Measurement of the proton scalar polarizabilities at MAMI

EuNPC 2018

Edoardo Mornacchi
on behalf of the A2 collaboration

Bologna, 6th September 2018

Institute for Nuclear Physics
Johannes Gutenberg University of Mainz

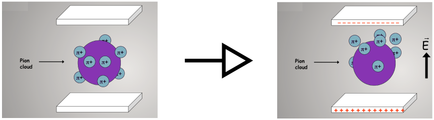
Main goal

Measurement of the proton scalar polarizabilities α_{E1} and β_{M1}

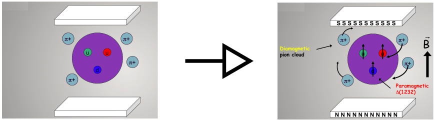
Why to measure them?

- Fundamental properties related to nucleon internal structure
- Limit the precision on different areas of physics
- Fertile meeting ground between theory and experiment

Electric dipole moment: $\vec{p} = \alpha_{E1}\vec{E}$



Magnetic dipole moment: $\vec{m} = \beta_{M1}\vec{H}$



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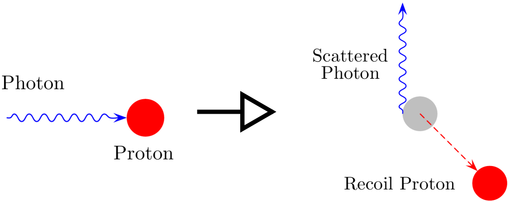
How to measure them?



$$\gamma(\mathbf{k}) + \mathbf{P}(\mathbf{p}) \rightarrow \gamma(\mathbf{k'}) + \mathbf{P}(\mathbf{p'})$$

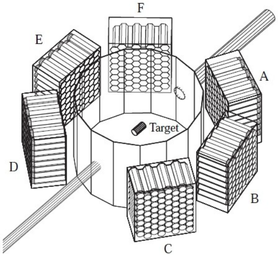
They can be accessed by measuring unpolarized cross-section and polarization observable for Compton scattering

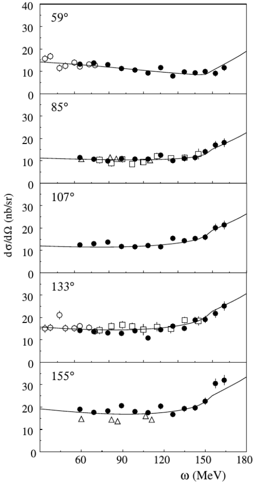
Existing data - TAPS dataset

- Highest statistics published data:

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

- 200 hours of Compton scattering
- $E_{beam} = 180$ MeV
- $E_\gamma = 55 - 165$ MeV, $\theta_\gamma = 59^\circ - 155^\circ$
- 1/3 acceptance of CB system





Triangles: P.S. Baranov et al.(1974)
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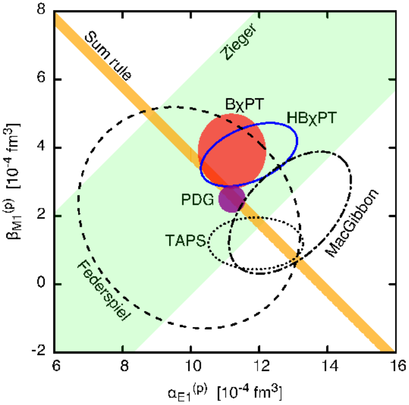


PDG (2012) values:

$$\alpha_{E1} = (12.0 \pm 0.6)\ 10^{-4}\ \text{fm}^3$$
$$\beta_{M1} = (1.9 \pm 0.5)\ 10^{-4}\ \text{fm}^3$$

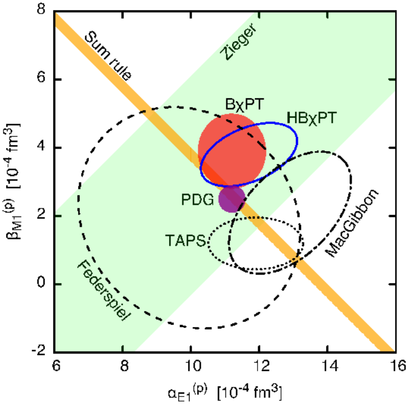
Current PDG values:

$$\alpha_{E1} = (11.2 \pm 0.4)\ 10^{-4}\ \text{fm}^3$$
$$\beta_{M1} = (2.5 \pm 0.4)\ 10^{-4}\ \text{fm}^3$$

Significant change between reviews without new experimental data

$\Rightarrow$ Dataset not fully consistent!

