Institut
für Kernphysik

Recent developements at the A2 real photon facility at MAMI

1.-Introduction Physics topics: Excitation of Nucleons and Polarizabilities

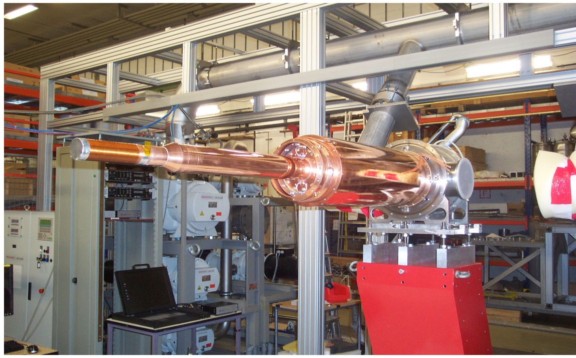
2.-Experimental setup: γ- beam and detector - Tagger + Crystal Ball@MAMI

Frozen Spin Target

3.-Active Target developement

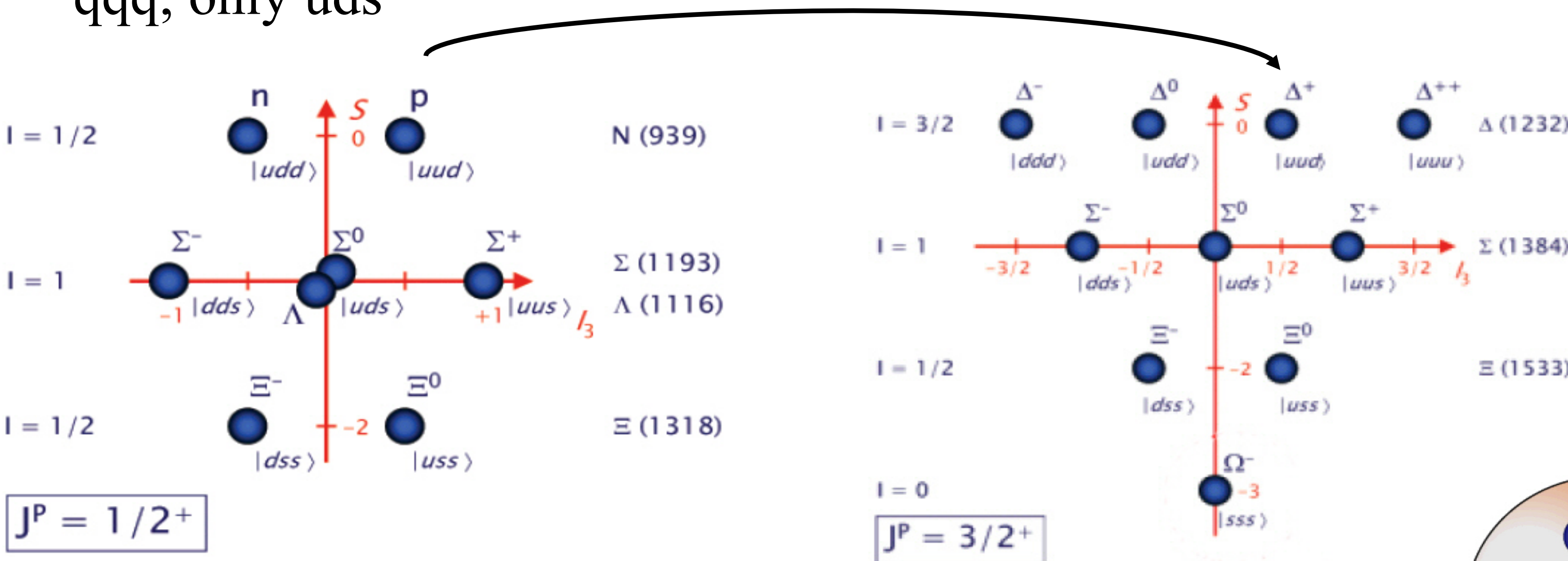
April 10th , 2019

Andreas Thomas
for the A2 Collaboration



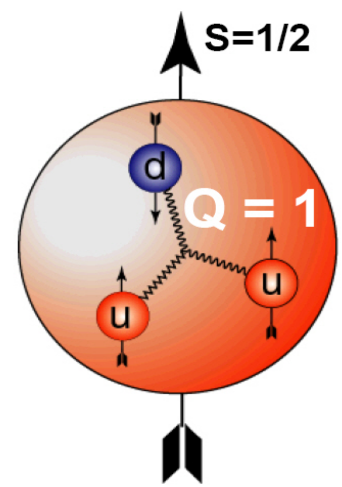
Introduction Physics:

Quark Model
Classification of Baryons
qqq; only uds



Oktett Dekuplett

Simple Constituent quark picture:

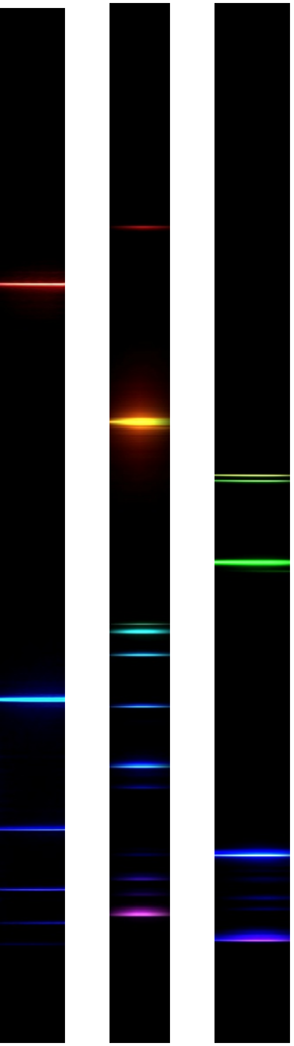


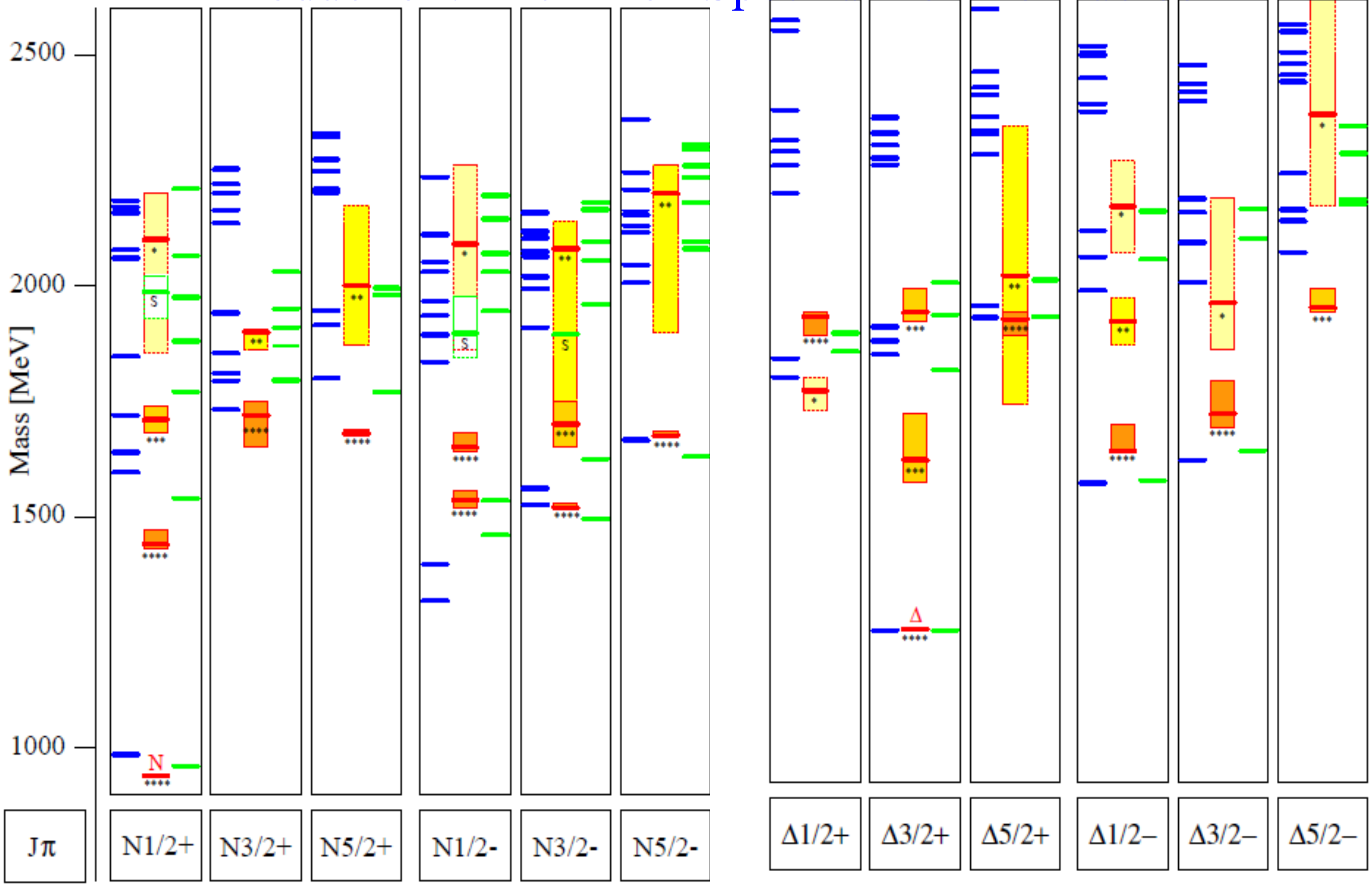
Proton p(938): |uud> ~ |↑↑↓> Spin 1/2

Delta Δ(1232): |uud> ~ |↑↑↑> Spin 3/2

M1-Transition
(Small 2.5% E2)

Introduction: Excitation Spectrum of the Nucleon





Löhrig, Metsch, Petry, Eur.Phys.J. A10 (2001) 395-446
The light baryon spectrum in a relativistic quark model

What is the nature of the Nucleon Resonances?

-Excitation inner deg. of freedom

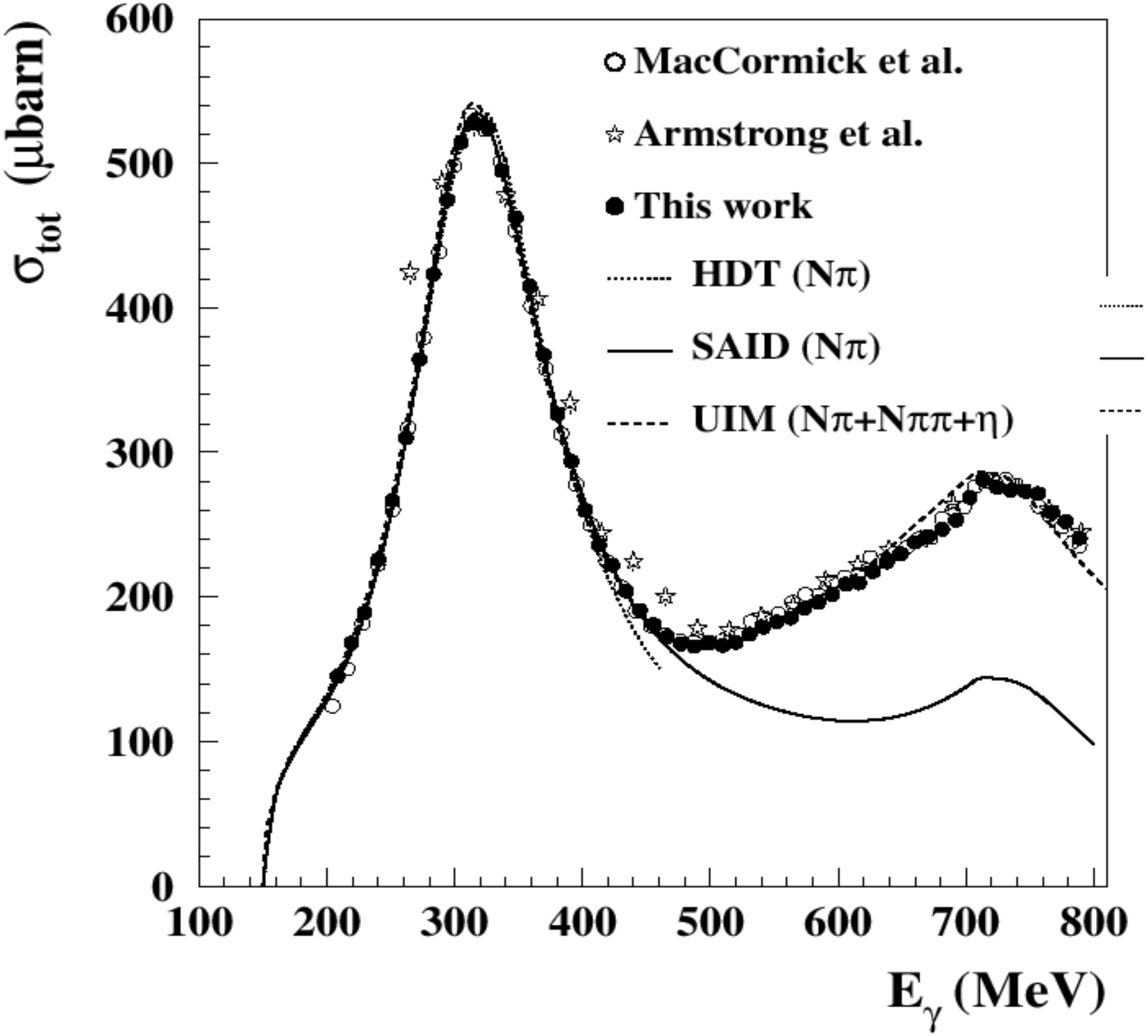
-Molecule

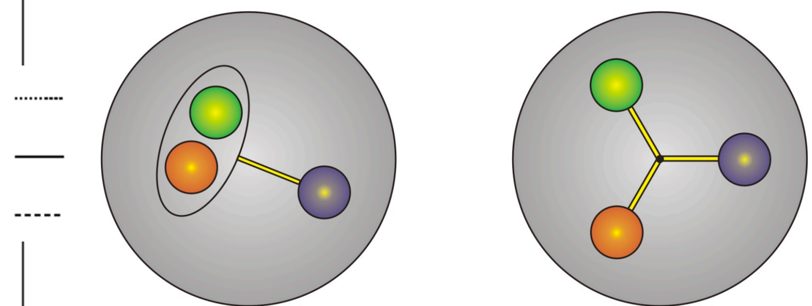
-Quark – Diquark Structure

-Dynamical Generation

- …….?

