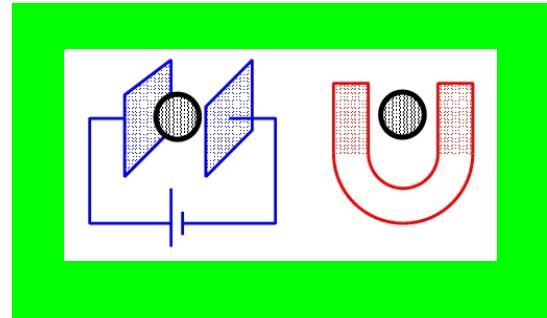


Nucleon Polarizabilities



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GDR PH-QCD 2011

content

- ★ Nucleon study:
Real and Virtual Compton Scattering
- ★ the Generalized Polarizabilities of the proton:
status and perspectives

Appearance	
clear (diamond) & black (graphite)	
	
Spectral lines of Carbon	
	

Physical properties	
Phase	Solid
Density (near r.t.)	amorphous: [1] $1.8\text{-}2.1 \text{ g}\cdot\text{cm}^{-3}$
Density (near r.t.)	graphite: $2.267 \text{ g}\cdot\text{cm}^{-3}$
Density (near r.t.)	diamond: $3.515 \text{ g}\cdot\text{cm}^{-3}$
Sublimation point	3915 K, 3642 °C, 6588 °F
Triple point	4600 K (4327°C), 10800 [2][3] kPa
Heat of fusion	117 (graphite) $\text{kJ}\cdot\text{mol}^{-1}$
Specific heat capacity	(25 °C) 8.517(graphite), 6.155(diamond) $\text{J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$
Atomic properties	
Oxidation states	4, 3 [4], 2, 1 [5], 0, -1, -2, -3, -4 [6]
Electronegativity	2.55 (Pauling scale)
Ionization energies (more)	1st: 1086.5 $\text{kJ}\cdot\text{mol}^{-1}$ 2nd: 2352.6 $\text{kJ}\cdot\text{mol}^{-1}$ 3rd: 4620.5 $\text{kJ}\cdot\text{mol}^{-1}$
Covalent radius	77(sp ³), 73(sp ²), 69(sp) pm
Van der Waals radius	170 pm

Miscellanea										
Magnetic ordering	diamagnetic [7]									
Thermal conductivity	(300 K) 119–165 (graphite) 900–2300 (diamond) $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$									
Thermal expansion	(25 °C) 0.8 (diamond) [8] $\mu\text{m}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$									
Speed of sound (thin rod)	(20 °C) 18350 (diamond) m/s									
Young's modulus	1050 (diamond) [8] GPa									
Shear modulus	478 (diamond) [8] GPa									
Bulk modulus	442 (diamond) [8] GPa									
Poisson ratio	0.1 (diamond) [8]									
Mohs hardness	1–2 (Graphite) 10 (Diamond)									
CAS registry number	7440–44–0									
Most stable isotopes										
Main article: Isotopes of carbon										
iso	NA	half-life	DM	DE (MeV)	DP 15					
¹² C	98.9%	¹² C is stable with 6 neutrons								
¹³ C	1.1%	¹³ C is stable with 7 neutrons								
¹⁴ C	trace	5730 y	β^-	0.156	¹⁴ N					

(From Wikipedia)

Response to a constraint

PDG : Baryon Particle Listings

p

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

p MASS (MeV)

VALUE (MeV)
 938.272013 ± 0.000023

p MAGNETIC MOMENT

VALUE (μ_N)
 $2.792847356 \pm 0.000000023$

Valence quarks: uud

p CHARGE RADIUS

VALUE (fm)
 0.8768 ± 0.0069

p ELECTRIC DIPOLE MOMENT

VALUE (10^{-23} e cm)
 < 0.54

p ELECTRIC POLARIZABILITY α_p

VALUE (10^{-4} fm 3)
 12.0 ± 0.6 OUR AVERAGE

p MEAN LIFE

LIMIT
(years)
 $>5.8 \times 10^{29}$
 $>2.1 \times 10^{29}$

PARTICLE
 n
 p

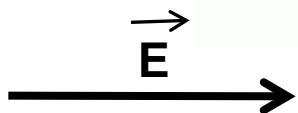
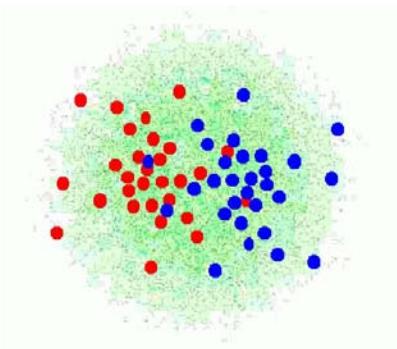
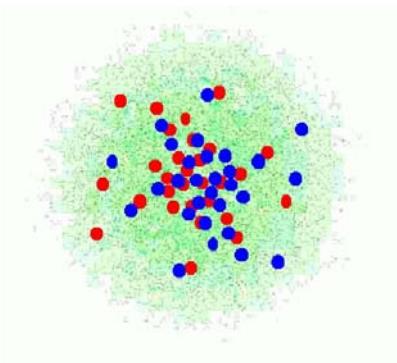
p DECAY MODES

