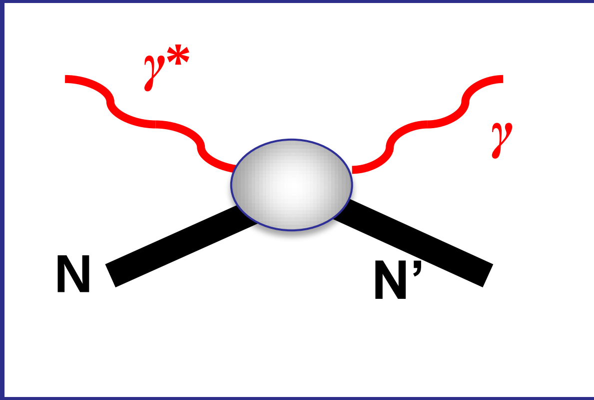
Virtual Compton Scattering on the proton at low energy



MERIEM BENALI

LPC-Clermont-Ferrand

November 09, 2016

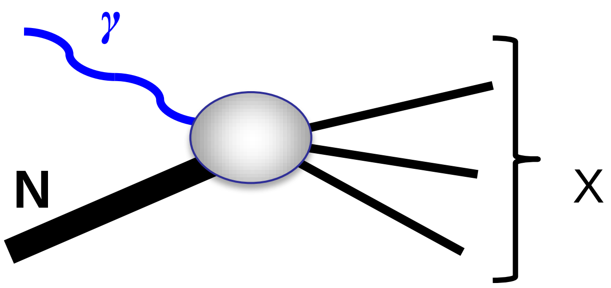
GDR-QCD

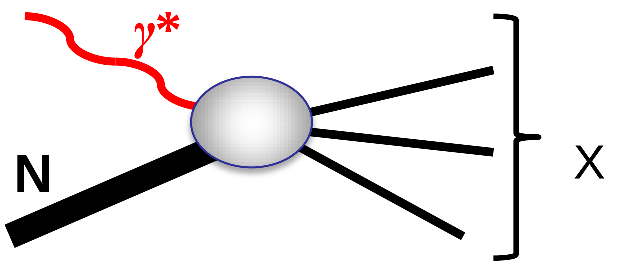
Plan

- **Generalized Polarizabilities (GPs) of the proton**
- **Extraction methods of GPs at Q^2=0.45 GeV^2:**
  - **Low Energy eXpansion approach (LEX)**
  - **Dispersion Relations model (DR)**
- **Conclusion**
- **VCS perspectives**

Why use EM probes?

- Powerful tool to study the internal structure of the nucleon
- An elementary and understood probe (QED)





Real Photon

Momentum = energy

$$(q = \nu)$$

Photon is massless

$$Q^2 = |q|^2 - \nu^2 = 0$$

Virtual Photon

Non-zero and negative squared mass

$$(q \neq \nu)$$

Virtuality $Q^2 = -\underline{q}^2 \neq 0$

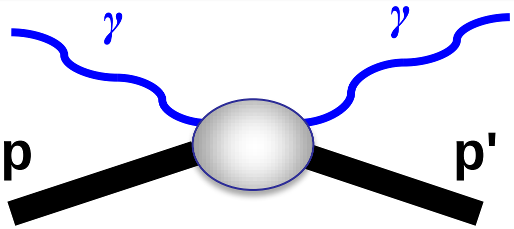
=

momentum transfer to the nucleon

=

Resolution of the probe $\lambda = 1/\sqrt{Q^2}$

Proton Scalar Polarizabilities



Real **C**ompton **S**cattering : **RCS**

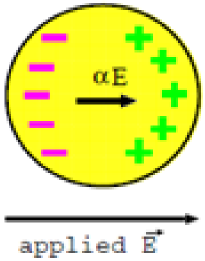
Polarizabilities: measures the response of the proton to an applied electromagnetic field.

Gives access to the electric and magnetic polarizabilities

α_E et β_M at $Q^2=0$ GeV²

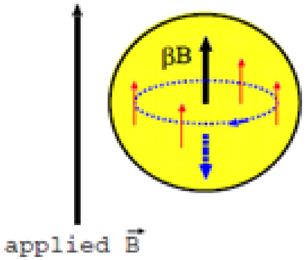
Electric polarizability

$$\vec{d}_E = \alpha_E \vec{E}$$



$\alpha_E = (12.1 \pm 0.3_{stat} \mp 0.4_{syst})\ 10^{-4}\ fm^3$

Magnetic polarizability



$$\vec{d}_M = (\beta_{para} + \beta_{dia})\vec{B} = \beta_M \vec{B}$$

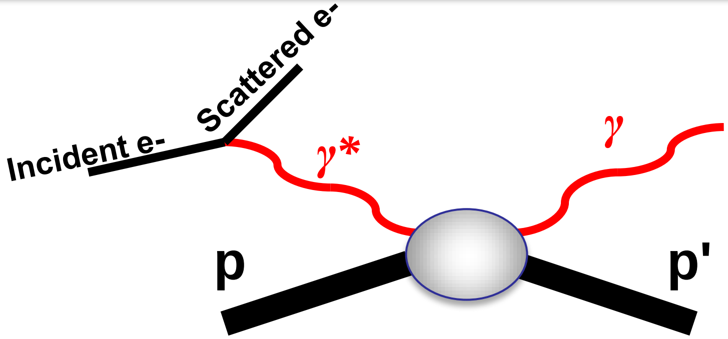
$\beta_M = (1.6 \pm 0.4_{stat} \pm 0.4_{syst})\ 10^{-4}\ fm^3$

(V.Olmos de Leon et al,Eur.Phys. J. A 10 (2001) 207)

✓ α_E and β_M in RCS are the integral of local deformation in différents points in the proton

To probe locally the polarizabilities ⇒ **Virtual Compton Scattering (VCS)**

From RCS to VCS



Virtual **C**ompton **S**cattering : **VCS**

$\gamma^* p \rightarrow \gamma p$

VCS gives access to **Generalized Polarizabilities GPs** **(Q²≠0)** ***α_E (Q²) et β_M (Q²)***

Electric Form Factor G_E

(Fourier transform)

Spatial density of electric charge

Generalized polarizabilities

(Fourier transform)

spatial density of polarization locally inside the deformed proton

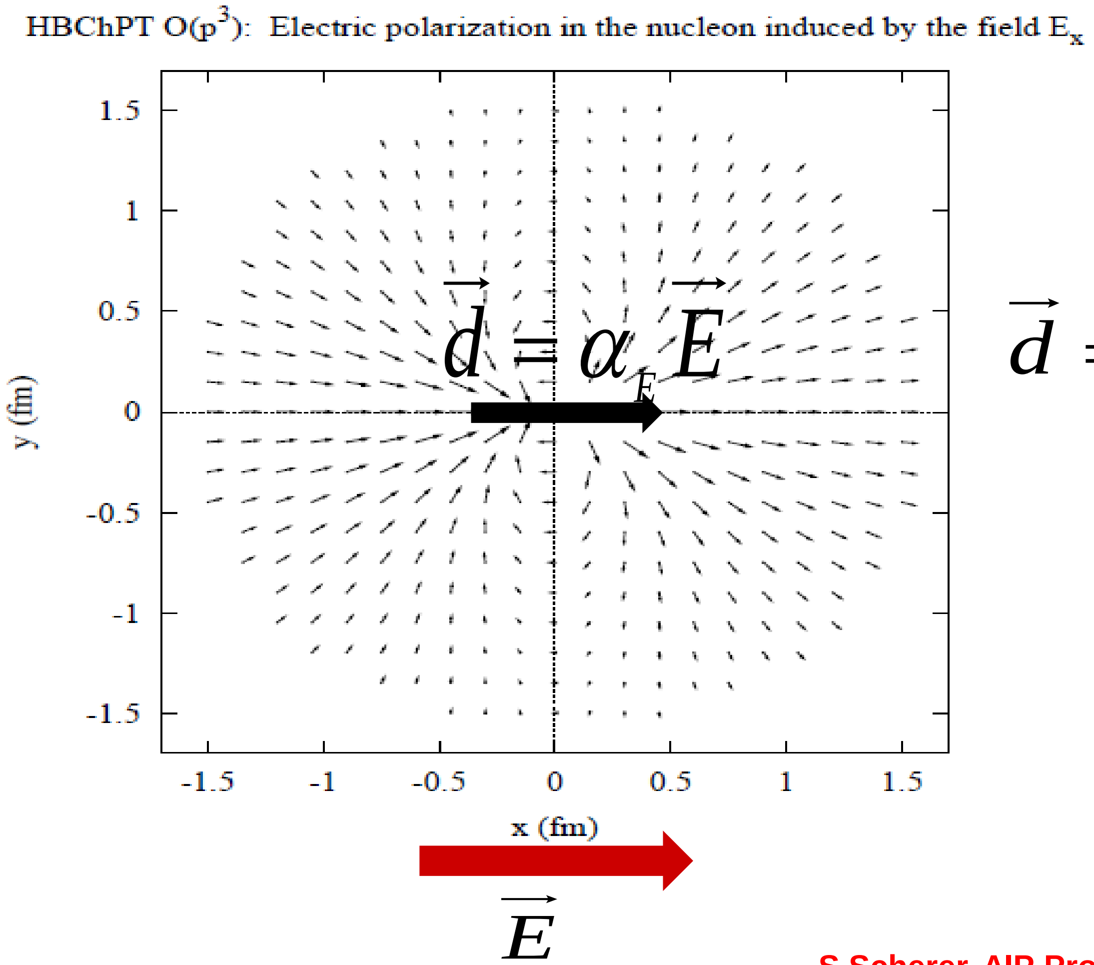
$\alpha_E (Q^2)$ and $\beta_M (Q^2)$ $\xrightarrow{Q^2 \rightarrow 0}$ α_E and β_M in RCS

Generalized Polarizabilities GPs

Theoretical picture obtained in the heavy–baryon chiral perturbation theory :

❖ Mapping the spatial distribution of the deformation (small dipoles) in the proton

❖ Parameterize **the local response** of a proton in an external field.

