Measurement of the proton scalar polarizabilities at MAMI

SFB-School 2019

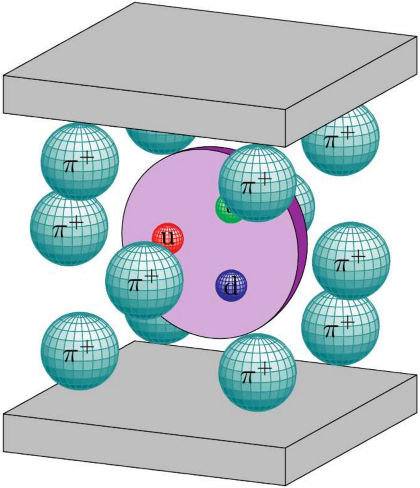
Edoardo Mornacchi

on behalf of the A2 collaboration

Institute for Nuclear Physics
Johannes Gutenberg University of Mainz

Boppard, October 23rd 2019

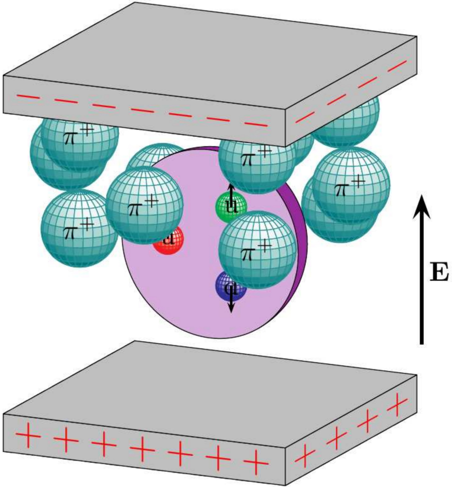
Electric scalar polarizability - α_{E1}



Picture: P. Martel

Describes the response of a proton to an applied electric field:

Electric scalar polarizability - α_{E1}



Picture: P. Martel

Describes the response of a proton to an applied electric field:

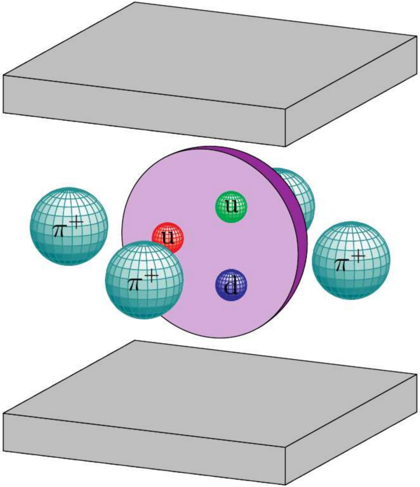
- Electric dipole moment:

$$\vec{p} = \boxed{\alpha_{E1}} \times \vec{E}$$

Electric polarizability

- “Stretchability” of the proton

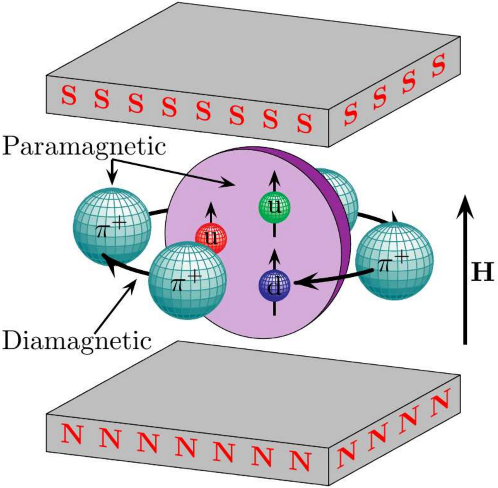
Magnetic scalar polarizability - β_{M1}



Picture: P. Martel

Describes the response of a proton to an applied magnetic field:

Magnetic scalar polarizability - β_{M1}



Picture: P. Martel

Describes the response of a proton to an applied magnetic field:

- Magnetic dipole moment:

$$\vec{m} = \boxed{\beta_{M1}} \times \vec{H}$$

Magnetic polarizability

- "Alignability" of the proton

Measure proton scalar polarizabilities

Why to measure them?

- Fundamental properties related to nucleon internal structure
- Limit precision to different area of physics:
  - two-photon exchange contribution to the Lamb shift and hyperfine structure in atomic physics
  - determination of the EM contribution to n-p mass difference
  - neutron star susceptibility
- Fertile meeting ground between theory and experiment

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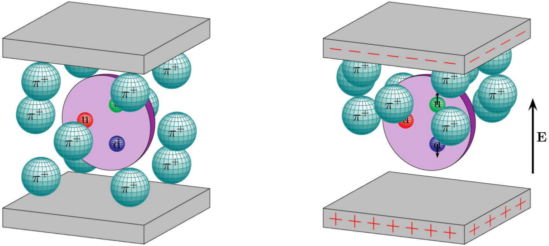
OK!! But how?

Measure proton scalar polarizabilities

How to measure them?

- We could place protons in a static electric field!



Picture: P. Martel

Ok, but how strong should it be to induce any appreciable polarizability?

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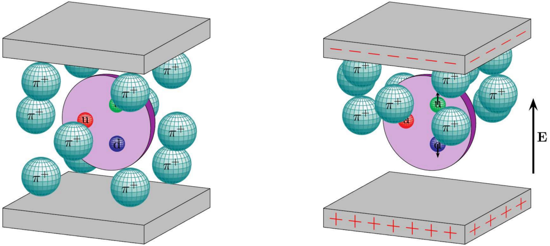

Picture: P. Martel

Ok, but how strong should it be to induce any appreciable polarizability?

For an atom the polarizability effect is proportional to the volume:

$$\alpha_{E_1} \propto r^3$$

How to measure them?

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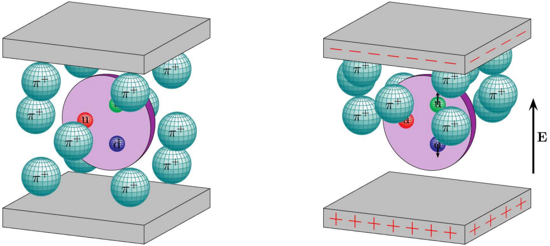

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Ok, but how strong should it be to induce any appreciable polarizability?

Assuming $r_p \approx 0.875$ fm, the polarizability should be:

$$\alpha_{E_1} \propto r^3 \approx 0.6 \text{ fm}^3$$

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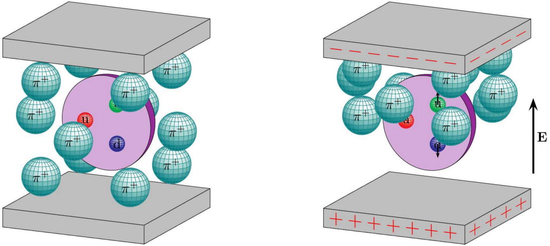

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Assuming $r_p \approx 0.875$ fm, the polarizability should be:
$\alpha_{E_1} \propto r^3 \approx 0.6\ \text{fm}^3$, but $\alpha_{E_1}^{\text{exp}} \approx 10 \times 10^{-4}\ \text{fm}^3$

Measure proton scalar polarizabilities

How to measure them?