p MAGNETIC POLARIZABILITY β_p

VALUE (10^{-4} fm 3)
 1.9 ± 0.5 OUR AVERAGE

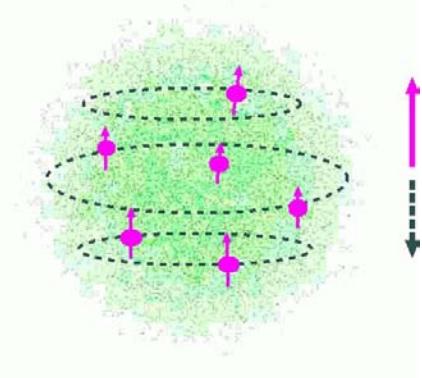
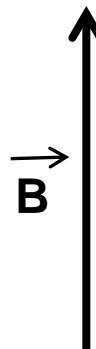
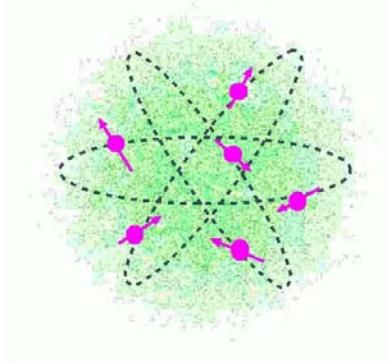
Response to a constraint

Electric polarizability:



$$\vec{d}_{induced} = \alpha \vec{E}$$

Magnetic polarizability:



$$\vec{\mu}_{induced} = \beta \vec{B}$$

Real Compton Scattering

V.Olmos de Leon et al.,
EPJA 10 (2001) 207

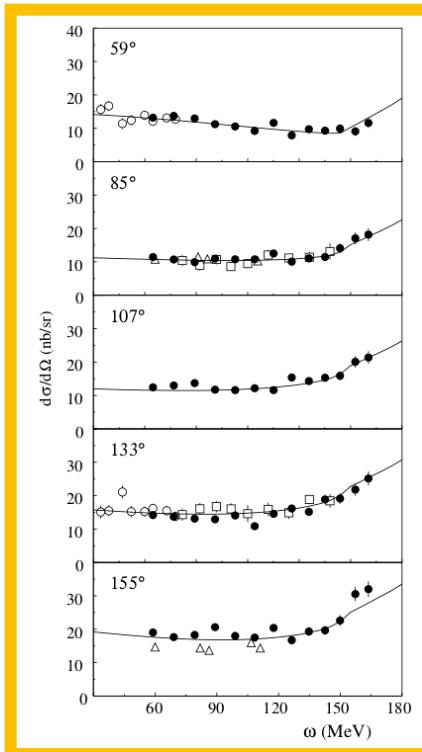
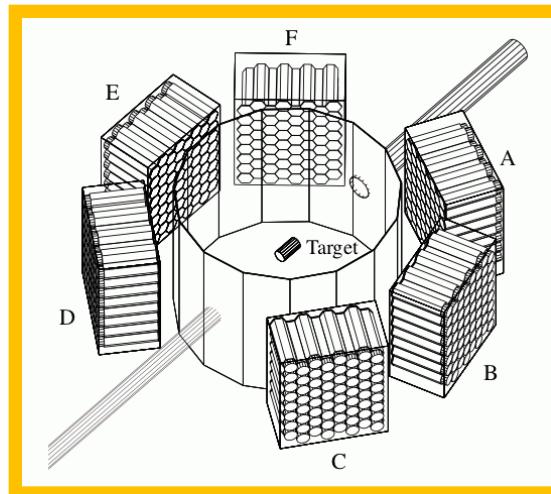


Fig. 5. The measured differential cross-sections in the lab system as obtained by the TAPS experiment (\bullet) [23]. The additional data are taken from ref. [26] (\circ), ref. [27] (\square) and ref. [25] (\triangle). The statistical errors are partially within the symbol size. The solid line shows the calculation of the dispersion relation approach using the π -production multipoles of Arndt *et al.* [15], solution SAID-SM99K. The polarizabilities were chosen to be: $\bar{\alpha} + \bar{\beta} = 13.8$, $\bar{\alpha} - \bar{\beta} = 10.5$ and $\gamma_\pi = -37.1$.

$$\left(\frac{d\sigma}{d\Omega} \right) = \left(\frac{d\sigma}{d\Omega} \right)_{\text{Point}} - \omega\omega' \left(\frac{\omega'}{\omega} \right)^2 \frac{e^2}{m} \left[\frac{\bar{\alpha} + \bar{\beta}}{2} (1+z)^2 + \frac{\bar{\alpha} - \bar{\beta}}{2} (1-z)^2 \right] + \dots$$



