Virtual Compton Scattering
(low energy)

A special tool to study nucleon structure

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SFB School,
Boppard, Aug. 2017

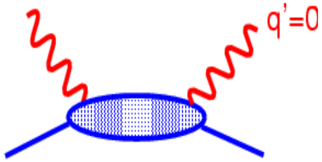
- RCS (Real Compton Scattering, polarizabilities)
- VCS (Generalized Polarizabilities GPs)
- the recent VCS experiment at MAMI-A1 (« vcsq2 »)

(experimentalist's talk)

RCS and Nucleon Polarizabilities

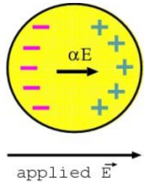
Real Compton Scattering

γ **N** $\rightarrow$ γ **N**



at q'=0 : the nucleon is put inside a static (E,B) field

Induced Dipoles :
Electric $d_E = \alpha_E \cdot E$
Magnetic $d_M = \beta_M \cdot B$



α_E , β_M = the 2 scalar P's of the nucleon, electric and magnetic.

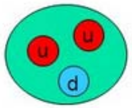
there are also 4 spin P's:
γ_{E1E1} , γ_{M1M1} , γ_{E1M2} , γ_{M1E2}

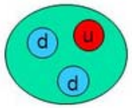
… And higher-order P's. There are as many as [polarization states ⊗ multipolarities] of the two photons. Need 5 quantum numbers to characterize each polarizability.

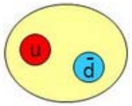
Proton, Neutron, Pion : Hadron Polarizabilities

Rather old values, not up to date, sorry!

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





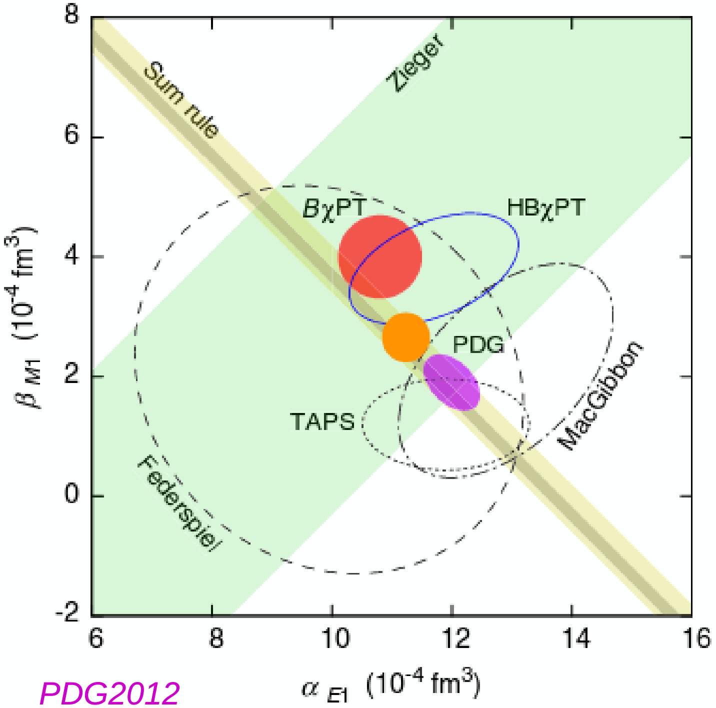


p , n , π : all the same order of magnitude!

Hadrons are extremely stiff objects due to strong binding.

Status of proton Polarizabilities

(in 10-4 fm3). From V.Pascalutsa, Talk LEPP workshop Mainz 2016



PDG2012
PDG2014

Scalar P's:

Analysis by Mc Govern,Phillips,Griesshammer, EPJA(2013)4912:

α_E = (10.7 +- 0.35 +- 0.2 +- 0.3) 10-4 fm3
β_M = (3.15 -+ 0.35 +- 0.2 -+ 0.3) 10-4 fm3

PDG2016:

α_E = (11.2 +- 0.4) 10-4 fm3
β_M = (2.5 +- 0.4) 10-4 fm3

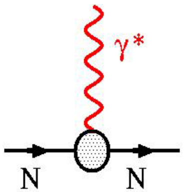
Spin P's:

All 4 measured separately for the first time by the MAMI-A2 collaboration // P.Martel et al, PRl114(2015)112501
(MAMI-A2 Compton program ongoing)

	Σ_{2x} and Σ_3^{LEGS}	Σ_{2x} and Σ_3^{MAMI}
$\bar{\gamma}_{E1E1}$	-3.5 ± 1.2	-5.0 ± 1.5
$\bar{\gamma}_{M1M1}$	3.16 ± 0.85	3.13 ± 0.88
$\bar{\gamma}_{E1M2}$	-0.7 ± 1.2	1.7 ± 1.7
$\bar{\gamma}_{M1E2}$	1.99 ± 0.29	1.26 ± 0.43

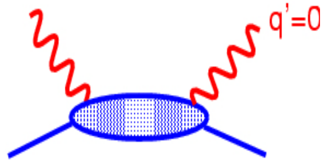
(in 10-4 fm4). Table from P.Martel, EPJWebConf 142(2017)

Introducing the Generalized Polarizabilities



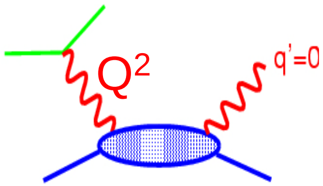
Real Compton Scattering

γ **N** $\rightarrow$ γ **N**



Virtual Compton Scattering

γ^* **N** $\rightarrow$ γ **N**



at q'=0: proton in a static (E,B) field

at q'=0: proton in a static (E,B) field

FF(Q^2)

Induced Dipoles :

Electric $d_E = \alpha_E \,.\, E$

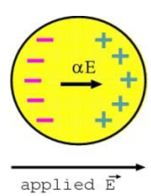
Magnetic $d_M = \beta_M \,.\, B$

Generalized Polarizabilities:

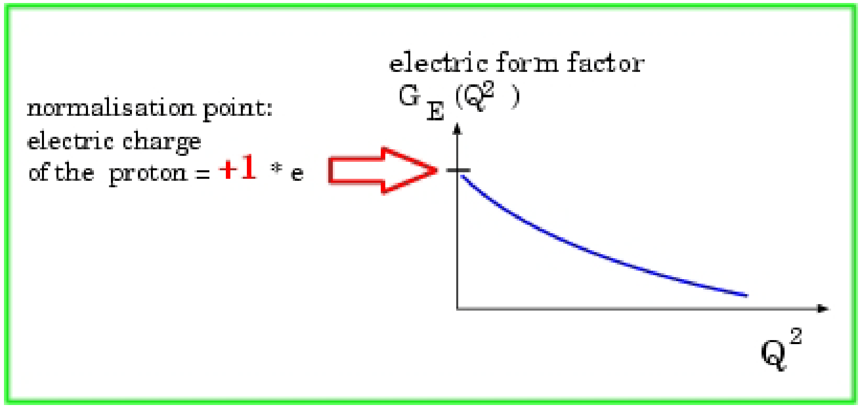
electric $\alpha_E(Q^2)$

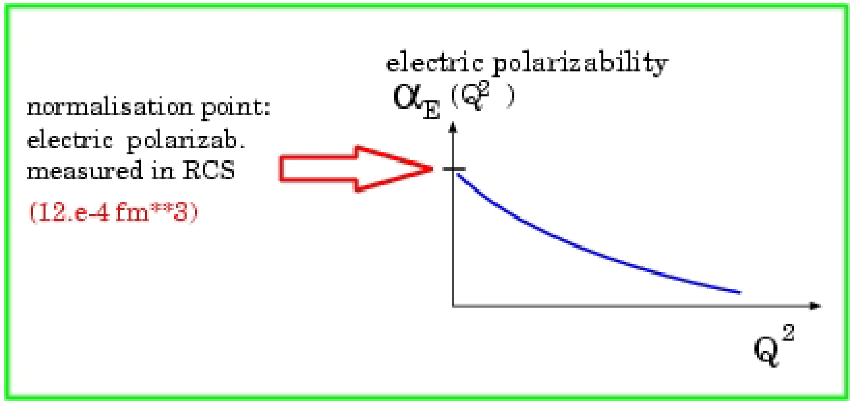
Magnetic $\beta_M(Q^2)$ **+ spin GPs**

Density of charge and magnetization



Density of electric and magnetic polarization of a deformed nucleon





- ***GP is like a FF, but of a deformed nucleon.***

- ***Contrary to elastic FF, GPs (and P's) are sensitive to the whole excitation spectrum of the nucleon:***

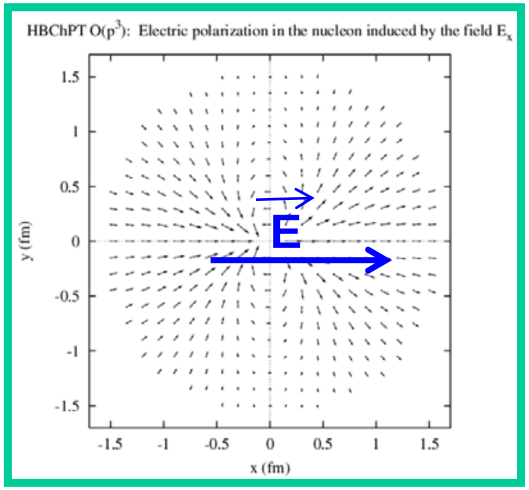
$$\alpha = 2 \sum_{n \neq 0} \frac{|\langle n^{(i)} | D_z | 0 \rangle|^2}{E_n^{(i)} - E_0^{(i)}} + Z^2 \frac{e^2 \langle r_E^2 \rangle}{3M}$$

- ***In VCS, GPs depend on Q^2 but more truly on q_{cm} = three-momentum of the virtual photon.***

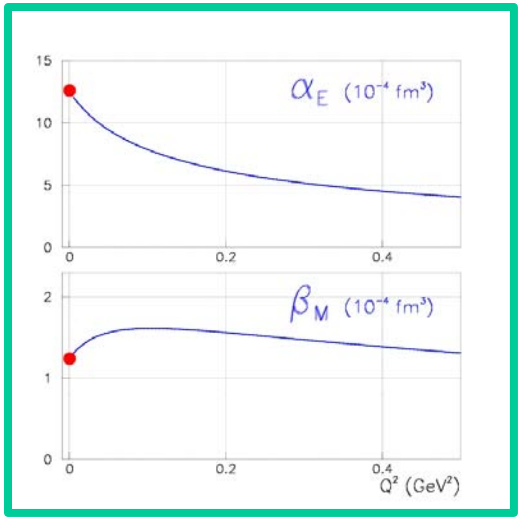
There is an equivalence between the two (see Guichon-Thomas 1995).

