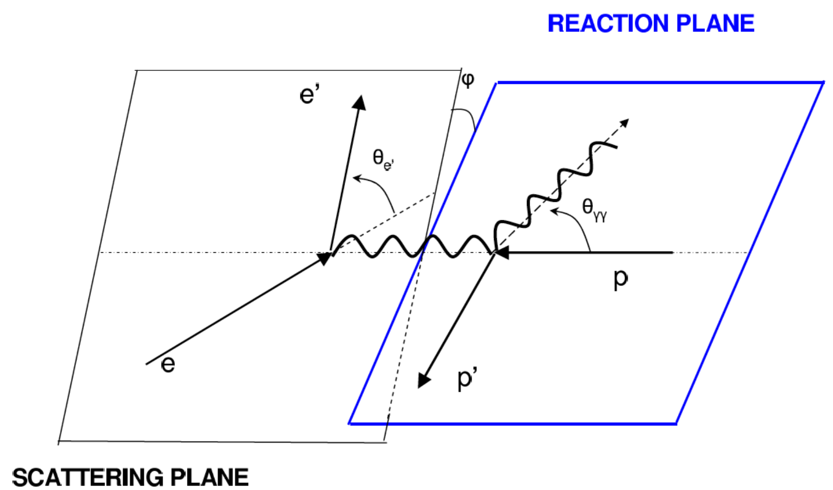
$\beta_{para} > 0$

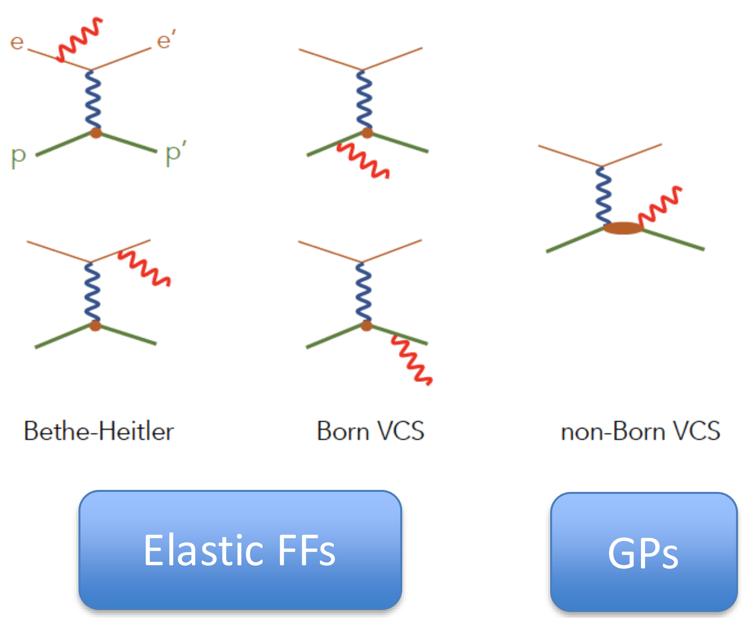
$\beta_{diam} < 0$

Paramagnetic: proton spin aligns with the external magnetic field

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

Virtual Compton Scattering





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

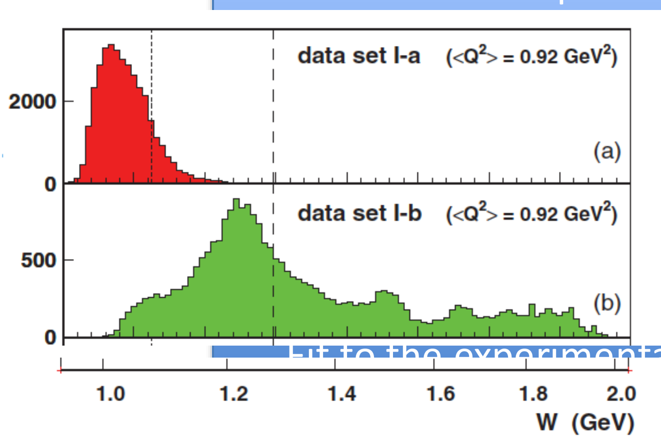
scalar GPs α_E and β_M

Virtual Compton Scattering

DR

valid below & above
Pion threshold

Dispersive integrals
for Non Born amplitudes



Fit to the experimental ... Q^2

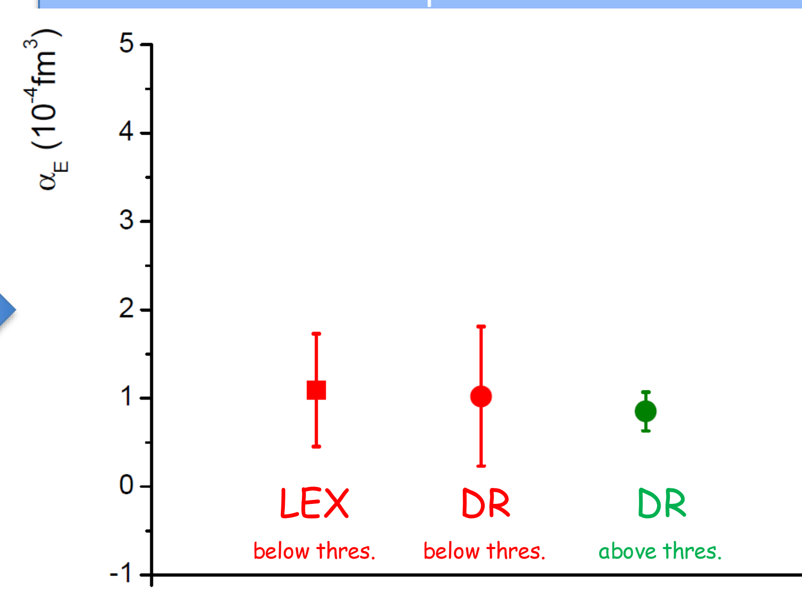
LEX

valid only below
Pion threshold

Response functions

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

P_{LT}



$P_{LT\ spin}]$

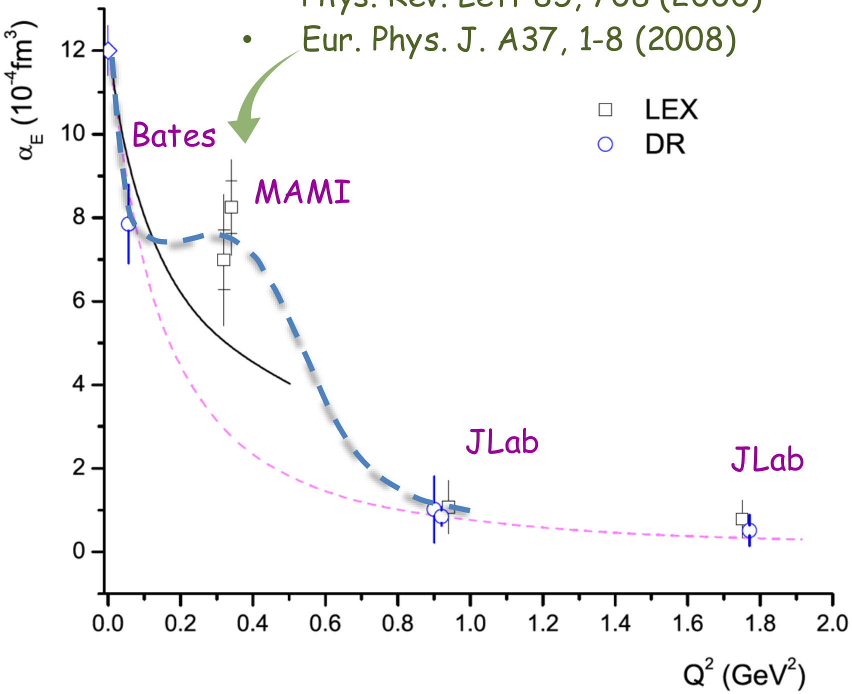
utilize DR

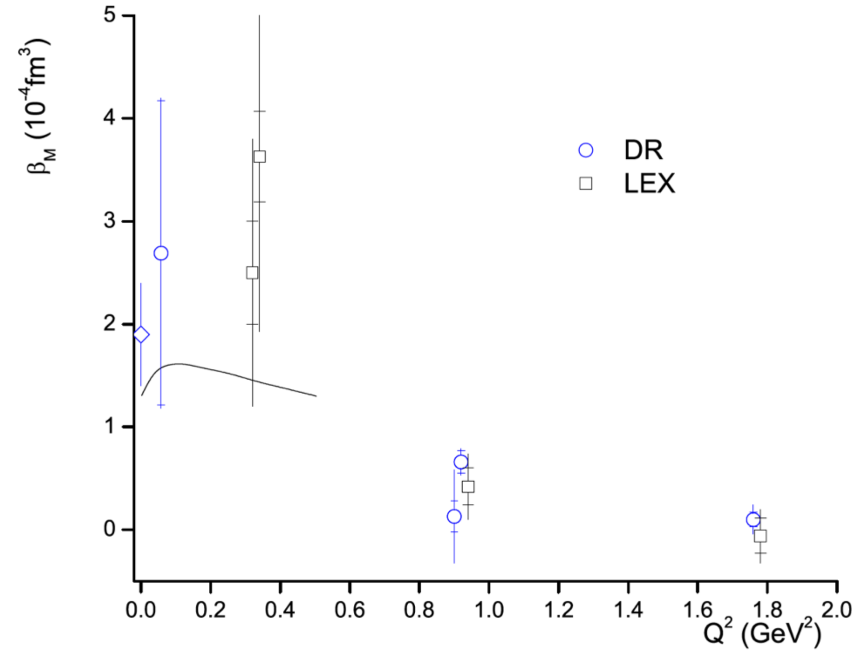
scalar GPs α_E and β_M

Early GP 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)





