Measurement of nucleon polarizabilities with TPC at MAMI

Vahe Sokhoyan (KPH Mainz)

TPC Collaboration Meeting
Mainz, 10.03.2020

Institut für Kernphysik

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

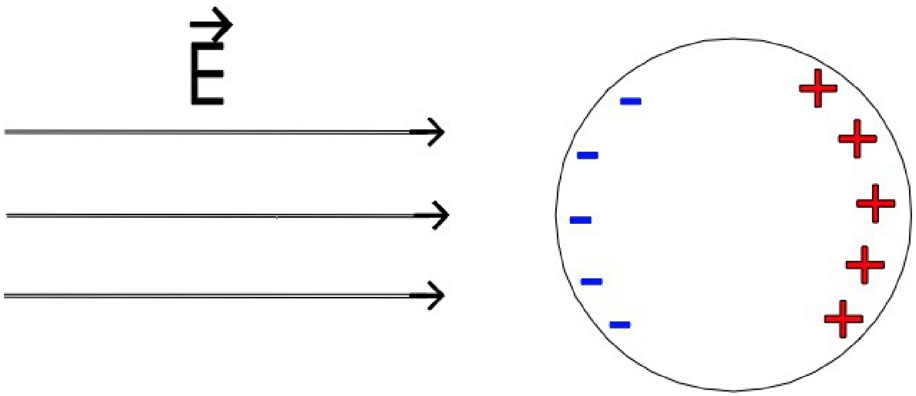
Contents

- Nucleon scalar polarizabilities
- Ongoing program within A2 Collaboration

- New idea: Combination of a high-pressure TPC with the Crystal Ball/TAPS setup at MAMI
- Measurement of nucleon polarizabilities
- Measurement of dilepton photoproduction → extract proton radius?
- Broader physics program with Crystal Ball in combination with TPC?

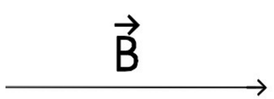
Scalar polarizabilities

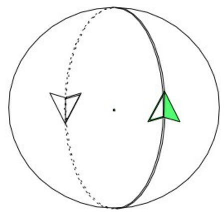
Proton Electric Polarizability



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

Proton Magnetic Polarizability

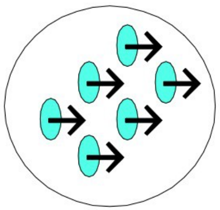




Diamagnetism

$\beta_{dia} < 0$

or



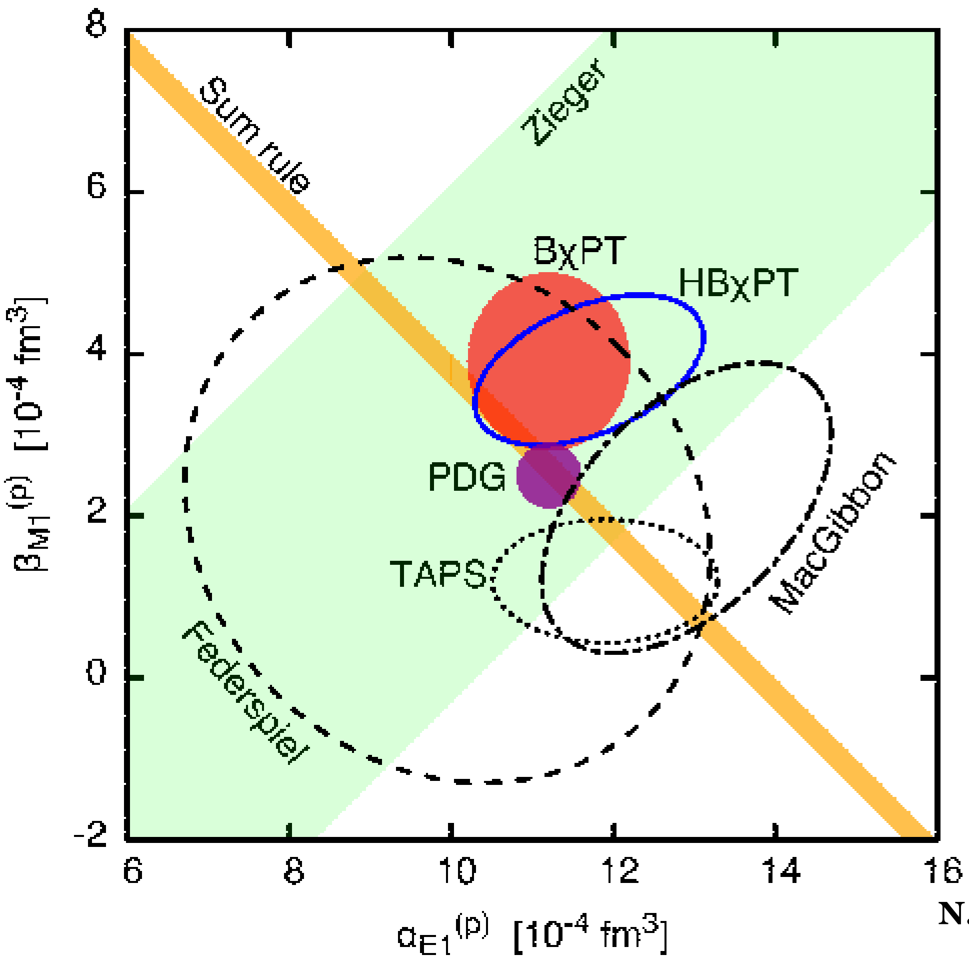
Paramagnetism

$\beta_{para} > 0$

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

- Fundamental properties of the proton
- Important to atomic physics, spin polarizability measurements etc (e.g. for proton radius puzzle)

Scalar polarizabilities



PDG (2012) values:

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

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

New (2014-2018) PDG values:

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

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

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

N. Krupina, V. Lensky, and V. Pascalutsa Phys.Lett. B 782, 34 (2018)

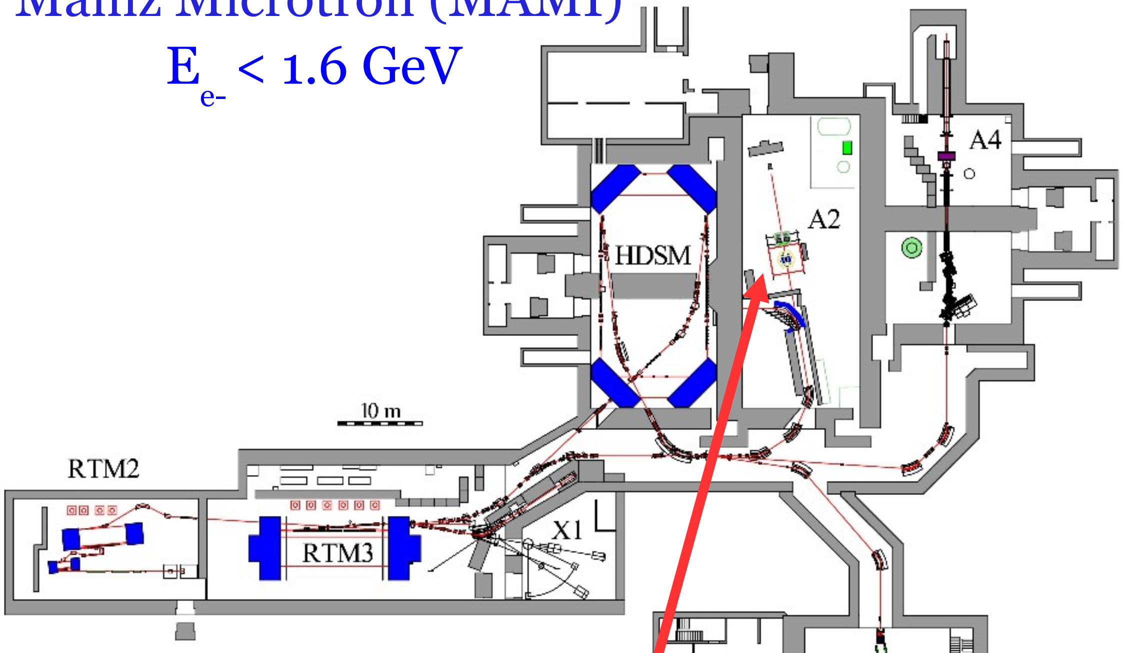
Goal: high-precision measurement of the scalar polarizabilities of the proton

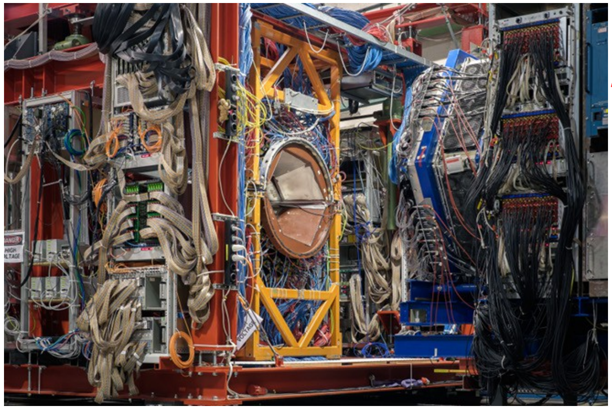
- New high-precision unpolarized cross-sections
- New high-quality data on the beam asymmetry Σ_3
- New single data set with small statistical and systematic errors

Experimental setup

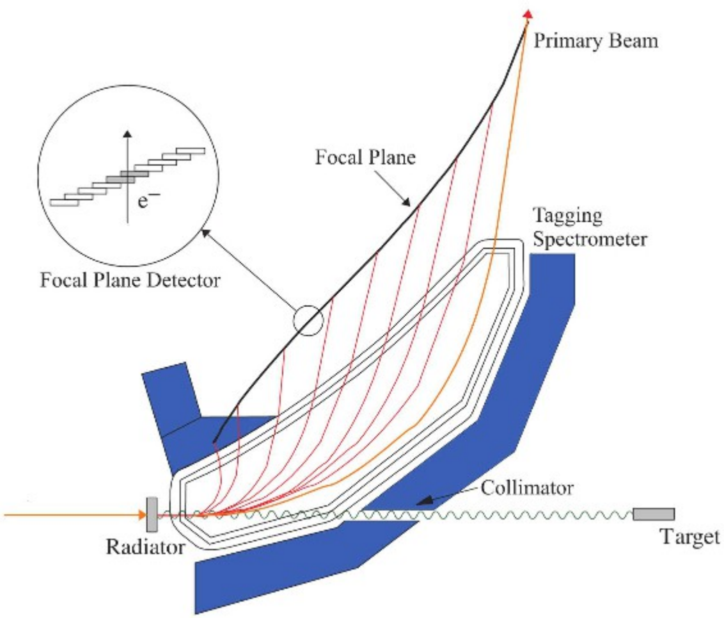
Mainz Microtron (MAMI)

$E_{e-} < 1.6$ GeV





Tagger/End point tagger



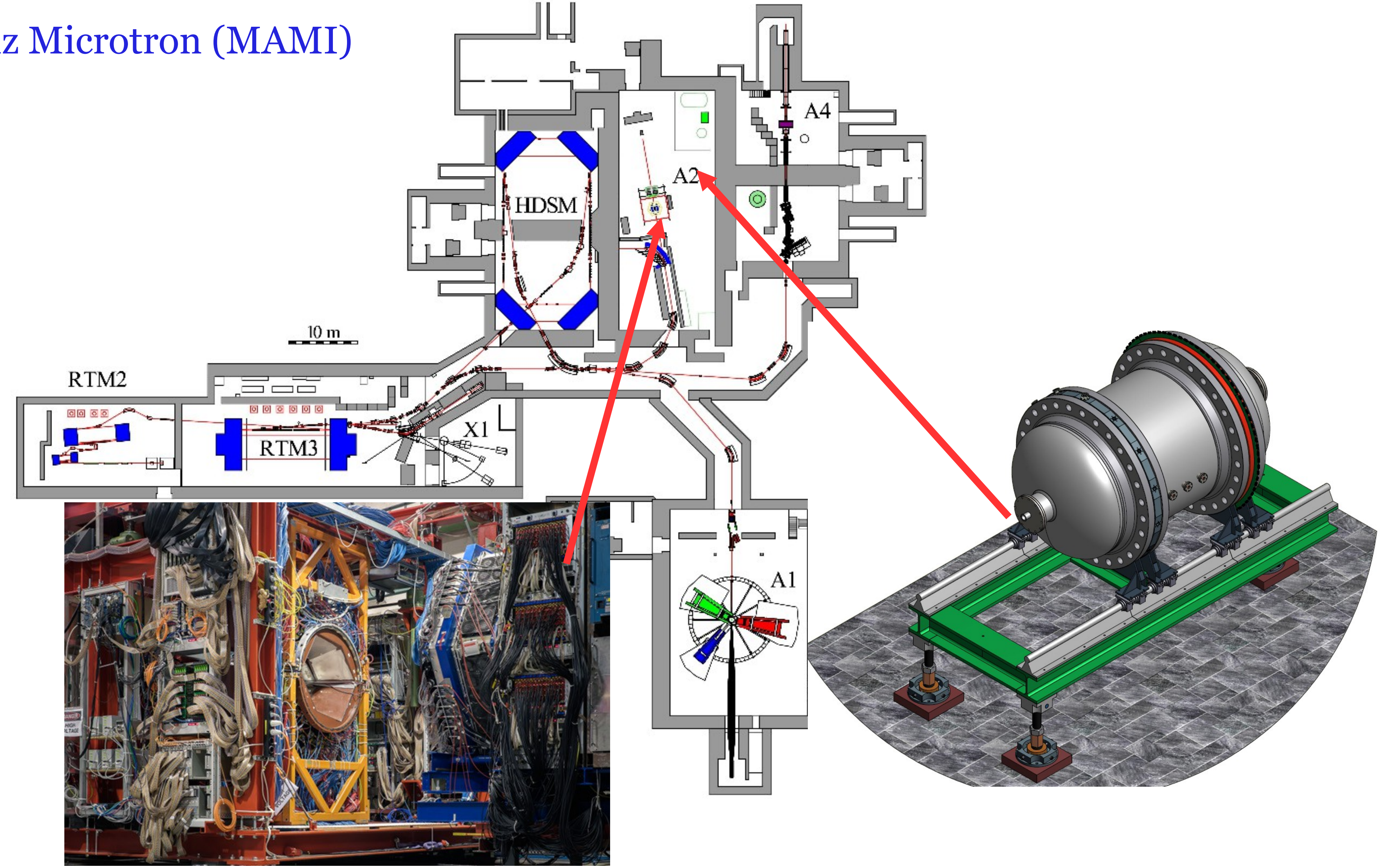
$$E_\gamma = E_{e-} - E_{tagg}$$

Upgrade → experiments with ~4 times higher rates is possible!