Existing data



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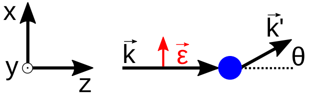
Significant change between reviews without new experimental data
$\Rightarrow$ Dataset not fully consistent!

$\Rightarrow$ New high-precision dataset is needed!

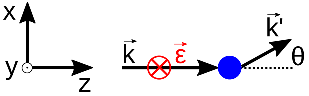
Method

- World existing dataset was previoulsy obtained using only unpolarized cross-section for Compton scattering
- At low energy, the measurement of the beam asymmetry Σ_3 provides an alternative way to extract β_{M1}

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}(\theta)\left[1 + p_\gamma \Sigma_3 cos(2\phi)\right], \text{ where } \boldsymbol{\Sigma_3} = \frac{\mathbf{d}\boldsymbol{\sigma}_\perp - \mathbf{d}\boldsymbol{\sigma}_\parallel}{\mathbf{d}\boldsymbol{\sigma}_\perp + \mathbf{d}\boldsymbol{\sigma}_\parallel}$$



PARA(LLEL)



PERP(ENDICULAR)

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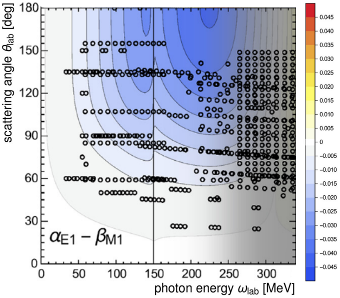
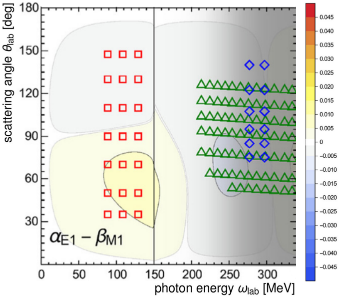
Unpolarized cross-section



Beam asymmetry Σ_3



Grießhammer, H.W., McGovern, J.A. & Phillips, D.R., Eur. Phys. J. A (2018) 54:37

Method

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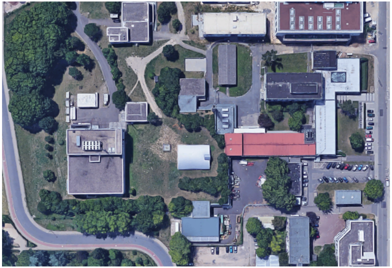
- At low energy, the measurement of the beam asymmetry Σ_3 provides an alternative way to extract β_{M1}

Ongoing experiment at A2

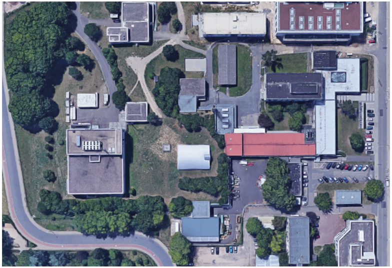
Simultaneous high-precision measurement of both Σ_3 and unpolarized cross-section using a linearly polarized photon beam and an unpolarized LH_2 target