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

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

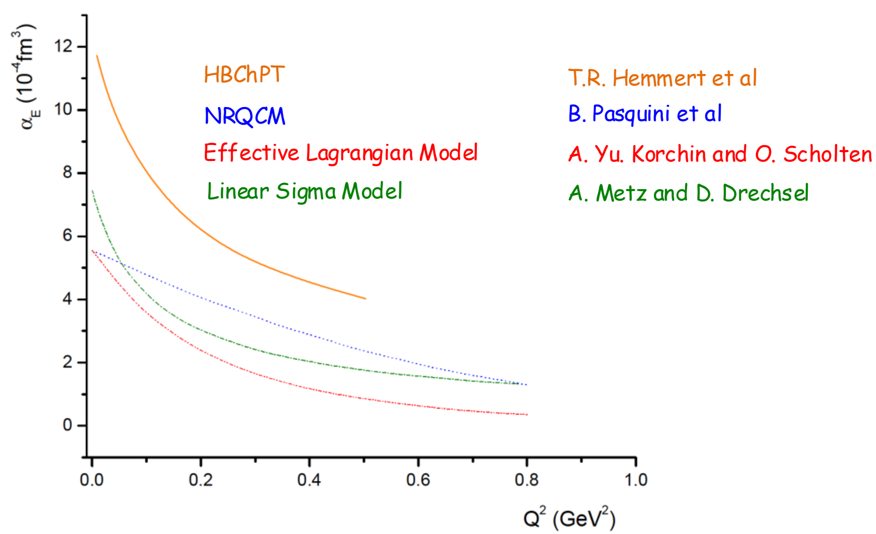
Theory: monotonic fall-off

β_M small ←→ cancellation of competing mechanisms

Large uncertainties

Higher precision measurements needed

➔ Quantify interplay between dia/para-magnetism

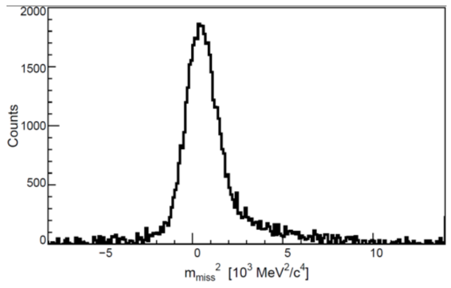


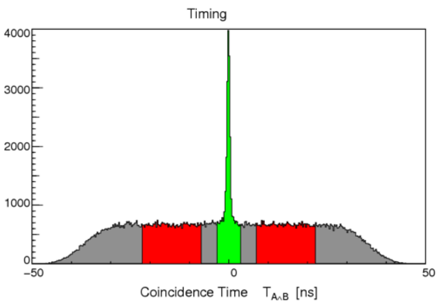
Recent Experiments

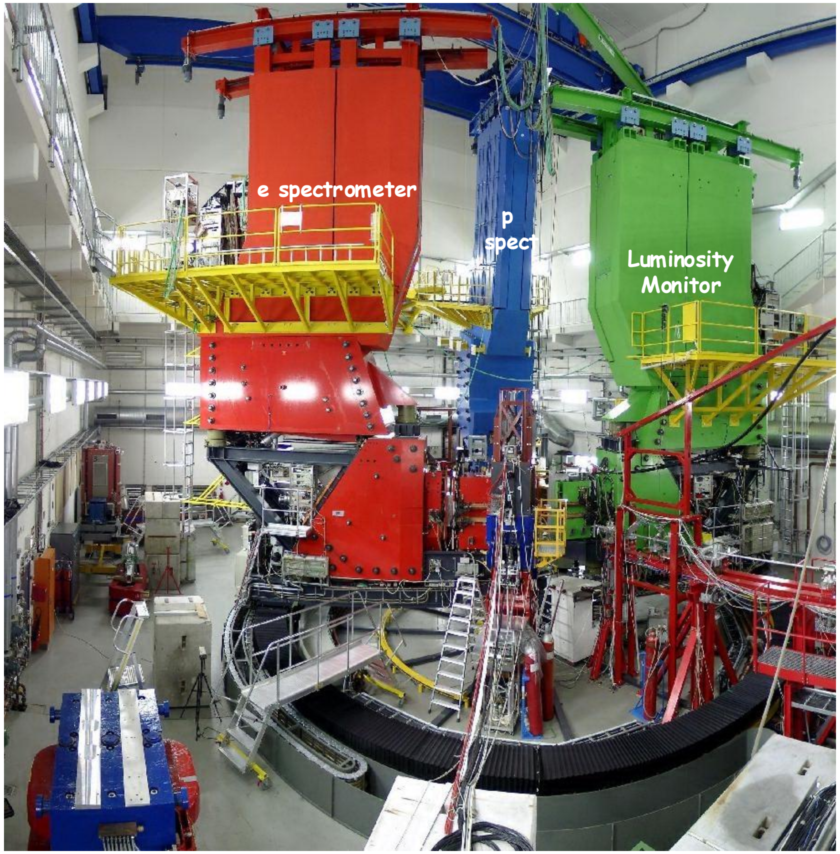
MAMI A1/1-09 (vcsq2) below threshold

MAMI A1/3-12 (vcsdelta) above threshold

Both experiments utilized the A1 setup at MAMI







A1/1-09 @ MAMI

~ 1.0 GeV beam

Q^2 = 0.1 $(GeV/c)^2$, 0.2 $(GeV/c)^2$, and 0.45 $(GeV/c)^2$

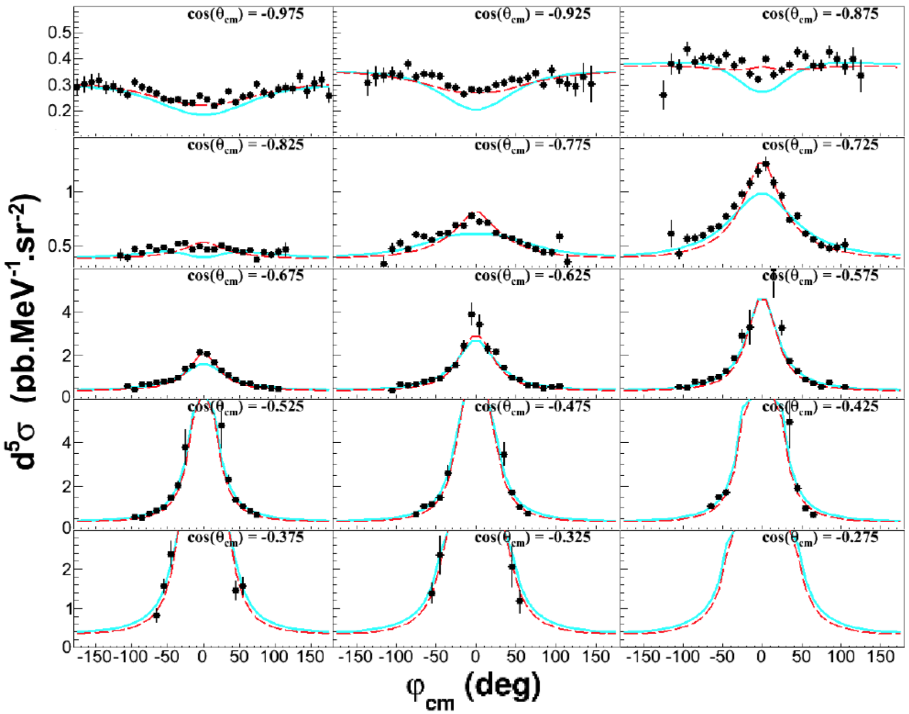


Figure 5.8: Setting INP: measured $ep \to ep\gamma$ cross section at fixed q'_{cm} = 112.5 MeV/c with respect to φ_{cm} for all the $cos(\theta_{cm})$-bins. The curves follow the convention of figure 5.6.

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

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

A1/1-09 @ MAMI

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

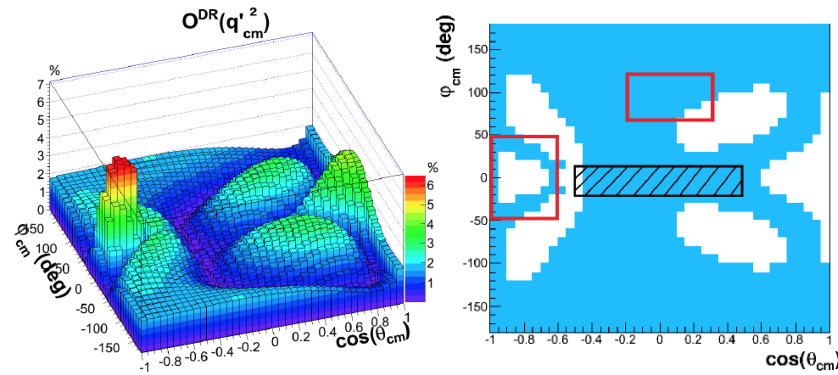
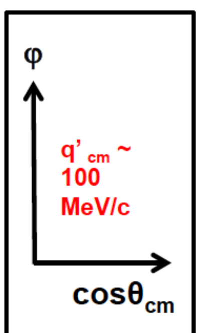
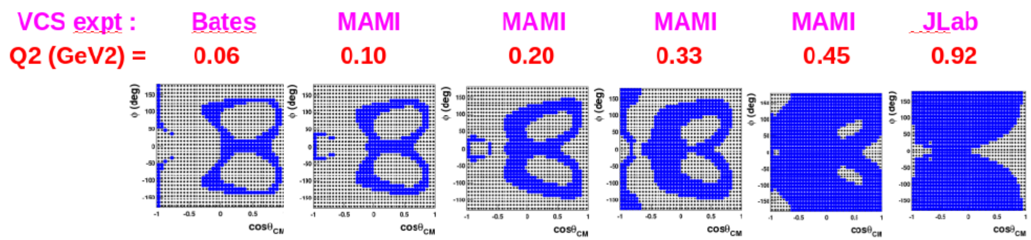


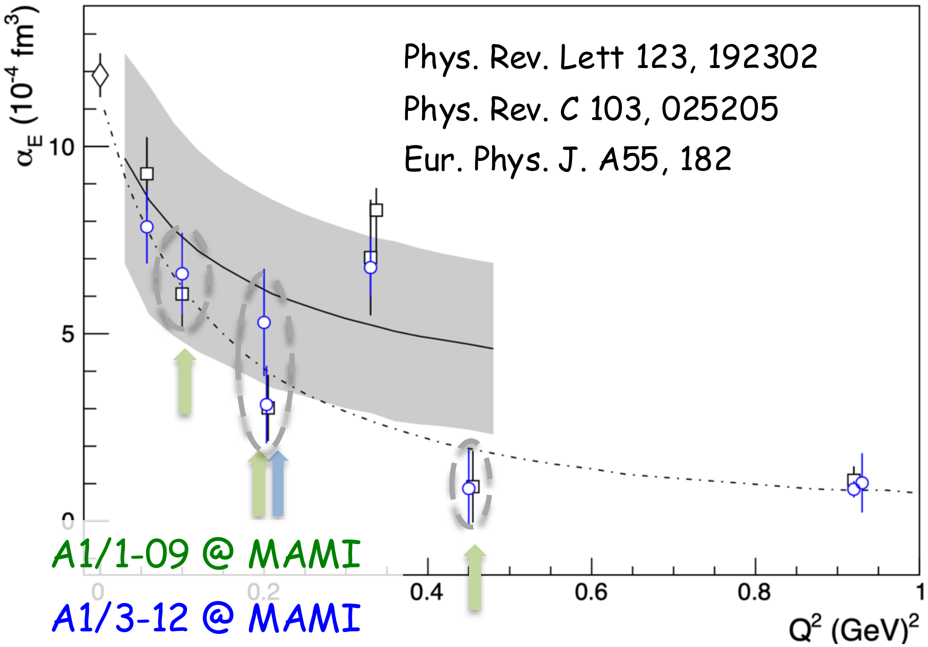
Figure 3.13: (Left) behavior of $\mathcal{O}^{DR}({q'_{cm}}^2)$ in the $(cos(\theta_{cm}),\varphi_{cm})$-plane at $q'_{cm} = 87.5\ MeV/c$ and (right) two-dimensional representation of the angular region where $\mathcal{O}^{DR}({q'_{cm}}^2) < 2\%$ (blue), the red squares correspond to the two areas of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

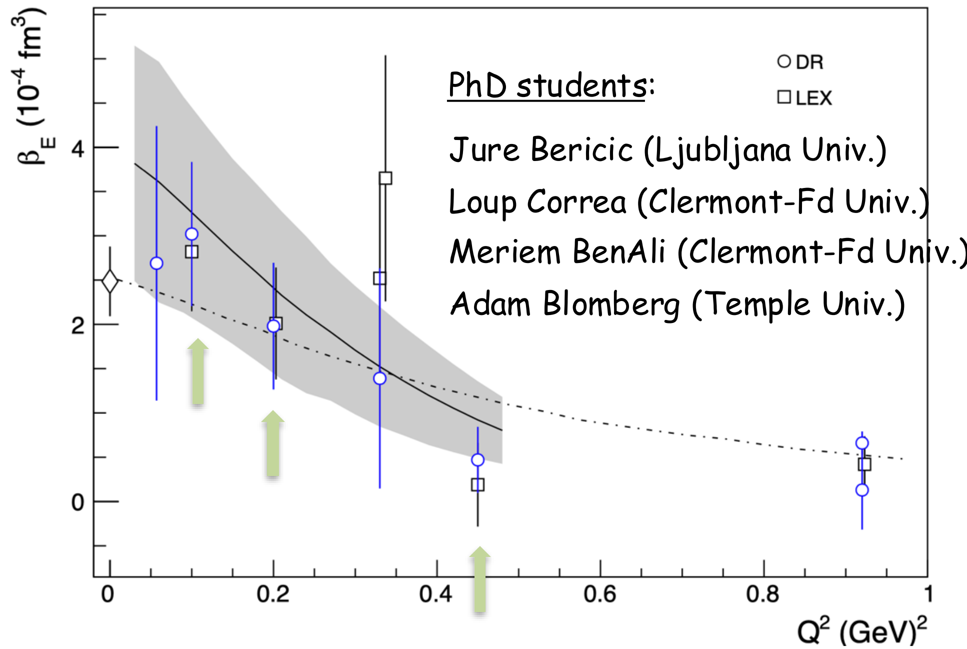
Blue bins = where the higher-order estimator is < 3% (LEX truncation « valid »)



