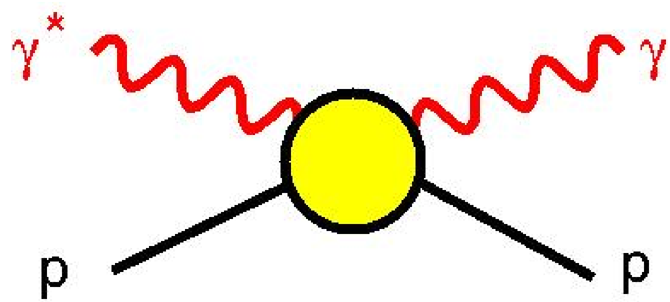
Low-energy Virtual Compton Scattering



Generalized Polarizabilities as a tool to study nucleon structure

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Milos, 09 / 2007

content

Virtual Compton Scattering and the GPs

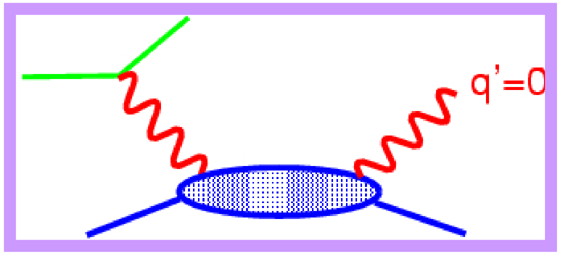
The dedicated low-energy experiments

Their results

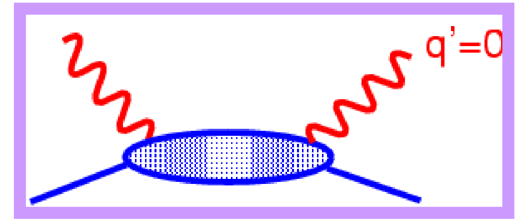
Perspectives

« low energy » : Below the DIS regime
$Q^2 < 1$ GeV^2 , $W < 2$ GeV
($W = \sqrt{s}$ of the γ-nucleon system)

Compton scattering: at the crossroads



Generalized Polarizabilities (GPs)



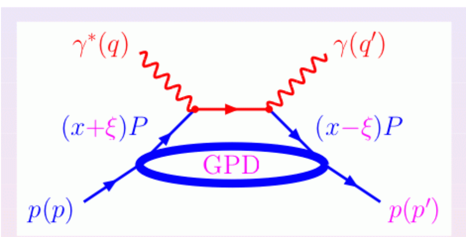
polarisabilities

γ N $\rightarrow$ γ N

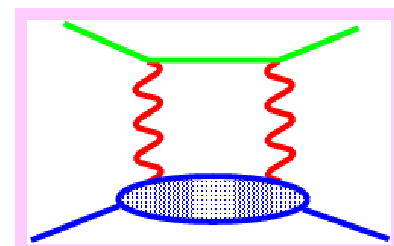
γ * N $\rightarrow$ γ N

γ N $\rightarrow$ γ * N

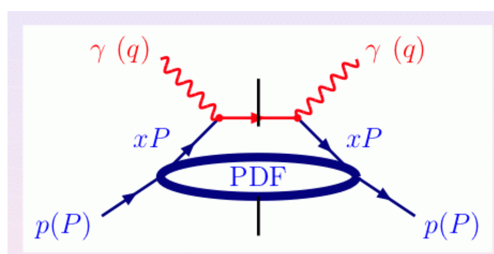
γ * N $\rightarrow$ γ * N



Generalized parton Distributions (GPDs)



2-photon exchange In elastic scattering



parton densities

Generalized Polarizabilities (GPs)

RCS

$\gamma\, p \rightarrow \gamma\, p$

$\alpha_E = (12.1 \pm 0.5).10^{-4}\ fm^{3}$

$\beta_M = (1.6 \pm 0.6).10^{-4}\ fm^{3}$

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

VCS

$\gamma^{*} p \rightarrow \gamma\, p$

$\alpha_E(Q^2)$

$\beta_M(Q^2)$

GPs = new observables = Polarizabilities as a function of the distance scale.

GPs = FF of a deformed nucleon = Fourier transform of charge and magnetization densities of a nucleon under an applied EM field

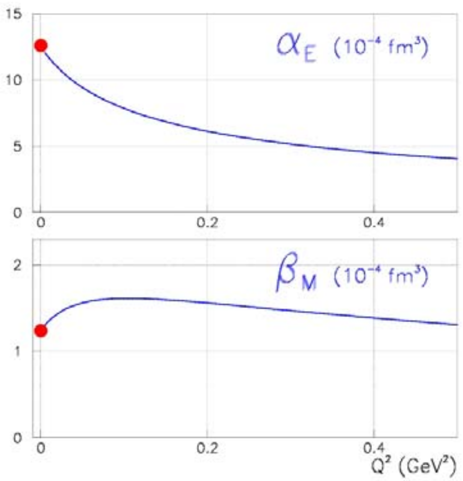
H.Arenhoevel et al., NPA 233 (1974) 153

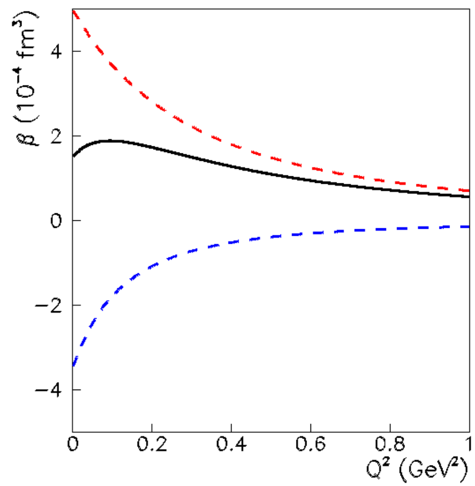
P.Guichon et al., NPA 591 (1995) 606

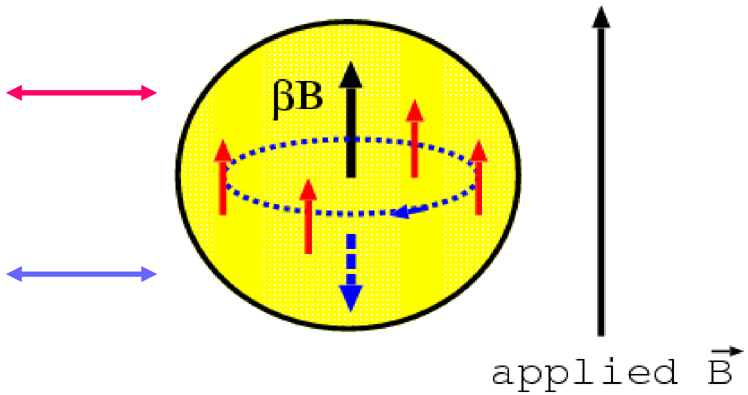
D.Drechsel et al.,Phys.Rev.C 55 (1997) 424

D.Drechsel et al.,Phys.Rev.C 57 (1998) 941

Generalized polarizabilities

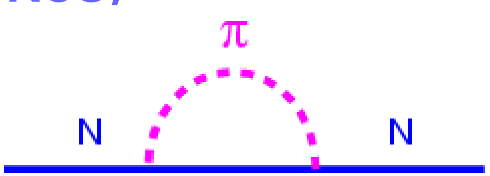






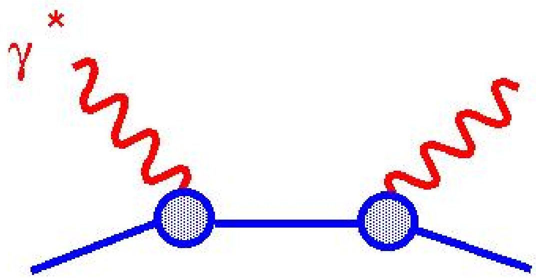
β_M **: para- and diamagnetic contributions $\Rightarrow$ not a single dipole shape**

One of the successes of ChPT : α_E and β_M (in RCS) determined by pion loops («pion cloud »)

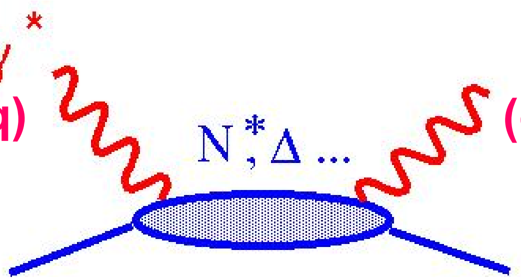


(V.Bernard et al, PRL 67 (1991) 1515).

Multipoles and GPs



VCS Born



VCS Non-Born (GPs)

Non-Born VCS amplitude : → Multipole Expansion

GP ~ limit $|_{q' \to 0}$ of $H_{non\text{-}Born}(q_{cm}, q'_{cm})$ multipole with quantum numbers of the two EM transitions:

ρ, ρ' = photon polarization states (0,1,2= longitudinal,magnetic,electric)