The Big Questions

S.Scherer, nucl-th/0410061



T.Hemmert et al. (HBChPT) PRL79(1997)

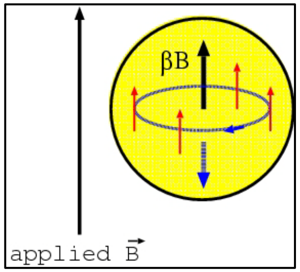


What do we want to learn with the GPs ?

- where does the polarizability manifest itself most? is it at the periphery of the nucleon? Or in the core?
-Measure a mean square radius!

-Are the GPs sensitive to the pion cloud? (more than FF?)

- the magnetic GP: is a complex phenomenon implying both dia- and paramagnetism: two contributions large and of opposite sign. How much do they cancel each other?



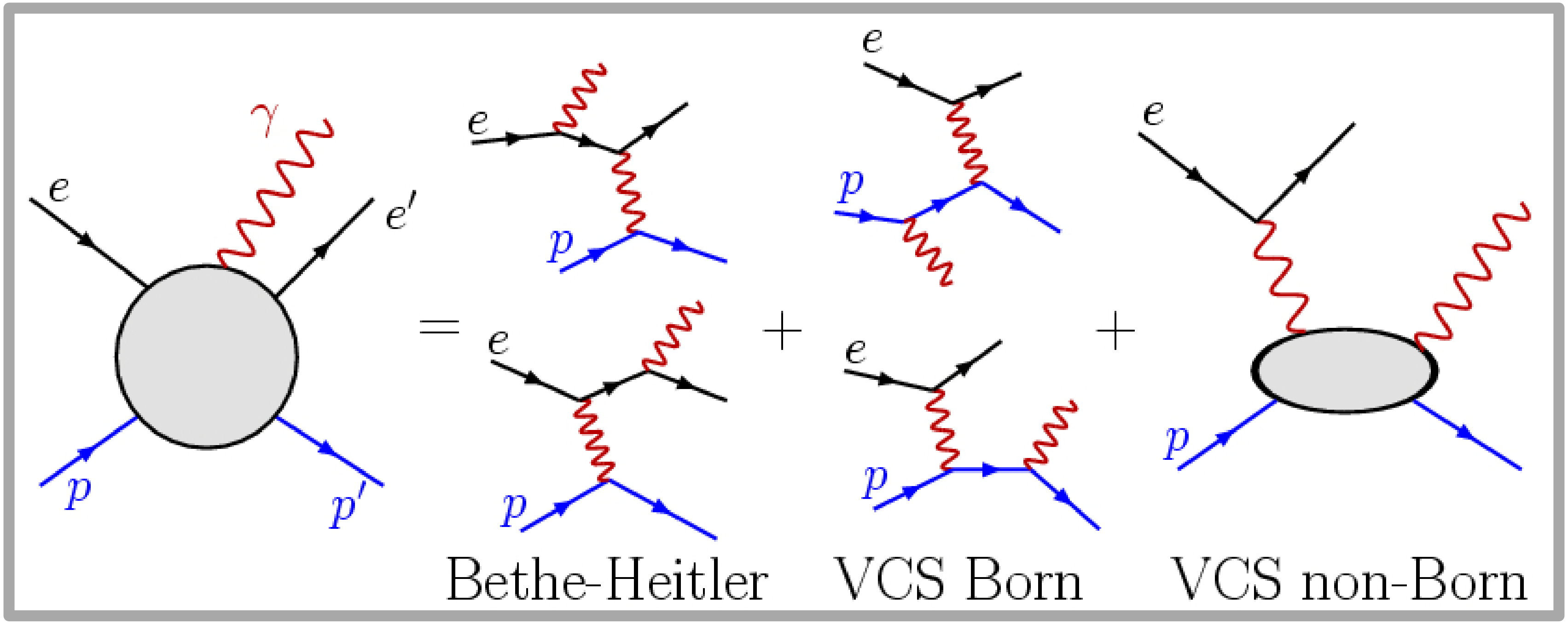
-Any good model of nucleon structure should reproduce P's and GPs measurements: good tests of models.

-Unfortunately, data on GPs are still rather scarce, (difficult to obtain).

How to measure GPs

GPs of the Proton only! (difficult enough)

photon electroproduction: e p → e p γ



The Founding Grandfathers

Arthur Compton
1892-1962
Nobel prize 1927

Theory of $\gamma e \rightarrow \gamma e$ scattering

Second Series | *May, 1923* | *Vol. 21, No. 5*

THE

PHYSICAL REVIEW

A QUANTUM THEORY OF THE SCATTERING OF X-RAYS BY LIGHT ELEMENTS

By Arthur H. Compton

Hans Bethe
1906-2005
Nobel prize 1967

Walter Heitler
1904-1981

Bremsstrahlung of electrons

83

On the Stopping of Fast Particles and on the Creation of Positive Electrons

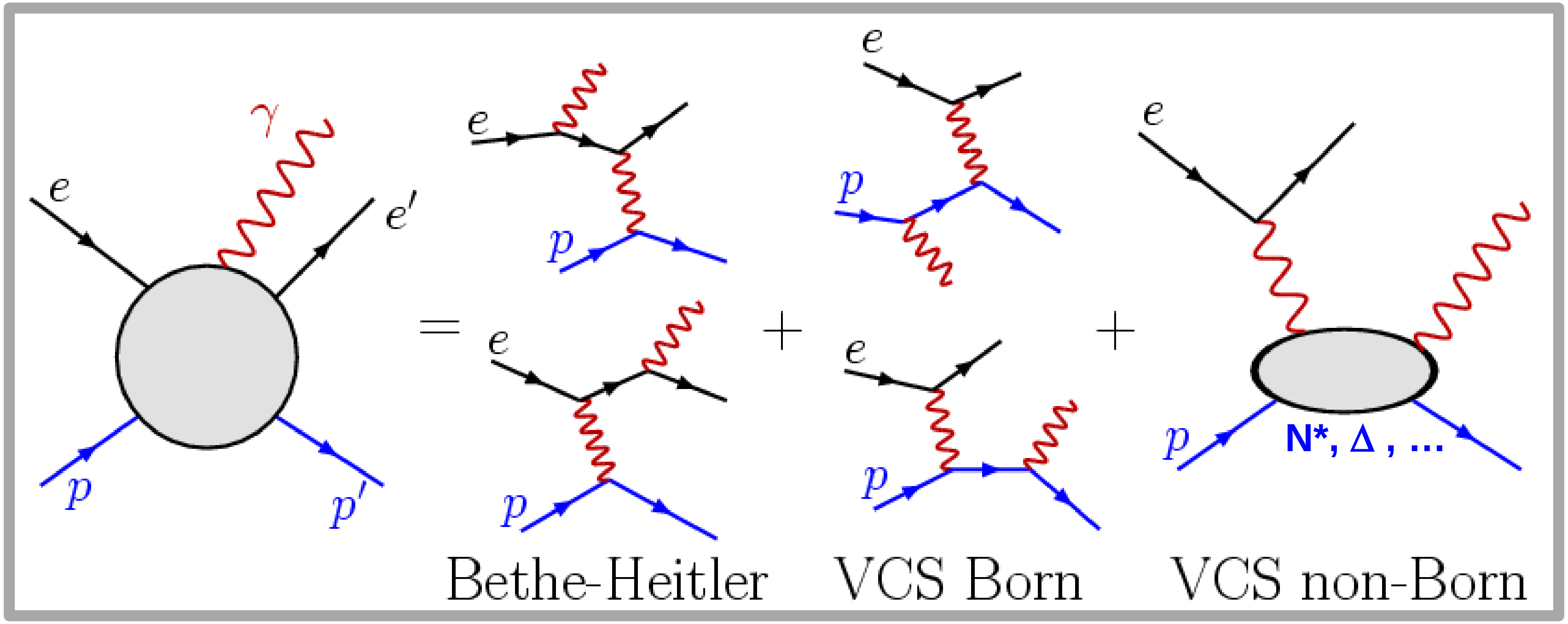
By H. Bethe, Manchester, and W. Heitler, Bristol

(Communicated by P. A. M. Dirac, F.R.S.—Received February 27, 1934)

Introduction

The stopping power of matter for fast particles is at present believed to be due to three different processes: (1) the ionization; (2) the nuclear scattering; (3) the emission of radiation under the influence of the electric field of a nucleus.

