Beam-Recoil Polarization in Virtual Compton Scattering from the Proton below Pion Threshold

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Outline

- Motivation
- Theoretical Aspects
- The Experiment
- Data Analysis and Results
- Conclusion and Outlook

(Virtual) Photons and the Nucleon

Nucleon Polarizabilities: α_E, β_M

Real Compton Scattering (RCS)

$$\gamma N \rightarrow \gamma N$$

Virtual Compton Scattering (VCS)

$$\gamma^* N \rightarrow \gamma N$$

High- E → **Generalized Parton Distributions (GPDs)**

Low- E → **Generalized Polarizabilities (GPs)**

Virtual^2 Compton Scattering (VVCS)

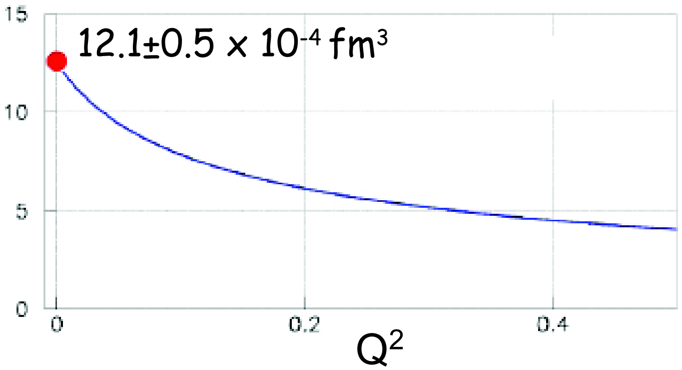
$$\gamma^* N \rightarrow \gamma^* N$$

Two photon corrections (FF)
Partonic Densities

V. Olmos de Leon EPJA 10 (2001) 207

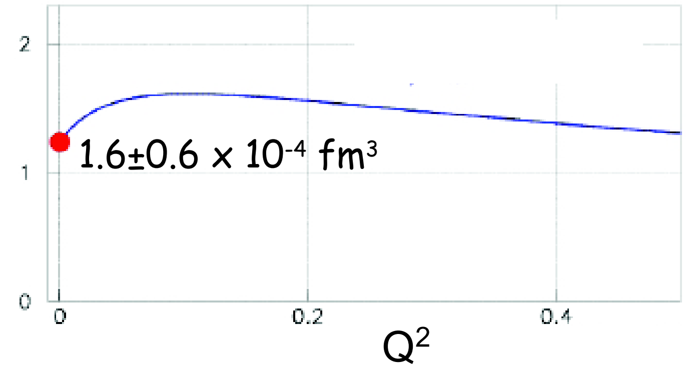
Generalized Polarizabilities

Electric Polarizability α



- Displacement of charges
- Induced dipole moment p=▯E
- Atomic Systems α/V~1
- Nucleons: $\alpha \sim 10^{-4}$ fm^3, V~1fm^3

Magnetic Polarizability β



Diamagnetism ($\beta < 0$)

- ChPT: Pions are the relevant degrees of freedom
- „Pion Cloud" : Induced eddy currents of spinless charged particles

Paramagnetism($\beta > 0$)

- Resonant structure of the Nucleon
- Example: N->Δ Transition

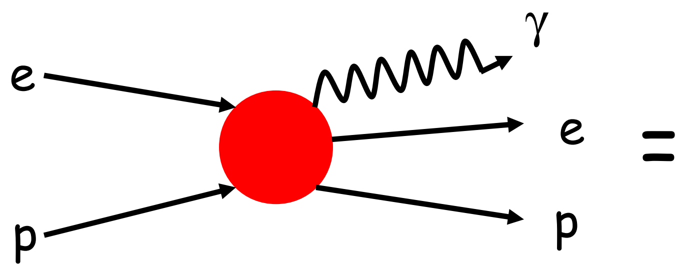
+ 4 "spin" GPs

History of the GPs:
H.Arenhoevel et al,, NPA 233 (1974) 153)
P. Guichon et al., NPA 591 (1995) 606
D. Drechsel et al., PRC 55 (1997) 424
D. Drechsel et al., PRC 57 (1998) 941

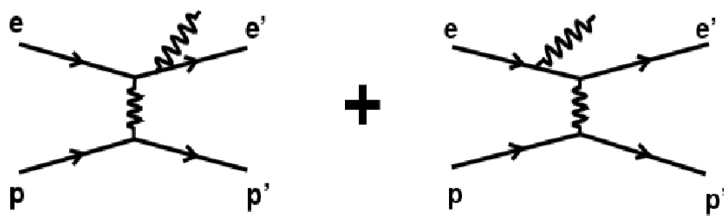
RCS data:
V. Olmos de Leon EPJA 10 (2001) 207

Virtual Compton Scattering

Photoelectronproduction

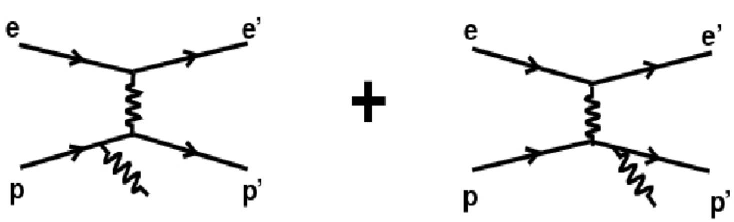


Bethe-Heitler Contribution



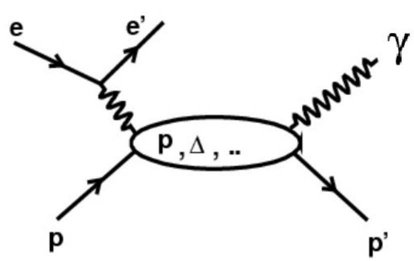
- Not separable from VCS
- Lorentz Boost:
  - in the direction of e
- Cross Section ~ 1/k
- Form Factors needed

Born Term



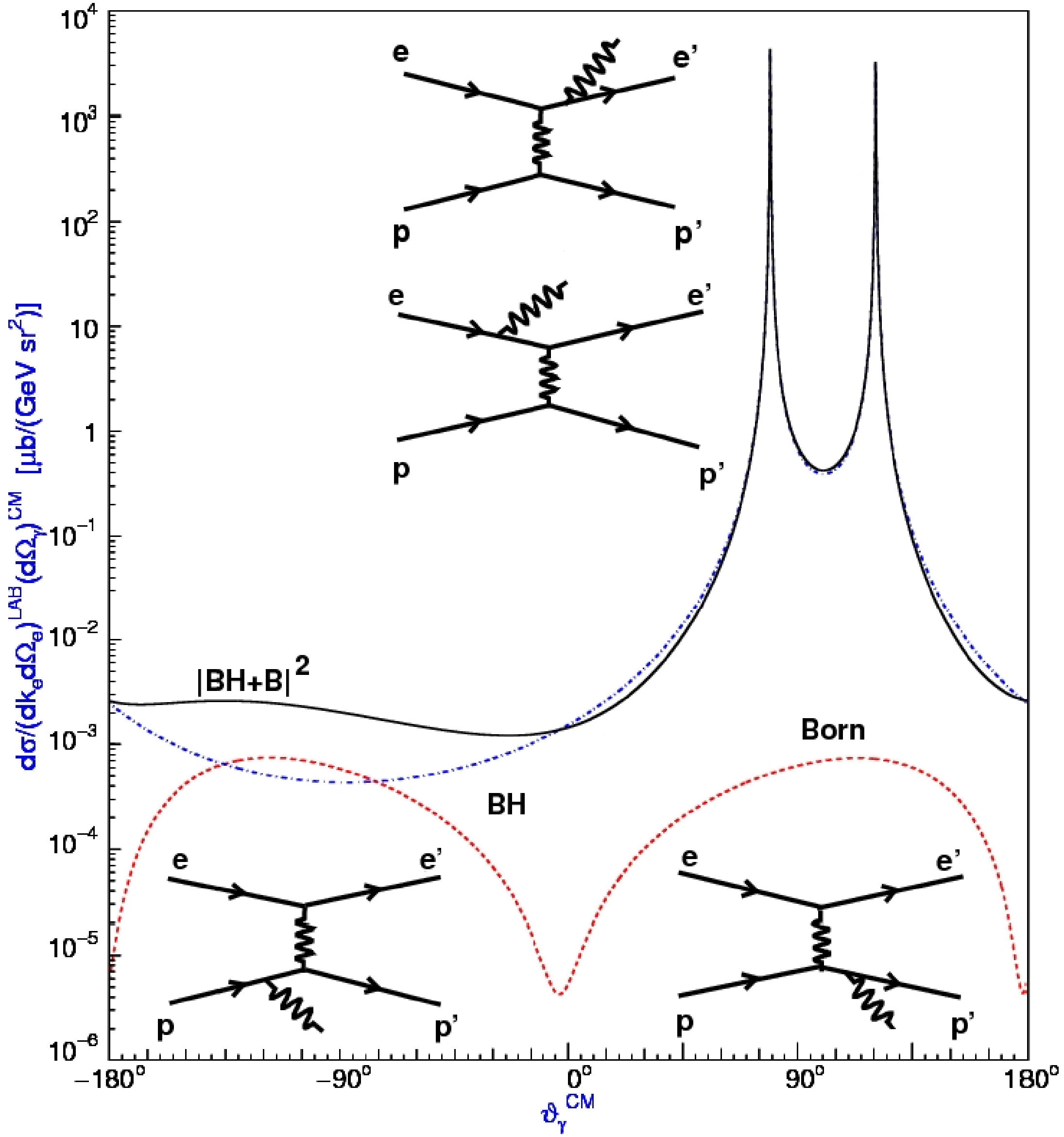
- First order term
- Suppressed by $1/m_p$
- Form Factors needed

