Recent result from the Crystal Ball Experiment at MAMI

1.-Introduction:	Symmetry Tests in η Decays
	The Nucleons Resonance Spectrum
2.-Experimental setup I:	Tagger + CBall@MAMI (η factory)
3.-Experimental setup II:	Frozen Spin Target (Double Polarised Exp.)
4.-Experiments :	Precision measurements of the Nucleons Excitations Determination of Fundamental Properties
5.-Conclusions and Outlook	

HEPD Seminar

St.Petersburg, 15th April 2010

Andreas Thomas

C and CP Violating Decays

Citation: C. Amsler *et al.* (Particle Data Group), PL **B667**, 1 (2008) (URL: http://pdg.lbl.gov)

TESTS OF DISCRETE SPACE-TIME SYMMETRIES

CHARGE CONJUGATION (*C*) INVARIANCE

$\Gamma(\pi^0 \to 3\gamma)/\Gamma_{total}$		$<3.1 \times 10^{-8}$, CL = 90%
η *C*-nonconserving decay parameters		
$\pi^+\pi^-\pi^0$ left-right asymmetry parameter		$(0.09 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ sextant asymmetry parameter		$(0.18 \pm 0.16) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ quadrant asymmetry parameter		$(-0.17 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\gamma$ left-right asymmetry parameter		$(0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$ parameter β (*D*-wave)		-0.02 ± 0.07 (S = 1.3)
$\Gamma(\eta \to \pi^0\gamma)/\Gamma_{total}$		$<9 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0\pi^0\gamma)/\Gamma_{total}$		$<5 \times 10^{-4}$, CL = 90%
$\Gamma(\eta \to \pi^0\pi^0\pi^0\gamma)/\Gamma_{total}$		$<6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to 3\gamma)/\Gamma_{total}$		$<1.6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 e^+ e^-)/\Gamma_{total}$	[a]	$<4 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 \mu^+ \mu^-)/\Gamma_{total}$	[a]	$<5 \times 10^{-6}$, CL = 90%
$\Gamma(\omega(782) \to \eta\pi^0)/\Gamma_{total}$		$<1 \times 10^{-3}$, CL = 90%
$\Gamma(\omega(782) \to 3\pi^0)/\Gamma_{total}$		$<3 \times 10^{-4}$, CL = 90%
c decay parameter of $\eta'(958)$		0.015 ± 0.018
asymmetry parameter for $\eta'(958) \to \pi^+\pi^-\gamma$ decay		-0.01 ± 0.04
$\Gamma(\eta'(958) \to \pi^0 e^+ e^-)/\Gamma_{total}$	[a]	$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to \eta e^+ e^-)/\Gamma_{total}$	[a]	$<2.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to 3\gamma)/\Gamma_{total}$		$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\pi^0)/\Gamma_{total}$	[a]	$<6.0 \times 10^{-5}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\eta)/\Gamma_{total}$	[a]	$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(J/\psi(1S) \to \gamma\gamma)/\Gamma_{total}$		$<2.2 \times 10^{-5}$, CL = 90%

Citation: C. Amsler *et al.* (Particle Data Group), PL **B667**, 1 (2008) (URL: http://pdg.lbl.gov)

CP INVARIANCE

$\mathrm{Re}(d_\tau^W)$	$<0.50 \times 10^{-17}$ *e* cm, CL = 95%
$\mathrm{Im}(d_\tau^W)$	$<1.1 \times 10^{-17}$ *e* cm, CL = 95%
$\Gamma(\eta \to \pi^+\pi^-)/\Gamma_{total}$	$<1.3 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0\pi^0)/\Gamma_{total}$	$<3.5 \times 10^{-4}$, CL = 90%
$\Gamma(\eta \to 4\pi^0)/\Gamma_{total}$	$<6.9 \times 10^{-7}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^+\pi^-)/\Gamma_{total}$	$<2.9 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^0\pi^0)/\Gamma_{total}$	$<9 \times 10^{-4}$, CL = 90%
$K^\pm \to \pi^\pm\pi^+\pi^-$ rate difference/average	(0.08 ± 0.12)%
$K^\pm \to \pi^\pm\pi^0\pi^0$ rate difference/average	(0.0 ± 0.6)%
$K^\pm \to \pi^\pm\pi^0\gamma$ rate difference/average	(0.9 ± 3.3)%
$K^\pm \to \pi^\pm\pi^+\pi^-$ $(g_+ - g_-)\,/\,(g_+ + g_-)$	$(-1.5 \pm 2.2) \times 10^{-4}$
$K^\pm \to \pi^\pm\pi^0\pi^0$ $(g_+ - g_-)\,/\,(g_+ + g_-)$	$(1.8 \pm 1.8) \times 10^{-4}$

Only weak upper limits

Improve upper limits by factor >10

Standart Model

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

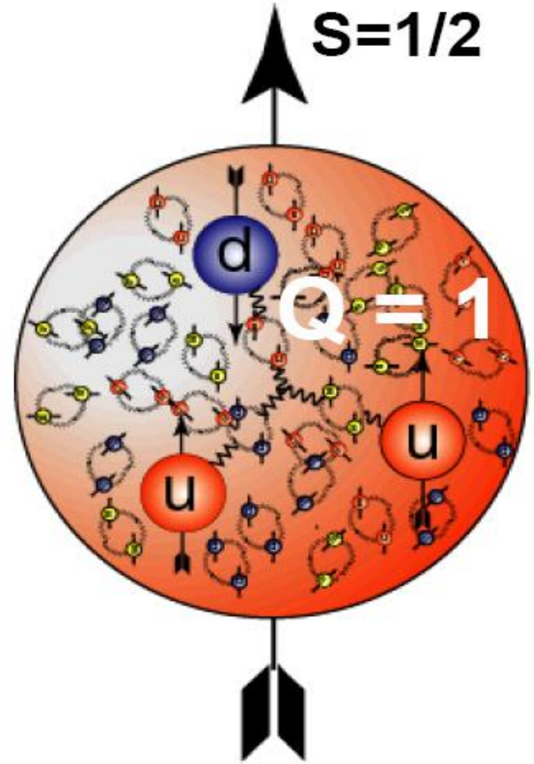
BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

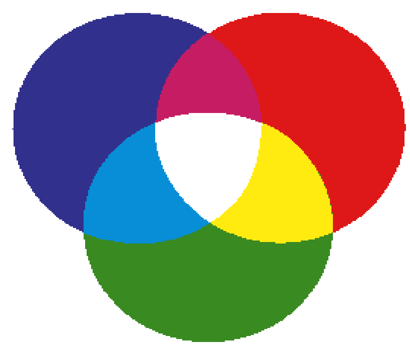
Picture of a Proton (Skale fm).



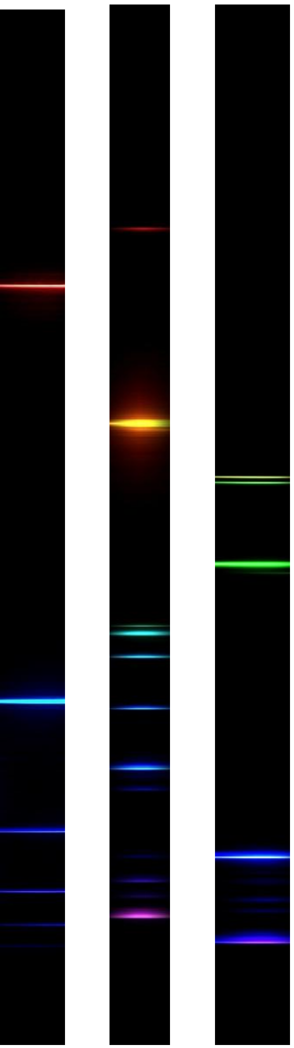
QCD Colourless objects:

Baryons (qqq)

Mesons ($q\bar{q}$)

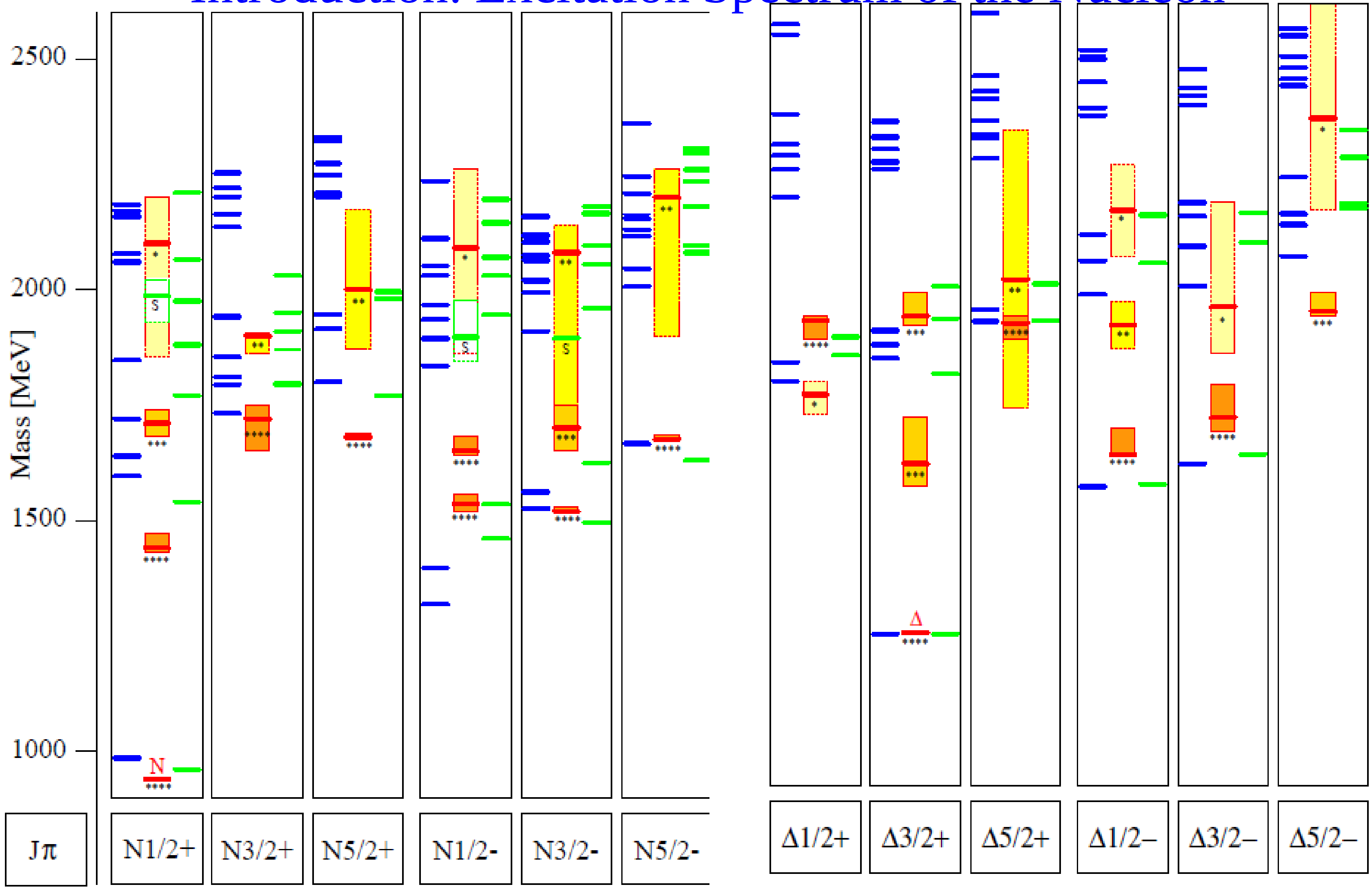


Introduction: Excitation Spectrum of the Nucleon



H He Hg

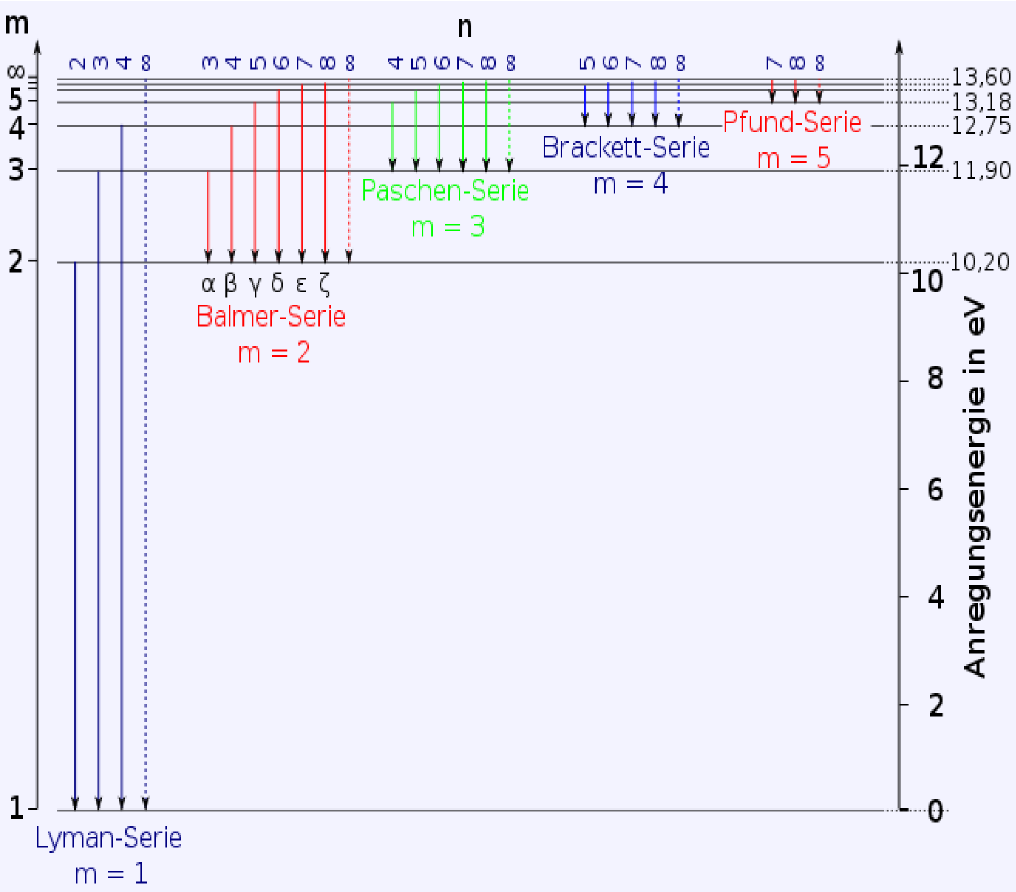
Atom

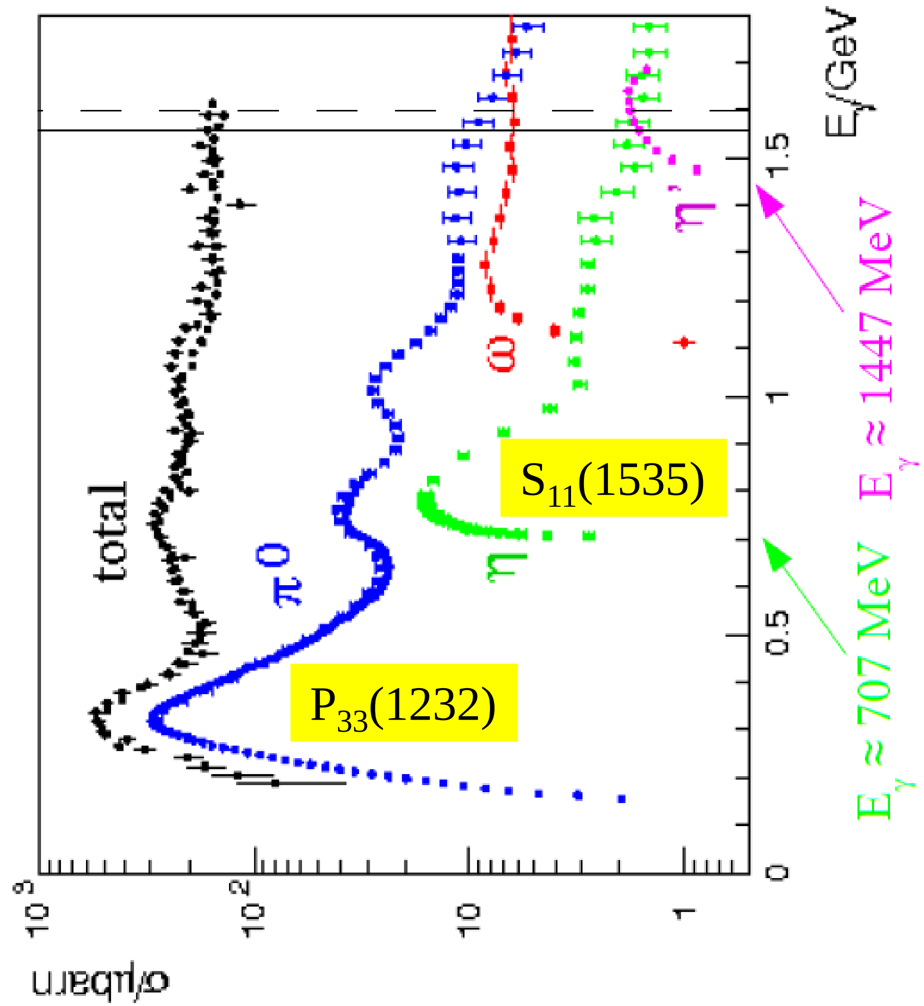


Nucleon

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

E[eV] E[GeV]





