Virtual Compton Scattering and Generalized Polarizabilities

Experimental Status

For the MAMI-A1 collaboration

Hélène Fonvieille
LPC-Clermont-Fd
France

New Vistas in Low Energy Precision Physics / CRC1044
Mainz, April 04-07, 2016

Content

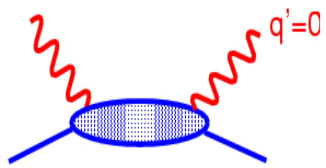
- -**Nucleon study:**
  Generalized Polarizabilities (GP) of the proton

- - **a recent experiment at MAMI-A1: « vcsq2 »**

- **- Perspectives**

Nucleon Polarizabilities: from γ to γ^*

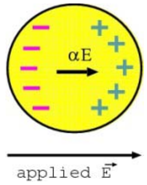
Real Compton Scattering $\gamma N \rightarrow \gamma N$



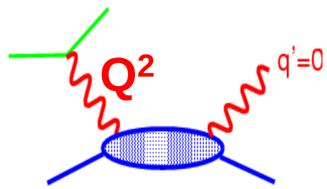
at q'=0: proton in an applied EM field

↓

Induced dipole:
$d_E = \alpha_E \,.\, E$
$d_M = \beta_M \,.\, B$



Virtual Compton Scattering



at q'=0: proton in an applied EM field

↓

Generalized Polarizabilities
$\alpha_E\,(Q^2)$
$\beta_M\,(Q^2)$

↓

Fourier Transform

↓

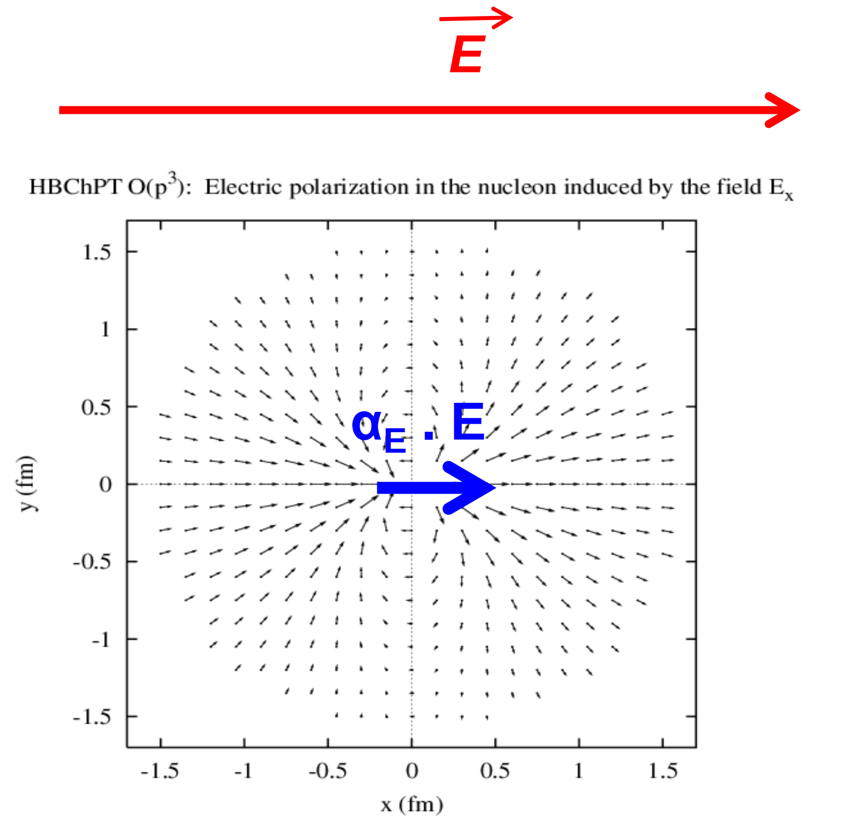
spatial density of polarization locally inside the deformed nucleon

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

Local polarization density

Probe of nucleon dynamics:
role of quark core versus pion cloud



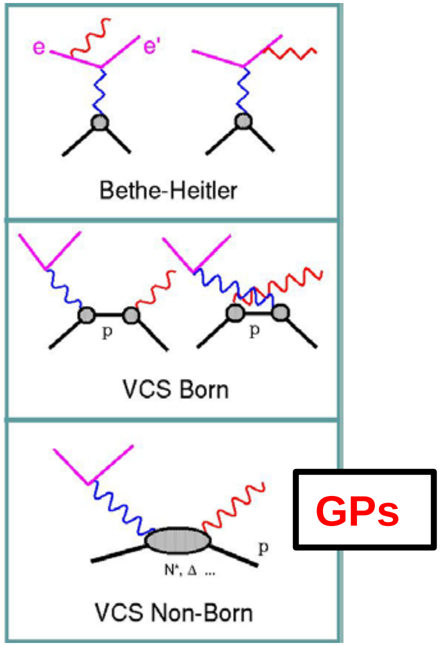
Scaled electric polarization $r^3 \alpha_{i1}$ $[10^{-3}\ \mathrm{fm}^3]$

Figure from S.Scherer, AIP Proc. Conf. 768 (2005) 110.

Measurement Methods

photon electroproduction $e\,p \rightarrow e\,p\,\gamma$

- **At low energy in the (γp) center-of- mass (W < m(Δ)= 1232 MeV)**
- **Detect e' and p' in magnetic spectrometers**
- **Identify the final photon by missing mass**



Cross section $d^5\sigma\,(e\,p \rightarrow e\,p\,\gamma)$

↓ ↓

Low Energy Theorem (LET or LEX)

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

↓

Extract VCS observables in a model-independent way

Dispersion Relations (DR)

B.Pasquini et al, EPJA 11 (2001) 185

↓

(model-dependent approach)

Measurement Methods

Low Energy Theorem

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

Known (FF)

Structure functions:

- $[\ ].\alpha_E(Q^2)$
- $[$ spin GP $]$
- $[\ ].\beta_M(Q^2)$ + spin GP

LEX fit

Dispersion Relations

- Calculation includes all orders in q'_{cm}

- Spin GPs are fixed

-Scalar GPs $\alpha_E(Q^2)$, $\beta_M(Q^2)$ have an unconstrained part $\rightarrow$ 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 exp. cross section

GP effect SMALL: ~ 0-15% of the ($ep \rightarrow ep\gamma$) cross section

BH+Born dominates !

