Measurement of Compton scattering at MAMI and extraction of nucleon polarizabilities

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for the A2 Collaboration

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A2

MAMI MAINZER MIKROTRON

Institut für Kernphysik

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

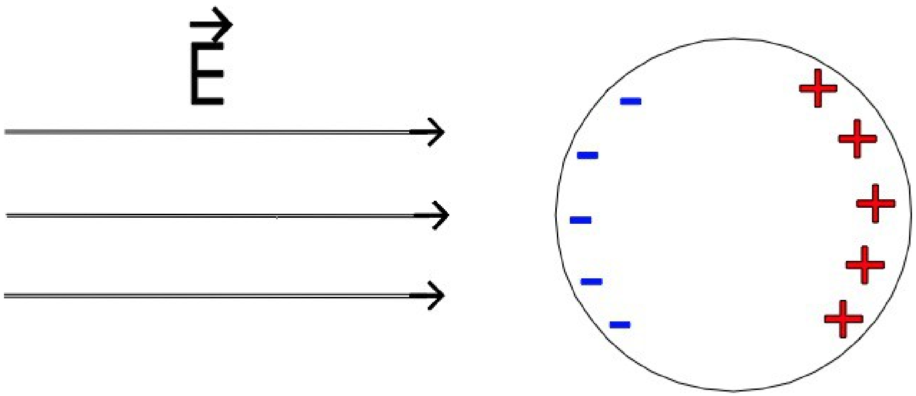
Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter
PRISMA

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Contents

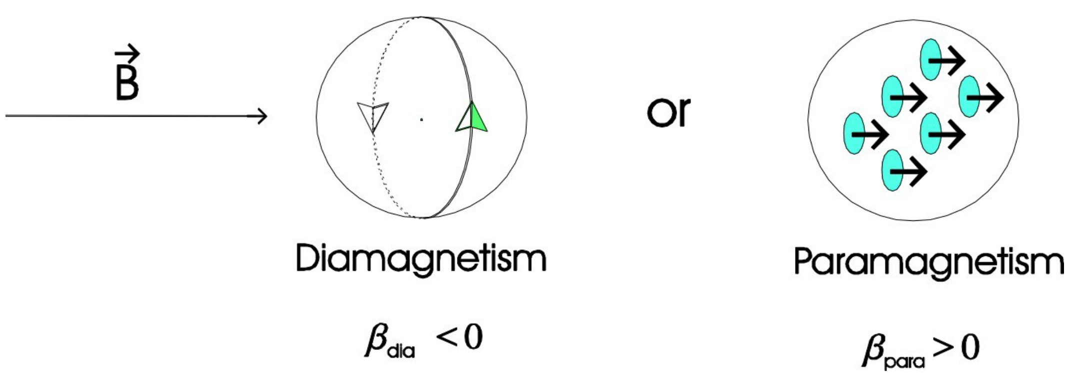
- Nucleon polarizabilities
- Crystal Ball/TAPS setup at MAMI
- Recent results for the proton polarizabilities from the A2 Collaboration
- Future plans for the measurement of neutron polarizabilities
- High pressure TPC as an active target for recoil detection
- Current status of the PRES experiment

Proton Electric Polarizability



- α_{E1}: electric polarizability
- Proton between charged parallel plates: "stretchability"

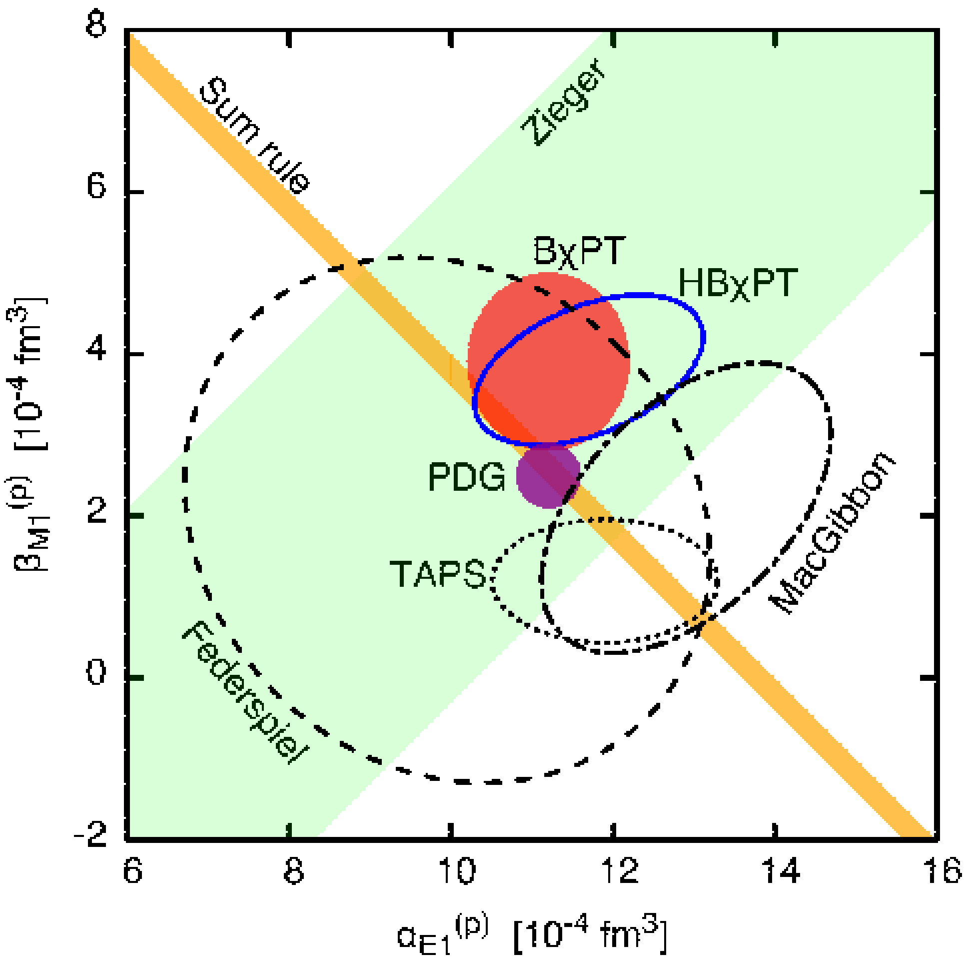
Proton Magnetic Polarizability



- β_{M1}: magnetic polarizability
- Proton between poles of a magnet: "alignability"

- **Fundamental properties of the proton**
- **Important to atomic physics (e.g. proton radius measurement in muonic hydrogen)**
- **Spin polarizability measurements etc**

Existing data and model predictions (without recently published data)



PDG (2012) values:

$\alpha = (12.0 \pm 0.6) \times 10^{-4}\ \mathrm{fm}^3$

$\beta = (1.9 \pm 0.5) \times 10^{-4}\ \mathrm{fm}^3$

New (2014-2018) PDG values:

$\alpha = (11.2 \pm 0.4) \times 10^{-4}\ \mathrm{fm}^3$

$\beta = (2.5 \pm 0.4) \times 10^{-4}\ \mathrm{fm}^3$

- Significant change between reviews without introducing new experimental data
- Global database not entirely consistent

Goal: high-precision measurement of the scalar polarizabilities of the proton

- New high-precision unpolarized cross-sections
- New high-quality data on the beam asymmetry Σ_3
- New single data set with small statistical and systematic errors

Spin polarizabilities

- These parameters describe the response of the proton spin to an applied electric or magnetic field
- Nucleon has 4 spin or vector polarizabilities: γ_{E1E1} γ_{M1M1} γ_{M1E2} γ_{E1M2}
- Fundamental properties of the proton!
- Low sensitivity at low energies →measurements at higher energies (Δ region)

1. Beam: circular, Target: longitudinal

$$\Sigma_{2z} = \frac{\sigma^R_{+z} - \sigma^L_{+z}}{\sigma^R_{+z} + \sigma^L_{+z}} = \frac{\sigma^R_{+z} - \sigma^R_{-z}}{\sigma^R_{+z} + \sigma^R_{-z}}$$

2. Beam: circular, Target: transverse

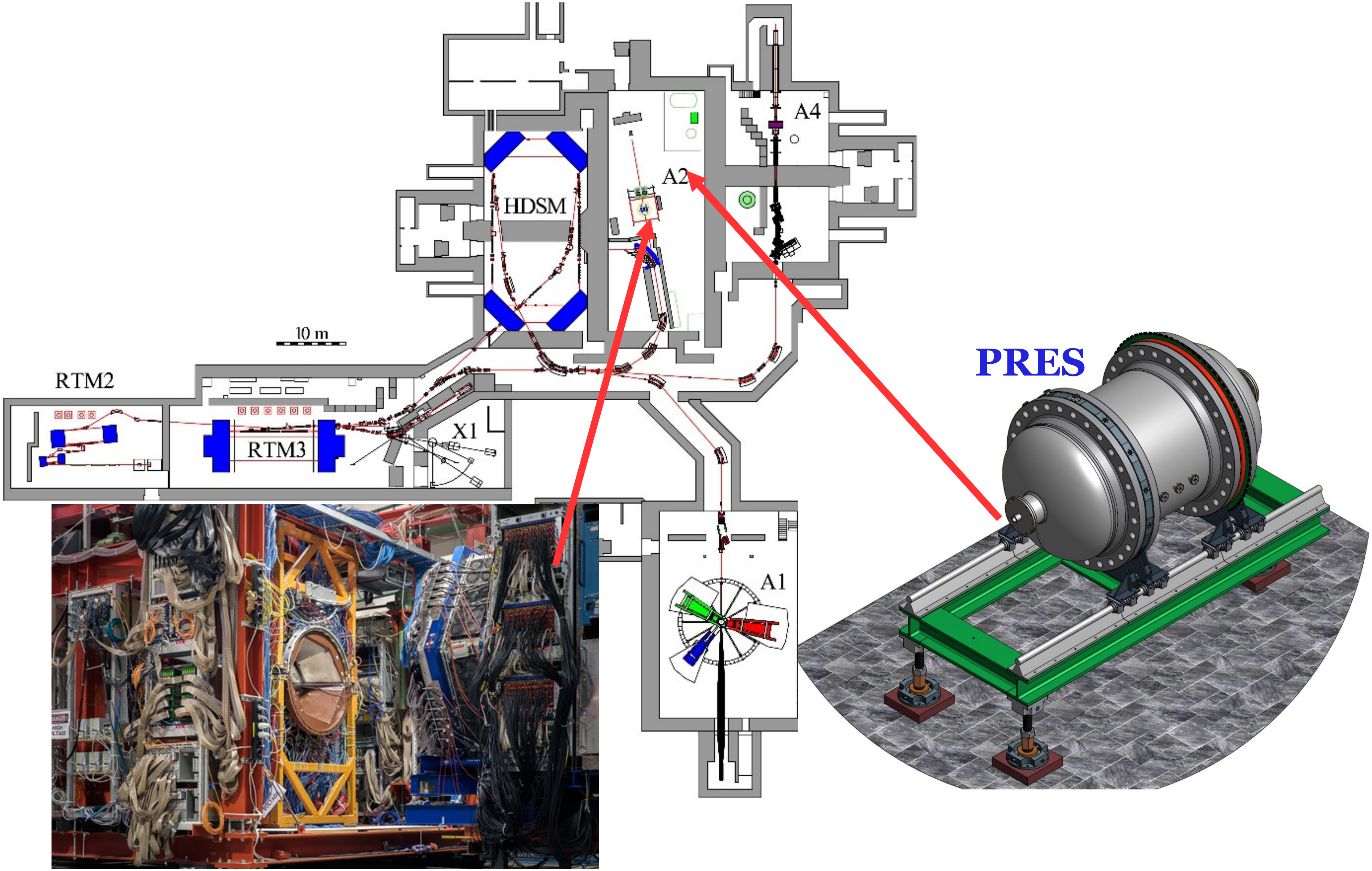
$$\Sigma_{2x} = \frac{\sigma^R_{+x} - \sigma^L_{+x}}{\sigma^R_{+x} + \sigma^L_{+x}} = \frac{\sigma^R_{+x} - \sigma^R_{-x}}{\sigma^R_{+x} + \sigma^R_{-x}}$$

3. Beam: linear, parallel and perpendicular to scattering plane
Target: unpolarized

$$\Sigma_3 = \frac{\sigma^{\parallel} - \sigma^{\perp}}{\sigma^{\parallel} + \sigma^{\perp}}$$

→Extractions of spin polarizabilities with small statistical, systematic, and model-dependent errors

Experiments with Crystal/Ball TAPS + TPC at MAMI



Crystal Ball/TAPS setup

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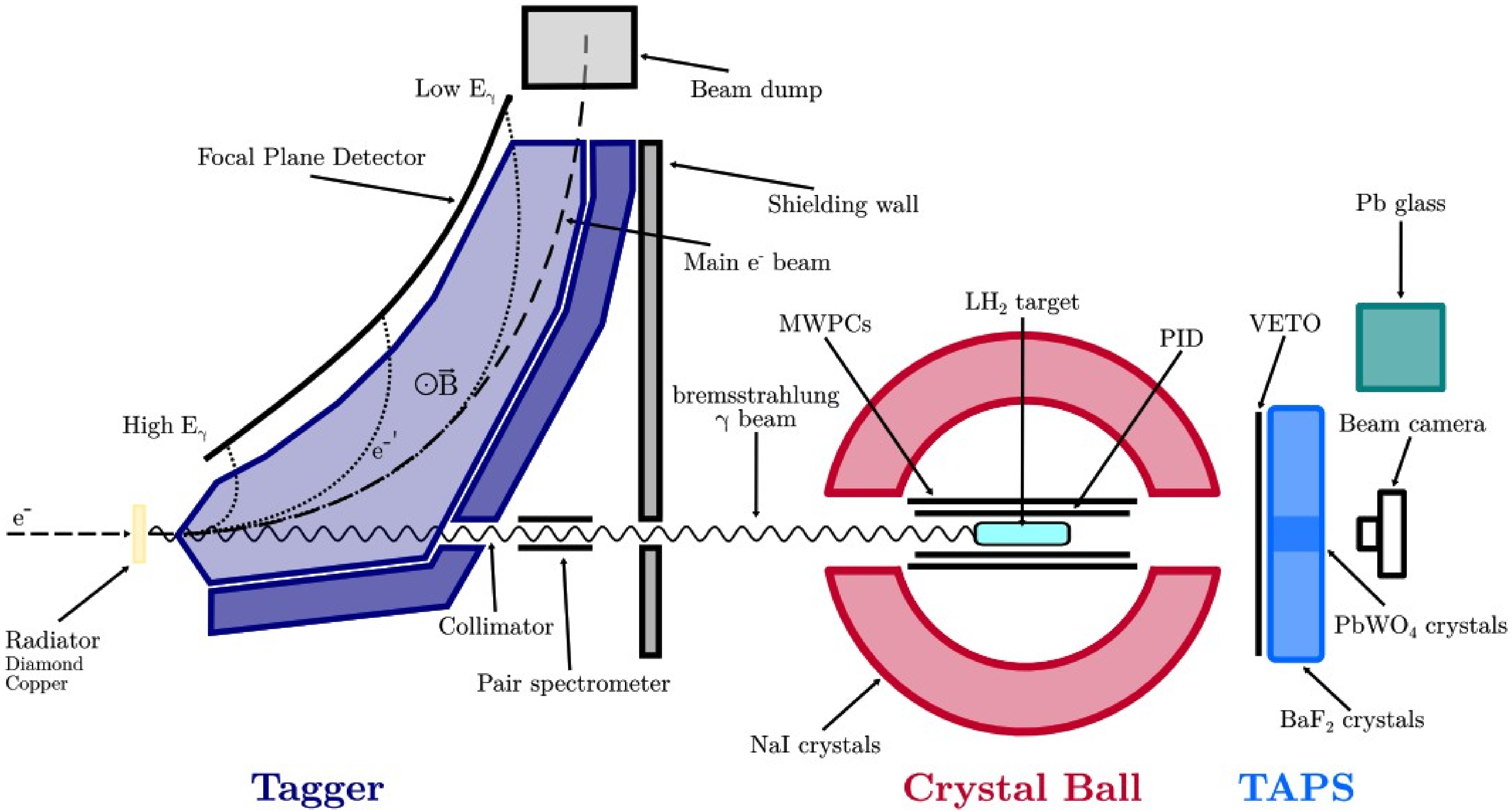
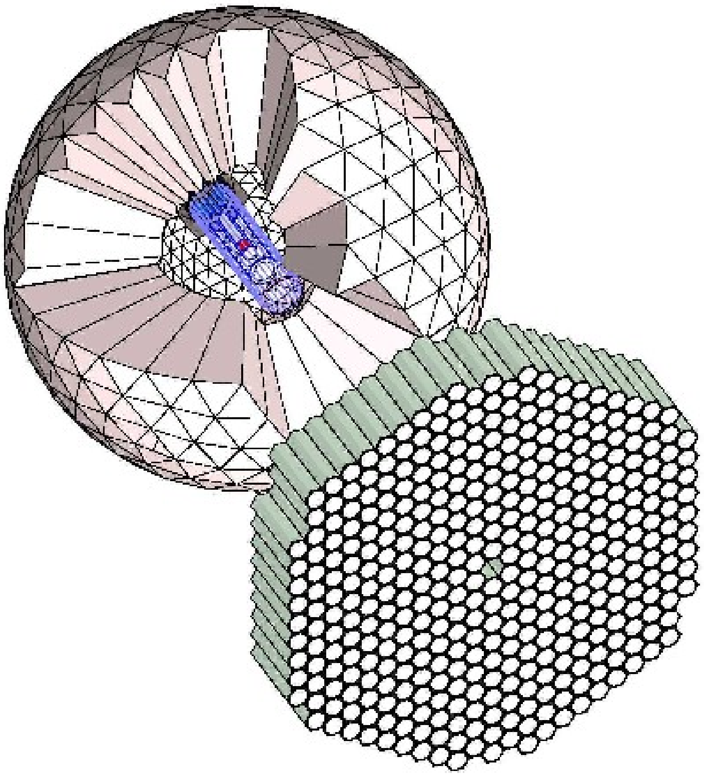
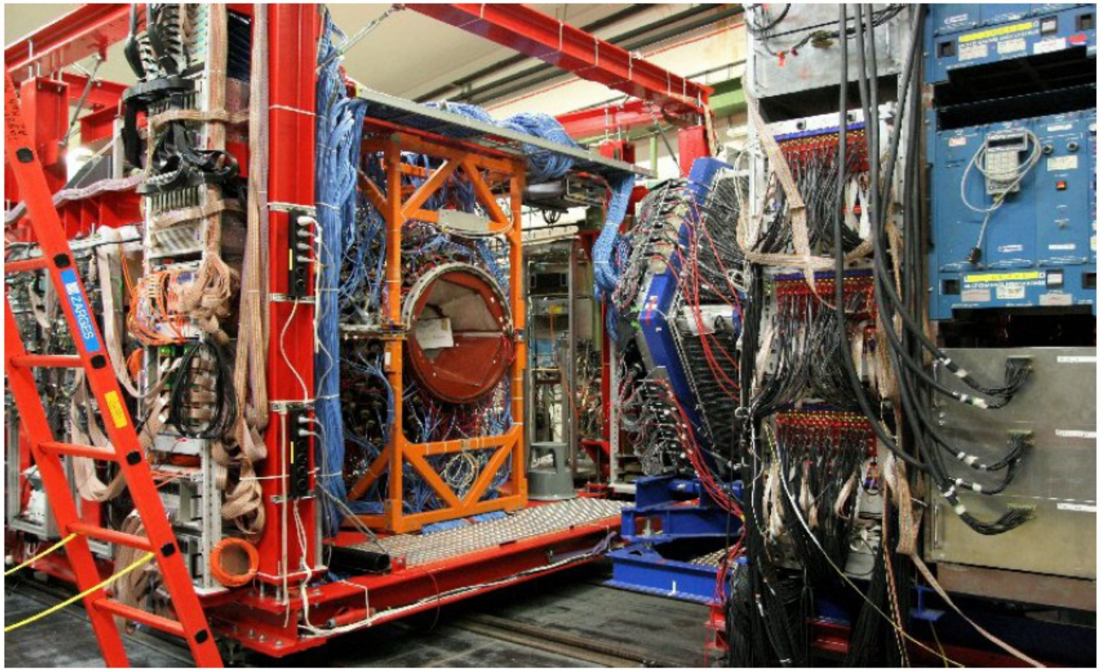


- High-Flux, Tagged, Bremsstrahlung Photon Beam:
  - Unpolarized, Linear, and Circular
  - Polarized and Unpolarized Targets
  - Development of active targets in progress

Crystal Ball/TAPS setup





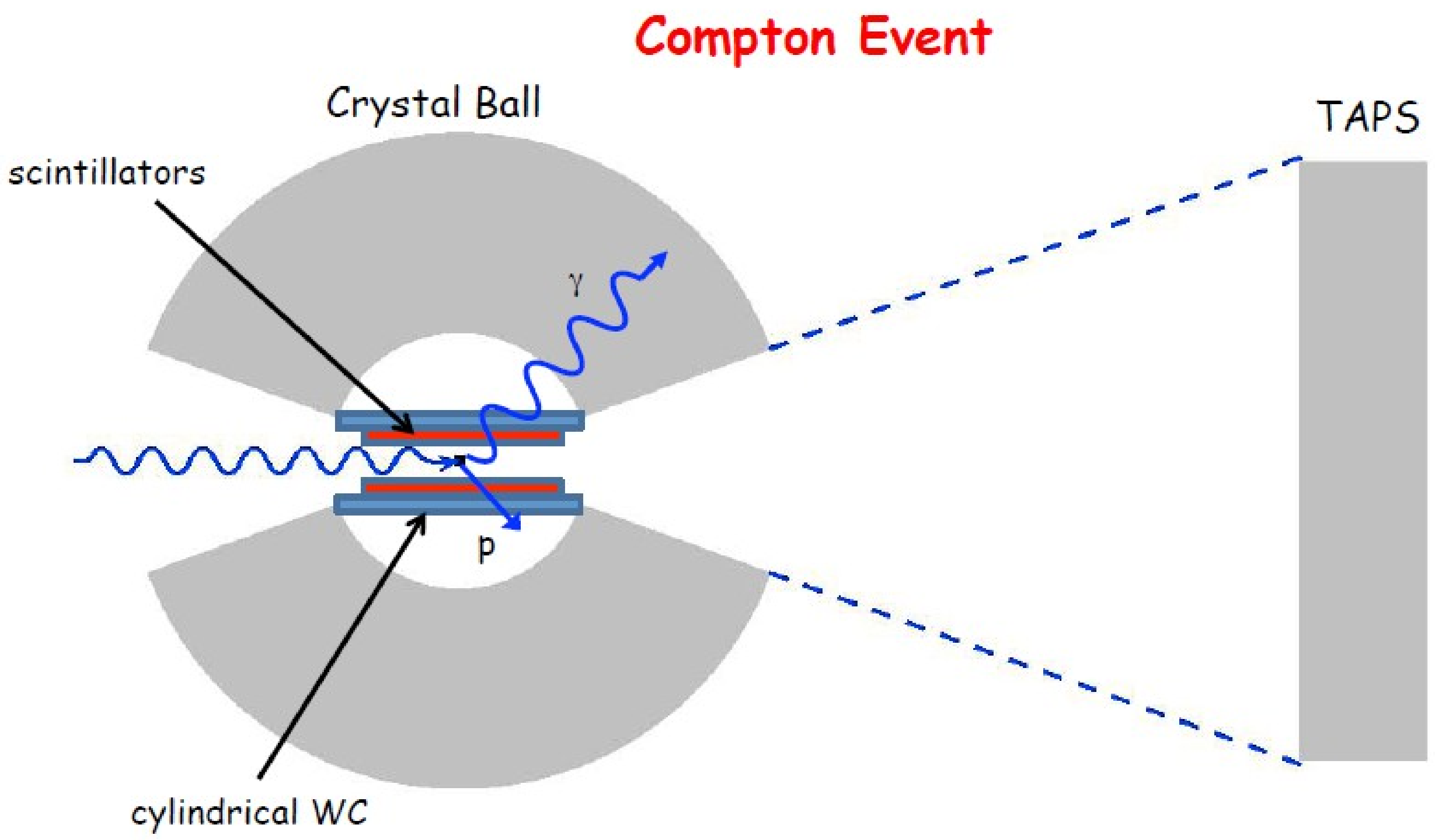
Crystal Ball:

- 672 NaI Crystals
- 24 Particle Identification Detector Paddles
- 2 Multiwire Proportional Chambers

TAPS:

- 366 BaF_2 and 72 $PbWO_4$ Crystals
- 384 Veto Detectors

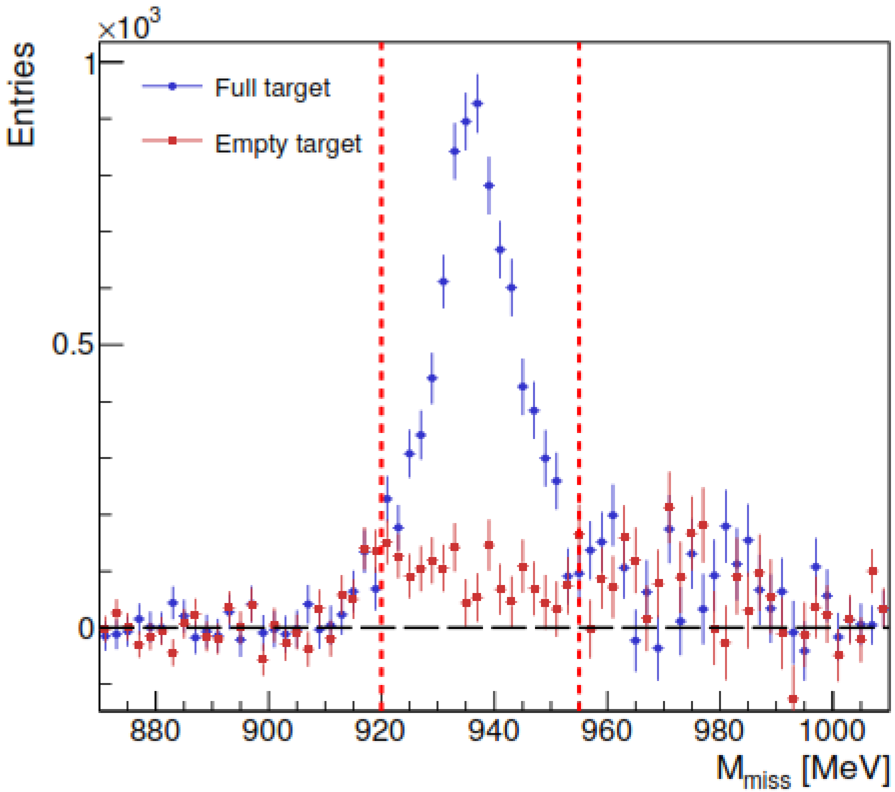
Compton scattering event

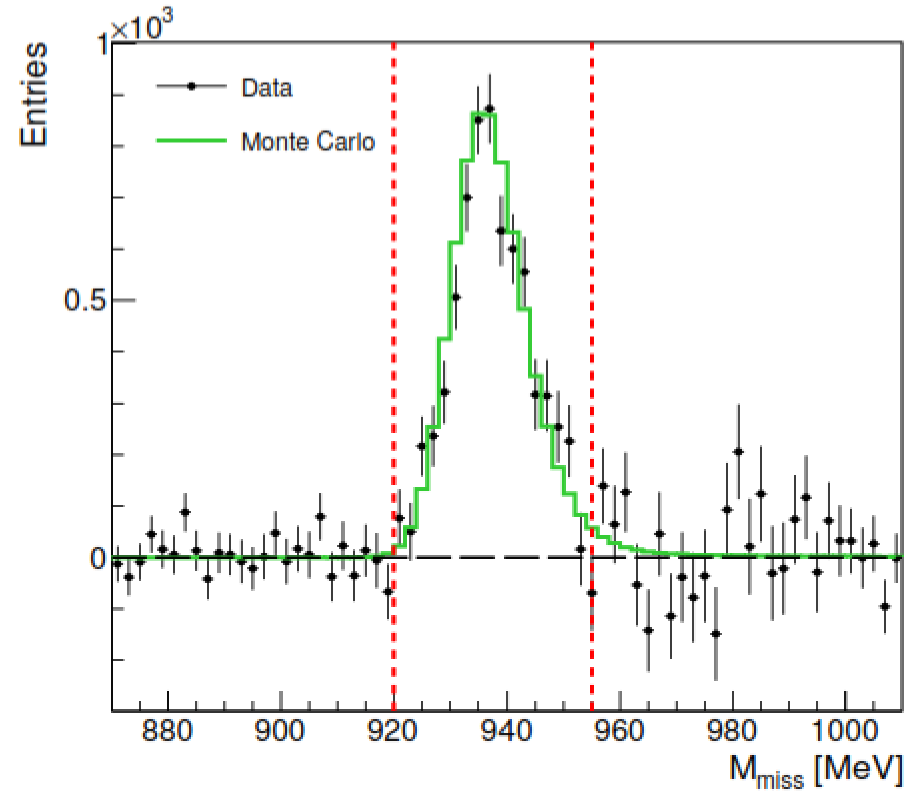


New measurement of the unpolarized cross section and Σ_3

Data analysis:

- Selection of events with one photon at 85-140 MeV and 30° - 150°
- Sampling and subtraction of the random background
- Subtraction of the empty target contribution
- Acceptance correction, flux normalization, estimates for the remaining background,...



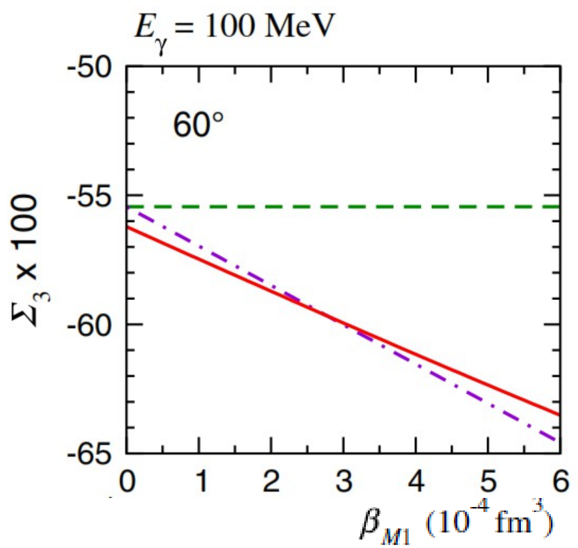


E. Mornacchi et al. [A2 Collaboration] Phys. Rev. Lett. 128, 132503

Improvement in statistics (85 – 140 MeV):

$1.2x10^6$ events: Highest statistics data set for Compton scattering below pion threshold

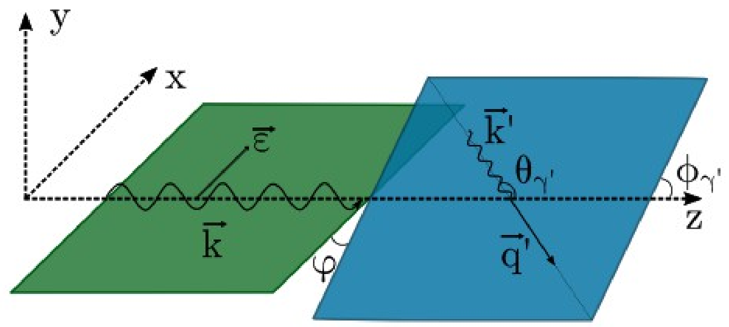
New measurement of the beam asymmetry Σ_3 at MAMI

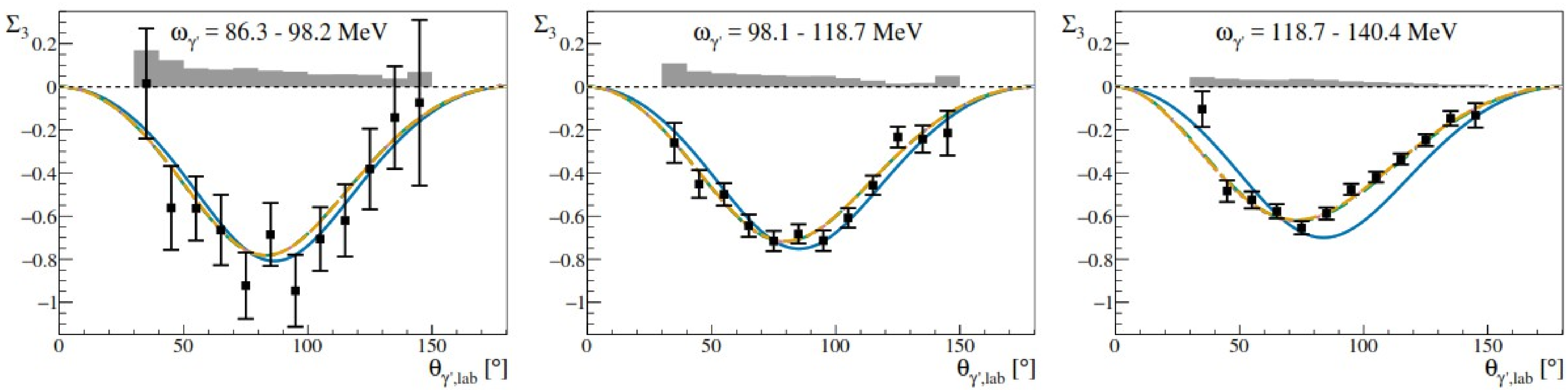


N. Krupina and V. Pascalutsa [PRL 110, 262001 (2013)]

Measured with linearly polarized photons and unpolarized target

$$\Sigma_3 = \frac{\sigma^{\parallel} - \sigma^{\perp}}{\sigma^{\parallel} + \sigma^{\perp}}$$





A2: Phys. Rev. Lett. **128** (2022)

Systematic errors

Born contribution

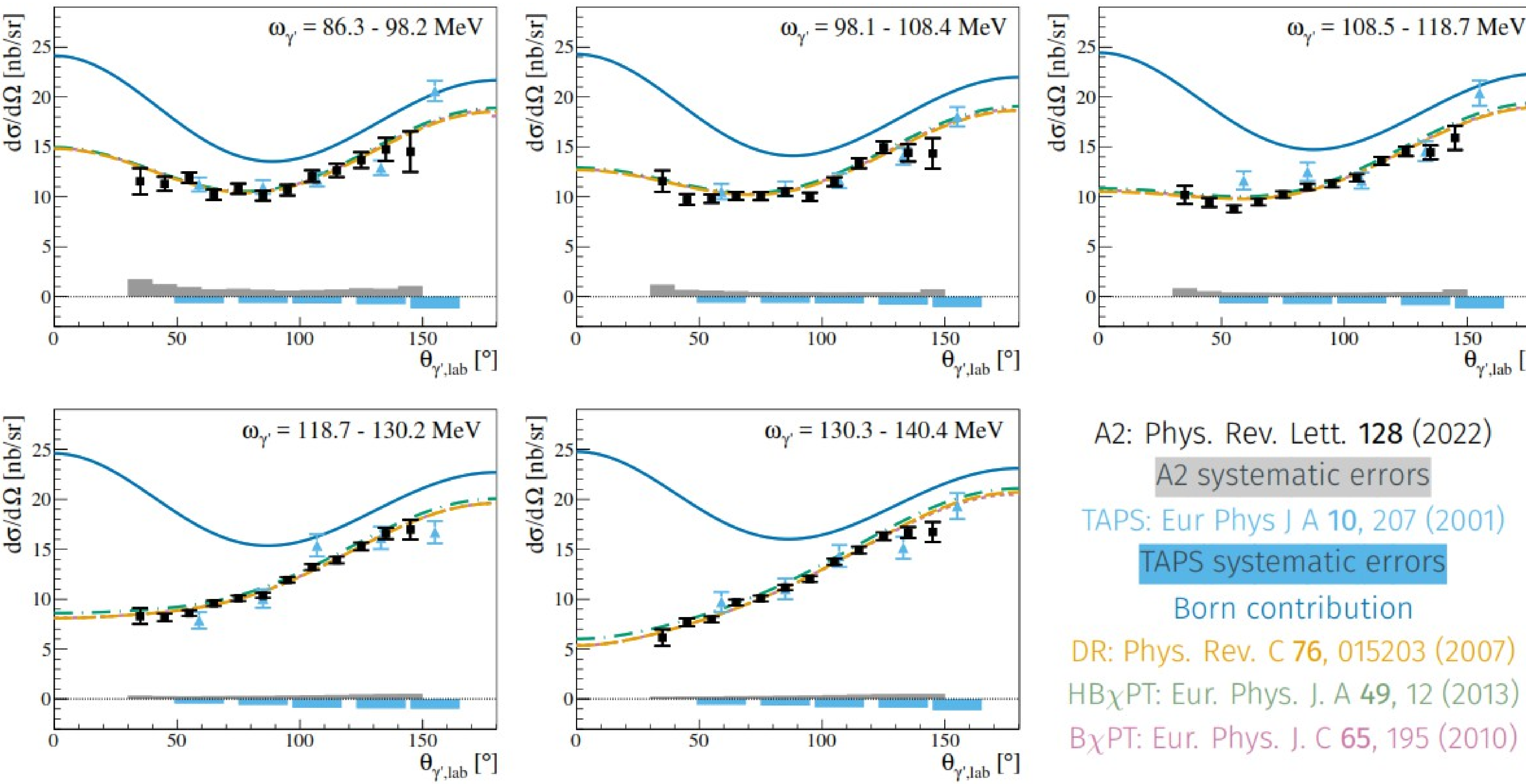
DR: Phys. Rev. C **76**, 015203 (2007)

BχPT: Eur. Phys. J. C **65**, 195 (2010)

HBχPT: Eur. Phys. J. A **49**, 12 (2013)

E. Mornacchi et al. [A2 Collaboration] Phys. Rev. Lett. 128, 132503

New measurement of the unpolarized cross section at MAMI



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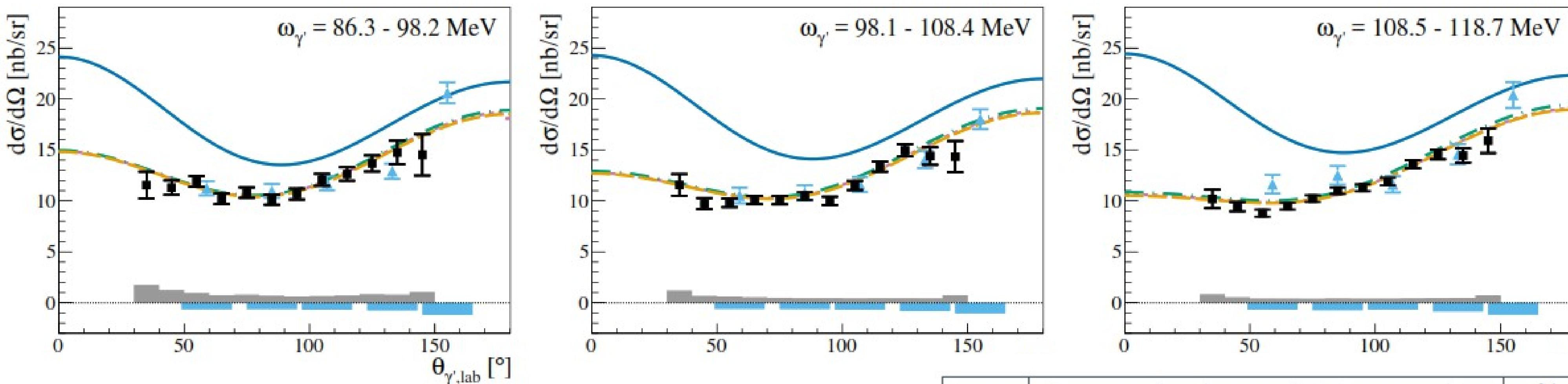
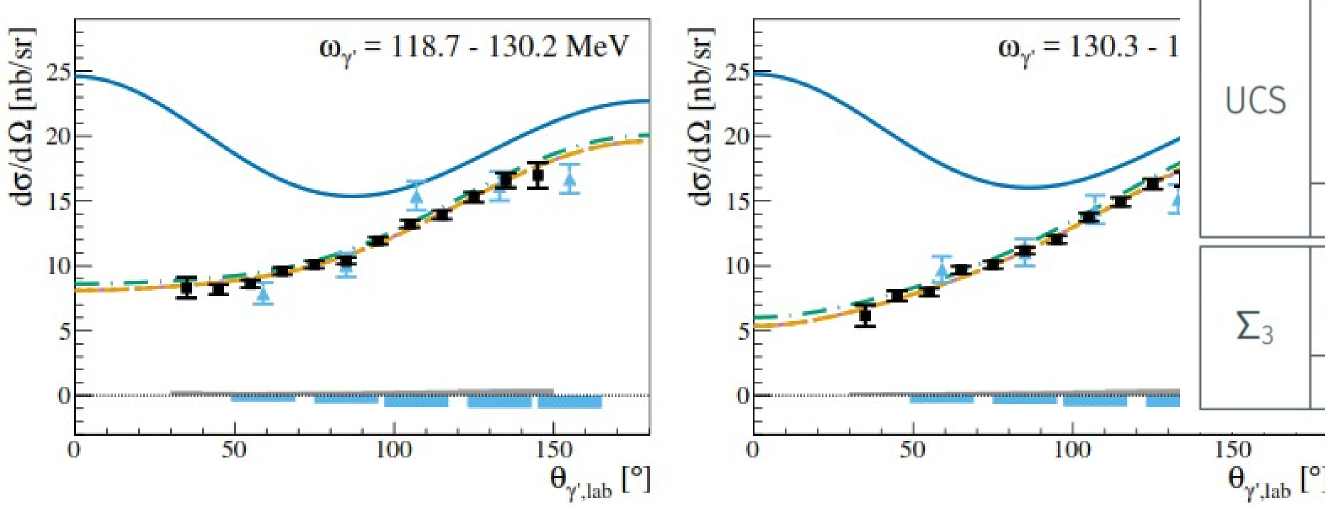


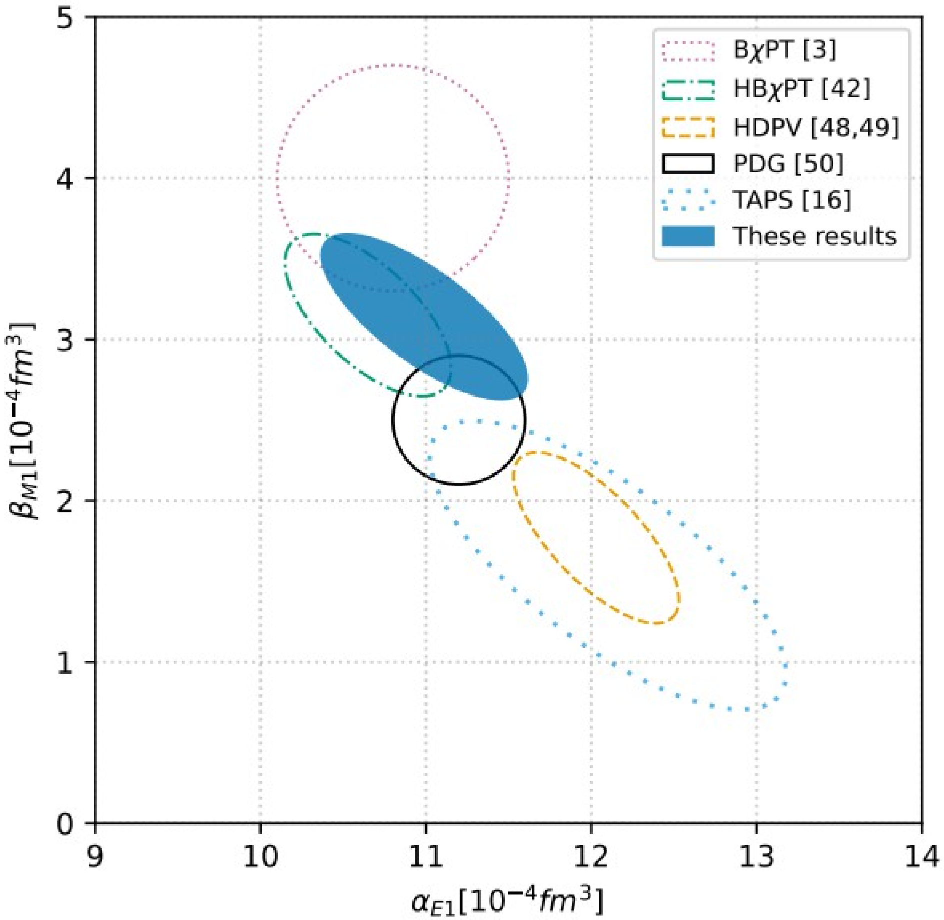


UCS	Event selection and MC correction	2%
	Target density	1%
	Flux normalization	2%
	Background	uncorr.
	TOTAL	**3%**
Σ_3	Linear polarization	5%
	Background	uncorr.
	TOTAL	**5%**

BχPT: Eur. Phys. J. C **65**, 195 (2010)

E. Mornacchi et al. [A2 Collaboration] Phys. Rev. Lett. 128, 132503

Extraction of the scalar polarizabilites of the proton



$$\alpha_{E1} = 10.99 \pm 0.16 \pm 0.47 \pm 0.17 \pm 0.34$$

$$\beta_{M1} = 3.14 \pm 0.21 \pm 0.24 \pm 0.20 \pm 0.35$$

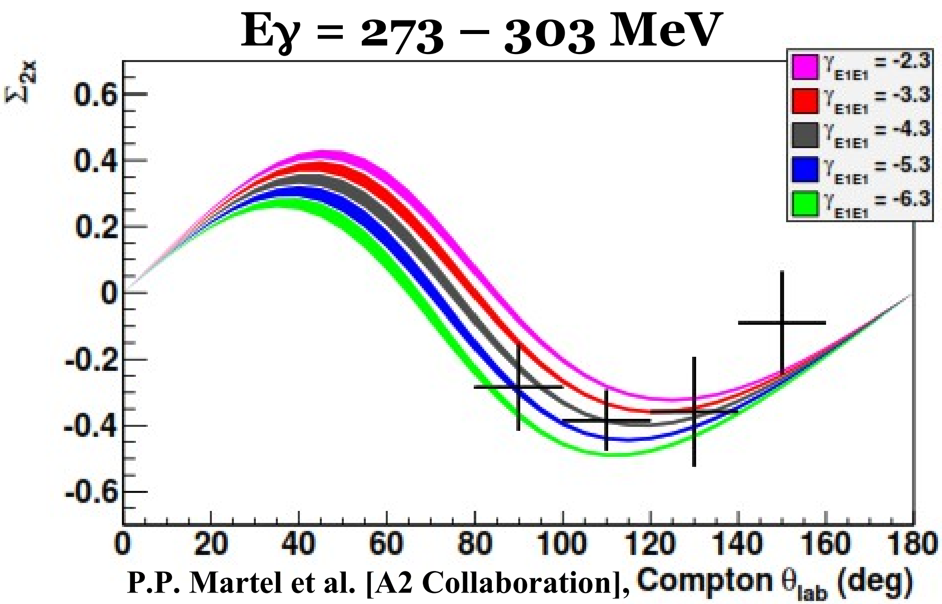
(stat) (syst) (spin pol.) (model dep.)