TAPS
MAMI-A2

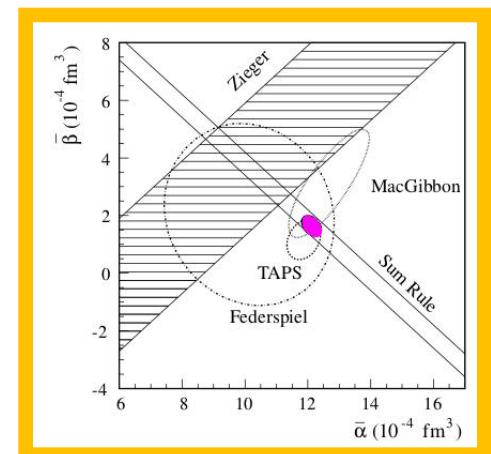


Fig. 6. Error contour plot in the $(\bar{\alpha}-\bar{\beta})$ -plane of the experiments in table 3 (last column) for which the errors are taken as the statistical ones only. The contours correspond to the values $\chi^2_{\min} + 1$ of the individual fits. Also shown are the sum rule constraint and the value $\bar{\alpha} - \bar{\beta}$ as follows from the experiment by Zieger *et al.* [28]. The thick solid line shows the result of the global fit, eq. (22).

What did we learn from RCS:

- Polarizabilities are small (strong binding force)
- Diamagnetism is important in the nucleon
- Similarity of proton and neutron polarizability

(among other things)

$$\alpha = 2 \sum_{n \neq 0} \frac{|\langle n^{(i)} | D_z | 0 \rangle|^2}{E_n^{(i)} - E_0^{(i)}} + Z^2 \frac{e^2 \langle r_E^2 \rangle}{3M}$$

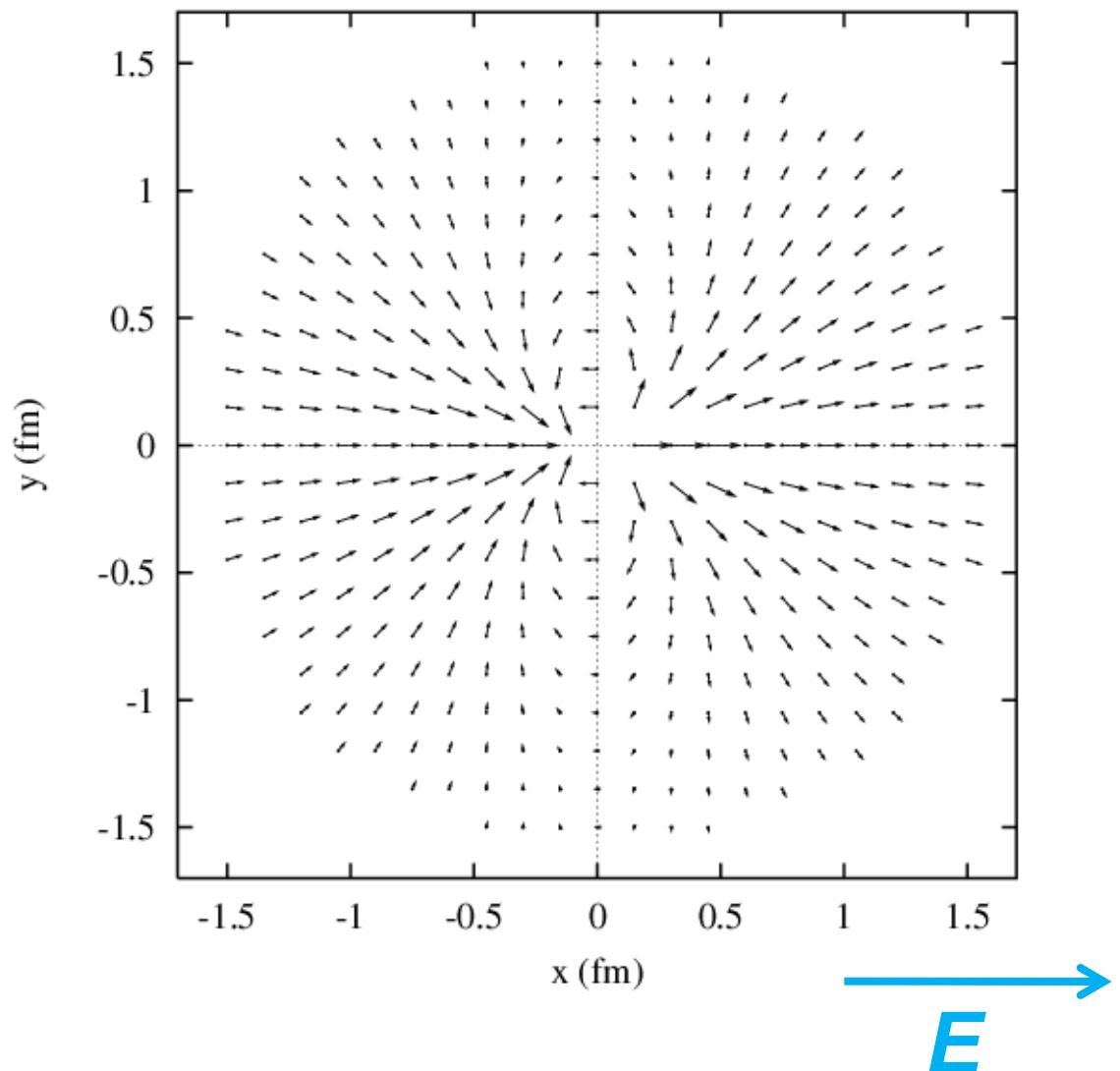
(NRQCM)