VCS Contribution

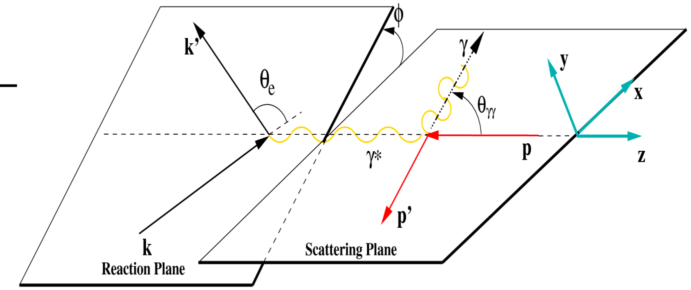


Parametrized by the ***Generalized Polarizabilities***

Virtual Compton Scattering



Low Energy Expansion



Cross Section

$$\frac{d^5\sigma}{dE' d\Omega' d\Omega_\gamma^{cm}} = d^5\sigma^{BH+Born} + \phi q' \Psi_0(q,\varepsilon,\theta,\phi) + O(q'^2)$$

$$\Psi_0 = v_1(\theta,\phi,\varepsilon)\left(\mathrm{P_{LL}}(q^2) - \mathrm{P_{TT}}(q^2)/\varepsilon\right) + v_2(\theta,\phi,\varepsilon)\mathrm{P_{LT}}(q^2)$$

P.A.M. Guichon, et al. , Nucl Phys A 591 (1995) 606-638

Double Polarization Observables

$$P_{x,y,z} = \frac{d^5\sigma^{\uparrow\uparrow} + d^5\sigma^{\downarrow\downarrow} - d^5\sigma^{\uparrow\downarrow} - d^5\sigma^{\downarrow\uparrow}}{d^5\sigma^{\uparrow\uparrow} + d^5\sigma^{\downarrow\downarrow} + d^5\sigma^{\uparrow\downarrow} + d^5\sigma^{\downarrow\uparrow}} = \frac{d^5\sigma^{h\uparrow} - d^5\sigma^{h\downarrow}}{2\, d^5\sigma}$$

Structure Functions

$$\Delta d^5\sigma^h_{x,y,z} = \Delta d^5\sigma^{BH+Born}_{x,y,z} + \phi\, q' \Delta\Psi_0^{x,y,z} + \phi\, O(q'^2)$$

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

M.Vanderhaeghen, PLB 402 (1997) 243

Generalized Polarizabilities

$P^{(\rho,L;\rho',L')S}$

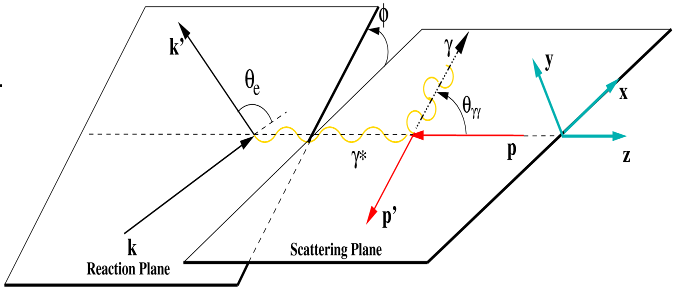
Init. Transition
ρ = E, M, L
L = 0,1,2,..

Fin. Transition

S=0/1: Spin Flip

$$\begin{aligned}
\mathbf{P_{LL}} &= aP^{C1\to E1} \\
\mathbf{P_{TT}} &= c_1 P^{M1\to M1(S)} + c_2\, P^{M2\to E1(S)} \\
\mathbf{P_{LT}} &= bP^{M1\to M1} + c_3\left[P^{C0\to M1(S)} + d_1 P^{C2\to M1(S)}\right] \\
\mathbf{P^z_{LT}} &= c_4 P^{M1\to M1(S)} + c_3\left[P^{C0\to M1(S)} + d_1 P^{C2\to M1(S)}\right] \\
\mathbf{P'^z_{LT}} &= c_5 P^{M1\to M1(S)} + c_6\left[P^{C0\to M1(S)} + d_1 P^{C2\to M1(S)}\right] \\
\mathbf{P'^\perp_{LT}} &= \left[d_2\, P^{C0\to M1(S)} + d_3 P^{C2\to M1(S)}\right]
\end{aligned}$$

Dispersion Relations



VCS defined by

$$Q^2 = -q^2$$

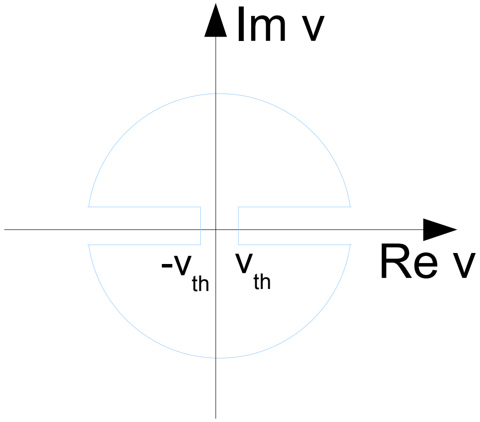
$$t = (q - q')^2$$

$$\nu = \frac{s-u}{4M} = E_\gamma^{LAB} + \frac{1}{4M}(t - Q^2)$$

Amplitudes analytical in ν, Unitarity, Crossing Symmetry

Analytical continuation

$$\Re F_i^{nB}(Q^2, \nu, t) = \frac{2}{\pi} \int_{\nu_{th}}^{\infty} d\nu \frac{\nu' \Im F_i(Q^2, \nu, t)}{\nu'^2 - \nu^2}$$