- Highest precision Compton scattering dataset below pion photoproduction threshold
- Most precise extraction of the proton scalar polarizabilities from a single dataset

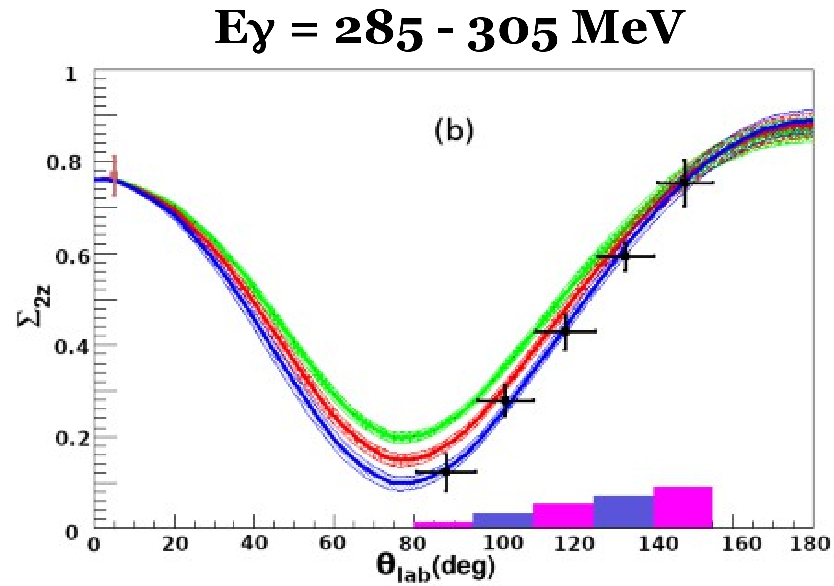
	HDPV	BχPT	HBχPT
α_{E1}	$11.23 \pm 0.16 \pm 0.46 \pm 0.02$	$10.65 \pm 0.16 \pm 0.47 \pm 0.04$	$11.10 \pm 0.16 \pm 0.47 \pm 0.17$
β_{M1}	$2.79 \pm 0.20 \pm 0.23 \pm 0.11$	$3.28 \pm 0.21 \pm 0.24 \pm 0.09$	$3.36 \pm 0.21 \pm 0.24 \pm 0.20$

E. Mornacchi et al. [A2 Collaboration] Phys. Rev. Lett. 128, 132503

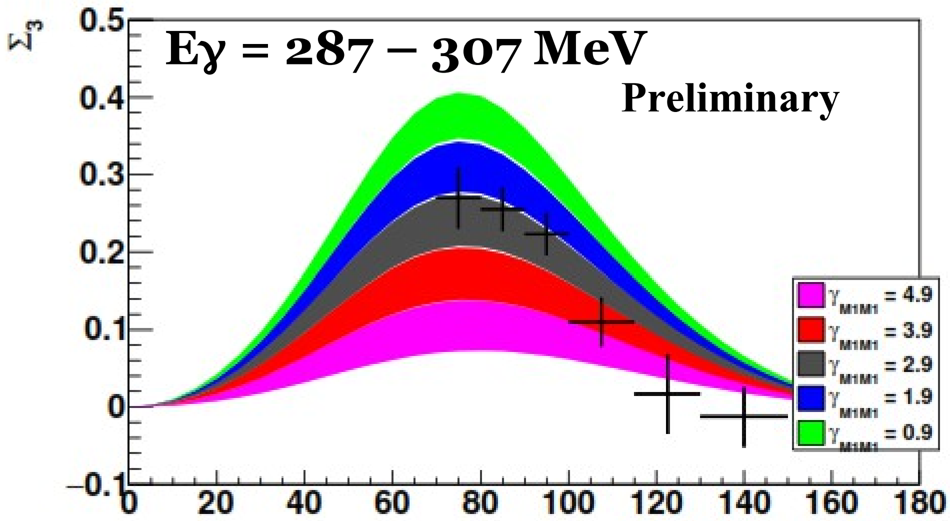
Spin polarizabilities



P.P. Martel et al. [A2 Collaboration], Phys. Rev. Lett. 114, 112501 (2015)



D. Paudyal, et al. [A2 Collaboration]
Phys. Rev. C 102, 035205 (2020)



C. Collicott et al. [A2 Collaboration]

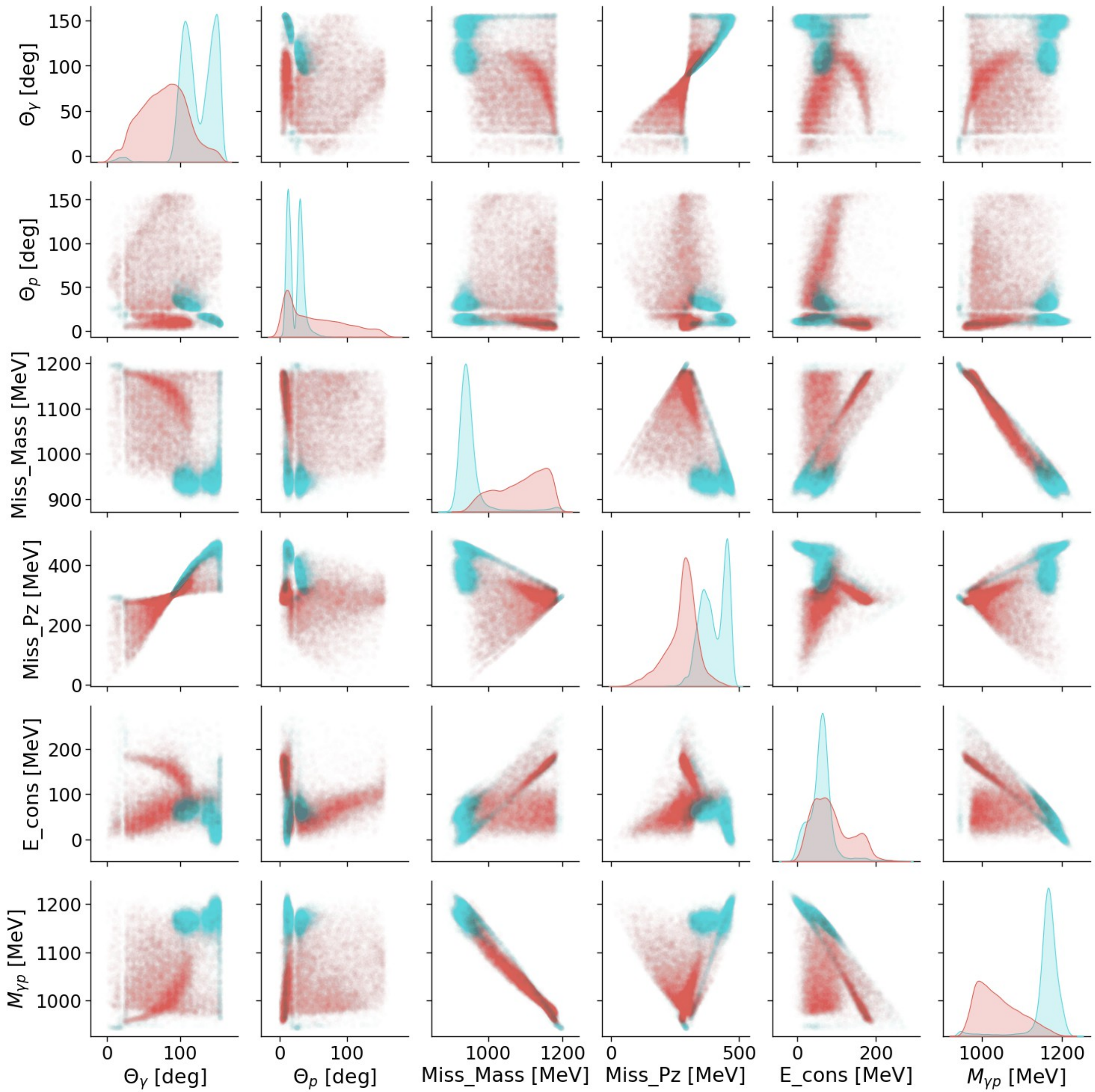
	Σ_{2z}, Σ_{2x}, and Σ_3^{LEGS} data fits		
	HDPV	BχPT	Weighted average
γ_{E1E1}	-3.18 ± 0.52	-2.65 ± 0.43	-2.87 ± 0.52
γ_{M1M1}	2.98 ± 0.43	2.43 ± 0.42	2.70 ± 0.43
γ_{E1M2}	-0.44 ± 0.67	-1.32 ± 0.72	-0.85 ± 0.72
γ_{M1E2}	1.58 ± 0.43	2.47 ± 0.42	2.04 ± 0.43
χ^2/dof	1.14	1.36	

The data sets in the Δ region suffer from the contamination with pion background:

$\gamma + p \rightarrow p + \pi^0 \rightarrow (p + \gamma) + \gamma$

→Development of Machine Learning-based methods for the selection of Compton events

Separation of pion and Compton events in the Δ region with AI (ML)

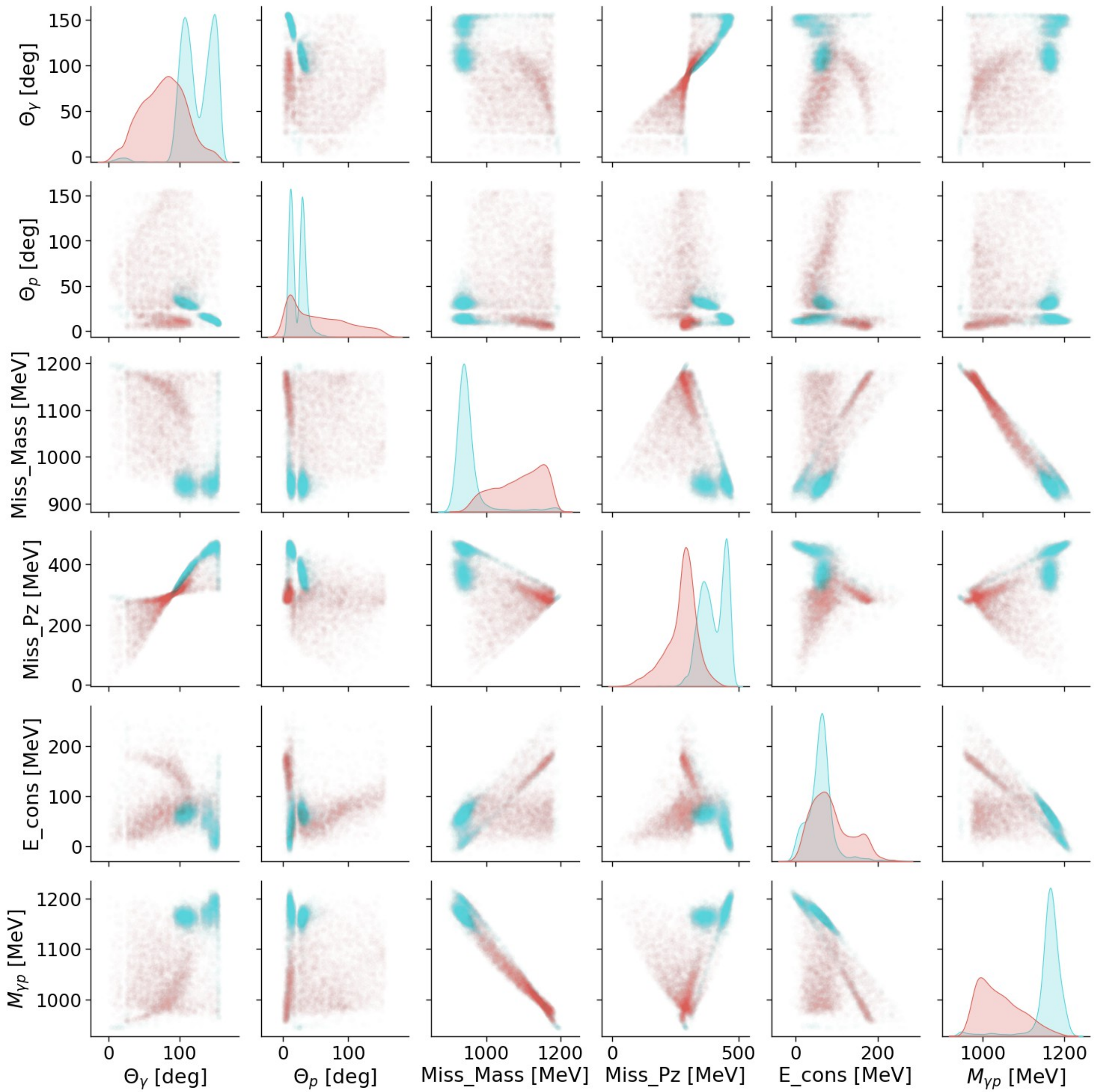


Input MC for model training:
→295 - 305 MeV, γ + p events
→Notable overlap in 1D
→Complex shapes in 2D with opportunity of separation

Processing the data:
→Mix Compton and pion events
→Reshuffle the (labeled) data
→Split the data into training and validation data sets
→Train and evaluate the model

Blue: Compton MC
Red: Pion MC

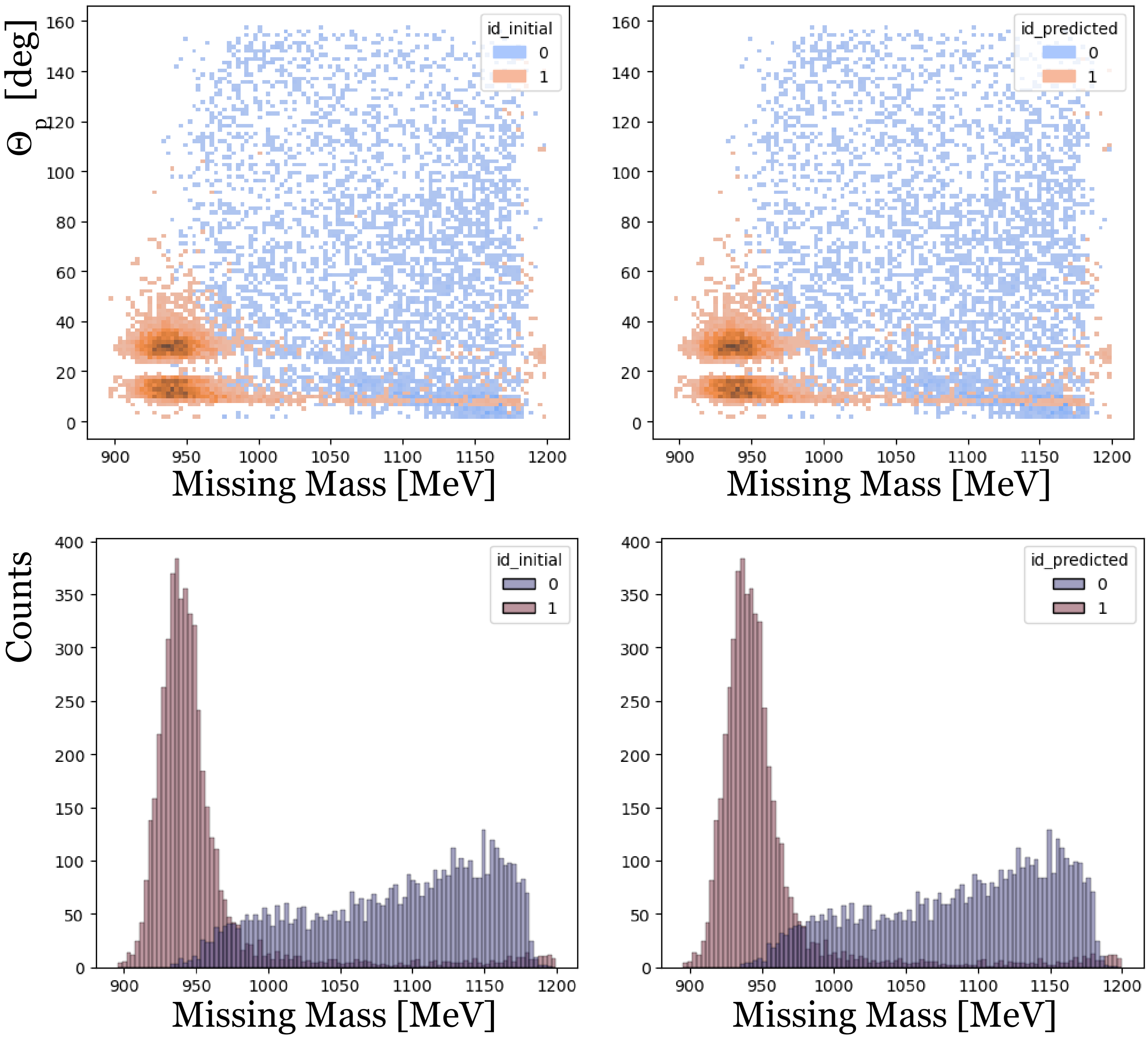
Separation of pion and Compton events in the Δ region with AI (ML)



Predicted distributions for the validation data set agree well with the initial MC data set (predicted with 99% accuracy) →Application on experimental data

Blue: Compton MC
Red: Pion MC

Separation of pion and Compton events in the Δ region with AI (ML)

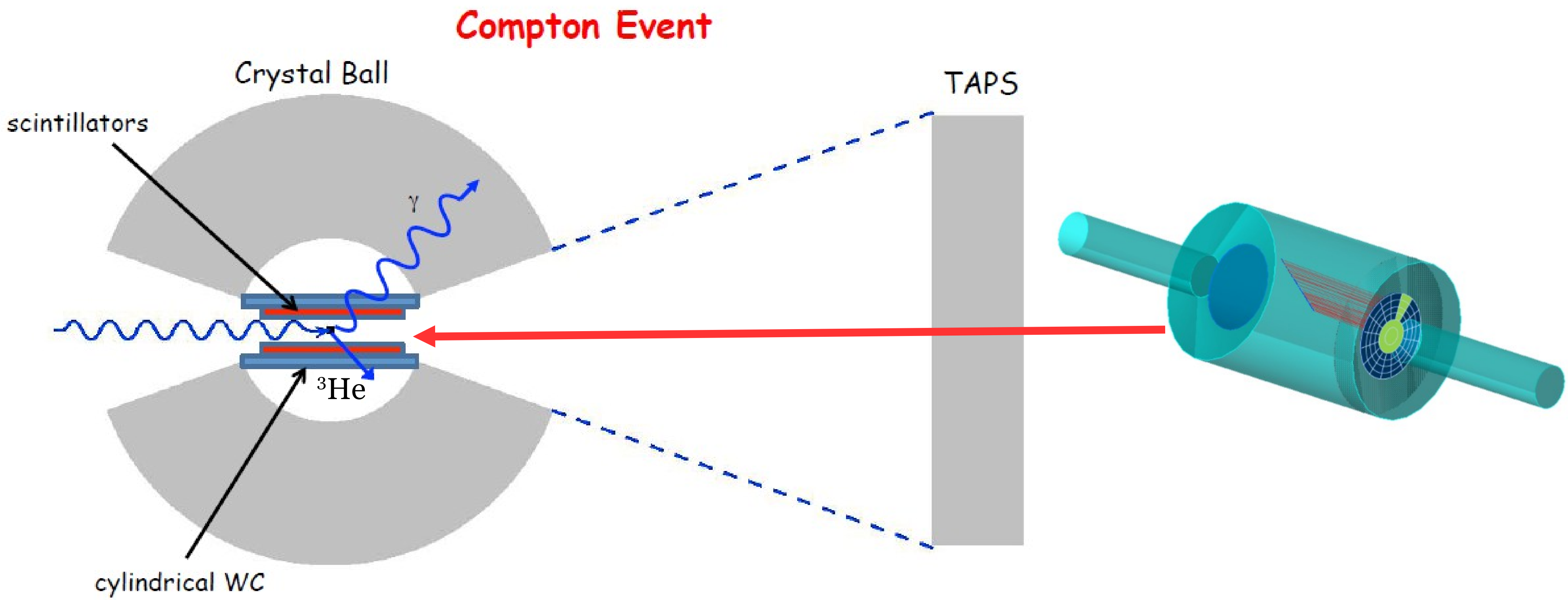


Initial and predicted MC agree (also in the overlap region)