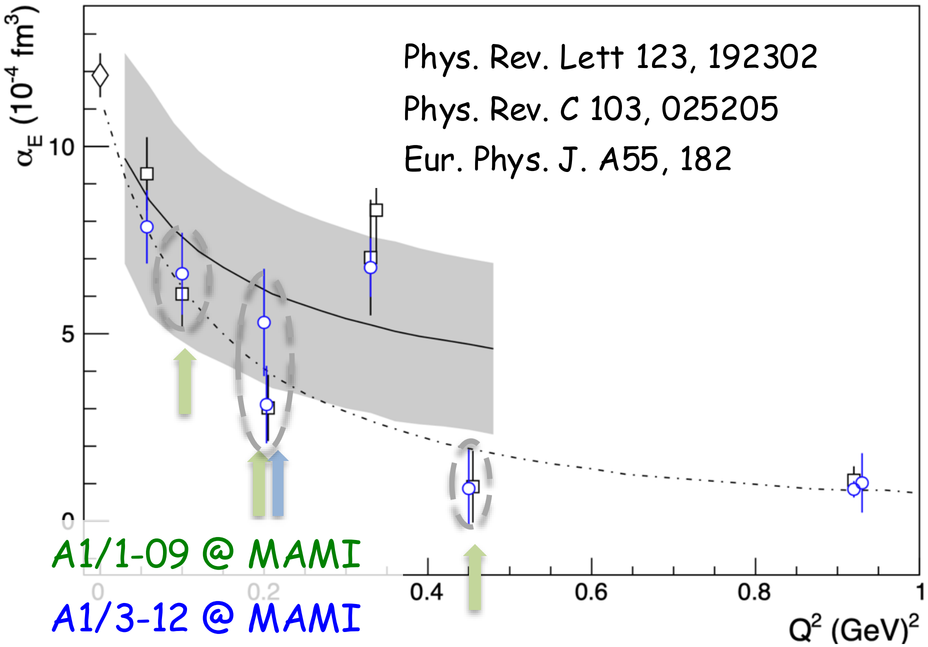


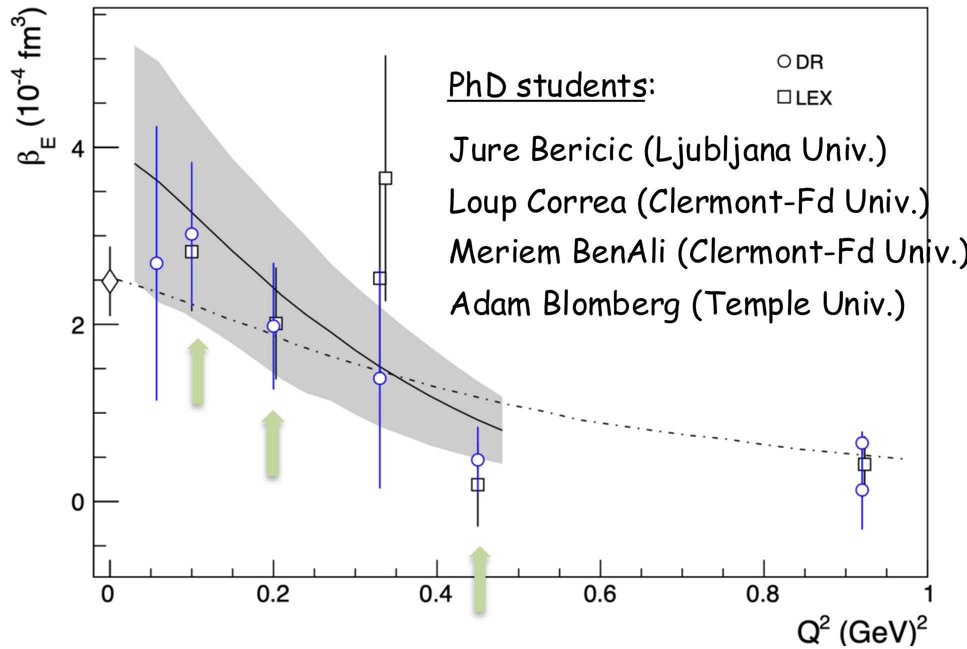
MAMI Results





MAMI Results

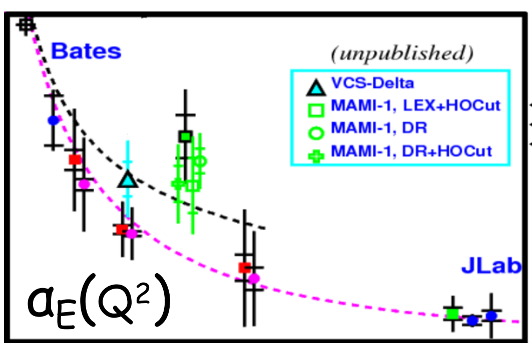




Revisiting the early MAMI data

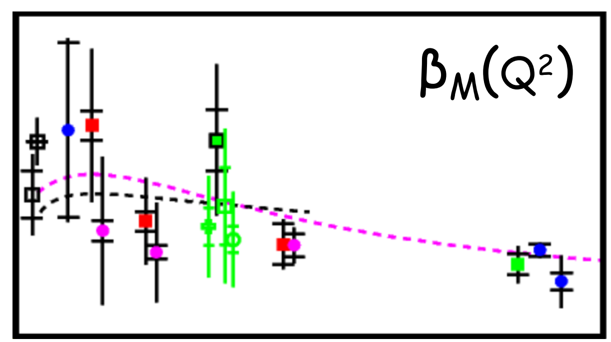
Analysis revisited at Q^2=0.33 GeV^2 (unpublished):

The α_E puzzle still holds



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

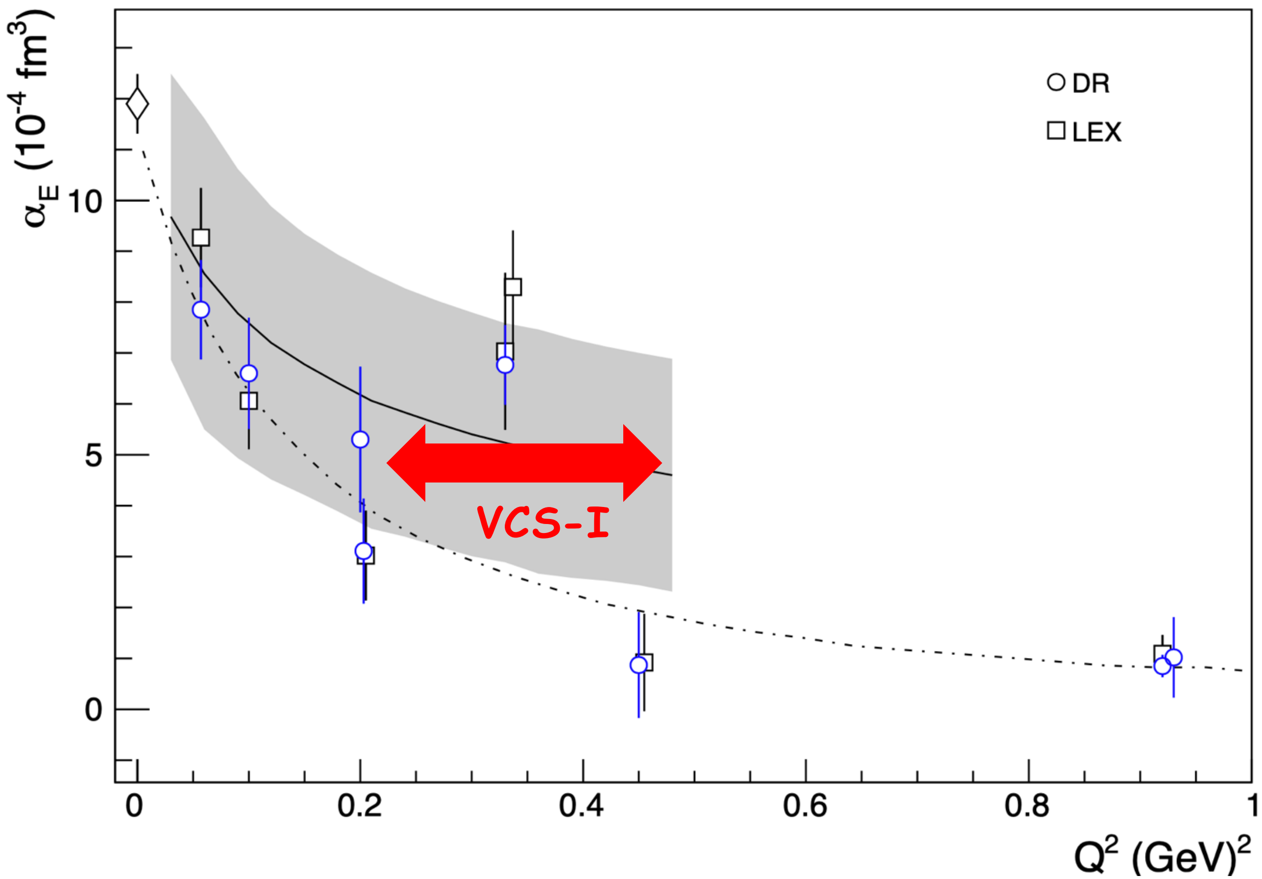
LEX and DR
Updated HO-cut



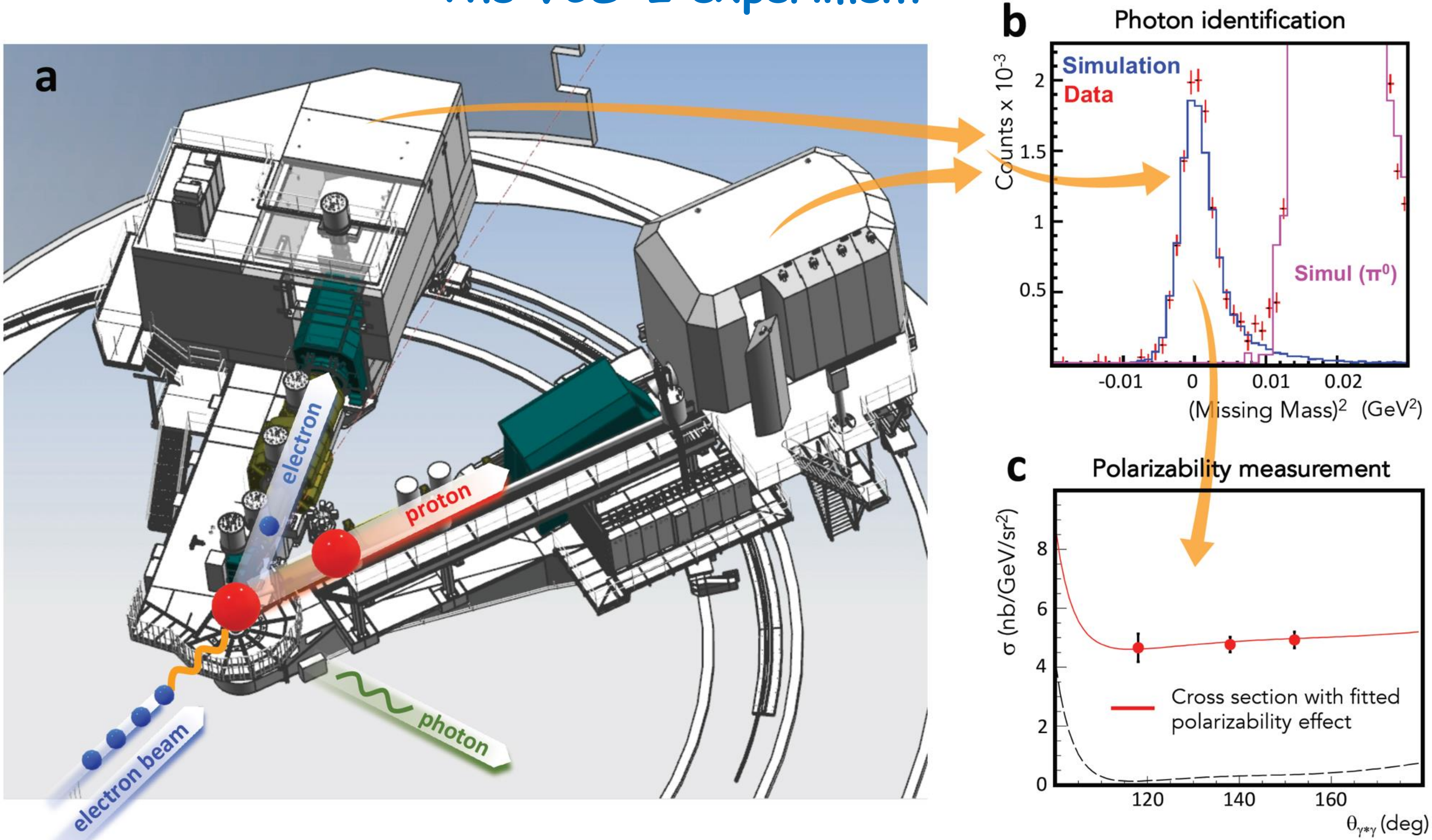
Jefferson Lab

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

High precision measurements targeting
explicitly the kinematics of interest for α_E