- High-Flux, Tagged, Bremsstrahlung Photon Beam: Unpolarized, Linear, and Circular
- Polarized and Unpolarized Targets
- Recoil polarimeter
- Development of an active He gas target in progress

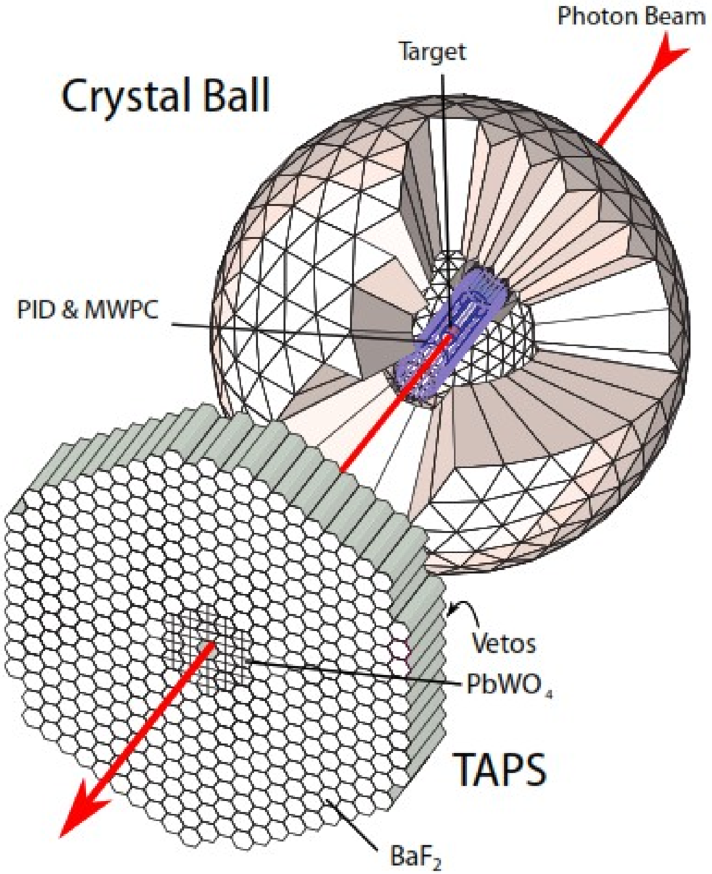
Experiments with active TPC at MAMI

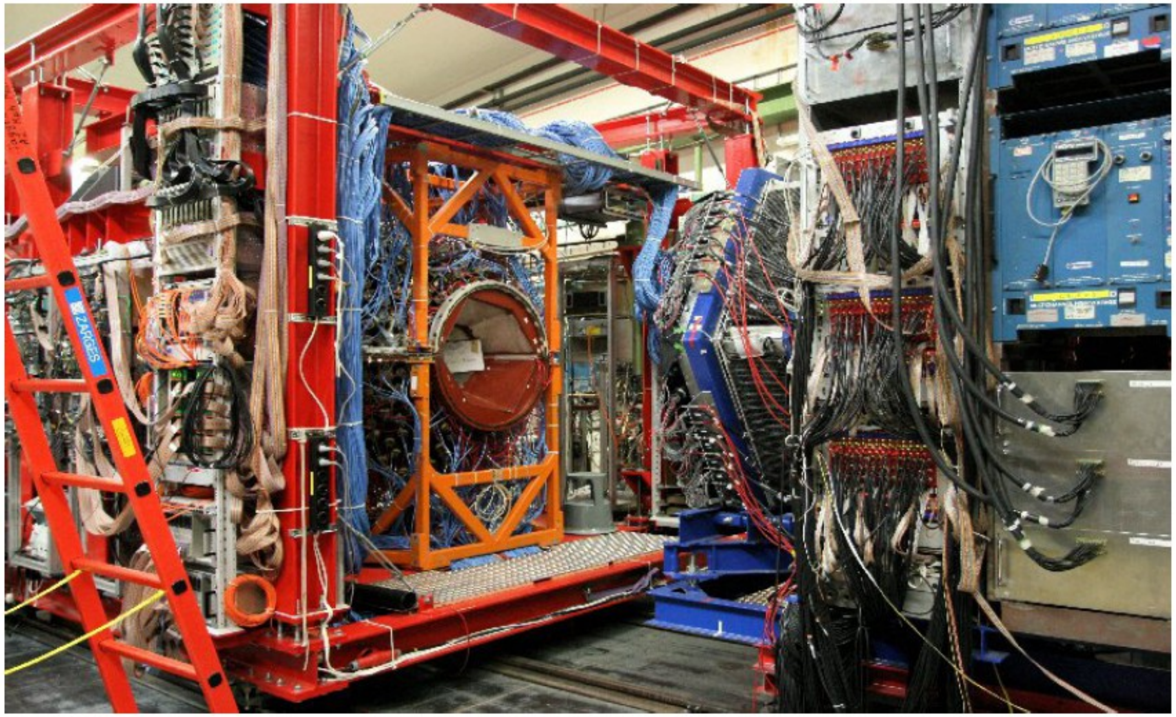
Mainz Microtron (MAMI)



- A2 setup: High-Flux, Tagged, Bremsstrahlung Photon Beam and various targets
  - High precision electron scattering experiments with a hydrogen TPC (at 720 MeV)
  - Experiments with tagged photons (in combination with A2 setup)

Crystal Ball/TAPS experiment





Crystal Ball:

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

TAPS:

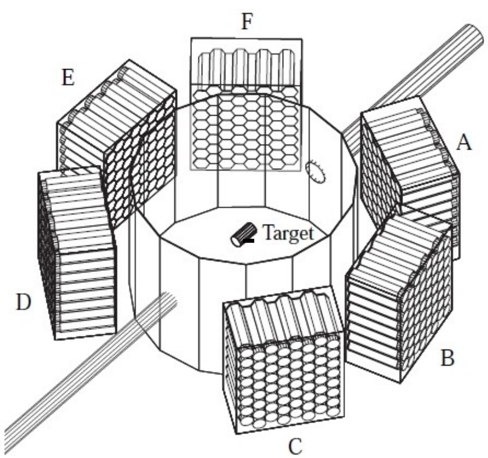
- 366 BaF_2 and 72 $PbWO_4$ Crystals
- 384 Veto Detectors

Compton scattering on the proton: Existing data

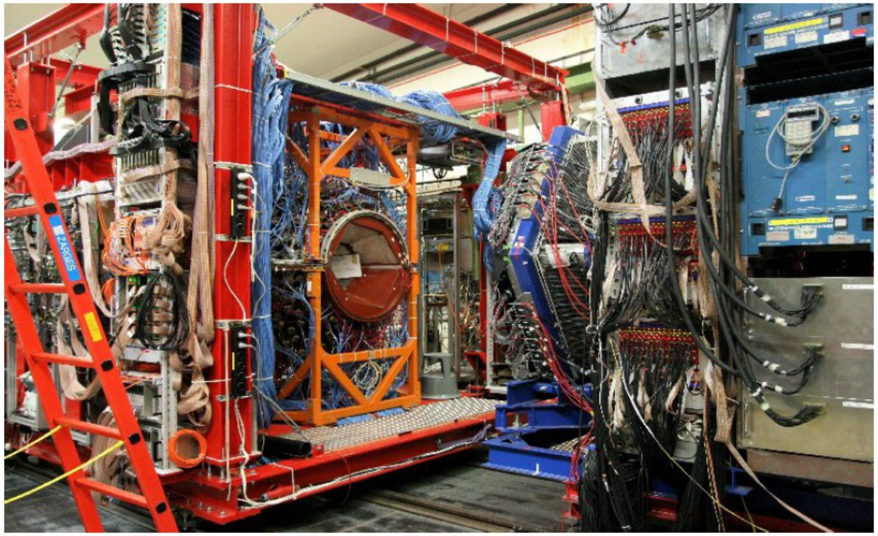
- Highest statistics data set:

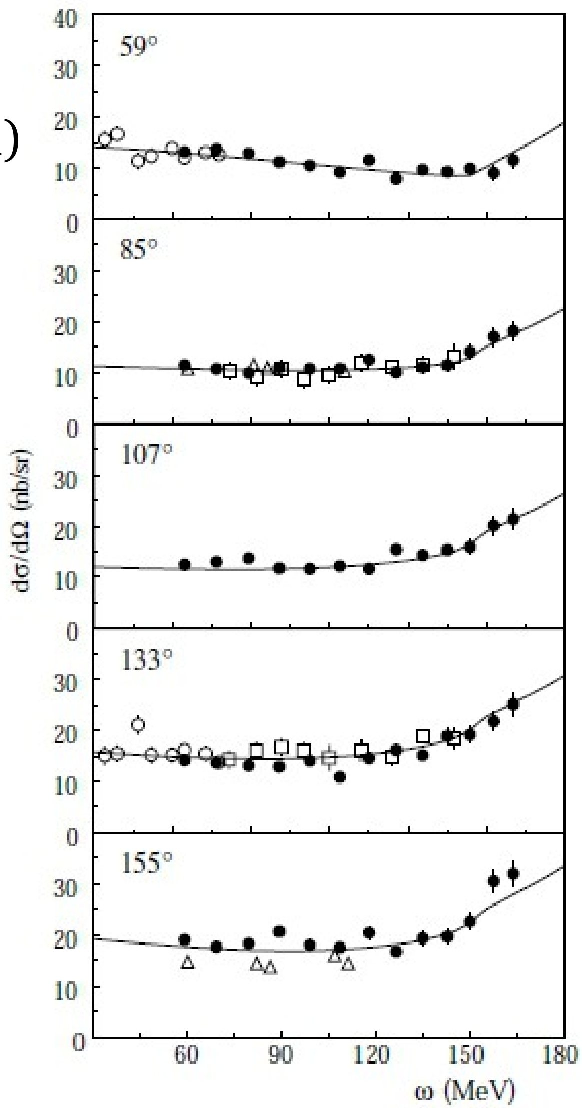
V. Olmos de Leon et al. Eur. Phys. J. A 10, 207–215 (2001)

- 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)

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

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

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

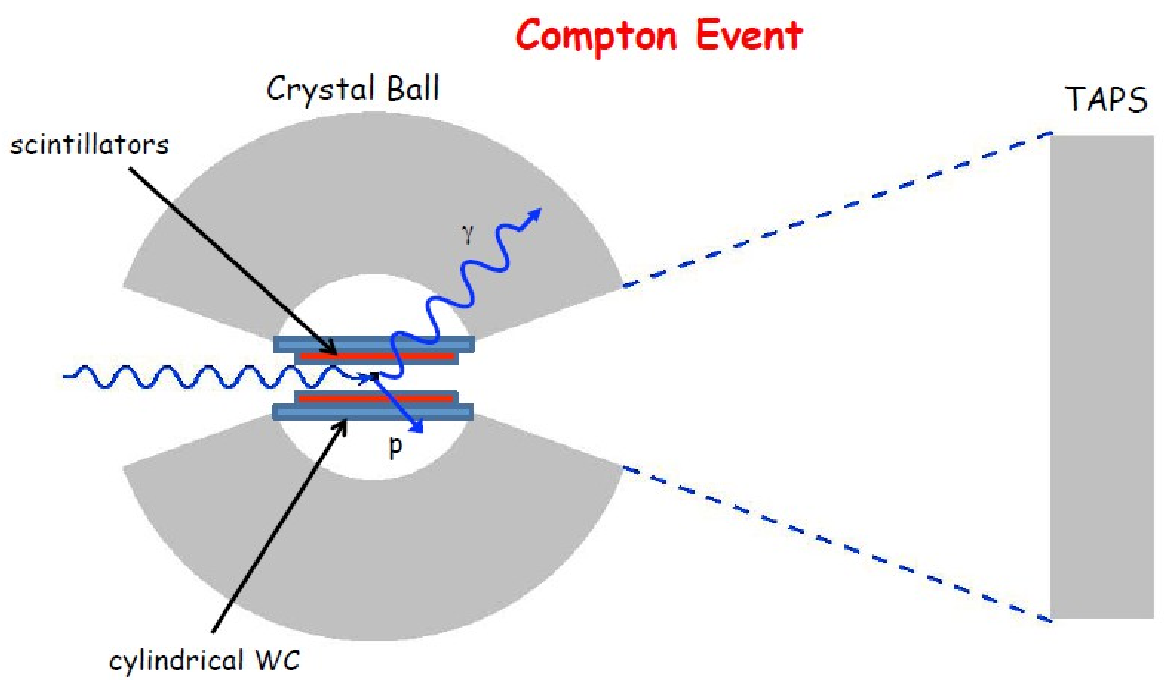
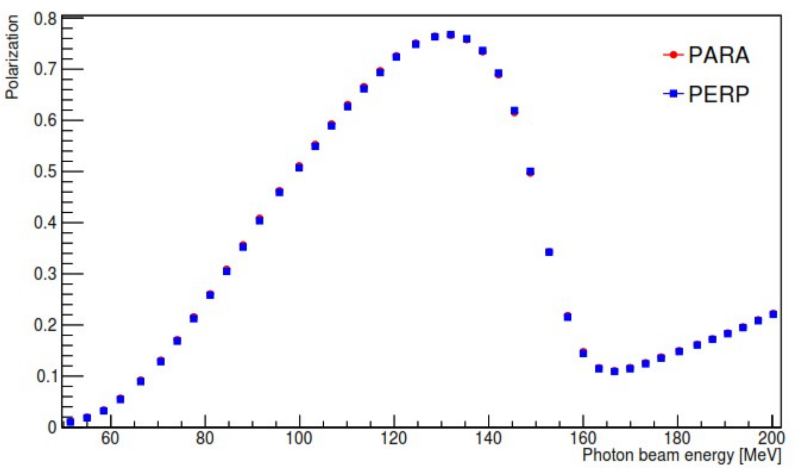


