The Generalized Polarizabilities of the proton

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Proton Polarizablities

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

Response of internal structure
& dynamics to external EM field

Sensitive to the full excitation
spectrum of the nucleon

Accessed experimentally through
Compton Scattering processes

Virtual Compton Scattering:

Virtuality of photon gives access to the Generalized Polarizabilities $\alpha_E(Q^2)$ & $\beta_M(Q^2)$

➔ mapping out the spatial distribution of the polarization densities

PDG

150 Baryon Summary Table

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

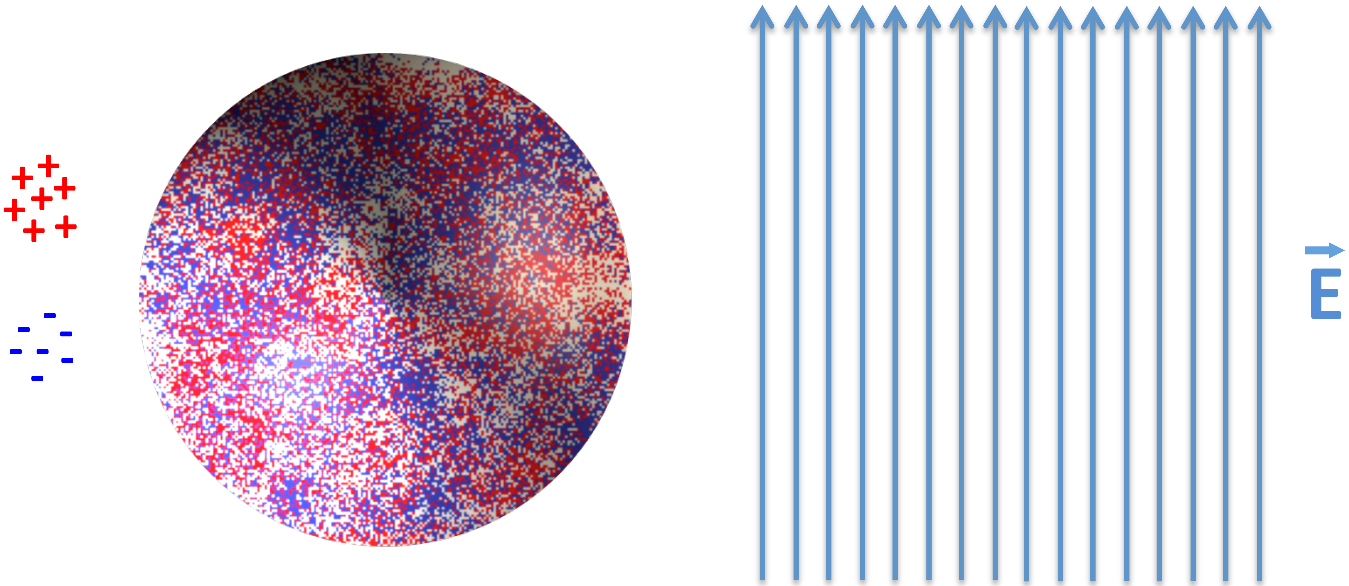
p $\qquad I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

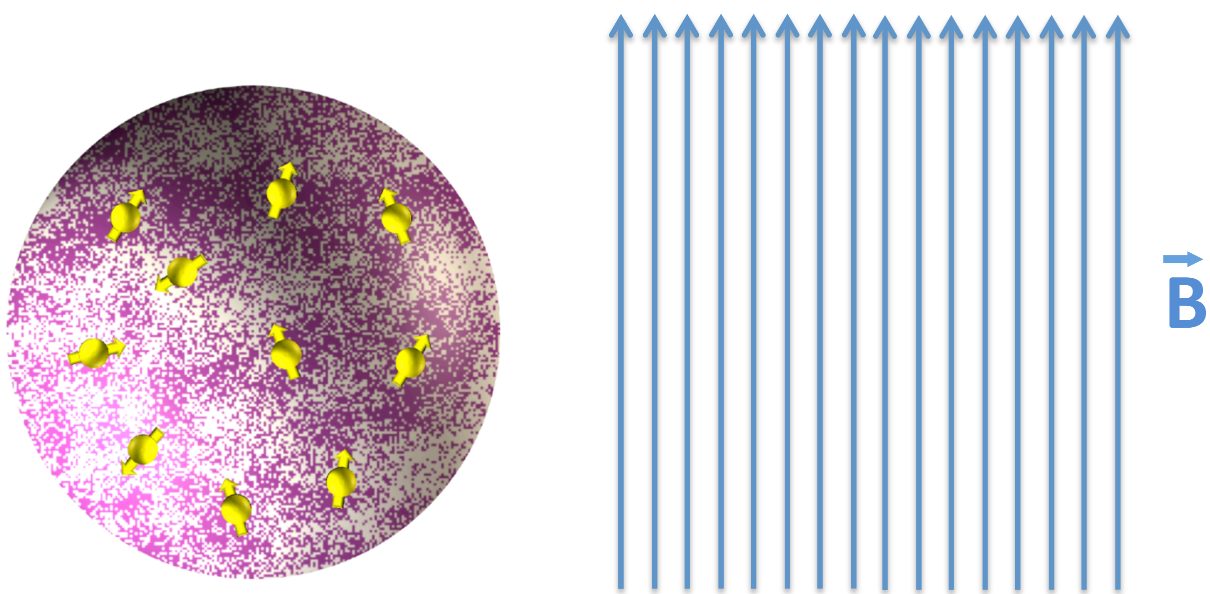
Mass $m = 1.00727646681 \pm 0.00000000009$ u
Mass $m = 938.272046 \pm 0.000021$ MeV [a]
$|m_p - m_{\overline{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]
$|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p}) = 0.99999999991 \pm 0.00000000009$
$|q_p + q_{\overline{p}}|/e < 7 \times 10^{-10}$, 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 $d < 0.54 \times 10^{-23}\ e\,\text{cm}$
Electric polarizability $\alpha = (11.2 \pm 0.4) \times 10^{-4}\ \text{fm}^3$
Magnetic polarizability $\beta = (2.5 \pm 0.4) \times 10^{-4}\ \text{fm}^3$ (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)

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

Scalar Polarizablities

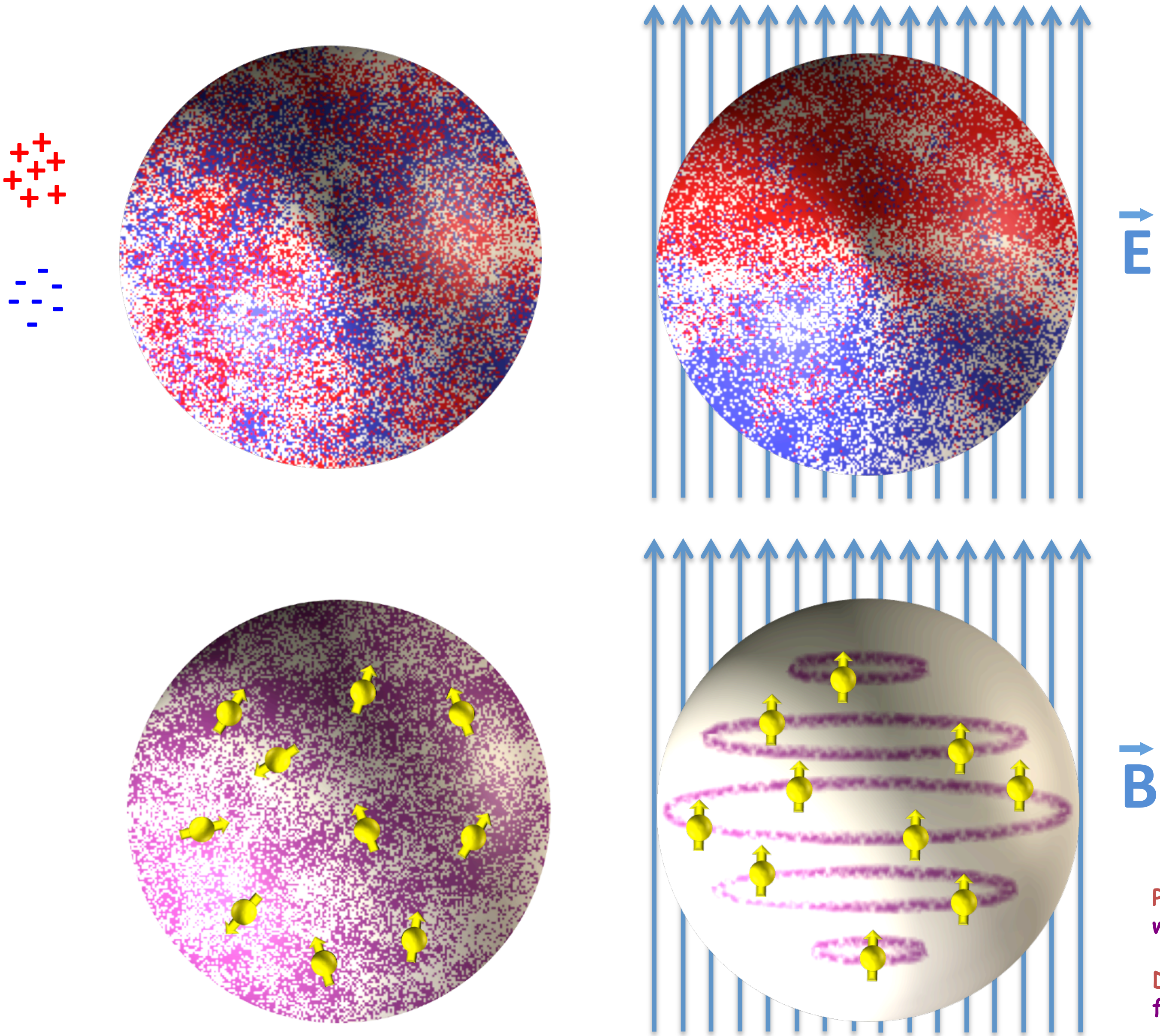
Response of internal structure to an applied EM field





Scalar Polarizablities

Response of internal structure to an applied EM field



“stretchability”

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

External field deforms the charge distribution

“alignability”

