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

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
$\boxed{\text{Electric polarizability } \alpha = (11.2 \pm 0.4) \times 10^{-4} \text{ fm}^3 \\ \text{Magnetic polarizability } \beta = (2.5 \pm 0.4) \times 10^{-4} \text{ fm}^3}$ (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)

Virtual Compton Scattering:

Virtuality of photon gives access to the
Generalized Polarizabilities $\alpha_E(Q^2)$ & $\beta_M(Q^2)$ (+ 4 spin GPs)

➔ 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

Proton GPs

Intense experimental effort on $\alpha_E(Q^2)$ & $\beta_M(Q^2)$:

- currently facing a puzzle with respect to the electric GP
- new results are coming up
- new experiments are coming up

Spin polarizabilities:

- They have been measured in RCS (A2/MAMI): PRL 114, 112501 (2015)
- VCS: only one measurement (A1/MAMI) of a structure function that is a combination of the electric GP and two spin GPs

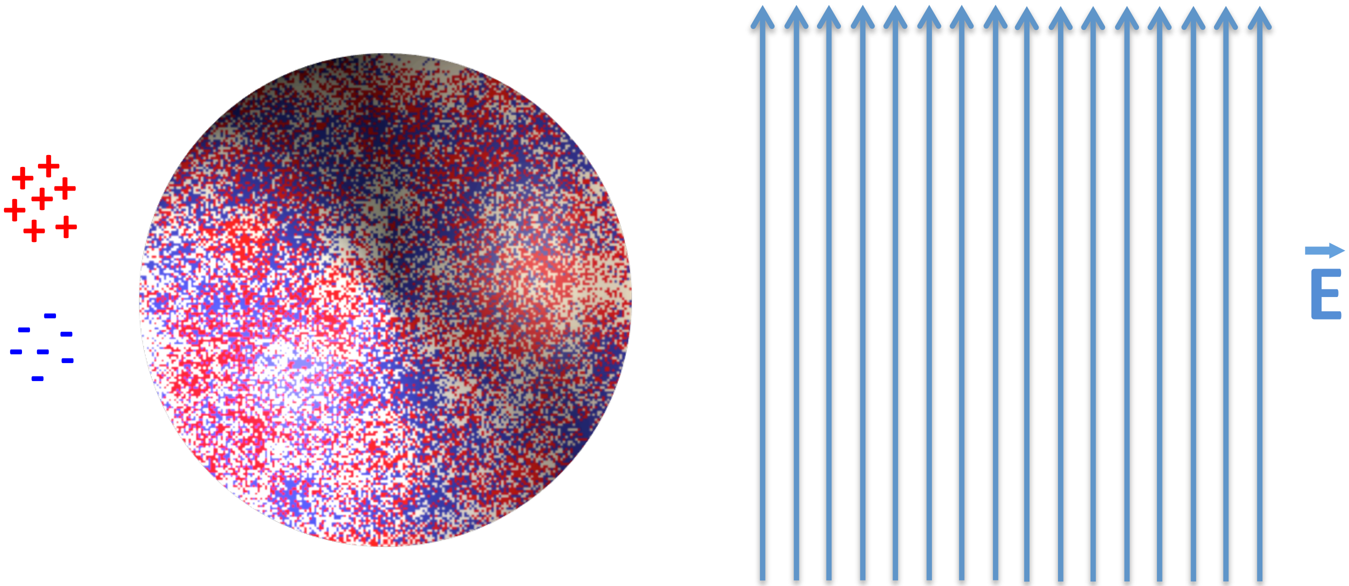
	$P_{LT}^{\perp}$ (GeV^{-2})
This experiment	$-15.4 \pm 3.3_{(\mathrm{stat.})}\ {}^{+1.5}_{-2.4}\,(\mathrm{syst.})$
DR model [16]	-3.7 (a) , -8.7 (b) , -10.8 (c)
HBChPT $\mathcal{O}(p^3)$ [17]	-10.6

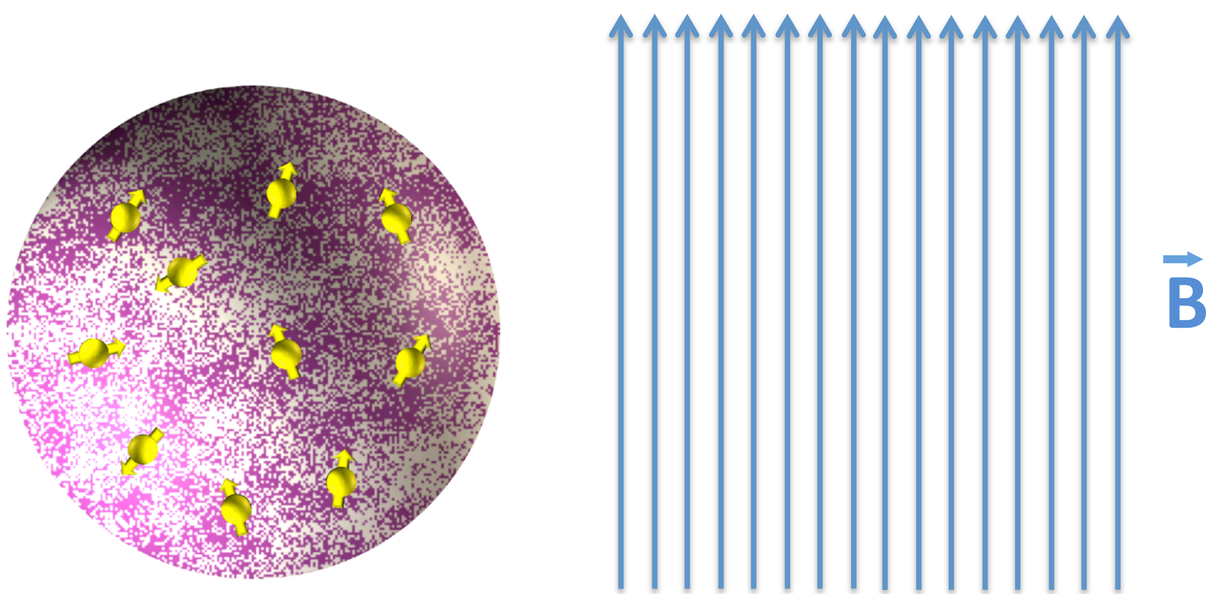
PRC 92 (2015) 054307

Beam-recoil polarization measurement at Q^2=0.33 $(\mathrm{GeV}/c)^2$

Scalar Polarizablities

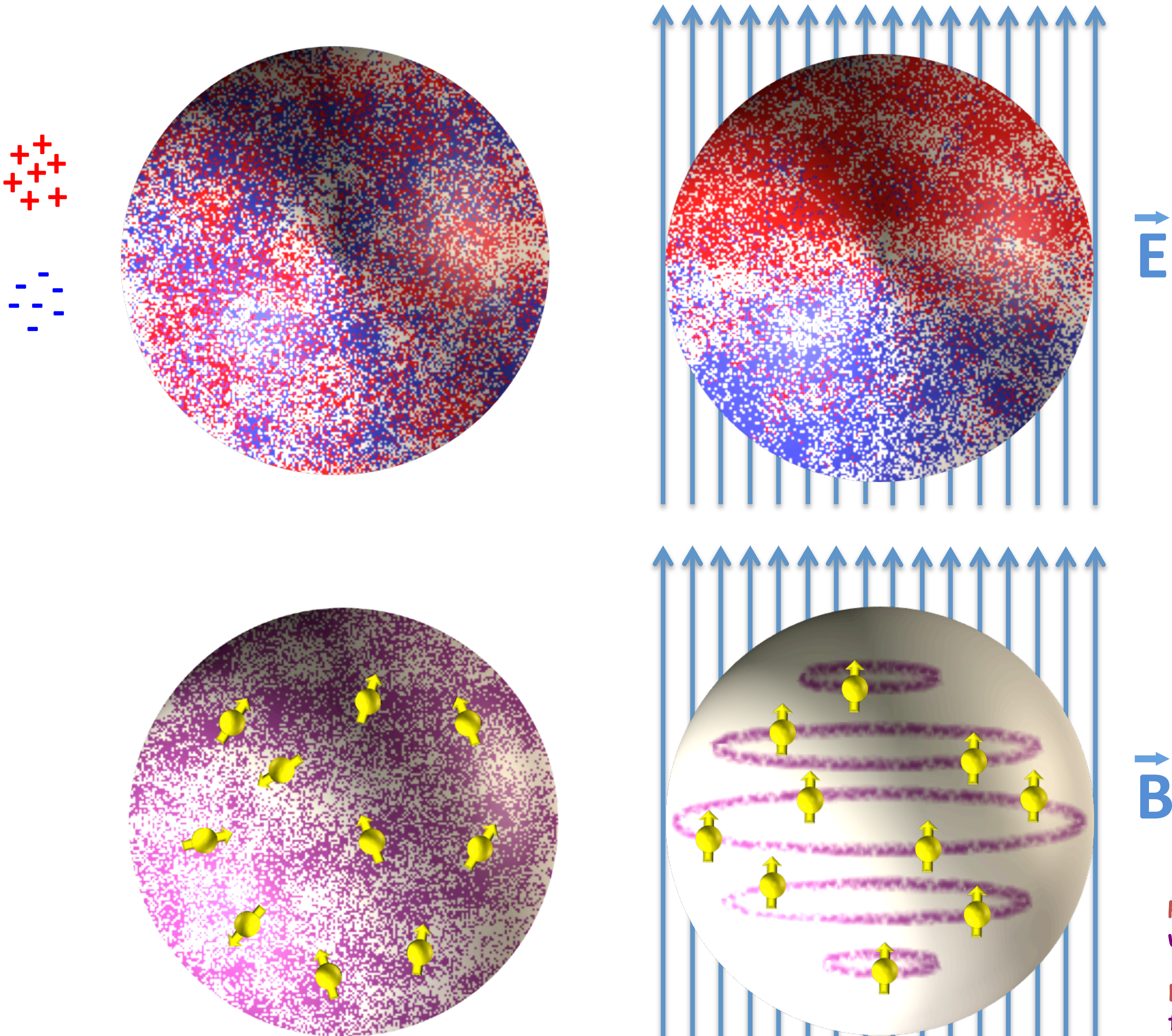
Response of internal structure to an applied EM field





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"