Unpolarised total photoabsorption cross section





Phys. Rev. Lett. 87, 022003 (2001)

Phys. Rev. Lett. 84, 5950 (2000)

Nucl. Phys. A642, 561 (1998)

Phys. Rev. C 53, 430 (1996); SP01

Nucl. Phys. A645, 145 (1999)

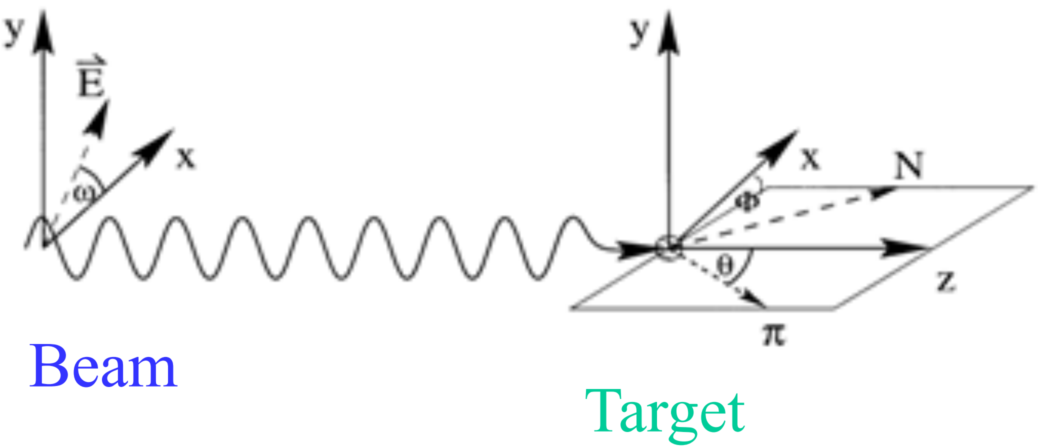
Nature and Properties of nucleon resonances

➡ Polarisation observables used to disentangle broad, overlapping resonances.

Observables in pseudoscalar meson prod.

(Barker, Donnachie & Storrow Nucl Phys B95 (1975))

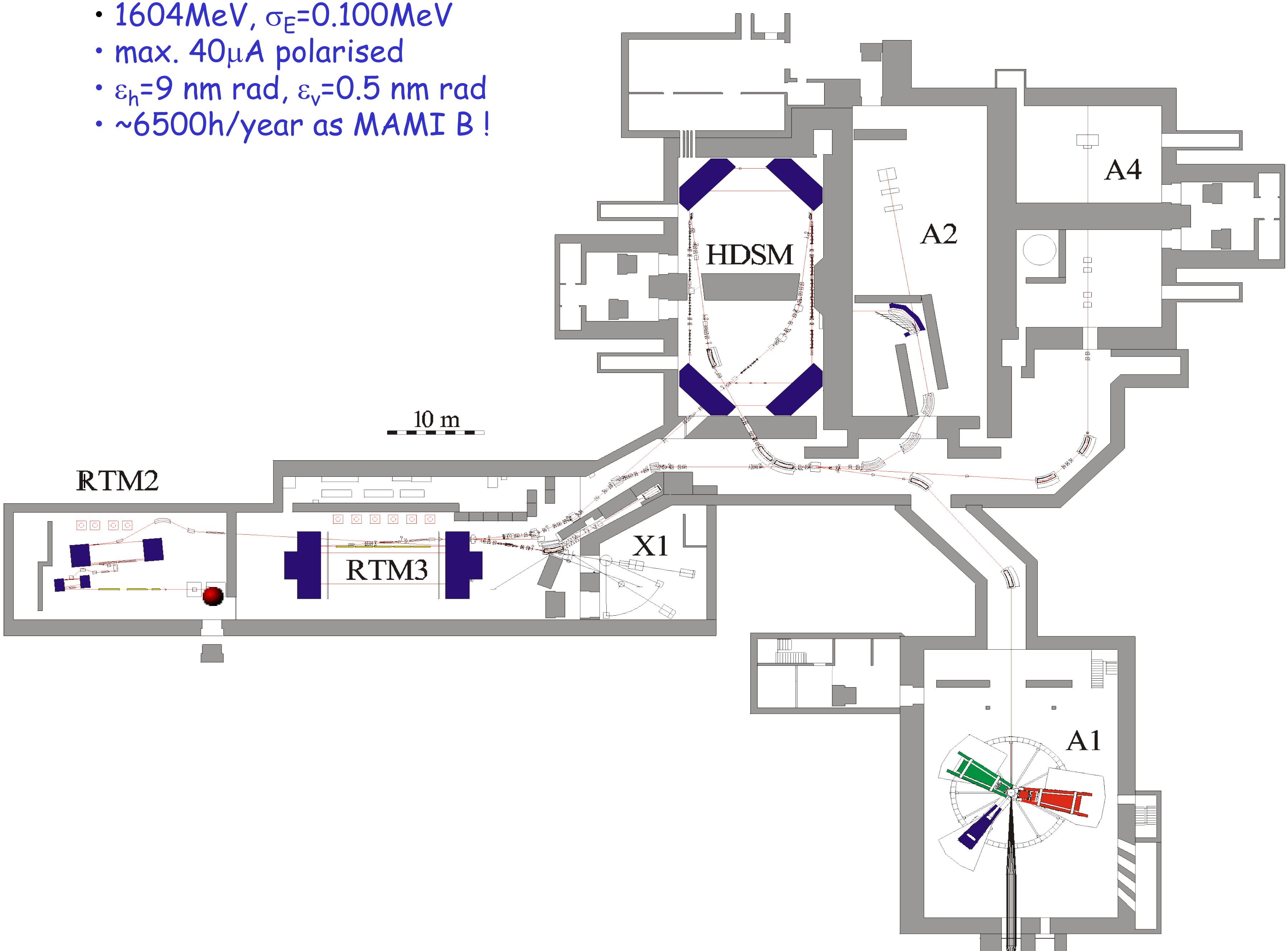
$$\rho_f \frac{d\sigma}{d\Omega} = \frac{1}{2}\left(\frac{d\sigma}{d\Omega}\right)_{unpol} \{1 - P_\gamma^{lin}\Sigma\cos 2\phi + P_x(P_\gamma^{circ}F + P_\gamma^{lin}H\sin 2\phi)$$
$$+ P_y(T - P_\gamma^{lin}P\cos 2\phi) + P_z(P_\gamma^{circ}E + P_\gamma^{lin}G\sin 2\phi)$$



Beam / Target	γ_{unpol}	P_γ^{lin} $\left(0, \frac{\pi}{2}\right)$	P_γ^{lin} $\left(+\frac{\pi}{4}, -\frac{\pi}{4}\right)$	P_γ^{circ}
P_{unpol}	$\left(\frac{d\sigma}{d\Omega}\right)$	$\Sigma(\theta)$	-	-
P_x	-	-	$H(\theta)$	$F(\theta)$
P_y	$T(\theta)$	$P(\theta)$	-	-
P_z	-	-	$G(\theta)$	$E(\theta)$

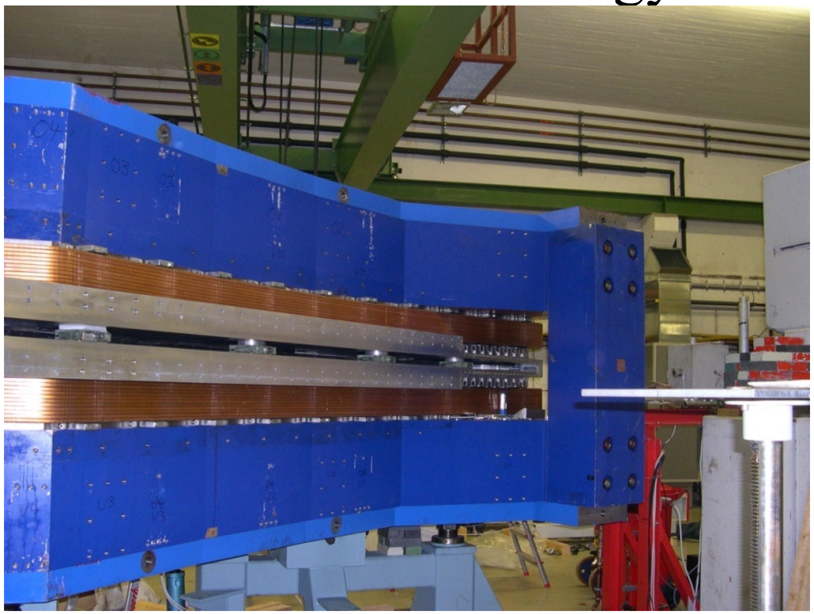
Parameter

- 1604MeV, σ_E=0.100MeV
- max. 40μA polarised
- ε_h=9 nm rad, ε_v=0.5 nm rad
- ~6500h/year as MAMI B !

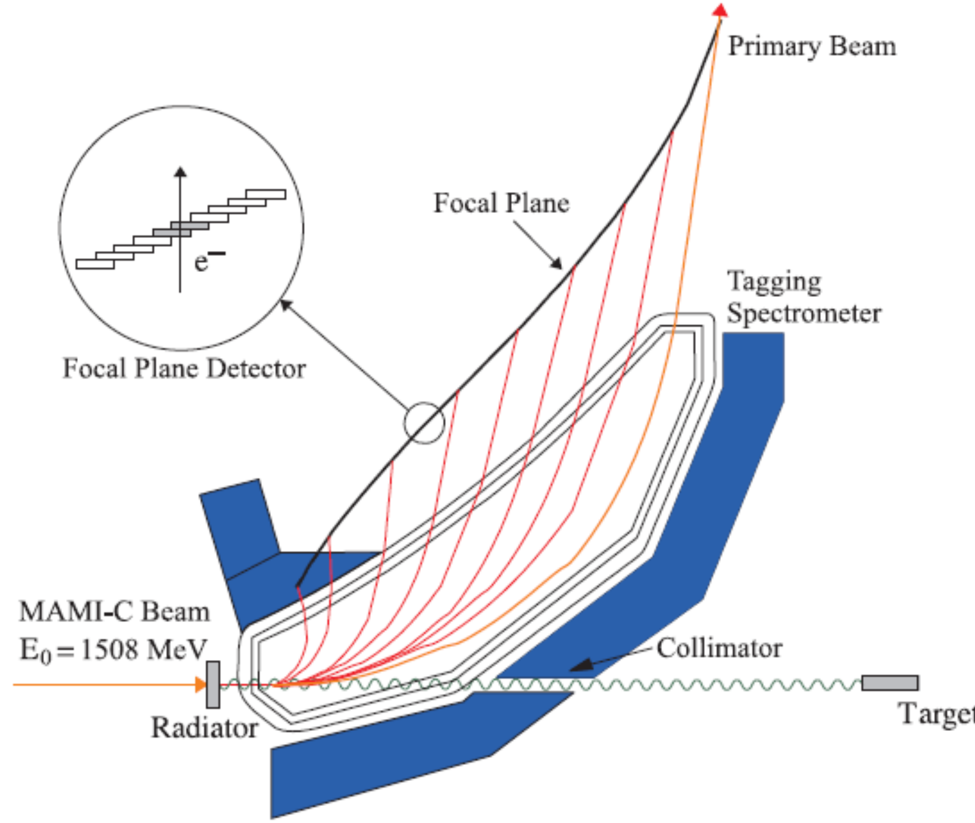


A2 Tagging system (Glasgow, Mainz)

1. Production and energy measurement of the Bremsstrahlung photons.



Glasgow Tagging Spectrometer
EPJ A 37, 129 (2008)

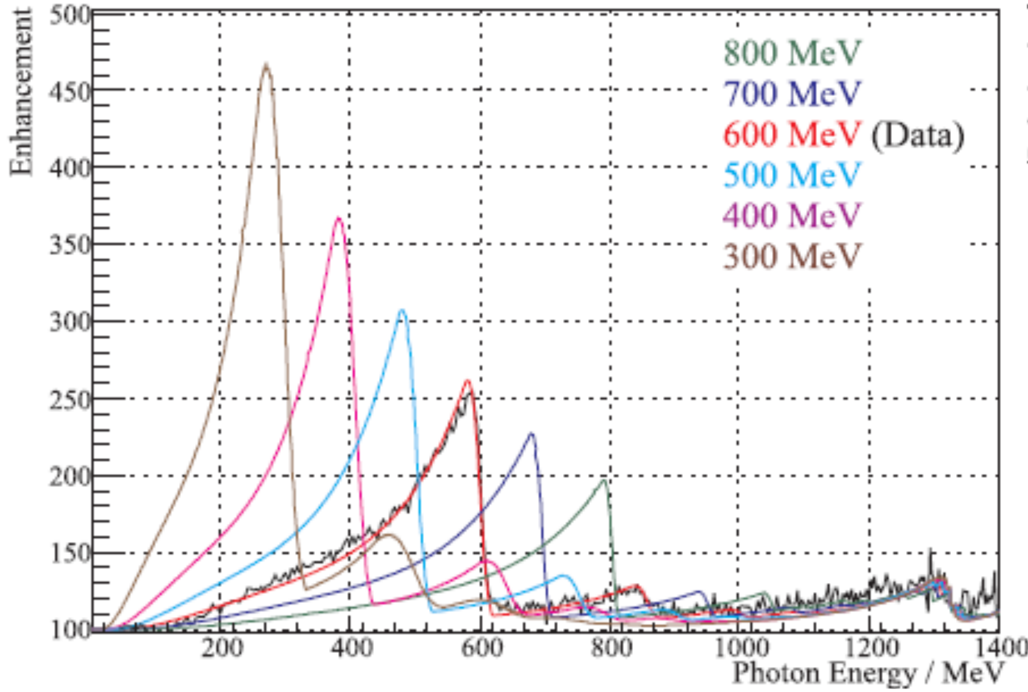


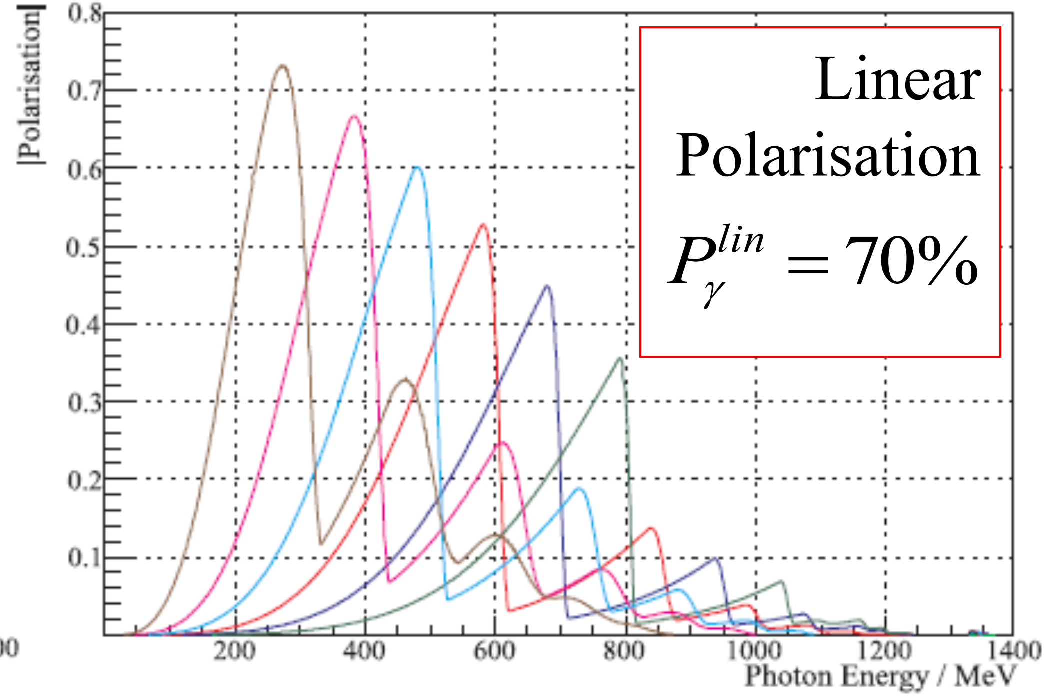
2. Determination of the degree of polarization of the electron beam (Moeller Polarimeter). Circularly pol. photons.