VCS on the proton: World data

(unpolarized experiments)

LEX fit

DR fit

True level of comparison

Structure functions

Structure functions

Need to subtract the spin-GP part (use DR model)

Scalar GPs of the proton (electric and magnetic)

Structure Functions

At $Q^2 = 0$:

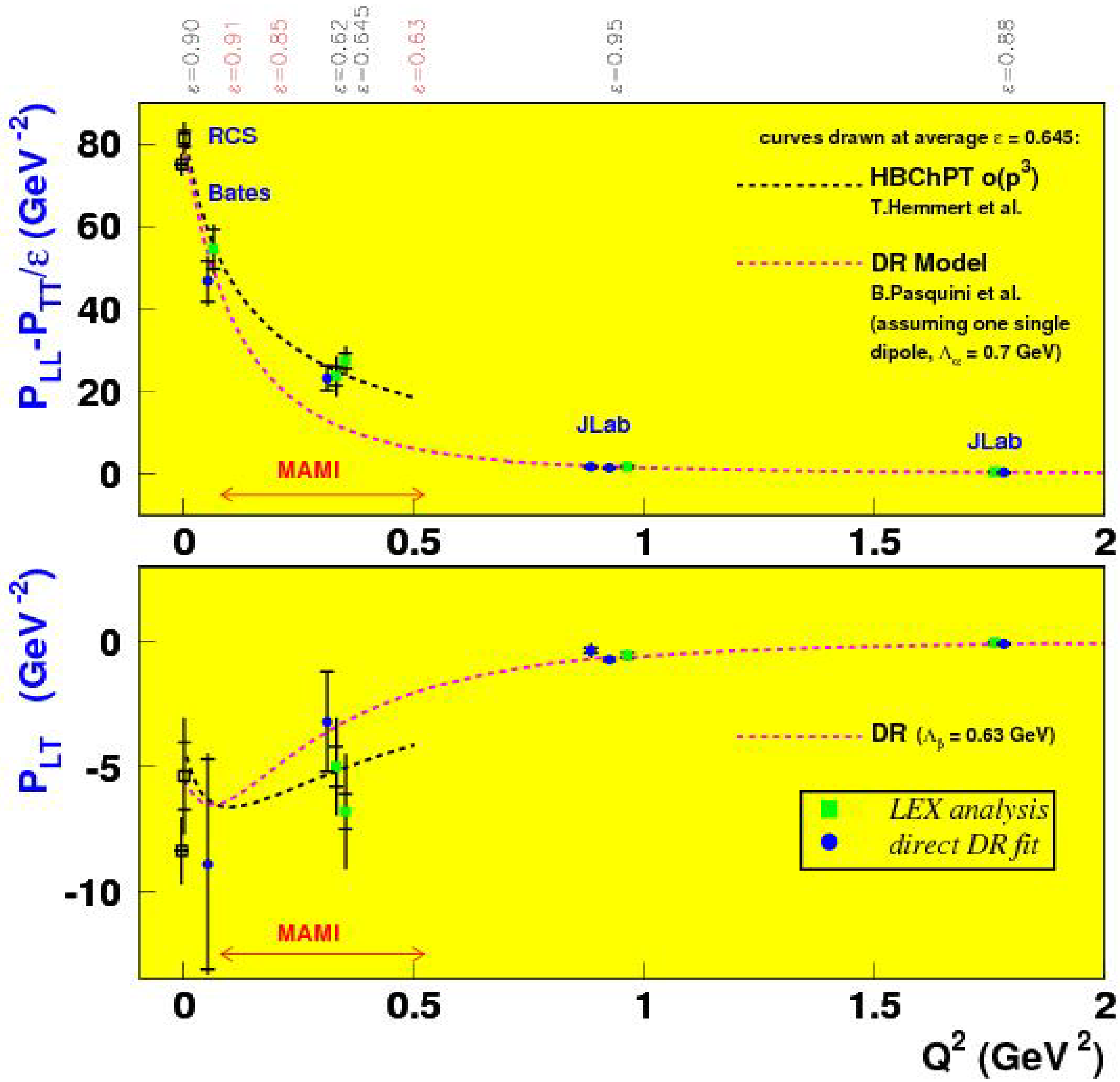
$P_{LL} - P_{TT} / \varepsilon = (cst)^* \, \alpha_E(0)$

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

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 (dipole, with Λ parameter = constant vs Q^2).



