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

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

A. Camsonne, M. Jones, M. Paolone, N. Sparveris (contact)

Proposal PR12-15-001 was conditionally approved (C2) by PAC43

PAC43 summary: "The PAC is excited about this proposed measurement, but believes that it is important to see the forthcoming MAMI results before a final decision can be made. The PAC can then perform a better evaluation of the impact the proposed measurements would have."

Other PAC comments:

Motivation: "Clearly, additional experimental information (and confirmation) is needed, which is what the present proposal aims at providing."

Measurement / feasiblity: "The PAC emphasizes that there is a lot of prior experience at JLab with measurements of generalized polarizabilities, so that there are no concerns regarding feasibility."

Kinematics: The PAC has asked that one more measurement at Q^2=0.33 (GeV/c)^2 is added as an integral part of this proposal.

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

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PAC43 summary: **"The PAC is excited about this proposed measurement, but believes that it is important to see the forthcoming MAMI results before a final decision can be made. The PAC can then perform a better evaluation of the impact the proposed measurements would have."**

Updates in this proposal:

Kinematics: A measurement at Q^2=0.33 $(GeV/c)^2$ has been added to the proposal ➔ 3 additional days of beam time.

MAMI measurements: Preliminary results have been released recently from the A1/1-09 and A1/3-13 MAMI experiments.

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

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

PDG

150 Baryon Summary Table

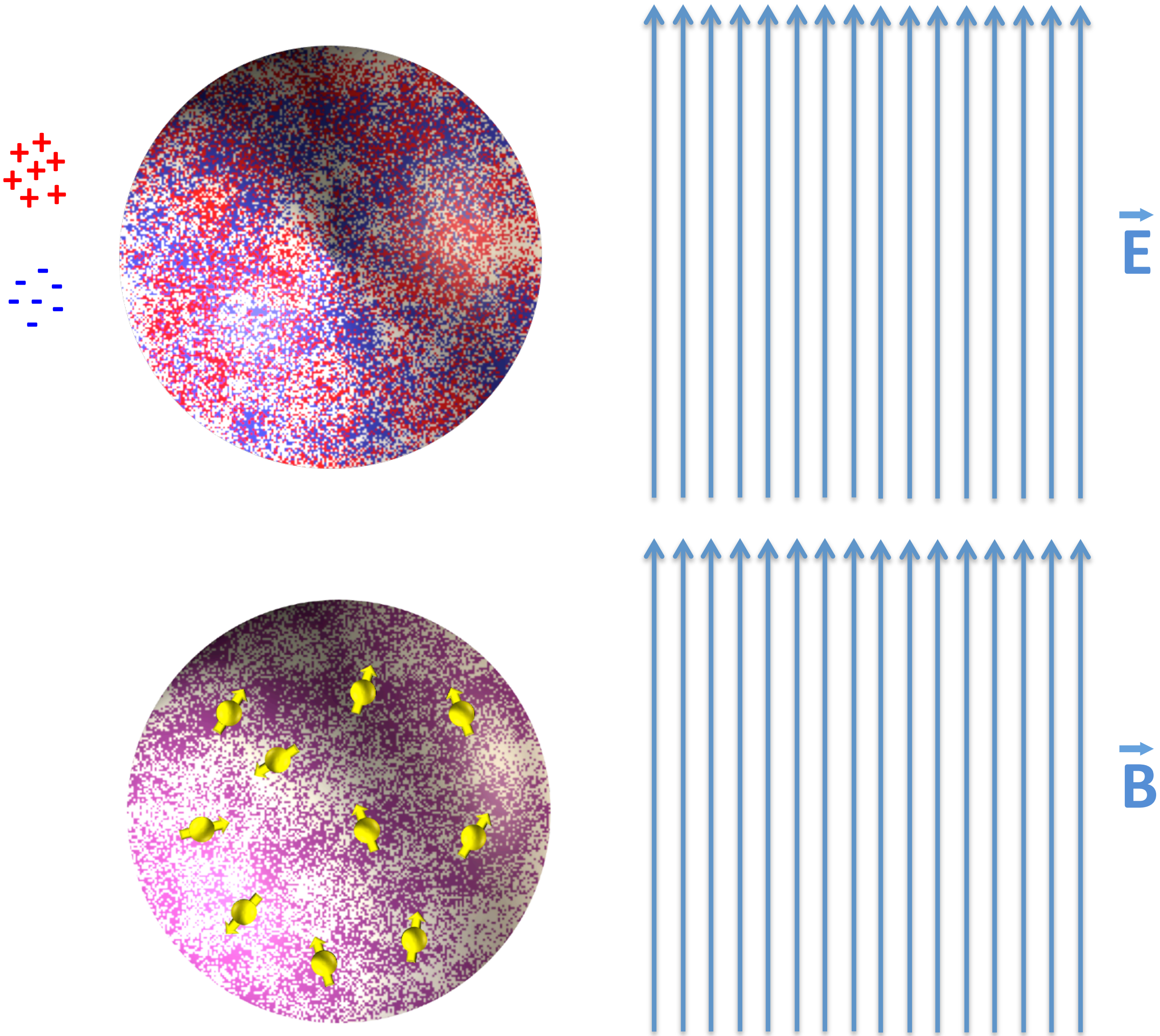
N BARYONS
$(S = 0, I = 1/2)$
$p, N^+ = uud$; $n, N^0 = udd$

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

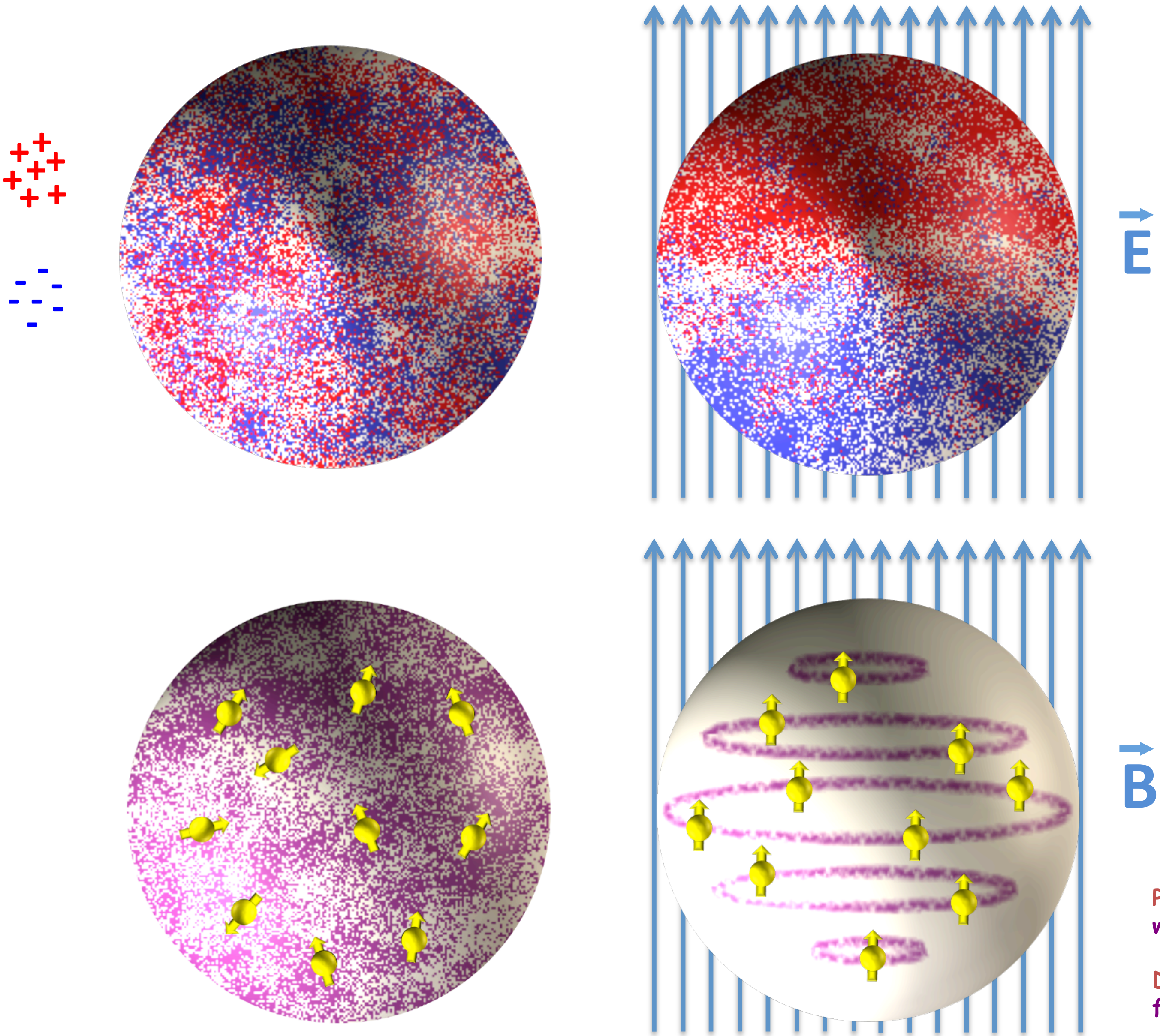
Scalar Polarizablities

Response of internal structure to an applied EM field



Scalar Polarizablities

Response of internal structure to an applied EM field



"stretchability"