Where

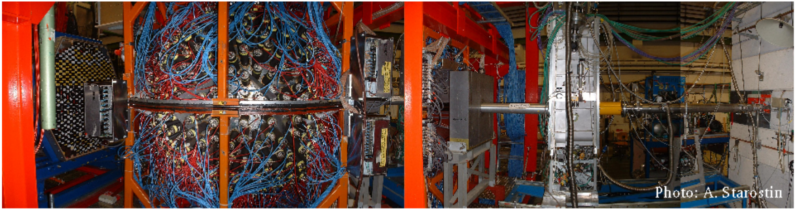
Insitut für Kernphysik - Mainz

Insitut für Kernphysik - Mainz

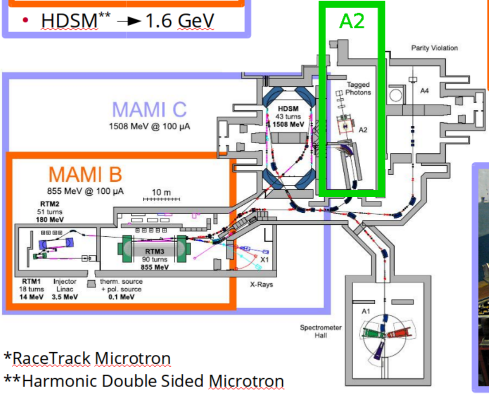


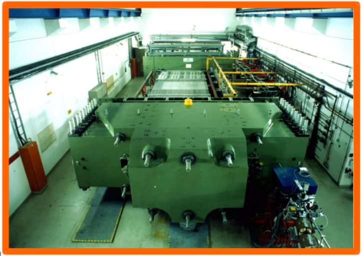
A2 experimental hall

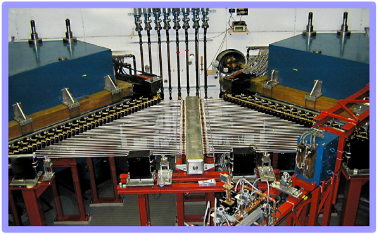


Experimental setup

- Injector → 3.5 MeV
- RTM1* → 14.9 MeV
- RTM2 → 180 MeV
- RTM3 → 883 MeV
- HDSM** → 1.6 GeV

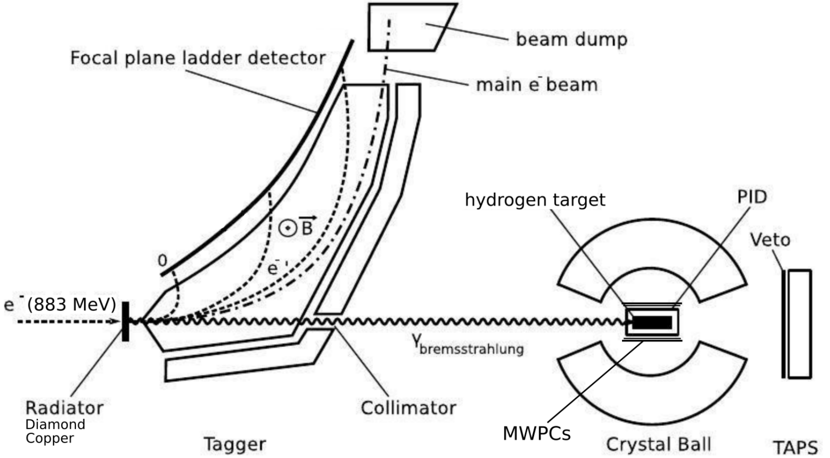






*RaceTrack Microtron
**Harmonic Double Sided Microtron

Apparatus

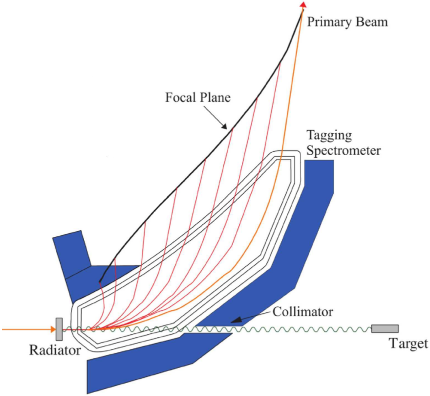


beam dump
Focal plane ladder detector
main e⁻ beam
B
0
e⁻
e⁻ (883 MeV)
hydrogen target
PID
Veto
γ bremsstrahlung
Radiator
Diamond
Copper
Tagger
Collimator
MWPCs
Crystal Ball
TAPS

Photon tagging system upgrade

High intensity beam of linearly polarized tagged photons:

$$E_\gamma = E_0 - E_{e^-}$$



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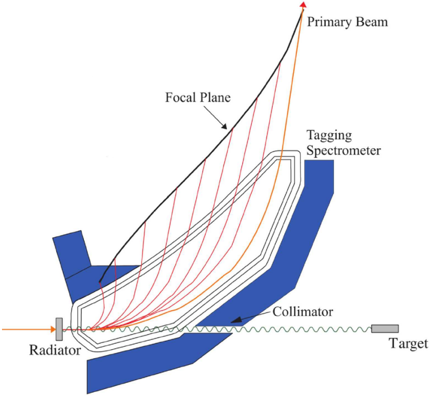
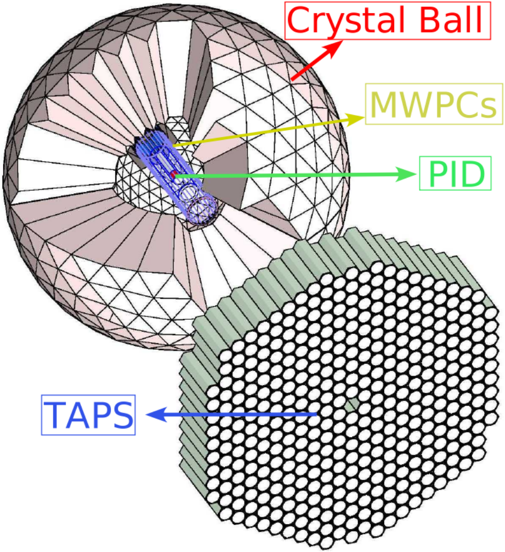