Spin-GP component is expected to be small === >

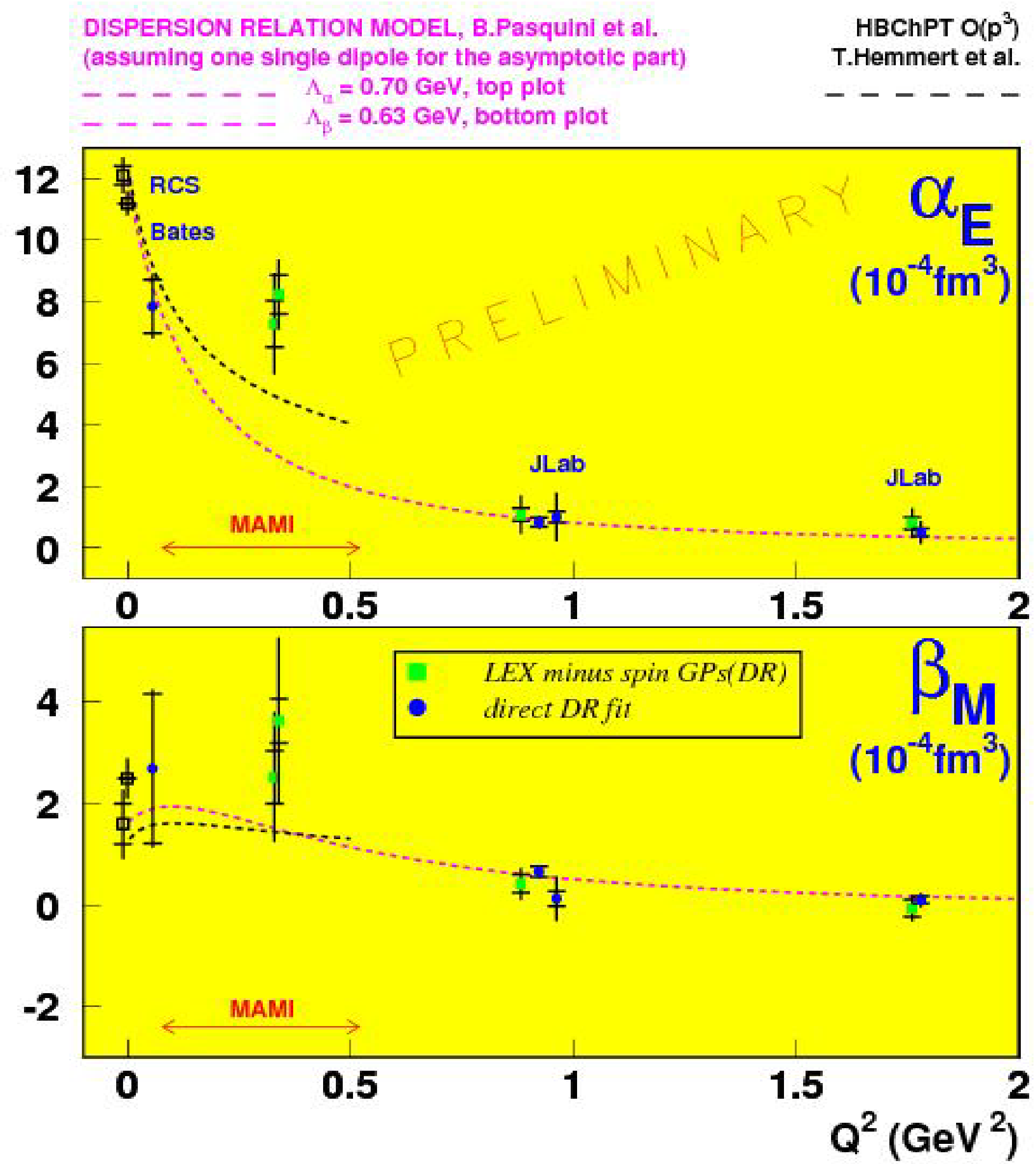
this is almost a picture of the scalar GPs

Electric and magnetic GP

2 RCS points:

- Olmos de Leon (EPJA 10 (2001) 207

-Particle Data Book 2014



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 , 0.45 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}/ε and P_{LT}

and α_E (Q^2) and β_M (Q^2)

using LEX and DR methods

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

3 PhD students:

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

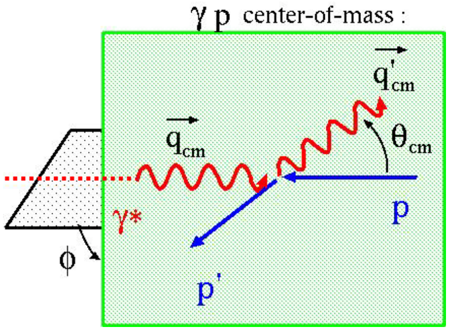
Loup Correa (Clermont-Fd Univ., France) Q^2 = 0.2 GeV^2

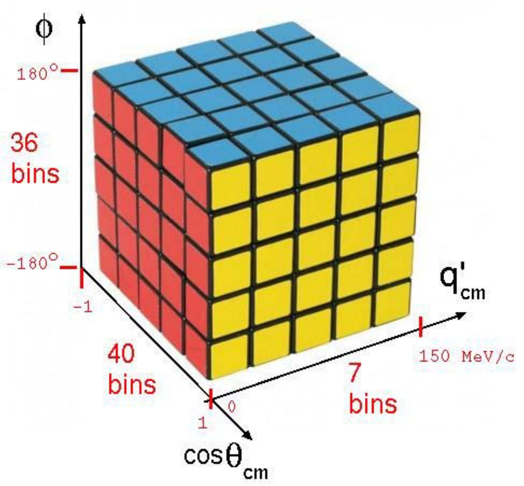
Meriem BenAli (Clermont-Fd Univ., France) Q^2 = 0.45 GeV^2

The «vcsq2 » experiment

MAMI-C cw electron beam, up to 1.03 GeV

A1 setup : 5 cm long cryotarget (liquid hydrogen) and high-resolution spectrometers (specA and specB) to detect the e' and p'





5-fold differential cross section

3D-binning: (the GP effect depends on these 3 variables)
high statistics experiment → fine binning → thousands of cross section points (with ≈12 kinematical settings)

Settings at low q'_{cm} for normalization tests

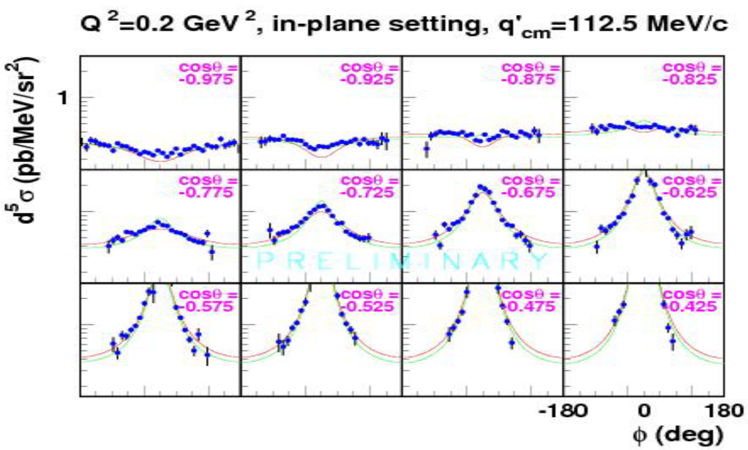
NEW: specific choice of angular phase ($\cos\theta_{cm}$, φ) to measure the cross section

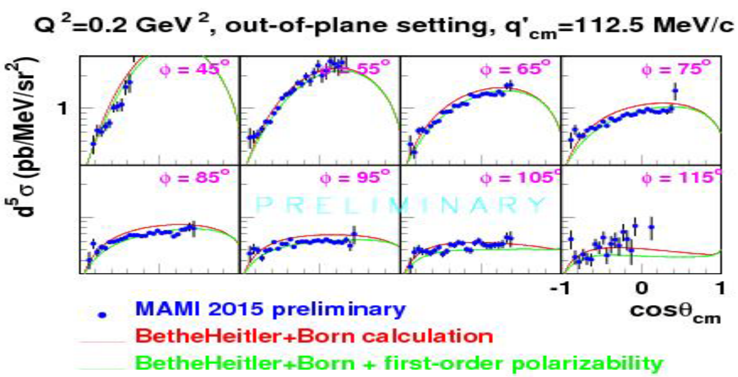
(triggered by the VCS-Bates experiment)