Hydrogen

t ~ 10^{-8} s

ΔE ~ 10^{-6} eV

Nucleon

t ~ 10^{-23} s

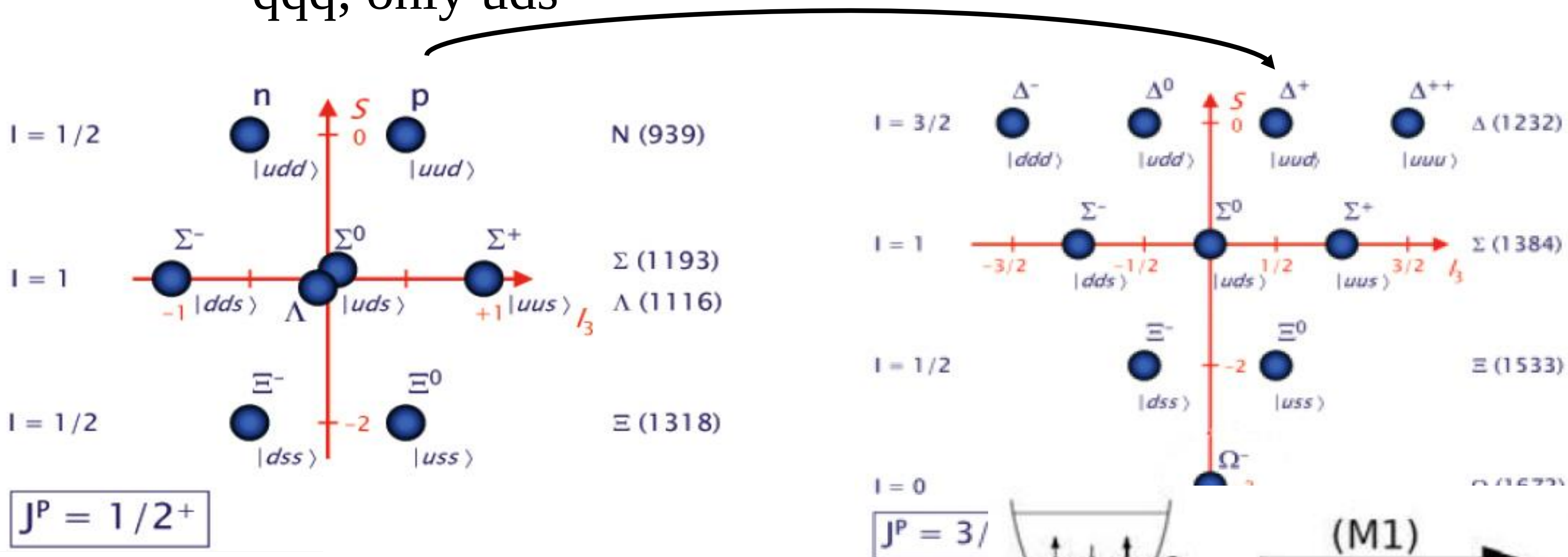
ΔE ~ 200 MeV

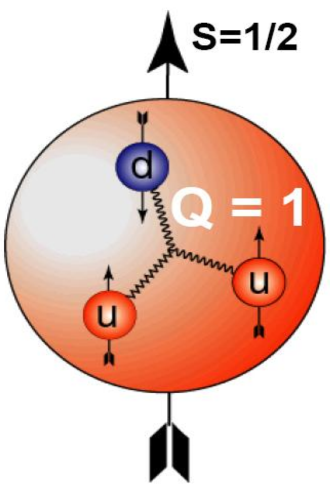
Introduction: Excitation Spectrum of the Nucleon

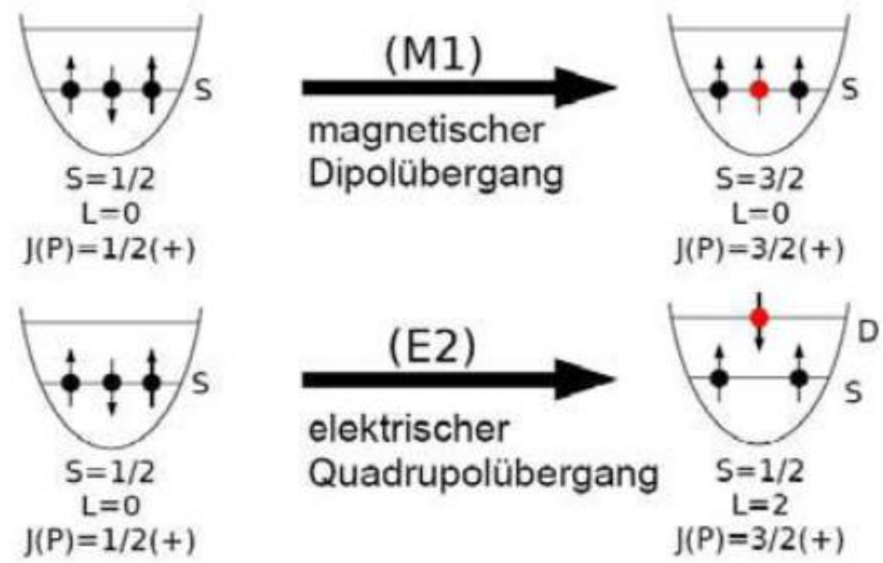
Quark Model (Simple Constituent quark picture)

Classification of Baryons

qqq; only uds







Nature and Properties of nucleon resonances

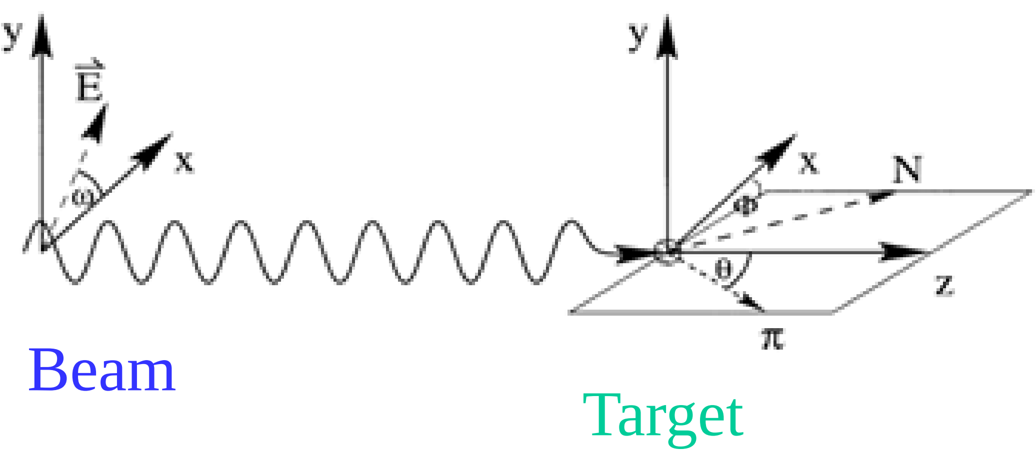
➡ Polarisation observables used to disentangle broad, overlapping resonances.

Observables in pseudoscalar meson prod.

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

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

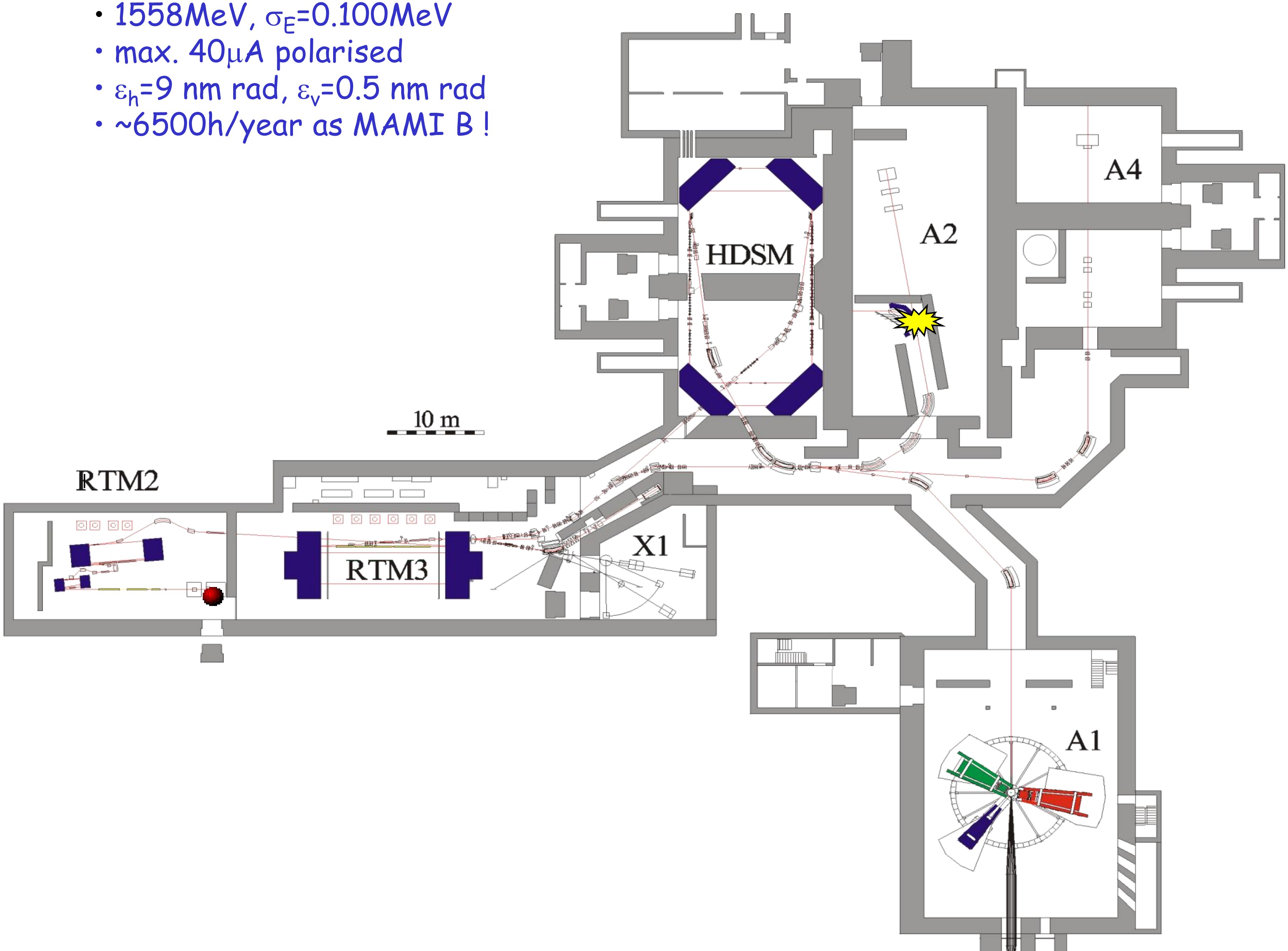
$$+ P_y\left(T - P_\gamma^{lin}P\cos 2\phi\right) + P_z\left(P_\gamma^{circ}E + P_\gamma^{lin}G\sin 2\phi\right)$$



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	-	-	$G(\theta)$	$E(\theta)$

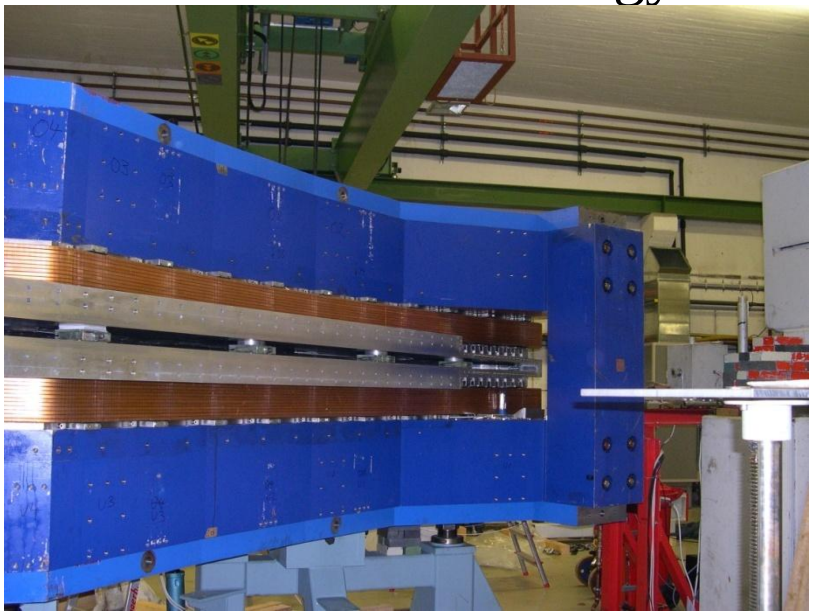
Parameter

- 1558MeV, σ_E=0.100MeV
- max. 40μA polarised
- ε_h=9 nm rad, ε_v=0.5 nm rad
- ~6500h/year as MAMI B !

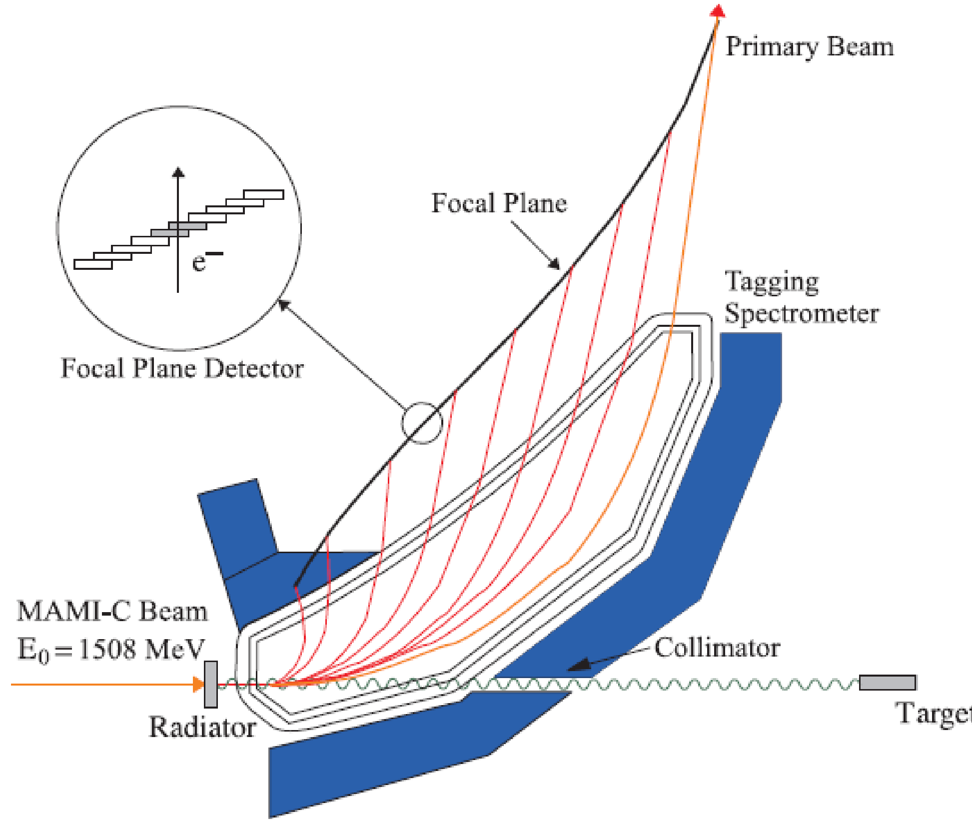


Upgraded A2 Tagging system (Glasgow, Mainz)

1. Production and energy measurement of the Bremsstrahlung photons.



Glasgow Tagging Spectrometer
EPJ A 37, 129 (2008)

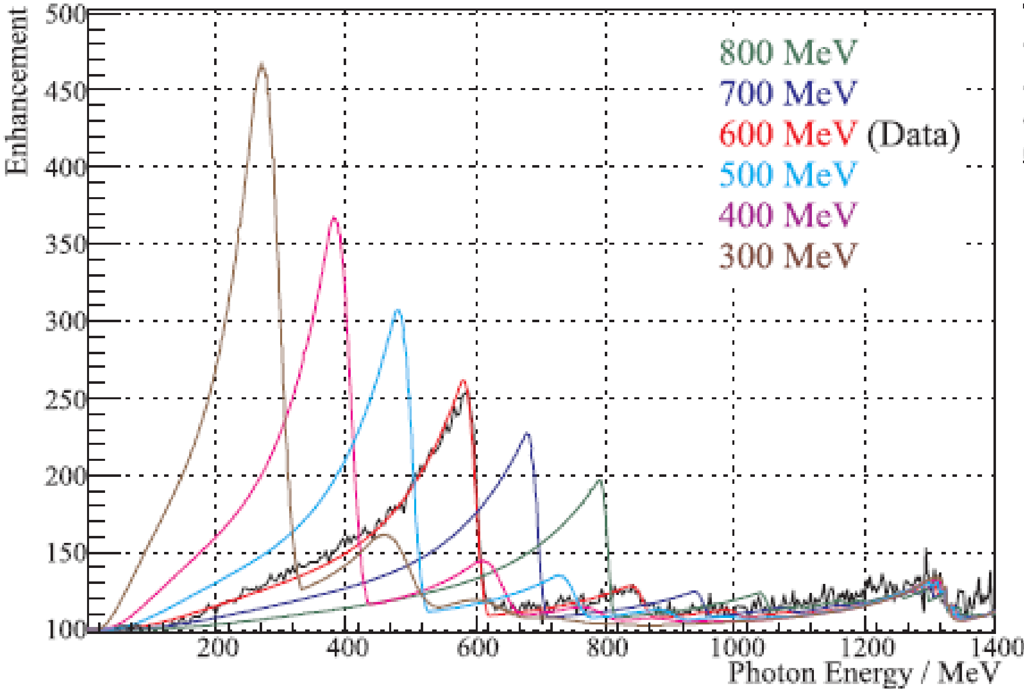


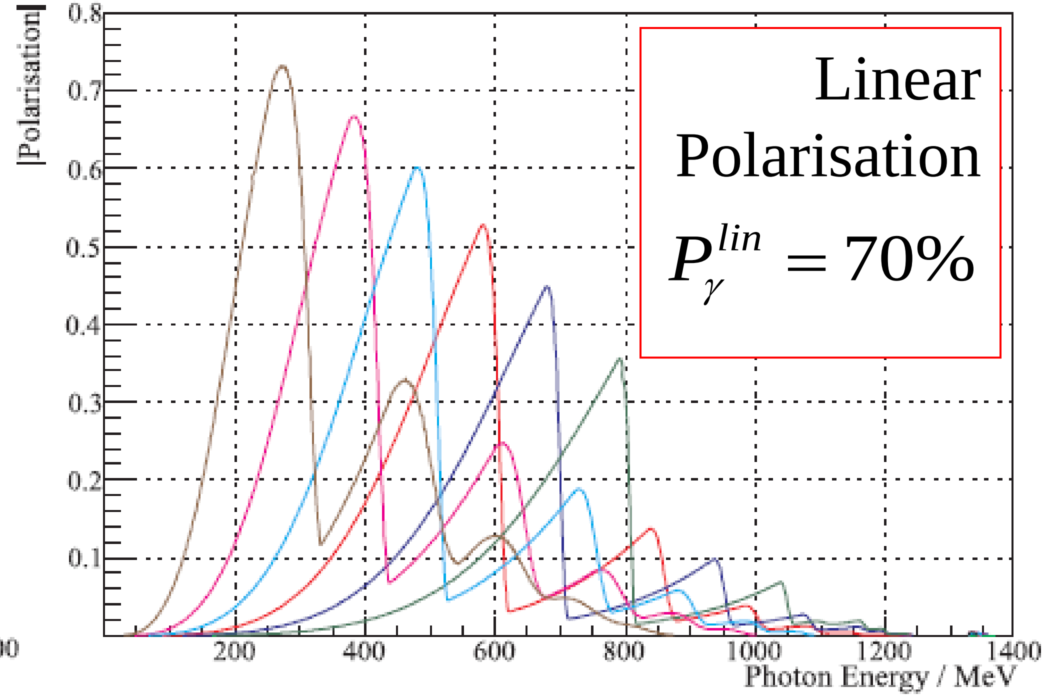
2. Determination of the degree of polarization of the electron beam (Moeller Polarimeter). Circularly pol. photons.