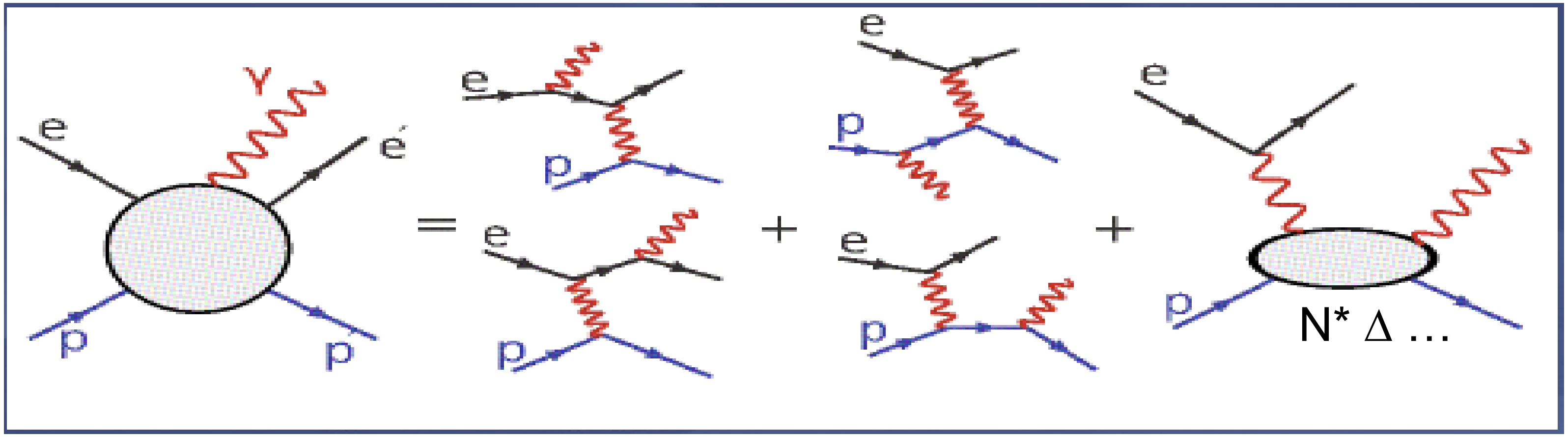


$$\vec{d} = \sum_i \vec{d}_i = \sum_i \alpha_i \vec{E}$$

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

Measurement Methods

The VCS amplitude is a coherent sum of the Bethe-Heitler, Born and Non-Born contributions:



Bethe-Heitler **VCS Born** **VCS Non-Born**

Known term
and
Calculated with elastic form factor

Unknown term
and
At low energy **parametrized by Generalized Polarisabilities GPs**

Measurement Methods

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

Low Energy Theorem (LEX)
Extract the GPs in a model-independent way
P.Guichon et al, NPA 591 (1995) 606

Dispersion Relations model (DR)
Model-dependent approach
B.Pasquini et al, EPJA 11 (2001) 185

Structure functions
(linear combinations of GPs)

Structure functions
(linear combinations of GPs)

Need to fix the spin-flip GPs

Scalar GPs of the proton electric α_E (Q^2) and magnetic β_M (Q^2)

Measurement Methods

1- Low Energy Theorem (LEX)

❖ Unpolarized cross section below threshold pion production:

expansion in powers of q'

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

new information on the structure of the proton

negligible term at low q'

- q' = momentum of real photon

{P.A.M. Guichon et al. Nucl. Phys. (1995)}

❖ 2 structure functions (linear combinations of GPs) :

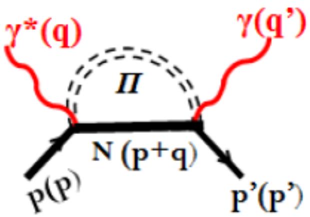
$$P_{LL} - \frac{P_{TT}}{\in} = (\ldots) \times \alpha_E(Q^2) + [\text{Spin flip GPs}]$$

$$P_{LT} = -(\ldots) \times \beta_M(Q^2) + [\text{Spin flip GPs}]$$

❖ For extraction of the scalar GPs, α_E (Q^2) and β_M (Q^2), spin-flip GPs need to be fixed using some theoretical model (example: **using DR Model**)

Measurement Methods

2- Dispersion Relations Model (DR)



❖ VCS amplitude is computed through dispersion integrals calculations by using MAID model for pion production by real or virtual photon

$$d\sigma(ep \to e'p'\gamma) = d\sigma(BH + Born) + [\dots]$$

{B. Pasquini et al. EPJA 11 (2001) 185.}

includes all orders in q'

Advantages of DR model :

- ✓ **Model is valid over a wide range in Q^2**
- ✓ **The calculation is valid above the pion production threshold**
- ✓ **Spin GPs are fixed by Dispersion Relations**

- ✓ **$\alpha_E(Q^2)$ and $\beta_M(Q^2)$ are directly parametrized by 2 free parameters Λ_α and Λ_β**

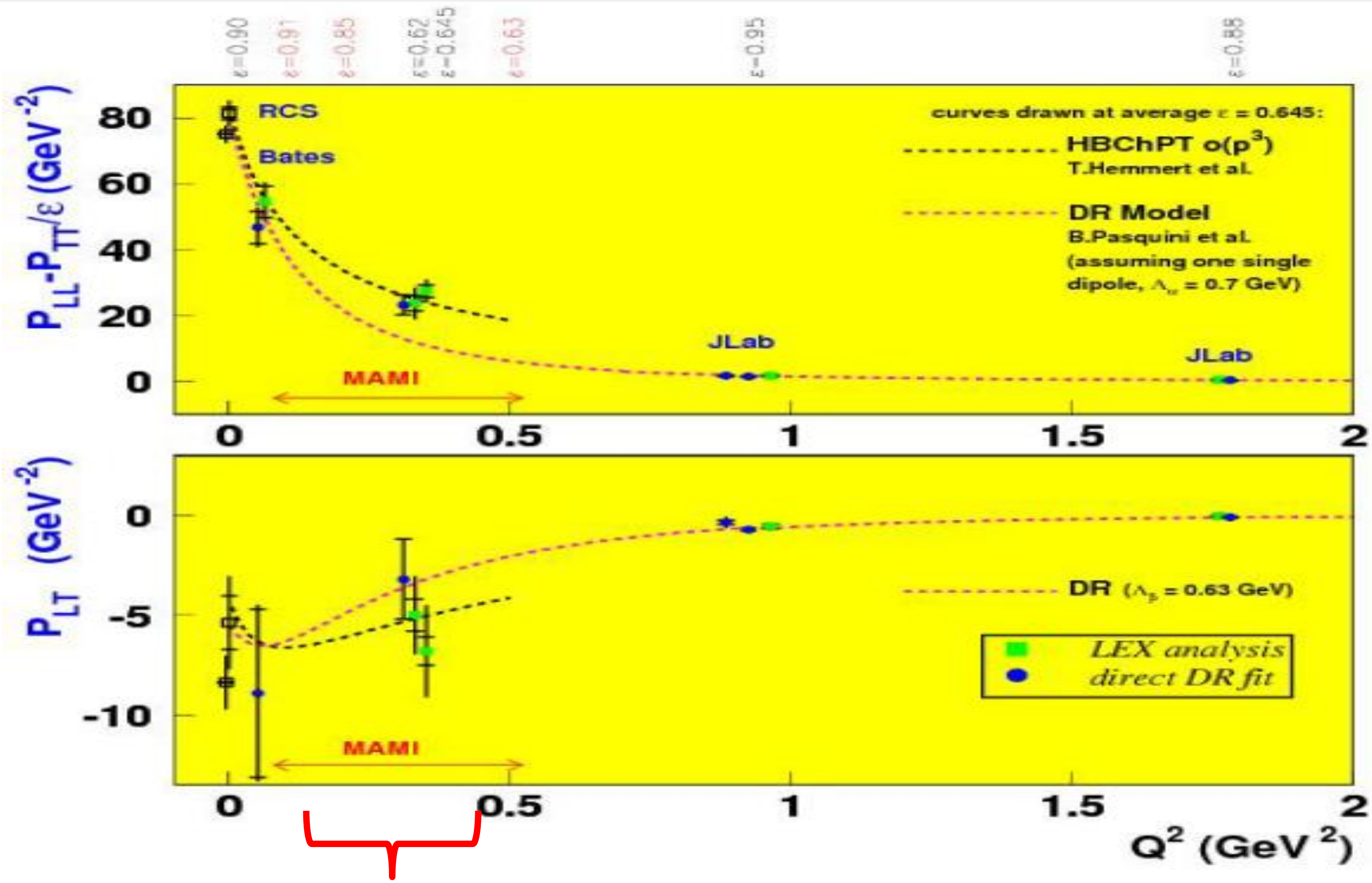
$$\alpha_E(Q^2) = \alpha_E^{\pi N}(Q^2) + \frac{(\alpha_E^{\exp} - \alpha_E^{\pi N})_{Q^2=0}}{\left(1 + \frac{Q^2}{\Lambda_\alpha^2}\right)^2}$$

Asymptotic part unconstrained by DR

$$\beta_M(Q^2) = \beta_M^{\pi N}(Q^2) + \frac{(\beta_M^{\exp} - \beta_M^{\pi N})_{Q^2=0}}{\left(1 + \frac{Q^2}{\Lambda_\beta^2}\right)^2}$$

Λ_α et Λ_β obtained by adjusting the $d^5\sigma^{exp}$ by $d^5\sigma^{DR}$ (predicted by the DR model)