Exploit the Out-Of-Plane (OOP) capability of specB

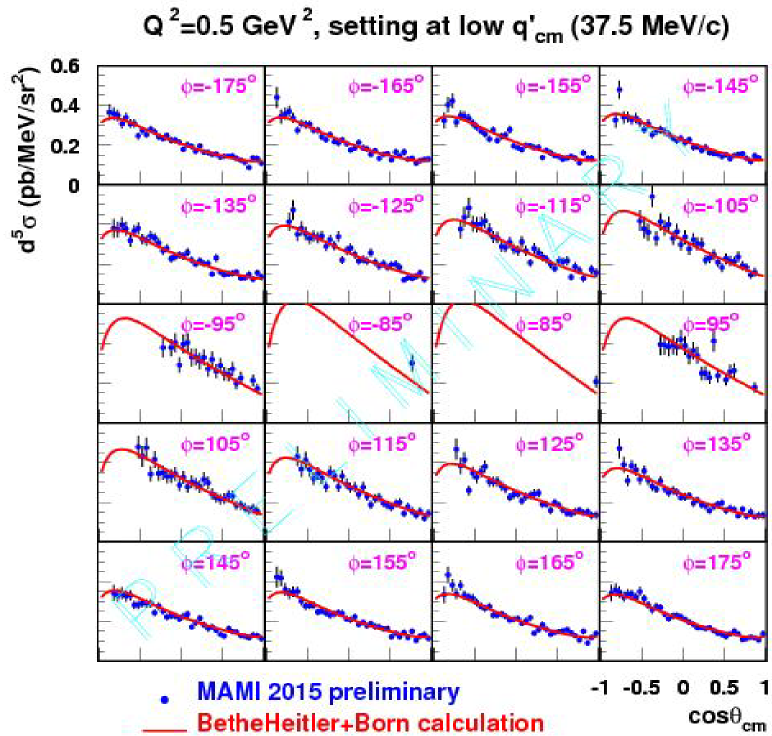
« vcsq2 »: experimental cross section

$Q^2 = 0.2$ GeV^2, high q'_{cm}





$Q^2 = 0.45$ GeV^2, low q'_{cm}



BH+B < == > NO GP effect

In green < == > with a GP effect

Specific choice of angular phase space (« bin masking »)

We designed a criterion to find angular kinematics where the Low Energy Theorem can be applied, i.e. where $O(q'^{2}_{cm})$ can be neglected :

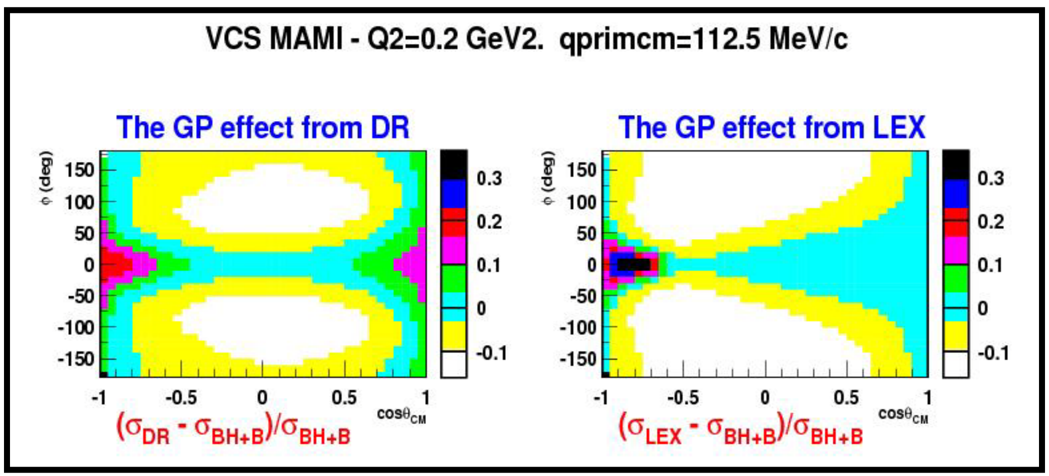
LEX : $d\sigma(ep \rightarrow ep\gamma) = d\sigma(\mathrm{BH+Born}) + [\ \ldots\ (q'_{cm})\ \ldots\ ] + O(q'^{2}_{cm})$

→ GP Effect from LEX $= [\ \ldots\ (q'_{cm})\ \ldots\ ]\ /\ d\sigma(\mathrm{BH+Born})$

DR : $d\sigma(ep \rightarrow ep\gamma) = d\sigma(\mathrm{BH+Born}) + [\ \ldots\ldots\ldots\ldots\ ]$ ← includes all orders in q'_{cm} !

→ GP Effect from DR $= [\ \ldots\ldots\ldots\ldots\ ]\ /\ d\sigma(\mathrm{BH+Born})$

Pure Theoretical study : compare the two effects, with the same input values of the Structure Functions $(P_{LL} - P_{TT}/\varepsilon)$ and (P_{LT})



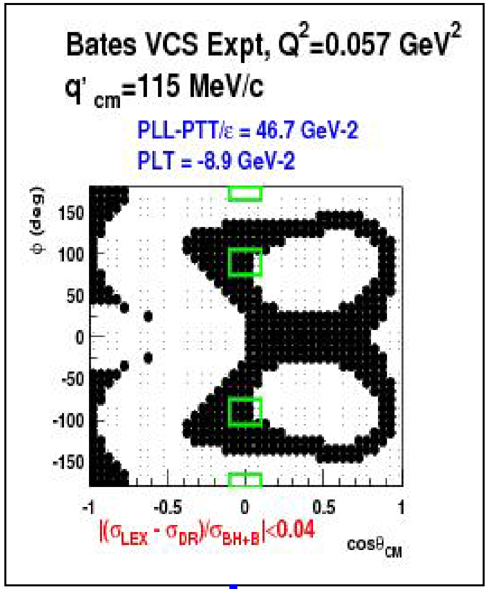
⇒ CRITERION = Put an upper limit on the absolute value of their difference $= |\ O(q'^{2}_{cm})\ /\ d\sigma(\mathrm{BH+Born})\ |$

(model-dependent!)