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

External field deforms the charge distribution

"alignability"

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

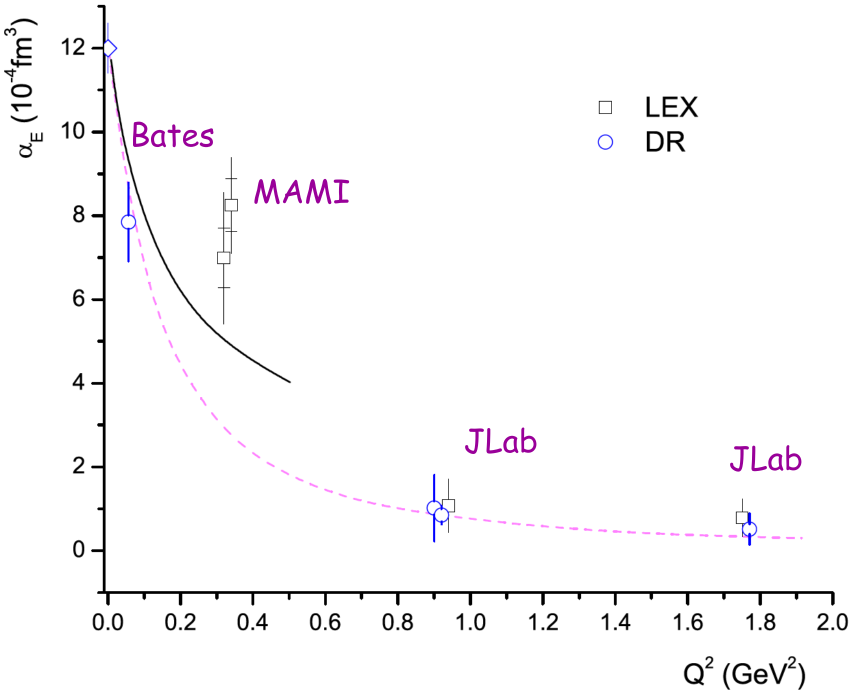
$\beta_{para} > 0$

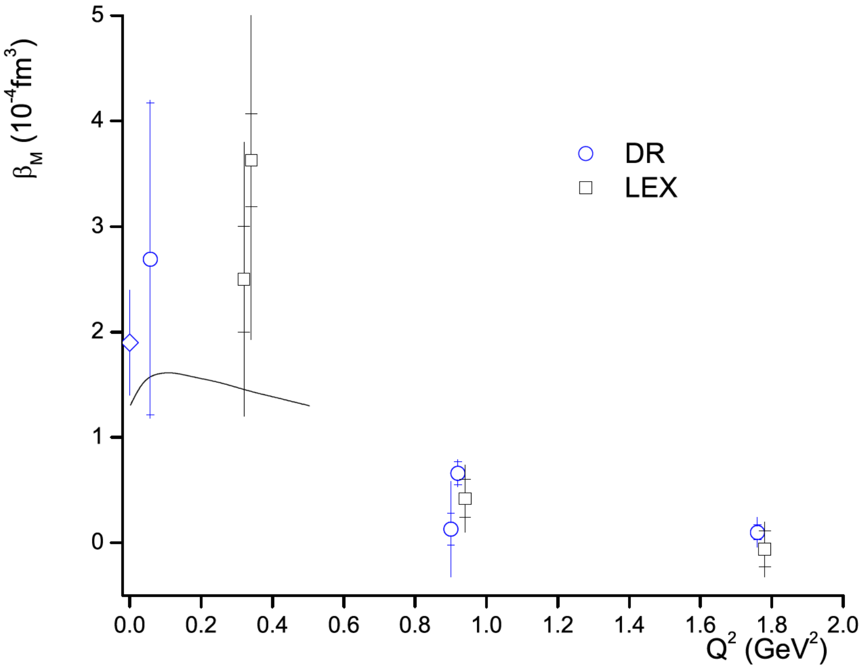
$\beta_{diam} < 0$

Paramagnetic: proton spin aligns with the external magnetic field

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

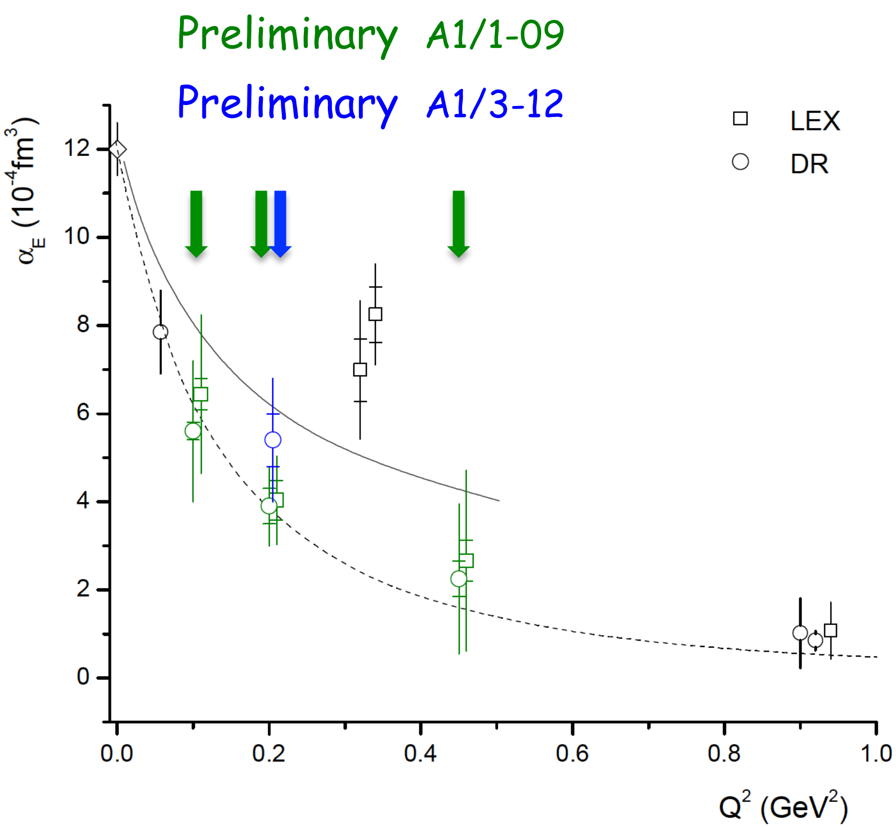
- more measurements needed (vs Q^2)
- Higher precision measurements needed

Ongoing Experimental Efforts

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 to the Q^2=0.33 $(GeV/c)^2$ measurements

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



Preliminary results:

LEPP conference, Mainz, April 2016

Clermont-Fd & Temple groups

4 PhD students

2 independent measurements at Q^2=0.20 (GeV)