l, l' = total angular momentum of initial (final) EM transition

S = proton spin-flip **(S=1, spin GP)** or non spin-flip **(S=0, scalar GP)**

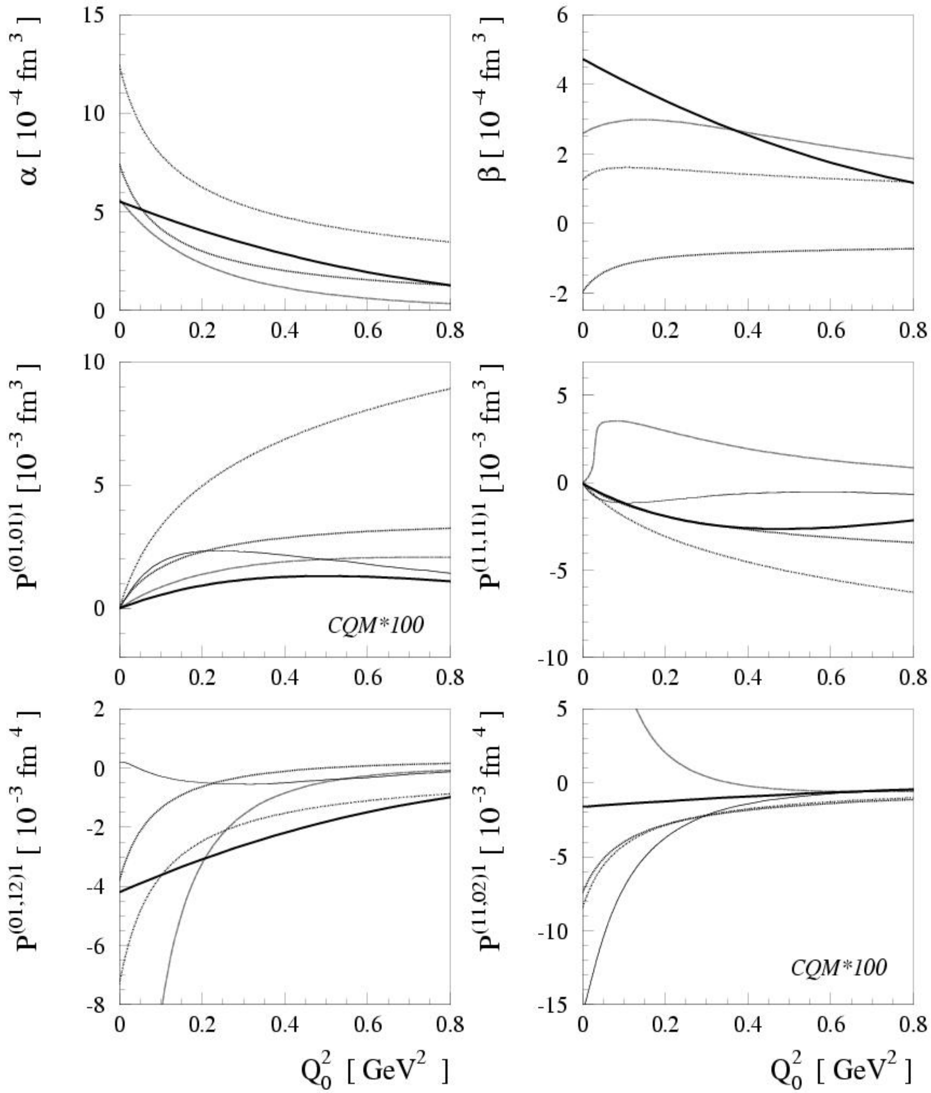
The six dipole GPs

Lowest order (l'=1) : 6 independent GPs

= 2 scalar GPs + 4 spin GPs

final γ	initial γ^*	S	$P^{(\rho' L', \rho L)S}(q_{cm})$	$P^{X \to Y}$	RCS limit $(Q^2 = 0)$	resonances involved
E1	C1	0	$P^{(01,01)0}$	$P^{C1 \to E1}$	$-\frac{4\pi}{e^2}\sqrt{\frac{2}{3}}\ \alpha_E$	D_{13}, S_{11}
M1	M1	0	$P^{(11,11)0}$	$P^{M1 \to M1}$	$-\frac{4\pi}{e^2}\sqrt{\frac{8}{3}}\ \beta_M$	P_{33}, P_{11}
E1	C1	1	$P^{(01,01)1}$	$P^{C1 \to E1}$	0	D_{13}, S_{11}
M1	M1	1	$P^{(11,11)1}$	$P^{M1 \to M1}$	0	P_{33}, P_{11}
E1	M2	1	$P^{(01,12)1}$	$P^{M2 \to E1}$	$-\frac{4\pi}{e^2}\frac{\sqrt{2}}{3}\ \gamma_3$	D_{13}
M1	C2	1	$P^{(11,02)1}$	$P^{C2 \to M1}$	$-\frac{4\pi}{e^2}\sqrt{\frac{8}{27}}\ (\gamma_2 + \gamma_4)$	P_{33}

Model Predictions for GPs



(plot courtesy of B.Pasquini)

NRQCM (B.Pasquini et al., nucl-th/0105074)

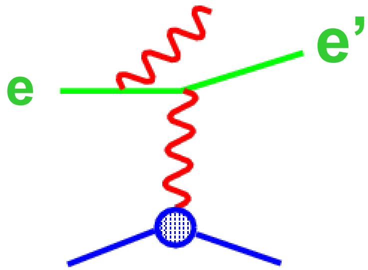
Linear Sigma Model (A.Metz et al., Z.Phys.A 356 (1996) 351)

HBChPT (T.Hemmert et al., Phys.Rev.D 62 (2000) 014013)

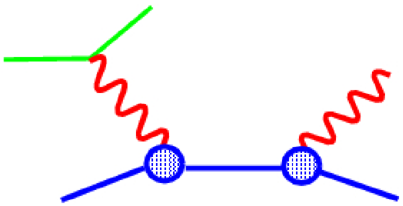
Effective Lagrangian (A.Korchin et al., Phys. Rev. C 58 (1998) 1098)

Dispersion Relation (B.Pasquini et al., Phys.Rev.C 62 (2000) 052201)

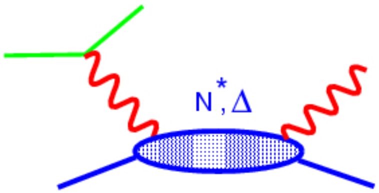
VCS experiments : $e\,p \rightarrow e\,p\,\gamma$



Bethe-Heitler



VCS Born



VCS non-Born

(GPs)

Dedicated experiments

High luminosity // high duty cycle // high resolution (rare process!)

Experiments at one fixed Q^2 and one fixed ε

Unpolarized experiments → cross sections, structure functions, electric and magnetic GPs

Polarized experiments → single, double polarization asymmetries

Expt	Q2 (GeV^2)	ε	W	Polar.	data (pub.)
MAMI-A1	0.33	0.62	< π thresh.	no	1995-97 (2000)
JLab E93050	0.9,1.8	0.95,0.88	< π thresh.	no	1998 (2004)
Bates E97-03	0.05	0.90	< π thresh.	no	2000 (2006)
MAMI-VCS-SSA	0.33	0.48	Δ(1232)	beam	2002-04 (2007)
MAMI-VCSPOL	0.33	0.645	< π thresh.	beam+fpp	2005-06

Interface between experiment and Theory

1. Model-independent approach:
   the Low energy theorem (« LEX »)

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

2. Model-dependent approach:
   dispersion relations (« DR »)

   B.Pasquini et al., Eur.Phys.J.A 11 (2001) 185
   D.Drechsel et al., Phys.Rept. 378 (2003) 99

1. The Low Energy Theorem

the unpolarized (epγ) cross section below pion threshold:

$$d\sigma(e\,p\,\gamma) =$$

$$d\sigma(BH+Born) + \Phi\, q' \,[\, v_1 (P_{LL} - P_{TT}/\varepsilon) + v_2 (P_{LT}) \,] + O(q'^2)$$

Known

(proton FF)

VCS Structure Functions =

P_{LL} , P_{TT} , P_{LT}

= combinations of GPs

One fixed ε $\rightarrow$ two structure functions

The VCS Structure Functions

( ) . α_E

$$P_{LL}(q_{cm}) = -2\sqrt{6}\, M_N\, G_E(\tilde{Q}^2)\, P^{(01,01)0}(q_{cm})$$

$$P_{TT}(q_{cm}) = -3\, G_M(\tilde{Q}^2)\, \frac{q_{cm}^2}{\tilde{q}_0} \times \left[P^{(11,11)1}(q_{cm}) - \sqrt{2}\tilde{q}_0\, P^{(01,12)1}(q_{cm}) \right]$$

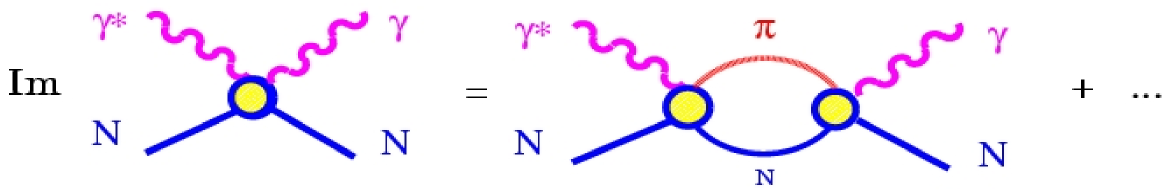
$$P_{LT}(q_{cm}) = \sqrt{\frac{3}{2}}\, \frac{M_N\ q_{cm}}{\tilde{Q}}\, G_E(\tilde{Q}^2)\, P^{(11,11)0}(q_{cm}) + \frac{3}{2}\, \frac{\tilde{Q}\ q_{cm}}{\tilde{q}_0}\, G_M(\tilde{Q}^2)\, P^{(01,01)1}(q_{cm})$$

( ) . β_M

GPs depend on q_{cm} *or equivalently* $Q^2 = 2M_p\,(\,[M_p^{\,2}+q_{cm}^{\,2}]^{1/2} - M_p\,)$

2. The Dispersion Relation Model for VCS

- Dispersive integrals for NonBorn amplitudes
- πN part given by MAID pion photo-& electro-production amplitudes:



- unconstrained: asymptotic parts and contributions beyond πN

- **Spin GPs are fixed by Dispersion Relations**

- **Scalar GPs have to be parametrized**

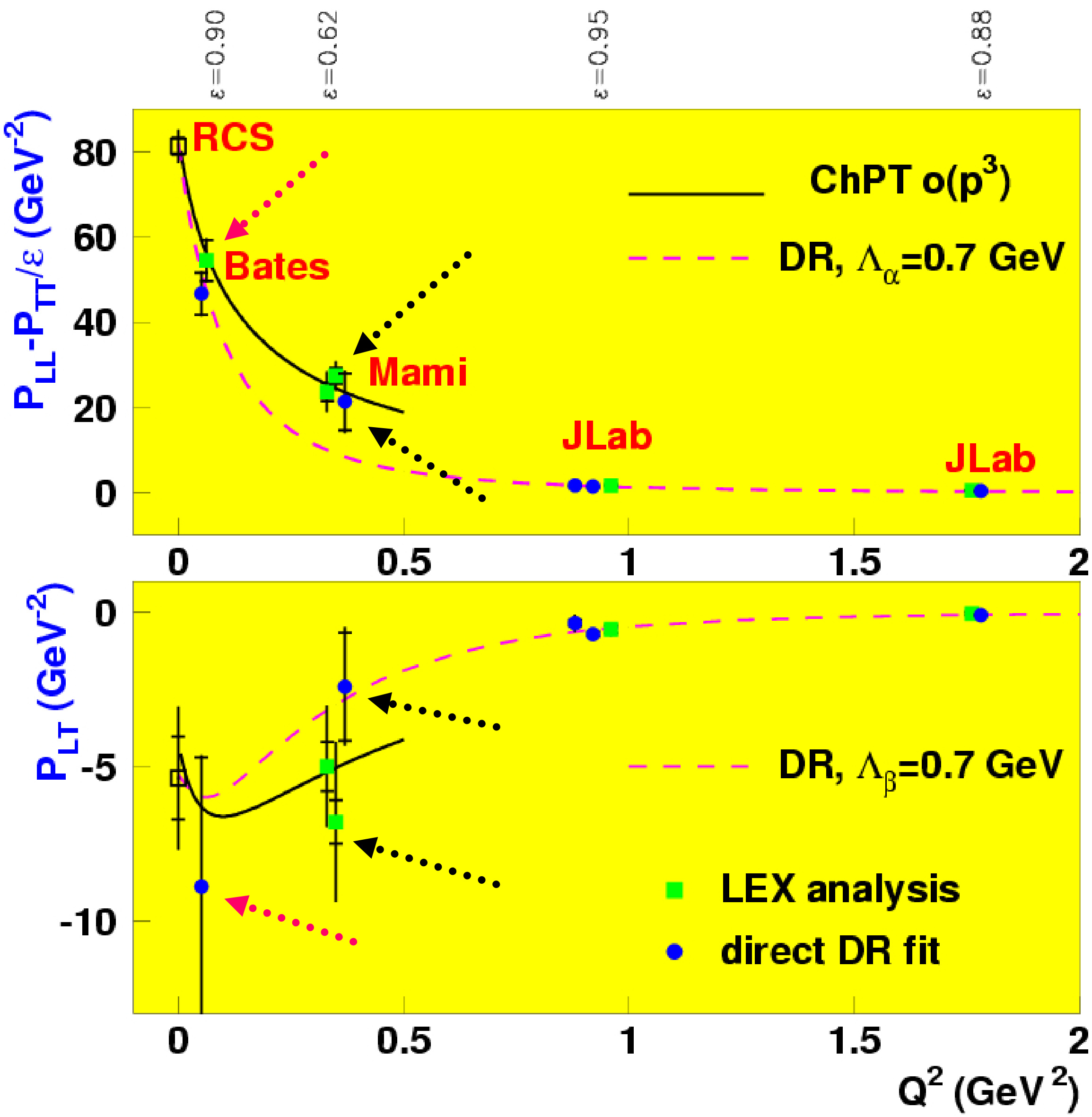
$$\alpha_E(Q^2) - \alpha_E^{\pi N}(Q^2) = \frac{[\alpha_E^{exp}(0) - \alpha_E^{\pi N}(0)]}{(1 + Q^2 / \Lambda_\alpha^2)^2}$$

(same for β_M)