The VCS-I experiment



Hall C: SHMS, HMS

4.56 GeV

20 μA

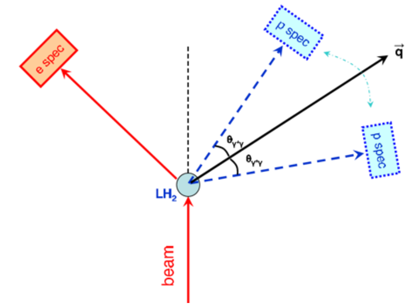
Liquid hydrogen 10 cm

cross sections & azimuthal asymmetries

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

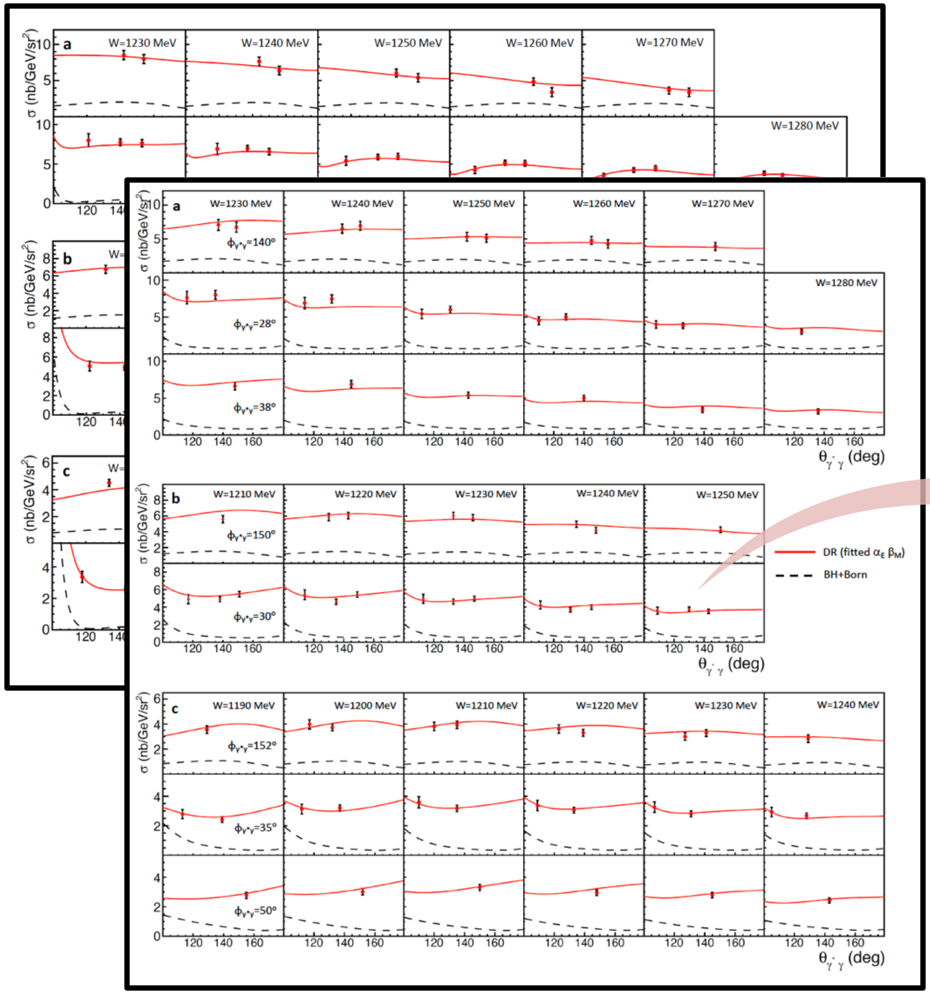
sensitivity to GPs

suppression of systematic asymmetries

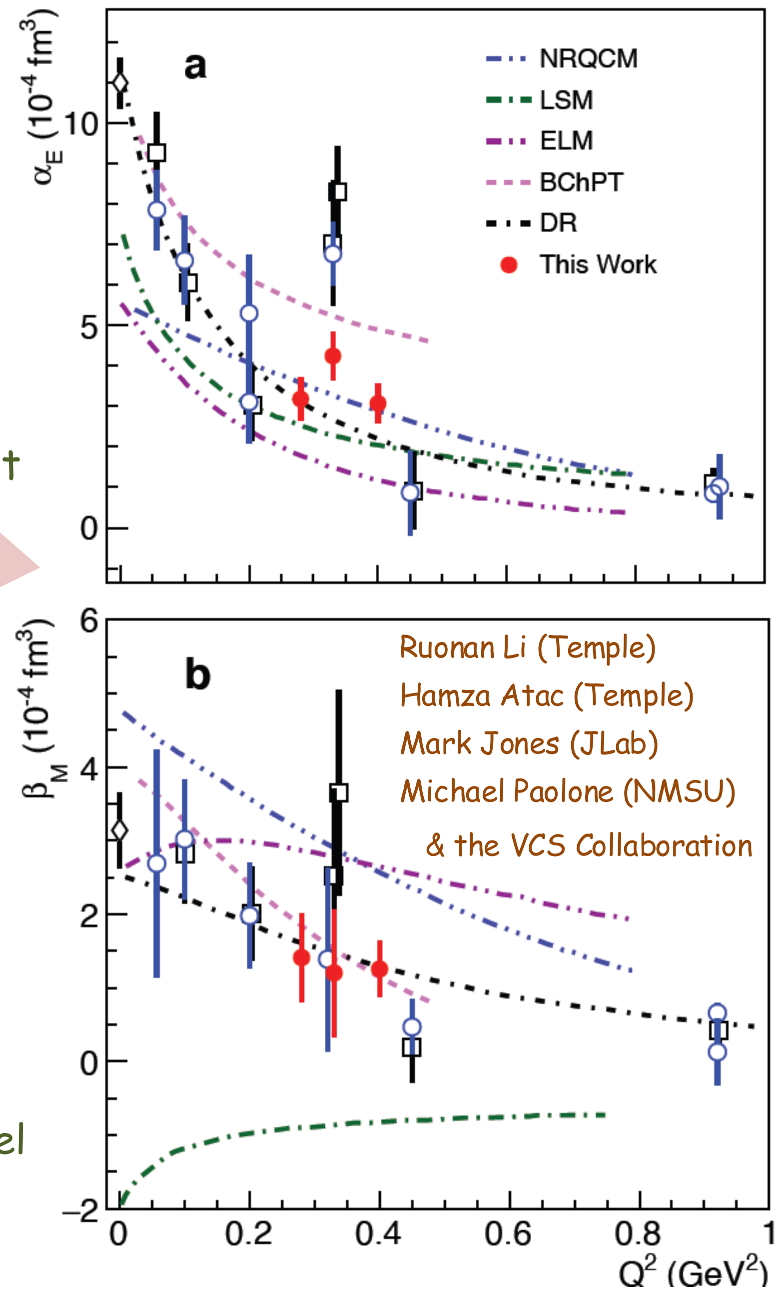


VCS-I results

Nature 611, 265 (2022)



DR fit

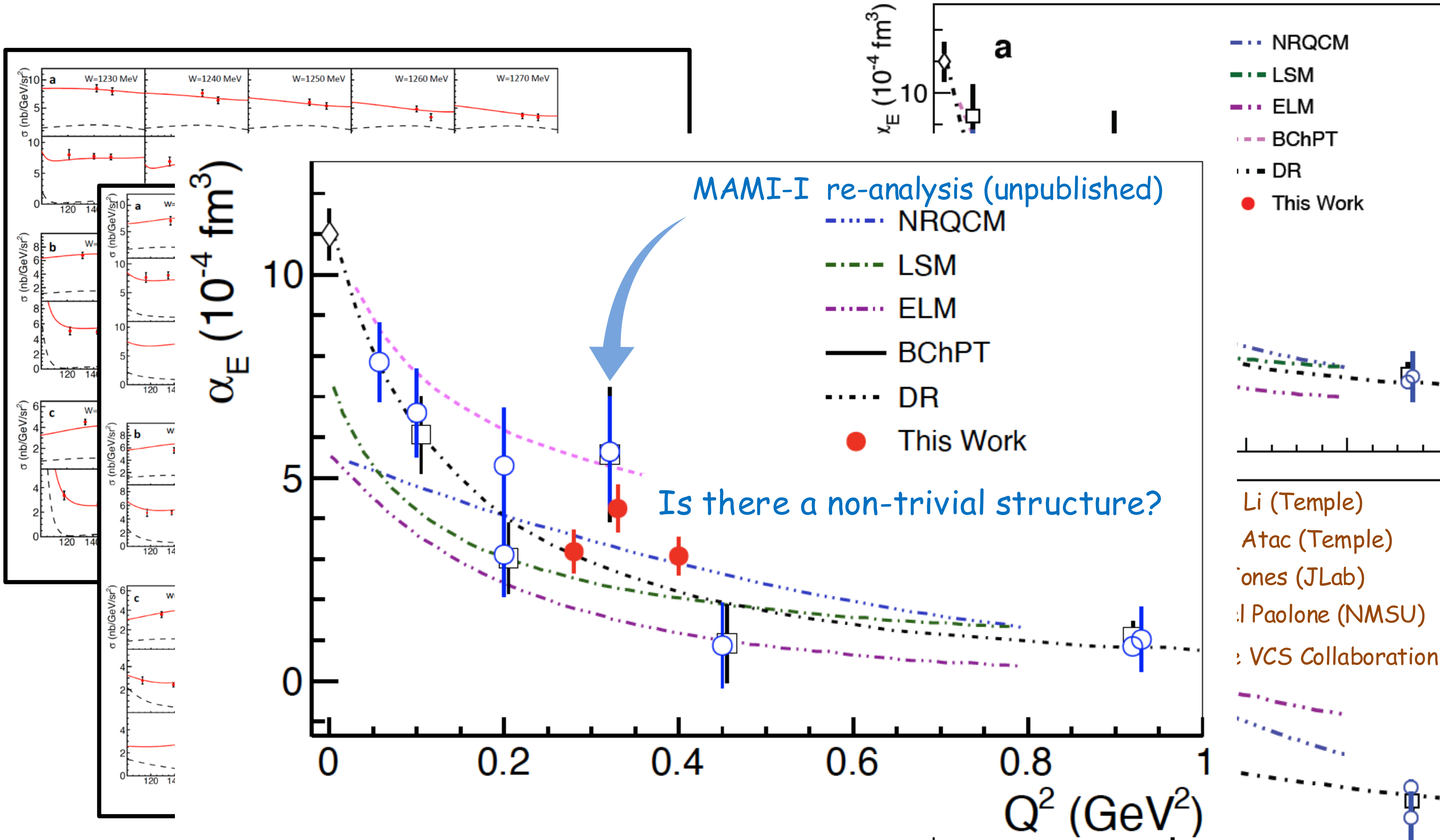


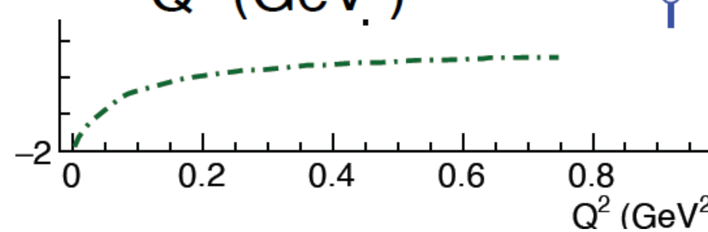
Experimental cross sections are compared to the DR model predictions for all possible values for the GPs

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

VCS-I results

Nature 611, 265 (2022)

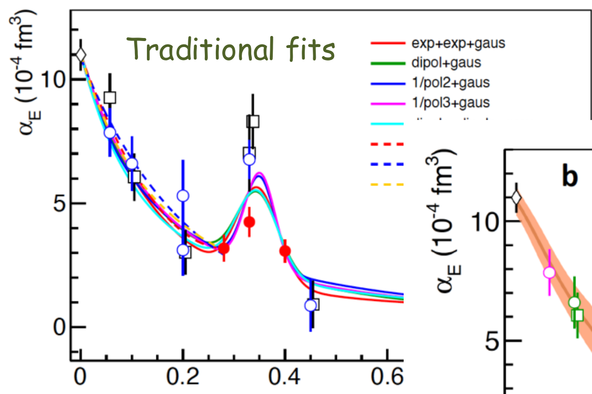




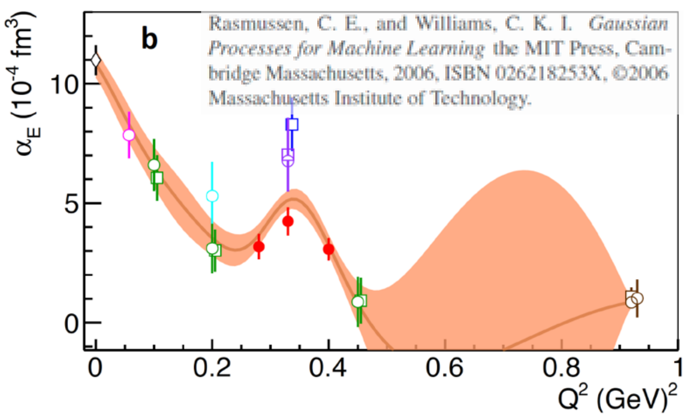
Experimental cross sections are compared to the DR model predictions for all possible values for the GPs

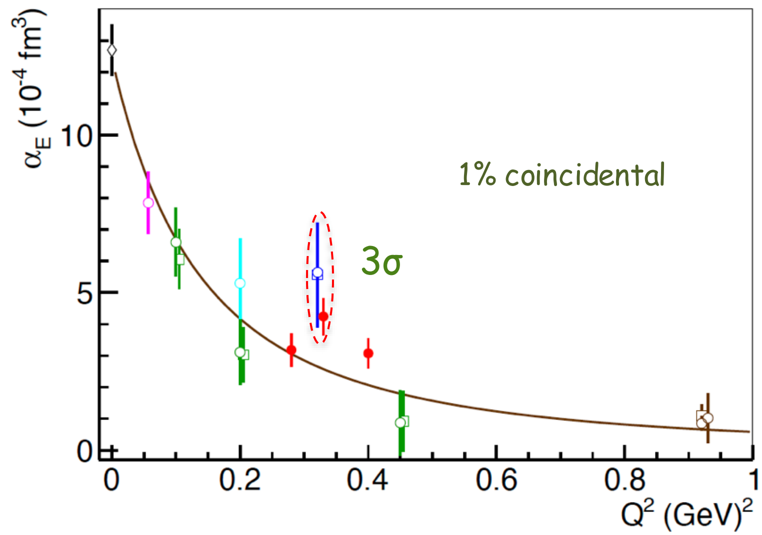
→ $\alpha_E(Q^2)$ and $\beta_M(Q^2)$ are fitted by a χ^2 minimization

Electric GP



Data-driven techniques:
no underlying functional
form is assumed





Is the observed α_E structure coincidental or not?

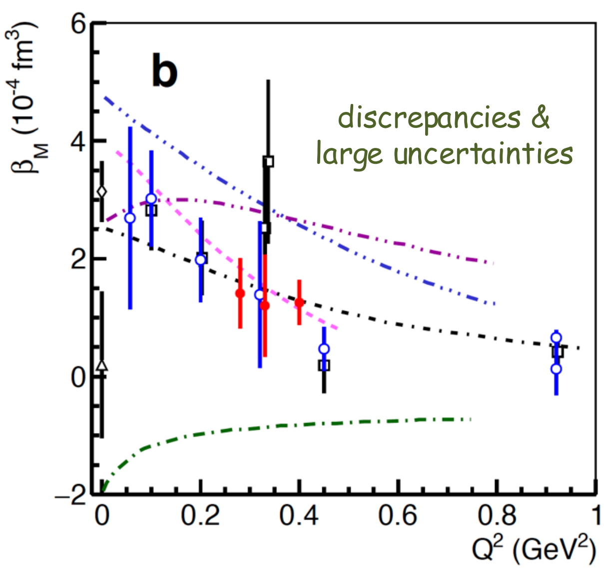
If true: Measure the shape precisely → input to theory

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

Strong tension between world data (?)

Things we do not yet understand well?
Underestimated uncertainties? ...