MAID Parameterization

D.Drechsel, S.S.Kamalov, L.Tiator, Nucl.Phys. A645 (1999) 145-174

Parameterization of α and β

Fit to the experimental data

Prediction for the 4 Spin GPs

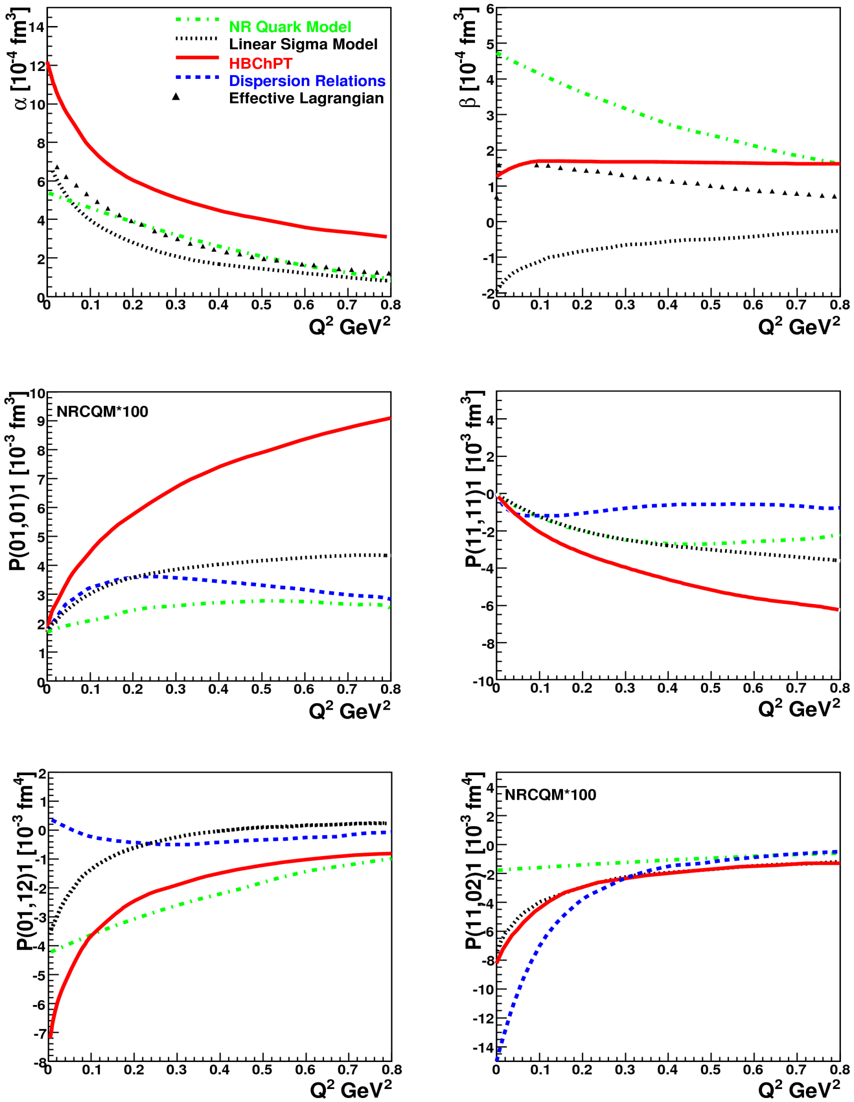
Dipole Form

$$\alpha(Q^2) - \alpha^{\pi N} = \frac{\alpha - \alpha^{\pi N}}{(1 + Q^2/\Lambda_\alpha^2)^2} \longrightarrow P^{(C1 \to E1)0}(Q^2) = -\sqrt{\frac{2}{3}} \frac{4\pi}{e^2} \alpha(Q^2)$$

$$\beta(Q^2) - \beta^{\pi N} = \frac{\beta - \beta^{\pi N}}{(1 + Q^2/\Lambda_\beta^2)^2} \longrightarrow P^{(M1 \to M1)0}(Q^2) = -\sqrt{\frac{8}{3}} \frac{4\pi}{e^2} \beta(Q^2)$$

B.Pasquini et al. , Eur. Phys. J. 11 (2001) 185-208

Theoretical Predictions



NRCQM

P.A.M.Guichon et al. NPA 591 (1996) 606

Pasquini et al. nucl-th/0105074

Linear Σγμ α Model

A.Metz et al. Z.Phys. A356 (1996) 351

HBChPT O(p3)