Fit the dipole mass parameters Λ_α , Λ_β

→ fit the scalar GPs at any given Q^2

World data on Structure Functions



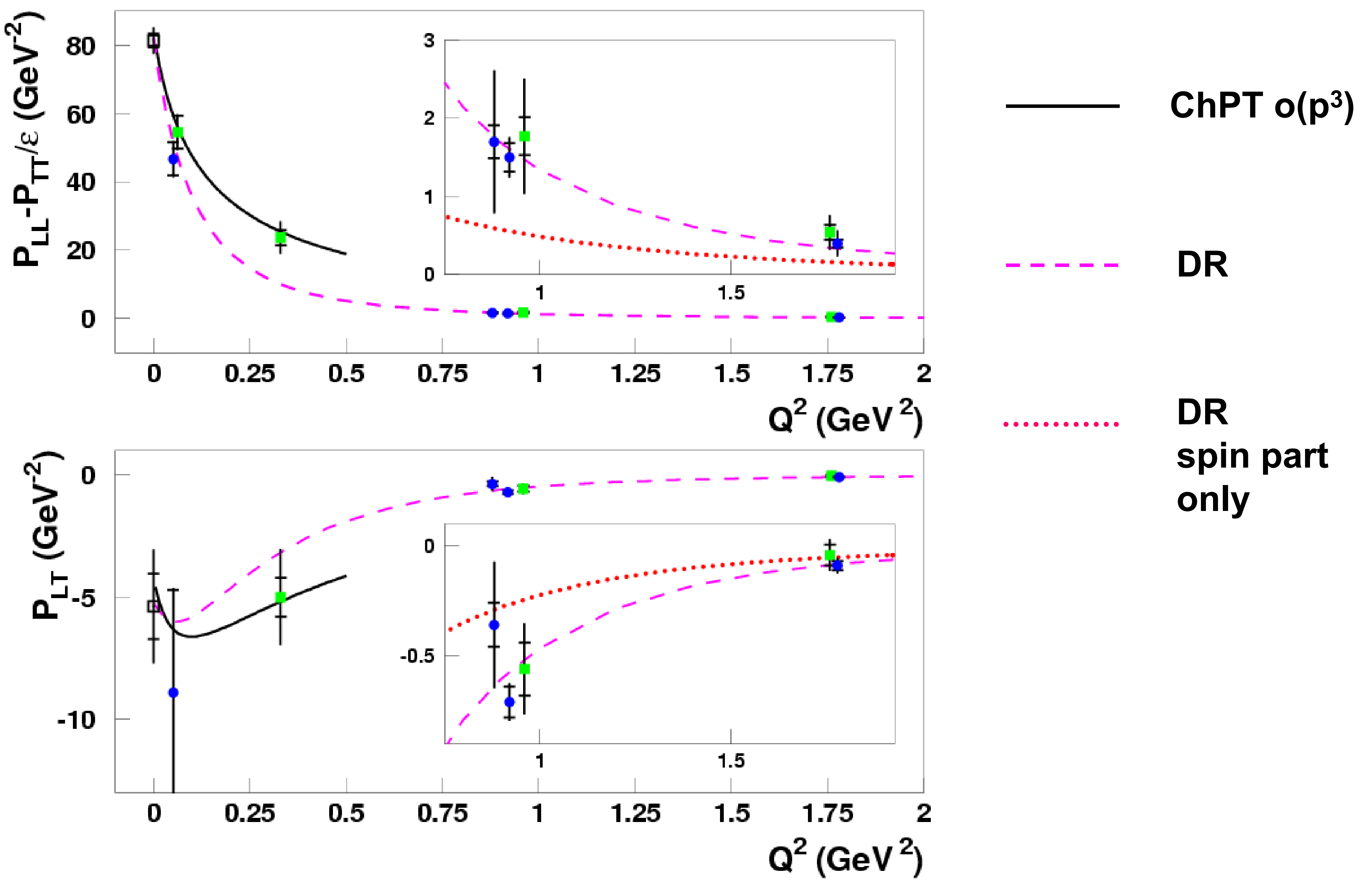
(DR model: single dipole assumption is not mandatory)

Most recent:

Bates , Q^2=0.06 GeV^2

2 new results at Q^2=0.33 GeV ^{2} :

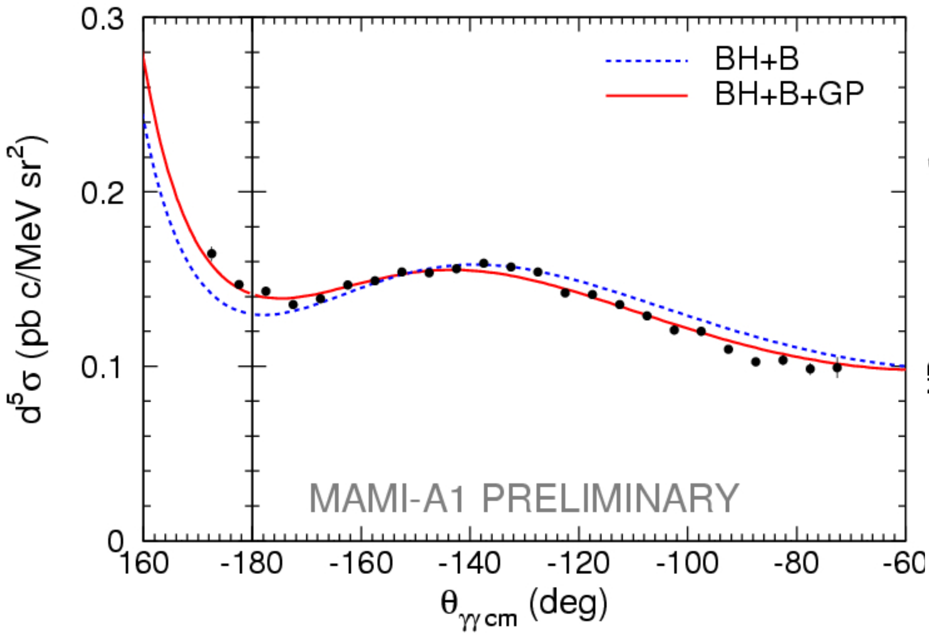
- LEX analysis on a new dataset
- global DR fit of 3 datasets

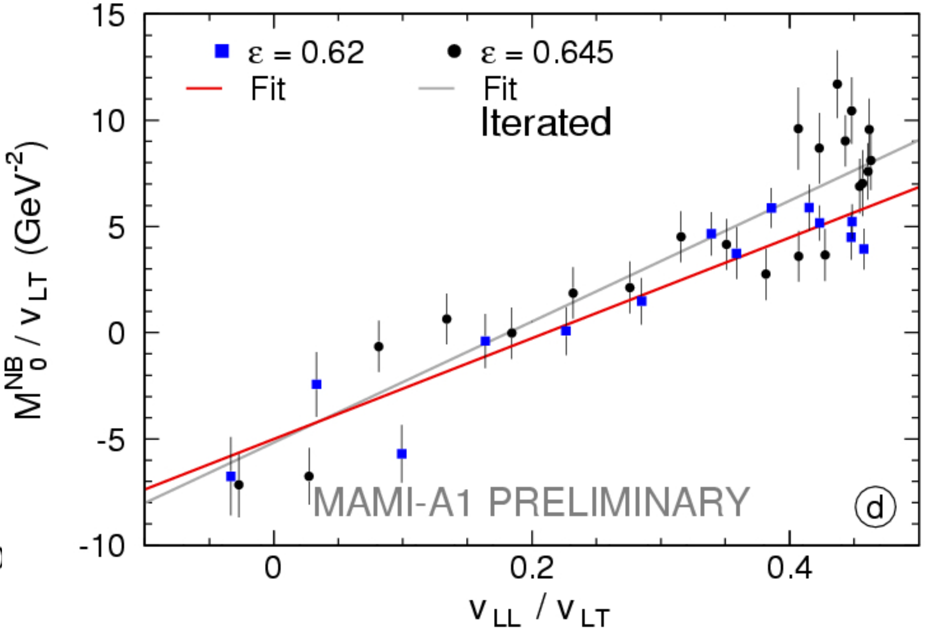


$P_{LL}-P_{TT}/\varepsilon$ (GeV^{-2})
P_{LT} (GeV^{-2})
Q^2 (GeV^2)
ChPT o(p^3)
DR
DR
spin part
only

New LEX analysis at $Q^2 = 0.33\ GeV^2$

VCSPOL experiment (double polarization)





$P_{LL} - P_{TT} / \varepsilon$	P_{LT}	(GeV^{-2})
23.7 ± 2.2 ± 4.3	- 5.0 ± 0.8 ± 1.8	1st MAMI Expt PRL85 (2000)
23.7 ± 1.9 ± 2.9	- 5.3 ± 0.7 ± 2.5	This expt, non-iterated
27.4 ± 1.9 ± 2.9	- 6.8 ± 0.7 ± 2.5	This expt, iterated

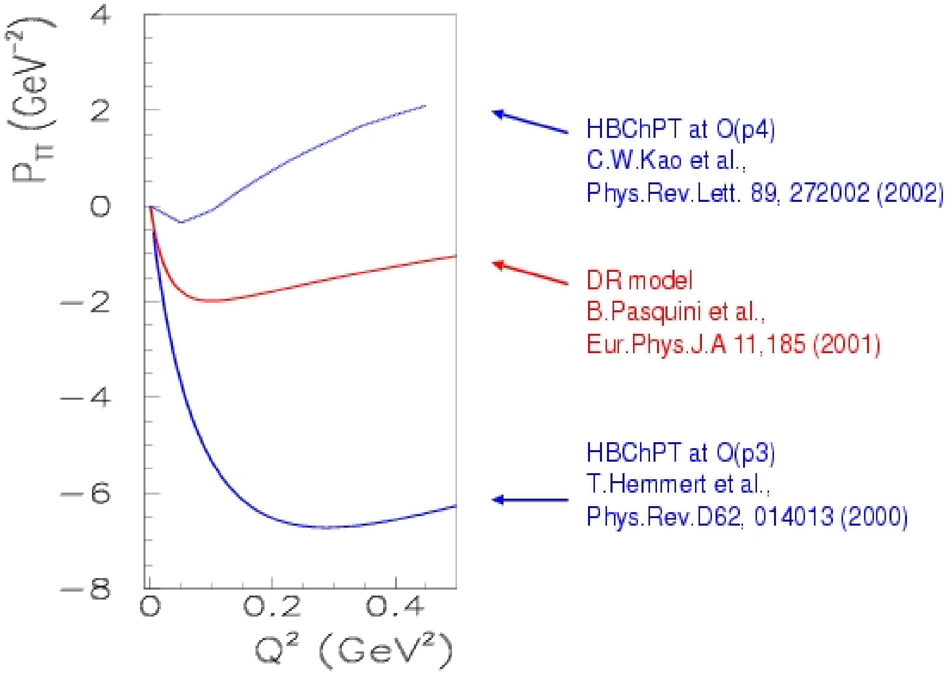
preliminary

Courtesy of Peter JANSSENS (PhD), Gent Univ.

From Structure Functions to GPs :

The LEX formalism contains only structure functions.

★ Unpolarized VCS: 2 (or 3) SFs
$P_{LL} - P_{TT/\varepsilon}$, P_{LT} for 6 GPs
→ **cannot disentangle scalar and spin GPs. NEED A MODEL.**
Subtract spin part using DR.