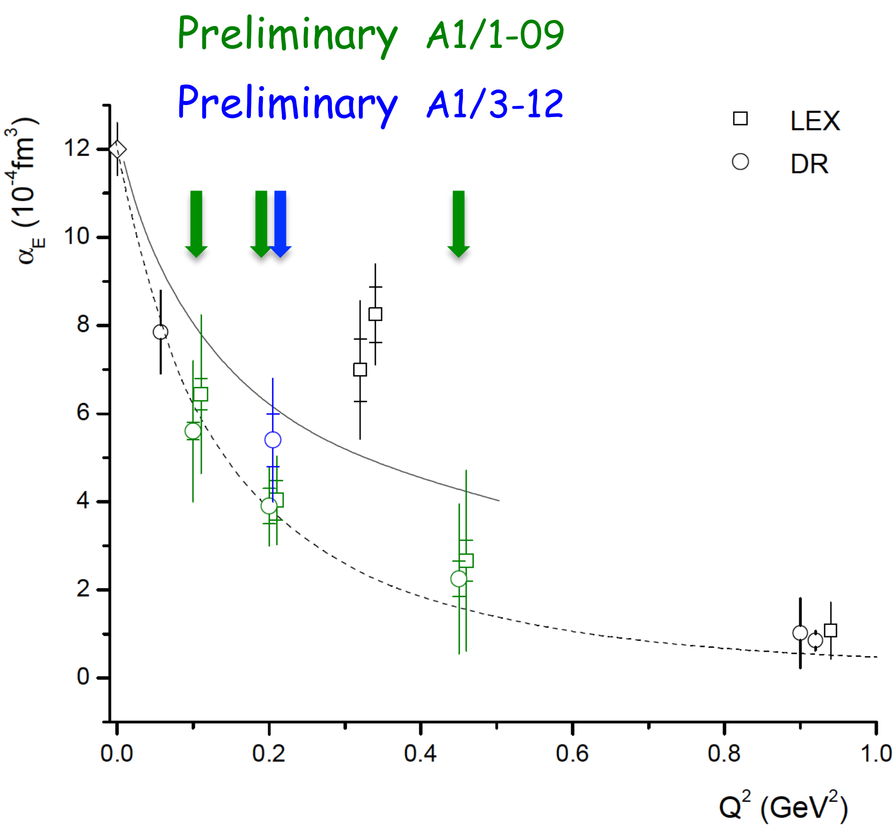
Revisiting the Q^2=0.33 $(GeV/c)^2$ measurements

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

Two different experiments – a few years apart

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

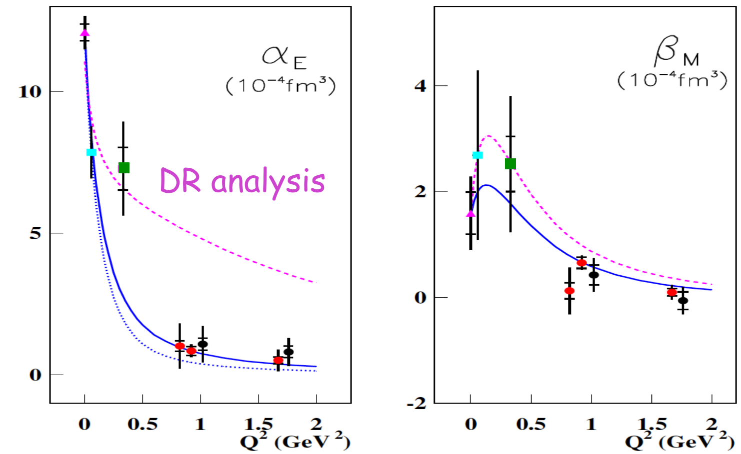
Results from both experiments through LEX



DR analysis of the data:

published in a review talk by N. d'Hose

Eur. Phys. J A 28, s1, 117 (2006)



DR – LEX agreement

Breakdown of uncertainties
not well documented

DR & LEX analysis recently revisited

Currently ongoing effort

Results so far still point out to an enhanced a_E value at Q^2=0.33 $(GeV/c)^2$

Ongoing Experimental Efforts

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

Jlab (This proposal)

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

ε=0.97 (Jlab)

ε=0.62 (MAMI)

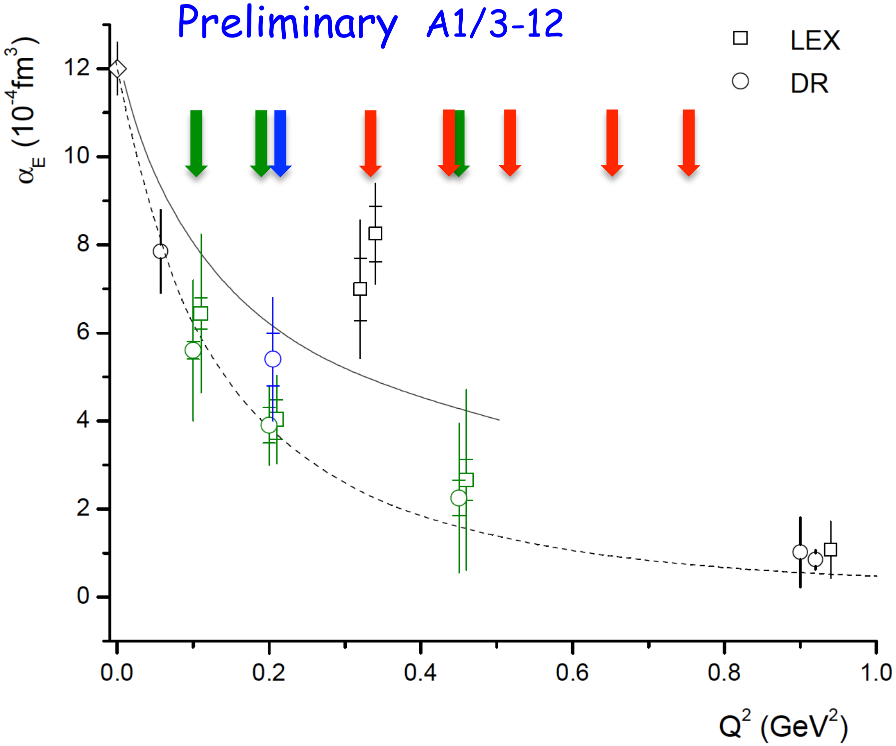
additional + :

Beam energy x 4

Beam current x 5

Preliminary A1/1-09

Preliminary A1/3-12



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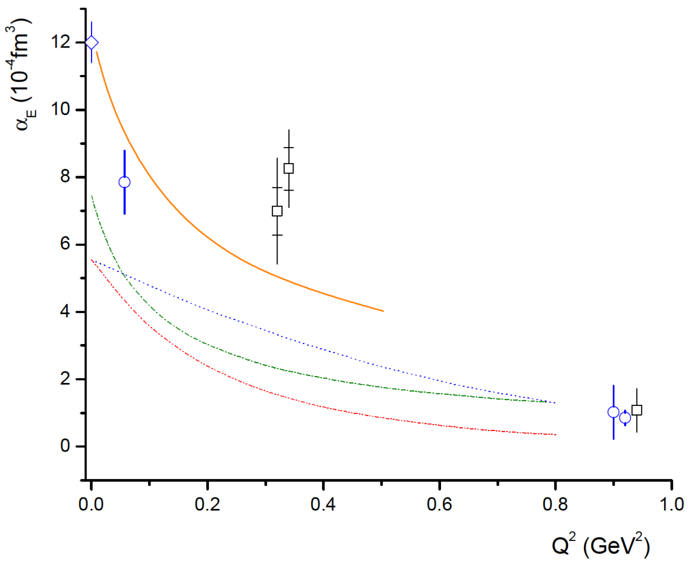
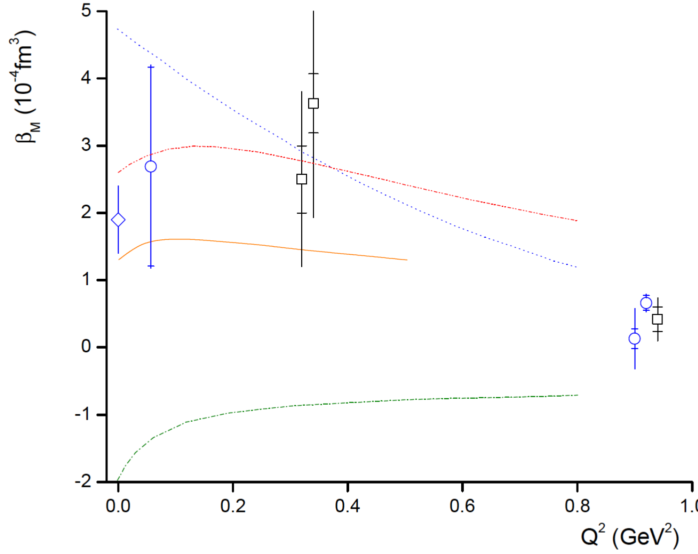
2 independent measurements at Q^2=0.20 (GeV)

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 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 external e.m. field:

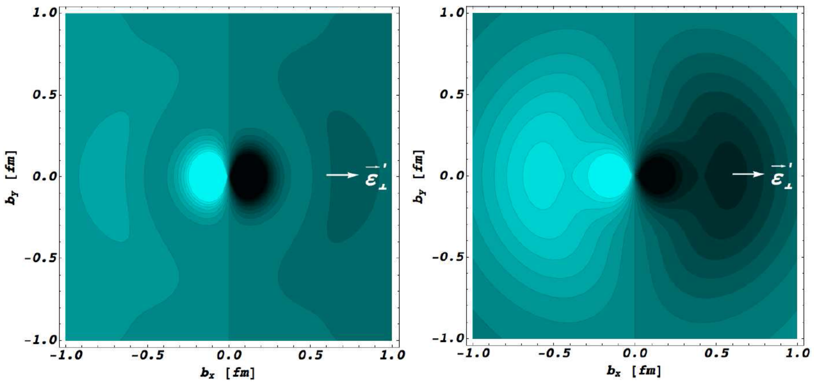
GPs ➔ spatial deformation of charge & magnetization densities under an applied e.m. field

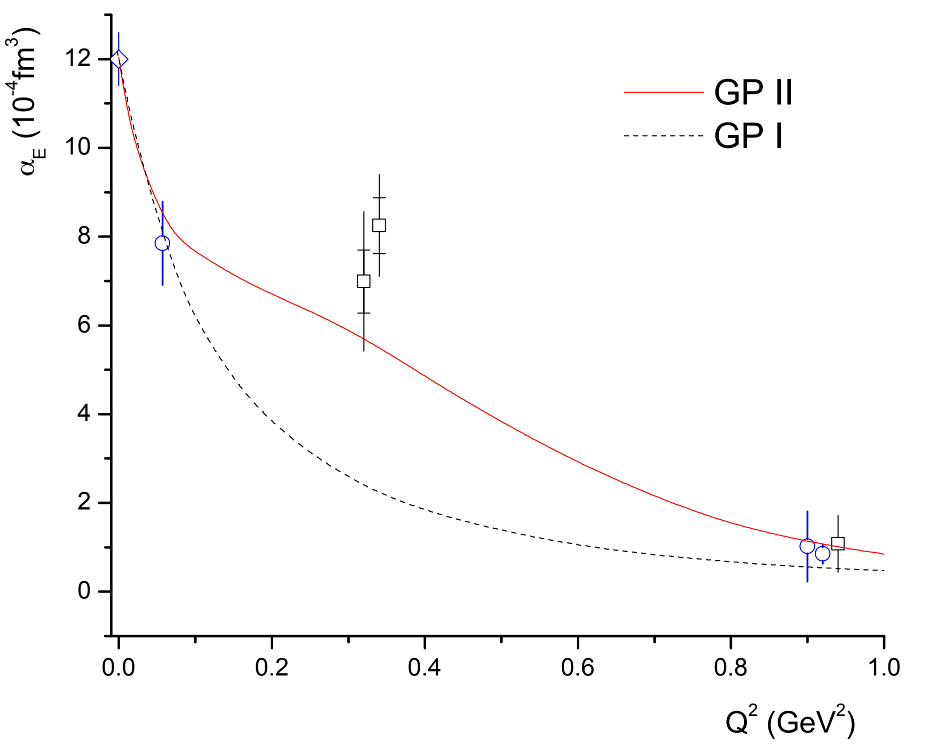
Induced polarization in a proton when submitted to an e.m. field

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

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

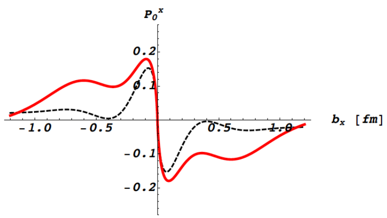
GP I GP II





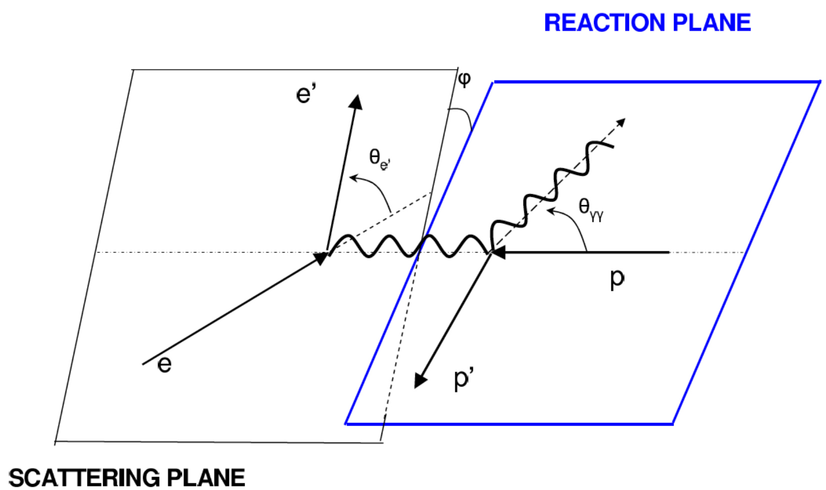
Light (**dark**) regions ➔ **largest** (**smaller**) values

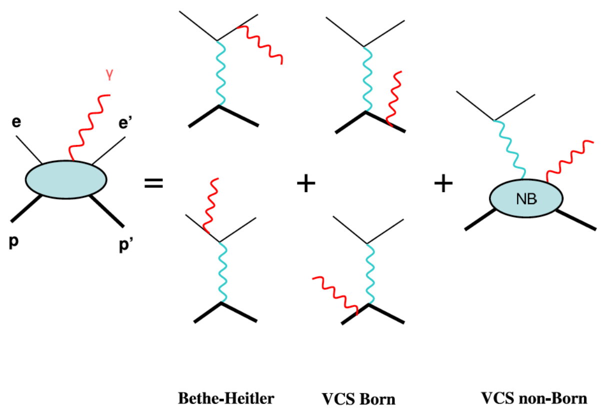
(photon polarization along x-axis, as indicated)