	$\bar{\alpha}$ ($10^{-4} fm^3$)	$\bar{\beta}$ ($10^{-4} fm^3$)
PROTON		
TAPS 2001 ($\bar{\alpha} + \bar{\beta}$) fixed	$12.1 \pm 0.4 \mp 1.0$	$1.6 \pm 0.4 \mp 0.8$
TAPS 2001 ($\bar{\alpha} + \bar{\beta}$) free	$11.9 \pm 0.5 \mp 1.3$	$1.2 \pm 0.7 \mp 0.3$
Schumacher 2005	12.0 ± 0.6	1.9 ∓ 0.6
NEUTRON		
Schumacher 2005	12.5 ± 1.7	2.7 ∓ 1.8
PION (π^+)		
Ahrens 2005 (MAMI A2)	$\bar{\alpha} - \bar{\beta} = 11.6 \pm 3.4$	

Polarizabilities are sensitive to the full excitation spectrum of the nucleon

HBChPT $O(p^3)$: Electric polarization in the nucleon induced by the field E_x

« Compton Scattering and
Generalized Polarizabilities »,
S.Scherer, AIP Proc. Conf. 768
(2005) 110.



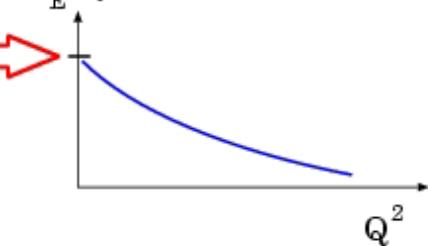
Scaled electric polarization $r^3 \alpha_{i1}$ [10^{-3} fm 3]

from γ (RCS) to γ^* (VCS)

$Q^2 \leftrightarrow$ distance scale

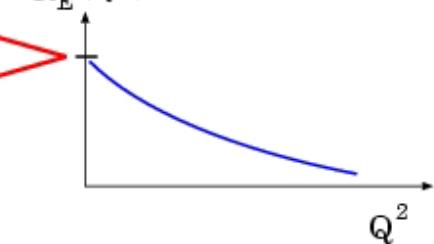
normalisation point:
electric charge
of the proton = $+1 * e$

electric form factor
 $G_E(Q^2)$



normalisation point:
electric polarizab.
measured in RCS
($12.e-4 \text{ fm}^{**3}$)

electric polarizability
 $\alpha_E(Q^2)$



Charge
↓
F.Factor
↓
Charge density

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

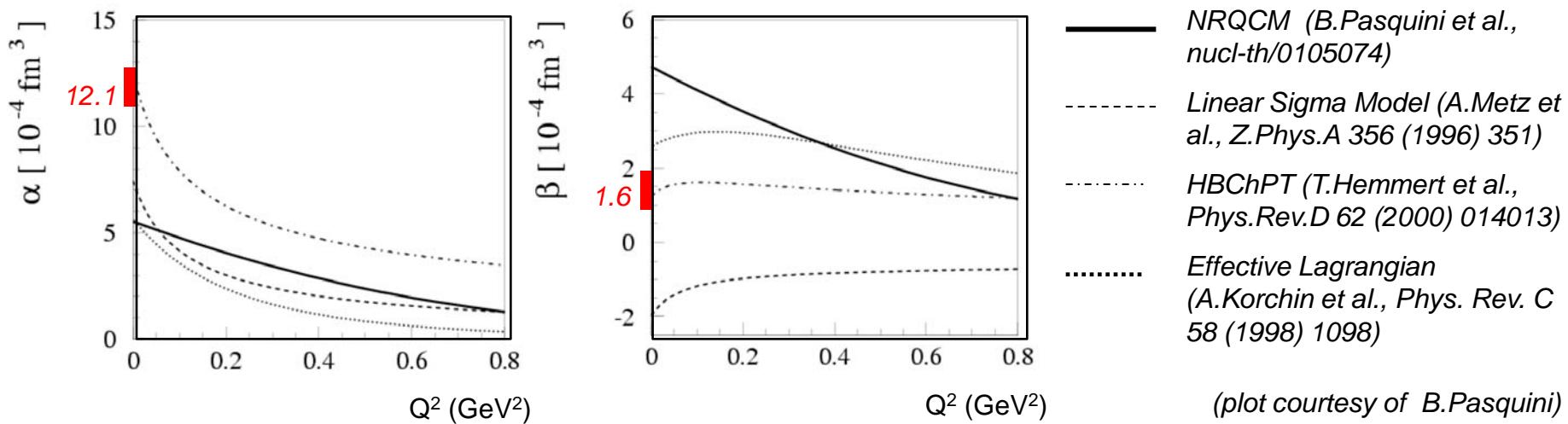
Polarizability
↓
Generalized Pol.
↓
Density of Pol.

