Measurement of the Generalized Polarizabilities of the Proton in Virtual Compton Scattering

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Scalar 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 (contrary to the elastic FFs)

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

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

PDG

150 Baryon Summary Table

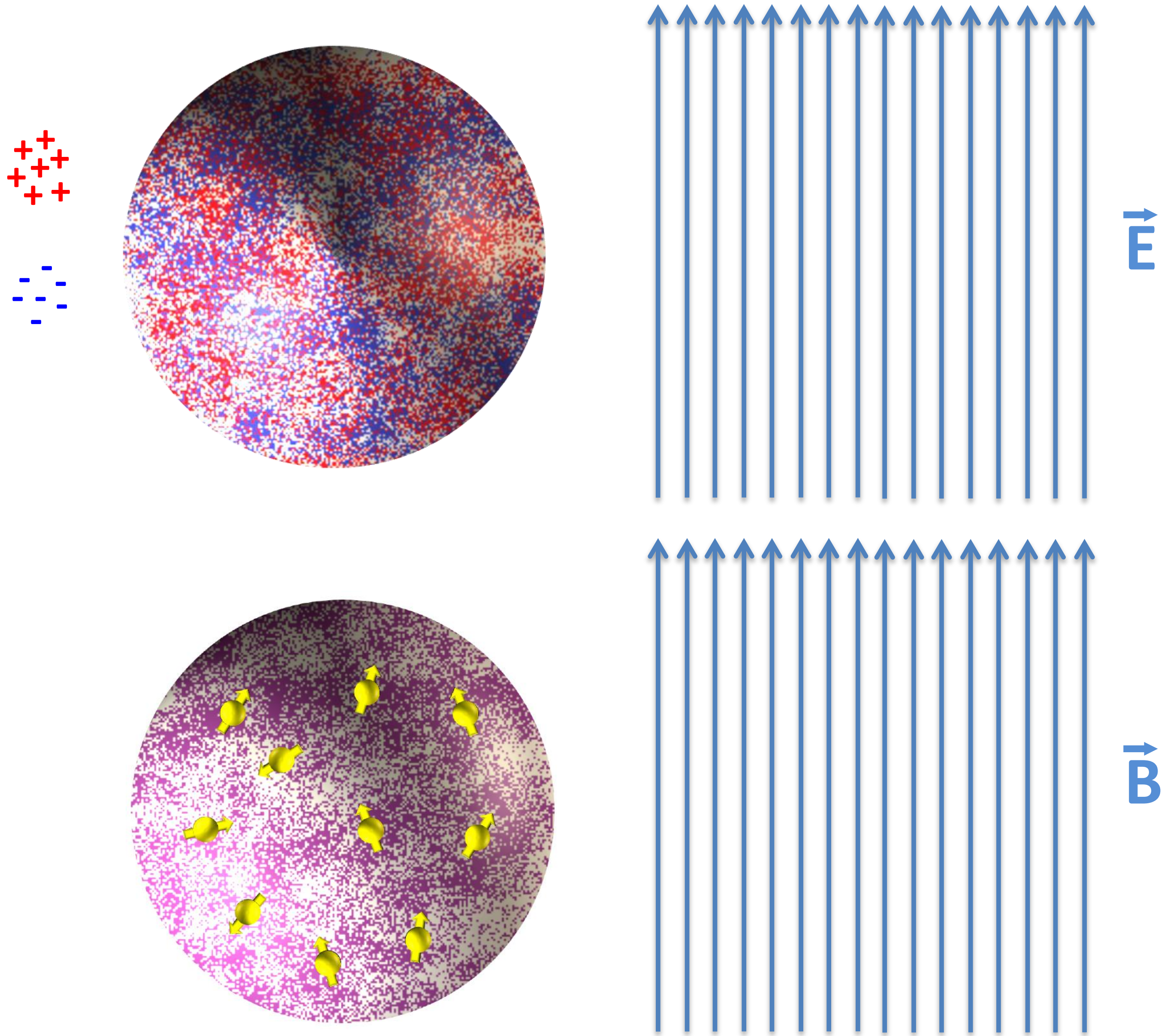
N BARYONS
($S = 0$, $I = 1/2$)
p, $N^+ = uud$; n, $N^0 = udd$

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)

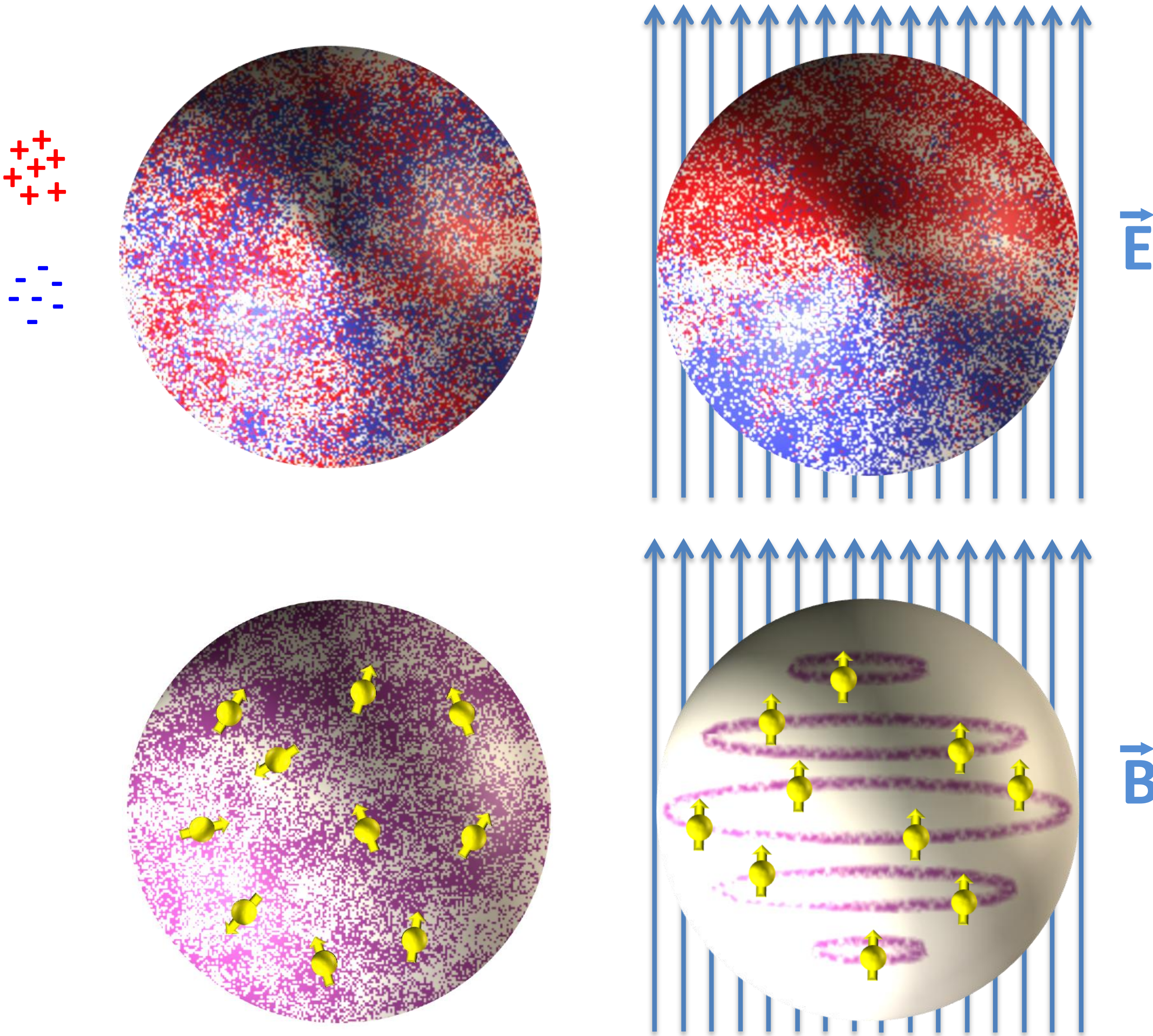
Scalar Polarizablities

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"