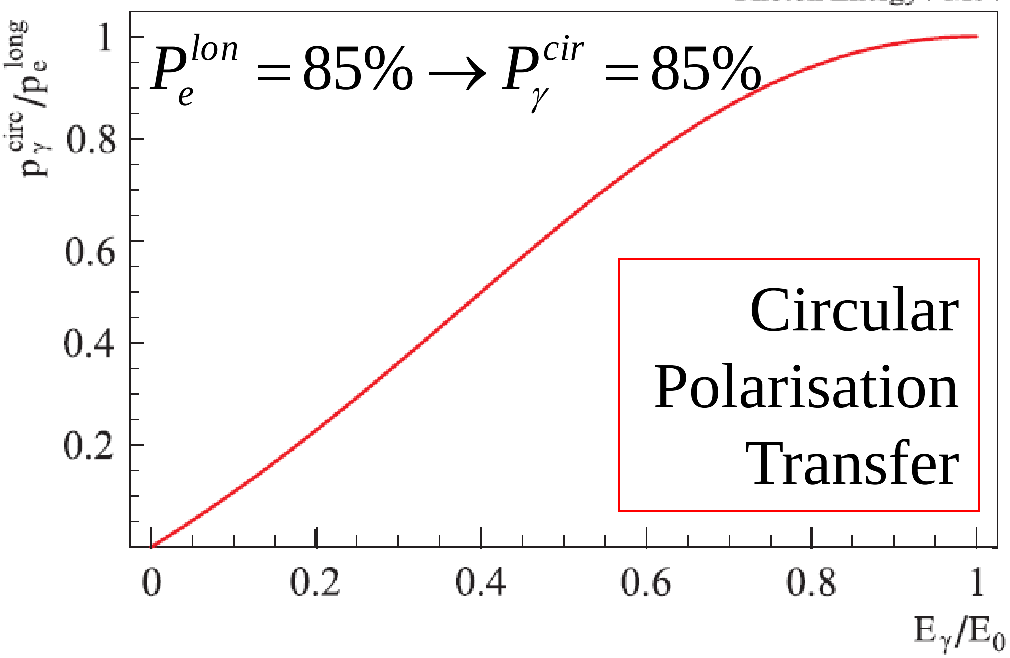
$$A = \frac{N^+ - N^-}{N^+ + N^-} = a\vec{p}_t\vec{p}_b\cos(z)$$

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

Polarised Photons @ MAMI C



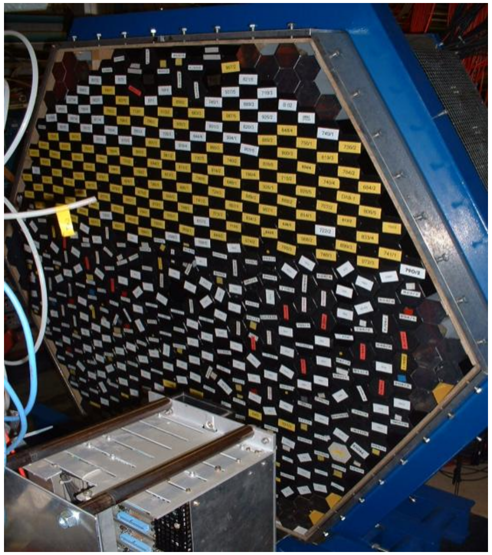


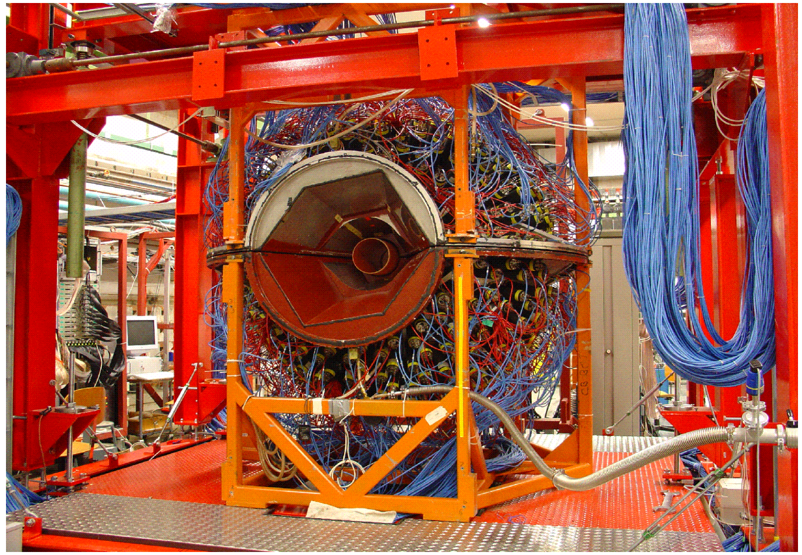


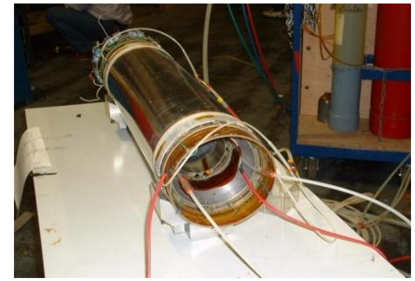
E_γ = 75 ... 1480 MeV
ΔE_γ = 4 MeV
N_γ = $2 \cdot 10^5\ s^{-1}\ MeV^{-1}$

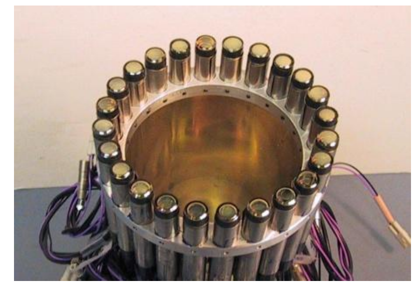
→ High Polarisation
High Photon Flux

Crystal Ball/TAPS Detector









TAPS (Giessen,Basel,Mz):

- 366 BaF_2 crystals
  72 PbWo inner det.
  (1-20^o)
- Individual charged
  particle vetos

Crystal Ball (UCLA):

672 NaI scintillators

(20-160^o)

PID and tracking:

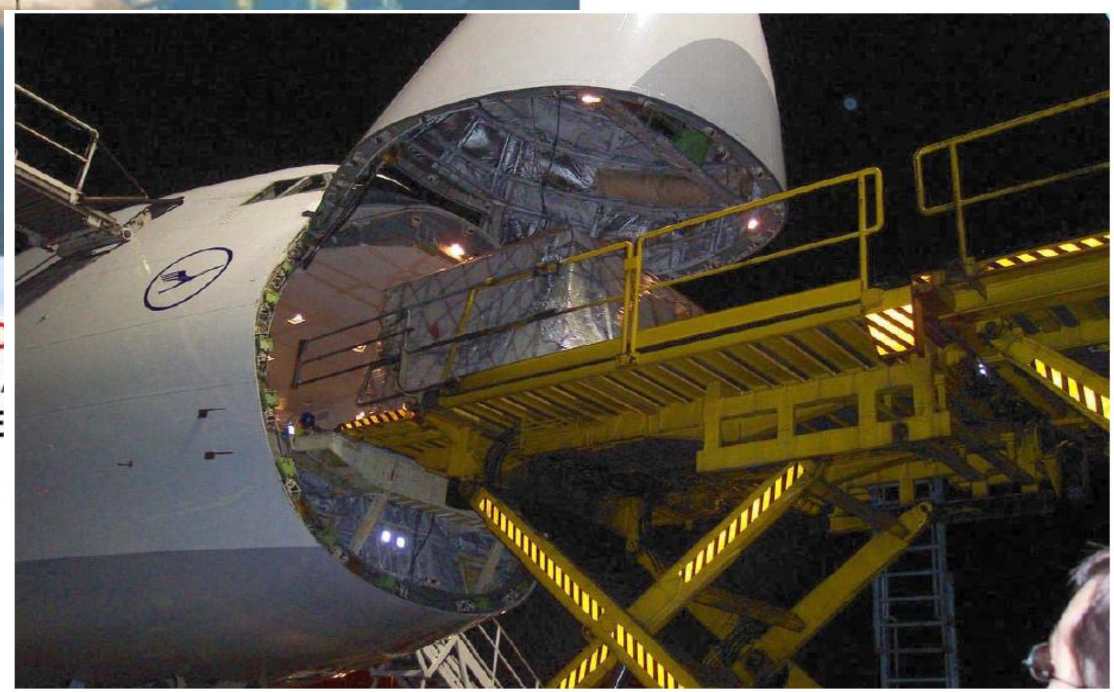
- Barrel of 24 plastic
  scintillators (Edinburgh)
- MWPC (Pavia)
- Carbon analyser for
  nucleon recoil polarimetry

History ‚Crystal Ball' Detector

1996-2002
BNL-AGS
(E_{cm} = 1.2 – 1.53 GeV)
N*, Δ, Λ*, Σ,
η decays, medium. mod

1982-1986
DORIS
(Ecm = 9 -10 GeV)
Y spectroscopy
radiative ϒ decays

1976
Conceived
1978 -1981
SPEAR
(E_{cm} = 3 - 7 GeV)
ψ,ψ′ spectroscopy
radiative φ decays
τ decays
D decays,
$\gamma\gamma \rightarrow \gamma\gamma$,
η, η′, *f*



[Frankfurt 2002]

4π photon Spectrometer @ MAMI

TAPS:

366 BaF_2 detectors

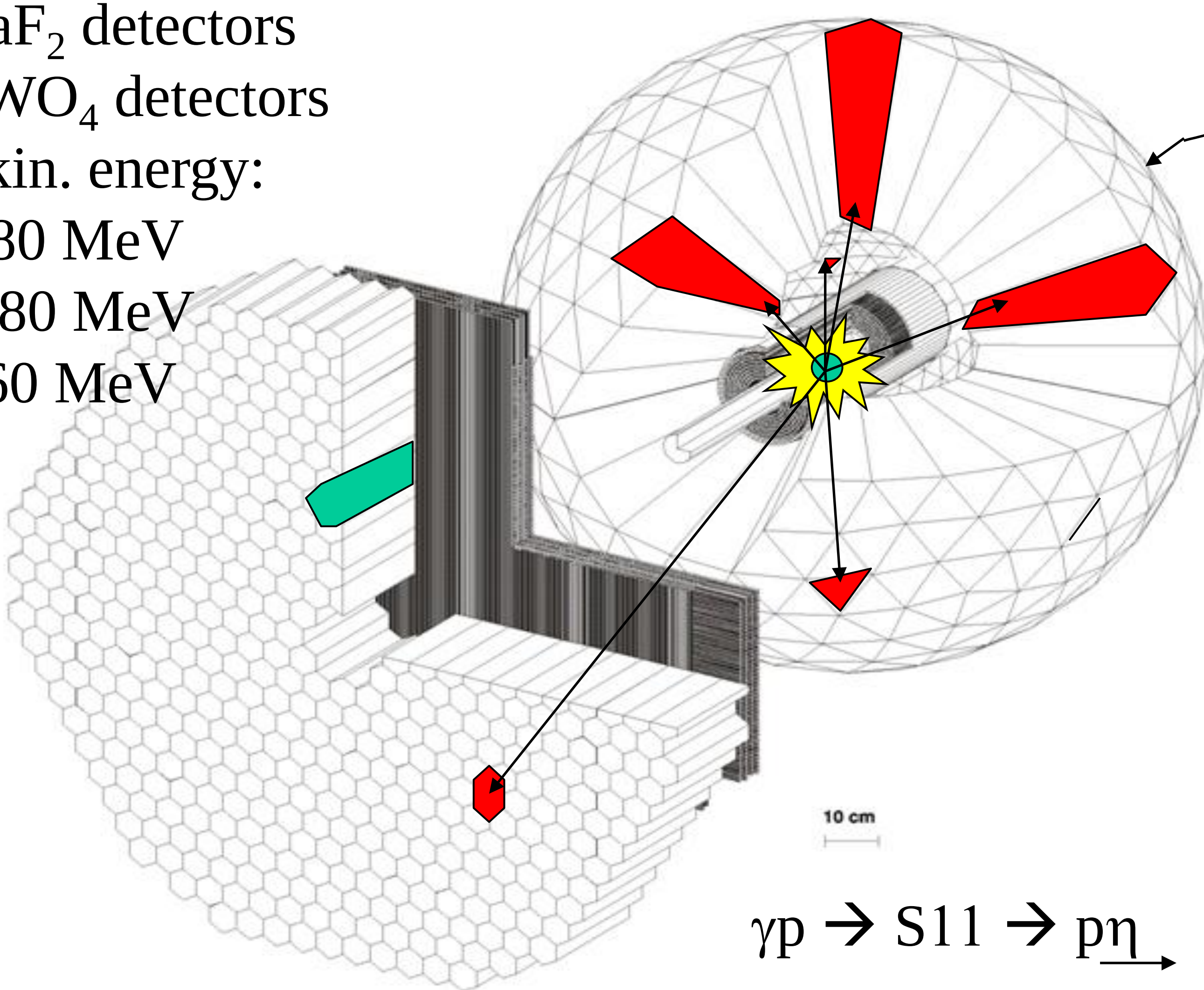
72 $PbWO_4$ detectors

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

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

First round with CB@MAMI B (882MeV) 2004 - 2005
and with CB@MAMI C (1558MeV) 2007- 2009 (only beam polarized)

Nucleon Resonances

1. Data set with high statistics for π , π π, πη, and η – production.
2. Helicity and Beam Asymmetries.
3. Magnetic Moment of the Δ-Resonance.