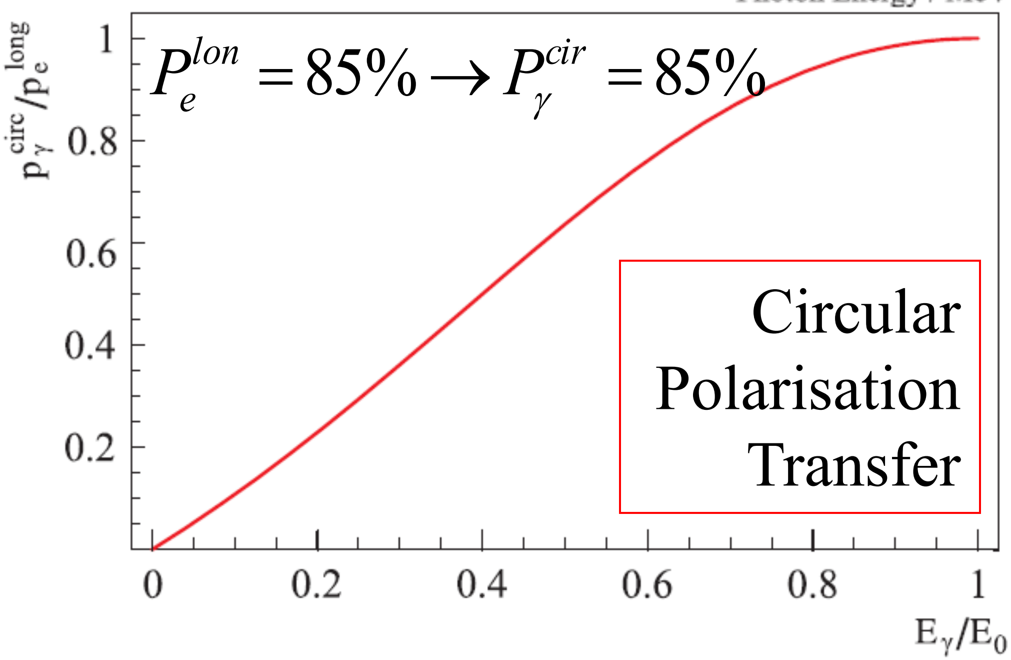
$$A = \frac{N^+ - N^-}{N^+ + N^-} = a\vec{p}_t\vec{p}_b\cos(z)$$

3. Coherent production of linearly polarized photons on a diamond radiator

Polarised Photons @ MAMI C





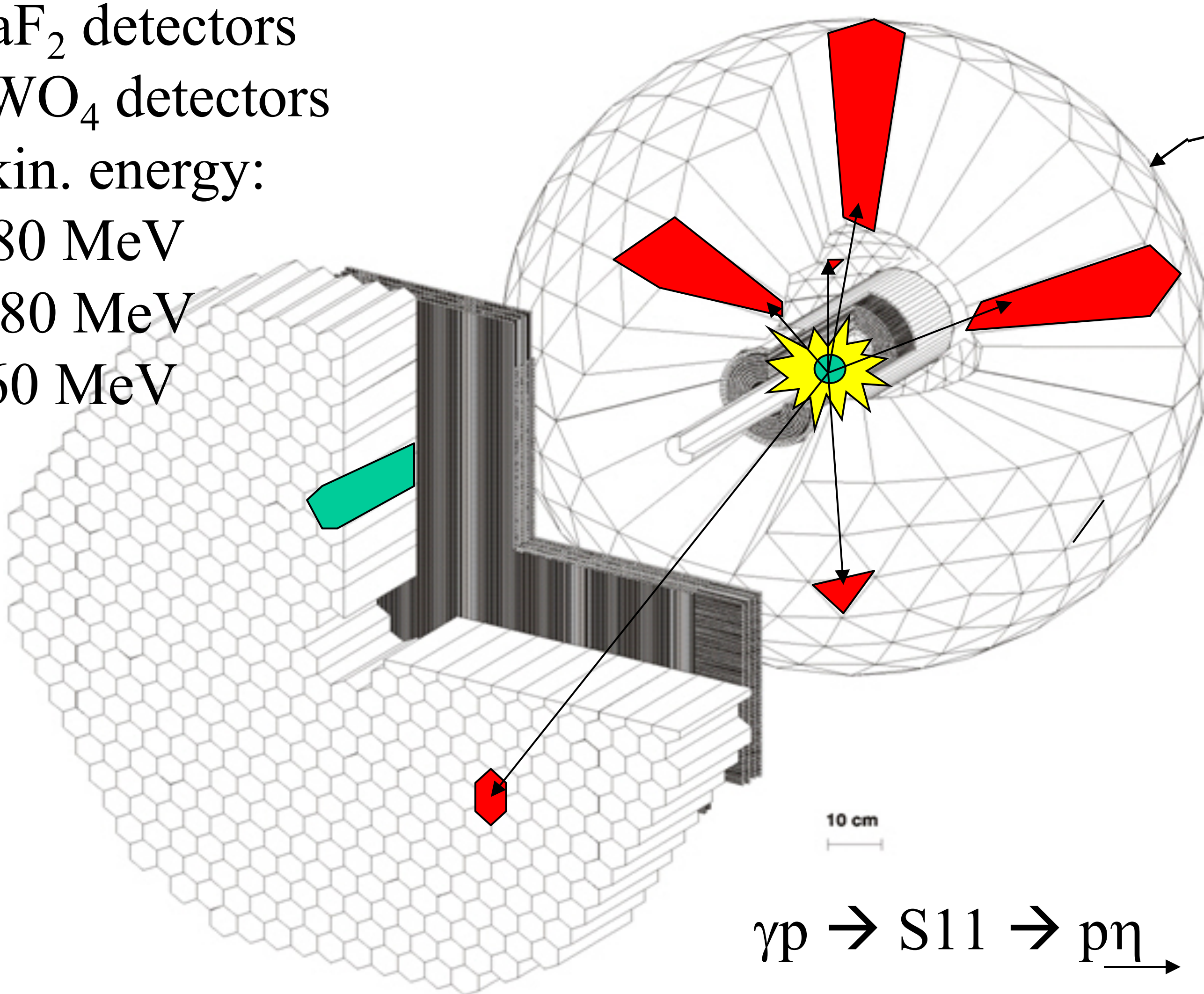


E_γ = 75 ... 1480 MeV
ΔE_γ = 4 MeV
N_γ = $2 \cdot 10^5$ s^{-1} MeV^{-1}

➡ High Polarisation
High Photon Flux

4π photon Spectrometer @ MAMI

TAPS:
366 BaF_2 detectors
72 $PbWO_4$ detectors
Max. kin. energy:
π^{+-} : 180 MeV
K^{+-} : 280 MeV
P : 360 MeV



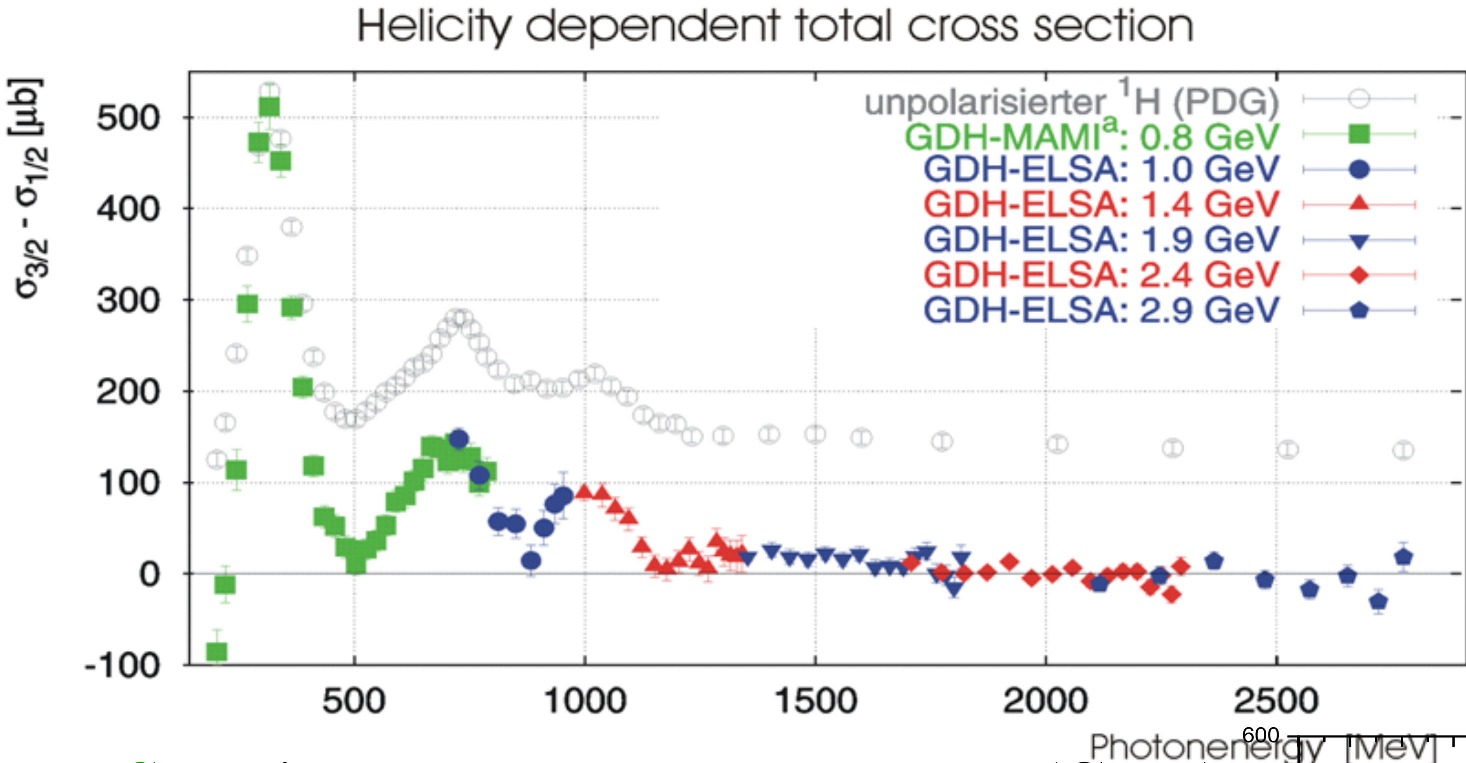
Crystal Ball:
672 NaJ detectors
Max. kin. energy:
μ^{+-} : 233MeV
π^{+-} : 240 MeV
K^{+-} : 341 MeV
P : 425 MeV

Vertex detector:
2 Cylindr. MWPCs
480 wires, 320stripes

PID detector:
24 thin plastic detectors

$\gamma p \rightarrow S11 \rightarrow p\eta \rightarrow \pi^0\pi^0\pi^0 \rightarrow \gamma\gamma\gamma\gamma\gamma\gamma$

Helicity Dependence E of Meson Photoproduction on the Proton and Neutron

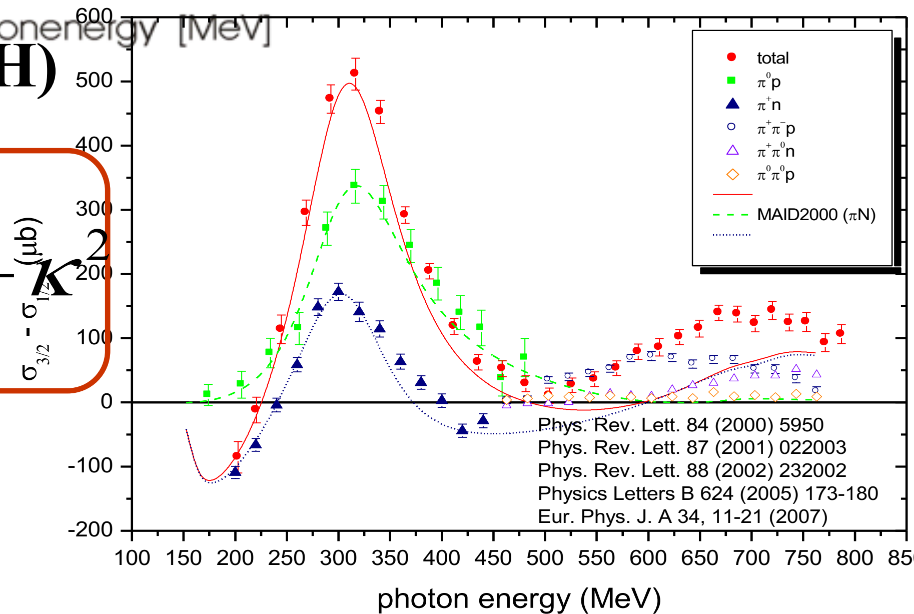


1998-2003 Mainz and Bonn

2010-2016 New Mainz Exp. with CBall

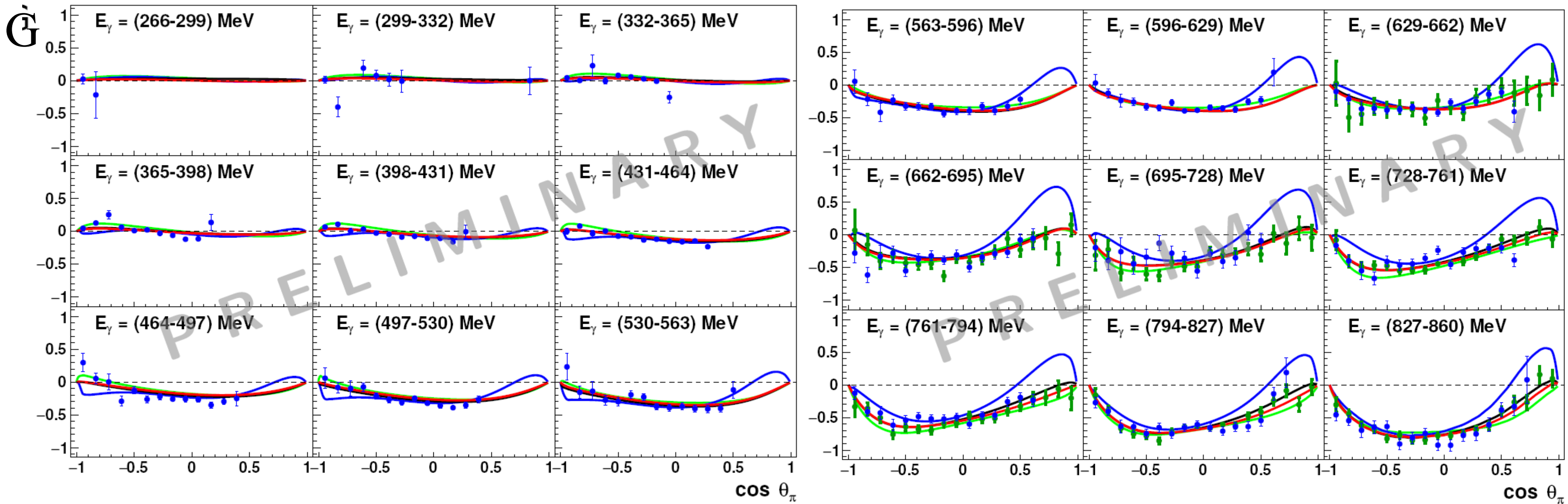
Gerasimov-Drell-Hearn sum rule (GDH)