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

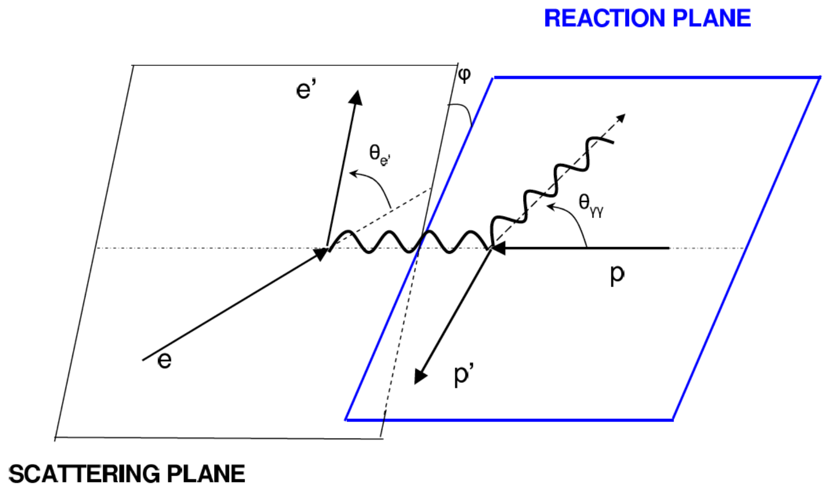
$$\beta_{para} > 0$$

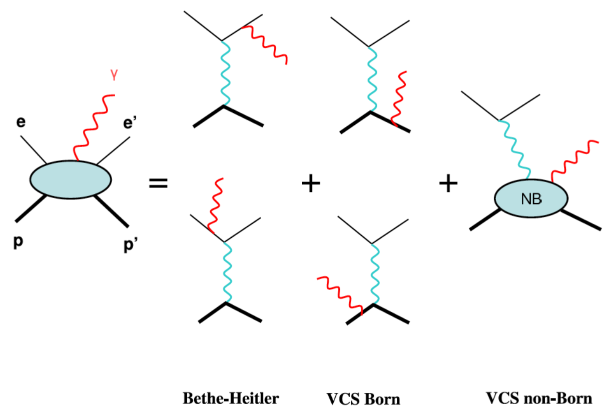
$$\beta_{diam} < 0$$

Paramagnetic: proton spin aligns with the external magnetic field

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

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

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

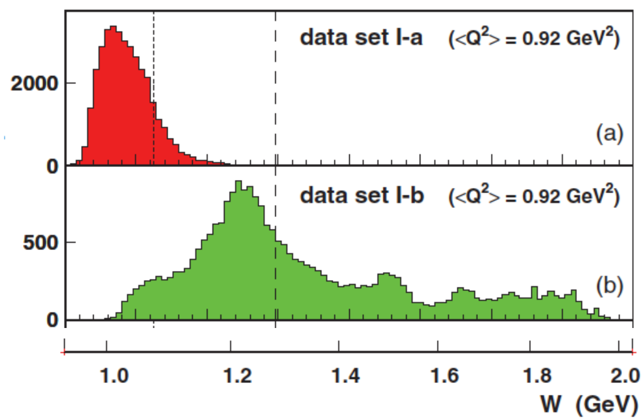
utilize DR

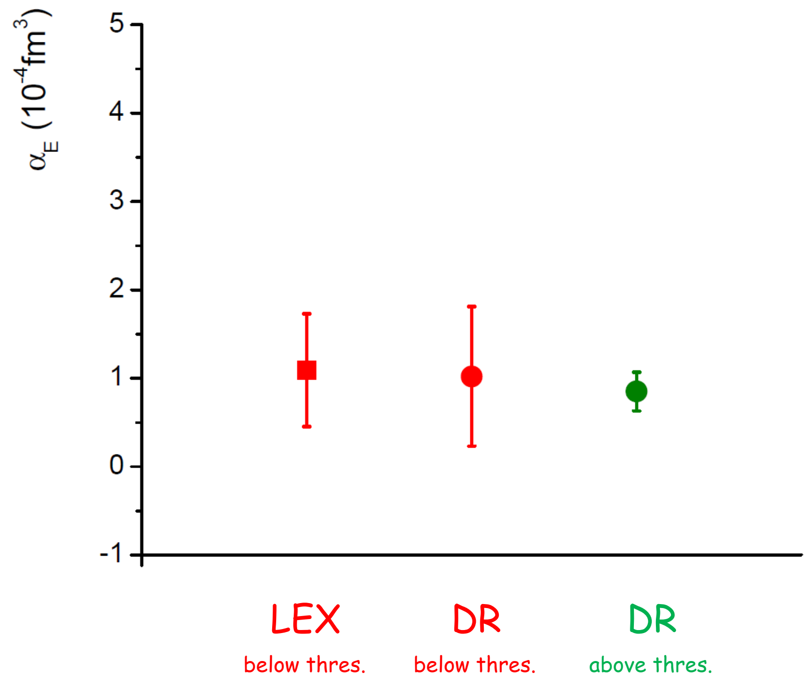
scalar GPs α_E and β_M

Virtual Compton Scattering

Phys. Rev C 86, 015210 (2012)

Phys. Rev Lett. 93, 122001 (2004)

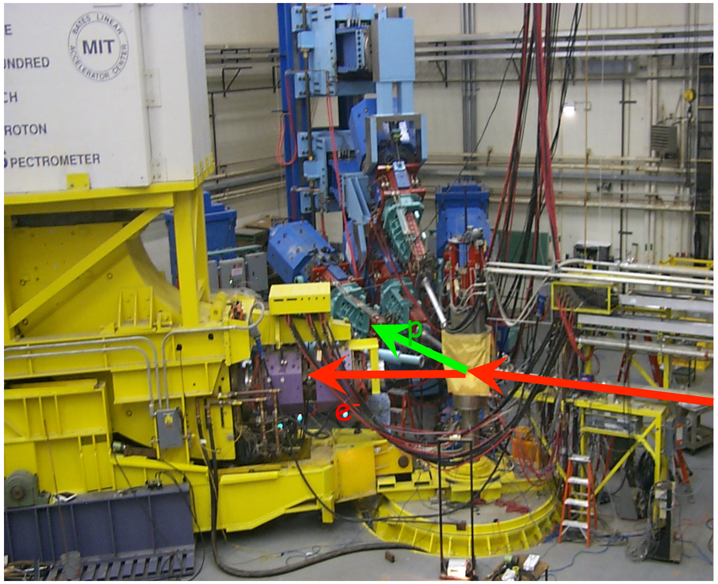




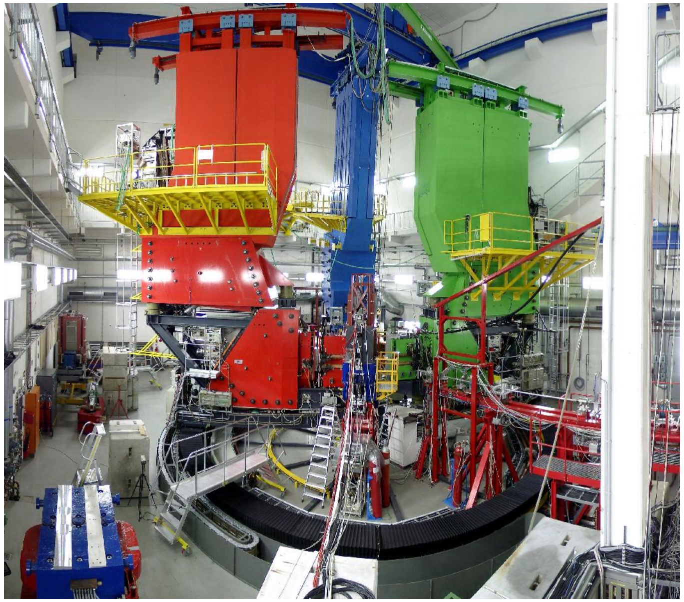
Sensitivity to the GPs grows with the photon energy

Early Experiments

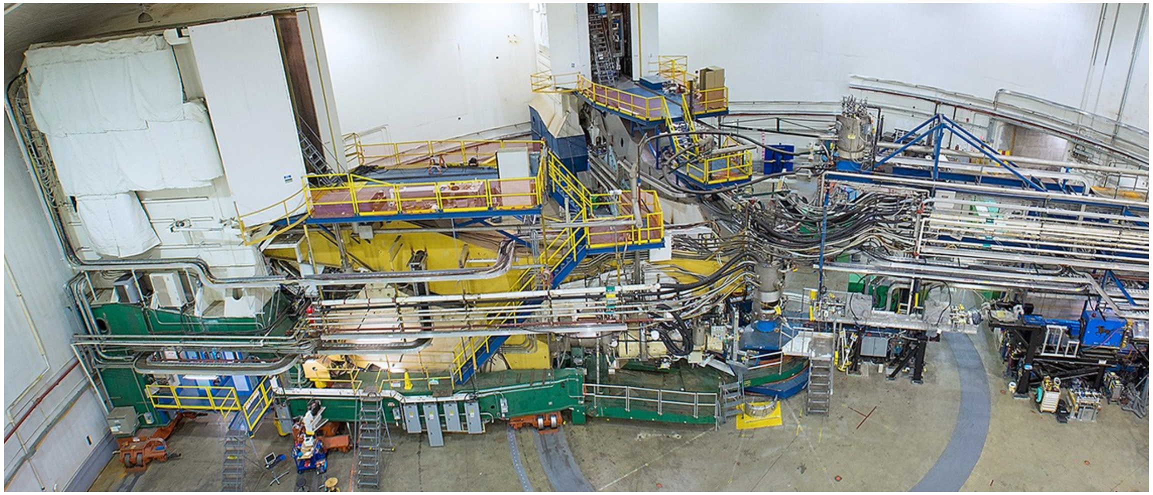
MIT-Bates @ Q^2=0.06 GeV^2



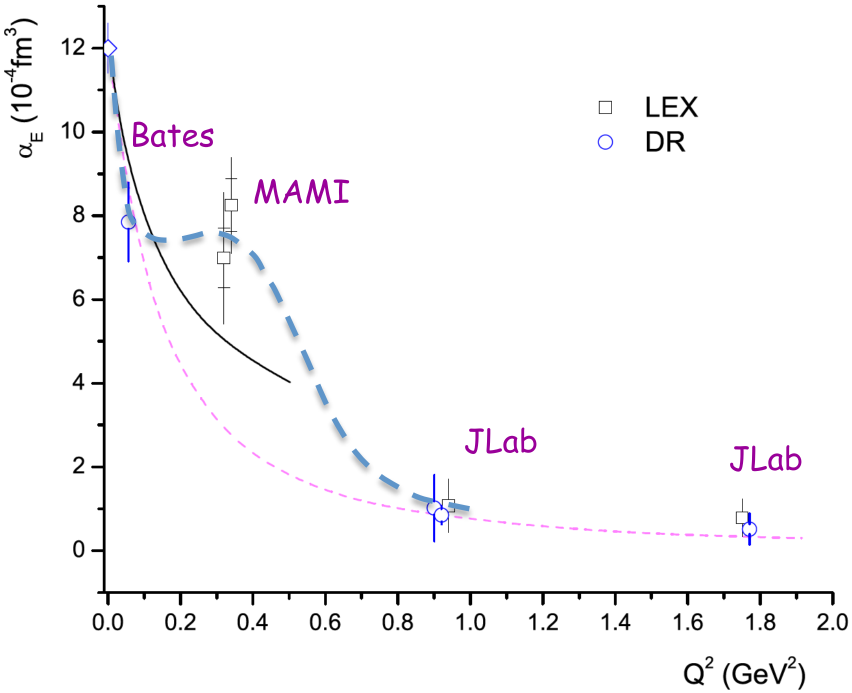
MAMI-A1 @ Q^2=0.33 GeV^2

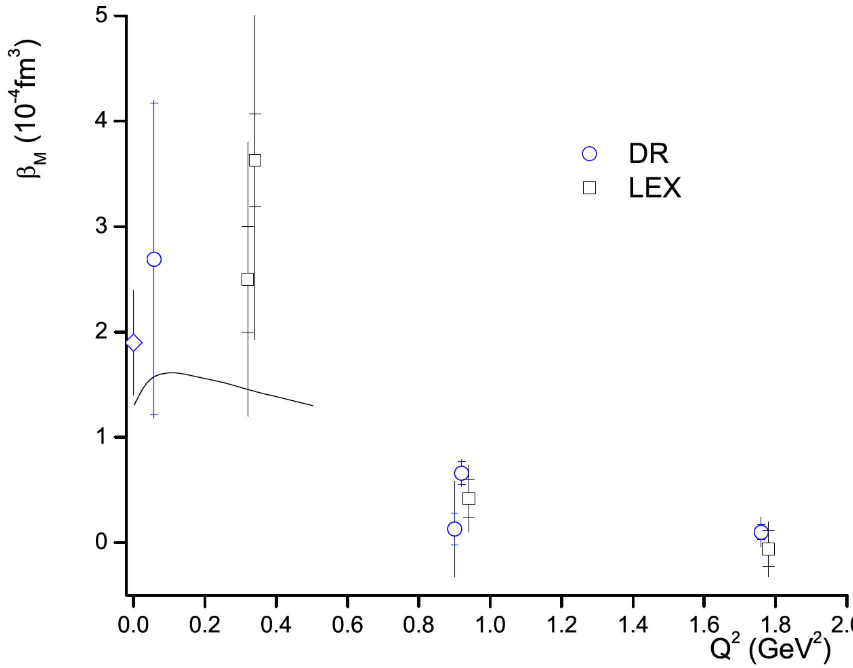


Jlab-Hall A @ Q^2=0.9 & 1.8 GeV^2



Early Experiments





$\alpha_E \approx 10^{-3}\, V_N$ (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

$Q^2 = 0.33\ (\mathrm{GeV}/c)^2$ 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

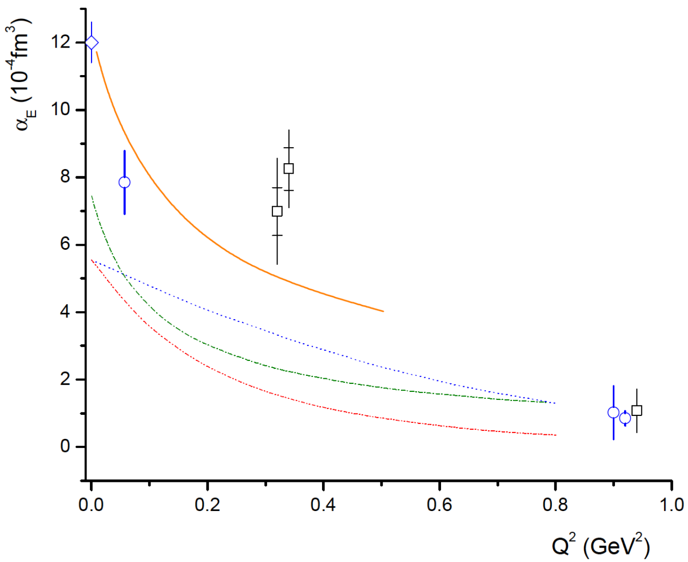
Current situation unsatisfactory:

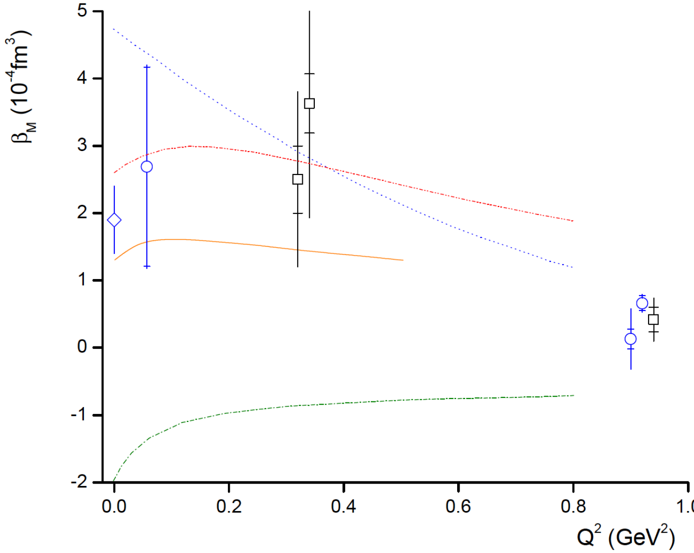
- more measurements needed (vs Q^2)
- Higher precision measurements needed

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

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

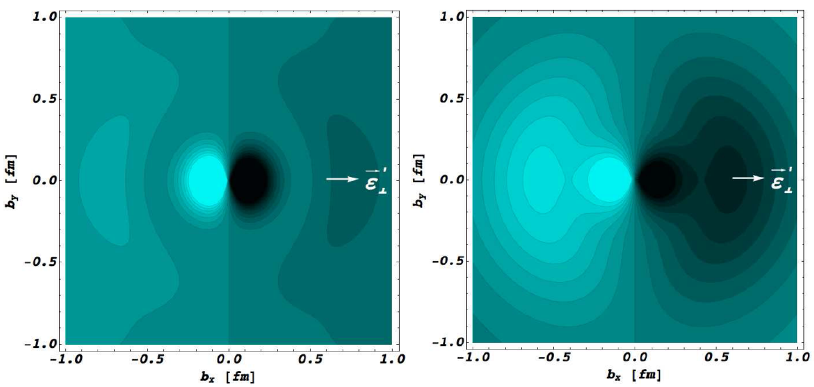
Nucleon form factor data ➔ light-front quark charge densities

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

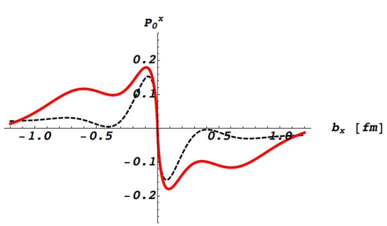
Induced polarization in a proton when submitted to an e.m. field

GP I GP II



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

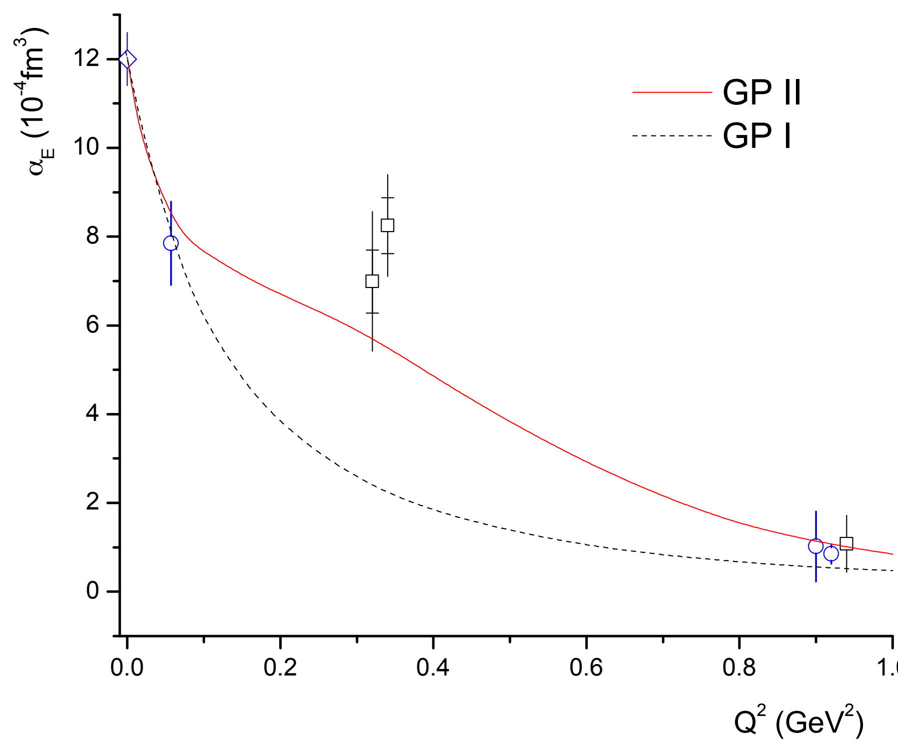
(photon polarization along x-axis, as indicated)



Induced polarization along b_y=0

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

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



Ongoing Experimental Efforts
MAMI

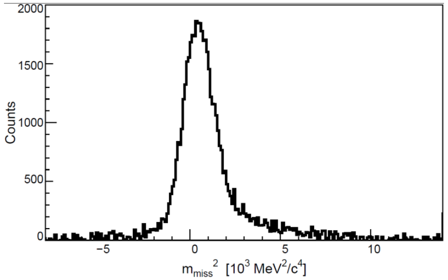
MAMI A1/1-09 (vcsq2) below threshold

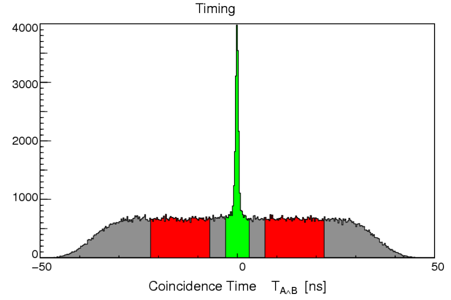
MAMI A1/3-12 (vcsdelta) above threshold

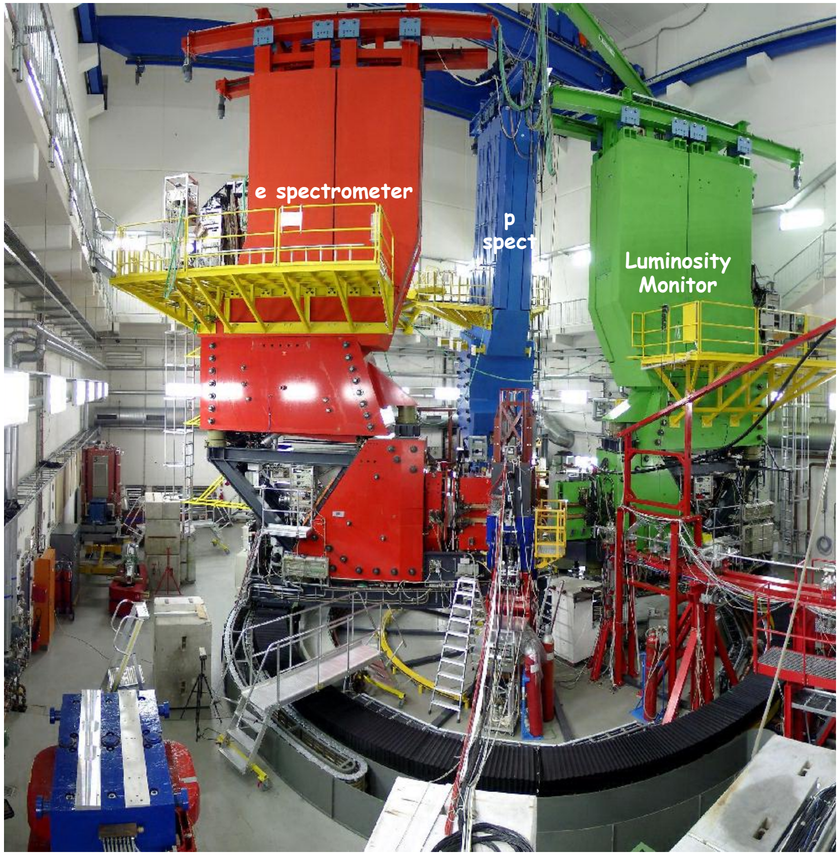
Both experiments utilized the A1 setup at MAMI

Preliminary results were recently released

Analysis is ongoing







vcsq2 @ MAMI

~ 1.0 GeV beam

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

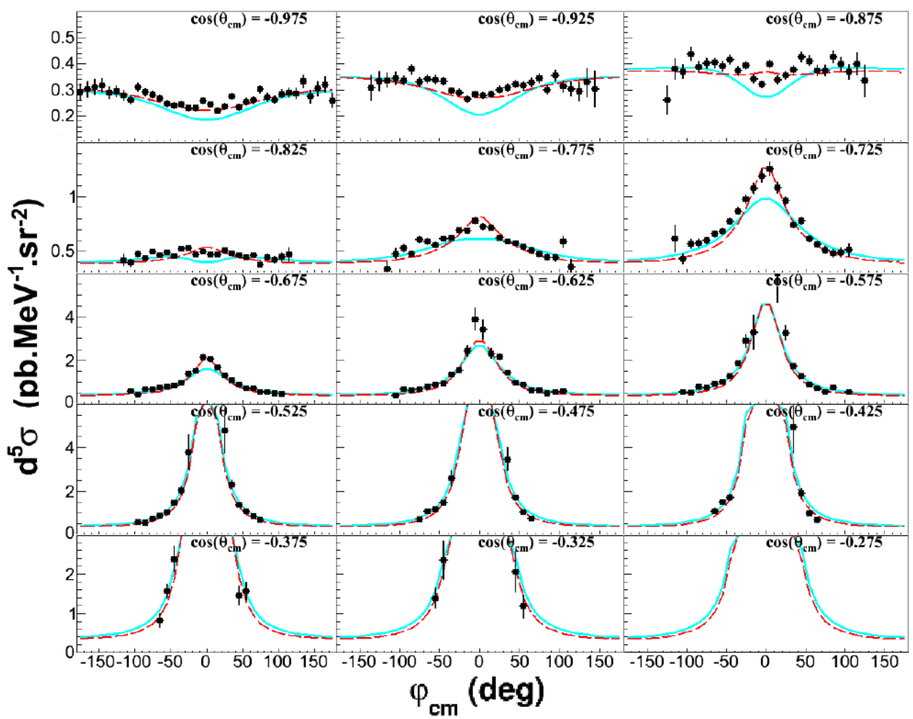


Figure 5.8: Setting INP: measured $ep \to ep\gamma$ cross section at fixed q'_{cm} = 112.5 MeV/c with respect to φ_{cm} for all the $cos(\theta_{cm})$-bins. The curves follow the convention of figure 5.6.