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

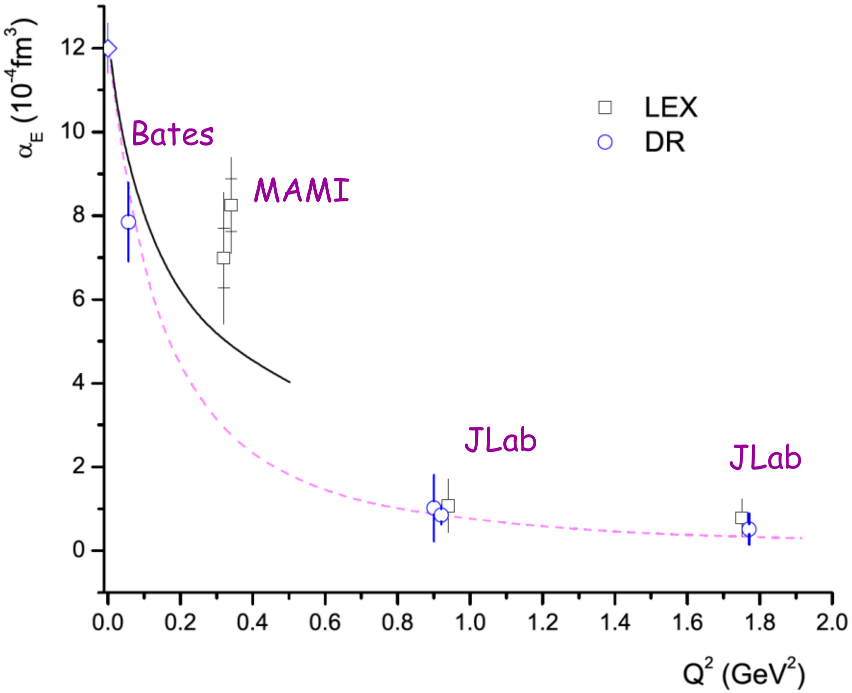
$$\beta_{para} > 0$$

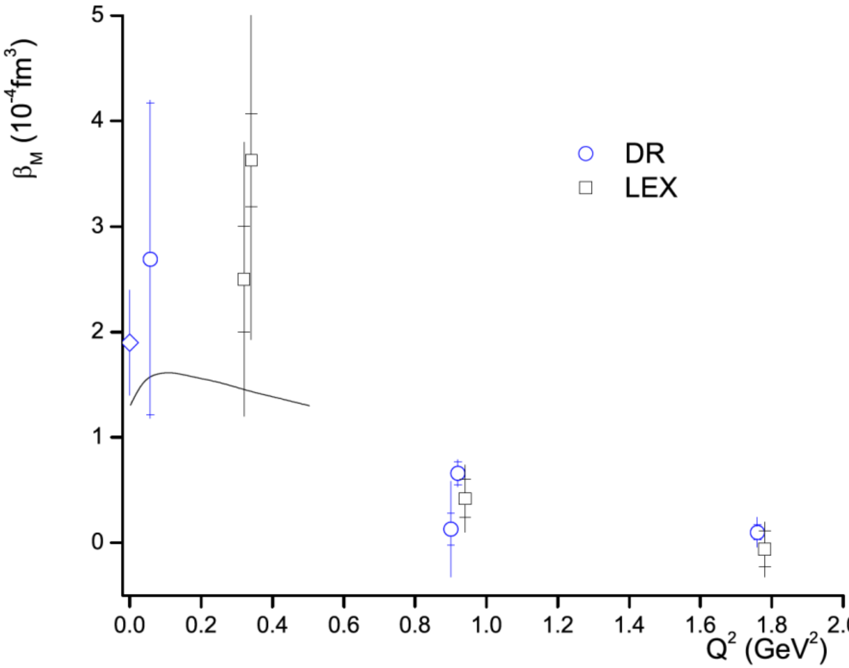
$$\beta_{diam} < 0$$

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

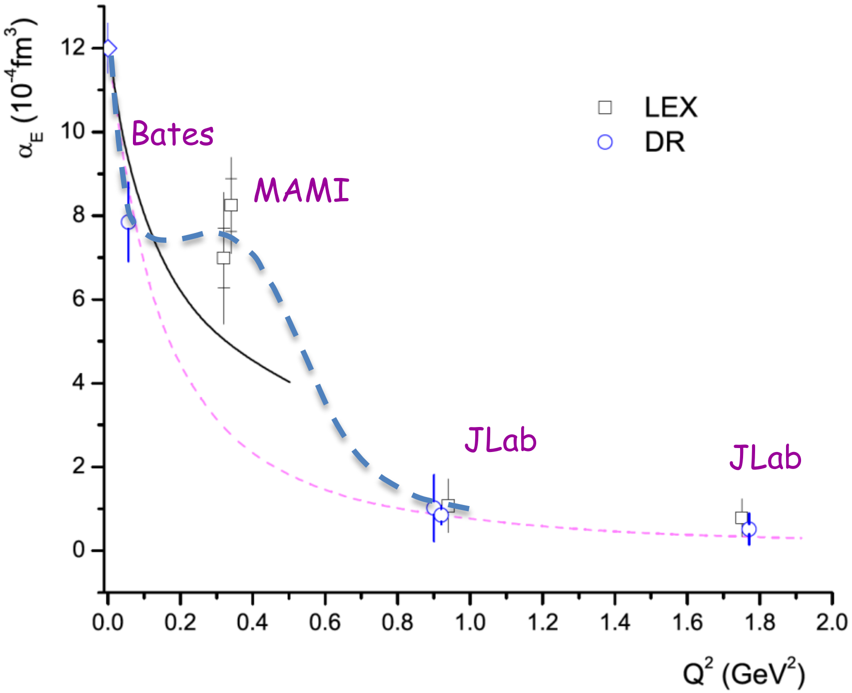
Higher precision measurements needed

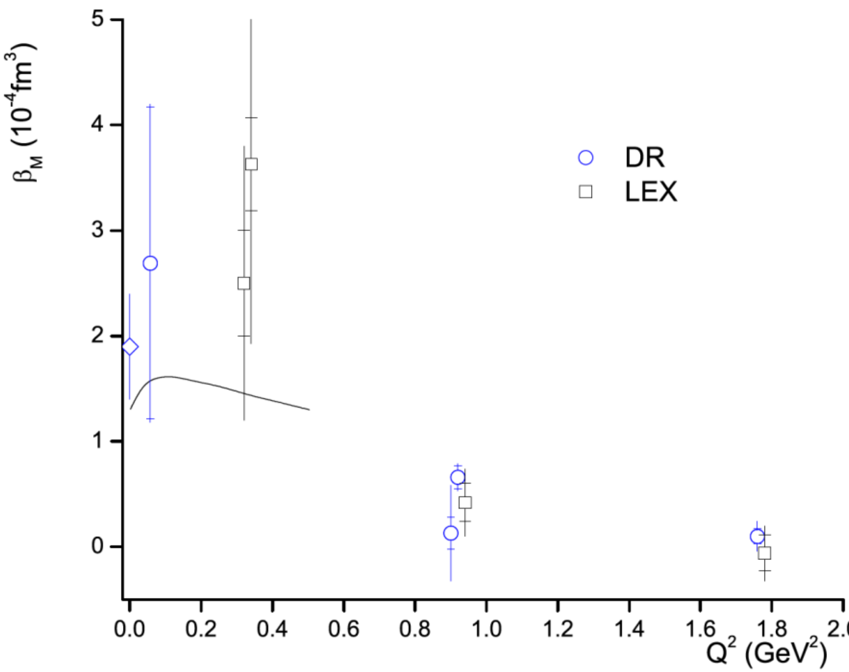
➔ Quantify the balance between diamagnetism and paramagnetism

Current situation unsatisfactory:

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

Experimental Landscape





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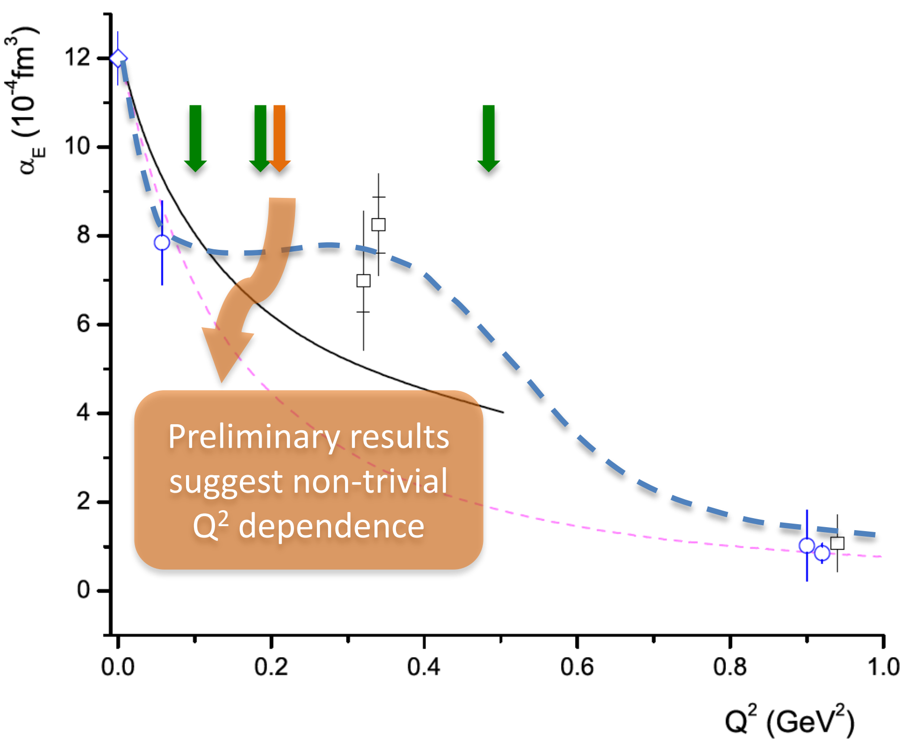
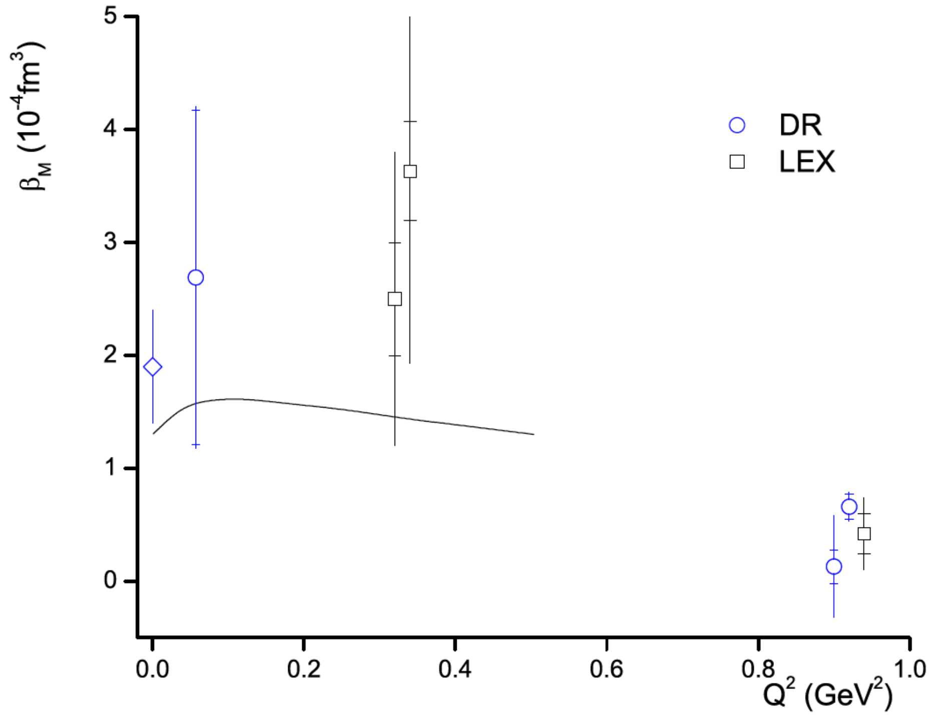
Ongoing Experiments