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

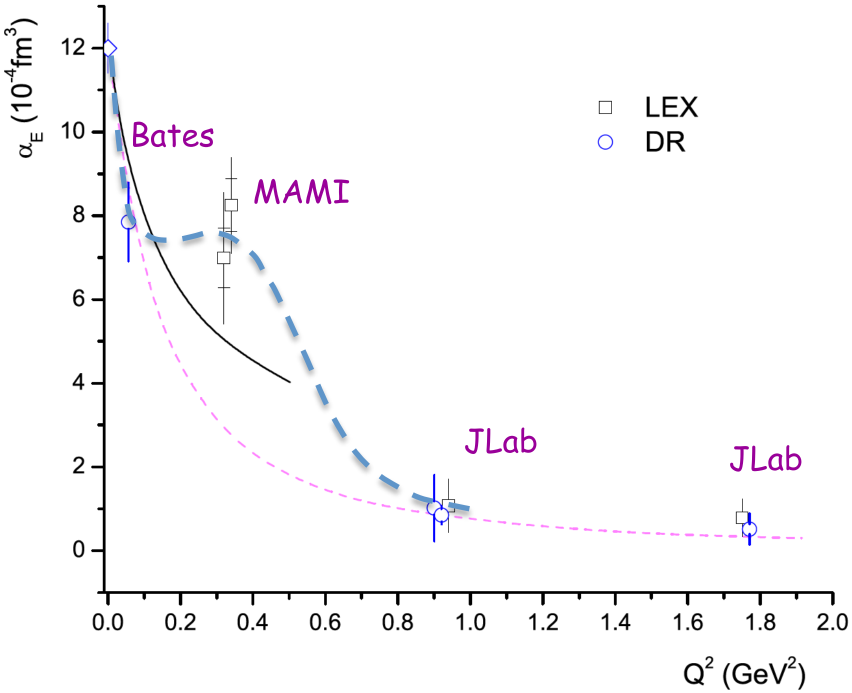
$\beta_{para} > 0$

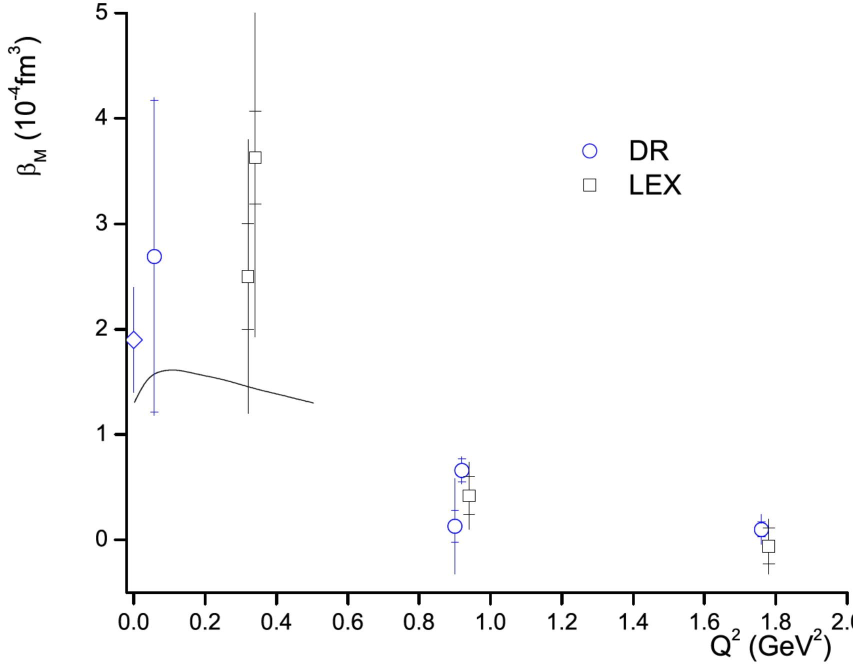
$\beta_{diam} < 0$

Paramagnetic: proton spin aligns with the external magnetic field

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

Experimental Landscape





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

Data suggest non-trivial Q^2 evolution of α_E

Current theoretical calculations not able to describe the enhancement at low Q^2

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

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

β_M small ←→ cancellation of competing mechanisms

Large uncertainties

Higher precision measurements needed

→ Quantify the balance between diamagnetism and paramagnetism

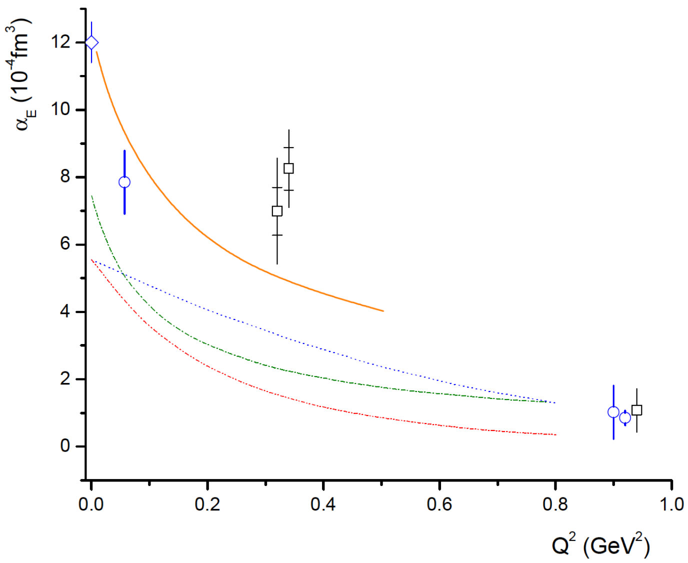
Current situation unsatisfactory:

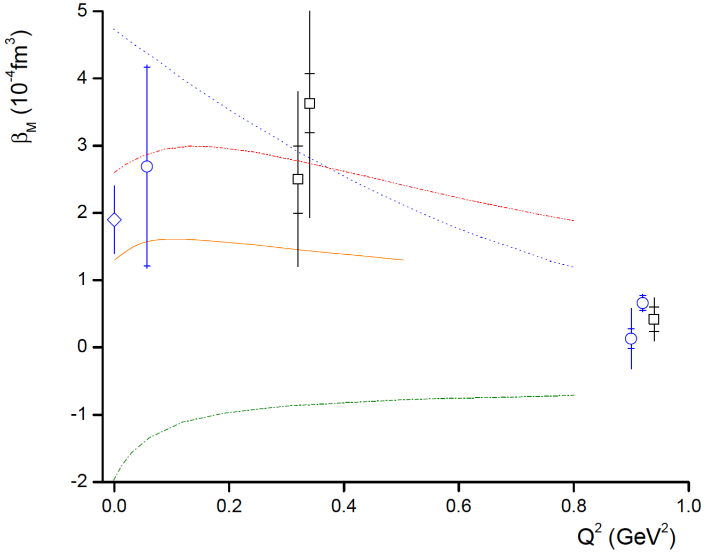
- more measurements needed (vs Q^2)
- Higher precision measurements needed

Theoretical Landscape

HBChPT
NRQCM
Effective Lagrangian Model
Linear Sigma Model

T.R. Hemmert et al — Phys. Rev. D 62, 014013 (2000)
B. Pasquini et al — Phys. Rev. C 63, 025205 (2001)
A. Yu. Korchin and O. Scholten — Phys. Rev. C 58, 1098 (1998)
A. Metz and D. Drechsel — Z. Phys. A 356, 351 (1996)





All theoretical calculations predict a smooth fall off for α_E

None of the models can account for the non trivial structure of α_E suggested by the data

Lattice QCD

Currently: $Q^2=0$ calculations exist but at unphysical quark masses

Near Future: calculations at the physical point for $Q^2=0$
first calculations for $Q^2\neq0$

Spatial dependence of induced polarizations on an external EM field

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

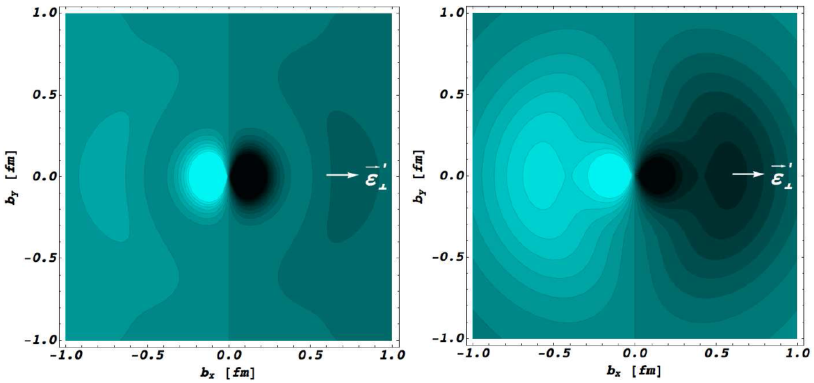
Induced polarization in a proton when submitted to an e.m. field

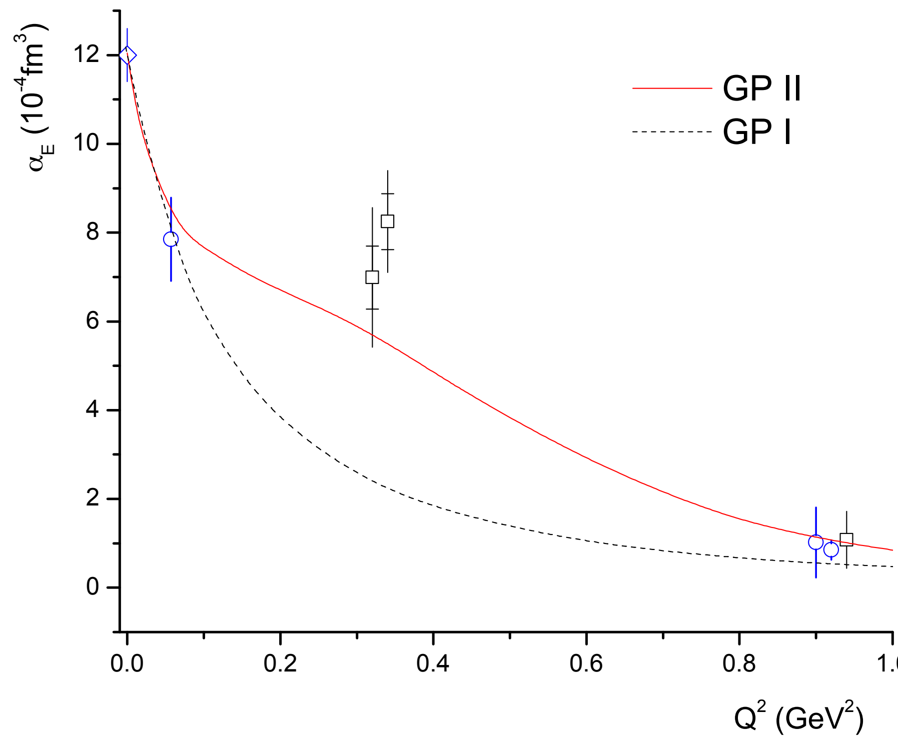
Phys. Rev. Lett. 104, 112001 (2010)