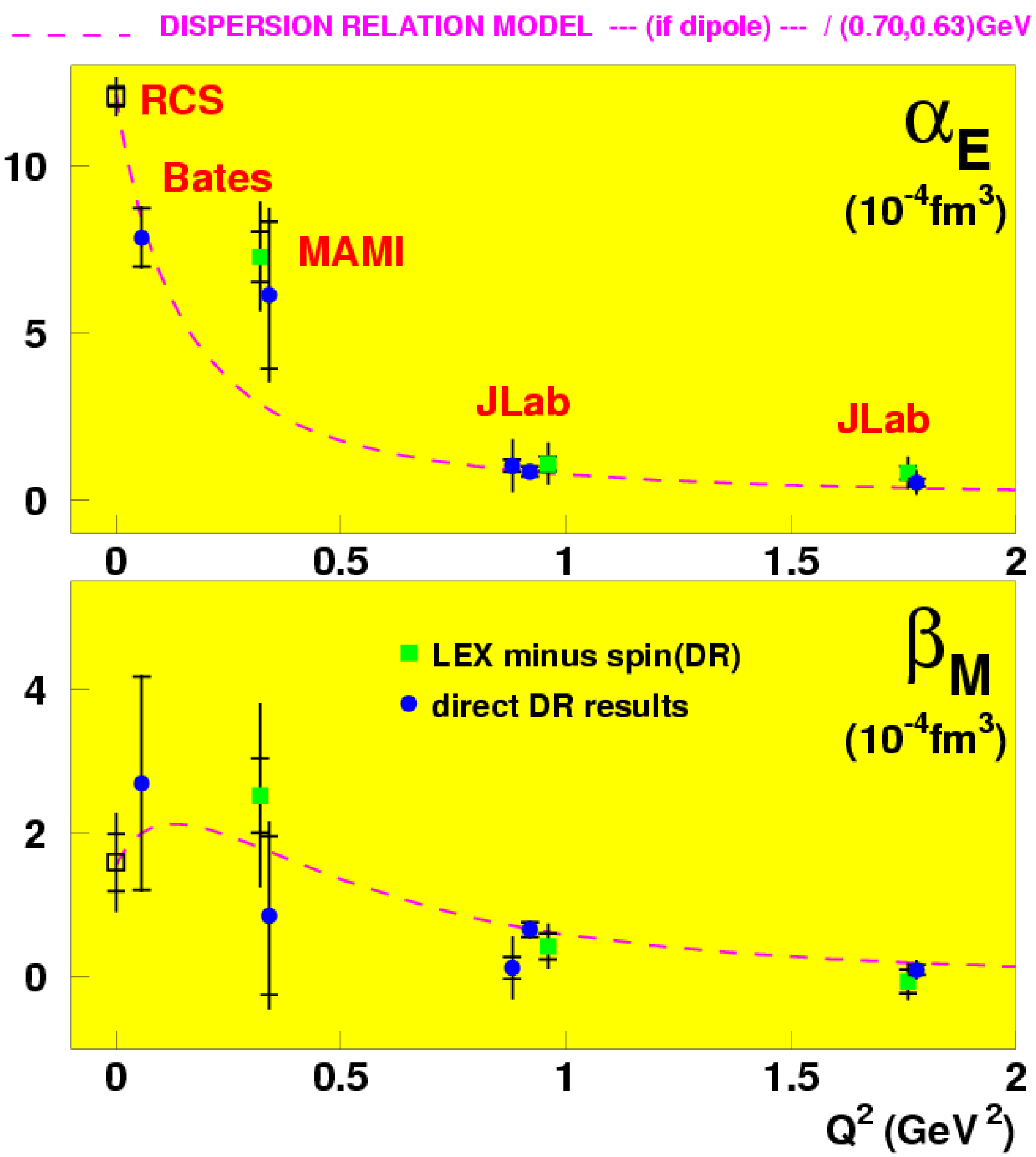


★ Doubly polarized VCS:
6 SFs for 6 GPs
→ in principle disentangling is possible, but difficult.

The DR model: not totally predictive: is a better feature !
Allows to fit directly the 2 scalar GPs.

also works in the Delta(1232) resonance region.
Gives consistent extractions of the GPs above and below pion threshold.

World data on proton GPs



(Model-dependent picture !)

α_E : fall-off does not look fully dipolar

β_M : extremum at low Q^2 seems confirmed

RCS + Bates → mean square electric polarizab. radius:

$<r^2>$	=	2.16 ± 0.31	fm^2
HBChPT	:	1.7	fm^2

(mesonic effects!)

Hard to get small error bars (RCS: 40 years, VCS: 10 years)

About experimental error bars in VCS:

The GP effect is 10-15 % of the (epγ) cross section.
Syst.errors on the cross section are about ±3 % , so about ±20-30 % of the GP effect itself.

Which uncertainties can be reduced ?

Statistical error

Radiative corrections ?

Solid angle ?

Proton form factors ?

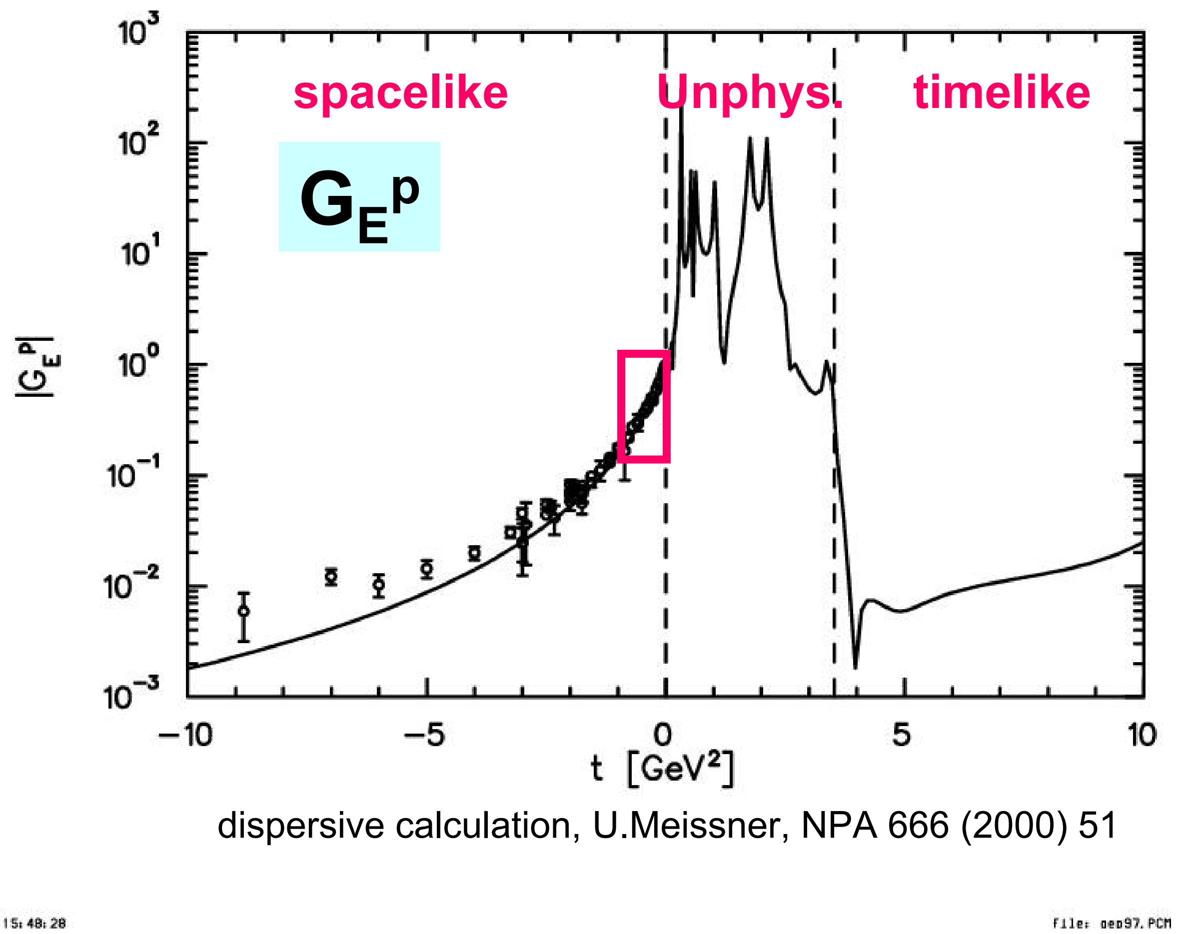
They enter the BH+Born cross section , and the GPs are always extracted by measuring the *deviation* to BH+Born.

Proton FF presently known to ~ ± 1.5 % in the low-Q^2 region : (0-1) GeV^2.
Know them better → better inputs to VCS , DVCS, PV experiments …

Nucleon elastic form factors

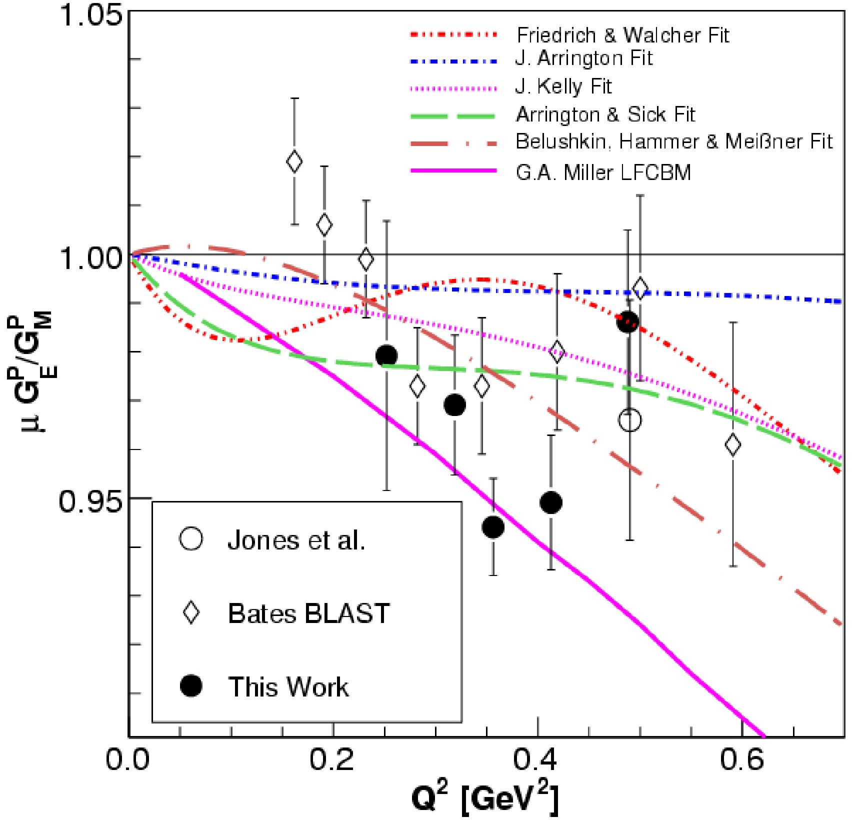
- Measured since 50 years

- Renewed interest recently



dispersive calculation, U.Meissner, NPA 666 (2000) 51

Nucleon elastic form factors



From LEDEX JLab expt, arxiv/0706.0128.
Ratio < 1 : comes mainly from G_E / G_{Dipole} < 1

Soon new measurements of G_E and G_M on the proton at JLab and MAMI at low Q^2, with better control of syst. errors.