Experiments and Angular phase space

Black bins = where the « Mask criterion » is OK according to the DR model, i.e. O(q'^2_{cm}) not too large (here, < 4% of (BH+Born))

Bates Experiment

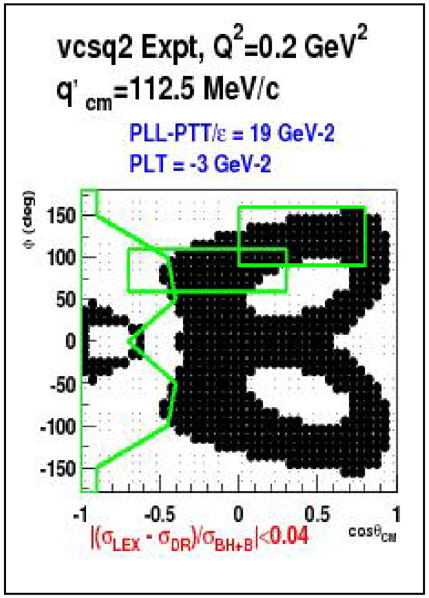


(ε = 0.90)

$\square$ = experimental acceptance

DR fit → P_{LT} = (-8.9 +- 4.2 +- 0.8) GeV^{-2}
LEX fit → P_{LT} = (-20.4 +- 2.9 +- 1.4) GeV^{-2}

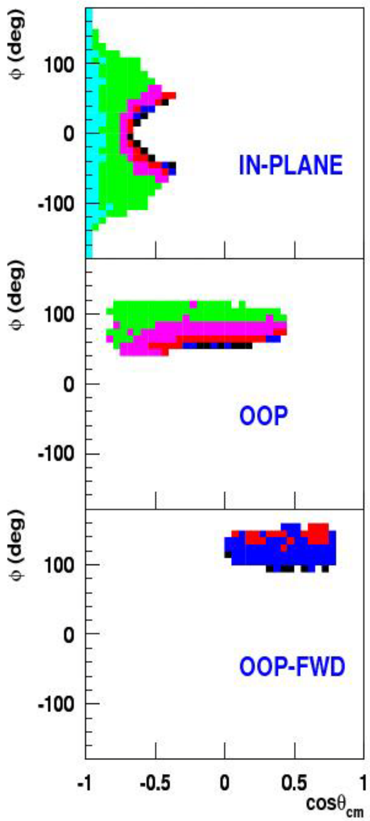
MAMI « vcsq2 » Expt



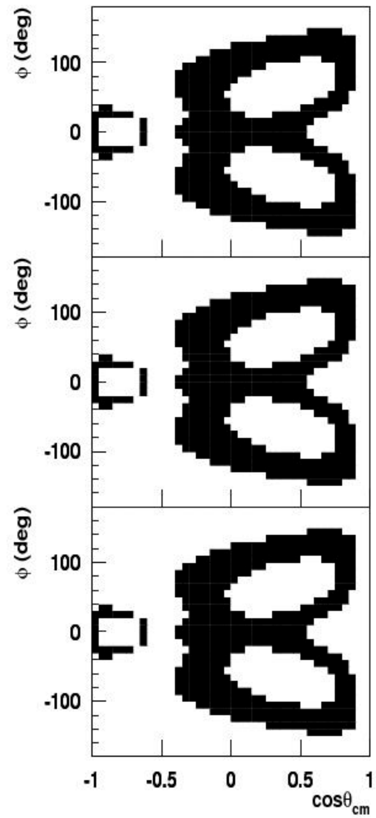
(ε = 0.85)

Example at Q^2=0.2 GeV^2: Applying the « bin masking » for the LEX fit

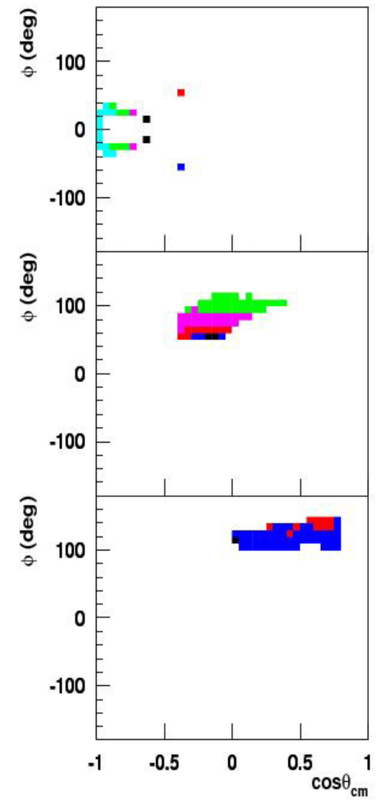
Exp. Cross section at q'_{cm} = 112.5 MeV/c



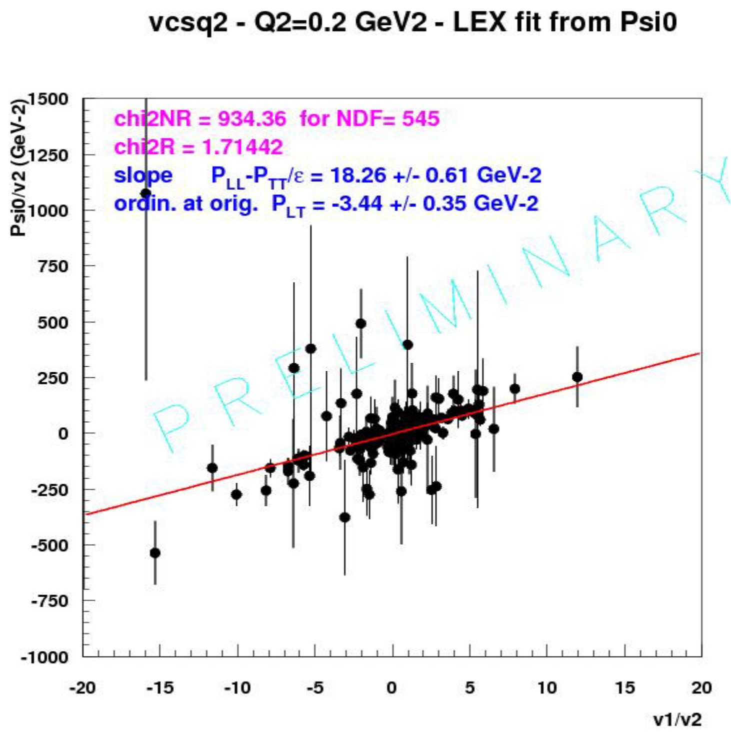
Criterion at 3%



Angular bins kept for the LEX fit



« vcsq2 » : LEX fit result at Q^2=0.2 GeV^2



LEX fit: ***with bin masking (but it's still a LEX fit!), q'_{cm} below pion threshold .***

