Virtual Compton Scattering on the proton: New measurements of Generalized Polarizabilities at MAMI

For the MAMI-A1 Collaboration

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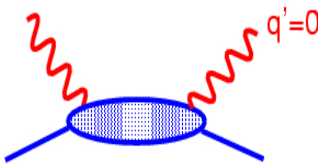
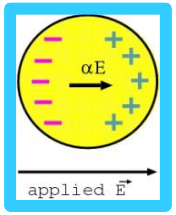
Generalized Polarizabilities

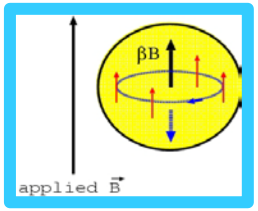
Real Compton Scattering
γ N $\rightarrow$ γ N



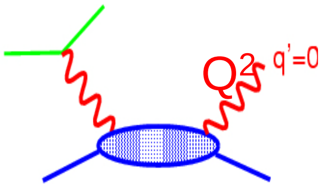
at q'=0: proton in a static (E,B) field

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





Virtual Compton Scattering
γ^* N $\rightarrow$ γ N

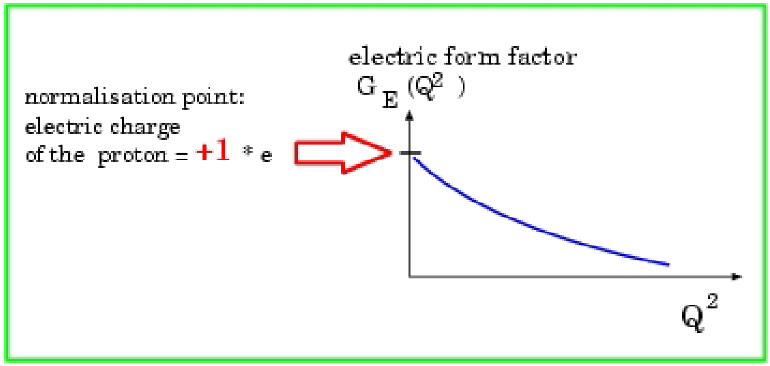


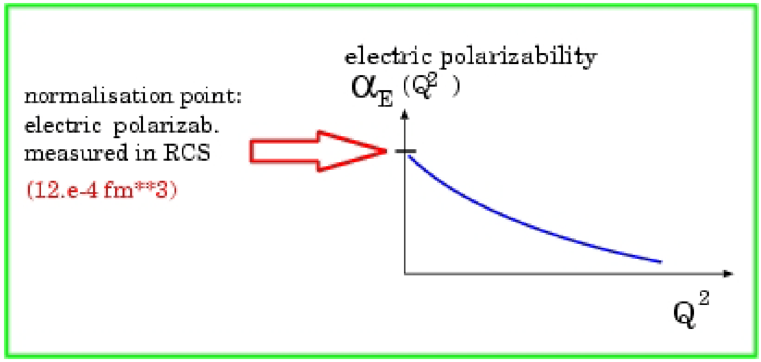
at q'=0: proton in a static (E,B) field

Generalized Polarizabilities:
electric $\alpha_E\ (Q^2)$
Magnetic $\beta_M\ (Q^2)$
+ spin GPs