Magnetic GP



Magnetic GP: Large uncertainties & discrepancies

Disentangle para/dia-magnetism in the proton

Ability to measure α_E and β_M with superb precision
and with consistent systematics across Q^2

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

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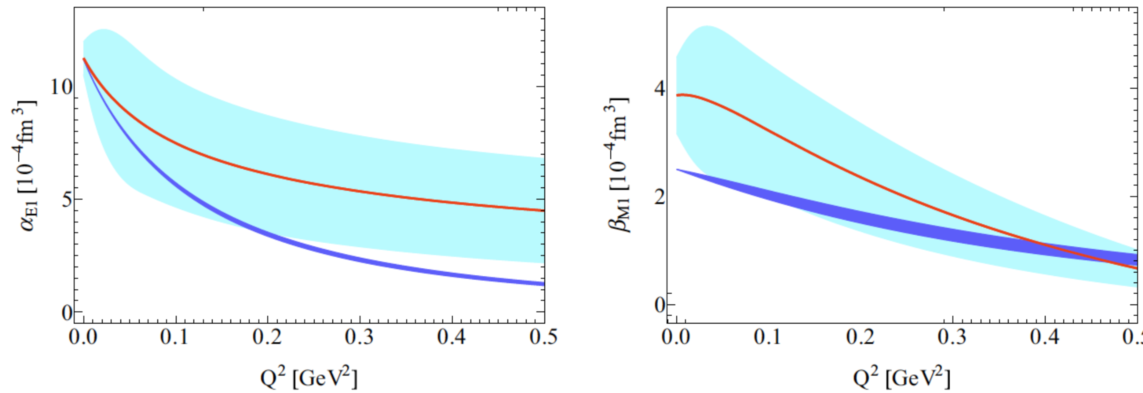
[2] Institute for Theoretical and Experimental Physics, Moscow 117218, Russia
[3] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow 115409, Russia

BχPT calculation to NLO in the δ-counting scheme

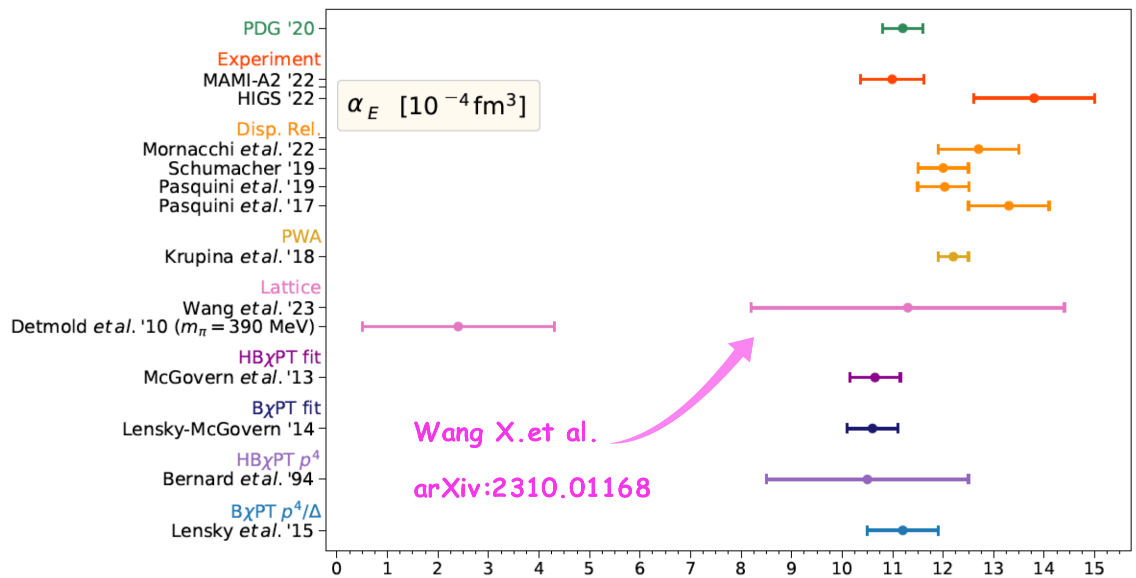
DR calculation
D. Drechsel, B. Pasquini, M. Vanderhaeghen, Phys. Rep. 378,99 (2003)



Theory: Lattice QCD

Lattice QCD results for the static polarizabilities

Next step: Lattice QCD calculations for the GPs



Analysis of the resonance contributions to the low-energy behavior of $\alpha_E(Q^2) + \beta_M(Q^2)$ within holographic QCD

Nucleon electric and magnetic polarizabilities in Holographic QCD

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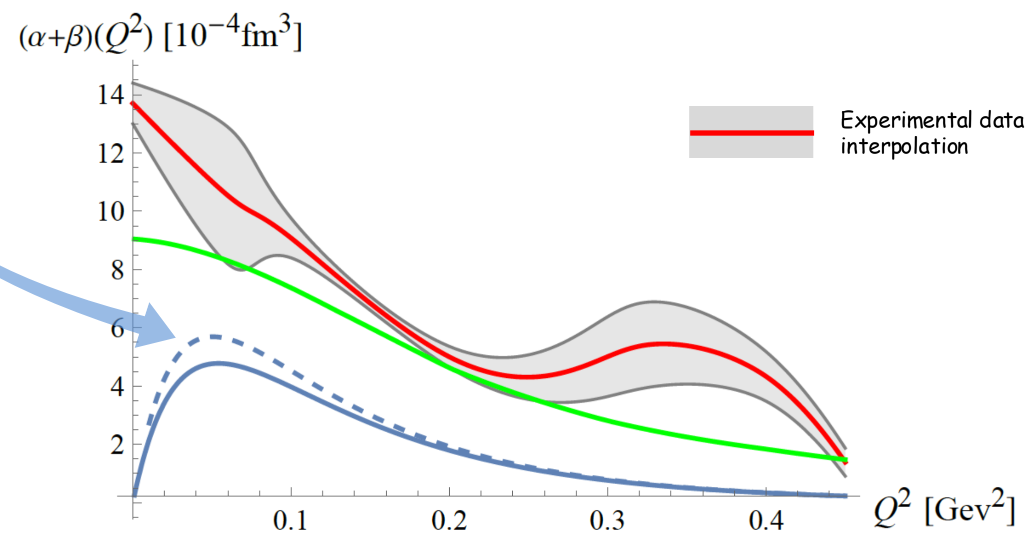
ABSTRACT: Novel experimental results for the proton generalized electric polarizability, suggest an unexpected deviation from current theoretical predictions at low momentum transfer squared Q^2. Motivated by this puzzle, we analyze the resonance contributions to the sum of the generalized electric and magnetic nucleon polarizabilities $\alpha_E(Q^2)$ and $\beta_M(Q^2)$, within the Holographic QCD model by Witten, Sakai, and Sugimoto (WSS). In particular, we account for the contributions from the first low-lying nucleon resonances with spin 1/2 and 3/2 and both parities. After having extrapolated the WSS model parameters to fit experimental data on baryonic observables, our findings suggest that the resonance contributions alone do not solve the above-mentioned puzzle. Moreover, at least for the proton case, where data are available, our results are in qualitative agreement with resonance contributions extracted from experimental nucleon-resonance helicity amplitudes.

Resonance contributions follow a smooth Q^2 dependence



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:

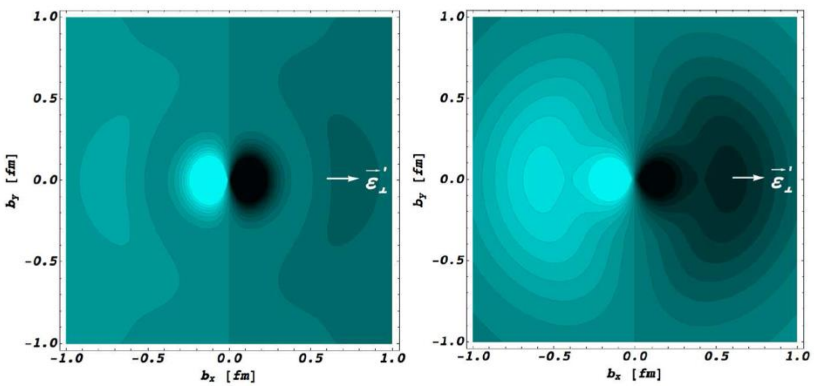
GPs ➔ spatial deformation of charge & magnetization densities under an applied e.m. field

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

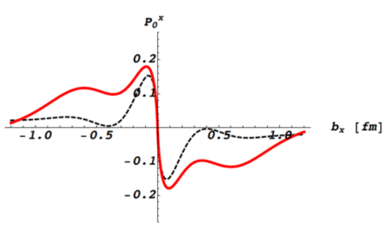
Phys. Rev. Lett. 104, 112001 (2010)

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

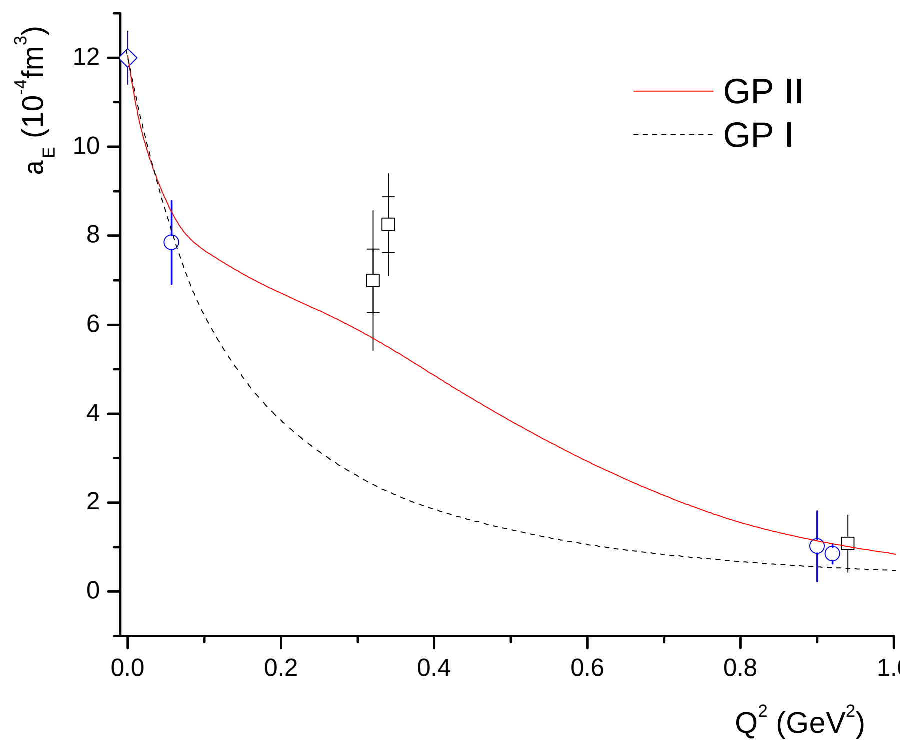
GP I GP II



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



Induced polarization along b_y=0



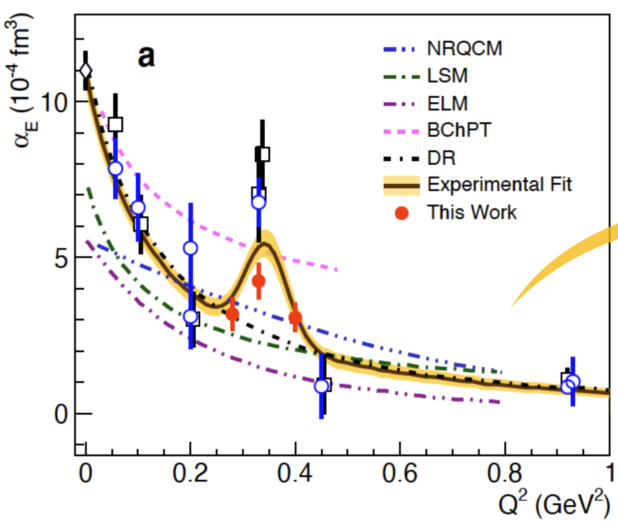
Spatial dependence of induced polarizations

Nucleon form factor data ➔ light-front quark charge densities

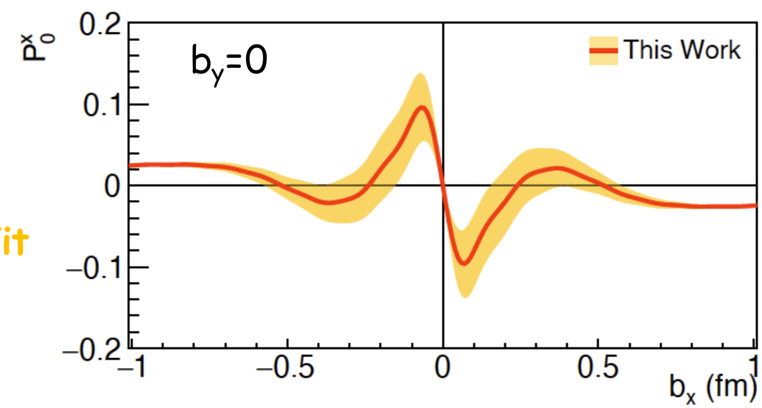
Formalism extended to the deformation of these quark densities when applying an external e.m. field:

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



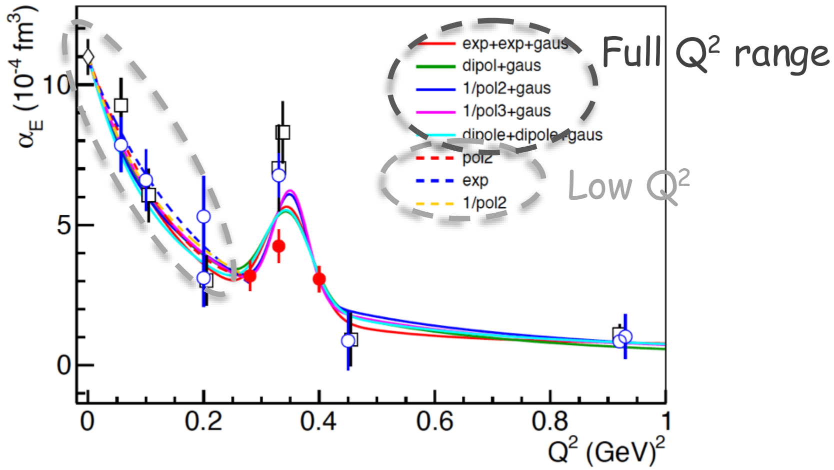
Experimental Fit

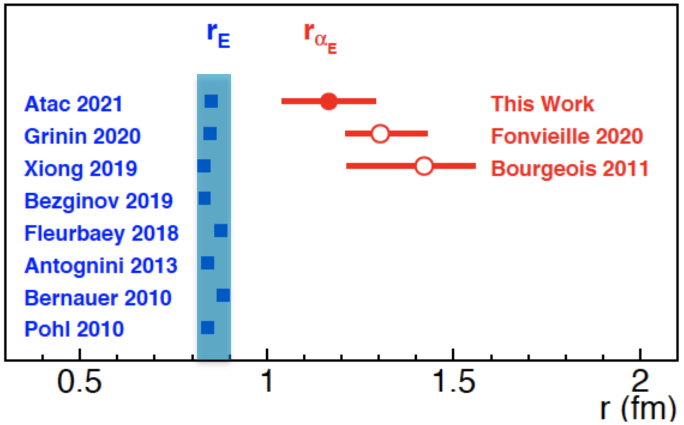


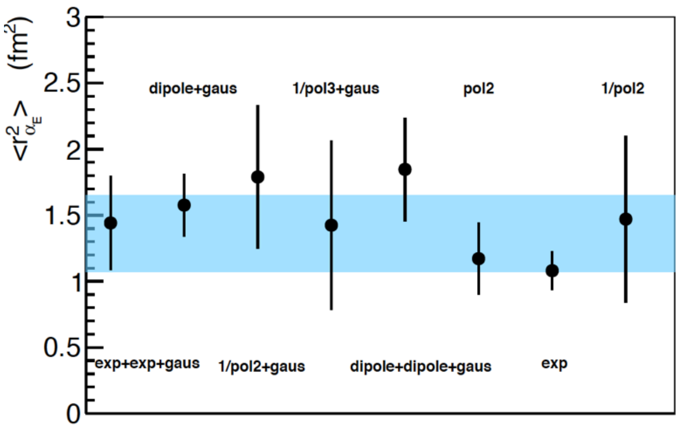
x-y defines the transverse plane with the z-axis being the direction of the fast-moving proton

Polarizability radii

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





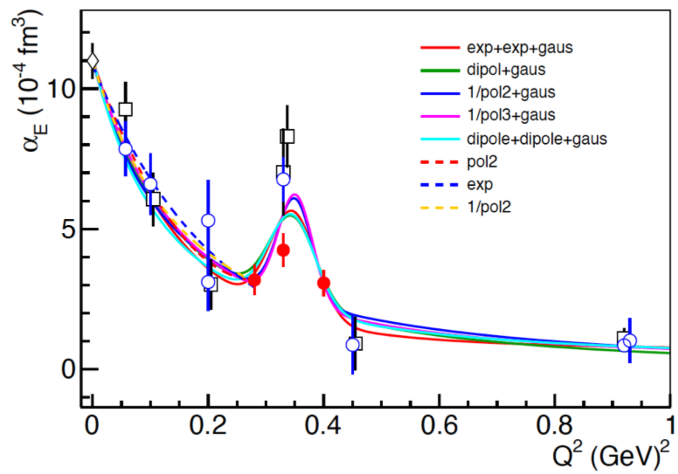


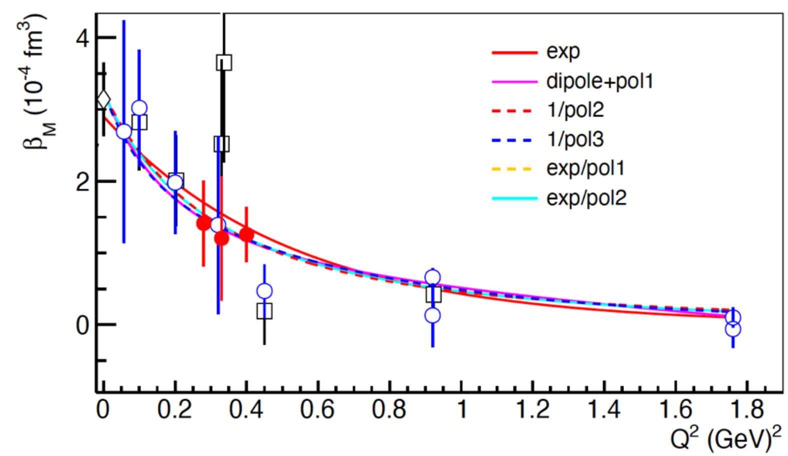
$$\langle r^2_{\alpha_E} \rangle = 1.36 \pm 0.29 \text{ fm}^2$$

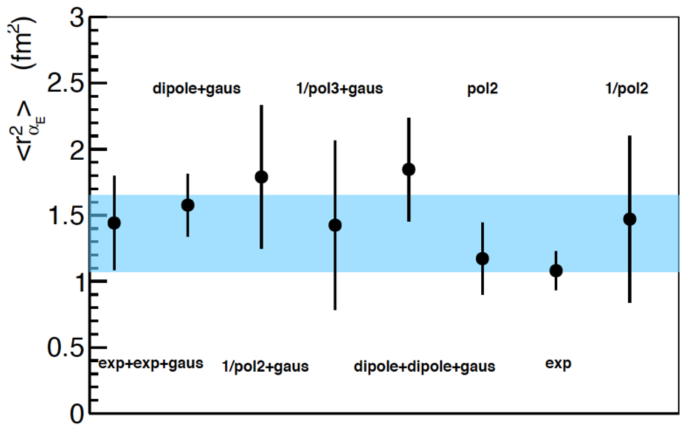
Polarizability radii

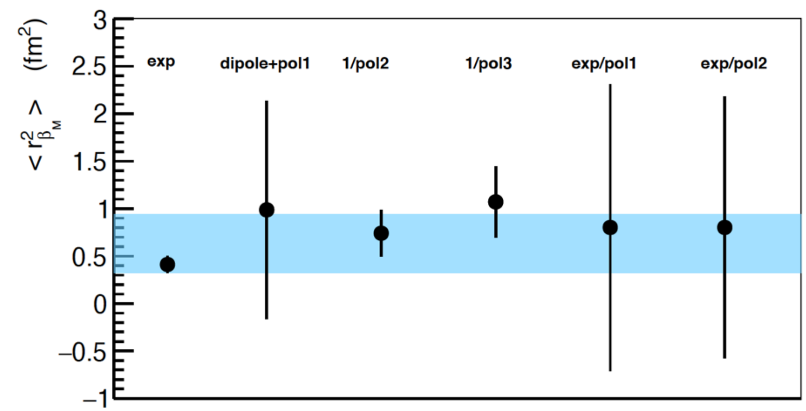
$$\langle r^2_{\alpha_E}\rangle = \frac{-6}{\alpha_E(0)}\cdot\frac{d}{dQ^2}\alpha_E(Q^2)\Big|_{Q^2=0}$$

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









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

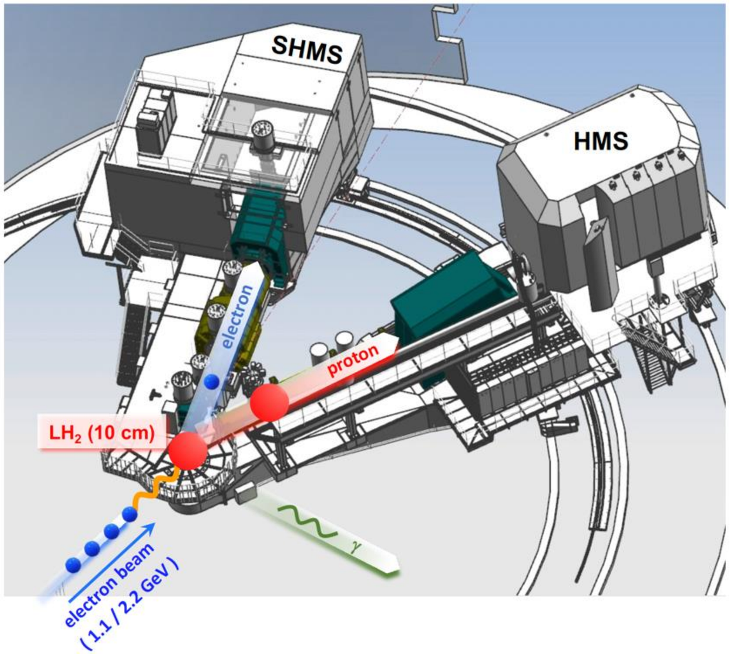
$$\langle r^2_{\beta_M}\rangle = 0.63 \pm 0.31\ \mathrm{fm}^2$$

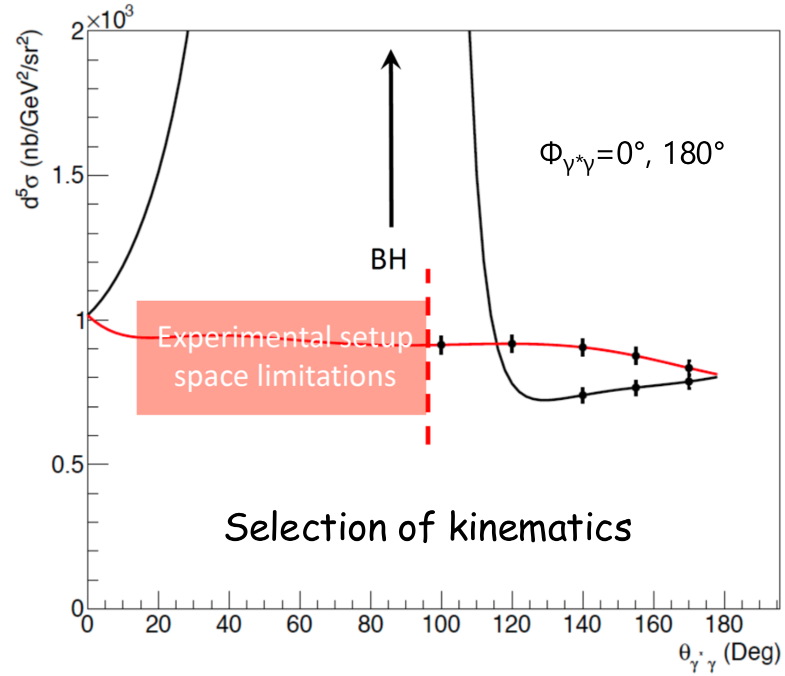
Upcoming Experiments

and prospects

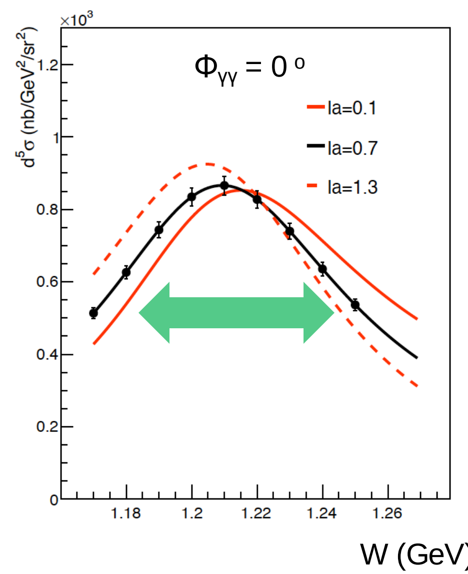
with positron & polarized electron beams

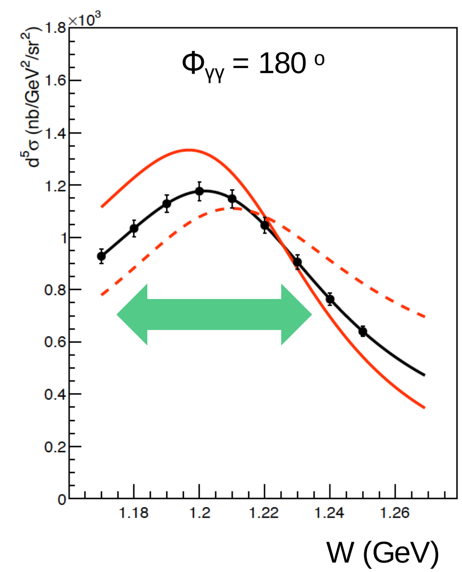
VCS-II (E12-23-001) @ JLab





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





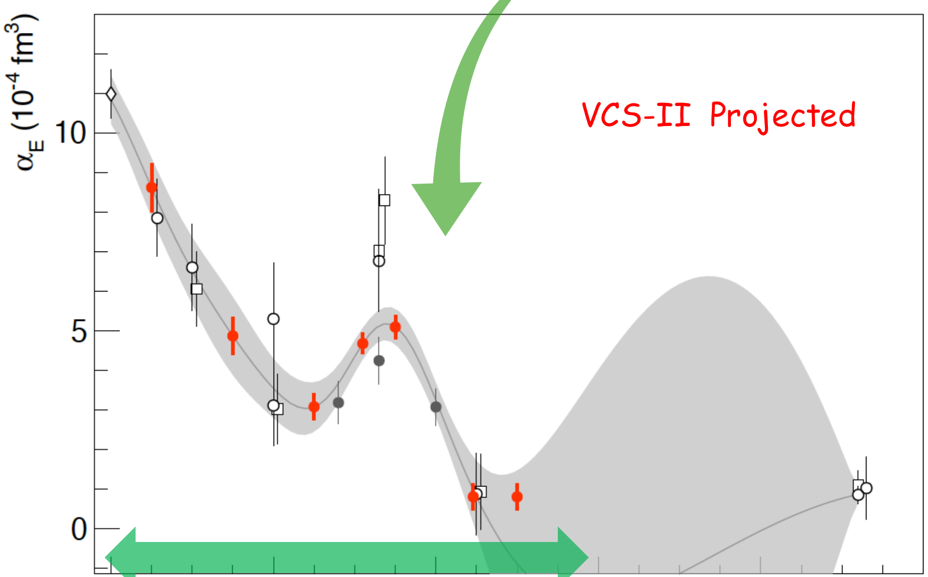
Production (E_o = 1.1 GeV) :	6 days
Production (E_o = 2.2 GeV) :	53 days
Studies (optics/dummy/calibrations) :	3 days