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

new MAMI measurements competitive / comparable to the Q^2=0.33 (GeV/c)^2 measurement

MAMI constraints Q^2 < 0.5 (GeV/c)^2





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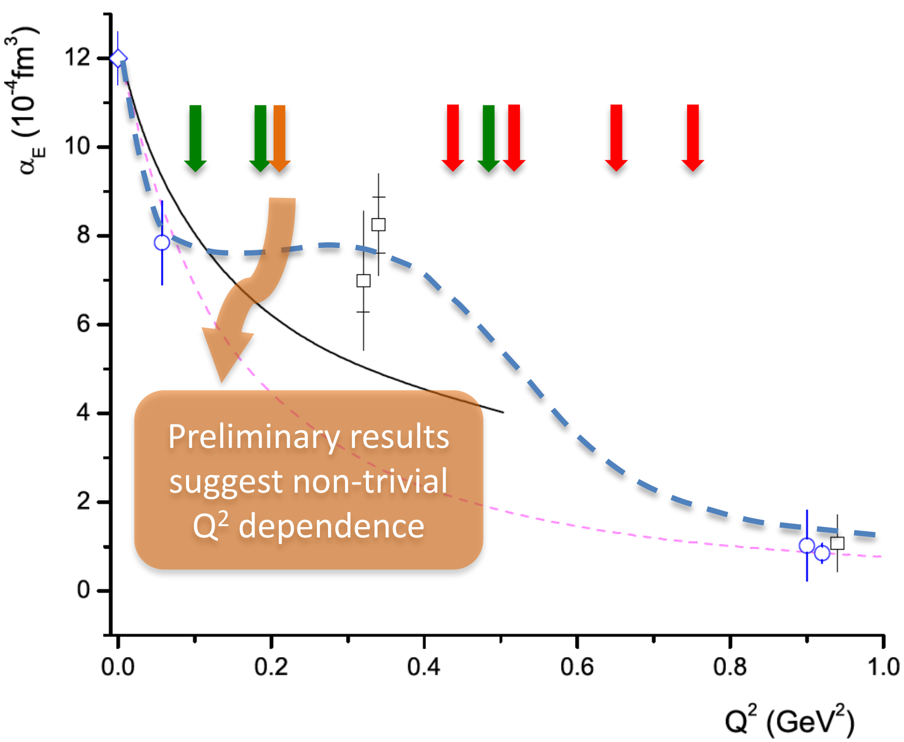
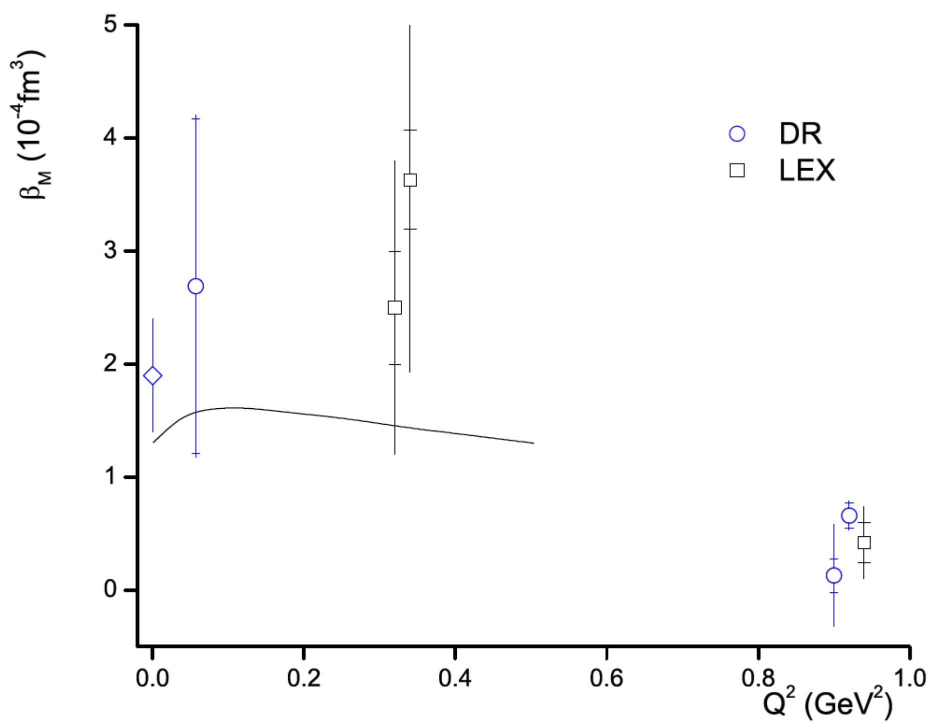
Jlab This proposal





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new MAMI measurements competitive / comparable to the Q^2=0.33 $(GeV/c)^2$ measurement

MAMI constraints $Q^2 < 0.5$ $(GeV/c)^2$

Jlab This proposal

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

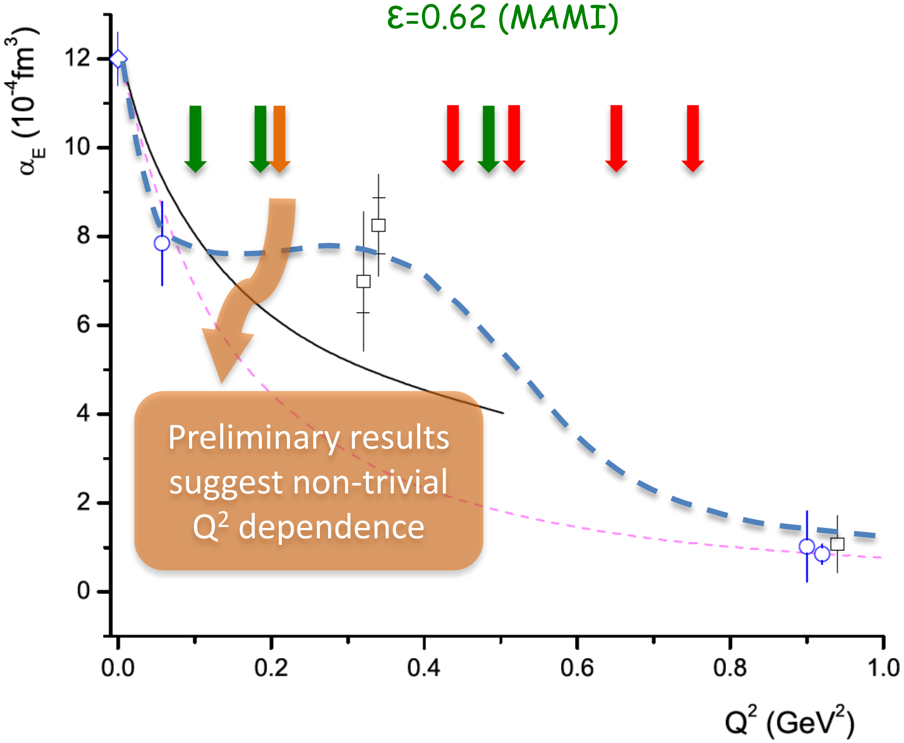
additional + :

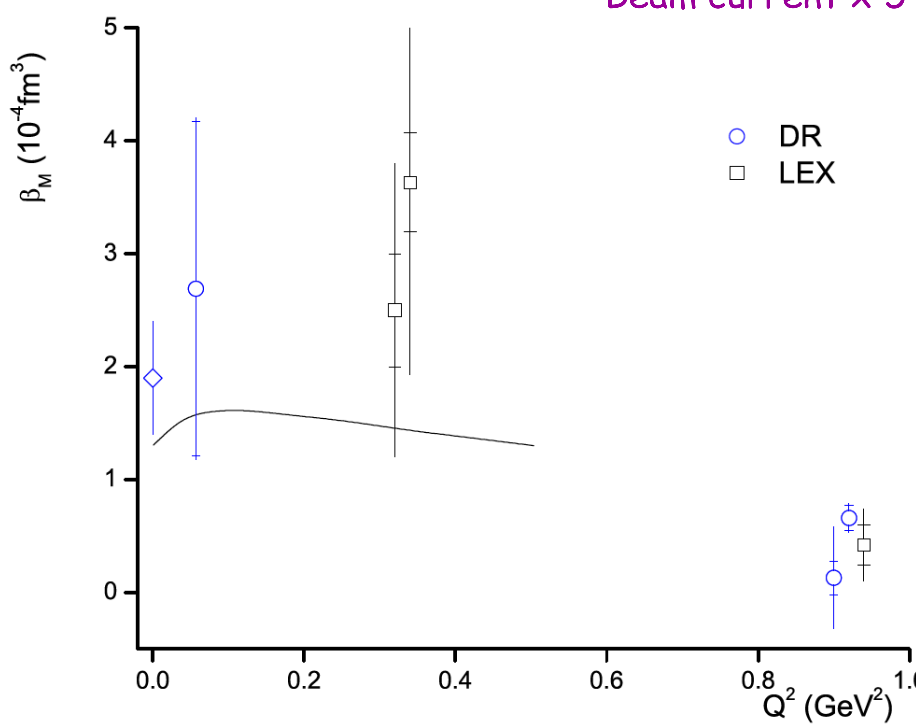
Beam energy x 4

Beam current x 5

ε=0.97 (Jlab)

ε=0.62 (MAMI)