First measurement with the upgraded focal plane detector

- Higher photon flux
- Higher efficiency
- Better control of systematic



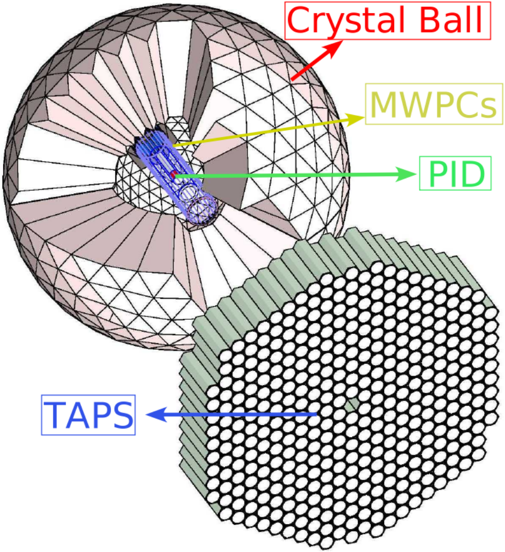
Crystal Ball

- 672 NaI(Tl) crystals
- Particle Identification Detector (PID): 24 scintillator paddles
- 2 Multiwire Proportional Chambers (MWPCs)

TAPS

- 366 BaF_2 and 72 $PbWO_4$ crystals
- 384 veto paddles

Experimental setup



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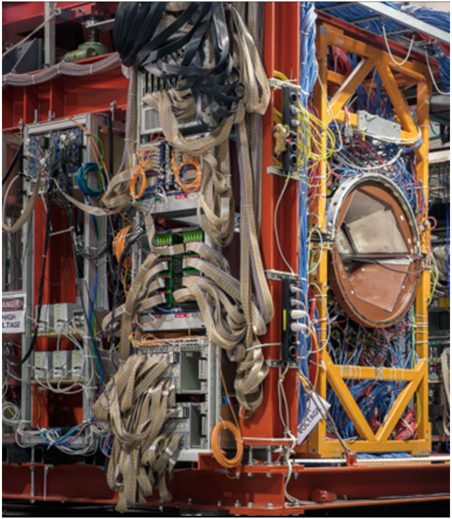
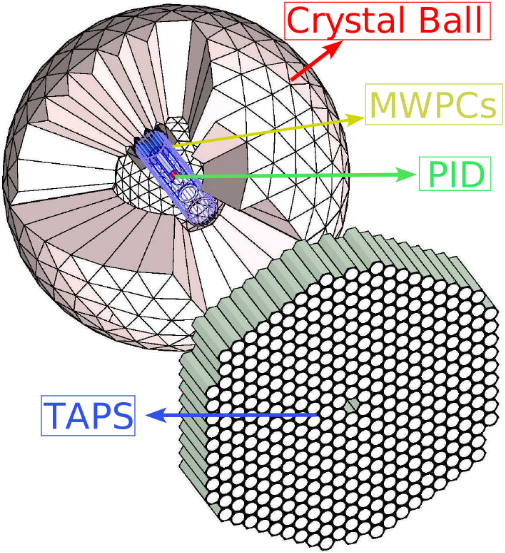
Detectors - Crystal Ball system



- Proposed at SLAC in 1974
- Used in SLAC, DESY, Brookheaven
- MAMI since 2002
- 672 NaI detectors
- $21^\circ < \theta < 159^\circ$
- Full ϕ coverage
- E resolution $\approx 3\%$
- θ resolution $\approx 2.5^\circ$

Experimental setup



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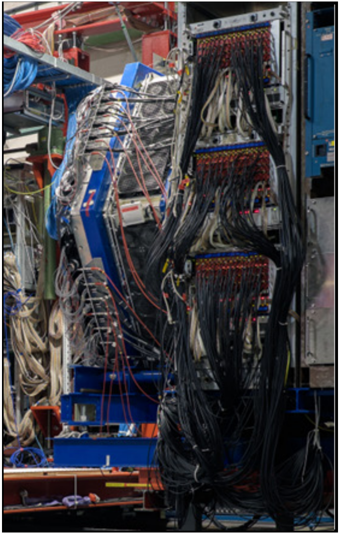
Detectors - TAPS

- Built in 1980s from TAPS collaboration
- Designed from many experiments in different configurations
- 366 BaF_2 detectors
- 72 $PbWO_4$ detectors
- Covers $\theta < 20^\circ$
- E resolution $\approx 3\%$
- θ resolution $\approx 0.7^\circ$



Analysis

Data collection:

- Pilot experiment: data collected in June 2013
- New experiment is ongoing: data were taken in the first half of 2018. 70% of the full dataset is already calibrated and partially analysed!