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

BH+B ---

Polarizability effect ---

GP effect typically 0 – 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

For LEX the higher order terms have to be negligible

$$d^5\sigma \;=\; d^5\sigma^{BH+Born} \;+\; q'_{cm} \cdot \phi \cdot \Psi_0 \;+\; \mathcal{O}(q'^2_{cm})$$

A phase space masking has to be applied to keep these terms smaller than the 2%-3% level

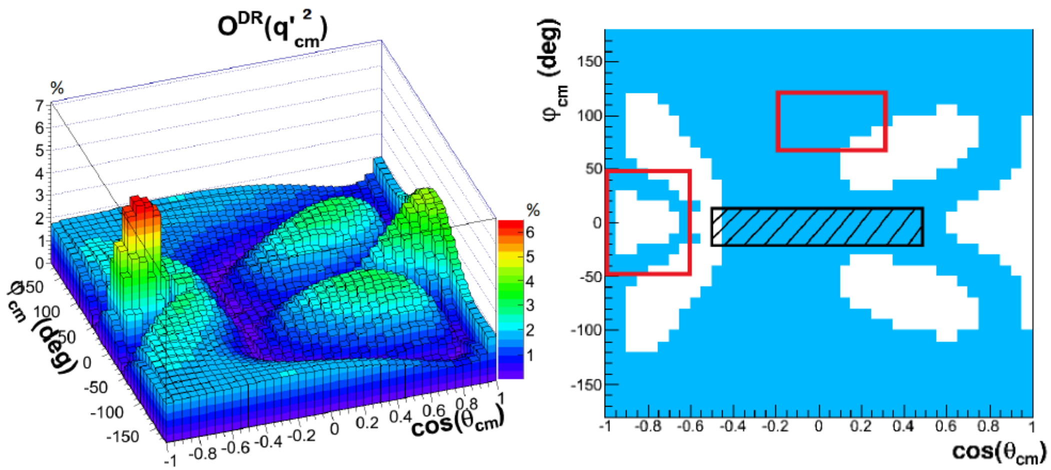
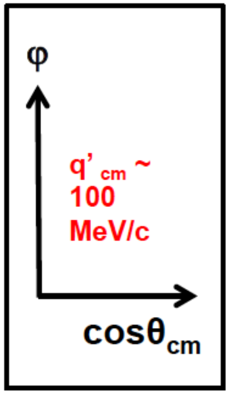


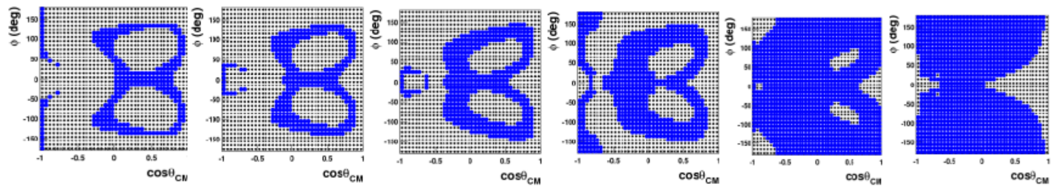
Figure 3.13: (Left) behavior of $\mathcal{O}^{DR}({q'_{cm}}^2)$ in the $(cos(\theta_{cm}),\varphi_{cm})$-plane at $q'_{cm} = 87.5\ MeV/c$ and (right) two-dimensional representation of the angular region where $\mathcal{O}^{DR}({q'_{cm}}^2) < 2\%$ (blue), the red squares correspond to the two areas of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

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

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



VCS expt :	Bates	MAMI	MAMI	MAMI	MAMI	JLab
Q2 (GeV2) =	0.06	0.10	0.20	0.33	0.45	0.92

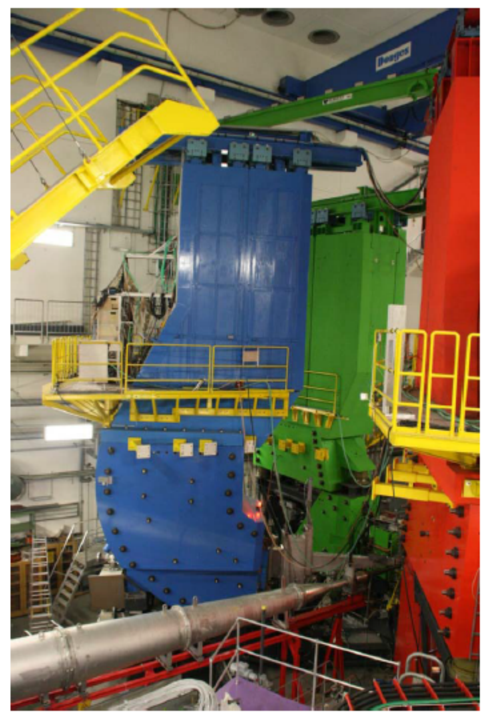


New « vcsq2 » data:

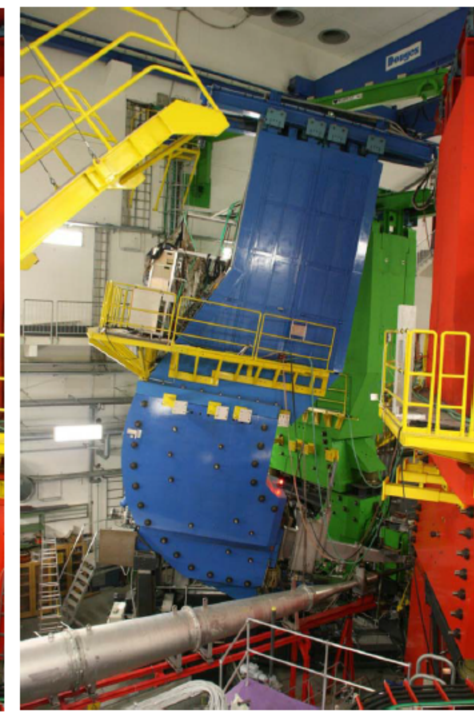
- **OOP kinematics (to access the blue region)**

-LEX Fit done with bin selection at Q^2 = 0.1 and 0.2 GeV^2.

- **was found not necessary at Q^2 = 0.45 GeV^2.**



In-plane



8.5 deg OOP

(material from H. Fonvieille)

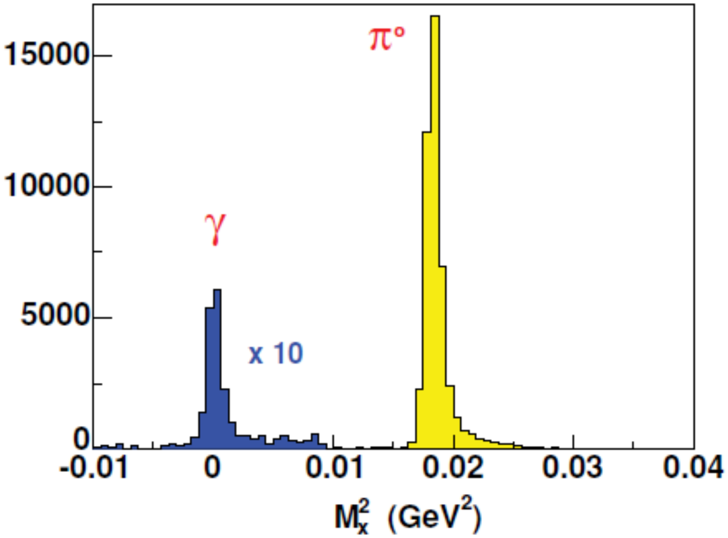
vcsdelta @ MAMI

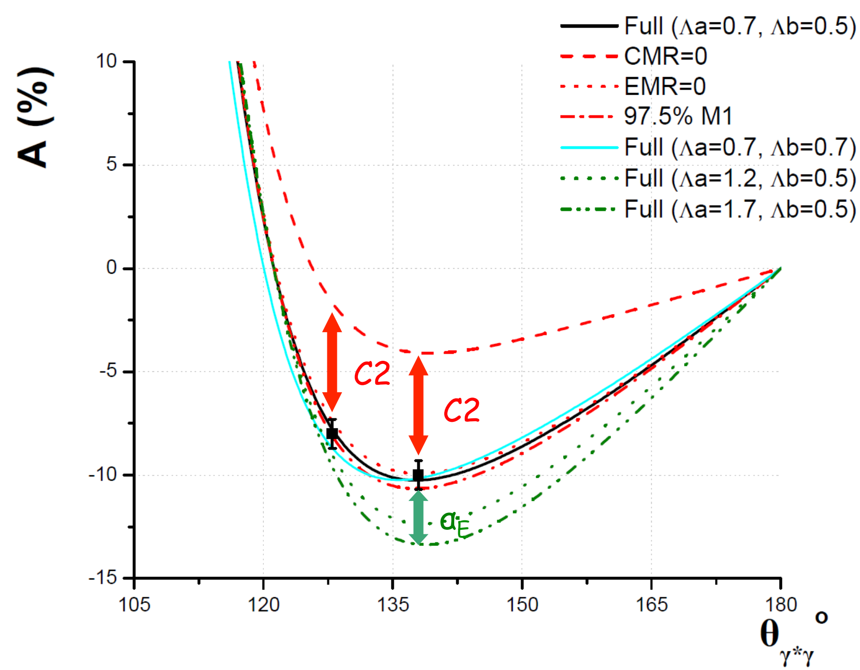
Goal 2-fold: 1) Measurement of the electric GP α_E

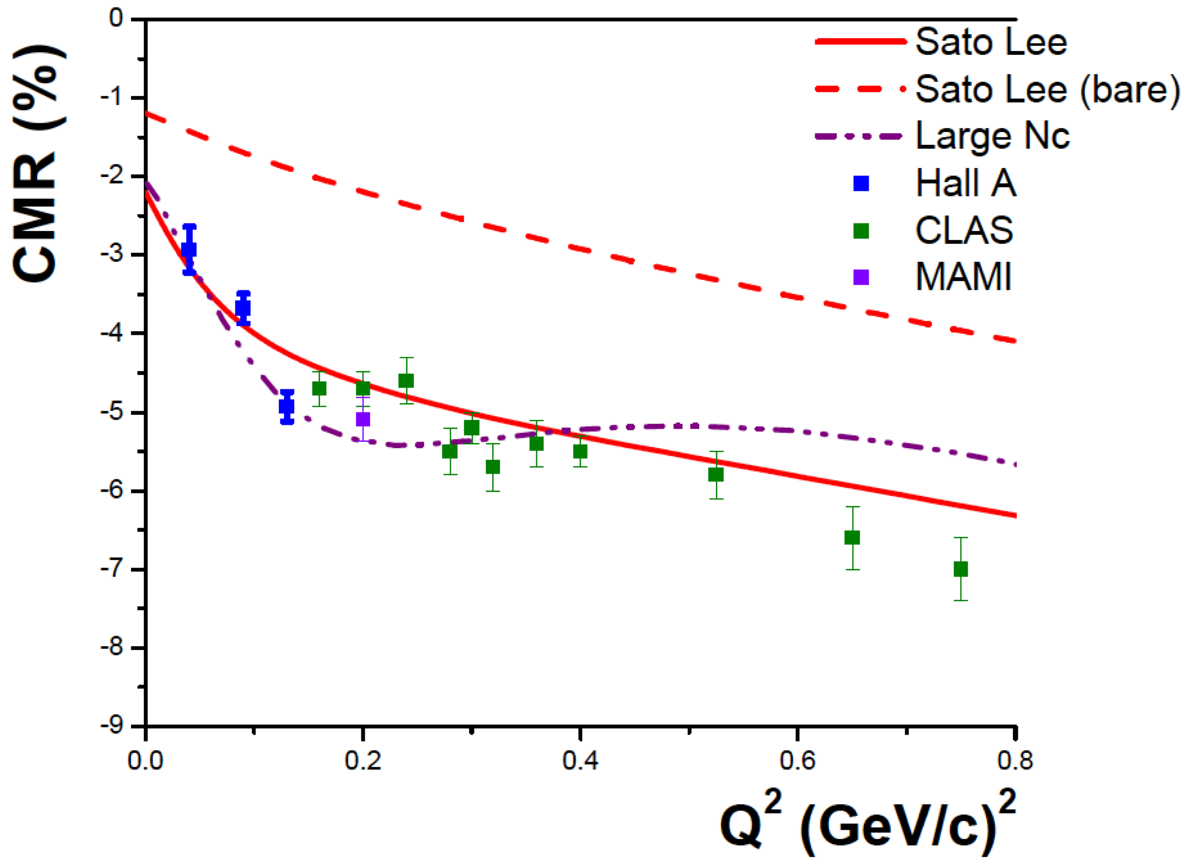
2) First measurement of N->Δ transition form factors through the γ channel