How to measure GPs



Electron bremsstrahlung

KNOWN

Proton bremsstrahlung

KNOWN

Parametrized by the GPs !

Small term !

In which kinematical domain can one work ?

- **a priori, any value of Q^2 of the initial virtual photon**

- **explored experimental range: 0.06 GeV^2 to 1.8 GeV^2**

- **energy of the final real photon, q', must not be too large (GP's are defined theoretically as limits of Compton amplitudes at q'=0!)**

-**In practice: stay below the pion threshold for the c.m. energy of the [γ*-nucleon] system (W < m_p+m_π , equivalent to q'_{cm} < 126 MeV/c) , or slightly above, up to the Delta(1232) region.**
(a bit similar to RCS)

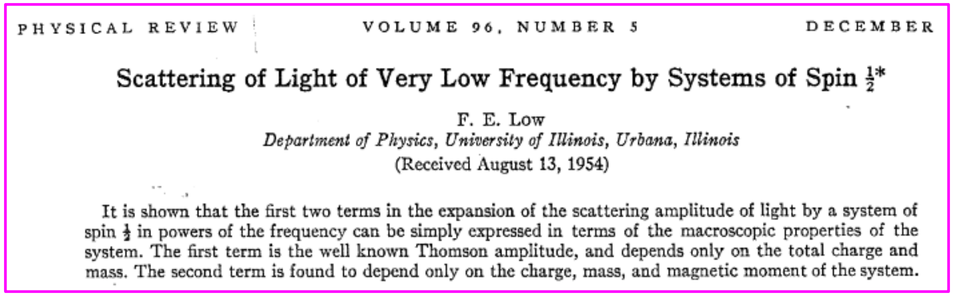
VCS: The Founding Fathers

D.Drechsel and H. Arenhoevel, NPA233(1974)153: γ^*+A $\rightarrow$ γ +A, first concept of Generalized Polarizabilities for nuclei
P.Guichon, G.Q.Liu and A.W. Thomas , NPA591(1995)606 : the nucleon case, establishment of a Low-Energy Theorem (LET), which led to an experimental program of VCS experiments at electron accelerators.

Another grandfather

Francis E.Low
1921-2007

The Low Energy Theorem (LET) is both
- **a theorem, or expansion, at low energy**
- **an energy theorem due to F.Low (1954)**


PHYSICAL REVIEW VOLUME 96, NUMBER 5 DECEMBER

Scattering of Light of Very Low Frequency by Systems of Spin $\frac{1}{2}$*

F. E. Low
Department of Physics, University of Illinois, Urbana, Illinois
(Received August 13, 1954)

It is shown that the first two terms in the expansion of the scattering amplitude of light by a system of spin $\frac{1}{2}$ in powers of the frequency can be simply expressed in terms of the macroscopic properties of the system. The first term is the well known Thomson amplitude, and depends only on the total charge and mass. The second term is found to depend only on the charge, mass, and magnetic moment of the system.

The Modelists and the Experimentalists for GPs

THEORY

- -D.Drechsel
- -M.Gorchtein
- -P.Guichon
- -T.Hemmert
- -B.Holstein
- -J.Kambor
- -C.W.Kao
- -M.Kim
- -G.Knochlein
- -Y.Korchin
- -V.Lensky
- -G.Q.Liu
- -A.L'vov
- -A.Metz
- -D.P.Min
- -V.Pascalutsa
- -B.Pasquini
- -S.Scherer
- -A.Thomas
- -C.Unkmeir
- -M.Vanderhaeghen

MODELS:

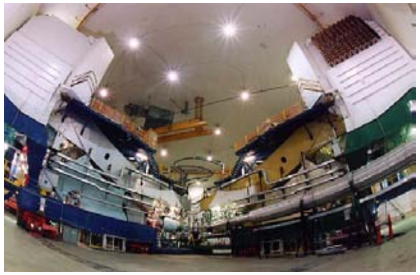
- -NR Constituant quarks
- - Skyrme model
- -Dispersion relations
- -Linear sigma
- -Effective Lagrangian
- -HBChPT
- -BChPT

EXPERIMENTS

MAMI-A1

MIT-Bates

JLab-Hall A



Models for Experiments

ONLY 2 models having a direct interface with VCS experiments:

-**The LET, or LEX, of Guichon-Thomas (model indep.!) ,** *NPA591(1995)606*
-**The Dispersion Relations Model of Barbara Pasquini et al.,** *EPJA 11(2001)185*

Other models give predictions for GPs but no way to access them from an experiment.

P's, and GPs, are always obtained by a FIT from data.

So it's like in RCS: measure cross sections, or asymmetries, and make a fit of polarizabilities.

RCS and VCS: Dispersion Relations extensively used (good models!)
RCS: ChPT also used

The low–energy expansion (LEX)

RCS

ω, ω' = Lab energies of initial and final photon

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

Scalar P's

Interf.between Thompson and polarizability amplitude

Spin P's

VCS

q'_{cm} = c.m. energy of final photon

$$d^5\sigma(ep\gamma) = d^5\sigma(\text{BH+Born}) + \Phi\, q' \left[v_{LL}\left(P_{LL} - P_{TT}/\varepsilon\right) + v_{LT}\left(P_{LT}\right)\right] + O(q'^2)$$

Scalar & Spin GPs

Interf.between BH+Born and polarizability amplitude (= NonBorn)

Born, BH+Born
1st-order LEX
Higher orders

Structure functions:

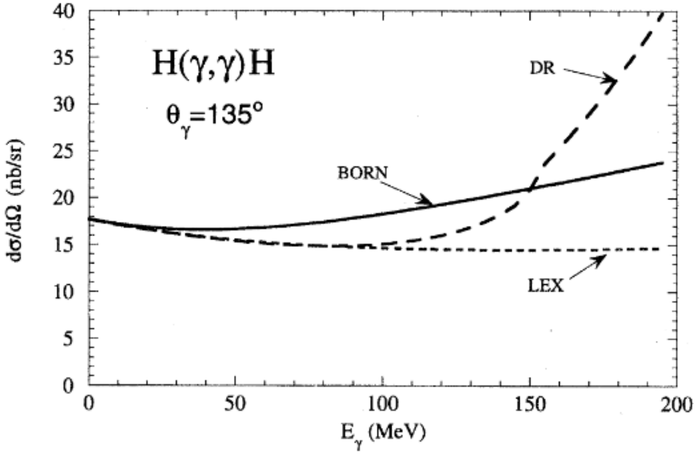
$P_{LL} = (\ldots)\ \alpha_E$

P_{TT} = [spin GPs]

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

LEX versus full energy dependence (DR)

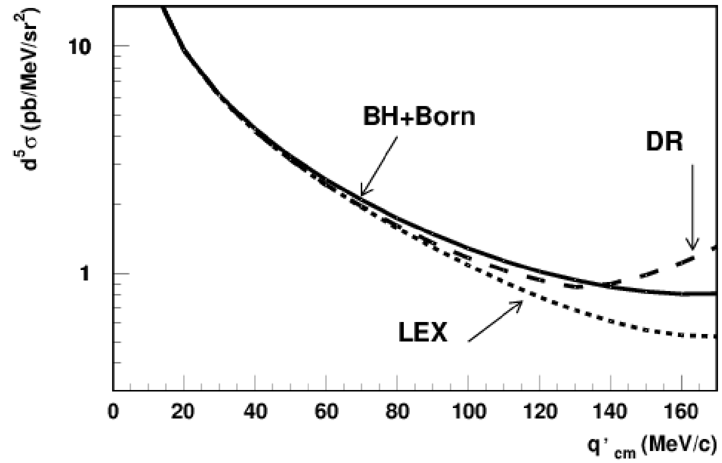
RCS



q'_{cm} : 0 82 167

Figure 4.1: CS cross sections calculated in the Born approximation (solid), the leading-order LEX (dotted) and a dispersion model calculation (dashed). Plot reproduced from MacGibbon et al. [12].

VCS



VCS-Bates kinematics
qcm=240 MeV, epsilon=0.90
thetacm=90deg, phicm=90deg
Q2=0.057 GeV2

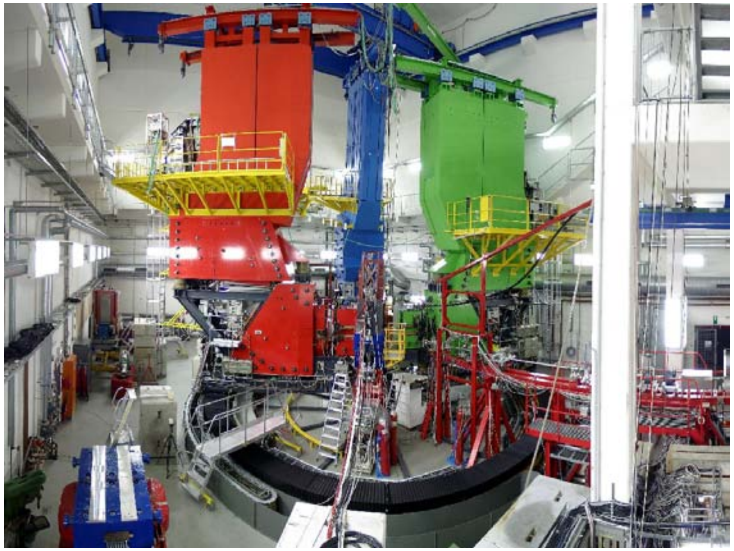
In both cases:
- **Born (or BH+Born) not enough except at very low photon energy q'**
- **LEX OK up to a certain energy but not above**
- **DR only gives the full energy dependency**