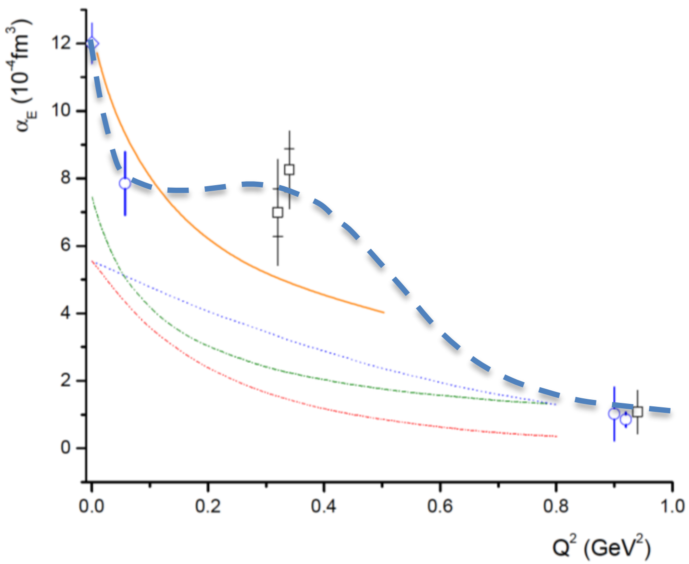


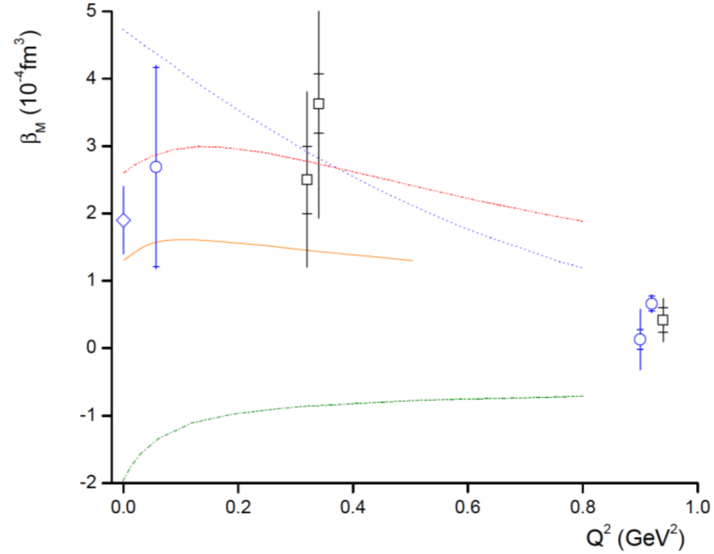


Theoretical Landscape

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 $Q^2 \neq 0$

Spatial dependence of induced polarizations in an external EM field

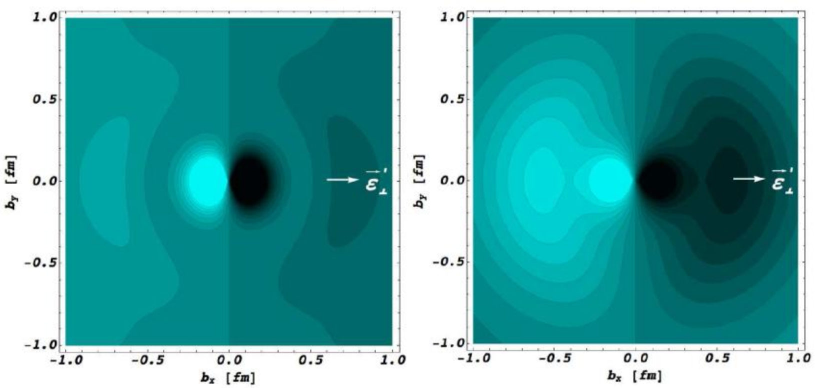
Nucleon form factor data ➔ light-front quark charge densities

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

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

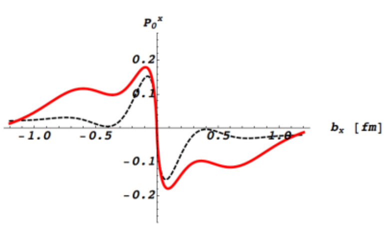
Induced polarization in a proton when submitted to an e.m. field

GP I　　　　GP II



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

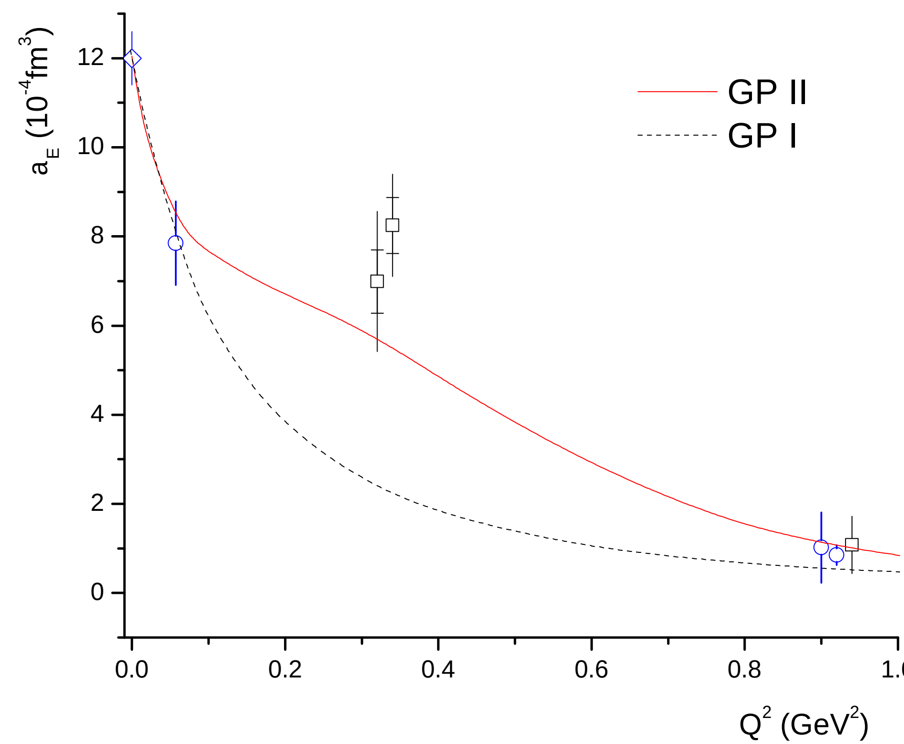
(photon polarization along x-axis, as indicated)



Induced polarization along b_y=0

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

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



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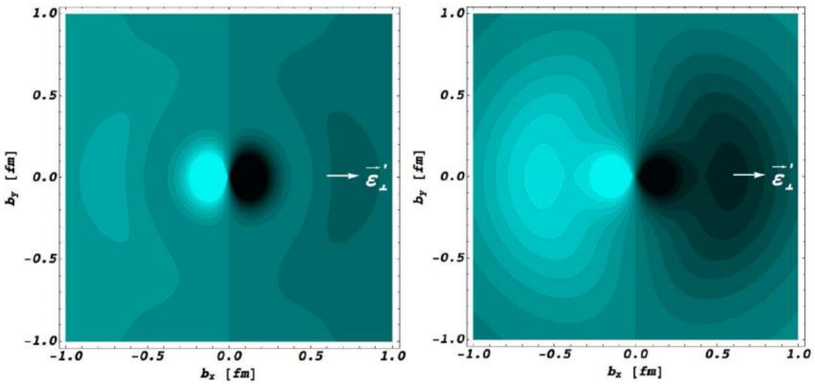
GP II



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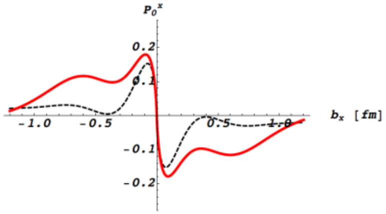

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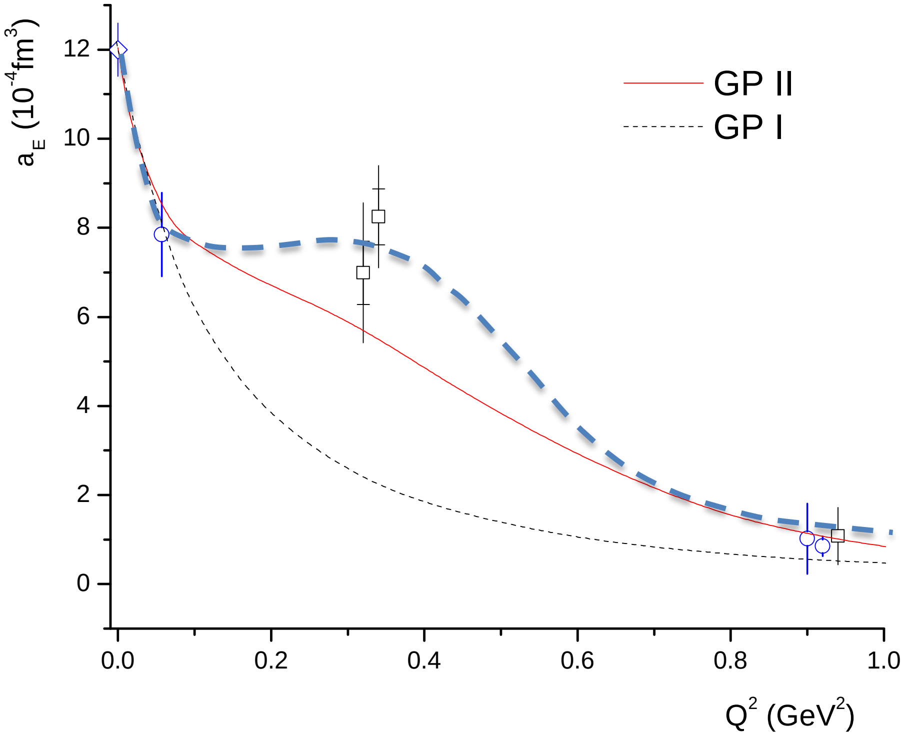
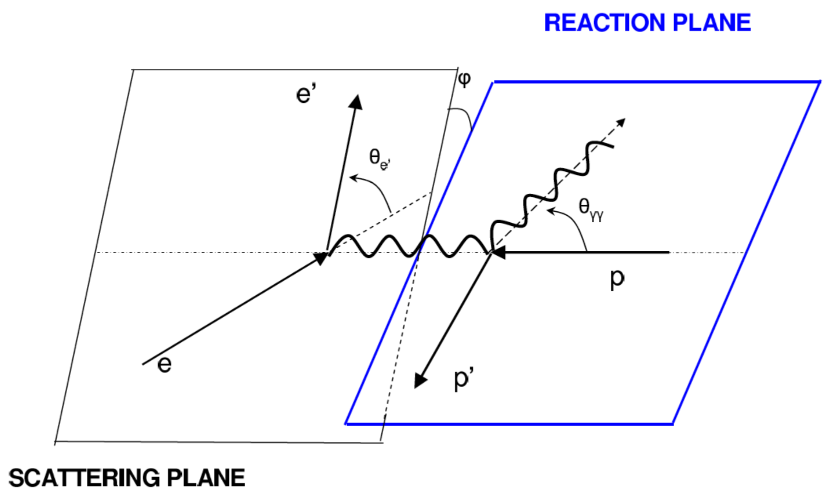
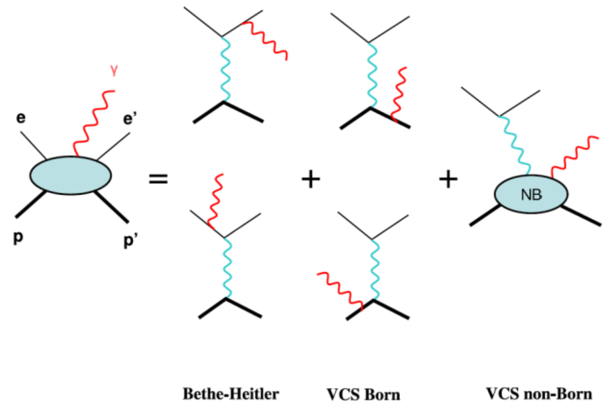


