



Status of the Polarized Target at Mainz

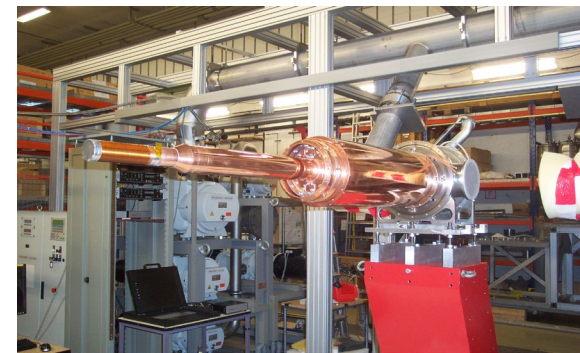
- 1.-Introduction: Why do we need polarisation to investigate structures and interactions of hadrons?
- 2.-Experimental setup I: Tagger + CBall@MAMI
- 3.-Experimental setup II: Frozen Spin Target
- 4.-Double Polarised Experiments : Precision measurements of the Nucleons Excitations
Determination of Fundamental Properties
- 5.- Technical challenges:
Target materials
Active polarized target – Maik's talk



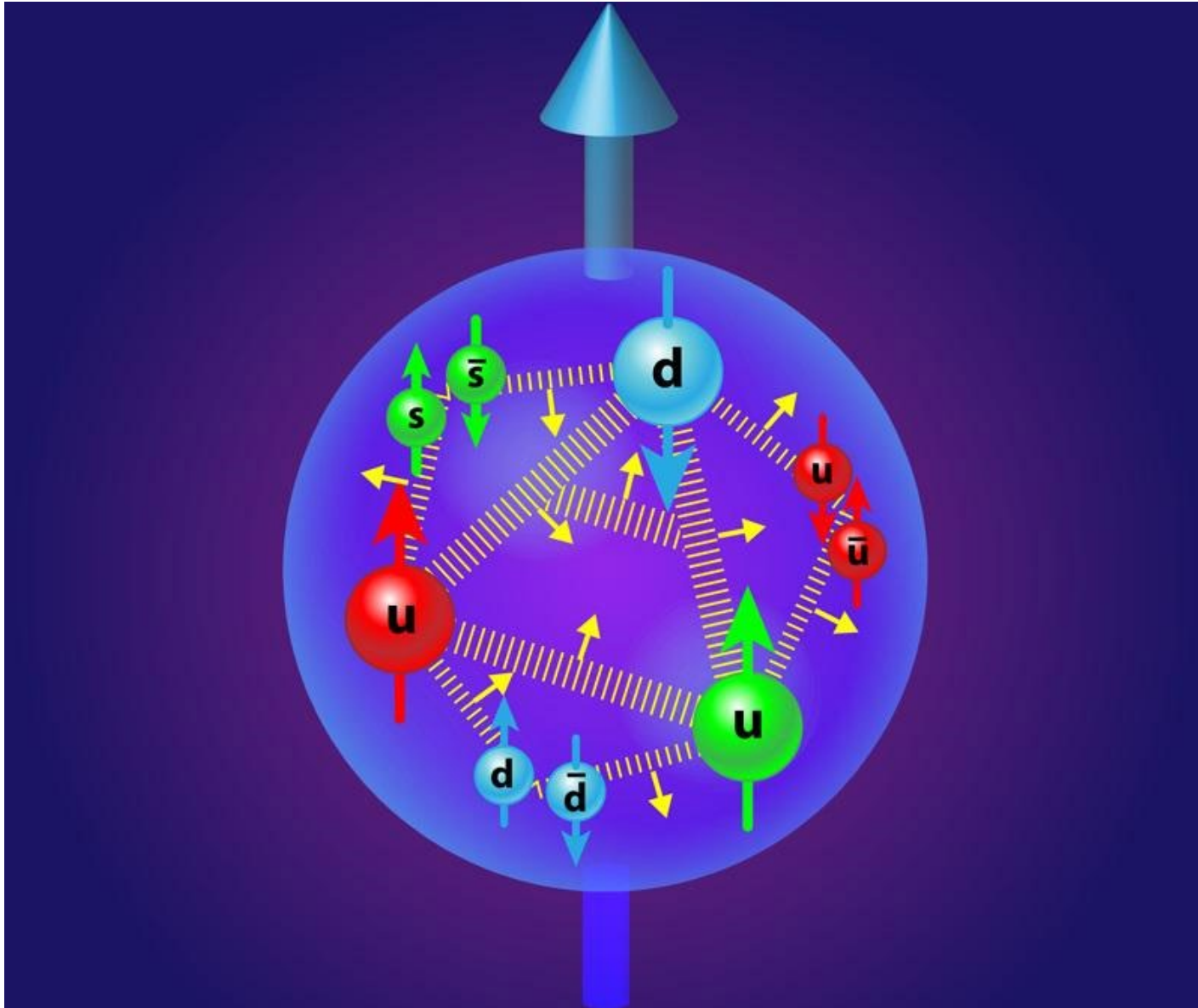
EU Strong 2020 – WP28 CRYPTA

Boppard, September 22nd, 2022

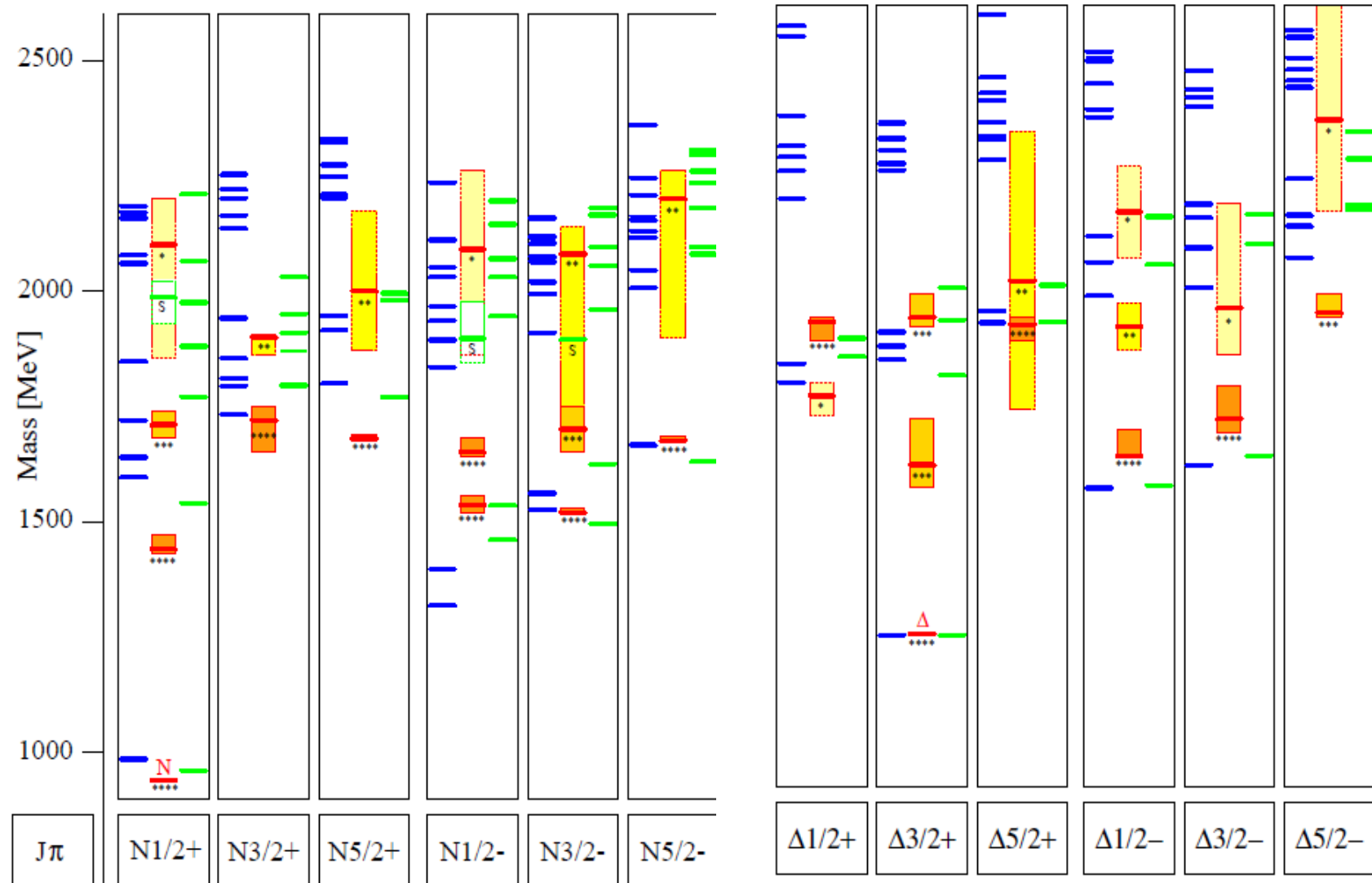
Andreas Thomas



,The' Proton



Introduction: Excitation Spectrum of the Nucleon

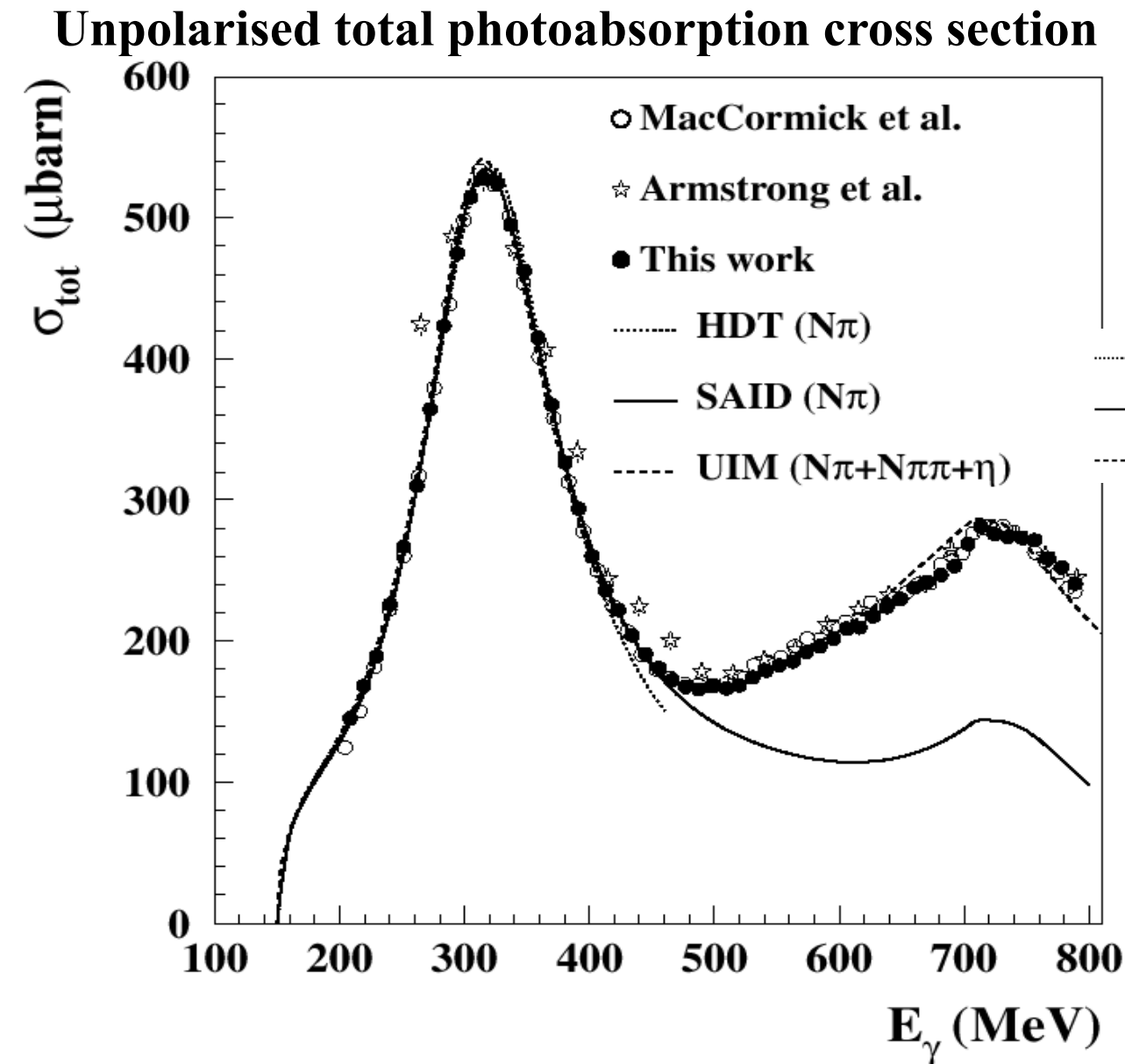


Löhrig, Metsch, Petry, Eur.Phys.J. A10 (2001) 395-446

The light baryon spectrum in a relativistic quark model

What is the nature of the Nucleon Resonances?

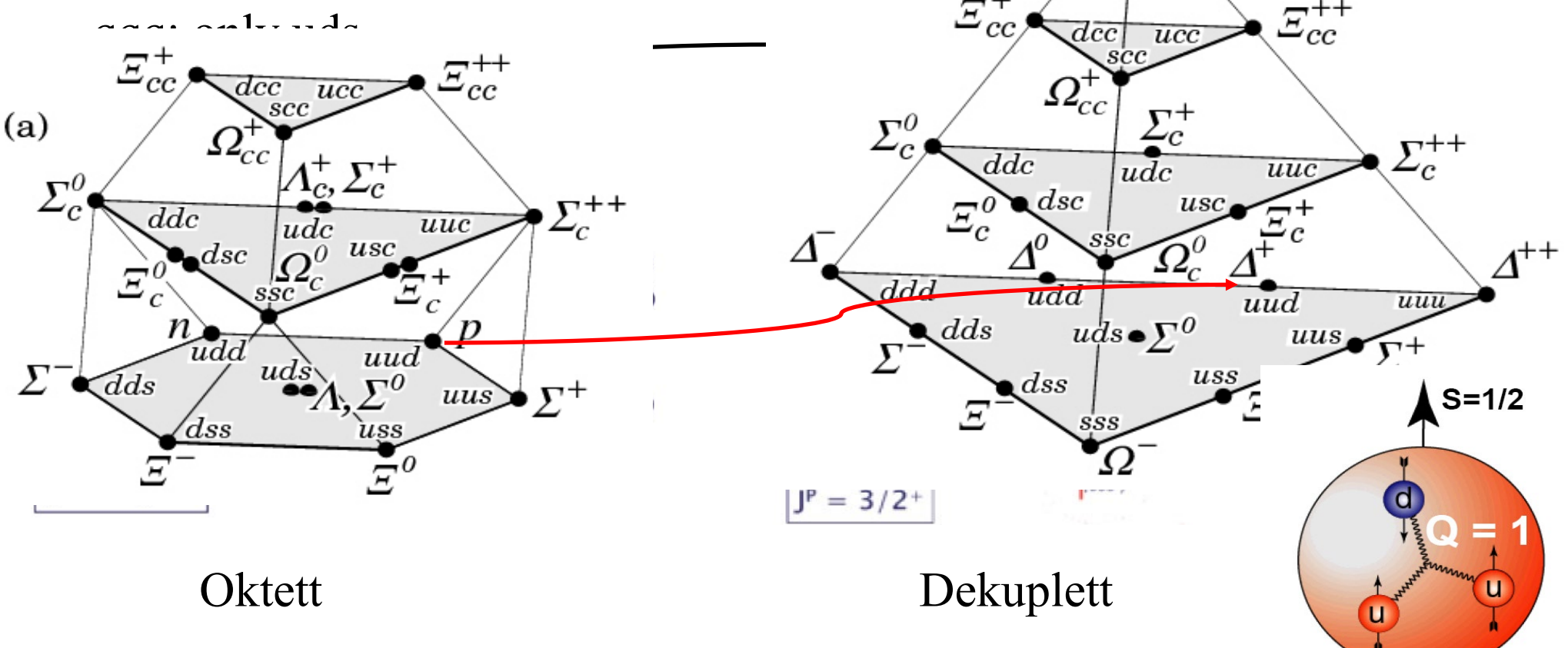
- Excitation inner deg. of freedom
- Molecule
- Quark – Diquark Structure
- Dynamical Generation
-?