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

GP I

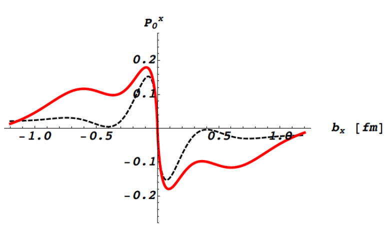
GP II





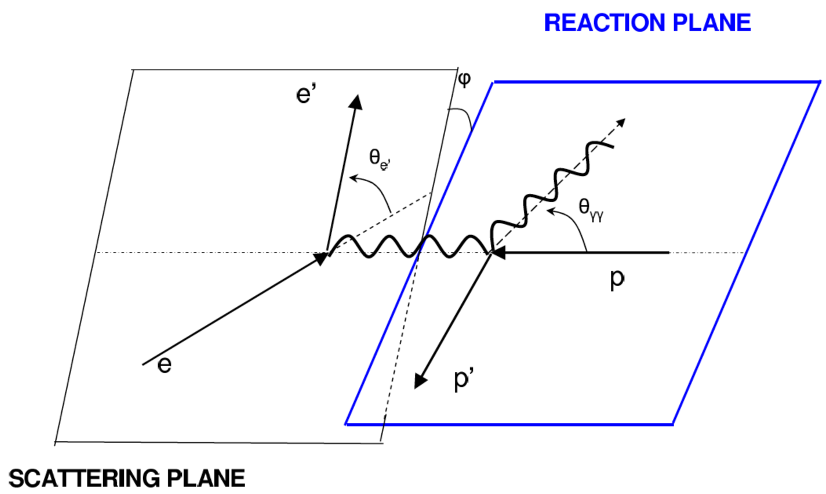
Light (**dark**) regions ➔ **largest** (**smaller**) values

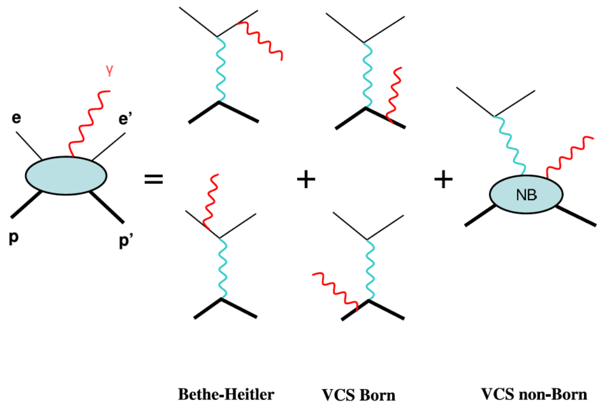
(photon polarization along x-axis, as indicated)



Induced polarization along b_y=0

Virtual Compton Scattering





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 section at each Q^2

LEX

valid only below
Pion threshold

Structure 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

Ongoing Experimental Efforts

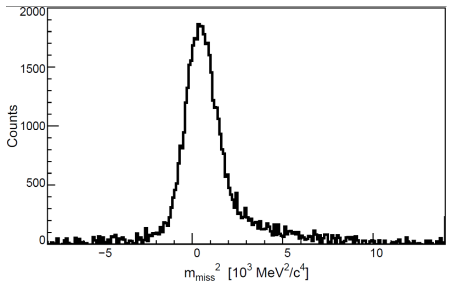
MAMI

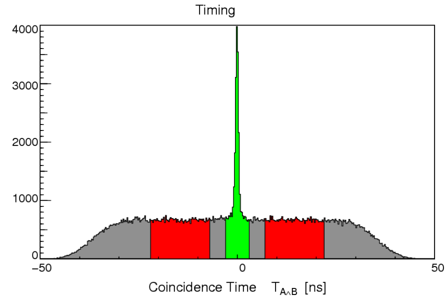
MAMI	A1/1-09	(vcsq2)	Fonvieille et al	below threshold
MAMI	A1/3-12	(vcsdelta)	Sparveris et al	above threshold

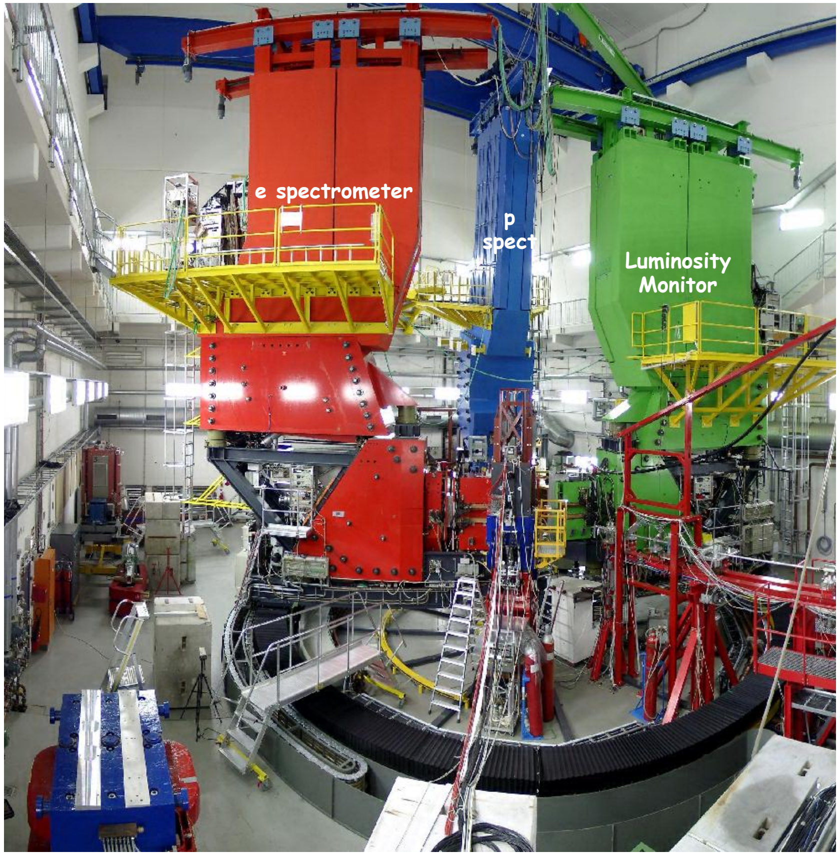
Both experiments utilized the A1 setup at MAMI

Preliminary results were recently released

Analysis is ongoing







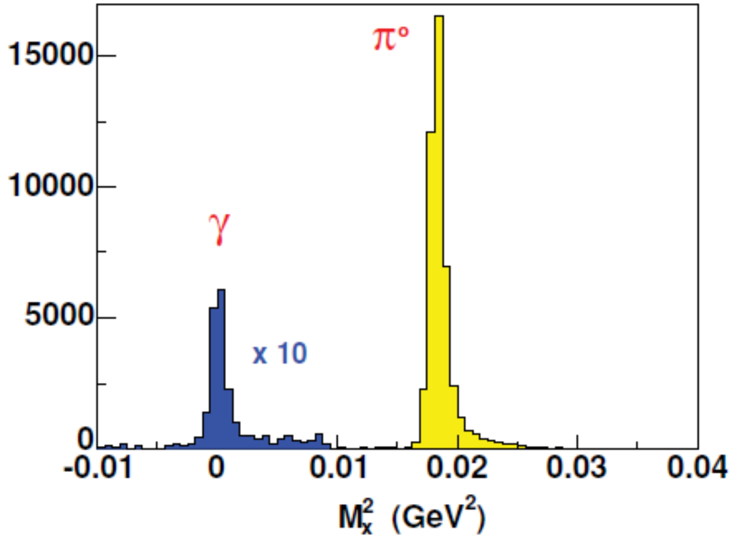
Ongoing Experimental Efforts
vcsdelta @ MAMI

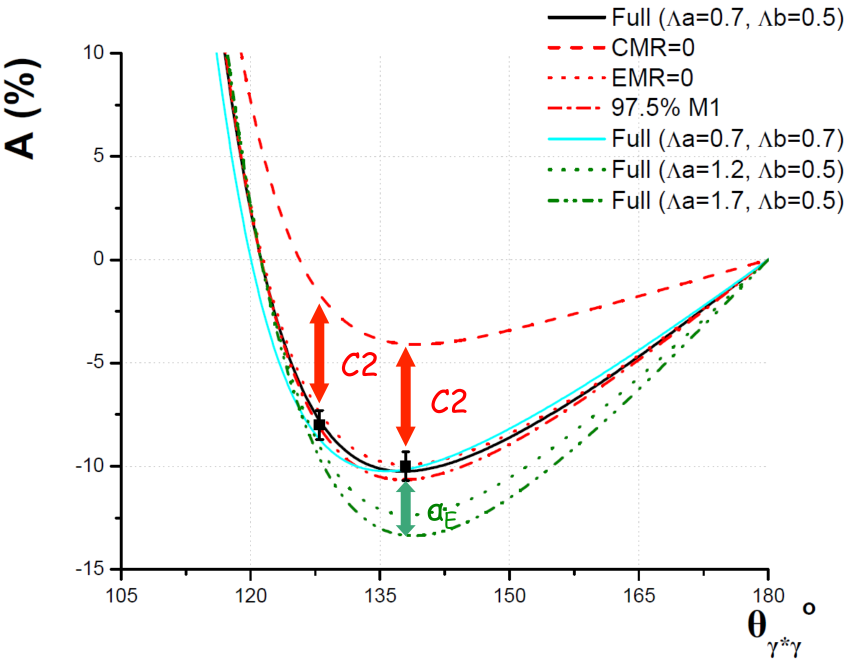
Goal 2-fold: 1) Measurement of the electric GP α_E