Virtual Compton Scattering





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

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

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

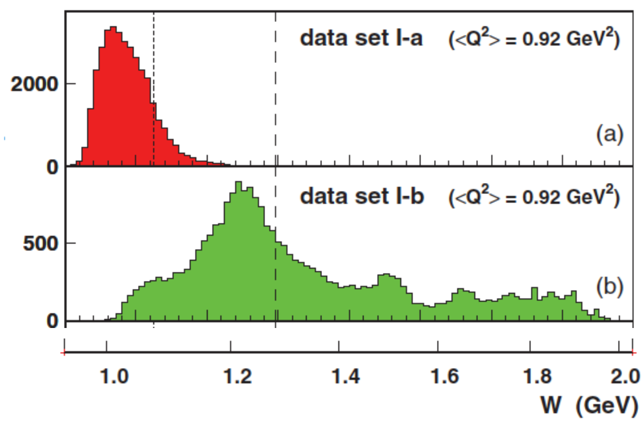
utilize DR

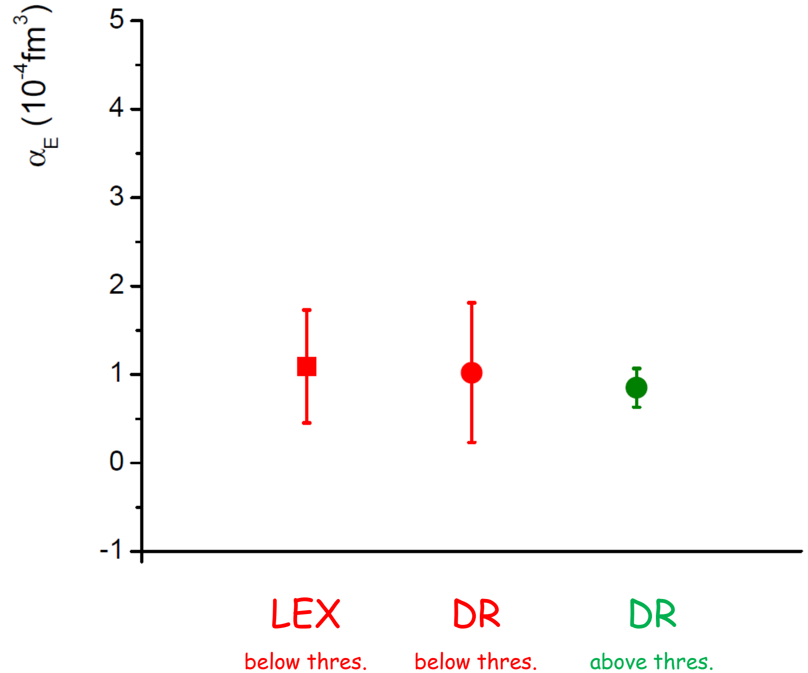
scalar GPs α_E and β_M

Virtual Compton Scattering

Phys. Rev C 86, 015210 (2012)

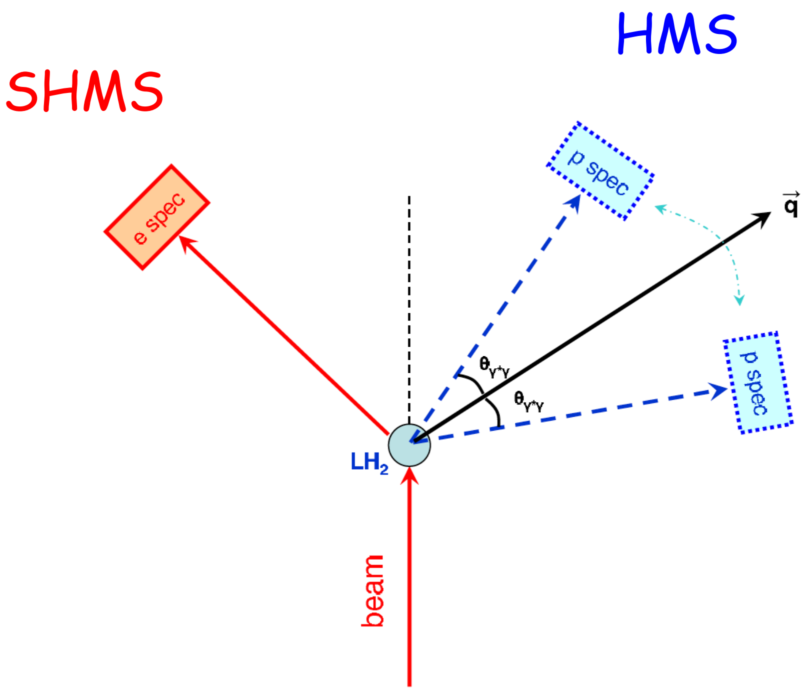
Phys. Rev Lett. 93, 122001 (2004)



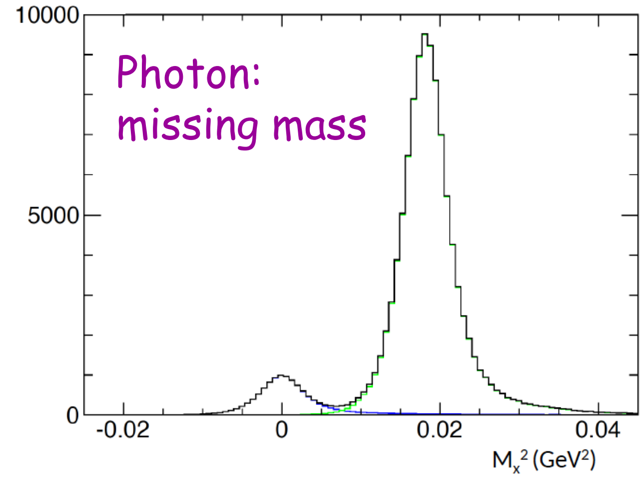


Sensitivity to the GPs grows with the photon energy

Experimental Setup



e & p detection in coincidence



Hall C: SHMS, HMS
4.4 GeV
45-85 μA
Liquid hydrogen 15 cm

cross sections

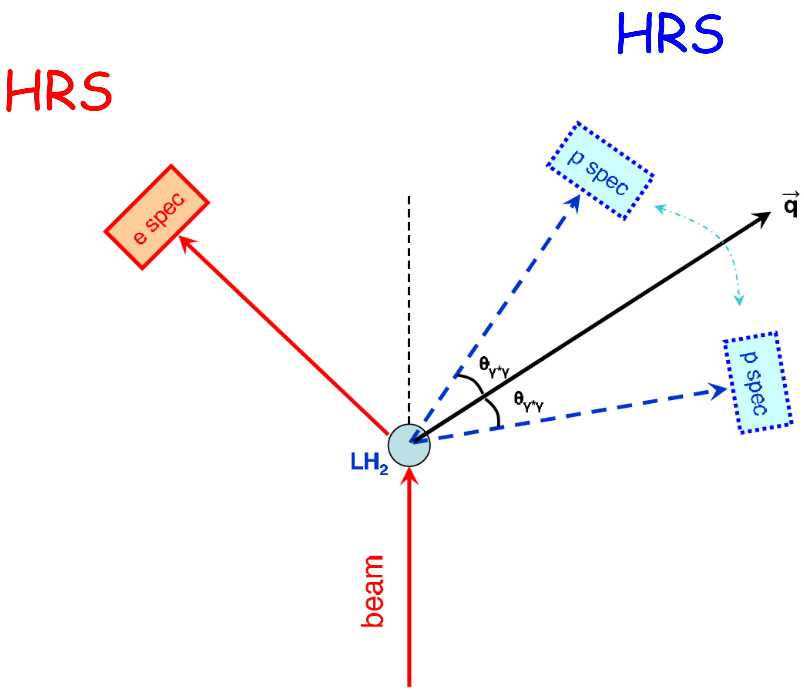
in-plane azimuthal asymmetries

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

sensitivity to GPs

suppression of systematic asymmetries

Experimental Setup



Hall A (?)