Figure: P.P Martel

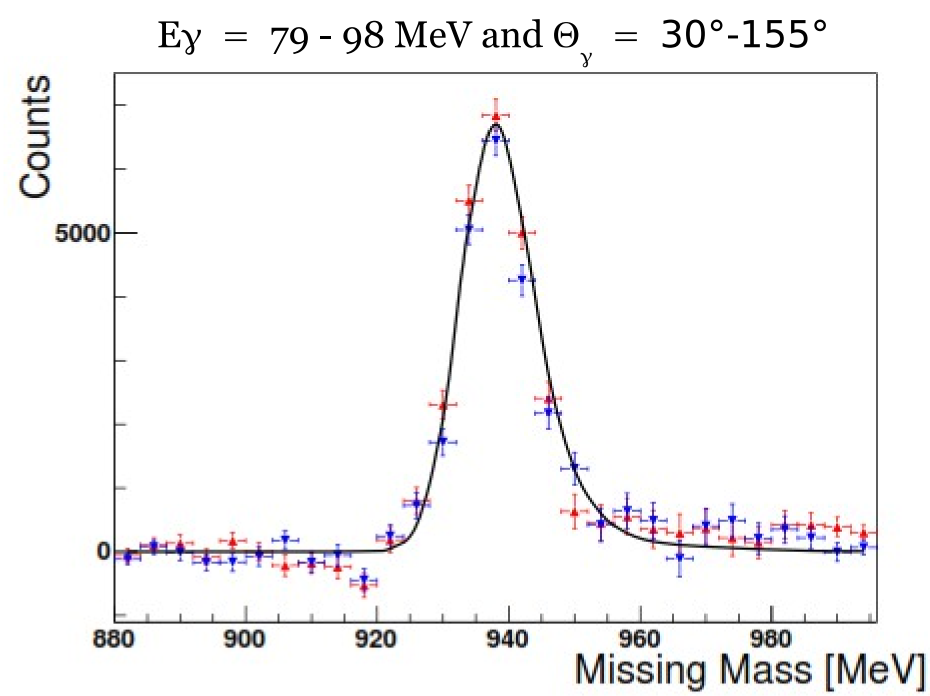


→ Event by event determination of the degree of linear polarization

Compton scattering 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
- Event by event determination of the degree of linear polarization

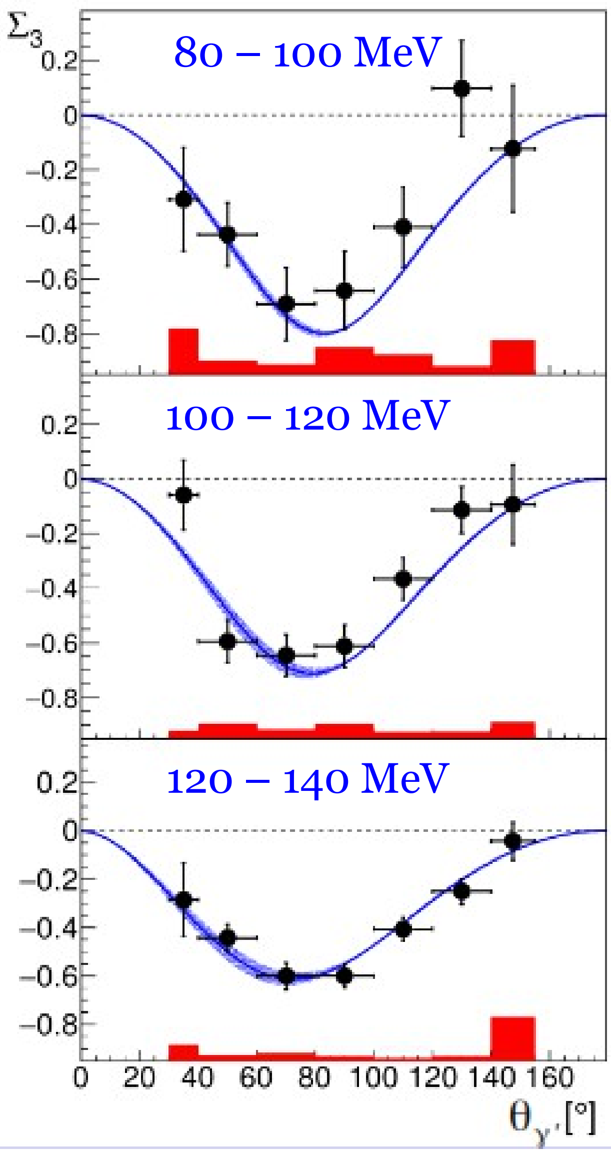


Different orientation of the polarization plane:
Parallel to the horizontal plane: PARA, perpedicular: PERP
Black curve : Monte Carlo

<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

Below pion threshold: Compton scattering (A2 data)



Fit result
Fit uncertainty
DATA
Systematic errors

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:

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

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

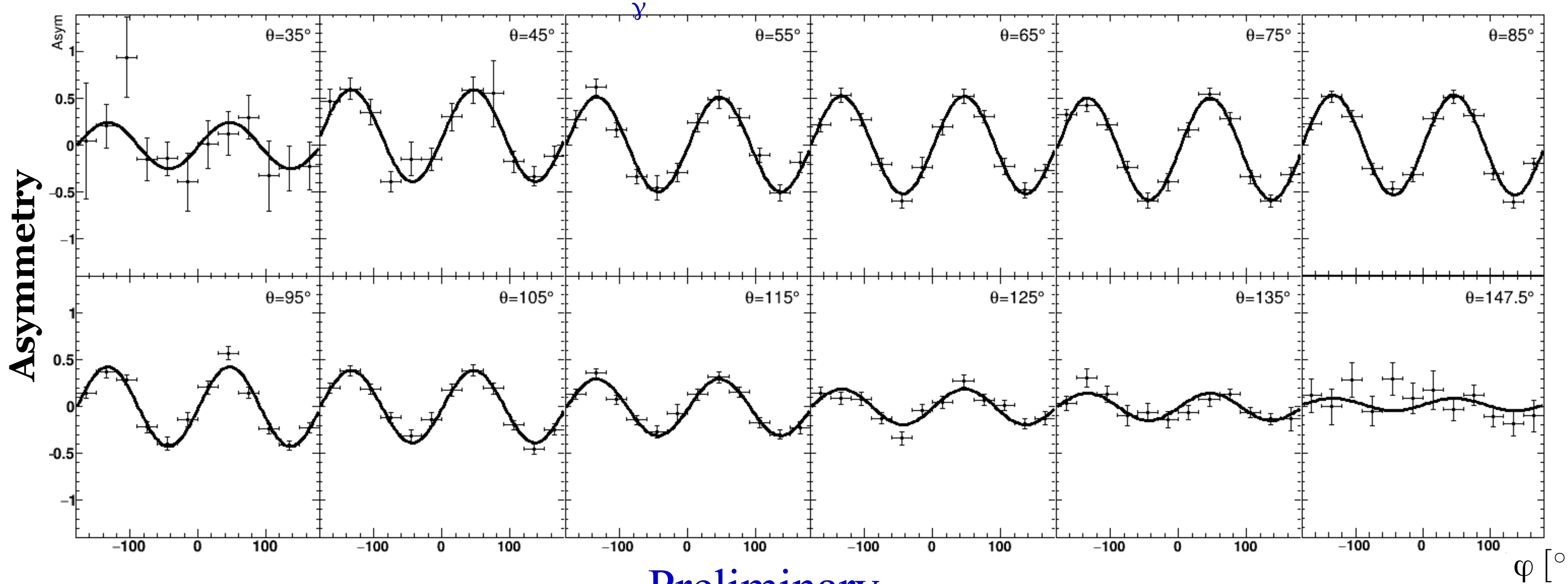
$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}(\theta)\left[1 + p_\gamma \Sigma_3 \cos(2\phi)\right] \quad \text{where} \quad \Sigma_3 = \frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}$$

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

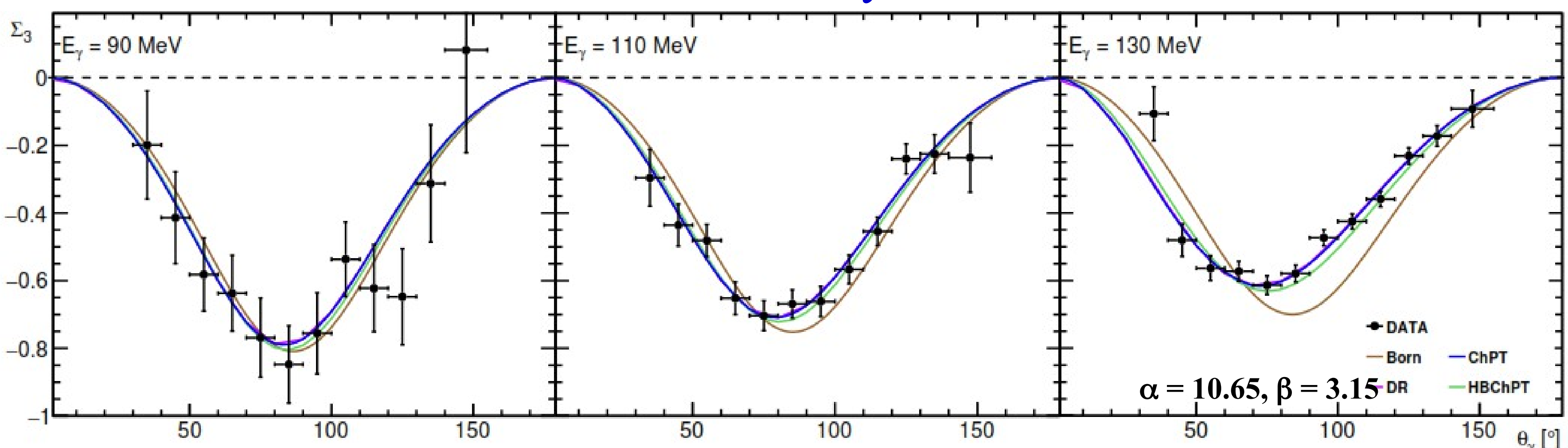
Presented a proposal to MAMI PAC →
recommendation to perform new measurement with highest priority

New experiment: beam asymmetry below pion threshold

E_γ = 120 -140 MeV



Preliminary

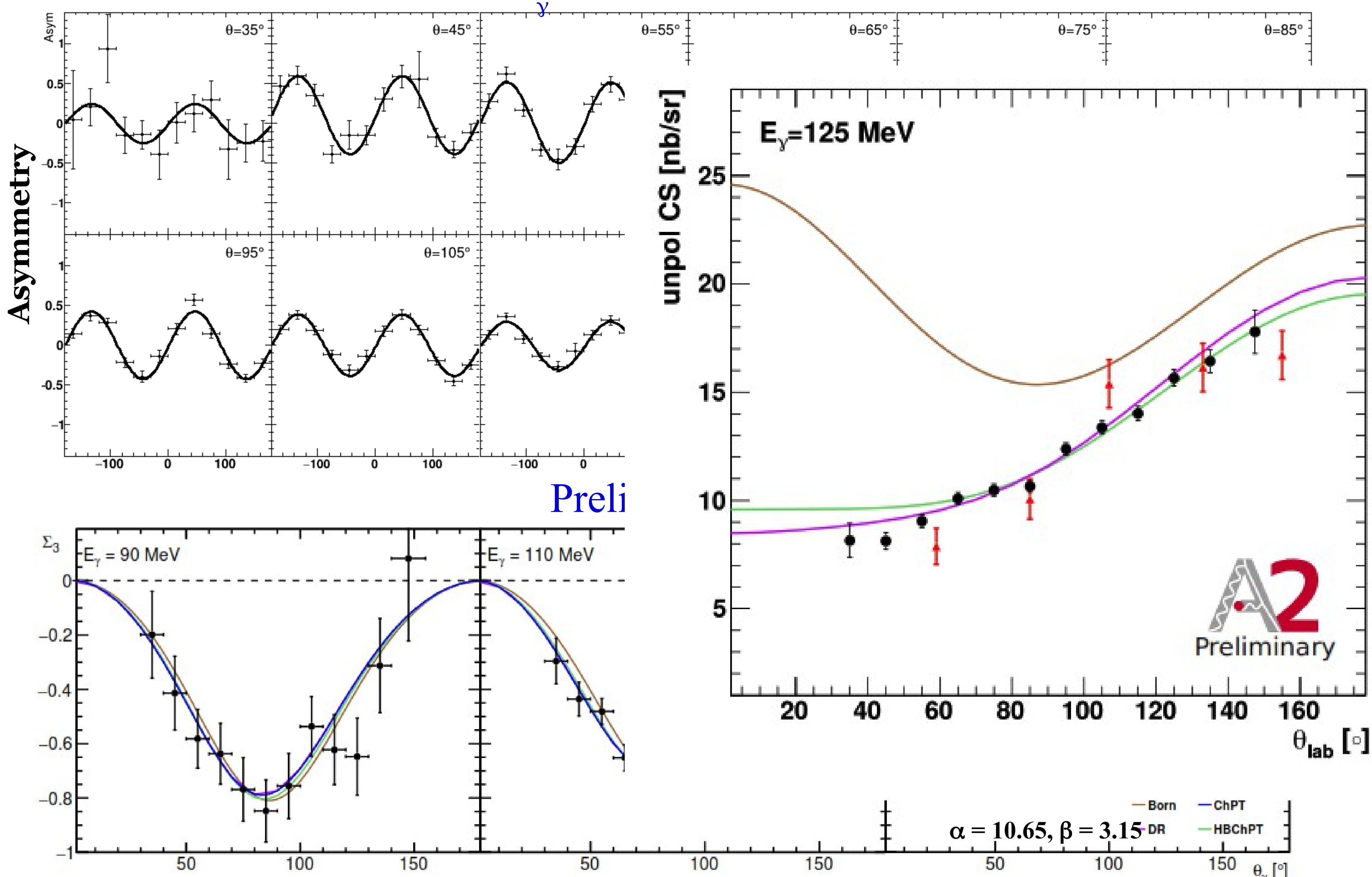


Significant improvement compared to the previous measurement!