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)

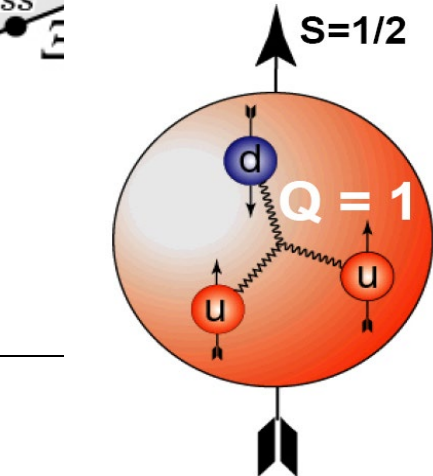
Introduction:

Quark Model Classification of Baryons



Simple Constituent quark picture:

Proton p(938):	$ uud\rangle \sim \uparrow\uparrow\downarrow\rangle$ Spin 1/2
Delta Δ (1232):	$ uud\rangle \sim \uparrow\uparrow\uparrow\rangle$ Spin 3/2



M1-Transition
(Small 2.5% E2)

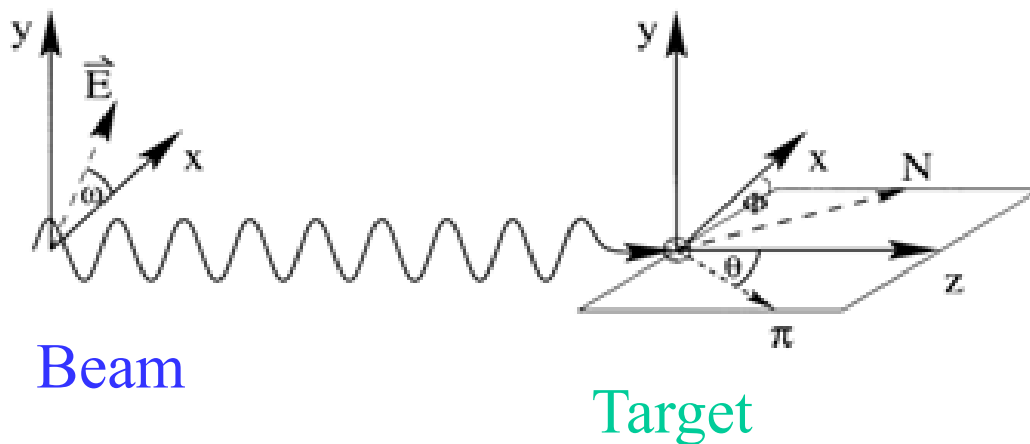
Nature and Properties of nucleon resonances

➔ Polarisation observables used to disentangle broad, overlapping resonances.

Observables in pseudoscalar meson prod.

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

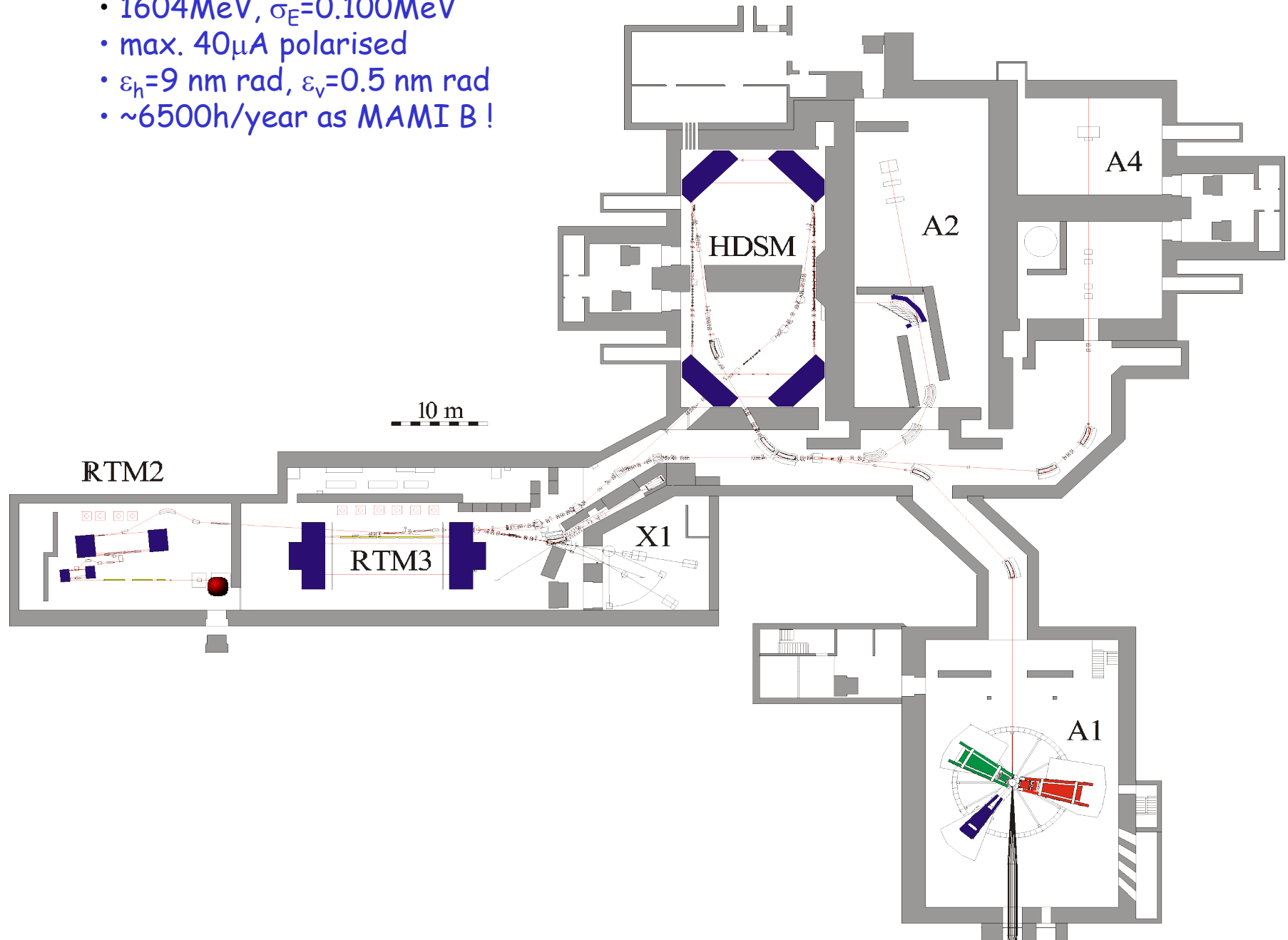
$$\rho_f \frac{d\sigma}{d\Omega} = \frac{1}{2} \left(\frac{d\sigma}{d\Omega} \right)_{unpol} \left\{ 1 - P_{\gamma}^{lin} \Sigma \cos 2\phi + P_x (P_{\gamma}^{circ} F + P_{\gamma}^{lin} H \sin 2\phi) \right. \\ \left. + P_y (T - P_{\gamma}^{lin} P \cos 2\phi) + P_z (P_{\gamma}^{circ} E + P_{\gamma}^{lin}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



Beam	γ_{unpol}	P_{γ}^{lin}	P_{γ}^{lin}	P_{γ}^{circ}
Target		$\left(0, \frac{\pi}{2}\right)$	$\left(+\frac{\pi}{4}, -\frac{\pi}{4}\right)$	
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	-	-	$G(\theta)$	$E(\theta)$

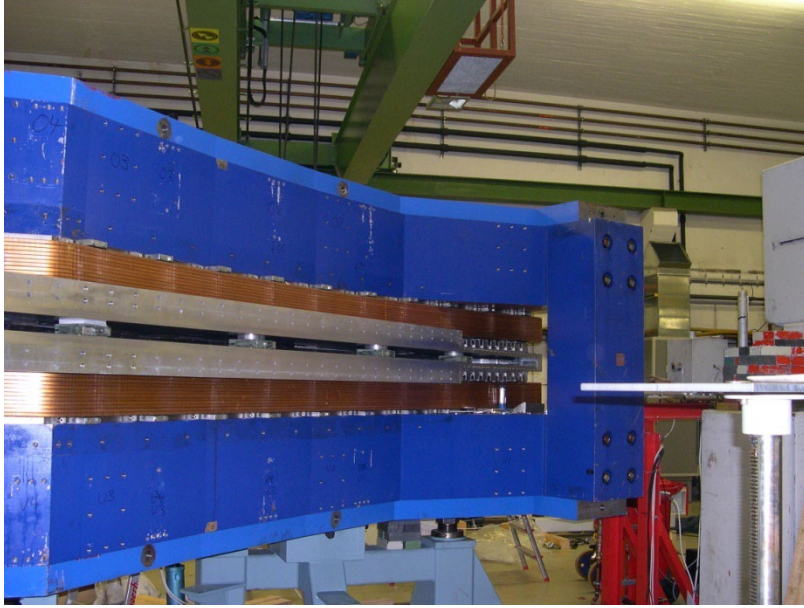
Parameter

- 1604 MeV, $\sigma_E = 0.100$ MeV
- max. 40 μ A polarised
- $\varepsilon_h = 9$ nm rad, $\varepsilon_v = 0.5$ nm rad
- ~6500h/year as MAMI B !

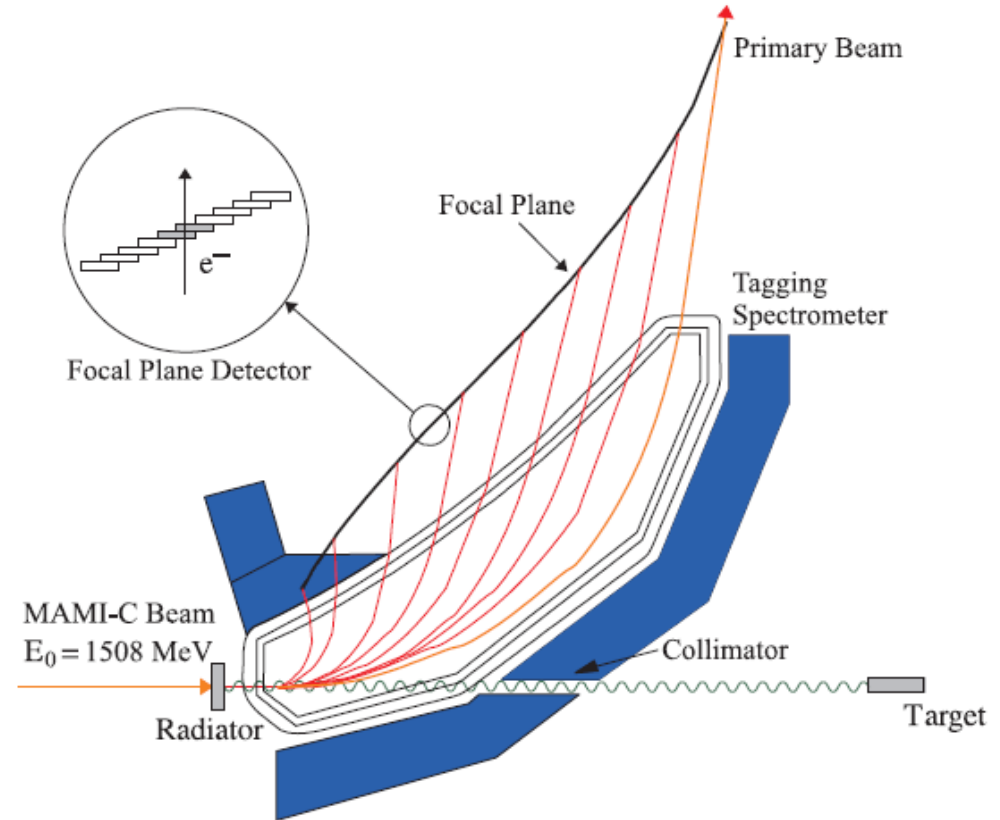


A2 Tagging system (Glasgow, Mainz)

1. Production and energy measurement of the Bremsstrahlung photons.



Glasgow Tagging Spectrometer
EPJ A 37, 129 (2008)