HRS min. angle = 12.5 deg

Can not run Part I with 4.4 GeV

Run Part I with a lower beam energy

Part I with 3.3 GeV:

- Reduced sensitivity to GPs
- Smaller cross section

➔ $\delta\alpha_E$ increased by 16.5%

(still very competitive measurement)

Hall A: HRS(e), HRS(p)

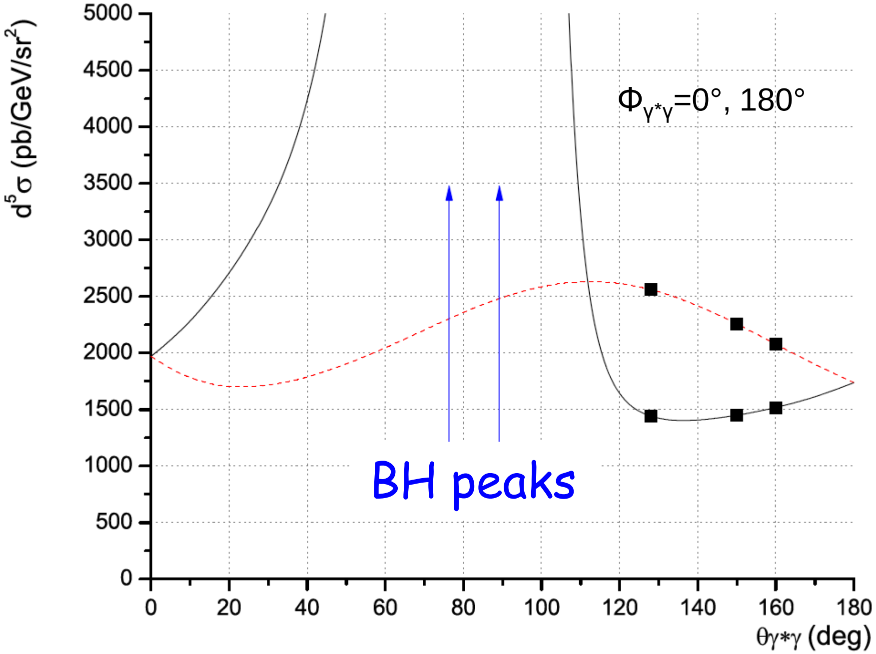
Hall A:	HRS(e), HRS(p)	
	3.3 GeV	3.5 days
	4.4 GeV	10.5 days

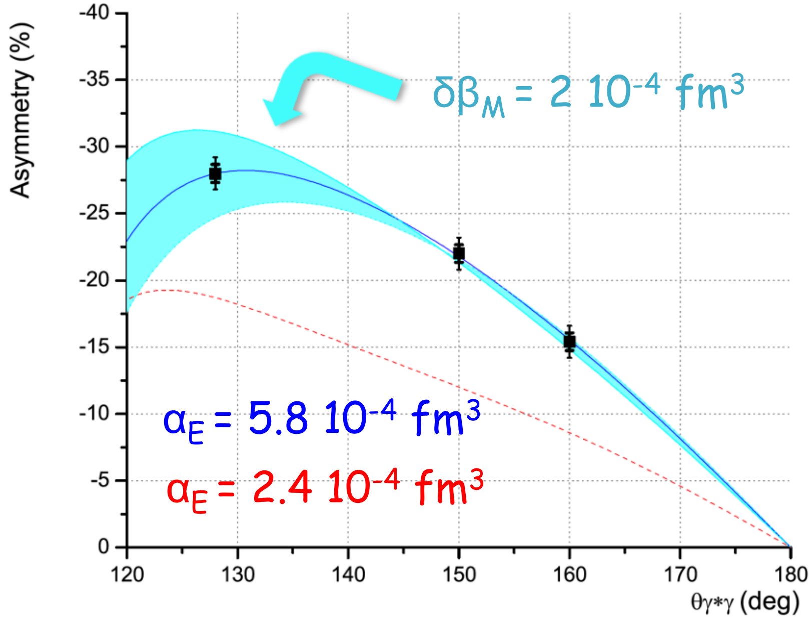
Will not be able to allow for the maximum beam energy to another Hall during Part I (3.5 days)

The high Q^2 Jlab measurements (E93-050) were done in Hall A with the two HRSs, a 15 cm LH2 target, and a 4 GeV beam

Measurements

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





avoid BH peaks

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

Measurements

	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	165	9.39	3820.5	40.85	1010.40	1.3	0.5
	Kin Ib	165	9.39	3820.5	48.45	1010.40	2.4	0.5
	Kin IIa	155	9.39	3820.5	38.34	995.20	1	0.5
	Kin IIb	155	9.39	3820.5	50.96	995.20	3.2	0.5
	Kin IIIa	128	9.39	3820.5	31.84	919.43	0.7	0.95
	Kin IIIb	128	9.39	3820.5	57.46	919.43	7.8	0.55
Part II	Kin IVa	165	11.54	3708.6	40.81	1175.25	2.6	1.5
	Kin IVb	165	11.54	3708.6	47.35	1175.25	5	2
	Kin Va	160	11.54	3708.6	39.73	1167.72	2.2	1.5
	Kin Vb	160	11.54	3708.6	48.43	1167.72	6.3	2
	Kin VIa	140	11.54	3708.6	35.52	1117.38	1.2	1.5
	Kin VIb	140	11.54	3708.6	52.64	1117.38	8	2

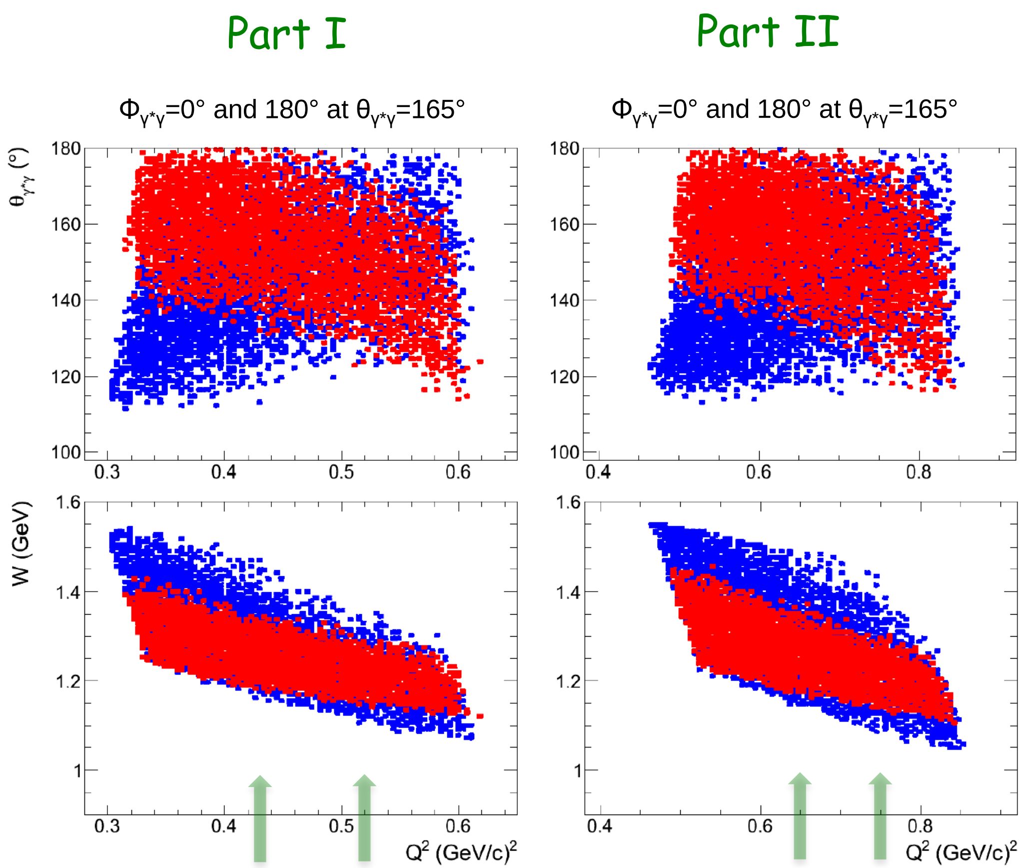
Part I 3.5 days

Part II 10.5 days

SHMS keeps same position & momentum through out Part I (Part II)

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

Measurements



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

Cross section: DR calculation, B. Pasquini

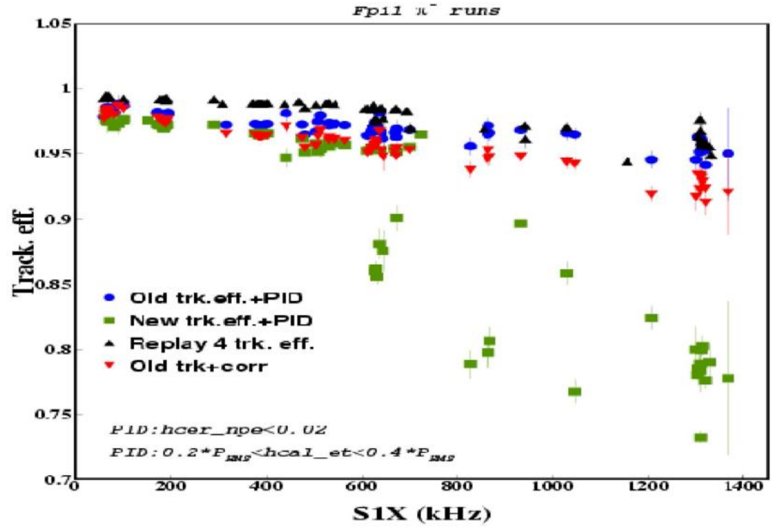
Part	I	I	II	II
Q^2	0.43 (GeV/c)^2	0.52 (GeV/c)^2	0.65 (GeV/c)^2	0.75 (GeV/c)^2

Measurements

HMS singles rates

	Kinematical Setting	HMS singles rates (kHz)
Part I	Kin Ia	213
	Kin Ib	91
	Kin IIa	290
	Kin IIb	68
	Kin IIIa	300
	Kin IIIb	34
Part II	Kin IVa	102
	Kin IVb	37
	Kin Va	122
	Kin Vb	31
	Kin VIa	244
	Kin VIb	16

HMS Tracking Efficiency



HMS singles rates kept below 300 kHz

Kin IIIa ➔ 45 μA

All other settings ➔ 85 μA

Measurements

Plus for systematics:

- Electron momentum & angle stays fixed through out Part I
- Electron momentum & angle stays fixed through out Part II
- Proton momentum stays fixed for the asymmetry pair ($\Phi_{\gamma^*\gamma}$=0°,180°) measurements
- No beam energy changes

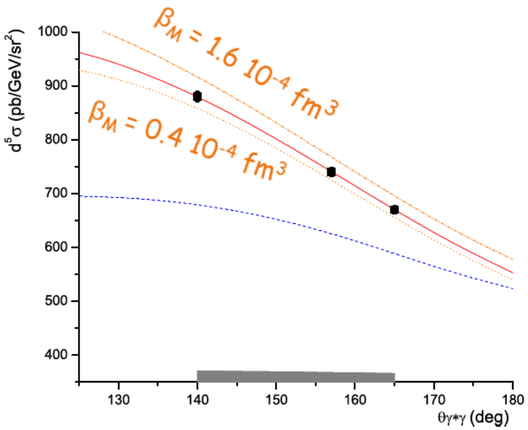
One day for normalization studies / system check out

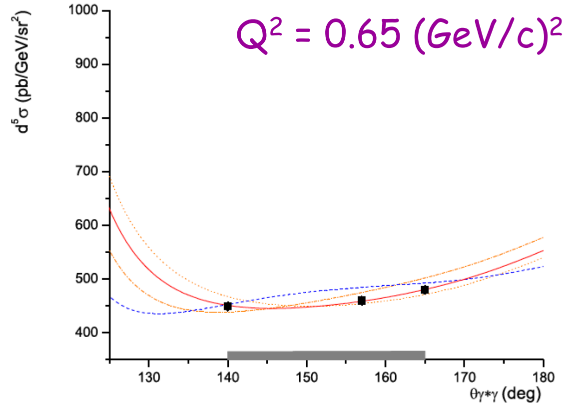
Time could be shared if running with group of other experiments

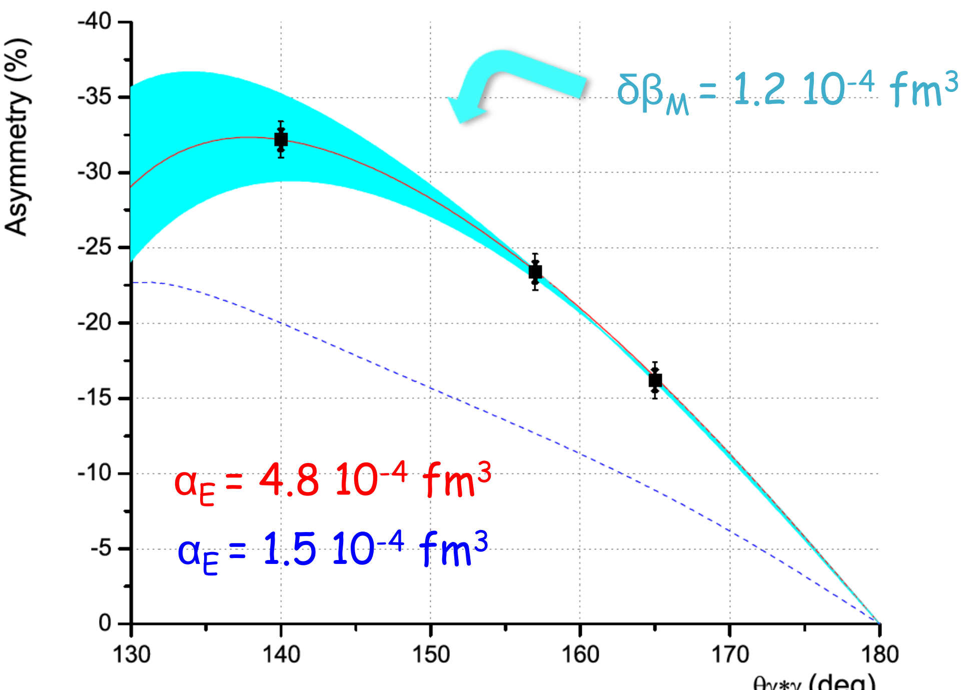
p(e,e'p)π^o measured for free

- High statistics
- Cross section very well known in this region
- Additional normalization per setting

Measurements



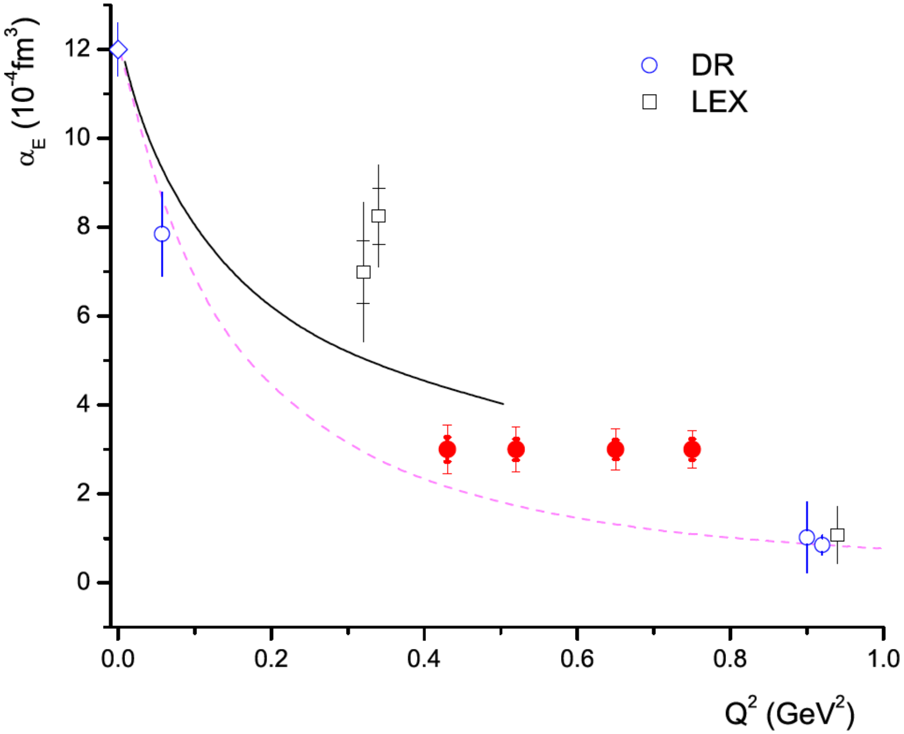


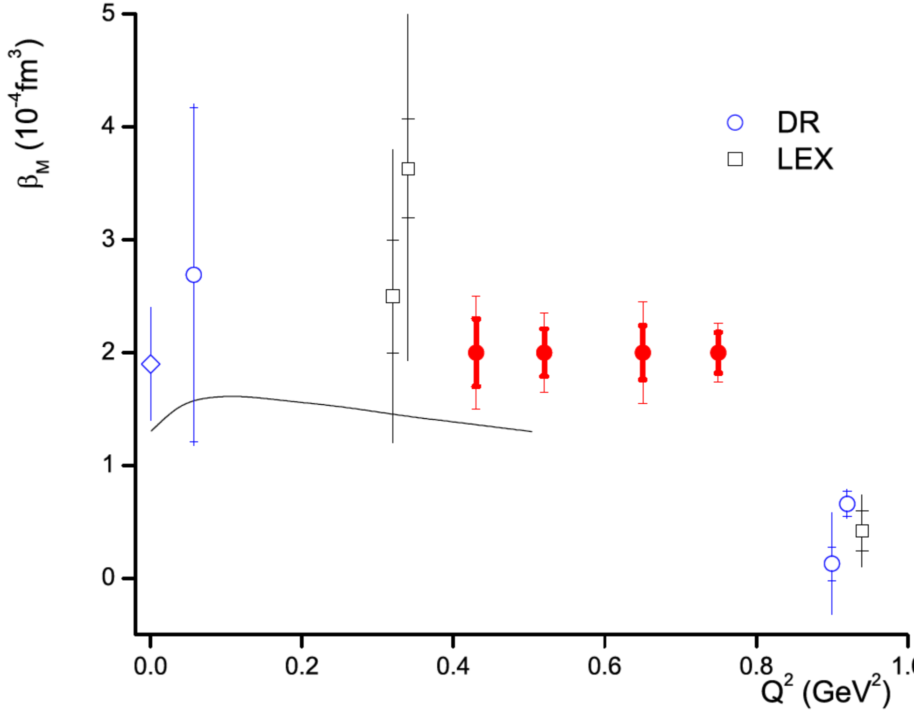


Statistical	< ±1.3%
Beam energy / scat. Angle	±1-2.5%
Target density	±0.5%
Detector efficiency	±0.5%
Acceptance	±0.5%
Target cell backgr.	±0.5%
Target length	±0.3%
Beam charge	±0.3%
Dead time	±0.3%
Pion contamination in MM	±0.3%
Rad. Corr.	±1.5%
Other	±0.5%

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

Projected Results





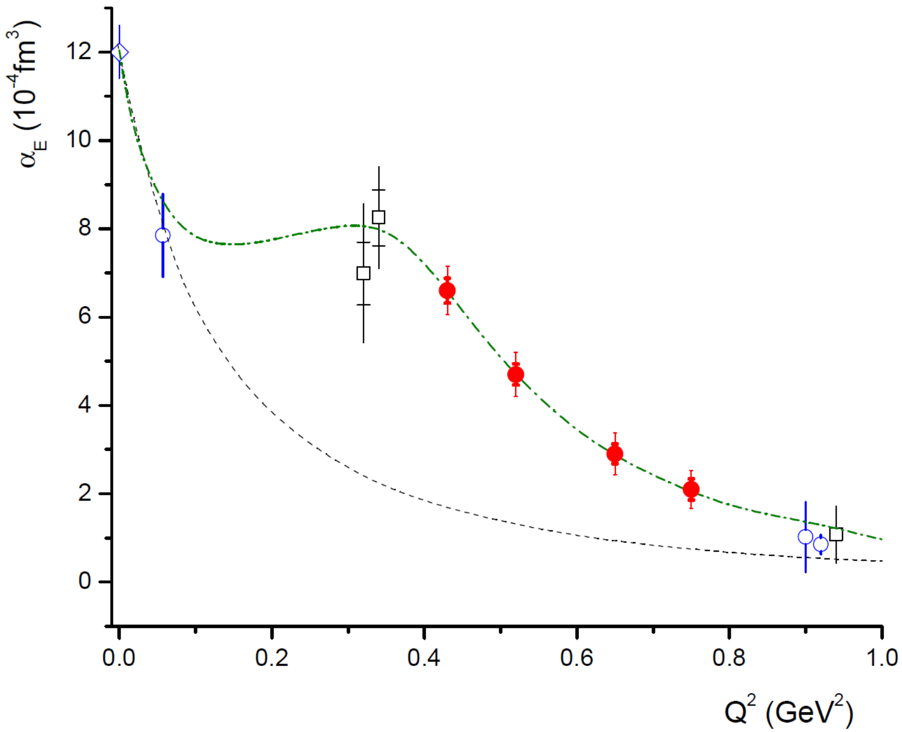
σ, A → Statistics; Systematics; Elastic/ transition FFs, DR multipoles → α_E, β_M