Main theoretical papers:

- H. Arenhoevel et al., NPA233 (1974) 153*
P.Guichon et al., Nucl.Phys.A 591 (1995) 606
D.Drechsel et al., Phys.Rev.C 55 (1997) 424
D.Drechsel et al., Phys.Rev.C 57 (1998) 941
A.L'vov et al., Phys.Rev.C 64 (2001) 015203

2 scalar GPs:

$$P(L1,L1)0 = (\alpha_E), \quad P(M1,M1)0 = (\beta_M) \quad \text{Data}$$



(plot courtesy of B.Pasquini)

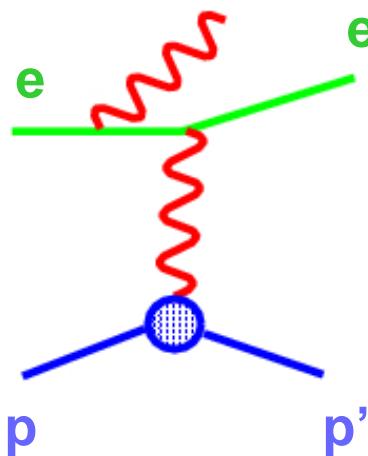
4 spin GPs:

$$P(L1,L1)1, \quad P(M1,M1)1, \quad P(L1,M2)1, \quad P(M1,L2)1 \quad \text{No Data}$$

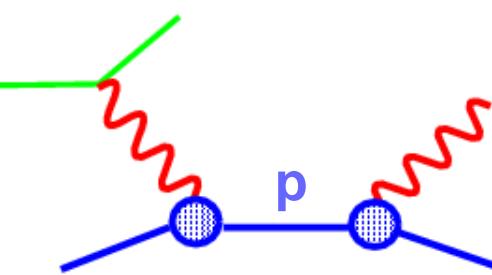
Virtual Compton Scattering (VCS)

$$e p \rightarrow e p \gamma$$

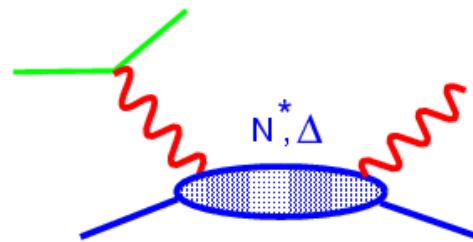
($e, e' p$) experiments:
 γ by missing mass



Bethe-Heitler



VCS Born



VCS non-Born
(GPs)

How to measure the GPs

Low Energy Theorem LET (or « LEX »)

P.Guichon et al., NPA 591 (1995) 606

M.Vanderhaeghen, PLB 402 (1997) 243

$$d\sigma(ep\gamma) = d\sigma(BH+Born) + \Phi q' [v_{LL}(P_{LL} - P_{TT}/\epsilon) + v_{LT}(P_{LT})] + O(q'^2)$$

Structure functions:

$$P_{LL} = (\dots) \alpha_E$$

$$P_{TT} = [\text{spin GPs}]$$

$$P_{LT} = (\dots) \beta_M + [\text{spin GPs}]$$

BH+Born known (proton FF)

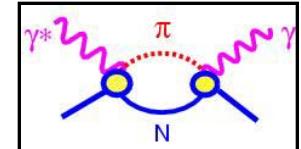
One $\epsilon \rightarrow$ two S.F. can be extracted

Dispersion Relations « DR »

B.Pasquini et al., Eur.Phys.J. A 11 (2001) 185

D.Drechsel et al., Phys.Rept. 378 (2003) 99

- Dispersive integrals for NonBorn amplitudes
- πN part: given by MAID
- $\gamma^*(*) N \rightarrow \pi N$ amplitudes



- Spin GPs are fixed
- Scalar GPs have an unconstrained part
→ must be parametrized:

$$\alpha_E(Q^2) - \alpha_E^{\pi N}(Q^2) = \frac{[\alpha_E^{\exp}(0) - \alpha_E^{\pi N}(0)]}{(1 + Q^2 / \Lambda_\alpha^2)^2}$$