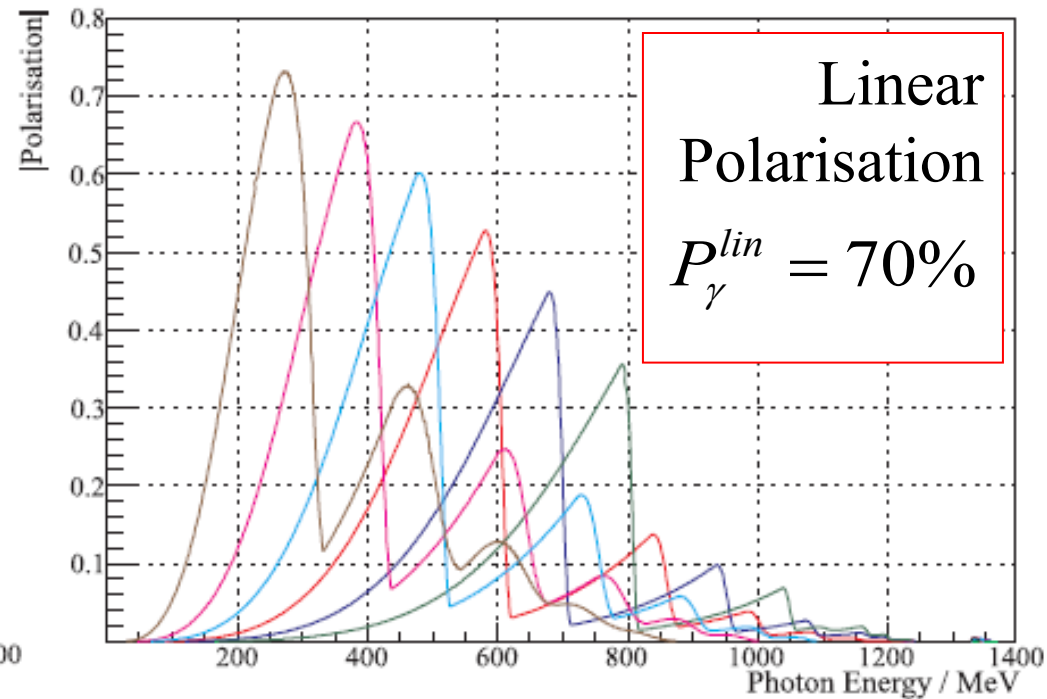
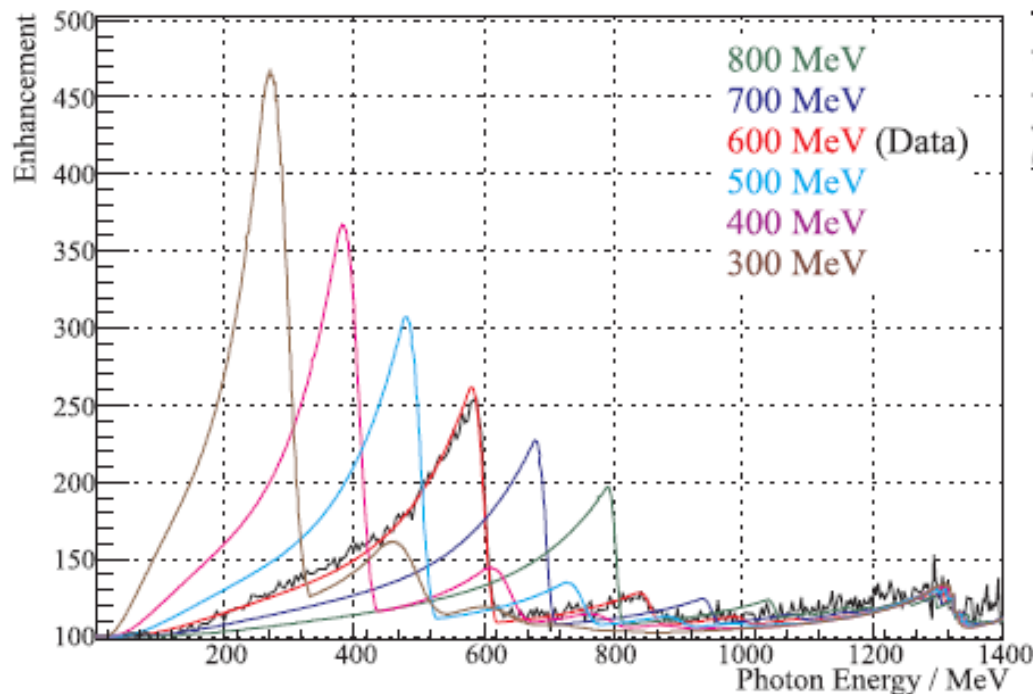


2. Determination of the degree of polarization of the electron beam (Moeller Polarimeter). Circularly pol. photons.

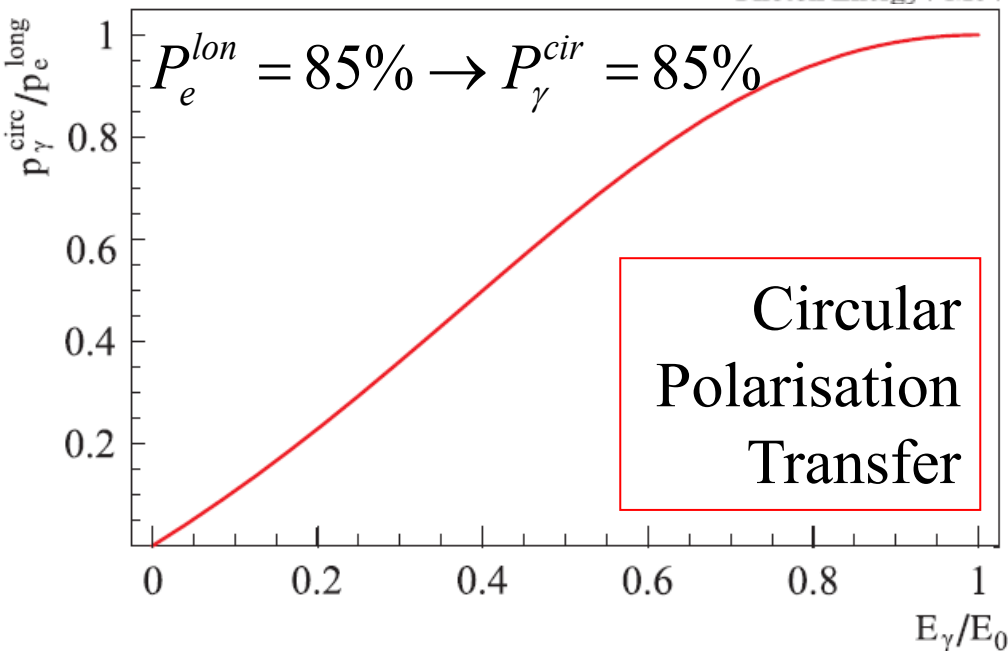
$$A = \frac{N^+ - N^-}{N^+ + N^-} = a \vec{p}_t \vec{p}_b \cos(z)$$

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

Polarised Photons @ MAMI C



Linear
Polarisation
 $P_{\gamma}^{lin} = 70\%$



$$P_e^{lon} = 85\% \rightarrow P_{\gamma}^{cir} = 85\%$$

$$\begin{aligned} E_{\gamma} &= 75 \dots 1480 \text{ MeV} \\ \Delta E_{\gamma} &= 4 \text{ MeV} \\ N_{\gamma} &= 2 \cdot 10^5 \text{ s}^{-1} \text{ MeV}^{-1} \end{aligned}$$



High Polarisation
High Photon Flux

4 π photon Spectrometer @ MAMI

TAPS:

366 BaF₂ detectors
72 PbWO₄ detectors
Max. kin. energy:
 π^{+-} : 180 MeV
 K^{+-} : 280 MeV
P : 360 MeV

Crystal Ball:

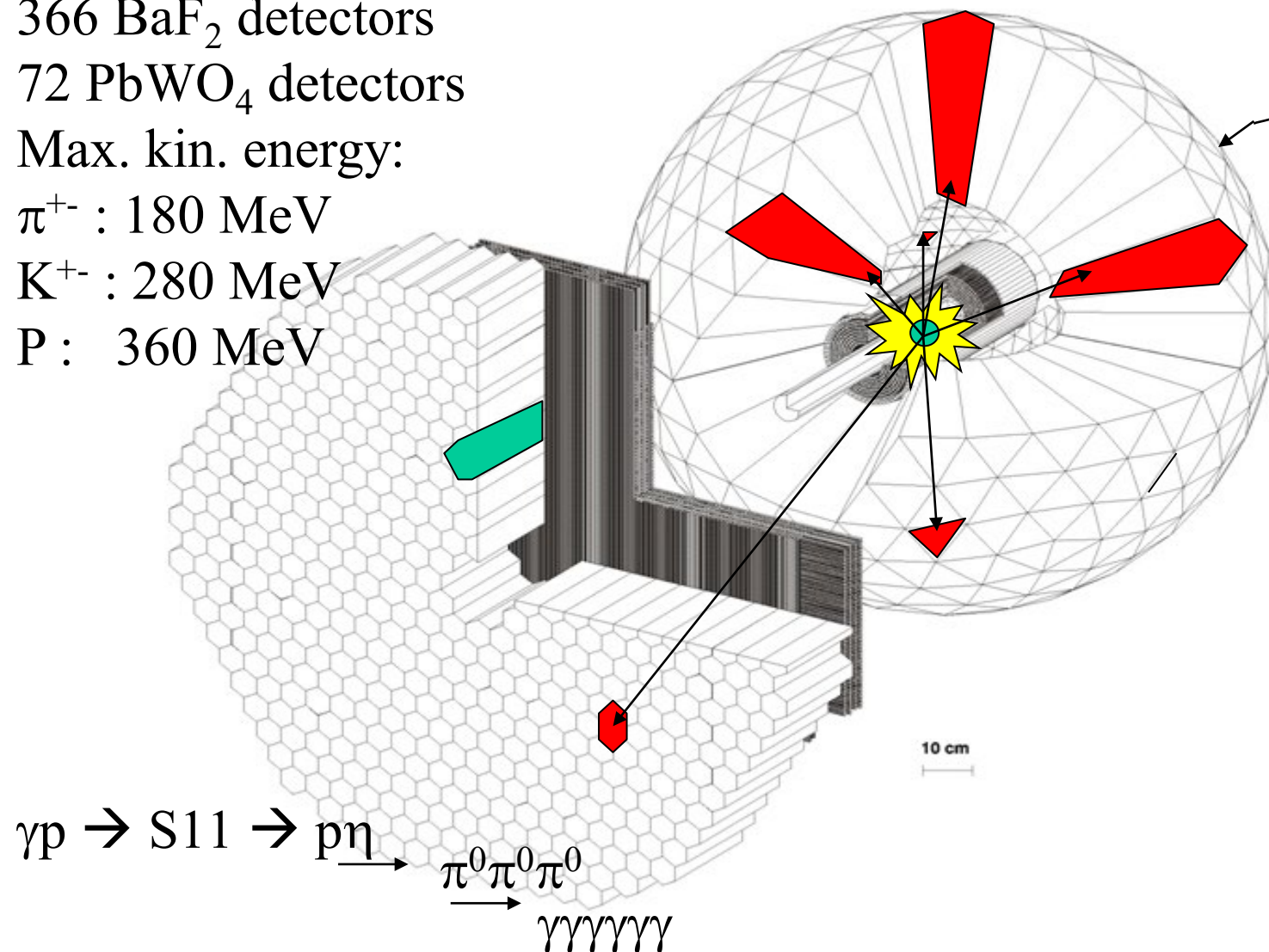
672 NaJ detectors
Max. kin. energy:
 μ^{+-} : 233 MeV
 π^{+-} : 240 MeV
 K^{+-} : 341 MeV
P : 425 MeV

Vertex detector:

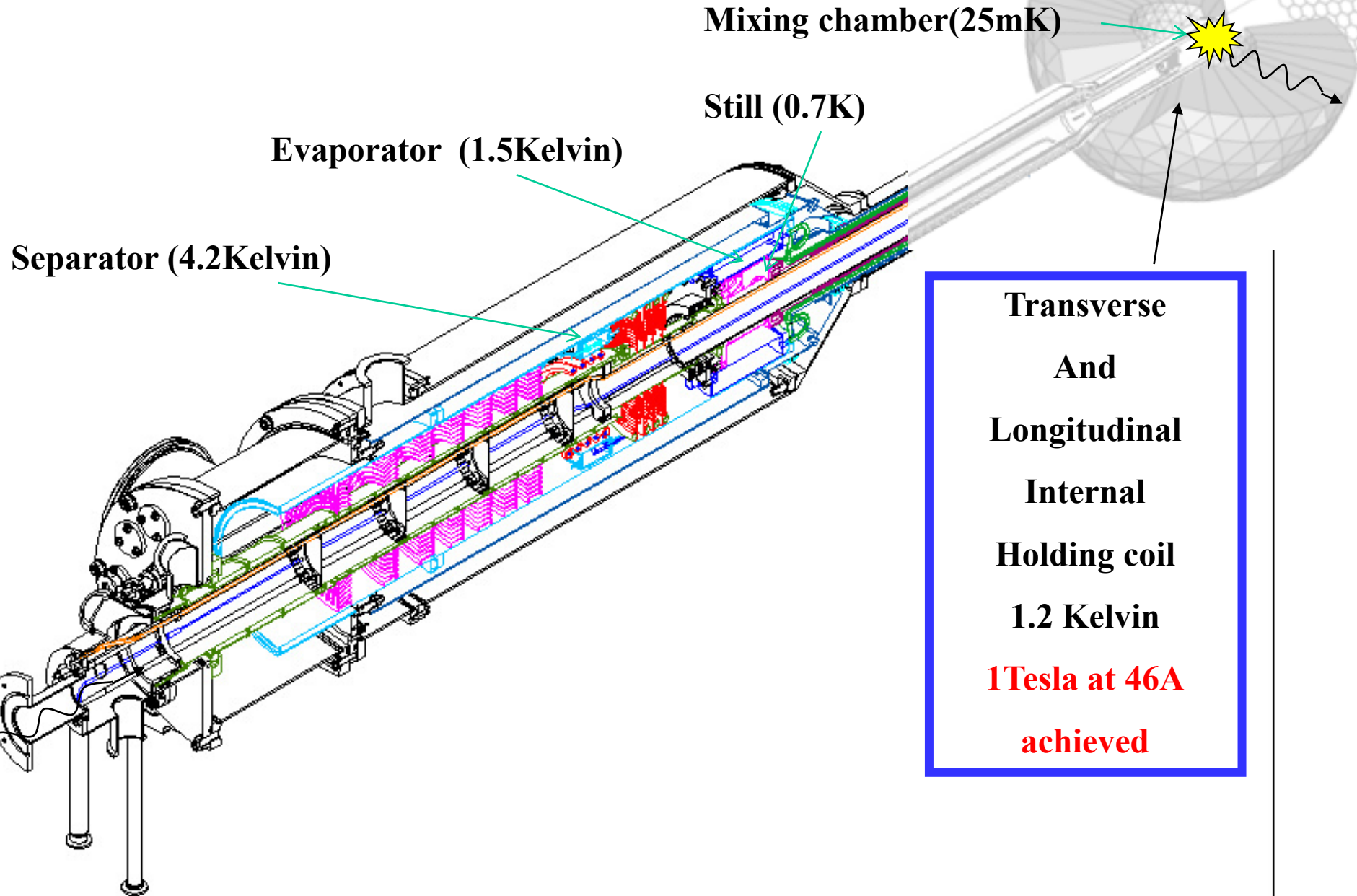
2 Cylindr. MWPCs
480 wires, 320 stripes

PID detector:

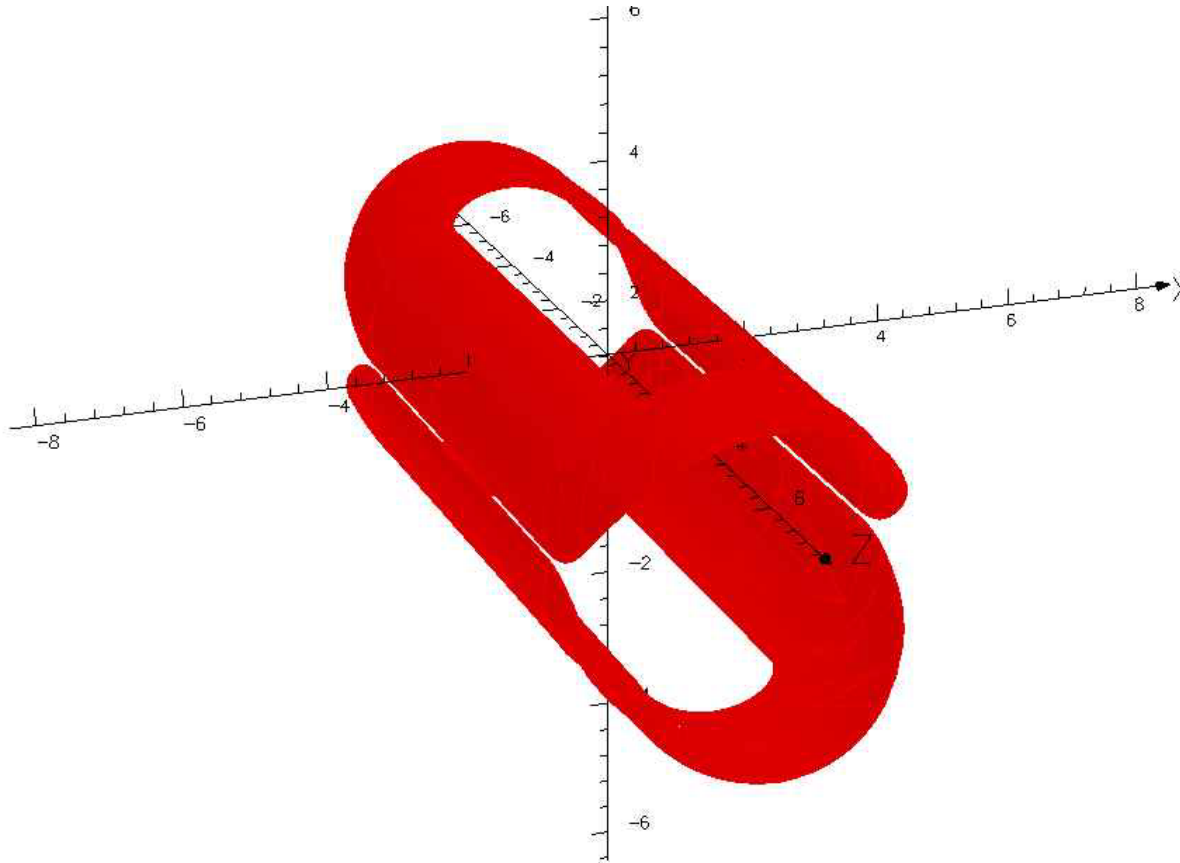
24 thin plastic
detectors



Mainz/Dubna Dilution refrigerator



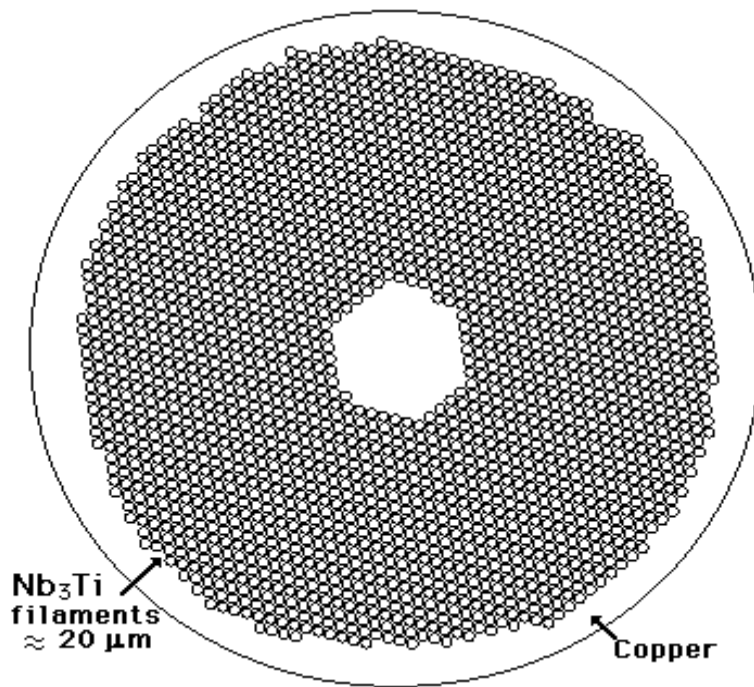
Internal transverse holding coil



V VECTOR FIELDS

Calculations done
with
Opera 3D
Diploma 2009.

Different layers are
used to
optimize the
homogeneity.



- Copper/scandium wire with 54 Nb-Ti filaments embedded in it.
- Cu:Sc=1.35:1
- Alloy composition: Nb47wt.%Ti
- Diameter=0.222mm
- It achieves currents up to 50A at 4.2K and 1T.



4-layer dipole:

$N_1=N_2=138$

$N_3=N_4=78$



150mm

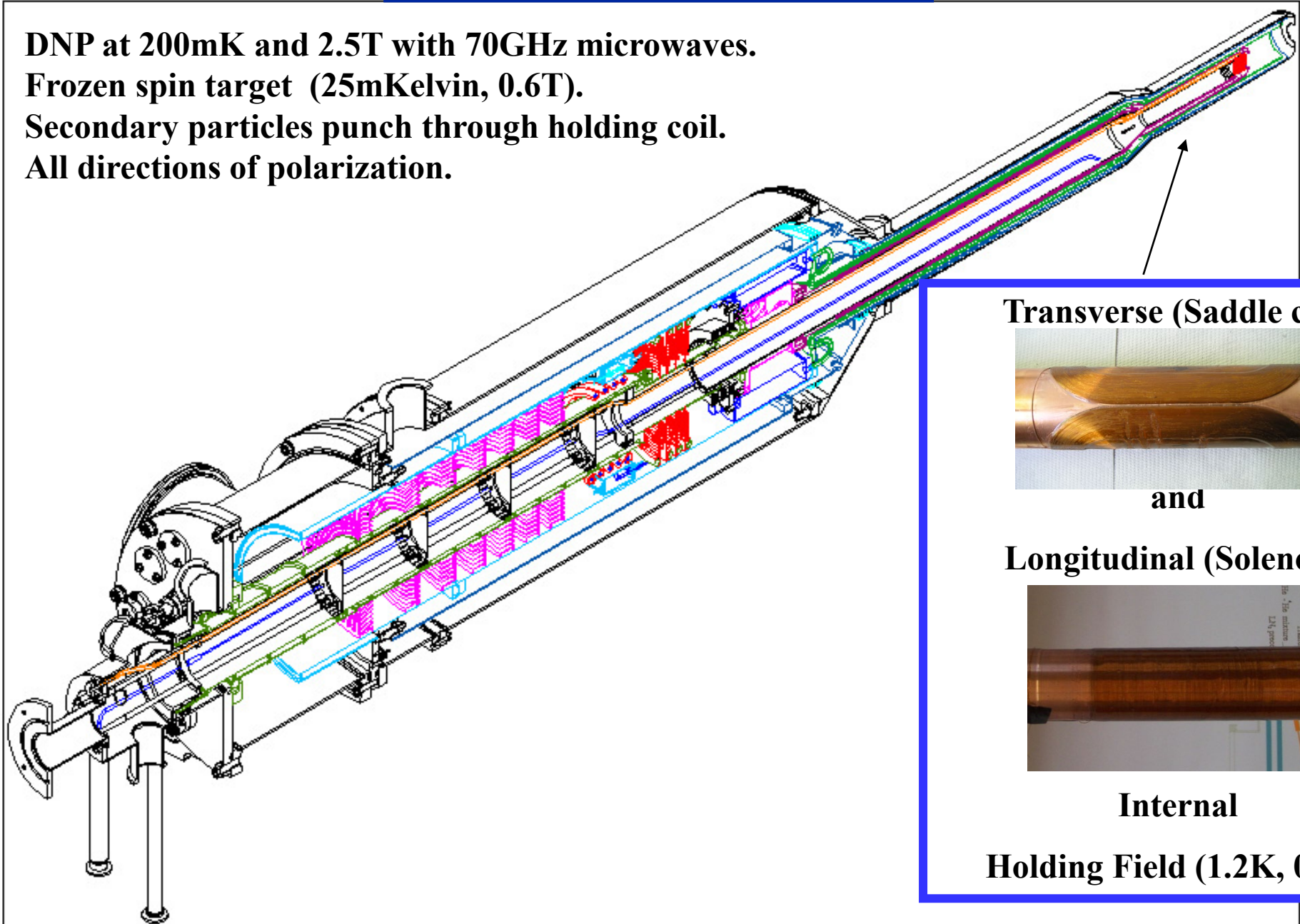
Magnet Technology

DNP at 200mK and 2.5T with 70GHz microwaves.

Frozen spin target (25mKelvin, 0.6T).

Secondary particles punch through holding coil.

All directions of polarization.



Transverse (Saddle coil)



and

Longitudinal (Solenoid)



Internal

Holding Field (1.2K, 0.6T)

Single and Double Polarized Experiments

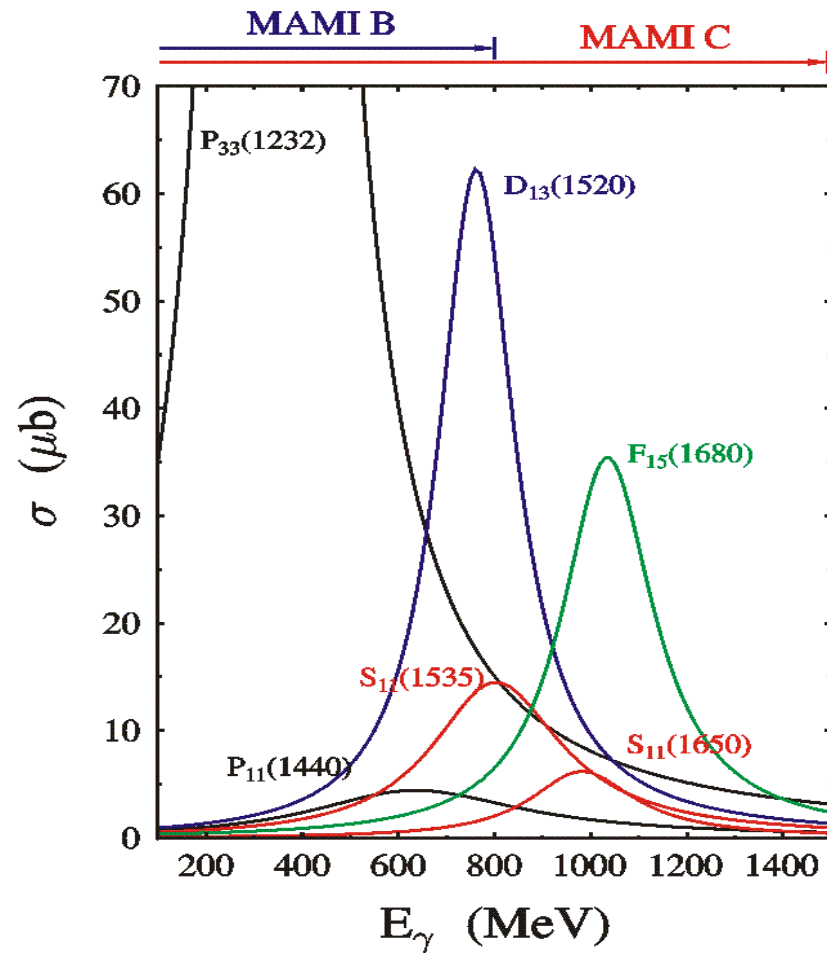
Excitation Spectrum

- 1.- Longitudinal PT:
 - a) E and G of Meson Photoproduction off protons
 - b) E and G of Meson Photoproduction off neutrons
 - c) Investigation in direction Hexaquark
 - 2.- Transverse PT:
 - a) T and F of Meson Photoproduction off protons
 - b) T and F of Meson Photoproduction off neutrons
-

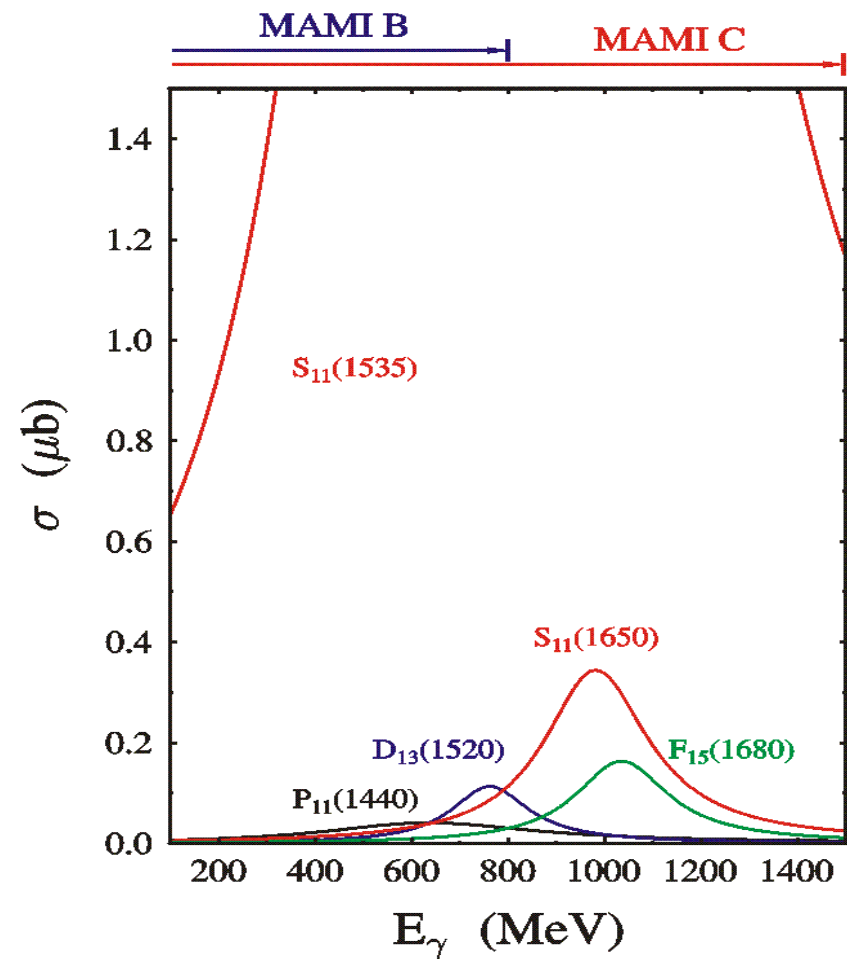
Additional measurements on Fundamental Properties

- 1.- Long. and trans. PT: Spin Polarisabilities and Polarizabilities in Compton process
- 2.- Transverse PT: Transverse asymmetries T and F in π -photoproduction in the threshold region $\rightarrow m_u - m_d$
- 3.- GDH on nuclei: New interest in ^7LiH and ^6LiD target (beside D-Butanol)