Hemmert et al. PRD 62 (2000) 014013

Dispersion Relations

B.Pasquini et al. PRC 62 (2000) 052201

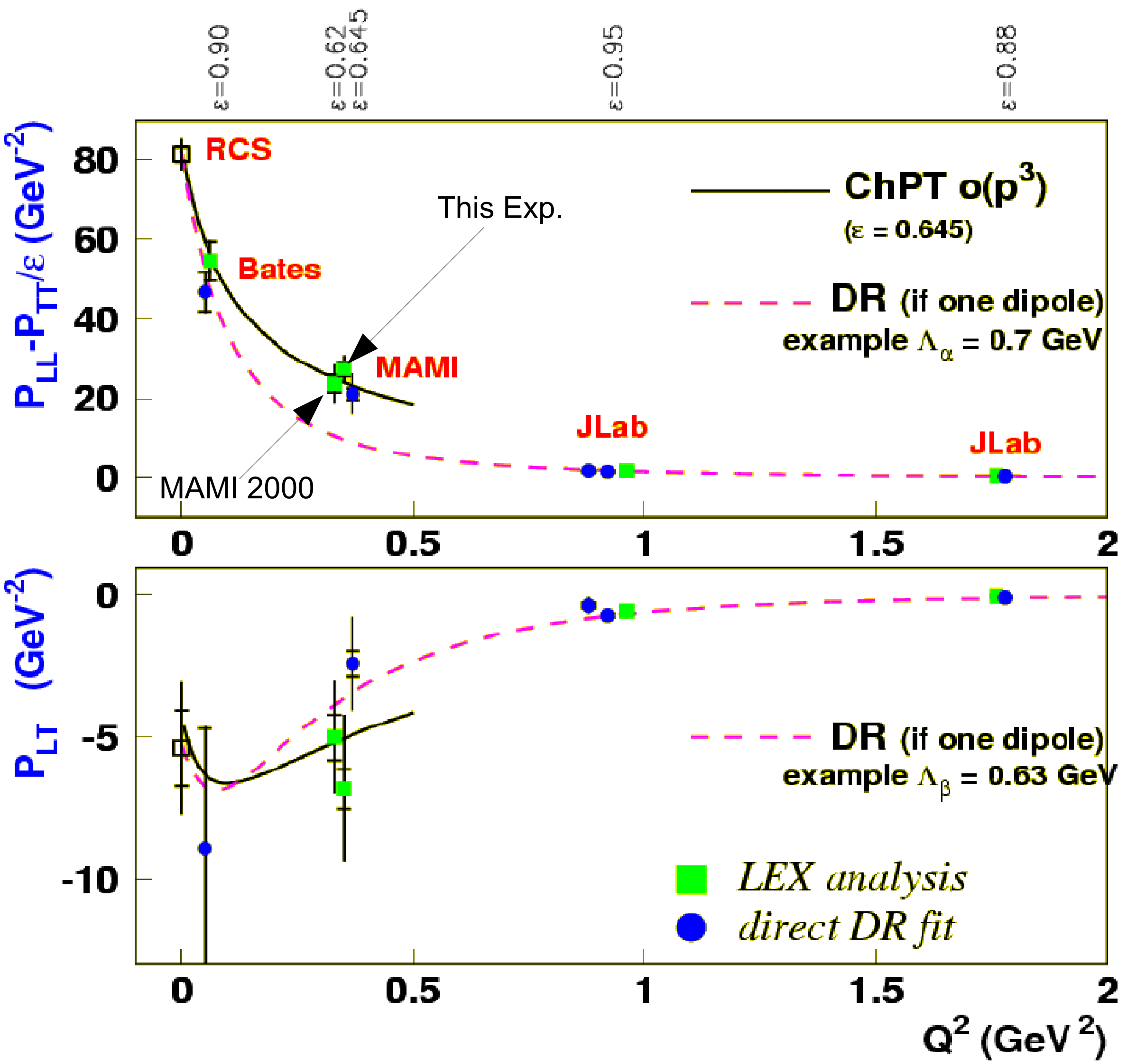
Effective Lagrangian Model

A.Korchin et al. PRC 58 (1998) 1098

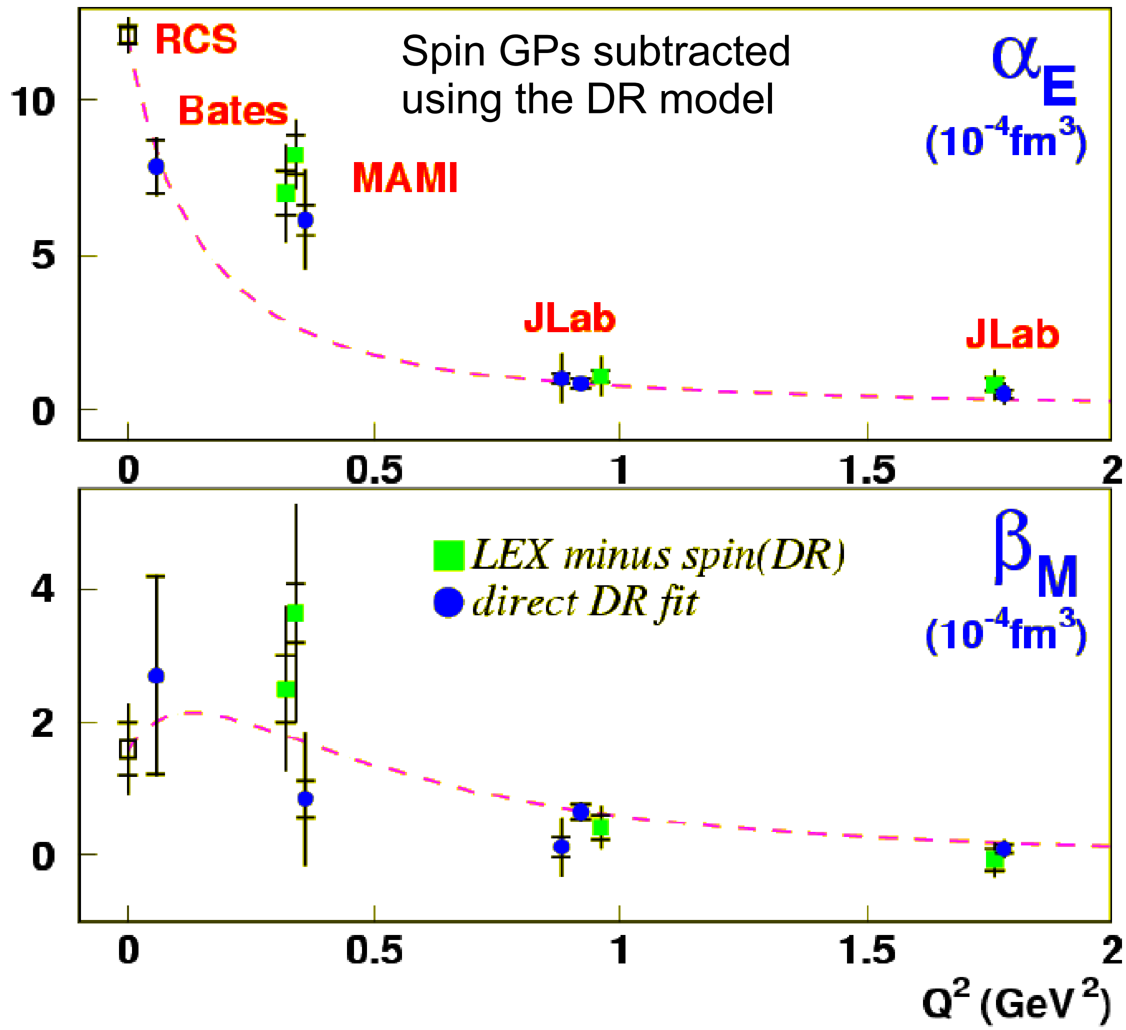
Other ChPT calculations:

- HBChPT O(4/5): Kao , Vanderhaeghen, PRD 70 (2004) 114004
- Covariant ChPT O(4) : D. Djukanovic (Mainz, PhD thesis)

World Data: Structure Functions

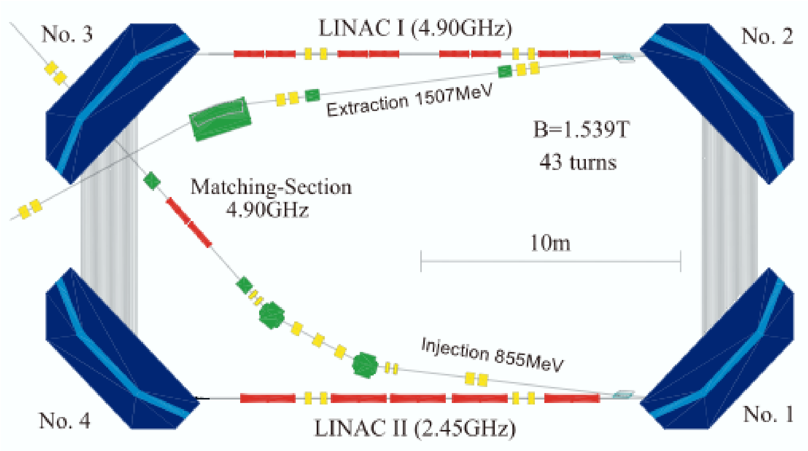


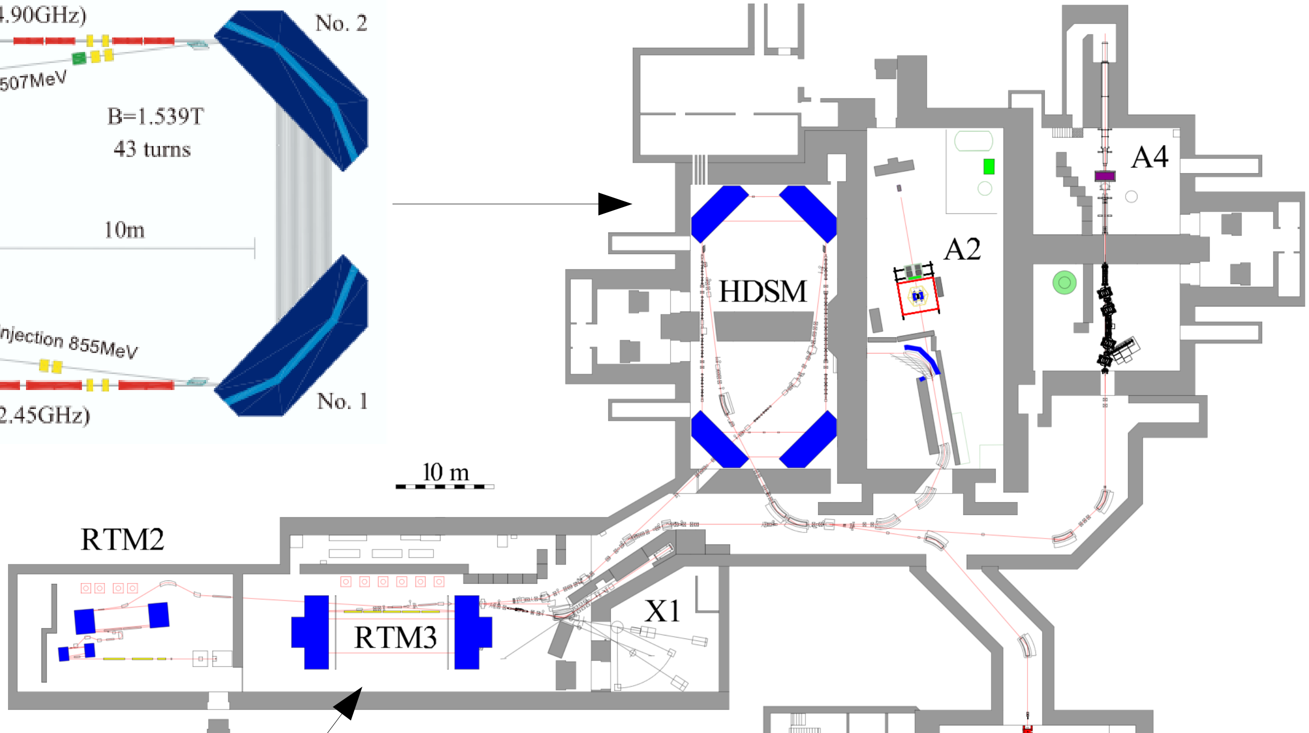
World Data: Scalar GPs

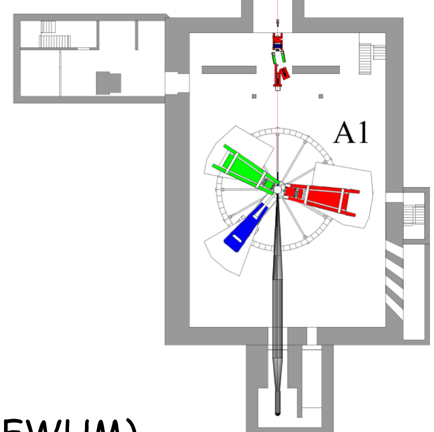


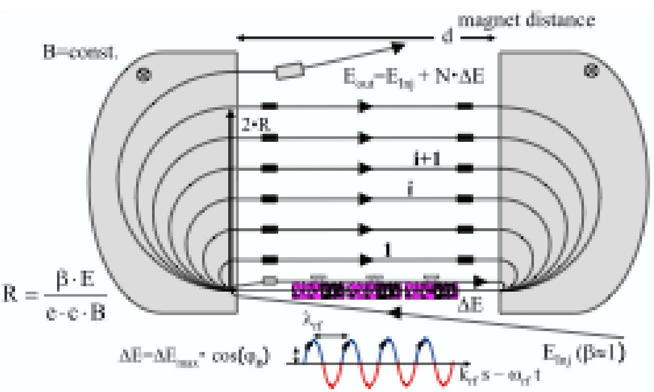
Experimental Setup

The MAMI Accelerator Complex (KPH Mainz)