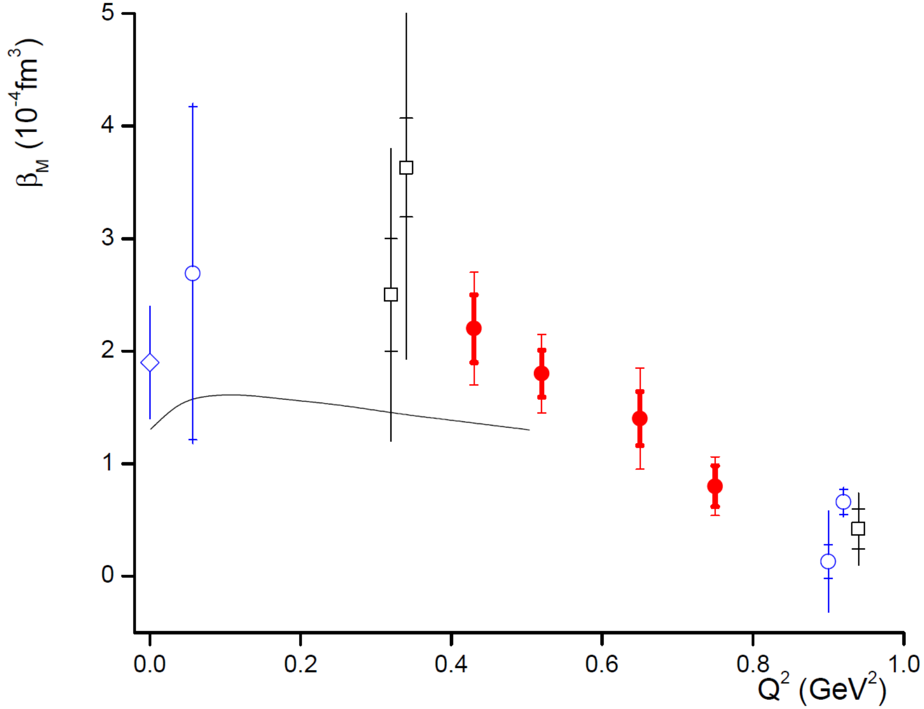
$\delta_{GPs(stat)} \approx 0.7\ \delta_{GPs(syst)}$

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

Beam time request

measurements arbitrarily projected



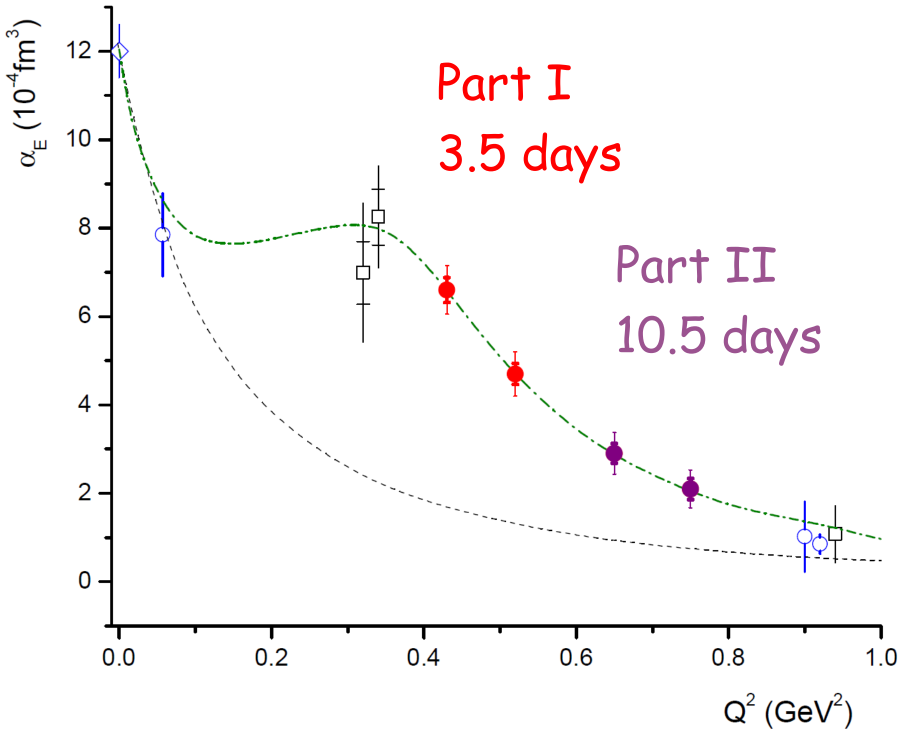


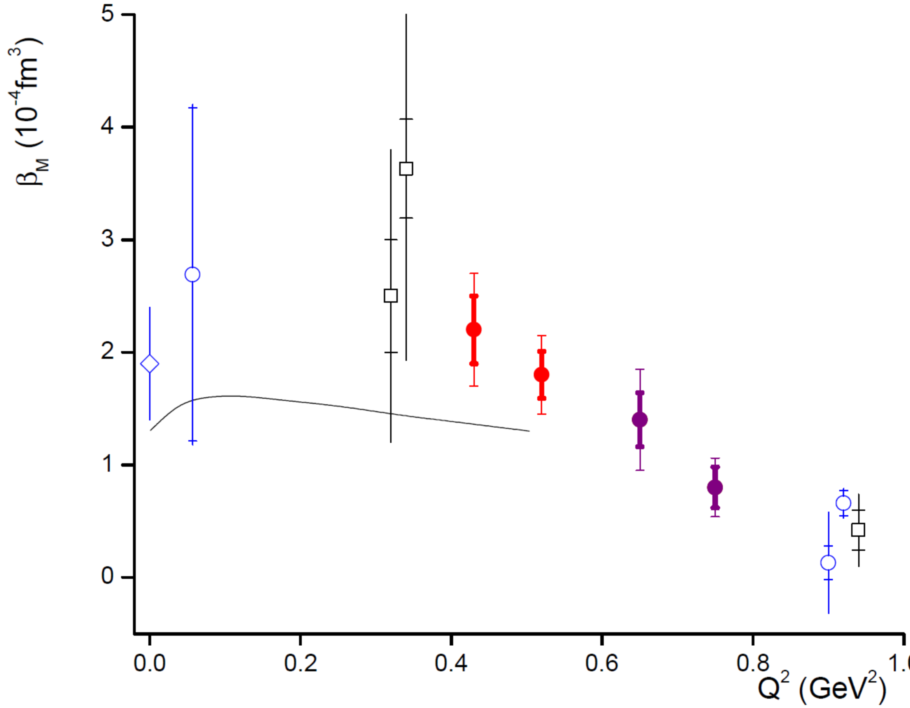
Beam time request: 15 days 4.4 GeV 85 μA Hall C

Could also run in Hall A with the HRS's
and two different beam energies (3.3 GeV and 4.4 GeV)

Beam time request

measurements arbitrarily projected





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Summary

High precision measurements of the electric and magnetic GPs

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

New measurements in a region very sensitive to the nucleon dynamics

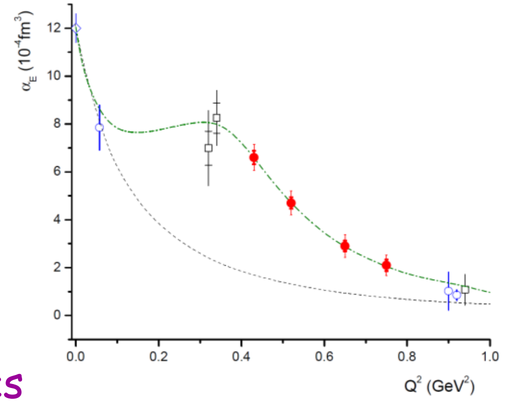
- will improve the precision of α_E and β_M by a factor of 2
- map vs Q^2 – bridge low Q^2 measurements – cross check measurements of other labs
- explore non trivial Q^2 dependence of α_E (mesonic cloud, something else … ?)
- quantify the balance between paramagnetism and diamagnetism through β_M
- will 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 – very important to cross check these calculations
- the new measurements are expected to trigger more theoretical activity

Beam time request:

- 15 days with 4.4 GeV in Hall C (standard setup)
- 3.5 days (Part I) advances greatly our current knowledge of α_E, β_M
- possible also in Hall A

Thank you!

Summary



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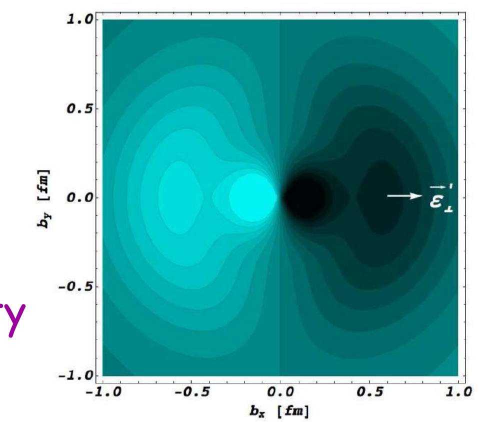

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