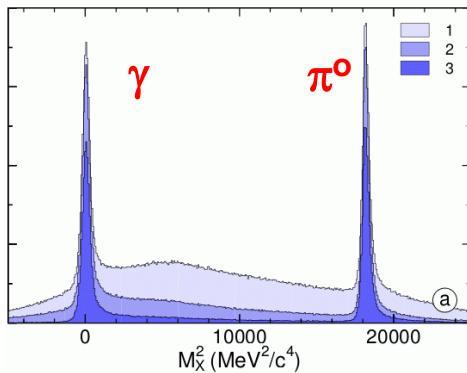
Λ_α , Λ_β fitted from experiment

Dedicated VCS experiments

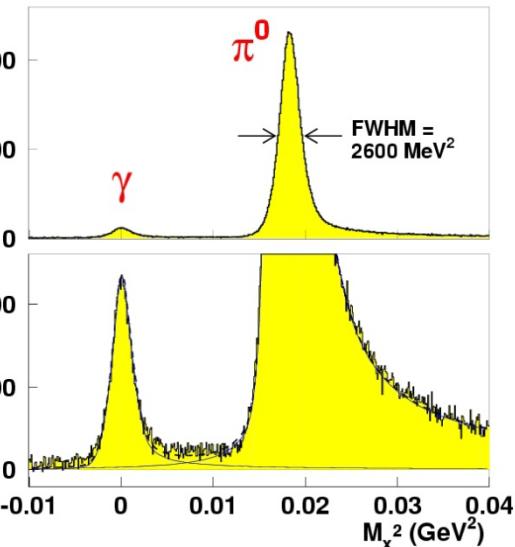
Experiment	Q^2 (GeV 2)	ε	data taking	published extractions	
MAMI-A1-1	0.33	0.61	1995-1997	SF (LEX)	2000
JLab/HallA	0.9, 1.8	0.90	1998	SF&GPs (LEX&DR)	2004
Bates	0.06	0.90	2000	SF&GPs (LEX&DR)	2006
MAMI-A1-2	0.33	0.48	2002-2004	SSA (\vec{e})	2007
MAMI-A1-3	0.33	0.64	2004-2006	SF (LEX) $(\vec{e}, \vec{p'})$	2008 + ...

Why are VCS experiments difficult ?

Resolution @ MAMI-A1 : great !



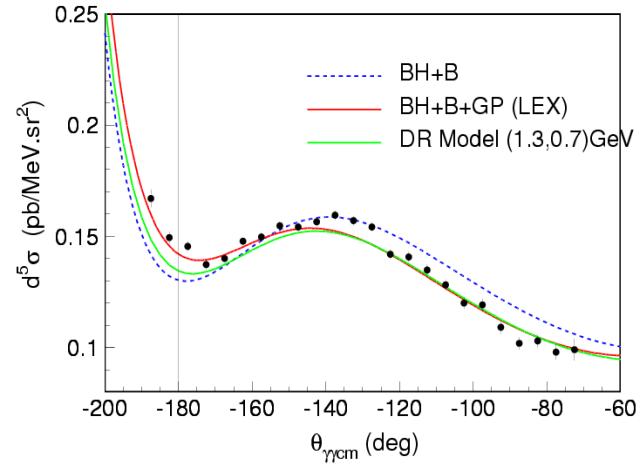
W = below
pion threshold



$ep \rightarrow epX$

W = region of
Delta(1232)

- Cross section: small
- Effect of GPs: small (10%)
- Need to control systematic errors to a tight level (high-precision experiments)



LET

extraction method
(unpolarized)

DR

extraction method

Structure functions

Need to subtract the spin
part (use DR model)

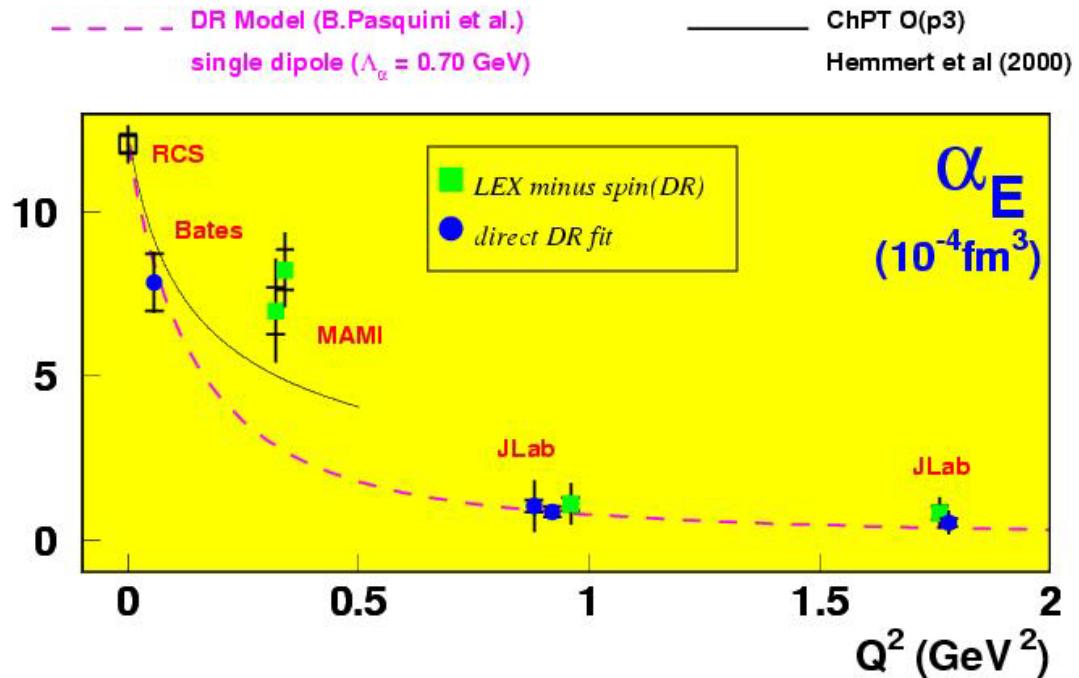
Scalar GPs of the proton (electric and magnetic)

Electric GP :

α_E : fall-off does not seem to be dipolar (all models: ~ dipole).
 ⇒ new puzzle ...