Orange: Compton MC
Blue: Pion MC

→ Application on the data

Neutron polarizabilities

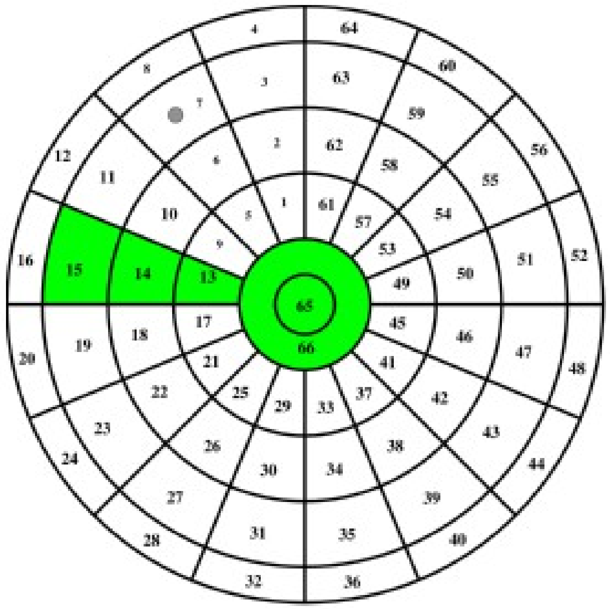


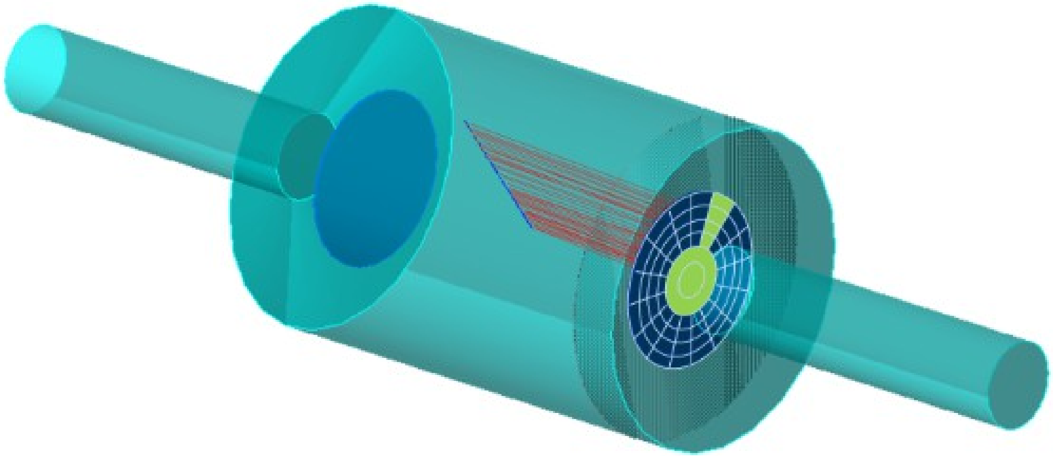
Detection of low-energy recoil particles with high energy resolution in combination with the scattered photon

- Simultaneous detection of the scattered photon and recoil nucleus
- Measurement of neutron polarizabilities via elastic scattering on light nuclei ($\gamma + {}^3He \rightarrow \gamma + {}^3He$, $\gamma + {}^4He \rightarrow \gamma + {}^4He$, $\gamma + d \rightarrow \gamma + d$)
- Measurement of form factors via dilepton photoproduction, lepton universality test

TPC properties (to be constructed)

Segmented anode

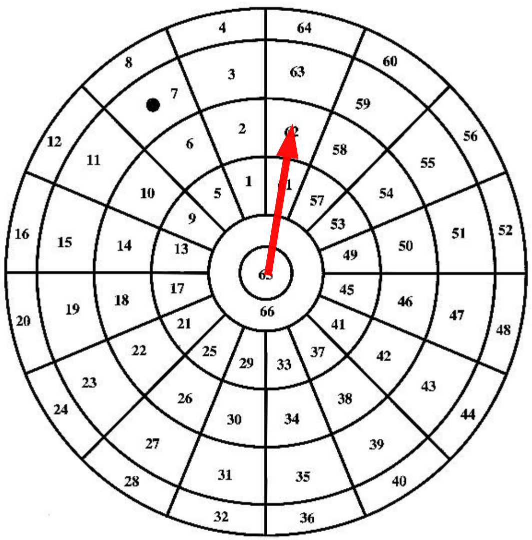




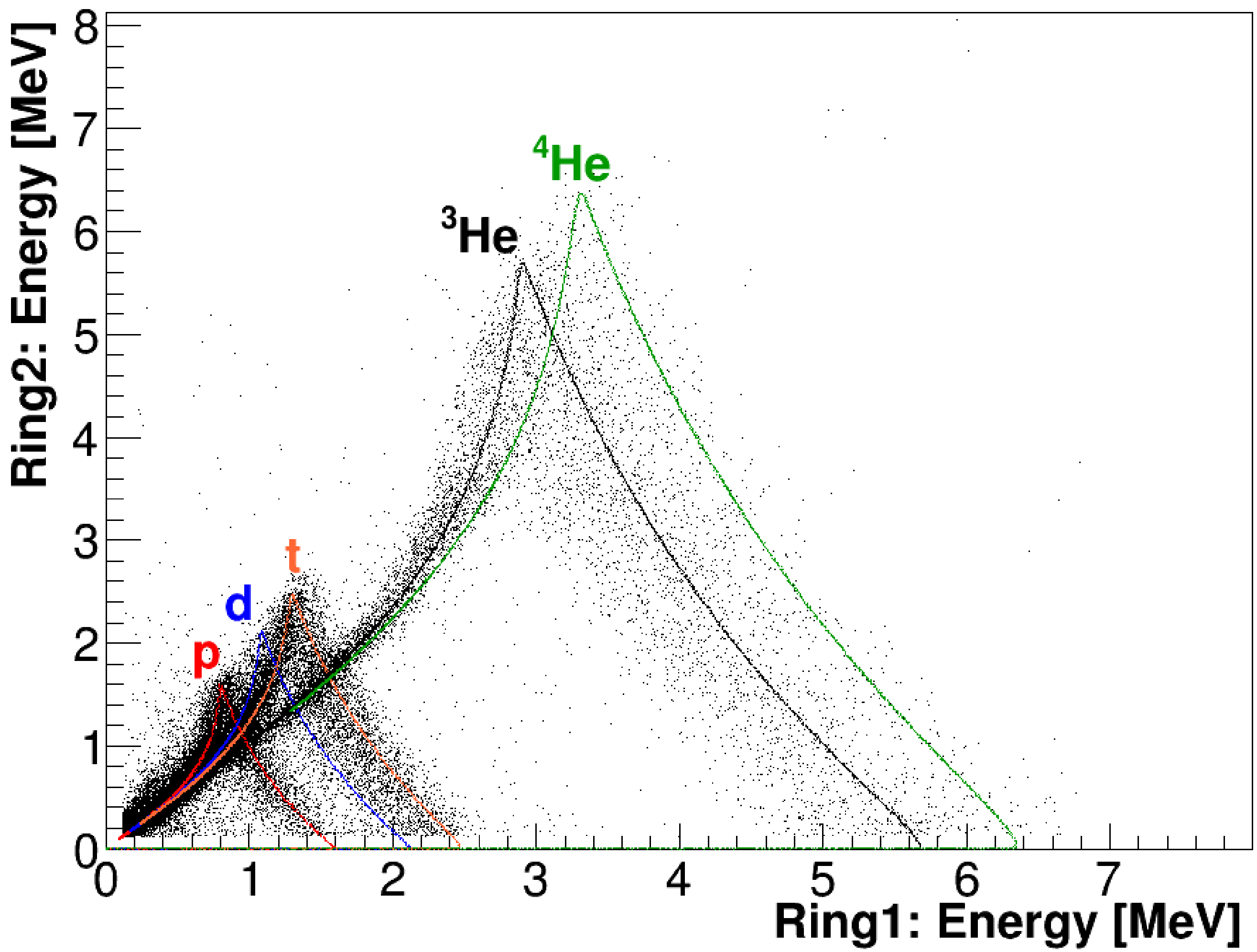
Possible parameters (based on prototype TPC performance and MC):

- Small size (diameter = 200 mm) in A2
- Length of the active volume: ~20 cm
- Pressure up to 25 bar, mixture of helium and hydrogen (~10%), pure hydrogen, ...
- Energy resolution: 20-30 keV, resolution in polar angle: 2-3°, azimuthal angle measurement possible if the anode is segmented in phi
- Vertex reconstruction (Z with resolution better than 0.5 mm)

Separation of recoil fragments with TPC



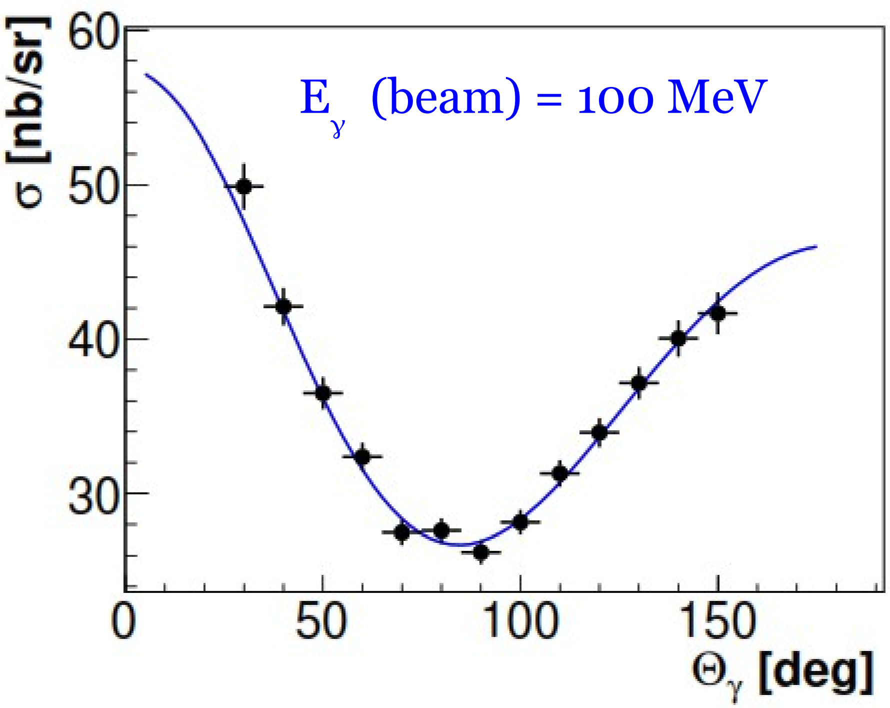
Anode structure of the prototype TPC (ACTAF2)

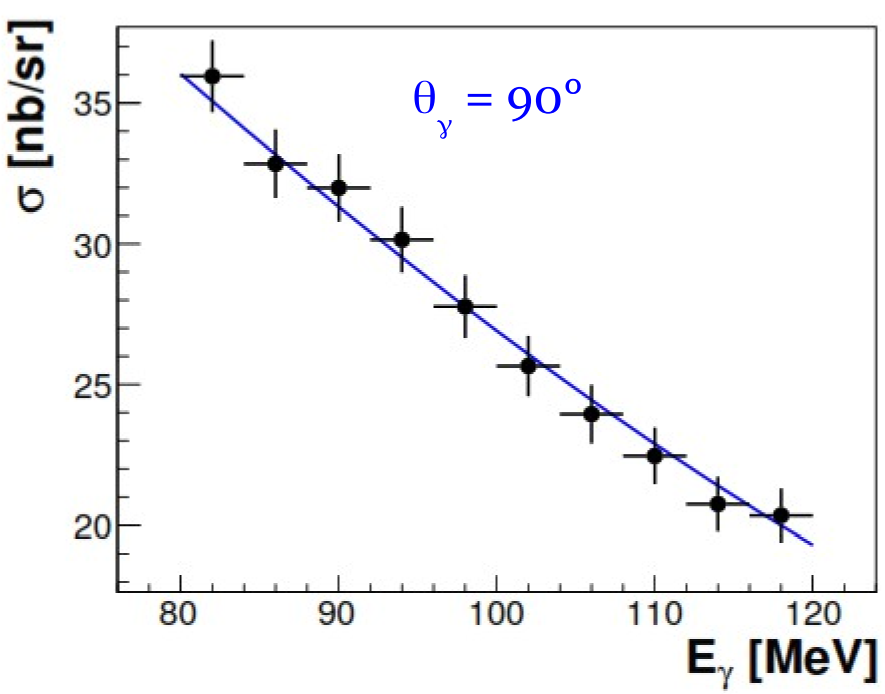


(Curves: Simulation by Alexander Inglessi (PNPI))

- Data taken with MAMI electron beam and a protype TPC at 10 bar
- Contributions corresponding to different recoil fragments clearly visible!

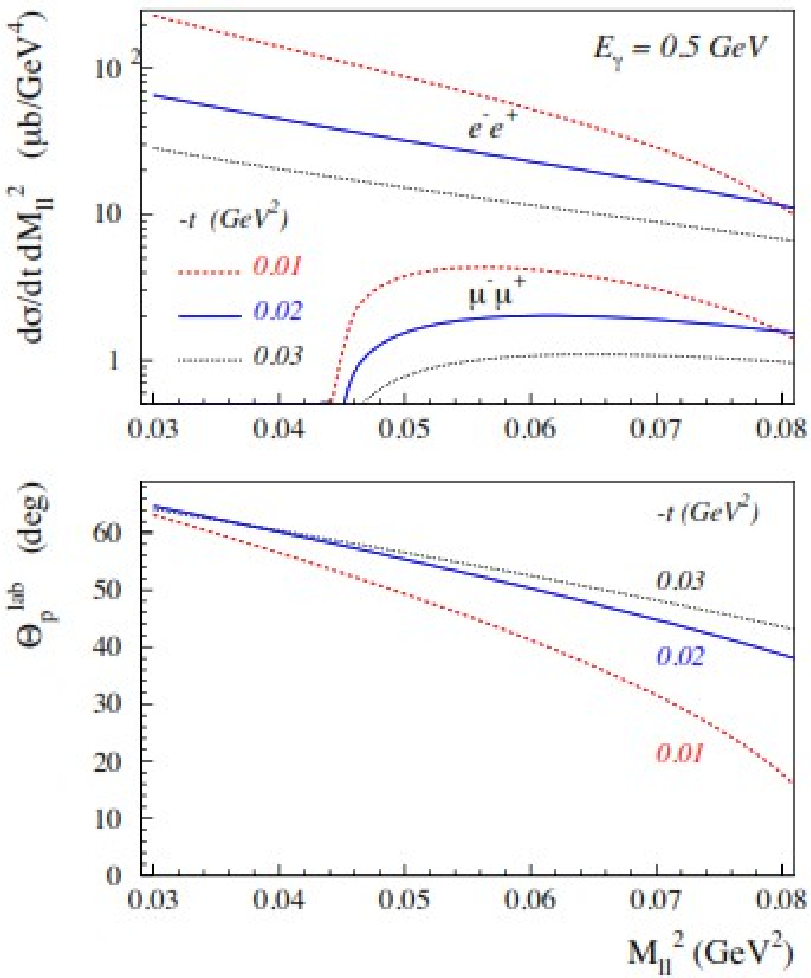
Expected accuracy for measurements with ^{3}He





Feasibility studies (Monte Carlo simulations) for the measurement of nucleon polarizabilities with TPC filled with ^{3}He (20 bar) in combination with the A2 setup:
→Fitting done with theoretical framework for ^{3}He from H. Grießhammer et al.
→Improvement in the uncertainties of the neutron polarizabilities by factor of 2

Measuring proton radius via dilepton photoproduction with TPC@A2



$$A_{lU} = \frac{d\sigma_{\parallel} - d\sigma_{\perp}}{d\sigma_{\parallel} + d\sigma_{\perp}},$$

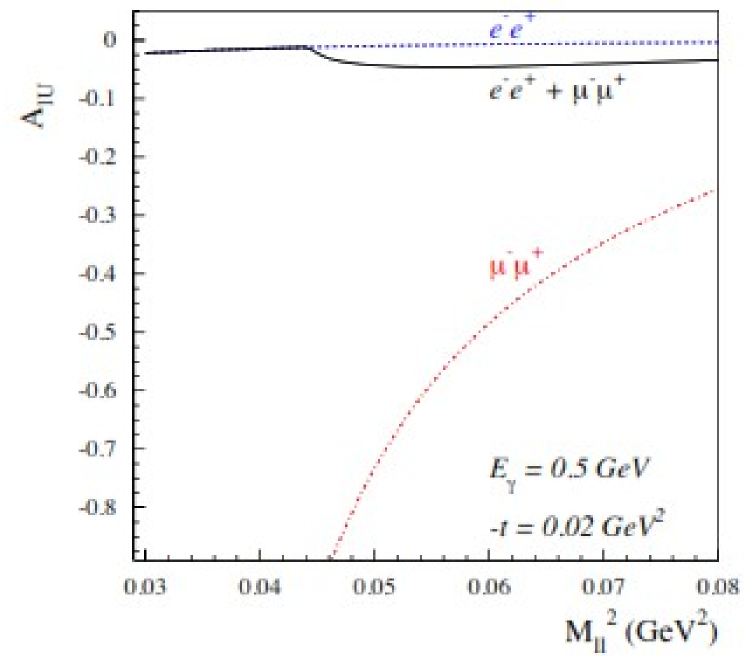


FIG. 4: Linear photon asymmetry A_{lU} of the $\gamma p \to (l^- l^+)\, p$ process. The dashed (blue) curve corresponds with e^-e^+ production; the dashed-dotted (red) curve corresponds with $\mu^-\mu^+$ production. The solid (black) curve is the asymmetry corresponding with the sum of the $e^-e^+ + \mu^-\mu^+$ channels according to Eq. (12).

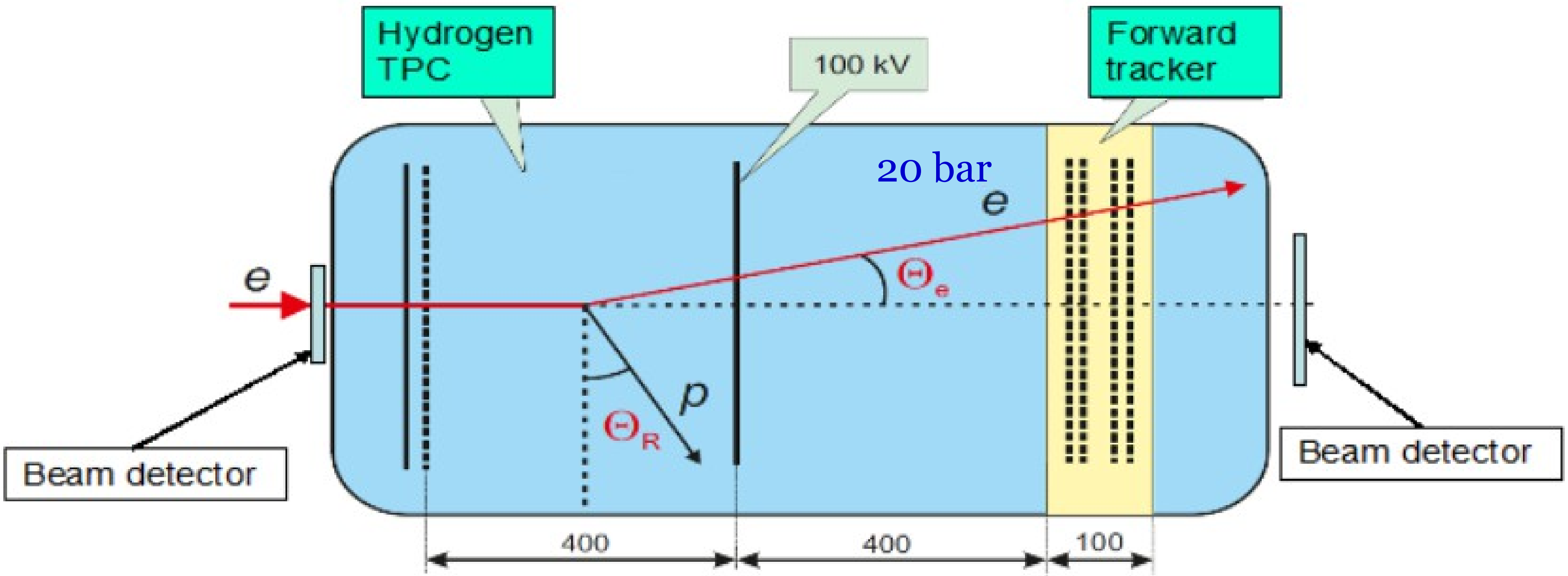
V. Pauk and M. Vanderhaeghen Phys.Rev.Lett. **115**, 221804 (2015)

- Range in Q^2 for the recoil proton corresponds to the coverage of the (potential) TPC
- Measurements possible for the proton, deuteron, helium,...
- Systematic studies + MC required
- The feasibility of the lepton universality test to be studied

PRES experiment: Measurements with active TPC at MAMI

Proton radius measurement with a completely different systematics:

- Electron scattering with detection of both recoil proton and scattered electron
- Measurement of polarizabilities, dilepton photoproduction, (A2 + small TPC)



- Measurements a low Q^2 ($0.001\ GeV^2 \leq Q^2 \leq 0.02\ (0.04)\ GeV^2$)
- TPC and Forward Tracker constructed at PNPI
- Hydrogen, deuterium, helium gas filling possible
- Close synergy with PRM@AMBER (lepton universality, input from TPC@MAMI …)

The experiment is presently on hold …

Summary

Measurement of nucleon polarizabilities with the A2 setup:

- High-statistics data set acquired: 1.2 • 10^6 Compton scattering events at 85 – 140 MeV
- Determination of scalar polarizabilities of the proton with unprecedented high precision from a single data set!
- Extraction of spin polarizabilities using Compton scattering data in the Δ region (AI-based analysis methods under development)

→Measurement of neutron polarizabilities with TPC as an active target

Measurement of the proton radius in the A2 Hall:

→Measurement of the proton radius with PRES experiment presently on hold

→Measurement of the proton radius via dilepton photoproduction with the CB/TAPS + TPC possible (detailed feasibility studies required)

Summary

Measurement of nucleon polarizabilities with the A2 setup:

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Thank you for your attention!