Density of electric and magnetic polarization of a deformed nucleon

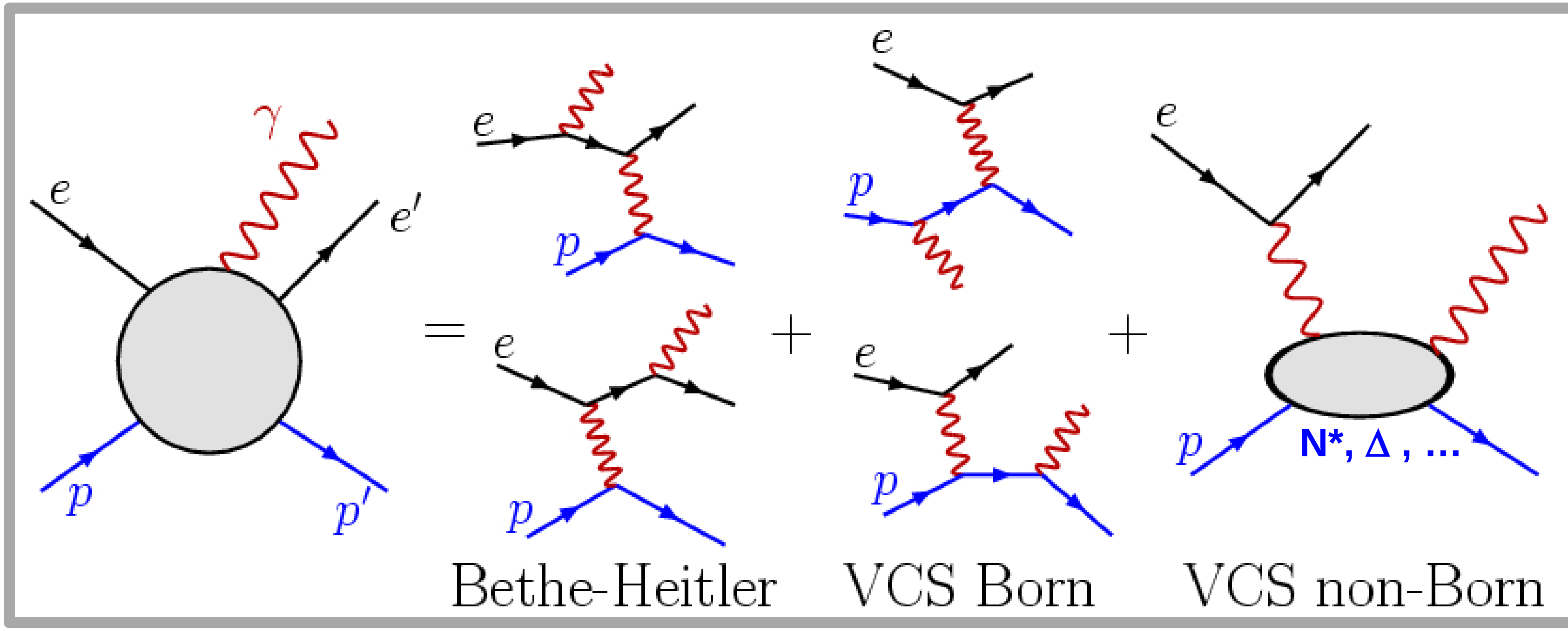
Generalized Polarizabilities





- ***GP is like a Form Factor, but of a deformed nucleon.***
- ***P's and GPs are intrinsic properties of the nucleon, and sensitive to its whole excitation spectrum.***
- ***Spatial density: where does the polarizability manifest itself most? How far does it extend ? → mean square radius …***
- ***Expected to be much more sensitive to the pion cloud than FF.***
  ChPT : $O(p^3)$ result is completely given by pion loops.
- ***Complexity of the magnetic GP: dia- and para-magnetism, almost cancelling each other.***

How to measure GPs



Electron bremsstrahlung

KNOWN

Proton bremsstrahlung

KNOWN

Parametrized by the GPs !

Small term !

Seminal Papers:

D.Drechsel and H. Arenhoevel, NPA233 (1974) 153: $\gamma^*+A \rightarrow \gamma+A$, 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 at electron accelerators.

D.Drechsel et al., PRC57 (1998) 941: 6 independent GPs at lowest order.

Models:

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

Kinematical range:

- any Q^2 ; explored experimental range: 0.06 GeV^2 to 1.8 GeV^2 .

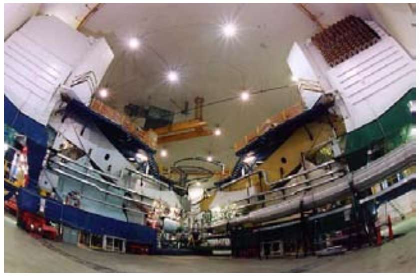
- Small W = c.m. energy of the [γ^*-nucleon] system
$\Leftrightarrow$ small energy of the final real photon q'

- In practice: stay below the pion threshold ($W < m_p+m_\pi$, equivalent to $q'_{cm} < 126$ MeV/c) , or slightly above, up to the Delta(1232) region.

Dedicated Experiments since 1995

MIT-Bates

MAMI-A1



JLab-Hall A

Detect e' and p' in coincidence and identify the reaction by the missing mass (γ)

Extraction of GPs:

1) measure ($ep \to ep\gamma$) cross section (5-fold differential $d^5\sigma / dk_{e'} . d\Omega_{e'} .d\Omega_{\gamma}^{cm}$)

2) make a fit of GPs, using either:

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

The low–energy expansion (LEX) in VCS

P.Guichon, G.Q.Liu and A.W. Thomas , NPA591 (1995) 606

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

1st-order LEX

Interference between BH+Born and polarizability amplitude (= NonBorn)

Higher orders

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

Structure functions:

$P_{LL} = (\,.\,.\,.\,)\ \alpha_E$

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

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

Polarizability fits

LEX fit

(at each Q^2 independently)

DR fit

LEX fit:

Fit $d\sigma_{exp}$ to the (truncated) LEX formula

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

Need to subtract the spin-GP part, using a model (DR)
« LEX minus Spin GPs(DR) »

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

DR fit:

Fit $d\sigma_{exp}$ to the DR calculation

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

spin-GPs are entirely fixed in the DR model

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

Structure Functions

(before the recent expts)

at $Q^2=0$:

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

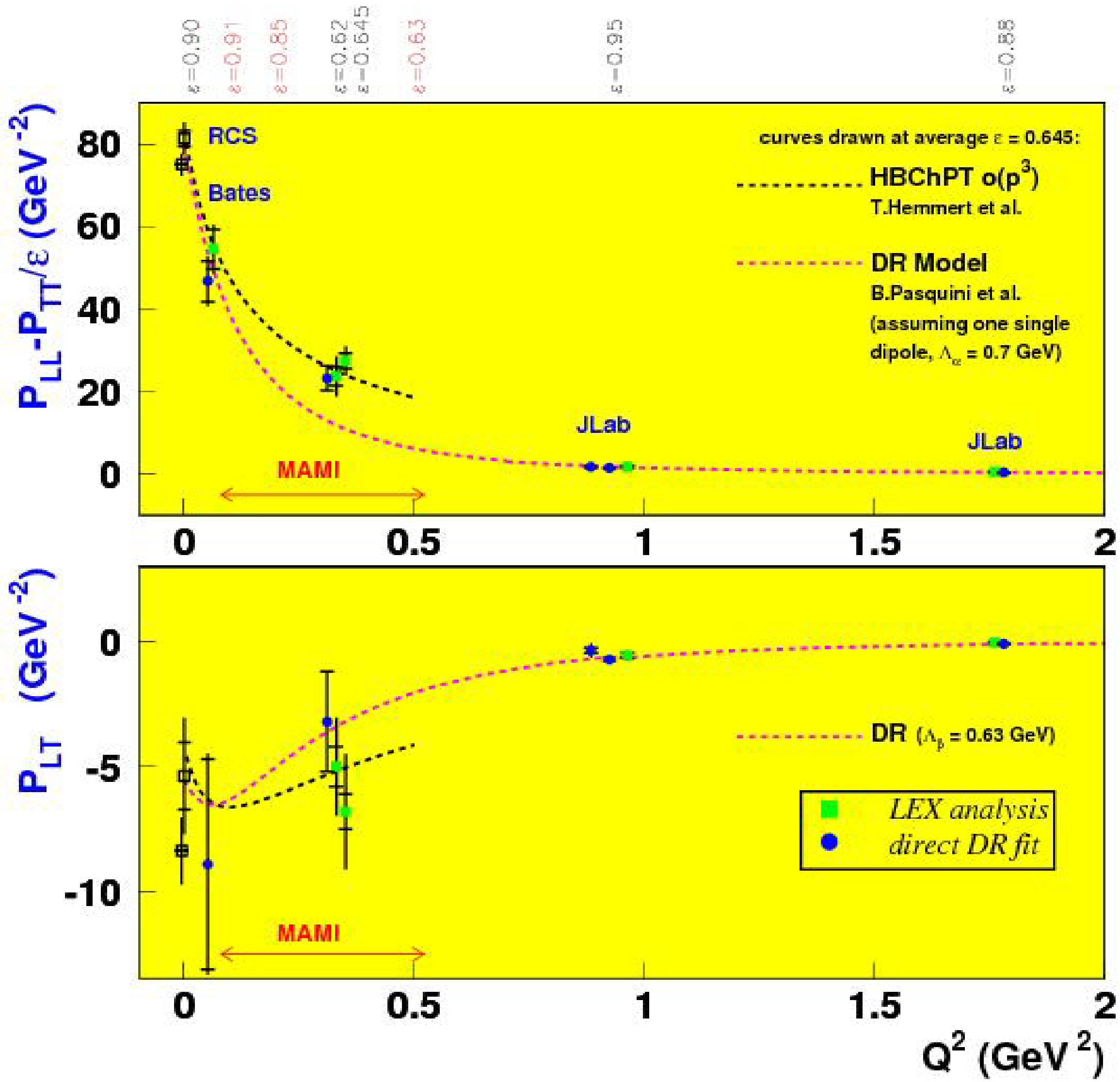
$P_{LT} = \text{(cst)}^* \beta_M(0)$

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).