Pion Production



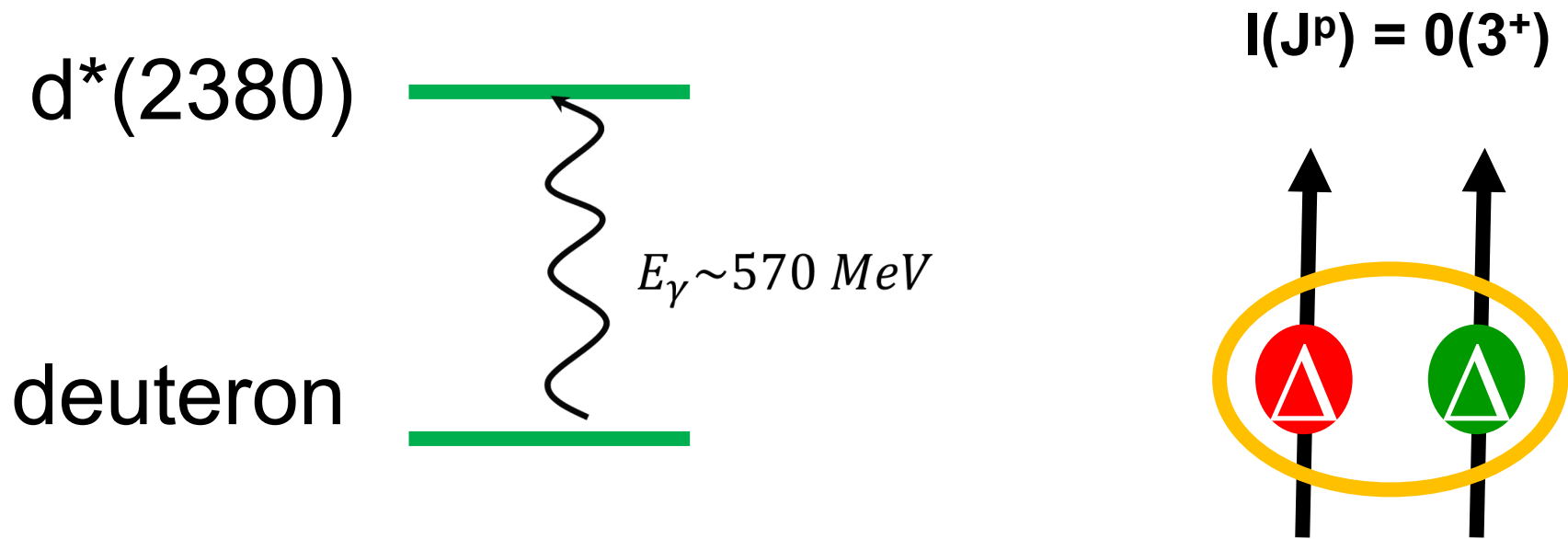
Eta Production



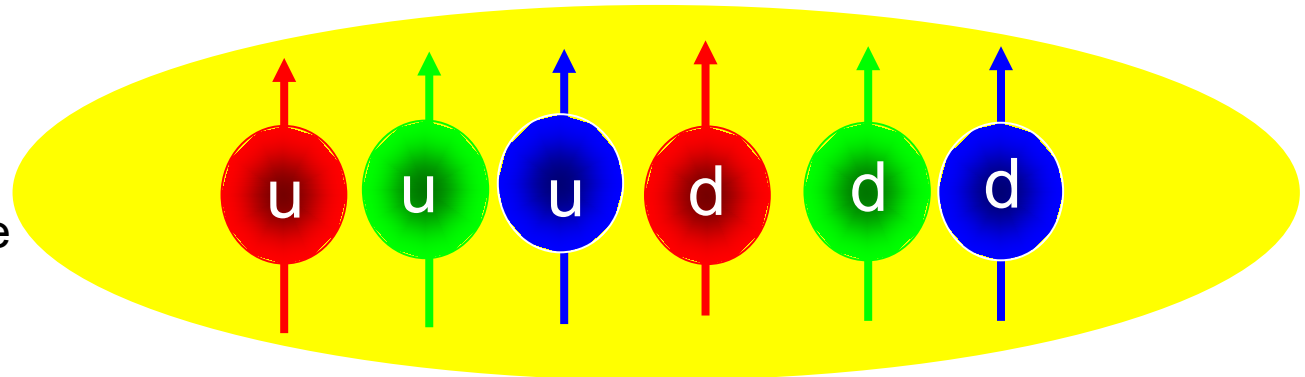
- ➡ Experiment: polarisation observables and different channels essential (Mainz, Bonn, JLAB)
- ➡ Theory: several models and PWA groups (MAID, BNGA, SAID, JuBo...)

$D^*(2380)$

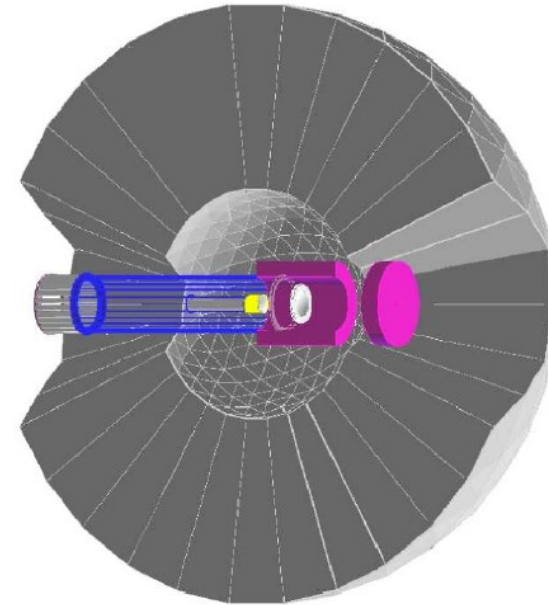
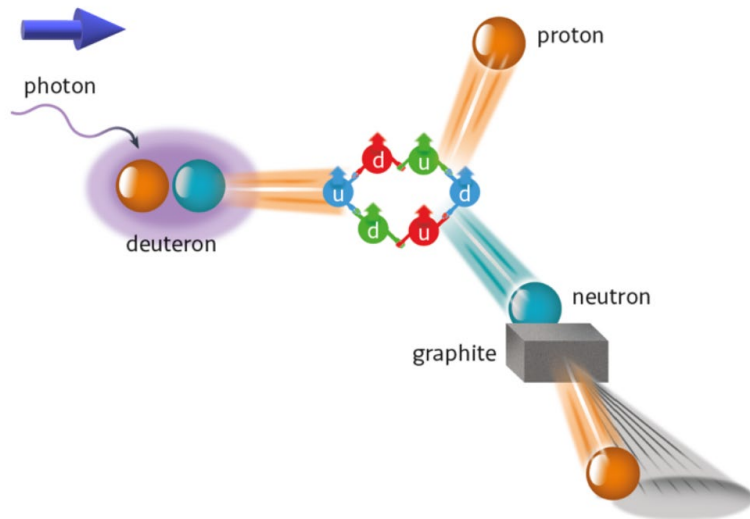
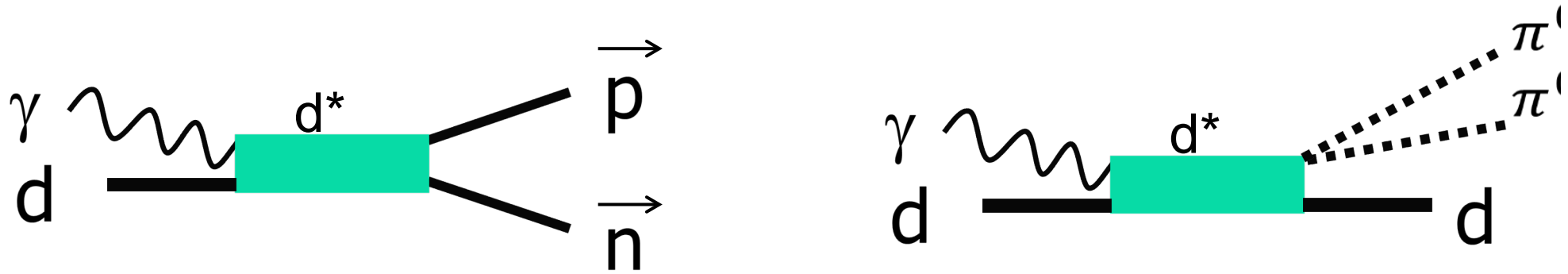
A2-MAMI proposal: Deuteron Photodisintegration in the energy region of the $d^*(2380)$ resonance



Hexaquark
Baryon-Baryon molecule



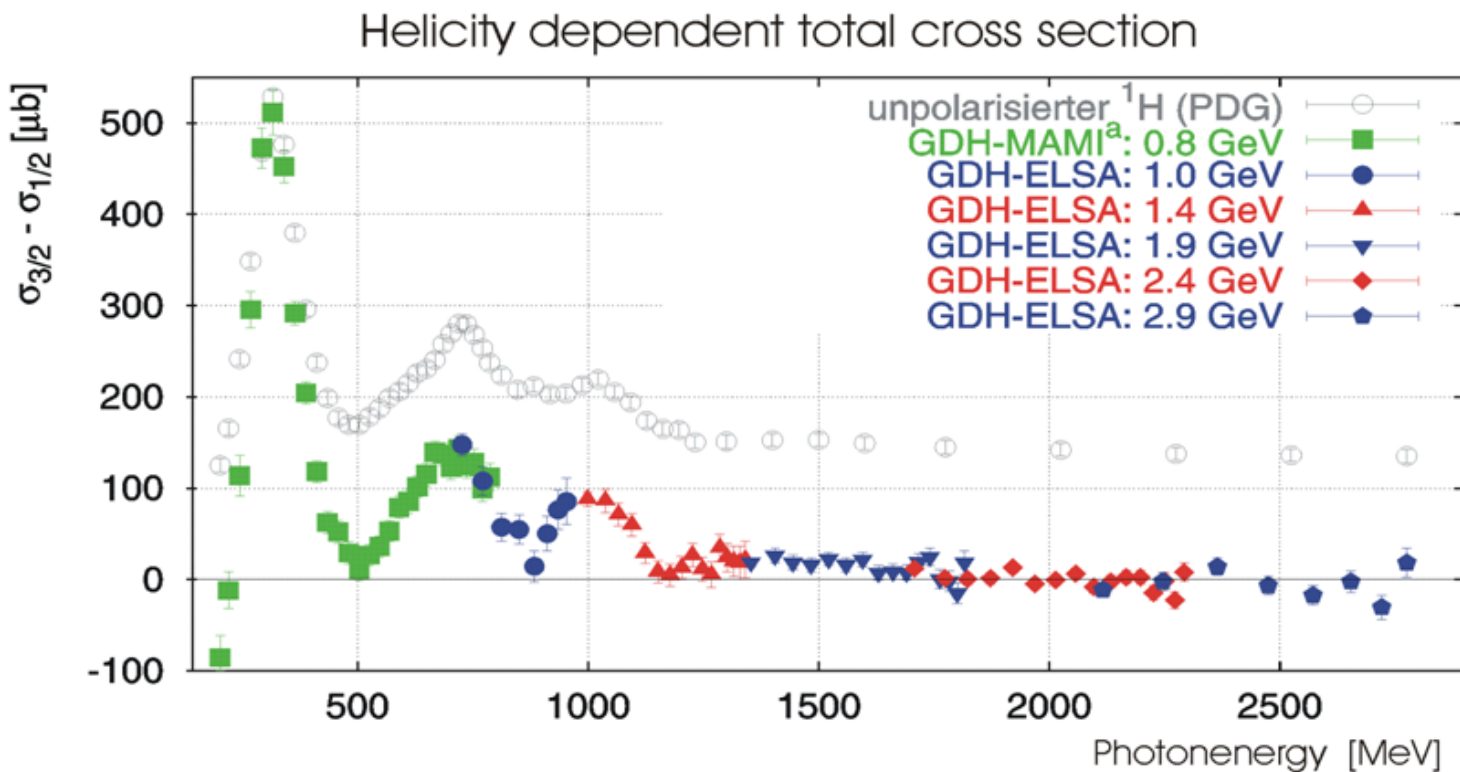
Photonreactions to investigate $d^*(2380)$



M.Bashkanov et al: First measurement of polarisation transfer C_x^n , in deuteron photodisintegration and signatures of the $d^*(2380)$ hexaquark.

<http://dx.doi.org/10.48550/arXiv.2206.12299>

Helicity Dependence E of Meson Photoproduction on the Proton



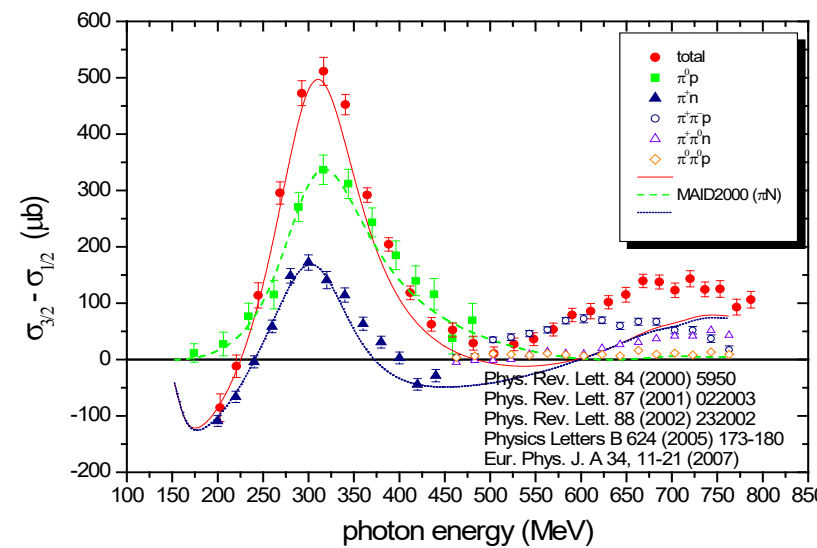
1998-
2003
Mainz
and
Bonn

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



GDH sum rule for nuclei

$$\int_0^\infty \frac{\sigma_a(\omega) - \sigma_p(\omega)}{\omega} d\omega = -4\pi\kappa^2 \frac{e^2}{m^2} S$$

	κ	ω_L [MHz]	I_{GDH} [μB]
Proton	1.79	106.7	-204
Neutron	-1.91		-233
Deuteron	-0.14	16.4	-0.65
³ Helium	-8.38	81.3	-497
⁶ Lithium	-0.53	15.7	-0.53
⁷ Lithium	19.84	41.5	-510

Deuteron

→

Partial reaction channels on quasifree neutron

³Helium

→

GDH-Integral with small systematic error

↑↑

P N

↑↓↑

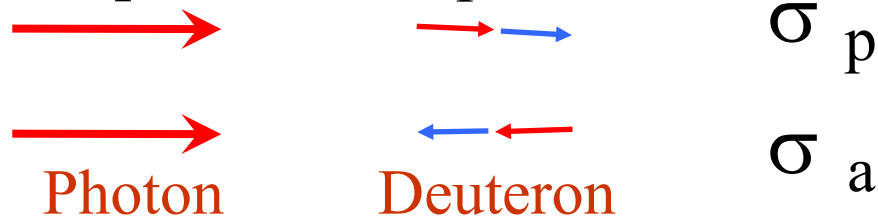
P P N

P(Neutron) ~ 0.92 P(Deuteron)