Is there a « structure » in α_E at low Q^2 ?
 (meson cloud ? Contrib. of some resonances ?)

Or experimental bias?



Mesonic effects : RCS + Bates point → $\langle r^2 \rangle$ of electric polarizability:

$$\begin{array}{lll} \langle r^2 \rangle & = & 2.16 \pm 0.31 \text{ fm}^2 \\ \text{HBChPT} & : & 1.7 \text{ fm}^2 \end{array}$$

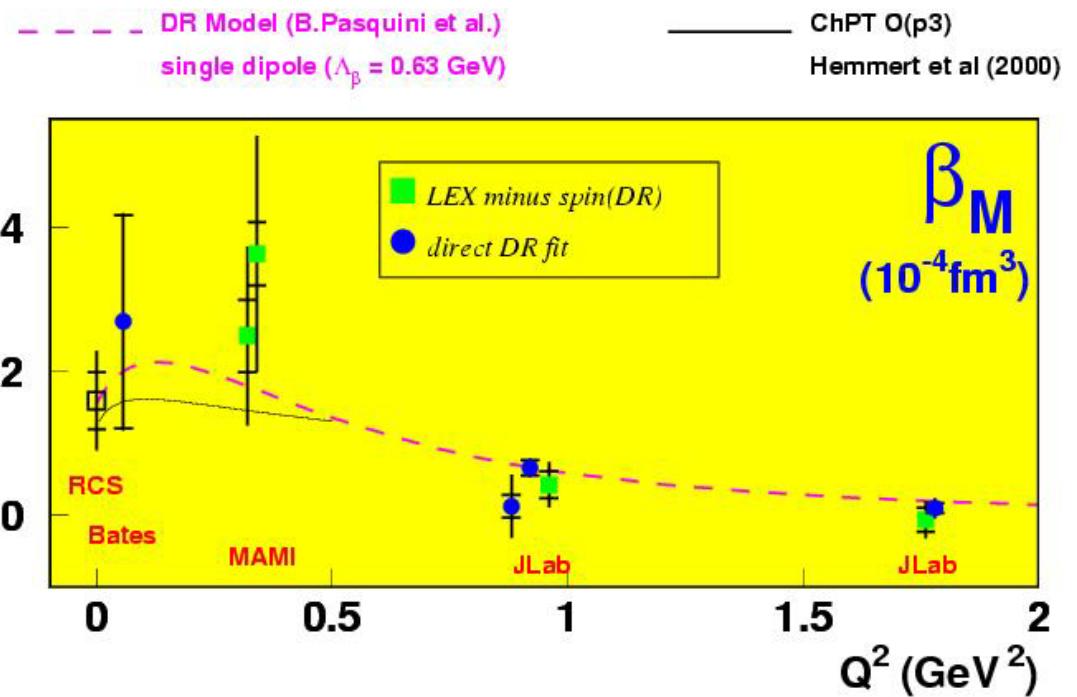
(P.Bourgeois et al., PRL 97 (2006) 212001)
 (T.Hemmert et al., PRD 55 (1997) 2630)

Magnetic GP :

β_M : extremum at low Q^2
seems confirmed,
although large relative
errors

Cancellation between
paramagnetism and
diamagnetism

Observable very sensitive to
absolute normalization, FF, etc.



The scalar GPs have a non-trivial Q^2 behavior

- Mesonic effects are known to be important in the polarizabilities of the nucleon:

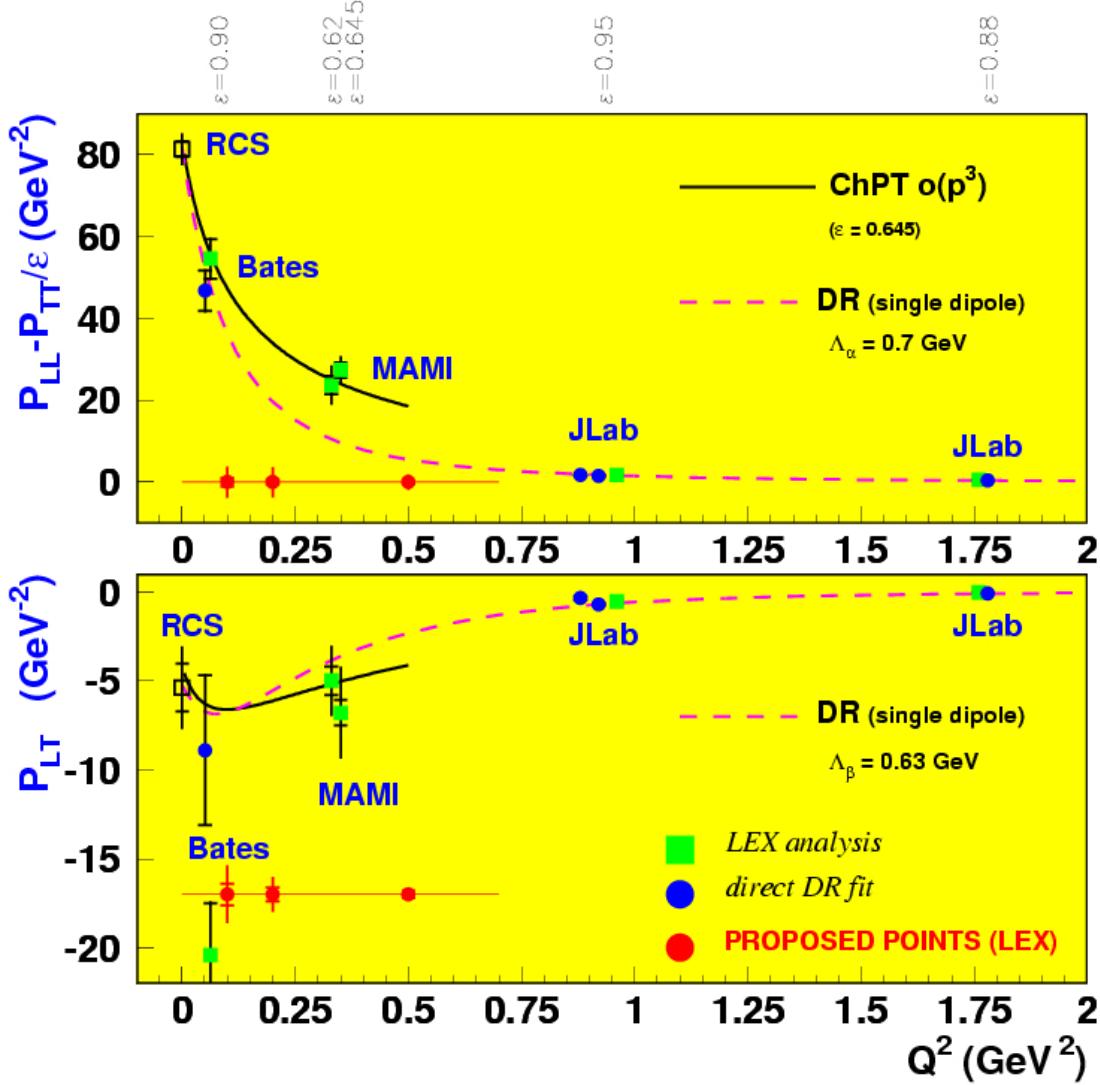
ChPT calculation of α_E and β_M in RCS :

« Nucleon EM polarizabilities to leading order in the chiral expansion are pure one-loop effect » (V.Bernard et al, PRL 67 (1991) 1515).

- effect of meson cloud is « enhanced » in polarizabilities w.r.t. form factors

to know more : need new measurements in the low- Q^2 region: [0 – 1] GeV²

A new VCS experiment in MAMI-A1



$Q^2 = 0.1, 0.2, 0.5$
GeV 2

Goal: measure
 $P_{LL} - P_{TT}/\varepsilon$ and P_{TT}
 and α_E and β_M
 using LEX and DR methods

Explore the non-trivial
 behavior of the electric and
 magnetic GPs of the proton

spin polarizabilities

- involving nucleon spin-flip in the Compton scattering process
- 4 of them at lowest order
 - In RCS: 2 combinations are measured
 - In VCS: ~nothing is known

Future plans: determine all 4 spin P's in RCS using polarisation (beam and/or target) , and MAMI-A2 and HIGS (TUNL), photon energies from 100 to 300 MeV.

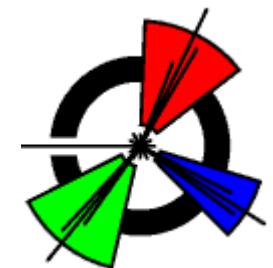
Conclusions

★ Compton Scattering to study nucleon EM structure:
an active field

★ MAMI: the ideal place to do this physics:
Strong theoretical support at KPH
A1 and A2 experimental Halls complementary

★ **MAMI : unique Lab to do VCS at low energy**

GPs = new observables of the nucleon,
sensitive in an original way to the pion cloud
and to the nucleon resonance spectrum.



Explore the non-trivial Q^2 - dependence of the
generalized polarizabilities in new experiments

The CRC 1044 Proposal (JGU, Mainz)

Collaborative Research Centre 1044 , Funding Proposal « The Low-Energy Frontier of the Standard Model : from Quarks and Gluons to Hadrons and Nuclei »

Research project for the 12 next years, for the physicists at MAMI (experimentalists and theoreticians)

Physics include: the future of MAMI (baryon form factors, meson structure, polarisabilities, parity violation, few-nucleon systems, lattice QCD, ...) + participation to BESIII (timelike and spacelike complementarity)

Coordinators: Achim DENIG and Marc VANDERHAEGEN

Last year: Pre-proposal

This year (2011): Symposium in february

Full proposal submitted in the Summer

CRC Review Presentation in september

Review process is ongoing

Answer in november 2011...