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We are selecting Compton scattering $\vec{\gamma}p \rightarrow \gamma p$ events with:

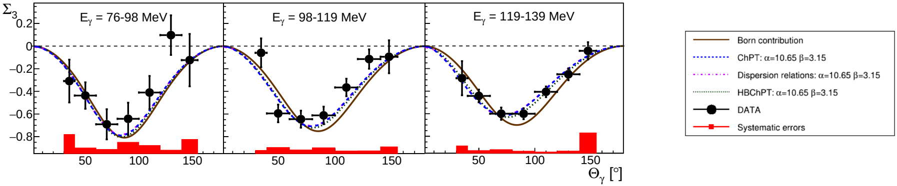
- $E_{\gamma_{beam}}$ = 80 - 140 MeV and $\theta_{\gamma_{out}} = 30^\circ - 155^\circ$
- 1 γ in the final state
- Random background subtraction
- Missing mass cut
- Subtraction of the empty target contribution
- Linear polarization correction event by event
- Constant flux monitor using the pair spectrometer

Pilot experiment

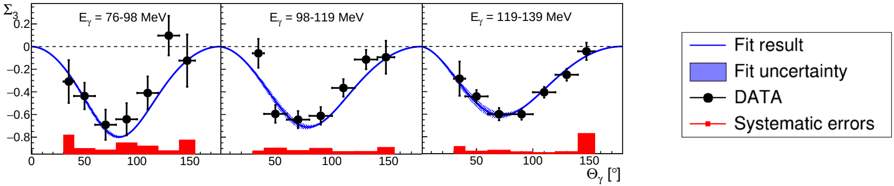
V. Sokhoyan, E.J. Downie, E. Mornacchi, J.A. McGovern, N. Krupina et al., Eur. Phys. J. A (2017) 53:14

$\sim$200k good Compton scattering event in the range $E_{\gamma_b} = 80$ - 140 MeV

- Theoretical predictions for fixed α_{E1} and β_{M1}:



- Fit results using only new Σ_3 data within ChPT framework:



Lensky, V. & Pascalutsa, V., Eur. Phys. J. C (2010) 65:195

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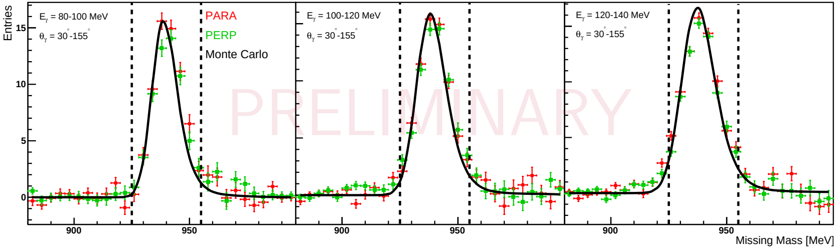
B. Pasquini, D. Drechsel, and M. Vanderhaeghen, Phys. Rev. C 76

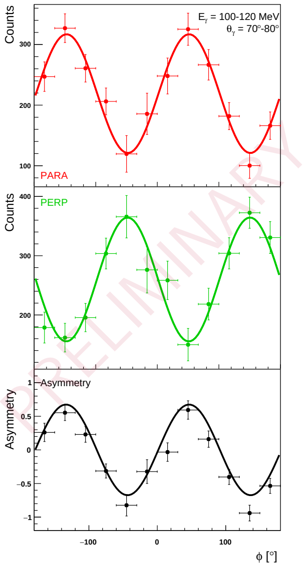


Missing Mass distribution

Good agreement between PARA, PERP and Monte Carlo simulation.

Very good statistics with low background!

New measurement - ϕ distributions



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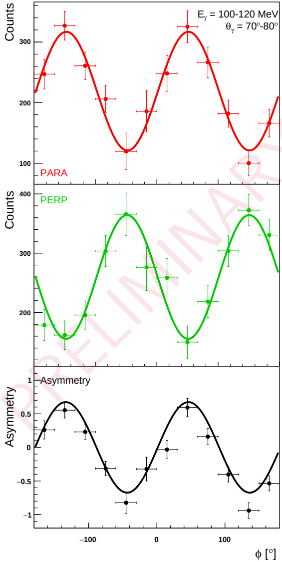
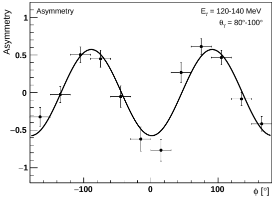
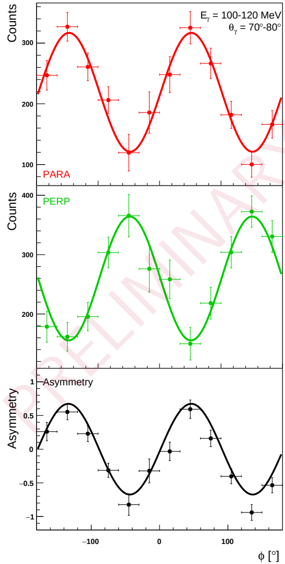