MAMI Accelerator

- E = 855 MeV/c^2
- Max. Current = 100 υA
- Duty Cycle: 100% (cw)
- Energy Spread 30 keV (FWHM)

Experimental Setup

3 Spectrometers

- Momentum Resolution: 10^{-4}
- A,C: QSDD, Acceptance 28msr
- B: Clamshell, Acceptance 5.6msr

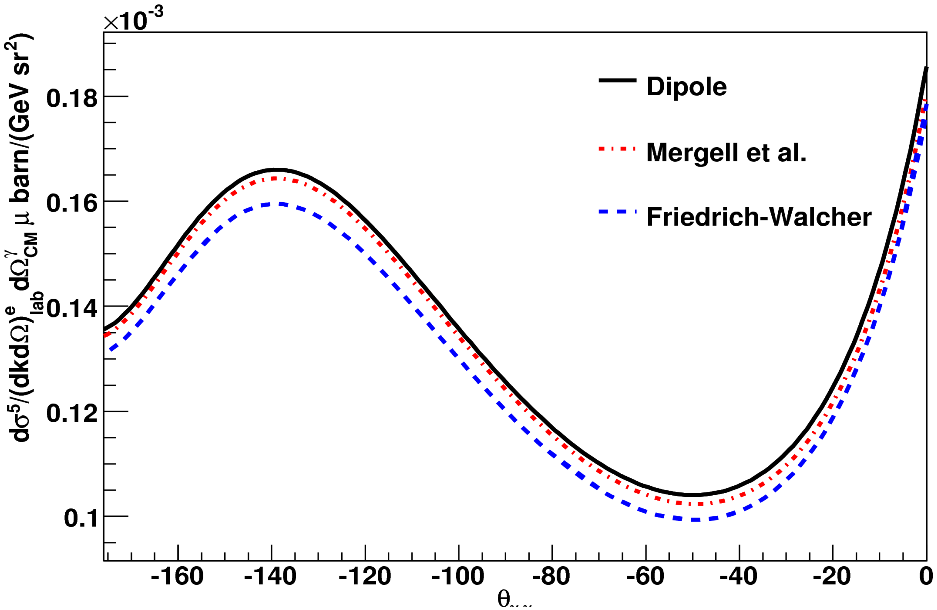
Detectors

- Čerenkov Detector (e/π id.)
- Vertical Driftchabers (4 Planes)
- 2 Scintillator Planes

K. I. Blomqvist et al., NIM A403 (1998) 263-301

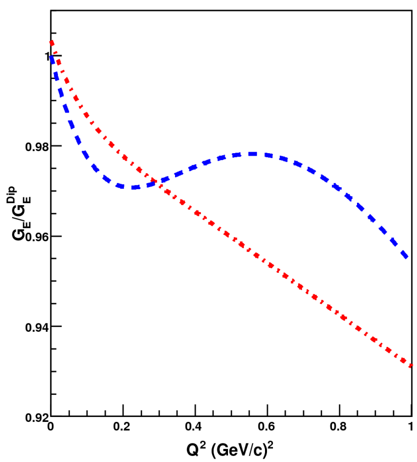
Unpolarized CrossSection

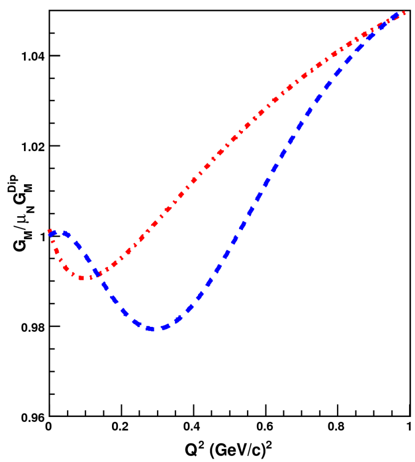
Form Factors



Cross Section

- ~10% Difference
- 2 different analyses





Parametrizations:

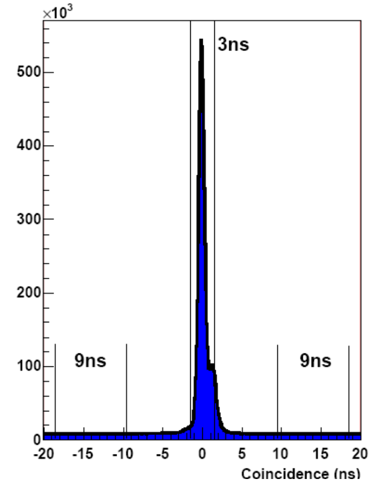
- Dipol: $$G_E(Q^2) = \frac{1}{(1+Q^2/\Lambda_d)^2}$$ $$G_M(Q^2) = \mu G_E(Q^2)$$
- Mergell et al.
- Friedrich und Walcher

P.Mergell et al. , Nucl.Phys. A596 (1996) 367-391

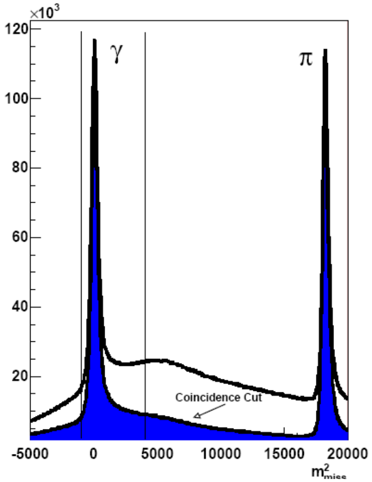
J. Friedrich and Th. Walcher, EPJ A 17 (2003) 607-623

Cross Section

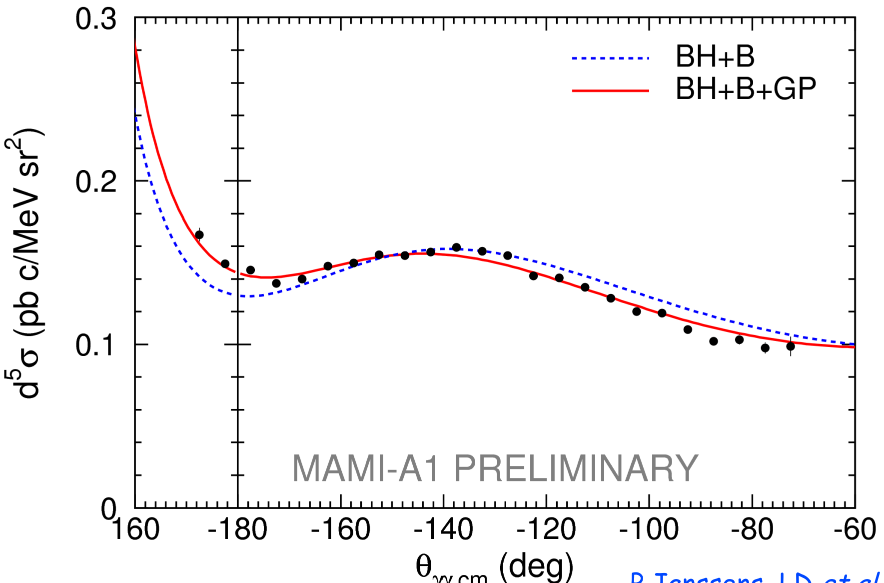
Coincidence

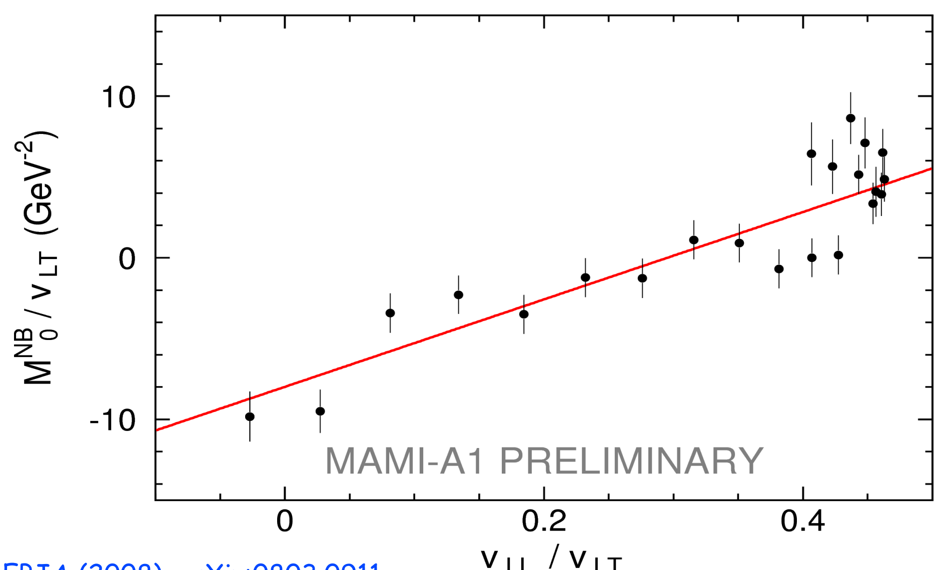


$m^2 = (k+p-k'-p')^2$



	Mergell et al.	FW	HBChPT O(p³)
$P_{¿} - (1/\epsilon) P_{TT}$	28.5±1.9±2.8	27.1±1.9±2.8	26.3/26.0 (GeV)$^{-2}$
P_{LT}	-5.2±0.7±2.1	-8.0±0.7±2.1	-5.5/-5.4 (GeV)$^{-2}$
	$\chi^2/DoF = 2.42$	$\chi^2/DoF = 2.63$	