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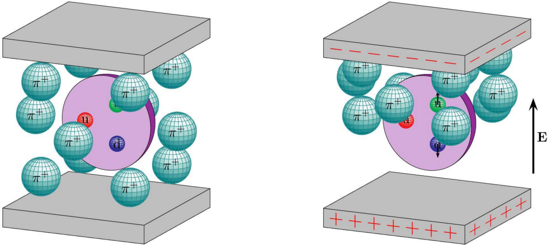


Picture: P. Martel

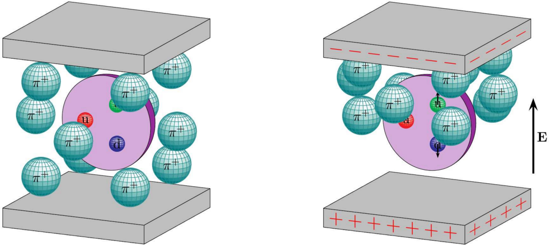
Ok, but how strong should it be to induce any appreciable polarizability?

> Nucleon mass is mostly coming from binding force!
> $\Rightarrow$ It is really stiff and strongly bound!

Measure proton scalar polarizabilities

How to measure them?

- We could place protons in a static electric field!



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Ok, but how strong should it be to induce any appreciable polarizability?

> From the energy level spacing and size of the nucleon, one can estimate: $E_{\text{crit}} \approx 10^{23}\ V/m$

Measure proton scalar polarizabilities

How to measure them?

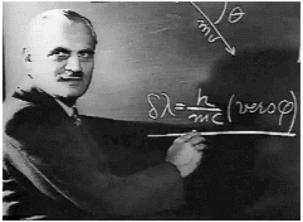
× We could **NOT** place protons in a static electric field!

Measure proton scalar polarizabilities

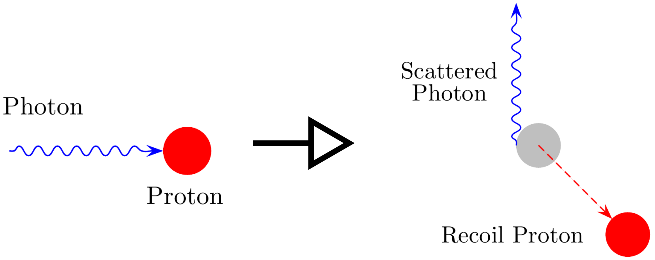
How to measure them?

× We could **NOT** place protons in a static electric field!

- We can use Compton scattering!
  - Observed for the first time by Arthur Compton in 1923
  - No classical explanation
  - Clear evidence of relativity and particle-like nature of the light



Nuclear Compton scattering



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

Internal structure of the proton can be accessed by measuring unpolarized cross-section and polarization observables for Compton scattering

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

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

- First order: anomalous magnetic moment

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

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}

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

Compton scattering - Hamiltonian

Scalar polarizabilities

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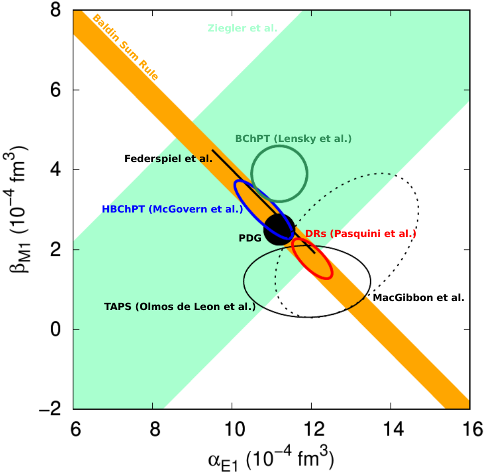
$$H_{\mathrm{eff}}^{(2)} = -4\pi \left[\frac{1}{2} \alpha_{E1} \vec{E}^2 + \frac{1}{2} \beta_{M1} \vec{H}^2 \right]$$

How is the current situation for the scalar polarizabilities measurements?

Existing data on scalar polarizabilities



B. Pasquini, P. Pedroni and S. Sconfietti, J. Phys. G **46**, no. 10, 104001 (2019).

PDG (2012) values:

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

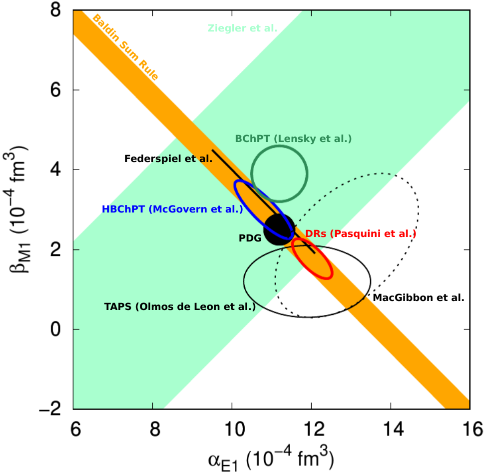
Current PDG values:

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

Significant change between reviews without new experimental data

$\Rightarrow$ Dataset not fully consistent!

Existing data on scalar polarizabilities



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

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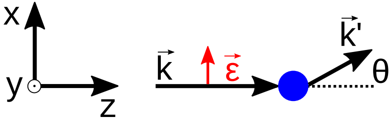
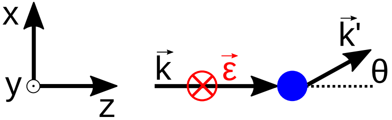
Method

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

$$\Sigma_3 = \frac{\mathbf{d}\boldsymbol{\sigma}_{\parallel} - \mathbf{d}\boldsymbol{\sigma}_{\perp}}{\mathbf{d}\boldsymbol{\sigma}_{\parallel} + \mathbf{d}\boldsymbol{\sigma}_{\perp}}$$

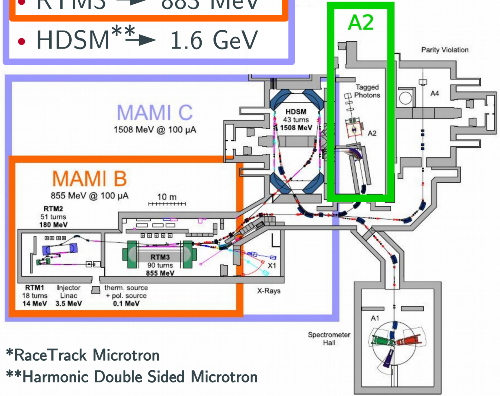


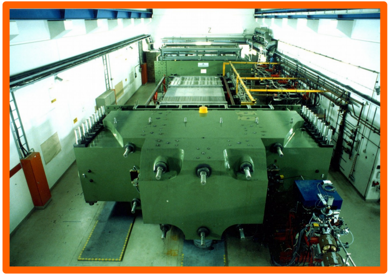
PARA(LLEL)

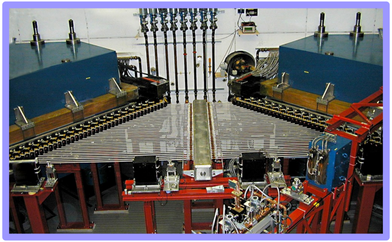


PERP(ENDICULAR)