Example of ϕ distribution from the pilot experiment dataset:





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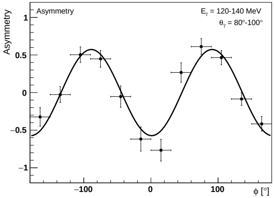
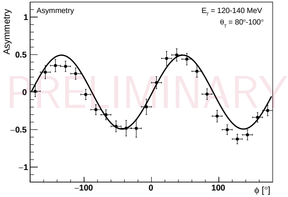


Same example for the new dataset, with double number of bins in ϕ!!



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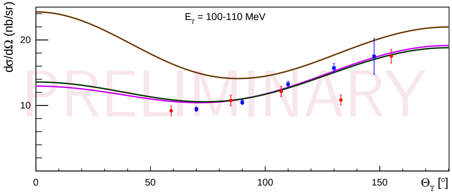

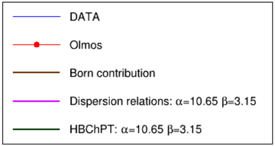

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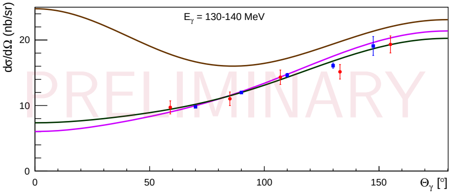

Good agreement with theoretical predictions and improvement in statistics compared to TAPS dataset!
Extension in the forward theta region is under analysis.

New measurement - Beam asymmetry Σ_3

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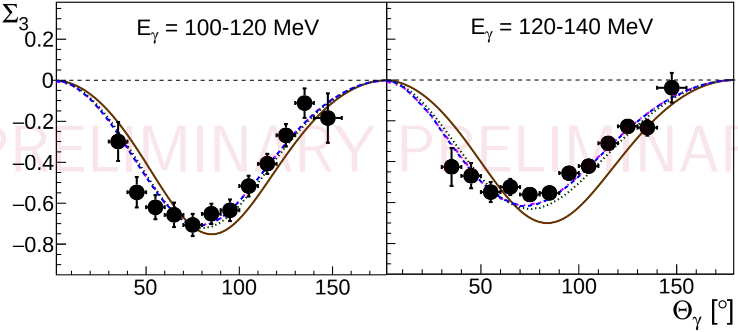

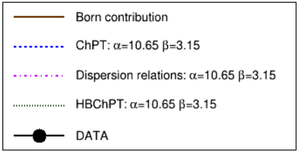

Big improvement in statistics compared to the pilot experiment!

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Summary and outlook

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- First successful measurement of beam asymmetry Σ_3 below pion threshold
- Extraction of β_{M1} from beam asymmetry Σ_3

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- Simultaneous measurement of unpolarized cross-section and beam asymmetry Σ_3
- Preliminary results are definitively very promising!
- A lot of work has still to be done

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New high precision experiment

- Successful data taking using the new Focal Plane Detector!
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New results are coming - STAY TUNED!

THANKS!

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and in particular...

THANKS TO YOU FOR YOUR ATTENTION!

BACKUP

Born term

Under the assumption of NO proton internal structure, the effective Hamiltonian can be written in terms of mass, electric charge and anomalous magnetic moment

- Zeroth order: mass and electric charge

$$H^{(0)}_{\text{eff}} = \frac{\vec{\pi}^2}{2m} + e\phi \qquad (\text{where } \vec{\pi} = \vec{p} - e\vec{A})$$

- First order: anomalous magnetic moment

$$H^{(1)}_{\text{eff}} = -\frac{e(1+k)}{2m}\vec{\sigma}\cdot\vec{H} - \frac{e(1+2k)}{8m^2}\vec{\sigma}\cdot\left[\vec{E}\times\vec{\pi} - \vec{\pi}\times\vec{E}\right]$$

Compton scattering

Scalar polarizabilities

Effective Hamiltonian at the second order includes scalar polarizabilities, which are related to the proton internal structure