1.1 GeV beam

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



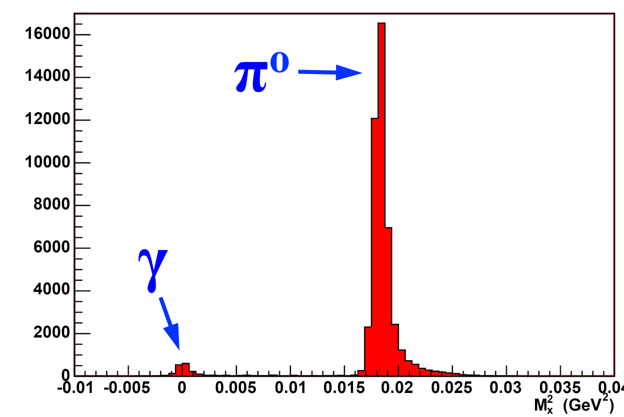


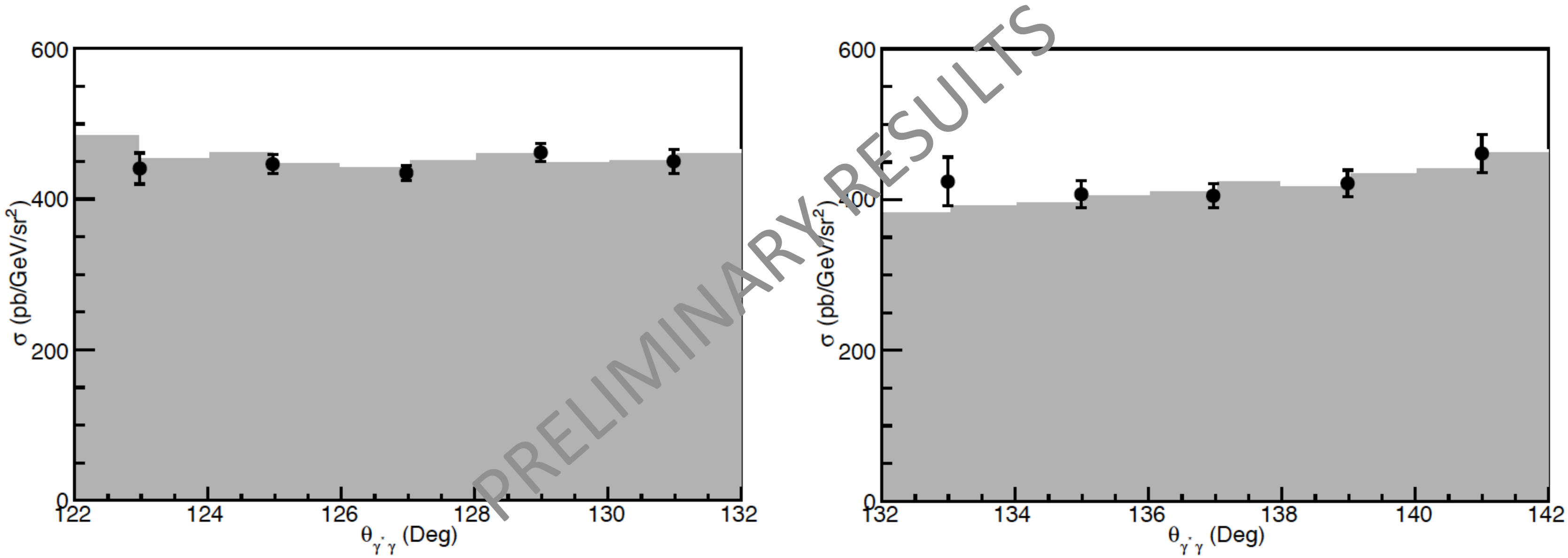


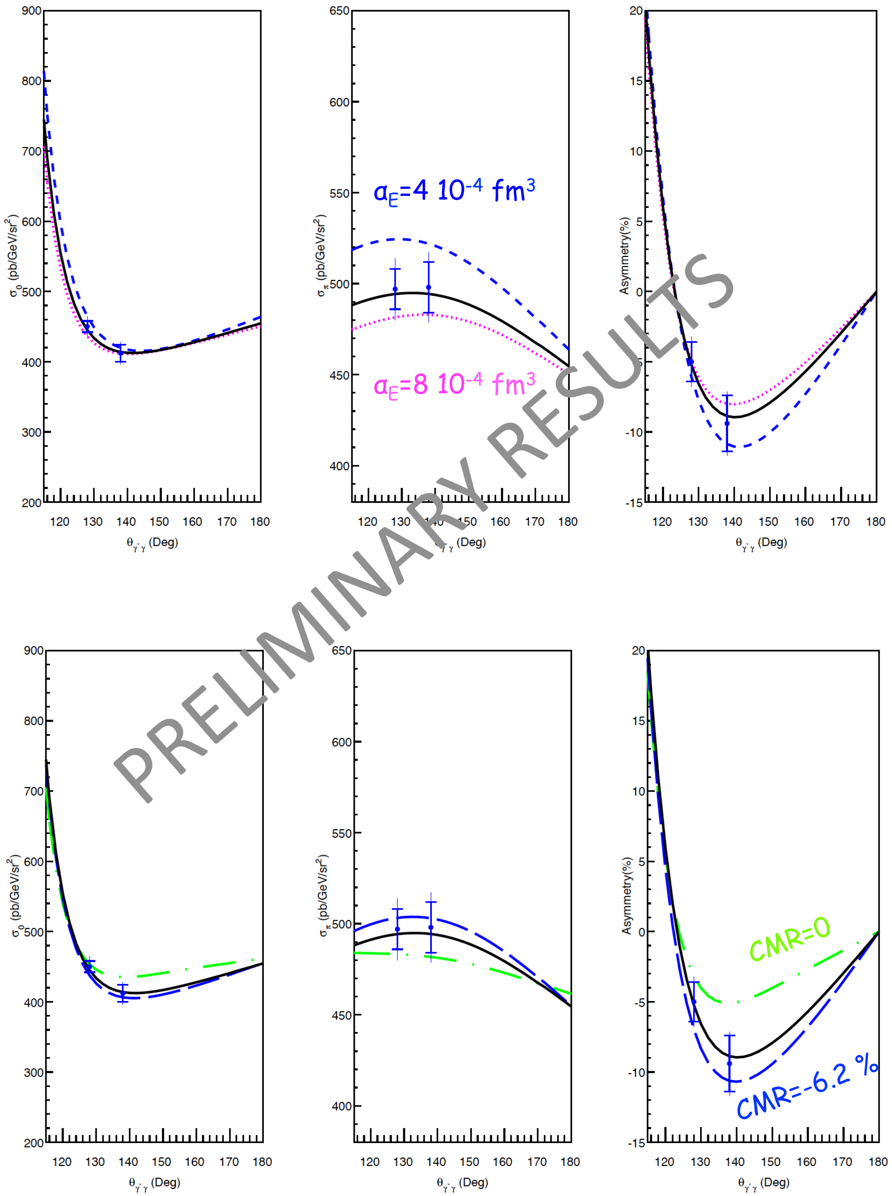
H(e,e′p)π^{o} ≈ 66%

H(e,e′π^{+})n ≈ 33%

H(e,e′p)γ ≈ 0.6%




600
400
200
0
σ (pb/GeV/sr^2)
122
124
126
128
130
132
$\theta_{\gamma^* \gamma}$ (Deg)
600
400
200
0
σ (pb/GeV/sr^2)
132
134
136
138
140
142
$\theta_{\gamma^* \gamma}$ (Deg)
PRELIMINARY RESULTS

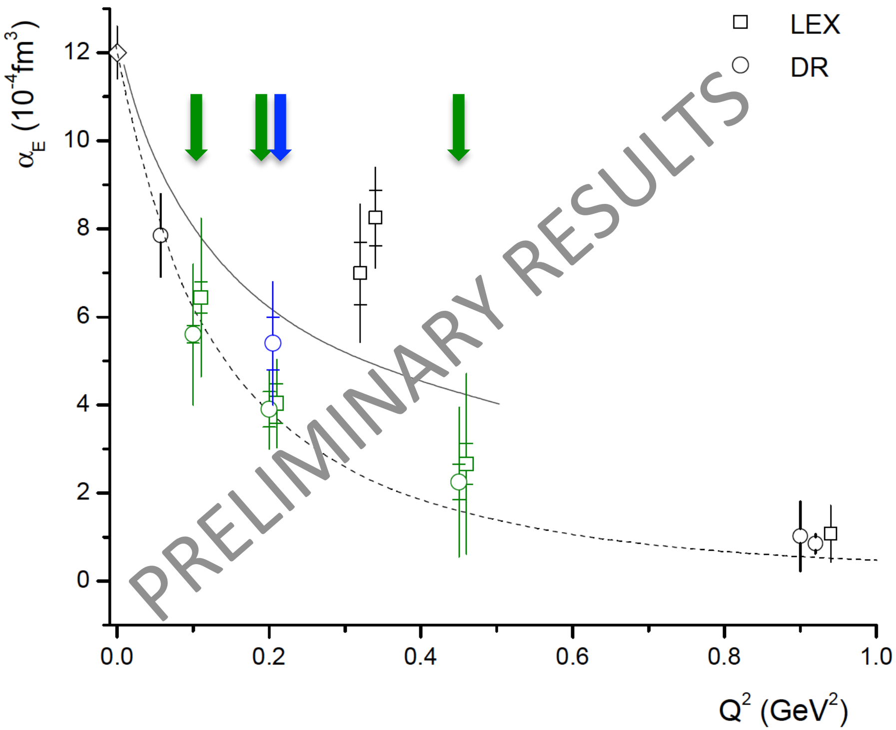


PRELIMINARY RESULTS
α_E=4 10^{-4} fm^3
α_E=8 10^{-4} fm^3
CMR=0
CMR=-6.2 %
σ_0 (pb/GeV/sr^2)
σ_π (pb/GeV/sr^2)
Asymmetry(%)
$\theta_{\gamma^*\gamma}$ (Deg)

MAMI Preliminary Results

Preliminary A1/1-09 (vcsq2)

Preliminary A1/3-12 (vcsdelta)



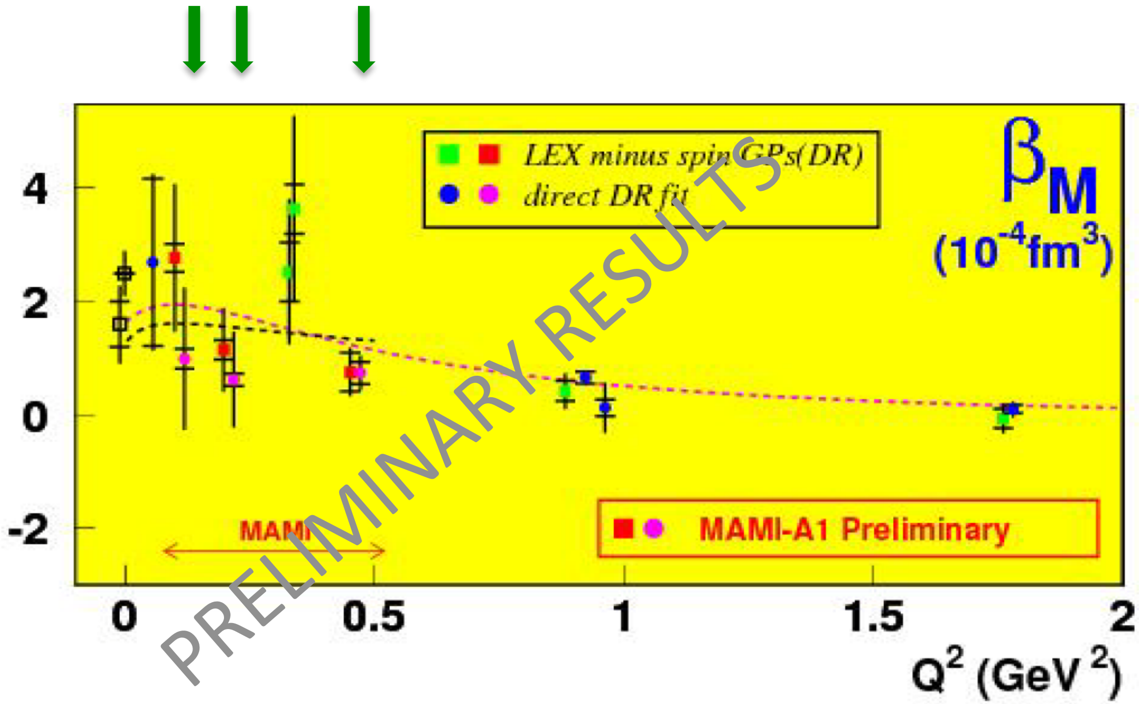
Data analyzed by 4 PhD students

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

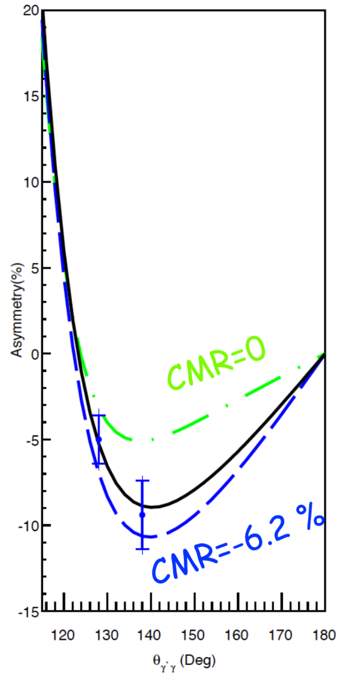
MAMI Preliminary Results

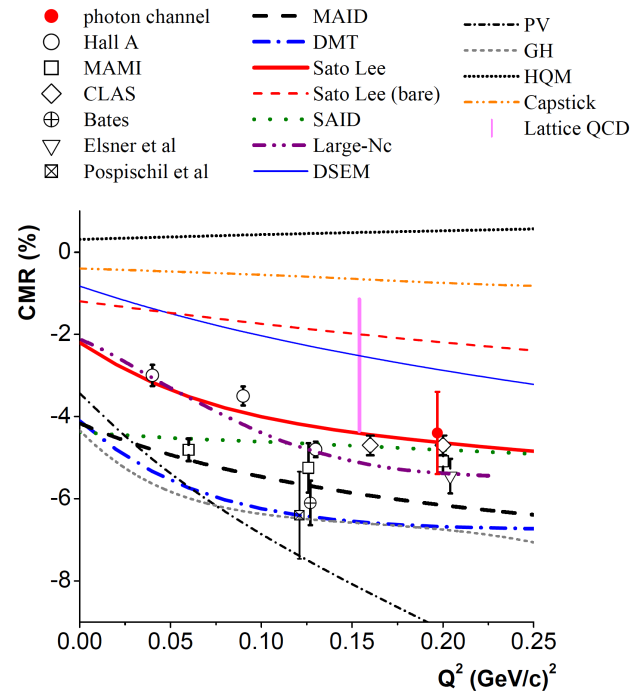
Preliminary A1/1-09 (vcsq2)