DR fit: ***no bin masking, all q'_{cm} (including above pion threshold) .***

« vcsq2 » experiment: Analysis status

- Statistical errors: small
- Systematic errors: dominant
- in first approximation, the systematic error is globally equivalent to a variation of the overall normalization of the cross section

Q^2 = 0.1 and 0.45 GeV^2 : first-pass results

Systematic errors **< === >** *+- 3% renormalization*

Q^2 = 0.2 GeV^2 : 2^{nd}-pass analysis, almost finalized.

Systematic errors **< === >** *+- 1.5% renormalization*

Structure Functions with the new MAMI data

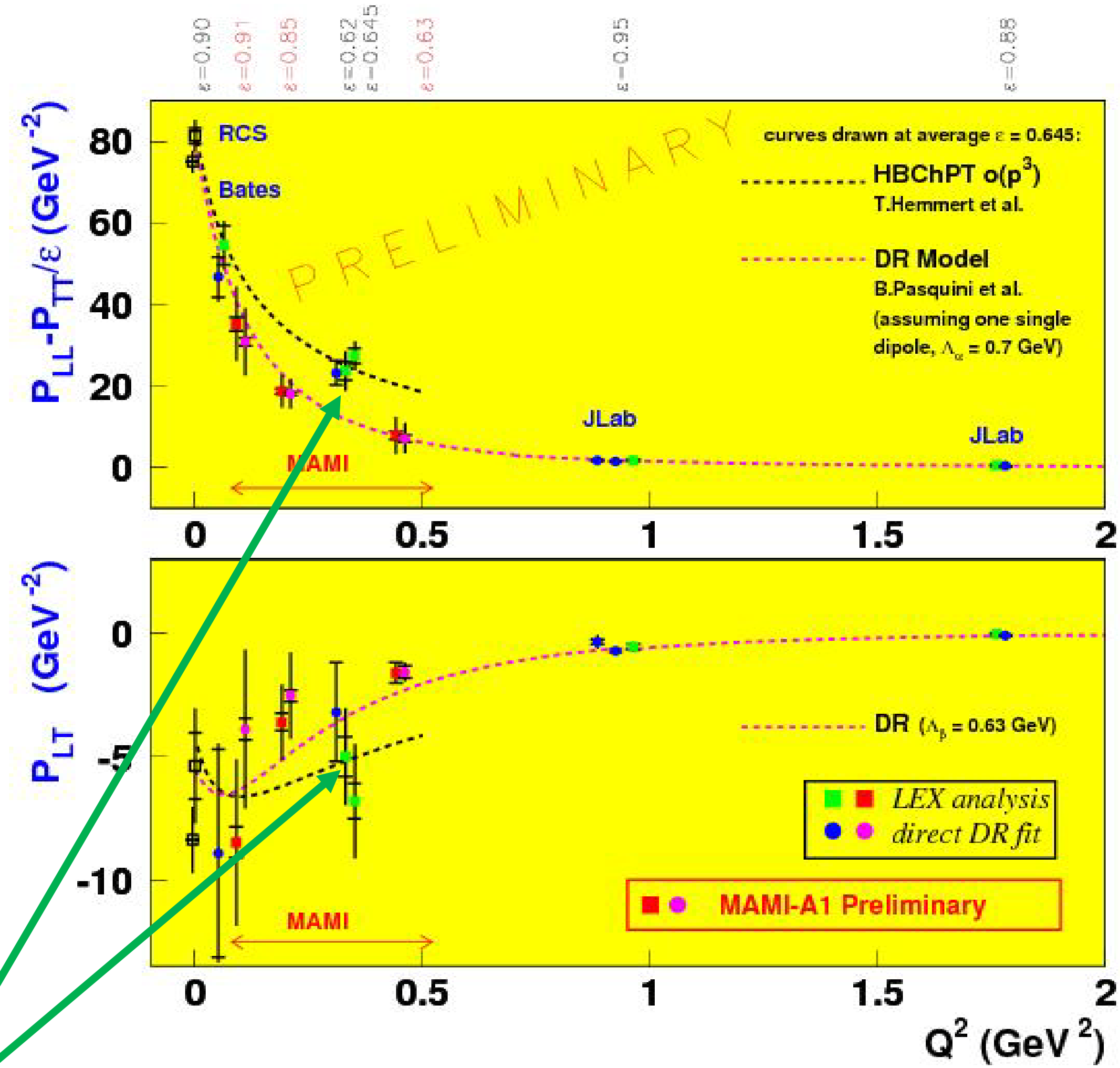
New data:

- P_{LL}-P_{TT}/ε compatible with a smooth fall-off vs Q^2

- P_{LT} : hard to confirm the presence of an extremum at low Q^2

- good agreement LEX/DR (at Q^2 = 0.2 & 0.45 GeV^2)

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



It all started here at MAMI !