2) First measurement of N->Δ transition form factors through the γ channel

1.1 GeV beam

Measurement at $Q^2 = 0.2\ (GeV/c)^2$





Ongoing Experimental Efforts
vcsq2 @ MAMI

~ 1.0 GeV beam

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

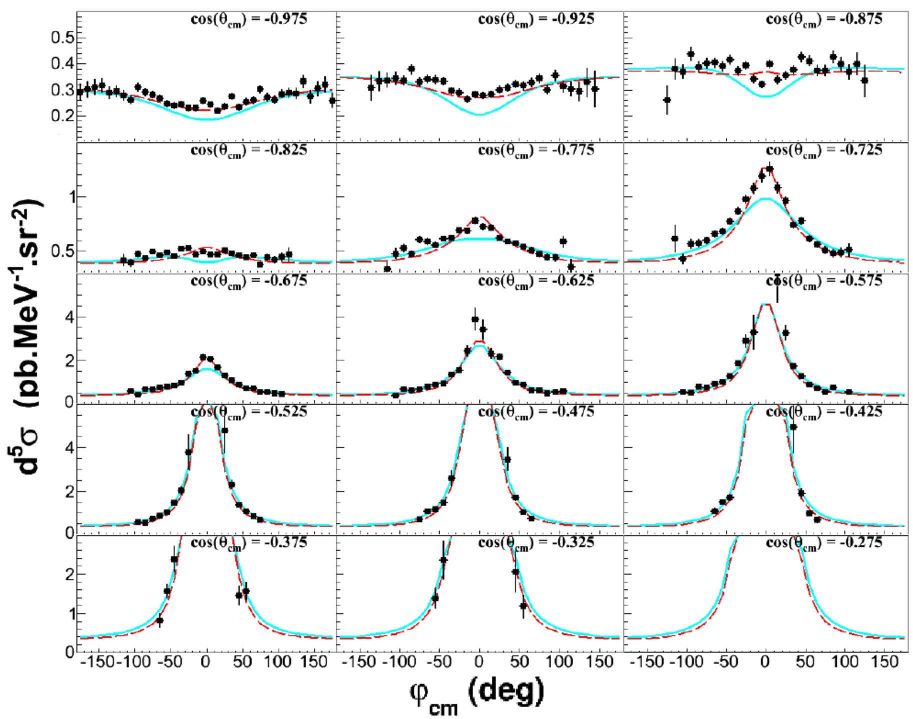


Figure 5.8: Setting INP: measured $ep \to ep\gamma$ cross section at fixed q'_{cm} = 112.5 MeV/c with respect to φ_{cm} for all the $cos(\theta_{cm})$-bins. The curves follow the convention of figure 5.6.

BH+B ---

Polarizability effect ---

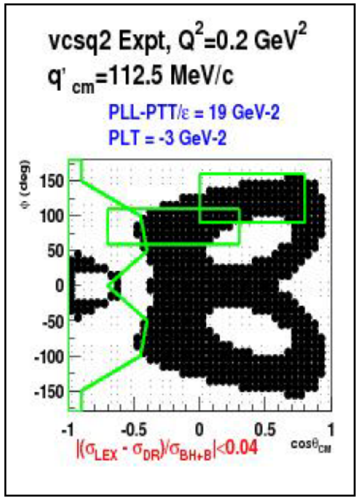


Figure from PhD thesis of L. Correa, Mainz / Cl. Ferrand, 2016

bin masking for LEX fit

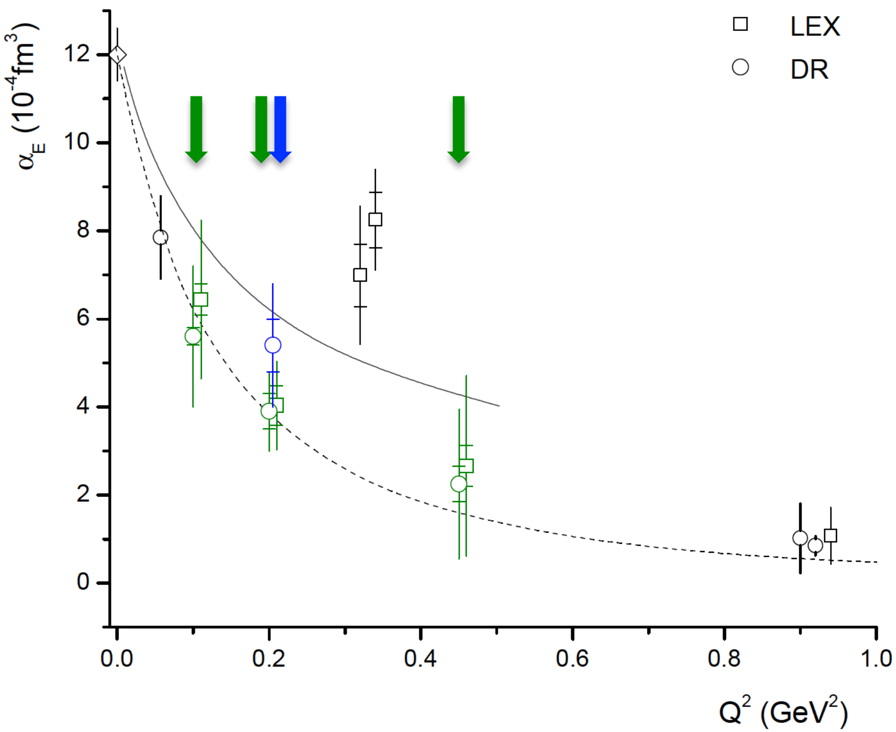
Ongoing Experimental Efforts @ MAMI

MAMI	A1/1-09	Fonvieille et al	VCS below threshold	data analysis ongoing
MAMI	A1/3-12	Sparveris et al	VCS above threshold	data analysis ongoing

MAMI setup constraints $Q^2 < 0.45\ (GeV/c)^2$

Preliminary A1/1-09 (vcsq2)

Preliminary A1/3-12 (vcsdelta)

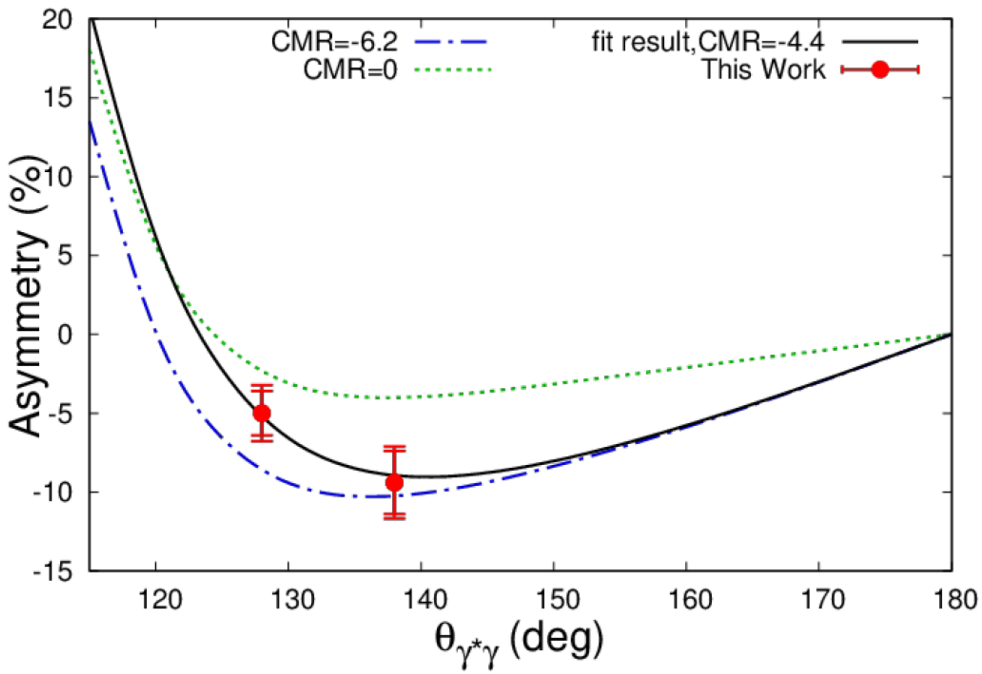


Data analyzed by 4 PhD students

Jure Bericic (Ljubljana Univ.)
Loup Correa (Clermont-Fd Univ.)
Meriem BenAli (Clermont-Fd Univ.)
Adam Blomberg (Temple Univ.)

2 independent measurements at $Q^2=0.20\ (GeV/c)^2$

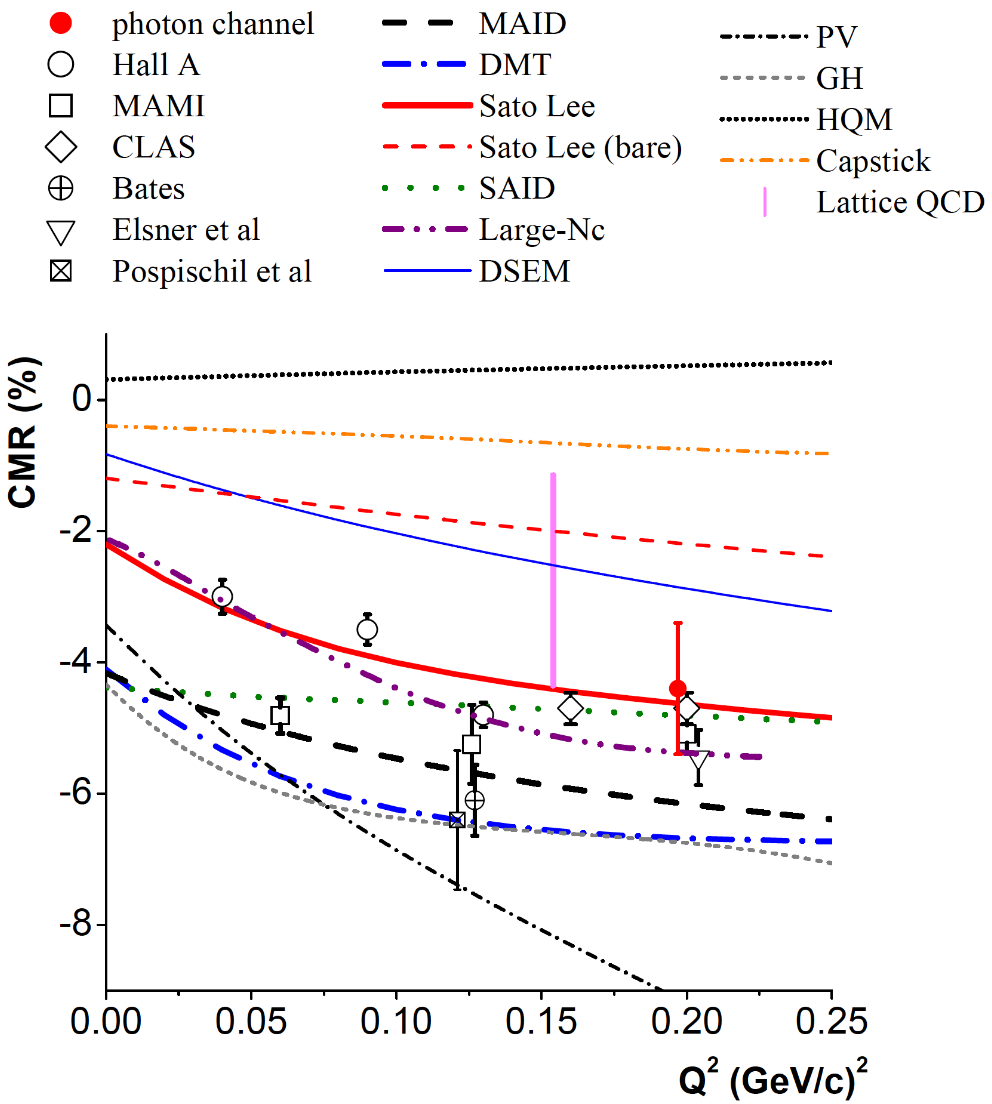
A1/03-12 Preliminary Results



First measurement of the N-Δ C2 amplitude through the photon channel

Important for cross check to the world data and for cross checking & constraining the model uncertainties