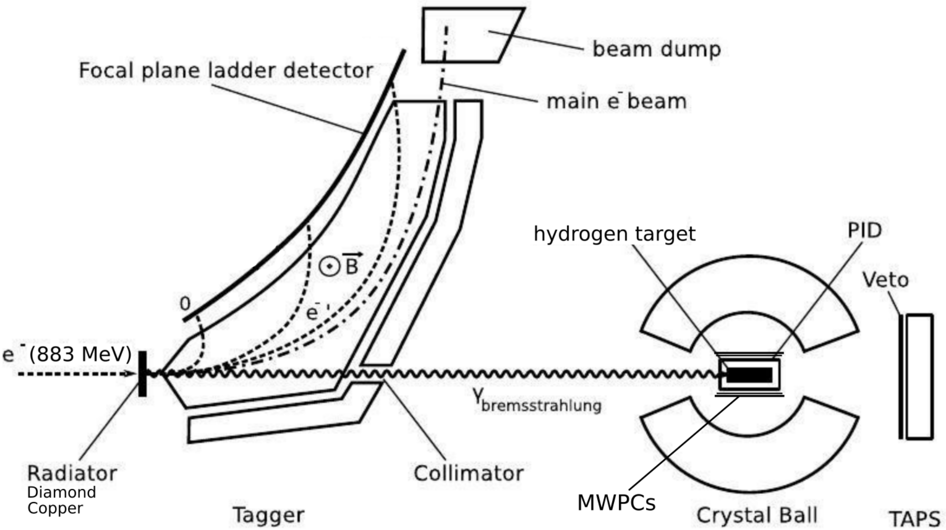
- Injector → 3.5 MeV
- RTM1* → 14.9 MeV
- RTM2 → 180 MeV
- RTM3 → 883 MeV
- HDSM** → 1.6 GeV



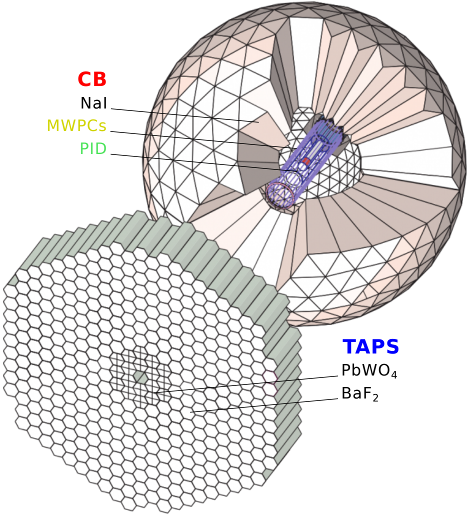




*RaceTrack Microtron
**Harmonic Double Sided Microtron


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

Experimental setup



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

Analysis

Data collection:

- Pilot experiment: data collected in June 2013
- New high precision experiment: data collected in the first half of 2018

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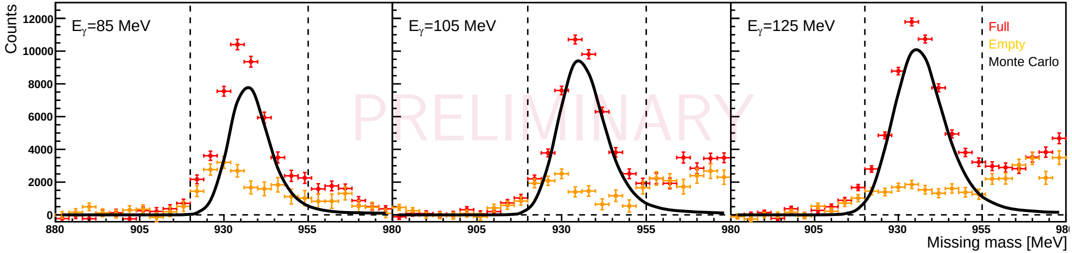
We are selecting Compton scattering $\vec{\gamma}p \rightarrow \gamma p$ events with:

$\Rightarrow E_{\gamma_{beam}} = 80$ - 140 MeV and $\theta_{\gamma_{out}} = 30°$ - $155°$

- Subtraction of random coincidences in the tagger
- 1 γ in the final state
- Subtraction of the empty target contribution
- Missing mass cut
- Linear polarization degree extraction event by event
- Constant flux monitoring using a pair spectrometer

Missing mass distribution — PARALLEL dataset

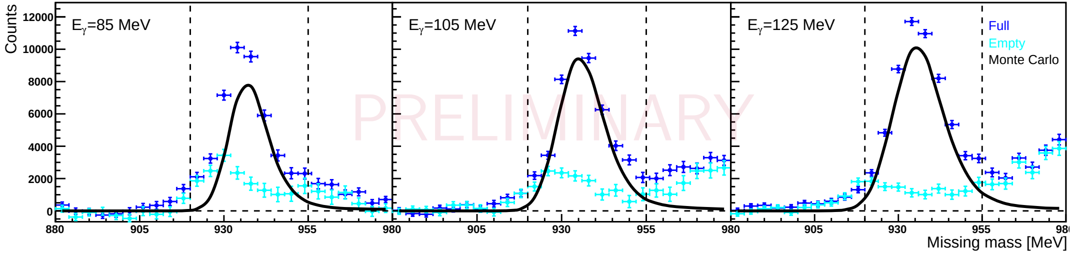
The LH_2 target requires separate data taking with the empty target to determine the contribution of the target cell itself



$$m_{miss} = \sqrt{(E_{\gamma_i} + m_p - E_{\gamma_f})^2 - (\vec{p_{\gamma_i}} - \vec{p_{\gamma_f}})^2} = m_p$$

Missing mass distribution — PERPENDICULAR dataset

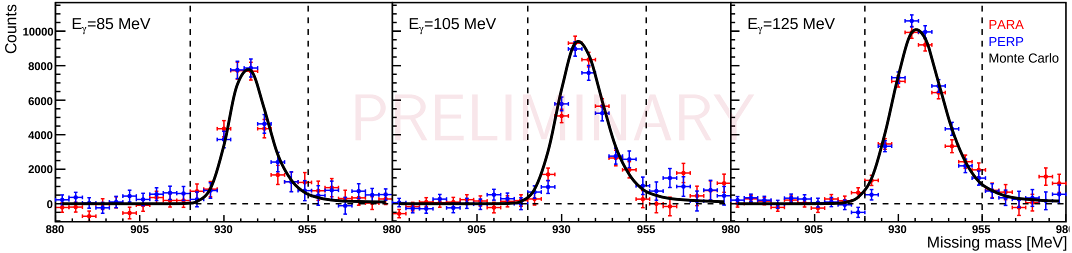
The LH_2 target requires separate data taking with the empty target to determine the contribution of the target cell itself



$$m_{miss} = \sqrt{(E_{\gamma_i} + m_p - E_{\gamma_f})^2 - (\vec{p_{\gamma_i}} - \vec{p_{\gamma_f}})^2} = m_p$$