World data on the VCS Structure Functions

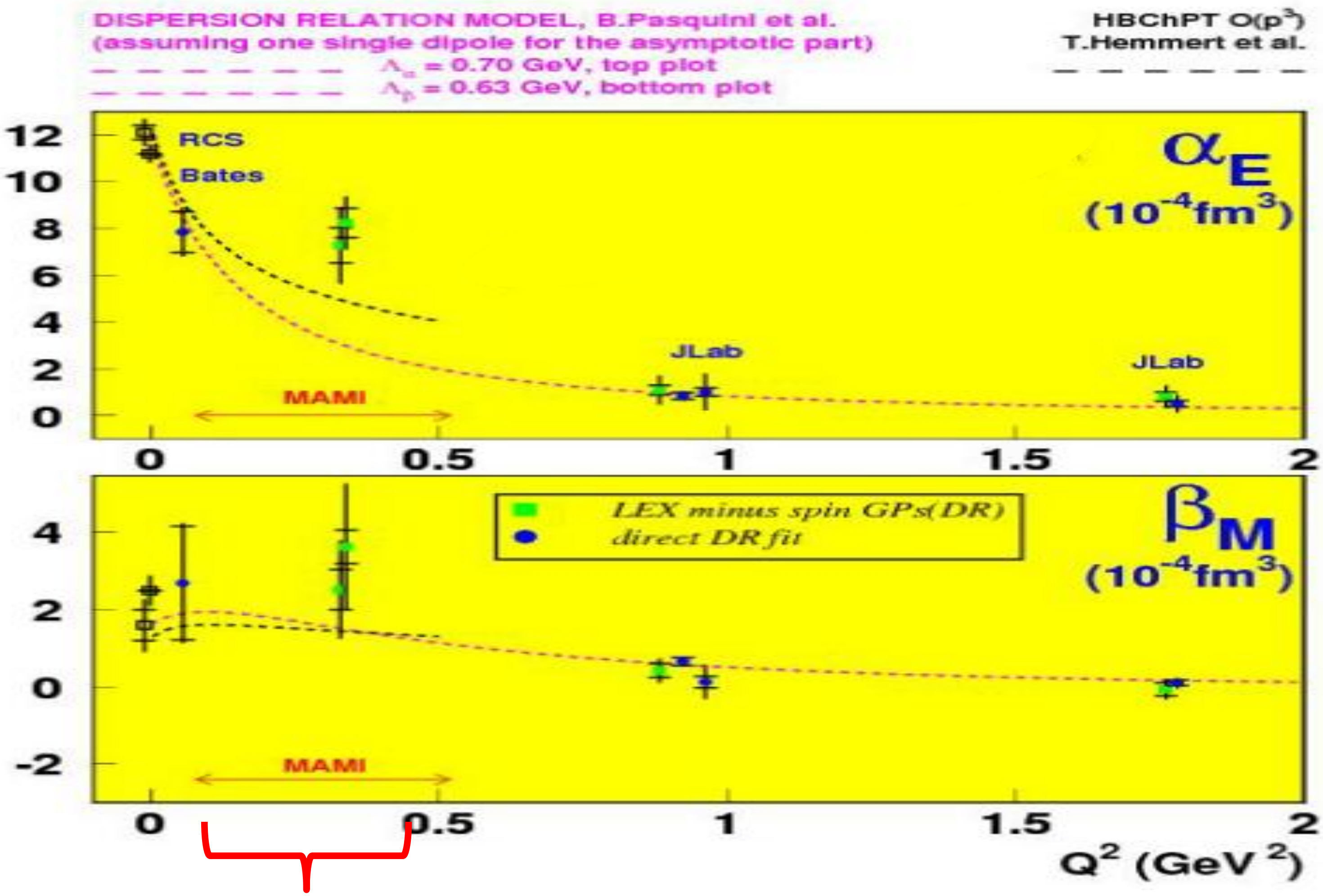


VCS experiment at MAMI-A1 (VCSq2)

3 new values of $Q^2 = 0.1$, 0.2 , 0.45 GeV²

(Figures constructed by H. FONVIEILLE)

World data on the VCS GPs



VCS experiment at MAMI-A1 (VCSq2)

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

(Figures constructed by H. FONVIEILLE)

Goal

Goal of VCSq2 experiment:

Measure the GPs of the proton at Q^2=0.1, 0.2 and 0.45 GeV^2 below pion threshold

My thesis Goal (at Q^2=0.45 GeV^2)

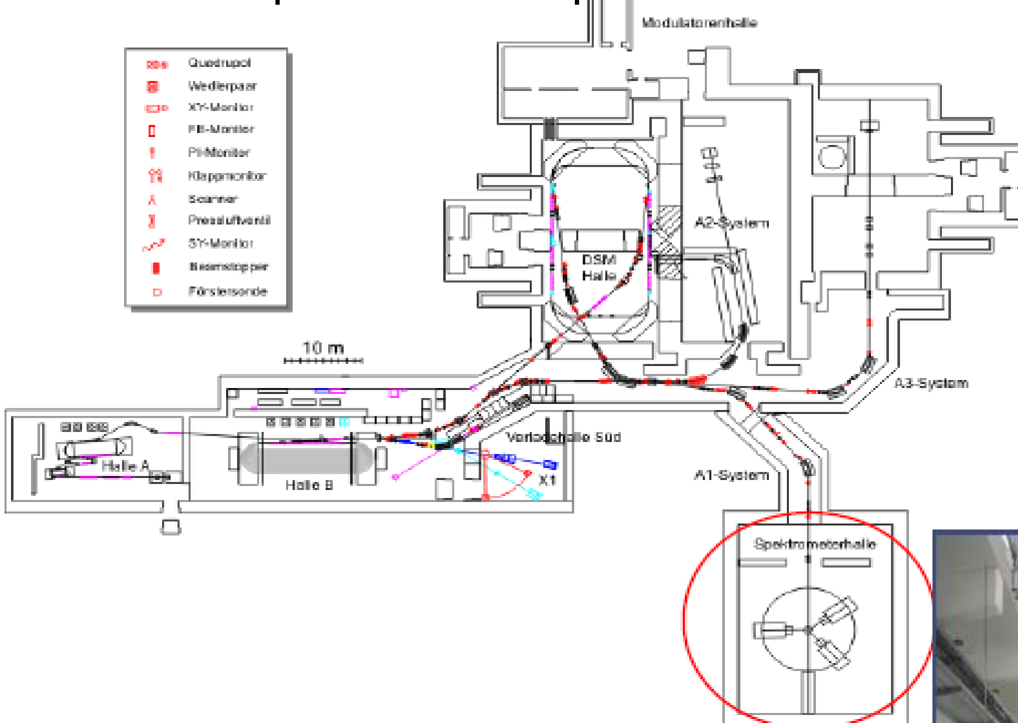
❖ Measure the 2 structure functions (using LEX approach and DR model):

$(P_{LL}-P_{TT}/\epsilon)$ and P_{LT}

❖ Measure the electric α_E (Q^2) and magnetic β_M (Q^2) **GPs**

Experimental Facility

The VCS experiment was performed at MAMI-A1 from 2011 to 2015



Mainz Microtron MAMI

❖Electron accelerator

- ✓ Polarized electron source
- ✓ Linac
- ✓ 4 microtrons
- ✓ Emax=1.6 GeV
- ✓ Imax=100 µA

❖ 4 experimentals Halls (A1 electron scattering, A2 tagged photons, A4 parity violation, X1 X-rays)

Hall A1 (3 spectrometers setup)

We used 2 Spectrometers A and B

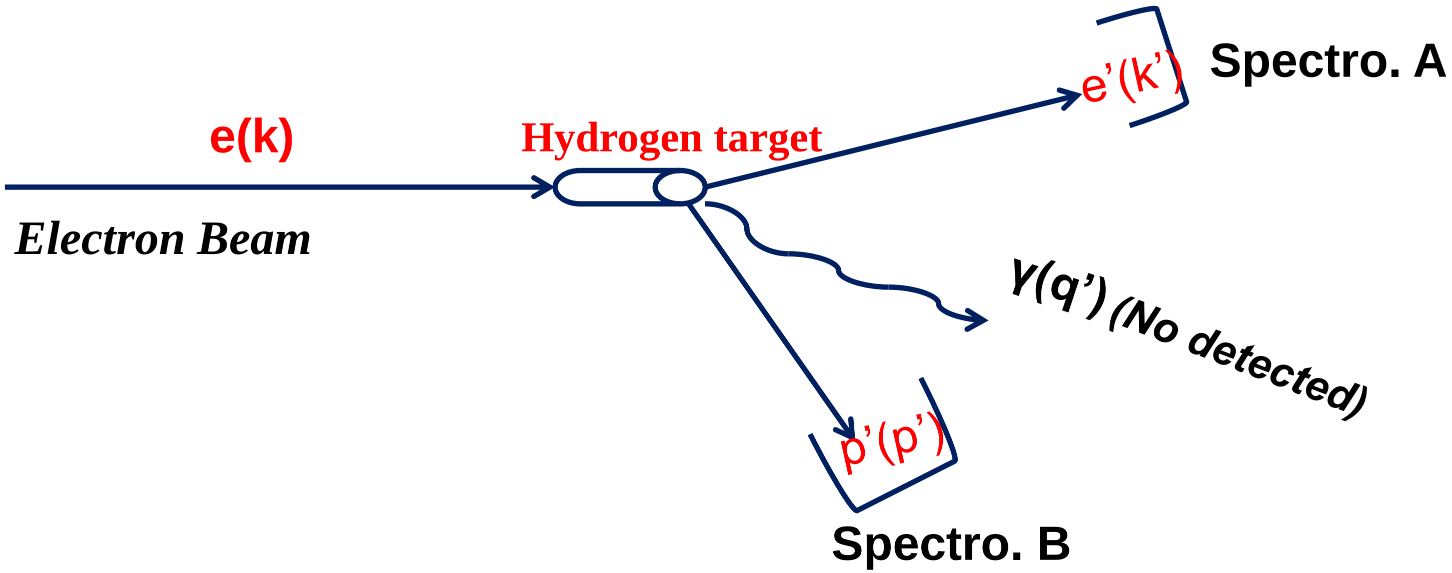
- ✓ momentum resolution ≤ 10 -4
- ✓ Angular resolution ≤ 3 mrad

Composed by

- ✓ 4 VDC planes
- ✓ 2 scintillators planes
- ✓ Cerenkov detector

Hall A1

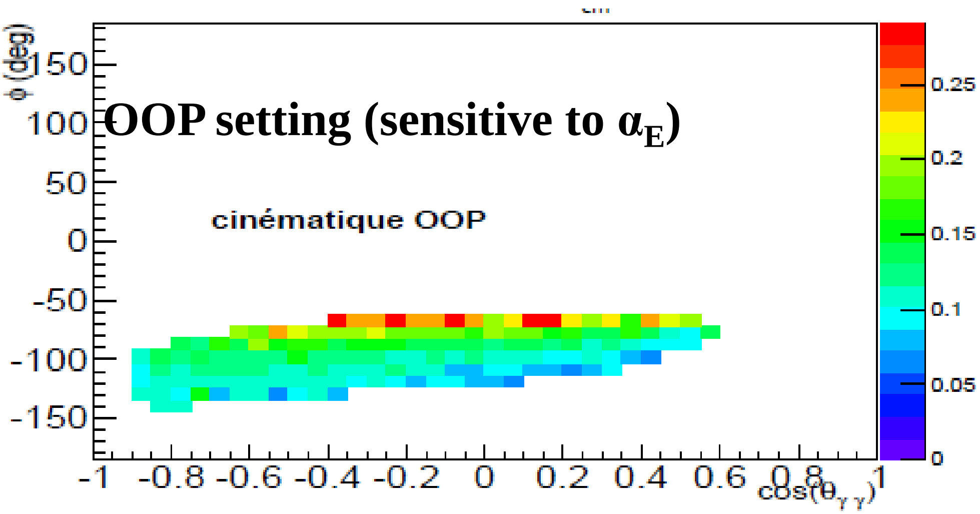
- In our experiment we detect the scattered electron in spectrometer B and the recoil proton in spectrometer A
- The emitted real photon is signed by a zero missing mass:

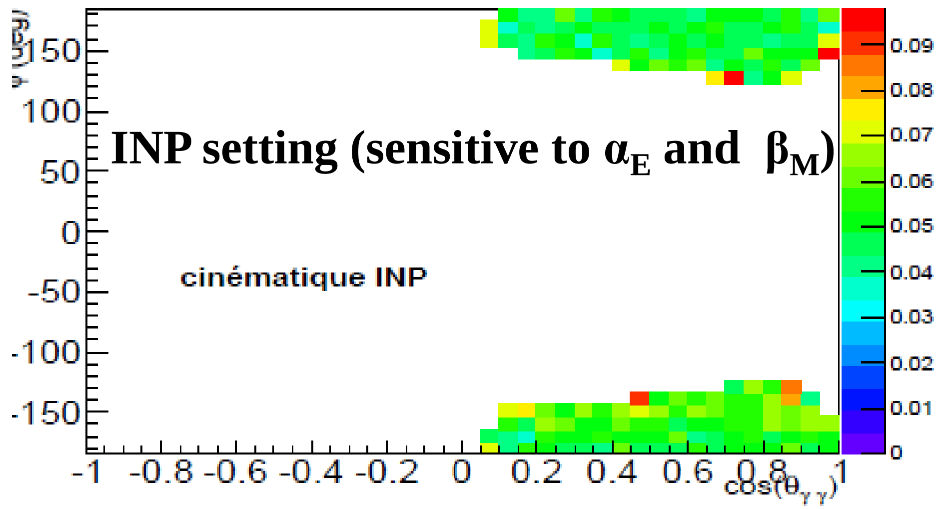


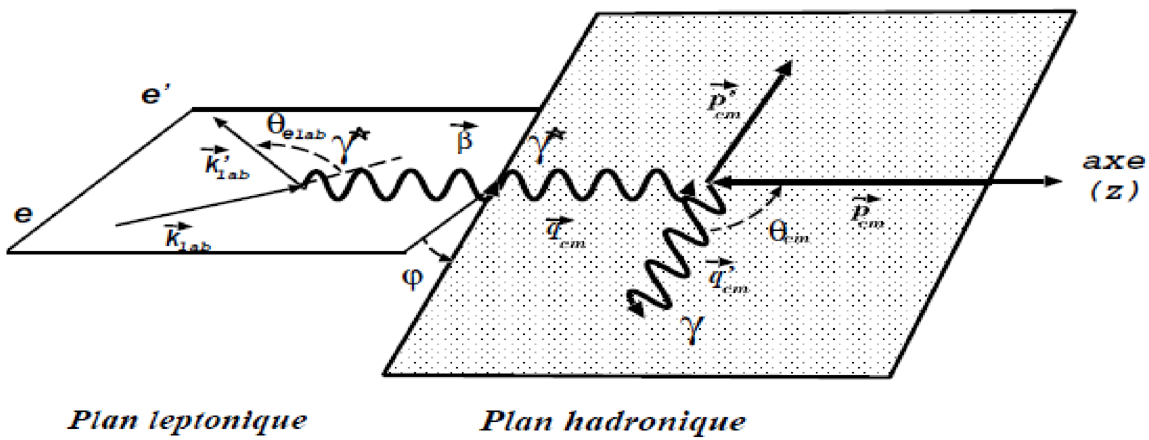
- ✓ Beam energy ≈ 1GeV .
- ✓ Q^2=0.45 GeV^2
- ✓ q'_{cm}= 0.104 GeV

Kinematics of the experiment

Our analyzed data are a combination out-of-Plane and In-Plane data, covering two different angular regions in (φ, cos (θ))







Kinematics of the experiment

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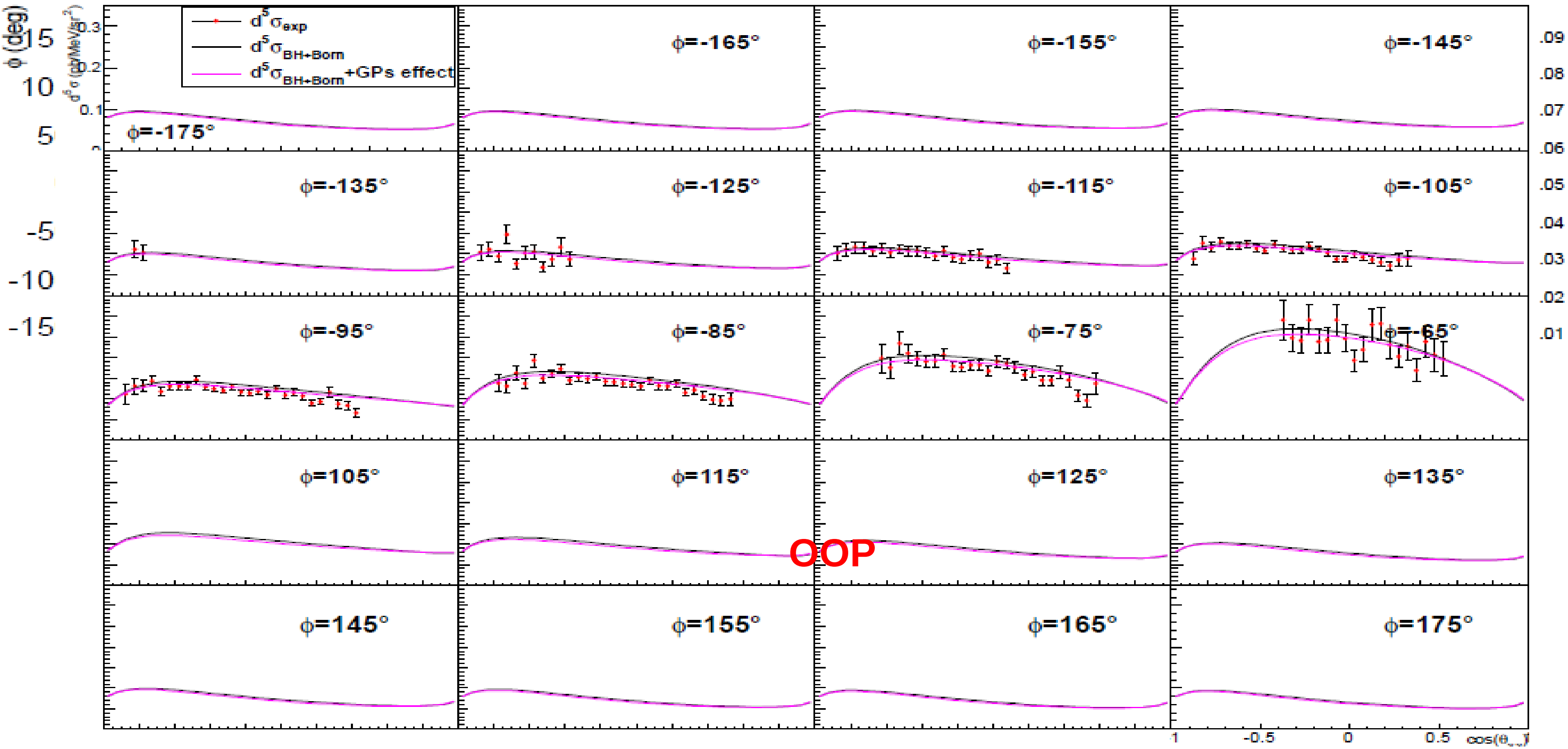
σ(exp) σ(BH+Born) : No GPs effect σ(BH+Born+GPs effect)



We measure the small deviation between σ(BH+Born) and σ(BH+Born+GPs) in order to extract the GPs

Kinematics of the experiment

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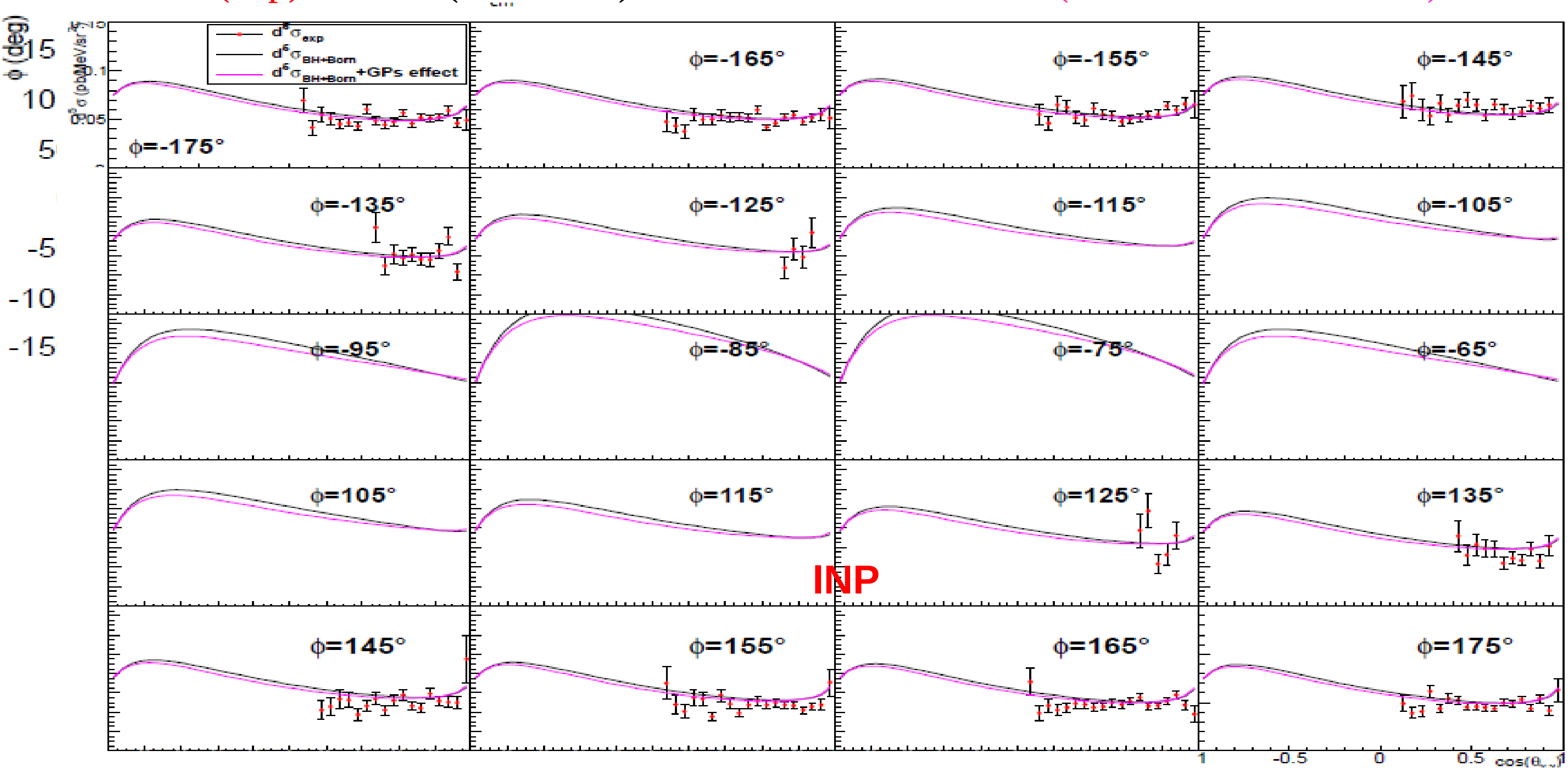