(material from H. Fonvieille)

MAMI Preliminary Results

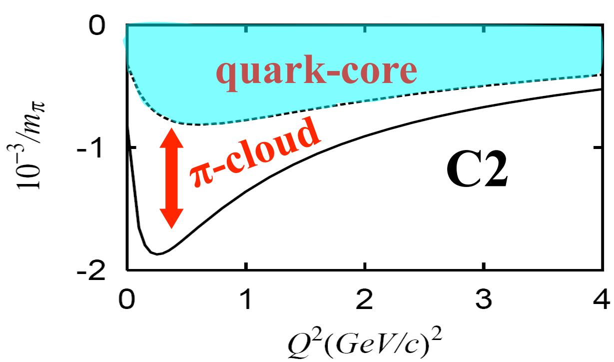




First measurement of the N-Δ C2 amplitude through the photon channel

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)



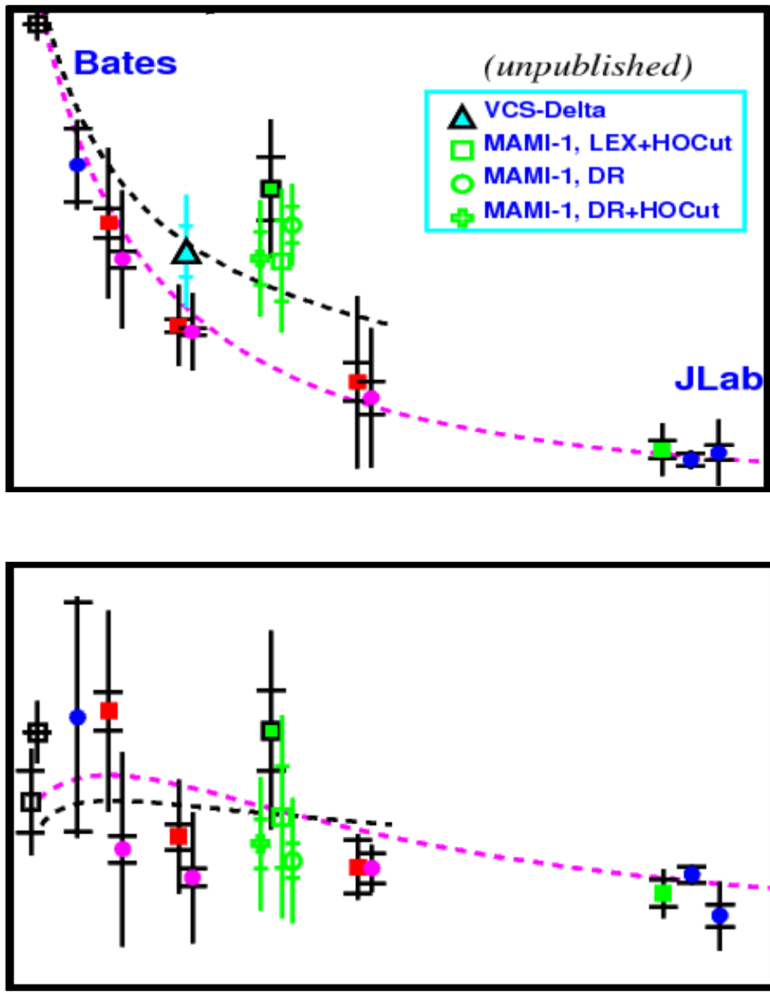
Revisiting the Q^2=0.33 GeV^2 data

Q^2 = 0.33 $(GeV/c)^2$ measured twice at MAMI - two different experiments

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

$\alpha_E(Q^2)$

$\beta_M(Q^2)$



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

LEX and DR

Updated HO-cut

The α_E puzzle still holds

(material from H. Fonvieille)

Ongoing Experimental Efforts

JLab

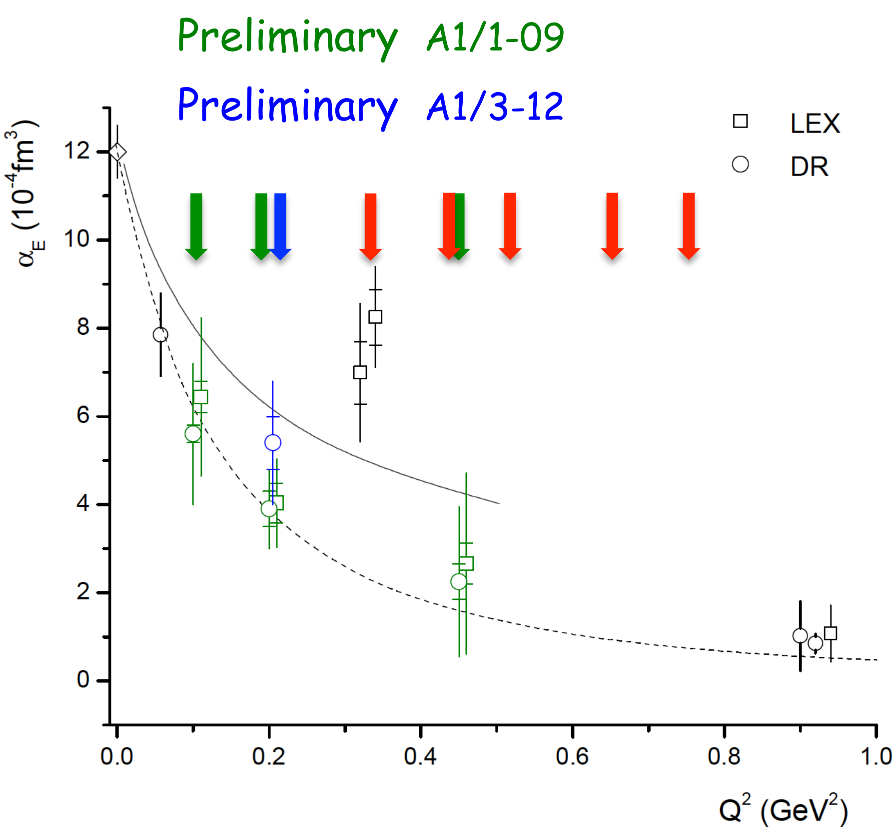
New Experiment

E12-15-001 (JLab)

Going from $\varepsilon = 0.6 \rightarrow 0.9$ doubles the sensitivity to the GPs

ε=0.97 (Jlab)

ε=0.62 (MAMI)



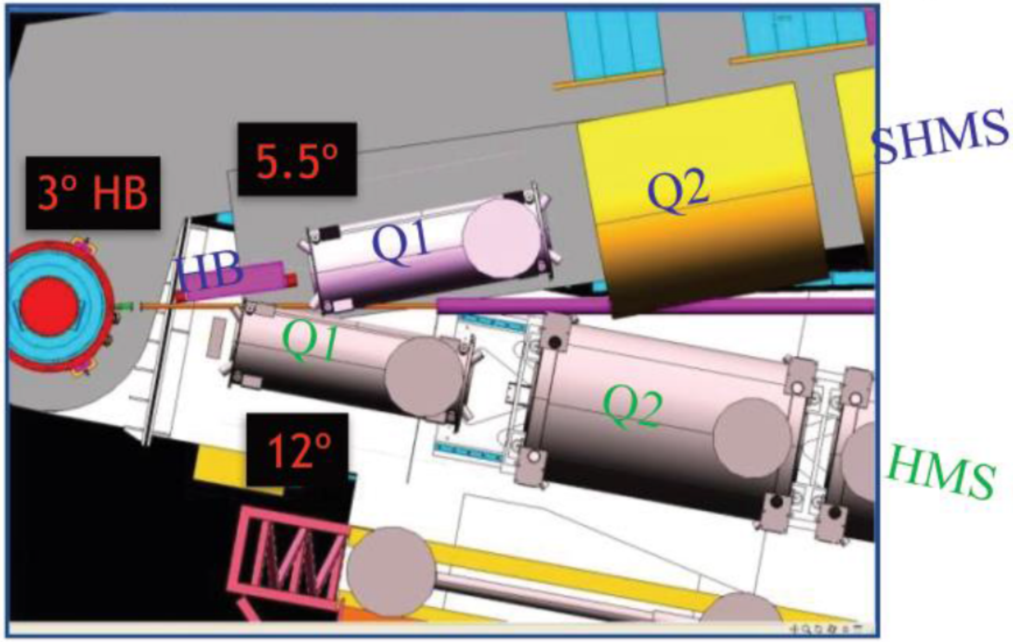
Beam energy x 4
Beam current x 5

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

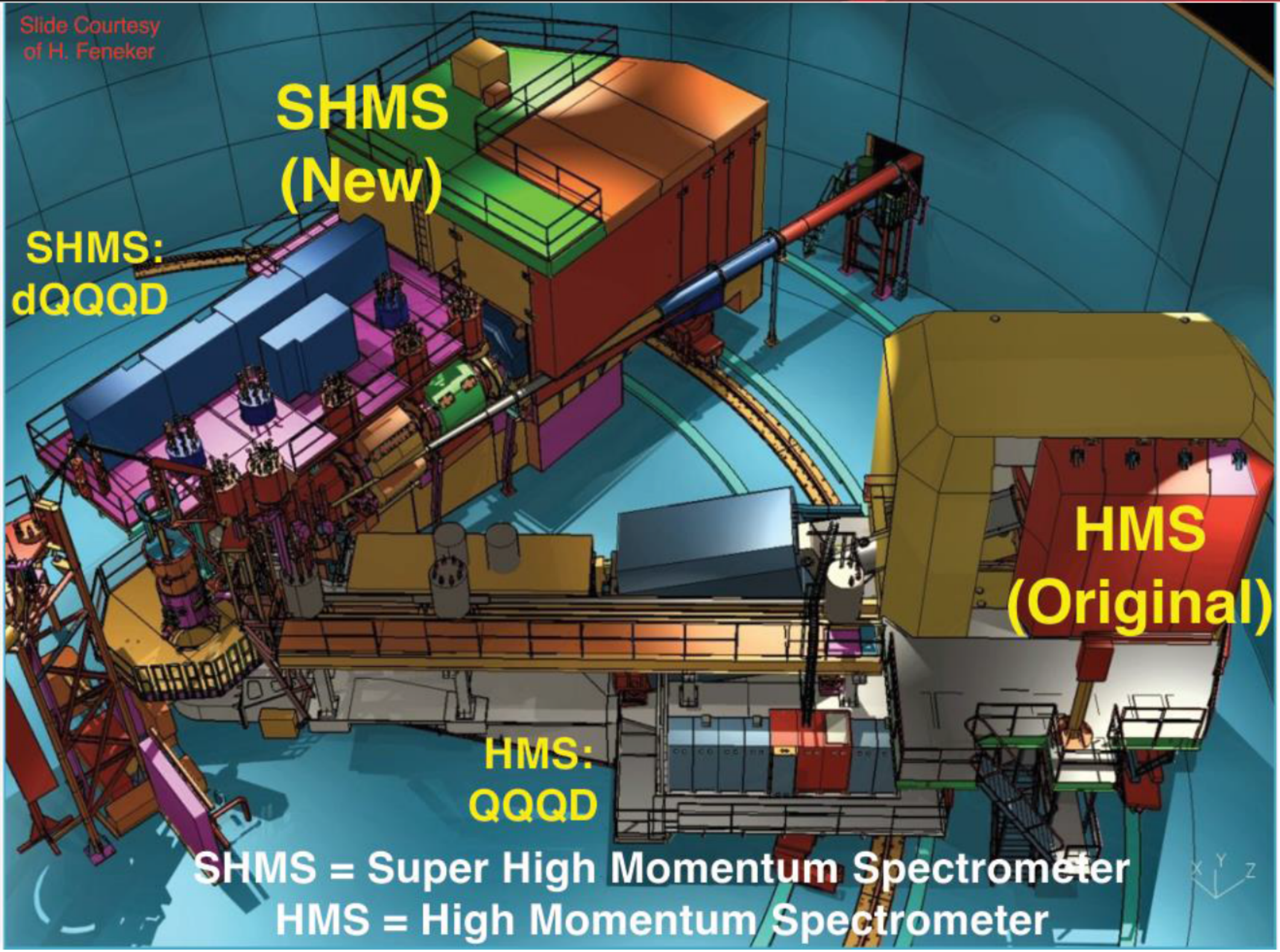
SHMS:
- 11-GeV Spectrometer
- Partner of existing 6-GeV **HMS**