Edoardo Mornacchi (Mainz), et al. [A2 Collaboration]

New experiment: beam asymmetry below pion threshold

E_γ = 120 -140 MeV



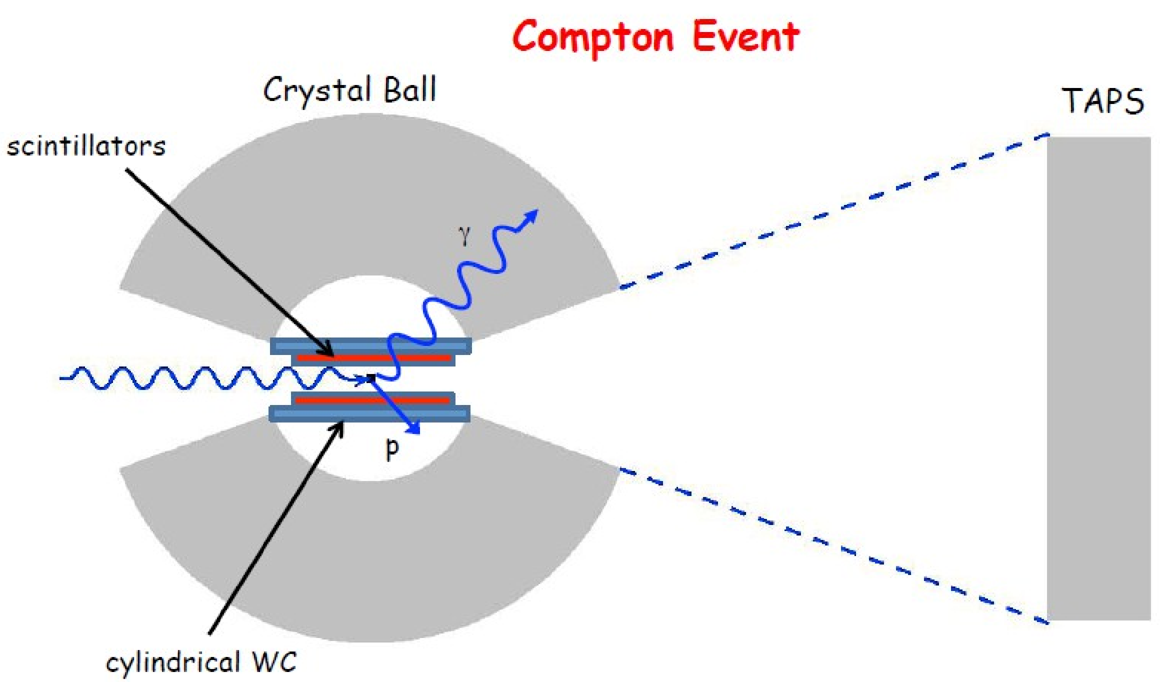
Significant improvement compared to the previous measurement!

Edoardo Mornacchi (Mainz), et al. [A2 Collaboration]

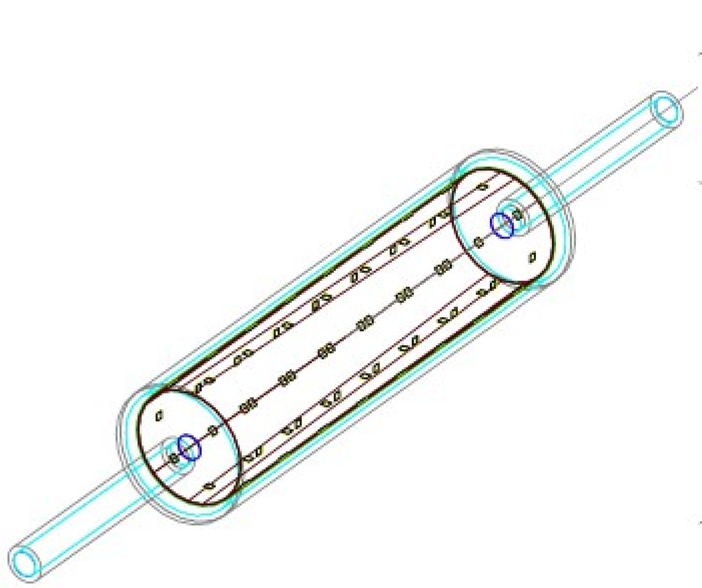
Next steps and ideas

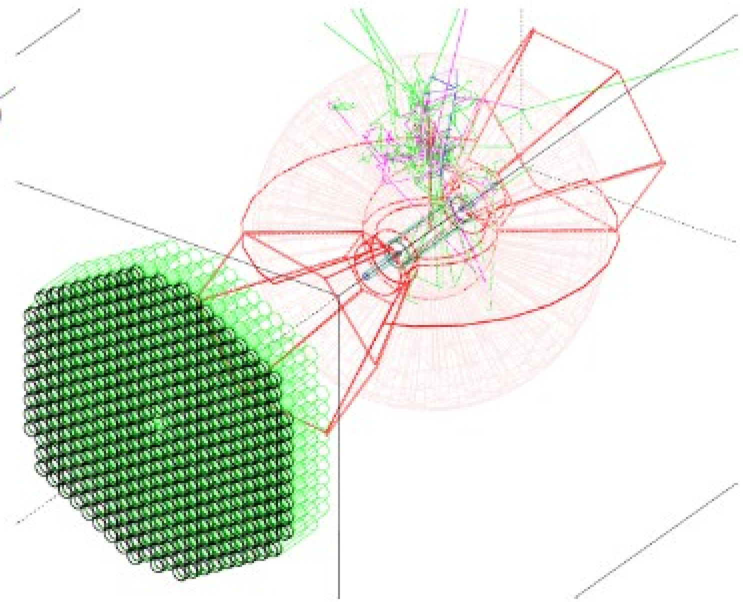
- Neutron polarizabilities: deuteron or helium targets
- No data on ^3He available (recoil detection needed!) but theory exists
- Data on ^4He taken recently by the A2 Collaboration with detection of the photon in the final state aiming for improvement of the existing database
- Theory needed to extract polarizabilities is under development.

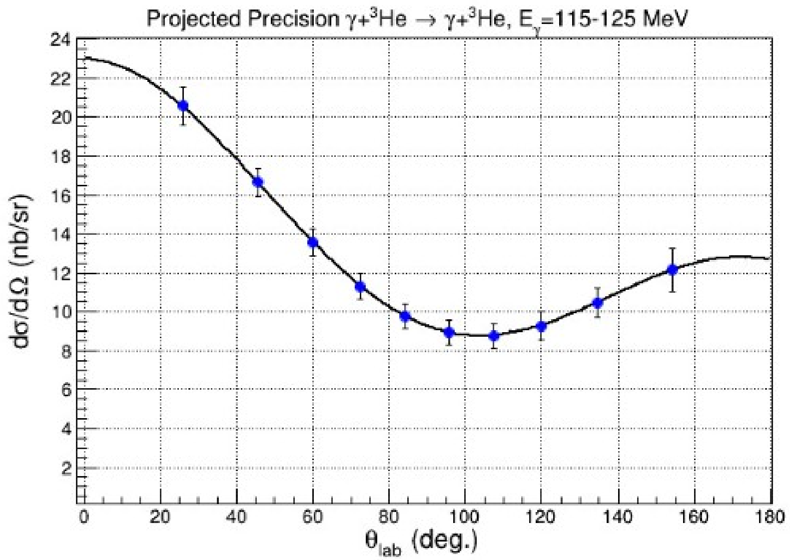
New approach → Combine the nearly 4π A2 setup with a TPC: Detection of the recoil in combination with incoming and scattered photons



Further ideas and opportunities



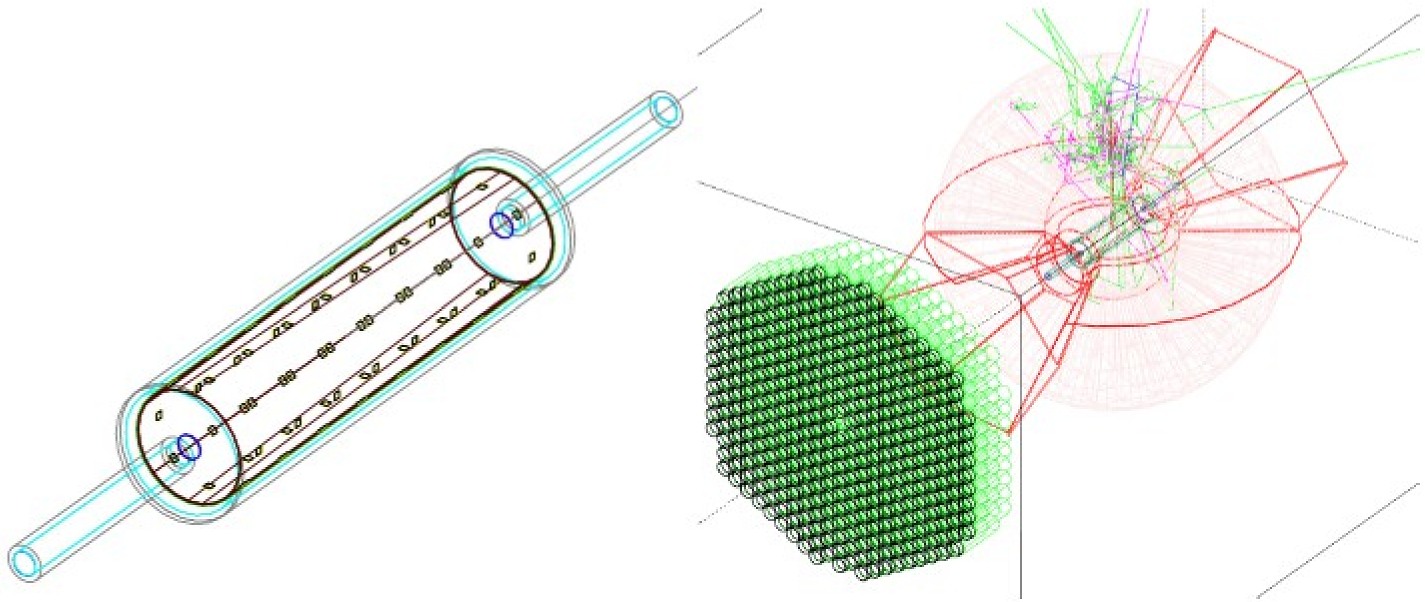




PAC proposal: J. Annand et al. (rating A from PAC)

- **New ideas: Use a TPC with the same geometry as for the active He target!**
- **Similar physics case: Neutron polarizabilities with He isotopes (PAC proposal (2020) : P. Martel et al.)**
- **Overdetermined kinematics with high energy resolution for He ions**
- **Detection of scattered photons in CB (tagged incoming photon beam)**

Further ideas and opportunities

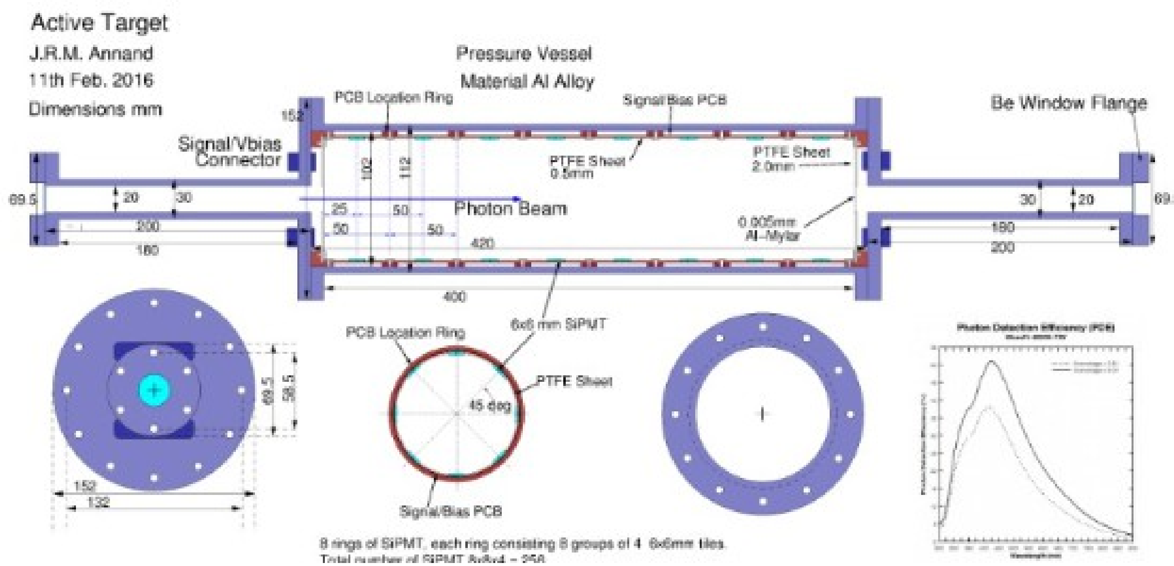


Ideas for the physics program:

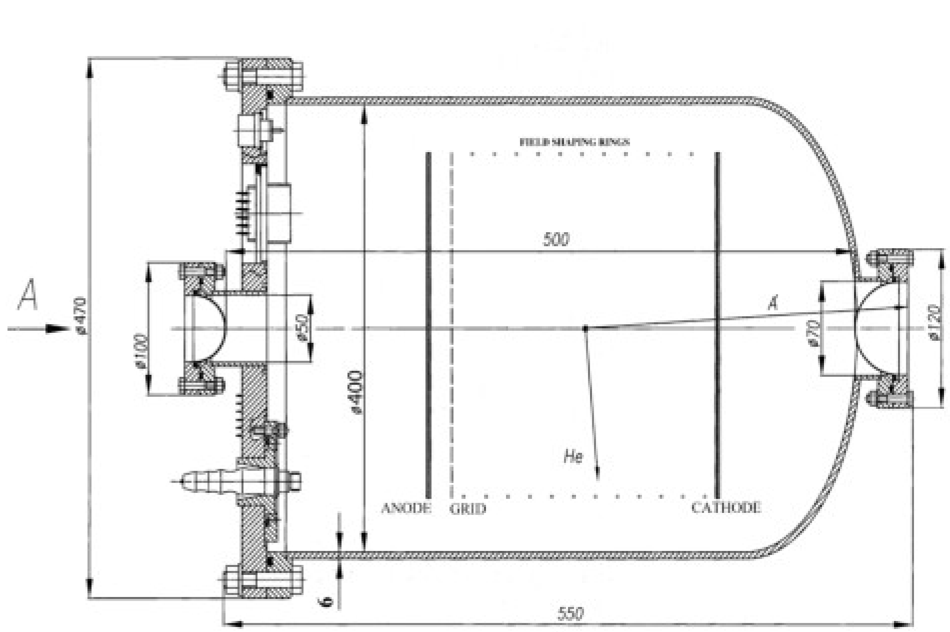
- Polarizability measurements with focus on helium (hydrogen, deuterium also possible)
- Measurement of the proton radius via dilepton final state (?)
- Search for narrow exotic states taking advantage of high energy resolution (?)
- Studying meson photoproduction in narrow kinematic ranges (e.g. accessing threshold-related effects)
- Meson photoproduction on nuclei (deuteron, $^{3,4}He$) → baryon spectroscopy and nuclear effects

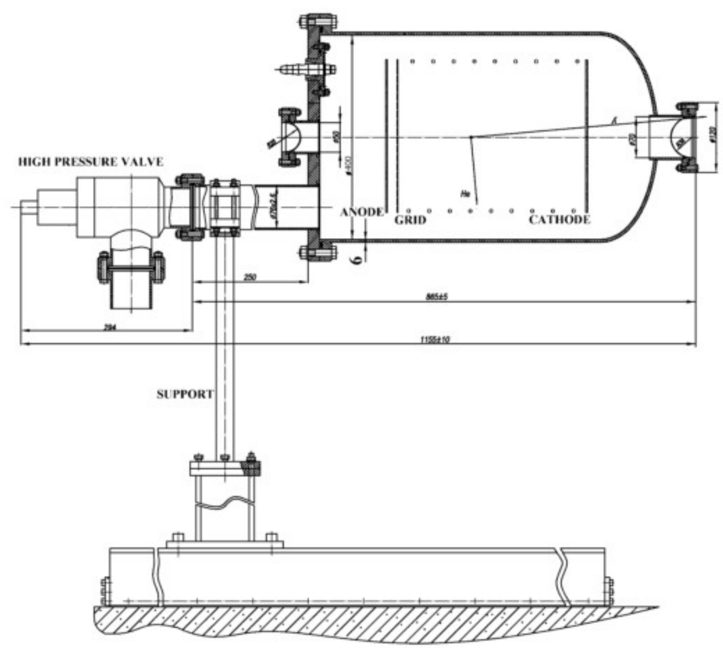
Technical possibilities and ideas

Similar to A2 active target prototype: could be easier to construct/install



Similar to ACTAF2: One flange, less material in the forward direction?





Summary and Outlook

- Broad and active program in A2 using tagged photon beam (polarizabilities, baryon spectroscopy, meson decays, search for modifications of hadrons in the nuclear medium,....)

- New opportunities can be opened with an active TPC!

- Nucleon polarizabilities, radii, searh for exotics, new opportunities for studying photoproduction of mesons on nuclei, ...

- Many experiments possible without notable safety restrictions ...

- Exploring, understanding → defining first steps?

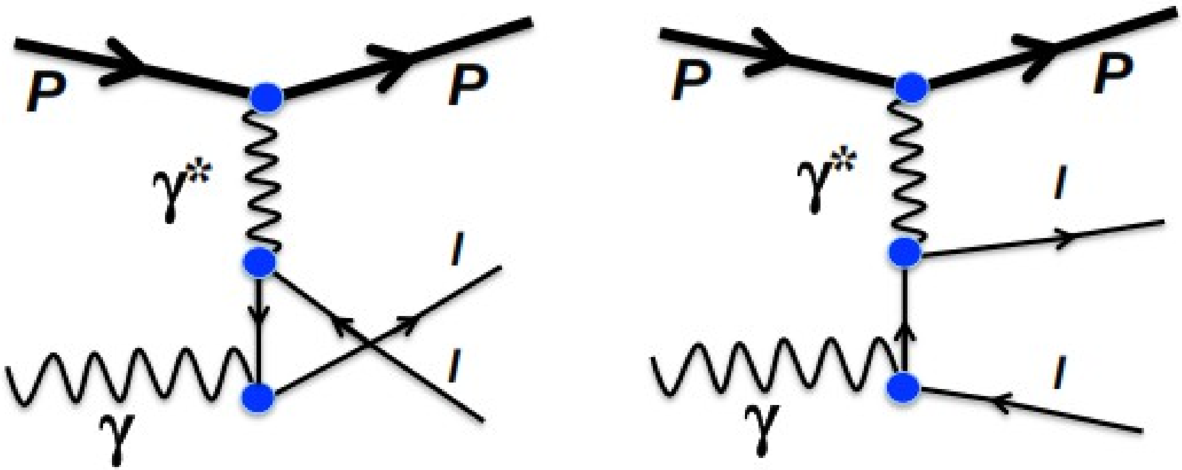
Thank you for your attention!

Backup

Backup (Patrik Adlarson)

Bethe–Heitler (BH) process

JOHANNES GUTENBERG UNIVERSITÄT MAINZ



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

Invariant mass sq lepton pair

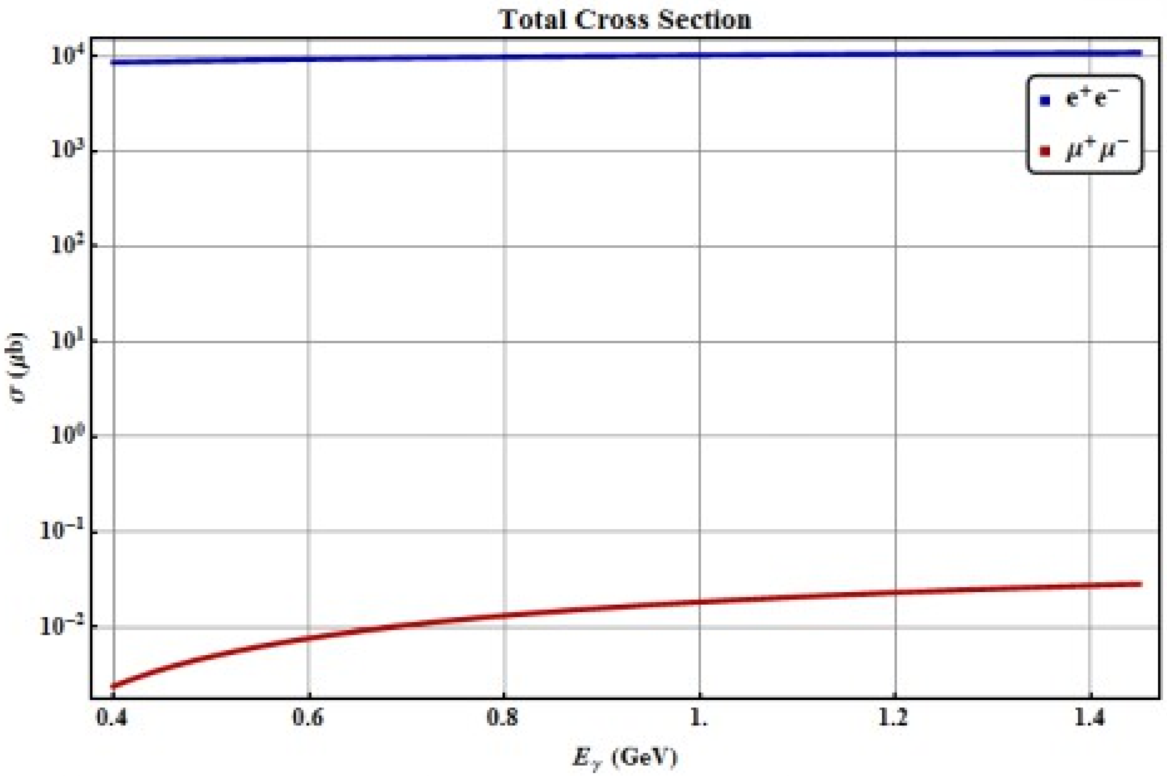
Proton mom transfer

Proton form factors

Backup (Patrik Adlarson)

Bethe–Heitler dσ/dEγ

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

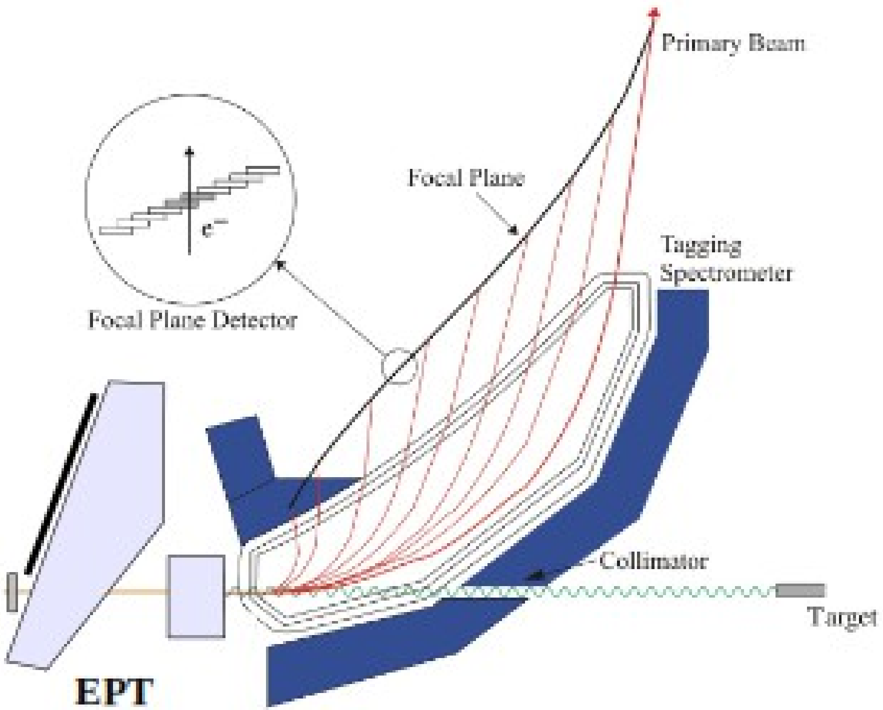


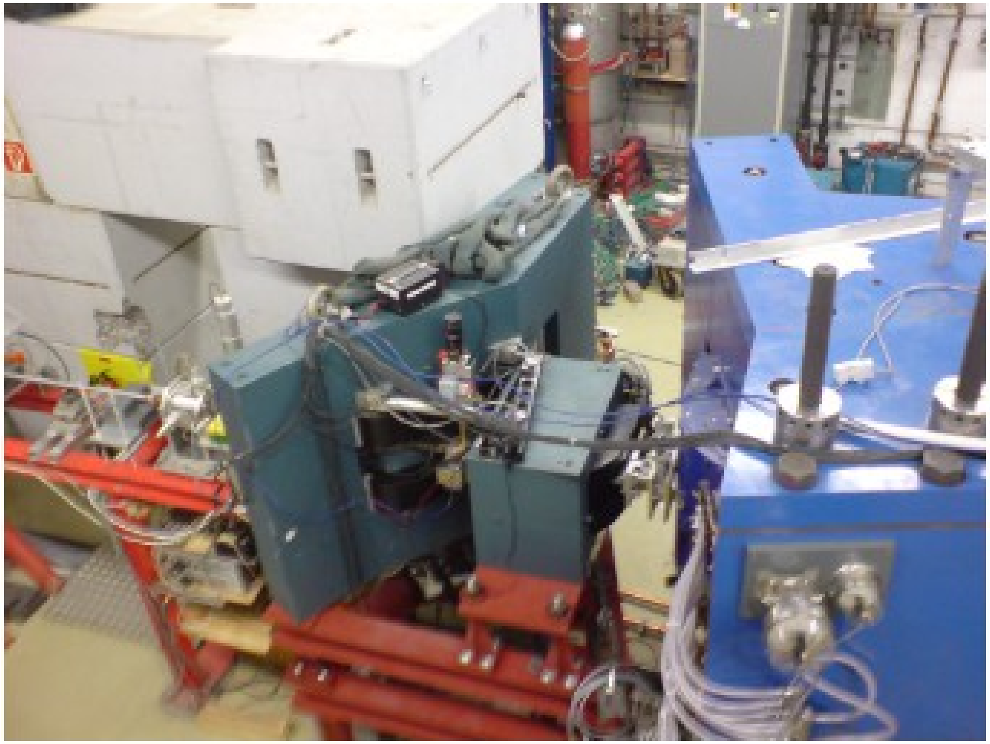
BH-ee (blue) and BH-μμ (red) cross section as function of beam energy