- Second order: scalar polarizabilities α_{E1} and β_{M1}
$$H_{\text{eff}}^{(2)} = -4\pi \left[\frac{1}{2}\alpha_{E1}\vec{E}^2 + \frac{1}{2}\beta_{M1}\vec{H}^2\right]$$

Spin polarizabilities

Effective Hamiltonian at the third order includes spin polarizabilities, which describe the response of the proton spin to an applied electric or magnetic field

- Third order: spin polarizabilities γ_{E1E1}, γ_{M1M1}, γ_{M1E2} and γ_{E1M2}
$$H_{\text{eff}}^{(3)} = -4\pi \Big[\frac{1}{2}\gamma_{E1E1}\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}}) + \frac{1}{2}\gamma_{M1M1}\vec{\sigma}\cdot(\vec{H}\times\dot{\vec{H}}) - \gamma_{M1E2}E_{ij}\sigma_i H_j + \gamma_{E1M2}H_{ij}\sigma_i E_j\Big]$$

Existing data - TAPS dataset

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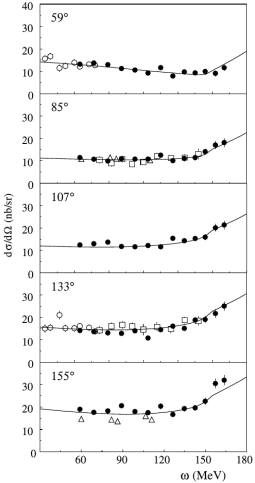
- 200 hours of Compton scattering
- $E_{beam} = 180$ MeV
- $E_\gamma = 55 - 165$ MeV, $\theta_\gamma = 59^\circ - 155^\circ$
- 1/3 acceptance of CB system

	with Baldin	without Baldin
α_{E1}	12.1 ± 1.08	11.9 ± 1.39
β_{E1}	1.6 ± 0.89	1.2 ± 0.76



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Open circles: F.J. Federspiel et al.(1991)
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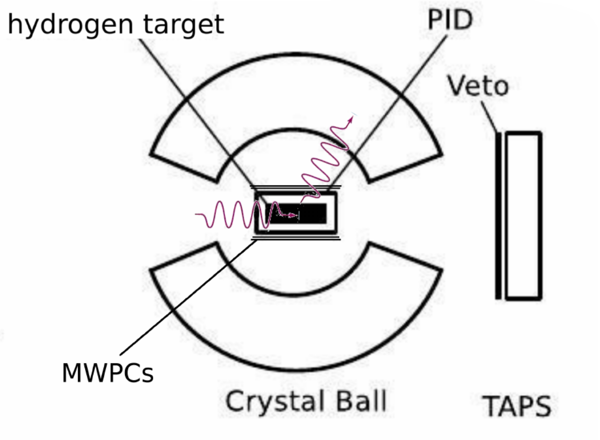
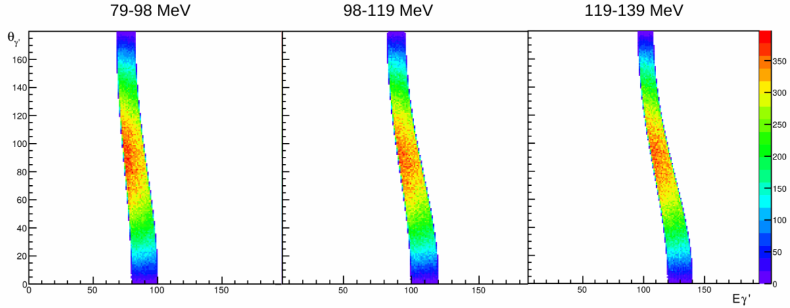
Event selection

Select event with JUST one photon. At this energy, the proton stops inside the target!



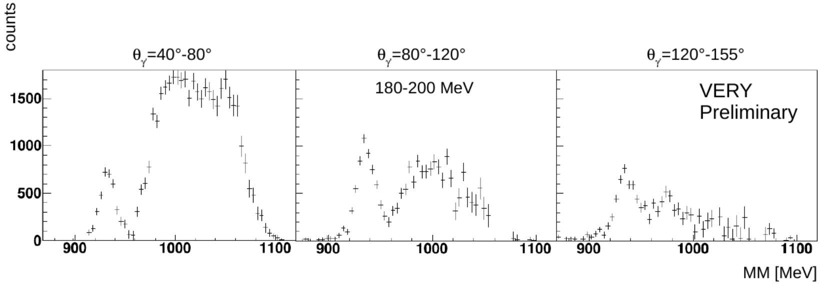
Outgoing photon energy cut

Kinematic gives a cut in the outgoing photon energy. It can be estimate from the MC simulation.