Backup

Proton: PDG status (2023)

p ELECTRIC POLARIZABILITY α_p	0.00112 ± 0.00004 fm^3
p MAGNETIC POLARIZABILITY β_p	$(2.5 \pm 0.4) \times 10^{-4}$ fm^3 (S = 1.2)

VALUE (10^{-4} fm^3)	*DOCUMENT ID*		*TECN*	*COMMENT*
11.2 ± 0.4 OUR AVERAGE				
$10.65 \pm 0.35 \pm 0.36$	MCGOVERN	2013	RVUE	χEFT + Compton scattering
$12.1 \pm 1.1 \pm 0.5$	[1] BEANE	2003		EFT + γp
$11.82 \pm 0.98\ ^{+0.52}_{-0.98}$	[2] BLANPIED	2001	LEGS	$p(\vec{\gamma},\gamma)$, $p(\vec{\gamma},\pi^0)$, $p(\vec{\gamma},\pi^+)$
$11.9 \pm 0.5 \pm 1.3$	[3] OLMOSDELEO..	2001	CNTR	γp Compton scattering
$12.1 \pm 0.8 \pm 0.5$	[4] MACGIBBON	1995	RVUE	global average

VALUE (10^{-4} fm^3)	*DOCUMENT ID*		*TECN*	*COMMENT*
2.5 ± 0.4 OUR AVERAGE Error includes scale factor of 1.2.				
$3.15 \pm 0.35 \pm 0.36$	MCGOVERN	2013	RVUE	χEFT + Compton scattering
$3.4 \pm 1.1 \pm 0.1$	[1] BEANE	2003		EFT + γp
$1.43 \pm 0.98\ ^{+0.52}_{-0.98}$	[2] BLANPIED	2001	LEGS	$p(\vec{\gamma},\gamma)$, $p(\vec{\gamma},\pi^0)$, $p(\vec{\gamma},\pi^+)$
$1.2 \pm 0.7 \pm 0.5$	[3] OLMOSDELEO..	2001	CNTR	γp Compton scattering
$2.1 \pm 0.8 \pm 0.5$	[4] MACGIBBON	1995	RVUE	global average

Neutron: PDG status (2023)

n ELECTRIC POLARIZABILITY α_n	0.00118 ± 0.00011 fm^3
n MAGNETIC POLARIZABILITY β_n	$(3.7 \pm 1.2) \times 10^{-4}$ fm^3

VALUE (10^{-4} fm^3)		*DOCUMENT ID*		*TECN*	*COMMENT*
11.8 ± 1.1	**OUR AVERAGE**				
$11.55 \pm 1.25 \pm 0.8$		MYERS	2014	CNTR	$\gamma\, d \to \gamma d$
$12.5 \pm 1.8\ ^{+1.6}_{-1.3}$		[1] KOSSERT	2003	CNTR	$\gamma\, d \to \gamma pn$
$12.0 \pm 1.5 \pm 2.0$		SCHMIEDMAY..	1991	CNTR	nPb transmission
$10.7\ ^{+3.3}_{-10.7}$		ROSE	1990B	CNTR	$\gamma\, d \to \gamma np$

VALUE (10^{-4} fm^3)		*DOCUMENT ID*		*TECN*	*COMMENT*
3.7 ± 1.2	**OUR AVERAGE**				
$3.65 \pm 1.25 \pm 0.8$		MYERS	2014	CNTR	$\gamma\, d \to \gamma d$
$2.7 \pm 1.8\ ^{+1.3}_{-1.6}$		[1] KOSSERT	2003	CNTR	$\gamma\, d \to \gamma pn$
$6.5 \pm 2.4 \pm 3.0$		[2] LUNDIN	2003	CNTR	$\gamma\, d \to \gamma d$

Dilepton photoproduction

$$\frac{d\sigma^{BH}}{dt\, dM_{ll}^2} = \frac{\alpha^3}{(s-M^2)^2} \cdot \frac{4\beta}{t^2(M_{ll}^2 - t)^4} \cdot \frac{1}{1+\tau} \times \left\{ C_E\, G_{Ep}^2 + C_M\, \tau\, G_{Mp}^2 \right\},$$

with $\alpha \equiv e^2/4\pi \approx 1/137$, where $\beta \equiv \sqrt{1 - \frac{4m^2}{M_{ll}^2}}$ is the lepton velocity in the $l^- l^+$ *c.m.* frame, with m the lepton mass, and where the proton FFs G_{Ep} and G_{Mp} are functions of t. The weighting coefficients multiplying the FFs in Eq. (4) have the following general structure :

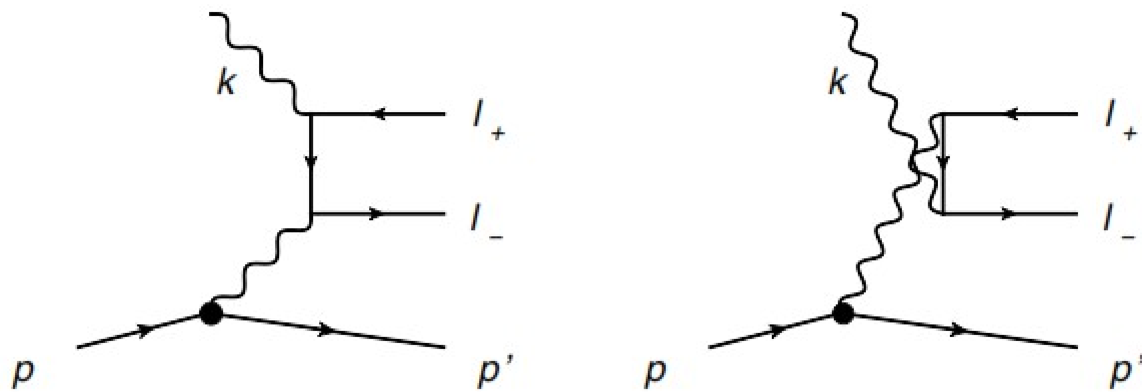


FIG. 1: Bethe-Heitler mechanism to the $\gamma p \to l^- l^+ p$ process, where the four-momenta of the external particles are: k for the photon, $p(p')$ for initial (final) protons, and l_-, l_+ for the lepton pair.

V. Pauk and M. Vanderhaeghen Phys.Rev.Lett. **115**, 221804 (2015)

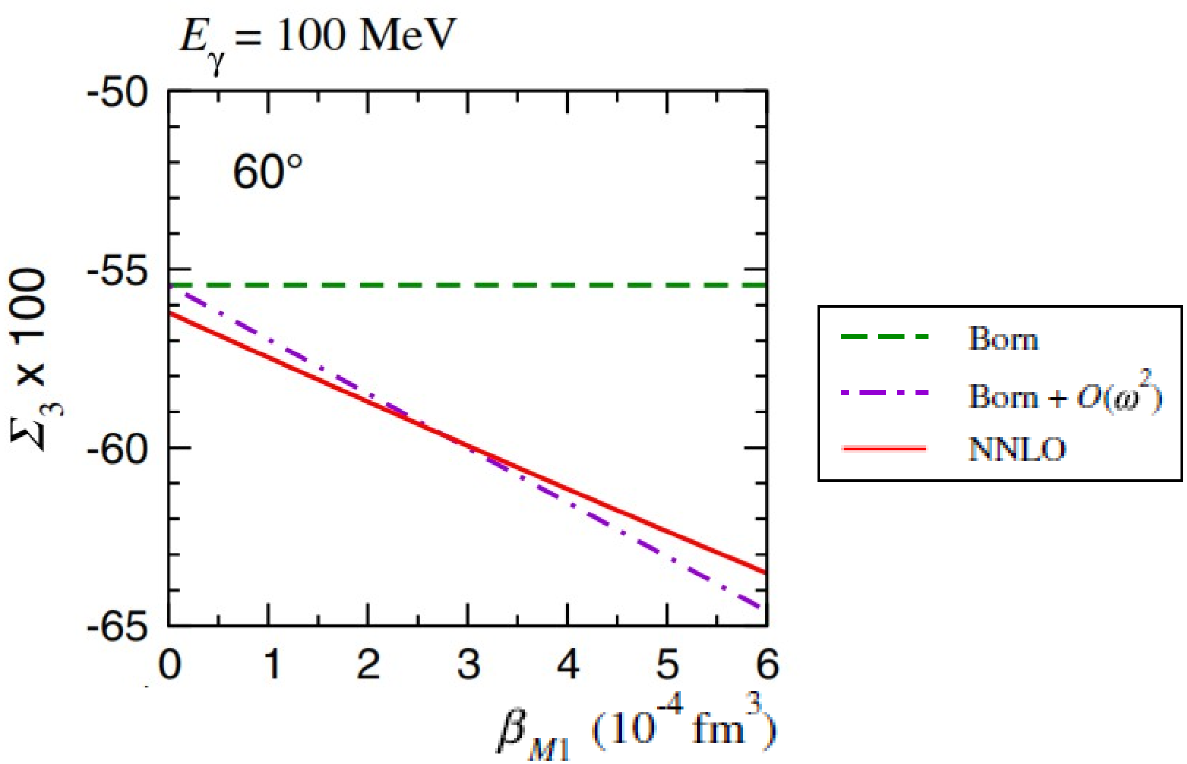
New approach: Beam asymmetry measurement

At low energies, the measurement of the beam asymmetry, Σ_3 is an alternative way to extract β_{M1} (N. Krupina and V. Pascalutsa [PRL 110, 262001 (2013)])

- Measurements with linearly polarized photons and liquid hydrogen target

$$\Sigma_3 \equiv \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}}$$

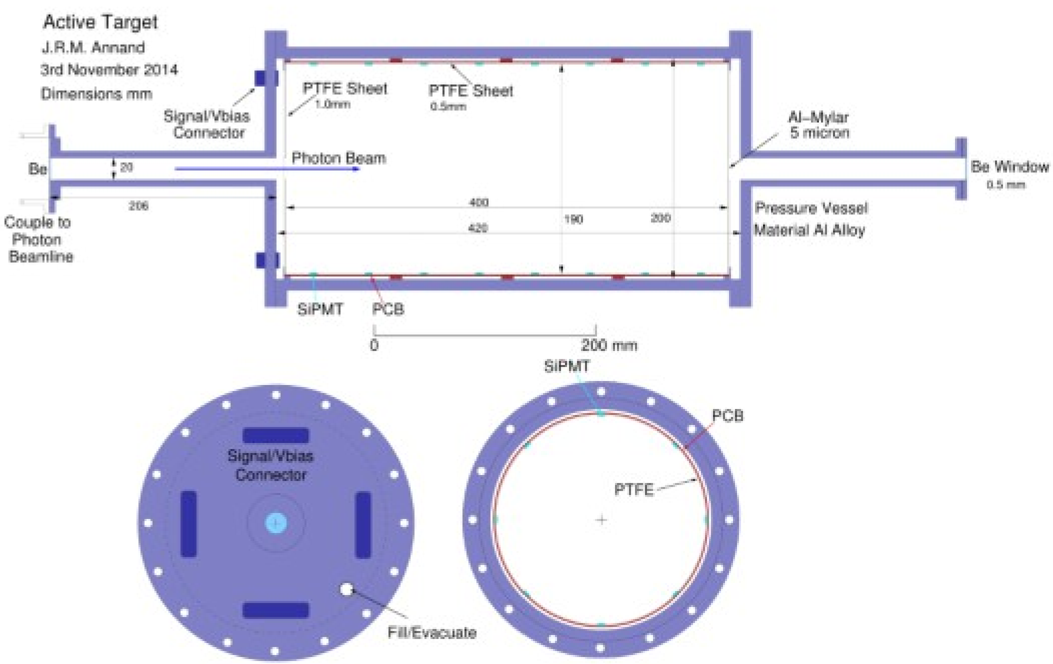
$$\sigma_{pol} = \sigma_{unpol}(1 \pm \delta_l \, \Sigma_3 \cos 2\phi)$$



New ideas and developments

Options:

- **Experiments with liquid helium target**
- **Active helium gas target (in prototyping phase)**



- Acting as a target: access to the reaction:
  $\gamma + {}^{3/4}He \rightarrow \gamma + {}^{3/4}He$
- Detection of the recoil nuclei in the active target and scattered photon in the Crystal Ball/TAPS
- Higher cross section and greater sensitivity compared to deuteron
- First prototype under development

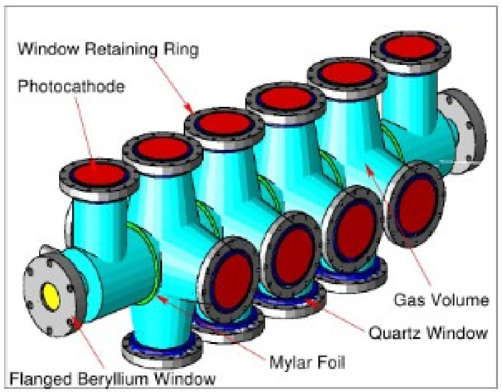
J .R. M Annand (Glasgow), J. Hillebrand (Mainz)

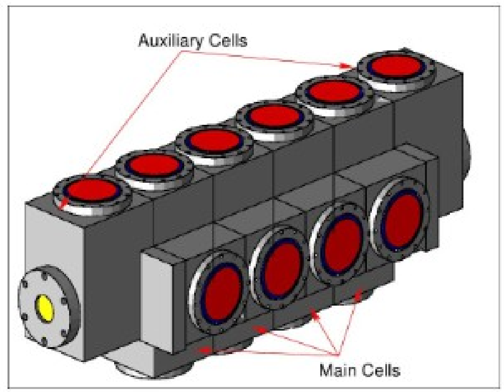
New ideas and developments

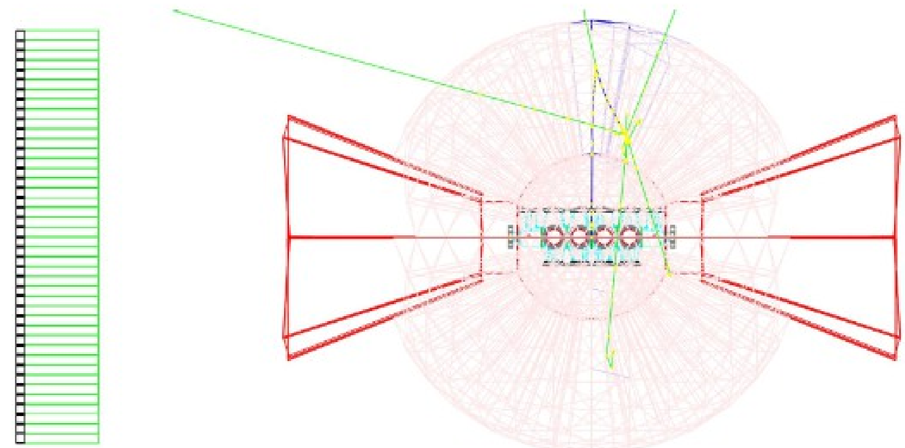
<u>Options:</u>

- **Experiments with liquid helium target**
- **Active helium gas target (in prototyping phase)**

Initial design used at MAX-lab





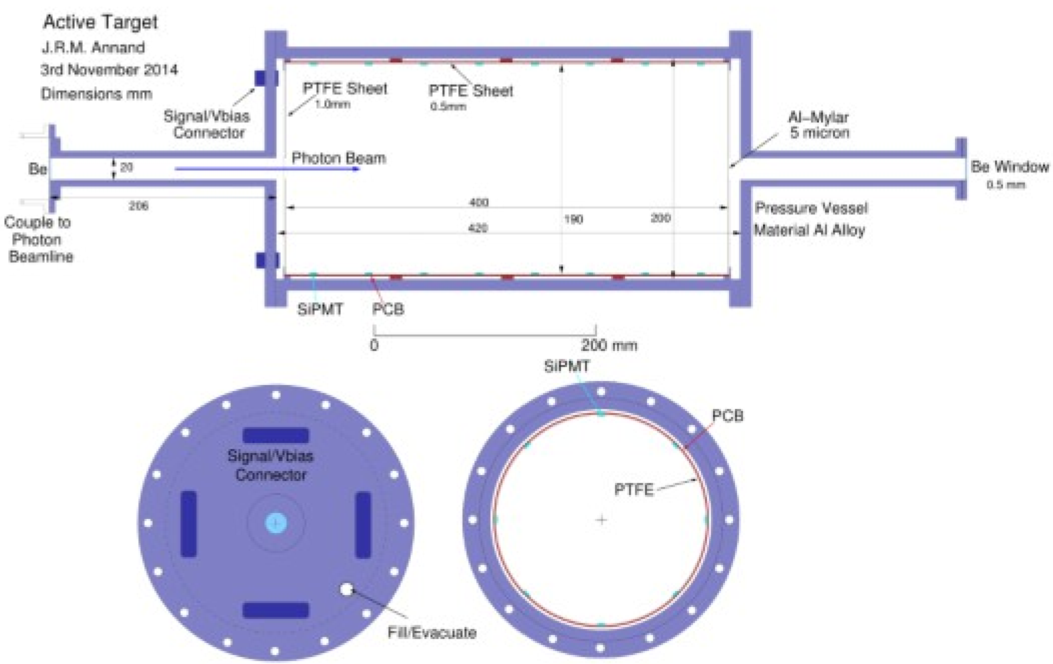


- Acting as a target: access to the reaction: $\gamma + {}^{3/4}He \rightarrow \gamma + {}^{3/4}He$
- Detection of the recoil nuclei in the active target and scattered photon in the Crystal Ball/TAPS
- Higher cross section and greater sensitivity compared to deuteron
- Inhomogeneity in the detection of the scattered photon (!?)

New ideas and developments

<u>Options:</u>

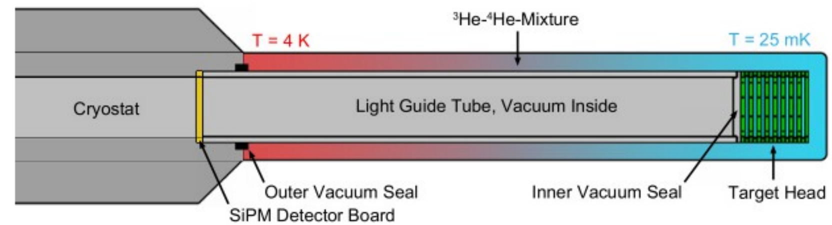
- **Experiments with liquid helium target**
- **Active helium gas target (in prototyping phase)**



- Acting as a target: access to the reaction: $\gamma + {}^{3/4}He \rightarrow \gamma + {}^{3/4}He$
- Detection of the recoil nuclei in the active target and scattered photon in the Crystal Ball/TAPS
- Higher cross section and greater sensitivity compared to deuteron
- First prototype under development

J .R. M Annand (Glasgow), J. Hillebrand (Mainz)

Active polarized target

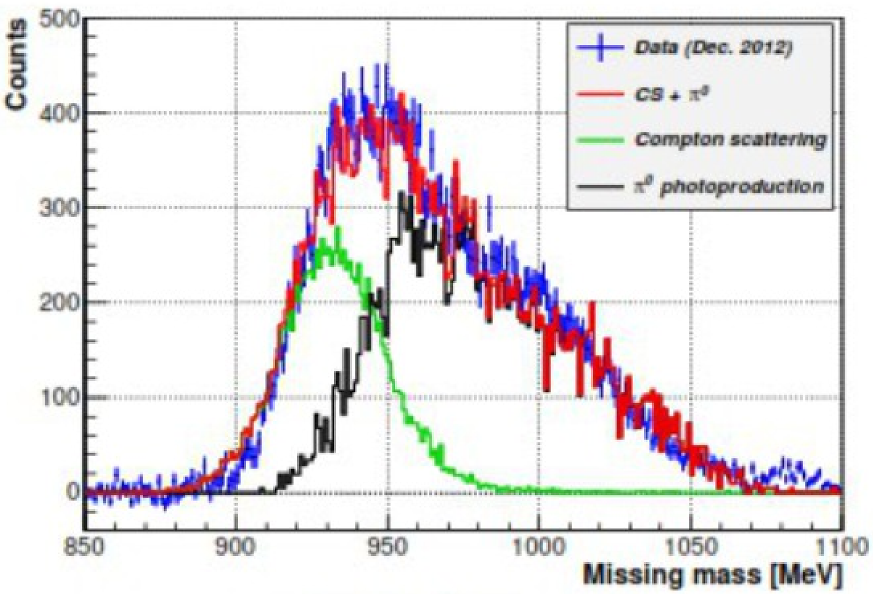


- Identification of the Compton scattering events using scattered photon in combination with a recoil proton candidate
- Suppression of the backgrounds and access to the low energy range
- First prototype tested, data under analysis

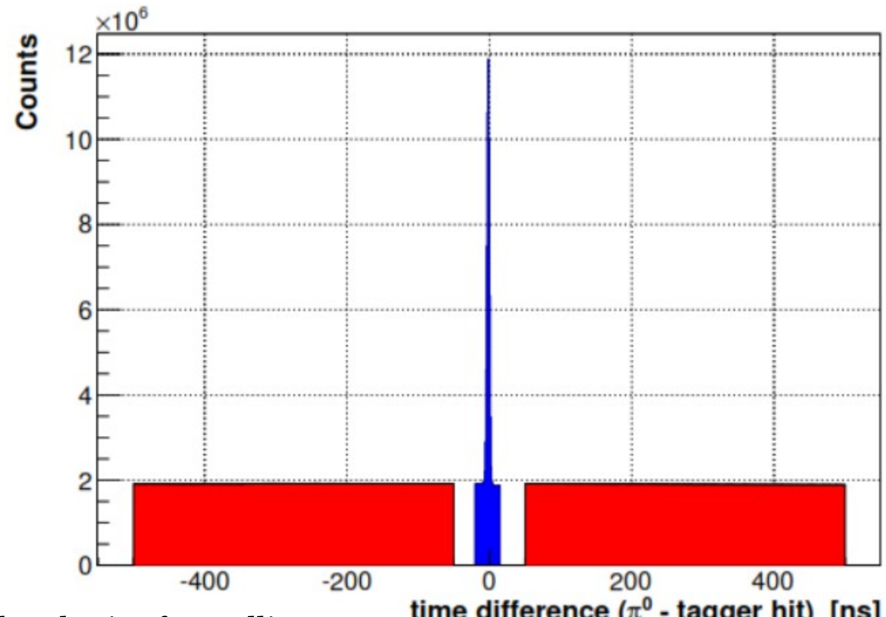
M . Biroth, et al. (Mainz)

Application of Machine Learning for Compton analysis

- Multiple (pre) analyzed data sets present for Compton scattering above pion threshold → improved background identification
- Separation of π^0 background is very challenging, in particular on an event-by event basis
- Presence of random timing background limits the accuracy of the measurements
  (as in most for most of the other analyses at A2 and tagged photon facilities in general)



(c) $\theta = 90^\circ$ to 100°

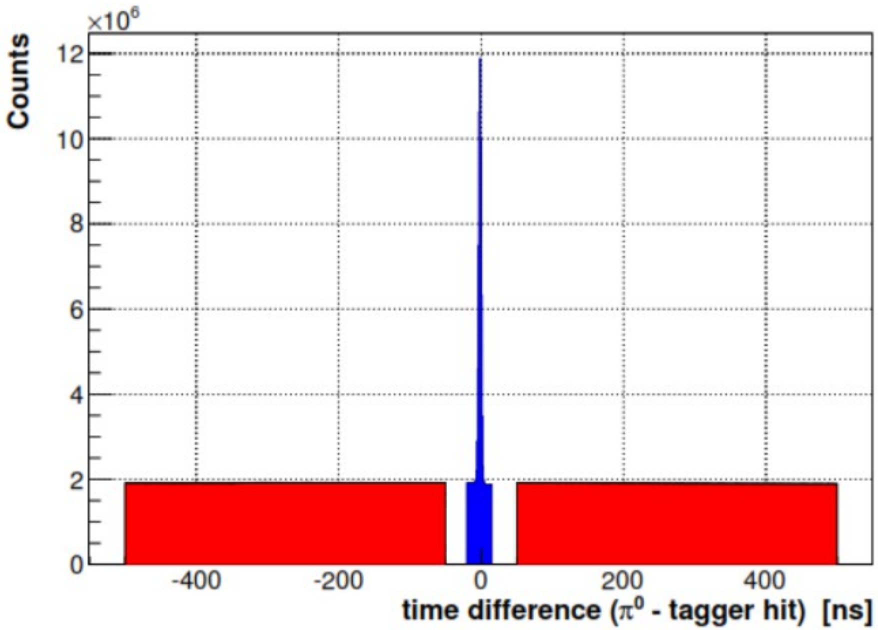


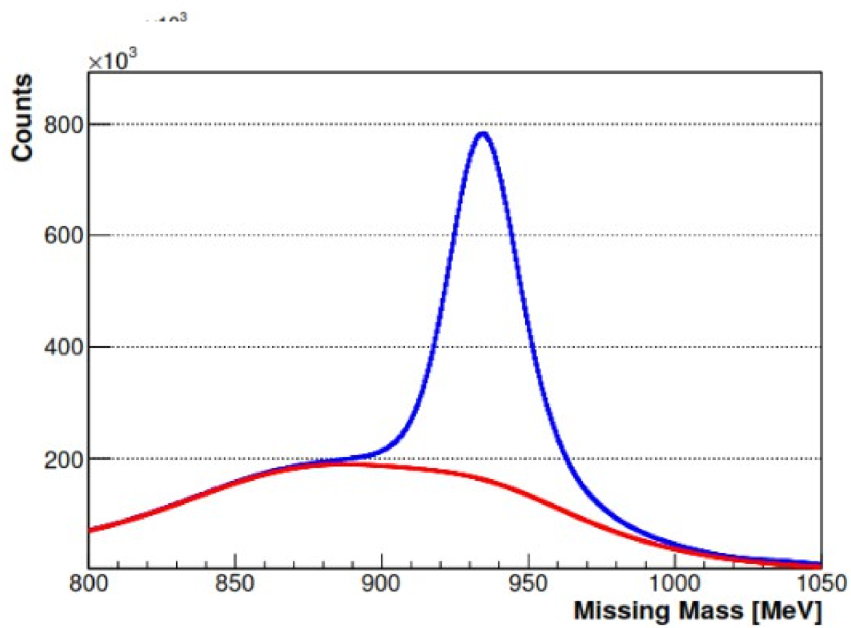
Figures from PhD thesis of C. Collicott

→ Separation of π^0 background from Compton events with Machine Learning

→New method for time background handling without random subtraction
→Outlook for the analysis of Compton scattering data with Machine Learning