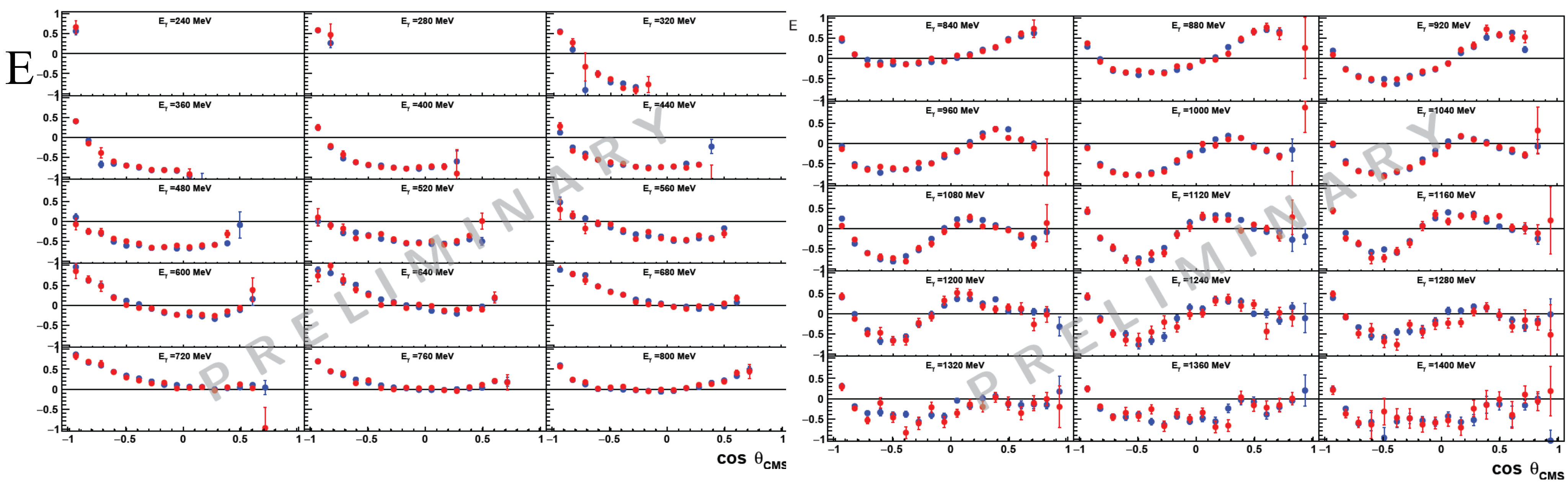
$$\int_0^\infty \frac{\sigma_{3/2}(\omega)-\sigma_{1/2}(\omega)}{\omega}\,d\omega = \frac{\pi e^2}{2m^2}\kappa^2$$



Simultaneous measurement of E and G

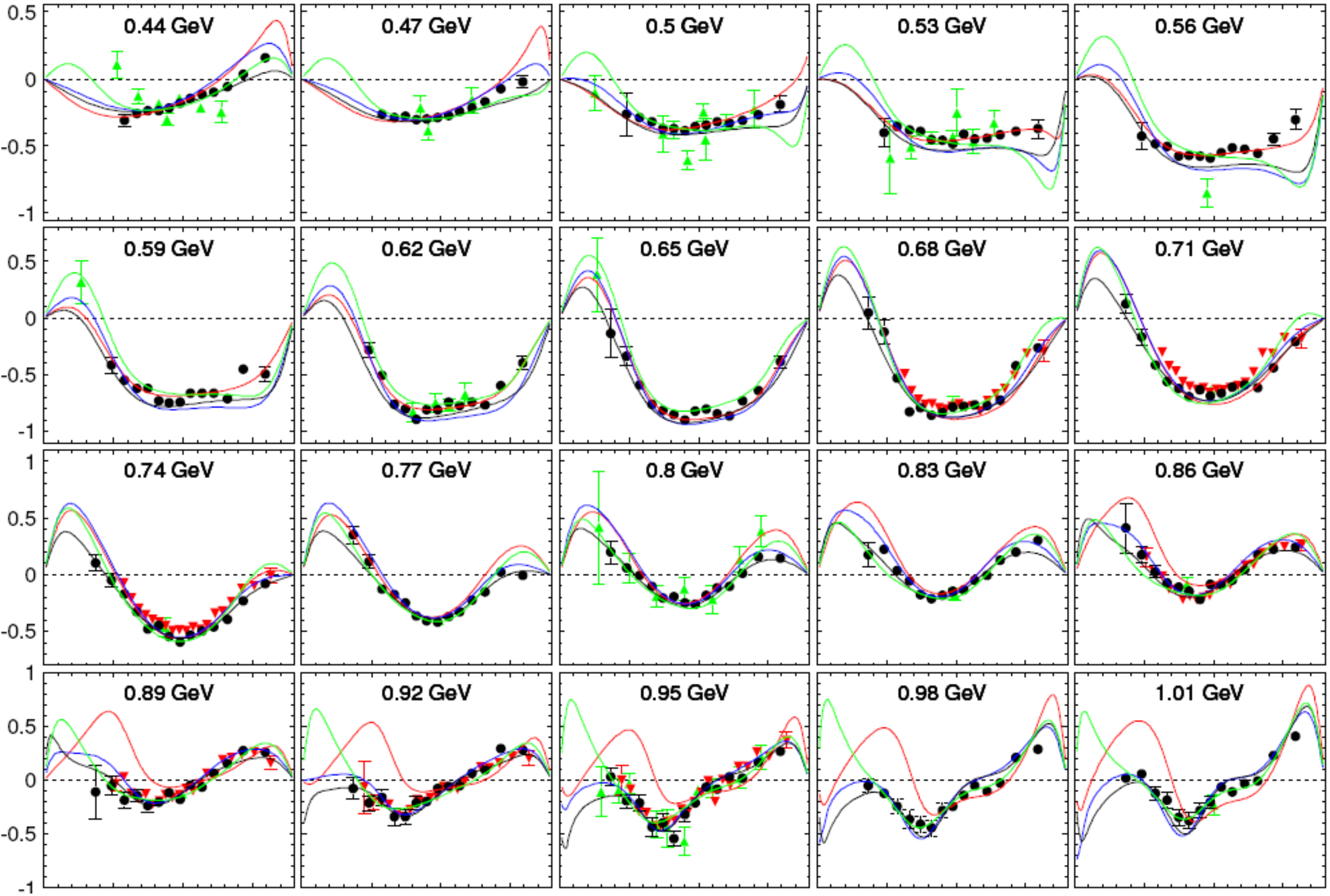
Simultaneous measurement of G and E for π^0 production (F.Afzal, K.Spieker)





T in π^0–photoproduction

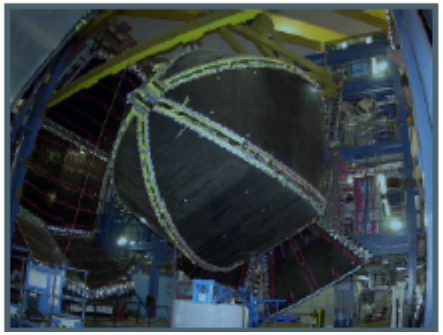
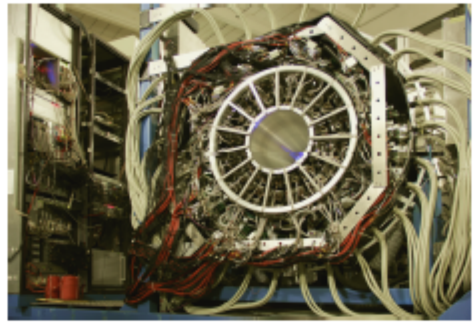
Red line: MAID 2007
blue line: SAID PR15
green line: JUBo2015-B
black line: BG2014-2



J. R.M. Annand *et al.* Phys. Rev. C 93, 055209 – Published 31 May 2016

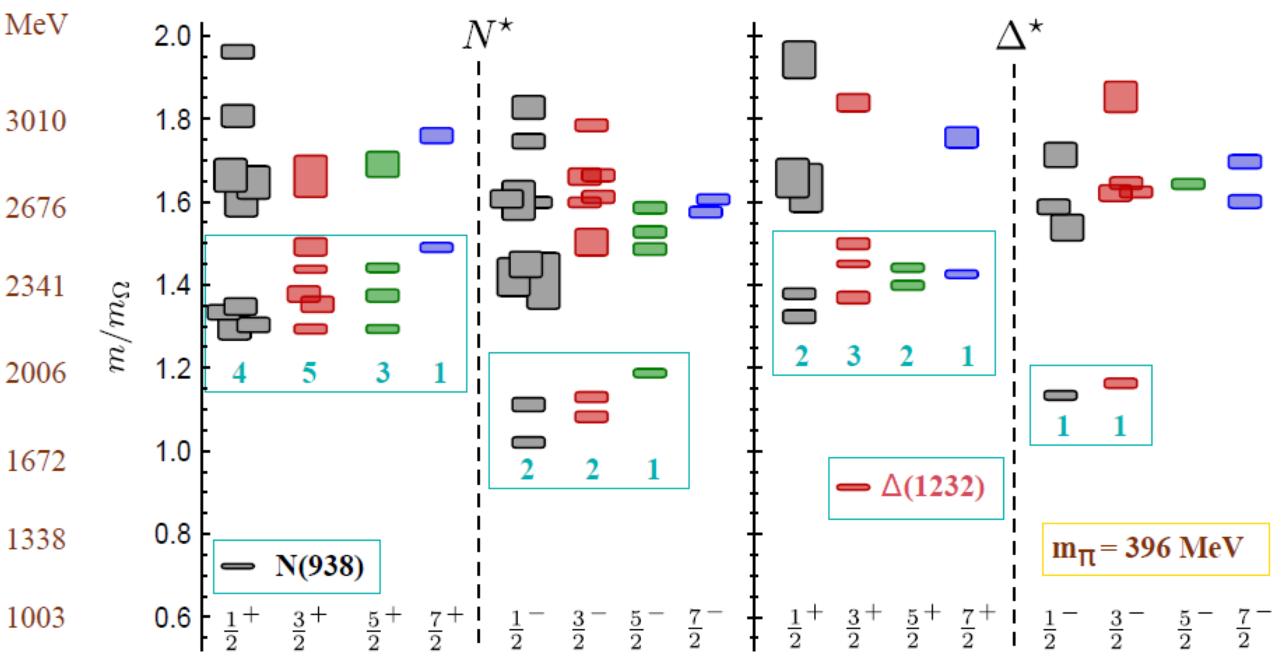
Black Circles – new MAMI Measurement, red triangles Bonn CBELSA, green triangles older data.

New double polarization data from several facilities


CLAS, Jlab   Crystal Barrel, ELSA   Crystal Ball, MAMI

With a variety of new measurements of spin observables it comes to a convergence of the multipoles in the region of leading resonances using PWA.



Excited baryons from Lattice QCD:

R.Edwards et al., Phys. Rev. D84 (2011) 074508

Proton Polarizabilities

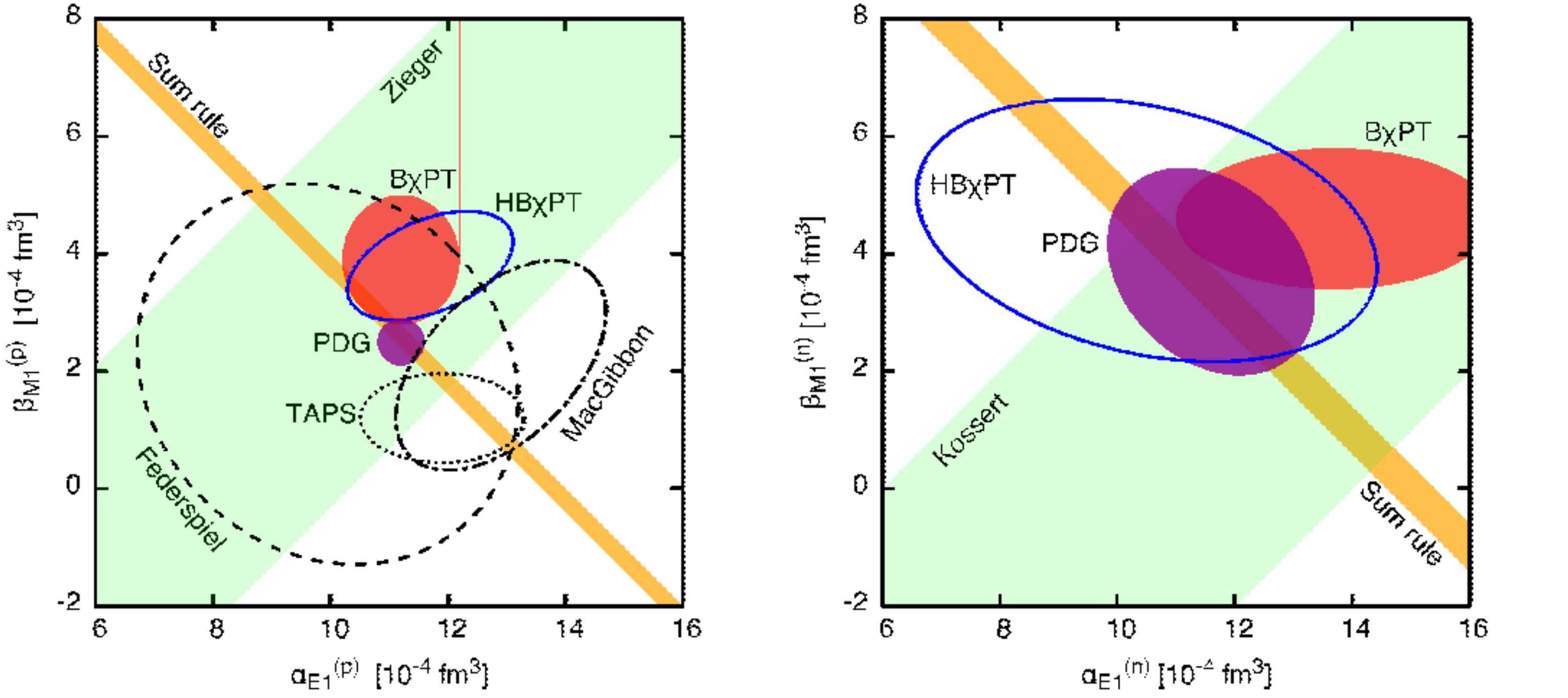


Figure 1: The scalar polarizabilities, β_{M1} versus α_{E1} for the proton (left) and neutron (right). "Sum rule" indicates the Baldin sum rule constraint. "PDG" represents the latest Particle Data Group value [14]. The covariant baryon chiral perturbation theory (BChPT) prediction [15] is shown by the red blob.