Dimuon cross section increases more for increasing beam energies

EPT (slide taken from M. Unverzagt)

- Installation of EPT during 2012





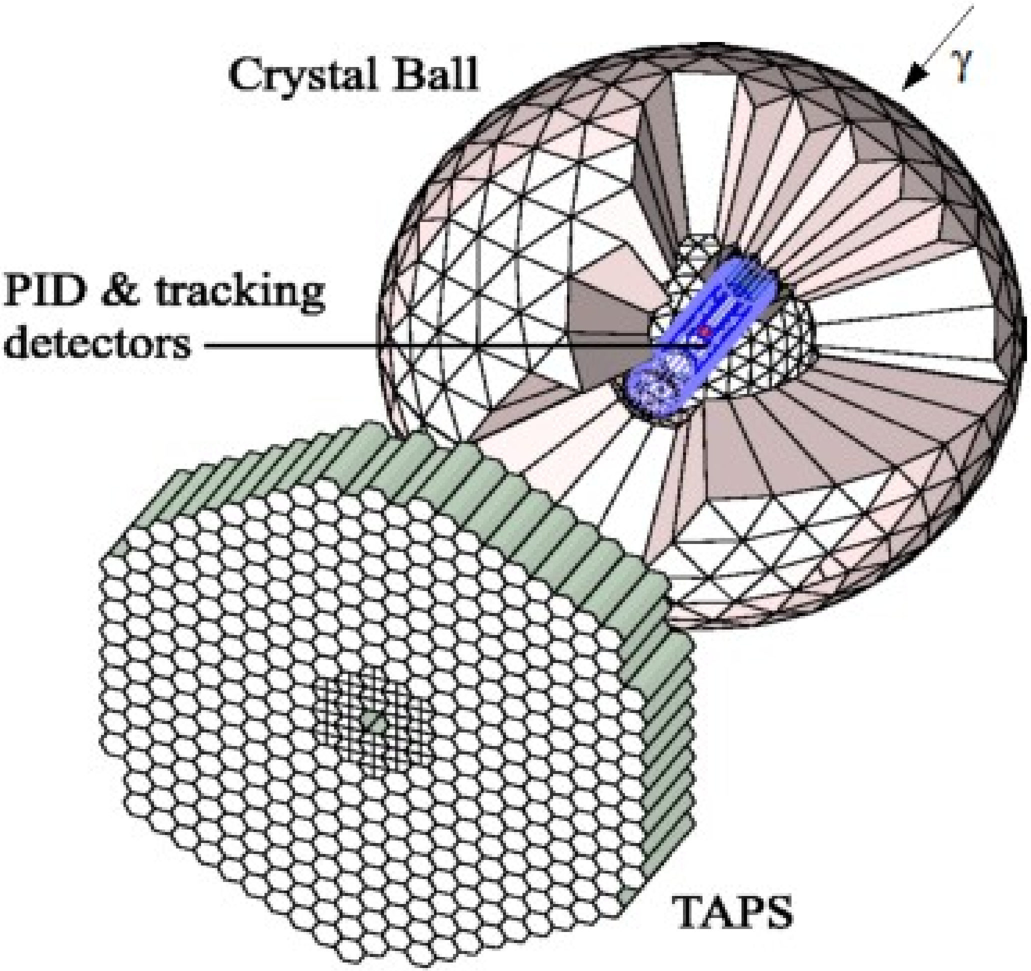
Same working principle as main tagging spectrometer

$E_\gamma \approx$1445-1595 MeV

$\Delta E_\gamma \approx$ 2.5MeV

Non-permanent installation infront of main Tagger

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



Crystal Ball:

672 NaI(Tl) crystals

93,3% of total solid angle

Each crystal equipped with PMT

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

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

TAPS:

Up to 510 BaF_2 crystals

Polar acceptance: 4-20°

$$\Delta t = 0.5 \text{ ns FWHM}$$

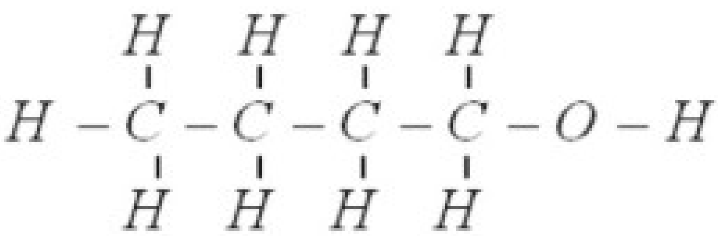
$$\frac{\sigma}{E_\gamma} = \frac{0{,}79\%}{\sqrt{E_\gamma/GeV}} + 1{,}8\%$$

Targets (slide taken from M. Unverzagt)

- LH_2/lD_2 used for high rate meson production (η/η')
  - Length: 3cm, 5cm, 10cm

- l^3He/l^4He

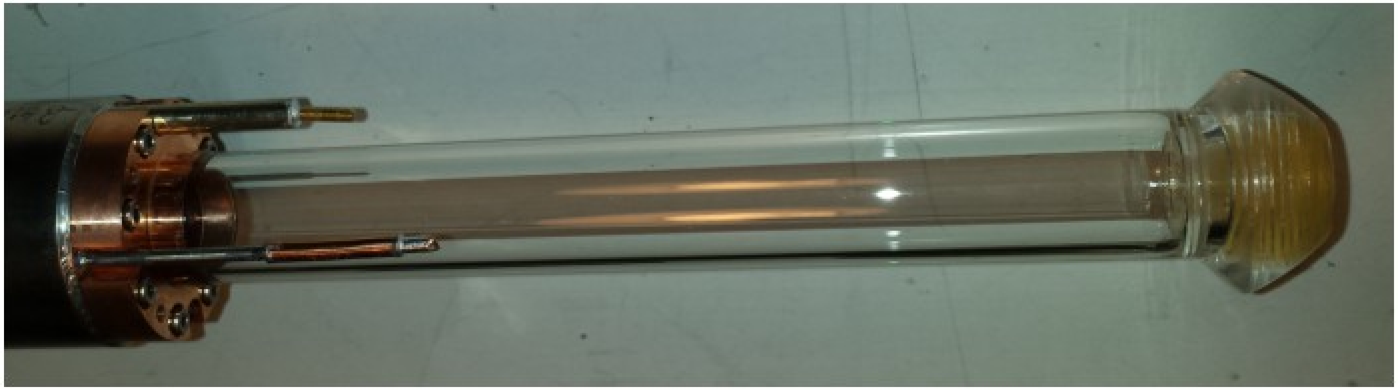
- Polarised Butanol/D-Butanol
  - Transverse and longitudinal polarisation
  - Lenght: 2 cm
  - Dynamic Nuclean Polarisation
  - Max. Polarisation: 90%
  - Holding filed: 0.44 T
  - Relaxation time: τ~1000h



- Solid Targets

Polarized active target (slide taken from R. Miskimen)

Target assembly

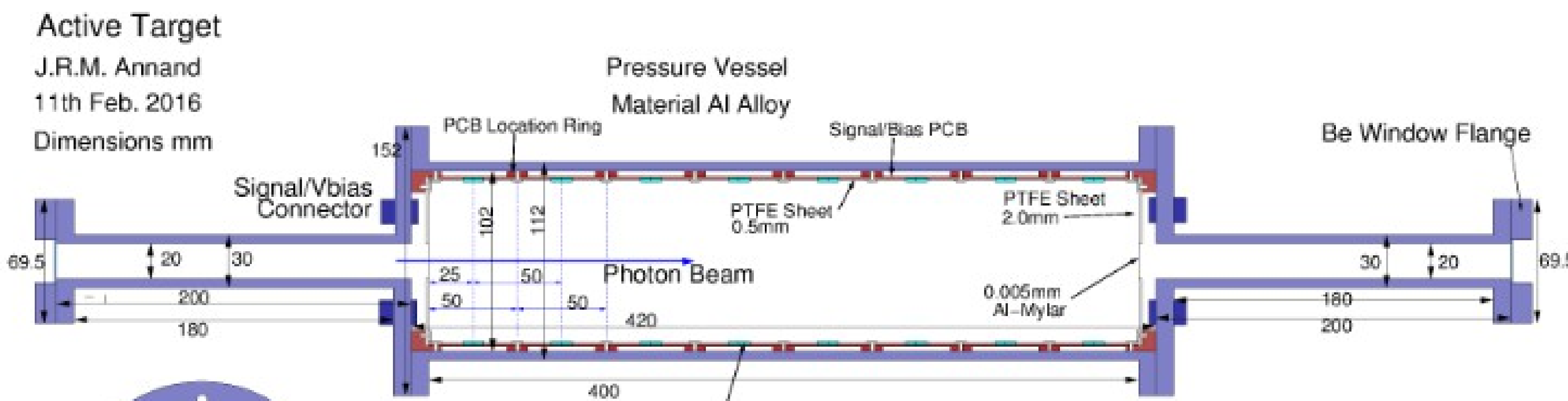


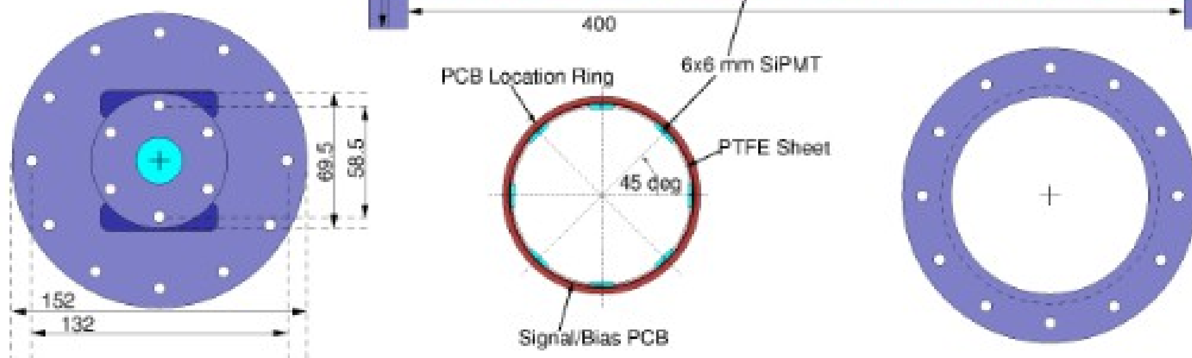
PhD, Maik Biroth, Mainz

He gas active target

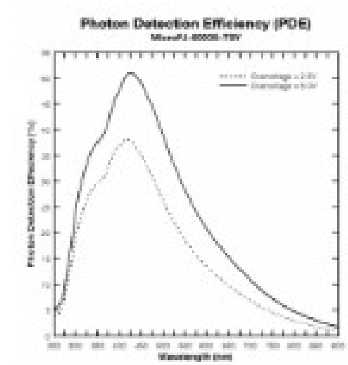
University of Glasgow

The New Active Target

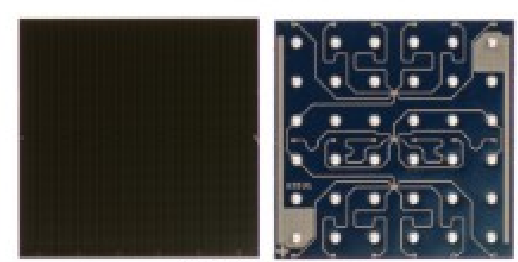




8 rings of SiPMT, each ring consisting 8 groups of 4 6x6mm tiles.
Total number of SiPMT 8x8x4 = 256.
Readout in groups of 16, each group connected to an op–amp.
16 signal outputs
2 vias–voltage inputs