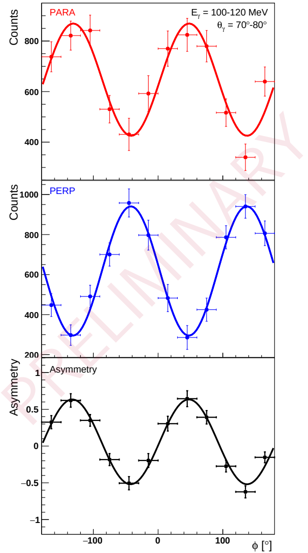
Missing mass distribution — after empty target subtraction

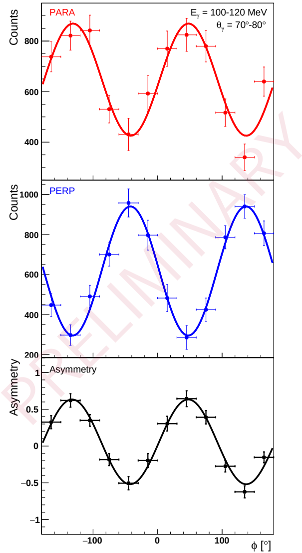
Good agreement between PARA, PERP and Monte Carlo simulation.
Very good statistics with low background!



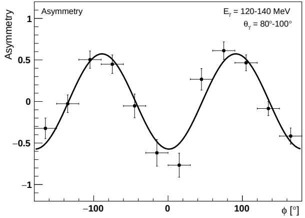
$$m_{miss} = \sqrt{(E_{\gamma_i} + m_p - E_{\gamma_f})^2 - (\vec{p_{\gamma_i}} - \vec{p_{\gamma_f}})^2} = m_p$$

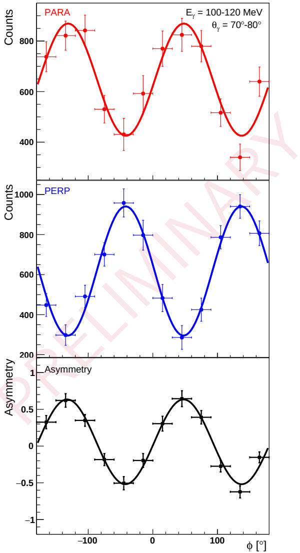
New measurement - ϕ distributions





Example of ϕ distribution from the pilot experiment dataset:





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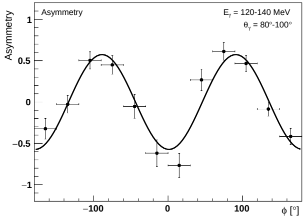
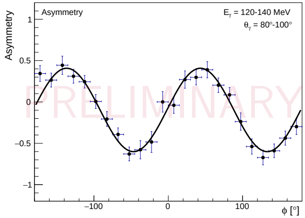
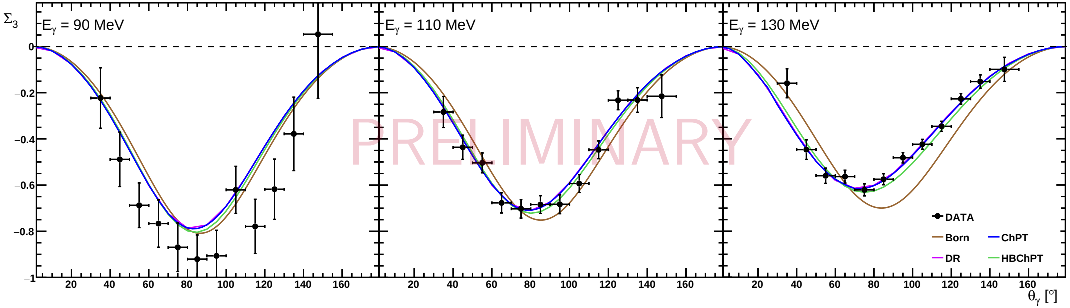


Same example for the new dataset, with double number of bins in ϕ!!





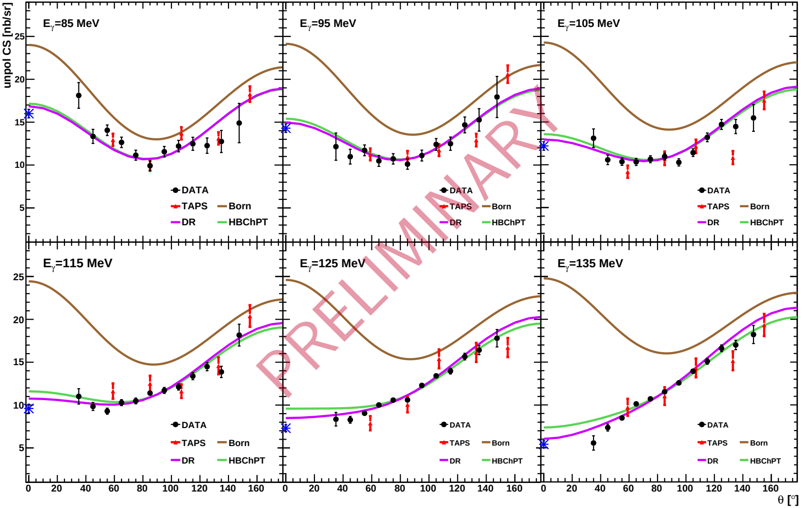
Big improvement in statistics compared to the pilot experiment!

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

McGovern, J.A., Phillips, D.R. & Grießhammer, H.W.,
Eur. Phys. J. A (2013) 49:12

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

New measurement - Unpolarized cross-section



Good agreement with theoretical predictions and improvement in statistics compared to TAPS dataset!

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

McGovern, J.A., Phillips, D.R. & Grießhammer, H.W., Eur. Phys. J. A (2013) 49: 12

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

Conclusions

- Successful first data taking with the new tagging system
- 1.2 million of good Compton scattering events in the relevant energy range
- Simultaneous high precision measurement of unpolarized cross-section and Σ_3
- Preliminary results are definitively very promising!
- Preliminary checks showed a small systematic error
- Preliminary fits for the extraction of the scalar polarizabilities showed a significant improvement compared to the biggest data-set currently published
- Analysis is almost finalized and a publication is expected soon

THANKS!

Special thanks to all the A2 collaboration members!

THANKS!

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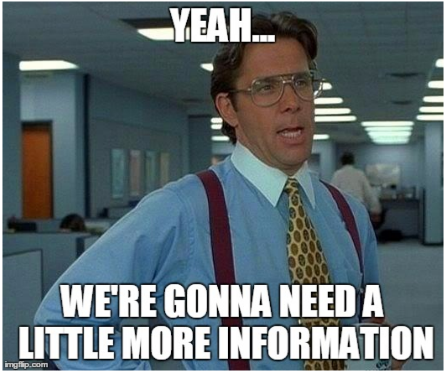
and in particular...

THANKS TO YOU FOR YOUR ATTENTION!

Backup!