- MAMI-A1: cross sections + global fit (or Rosenbluth)
Goal: uncertainty on FF << 1 %
(errmax ~1 % on G_E at Q^2 = 1 GeV^2)

- JLab: Rosenbluth + polarisation transfer

Polarized VCS. Single Polarization

Beam spin asymmetry in the Delta(1232) resonance region with longitudinally polarized beam

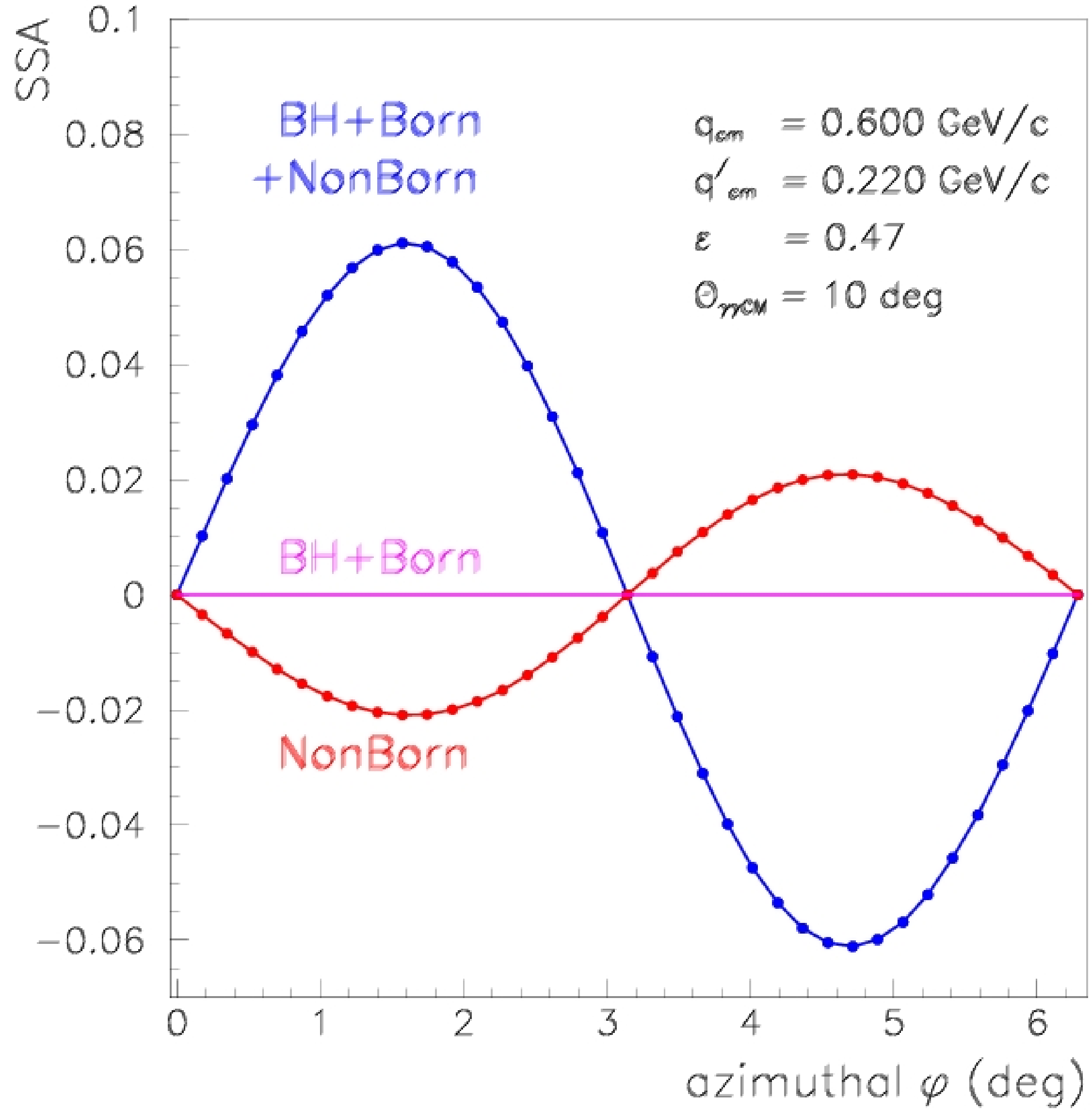
Numerator = $\Delta\sigma$ (VCS) + $\Delta\sigma$ (Interf. VCS-BetheHeitler)
= proportional to Im(VCS amplitude)

SSA measurement = direct test of Im(VCS)

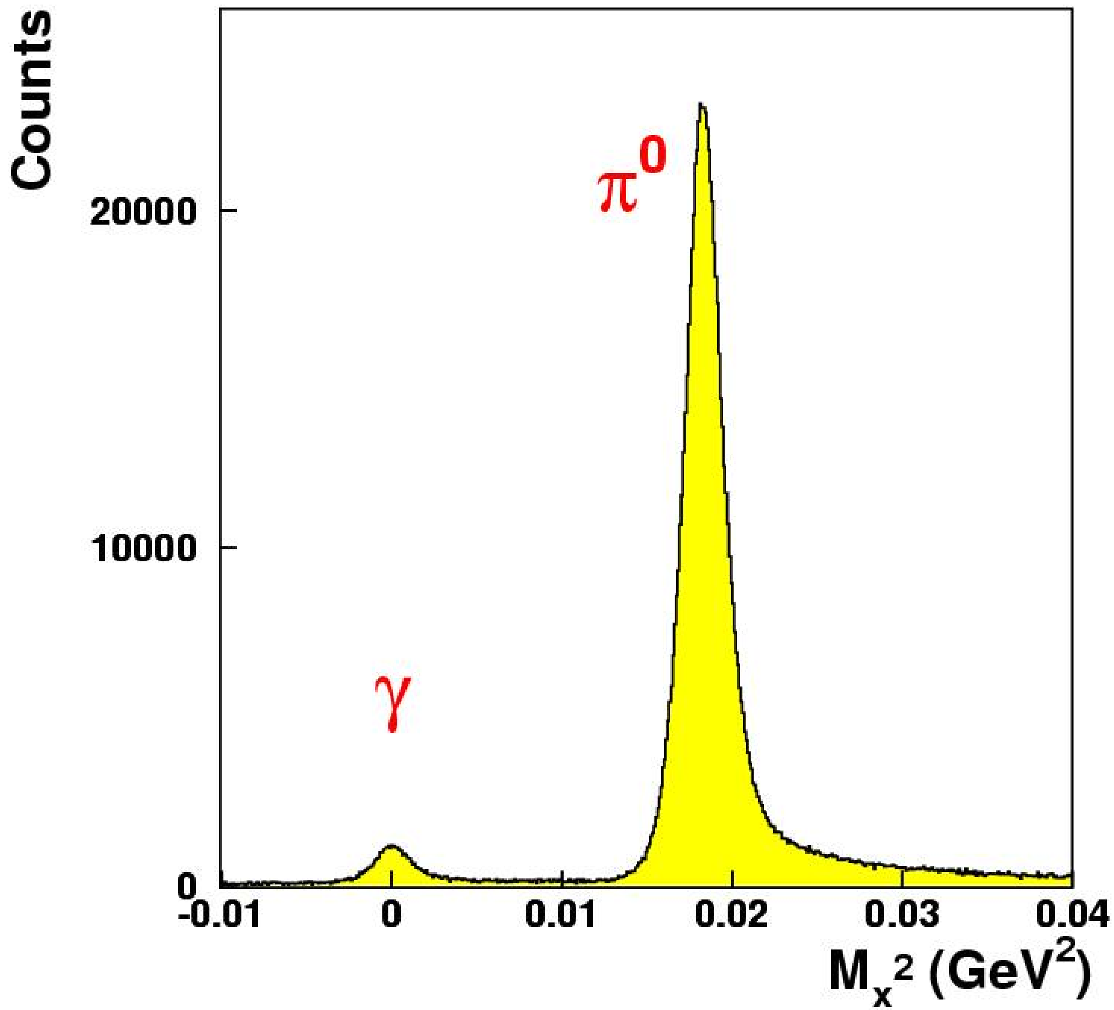
Unitarity relates photon and pion electroproduction.
In the DR formalism for VCS, test of the dispersive input = MAID π-N multipoles (should be the dominant contribution in the Δ(1232) region).

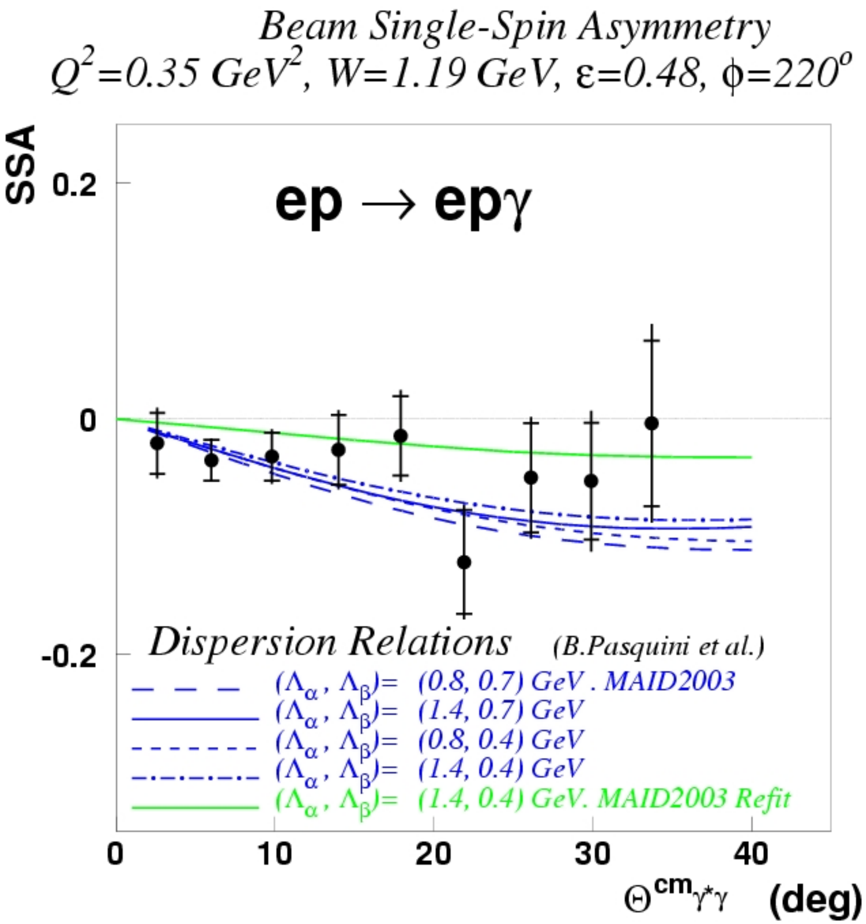
Same asymmetry as in DVCS but different interpretation.
BetheHeitler process: amplifies the asymmetry.

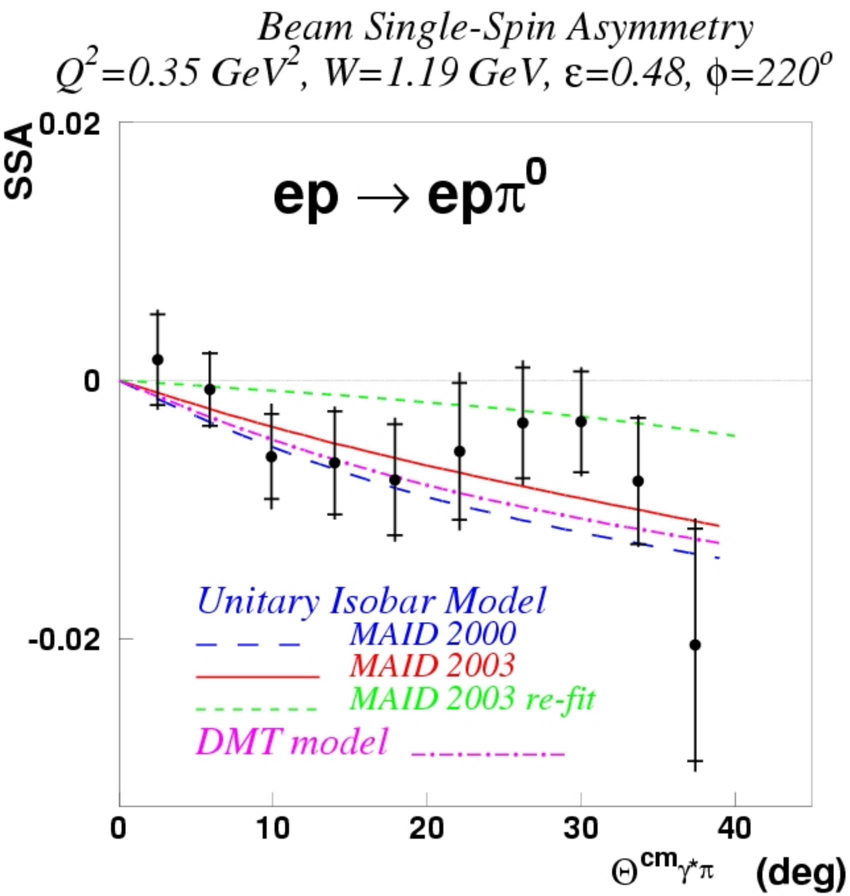
Interference with Bethe-Heitler Process



Missing mass squared: e p → e' p' X with X = γ or π^0







Complementary diagnostic w.r.t. more traditional measurements in pion electroproduction

Sensitivity to the interf. between the dominant M1+ multipole and small non-resonant ones: S0+, S1+.