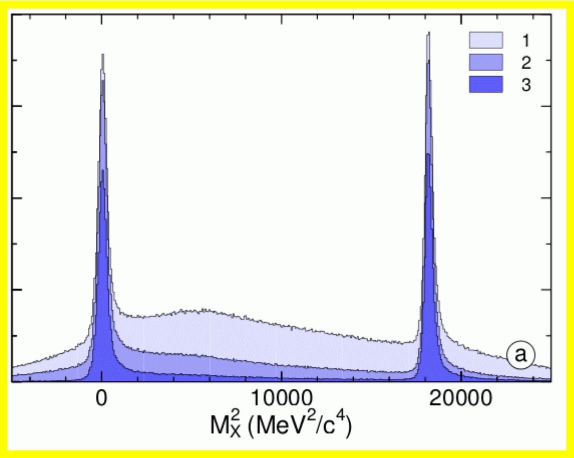
Measuring ep $\rightarrow$ epγ cross sections at MAMI-A1

Electron beam (1.5 GeV)
Cryotarget: liquid hydrogen
e' detected in a spectrometer
p' detected in a spectrometer

photon = the only missing particle
→ identify it by missing mass

Five-fold differential cross section



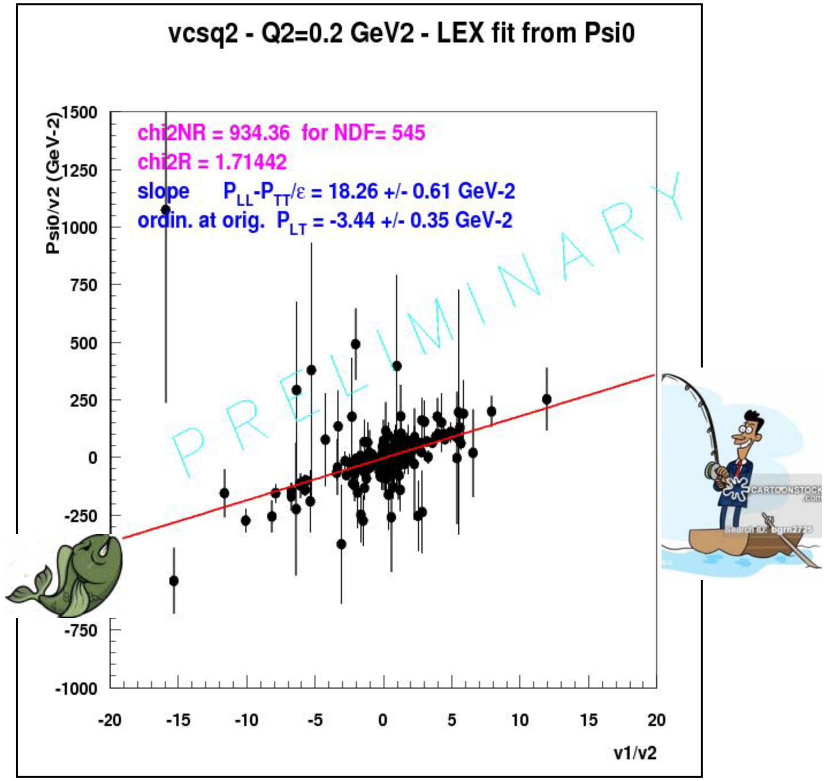


Once you have cross sections: GP fit # 1 = LEX fit

Use the LEX,
Neglect the O(q'²) !
Then it's a linear fit of
two unknowns , e.g. :

$$[\, d^5\sigma\,(ep\gamma) - d^5\sigma\,(BH+Born)\,] \,/\, [\Phi\, q' \,.\, v_{LL}\,]$$

$$= \quad (P_{LL} - P_{TT}/\varepsilon) + [v_{LT} / v_{LL}]\,.\,(P_{LT})$$

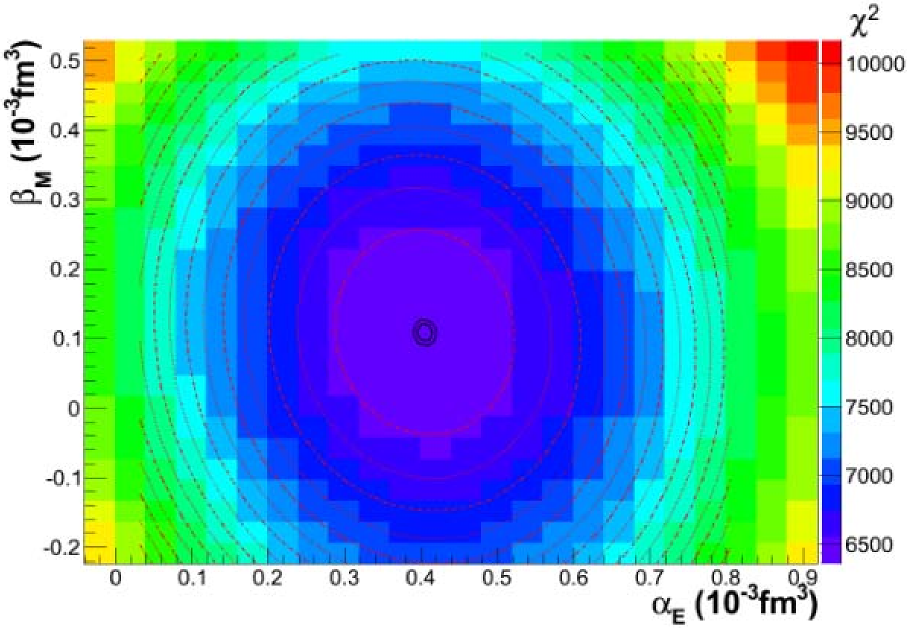


Once you have cross sections: GP fit # 2 = DR fit

Compare the measured cross sections to the ones calculated by the model, for all values of the electric GP $\alpha_E\ (Q^2)$ and the magnetic GP $\beta_M\ (Q^2)$ which are free parameters of the model.

The DR cross section does NOT neglect the $O(q'^2)$!

Make a χ^2 and minimize it.



DR model for Compton Scattering on the nucleon: see Lectures of Barbara Pasquini at BOSEN school 2007 !

DR fit sometimes more difficult than the LEX fit …

proton GPs: World data

LEX fit

DR fit

Structure functions
$P_{LL} - P_{TT} / \varepsilon$ **and** P_{LT}

True level of comparison

Structure functions
$P_{LL} - P_{TT} / \varepsilon$ **and** P_{LT}

Structure Functions

(before the recent expts)

at $Q^2=0$:

$P_{LL} - P_{TT} / \varepsilon =$ (cst)* $\alpha_E(0)$

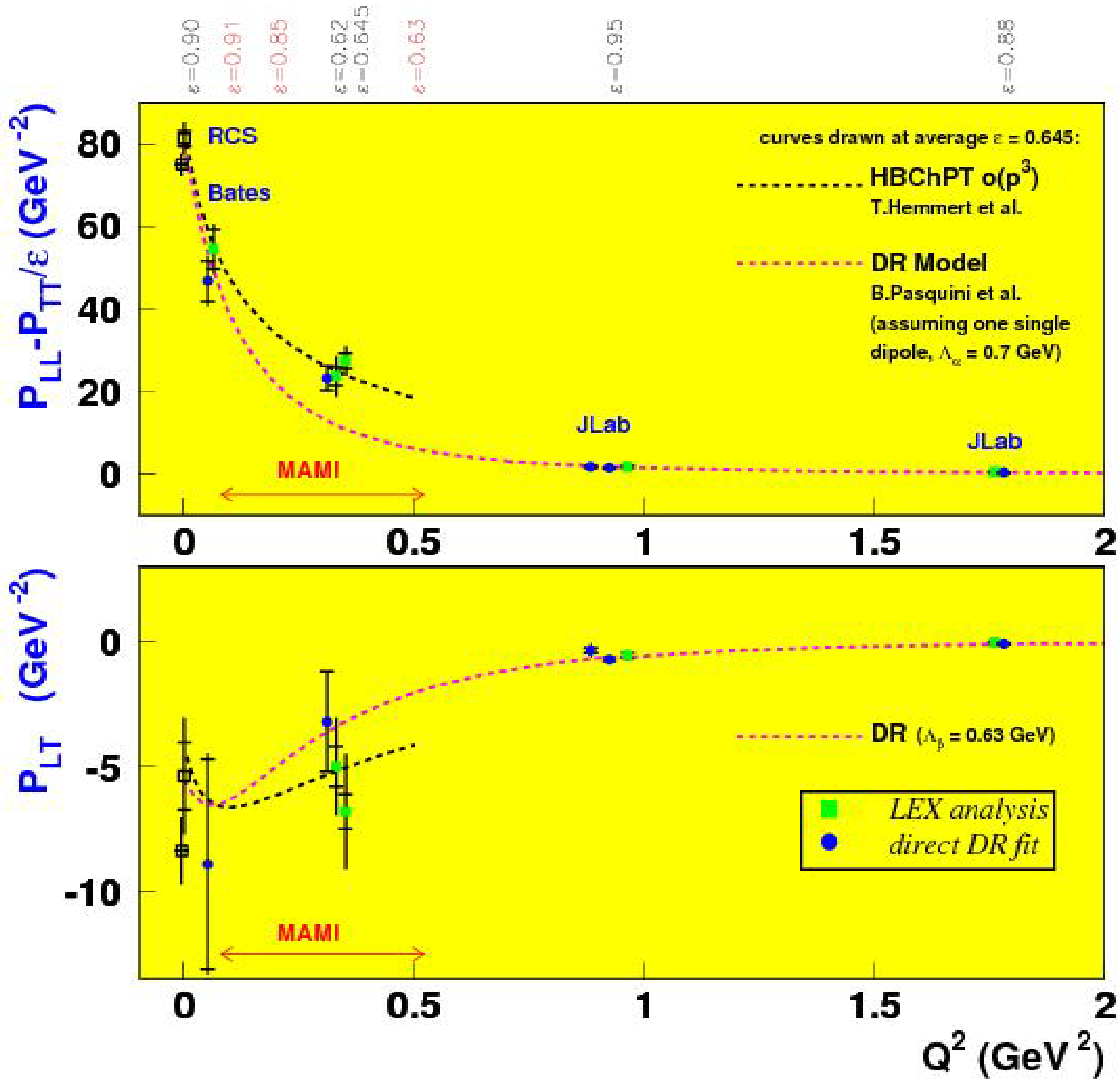
$P_{LT} =$ (cst)* $\beta_M(0)$

2 RCS points:

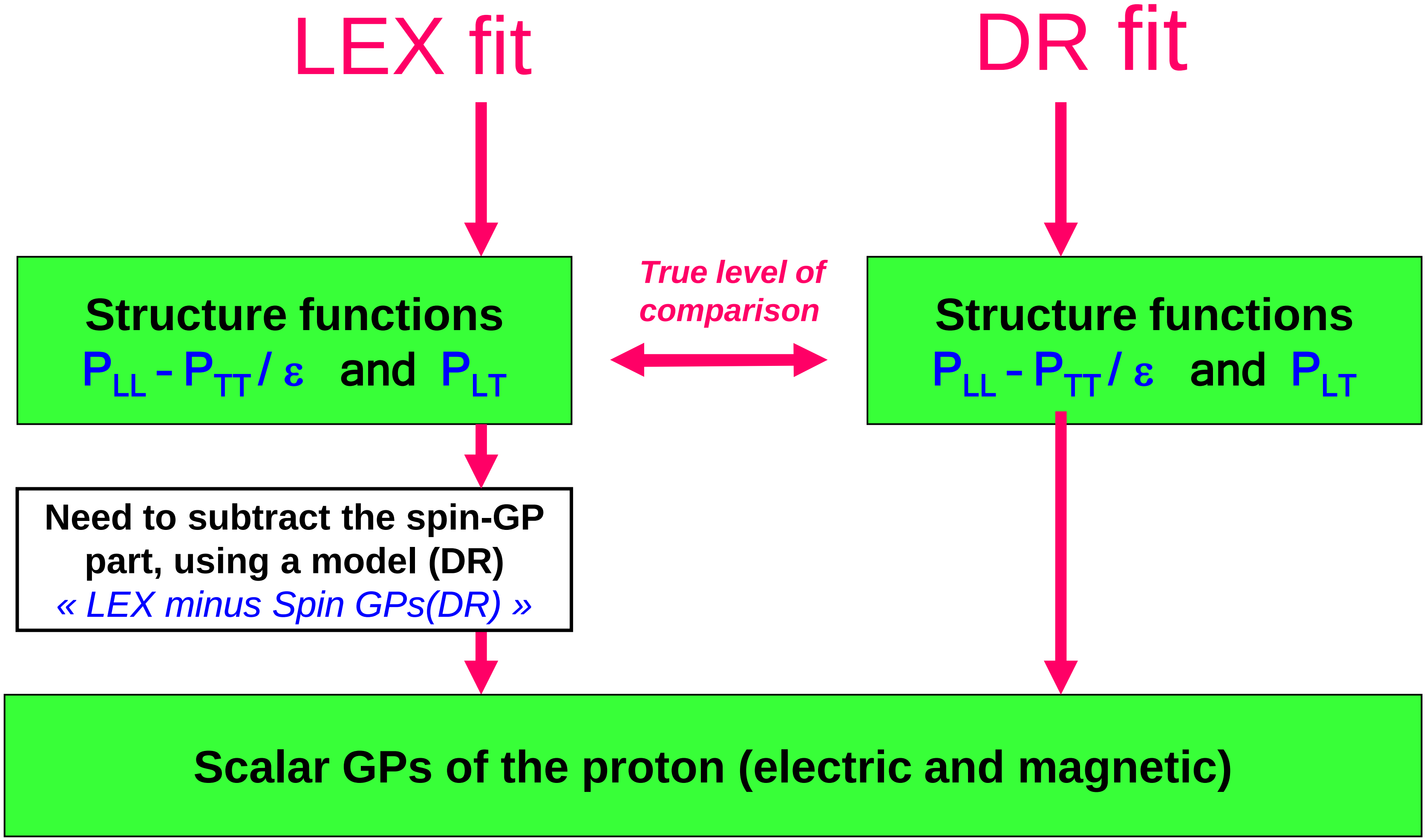
- Olmos de Leon (EPJA 10 (2001) 207

- Particle Data Book 2014

DR model does NOT predict the scalar GPs. The « DR curve » here includes a further assumption in the model (dipole, with Λ parameter = constant vs Q^2, and fitted on data).



proton GPs: World data



Electric and magnetic GP

2 RCS points:

- Olmos de Leon (EPJA 10 (2001) 207

-Particle Data Book 2014

RCS point + Bates point → slope of α_E

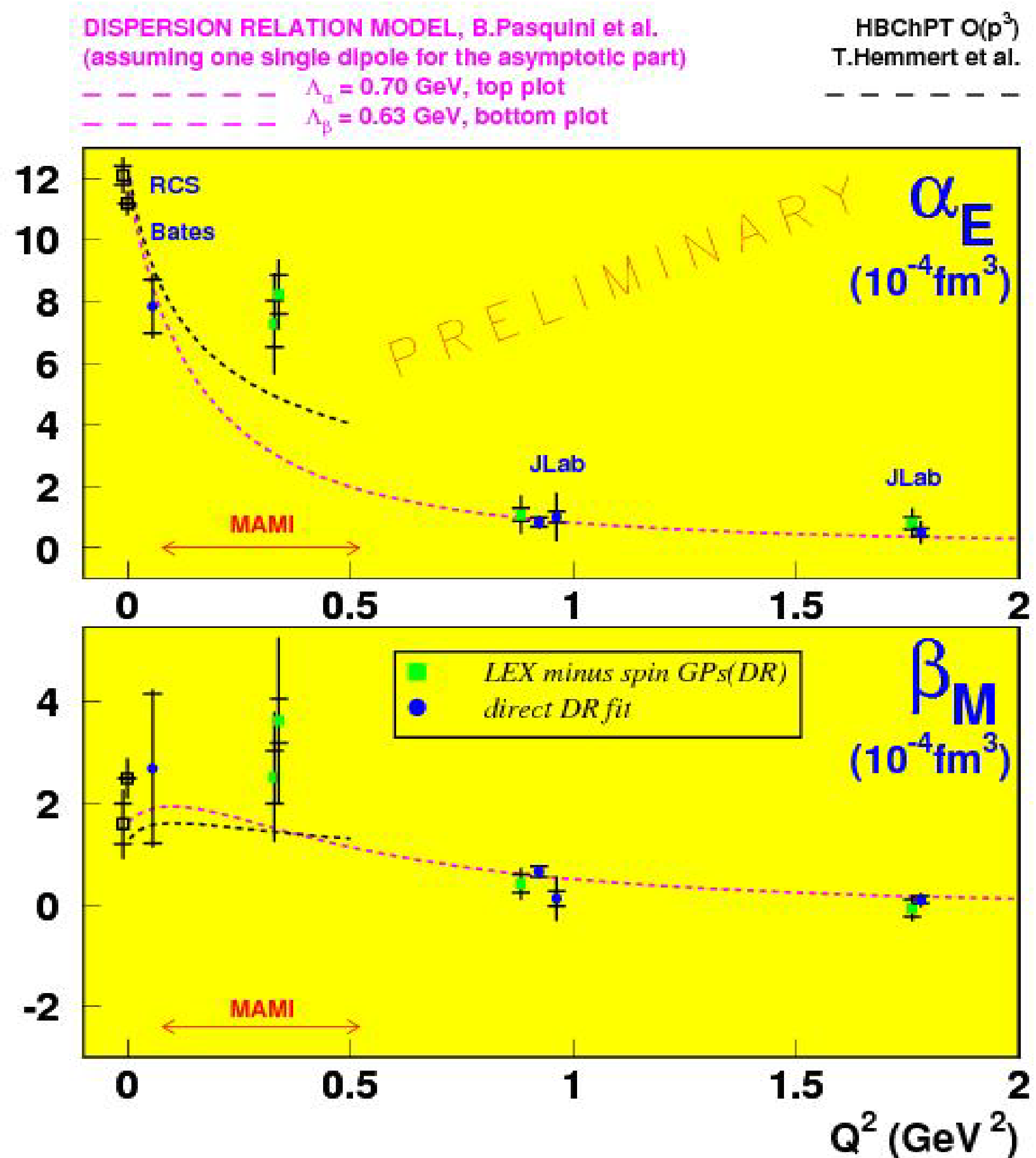
Proton electric polarizability sq.radius =

$< r^2_{\alpha E} > = 2.02\ (+0.39\ -0.59)\ fm^2$

Proton charge sq.radius =

$< r^2_p > = 0.77\ (+/-\ 0.01)\ fm^2$

MESON CLOUD !