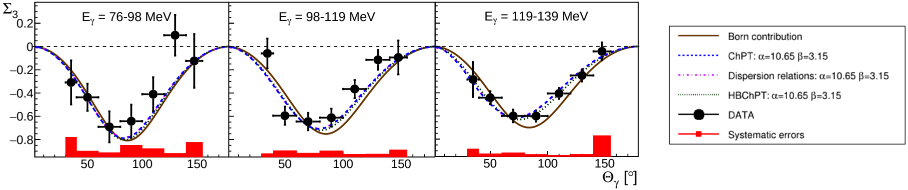


Pilot experiment

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}:



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

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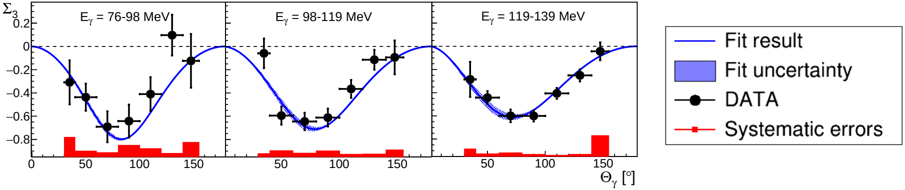
B. Pasquini, D. Drechsel, and M. Vanderhaeghen, Phys. Rev. C 76

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



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

Low-energy expansion

The low-energy expansion, developed by Petrun'kin, calculate the Compton scattering amplitude to the order of ω^2:

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Born}} + \left(\frac{d\sigma}{d\Omega}\right)_{\text{NB}},$$

where:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Born}} = \frac{1}{2}\left(\frac{e^2}{m}\right)^2\left(\frac{\omega'}{\omega}\right)^2 \times \left\{1+\cos^2\theta_{\gamma'} + \frac{\omega\omega'}{m^2}\left([1-\cos\theta_{\gamma'}]^2 + a_0 + a_1\cos^2\theta_{\gamma'} + a_2 z^2\right)\right\},$$

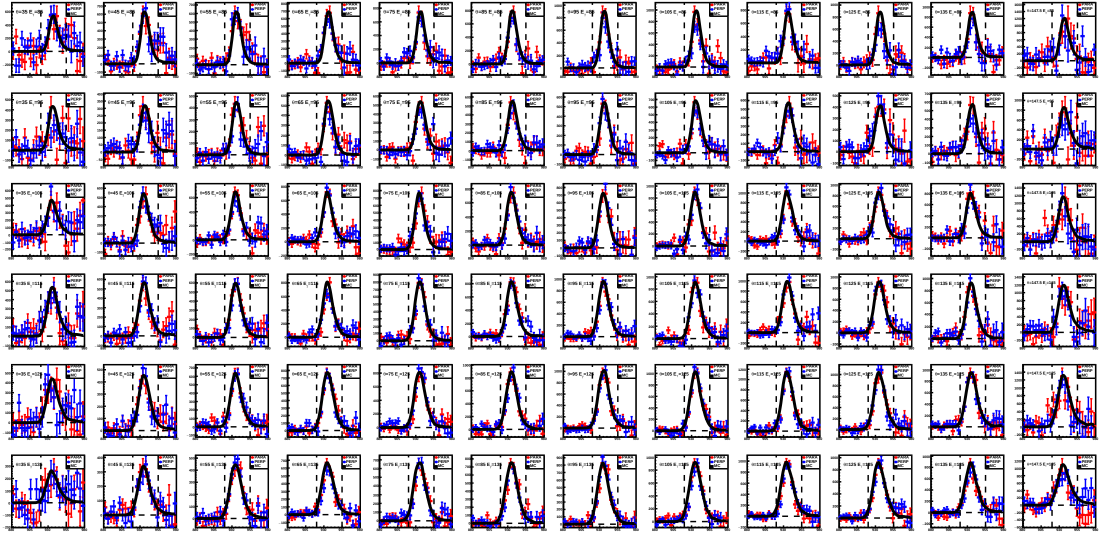
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{NB}} = -\omega\omega'\left(\frac{\omega'}{\omega}\right)^2\frac{e^2}{m}\left[\frac{\alpha_{E_1}+\beta_{M_1}}{2}(1+\cos\theta_{\gamma'})^2 + \frac{\alpha_{E_1}+\beta_{M_1}}{2}(1-\cos\theta_{\gamma'})^2\right].$$

Here ω' is the energy of the scattered photon, given by:

$$\omega' = \frac{\omega}{1+(\omega/m)(1+\cos\theta_{\gamma'})},$$

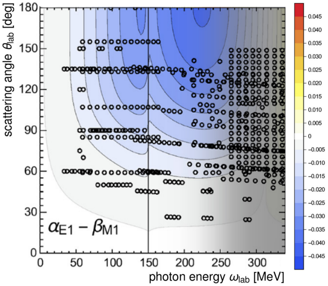
while the coefficients a_0, a_1 and a_2 are combination of the anomalous magnetic moment k.

Missing Mass empty target subtracted

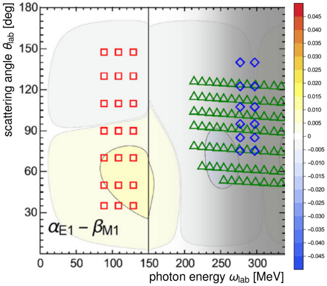


Sensitivity

Unpolarized cross-section



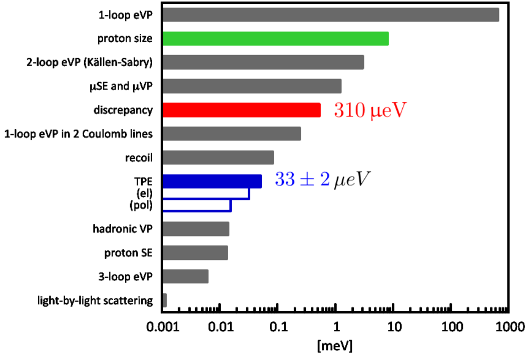
Beam asymmetry Σ_3



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

Motivation - muonic hydrogen 2S-2P Lamb shift

The two-photon exchange contributions to the muonic hydrogen Lamb shift are usually divided into an elastic part and an inelastic part (proton polarization contribution ΔE_P).



F. Hagelstein, R. Miskimen & V. Pascalutsa, Progress in Particle and Nuclear Physics 88 (2016)

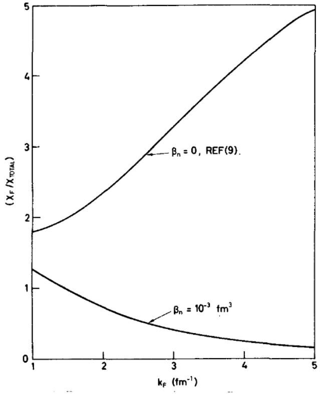
TABLE I. Numerical results for the $O(\alpha^5)$ proton structure corrections to the Lamb shift in muonic hydrogen. Energies are in μeV.