Electric and magnetic GP

2 RCS points:

- Olmos de Leon (EPJA 10 (2001) 207

-Particle Data Book 2014

RCS point + Bates point (PRC84 (2011) 035206) ➔ slope of α_E :

Proton electric polarizability sq.radius =

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

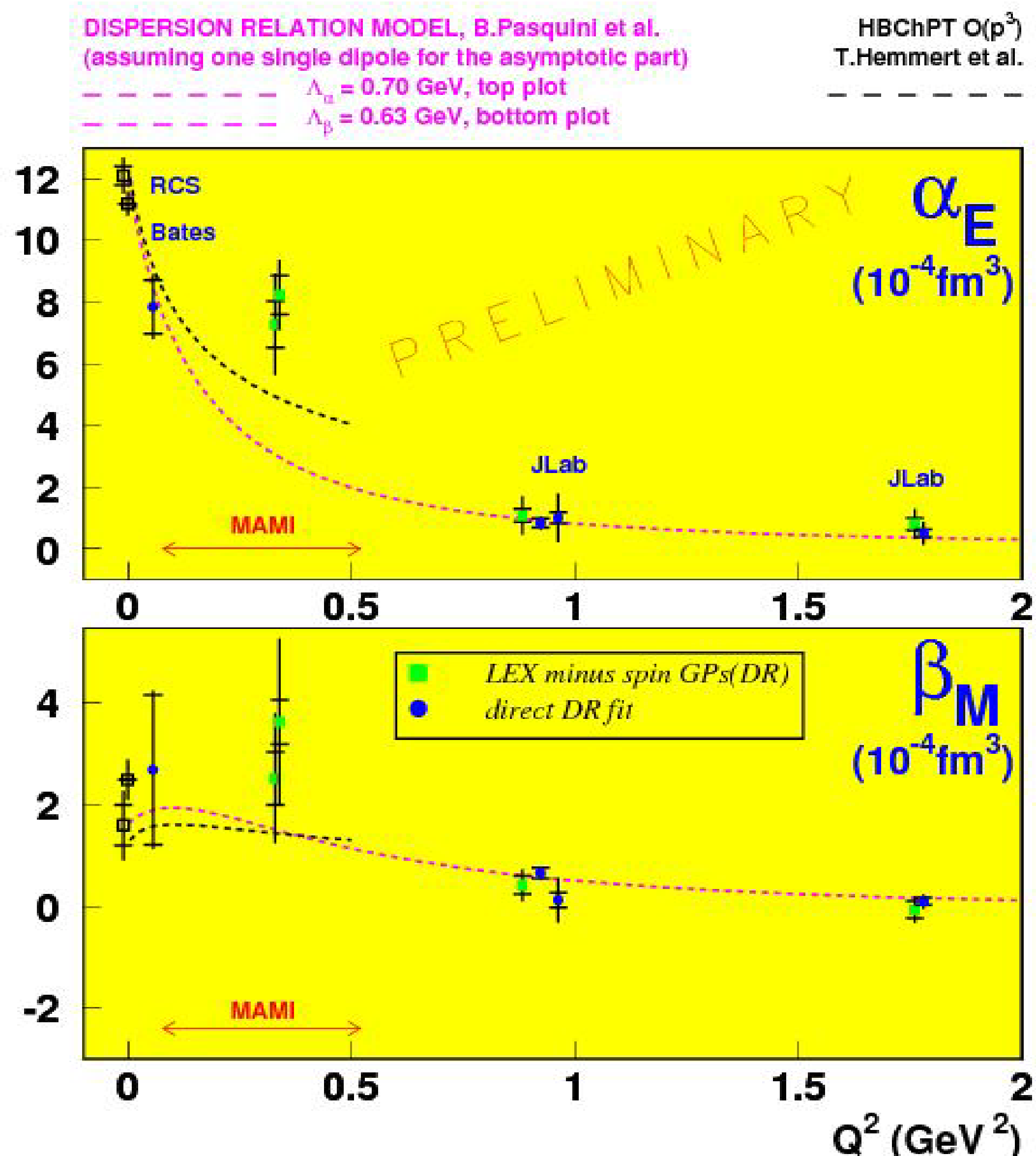
Proton charge sq.radius =

$< r^2_p > \sim 0.77 \ fm^2$

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 (3) fixed q_{cm} and 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

- - High-statistics
  - Systematics: dominant, as in almost all VCS experiments
  $\Rightarrow$ need to reduce them as much as possible !

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

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

- In order to measure the GPs with small error (reminder: the GP effect is ~ 0-15% of the cross section!)

- Analysis still ongoing, results are PRELIMINARY

-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

Polarizability fits

DR fit: **the DR calculation includes the full dependency in q'_{cm} :**
All experimental phase-space bins are OK a priori .
LEX fit: **is truncated in q'_{cm} . Are all bins valid ?**

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

Higher-Order estimator

(model-dep.)

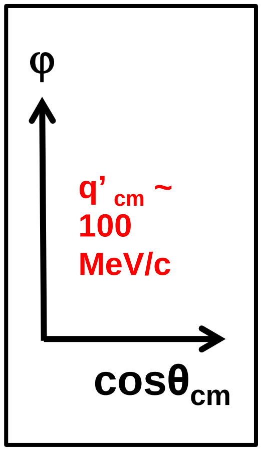
Need input GPs to calculate this! Take them from experiment.