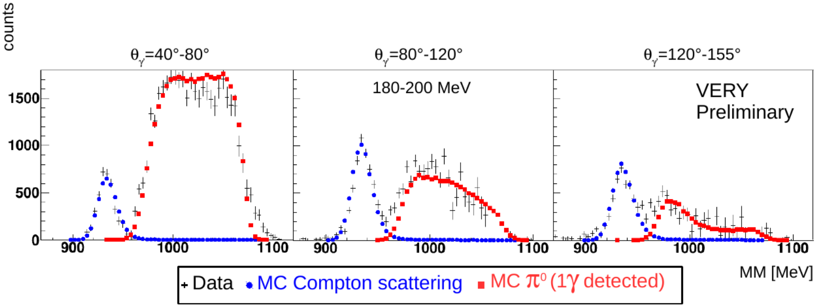
Above threshold

- ✔ Above π-threshold, the unpolarised cross-section is more sensitive to β_{M1}
- ✗ β_{M1} extraction: model dependence increases
- ✗ Background coming from π^0-photoproduction: ~100 times higher cross section. If one of the photons is lost, this could look like Compton



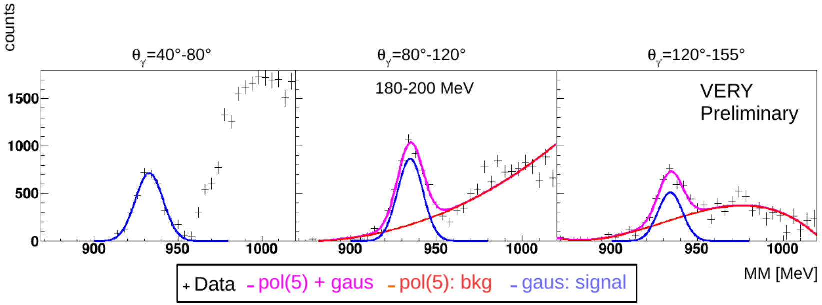
Above threshold

- ✔ Above π-threshold, the unpolarised cross-section is more sensitive to β_{M1}
- ✗ β_{M1} extraction: model dependence increases
- ✗ Background coming from π^0-photoproduction: ~100 times higher cross section. If one of the photons is lost, this could look like Compton
- ✔ Background can be well described using MC simulation



Above threshold

- ✔ Above π-threshold, the unpolarised cross-section is more sensitive to β_{M1}
- ✗ β_{M1}extraction: model dependence increases
- ✗ Background coming from π^0-photoproduction: ~100 times higher cross section. If one of the photons is lost, this could look like Compton
- ✔ Background can be well described using MC simulation
- ✔ Below 200 MeV, the signal can be reasonably separated from the π^0-background



Target

Unpolarized target (Σ_3):

- Liquid hydrogen target (LH_2)
- 10 cm long cell
- T=20 k

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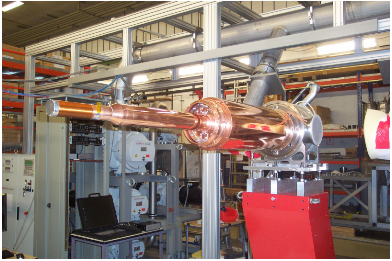
Polarized target (Σ_{2x}&Σ_{2z}):

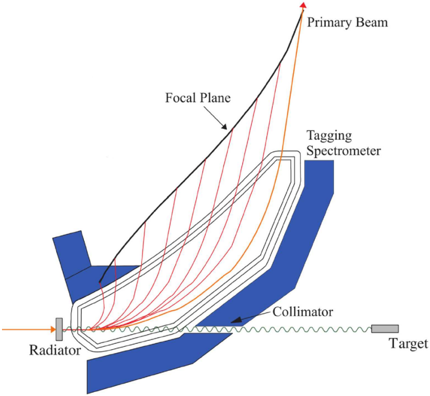


- Butanol (C_4H_9OH)
- 2 cm long cell
- T=25 mK
- Polarization $>$ 90%
- Relaxation time $>$ 1000 h

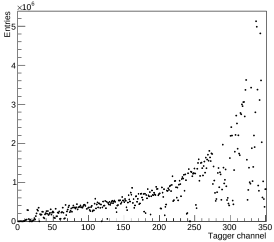
Photon tagging system upgrade

High intensity beam of linearly polarized tagged photons:

$$E_\gamma = E_0 - E_{e^-}$$



Hits distribution in the old FPD



Hits distribution in the new FPD