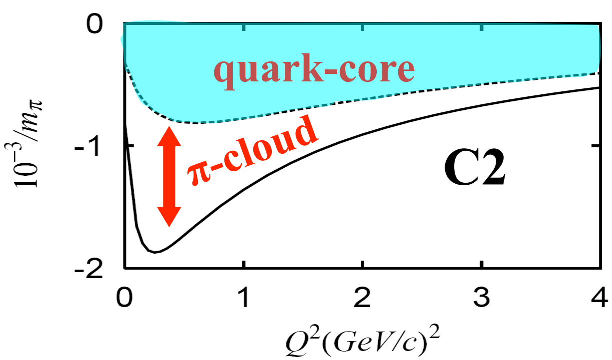
A1/03-12 Preliminary Results



First measurement of the N-Δ C2 amplitude through the photon channel

Important for cross check to the world data and for cross checking & constraining the model uncertainties

Sato Lee
Phys. Rev. C 54, 2660 (1996)
Phys. Rev. C 63, 055201 (2001)



Ongoing Experimental Efforts
JLab

New Proposal

E12-15-001 (JLab)

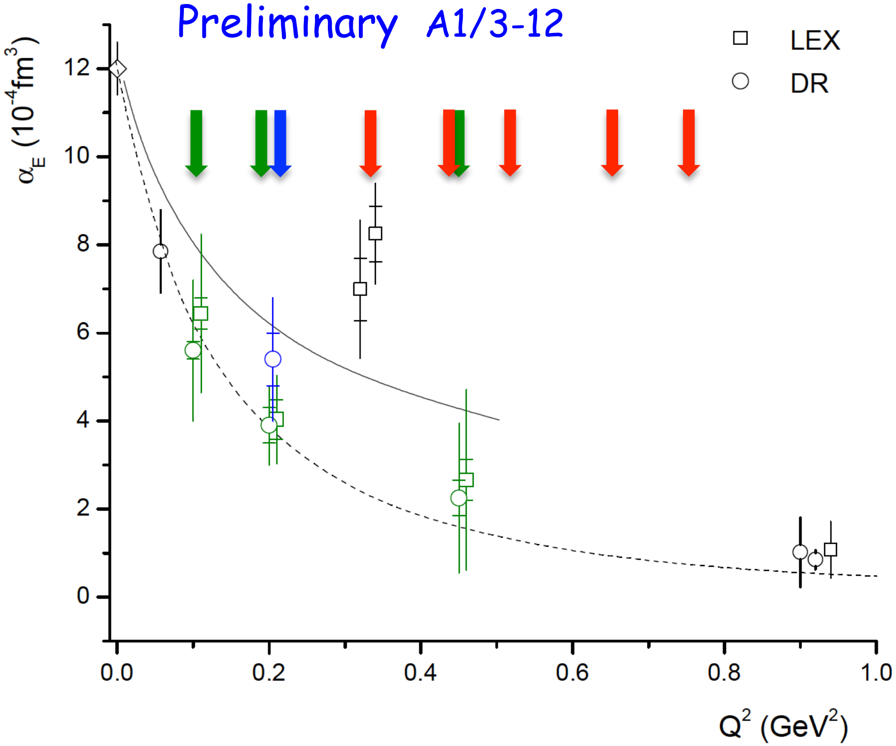
Going from ε = 0.6 ➔ 0.9 doubles the sensitivity to the GPs

ε=0.97 (Jlab)

ε=0.62 (MAMI)

Preliminary A1/1-09

Preliminary A1/3-12



additional + :

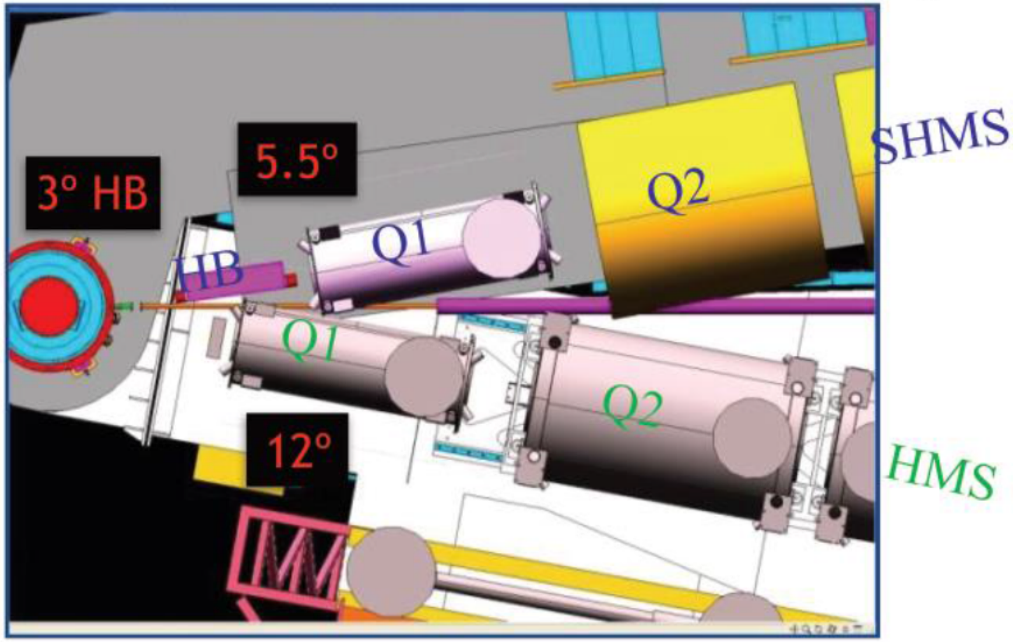
Beam energy x 4
Beam current x 5

JLab Hall C with 12 GeV upgrade

- Super High Momentum Spectrometer
  - HB, 3 Quads, Dipole
  - P ➛ 2 - 11 GeV
  - Resolution: $\delta < 0.1\%$
  - Acceptance: δ ➛30%, 4 msr
  - $5.5° < \theta < 40°$
  - Good e/π/K/p PID
- High Momentum Spectrometer
  - 3 Quads, Dipole
  - P ➛ 7.5 GeV
  - Resolution: $\delta < 0.1\%$
  - Acceptance: δ ➛18%, 6.5 msr
  - $10.5° < \theta < 90°$
  - Good e/π/K/p PID
- Minimum opening angle ~17°

Slide Courtesy of S. Wood

- Well shielded detector huts
- 2 beam line polarimeters
- Ideal facility for:
  - Rosenbluth (L/T) separations
  - Exclusive reactions
  - Low cross sections (neutrino level)



Hall C HMS and SHMS

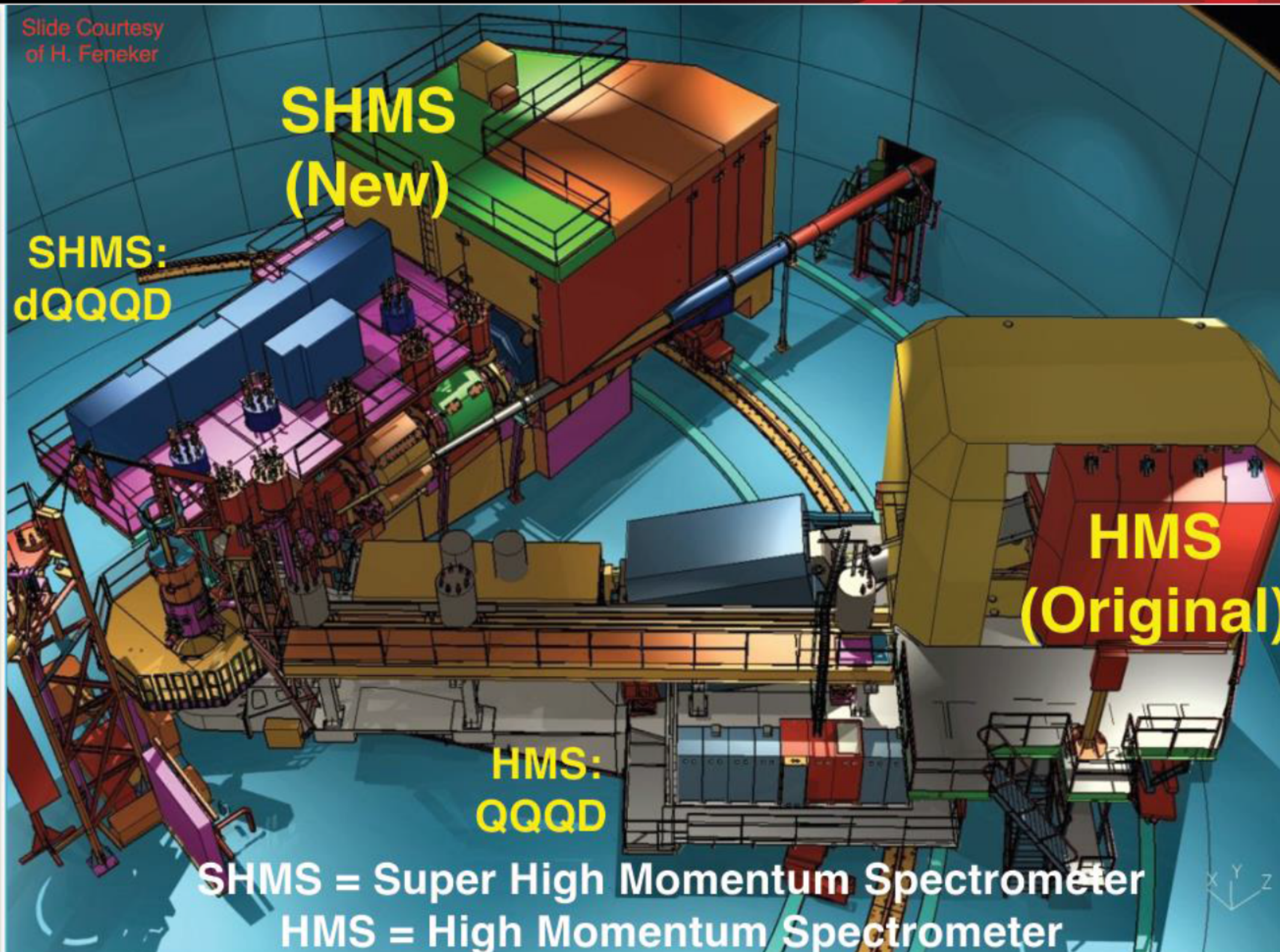
SHMS:
- 11-GeV Spectrometer
- Partner of existing 6-GeV **HMS**