η Factory

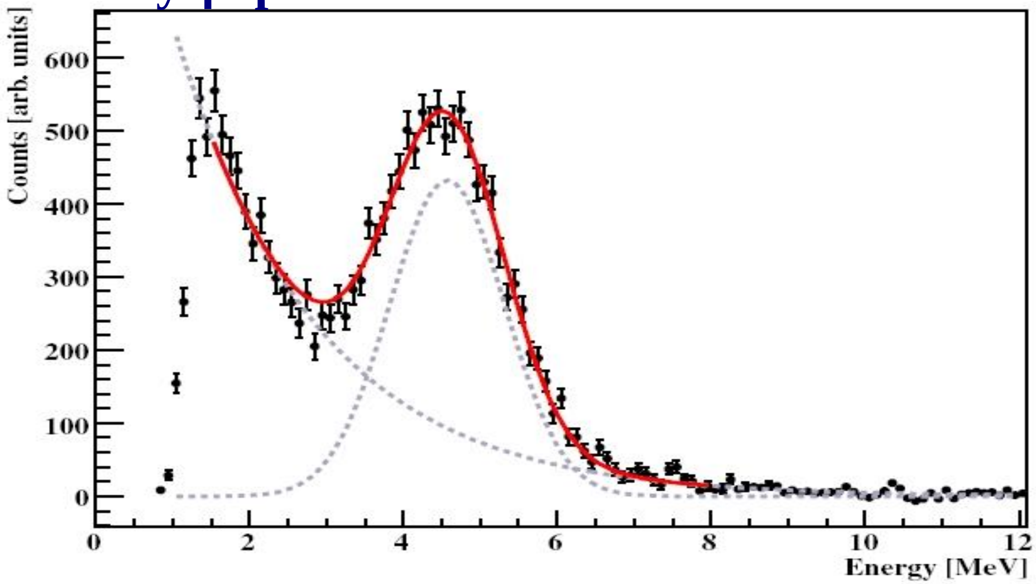
4. Dalitz Plot Slope Parameter α in the η -> $\pi^0\pi^0\pi^0$ decay. Sensitive to the quark-mass-differenz m_u-m_d.
5. Precision measurement to determine the η-mass.
6. $30*10^6$ η produced for the investigation of rare η-decays (C, CP-Violation) and the η - Dalitz-decay η -> $e^+e^-\gamma$.
7. Investigation of η-mesic nuclei (^{7}Li-, ^{3}He-target). [PNPI, Basel]

Nuclear medium effects

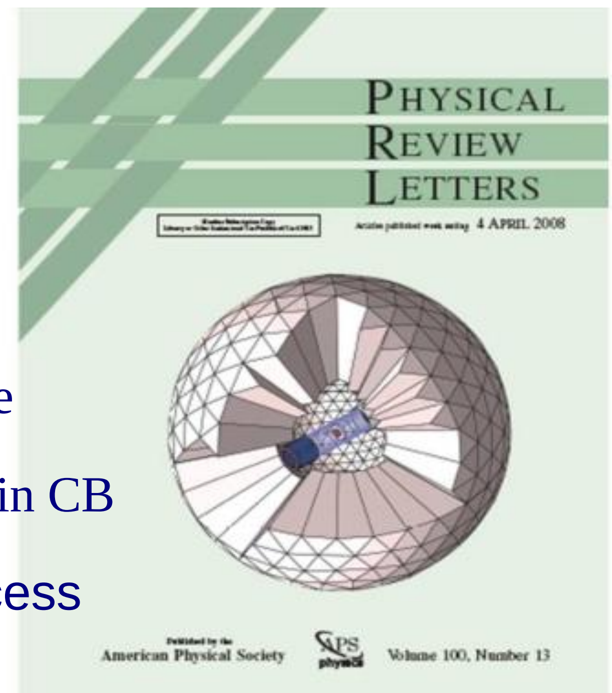
8. Data set on nuclei (modified ππ Interaction in nuclear matter, mass shift of ω in nuclear medium).
9. Coherent π^0 production on nuclei.

Technical Capabilities: Incoherent π^0 photoproduction on ^{12}C

Decay γ spectrum in coinc. with π^0 4.4 MeV 2+ state

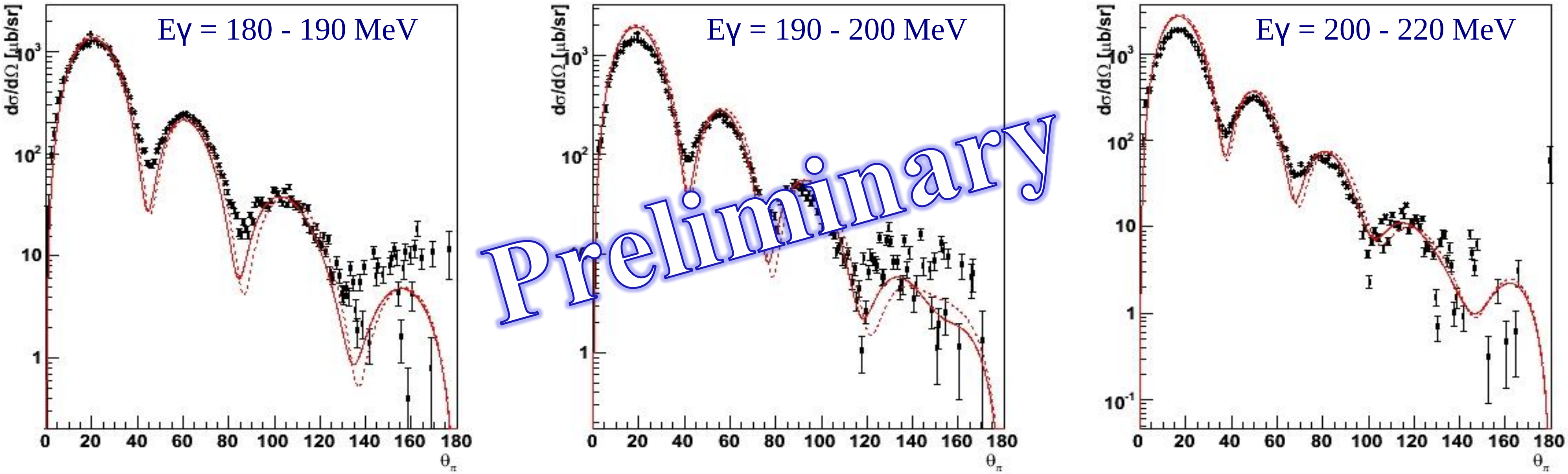


$$\gamma\,^{12}C \rightarrow\, ^{12}C^*\,\pi$$
$$\downarrow$$
$$^{12}C\,\gamma(4.4\text{ MeV})$$



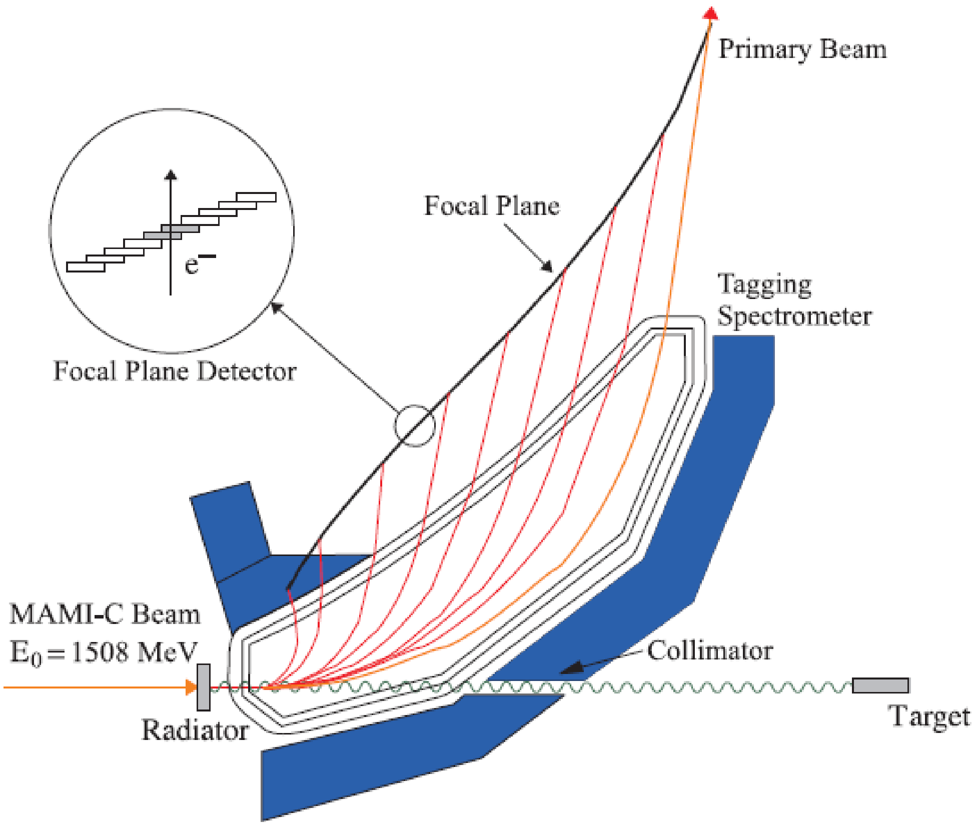
- First report of $\sigma(\gamma,\pi^0)$ for a specific excited state
- **Simultaneous detection** of $\boldsymbol{\pi^0}$ and **4.4 MeV decay γ** in CB
- Important first step in isolation of coherent process
- PRL **100**, 132301 (2008)

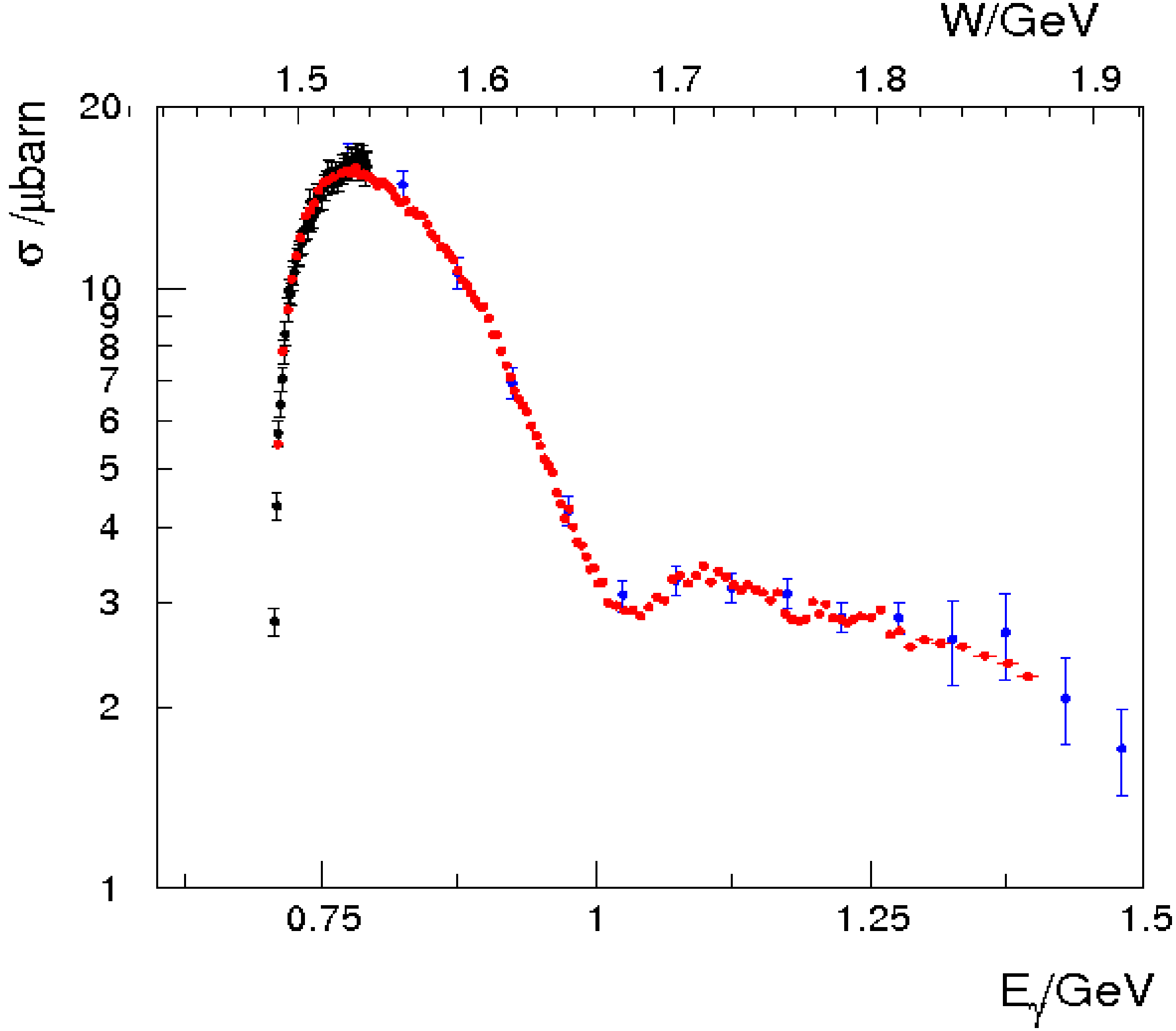
Coherent π^0 photoproduction on ^{208}Pb



- Do heavy stable nuclei have a neutron skin?
- Mass Radii, Fundamental property of nuclear physics
- Size of skin gives direct information on equation of state of n-rich matter
- Astrophysics: Skin size gives important new insights into neutron star physics (cooling mechanisms, mass radii relationships)
- Publication in preparation: D. P. Watts and C. Tarbert, Edinburgh Uni.

η Photoproduction with the A2 Tagging system



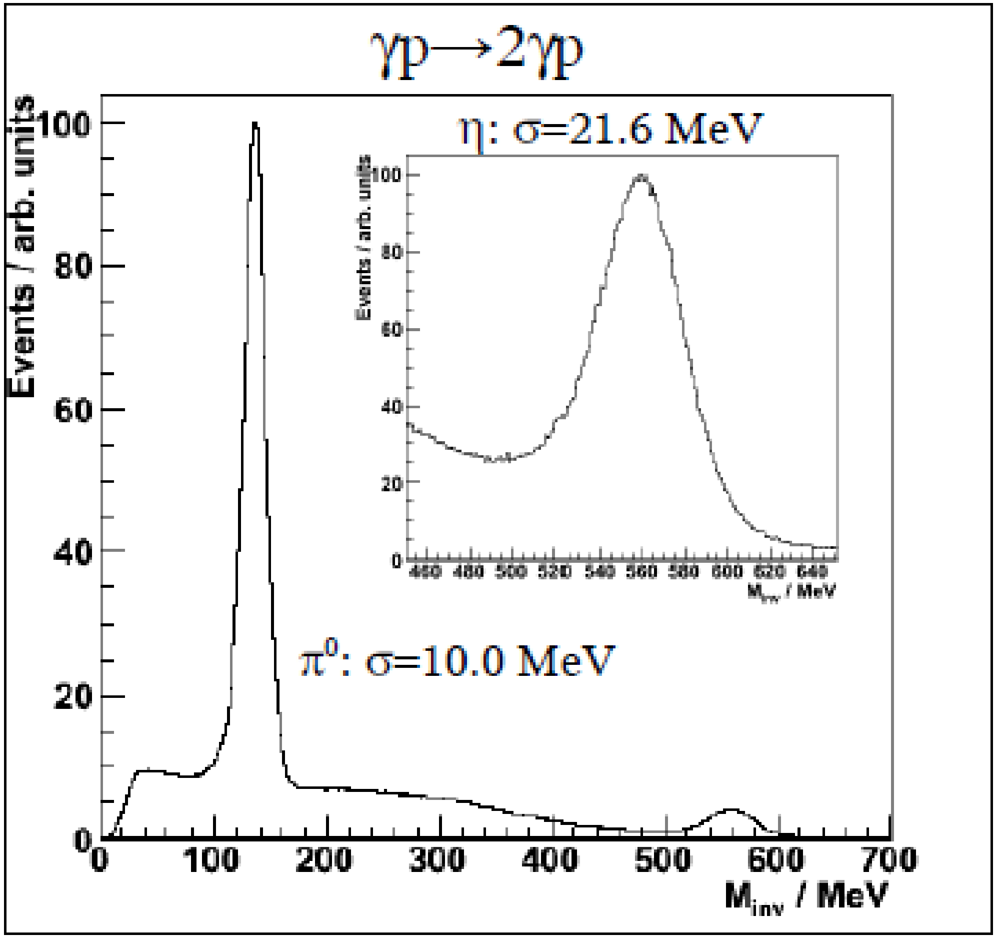


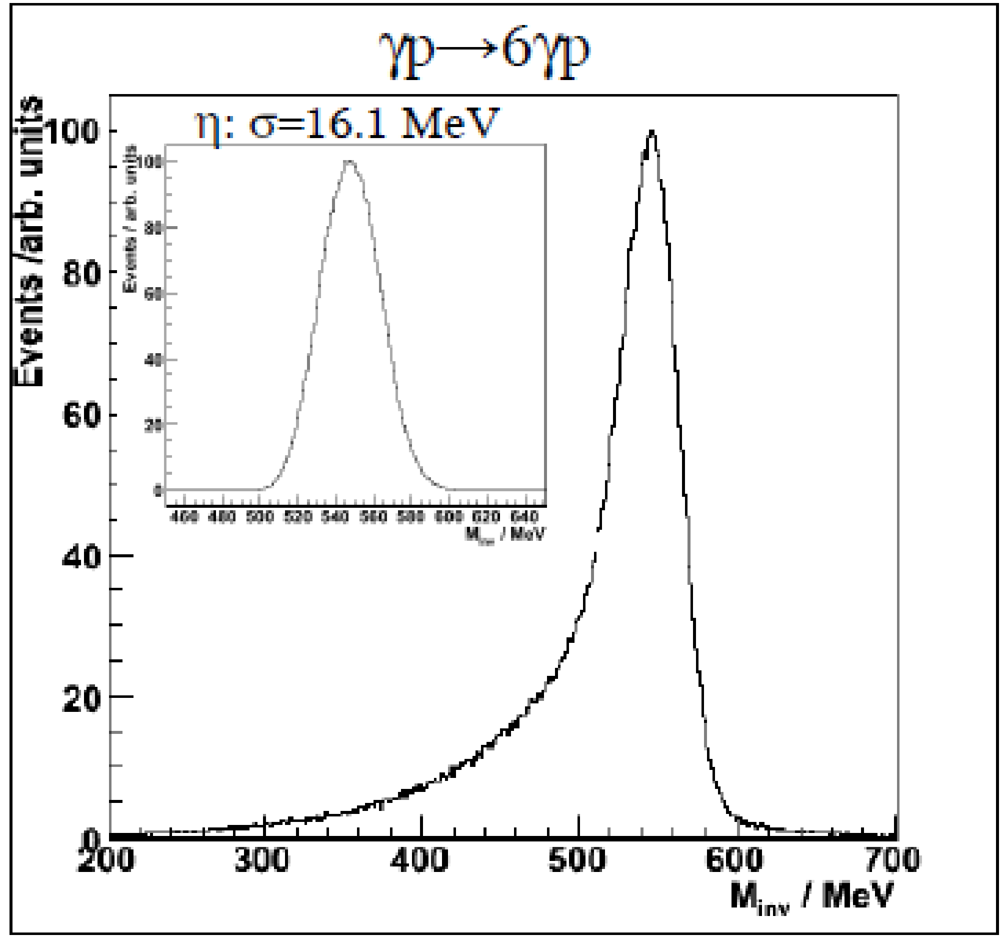
$$E_\gamma = E_0 - E_{e-}$$

Two main η decay modes:

BR($\eta \rightarrow 2\gamma$)=39.38%

BR($\eta \rightarrow 3\pi^0$)=32.51%





$3 \cdot 10^6$ $\eta \rightarrow 3\pi^0$ analysed from ~6 weeks → 30M η produced

Dalitz Plot SlopeParameter α

Decay is isospin breaking ($I(\eta)=0; I(3\pi^0)=1$)

$$H_{\Delta I=1} = \frac{1}{2}(m_u - m_d)(\bar{u}u - \bar{d}d)$$

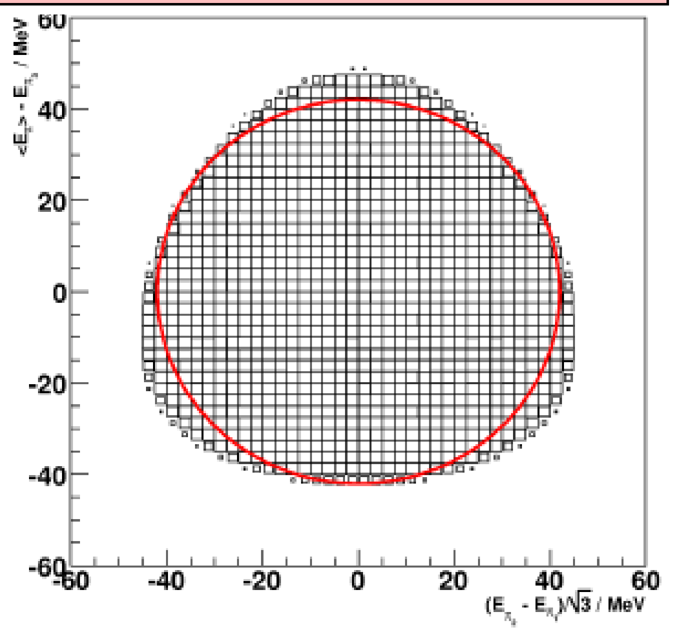
$$A(\eta \to 3\pi^0) = \frac{B_0(m_u - m_d)}{3\sqrt{3}F_\pi^2} \sim m_u - m_d$$

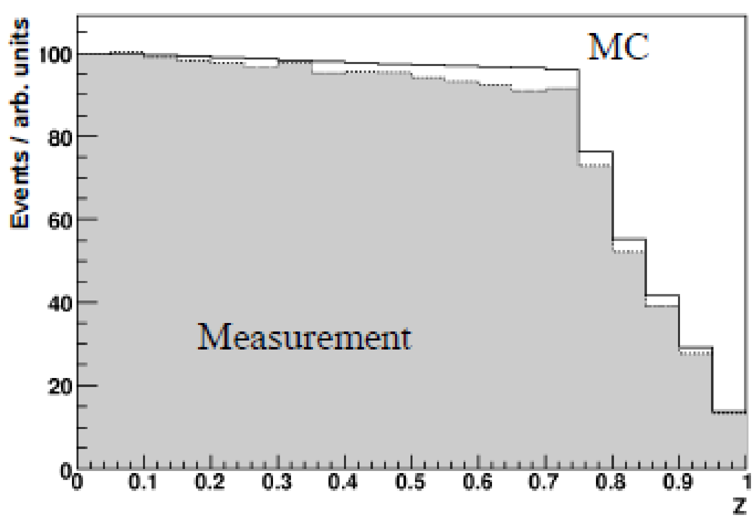
$$|A(\eta \to 3\pi^0)|^2 = |N|^2[1 + 2\alpha z + \ldots]$$

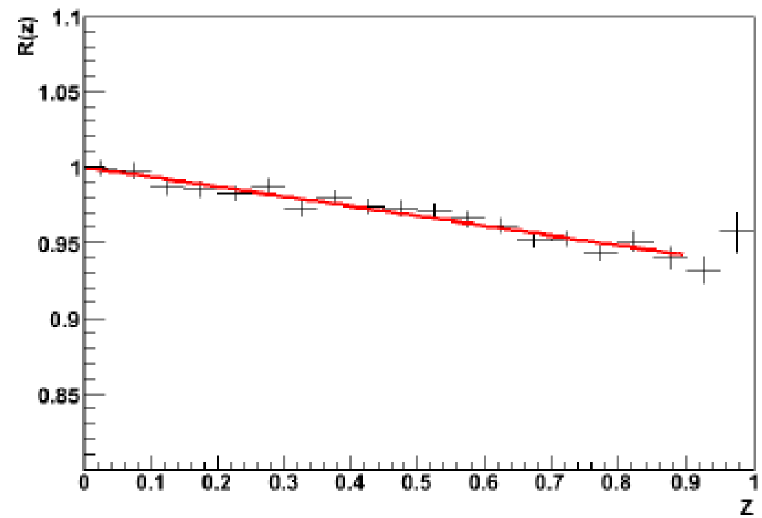
$$z = 6\sum_{i=1}^{3}\left(\frac{E_i - m_\eta/3}{m_\eta - 3m_{\pi^0}}\right)^2 = \frac{\rho^2}{\rho_{max}^2}$$

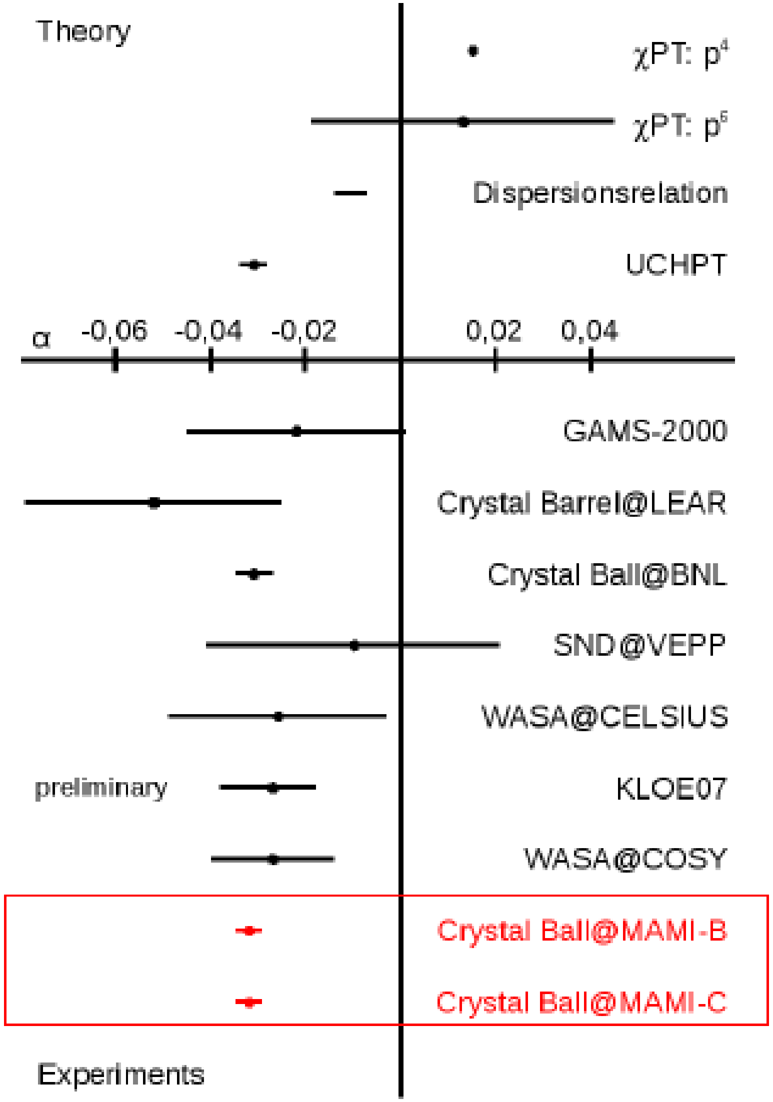
E_i: π^0 energies in η rest frame,

ρ: radial distance to center of Dalitz plot









Experiment	α	Statistics / 10^3
CB at MAMI-B	$-0.032 \pm 0.002 \pm 0.002$	1840
CB at MAMI-C	$-0.032 \pm 0.001 \pm 0.002$	3000
CB at BNL	-0.031 ± 0.004	950
WASA/CELSIUS	$-0.026 \pm 0.010 \pm 0.010$	75
WASA at COSY	$-0.027 \pm 0.008 \pm 0.005$	120
KLOE	$-0.027 \pm 0.004^{+0.004}_{-0.006}$	650
Dispersionrel.	$-0.007 \ldots -0.014$	----
UCHPT	-0.031 ± 0.003	----

World highest statistics on $\eta \rightarrow 3\pi^0$ decays

M. Unverzagt, PhD thesis, University Bonn (2008)
http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2008/unverzagt_marc/index.htm
M. Unverzagt *et al.*, Eur. Phys. J. A39, 169-177 (2009).
S. Prakhov *et al.*, Phys. Rev. C79, 035204 (2009).

Setup improvements: 10cm lH2-target,

PbWO4 crystals in TAPS

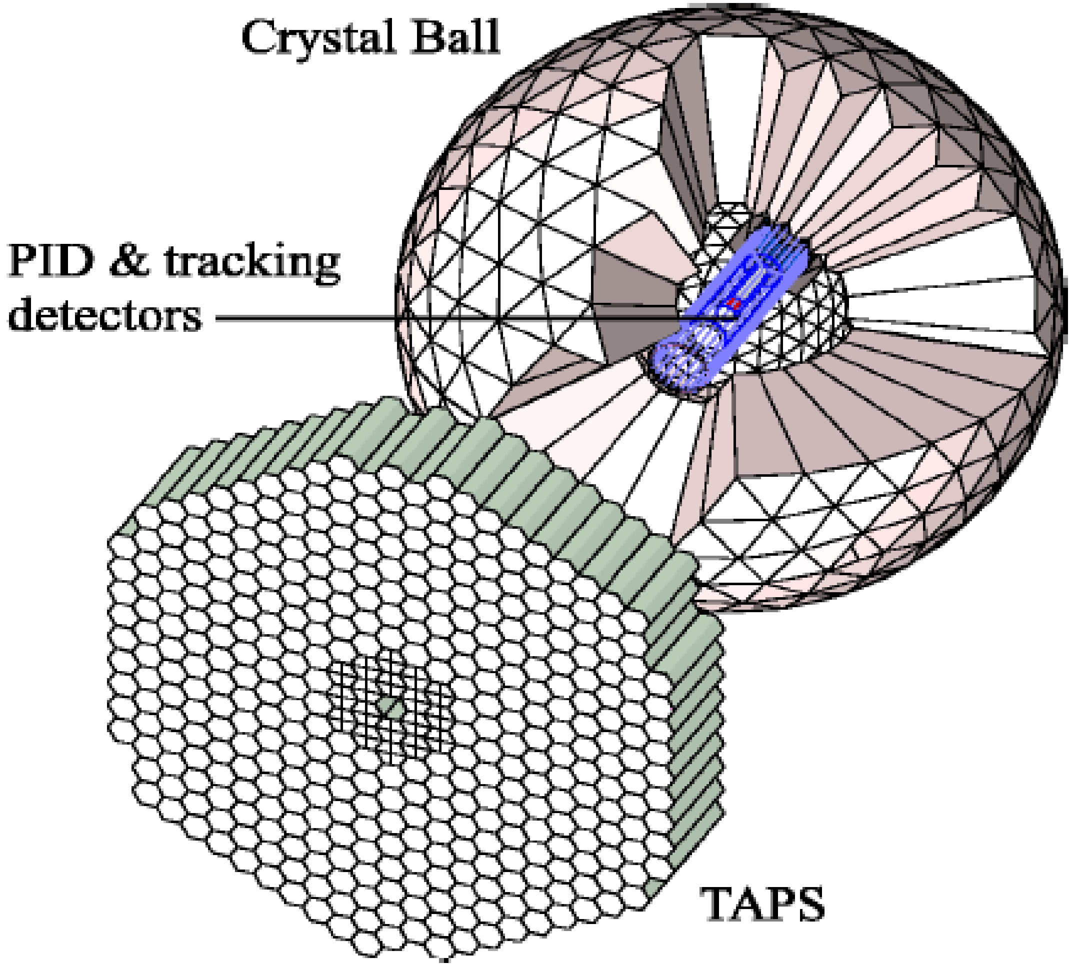
Produce 250 million η in order to improve by 10-20 upper limits of C and CP violating η decays:

$$\eta \rightarrow 2\pi^0\gamma$$

$$\eta \rightarrow 3\pi^0\gamma$$

$$\eta \rightarrow 3\gamma$$

$$\eta \rightarrow 4\pi^0$$



C and CP Violating Decays

Citation: C. Amsler et al. (Particle Data Group), PL B667, 1 (2008) (URL: http://pdg.lbl.gov)

TESTS OF DISCRETE SPACE-TIME SYMMETRIES

CHARGE CONJUGATION (C) INVARIANCE

$\Gamma(\pi^0 \to 3\gamma)/\Gamma_{total}$		$<3.1 \times 10^{-8}$, CL = 90%
η C-nonconserving decay parameters		
$\pi^+\pi^-\pi^0$ left-right asymmetry parameter		$(0.09 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ sextant asymmetry parameter		$(0.18 \pm 0.16) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ quadrant asymmetry parameter		$(-0.17 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\gamma$ left-right asymmetry parameter		$(0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$ parameter β (D-wave)		-0.02 ± 0.07 (S = 1.3)
$\Gamma(\eta \to \pi^0\gamma)/\Gamma_{total}$		$<9 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0\pi^0\gamma)/\Gamma_{total}$		$<5 \times 10^{-4}$, CL = 90%
$\Gamma(\eta \to \pi^0\pi^0\pi^0\gamma)/\Gamma_{total}$		$<6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to 3\gamma)/\Gamma_{total}$		$<1.6 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 e^+ e^-)/\Gamma_{total}$	[a]	$<4 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 \mu^+ \mu^-)/\Gamma_{total}$	[a]	$<5 \times 10^{-6}$, CL = 90%
$\Gamma(\omega(782) \to \eta\pi^0)/\Gamma_{total}$		$<1 \times 10^{-3}$, CL = 90%
$\Gamma(\omega(782) \to 3\pi^0)/\Gamma_{total}$		$<3 \times 10^{-4}$, CL = 90%
c decay parameter of $\eta'(958)$		0.015 ± 0.018
asymmetry parameter for $\eta'(958) \to \pi^+\pi^-\gamma$ decay		-0.01 ± 0.04
$\Gamma(\eta'(958) \to \pi^0 e^+ e^-)/\Gamma_{total}$	[a]	$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to \eta e^+ e^-)/\Gamma_{total}$	[a]	$<2.4 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to 3\gamma)/\Gamma_{total}$		$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\pi^0)/\Gamma_{total}$	[a]	$<6.0 \times 10^{-5}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\eta)/\Gamma_{total}$	[a]	$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(J/\psi(1S) \to \gamma\gamma)/\Gamma_{total}$		$<2.2 \times 10^{-5}$, CL = 90%

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CP INVARIANCE

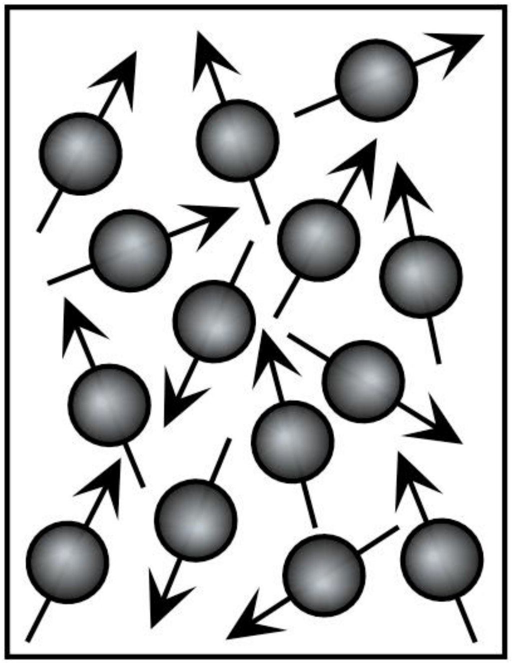
$\mathrm{Re}(d_\tau^W)$	$<0.50 \times 10^{-17}$ e cm, CL = 95%
$\mathrm{Im}(d_\tau^W)$	$<1.1 \times 10^{-17}$ e cm, CL = 95%
$\Gamma(\eta \to \pi^+\pi^-)/\Gamma_{total}$	$<1.3 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0\pi^0)/\Gamma_{total}$	$<3.5 \times 10^{-4}$, CL = 90%
$\Gamma(\eta \to 4\pi^0)/\Gamma_{total}$	$<6.9 \times 10^{-7}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^+\pi^-)/\Gamma_{total}$	$<2.9 \times 10^{-3}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^0\pi^0)/\Gamma_{total}$	$<9 \times 10^{-4}$, CL = 90%
$K^\pm \to \pi^\pm\pi^+\pi^-$ rate difference/average	$(0.08 \pm 0.12)\%$
$K^\pm \to \pi^\pm\pi^0\pi^0$ rate difference/average	$(0.0 \pm 0.6)\%$
$K^\pm \to \pi^\pm\pi^0\gamma$ rate difference/average	$(0.9 \pm 3.3)\%$
$K^\pm \to \pi^\pm\pi^+\pi^-$ $(g_+ - g_-)\,/\,(g_+ + g_-)$	$(-1.5 \pm 2.2) \times 10^{-4}$
$K^\pm \to \pi^\pm\pi^0\pi^0$ $(g_+ - g_-)\,/\,(g_+ + g_-)$	$(1.8 \pm 1.8) \times 10^{-4}$