New measurement of the Proton Scalar Polarisabilities via beamasymmetry in Compton process finished in July 2018. [PhD E.Mornacchi] more than 1 Million Comptons!

Determination of the scalar polarizabilities of the proton using beam asymmetry Σ_3 in Compton scattering

V.Sokhoyan et al., Eur. Phys. J. A (2017) 53

Spin Polarizabilities

- Spin Vector polarizabilities describe spin response to an incident photon
- Four vector pol. (γ_{E1E1} γ_{M1M1} γ_{E1M2} γ_{M1E2}) appear at 3rd order in eff. Hamiltonian

$$H_{eff}^{(3),spin} = -\frac{1}{2}4\pi\left(\gamma_{E1E1}\vec{\sigma}\cdot\vec{E}\times\dot{\vec{E}} + \gamma_{M1M1}\vec{\sigma}\cdot\vec{B}\times\dot{\vec{B}} - 2\gamma_{M1E2}E_{ij}\sigma_j H_j + 2\gamma_{E1M2}H_{ij}\sigma_j E_j\right)$$

- Only two linear combinations of vector polarizabilities measured:

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{M1M1} - \gamma_{E1M2} - \gamma_{M1E2} = -1.01 \pm 0.08 \pm 0.10 \times 10^{-4} fm^4$$

$$\gamma_\pi = -\gamma_{E1E1} + \gamma_{M1M1} - \gamma_{E1M2} + \gamma_{M1E2} = 8.0 \pm 1.8 \times 10^{-4} fm^4$$

The Forward S.P. γ_0 was determined in GDH-Experiment at ELSA and MAMI (DAPHNE) :

$$\gamma_0 = \frac{-1}{4\pi^2}\int_0^\infty \frac{\sigma_{3/2}(\omega) - \sigma_{1/2}(\omega)}{\omega^3} d\omega$$

The Backward S.P. γ_π was determined from dispersive analysis of backward angle Compton scattering. [B. Pasquini *et al.*, Proton Spin Polarizabilities from Polarized Compton Scattering (2007).]

Theory: Nucleon Vector Spin Polarisibilities

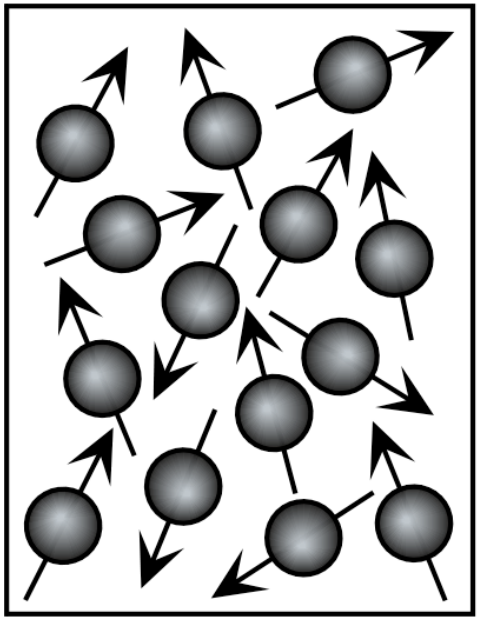
Status 2014

γ	Theory / 10^{-4}fm^4								Experiment / 10^{-4}fm^4
	$\mathcal{O}(p^4)$ [1]	$\mathcal{O}(p^5)$ [2]	LC4 [3]	SSE [4]	BGLMN [5]	HDPV [6]	KS [7]	DPV [8]	
E1E1	-1.4	-1.8	-2.8	-5.7	-3.4	-4.3	-5.0	-4.3	no data
M1M1	3.3	2.9	-3.1	-3.1	2.7	2.9	3.4	2.9	no data
E1M2	0.2	0.7	0.8	0.98	0.3	-0.01	-1.8	0	no data
M1E2	1.8	1.8	0.3	0.98	7.9	2.1	1.1	2.1	no data
0	3.9	-3.6	4.8	0.64	-1.5	-0.7	2.3	-0.7	$-1.01 \pm 0.08 \pm 0.13$ [9]
π	6.3	5.8	-0.8	8.8	7.7	9.3	11.3	9.3	8.0 ± 1.8 [10]

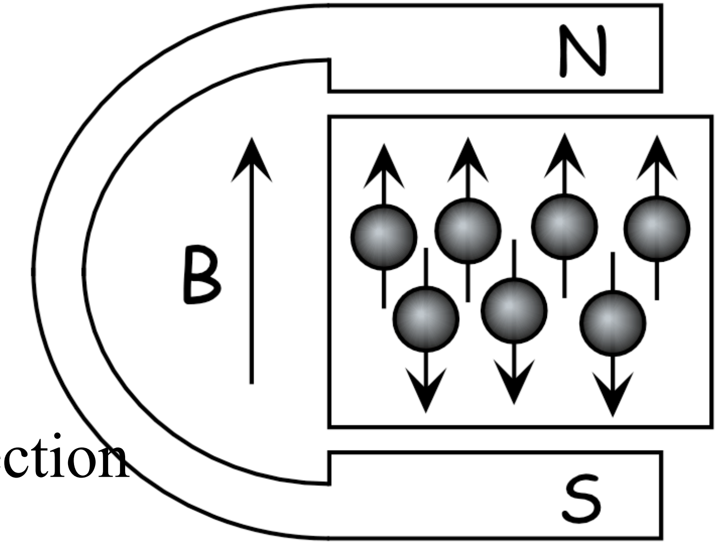
1. G. Gellas, T. Hemmert, and Ulf-G. Meißner, Phys. Rev. Lett. 85, 14 (2000).
2. K.B. Vijaya Kumar, J.A. McGovern, M.C. Birse, Phys. Lett. B 479, 167 (2000).
3. D. Djukanovic, Ph.D. Thesis, University of Mainz, 2008.
4. R.P. Hildebrant et al., Eur. Phys. J. A 20, 293 (2004).
5. D. Babusci et al., Phys. Rev. C 58, 1013 (1998).
6. B. Holstein, D. Drechsel, B. Pasquini, and M. Vanderhaeghen, Phys. Rev. C 61, 034316 (2000).
7. S. Kondratyuk and O. Scholten, Phys. Rev. C 64, 024005 (2001).
8. B. Pasquini, D. Drechsel, and M. Vanderhaeghen, Phys. Rev. C 76, 015203 (2007).
9. J. Ahrens et al., Phys. Rev. Lett. 87, 022003 (2001).
10. M. Schumacher, Prog. Part. Nucl. Phys. 55, 567 (2005).

Polarized Target

Polarization = Orientation of Spins in a magnetic field



$$P = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}$$



Ideally: All spins in field direction

P=100%

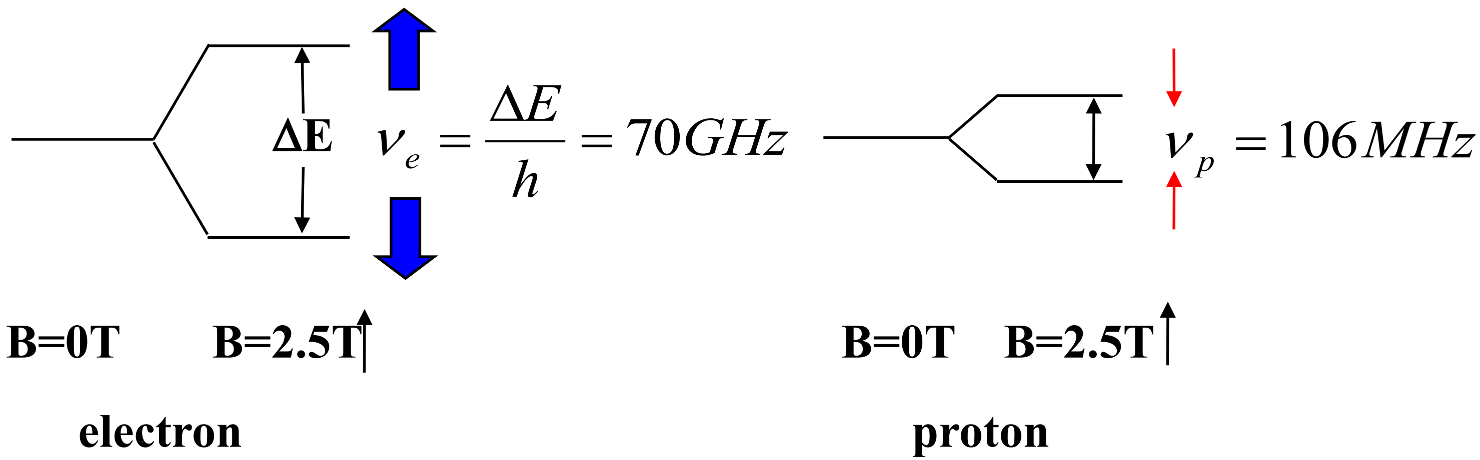
Complicated interplay between

Polarising force ~ magnetic field B

and

Depolarising force ~ thermal motion of spin particles (temperature T – relaxation)

Magnetic moment in magnetic field: $E = -\vec{\mu} \cdot \vec{B} = -g\mu_o mB$



Thermal equilibrium
Boltzmann distribution $\frac{N(E+\Delta E)}{N(E)} = e^{-\frac{\Delta E}{kT}}$

$$P = \frac{N_+ - N_-}{N_+ + N_-} = \tanh \frac{\mu B}{kT}$$

B [Tesla]	T [mK]	e^- [%]	p [%]	d [%]
2,5	100	99,8	0,51	0,10
	1000	93,3	0,25	0,05
5,0	100	100,0	5,09	1,05
	1000	99,8	1,28	0,11

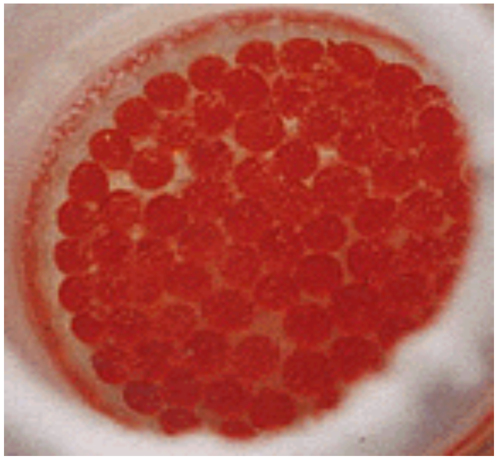
Trick: Transfer of the high electron polarization to the nucleon via μ-wave irradiation (DNP)

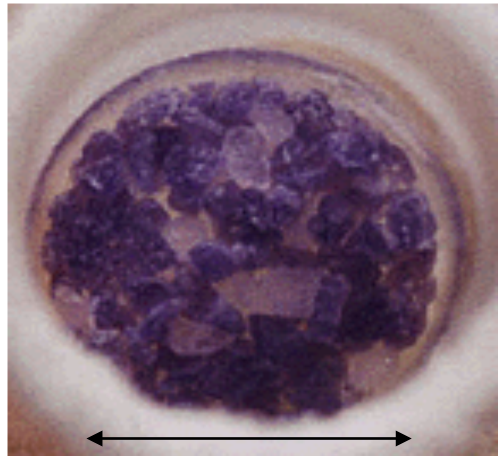
Target material

Saturated electrons of target material not polarized (Pauli principle)

Free electrons ⇨ **Radicals in material by chemical or radiative doping**

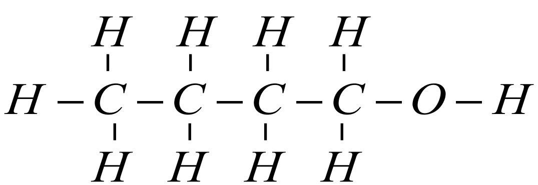
$$\frac{\#radicals}{\#protons} \approx 10^{-4}$$