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

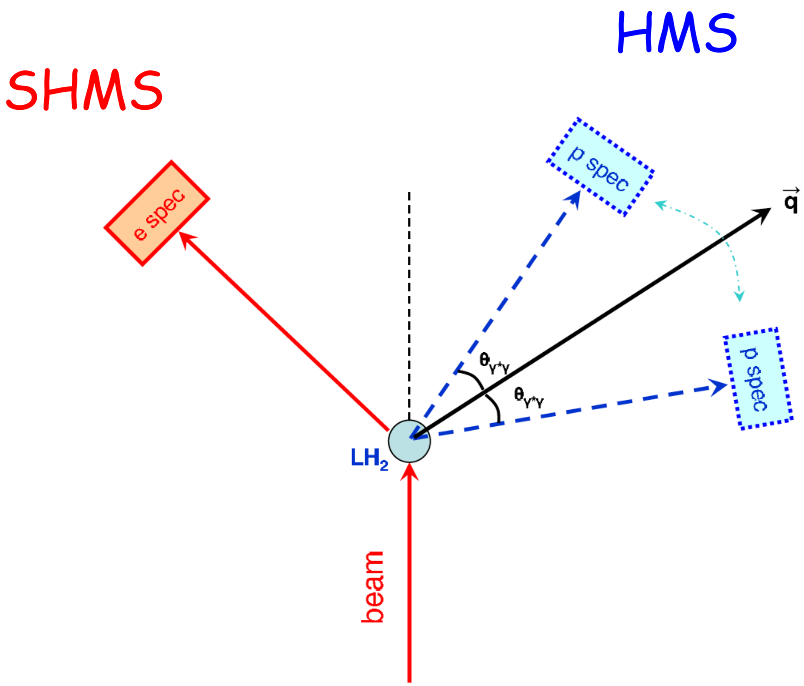
Detector Package:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter
- All derived from existing HMS/SOS detector designs

Well-Shielded Detector Enclosure

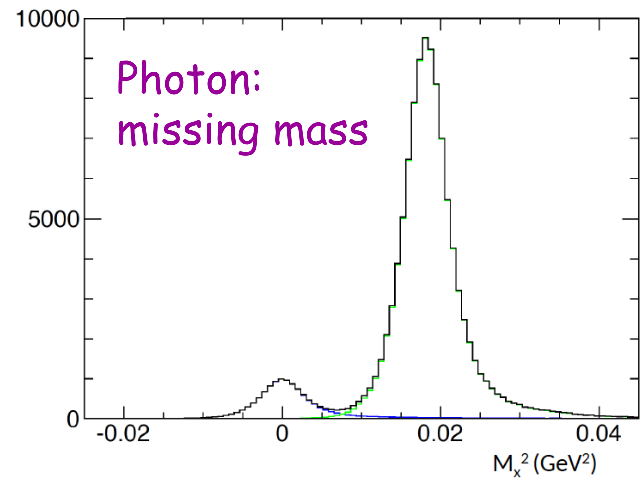
Rigid Support Structure
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS



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

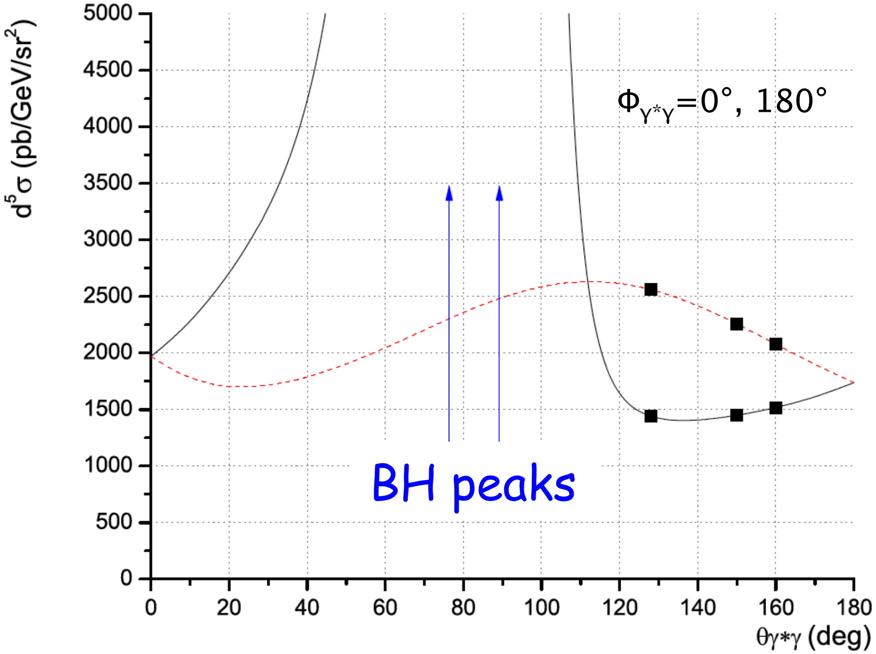
in-plane azimuthal asymmetries

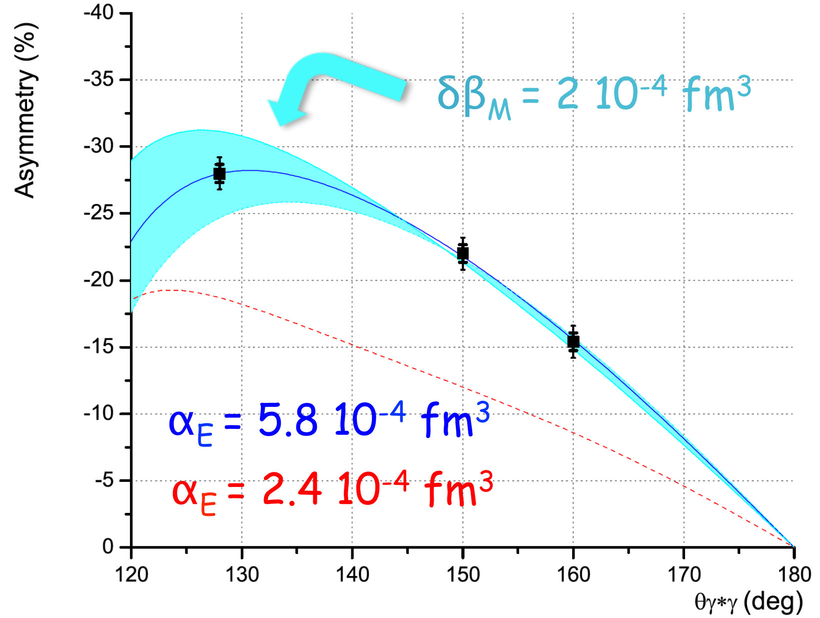
$$A_{(\phi_{\gamma*\gamma}=0,\pi)} = \frac{\sigma_{\phi_{\gamma*\gamma}=0} - \sigma_{\phi_{\gamma*\gamma}=180}}{\sigma_{\phi_{\gamma*\gamma}=0} + \sigma_{\phi_{\gamma*\gamma}=180}}$$

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

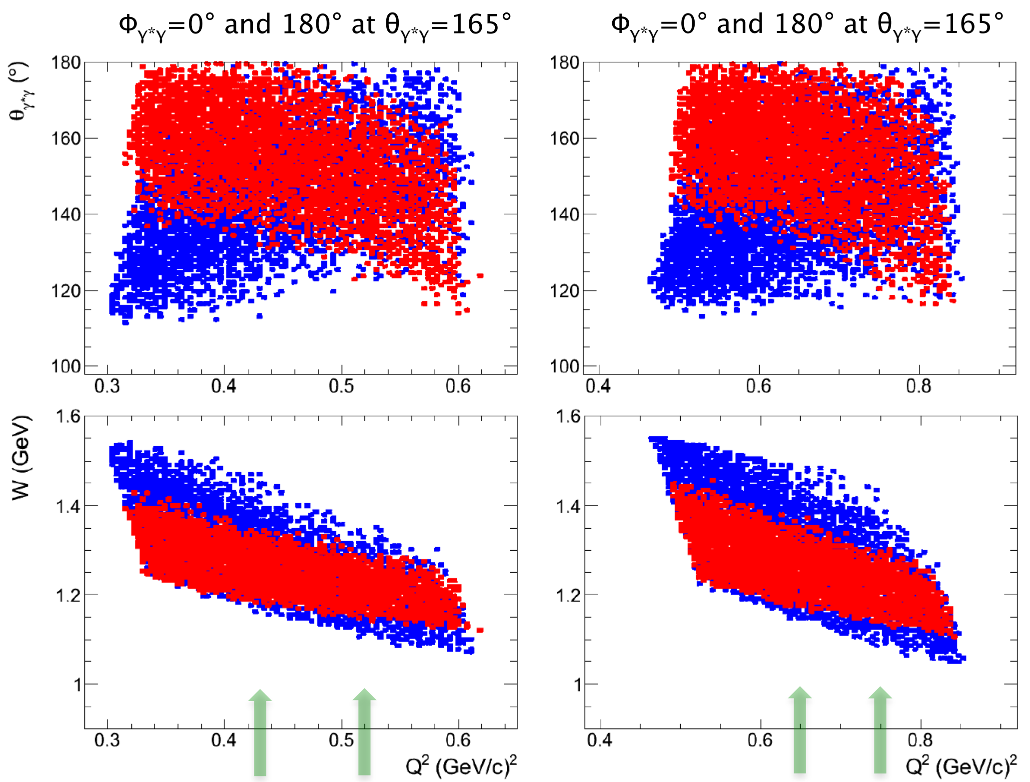
same position & momentum through out Part II

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



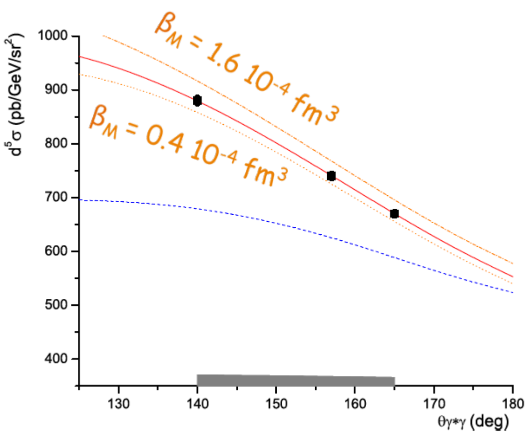
Phase space binned in Q^2, W, $\theta_{\gamma^*\gamma}$, $\Phi_{\gamma^*\gamma}$

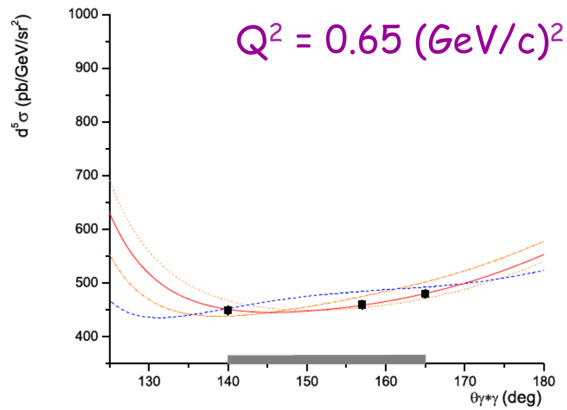
Cross section: DR calculation, B. Pasquini