MAGNETIC OPTICS:
- Point-to Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

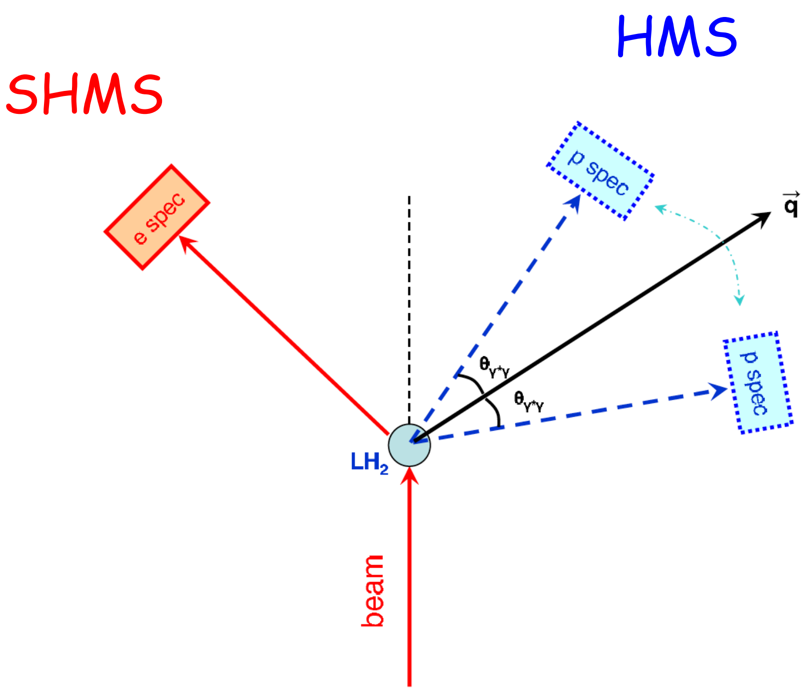
Detector Package:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter
- All derived from existing HMS/SOS detector designs

Well-Shielded Detector Enclosure

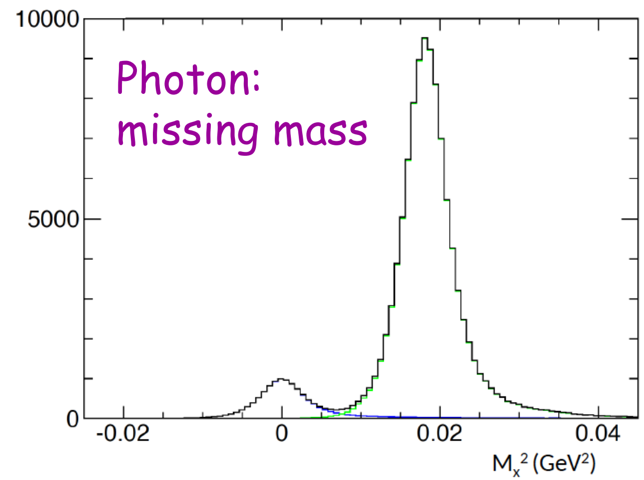
Rigid Support Structure
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS



E12-15-001 Experimental Setup



e & p detection in coincidence



Hall C: SHMS, HMS

4.4 GeV

40-85 μA

Liquid hydrogen 15 cm

cross sections

in-plane azimuthal asymmetries

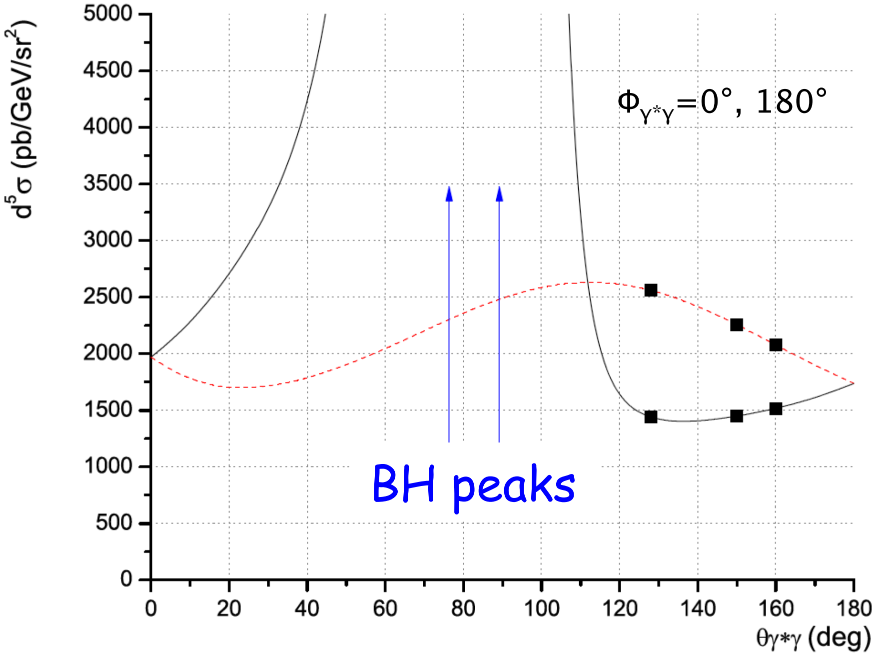
$$A_{(\phi_{\gamma^*\gamma}=0,\pi)} = \frac{\sigma_{\phi_{\gamma^*\gamma}=0} - \sigma_{\phi_{\gamma^*\gamma}=180}}{\sigma_{\phi_{\gamma^*\gamma}=0} + \sigma_{\phi_{\gamma^*\gamma}=180}}$$

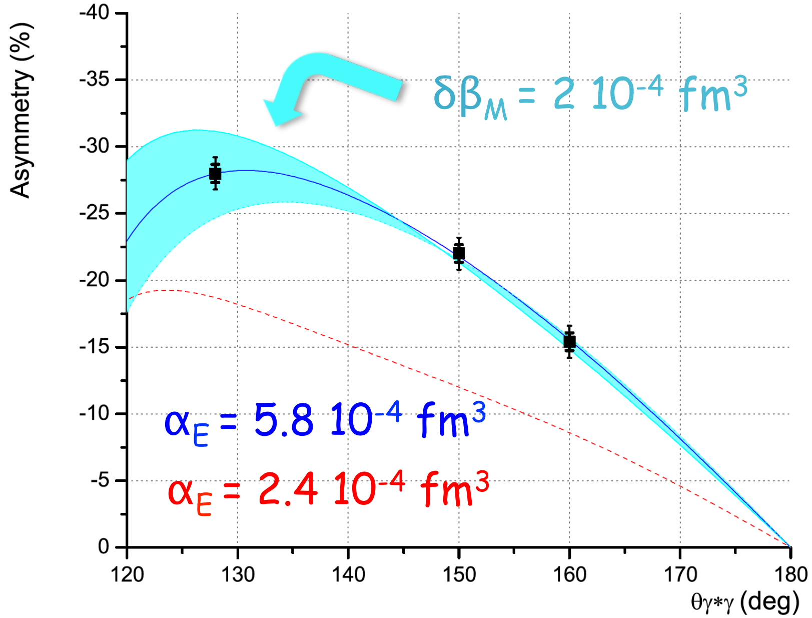
sensitivity to GPs

suppression of systematic uncertainties

Projected Measurements

$Q^2 = 0.43\ (GeV/c)^2$





avoid BH peaks

stay at $\theta_{\gamma^*\gamma} > 120°$

Kinematical Settings

	Kinematical Setting	$\theta_{\gamma^*\gamma}$°	θ_e°	$P'_e(MeV/c)$	θ_p°	$P'_p(MeV/c)$	S/N	beam time (days)
Part I	Kin Ia	155	7.97	3884.4	37.20	893.20	1.1	0.5
	Kin Ib	155	7.97	3884.4	51.26	893.20	2.7	0.5
	Kin IIa	140	7.97	3884.4	33.08	859.90	1	0.45
	Kin IIb	140	7.97	3884.4	55.38	859.90	3.7	0.55
	Kin IIIa	120	7.97	3884.4	27.85	794.68	0.9	0.45
	Kin IIIb	120	7.97	3884.4	60.61	794.68	6.2	0.55
	Kin IVa	165	9.39	3820.5	40.85	1010.40	1.3	0.5
	Kin IVb	165	9.39	3820.5	48.45	1010.40	2.4	0.5
	Kin Va	155	9.39	3820.5	38.34	995.20	1	0.5
	Kin Vb	155	9.39	3820.5	50.96	995.20	3.2	0.5
	Kin VIa	128	9.39	3820.5	31.84	919.43	0.7	0.95
	Kin VIb	128	9.39	3820.5	57.46	919.43	7.8	0.55
Part II	Kin VIIa	165	11.54	3708.6	40.81	1175.25	2.6	1.5
	Kin VIIb	165	11.54	3708.6	47.35	1175.25	5	2
	Kin VIIIa	160	11.54	3708.6	39.73	1167.72	2.2	1.5
	Kin VIIIb	160	11.54	3708.6	48.43	1167.72	6.3	2
	Kin IXa	140	11.54	3708.6	35.52	1117.38	1.2	1.5
	Kin IXb	140	11.54	3708.6	52.64	1117.38	8	2