(μeV)	This work	Refs. [11,12]	Ref. [22]
ΔE^{subt}	5.3 ± 1.9	1.8	2.3
ΔE^{inel}	-12.7 ± 0.5	-13.9	-13.8
ΔE^{el}	-29.5 ± 1.3	-23.0	-23.0
ΔE	-36.9 ± 2.4	-35.1	-34.5

C. E. Carlson & M. Vanderhaeghen, Phys. Rev. A 84 (2011)
[11] K. Pachucki, Phys. Rev. A 53 (1996)
[12] K. Pachucki, Phys. Rev. A 53 (1999)
[22] A. P. Martynenko, Phys. At. Nucl. 69 (2006)

Motivation - neutron star

In the case of $\beta^N_{M1} \approx 10^{-3}$ fm^3, the intrinsic neutron polarizability $\chi_n = \beta_n \rho = \beta_n k_F^3 / 3\pi^2$ is the dominant contribution to the neutron star susceptibility, compare to the Pauli paramagnetic contribution $\chi_F = \mu^2 m_n k_F / \pi$



Effect of the magnetic polarizability on the paramagnetic susceptibility as a function of the Fermi wave vector

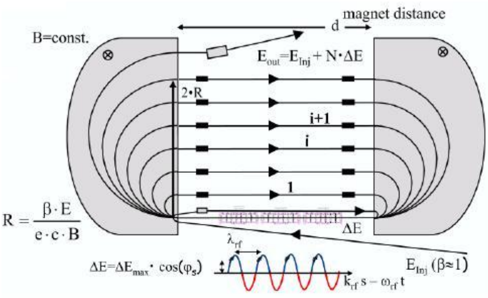
J. Bernabeu, T. E. O. Ericson, and C. Ferro Fontan, Phys. Lett. B, 49:381, 1974.

Motivation - EM contribution to the proton-neutron mass

The determination of the electromagnetic self-energy contribution to the proton-neutron mass difference is limited by our knowledge of the difference between the proton and neutron scalar magnetic polarizabilities, for which even the sign is presently unknown.

A. Walker-Loud, C. E. Carlson, and G. A. Miller, Phys. Rev. Lett. 108 (2012).

Race Track Mictrotron



- Every lap, the electrons are accelerated by the LINAC:

$$\Delta E = \frac{ec^2 B}{2\pi\nu_{fr}}$$

- The final energy is give by:

$$\Delta E_{\text{out}} = E_i + N\Delta E$$

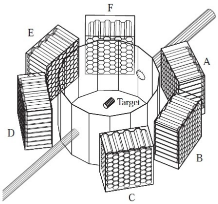
Existing data on Compton scattering on the proton - TAPS dataset

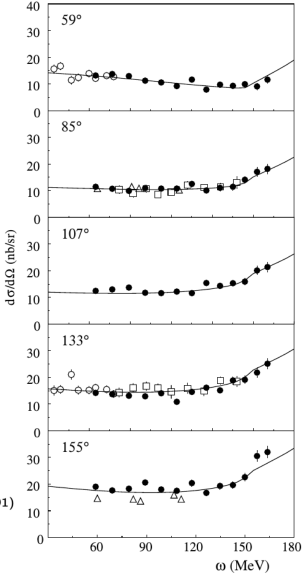
- Highest statistics published data:

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

- 200 hours of Compton scattering
- $E_{\text{beam}} = 180$ MeV
- $E_\gamma = 55 - 165$ MeV, $\theta_\gamma = 59^\circ - 155^\circ$
- $\sim 1/3$ acceptance of the A2 apparatus

$$\alpha_{E1} = (12.1 \pm 1.08)\ 10^{-4}\ \text{fm}^3$$
$$\beta_{M1} = (1.6 \mp 0.89)\ 10^{-4}\ \text{fm}^3$$



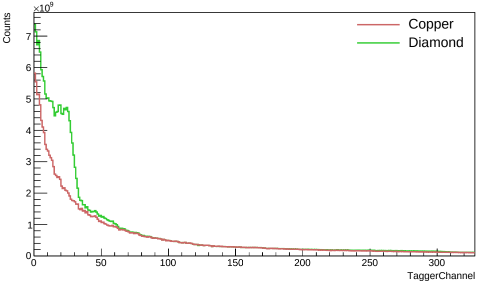


Triangles: P.S. Baranov et al.(1974)
P.S. Baranov et al.(1975)
Open circles: F.J. Federspiel et al.(1991)
Squares B.E. MacGibbon et al.(1995)
Curve: R.A. Arndt et al.(1996)

Polarized photon beam

A high energy electron can produce Bremsstrahlung photons when slowed down by a dense material.

- From an unpolarized electron beam, one can produce unpolarized photons using an amorphous radiator or polarized photons using a diamond radiator

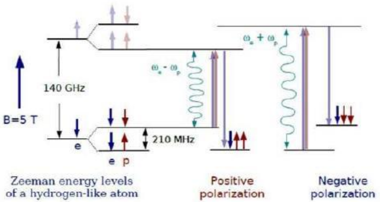


- From a longitudinally polarized electron beam, one can produce circularly polarized photons

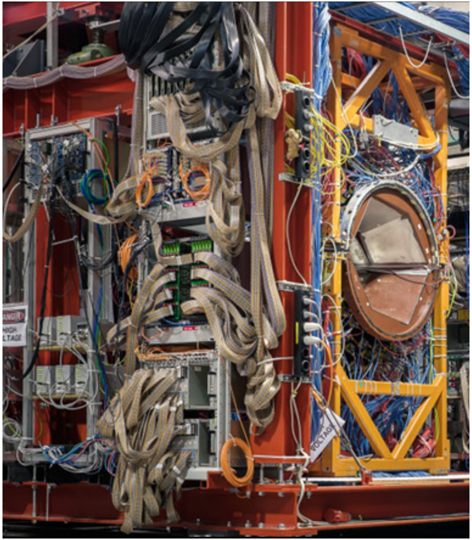
Frozen spin target

Protons are polarized via Dynamic Nuclear Polarization (DNP):

- coll target to 0.2 K
- use 2.5 T to align electron spins
- pump $\approx$ 70 GHz microwaves (just above, or below, the electron spin resonance frequency), causing spin-flips between electrons and protons
- cool target to 0.025 K in order to freeze the proton spins
- remove the polarizing magnet and turn on 0.6 T in the cryostat to maintain the polarization
- get a relaxation time $>$ 1000h and a polarization up to 90%