We measure the small deviation between σ(BH+Born) and σ(BH+Born+GPs) in order to extract the GPs

Fit of structure functions – LEX

LEX cross section: $$\sigma^{LEX} = \sigma(BH + Born) + \Phi q' \Psi_0 + O(q'^2)$$

$$\Psi_0 = v_{LL}\left(P_{LL} - \frac{P_{TT}}{\varepsilon}\right) + v_{LT} P_{LT}$$

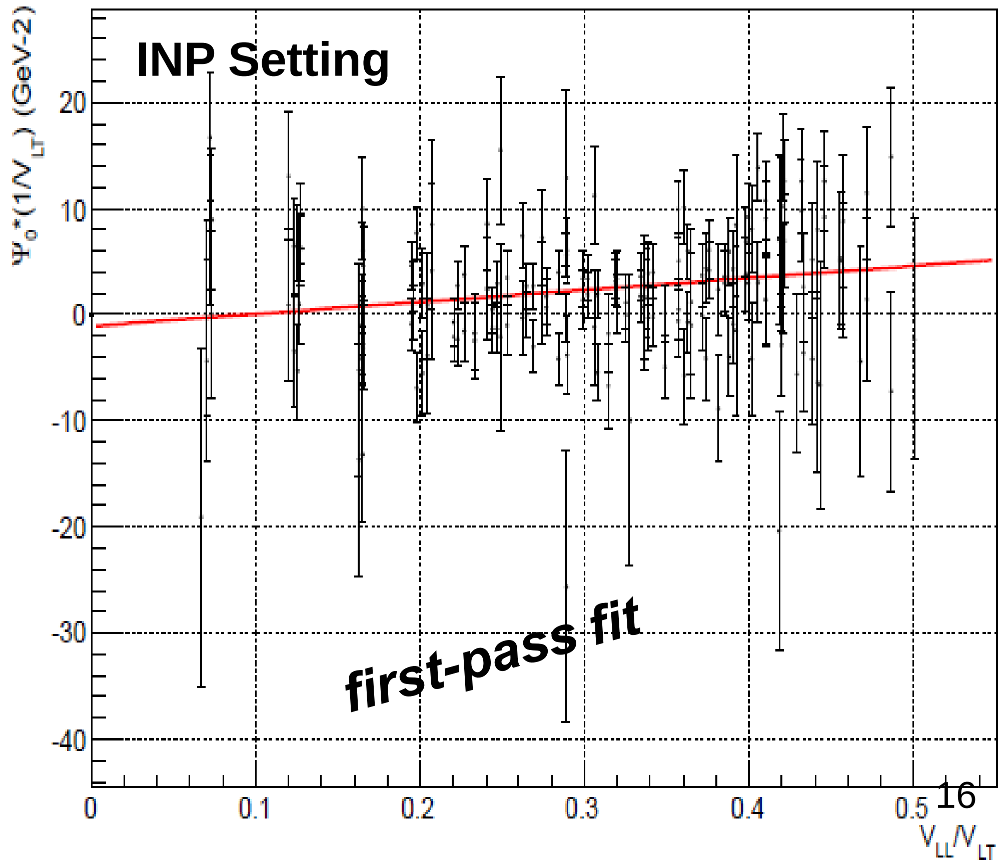
Adjustment : $$\chi^2 = \sum_i \left[\frac{\sigma_i^{exp} - \sigma_i^{LEX}}{\Delta\sigma_i^{exp}}\right]^2$$

At low q' :

$$\frac{\Psi_0}{v_{LT}} = \frac{\sigma^{exp} - \sigma(BH + Born)}{\Phi q' v_{LT}}$$

$$= \frac{v_{LL}}{v_{LT}} \left(P_{LL} - \frac{P_{TT}}{\varepsilon}\right) + P_{LT}$$

slope — intercept



Normalization step

Interest: At low *q'(**37.5 MeV/c** in our case)* the experimental cross section is dominated by the (BH+Born) cross section :

$$\sigma^{LEX} = \sigma^{BH+B} + q'[\ldots] \quad \xrightarrow{\text{Low energy theoreme}} \quad \begin{cases} q' \to 0 \\ \sigma^{exp} \to \sigma^{BH+B} \end{cases}$$

- ***GPs effect at low q' ~ 1 %***
- ***Renormalize the σ^{exp} on σ^{LEX} at low q' (χ^2 minimization)***
- ***Renormalization is* Form factors depends**

$(P_{LL} - P_{TT}/\epsilon)$ (GeV^{-2})

Form factors	Fnorm	before normalisation	After normalisation
Bernauer Phys.Rev.Lett. 105:242001, 2010	1.052	15.29 ± 0.96	7.39 ± 1.02
F-Walcher Eur.Phys, J.A17 :607 2003	1.026	10.62 ± 0.96	6.88 ± 0.98
Arrington Phys.Rev.C76:035205, 2007	1.032	11.80 ± 0.96	7.14 ± 1.00

Result fit LEX

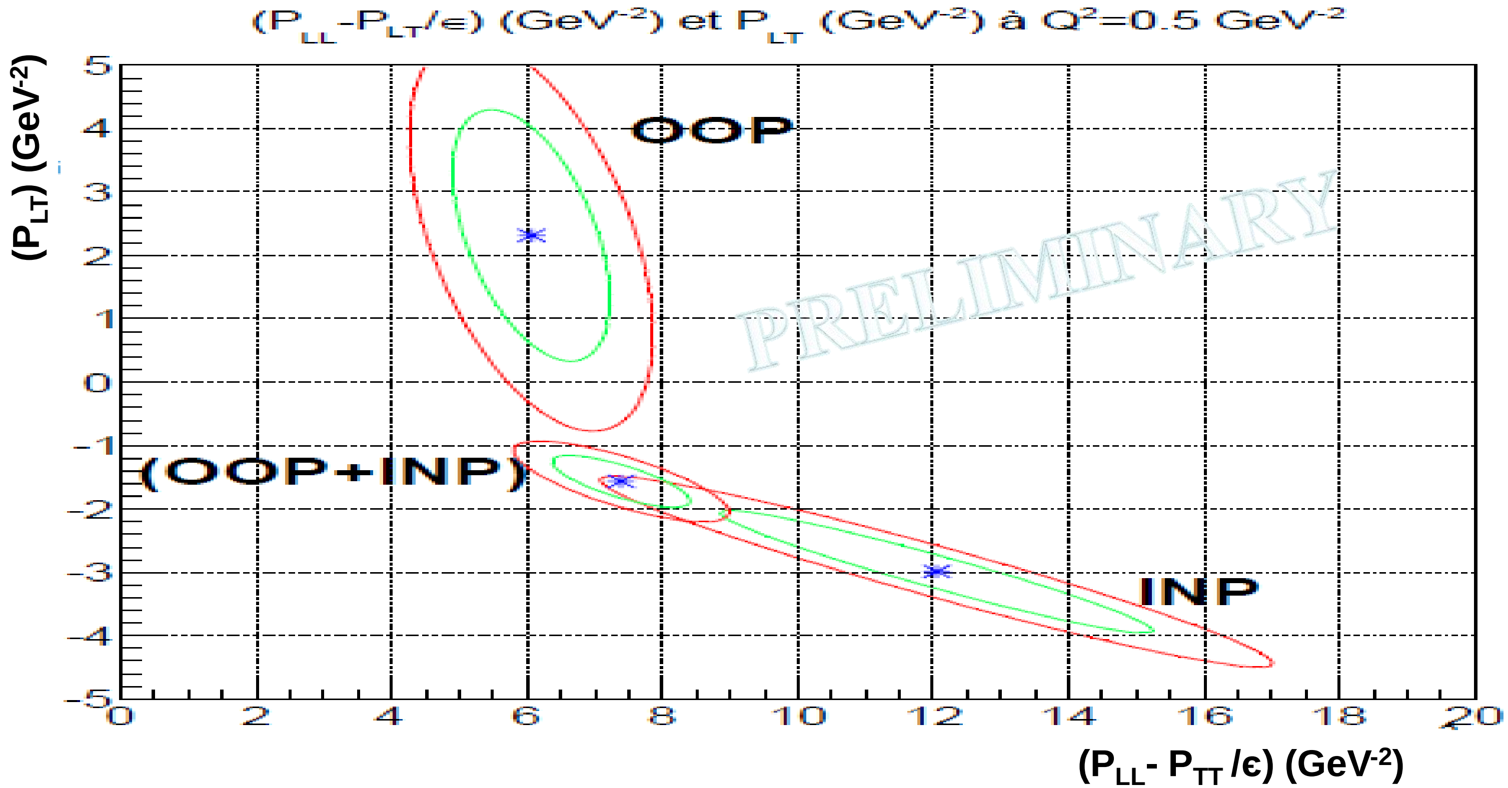
Preliminary results of structure functions extracted with LEX approach,

(The systematic error is obtained from 2% overall error on the cross section)

P_{LL}-P_{TT}/ϵ = 7.39 (±1.02)$_{stat}$ (±2.52)$_{syst}$ GeV^{-2}

P_{LT} = -1.56 (±0.41)$_{stat}$ (±0.04)$_{syst}$ GeV^{-2}

$X^2_{reduced}$ = 1.35



Generalized polarizabilities fit – DR

Method:

$$\chi^2_{DR} = \sum_i \left[\frac{\sigma_i^{exp} - \sigma_i^{DR}(\alpha_E, \beta_M)}{\Delta\sigma_i^{exp}}\right]^2$$