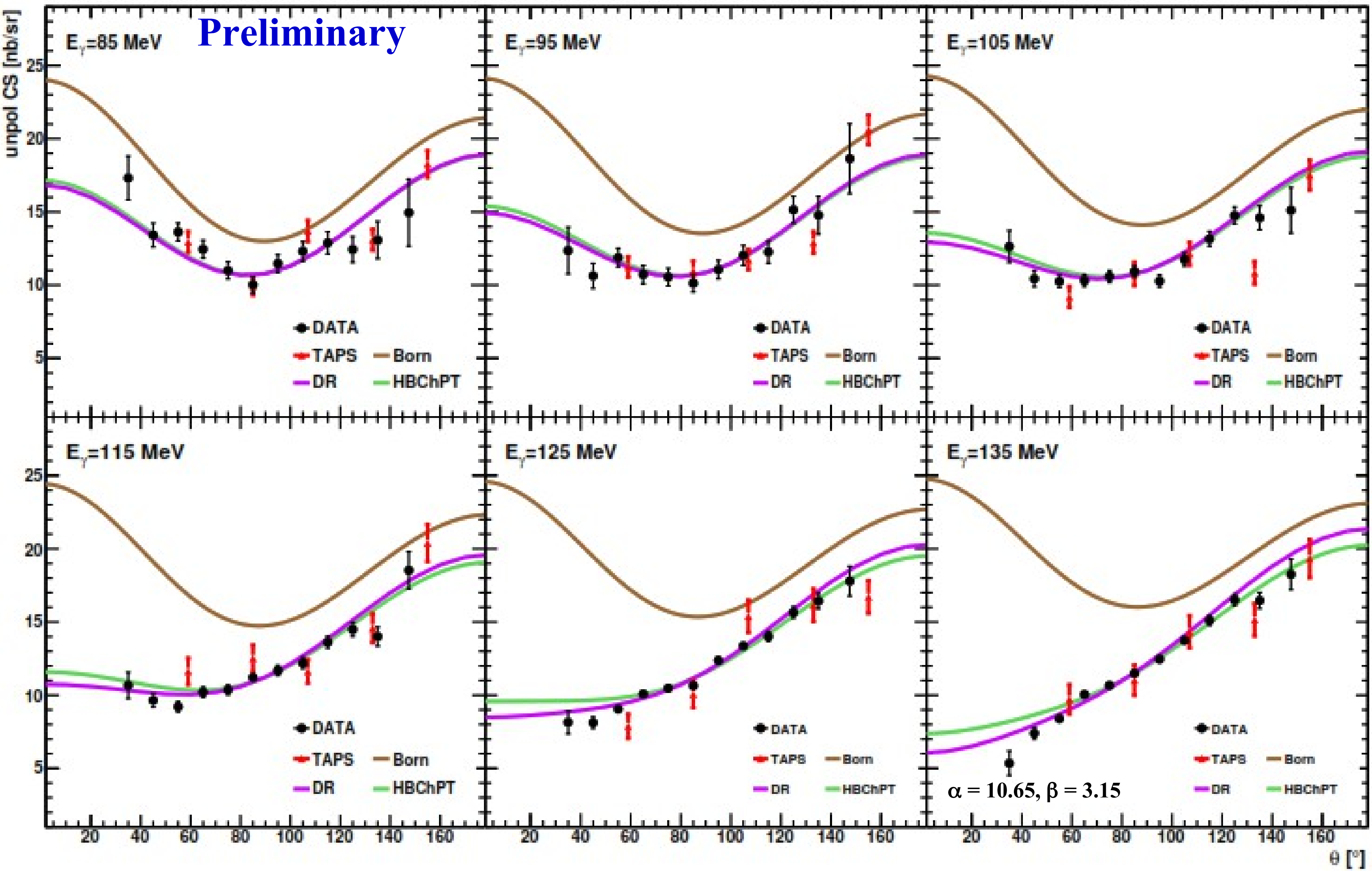


- Al pressure vessel, no welds
- Reuse Be outer windows from original Active Target
- PTFE sheet covers printed circuit board, windows cut for SiPMT



6 x 6mm J-Series SiPMT

New experiment: unpolarized cross section below pion threshold

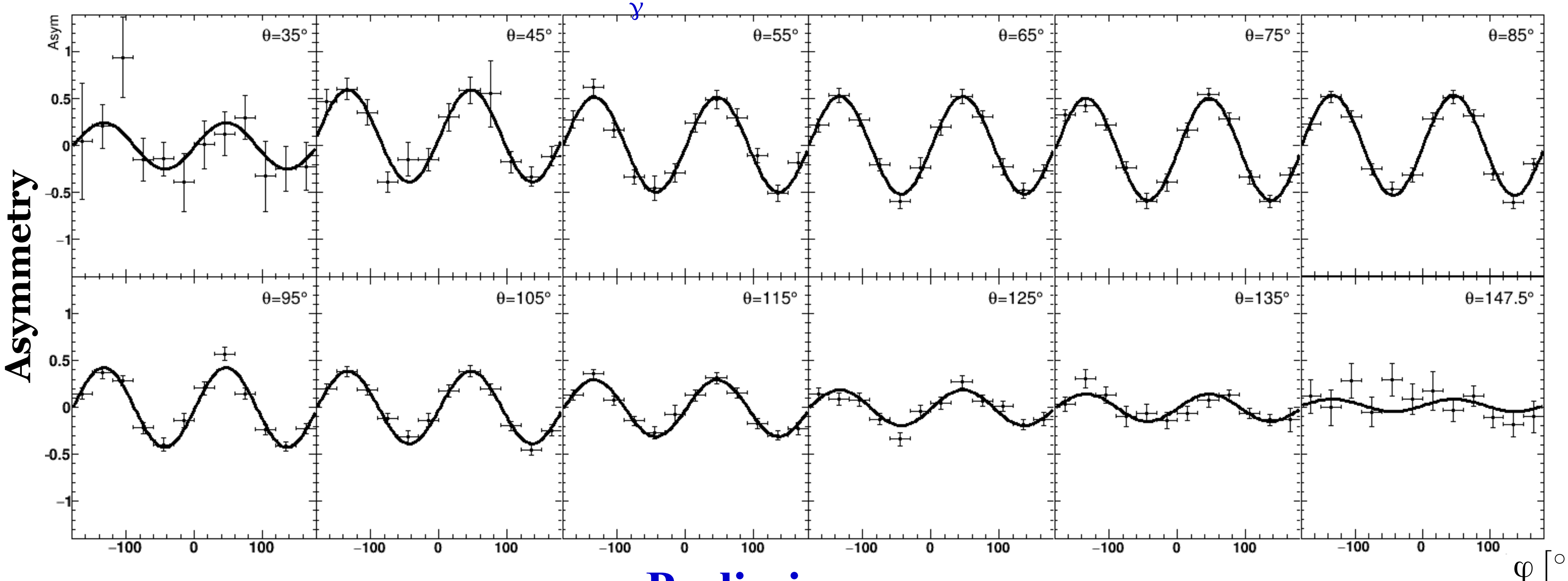


Significant improvement compared to all previous measurements!

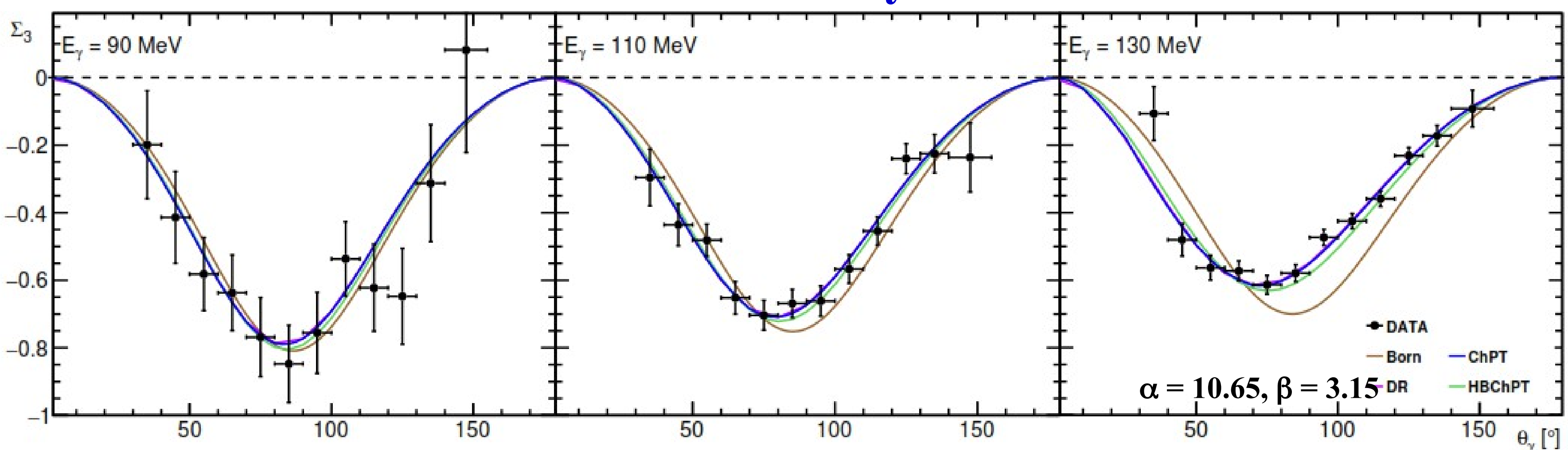
Edoardo Mornacchi (Mainz), et al. [A2 Collaboration]

New experiment: beam asymmetry below pion threshold

E_γ = 120 -140 MeV



Preliminary



Significant improvement compared to the previous measurement!

Edoardo Mornacchi (Mainz), et al. [A2 Collaboration]

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.

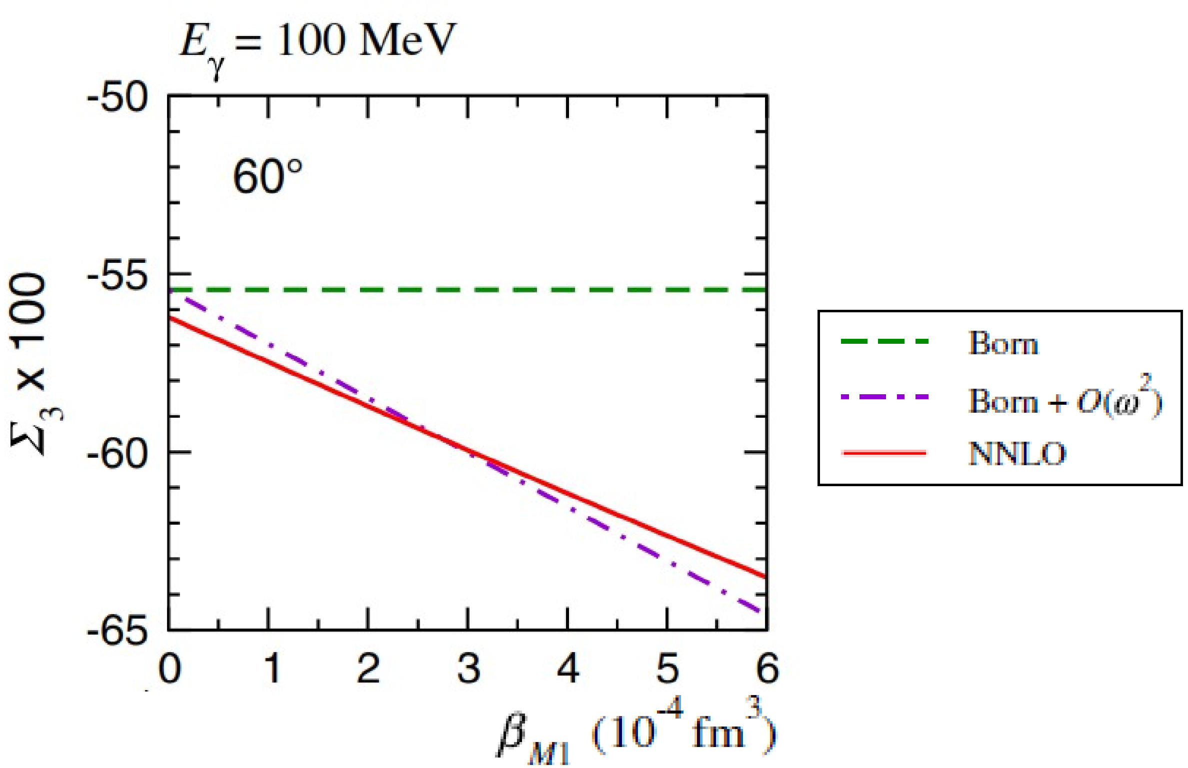
New approach: Beam asymmetry measurement

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

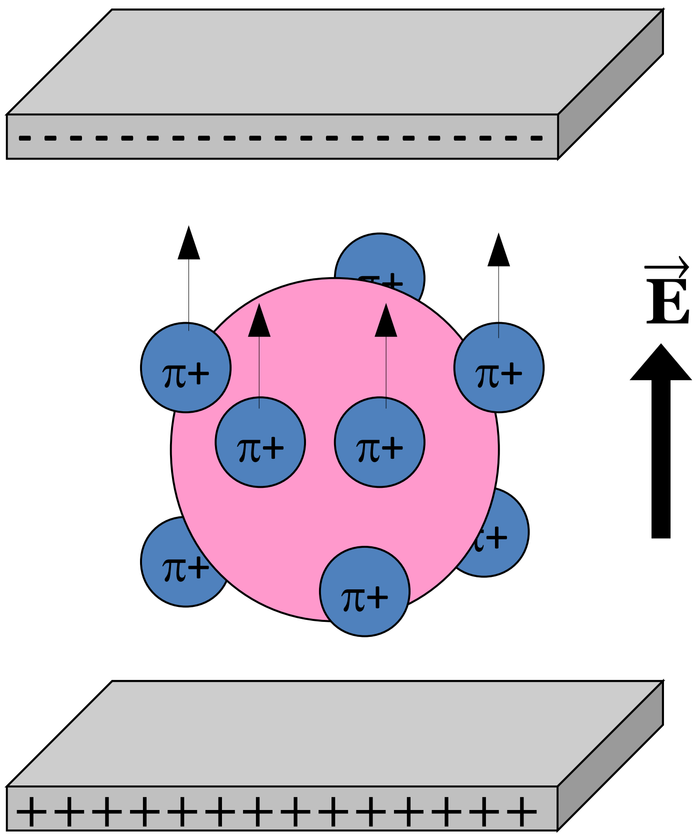
$$\Sigma_3 \equiv \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}}$$