(MAMI-A1) I.Bensafa et al., EPJA 32 (2007) 69.

Polarized VCS. Double Polarization

Polarized LET below pion threshold / M.Vanderhaeghen, PLB 402 (1997) 243

$$P_x = \frac{d^5\sigma_x^{\uparrow} - d^5\sigma_x^{\downarrow}}{d^5\sigma_x^{\uparrow} + d^5\sigma_x^{\downarrow}} = \frac{\Delta d^5\sigma_x}{2\ d^5\sigma}$$

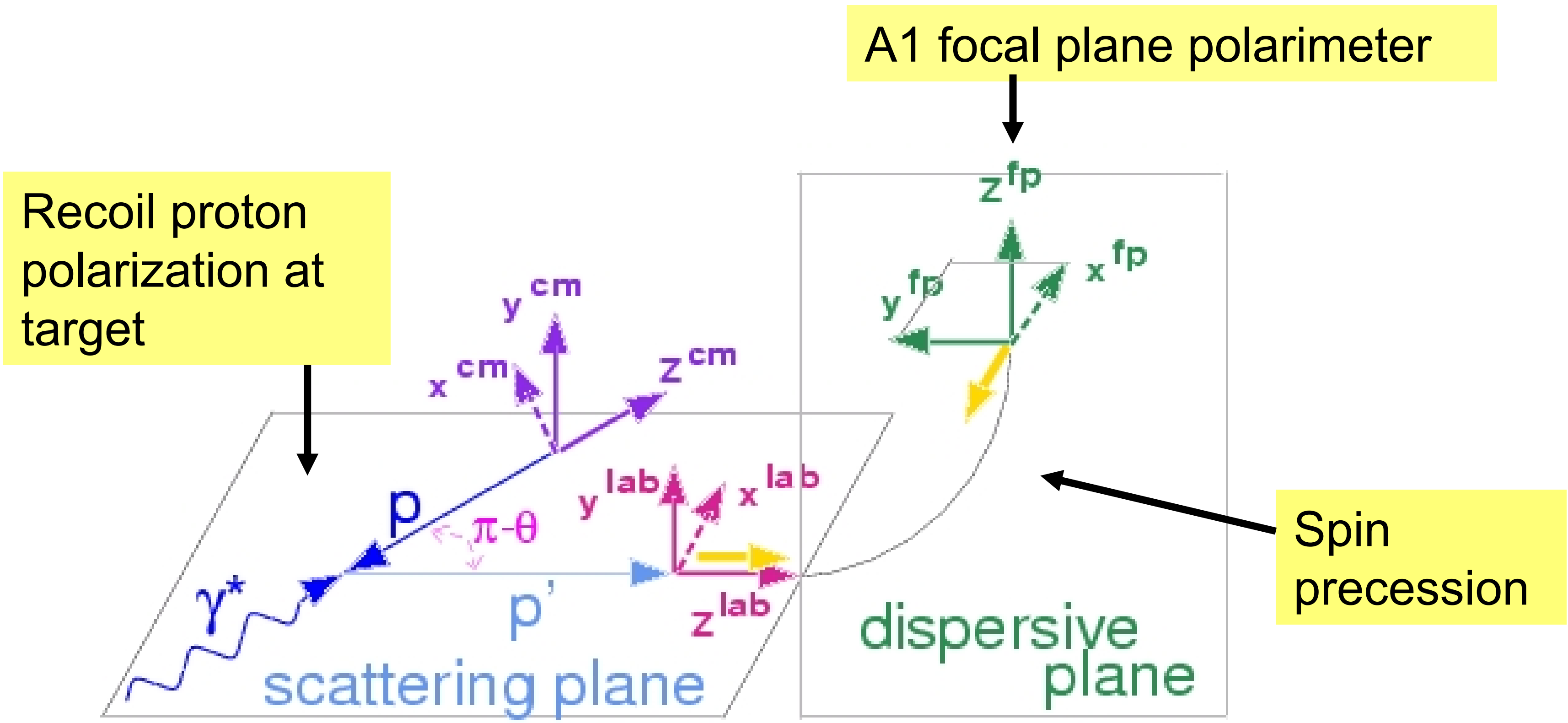
$$\boxed{\Delta d^5\sigma_i^h = \Delta d^5\sigma_i^{BH+Born} + \phi \mathrm{q}' \Delta\Psi_0^i + \phi\mathcal{O}(\mathrm{q}'^2)}$$ ← LET

$$\begin{aligned}
\Psi_0 &= v_1(\mathbf{P_{LL}} - \mathbf{P_{TT}}/\epsilon) + v_2\mathbf{P_{LT}} \\
\Delta\Psi_0^z &= 4\ h\ [v_1^z\ \mathbf{P_{TT}} + v_2^z\mathbf{P^z_{LT}} + v_3^z\ \mathbf{P'^z_{LT}}] \\
\Delta\Psi_0^x &= 4\ h\ [v_1^x\ \mathbf{P^{\perp}_{LT}} + v_2^x\ \mathbf{P^{\perp}_{TT}} + v_3^x\ \mathbf{P'^{\perp}_{TT}} + v_4^x\ \mathbf{P'^{\perp}_{LT}}] \\
\Delta\Psi_0^y &= 4\ h\ [v_1^y\ \mathbf{P^{\perp}_{LT}} + v_2^y\ \mathbf{P^{\perp}_{TT}} + v_3^y\ \mathbf{P'^{\perp}_{TT}} + v_4^y\ \mathbf{P'^{\perp}_{LT}}]
\end{aligned}$$

$P_{LL} =$	$(\ )\ P^{(01,01)0}$					
$P_{TT} =$			$(\ )\ P^{(11,11)1}$	$+(\ )\ P^{(01,12)1}$		
$P_{LT} =$		$(\ )\ P^{(11,11)0}$			$+(\ )\ P^{(01,01)1}$	
$P^z_{LT} =$			$(\ )\ P^{(11,11)1}$		$+(\ )\ P^{(01,01)1}$	
$P'^z_{LT} =$			$(\ )\ P^{(11,11)1}$		$+(\ )\ P^{(01,01)1}$	
$P^{\perp}_{LT} =$	$(\ )\ P^{(01,01)0}$		$+(\ )\ P^{(11,11)1}$	$+(\ )\ P^{(01,12)1}$		
$P^{\perp}_{TT} =$		$(\ )\ P^{(11,11)0}$	$+(\ )\ P^{(11,11)1}$			
$P'^{\perp}_{TT} =$		$(\ )\ P^{(11,11)0}$	$+(\ )\ P^{(11,11)1}$			
$P'^{\perp}_{LT} =$					$(\ )\ P^{(01,01)1}$	$+(\ )\ P^{(11,02)1}$

Need to measure the polarization components **Px, Py, Pz** of the recoil proton in the γp center-of-mass

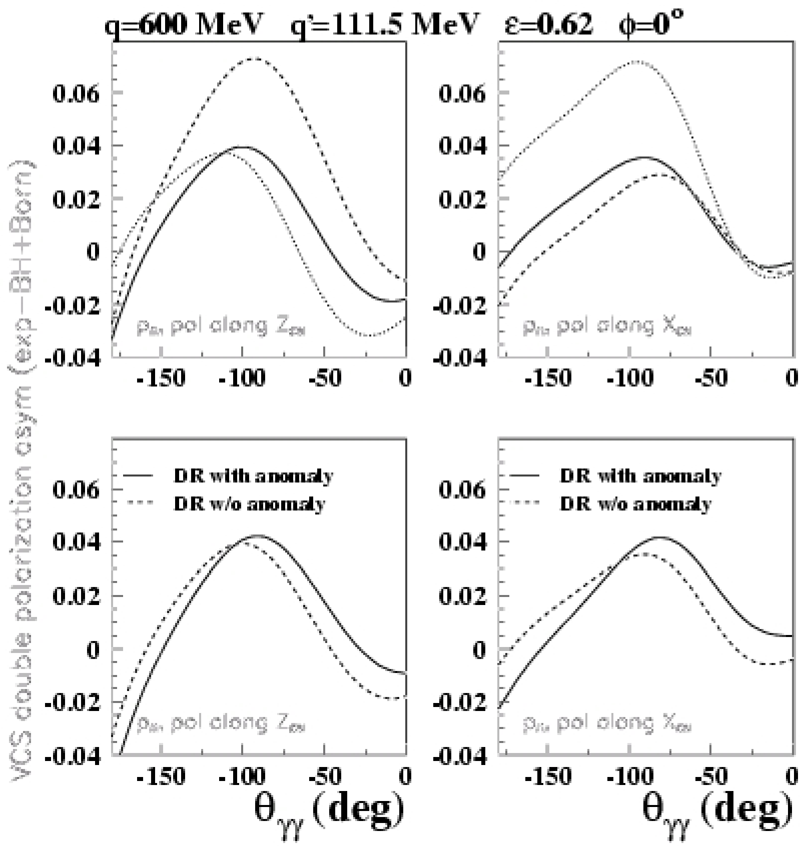
measurement over a wide enough range in $\theta\gamma\gamma_{CM}$ → in principle enough constraints to extract 5 GPs (or 6 if out-of-plane)



Expected Double Polarization Asymmetries

(Mami Kinem.)

From C.W.Kao et al., hep-ph/0408095



Large asymm. from BH+Born (30-50 %)

Small asymm. from VCS Non-Born (polarizabilities) (2-6 %)

FIG. 3: Deviation of the double-polarization VCS asymmetry from the BH+Born result, calculated within the LEX formalism in MAMI kinematics as function of the photon scattering angle. Upper panels: lowest order HBChPT predictions from Refs. [4, 5] (dotted curves); results including the next order HBChPT corrections for the spin-flip GPs, as calculated in this work, and using the leading order predictions for the spin-independent GPs (dashed curves); dispersion relation results [16, 18] (solid curves). The effect of the anomaly contribution (i.e. t-channel π^0 pole) is neglected in all the three model-predictions. In the lower panels, a comparison is shown between the dispersive predictions without the anomaly contribution (dashed curves) and with the anomaly contribution (solid curves).