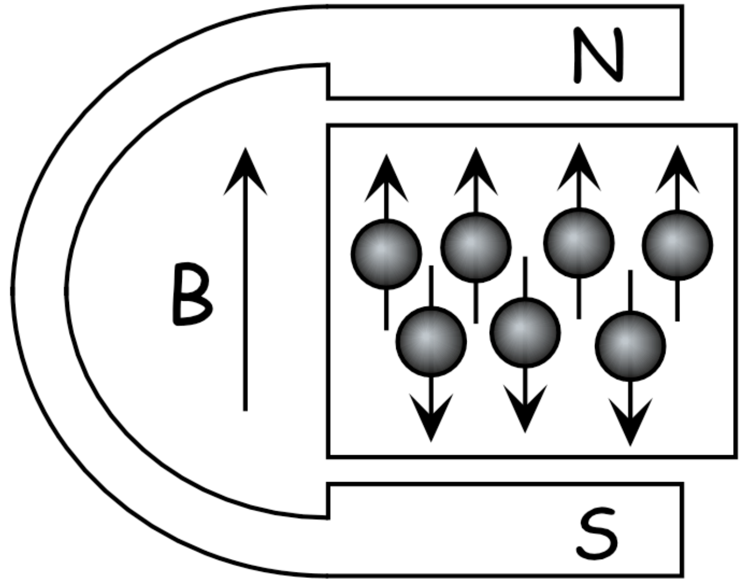
Only weak upper limits

Improve upper limits by factor >10

Polarised Target

Polarisation = 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%

P=100% in reality not so easy to realise:
Complicated interplay between

Polarising force	~	magnetic field B
and		
Depolarising force	~	thermal motion of spin particles (temperature T – relaxation)

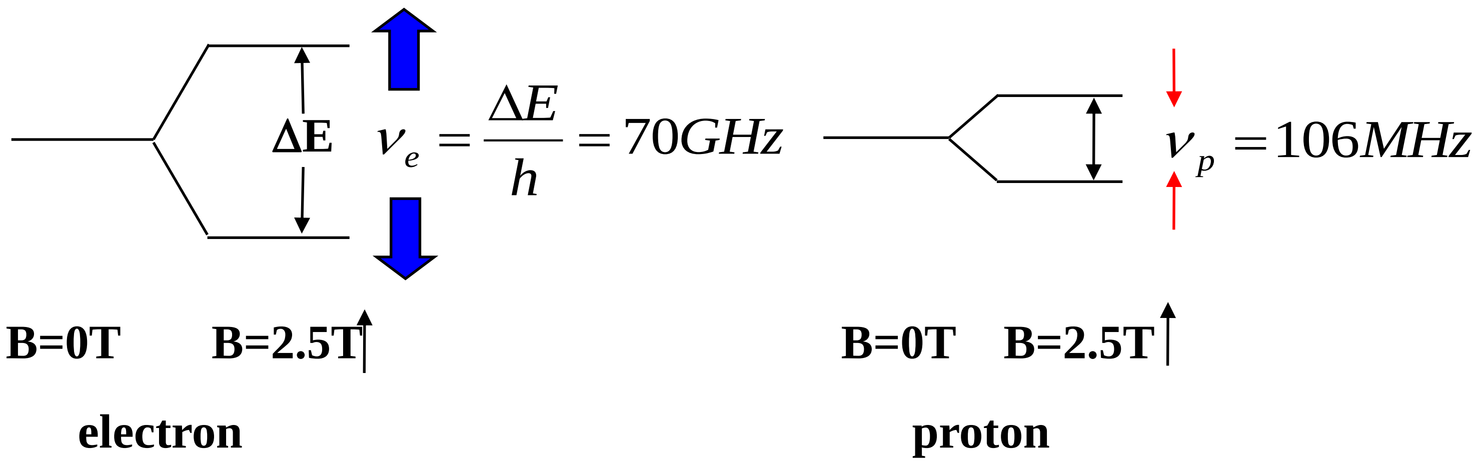
Examples:

$B = 10^{-5}$ Tesla (earth magnetic field)
T = 25° Celsius (room temperature) ➡ $P = 10^{-12}\%$

B = 2.5 Tesla (superconducting magnets)
T = -273° Celsius (refrigerators) ➡ P = 100%DNP (particle physics)

B = 1 Tesla (superconducting magnets)
T = 37° Celsius (body temperature) ➡ $P = 10^{-8}\%$ MRI (medicine)

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



$$\nu_e = \frac{\Delta E}{h} = 70GHz$$

$$\nu_p = 106MHz$$

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)

Model: Solid State Effect (SSE)

$$H = H_{SZ} + H_{IZ} + H_{IS} + H_{II} + H_{ss}$$

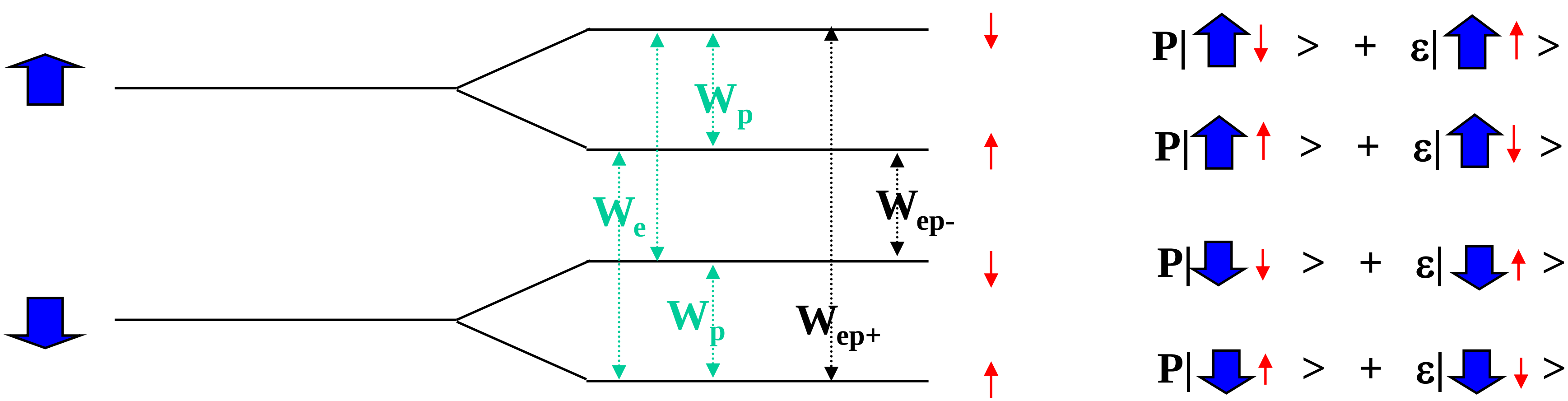
- H_{SZ}: $g_e \mu_e \sum_k B S_k$
- H_{IZ}: $g_p \mu_p \sum_j B I_j$
- H_{II}: small, $\frac{g_e \mu_e}{g_p \mu_p} \approx 660$
- H_{ss}: small distance e- big (~r^{-3})

Zeemann

Dipol-Dipol : $H_{IS} = g_e \mu_e g_p \mu_p \sum_{i,k} r_{ik}^{-3} \left[I_i \cdot S_k - \frac{3(I_i r_{ik})(S_k r_{ik})}{r_{ik}^2} \right]$

Mixing of the energylevels

$$\varepsilon \approx \frac{B_l}{B} \approx 10^{-2} \qquad B_l \propto \frac{\mu_e S_k}{r^3}$$



Magnetic Dipole transition allows Spin flip (Δm=+-1) of electrons or protons.

Probability to pump forbidden transitions W_{ep+} or W_{ep-} ~ ε^2

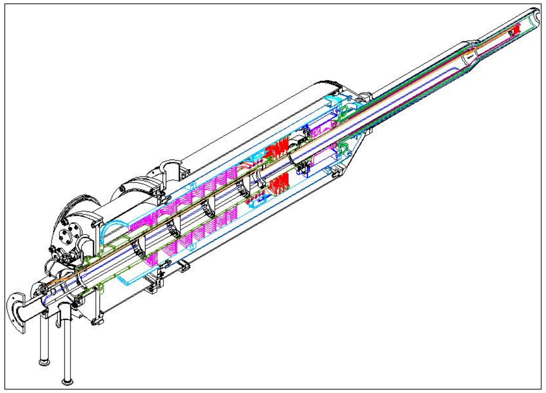
Components of the polarized target for the Crystal Ball detector

Similar to Bonn Target
[C.Bradtke et al., NIM **A436**, 430 (1999)]

He^3/He^4 Roots
$4000m^3/h$
Vacuum system

Targetmaterial
[Meyer, Bochum]
H-Butanol
D-Butanol

Mikrowaves
70GHz
Dynamic
Nuclear
Polarization



NMR-Apparatus
106MHz
Polarisation meas.

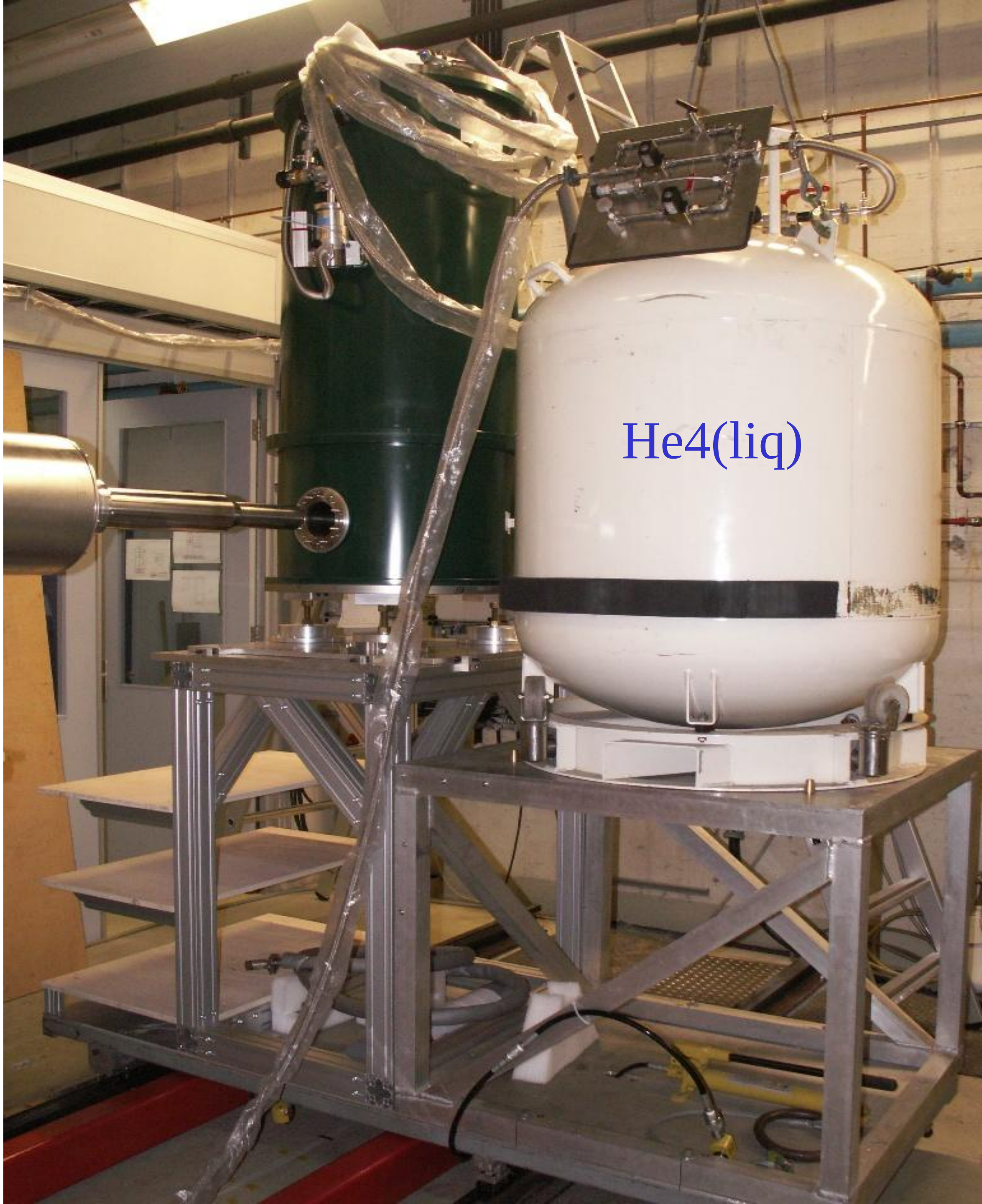
Horizontal He^3/He^4
Dilutionrefrigerator
(30mKelvin)
with internal
Holding coil

Superconducting
Polarization magnet
5Tesla

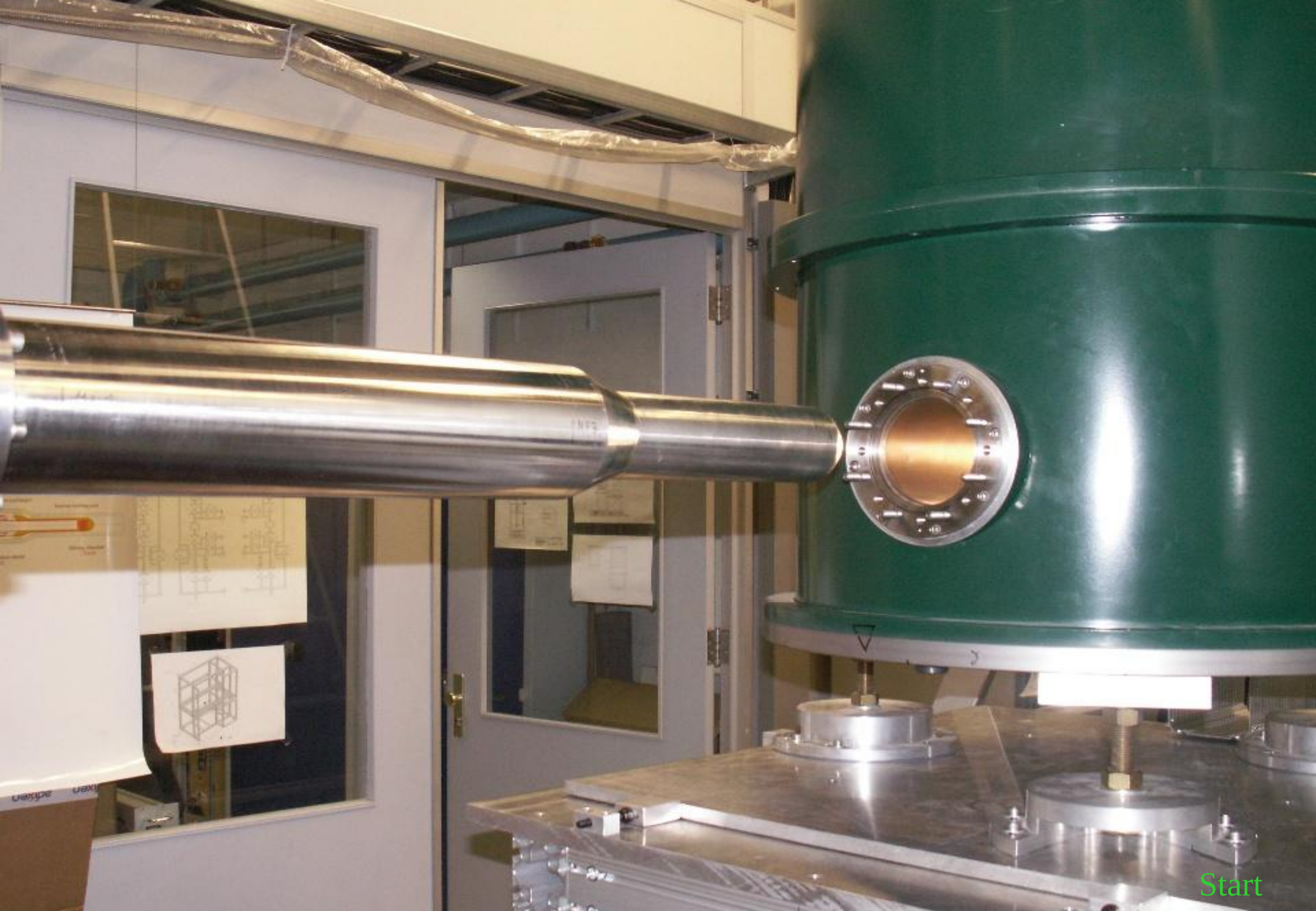
Polarizing magnet

Problem:

With this big magnet
a 4π acceptance
is not possible




Stop



Start

Polarized Target for Crystal Ball

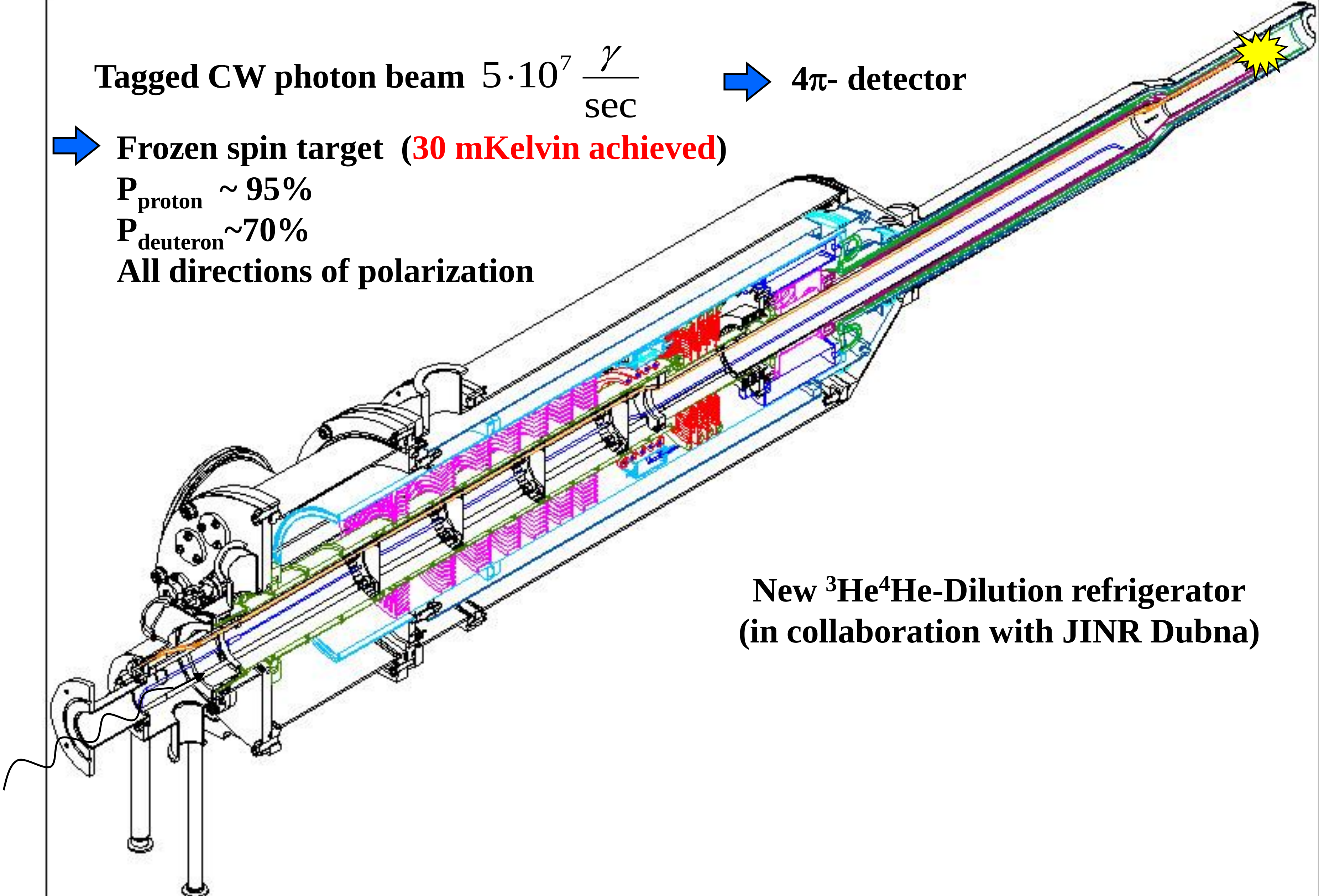
Tagged CW photon beam $5 \cdot 10^7 \frac{\gamma}{\text{sec}}$ ➡ **4π- detector**

➡ **Frozen spin target (30 mKelvin achieved)**

P_{proton} ~ 95%

$P_{deuteron}$~70%

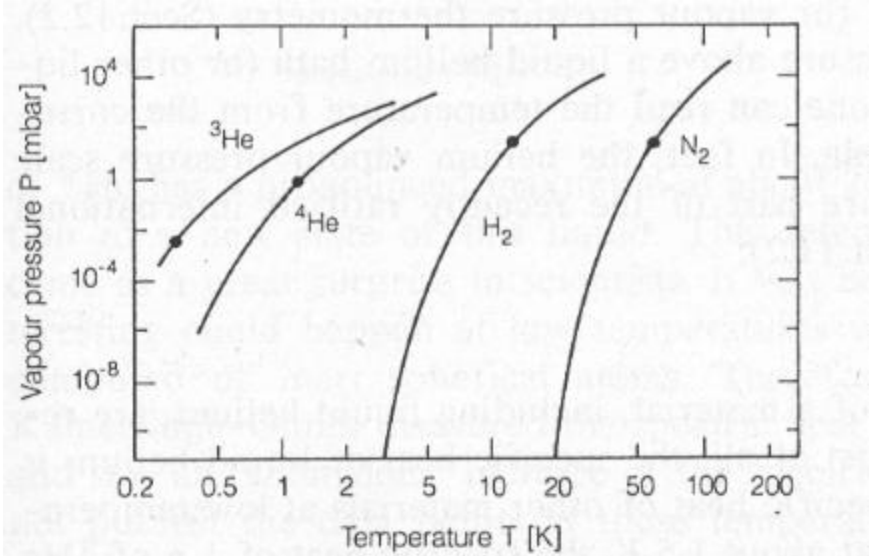
All directions of polarization



New $^3He^4He$-Dilution refrigerator

(in collaboration with JINR Dubna)

Cryogenics



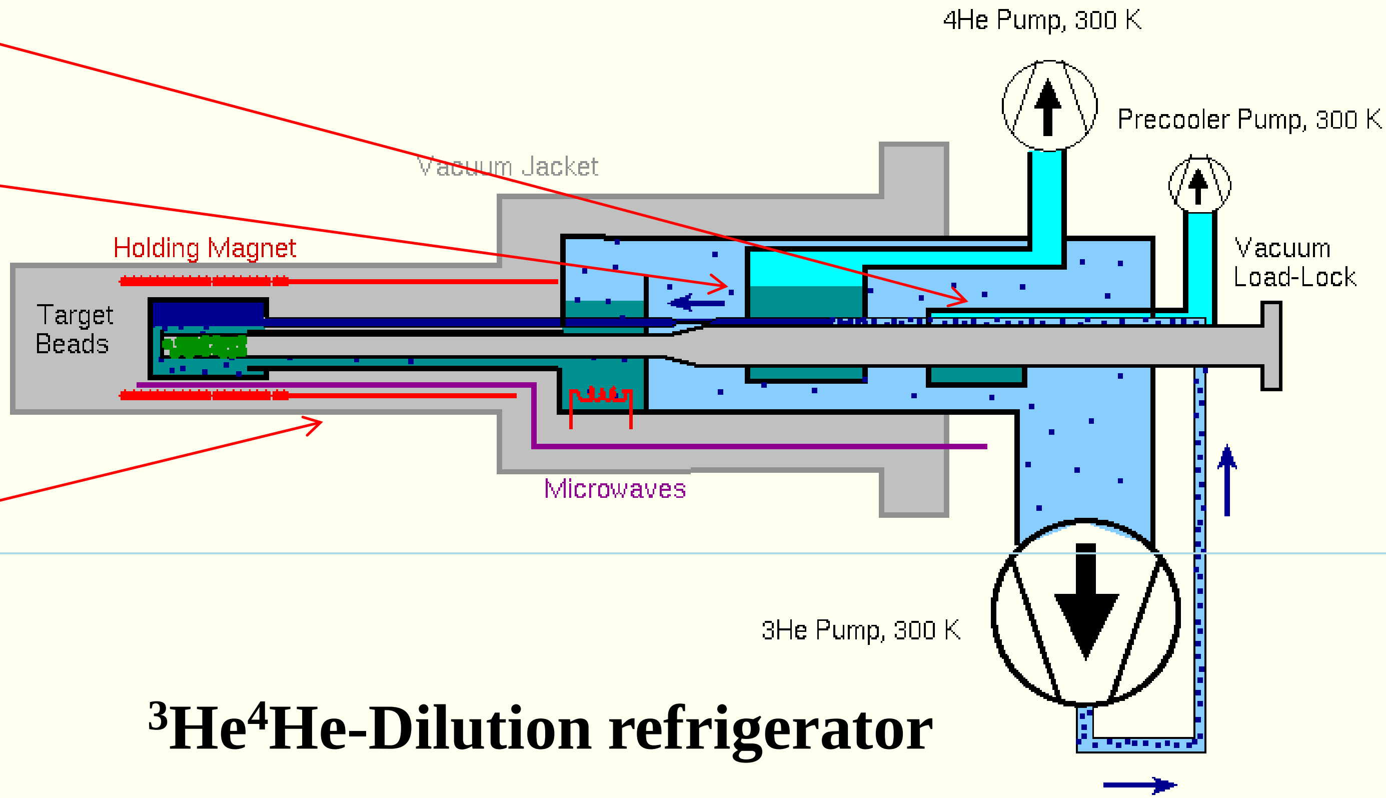
Evaporation cooling

2 Precooling stages:

Separator (4.2Kelvin pot)

Evaporator (1.5Kelvin)

Dilution circuit (0.03Kelvin)

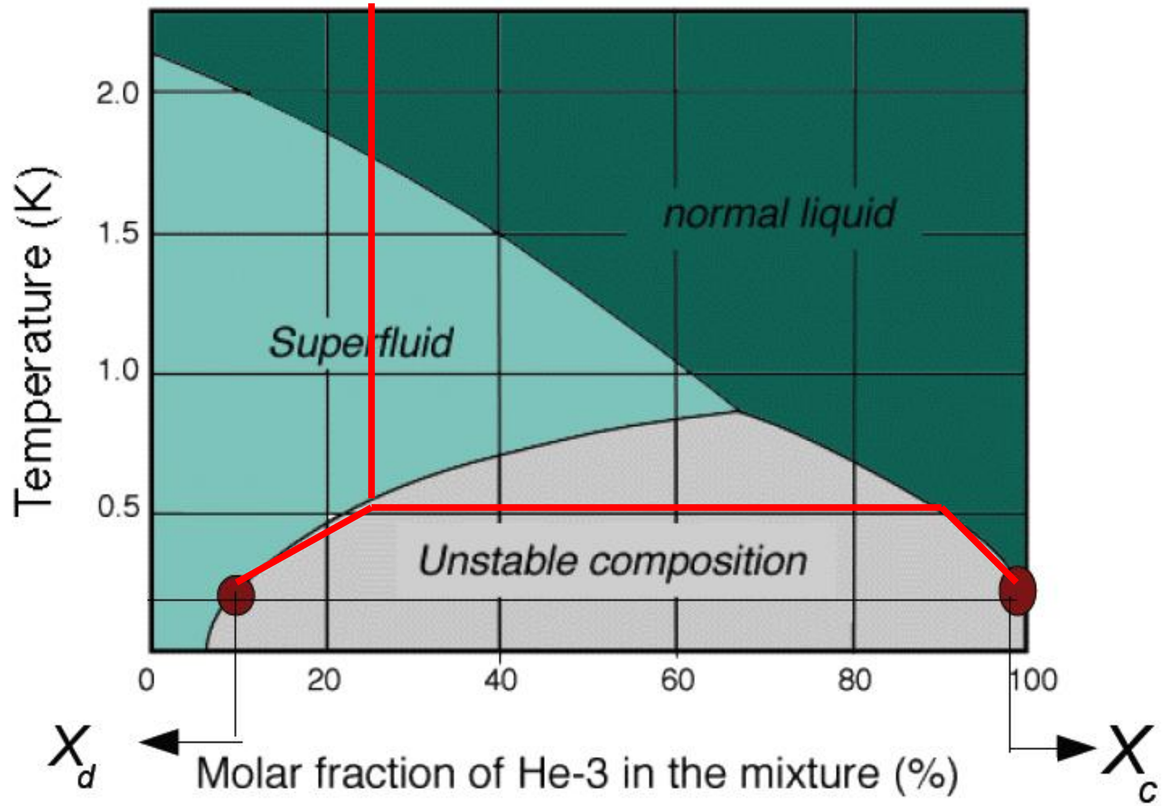


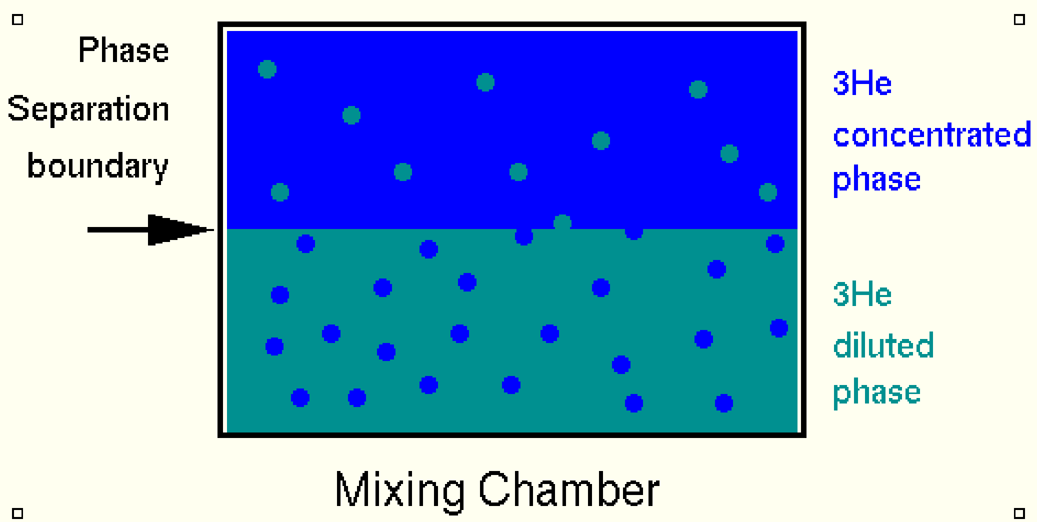
^{3}He^{4}He-Dilution refrigerator

^{3}He-^{4}He-Dilution Cooling

^{3}Helium: Spin ½, Fermion
^{4}Helium: Spin 0, Boson

Cooling a 25%- gas-mixture
from 300K to 0.6K





Separation of both phases

Further cooling using „dilution effect“

[3]Helium absorbs energy when it dissolved into diluted phase

$$Q = n \cdot [H_d(T) - H_c(T)] \approx 82nT^2$$

Heat Q absorbed by n moles 3Helium

Distillation in the „Still“ at 0.7K

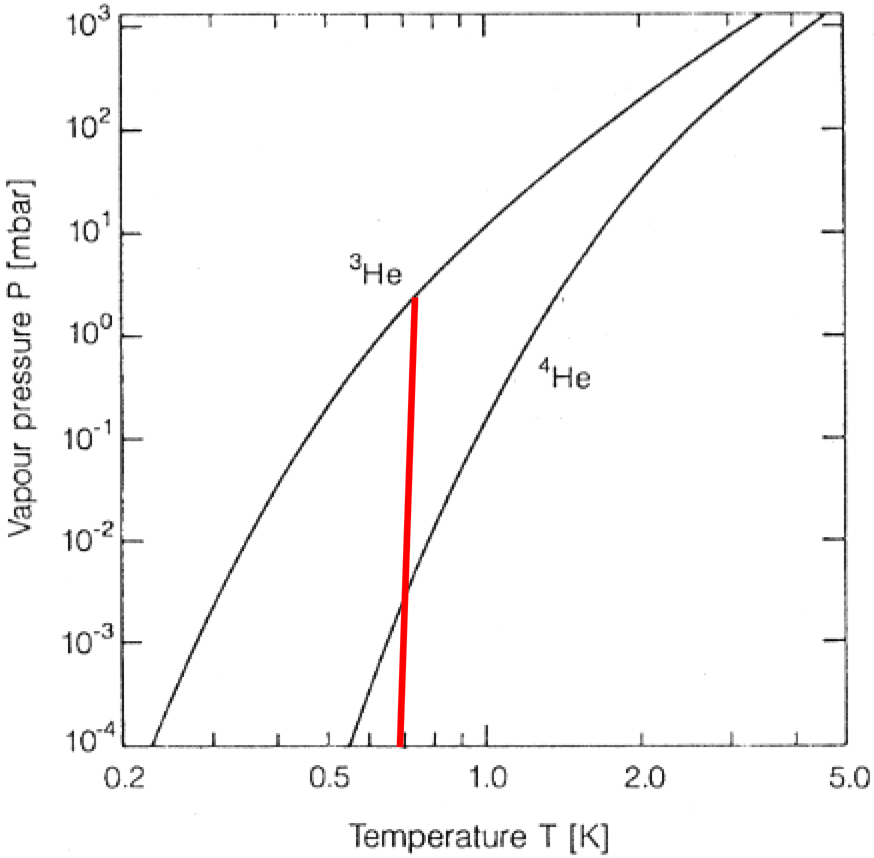
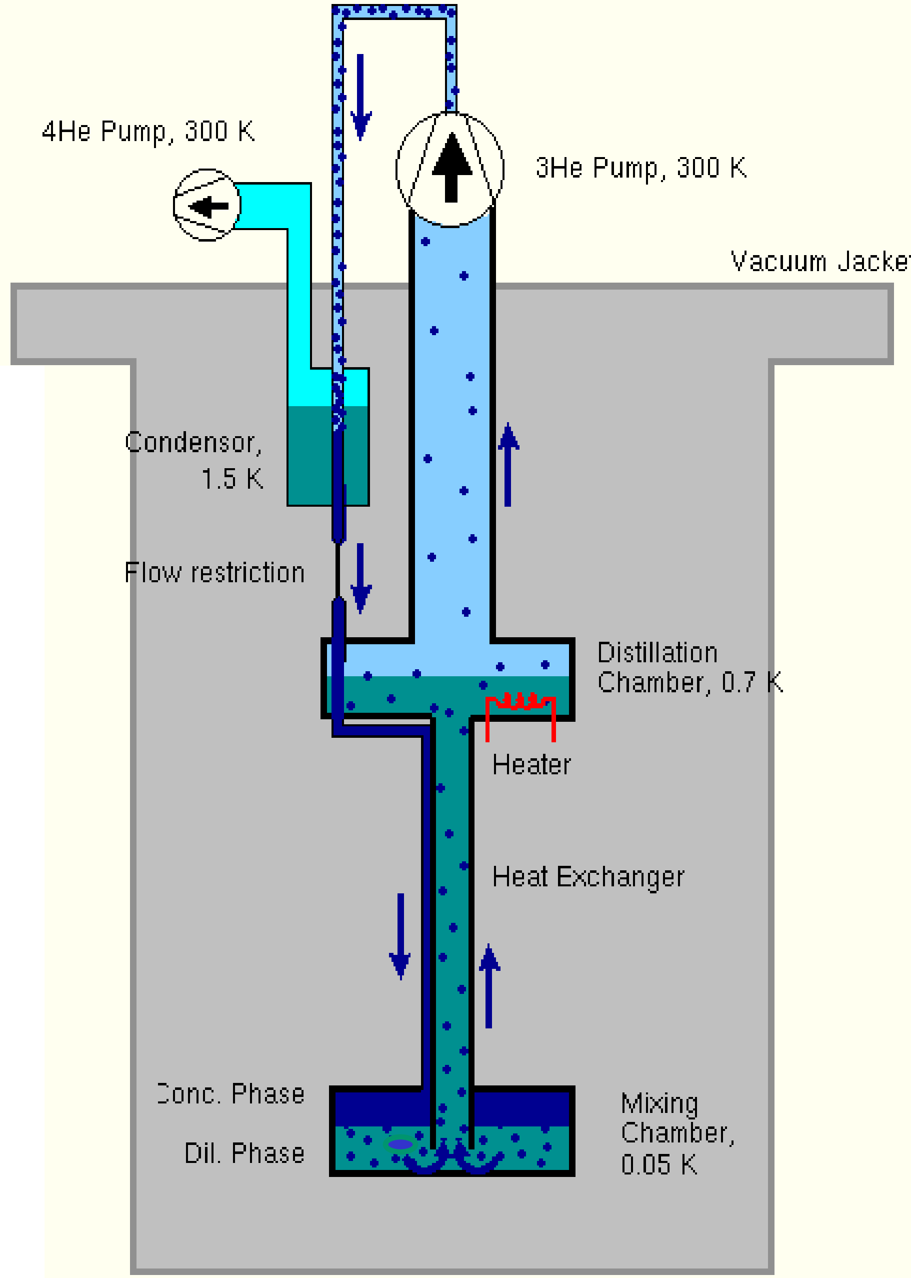