Electric GP does not seem to have a smooth fall-off (e.g.a dipole)

Magnetic GP: small values, therefore large error bars in relative

Scarce data! Explore the region around Q^2=0.33 GeV^2 in more detail …

A recent VCS experiment at MAMI-A1: « vcsq2 »

3 new values of Q^2 = 0.1 , 0.2 , [0.33] , 0.45 GeV^2

Goal: measure the ($e\,p \rightarrow e\,p\,\gamma$) cross section,

essentially below pion threshold, at fixed q_{cm} and fixed ε

extract $P_{LL} - P_{TT}/\varepsilon$ and P_{LT}

and $\alpha_E(Q^2)$ and $\beta_M(Q^2)$

using LEX and DR methods (+ specificities)

Data taking: 2011 to 2015 (1500 hours of beamtime)

3 PhD students:

Jure Bericic (Ljubljana Univ., Slovenia) $Q^2 = 0.1$ GeV^2

Loup Correa (Clermont-Fd Univ., France) $Q^2 = 0.2$ GeV^2

Meriem BenAli (Clermont-Fd Univ., France) $Q^2 = 0.45$ GeV^2

« vcsq2 » experiment: Analysis status

- Statistical errors: small (high-statistics experiment)
-Systematic errors: dominant, as in almost all VCS experiments
- need to reduce them as much as possible !

GOAL: bring the systematic error down to +/- 1.5% on the cross section.
Very difficult! Presently at the level of +/- 3%

- High quality of the MAMI-A1 setup and data taking

In order to measure the GPs with small error
(reminder: the GP effect is 0-10% of the cross section!)

Analysis still ongoing, results are PRELIMINARY …
as presented in 2016 at the Mainz LEPP Workshop

Data analyses

→ **1. Getting the cross section right**

(with minimized systematic error)

- **Adjustment of all experimental parameters**
- **Absolute normalization of the cross section**
- **Dealing properly with the proton form factors**
- **Having a reliable Monte-Carlo simulation of the experiment**

→ **2. Getting the polarizability fit right**

Validity of the LEX fit?

when can we use the functional form given by the truncated LEX formula?

$$d^5\sigma\,(ep\gamma) = d^5\sigma\,(BH+Born) + \Phi\, q'\,[\,v_{LL}\,(P_{LL} - P_{TT}/\,\varepsilon) + v_{LT}\,(P_{LT}\,)] + \cancel{O(q'^2)}$$

It's a fitting issue …

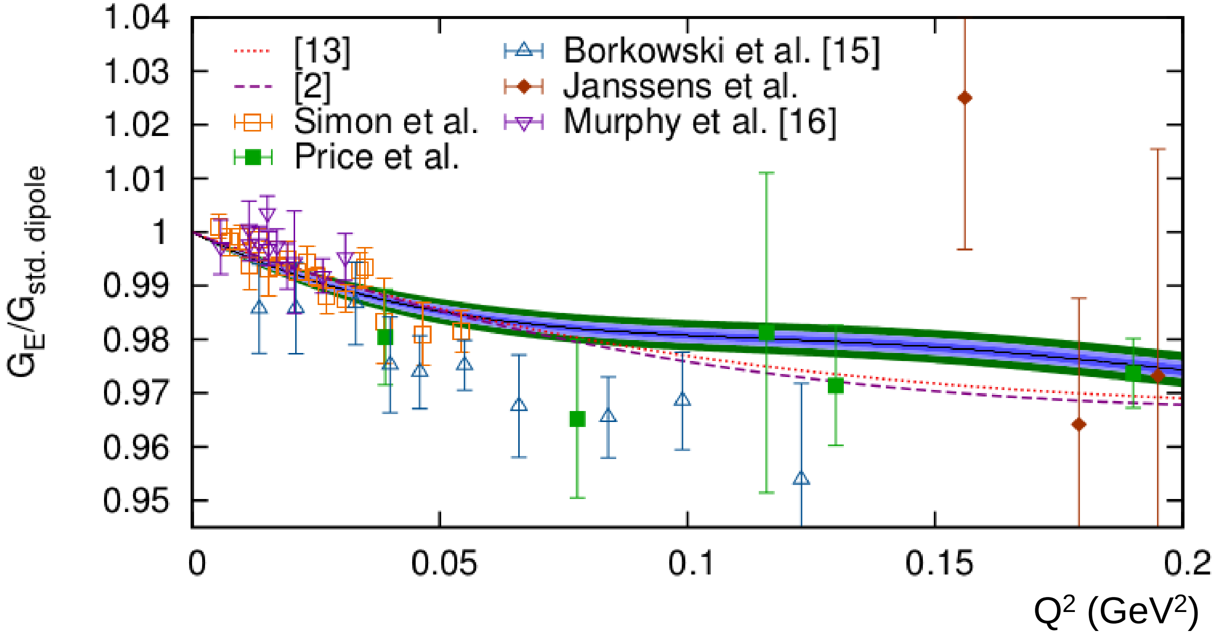
Digression: $\langle r_p \rangle$ in electron scattering

Measure the slope at origin : $G_E^p(q^2) = G_E^p(0) - (1/6)\, q^2 \langle r_p^2 \rangle / \hbar^2 + \ldots$

Figure from J.Bernauer et al., PRL 105 (2010) 242001

Q^2_{min} reached = 0.004 GeV^2

Smaller Q^2 reached in the first ISR experiment at MAMI



Extrapolate to Q^2=0 using a functional form

$$\langle r_E^2 \rangle^{\frac{1}{2}} = 0.879(5)_{\mathrm{stat.}}(4)_{\mathrm{syst.}}(2)_{\mathrm{model}}(4)_{\mathrm{group}}\ \mathrm{fm}$$

VCS: How to test the Validity of the LEX fit?

Use DR model to estimate the O(q'^2_{cm}) that is neglected in the LEX fit:

1st-order only in q'_{cm} | All orders in q'_{cm} | Higher-Order estimator

$$\frac{d\sigma(LEX) - d\sigma(DR)}{d\sigma(BH+Born)} = \frac{O(q'^2_{cm})}{d\sigma(BH+Born)}$$

CRITERION = Put an upper limit on the absolute value of this HO-estimator, e.g. < 3%

Need input GPs for this!

« vcsq2 » is the first experiment which tried to anticipate this issue.

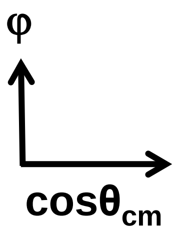
Calculation of the HO-estimator: theoretical exercise that can be done retrospectively for all VCS experiments performed so far.

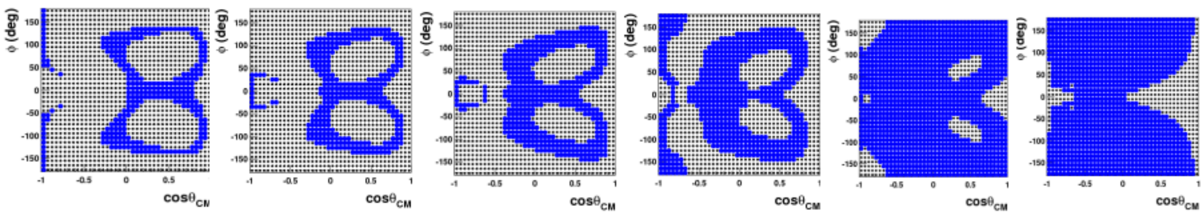
Will show result of the exercise for high q'_{cm} (around 100 MeV/c) in the 2D phase-space of (cosθ and φ) of the Compton process in its center-of-mass frame: these are variables on which all VCS experiments bin.

Bin selection using the HO-estimator

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





epsilon =	0.90	0.91	0.85	0.62	0.63	0.95
q'_{cm} (MeV/c) =	115	112.5	112.5	111.5	104	105
q_{cm} (MeV/c) =	240	320	458	600	714	1080
ratio q'_{cm}/q_{cm} =	0.48	0.35	0.25	0.19	0.15	0.10

VCS: The low-energy expansion is actually in q'_{cm} / q_{cm} ….

Lesson from the VCS-Bates experiment ….