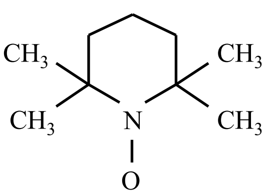




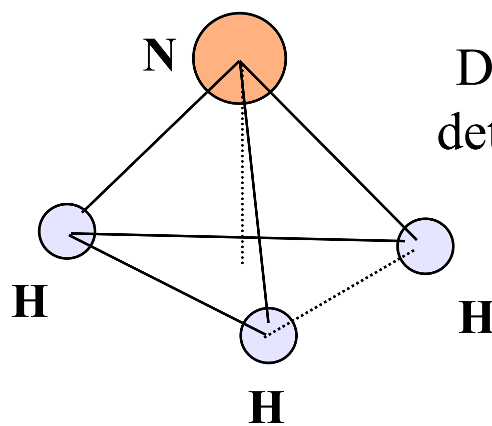
30mm

Butanol **Ammonia** **LiD**



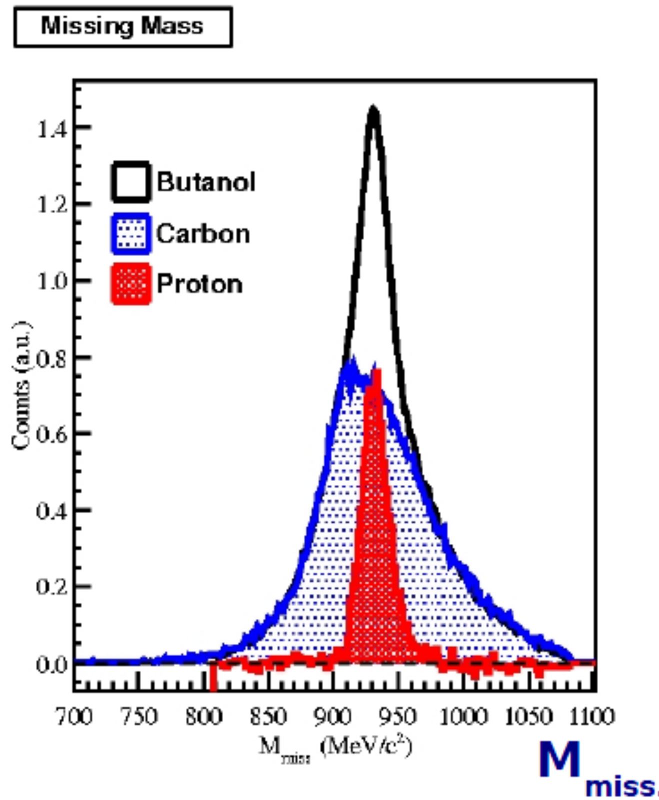


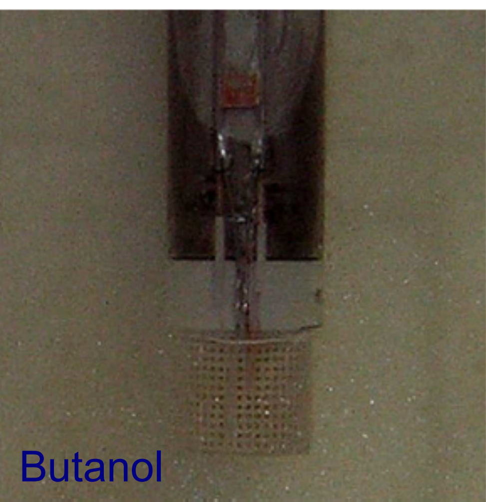
Tempo

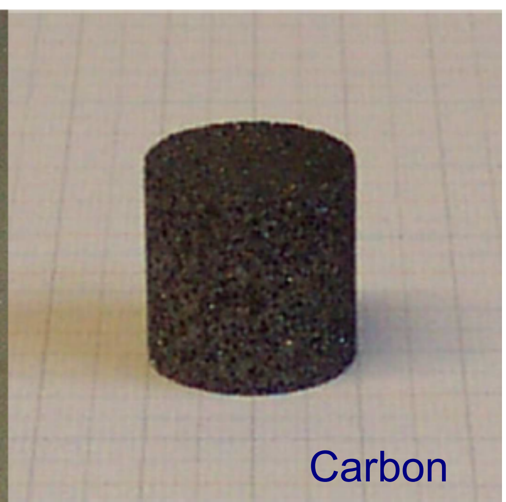


Dilution factor (e.g. $f_{Butanol}$=10/74) determines quality of target material

Additional challenges for the analysis of experiments with Frozen Spin Target → Dilution Factor.



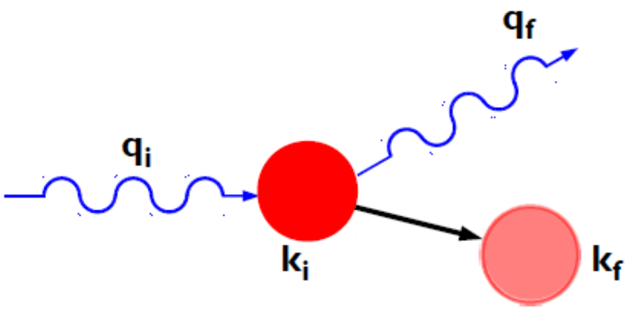




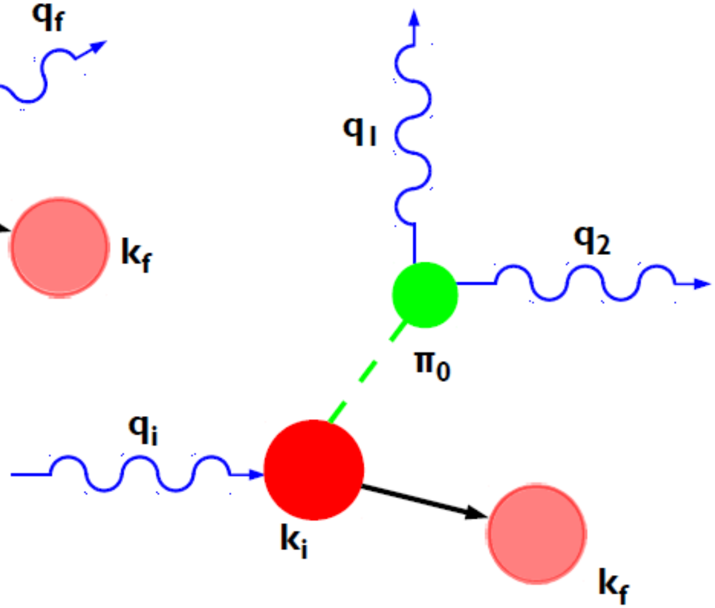
Hydrogen

Event Selection

- Compton Scattering



- Pion Photoproduction



Pion photoproduction off of a proton is 75-100 times more likely than Compton (in the 240-280 MeV range) →

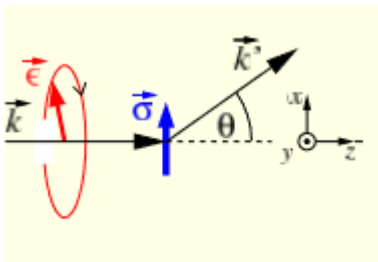
Kinematic overdetermination used for cuts (missing mass, proton angle, …).

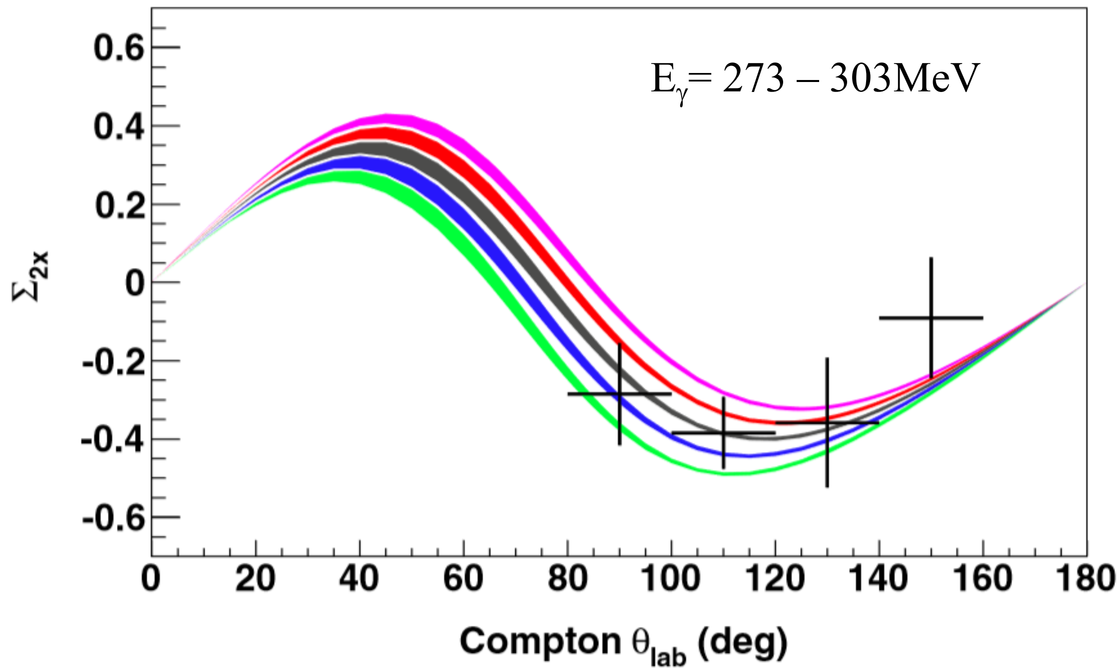
Test with ‘substraction target’.

Measurements of the Proton Spin-Polarizabilities with Double-Polarized Compton Scattering

P.P.Martel et al., **PRL 114 (2015) 112501**

$$\Sigma_{2x} = \frac{\sigma_\perp^R - \sigma_\perp^L}{\sigma_\perp^R + \sigma_\perp^L}$$

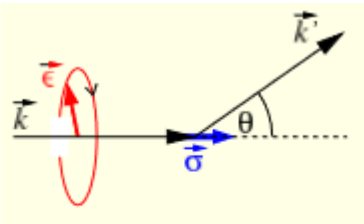


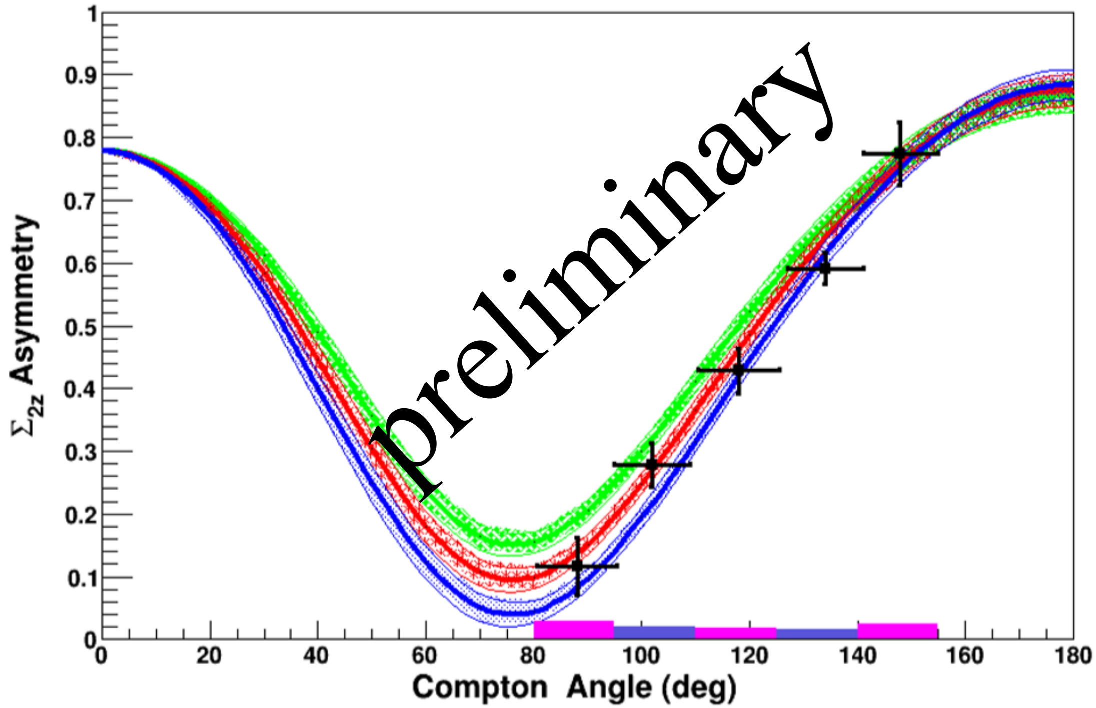


	$O(\epsilon^3)$	$O(p^4)_a$	$O(p^4)_b$	K matrix	HDPV	DPV	L_χ	HBχPT	BχPT	Experiment
γ_{E1E1}	−1.9	−5.4	1.3	−4.8	−4.3	−3.8	−3.7	−1.1 ± 1.8 (theory)	−3.3	−3.5 ± 1.2
γ_{M1M1}	0.4	1.4	3.3	3.5	2.9	2.9	2.5	2.2 ± 0.5(stat) ± 0.7(theory)	3.0	3.16 ± 0.85
γ_{E1M2}	0.7	1.0	0.2	−1.8	−0.02	0.5	1.2	−0.4 ± 0.4 (theory)	0.2	−0.7 ± 1.2
γ_{M1E2}	1.9	1.0	1.8	1.1	2.2	1.6	1.2	1.9 ± 0.4 (theory)	1.1	1.99 ± 0.29
γ_0	−1.1	1.9	−3.9	2.0	−0.8	−1.1	−1.2	−2.6	−1.0	−1.01 ± 0.08 ± 0.10 [3,4]
γ_π	3.5	6.8	6.1	11.2	9.4	7.8	6.1	5.6	7.2	8.0 ± 1.8 [5]

Next Step: Compton with longitudinal Polarized Target

$$\Sigma_{2z} = \frac{\sigma_{\parallel}^{R} - \sigma_{\parallel}^{L}}{\sigma_{\parallel}^{R} + \sigma_{\parallel}^{L}}$$





Spin polarizabilities of the proton by measurement of Compton double-polarization observables

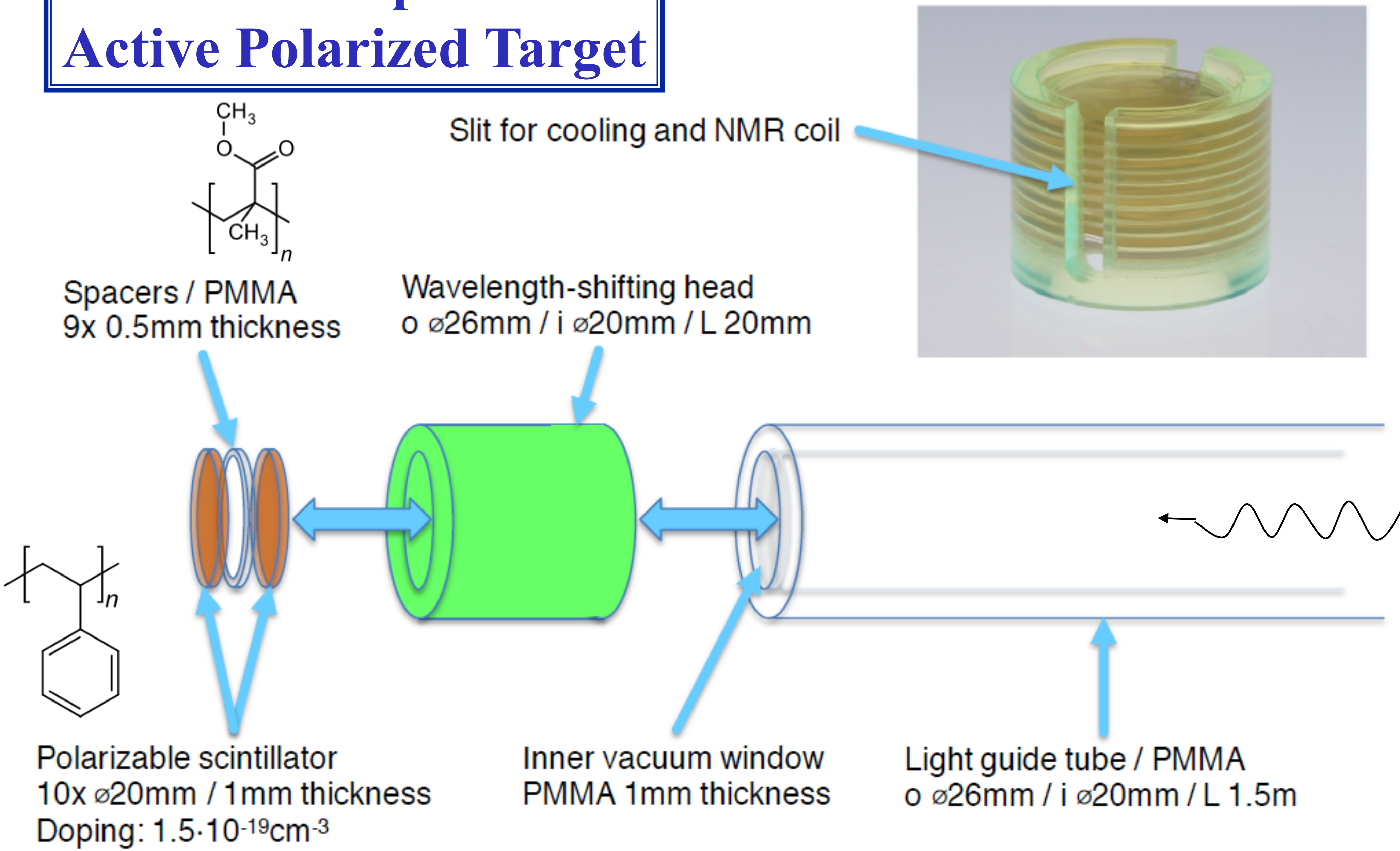
D. Paudyal, G.Huber et al., to be published 2019