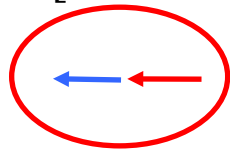
$I_{\text{exp}}^d \approx I_{GDH}^n + I_{GDH}^p + I_{nucl.eff}.$

$I_{\text{exp}}^{he} \approx I_{GDH}^n + \underset{\substack{\uparrow \\ \approx 0.1}}{\alpha} \cdot I_{GDH}^p + I'_{nucl.eff}.$

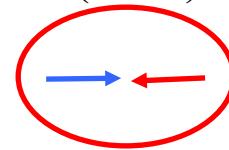
Absorption of circularly polarized real photons by longitudinally polarized deuterons



Helicity dependent deuteron photodesintegration [Arenhövel et al. , Physics Letters B 407 (1997) 1-7]

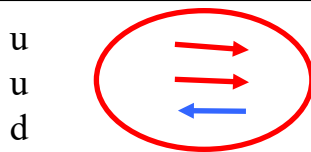


3S_1 deuteron ground state

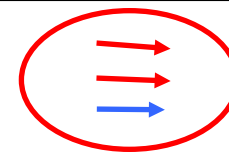


1S_0 resonant state at 68KeV

The resonant 1S_0 state can preferred be reached if the initial spins are **antiparallel** at energies close to break-up threshold (2-3MeV)



proton (neutron)

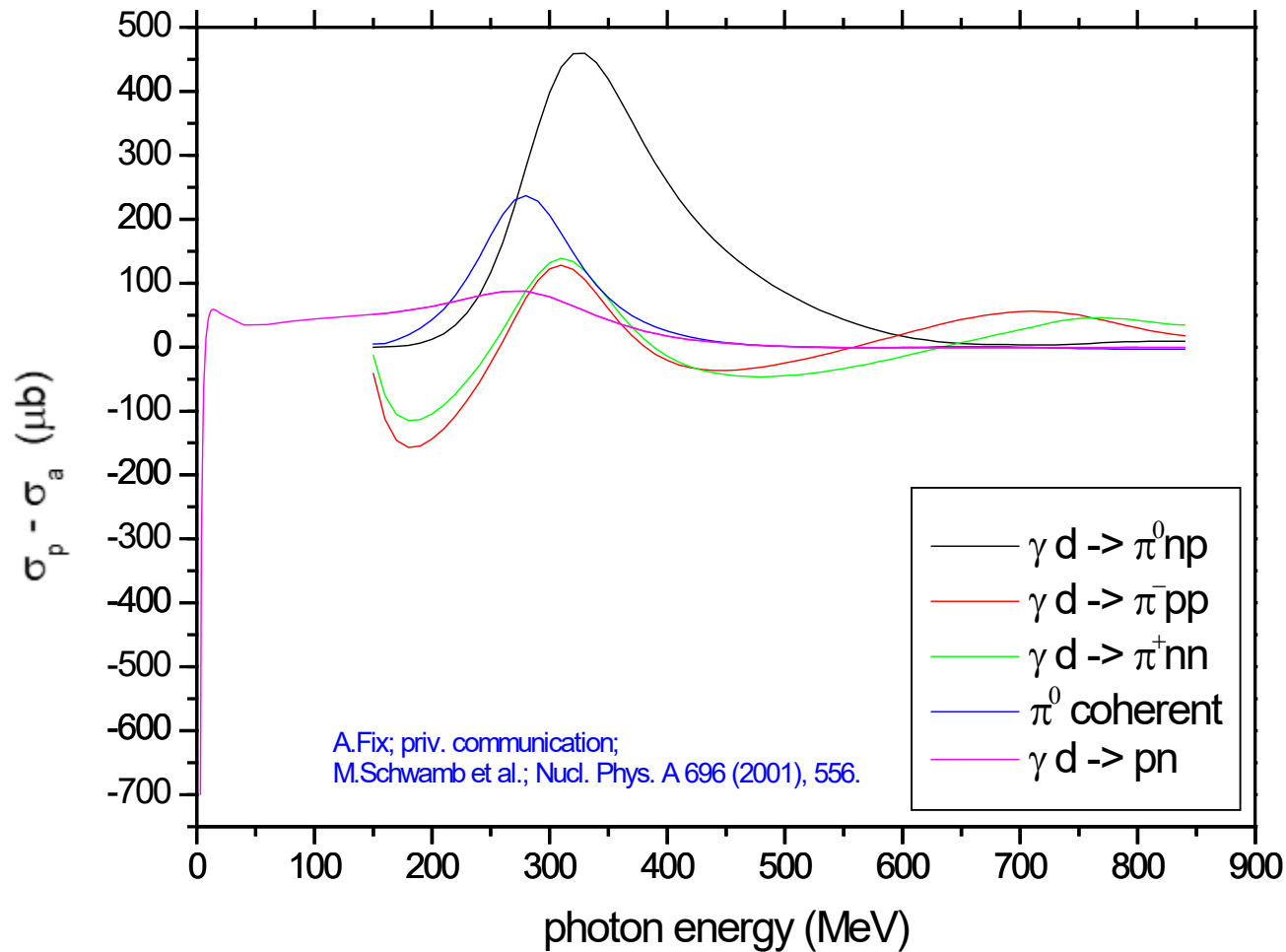


$\Delta(1232)$ -resonance

The Δ resonance can preferred be reached if the initial spins are **parallel** at 300MeV

$\Rightarrow I_{GDH} = 0.65\mu b$

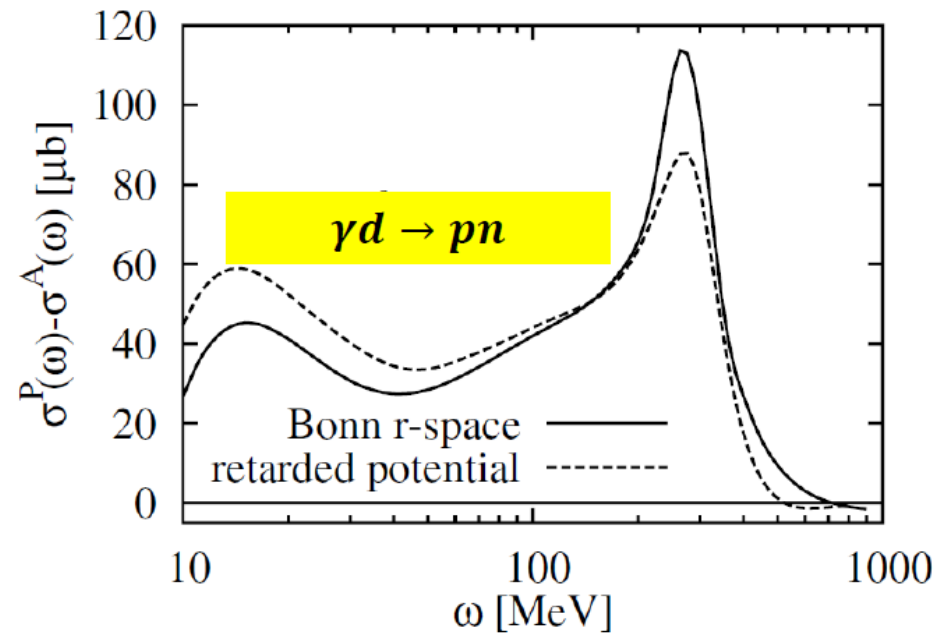
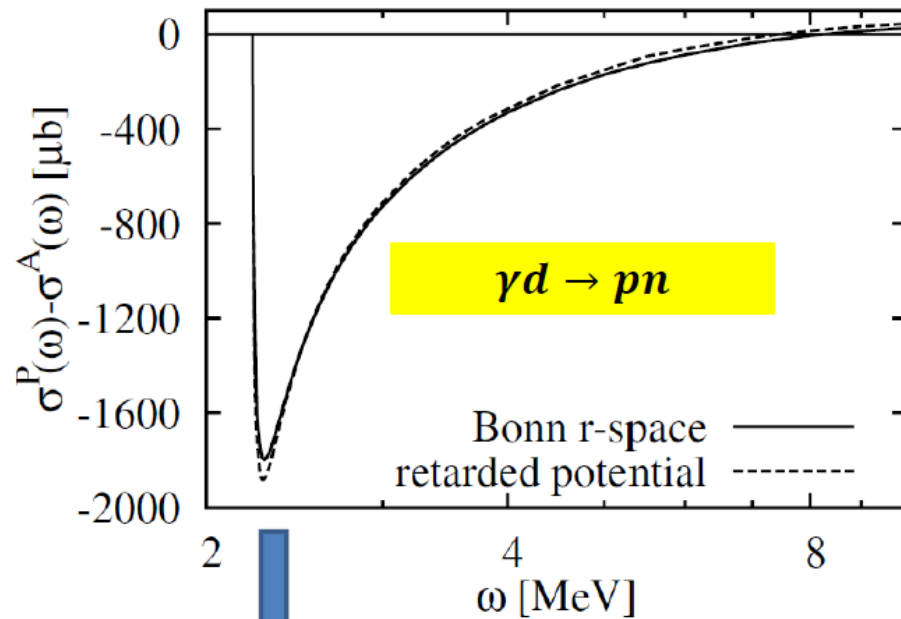
Helicity dependent deuteron photodesintegration



- Nucleon Nucleon Interaction
- Meson Exchange currents
- Final State Interaction
- Relativistic Effects, Retardation

AFS model

PRL 93, 202301 (04)



Dominant $M1$ transition from the bound 3S_1 state to the continuum 1S_0 state can only be reached for antiparallel photon and deuteron spins

(state notation: $^{2S+1}L_J$)

Other Target Materials

Jlab proposal PR12-14-001 The EMC Effect in Spin Structure Functions

A 12 GeV Proposal

→ GDH sum rule for nuclei

JLab proposes to use polarized ^7Li

~ 86-88 % of nucleus polarization carried by valence proton (See also PhD Arne Meier)

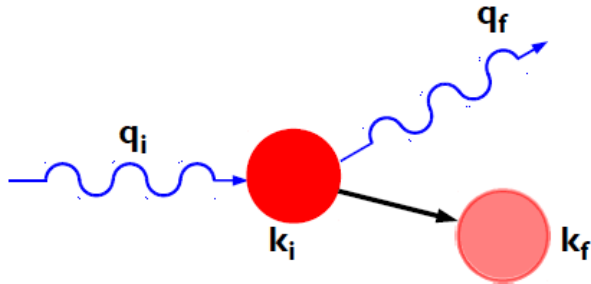
If take ρ as ~20% of ρ_0 , then effect ~ 20% enhancement in GDH integral (talk S.Bass 'Meson and Hyperon interaction with nuclei' 2022)

Use of ^7LiH and ^6LiD targets.

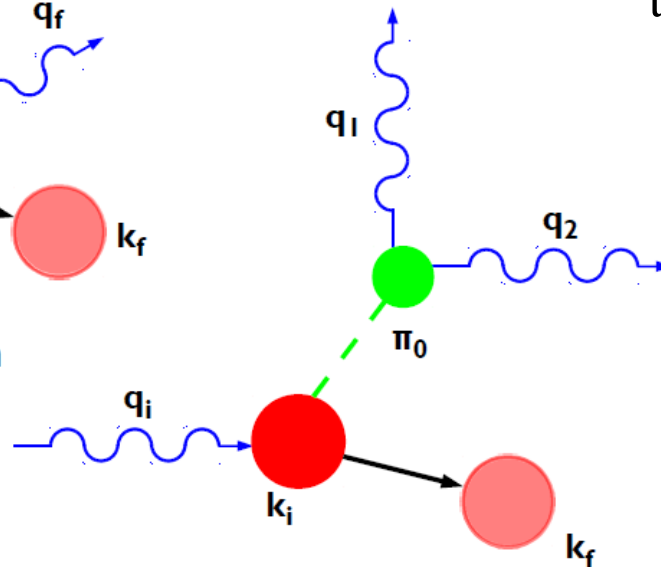
,Complicated' channels and Threshold Production

Event Selection

Compton Scattering



Pion Photoproduction



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

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

Test with 'subtraction target'.