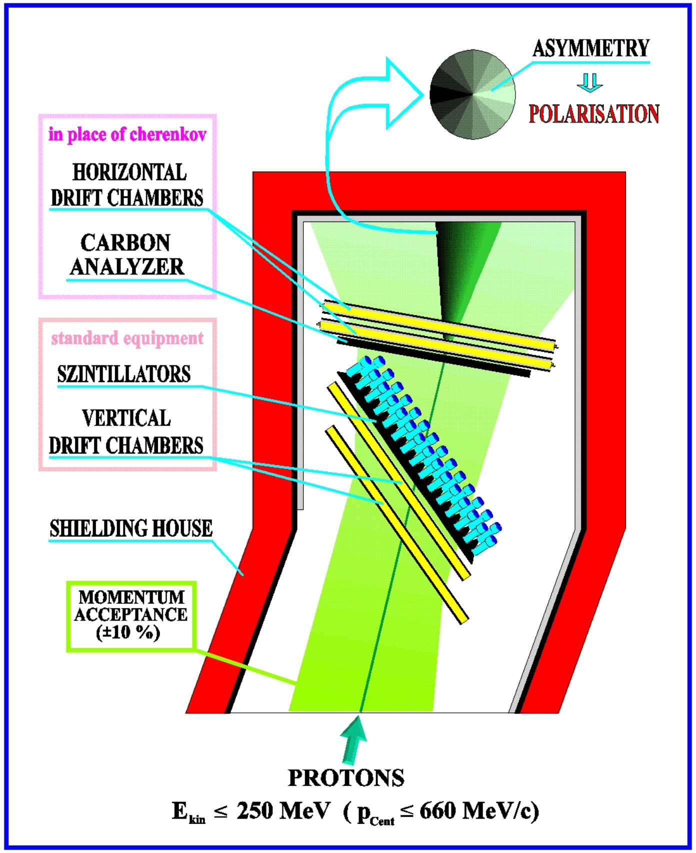


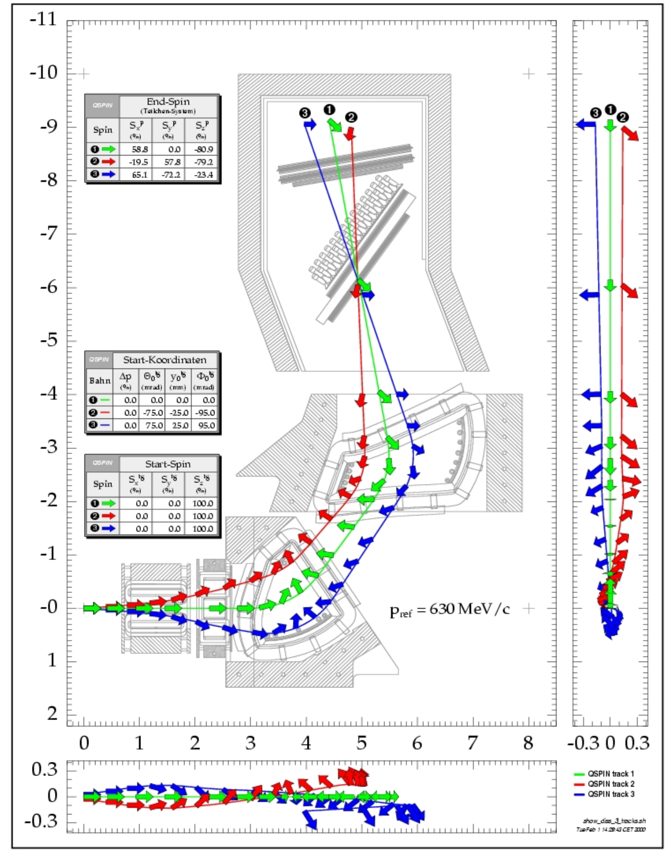
P.Janssens, LD *et al.*, EPJA (2008), arXiv:0803.0911

Double Polarization Observables

Recoil Proton Polarimetry

Th. Pospischil, NIM A483 (2002) 746-733





- Cross Section pC^{12} :

$$\sigma \propto 1 + P_b A_C(\Phi_i, E_i)\left(P_y^{fp} \sin \Phi_i - P_x^{fp} \cos \Phi_i\right)$$

Reconstruction of the Polarization

- 3 Components measurable
- Full spin precession calculated

Systematcal Errors

- Px ~ ± 0.8%
- $P_{y,z}$ ~ ± 1.1%

Maximum Likelihood Method

Spin rotation, Lorentz Boost,..

- Parametrized in one single rotation
- 3 Parameters
- Computed for each event
- Rotation dependent on: Momentum, Target Coordinates, Spectrometer Angle

$$\begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix}^{fp} = \begin{pmatrix} a_{xx} & a_{xy} & a_{xz} \\ a_{yx} & a_{yy} & a_{yz} \\ a_{zx} & a_{zy} & a_{zz} \end{pmatrix} \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix}^{cm}$$

Likelihood:

- Three Polarization Components

$$\ln L = \sum_i \ln[1 + P_b h A_C(\Phi_i, E_i)(P_y^{fp} \sin\Phi_i - P_x^{fp} \cos\Phi_i)]$$

$$\ln L = \sum_i \ln[1 + P_b h A_C(\Phi_i, E_i) P_x^{cm}(a_{xx}^i \cos\Phi_i - a_{xy}^i \sin\Phi_i)$$