(First VCS Experiment)

Electric and magnetic GP with the new MAMI data

Q^2=0.1 and 0.45 GeV^2 are still first-pass (preliminary)

Another measurement of α_E (Q^2) soon to come out at Q^2=0.2 GeV^2:

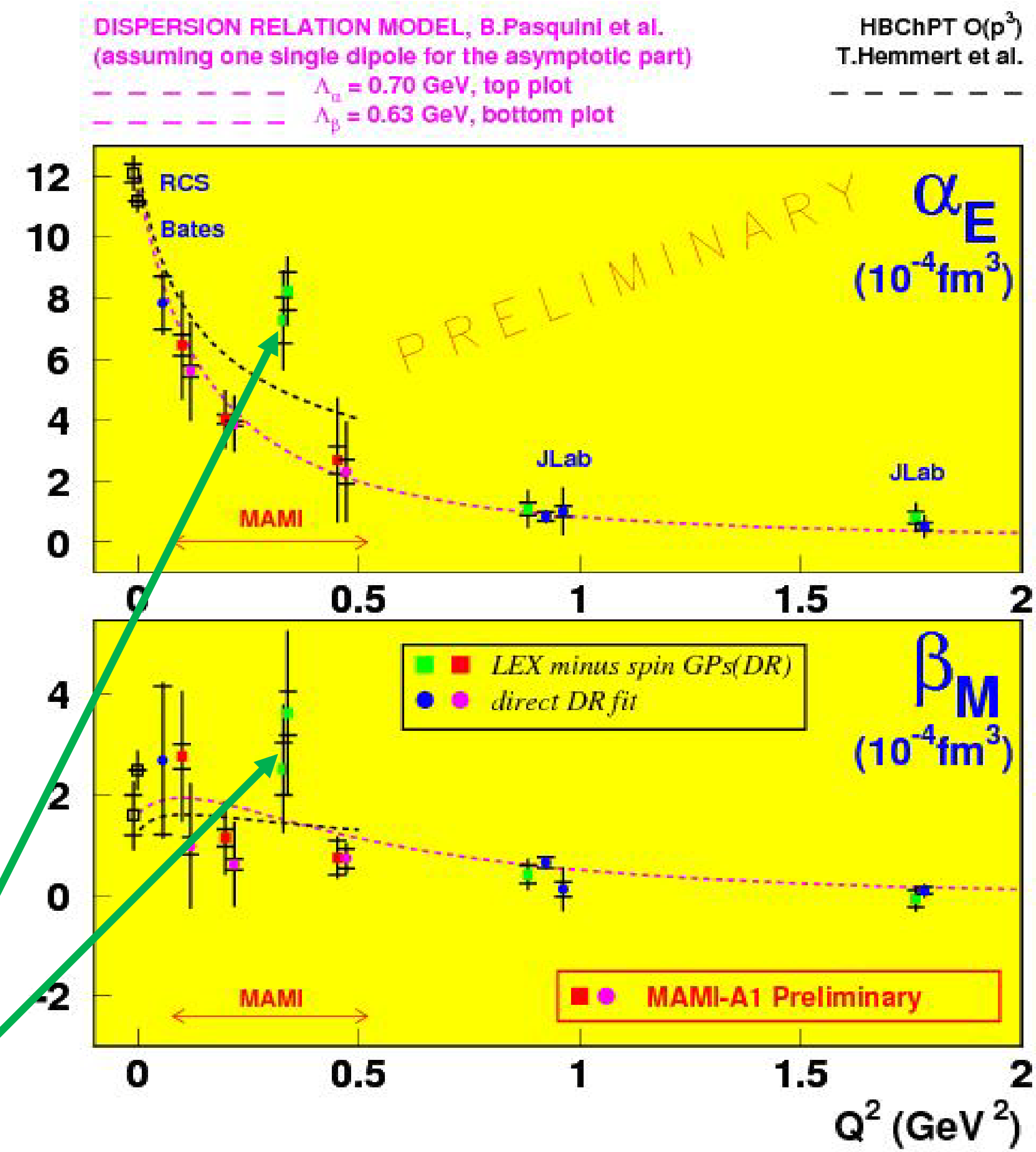
« vcsDelta » experiment at Mainz

(N.Sparveris et al.), data taken in 2013

W= Δ(1232) region

PhD Thesis of A.Blomberg (Temple U.)

Asymmetry between (cross section at ϕ =180° and at ϕ = 0°) + use the DR model (extracts also the CMR of N $\rightarrow$ Δ transition).



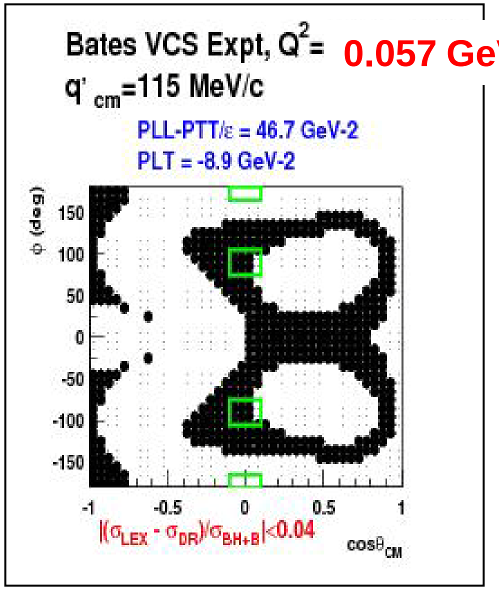
Is this physical or not ?