Machine Learning approach for handling random background





Figures from PhD thesis of C. Collicott

- Handle timing background needed for ML-based data analysis
- Limits precision of many experiments due to subtraction of the background in the classical method

Separation of the prompt (signal) events with Machine Learning:

→Multidimensional clustering without labels (purely statistical approach)

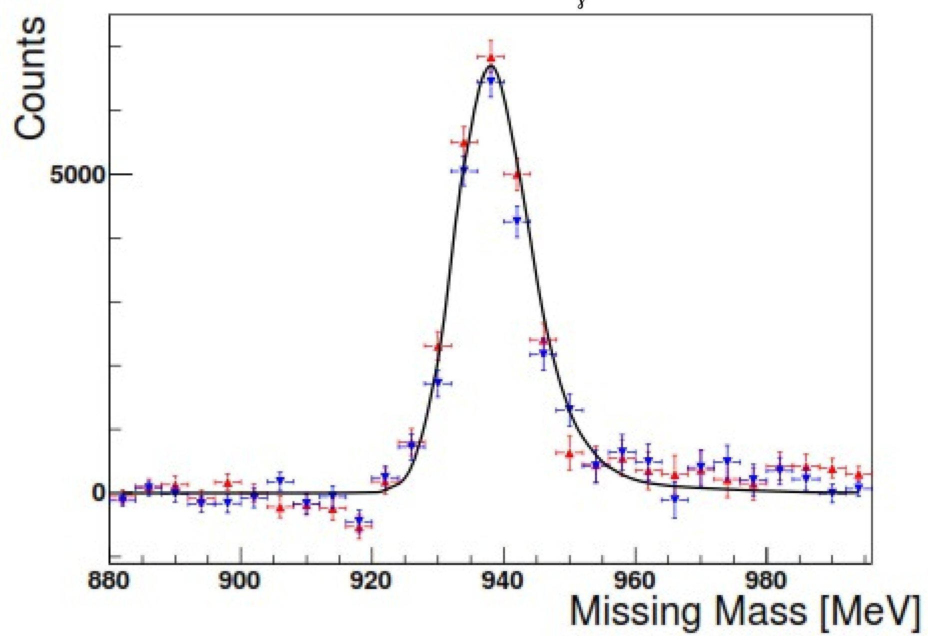
→MC-based approach using the simulation of the known reaction and measured background for training ML models (requires agreement between data and MC)

Event selection below pion theshold

Selection of $\gamma p \rightarrow \gamma p$:

- $E\gamma_{(beam)} = 79 - 139$ MeV
- Selecting events with 1 γ
- Missing mass cut
- Subtraction of random timing background
- Subtraction of empty target contribution

$E\gamma$ = 79 - 98 MeV and Θ_{γ} = 30°-155°



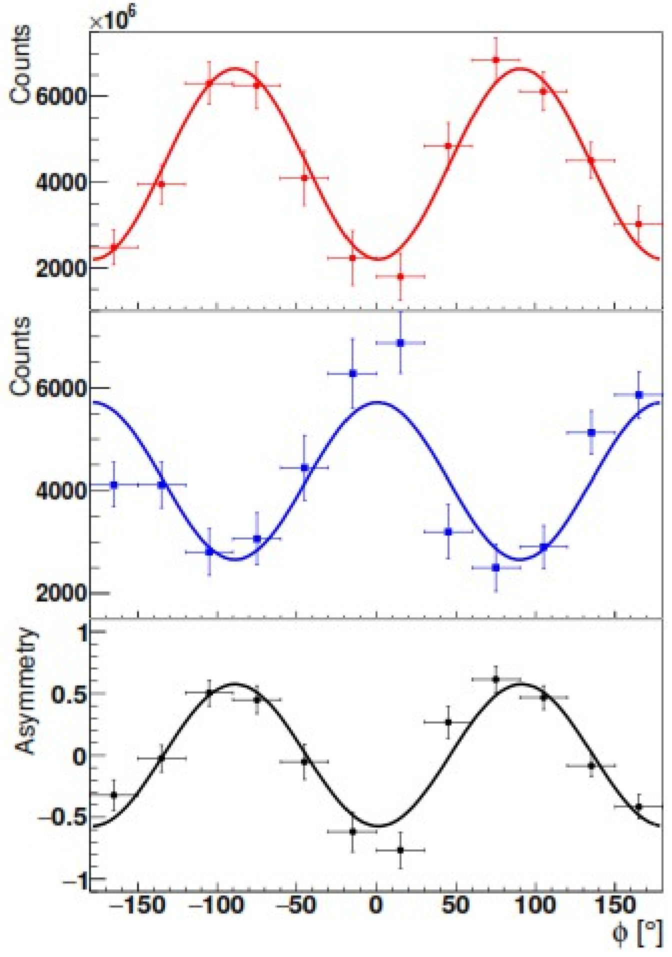
Different orientation of the polarization plane:
Parallel to the horizontal plane: PARA, perpedicular: PERP
Black curve : Monte Carlo

<u>Pilot experiment</u>:

- More than 200,000 Compton scattering events ($E\gamma$ = 79 - 139 MeV and Θ_{γ} = 30°-155°)
- Low background contamination in all energy bins
- Good agreement between PARA and PERP for the unpolarized component

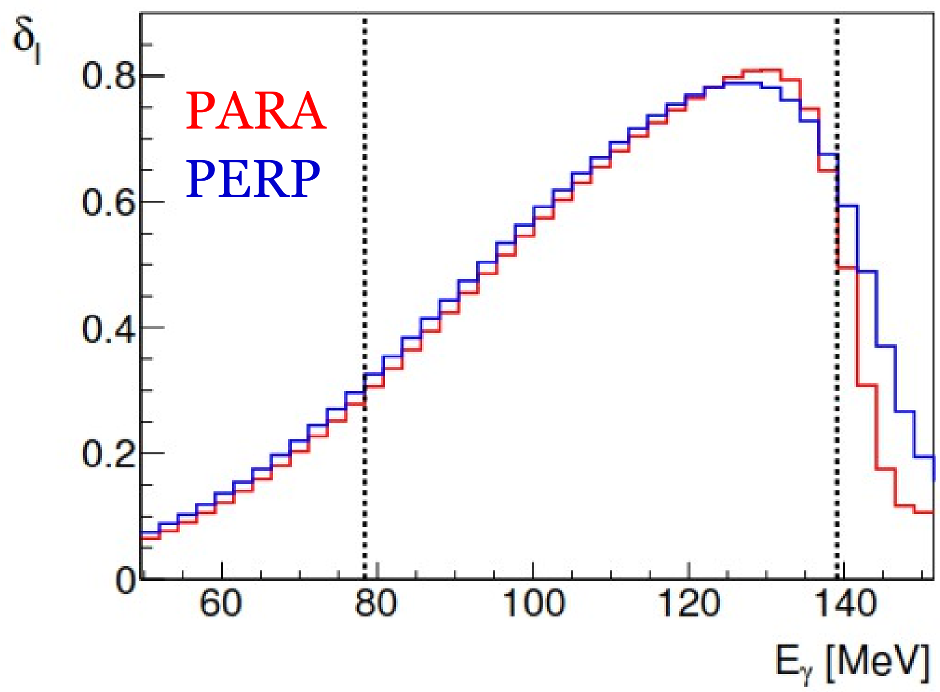
Pilot experiment: Data quality

$$\sigma_{pol} = \sigma_{unpol}(1 \pm \delta_l\, \Sigma_3 \cos 2\phi)$$



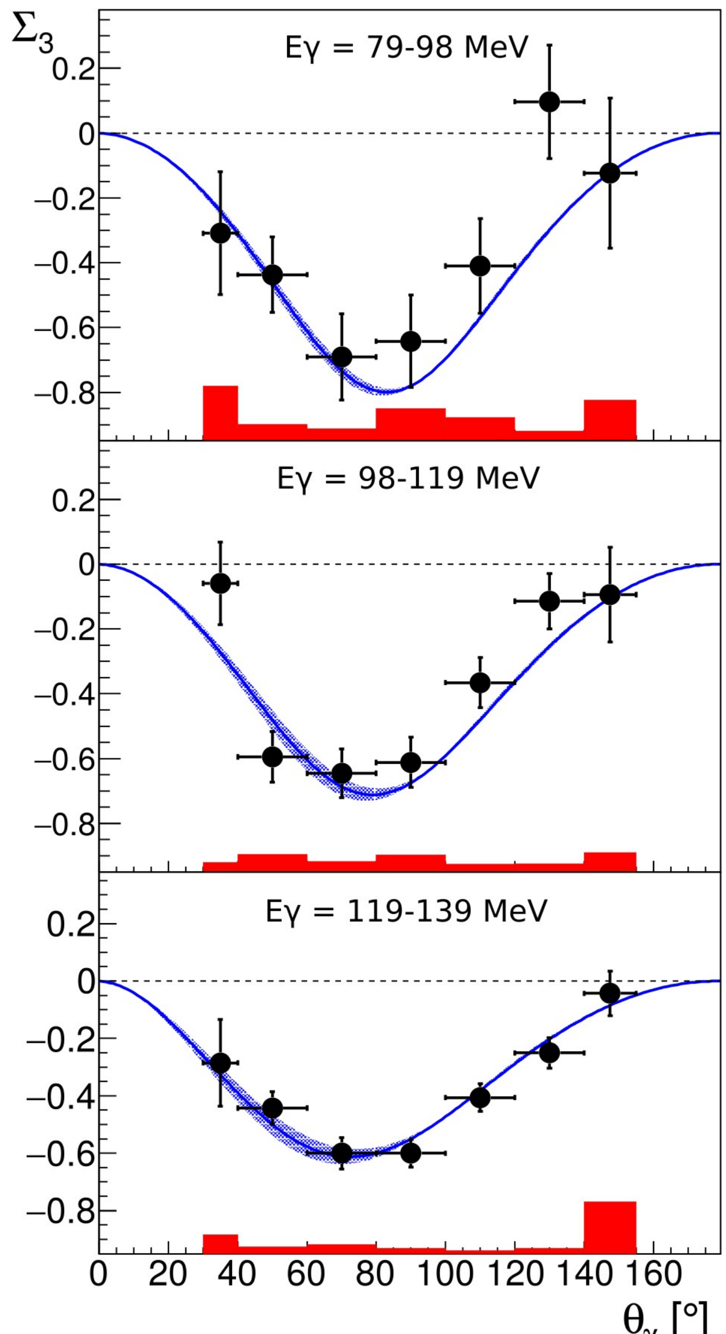
PARA and PERP, Asymmetry

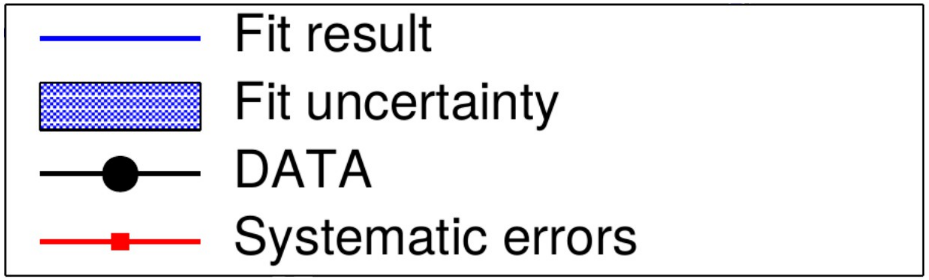
Degree of linear polarization (averaged)



Improved systematics: Event by event determination of the degree of linear polarization

Pilot experiment: Beam asymmetry





Fit on our Σ_3 results using Baldin sum rule constraint gives:

BChPT framework:

$$\beta_{M1} = 2.8^{+2.3}_{-2.1} \times 10^{-4}\ \text{fm}^3$$
$$\chi^2/\text{ndf} = 19.2/20$$

HBChPT framework:

$$\beta_{M1} = 3.7^{+2.5}_{-2.3} \times 10^{-4}\ \text{fm}^3$$
$$\chi^2/\text{ndf} = 17.1/20$$

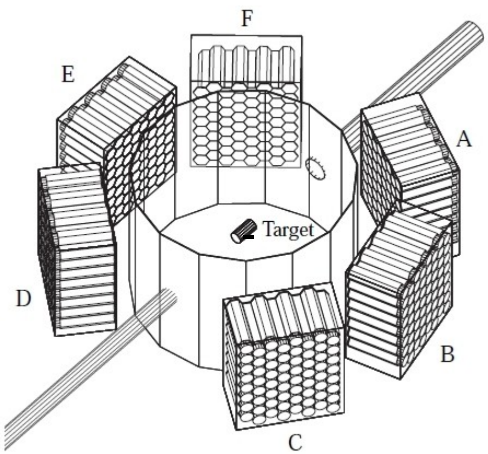
V. S., E.J. Downie, E. Mornacchi, J.A. McGovern, N. Krupina, et al., [A2 Collaboration], Eur.Phys.J. A53 (2017) no.1, 14

Compton scattering on the proton: Existing data

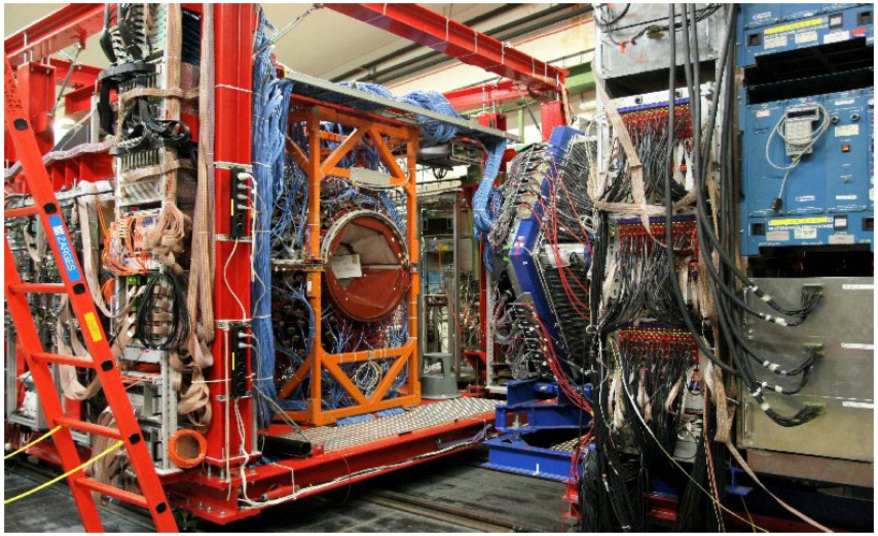
- Highest statistics data set:

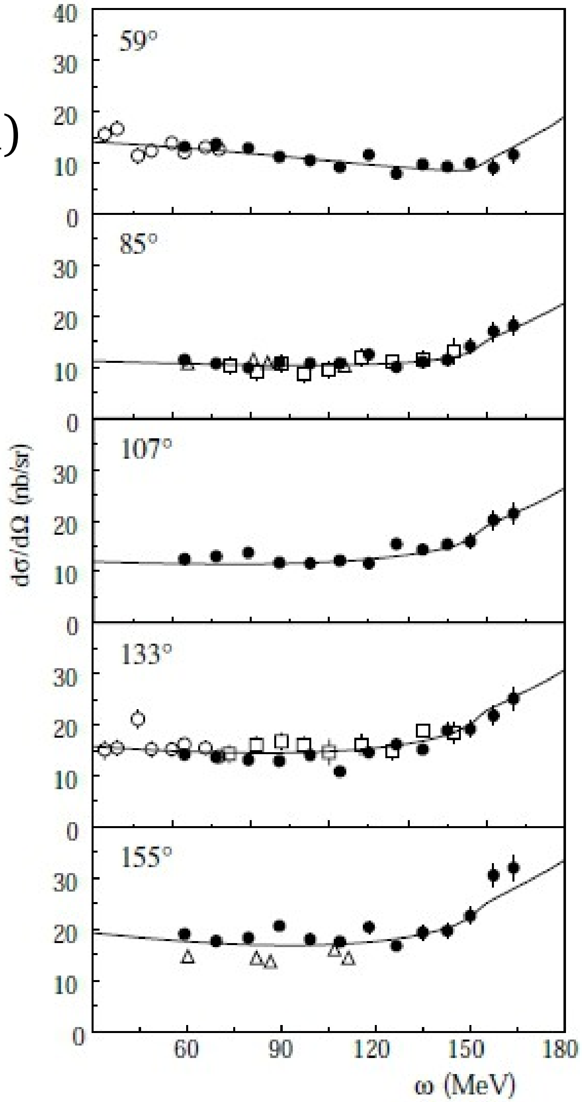
V. Olmos de Leon et al. Eur. Phys. J. A 10, 207–215 (2001)

- 1/3 acceptance of CB System!



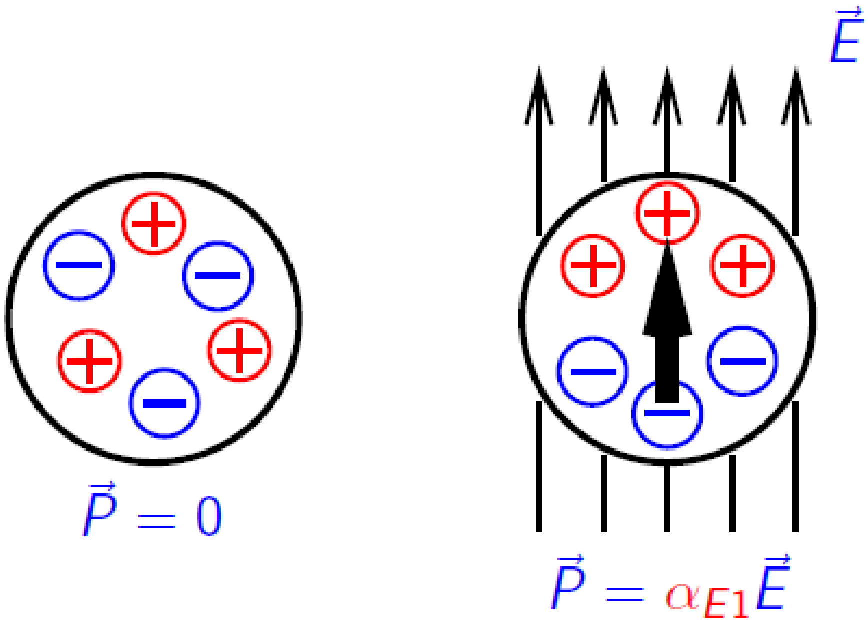
Crystal Ball/TAPS: Nearly 4π coverage





Triangles: P.S. Baranov et al., Phys. Lett. B 52, 22 (1974); P.S. Baranov et al., Sov. J. Nucl. Phys. 21, 355 (1975)
Open circles: F.J. Federspiel et al., Phys. Rev. Lett. 67, 1511 (1991)
Squares B.E. MacGibbon et al., Phys. Rev. C 52, 2097 (1995)
Curve: R.A. Arndt et al., Phys. Rev. C 53, 430 (1996)

Electric Dipole Polarizability

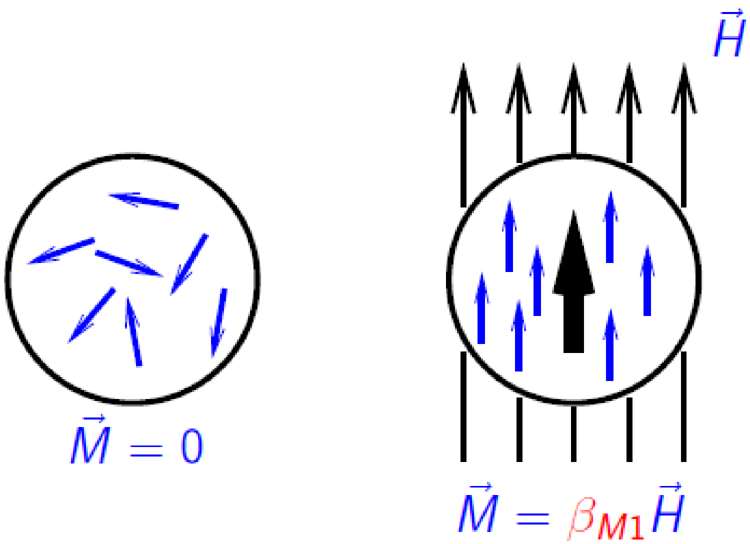


- Apply an electric field to a composite system
- Separation of Charge, or **"Stretchability"**
- Proportionality constant between electric dipole moment and electric field is the electric dipole polarizability, α_{E1}.

Provides information on force holding system together.

Scalar Polarizabilities – Conceptual

Magnetic Dipole Polarizability



- Apply a magnetic field to a composite system
- Alignment of dipoles or **"Alignability"**
- Proportionality constant between magnetic dipole moment and magnetic field is the magnetic dipole polarizability, β_{M1}.
- Two contributions, paramagnetic and diamagnetic, and they cancel partially, giving $\beta_{M1} < \alpha_{E1}$.

Provides information on force holding system together.

Real Compton Scattering – Hamiltonian

Expand the Hamiltonian in incident-photon energy.