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

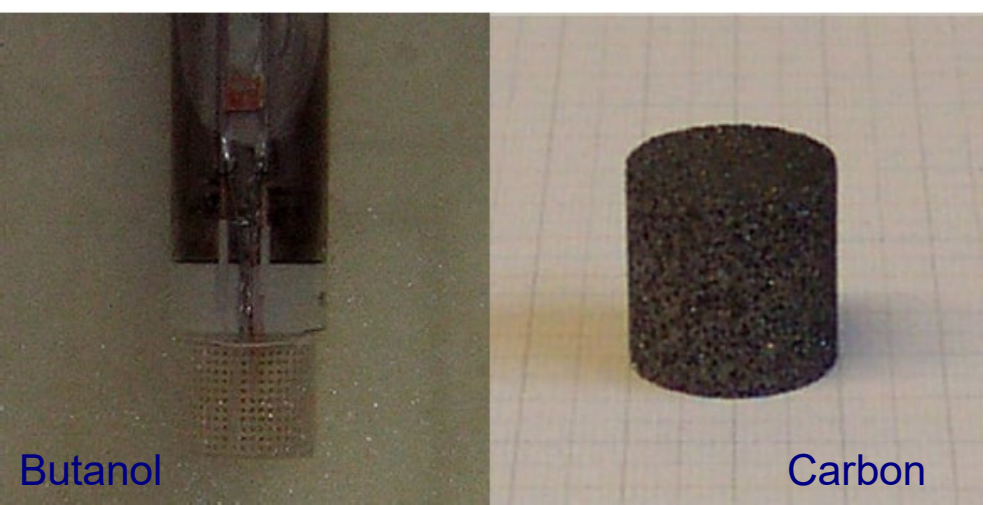
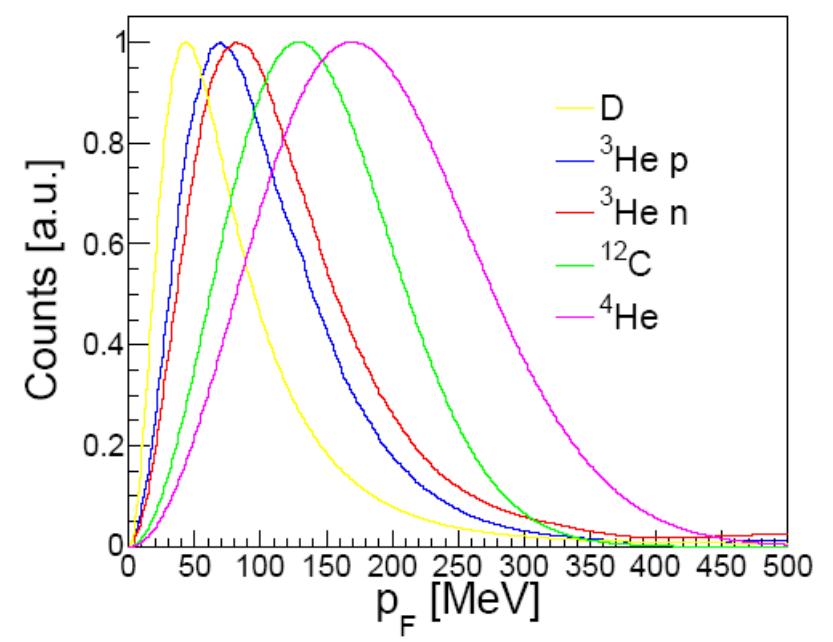
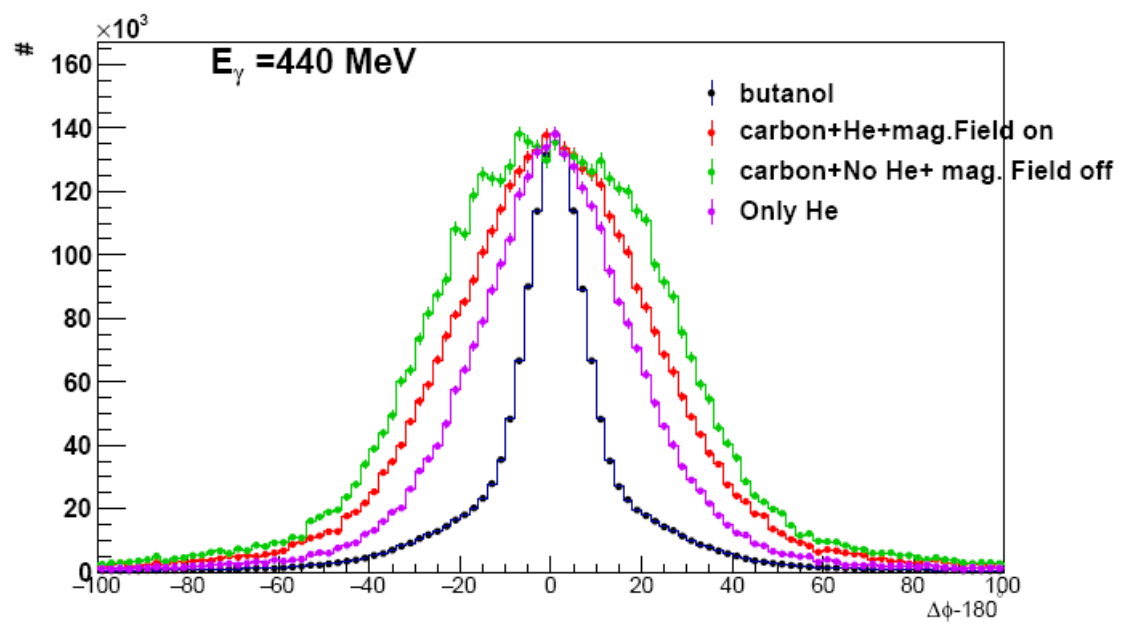
P.P.Martel et al., PRL 114 (2015) 112501

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, $\kappa \sim 13\%$).

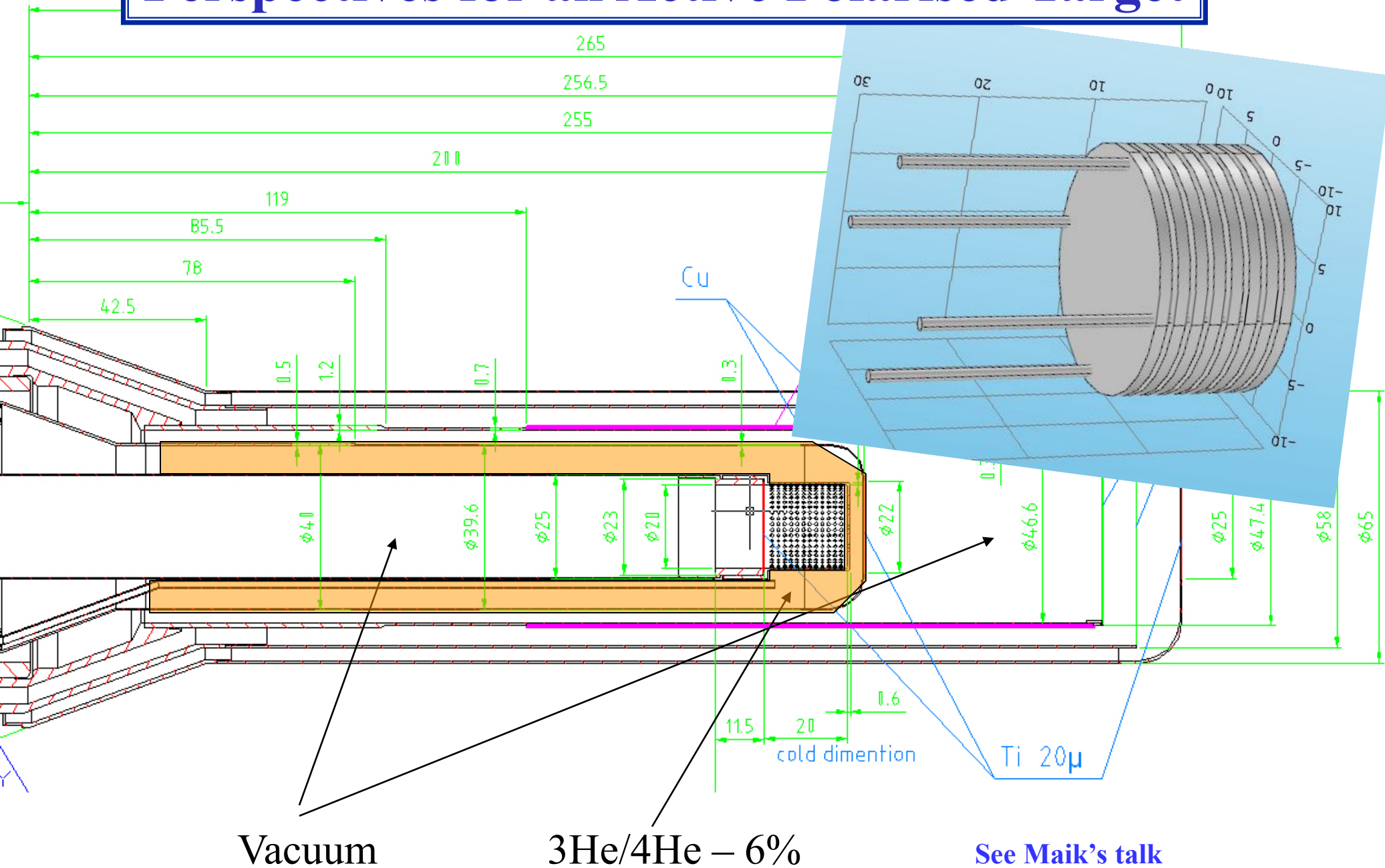
Challenges for the analysis of experiments with Frozen Spin Target $\rightarrow$ Dilution Factor.

Data taken in 2013 -2015, Analysis: F.N. Afzal



Hydrogen

Perspectives for an Active Polarised Target



Conclusions and outlook

- **The Frozen Spin Target is very reliable apparatus** for data taking with **CBall TAPS detector since 2010 at MAMI C**. All directions of polarization have been measured. Since 2017 the cryostat is successfully working in the **Bonn Polarized Target at ELSA**.
- **With a variety of new measurements of spin observables** it comes to a convergence of the multipoles in the region of leading resonances.
- **Still a lot of precise experiments have to be done with polarised targets, especially at higher energies and in the threshold regions:**
 - Measurement of the 4 Vector Spin Polarizabilities in Compton Scattering.
 - $d^*(2380)$ investigation.
 - F and T in π -threshold region (Light quark mass difference. Isospin breaking).
 - GDH sumrule on nuclei.
- **Hopefully, further developements of the active polarised target and ,new‘ other targets with light nuclei** will be an important part of the investigations in cooperation with polarized target groups around the world.

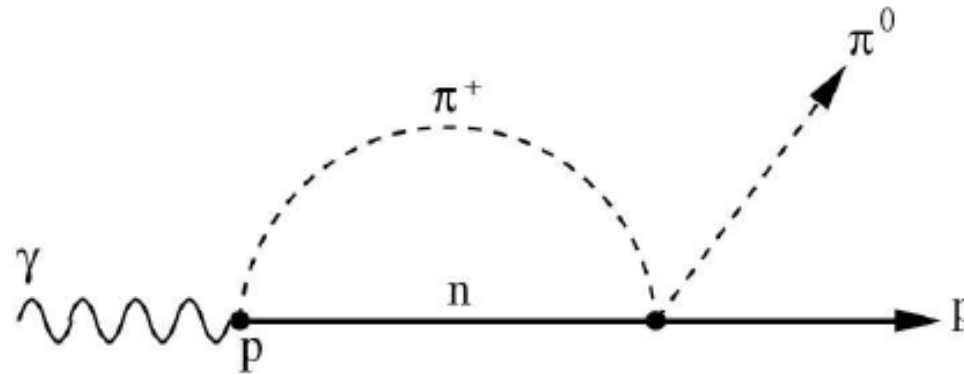
Thank You!

Asymmetries T and F in $\gamma p \rightarrow p\pi^0$ at threshold

→ Study of the dynamic consequences of $m_d - m_u > 0$.

$$m_{\pi^0} = 135 \text{ MeV} \quad \frac{1}{\sqrt{2}} \cdot (|u\bar{u}\rangle - |d\bar{d}\rangle)$$

$$m_{\pi^+} = 139.6 \text{ MeV} \quad |u\bar{d}\rangle$$

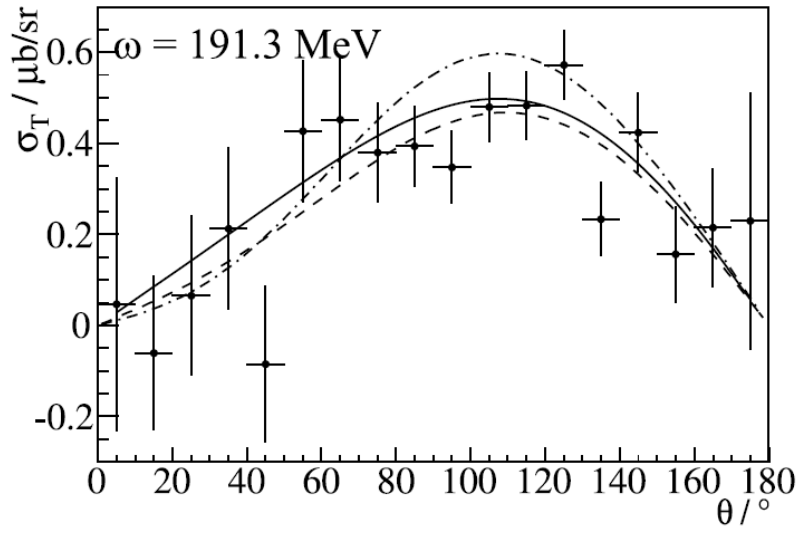
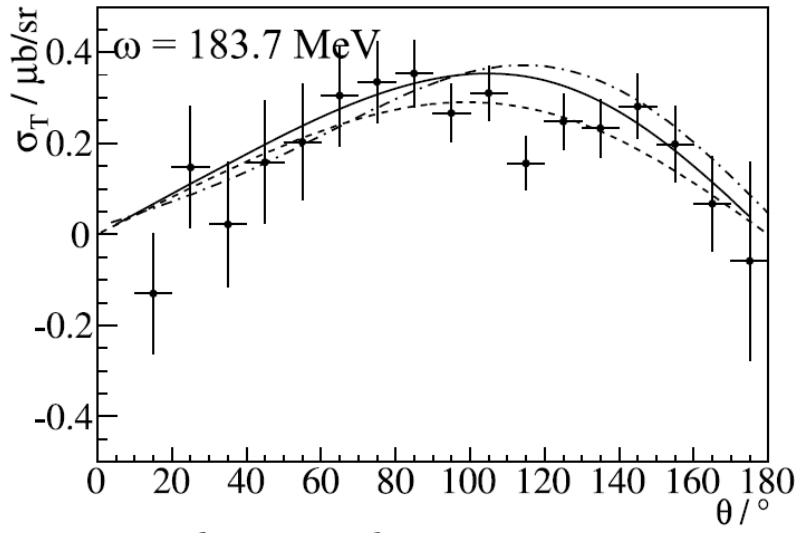
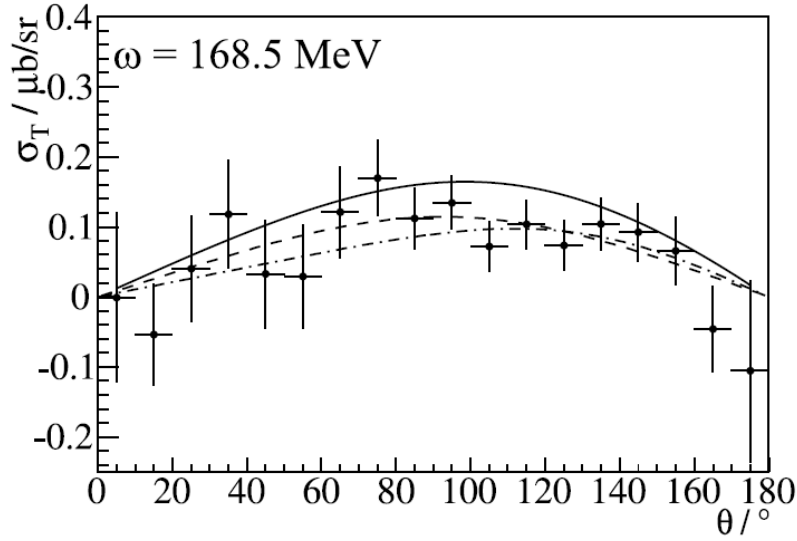
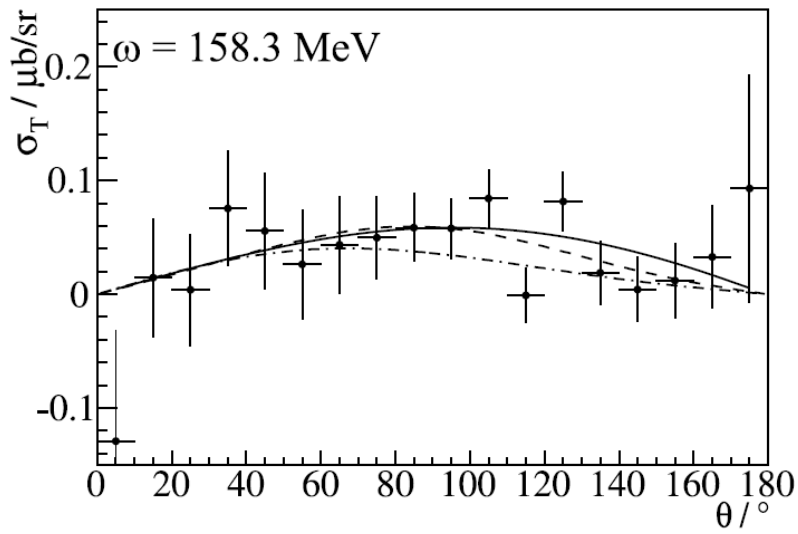


Rescattering diagram responsible for the unitary cusp observed in $E0+(\gamma p \rightarrow p\pi^0)$

→ Precision experiment to test the **unitary calculations** [Bernstein et al. arXiv:0902.3412 [nucl-th] and **ChPT calculations** [V.Bernard, N.Kaiser, and U.G.Meissner, Eur. Phys. J. A11, 209 (2001)] of $\text{Im}E0+$.