$$+ P_y^{cm}(a_{yx}^i \cos\Phi_i - a_{yy}^i \sin\Phi_i)$$

$$+ P_z^{cm}(a_{yz}^i \cos\Phi_i - a_{xz}^i \sin\Phi_i) \;]$$

Maximum Likelihood Method

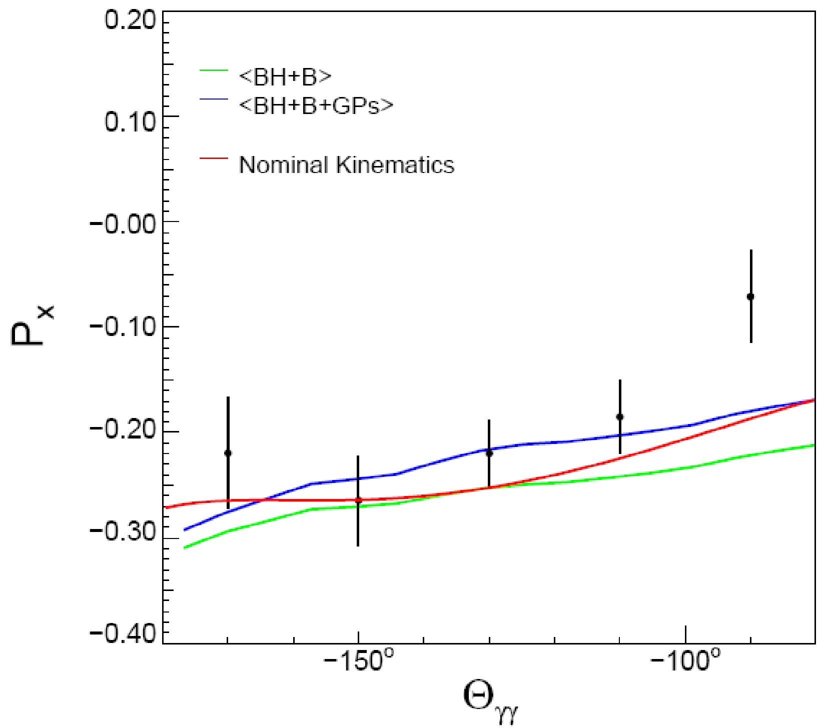
General Procedure

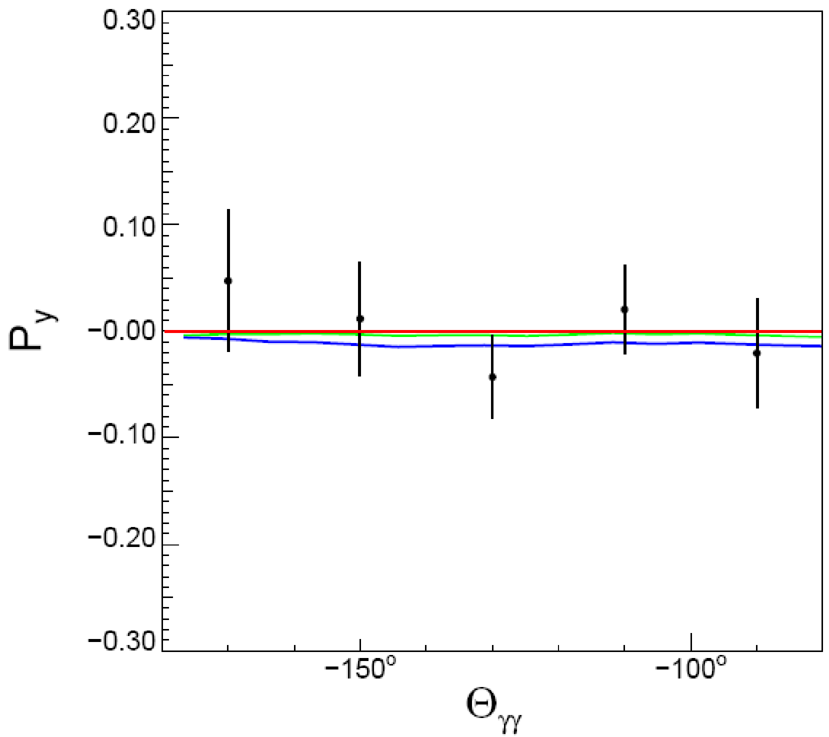
- Measurement of the kinematics (FP angles, Target coordiantes, ..)
- Single Event Probability: $p_i = 1 + P_b h A_C(\Phi_i, E_i)(P_y^{fp} \sin\Phi_i - P_x^{fp} \cos\Phi_i)$
- Lorentz Boost, Spin Rotation $P^{fp} \leftarrow\rightarrow P^{cm}$
- Likelihood: $L = \prod_i p_i \rightarrow \ln L = \sum_i \ln p_i$
- Maximize: $\frac{\partial \ln L}{\partial P^{cm}_{x,y,z}} = 0 \rightarrow \langle P^{cm}_{x,y,z} \rangle$
- Statistical Error: $\sigma_{ij} = \sqrt{\left(\frac{\partial^2 \ln L}{\partial P_i \partial P_j} \right)^{-1}}$

Advantages

- No binning needed
- Statistically robust
- Efficient use of the information
- Fast algorithm on modern PCs

Double Polarization Observables

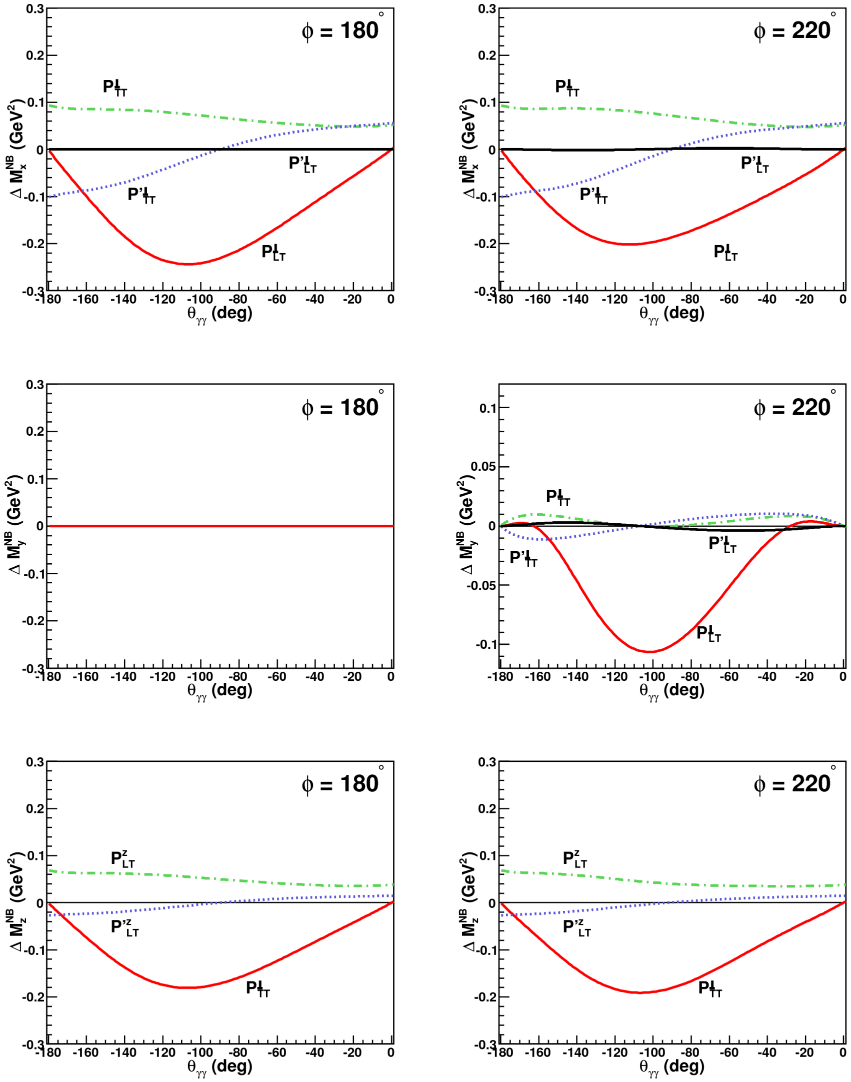




- False and background asymmetries negligible

- P_x bigger than BH+B
- P_y consistent with 0
- P_z fixed on BH+B
  - Small correlation with P_x

Sensibility to the Structure Functions



$$P_{x,y,z} = \frac{d^5\sigma^{\uparrow\uparrow} + d^5\sigma^{\downarrow\downarrow} - d^5\sigma^{\uparrow\downarrow} - d^5\sigma^{\downarrow\uparrow}}{d^5\sigma^{\uparrow\uparrow} + d^5\sigma^{\downarrow\downarrow} + d^5\sigma^{\uparrow\downarrow} + d^5\sigma^{\downarrow\uparrow}} = \frac{d^5\sigma^{h\uparrow} - d^5\sigma^{h\downarrow}}{2\, d^5\sigma}$$

$$\Delta d^5\sigma^h_{x,y,z} = \Delta d^5\sigma^{BH+Born}_{x,y,z} + \phi\, q' \Delta\Psi_0^{x,y,z} + \phi\, O(q'^2)$$

$$\Psi_0 = v_1(\mathbf{P_{LL}} - \mathbf{P_{TT}}/\varepsilon) + v_2 \mathbf{P_{LT}}$$
$$\Delta\Psi_0^z = 4\, h\, [v_1^z\, \mathbf{P_{TT}} + v_2^z \mathbf{P^z_{LT}} + v_3^z\, \mathbf{P'^z_{LT}}]$$
$$\Delta\Psi_0^x = 4\, h\, [v_1^x\, \mathbf{P^\perp_{LT}} + v_2^x\, \mathbf{P^\perp_{TT}} + v_3^x\, \mathbf{P'^\perp_{TT}} + v_4^x\, \mathbf{P'^\perp_{LT}}]$$
$$\Delta\Psi_0^y = 4\, h\, [v_1^y\, \mathbf{P^\perp_{LT}} + v_2^y\, \mathbf{P^\perp_{TT}} + v_3^y\, \mathbf{P'^\perp_{TT}} + v_4^y\, \mathbf{P'^\perp_{LT}}]$$

- Larger effect from $P^\perp_{LT}$
- Few Information from P_y
- P_z (still) not precise enough