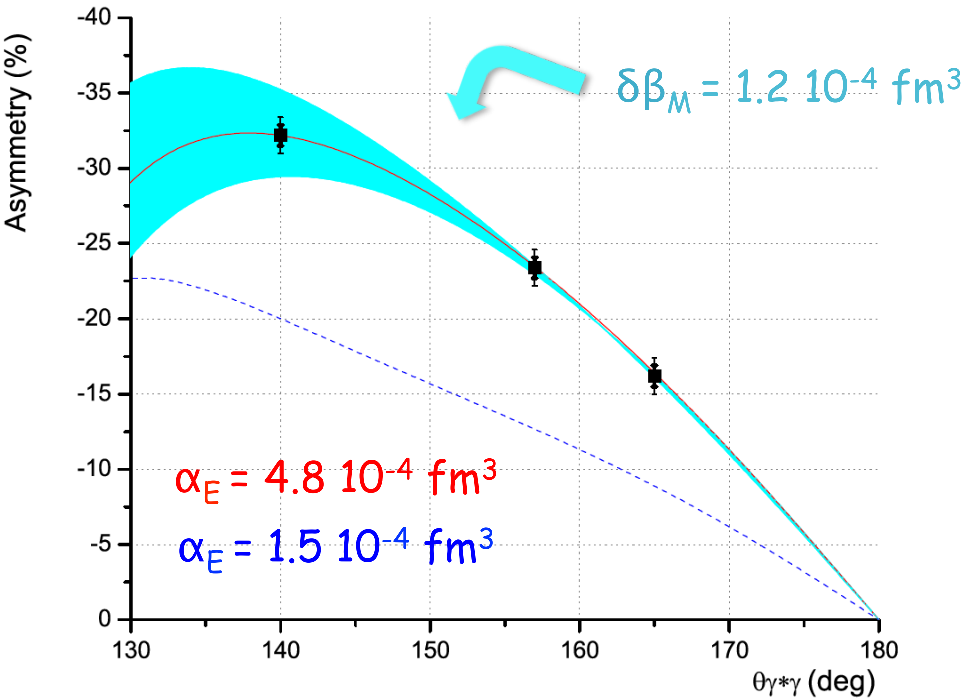
Eur. Phys. J. A11 (2001) 185-208
Phys. Rept. 378 (2003) 99-205

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



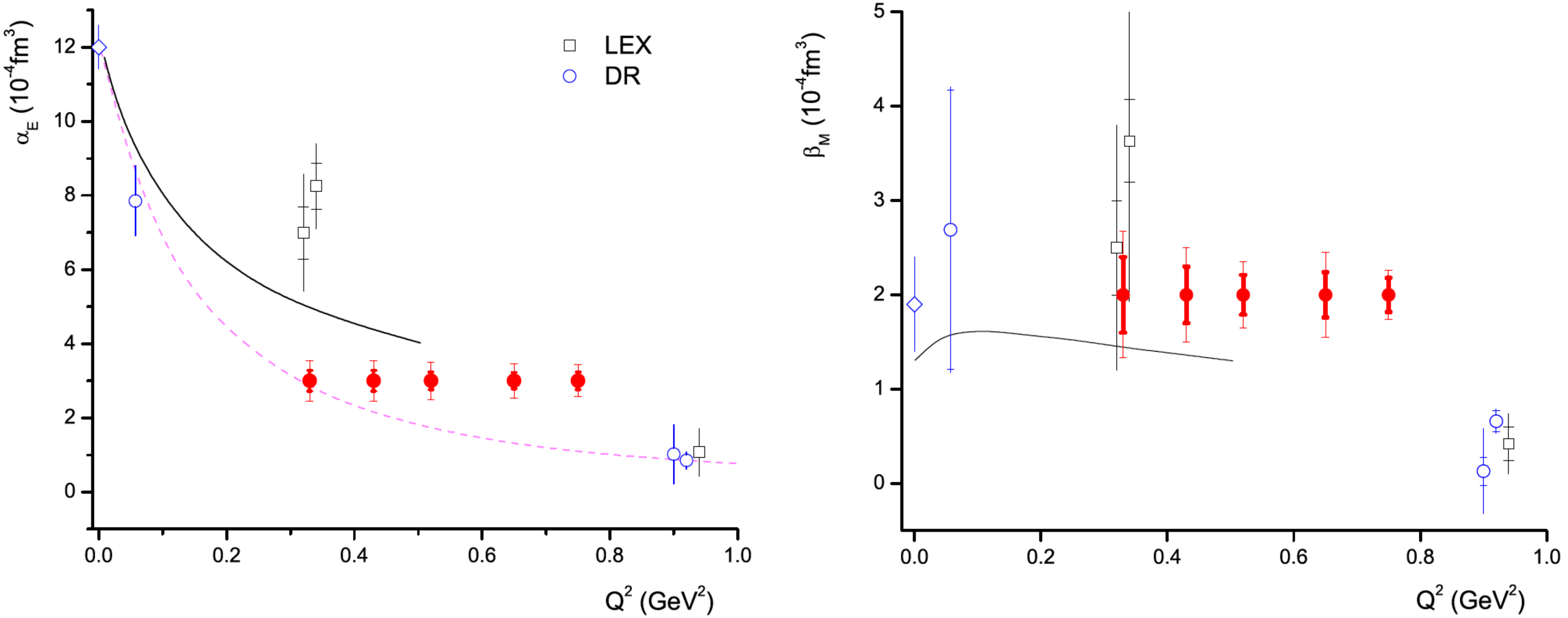




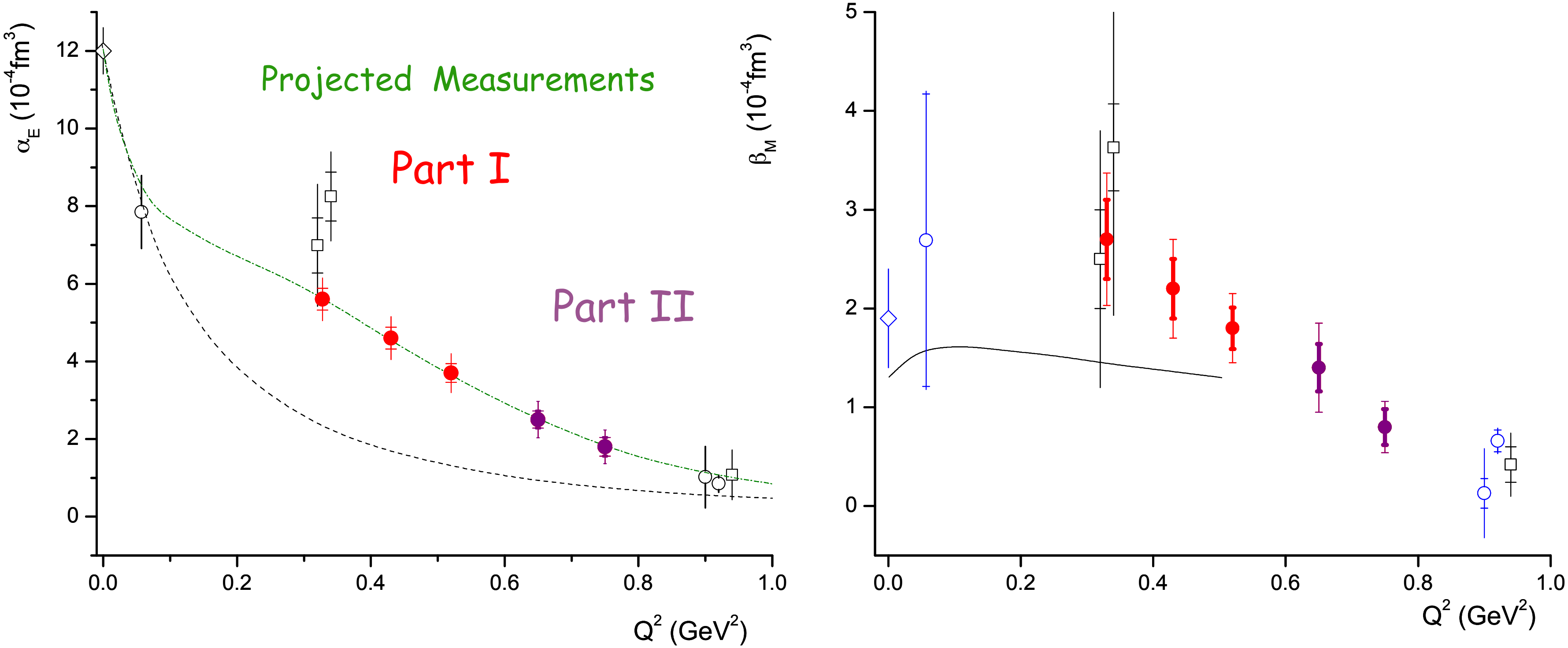
Statistical	< ±1.3%
Beam energy / scat. Angle	±1-2.5%
Target density	±0.5%
Detector efficiency	±0.5%
Acceptance	±0.5%
Target cell backgr.	±0.5%
Target length	±0.3%
Beam charge	±0.3%
Dead time	±0.3%
Pion contamination in MM	±0.3%
Rad. Corr.	±1.5%
Other	±0.5%

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

Projected Measurements



Status of E12-15-001



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

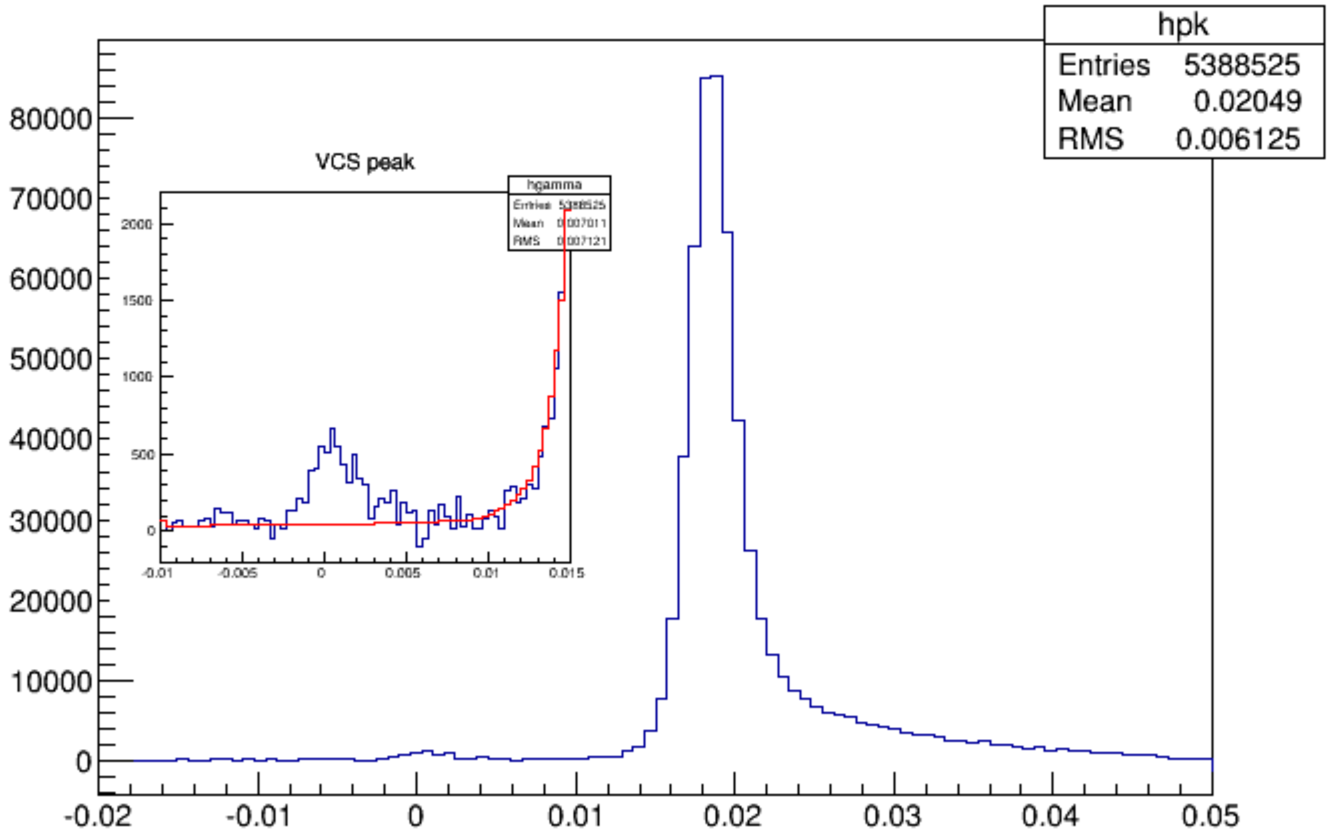
Current plan is to take data in June 2019

Other ongoing efforts

E08-010 (Hall-A/Jlab): γ-channel

parasitic access to VCS - data analysis ongoing

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 an upcoming 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 – very important to cross check these calculations
- the new measurements will trigger more theoretical activity

Thank you!