Induced polarization along b_y=0

Virtual Compton Scattering

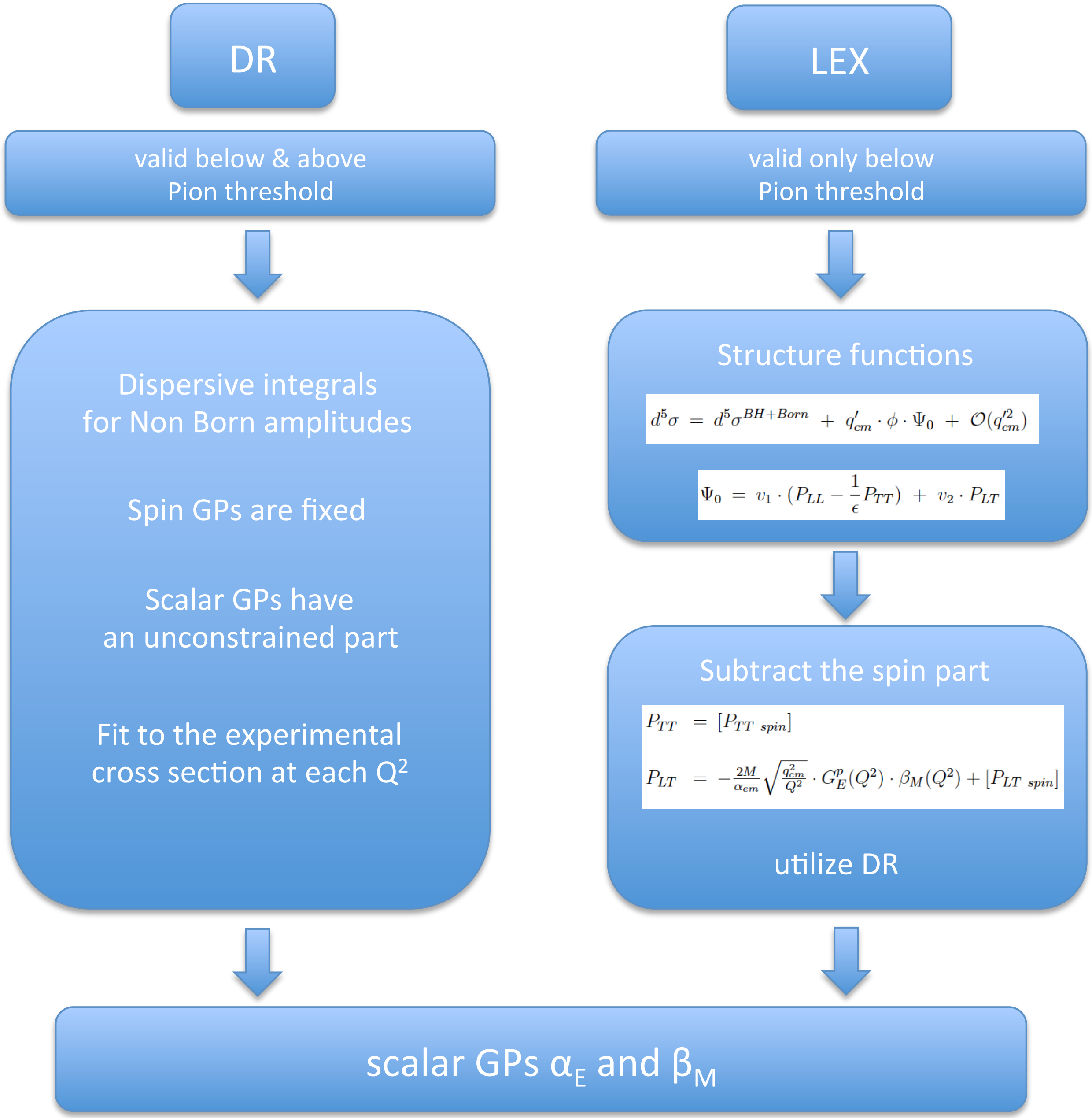




Elastic FFs

GPs

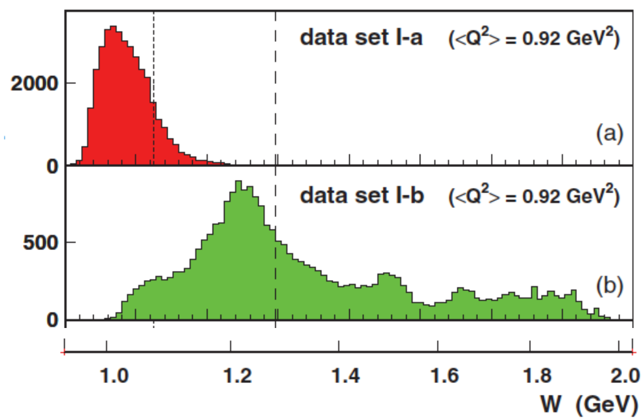
Virtual Compton Scattering

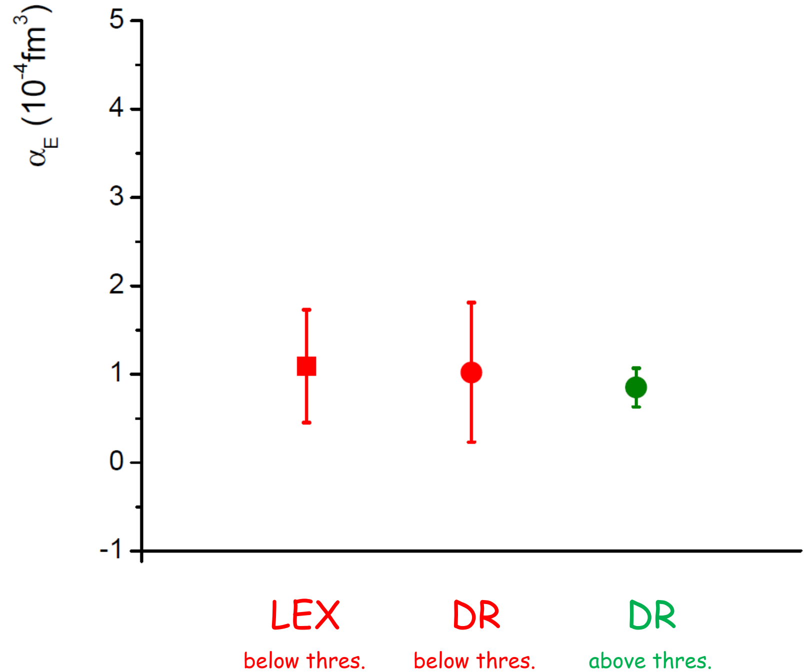


Virtual Compton Scattering

Phys. Rev C 86, 015210 (2012)

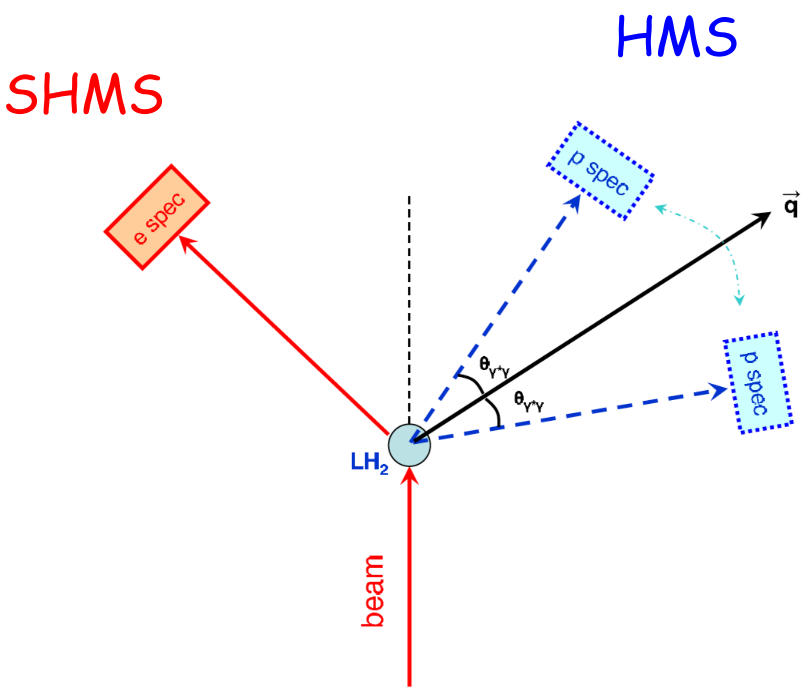
Phys. Rev Lett. 93, 122001 (2004)



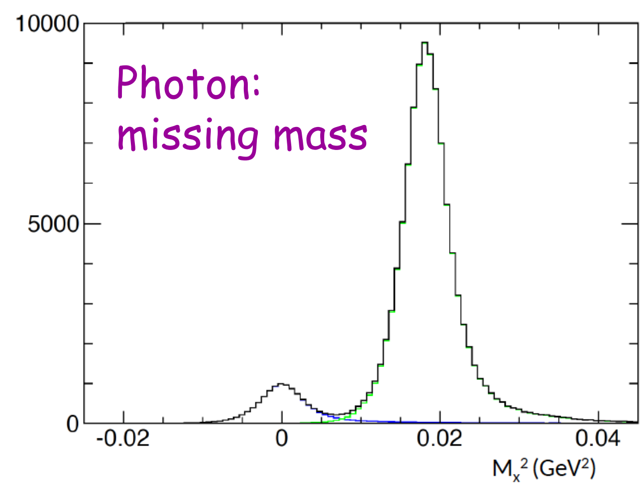


Sensitivity to the GPs grows with the photon energy

Experimental Setup



e & p detection in coincidence



Hall C: SHMS, HMS
4.4 GeV
40-85 μA
Liquid hydrogen 15 cm

cross sections

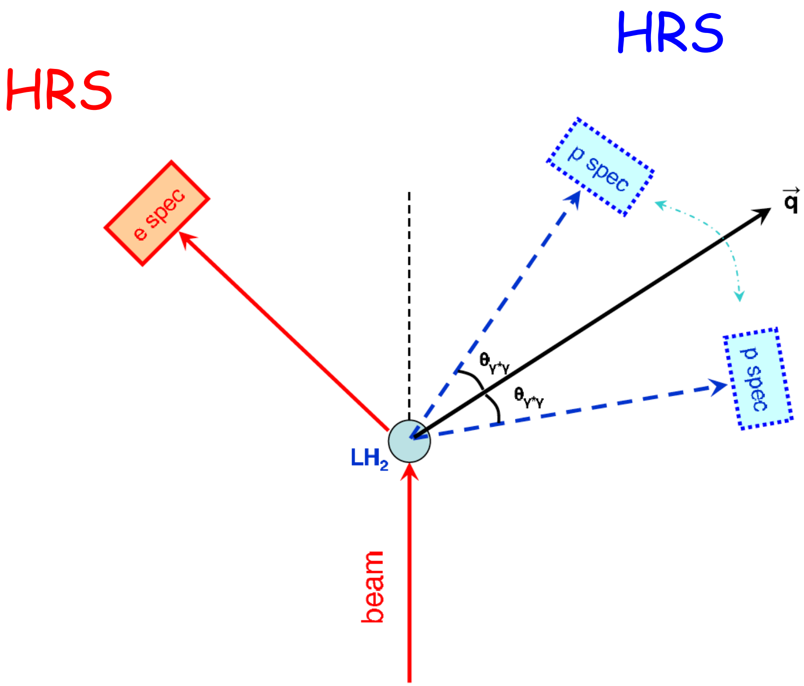
in-plane azimuthal asymmetries

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

sensitivity to GPs

suppression of systematic 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 17%