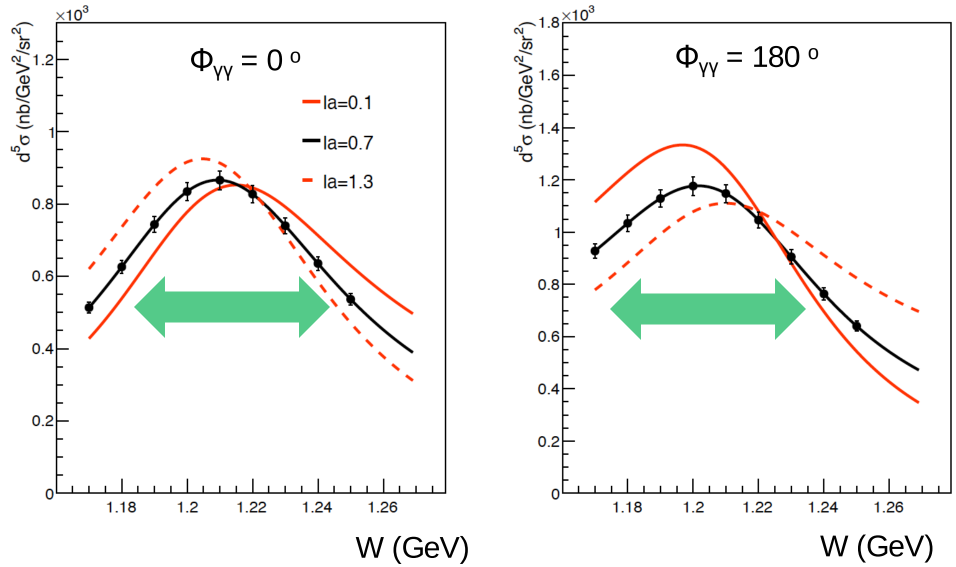
Total: 62 days

VCS-II Projected Measurements

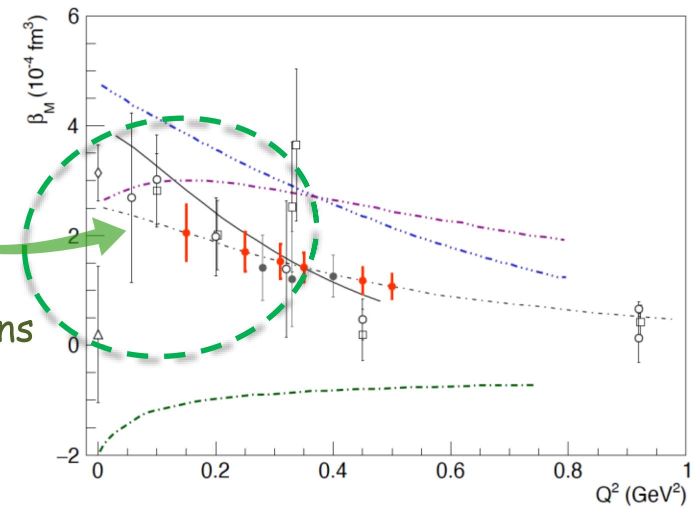
High precision measurements combined with a fine mapping in Q^2

Targeted measurements to fully exploit the sensitivity to the GPs





systematically consistent measurements throughout Q^2



Improve upon β_M :

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

Scheduled to acquire data from February – July 2026

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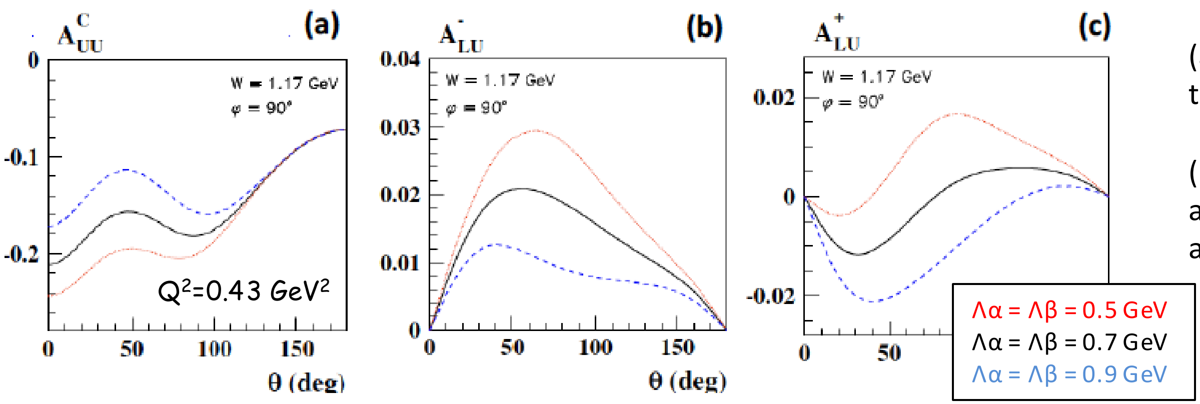
[1]Dipartimento di Fisica, Università degli Studi di Pavia, 27100 Pavia, Italy
[2]Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, 27100 Pavia, Italy
[3]Institut für Kernphysik and PRISMA+ Cluster of Excellence, Johannes Gutenberg Universität, D-55099 Mainz, Germany



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

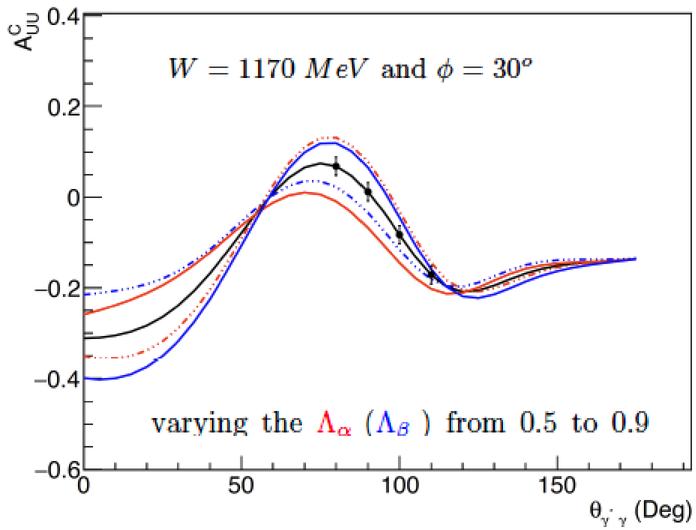
(b) & (c): The electron and positron beam-spin asymmetry as a function of the photon scattering angle for out-of-plane kinematics.

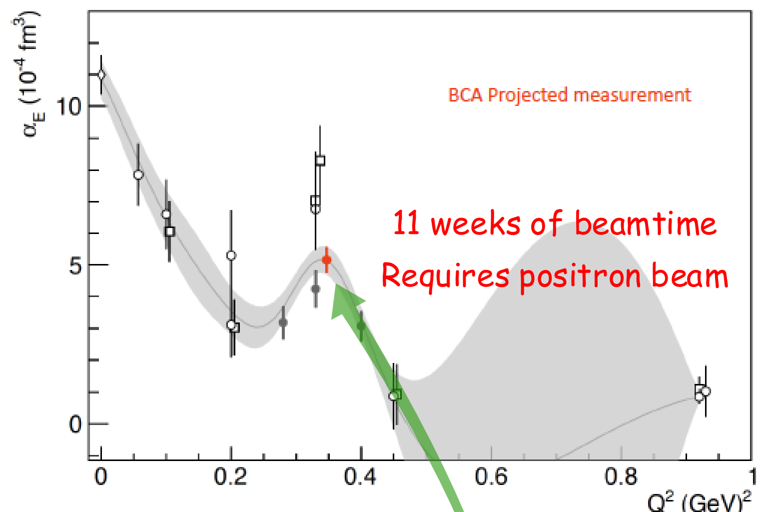
Unpolarized beam charge asymmetry (BCA) : $A^C_{UU} = \frac{(d\sigma^+_+ + d\sigma^+_-) - (d\sigma^-_+ + d\sigma^-_-)}{d\sigma^+_+ + d\sigma^+_- + d\sigma^-_+ + d\sigma^-_-}$

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

BCA (electrons & positrons)

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)

BCA measurements offer superb precision!!

e^- : ~ 1 week @ 50 μA

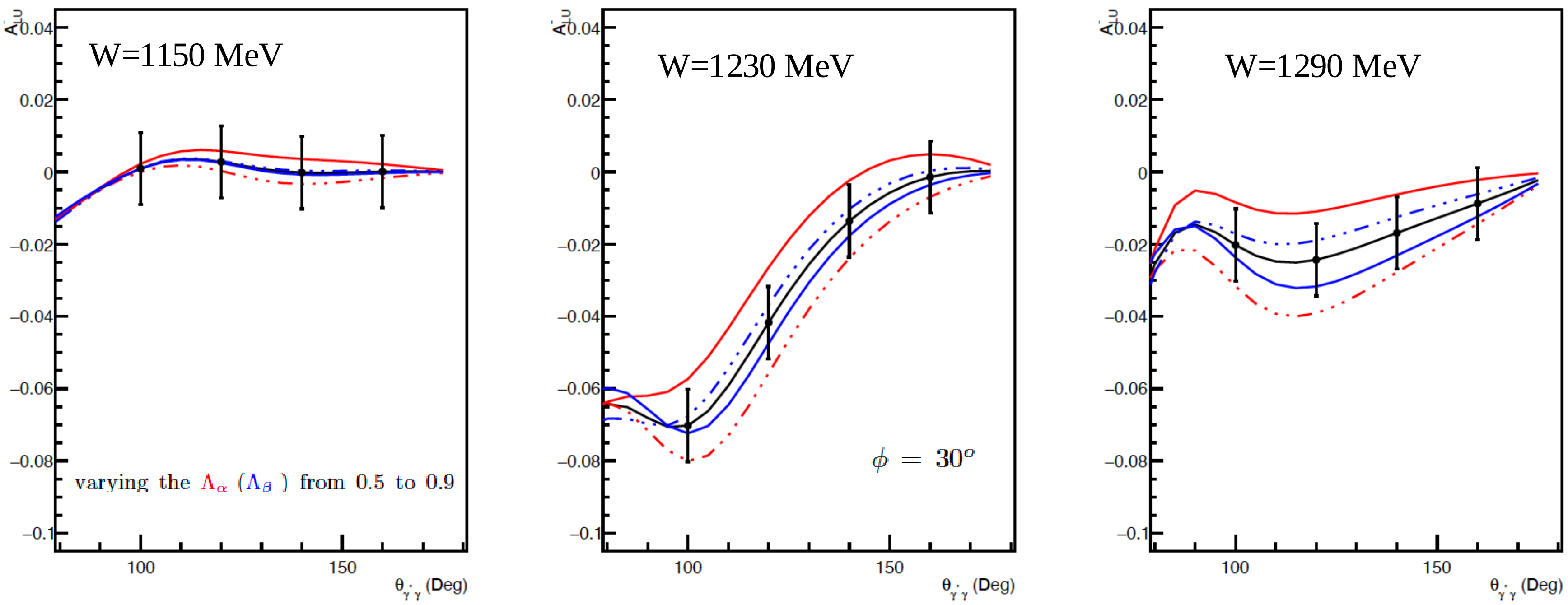
and

e^+ : ~ 10 weeks @ ~ μA

BSA (electrons or positrons)