experimental status

More than 2000 hours of beamtime (2005-2006) . ~ 10^5 usable events

Analysis in progress . Likelihood method :

$$\mathcal{L} = \prod_{i=1}^{N} \left[1 - A_C(\theta_{fpp}, T_{CC}) \cdot P_{beam} \cdot \left(P^y_{fpp} \cos\phi_{fpp} - P^x_{fpp} \sin\phi_{fpp} \right)\right]$$

$$P^y_{fpp} = a^i_{yx} P^x_{cm} + a^i_{yy} P^y_{cm} + a^i_{yz} P^z_{cm}$$

$$P^x_{fpp} = a^i_{xx} P^x_{cm} + a^i_{xy} P^y_{cm} + a^i_{xz} P^z_{cm}$$

Two polarization components of the proton in the focal plane

→ three components at the target

analysis overview

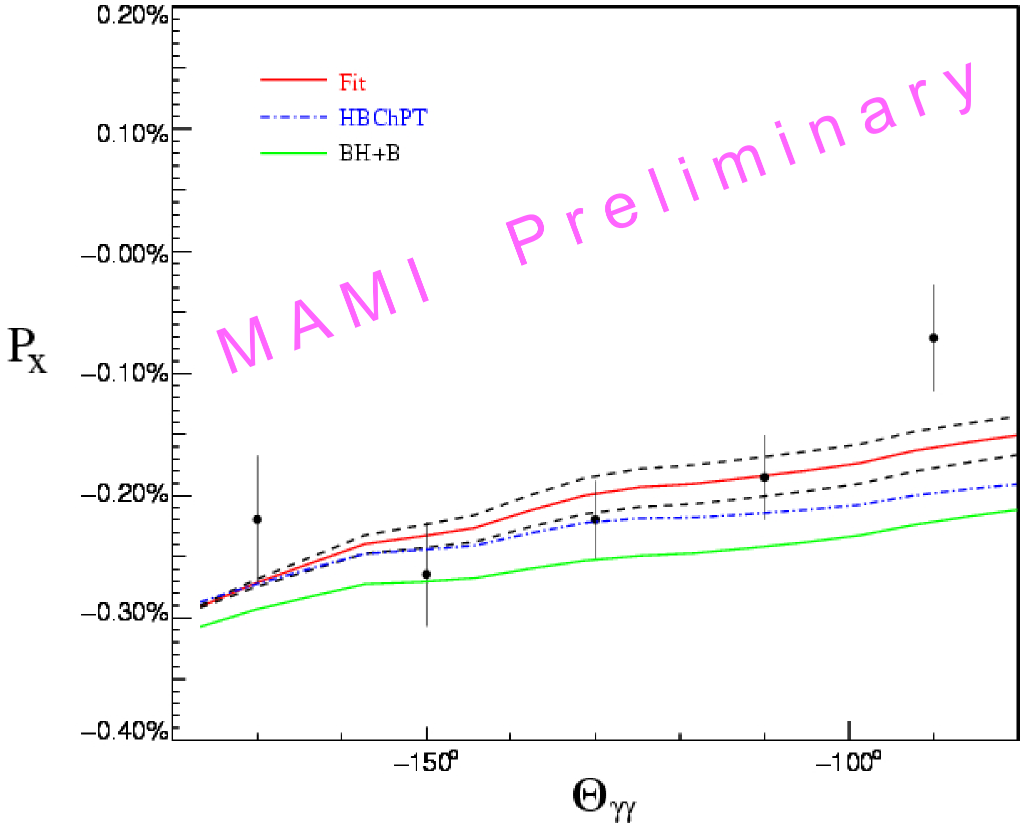
P_{cm} : contains six independent structure functions (or 6 indep. GPs)

Present data: cannot extract all GPs
GP signal too small and/or limited statistics

Have to use physical constraints, like $P_{z\ cm}$ given by BH+Born evt/evt

Presently fit ONE structure function, which has the largest effect on the asymmetry : $P_{LT}^{\perp}$

Use unpolarized results ($P_{LL} - P_{TT} / \varepsilon$, P_{LT}) at denominator of asymm.



Courtesy of Luca DORIA (PhD), Mainz Univ.

Bins in Θ are made only for graphical representation

Stat.error of ± 3-5 % on P_x

(wiggles: due to not yet projected to nominal kinematics)

$P_{LT}^{\perp}$ (GeV^{-2})		
This expt (prelim.)	**- 13.7**	**± 2.8 $_{stat}$ ± 2.2 $_{syst}$**
HBChPT	**- 10.7**	
Disp.Rel.	**- 9.0**	

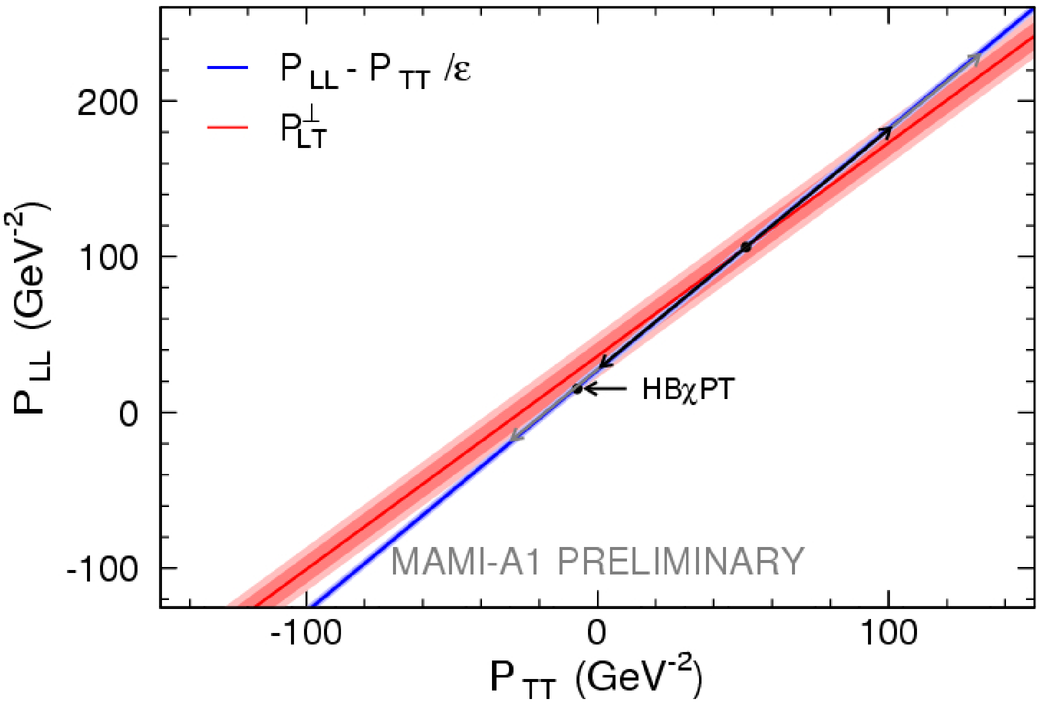
Exp. result almost insensitive to the choice of proton FF.

Syst.err. includes: variation of the constraints on other SFs, and beam pol.

Can one separate P_{LL} and P_{TT} using these data?

$$P_{LT}^{\perp} = -\frac{Q}{4M_p} \cdot \frac{G_M^p}{G_E^p} \cdot P_{LL} + \frac{M_p}{Q} \cdot \frac{G_E^p}{G_M^p} \cdot P_{TT}$$

$$\text{unpol. SF} = P_{LL} - P_{TT} \cdot \frac{1}{\epsilon}$$



at Q^2 = 0.33 GeV^2

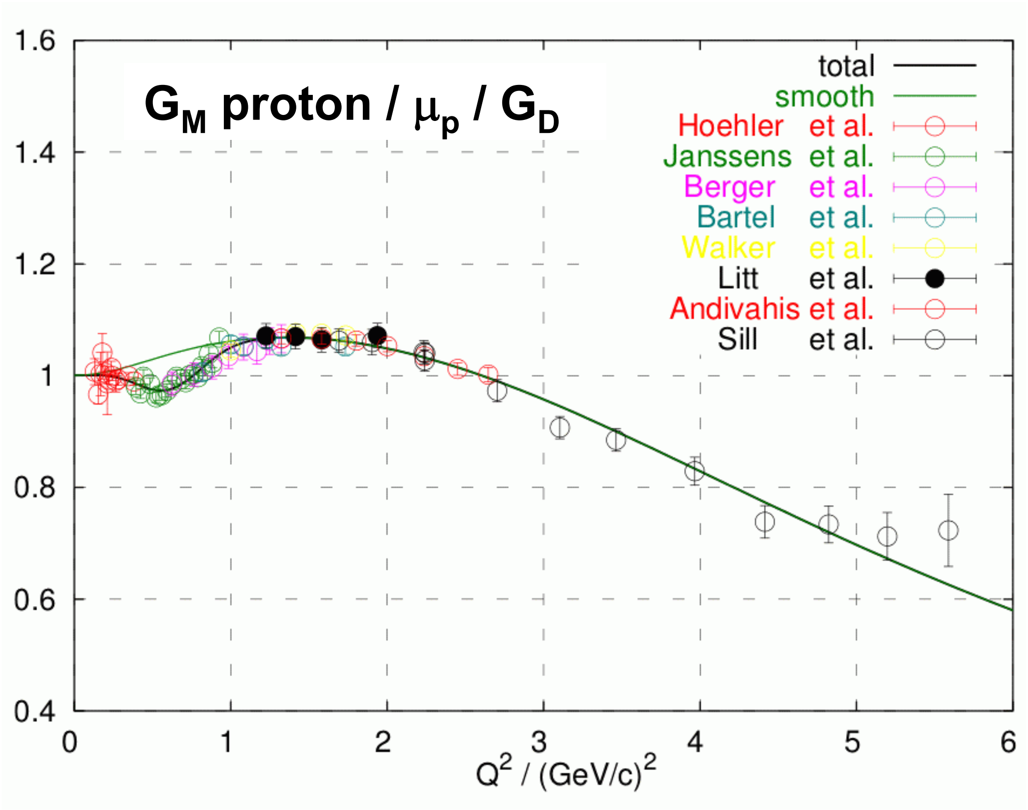
In principle possible … with better kinematics !

Courtesy of Peter JANSSENS (PhD), Gent Univ.

Nucleon FF at low Q^2

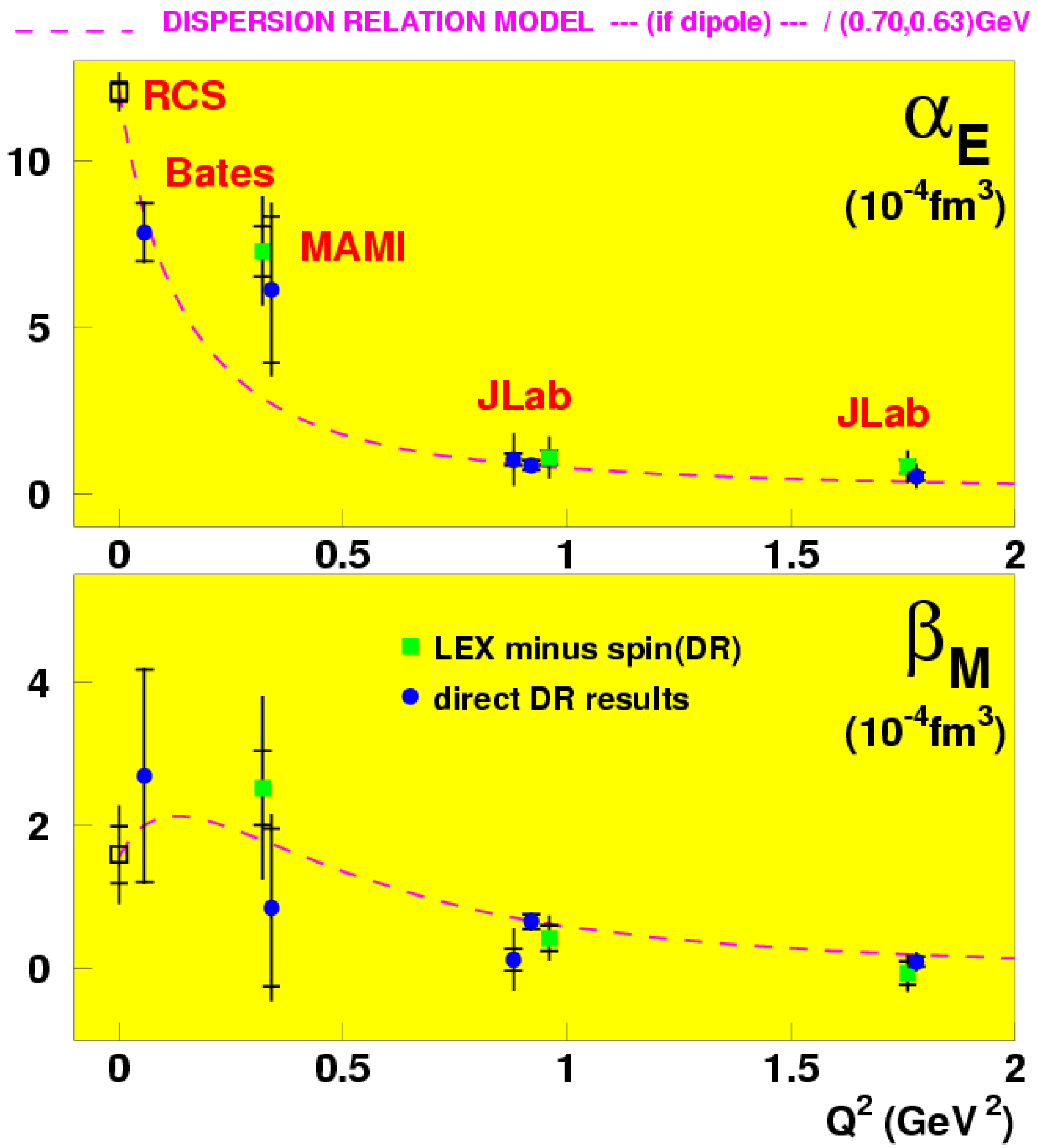
Friedrich-Walcher fit: (EPJA 17 (2003) 607)
Smooth part (dipole) + bump/dip in region 0.2- 0.5 GeV^2
= Constituent quarks + pion cloud