Unlike χ^2_{LEX}, the χ^2_{DR} is not linear with α_E et β_M

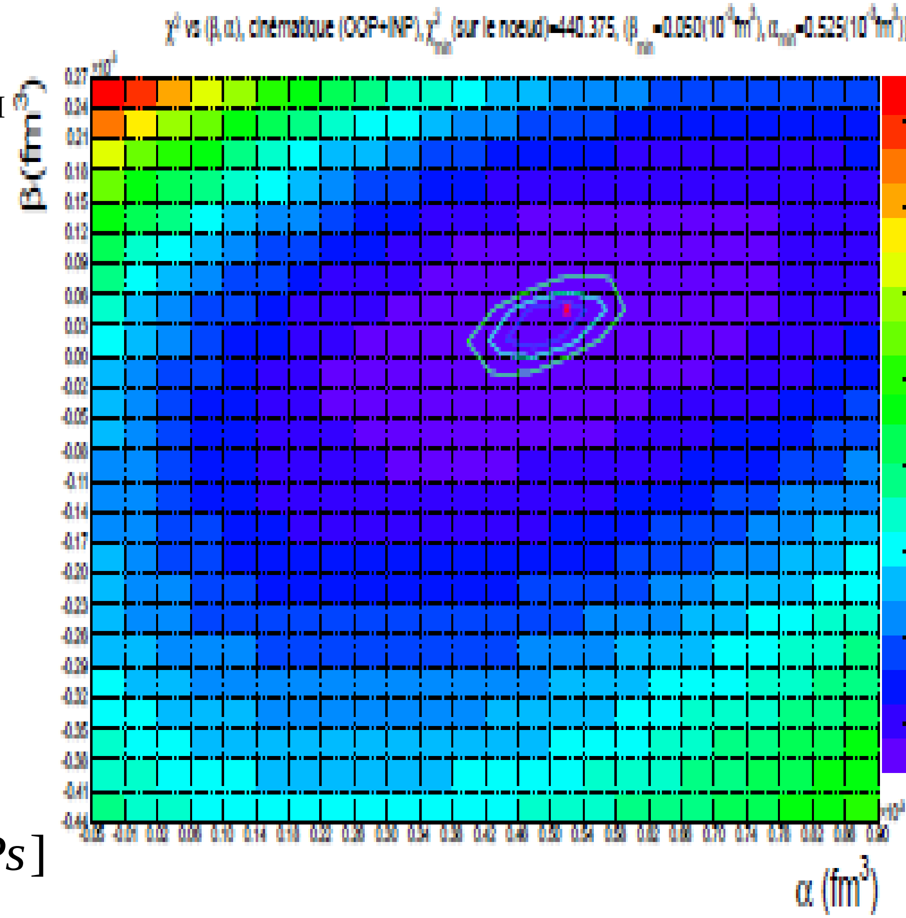
- Construct a grid in the plan (α_E, β_M)
- Calculate χ^2 for each bin

Find the χ^2_{min} using paraboloid fit

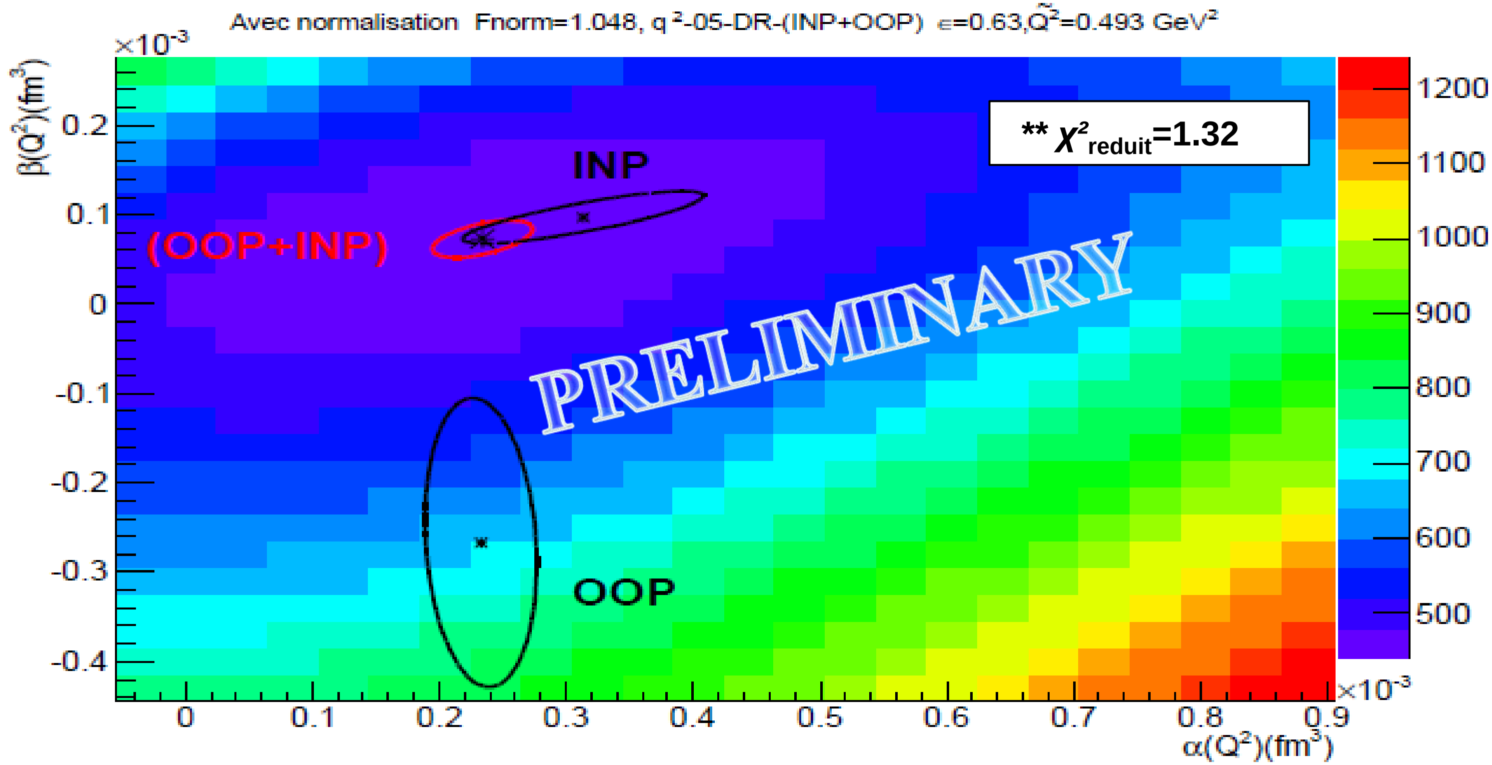
Optimal values of α_E and β_M

$$P_{LL} - \frac{P_{TT}}{\epsilon} = (\ldots) \times \alpha_E(Q^2) + [Spin\_flip\_GPs]$$

$$P_{LT} = -(\ldots) \times \beta_M(Q^2) + [Spin\_flip\_GPs]$$



Generalized polarizabilities fit – DR

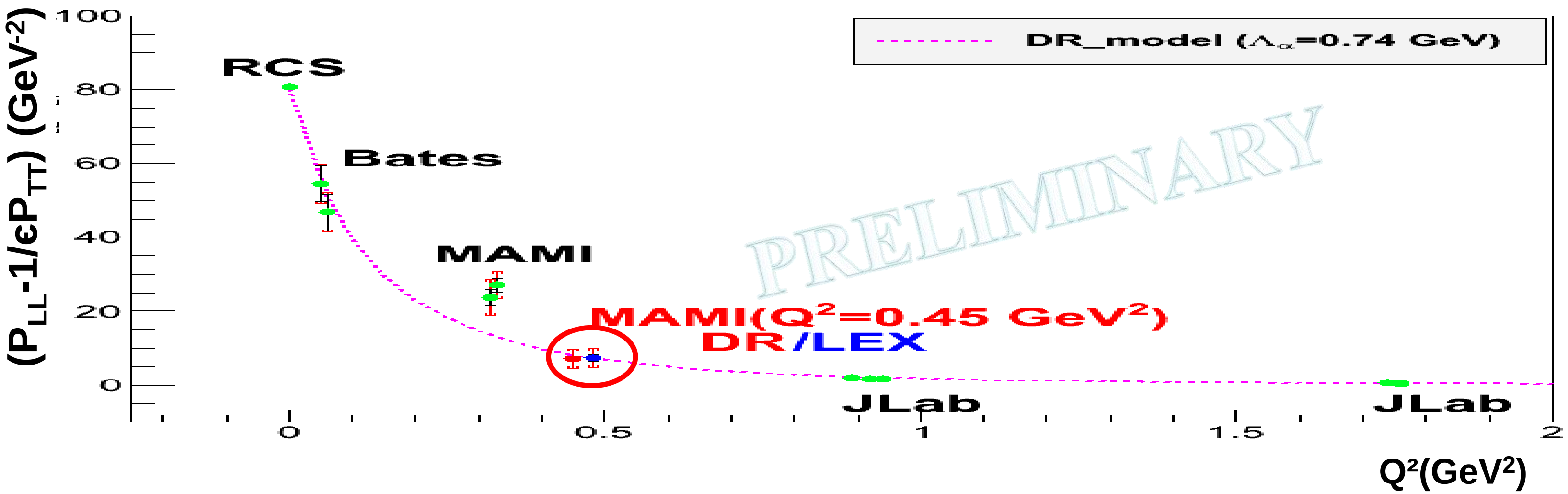


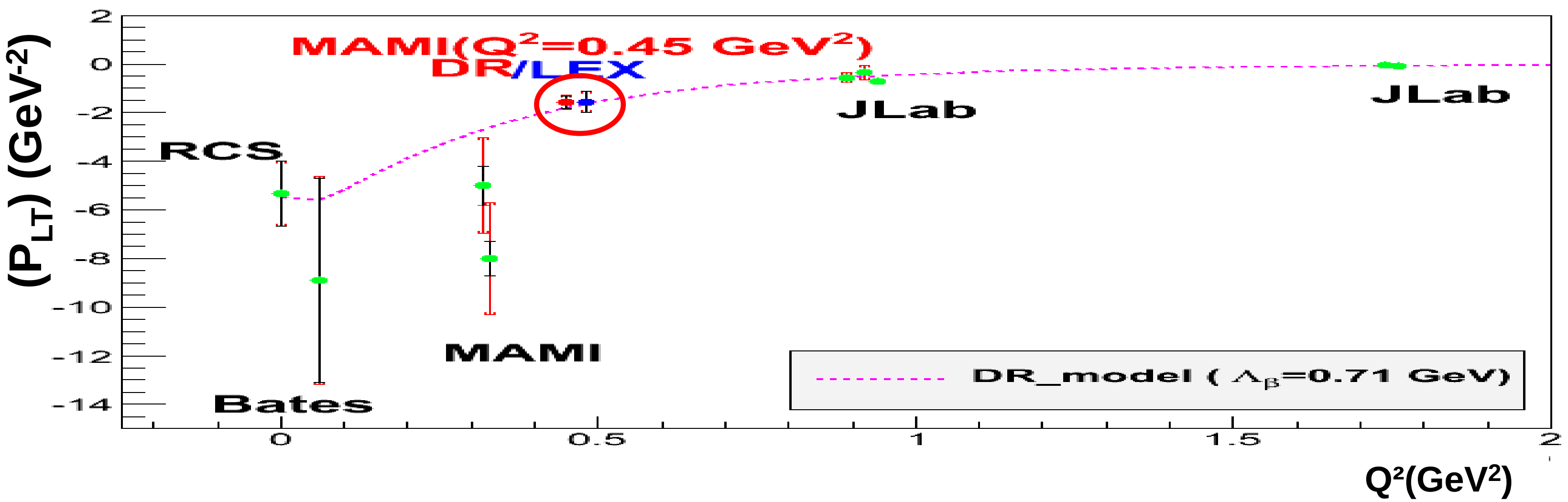
- Contour at (χ^2_{min}+1) , 70% probability that each parameter is inside separately
- Systematic errors obtained from ±2% normalization error on the cross section.