Main problems:

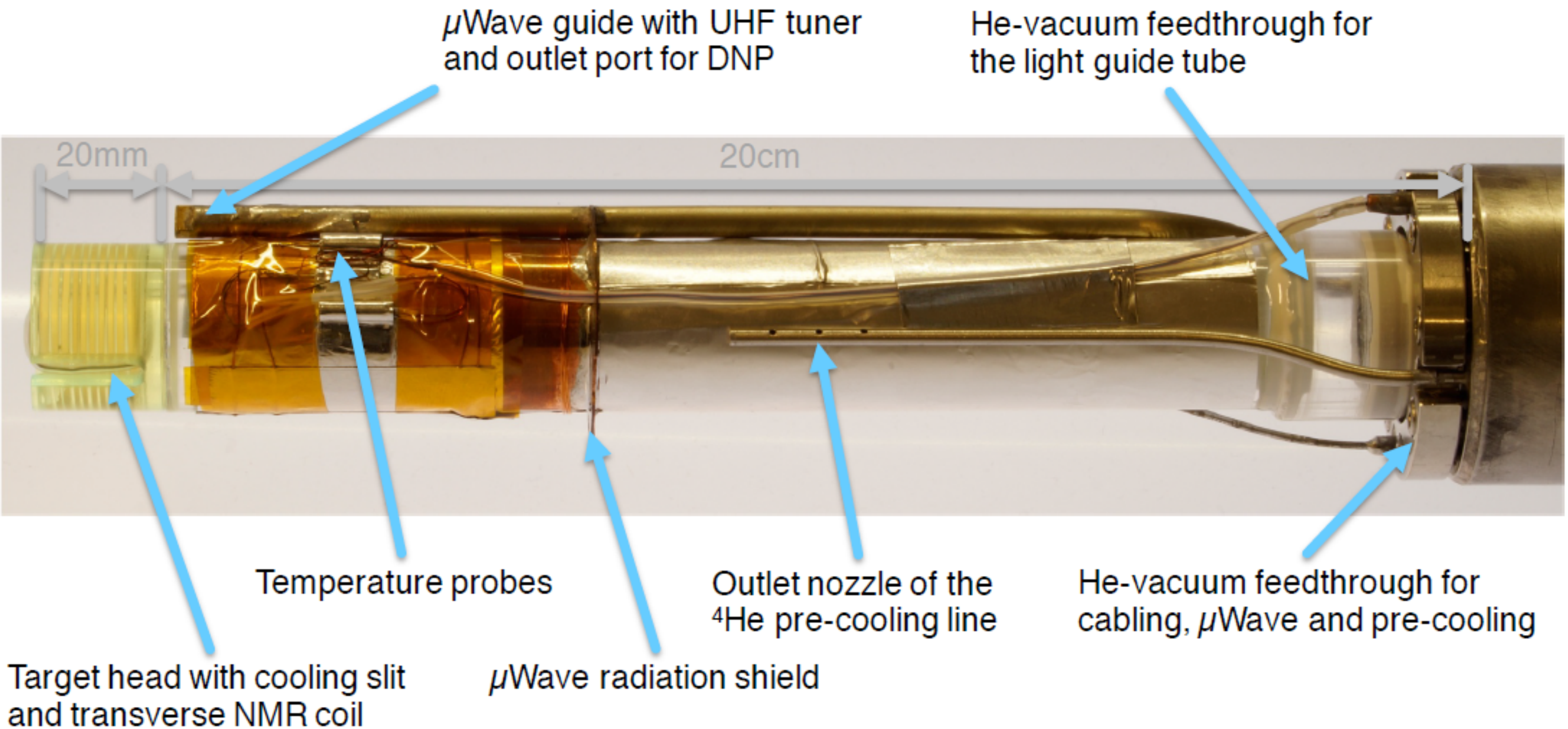
•Low energetic recoil protons do not escape from the target and do not reach the detector.

•Events are produced on the background nuclei (Carbon, coherent, incoherent, κ~13%).).

New Developement: Active Polarized Target



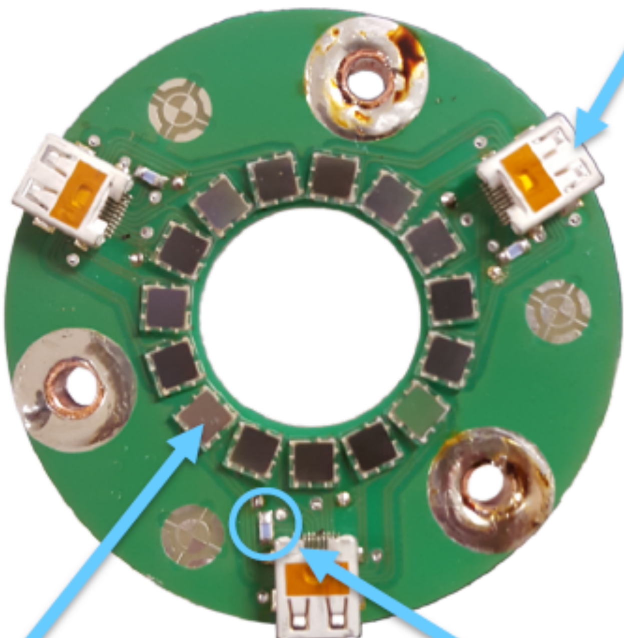
Active Polarized Target

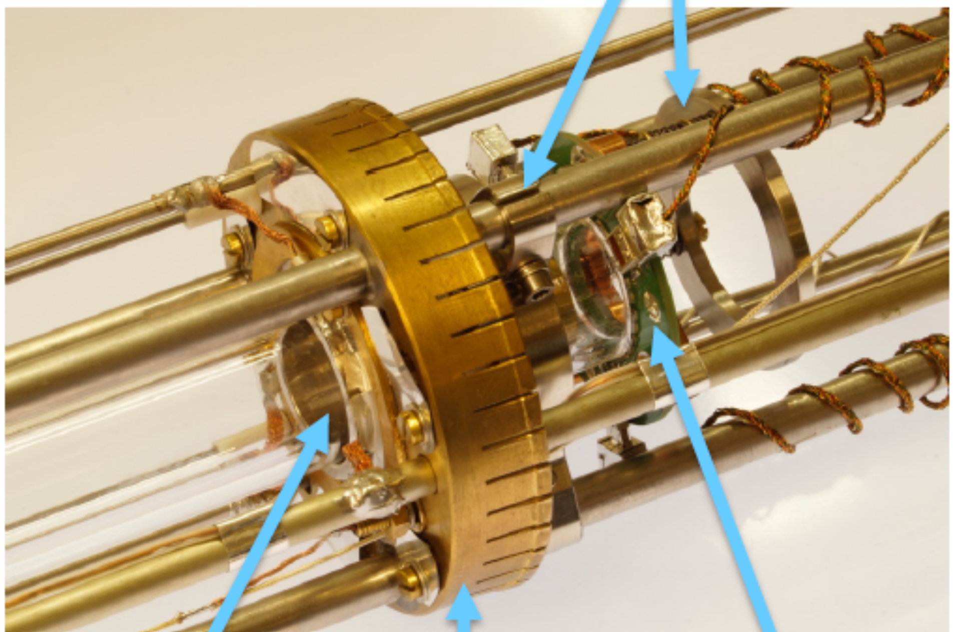


T=45mKelvin after 5 days by ^{3}He/^{4}He mixture ← ←Vacuum in beampipe

Detector Electronics at 150Kelvin

[M.Biroth et al., IEEE Transaction on Nuclear Science, Vol. 64, Issue 6, June 2017]



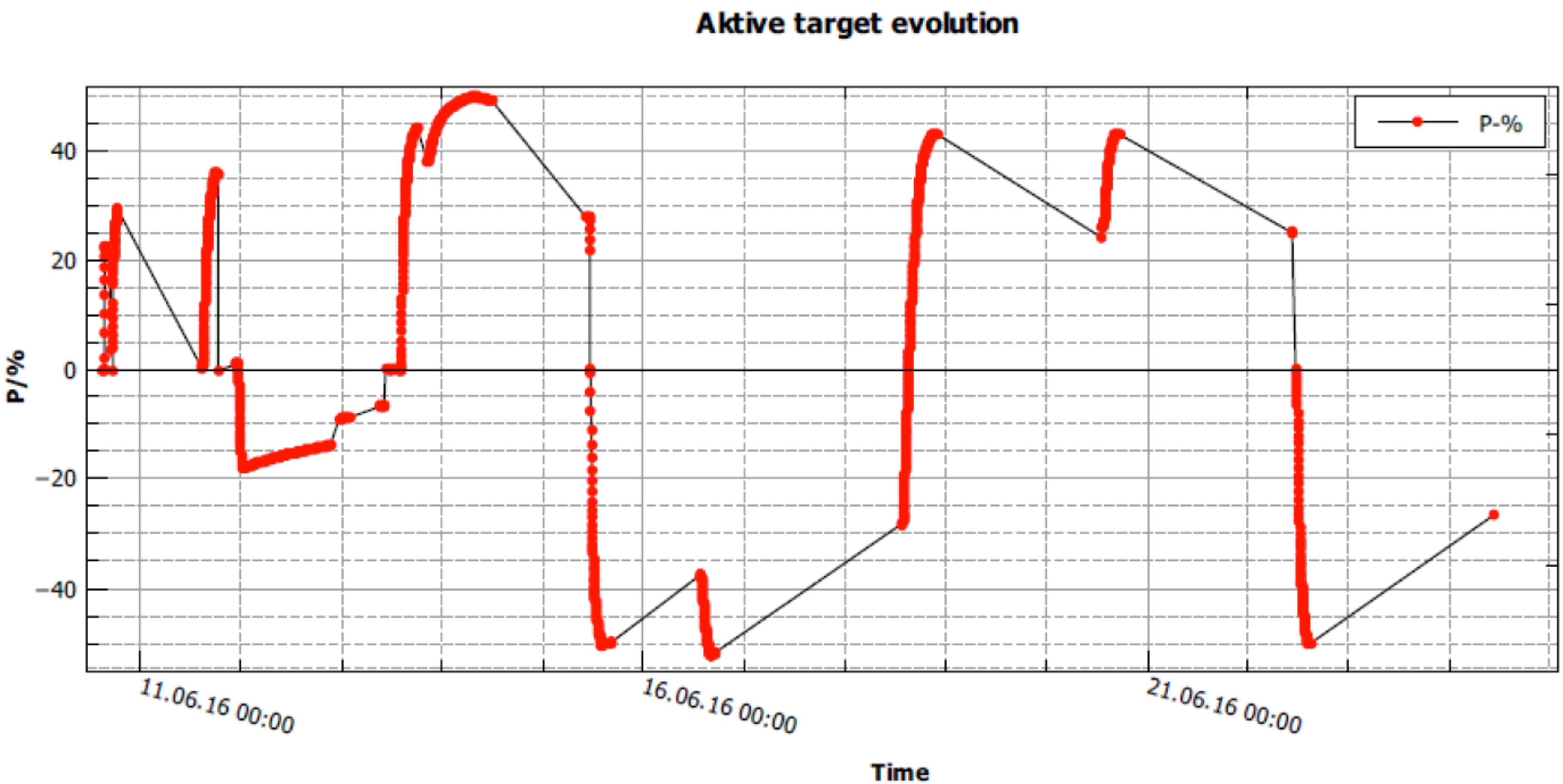


SiPMs gain depends strongly from the temperature ~1% K-1. Therefore it is necessary to control the 25V bias voltage to ~10mV and to have a stable temperature. [PhD M.Biroth, Mainz]