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

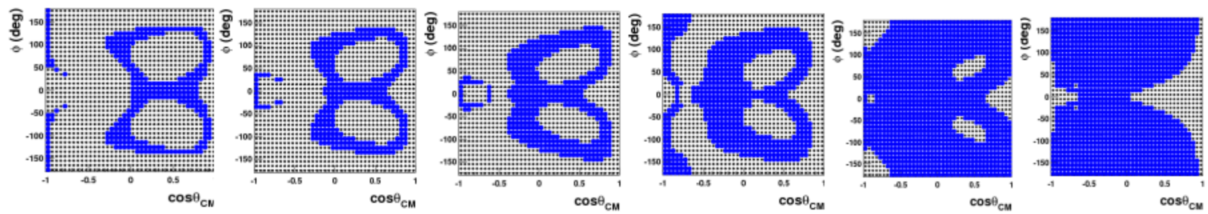
« vcsq2 » is the first experiment which tried to anticipate this issue.

Bin selection using the higher-order 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



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

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

Lesson from the Bates expt …
(PRL97 (2006) 212001)

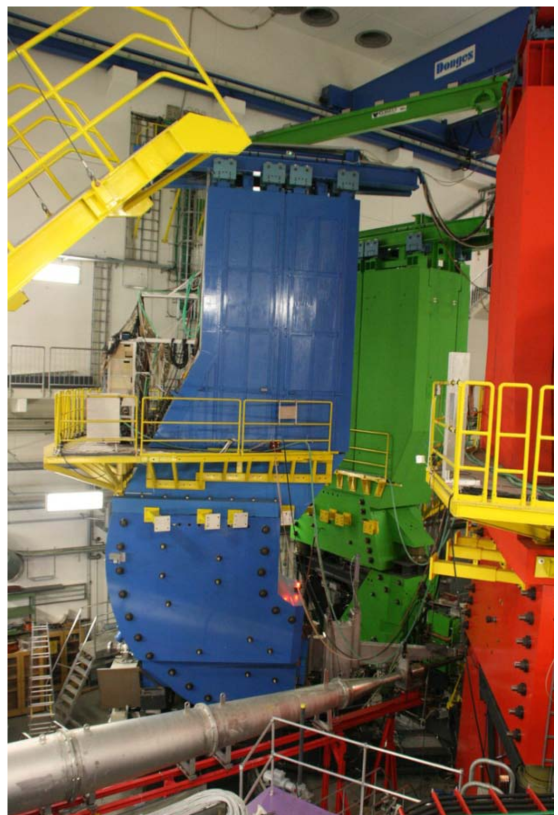
Important guideline for a LEX fit in VCS !

New « vcsq2 » data:

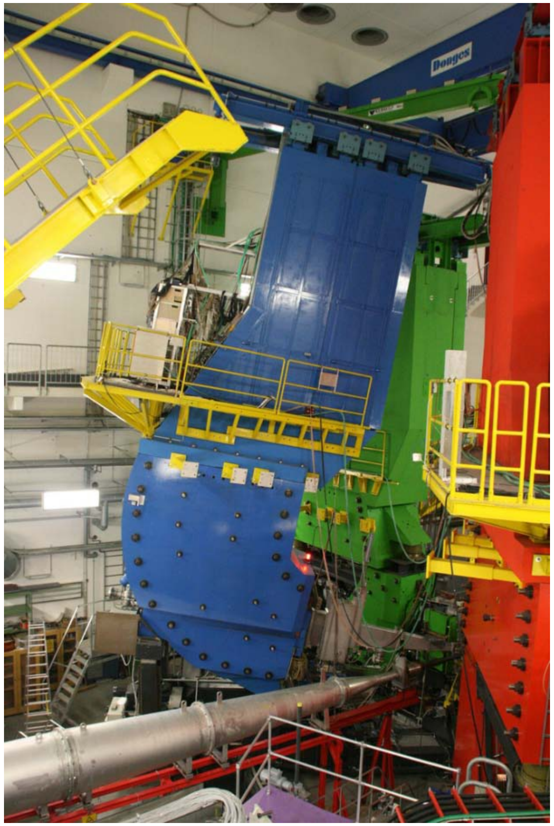
- OOP kinematics (to access the blue region)