0th order $\longrightarrow$ charge, mass

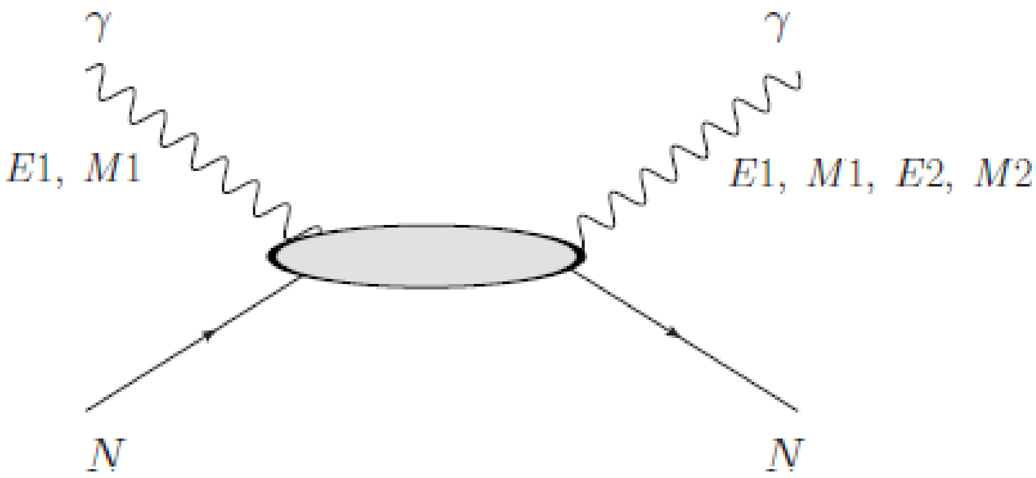
1st order $\longrightarrow$ magnetic moment

2nd order $\longrightarrow$ **scalar polarizabilities**:

$$H_{\text{eff}}^{(2)} = -4\pi\left[\frac{1}{2}\alpha_{E1}\vec{E}^2 + \frac{1}{2}\beta_{M1}\vec{H}^2\right]$$

3rd order $\longrightarrow$ **spin (or vector) polarizabilities**:

$$H_{\text{eff}}^{(3)} = -4\pi\left[\tfrac{1}{2}\gamma_{E1E1}\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}}) + \tfrac{1}{2}\gamma_{M1M1}\vec{\sigma}\cdot(\vec{H}\times\dot{\vec{H}})\right.$$
$$\left. -\gamma_{M1E2}E_{ij}\sigma_i H_j + \gamma_{E1M2}H_{ij}\sigma_i E_j\right]$$



quantity	incident γ	scattered γ
α_{E1}	$E1$	$E1$
β_{M1}	$M1$	$M1$
γ_{E1E1}	$E1$	$E1$
γ_{M1M1}	$M1$	$M1$
γ_{M1E2}	$M1$	$E2$
γ_{E1M2}	$E1$	$M2$

Nucleon has $J^\pi = \frac{1}{2}^+$. Photons have parity given by

$$EL : \pi = (-1)^L$$
$$ML : \pi = (-1)^{L+1}$$

The usual QM selection rules for angular momentum and parity apply.

Compton scattering: Polarisabilities

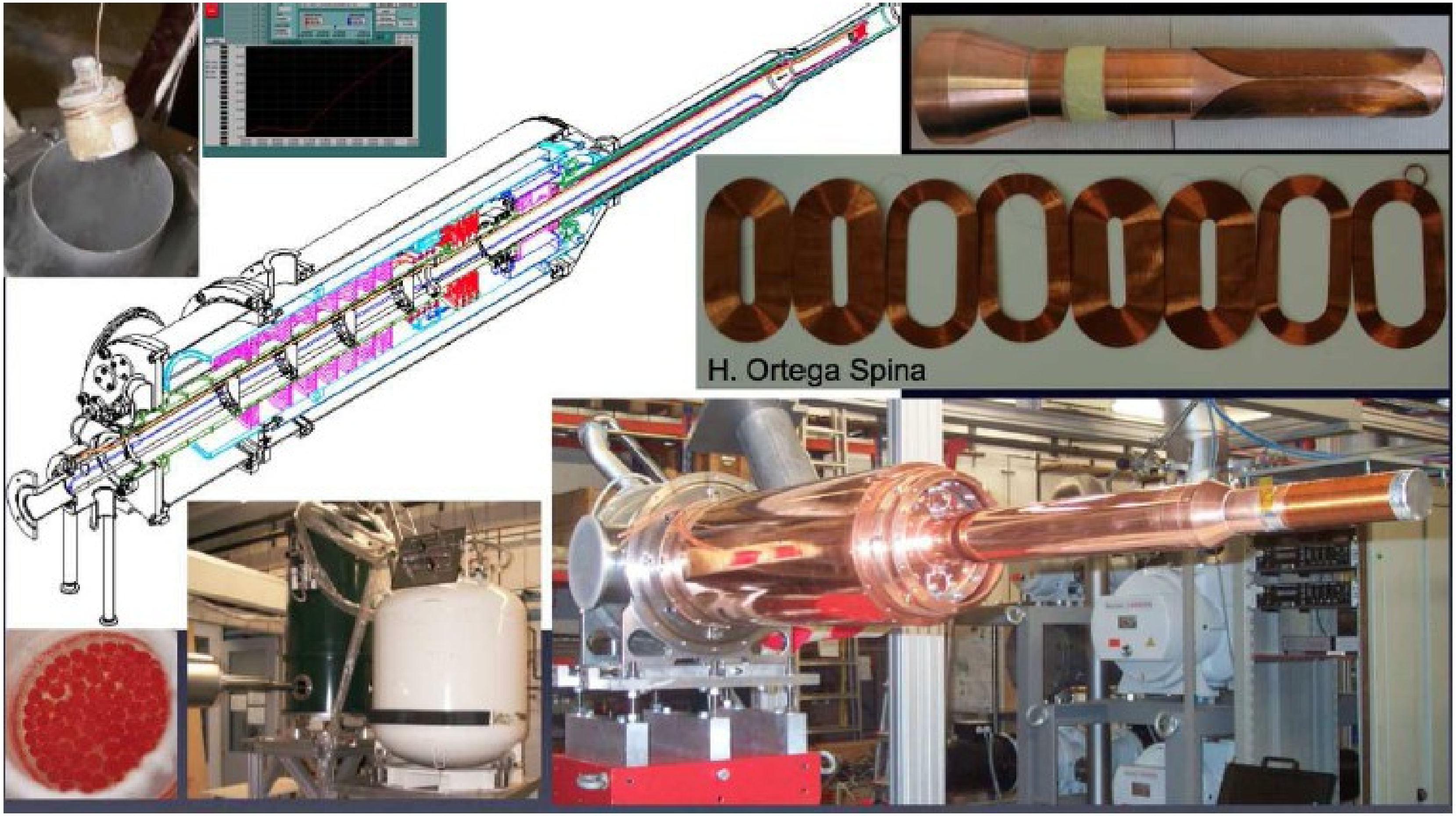
The polarisabilities can be defined in terms of the angular momentum and parity of the incident and scattered photon.

A photon with total angular momentum L, is said to be electric (EL) or magnetic (ML) if its parity satisfies:

$$\pi_{EL} = (-1)^L \qquad \pi_{ML} = (-1)^{L+1}$$

The γ_{M1E2} polarisability, for example, can now be described in terms of the incoming and outgoing photon properties. In this case, the incoming and outgoing photons carry total angular momentum and parity given by 2^+ and 1^+ respectively.

Polarized Target



Dynamical Nucleon Polarization

Target material is butanol, $C_4H_{10}O$

Dilution cryostat with bath of liquid ^{3}He/^{4}He, $T < 30\,\mathrm{mK}$

$P_p \approx 90\%$ with a relaxation time of $\tau > 1000$ hours.

Frozen Spin Target

Polarizing protons through Dynamic Nuclear Polarization (DNP):

- Cool target to 0.2 Kelvin.
- Use 2.5 Tesla magnet to align electron spins.
- Pump $\approx$ 70 GHz microwaves (just above, or below, the Electron Spin Resonance frequency), causing spin-flips between the electrons and protons.
- Cool target to 0.025 Kelvin, 'freezing' proton spins in place.
- Remove polarizing magnet.
- Energize 0.6 Tesla 'holding' coil in the cryostat to maintain the polarization.
- Relaxation times $>$ 1000 hours.
- Polarizations up to 90%.

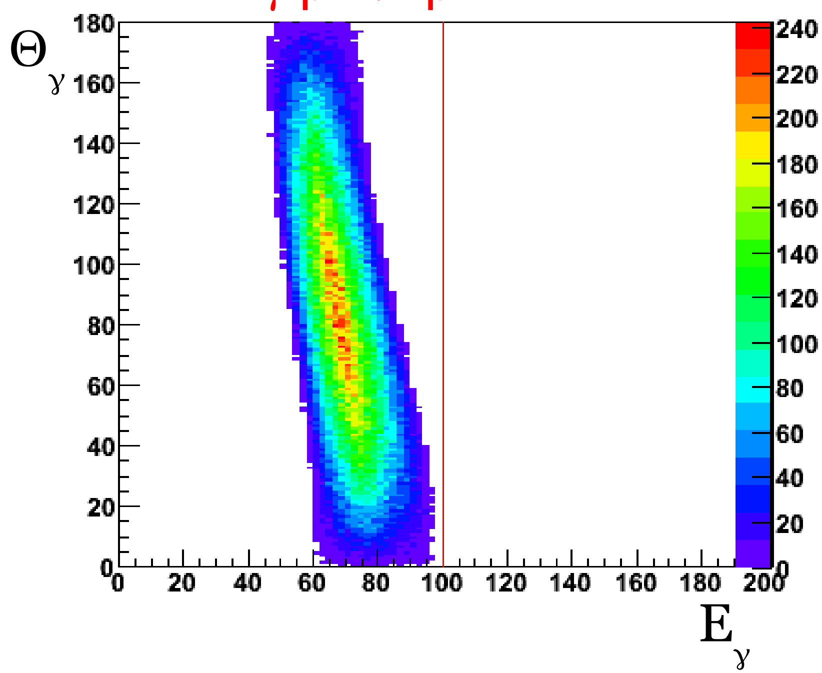
Elimination of π^0 background

- Main background source for Compton scattering: $\gamma\, p \rightarrow p\pi^0$
- Background production mechanism: 1 γ lost
- Kinematics similar to Compton scattering
- Significantly (~100 times) higher cross-section

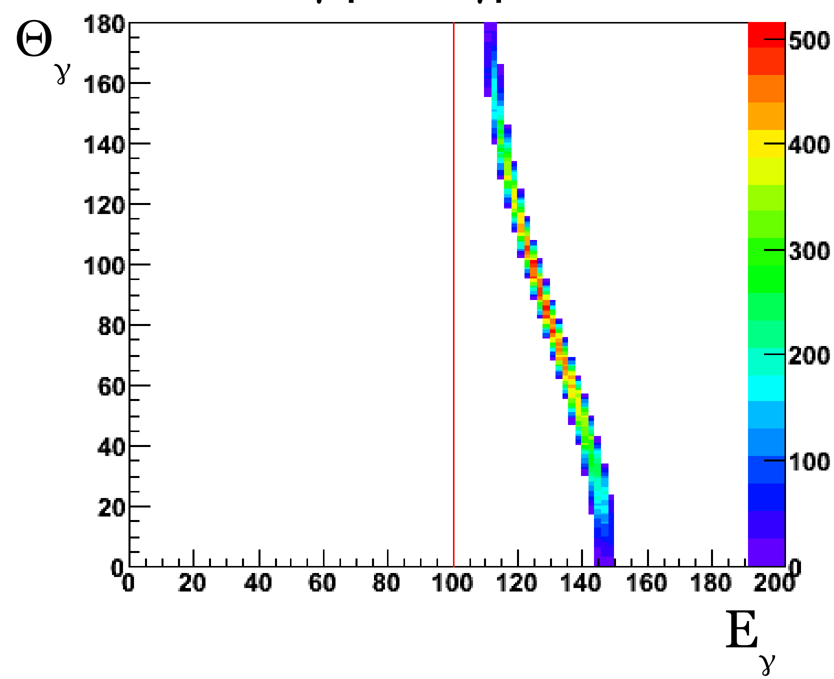
Low energy range:

- Can be removed at ~ 150 MeV (e.g. 145 – 150 MeV)
- Cut on E_γ

$\gamma\, p \rightarrow p\pi^0$



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



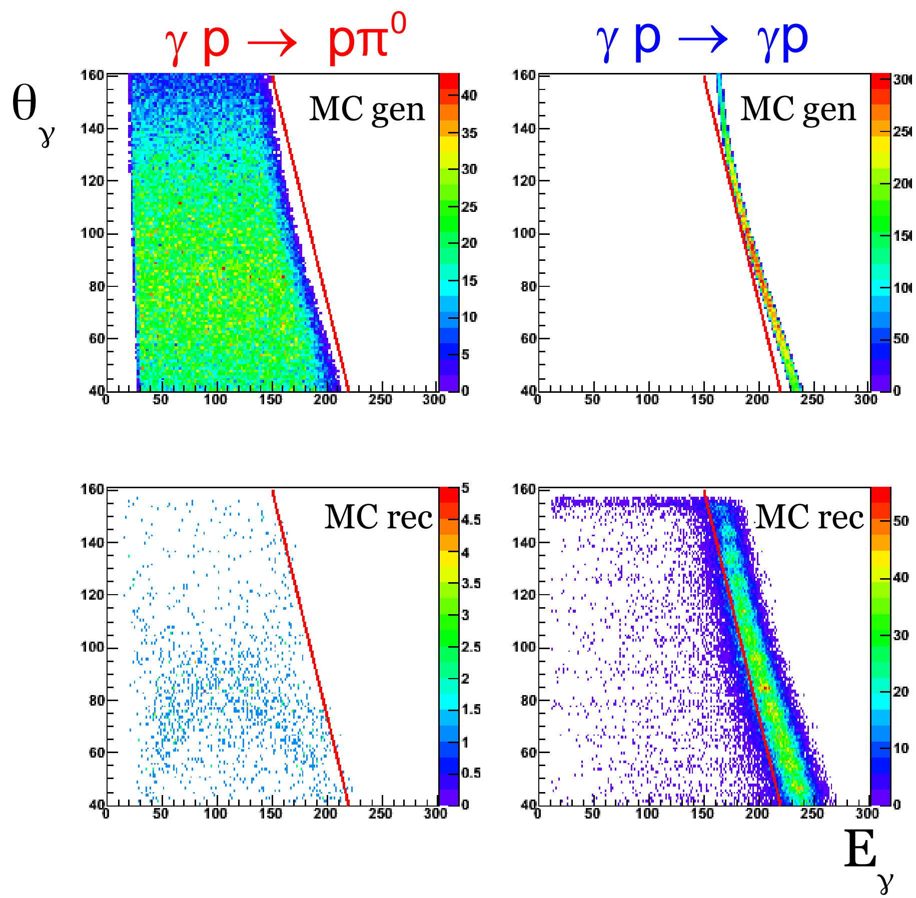
Elimination of π^0 background

- Main background source for Compton scattering: $\gamma\, p \rightarrow p\pi^0$
- Background production mechanism: 1 γ lost
- Kinematics similar to Compton scattering
- Significantly higher cross-section
- Higher energies: 1 γ can take the largest part of the π^0 energy

Up to ~ 250 MeV:

2D (E, θ) cut!

Eγ = 245-255 MeV



Spin polarizabilities

γ	Theory p^4HB	ϵ^3SSE	NNLO	DRs	Kmatrix	Experiment
$E1E1$	−1.4	−5.4	−4.5	−4.3	−5.0	no data
$M1M1$	3.3	1.4	3.7	2.9	3.4	no data
$E1M2$	0.2	1.0	−0.9	0.0	−1.8	no data
$M1E2$	1.8	1.0	2.2	2.1	1.1	no data
0	−3.9	2.0	−0.7	−0.7	2.3	$-1.01 \pm 0.08 \pm 0.13$
π	6.3	6.8	11.3	9.3	11.3	8.0 ± 1.8

- Proton spin polarizability predictions and measurements in units of 10^{-4} fm^4
- Note the large absolute error on γ_π

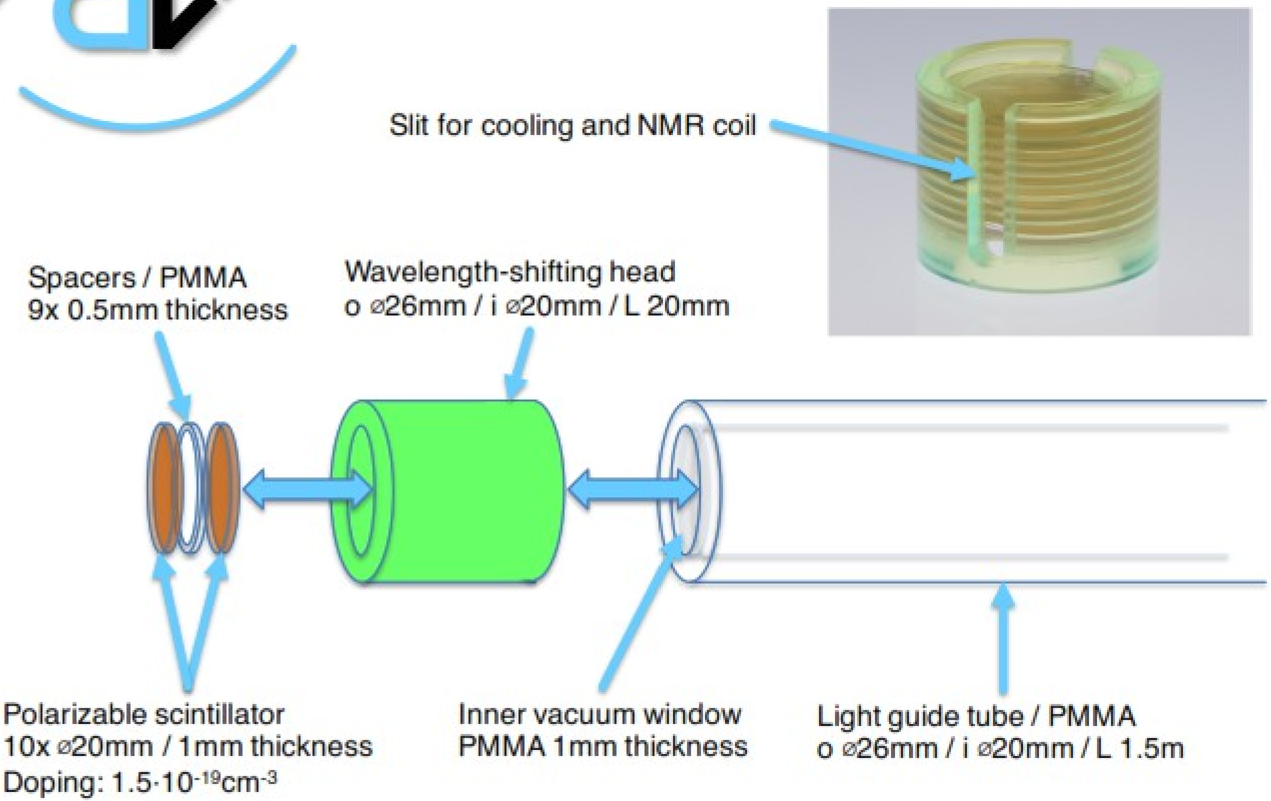
- Forward spin polarizability has been determined by a "GDH-type" of sum rule

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{M1M1} - \gamma_{E1M2} - \gamma_{M1E2}$$

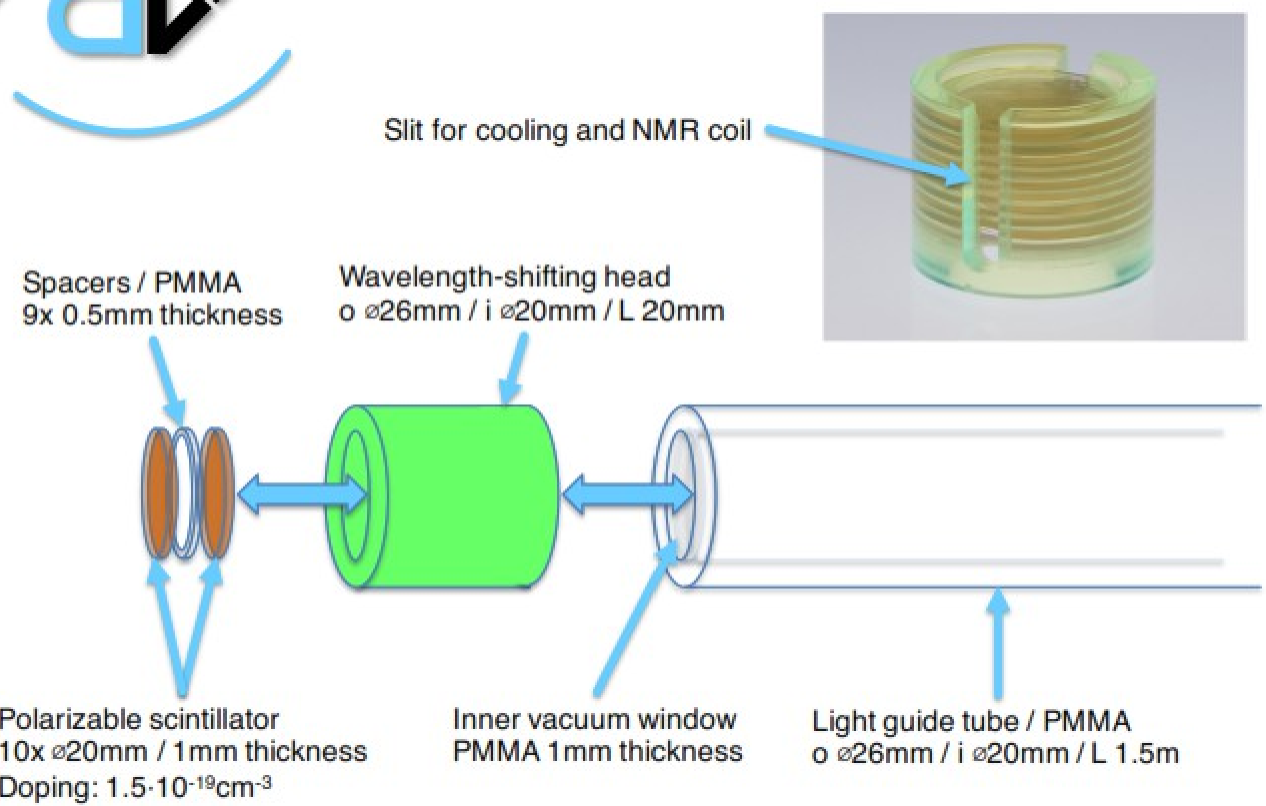
- Backward spin polarizability has been determined from a dispersive analysis of backward-angle Compton scattering

$$\gamma_\pi = -\gamma_{E1E1} + \gamma_{M1M1} - \gamma_{E1M2} + \gamma_{M1E2}$$

Backup


Slit for cooling and NMR coil
Spacers / PMMA
9x 0.5mm thickness
Wavelength-shifting head
o ⌀26mm / i ⌀20mm / L 20mm
Polarizable scintillator
10x ⌀20mm / 1mm thickness
Doping: 1.5·10-19cm-3
Inner vacuum window
PMMA 1mm thickness
Light guide tube / PMMA
o ⌀26mm / i ⌀20mm / L 1.5m