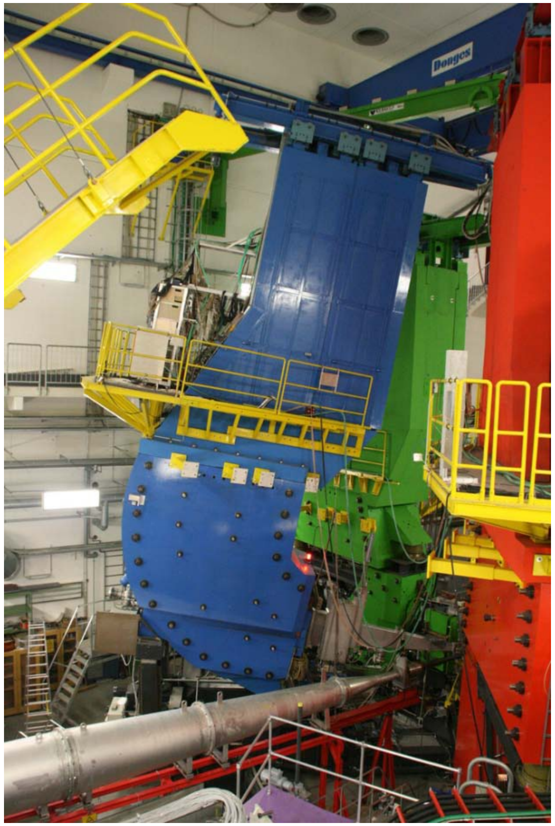
One way to reach good kinematics for the LEX fit:

Go out-of-plane, measure e.g. at phi=90 deg

MAMI-A1: moving spectrometer B out-of-plane

In-Plane

MAMI-A1: moving spectrometer B out-of-plane



8.5 deg OOP

New « vcsq2 » data:

- OOP kinematics

-**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.**

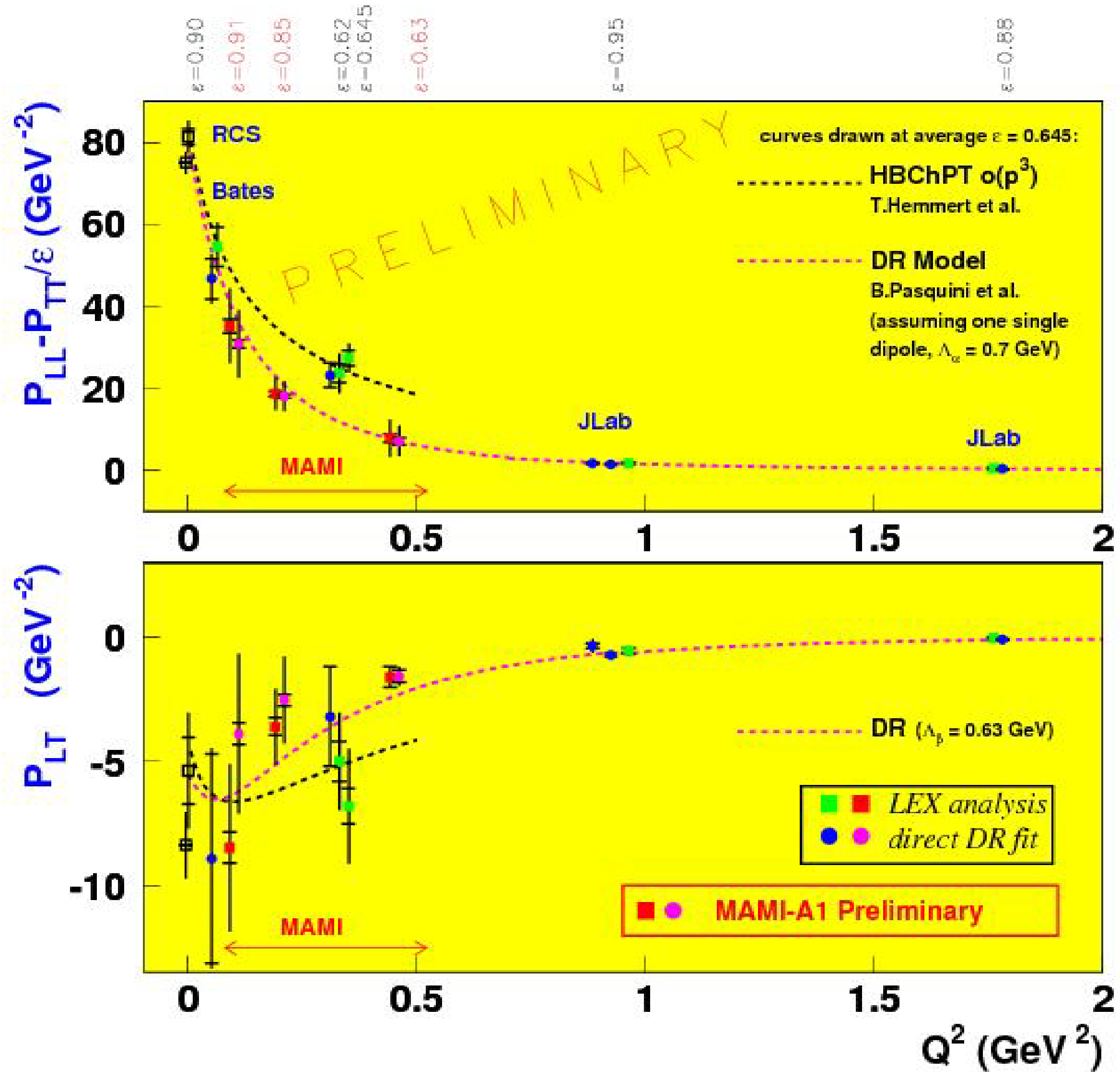
Structure Functions with the new « vcsq2 » data

New data:

- P_{LL}-P_{TT}/ε more compatible with a smooth fall-off vs Q^2
- P_{LT} : hard to confirm the presence of an extremum at low Q^2

Still preliminary!

The « puzzle » remains in the region around Q^2=0.33 GeV²



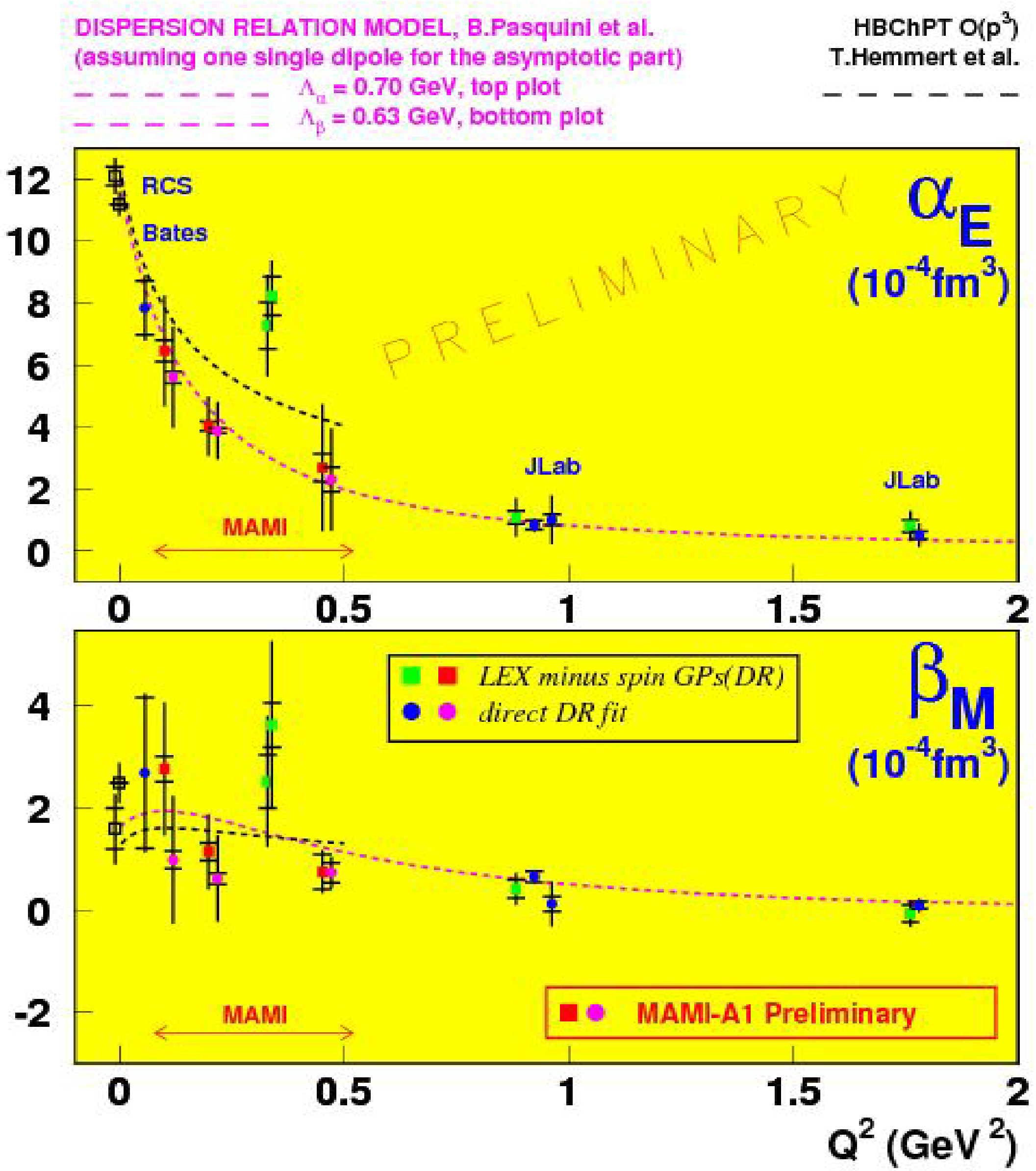
Electric and magnetic GP with the new MAMI data

« vcsq2 » :

still preliminary !

working out the systematic error bars!

Another measurement to come of $\alpha_E(Q^2)$ at Q^2=0.2 GeV^2, also preliminary !



VCS in the Delta(1232) region

Another method to measure GPs:

Explored by Nikos Sparveris et al:

- « vcsDelta » experiment done at MAMI-A1 in 2013 at $Q^2 = 0.2$ GeV^2

- **Future experiment at JLab at higher Q^2 : 0.3 to 0.7 GeV^2**

- do $ep \to ep\gamma$ at $W = m_\Delta$, i.e. above the pion threshold.

- LEX does not hold. DR model (Barbara Pasquini) is used.

« vcsDelta » experiment done at MAMI-A1 in 2013

(Q^2 = 0.2 GeV^2)

Sensitivity not only to the GPs but also to some multipoles of the N-to-Delta transition: the CMR (C2 to M1 ratio), related to the non-spherical component of the nucleon wave function.