(still very competitive measurement)

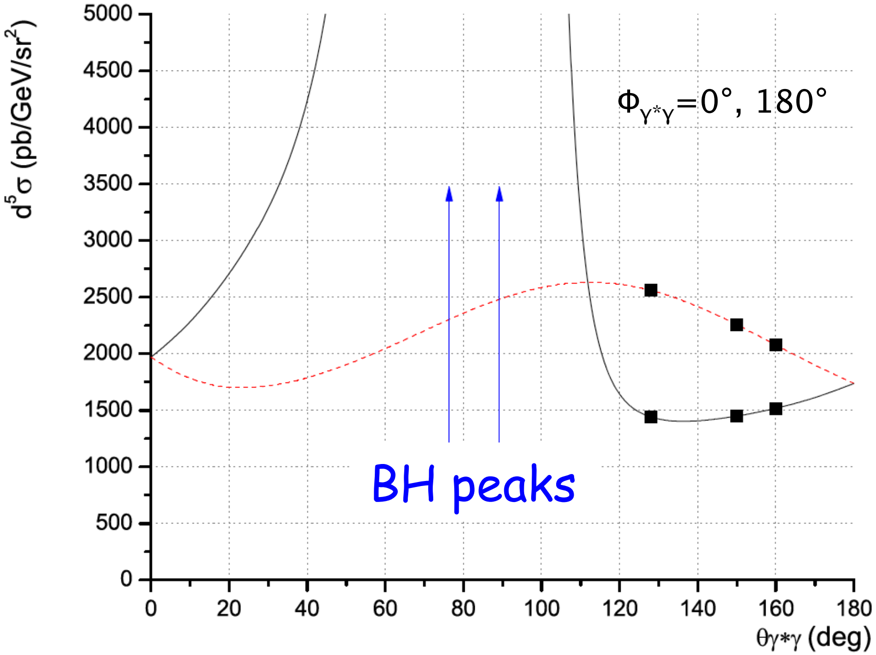
Hall A:	HRS(e), HRS(p)	
	3.3 GeV	6.5 days
	4.4 GeV	10.5 days

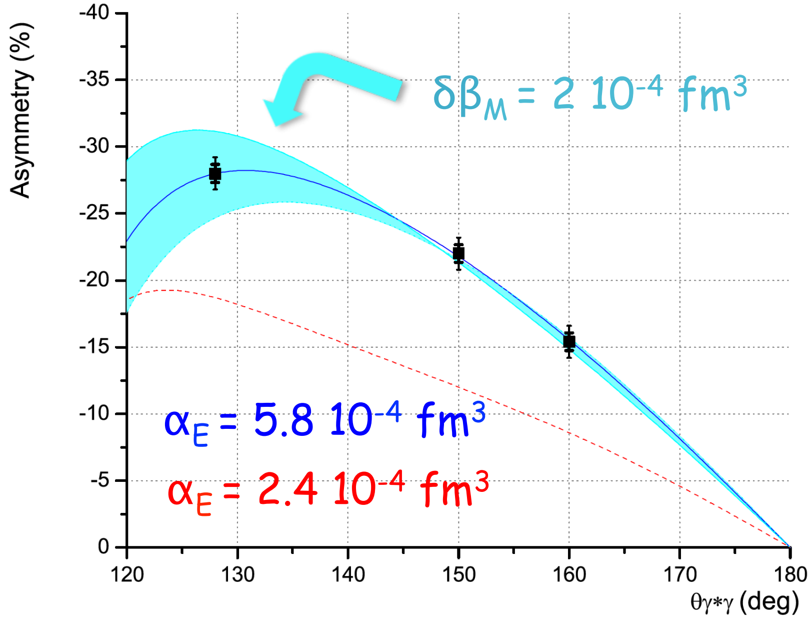
Will not be able to allow for the maximum beam energy to another Hall during Part I (6.5 days)

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	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 6.5 days

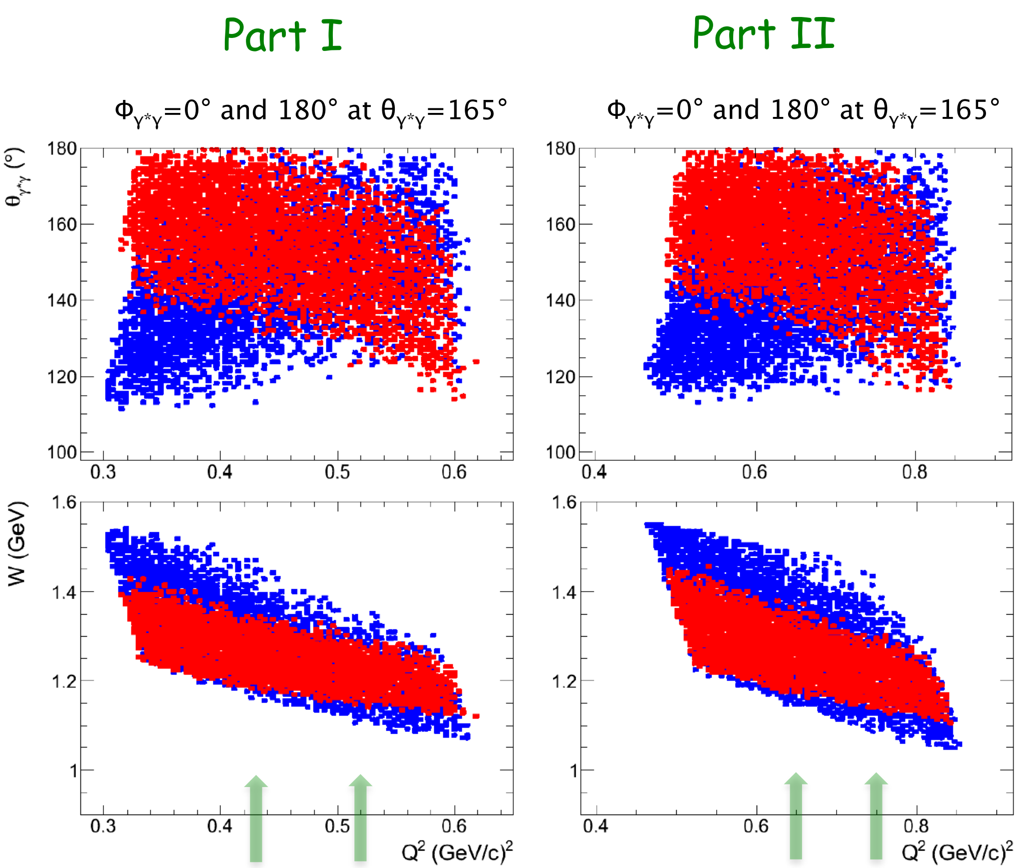
Part II 10.5 days

SHMS: one change of setting through Part I

same position & momentum through out Part II

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 $(GeV/c)^2$

Measurements



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

Cross section: DR calculation, B. Pasquini

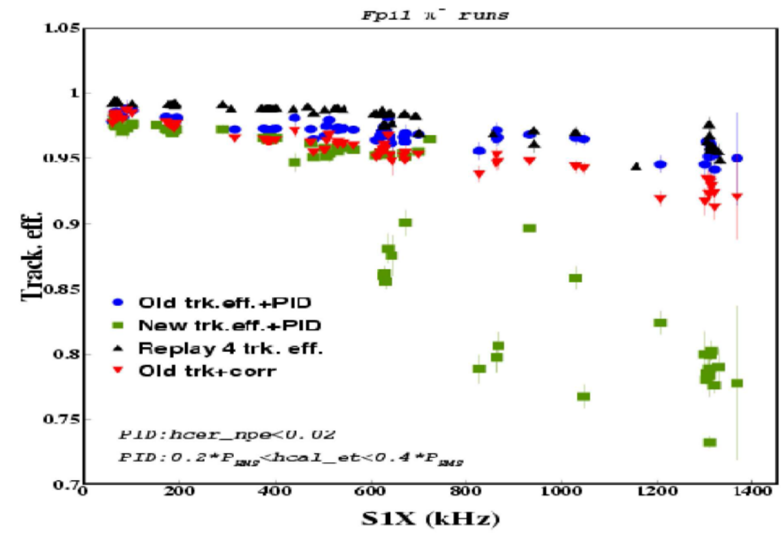
Part	I	I	I	II	II
Q^2	0.33 (GeV/c)	0.43 (GeV/c)^2	0.52 (GeV/c)^2	0.65 (GeV/c)^2	0.75 (GeV/c)^2