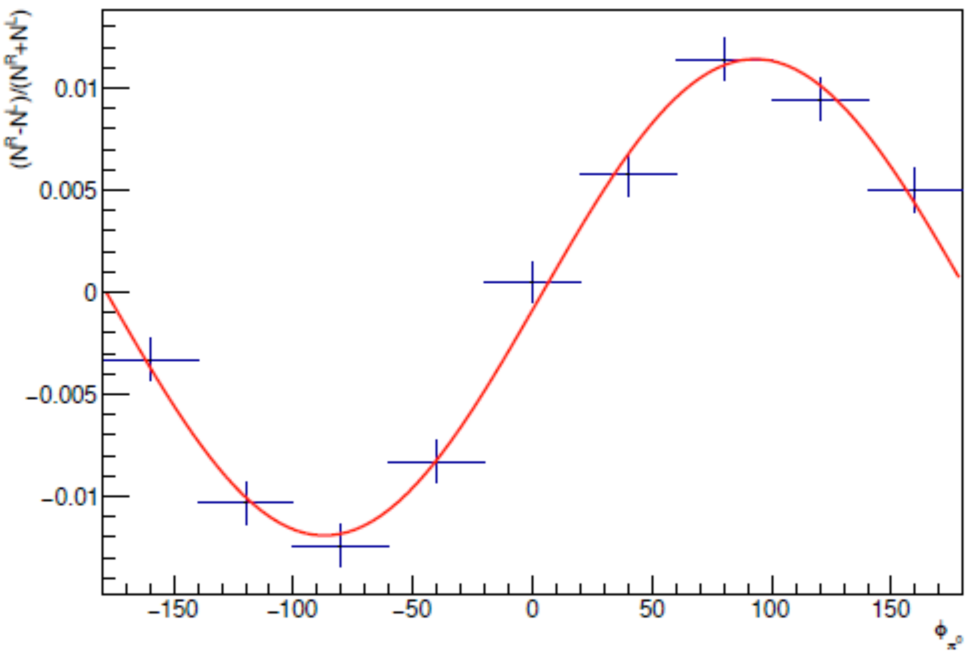
Run June 2016

Holding coil 437.5mT, temperature 45mK

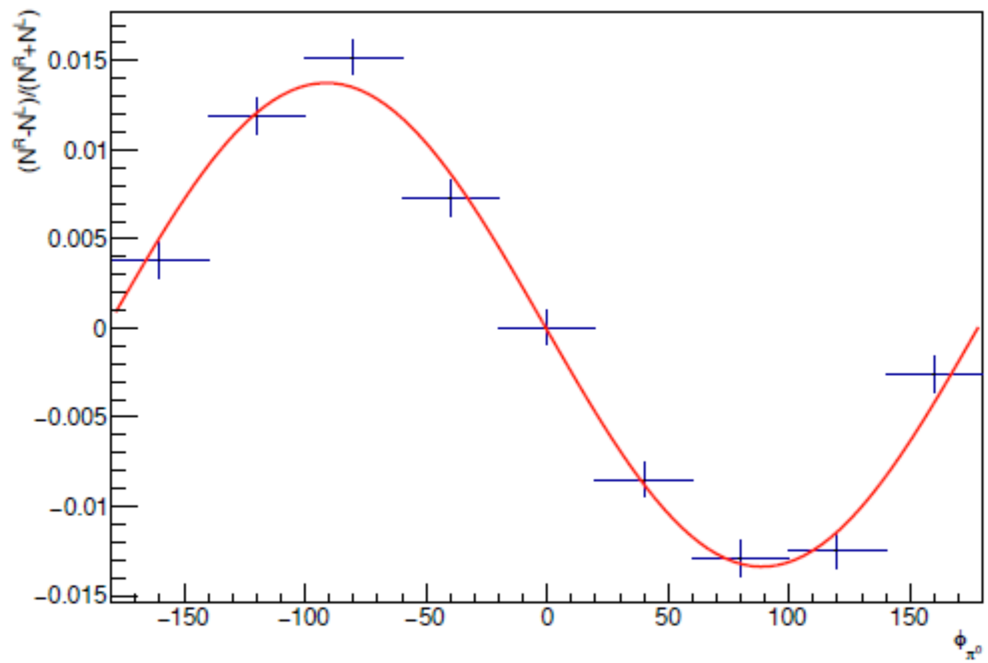
Spin setting	Max. Polarization	Max. Relaxation Time
Positive	(46±1)%	78.3h
Negative	(49±1)%	74.1h



First count rate asymmetries from June 2016
ϕ distribution for π^0 production



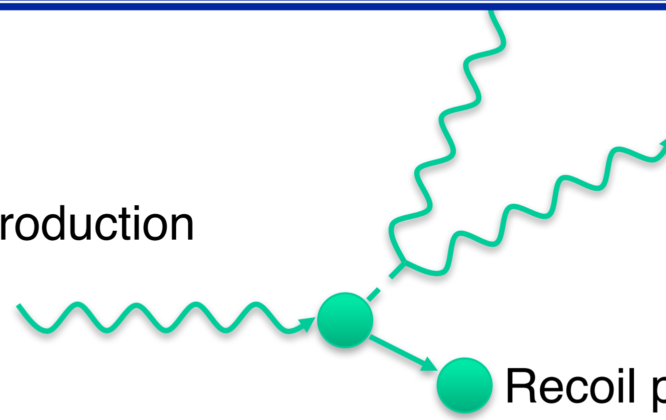
Target +



Target -

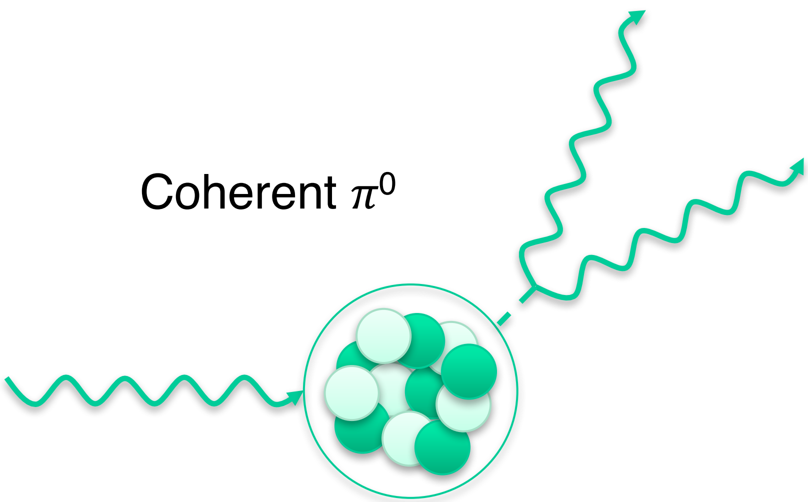
Investigation of dilution factor for π^0 production

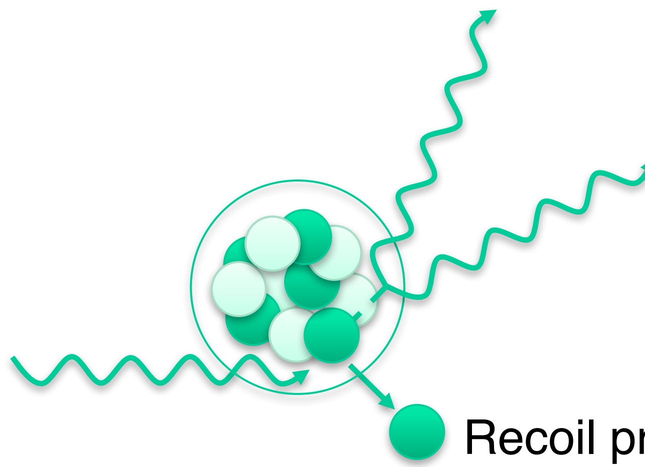
Proton π^0 photo production

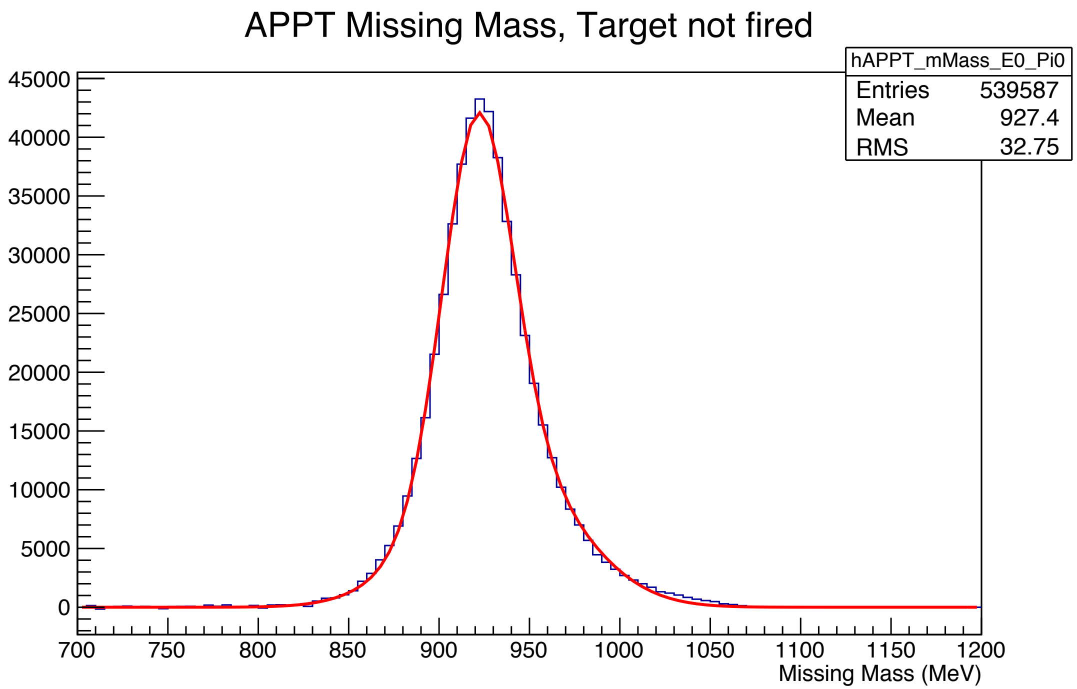


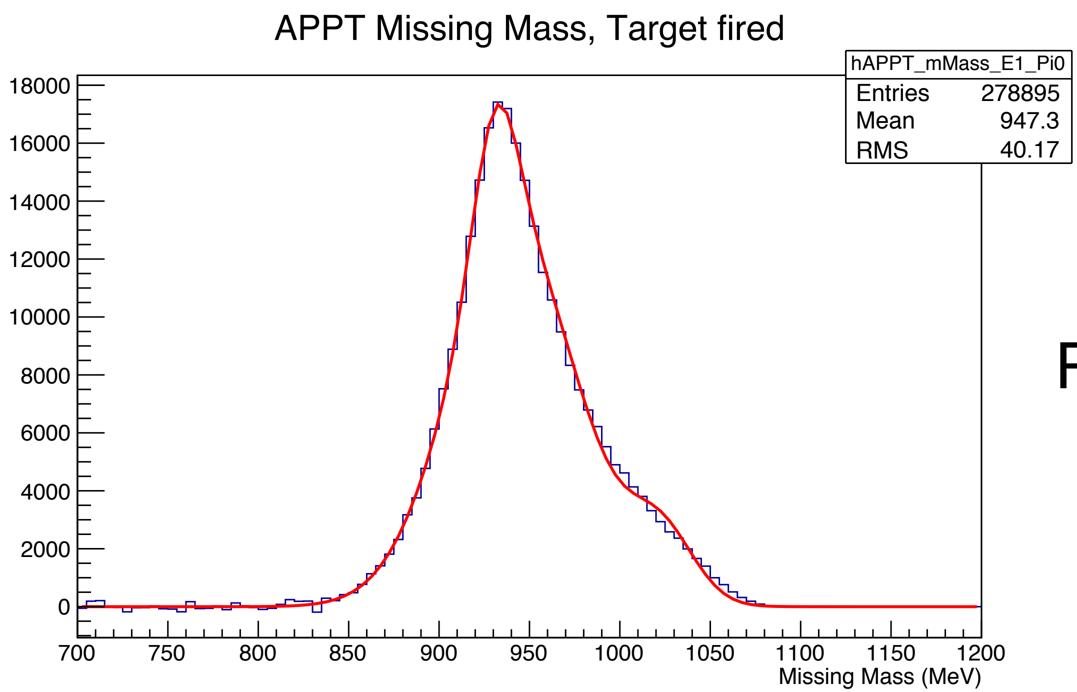
Background reactions by scattering on ^{12}C or heavy nuclei

Coherent π^0









Recoil protons from scattering on H and a broad distribution from incoherent scattering on ^{12}C

Conclusions

- Data taking with **CBall TAPS detector system started 2010 at MAMI C.** All directions of polarization were measured for protons and deuterons in Butanol. Analysis for meson production and Compton process is ongoing.
- **The active polarised proton target was in operation in our 4π detector system in 2016.**

Outlook

- **R&D for polarised active szintillator target for threshold production and Compton will continue. Analysis of first data proofs light output. New active target insert with better light transport system, fibers, Scintillating target container with Butanol.**
- **Measurement of 4 Vector Spin Polarisabilities in Compton process.**
- **Neutron Scalar Polarisabilities with helium target starts in 2019.**

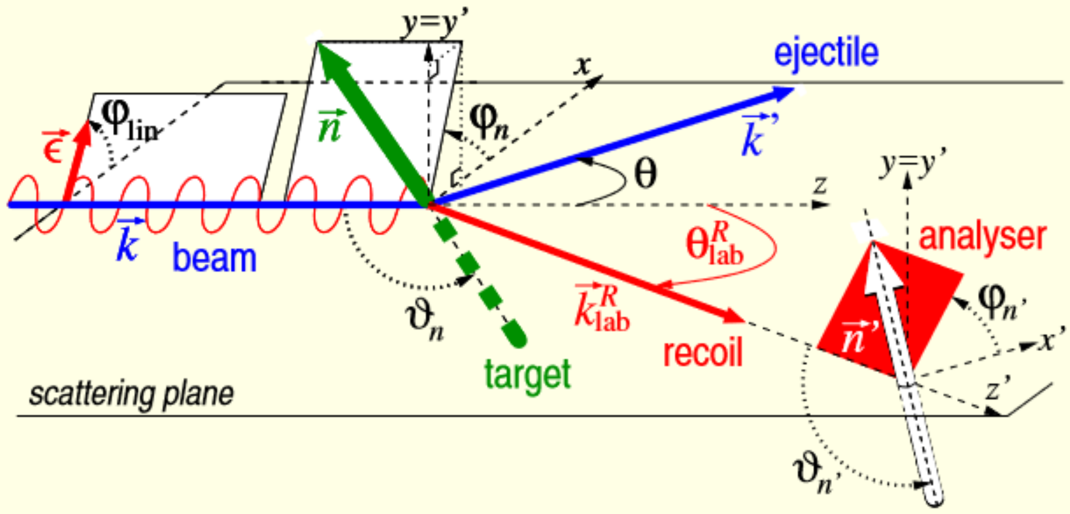
Thank You!

M. Biroth, P. Achenbach, E. Downie, and A. Thomas, “Silicon photomultiplier
properties at cryogenic temperatures,” Nucl. Instrum. Methods Phys. Res. A, vol. 787, pp. 68–71, Jul. 2015.

P. Achenbach, M. Biroth, E. Downie, and A. Thomas, “On the operation of silicon photomultipliers at temperatures of 1–4 kelvin,” Nucl. Instrum. Methods Phys. Res. A, vol. 824, pp. 74–75, Jul. 2016.

M. Biroth, P. Achenbach, E. Downie, and A. Thomas, “A low-noise and fast pre-amplifier and readout system for SiPMs,” Nucl. Instrum. Methods Phys. Res. A, vol. 787, pp. 185–188, Jul. 2015.

Other asymmetries and polarisability transfer observables



$$\Sigma_{2x}$$

Numerical index: polarisation of light

- 3: linear, 0 or π
- 1: linear, $\pm\frac{\pi}{2}$
- 2: right/left circular

Cartesian index: polarisation of nucleon

- z: along beam
- y: $\perp$ to reaction plane
- x: in reaction plane, $\perp$ to z

Prime on either indicates scattered photon or nucleon: polarisation transfer.
polarised scattered nucleon might be detectable.