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

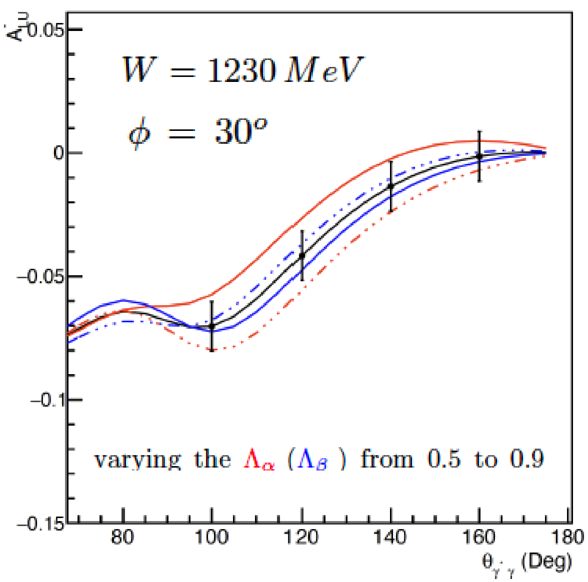
electrons

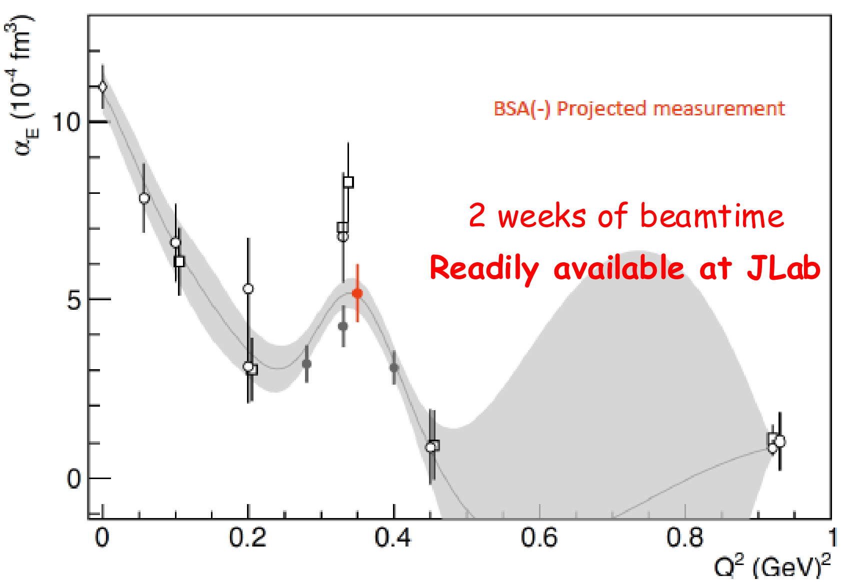


Projected measurements with SHMS / HMS

BSA (electrons or positrons)

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



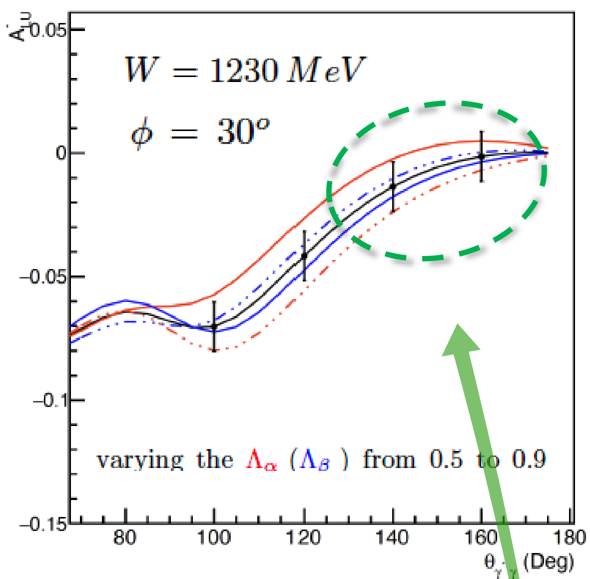


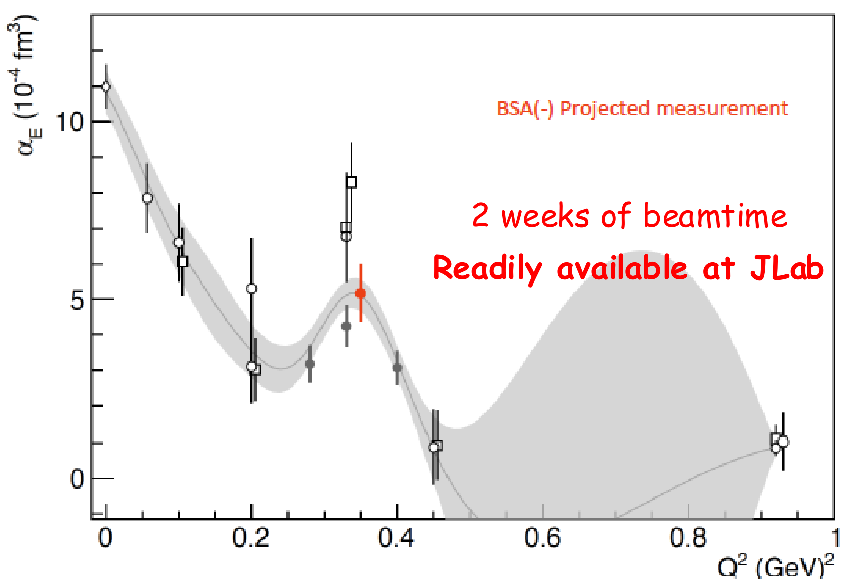
e^- (pol. 85% @ 70 μA)

~ 2 weeks of beamtime

BSA (electrons or positrons)

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





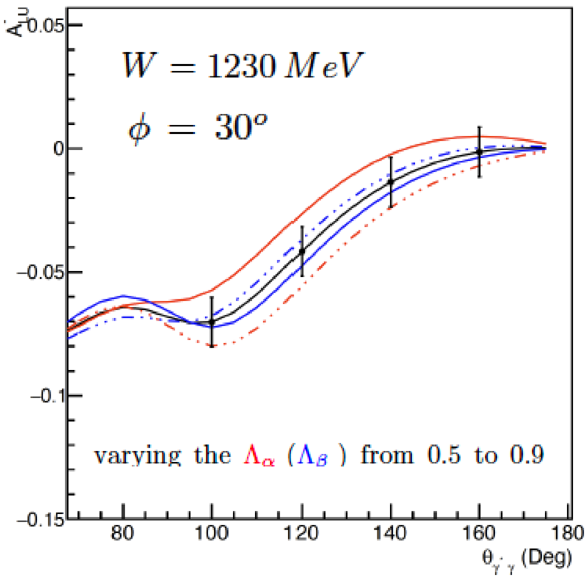
e^- (pol. 85% @ 70 μA)

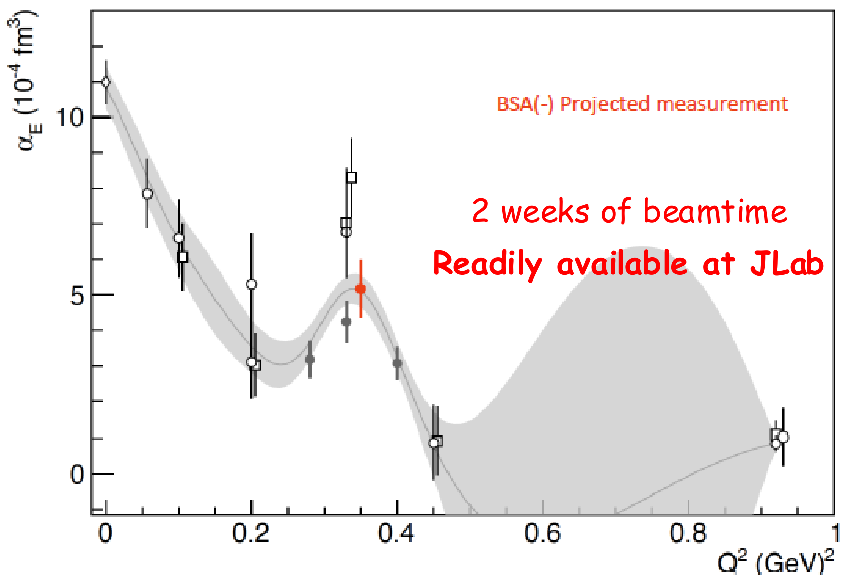
~ 2 weeks of beamtime

Can take advantage of the VCS-II beam-time (2026)
for part of the kinematics that overlap
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)

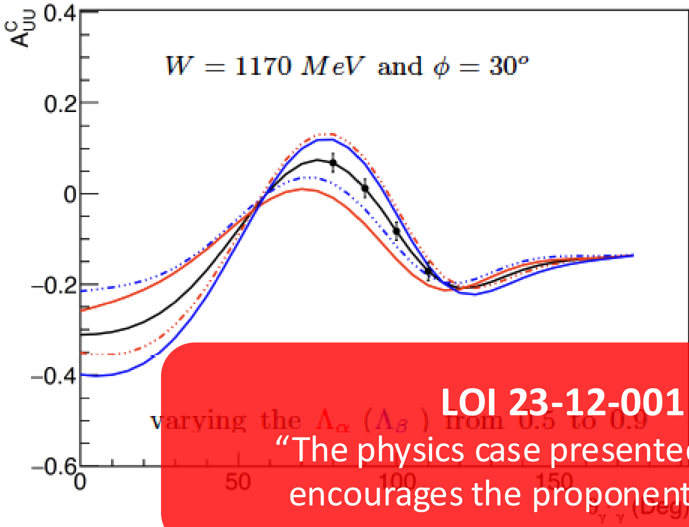
~ 2 weeks of beamtime

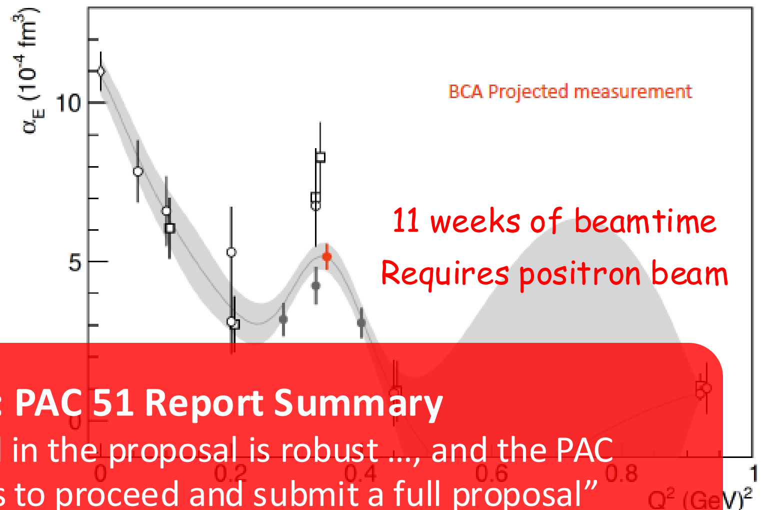
or

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

~ 3 orders of magnitude more beamtime

BCA (electrons & positrons)





Hall C (SHMS / HMS)

e^- : ~ 1 week @ 50 μA

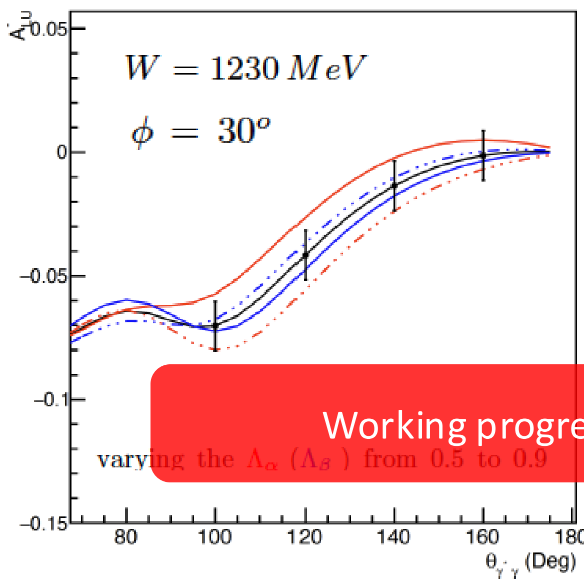
and

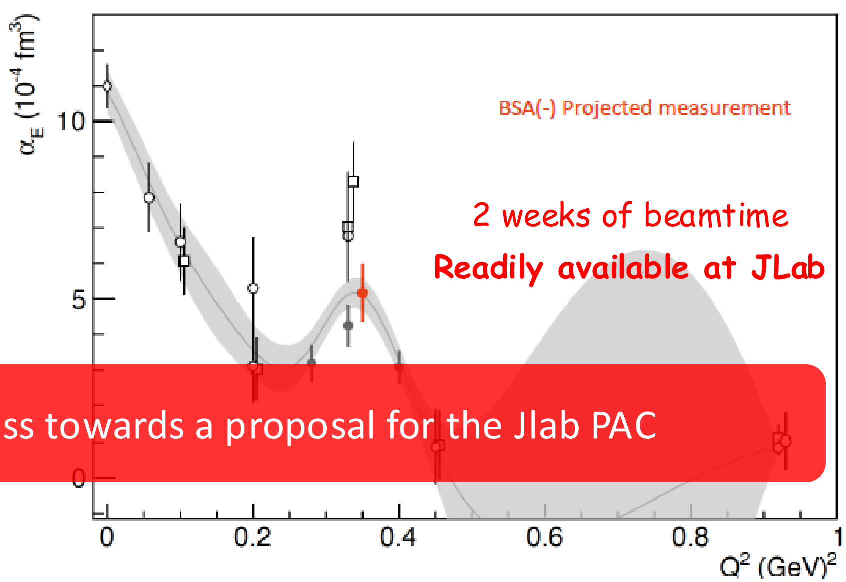
e^+ : ~ 10 weeks @ 5 μA

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"

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~~

Working progress towards a proposal for the Jlab PAC
~~~

Summary

GPs : fundamental properties of the proton

Insight to spatial deformation of the nucleon densities under an applied EM field,
polariz. mechanisms / 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:

Vibrant experimental program at JLab is ongoing

Stringent experimental constraints to theoretical predictions & benchmark data for LQCD

Theoretical challenges

Future experiments:

Pin down the shape of the α_E structure (if it exists?)
& provide important input for the theory

BS asymmetries & positrons provide a powerful path
to measure via a different experimental channel and
conduct an independent cross-check

Thank you!