$\Lambda\alpha$ (GeV)	0.74 $(\pm 0.06)_{stat}$ $(\pm 0.16)_{syst}$
$\Lambda\beta$ (GeV)	0.71 $(\pm 0.04)_{stat}$ $(\pm 0.02)_{syst}$
$\alpha_E(10^{-4}\ fm^3)$	2.34 $(\pm 0.40)_{stat}$ $(\pm 1.07)_{syst}$
$\beta_M(10^{-4}\ fm^3)$	0.73 $(\pm 0.20)_{stat}$ $(\pm 0.13)_{syst}$
$P_{LL}-P_{TT}/\epsilon(GeV^{-2})$	7.08 $(\pm 0.90)_{stat}$ $(\pm 2.40)_{syst}$
$P_{LT}(GeV^{-2})$	-1.58 $(\pm 0.25)_{stat}$ $(\pm 0.16)_{syst}$

LEX and DR comparaison

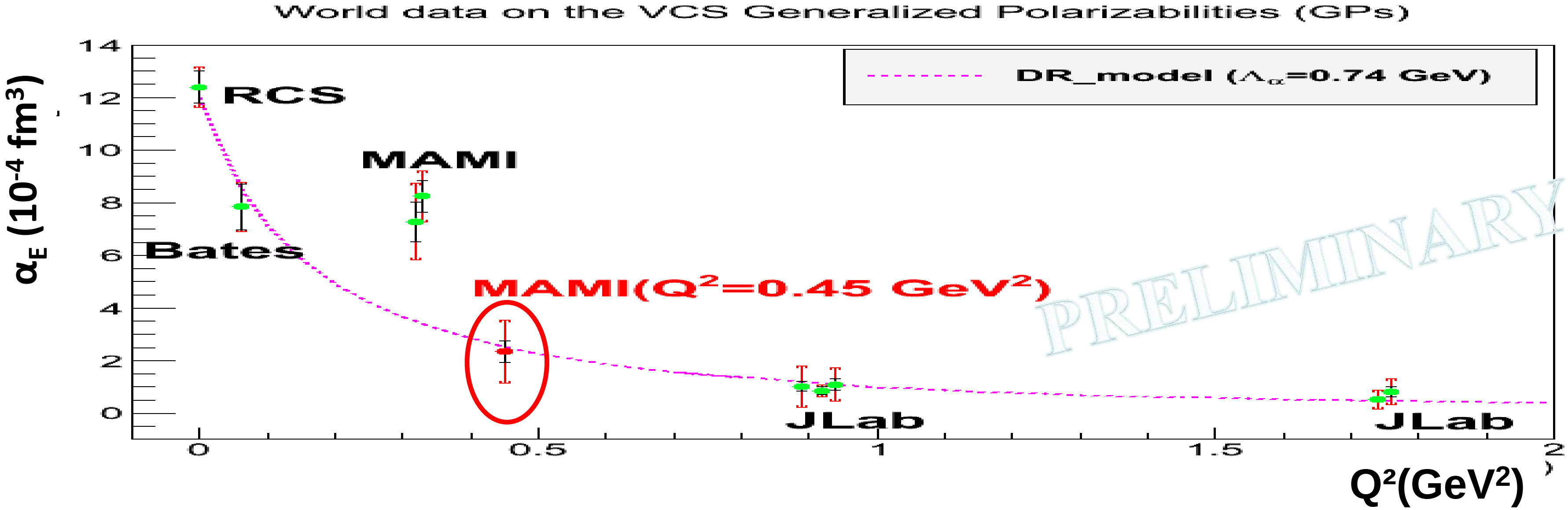
- **A good agreement between the LEX and DR Fit at Q^2=0.45 GeV²**

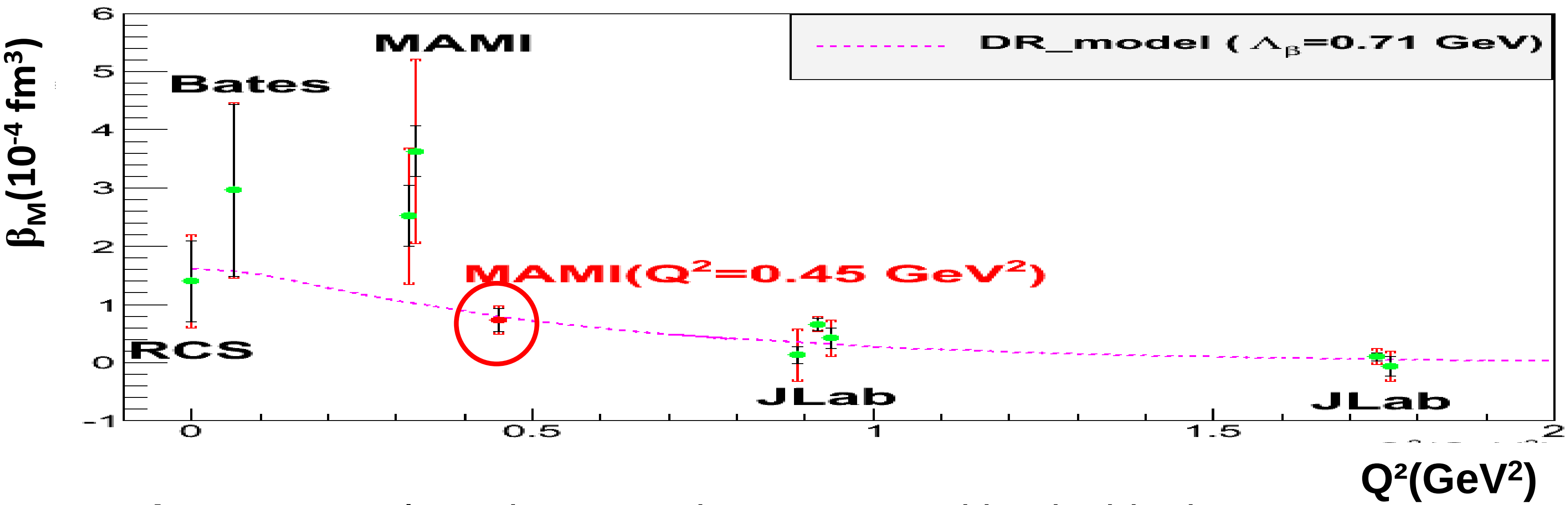




DR model does NOT predict the structure functions, the " DR curve" includes another assumption: fixing the two free parameters to a constant, independently of Q^2

GPs DR extraction at Q^2=0.45 GeV^2



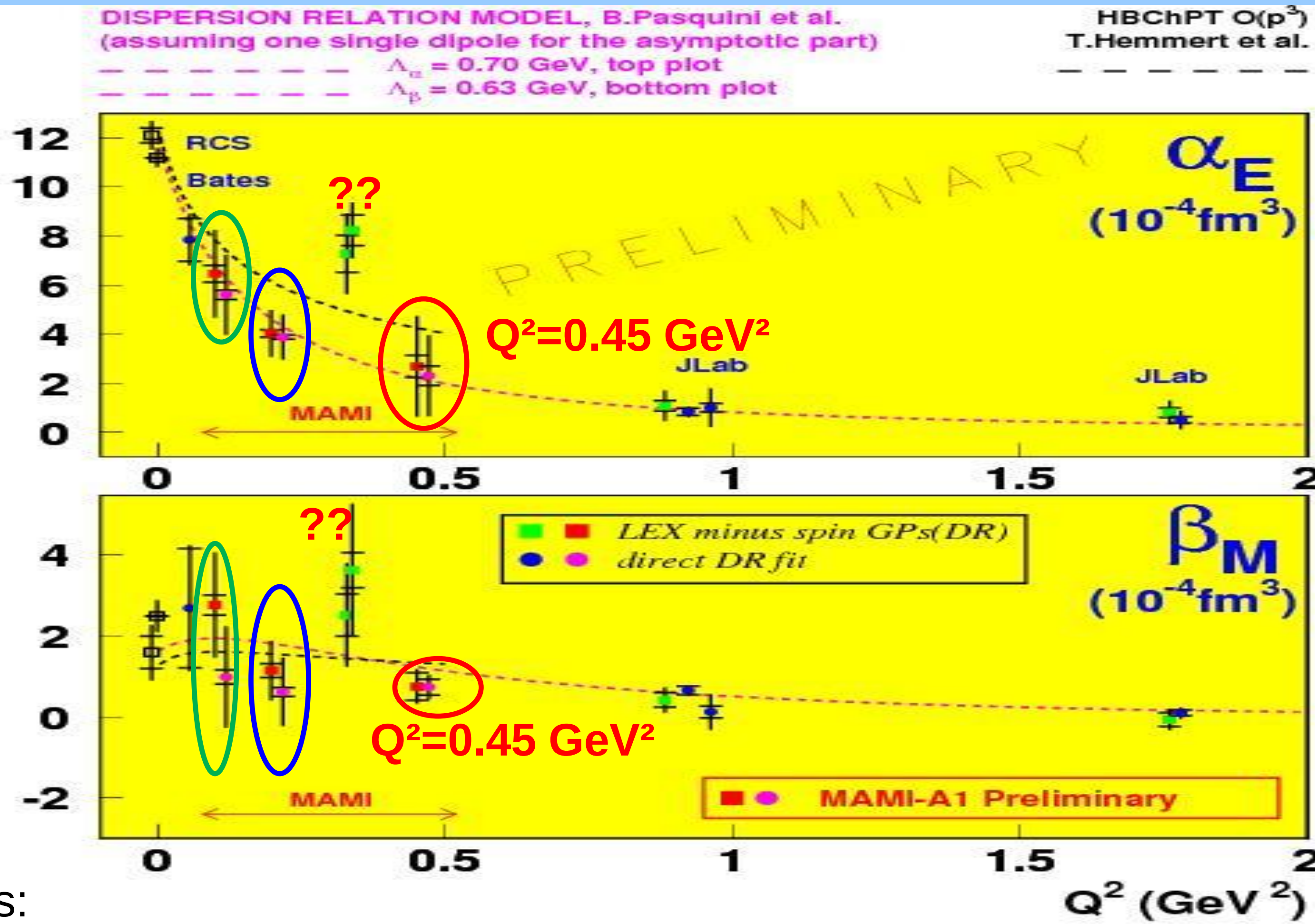


→ More complete picture on the GPs repartition inside the proton

Conclusion

- **Fit of the electric (α_E) and magnetic (β_M) Generalised Polarizabilities at (Q^2=0.45GeV^2) via the Dispersion Relations model and deduce the structure functions values P_{LL}- P_{TT} /ϵ and P_{LT}.**
- **Extracting the same two structure functions via LEX approach**
  - **A good agreement between the results of the two extractions**
  - **New constraint on nucleon structure at low energy**