-**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.**

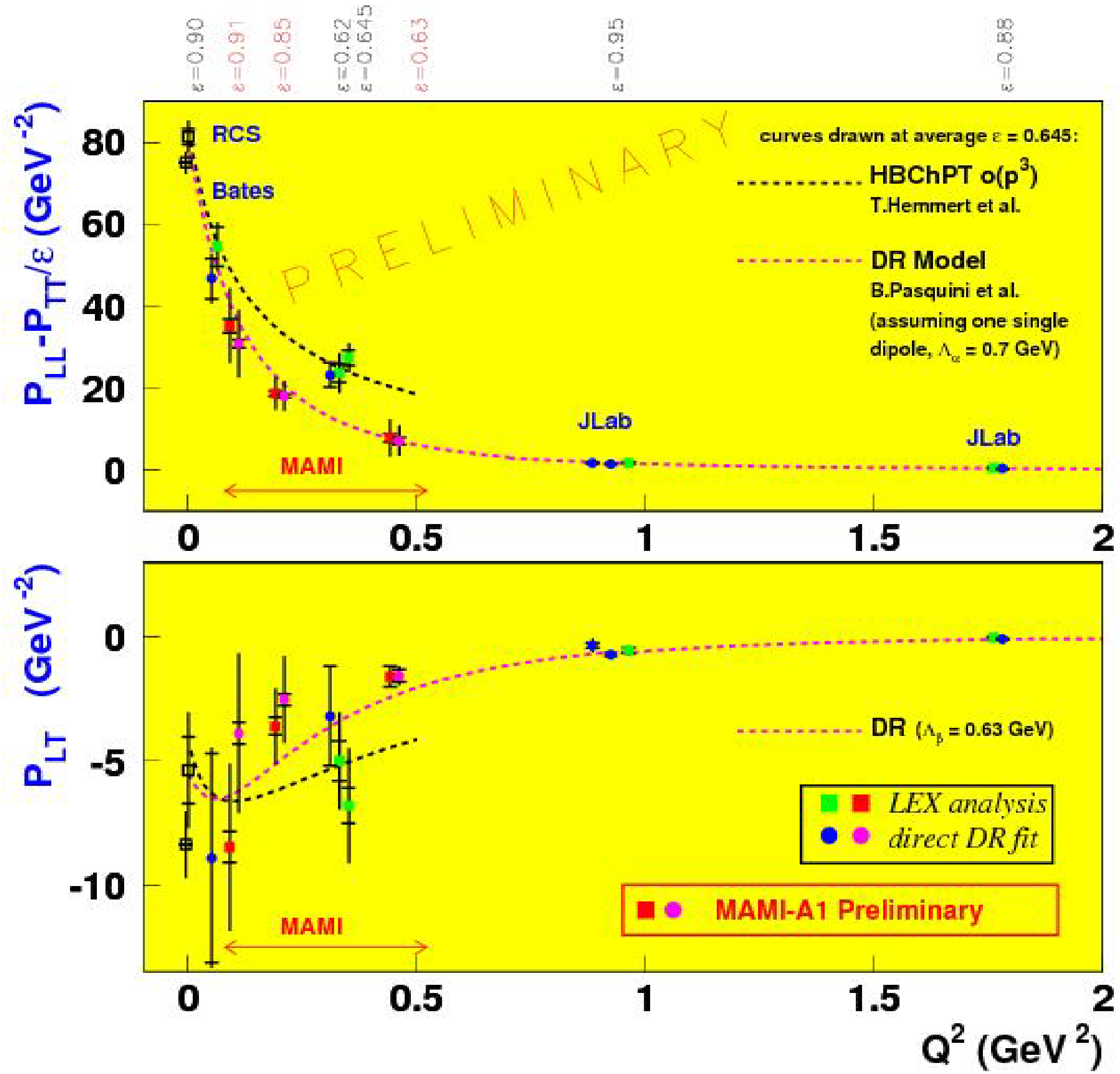


In-Plane



8.5 deg OOP

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 GeV^2

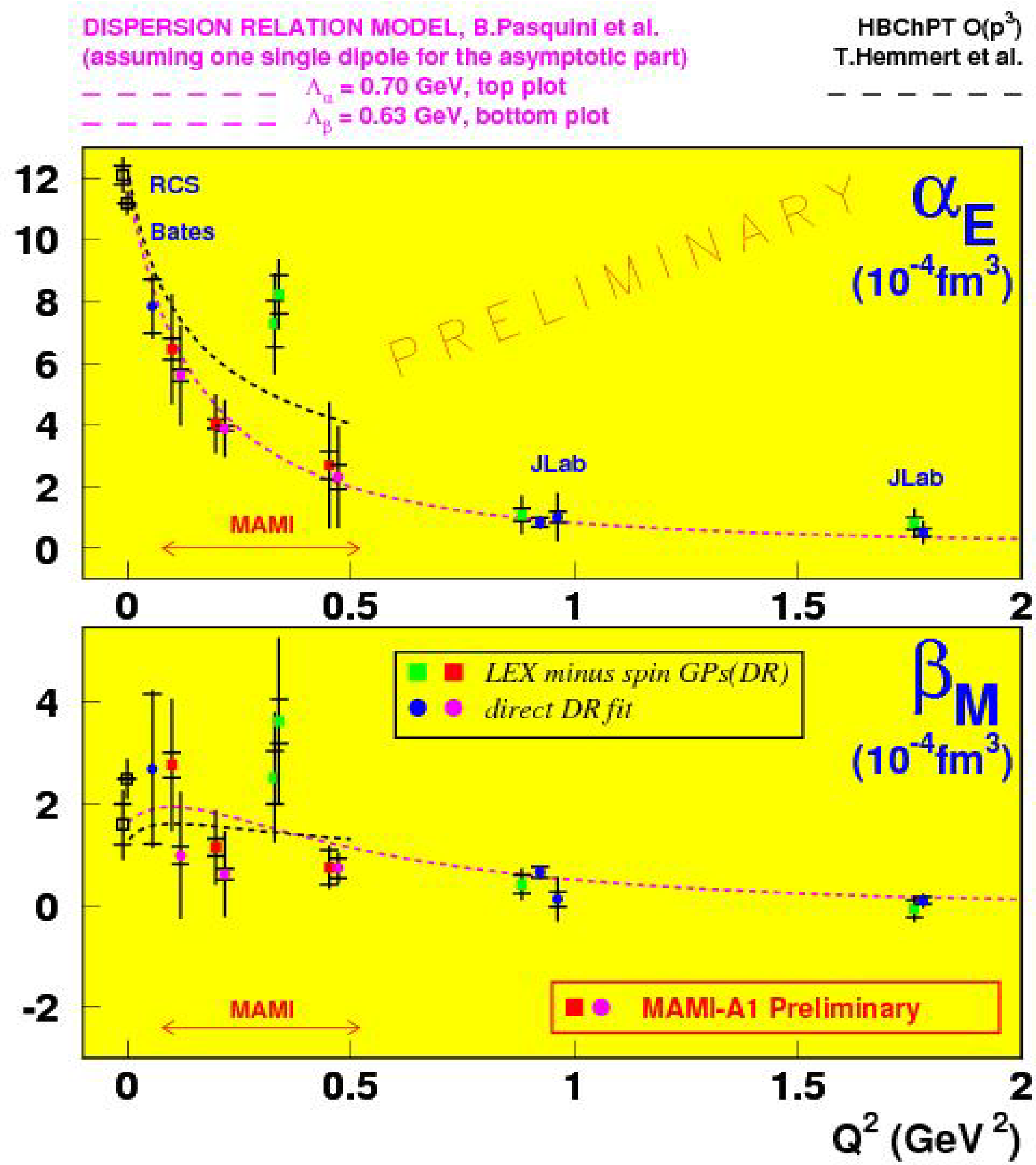
Electric and magnetic GP with the new MAMI data

« vcsq2 » :

still preliminary !

working out the systematic error…

Another measurement performed of $\alpha_E(Q^2)$ at Q^2=0.2 GeV^2



VCS in the Delta(1232) region

Another method to measure GPs,

explored by Nikos Sparveris (Temple Univ.) et al:

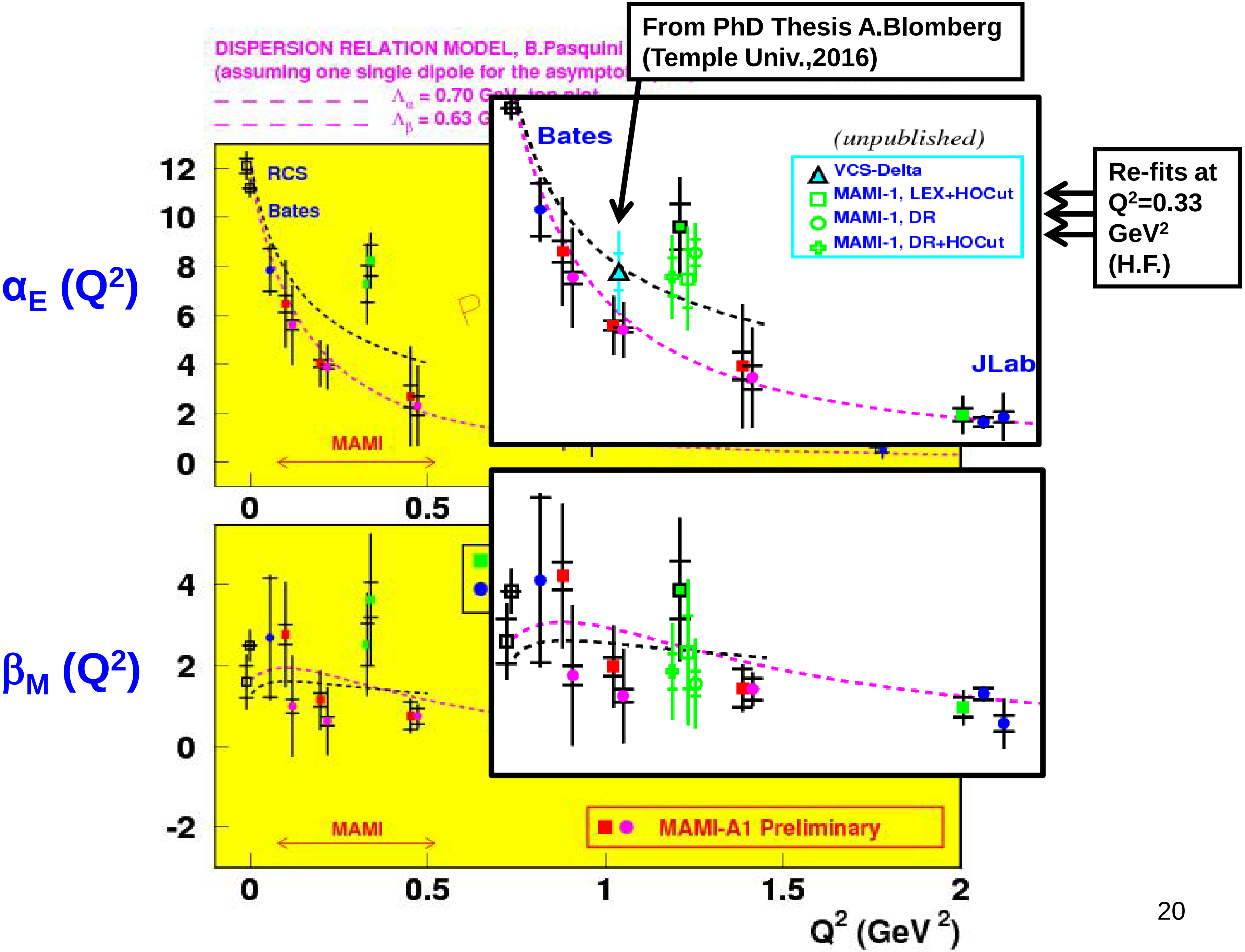
- **do (ep $\rightarrow$ epγ) at W= m_{Δ} , i.e. above the pion threshold.**
- **LEX does not hold. Use the DR model (B.Pasquini et al.) .**

1) « vcsDelta » experiment done at MAMI-A1 in 2013

- **Can fit GPs but also multipoles of the N-to-Delta transition.**
- **Here the electric GP and the CMR (C2 to M1 ratio) at Q^2 = 0.2 GeV^2**

2) Future VCS experiment at JLab Hall C (PR12-15-001)

- **Extract the electric and magnetic GPs at several Q^2 in the range 0.3 to 0.7 GeV^2 using the HMS and SHMS. Cross sections at phi=0 and 180 deg , and phi-asymmetries, + DR fit.** *(Approved Expt, PAC44, 2016)*



From PhD Thesis A.Blomberg (Temple Univ.,2016)
Re-fits at Q^2=0.33 GeV^2 (H.F.)
DISPERSION RELATION MODEL, B.Pasquini
(assuming one single dipole for the asymptot
Λ_α = 0.70 GeV, top plot
Λ_β = 0.63 G
$\alpha_E (Q^2)$
$\beta_M (Q^2)$
RCS
Bates
MAMI
(unpublished)
VCS-Delta
MAMI-1, LEX+HOCut
MAMI-1, DR
MAMI-1, DR+HOCut
JLab
MAMI-A1 Preliminary
Q^2 (GeV^2)

Conclusions

- **Two recent VCS experiments at MAMI:**
  -new measurement of the scalar GPs at Q^2 = 0.1, 0.2 and 0.45 GeV^2
  (below pion threshold, trying to do better LEX fit $\leftarrow$ better kinematics)
  - new measurement of α_E at Q^2 = 0.2 GeV^2 (VCS in the Delta region)

- **$\rightarrow$ deeper insight of the Q^2-dependence of GPs: changes the picture !**

- **puzzle w.r.t. previous VCS measurements at Q^2=0.33 GeV^2 :**
  partly remains (for the electric GP) with « selective » LEX fit.
  Open issue! See what future measurements will get…

- **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) , …**

- **Richness of photon electroproduction: GPs (VCS, low energy) and GPDs (DVCS, high energy)** *… They even start to be connected formally: « Compton Scattering: from deeply virtual to quasi-real », A.Belitsky, D.Mueller and Y.Ji, NPB878 (2014) 214.*