Measurements

HMS singles rates

	Kinematical Setting	HMS singles rates (kHz)
Part I	Kin Ia	163
	Kin Ib	43
	Kin IIa	244
	Kin IIb	31
	Kin IIIa	300
	Kin IIIb	21
	Kin IVa	213
	Kin IVb	91
	Kin Va	290
	Kin Vb	68
	Kin VIa	300
	Kin VIb	34
Part II	Kin VIIa	102
	Kin VIIb	37
	Kin VIIIa	122
	Kin VIIIb	31
	Kin IXa	244
	Kin IXb	16

HMS Tracking Efficiency



HMS singles rates kept below 300 kHz

Kin I, I, III, VIa ➔ 40 - 50 μA

All other settings ➔ 85 μA

Measurements

Plus for systematics:

- Electron momentum & angle: one change during 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

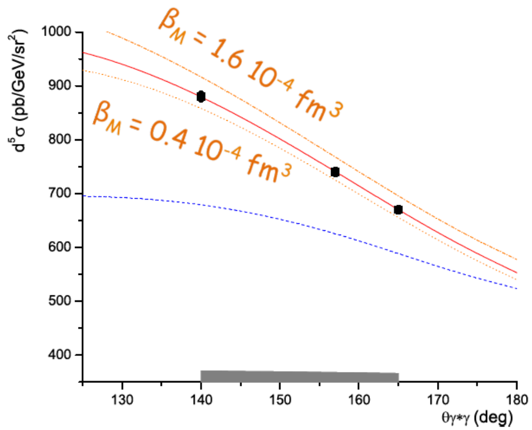
One day for normalization studies / system check out

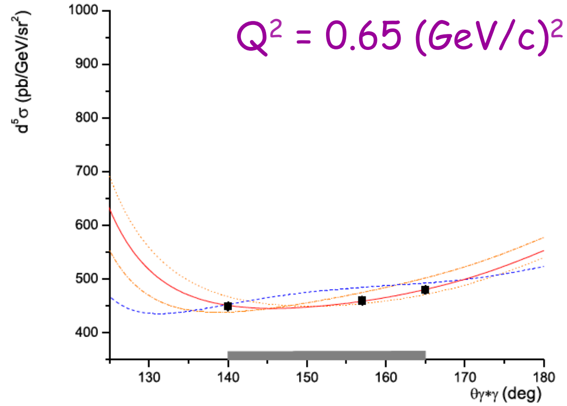
Time could be shared if running with group of other experiments

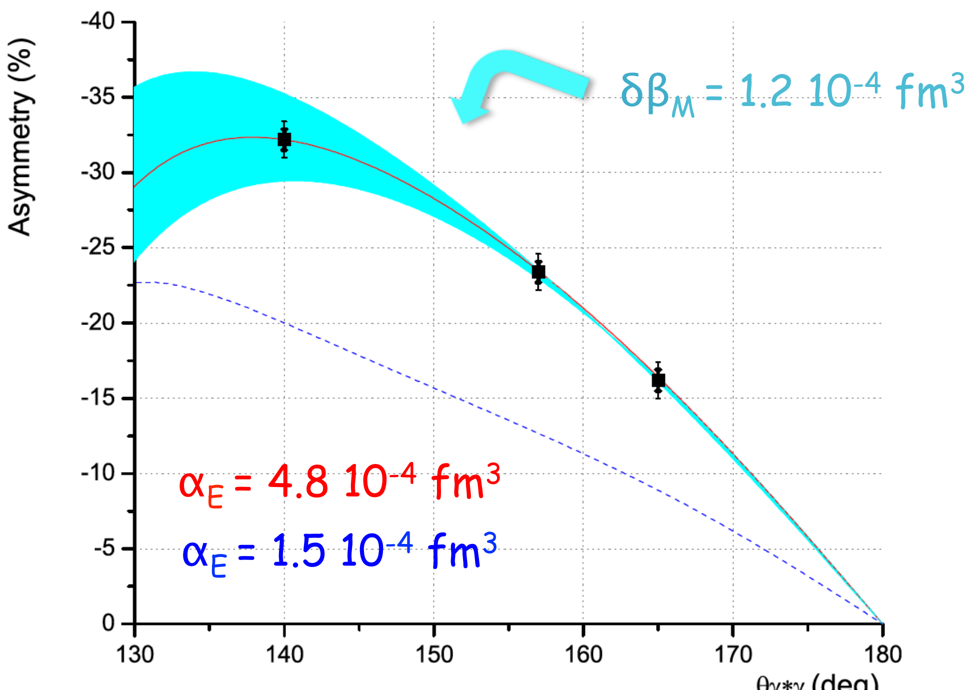
$p(e,e'p)\pi^o$ measured for free

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

Measurements



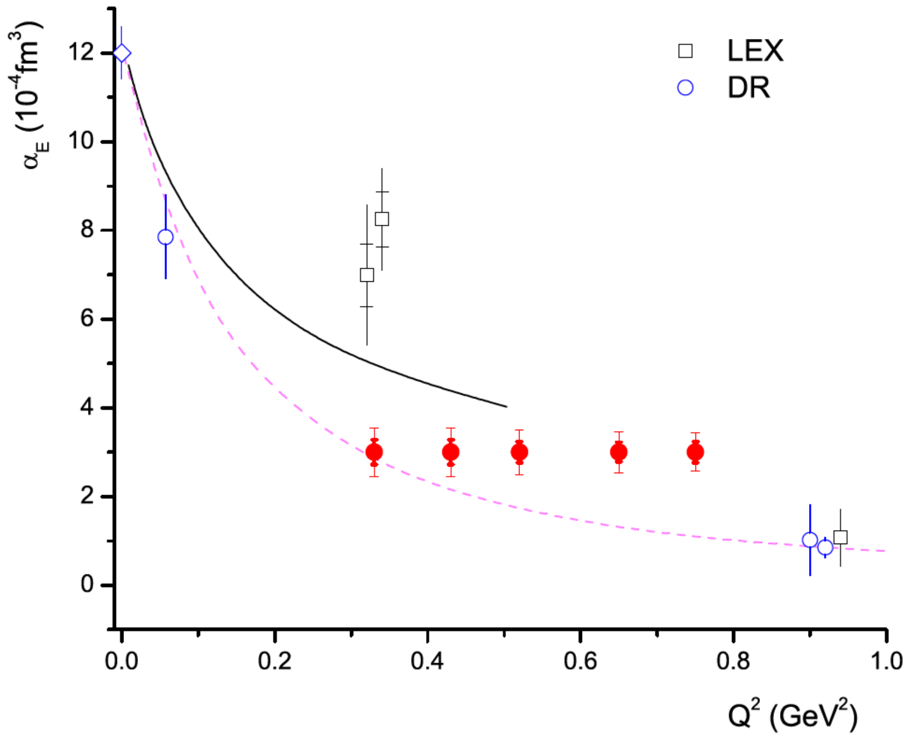


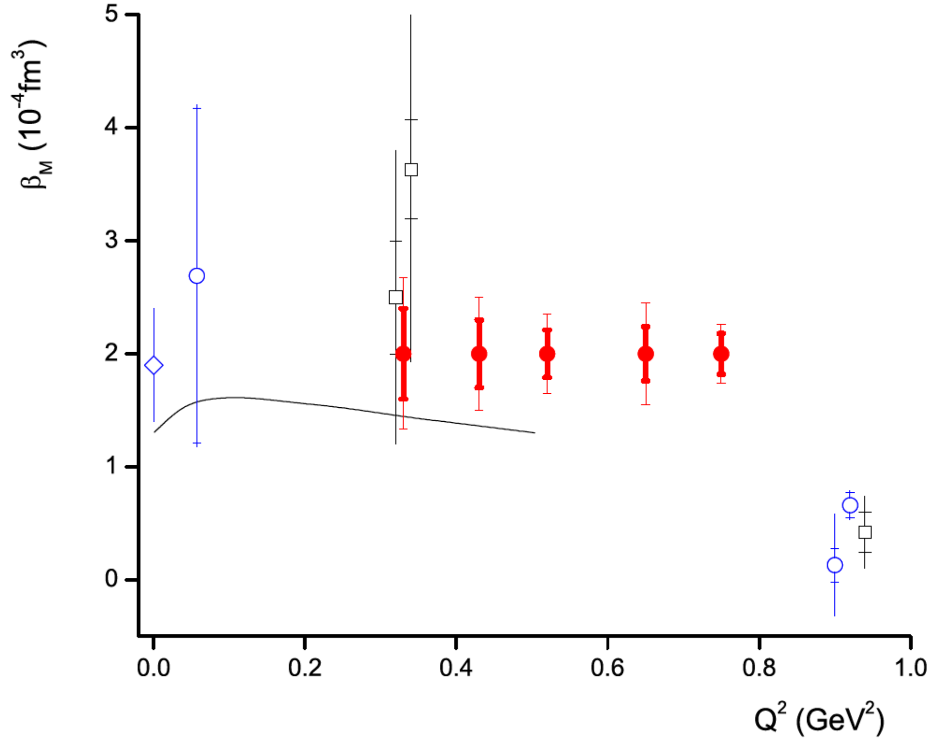


Statistical	< ±1.3%
Beam energy / scat. Angle	±1.3-2.6%
Target density	±0.7%
Detector efficiency	±0.7%
Acceptance	±1.3%
Target cell backgr.	±0.5%
Target length	±0.4%
Beam charge	±0.5%
Dead time	±0.3%
Pion contamination in MM	±0.3%
Rad. Corr.	±1.5%
Other	±0.5%