Backup



Maik Biroth, Institut für Kernphysik, Mainz, Germany mbiroth@uni-mainz.de

Measurement of α and β

$$\Sigma_3 = \Sigma_3^{(\mathrm{B})} - \frac{4M\omega^2 \cos\theta \sin^2\theta}{\alpha_{em}(1+\cos^2\theta)^2}\,\beta_{M1} + O(\omega^4), \qquad (6)$$

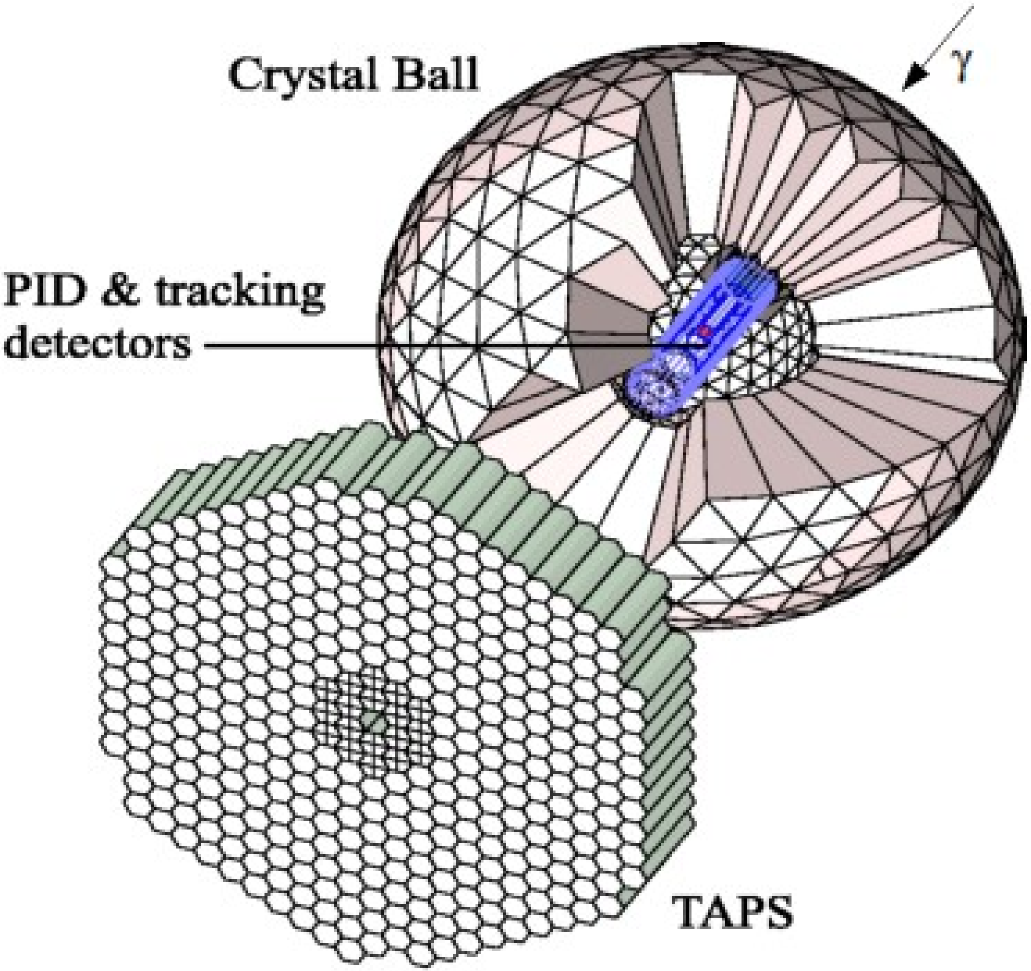
where $\Sigma_3^{(\mathrm{B})}$ is the pure Born contribution, while

$$\omega = \frac{s - M^2 + \frac{1}{2}t}{\sqrt{4M^2 - t}}, \quad \theta = \arccos\left(1 + \frac{t}{2\omega^2}\right) \qquad (7)$$

are the photon energy and scattering angle in the Breit (brick-wall) reference frame. In fact, to this order in the LEX the formula is valid for ω and θ being the energy and angle in the lab or center-of-mass frame.

N. Krupina and V. Pascalutsa [PRL 110, 262001 (2013)]

Crystal Ball/TAPS (slide taken from M. Unverzagt)



<u>Crystal Ball:</u>

672 NaI(Tl) crystals

93,3% of total solid angle

Each crystal equipped with PMT

$$\frac{\sigma}{E_\gamma} = \frac{2\%}{(E_\gamma/GeV)^{0.25}} \qquad \sigma(\theta) = 2^\circ \dots 3^\circ$$

$$\Delta t = 2.5 \text{ ns FWHM} \qquad \sigma(\phi) = \frac{2^\circ \dots 3^\circ}{\sin(\theta)}$$

<u>TAPS:</u>

Up to 510 BaF_2 crystals

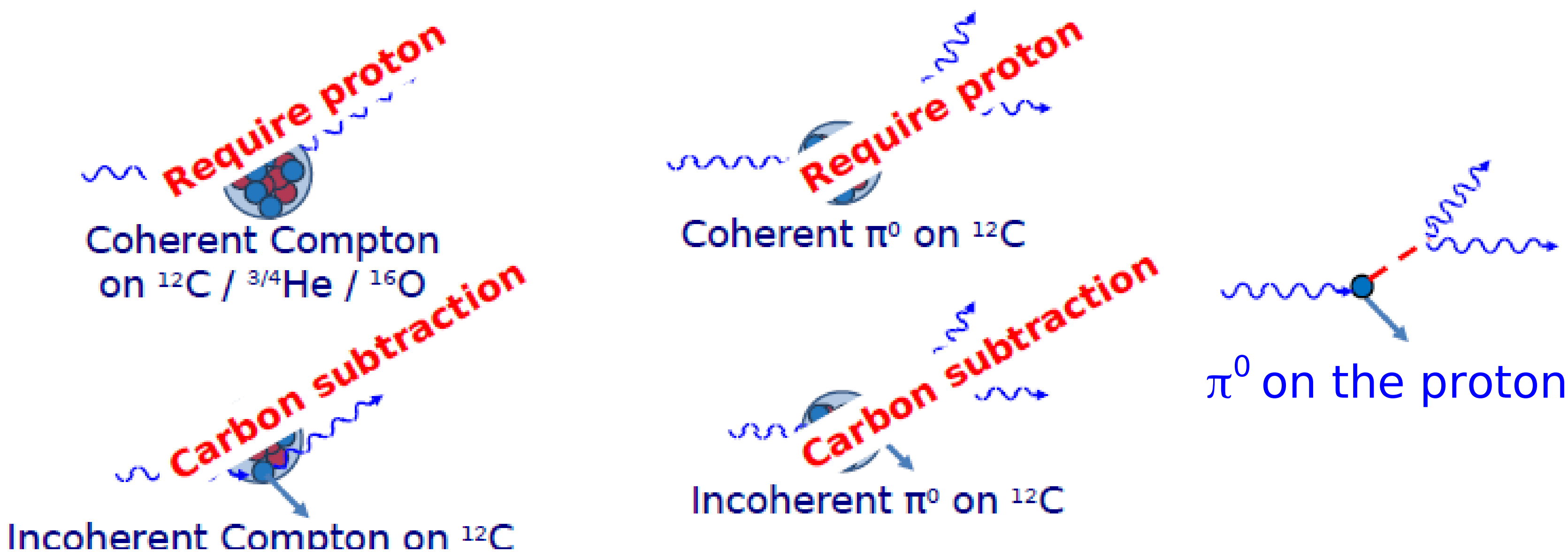
Polar acceptance: 4-20°

$\Delta t = 0.5$ ns FWHM

$$\frac{\sigma}{E_\gamma} = \frac{0{,}79\%}{\sqrt{E_\gamma/GeV}} + 1{,}8\%$$

Σ_{2x} : Experimental challenges

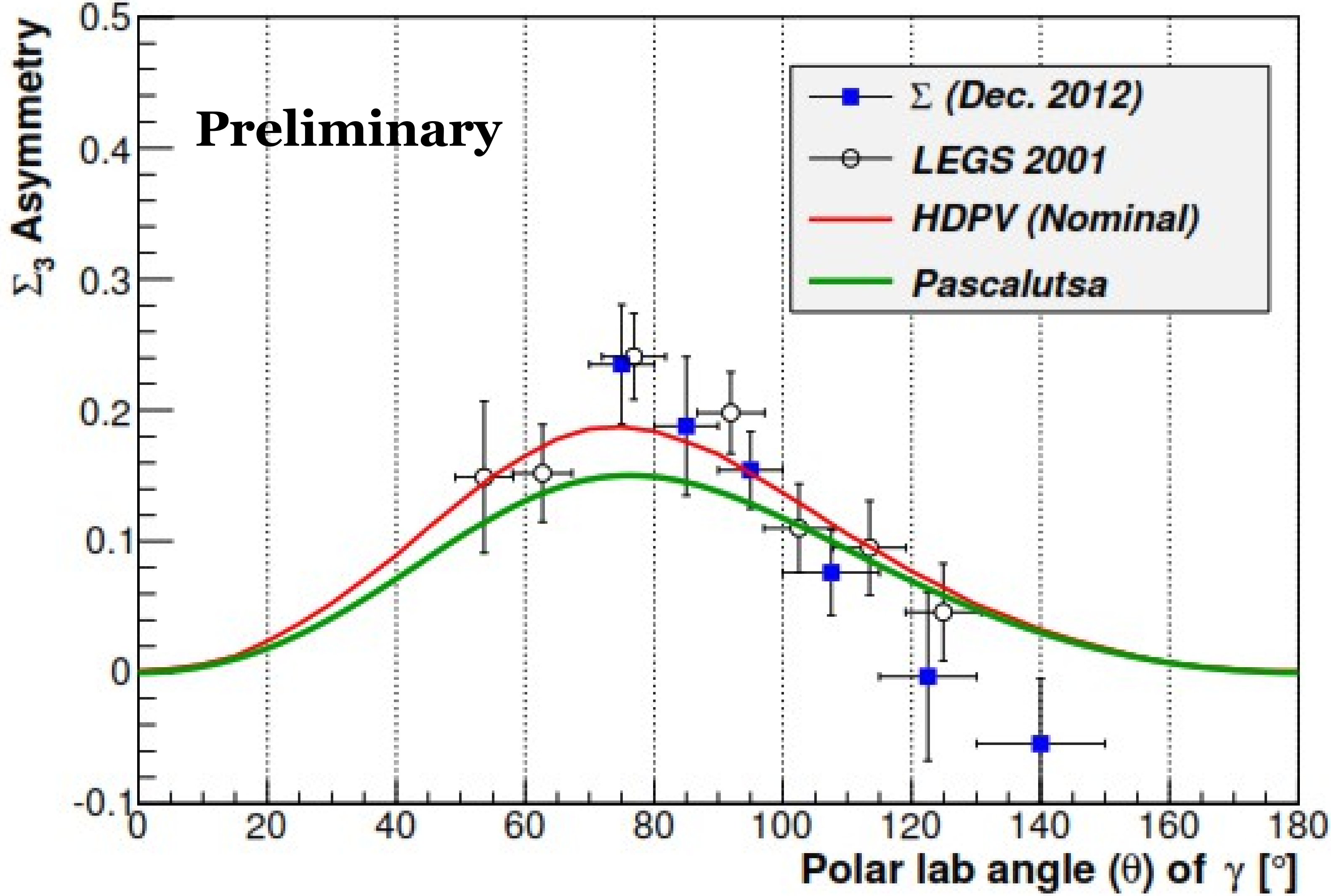
- Small Compton scattering cross sections
- Large backgrounds
- Butanol target (C_4H_9OH): Coherent and incoherent reactions off C, O and He
- Proton tracks are required to suppress backgrounds, but energy losses e.g. in the target are considerable.



P. Martel (UMass, KPH Mainz)

Σ_3 at higher energies: Preliminary results

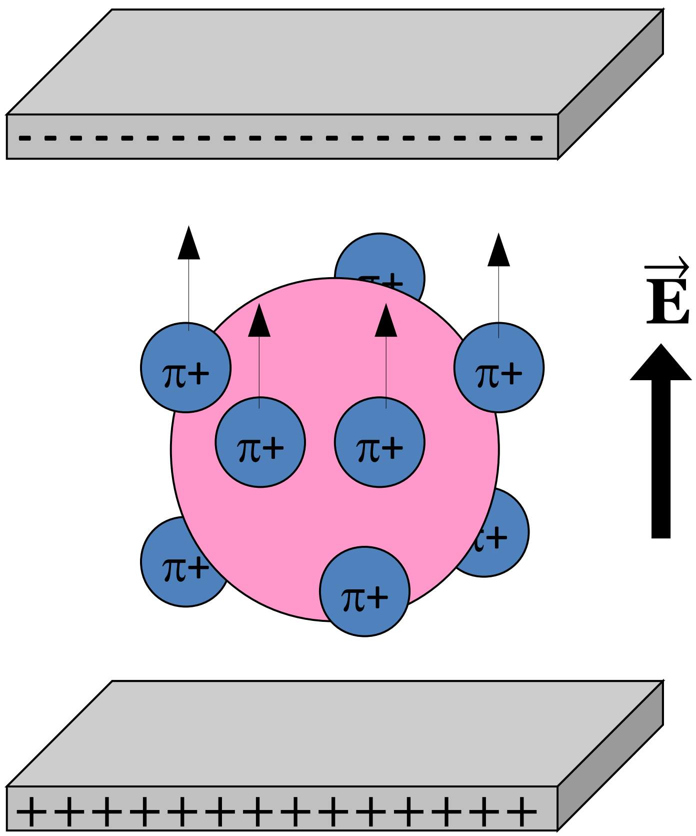
Eγ = 277.1 ± 10.1 MeV



Cristina Collicott, et al. [A2 Collaboration]

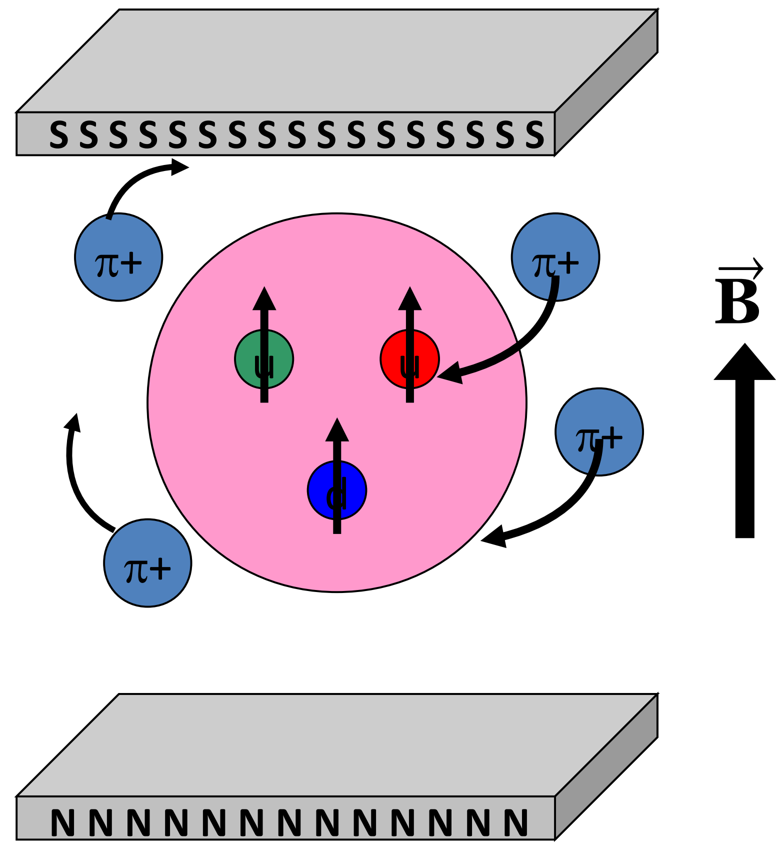
Scalar polarizabilities

Proton Electric Polarizability



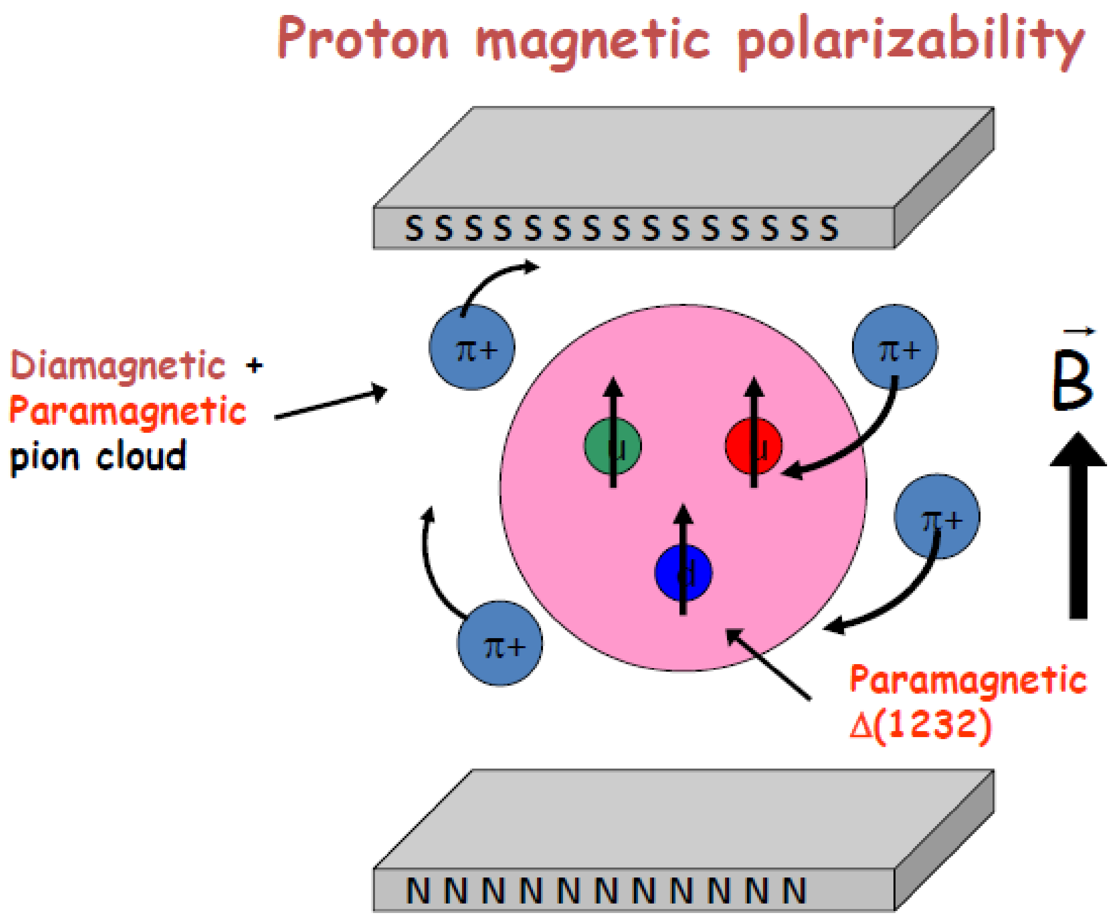
- α: electric polarizabilty
- Proton between charged parallel plates: “stretchability”

Proton Magnetic Polarizability



- β: magnetic polarizability
- Proton between poles of a magnet: “alignability”

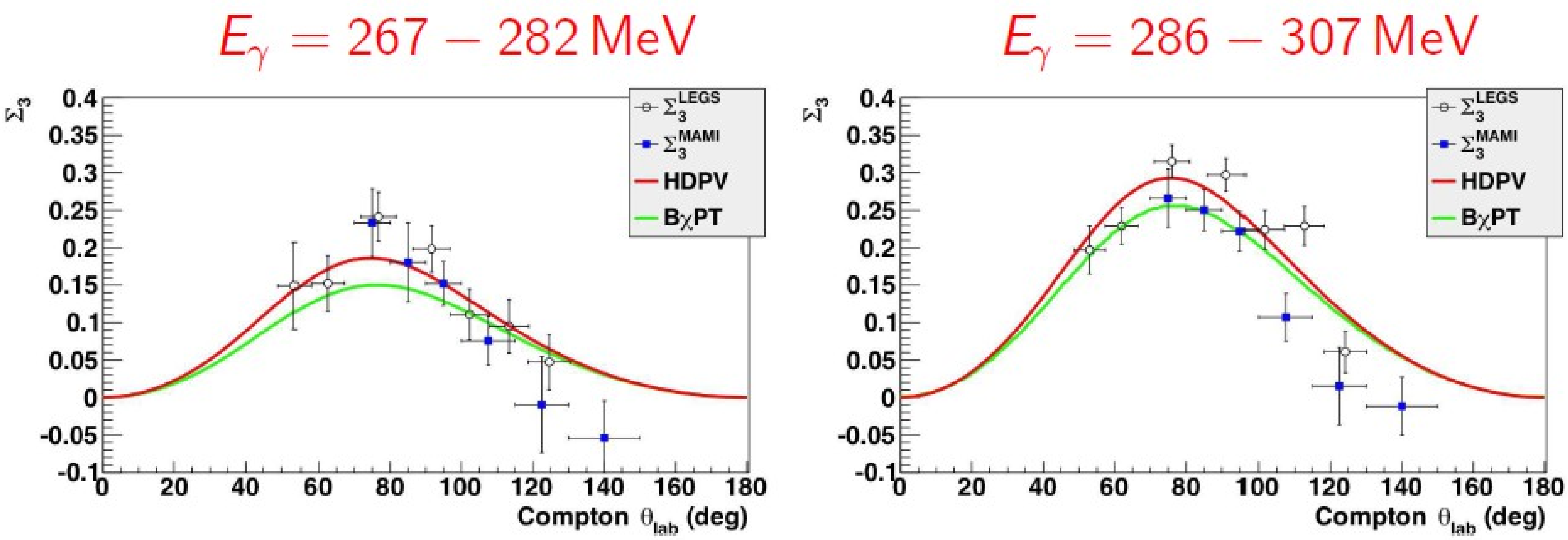
First look in December 2012 data



Magnetic polarizability: proton between poles of a magnetic

Rory Miskimen (Bosen 2009)

Spin polarizabilites



- Recent data (MAMI) and older data (LEGS) are shown along with Dispersion Relation (HDPV) and ChPT (BχPT) predictions.

G. M. Huber, C. Collicott, arXiv:1508.07919 (2015)