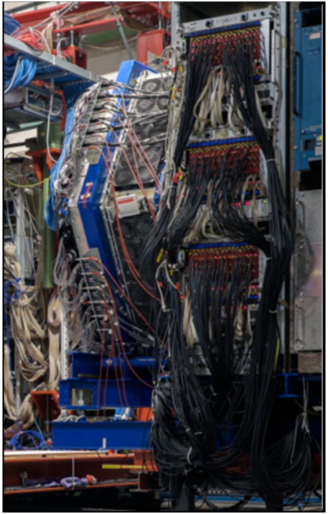
Detectors - Crystal Ball system



- 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 $\approx 2.5^\circ$

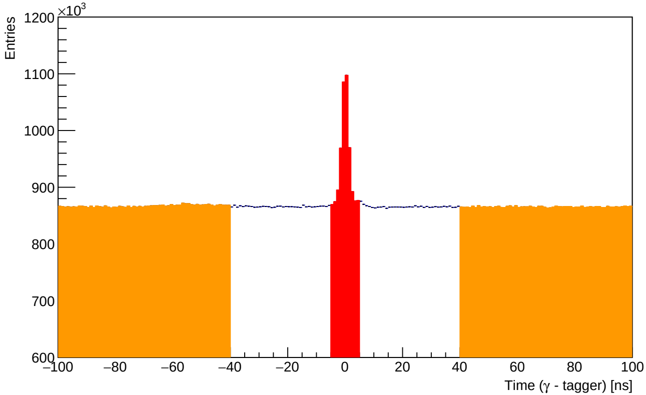
Detectors - TAPS

- 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 $\approx 0.7^\circ$



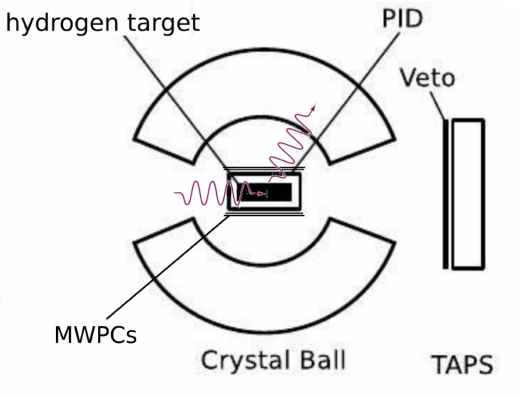
Random coincidences subtraction

Cut on prompt and random photons in the time spectra. Randoms are scaled according to the time interval and subtracted from the prompts, in order to remove accidental coincidences.



Event selection

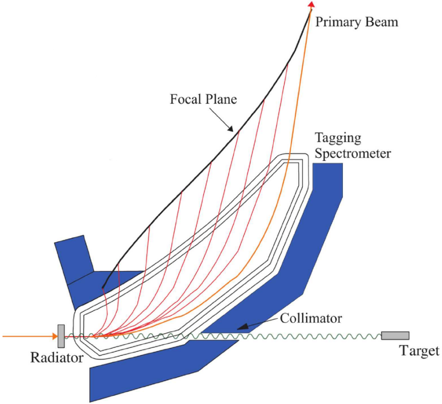
Select event with ONLY one photon. At this energy, the proton stops inside the target!



Photon tagging system

High intensity beam of linearly polarized tagged photons:

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



Photon tagging system

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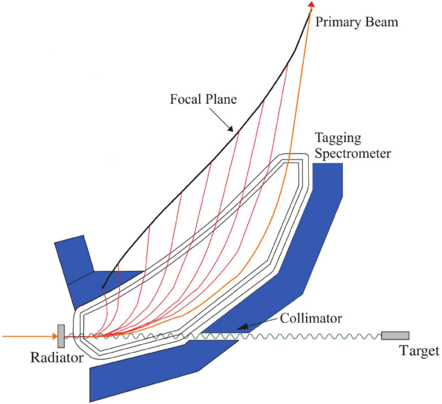
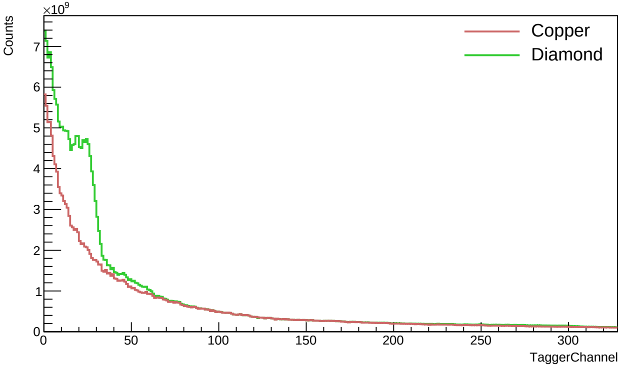


Upgrade of the focal plane detector

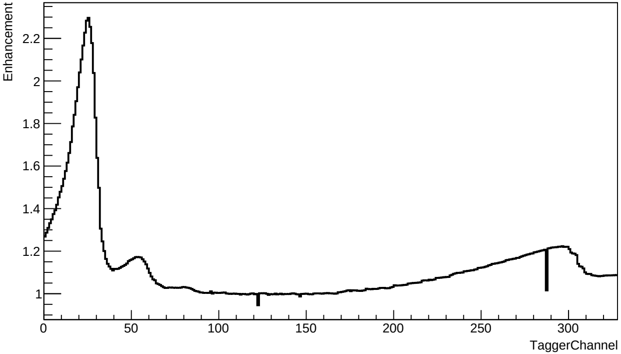
- Higher photon flux
- Higher efficiency
- Better control of systematic

The amorphous reference is taken every $\sim$ 24 hours to account for possible variation in the bremsstrahlung distribution



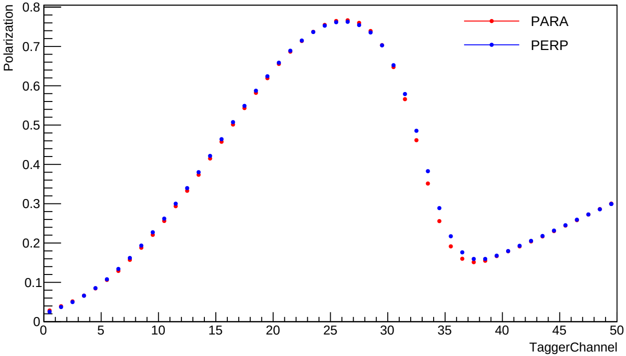
Linear polarization

The enhancement is obtained dividing the polarized and the amorphous. It is then fitted every ~ 2 seconds to determine the polarization

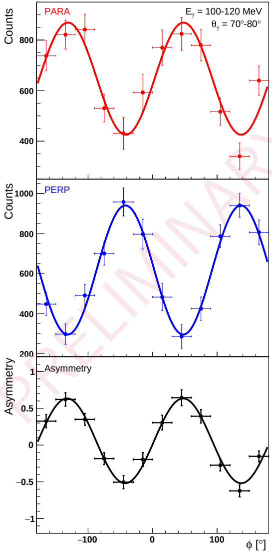


Linear polarization

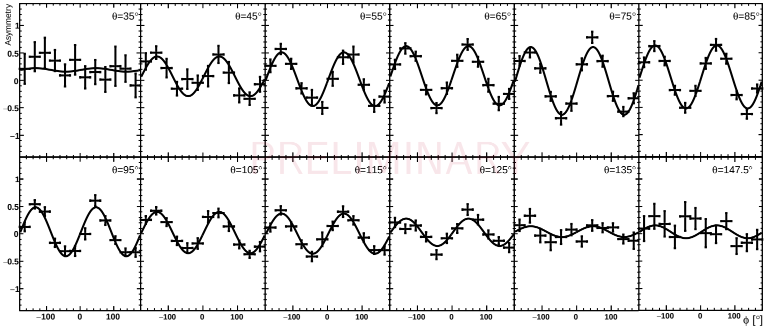
The polarization degree is then determined for different beam energies both for the parallel and the perpendicular dataset