Part I

Part II

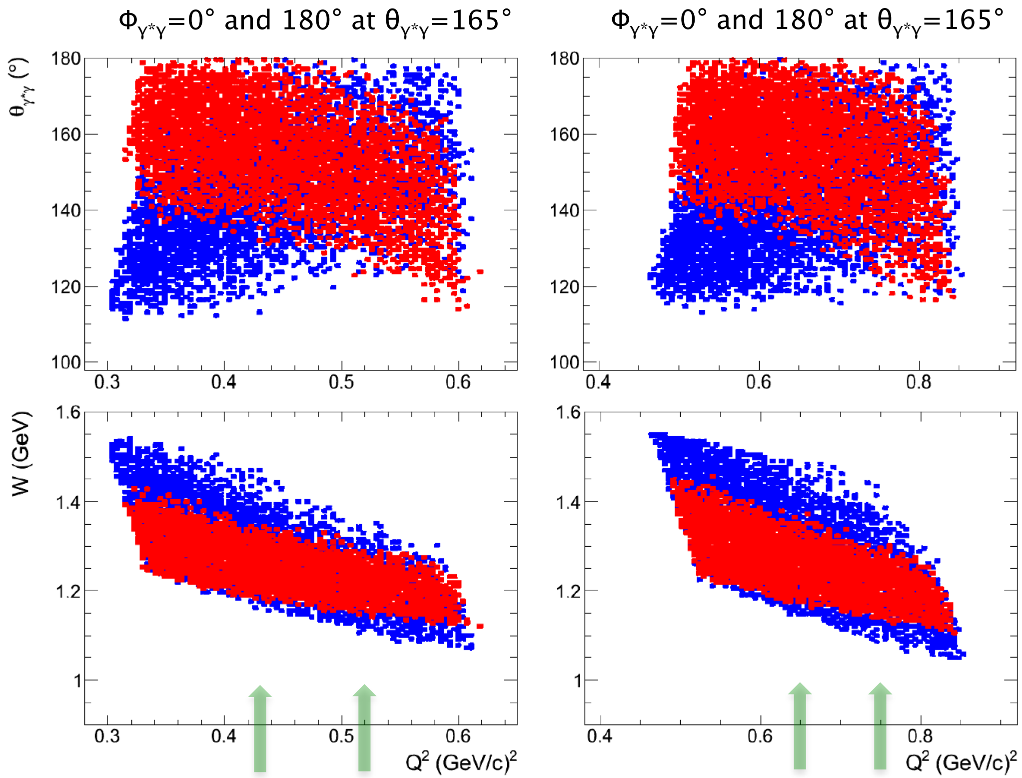
SHMS: one change of setting through Part I
same position & momentum through out Part II

Same beam energy for all settings

Part	I	I	I	II	II
Q^2	0.33 (GeV/c)	0.43 $(GeV/c)^2$	0.52 $(GeV/c)^2$	0.65 $(GeV/c)^2$	0.75 $(GeV/c)^2$

Phase Space

Part I | Part II



Phase space binned in Q^2, W, $\theta_{\gamma^*\gamma}$, $\Phi_{\gamma^*\gamma}$

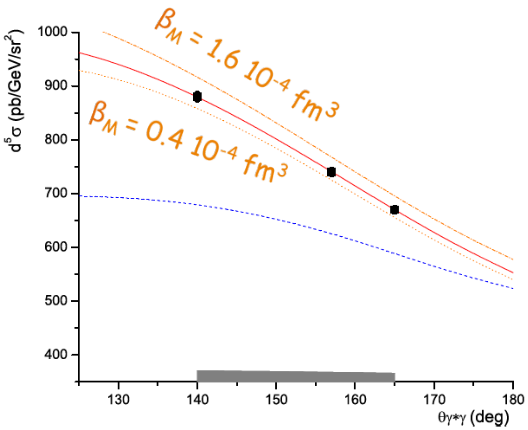
Cross section: DR calculation, B. Pasquini

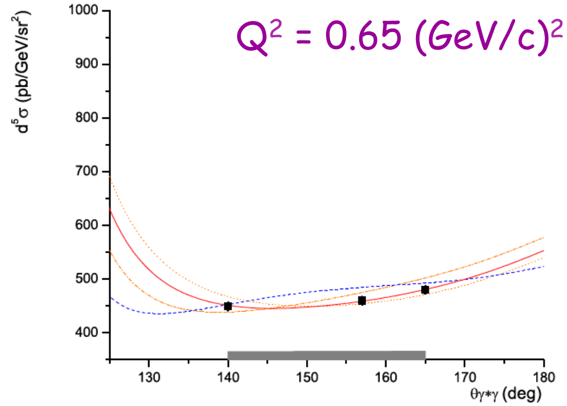
Eur. Phys. J. A11 (2001) 185-208

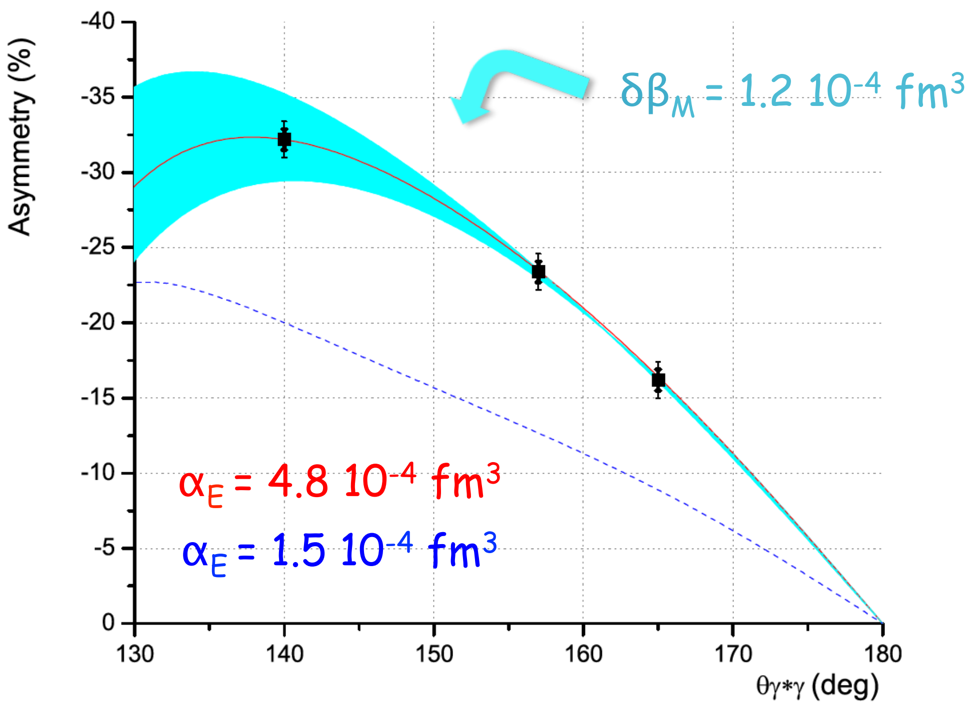
Phys. Rept. 378 (2003) 99-205

Part	I	I	I	II	II
Q^2	0.33 (GeV/c)	0.43 $(GeV/c)^2$	0.52 $(GeV/c)^2$	0.65 $(GeV/c)^2$	0.75 $(GeV/c)^2$