σ	< ±1.3% (stat)	< ±3.5% (syst)
A	≈ ±0.7% (stat)	≈ ±1.1% (syst)

Projected Results





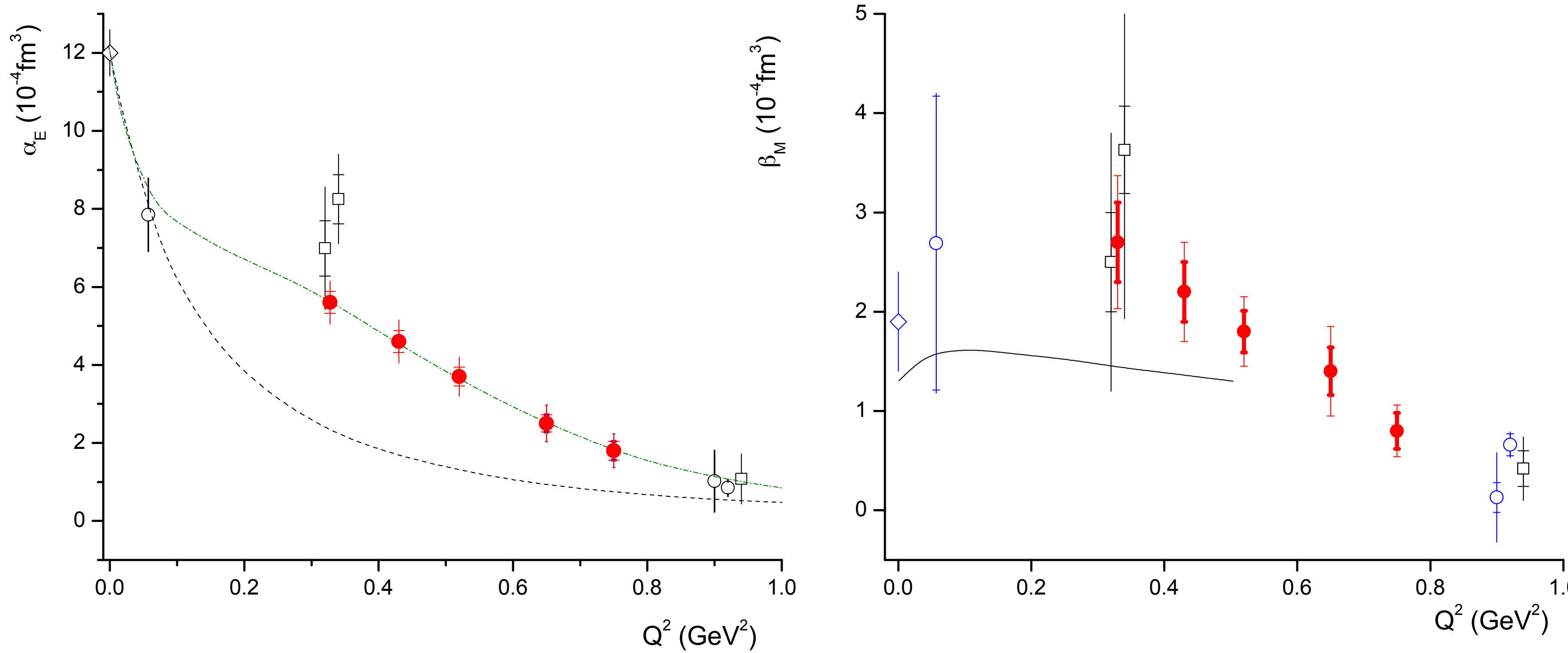
σ, A → Statistics; Systematics; Elastic/ transition FFs, DR multipoles → α_E, β_M

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

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

Beam time request

measurements arbitrarily projected

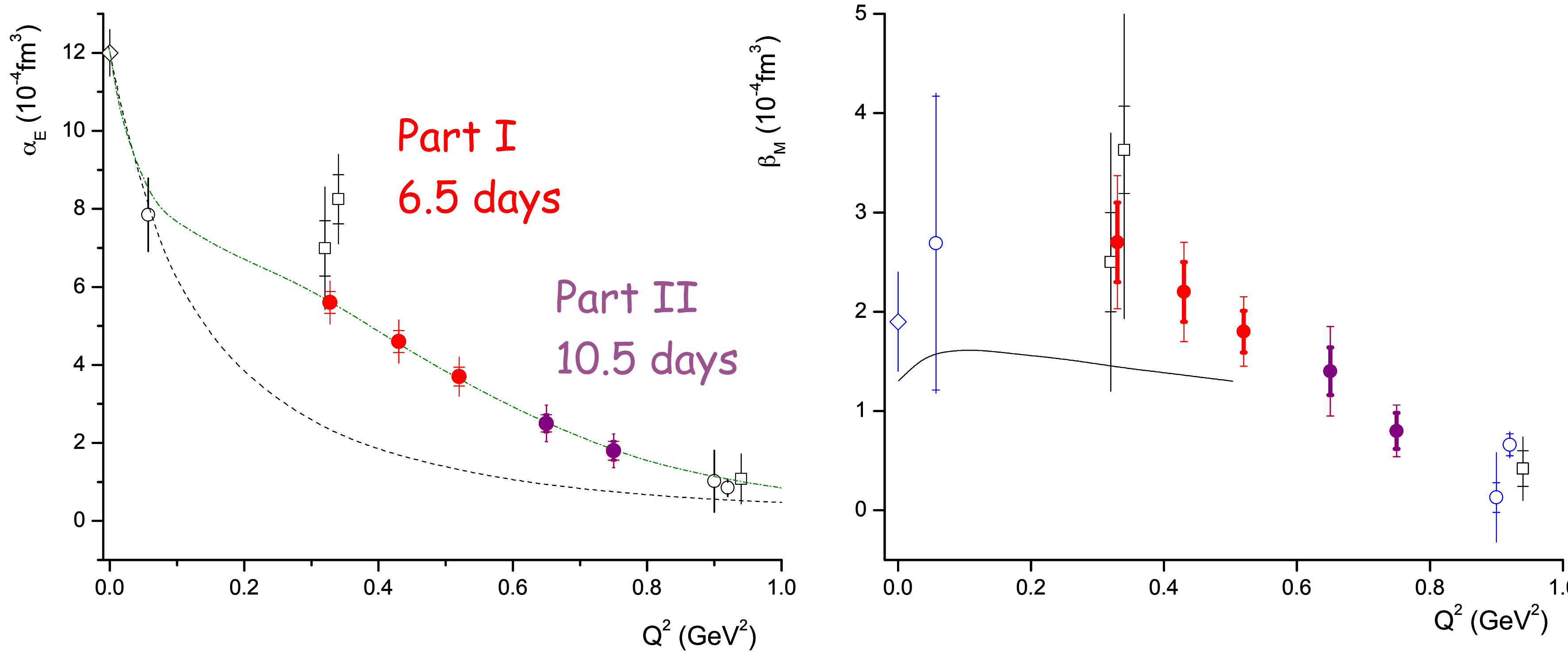


Beam time request: 18 days 4.4 GeV 85 μA Hall C

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



Beam time request: 18 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)

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

- 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 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
- pin down, with high precision, the spatial deformation of charge densities in 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 will trigger more theoretical activity

Thank you!

Beam time request:

- 17+1 days with 4.4 GeV in Hall C (standard setup)
- possible also in Hall A