GPs from the VCSq2 MAMI experiment at Q^2=0.1, 0.2 and 0.45 GeV^2



GPs:

at Q^2=0.1 GeV^2, J.Bericic, PhD student, Ljubljana university, Slovenia

at Q^2=0.2 GeV^2, L.Correa, PhD student (LPC Clermont Ferrand, France)

- Understand the region around Q^2=0.33 GeV^2

Perspectives in VCS

JLab VCS proposal in Hall C to measure the electric (α_E) and magnetic (β_M)

at Q^2 = 0. 3 GeV^2 to 0.75 GeV^2 (**+ one more measurement at Q^2 = 0. 33 GeV^2**):

- Using asymmetry of the (ep → epγ) cross section in the Δ(1232) region
- Using the DR model

N.Sparveris, M.Paolone, A.Camsonne, M.Jones et al (2016)

Measurement of the Generalized Polarizabilities of the Proton in Virtual Compton Scattering

Proposal to Jefferson Lab PAC-44

H. Atac, H. Banjade, A. Blomberg, S. Joosten, Z.E. Meziani,
M. Paolone (spokesperson), N. Sparveris (spokesperson / contact person)
Temple University, Philadelphia, PA, USA

A. Camsonne (spokesperson), J.P. Chen, M. Jones (spokesperson)
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA

. Badman, S. Li, E. Long, K. McCarty, C. Meditz, M. O'Meara, R. Paremuzyan,
S. Santiesteban, P. Solvignon-Slifer, K. Slifer, B. Yale, R. Zielinski
University of New Hampshire, Durham NH, 03824

K. Allada, A. Bernstein, S. Gilad

...

THANK YOU FOR YOUR ATTENTION

Back-up

Normalization step of the $d\sigma^{exp}$ cross section

Interest: At low *q'(37.5 MeV/c in our case)* the experimental cross section is dominated by the (BH+Born) cross section :

$$\sigma^{exp} = \sigma^{BH+B} + q'[\ldots]$$

Low energy theoreme → $\left\{ \begin{array}{l} q' \to 0 \\ \sigma^{exp} \to \sigma^{BH+B} \end{array} \right.$

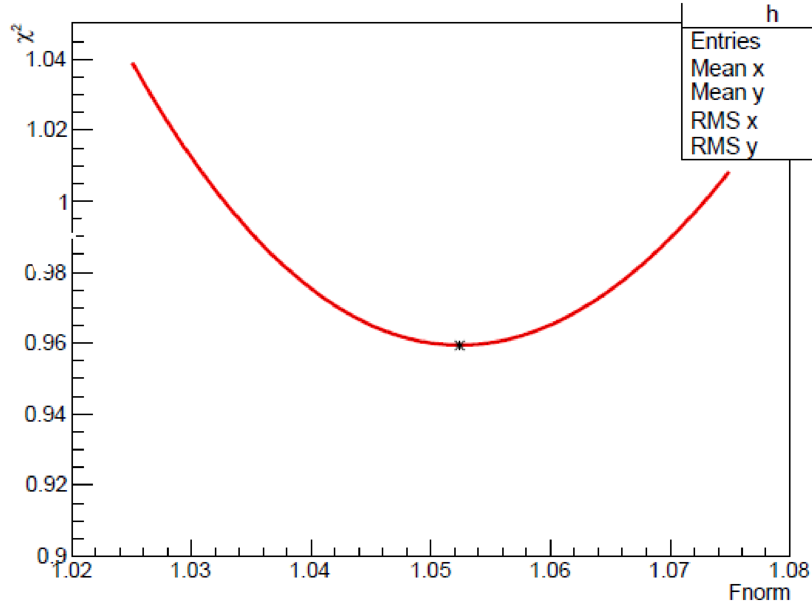
At low q', the GPs effect accounts for about ~ 1.0% (but att high q'=104 MeV/c → GPs effect ~ 6%) of the cross section. Using the value of the structure functions from our first-pass fit → we can basically FIX the term […] and test if our measured cross section needs to be renormalized globally:

Method:

$$\chi^2 = \sum_i \left[\frac{F_{norm} \times \sigma_i^{exp} - \sigma^{LEX}_{(low\ q')}}{F_{norm} \times \Delta\sigma_i^{exp}} \right]^2$$

$$F_{norm} = 1.052$$

Using Bernauer Form factors



→ this is of the order of an GPs effect at important q' !!!

Our hypothesis: this percentage (5.2%) depends on the choice of proton form factors, because the (BH+Born) cross section depends on this FF choice.

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Normalization step of the $d\sigma^{exp}$ cross section

Interest: At low *q'(37.5 MeV/c in our case)* the experimental cross section is dominated by the (BH+Born) cross section :

$$\sigma^{exp} = \sigma^{BH+B} + q'[\ldots] \quad \xrightarrow{\text{Low energy theoreme}} \quad \begin{cases} q' \to 0 \\ \sigma^{exp} \to \sigma^{BH+B} \end{cases}$$

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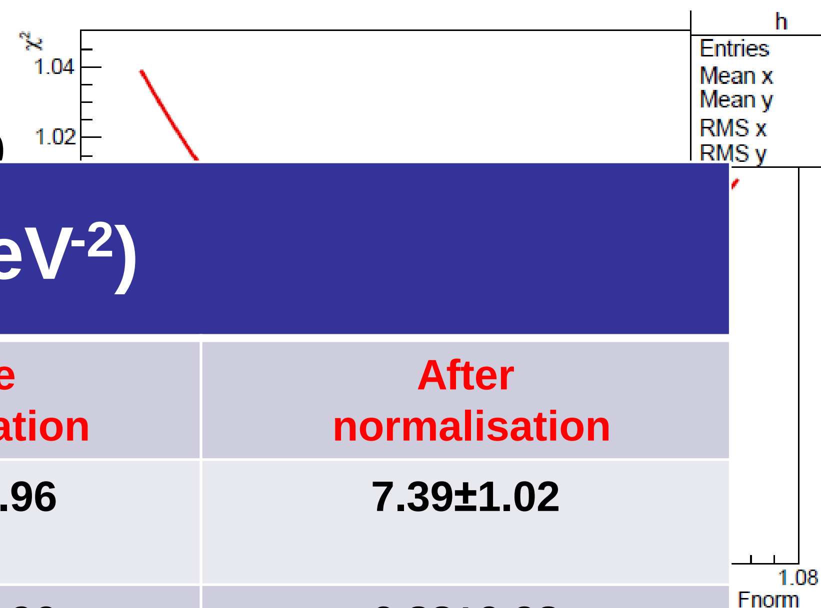
Method:

$(P_{l} - \frac{P_{TT}}{\ })$ et P de (OOP + INP) (From first pass fit)



λ

$(P_{LL} - P_{TT}/\epsilon)$ (GeV^{-2})			
Form factors	**Fnorm**	**before normalisation**	**After normalisation**
Bernauer Phys.Rev.Lett. 105:242001, 2010	**1.052**	**15.29±0.96**	**7.39±1.02**
F-Walcher Eur.Phys, J.A17 :607 2003	**1.026**	**10.62±0.96**	**6.88±0.98**
Arrington Phys.Rev.C76:035205, 2007	**1.032**	**11.80±0.96**	**7.14±1.00**

!!!

Normalization step of the $d\sigma^{exp}$ cross section

Interest: At low *q'(37.5 MeV/c in our case)* the experimental cross section is dominated by the (BH+Born) cross section :

$$\sigma^{exp} = \sigma^{BH+B} + q'[\ldots]$$

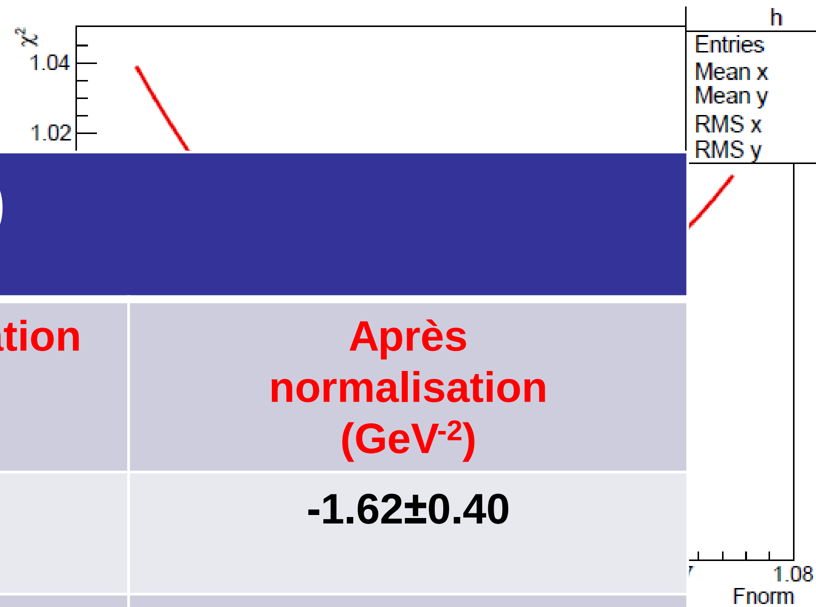
Low energy theoreme →

$$\begin{cases} q' \to 0 \\ \sigma^{exp} \to \sigma^{BH+B} \end{cases}$$

At low q' , the GPs effect accounts for about ~ 1.0% (but att high q'=104 MeV/c → GPs effect ~ 6%) of the cross section. Using the value of the structure functions from our first-pass fit → we can basically FIX the term […] and test if our measured cross section needs to be renormalized globally:

Method:

$(P_{LL} - \frac{P_{TT}}{\epsilon})$ et P de (OOP + INP) (From first pass fit)



χ^2

P_{LT} (GeV^{-2})			
Facteurs de forme	**Fnorm**	**Avant normalisation (GeV^{-2})**	**Après normalisation (GeV^{-2})**
Bernauer Phys.Rev.Lett. 105:242001, 2010	**1.052**	**-1.57±0.39**	**-1.62±0.40**
F-Walcher Eur.Phys, J.A17 :607 2003	**1.026**	**-1.74±0.38**	**-1.76±0.40**
Arrington Phys.Rev.C76:035205, 2007	**1.032**	**-1.65±0.38**	**-1.68±0.40**

q' !!!