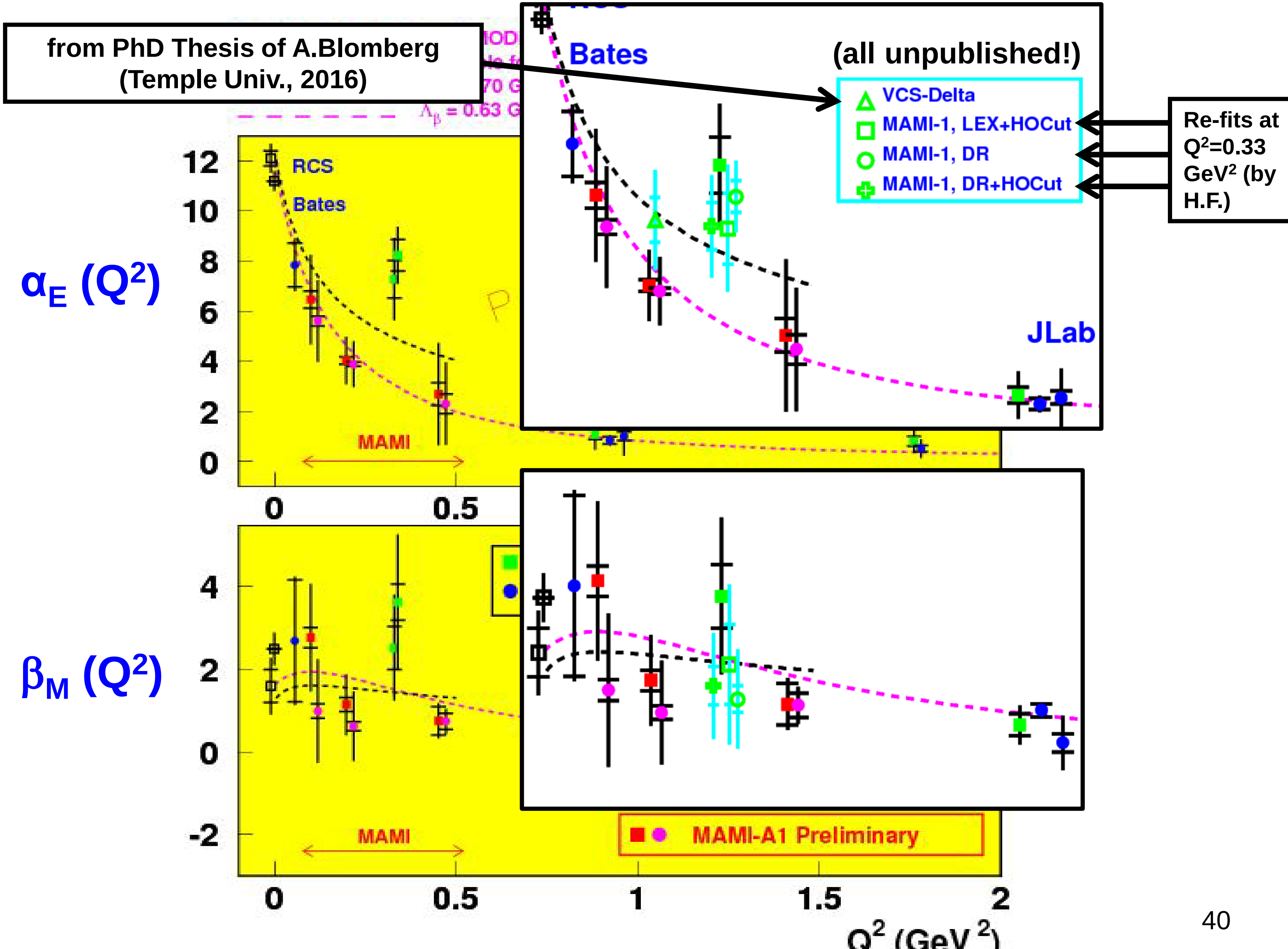
$$CMR = \frac{S_{1+}^{3/2}}{M_{1+}^{3/2}}$$

CMR is usually measured in ep → ep π^0, here in photon electroproduction!

- Measure (unpol.) ep → epγ cross sections in selected angular kinematics: $\theta_{\gamma^*\gamma}$ = 128deg and 138deg, at ϕ =0 and 180 deg

-4 cross-section points, → two ϕ-asymmetries ,
→ fit two params: the CMR and the electric GP

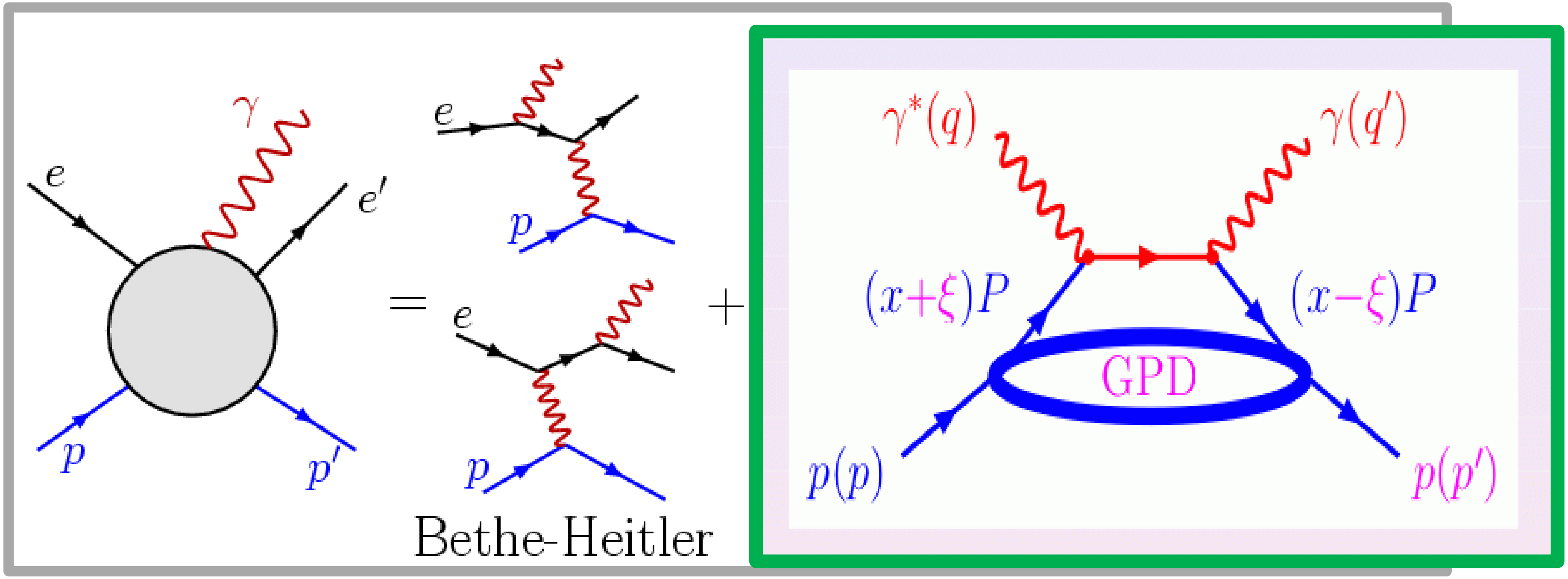
-Compared to this, the LEX is very costly!



from PhD Thesis of A.Blomberg
(Temple Univ., 2016)
(all unpublished!)
VCS-Delta
MAMI-1, LEX+HOCut
MAMI-1, DR
MAMI-1, DR+HOCut
Re-fits at Q²=0.33 GeV² (by H.F.)
αE (Q²)
βM (Q²)
RCS
Bates
JLab
MAMI
MAMI-A1 Preliminary
12
10
8
6
4
2
0
-2
0.5
1
1.5
2
Q² (GeV ²)

Digression: Deep VCS

At High energy (W>2 GeV) and high Q^2: VCS is used to determine Generalized Parton Distributions (GPDs)



Electron bremsstrahlung

Handbag diagram of DVCS (Compton Scattering on a quark)

A new link between DVCS and VCS formalisms:

Compton scattering: from deeply virtual to quasi-real
Andrei V. Belitsky (Arizona State U.), Dieter Müller (Ruhr U., Bochum), Yao Ji (Arizona State U.). Dec 2012. 55 pp.
Published in **Nucl.Phys. B878 (2014) 214-268**
DOI: 10.1016/j.nuclphysb.2013.11.014
e-Print: **arXiv:1212.6674 [hep-ph] | PDF**

Unified framework for Virtual Compton Scattering, that uses helicity Compton Form Factors (CFF) for the analysis of different regimes:

DVCS and the Generalized Parton Distributions
as well as
VCS at low energy and the Generalized Polarizabilities!

Conclusions

- recent VCS experiments at MAMI:
  new measurement of the scalar GPs at Q^2 = 0.1, 0.2 and 0.45 GeV^2 +
  new measurement of α_E at Q^2 = 0.2 GeV^2
  → deeper insight of the Q^2-dependence of GPs (to be published …)

- puzzle w.r.t. previous VCS measurements at Q^2=0.33 GeV^2 :
  can it be partly understood by a limit of validity of the LEX?
  An open question …

- VCS continues to be an active field : new experimental proposal at Jlab (N.Sparveris et al.), new theoretical developments (Pascalutsa, Lensky, Vanderhaeghen et al.) : polarizability sum rules connecting RCS and VCS, Baryon ChPT (manifestly Lorentz-invariant) , …