All 4 FF show this «structure» (a tiny 2-3 % effect)



(plot courtesy of J.Bernauer, MAMI-A1)

World data on proton GPs



Pion cloud :

Old notion (1950)
Central to the nucleon structure at low energy

π = manifestation of Chiral Symmetry of QCD

enhanced effect of the pion cloud in the polarizabilities w.r.t. FF …

Need to map out α_E and β_M in the low Q^2 region !

other polarizability-related measurements

Photoabsorption cross sections | **(e,e') cross sections**

$$\text{(GDH)} \quad \frac{\pi e^2 \kappa_N^2}{2M^2} = (\,)\int \frac{\sigma_{3/2}(\nu) - \sigma_{1/2}(\nu)}{\nu}\, d\nu \quad \rightarrow \quad I(Q^2) = (g_1, g_2)$$

$$\text{(Baldin)} \quad \alpha + \beta = (\,)\int \frac{\sigma_{3/2}(\nu) + \sigma_{1/2}(\nu)}{\nu^2}\, d\nu \quad \rightarrow \quad [\alpha + \beta](Q^2) = (\,)\int 2x\ F_1\ dx$$

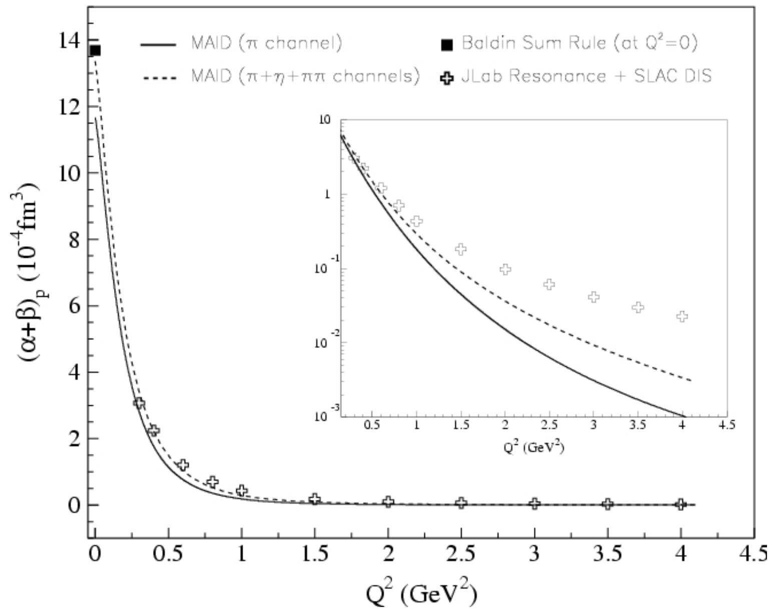
$$\text{(Forwd)} \quad \gamma_0 = (\,)\int \frac{\sigma_{3/2}(\nu) - \sigma_{1/2}(\nu)}{\nu^3}\, d\nu \quad \rightarrow \quad \gamma_0(Q^2) = (g_1, g_2)$$

$$\text{(LT)} \quad \delta_{LT} = (\,)\int \frac{K}{\nu}\ \frac{\sigma_{LT}(\nu, Q^2)}{Q\nu^2}\, d\nu \quad \rightarrow \quad \delta_{LT}(Q^2) = (g_1, g_2)$$

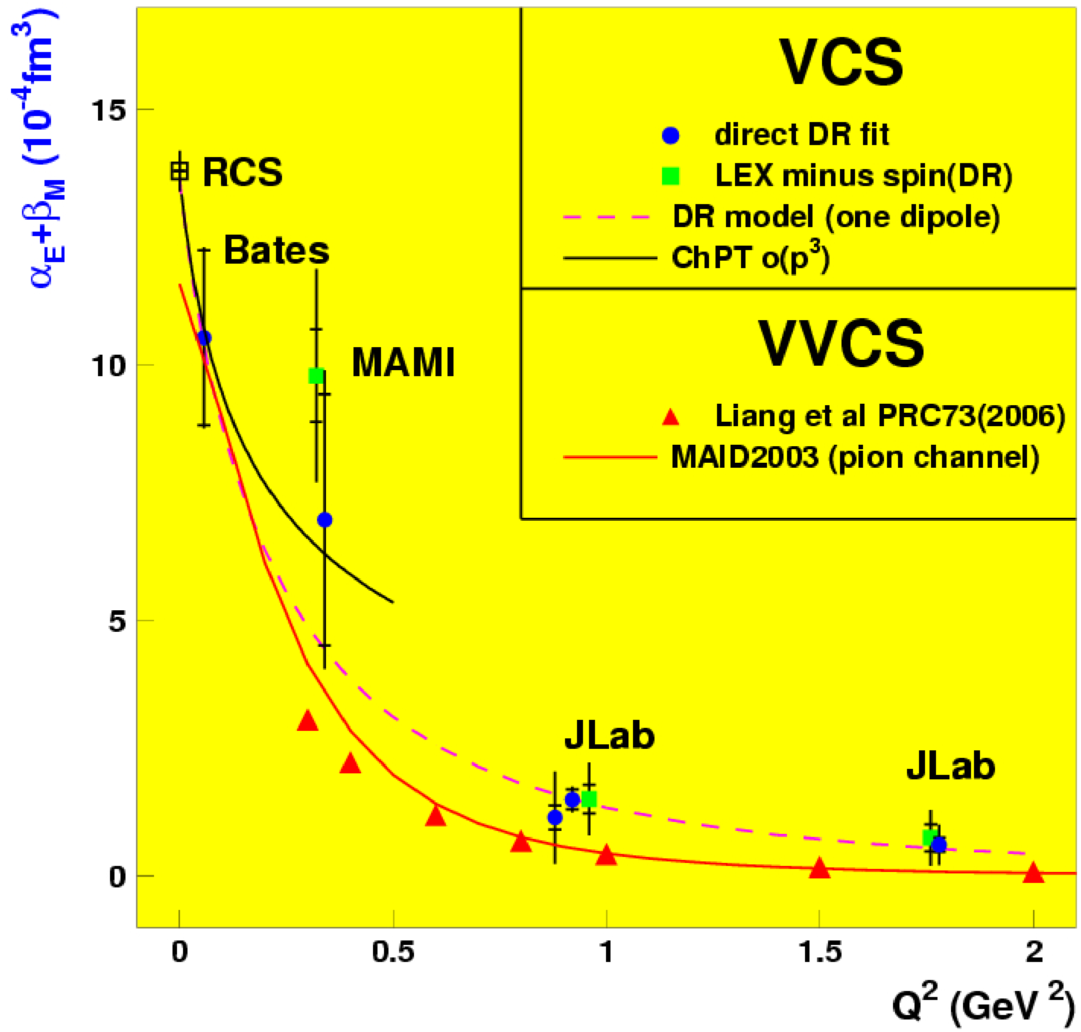
Generalized Baldin Sum Rule on the proton

$[\,\alpha + \beta\,](Q^2, Q^2)$

Y.Liang et al., PRC 73 (2006) 065201
(JLab)



Generalized Baldin Sum Rule on the proton in VVCS and (α+β) in VCS



Perspectives

★ **Performant machines:**
MAMI (1.5 GeV) / JLab (e)
HIGS (γ) spin polarizabilities
*** * * Polarization degrees of freedom: beam, target, recoil**

★ **Ongoing theoretical activity in the field**
Calculation of VCS observables in covariant ChPT at order p^4 (S.Scherer, N.Gegelia, D.Djukanovic, B.Pasquini)

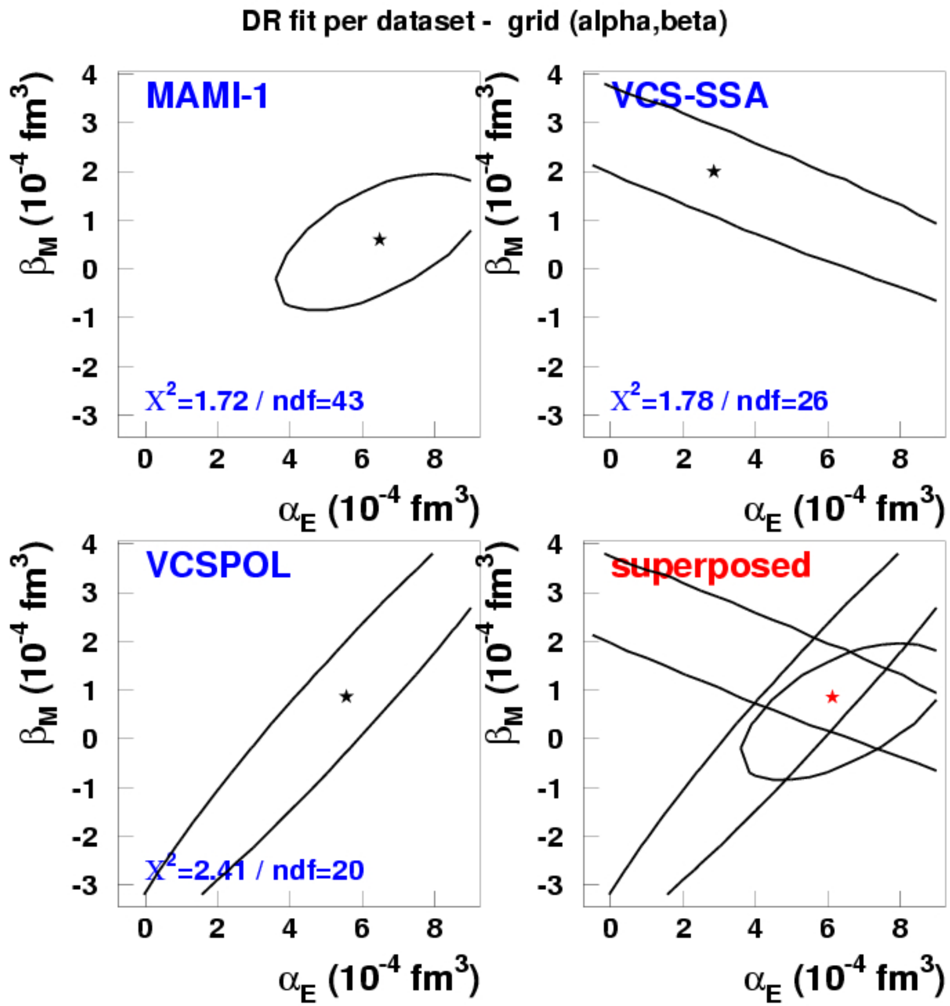
★ **GPs = new physics observables**
Can be measured more extensively at low Q^2
Must work out more precise measurements
GPs sensitive to the pion cloud and to the nucleon resonance spectrum.

Learn more about nucleon structure …

New global DR fit at $Q^2 = 0.33\ GeV^2$

- All photon electroproduction cross sections (3 data sets)

-Fit the 2 free parameters of the model by comparison to exp. data (χ^2 minimization).
-Contour plots at $\chi^2_{min} + 1$.



- combined →

$\alpha_E = (\ 6.1\ \pm 2.2 \pm 1.0)\ 10^{-4}\ fm^3$

$\beta_M = (\ 0.8\ \pm 1.1 \pm 0.5)\ 10^{-4}\ fm^3$

preliminary