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

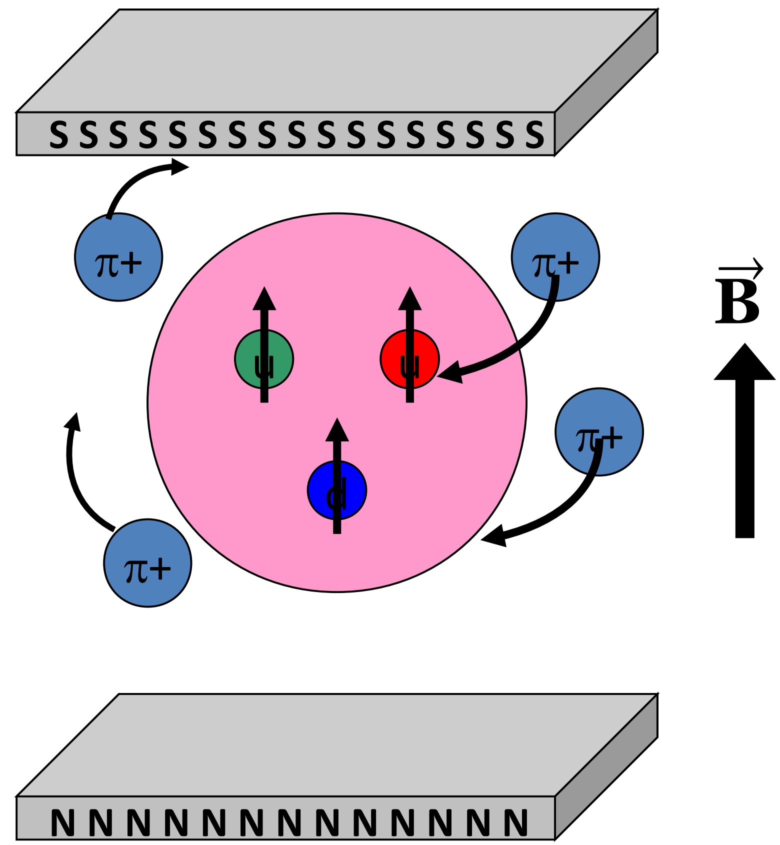


Scalar polarizabilities

Proton Electric Polarizability



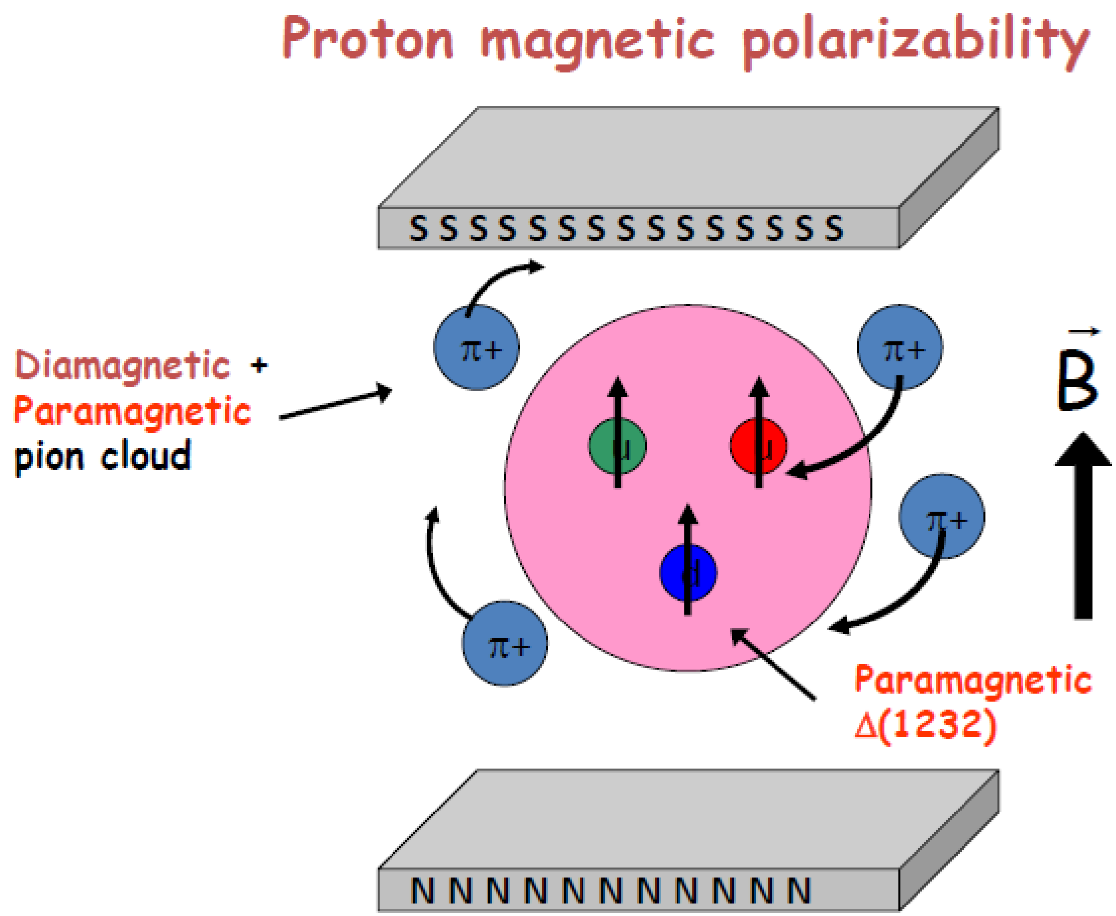
Proton Magnetic Polarizability



- α: electric polarizabilty
- Proton between charged parallel plates: "stretchability"

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

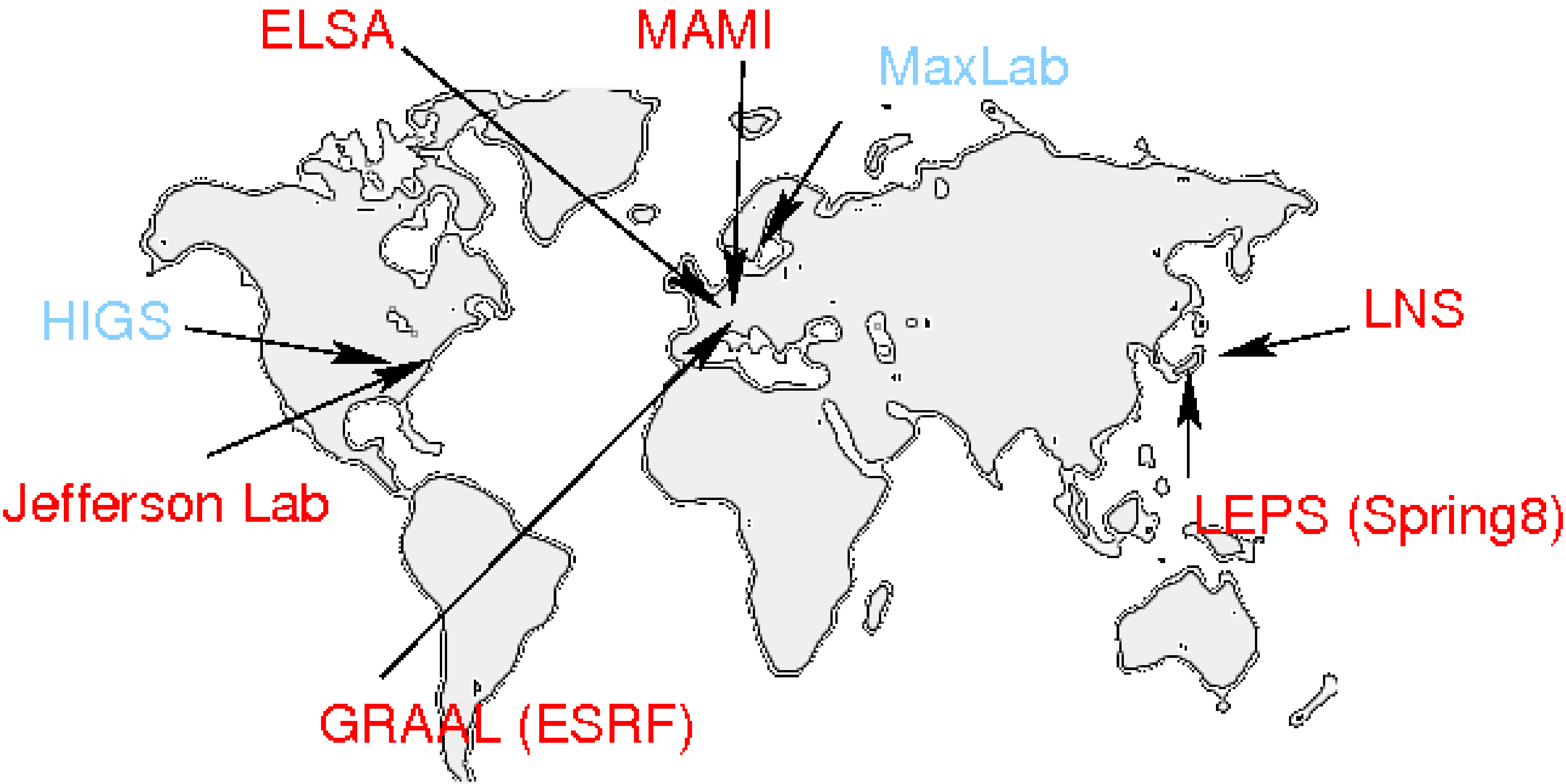
First look in December 2012 data



Magnetic polarizability: proton between poles of a magnetic

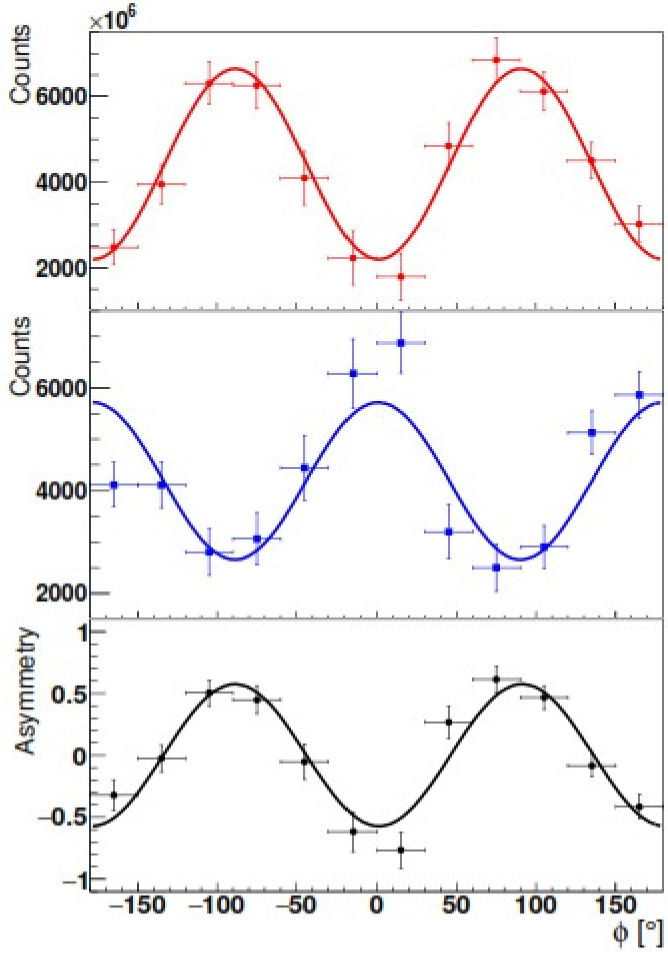
Rory Miskimen (Bosen 2009)

Experiments



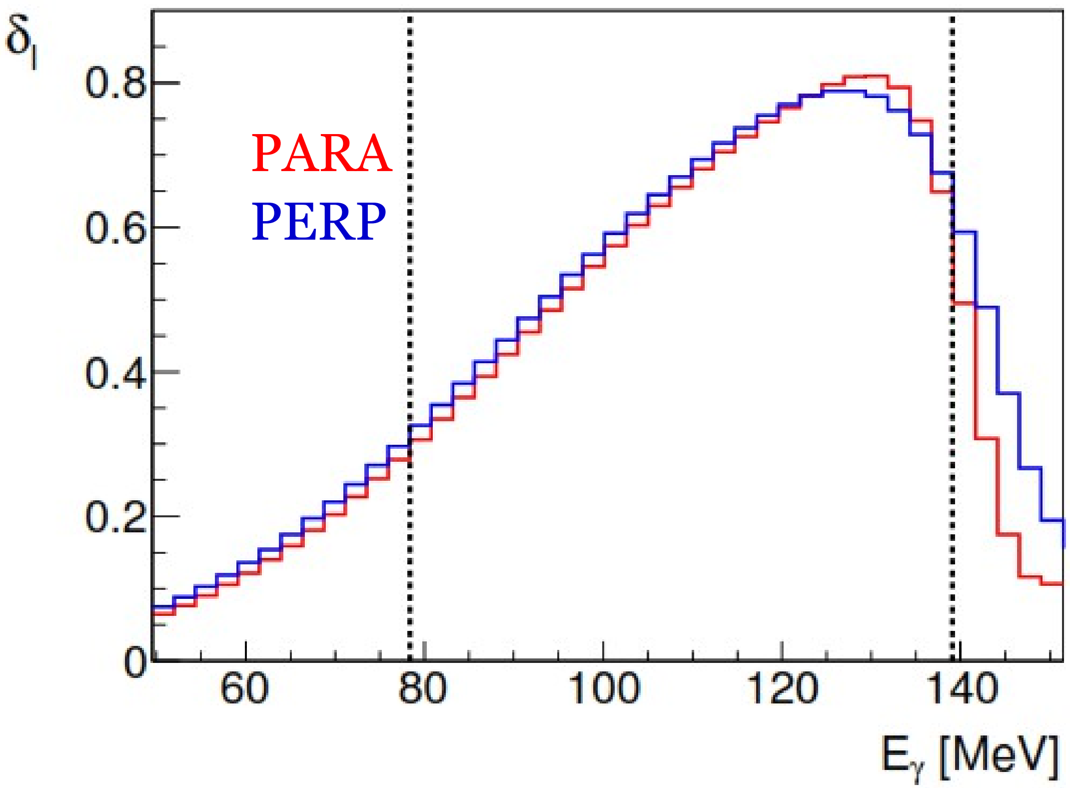
Compton scattering: Example spectra

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



PARA and PERP, Asymmetry

Degree of linear polarization (averaged)



→ Event by event determination of the degree of linear polarization