New measurement - ϕ distributions

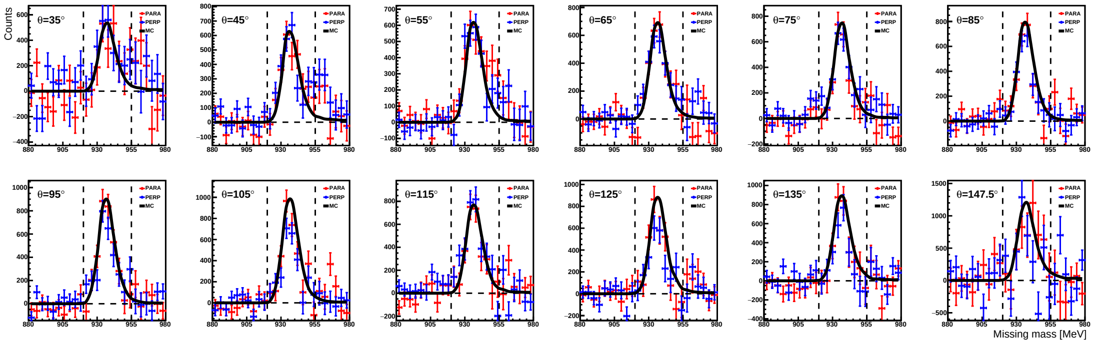


$E_{\gamma} = 130$ MeV:

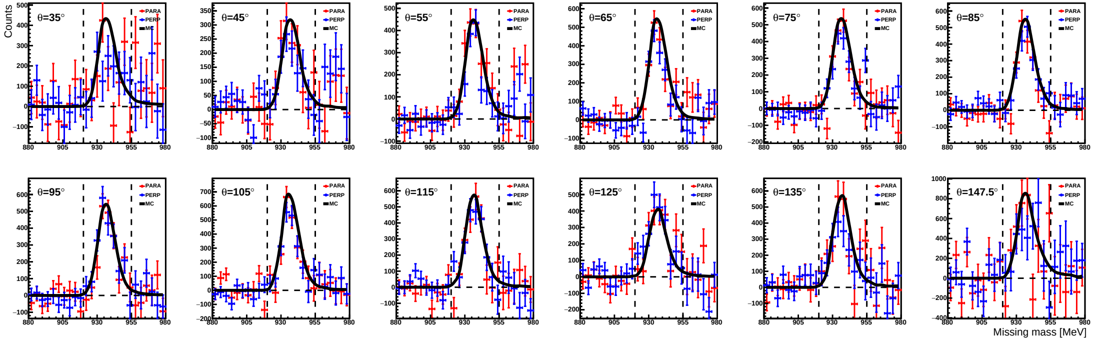


$$\frac{d\sigma}{d\Omega}(E,\theta,\phi) = \frac{d\sigma}{d\Omega}(E,\theta)\left[1 + \mathrm{p}_{\gamma}(E)\Sigma_3(E,\theta)cos(2\phi)\right]$$

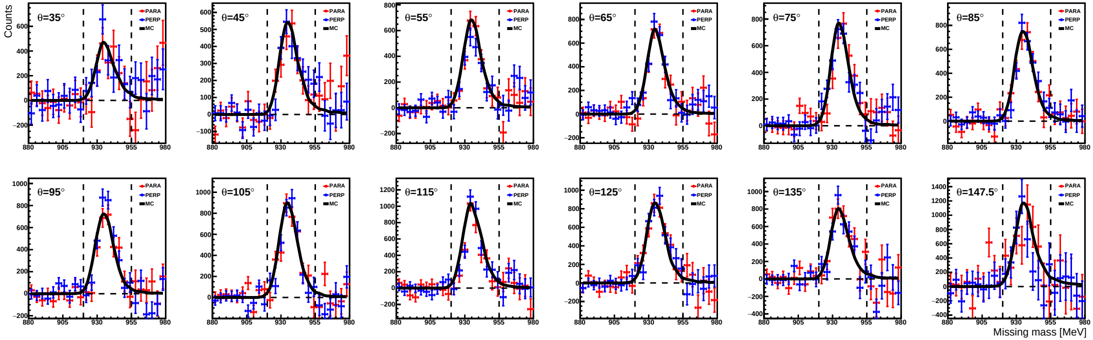
Missing mass $E_\gamma = 85$ MeV



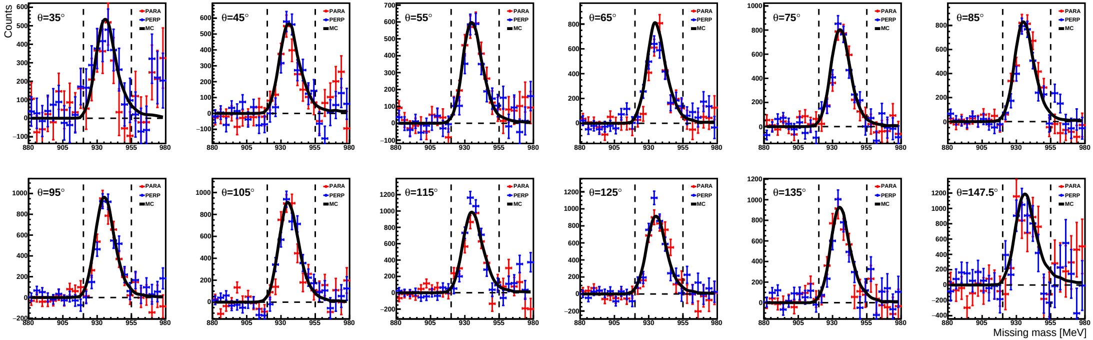
Missing mass $E_\gamma = 95$ MeV



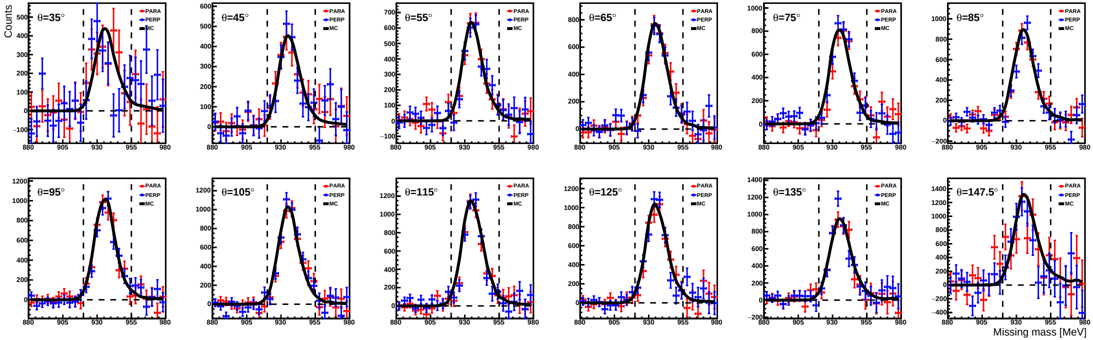
Missing mass $E_\gamma = 105$ MeV



Missing mass $E_\gamma = 115$ MeV



Missing mass $E_\gamma = 125$ MeV



Missing mass $E_\gamma = 135$ MeV