Threshold π^0 photoproduction on transverse polarised protons at MAMI, S.Schumann et al., **PLB 750 (2015) 252- 258**

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



$$\sigma_T = \sigma_0 T = \frac{1}{P_{\text{eff}}^y} \cdot \frac{N_+^{\text{but}} - N_-^{\text{but}}}{\varepsilon \cdot \rho_p} \cdot \frac{1}{2\pi \sin \theta}.$$

$$T = \frac{1}{P_{\text{eff}}^y} \cdot \frac{N_+^{\text{but}} - N_-^{\text{but}}}{2N^{\text{H}}} \cdot \frac{\rho_p^{\text{H}}}{\rho_p^{\text{but}}}$$

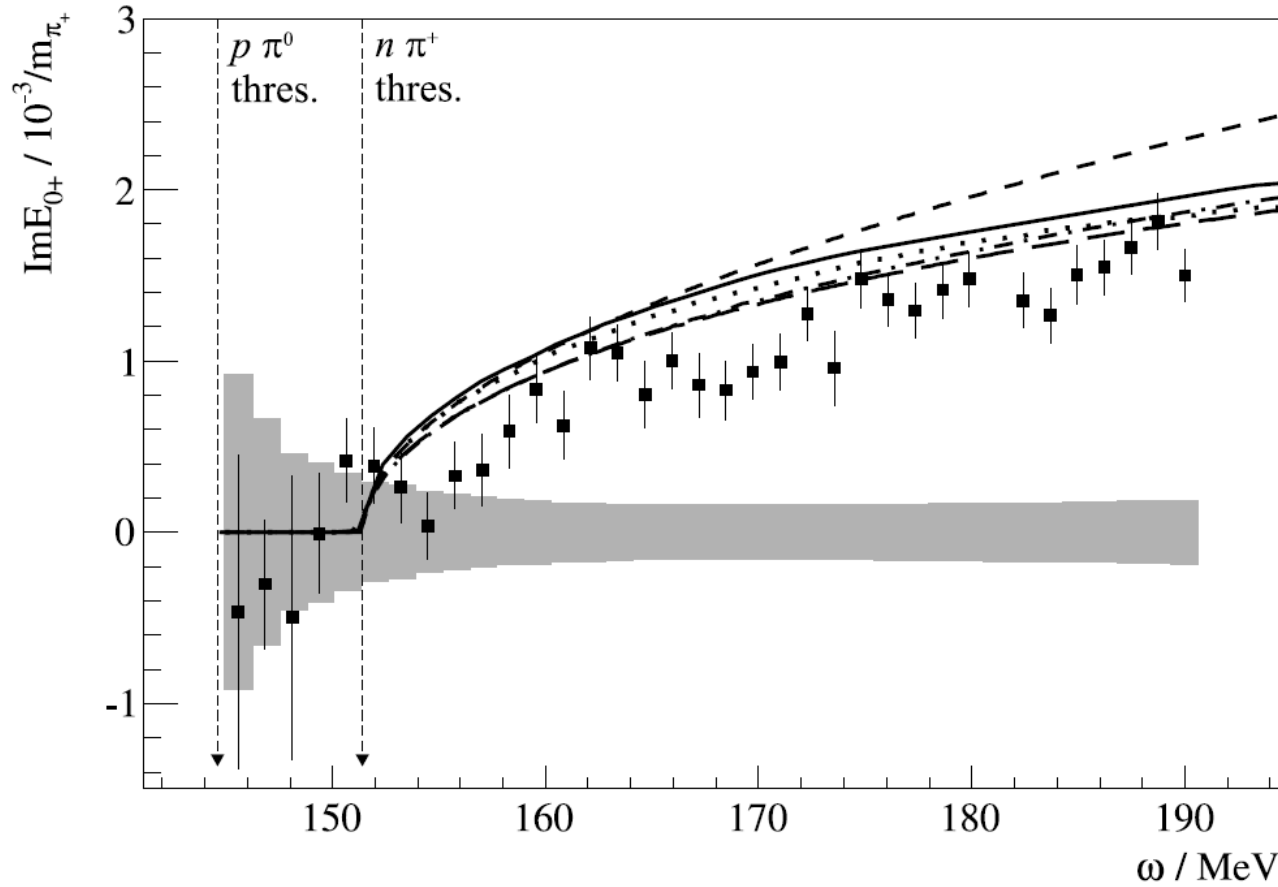


Fig. 5. Imaginary part of E_{0+} from single-energy fits to σ_T . Data points show experimental results with statistical uncertainties (error bars) and absolute systematic uncertainties (grey shaded band). The lines are the DMT model prediction (solid), the naïve parametrisation of Eq. (1) with constant $\beta = 3.35 \cdot 10^{-3}/m_{\pi^+}$ (short-dashed), a prediction of Gasparyan, Lutz [38] (long-dashed), the ChPT4 description in Ref. [8] (dashed-dotted), and a HBChPT4 calculation from Ref. [11] (dotted), scaled by a factor $3.35/2.71$ to match the unitary value of β at the $n\pi^+$ threshold.

Polarisabilities

- Polarisabilities are fundamental structure constants of the nucleon
- Scalar polarisabilities (α, β) describe spin response to static EM field
- Scalar polarisabilities measured in real Compton Scattering for the proton
[M.Schumacher, Prog.Part. and Nucl.Phys.55, 567 (2005).] :

$$\frac{d\sigma}{d\Omega}(\omega, \theta) = \frac{d\sigma}{d\Omega}^B(\omega, \theta) - \frac{e^2}{4\pi M} \left(\frac{\omega'}{\omega} \right)^2 (\omega\omega') \left[\frac{\alpha + \beta}{2} (1 + \cos \theta)^2 + \frac{\alpha - \beta}{2} (1 - \cos \theta)^2 \right]$$

$$\alpha_{E1}^p = [12.21 \pm 0.3(stat.) \mp 0.4(syst.) \pm 0.3(mod.)] \times 10^{-4} fm^3$$
$$\beta_{M1}^p = [1.6 \pm 0.4(stat.) \pm 0.4(syst.) \pm 0.4(mod.)] \times 10^{-4} fm^3$$

Real compton scattering with polarized beam and polarized target

$\alpha, \beta, \gamma_1, \gamma_2, \gamma_3, \gamma_4$



Dispersion relation, χ PT, lattice QCD..?

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

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

- Only two linear combinations of vector polarizabilities measured:

$$\begin{aligned} \gamma_0 &= -\gamma_{E1E1} - \gamma_{M1M1} - \gamma_{E1M2} - \gamma_{M1E2} = -1.01 \pm 0.08 \pm 0.10 \times 10^{-4} fm^4 \\ \gamma_\pi &= -\gamma_{E1E1} + \gamma_{M1M1} - \gamma_{E1M2} + \gamma_{M1E2} = 8.0 \pm 1.8 \times 10^{-4} fm^4 \end{aligned}$$

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 Polarisabilities

γ	$\mathcal{O}(p^4)$ [1]	$\mathcal{O}(p^5)$ [2]	LC4 [3]	Theory / 10^{-4}fm^4					Experiment / 10^{-4}fm^4
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]

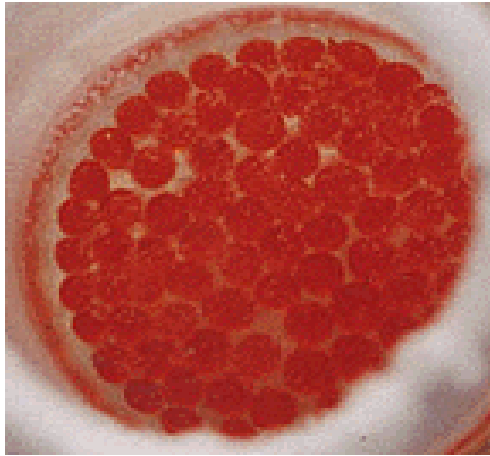
1. G. Gellas, T. Hemmert, and Ulf-G. Meißner, Phys. Rev. Lett. 85, 14 (2000).
2. K.B. Vijaya Kumar, J.A. McGovern, M.C. Birse, Phys. Lett. B 479, 167 (2000).
3. D. Djukanovic, Ph.D. Thesis, University of Mainz, 2008.
4. R.P. Hildebrant et al., Eur. Phys. J. A 20, 293 (2004).
5. D. Babusci et al., Phys. 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).

Target material

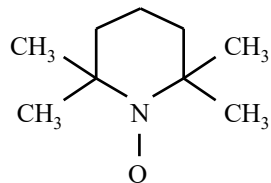
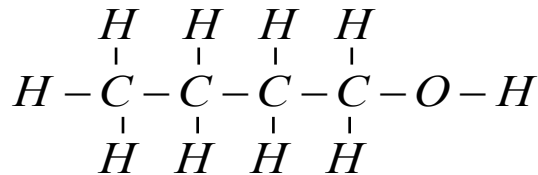
Saturated electrons of target material not polarized (Pauli principle)

Free electrons $\rightarrow$ Radicals in material by
chemical or
radiative doping

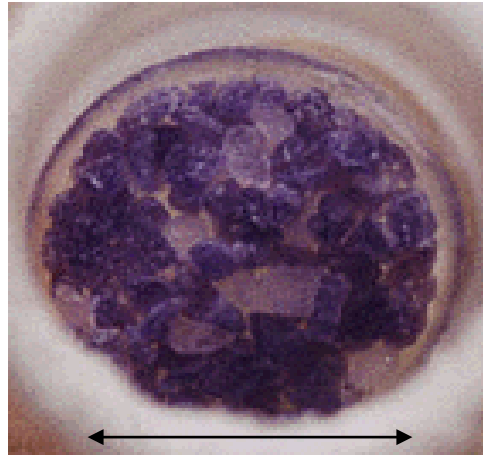
$$\frac{\# radicals}{\# protons} \approx 10^{-4}$$



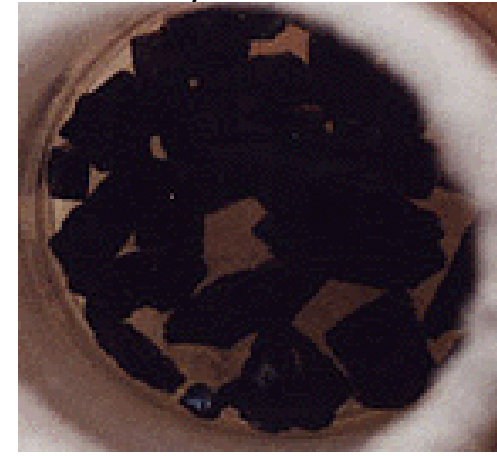
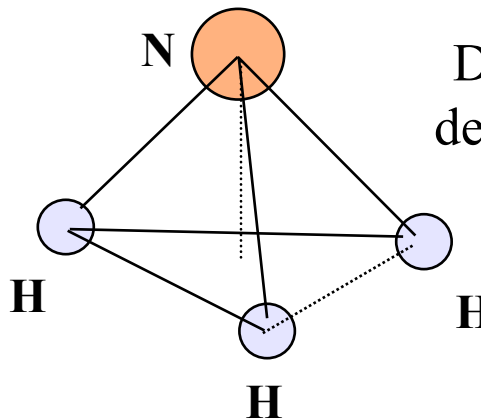
Butanol



Tempo



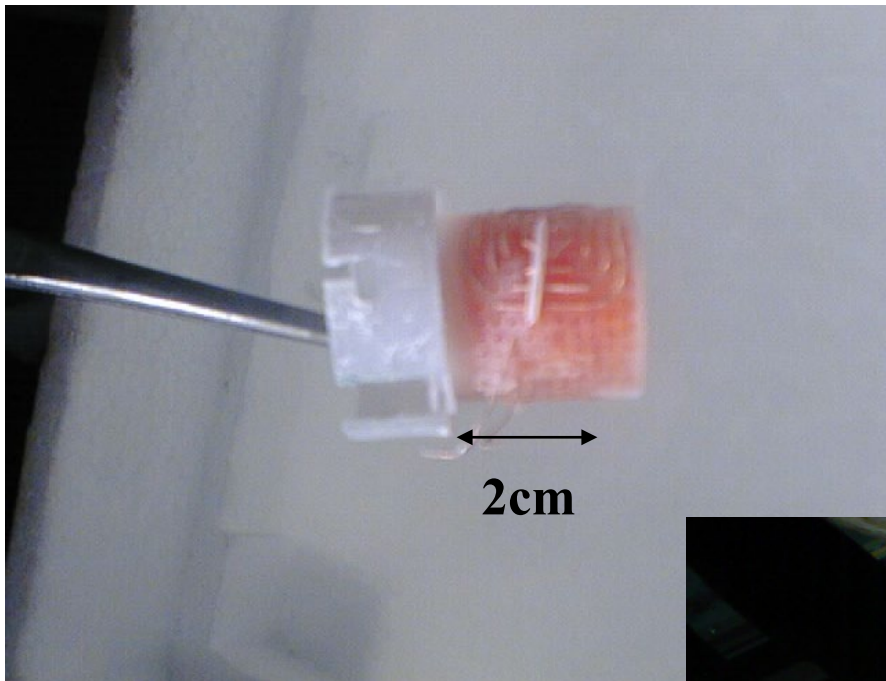
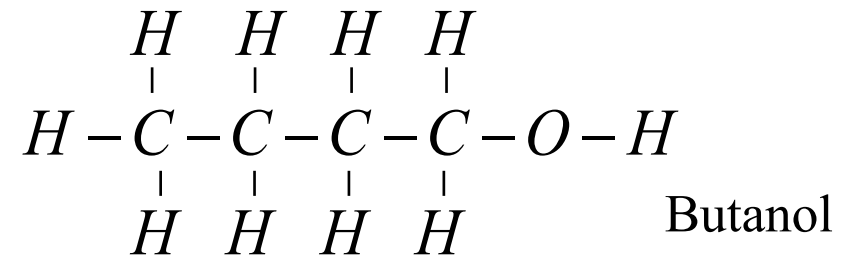
**30mm
Ammonia**



LiD

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

Target Material Frozen Spin Target



X-ray picture with
Beamspace and
NMR coil



Loading of the target material