Projected Measurements



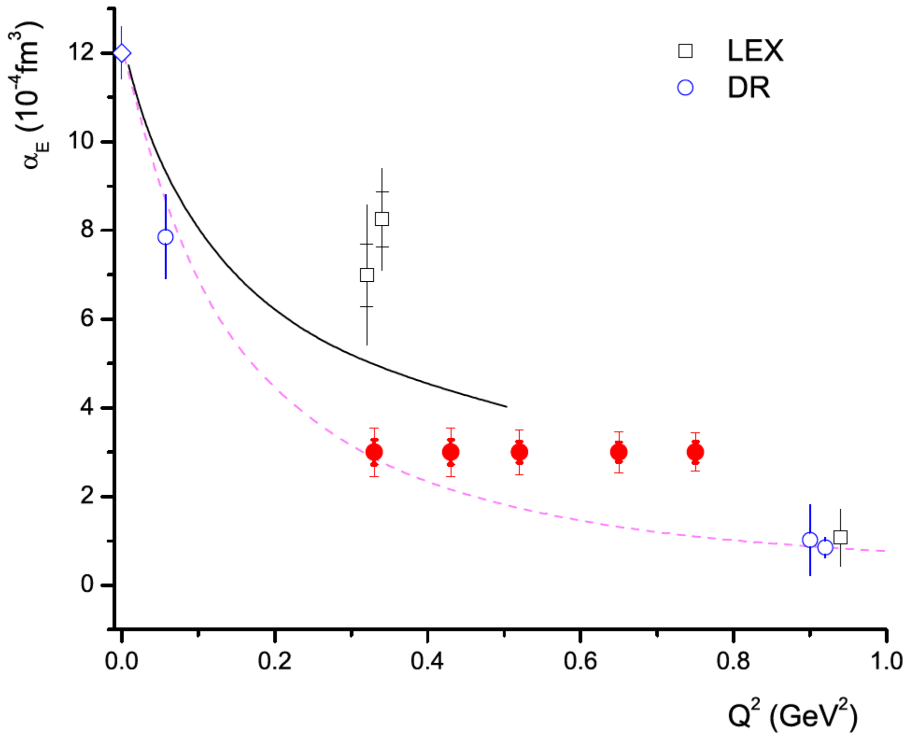


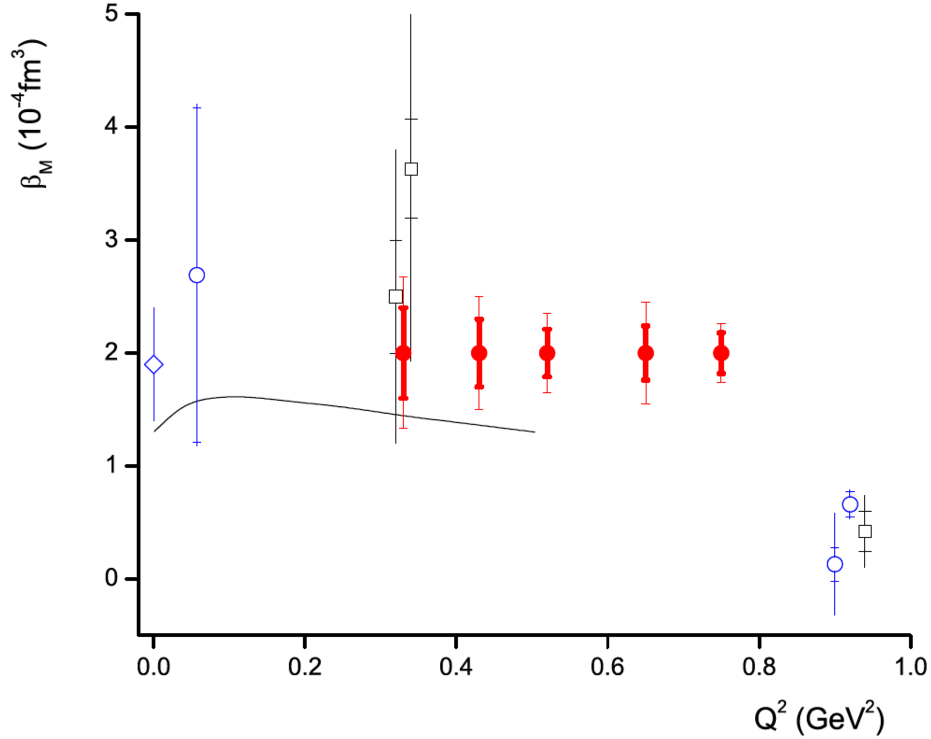


Statistical	< ±1.3%
Beam energy / scat. Angle	±1-2.5%
Target density	±0.5%
Detector efficiency	±0.5%
Acceptance	±0.5%
Target cell backgr.	±0.5%
Target length	±0.3%
Beam charge	±0.3%
Dead time	±0.3%
Pion contamination in MM	±0.3%
Rad. Corr.	±1.5%
Other	±0.5%

σ	< ±1.3% (stat)	< ±3.3% (syst)
A	≈ ±0.7% (stat)	≈ ±1.1% (syst)

Projected Measurements



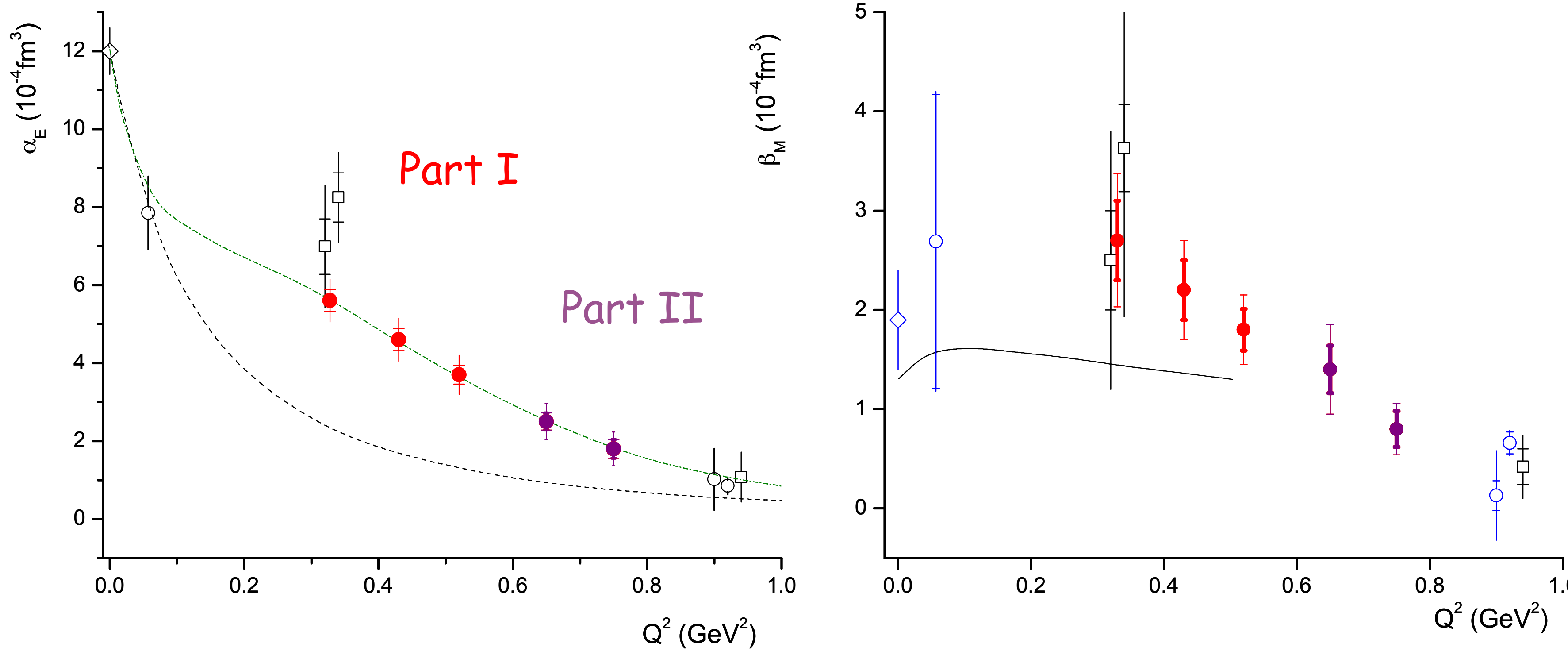


σ, A → Statistics, Systematics, FFs, DR multipoles → α_E, β_M

$\delta_{GPs(stat)} \approx 0.7\ \delta_{GPs(syst)}$

$\delta_{GPs(syst)} \approx \delta_{GPs(FFs/DRmult)}$

Status of E12-15-001



Part I approved in summer 2016 (Jlab PAC 44): (4.4 GeV, 85 μA, Hall C)

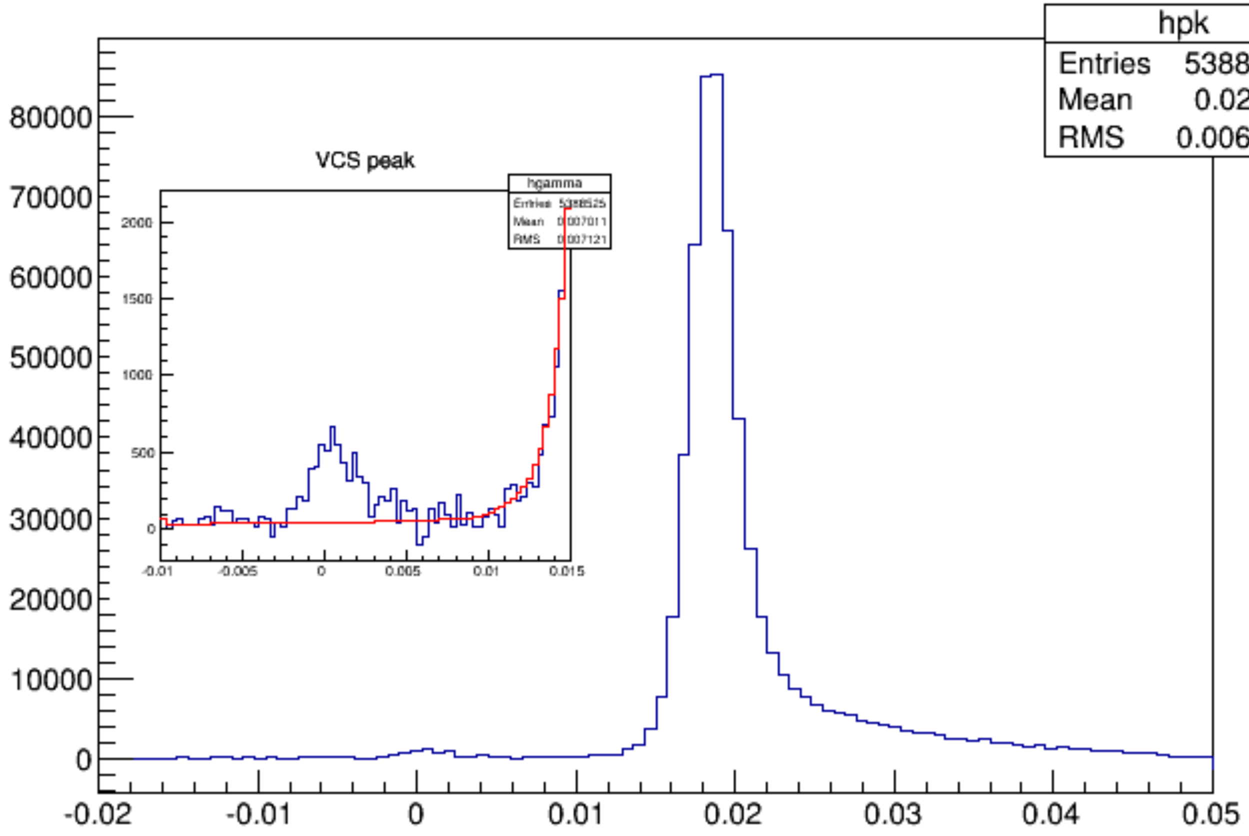
Other ongoing efforts

E08-010 (Hall-A/Jlab): γ-channel

parasitic access to VCS at very low Q^2

data analysis is ongoing (and very challenging)

Q^2=0.04 (GeV/c)^2 to 0.13 (GeV/c)^2



Summary

Intense experimental effort focusing on the measurement of the electric and magnetic GPs

- fundamental structure constants
- internal structure and dynamics of the nucleon
- complementary information to elastic & transition FFs, GPDs, TMDs, …

Puzzle w.r.t. α_E

New results (MAMI) and a recently approved new experiment (Jlab)
in a region very sensitive to the nucleon dynamics

- improve the precision of α_E and β_M by a factor of 2
- GPs Q^2 signature
- explore mechanism for the non trivial Q^2 dependence of α_E
- quantify the balance between paramagnetism and diamagnetism through β_M
- provide, with high precision, the spatial deformation of charge & magnetization densities under an applied e.m. field (currently a profound structure is suggested in the region 0.5 fm – 1 fm)
- Lattice QCD results will be emerging in the next few years – high precision benchmark data to cross check these calculations
- the new measurements will trigger more theoretical activity

Thank you!