Results (MAMI Double Pol. Experiment)

Form Factors	$P_{LT}^{\perp}\ (GeV^{-2})$
Arrington *et al.* [1]	-17.6 ± 3.3
Hammer *et al.* [2]	-17.7 ± 3.3
F-W [3]	-17.8 ± 3.3

Overall Systematical Error: +2.12, -0.38

Sources:

- Beam Polarization
- Constraints
- CrossSection Input
- Effect of other Structure Functions

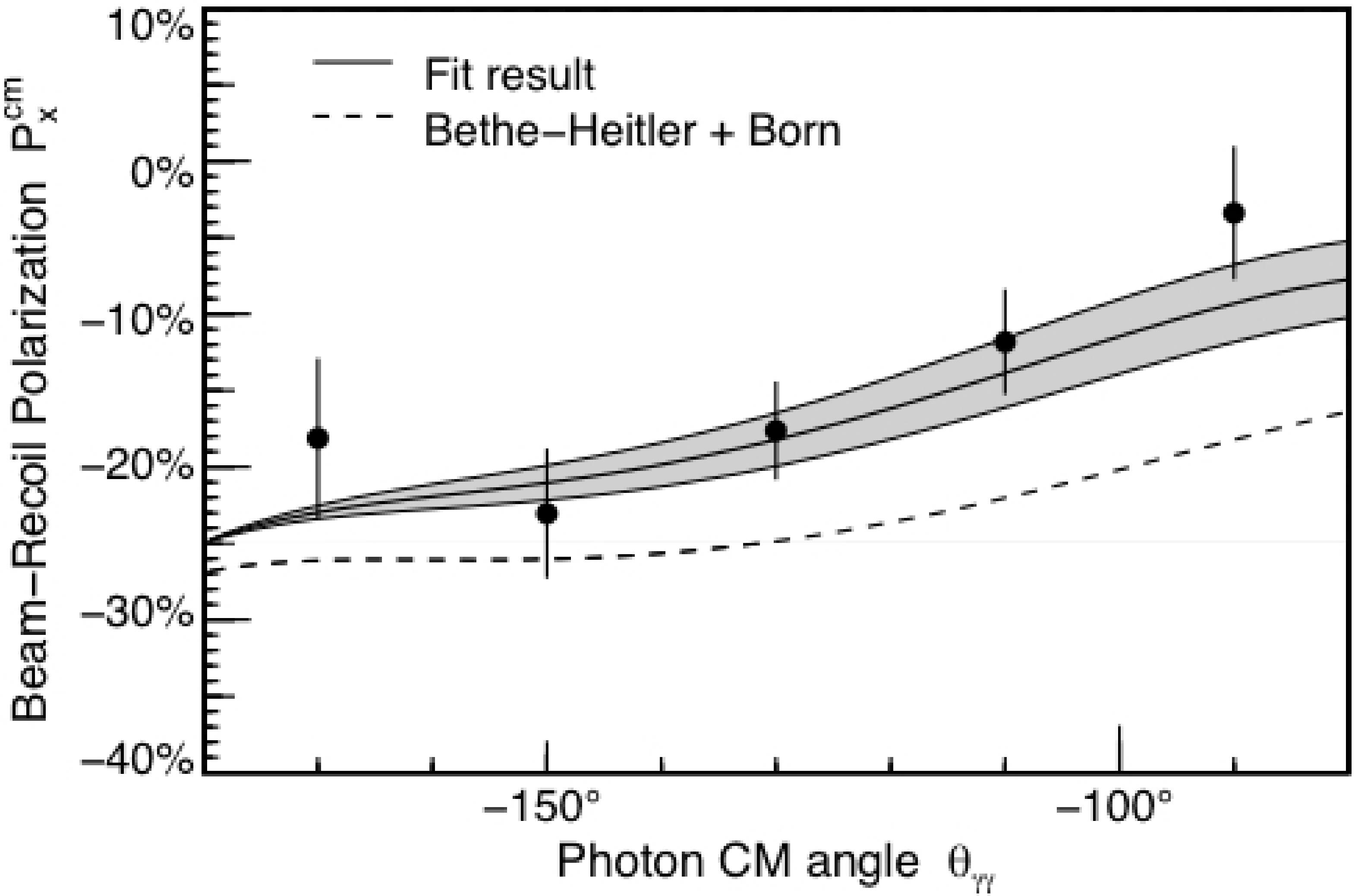
Theoretical Models

HBChPT O(p³): $P_{LT}^{\perp} = -10.4\, GeV^{-2}$

DR Model: $P_{LT}^{\perp} = -12.7\, GeV^{-2},\ \Lambda_{\alpha} = \infty$

[1] J. Arrington et al. PRC 76, 035205 (2007)
[2] H.-W. Hammer et al., PRC 75, 035202 (2007)
[3] J.Friedrich, Th.Walcher, EPJ A17, 607 (2003)

Extraction of $P_{LT}^{\perp}$



LD, P.Janssens, *et al.*, in preparation

Conclusions

Virtual Compton Scattering

- Intuitive physical interpretation
- Fundamental as the Form Factors
- Contribution from different low-q QCD degrees of freedom
- New test for the nucleon models

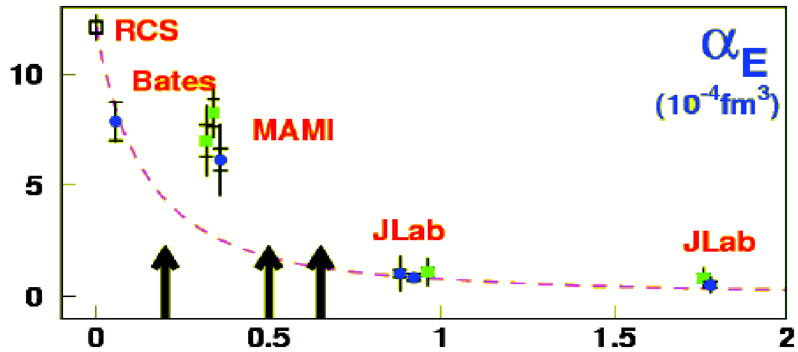
Experimental Activity

- Measurement through Photonelectroproduction
- First unpolarized experiment at MAMI (Q^2=0.33 GeV^2/c^2)
- Experiments at MIT-Bates (Q^2=0.05 GeV^2/c^2) and JLab (Q^2 = 0.92 ; 1.76 GeV^2/c^2)
- Measurement of the Single Spin Asymmetry at MAMI I. Bensafa et al., Eur. Phys. J. A 32, (2007) 69-75
- NOW: First Double polarization observables

Outlook

The Future

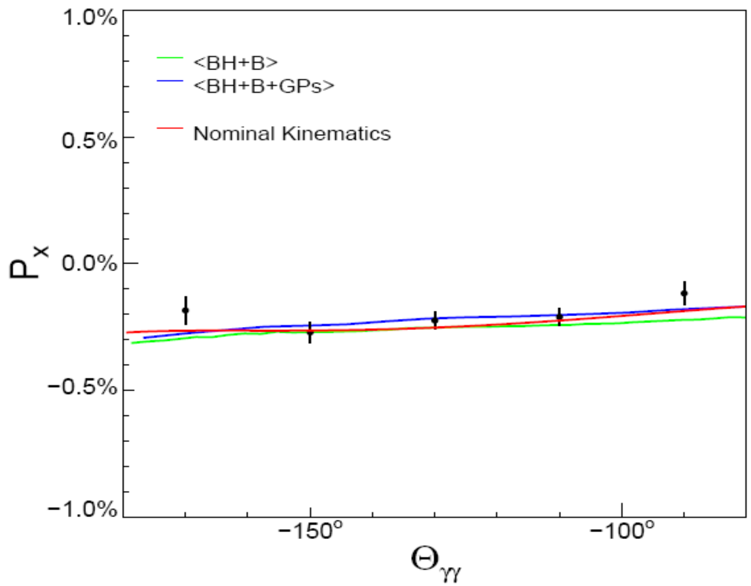
- More Statistics for the double polarization experiments: Separation of the GPs
- Measurement of new kinematics for clarifying the Q^2 dependence of α and β



Q^2 = 0.20, 0.50, 0.65 GeV^2

- New kinematical ranges with MAMI-C

Double Polarization Observables



Reconstruction of 3 components in the CM system

P_x well reconstructed

- Small spin precession

Correlation between P_y and P_z

- Strong Spin Precession
- How to correct? ⟶ Constraint