A tentative to understand the « puzzle » around Q^2=0.33 GeV^2

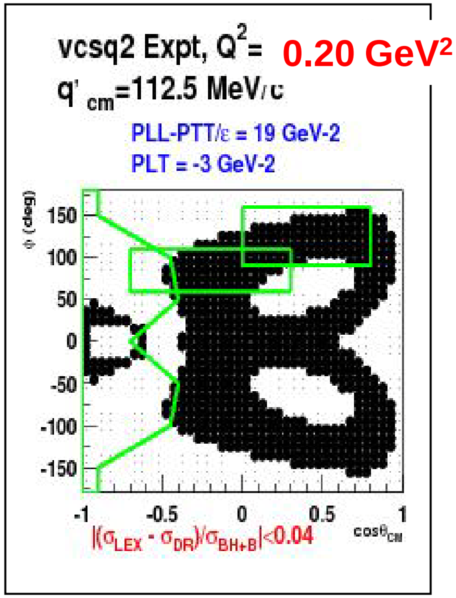
= experimental acceptance

Black bins : | O(q'$_{cm}^2$) / d σ(BH+Born) | < 4%

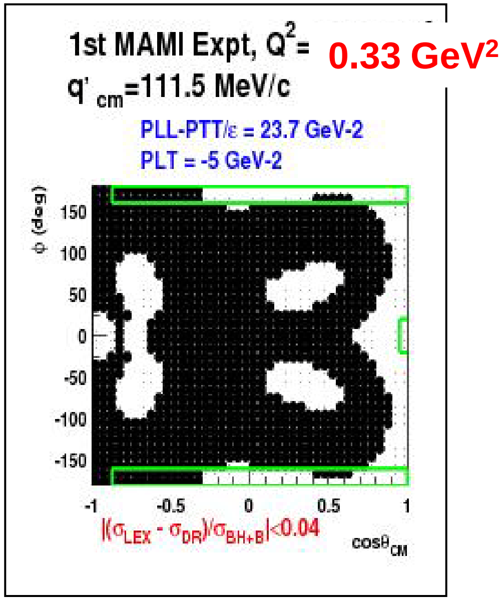
Bates Experiment



« vcsq2 » Expt



First Expt at MAMI



- Measured cross sections are fine

- Maybe we are learning that the LEX fit has to be applied with more care…

- it would be interesting to complete the measured angular phase space:

In-Plane at Q^2=0.2 GeV^2 and/or Out-of-Plane at Q^2=0.33 GeV^2

- DR fit for the data of the first MAMI experiment: to be updated …

Perspectives in VCS ($\gamma^* p \rightarrow \gamma p$)

two recent experiments performed at MAMI will provide two independent measurements of the GP $\alpha_E(Q^2)$ at $Q^2=0.2$ GeV^2 :
« vcsq2 » and « vcsDelta »

JLab VCS proposal (conditionally approved) in Hall C to measure the GP $\alpha_E(Q^2)$ and $\beta_M(Q^2)$ at Q^2 = 0.43, 0.52, 0.65 and 0.75 GeV^2, by asymmetry of the (ep $\rightarrow$ epγ) cross section in the Δ(1232) region
+ use the DR model

N.Sparveris, M.Paolone, A.Camsonne, M.Jones et al (2015)

VCS at lower Q^2 : what can be done? (Q^2 << 0.1 GeV^2)

VCS at very low Q^2 / theoretical aspects

★ **Covers the transition region from VCS to RCS**

→ **important test of continuity**

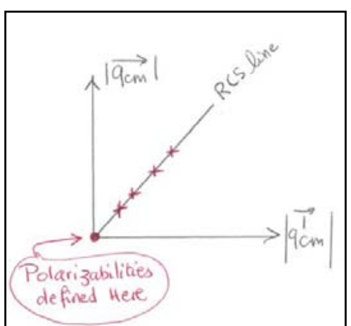
★ **Theoretical Tools:**

DR model **for VCS (B.Pasquini): is OK, no limitation at low Q^2 .**

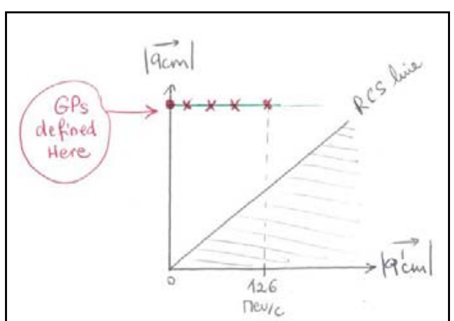
Low Energy Theorem :

→ the LET as established by Guichon et al. (NPA 591(1995) 606) may not work so well when q_{cm} is as small as q'_{cm} , typically $q_{cm} \sim q'_{cm} \sim$ 100 MeV/c …

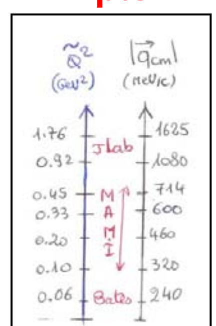
RCS



VCS



Expts



($q_{cm} >> q'_{cm}$)

Scherer, Korchin & Koch, PRC54 (1996)904
Drechsel,Knoechlein,Korchin,Metz & Scherer, PRC58 (1998) 1751

A new expansion of the VCS amplitude is made for both low q_{cm} and low q'_{cm} → another approach (how to exploit it experimentally ?)

VCS at very low Q^2 / experimental aspects

With a machine like MESA:

- *electron beam energy of 150 MeV*

- *value of q_{cm} = 100 MeV/c (Q^2tilde=0.01 GeV^2)*
- *value of q'_{cm} = 95 MeV/c (and below)*

- *cannot go to higher than ε =0.5, but even at this ε the GP effect (as calculated using the DR model with some input structure functions) seems not too small (0-10%)*

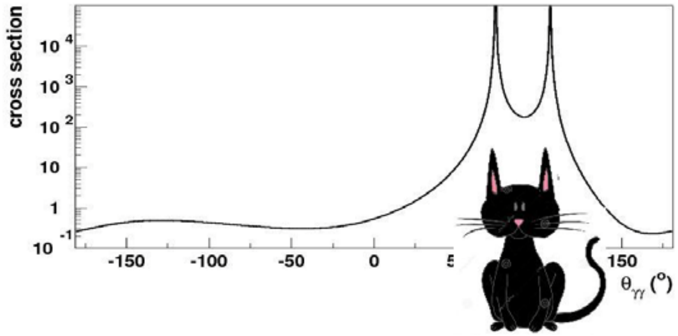
- *still need high-accuracy cross section measurement*

- *detection of e' in MAGIX compact spectrom. (43 MeV/c, angle 24^o)*

- *need to detect another particle in coincidence (need cw beam):*
    - *recoil proton ? (100-200 MeV/c lab momentum, cone angle=+-71^o)*
    - *final photon ? (80 MeV lab energy, large angles; extra-detector)*

Conclusions

★ « vcsq2 » experiment at MAMI:
new measurement of the scalar GPs at Q^2 = 0.1, 0.2 and 0.45 GeV^2
→ new insight of the Q^2-dependence
results to be finalized (end of 2016)
+ results of the « vcsDelta » Expt



★ puzzle remains w.r.t. previous measurements at Q^2=0.33 GeV^2

★ VCS continues to be an active field : new proposal at JLab, new theoretical developments
(polarizability sum rule (Pascalutsa & Vanderhaeghen, PRD 91 (2015) 051503), covariant ChPT for RCS and VCS (Pascalutsa et al), …

★ First look into VCS at very low Q^2 with MESA …