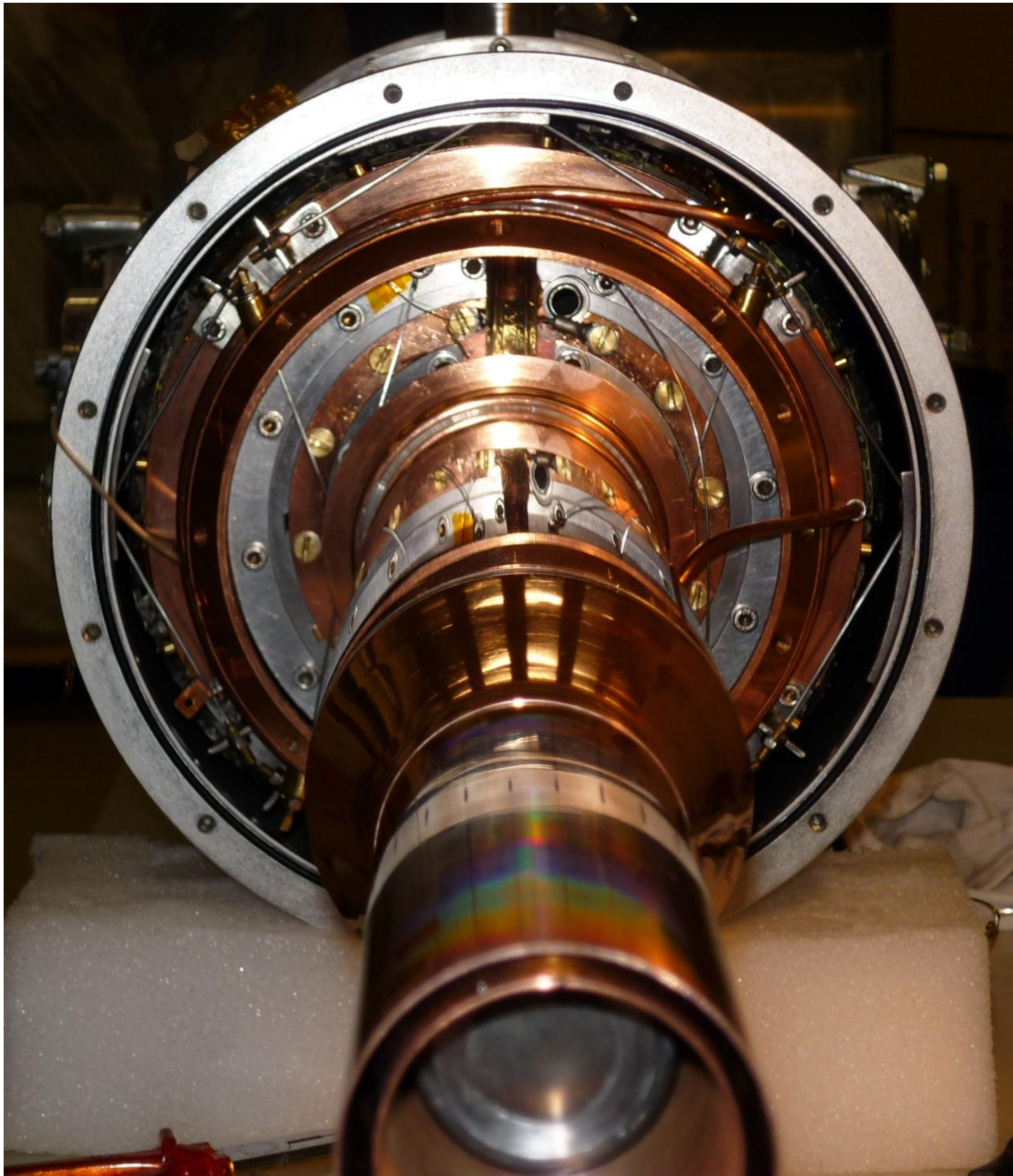
Fig.2.6. Vapour pressures of liquid ^{3}He and liquid ^{4}He



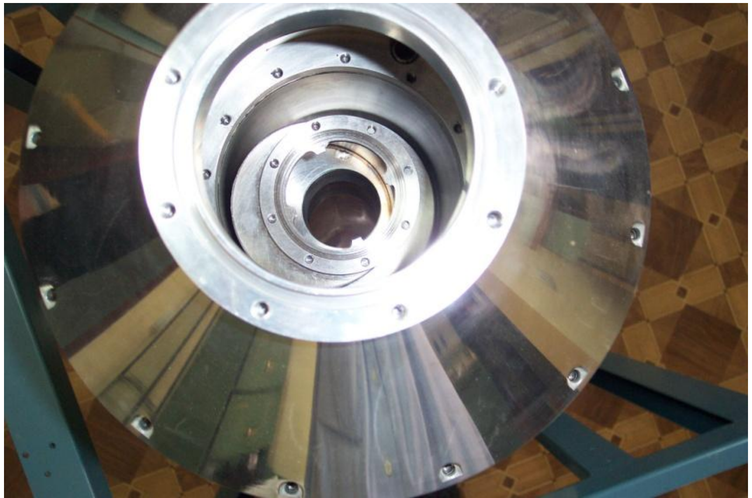
Impressions from the technical realisation

High temperature heat exchanger

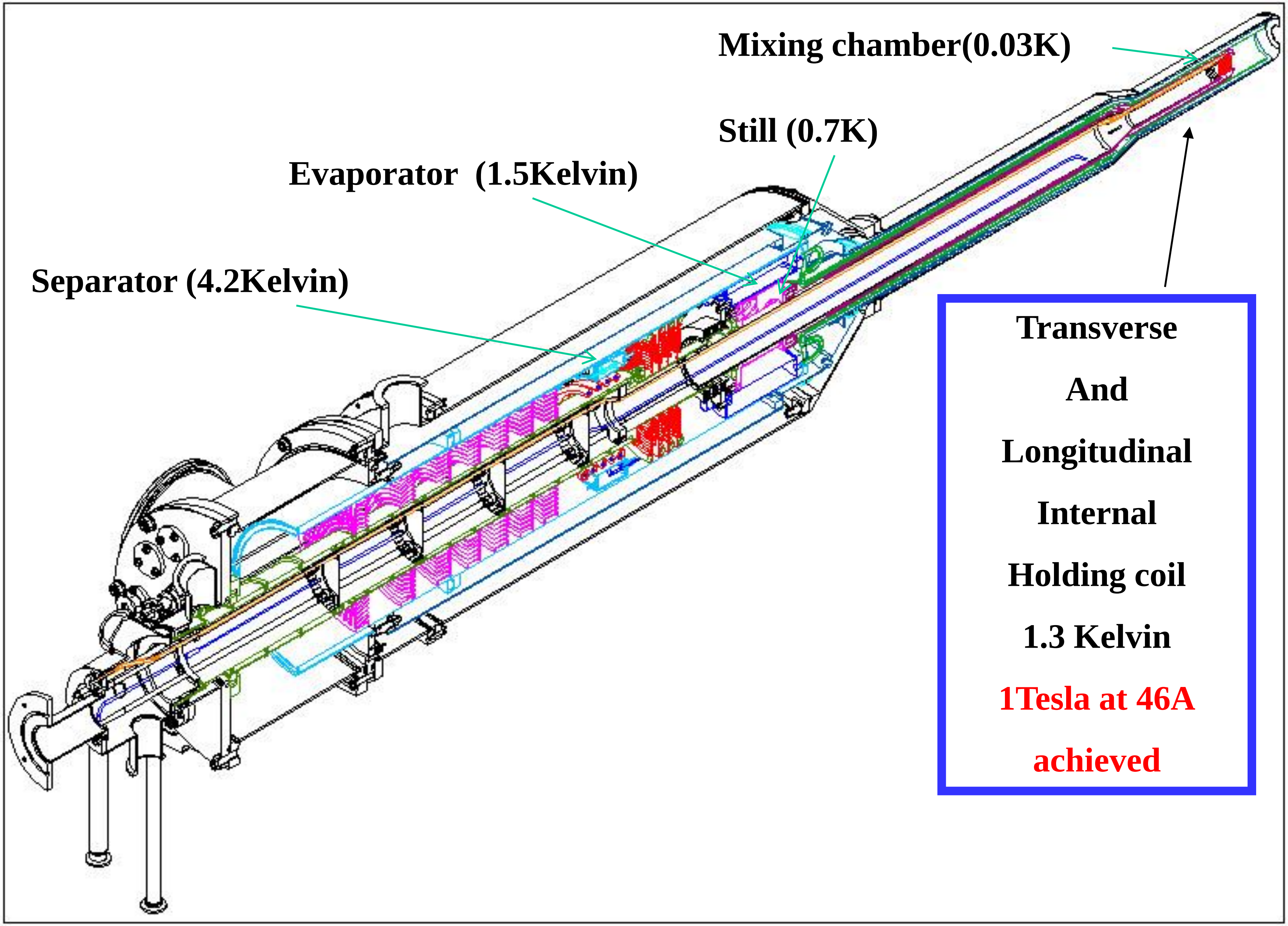
Alignment thermal radiation shields



Alignment still and evaporator



Mainz/Dubna Dilution refrigerator



Transverse

And

Longitudinal

Internal

Holding coil

1.3 Kelvin

1Tesla at 46A

achieved

Holding Coil

Coil has to be as thin as possible to allow low energetic particles to punch through.

➡

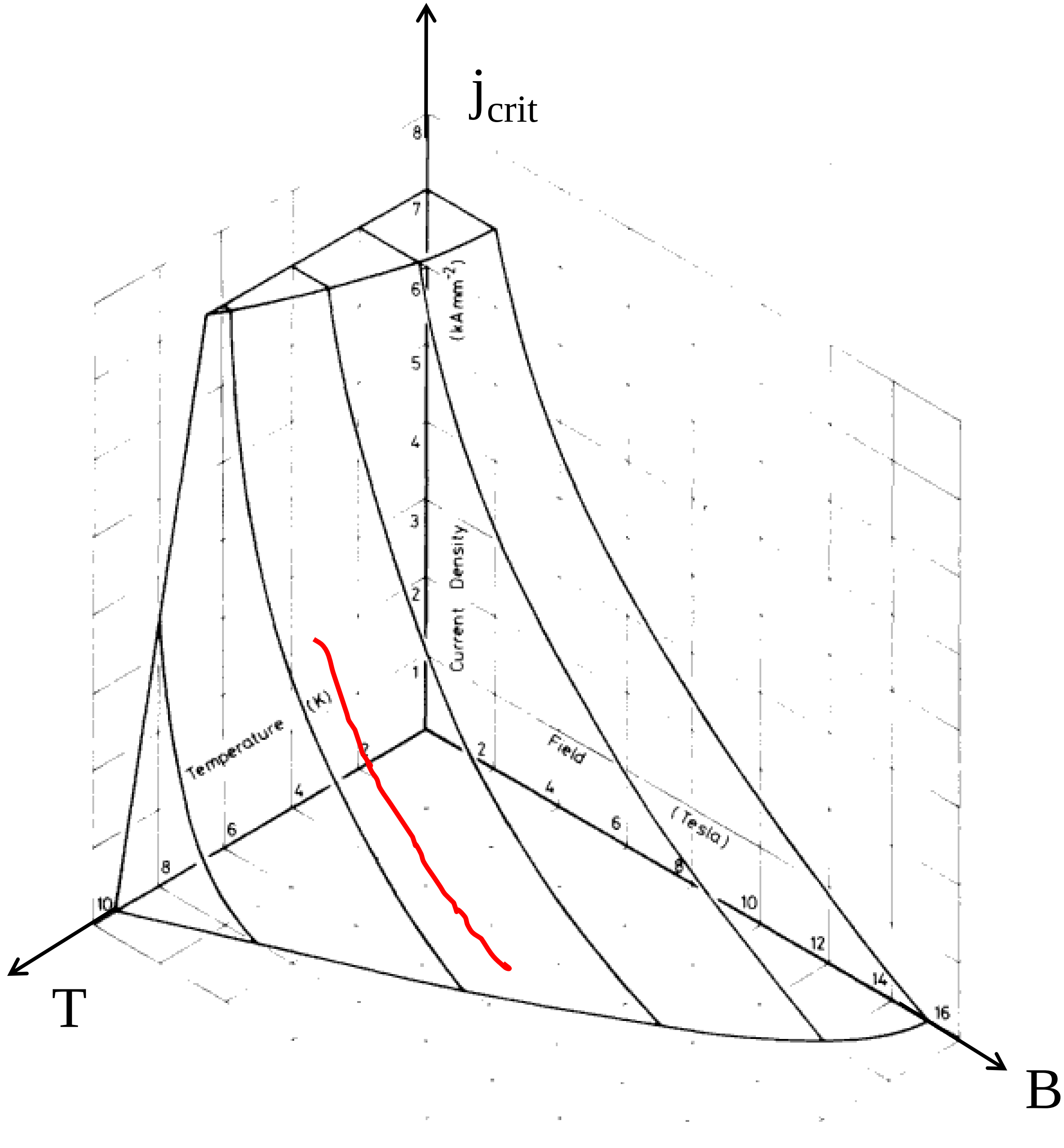
Subcooled Superconductor

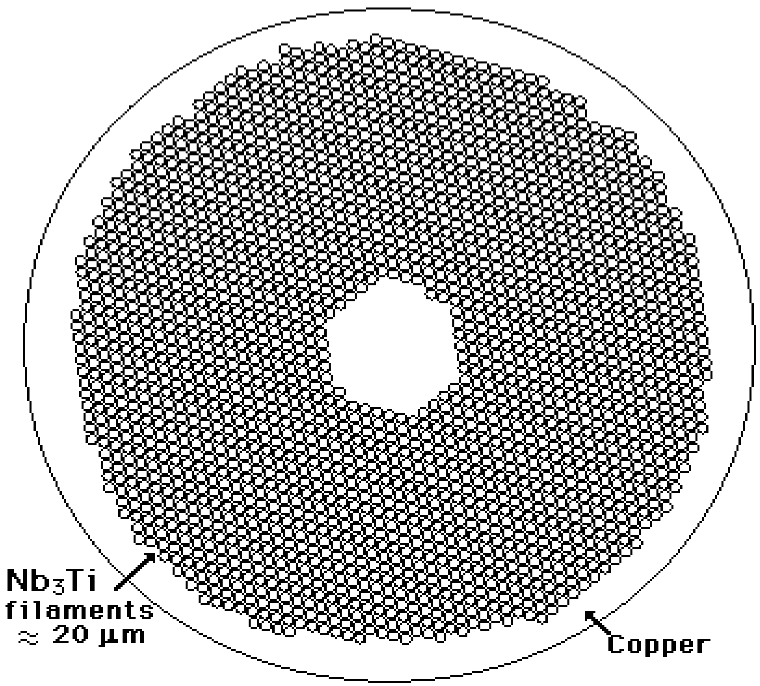
F54-1.35(0.20)TV

	1 T	2 T	3 T	4 T
I_c (A)	51.8	39.1	33.5	29.5

@4.2Kelvin

➡ @1.3Kelvin

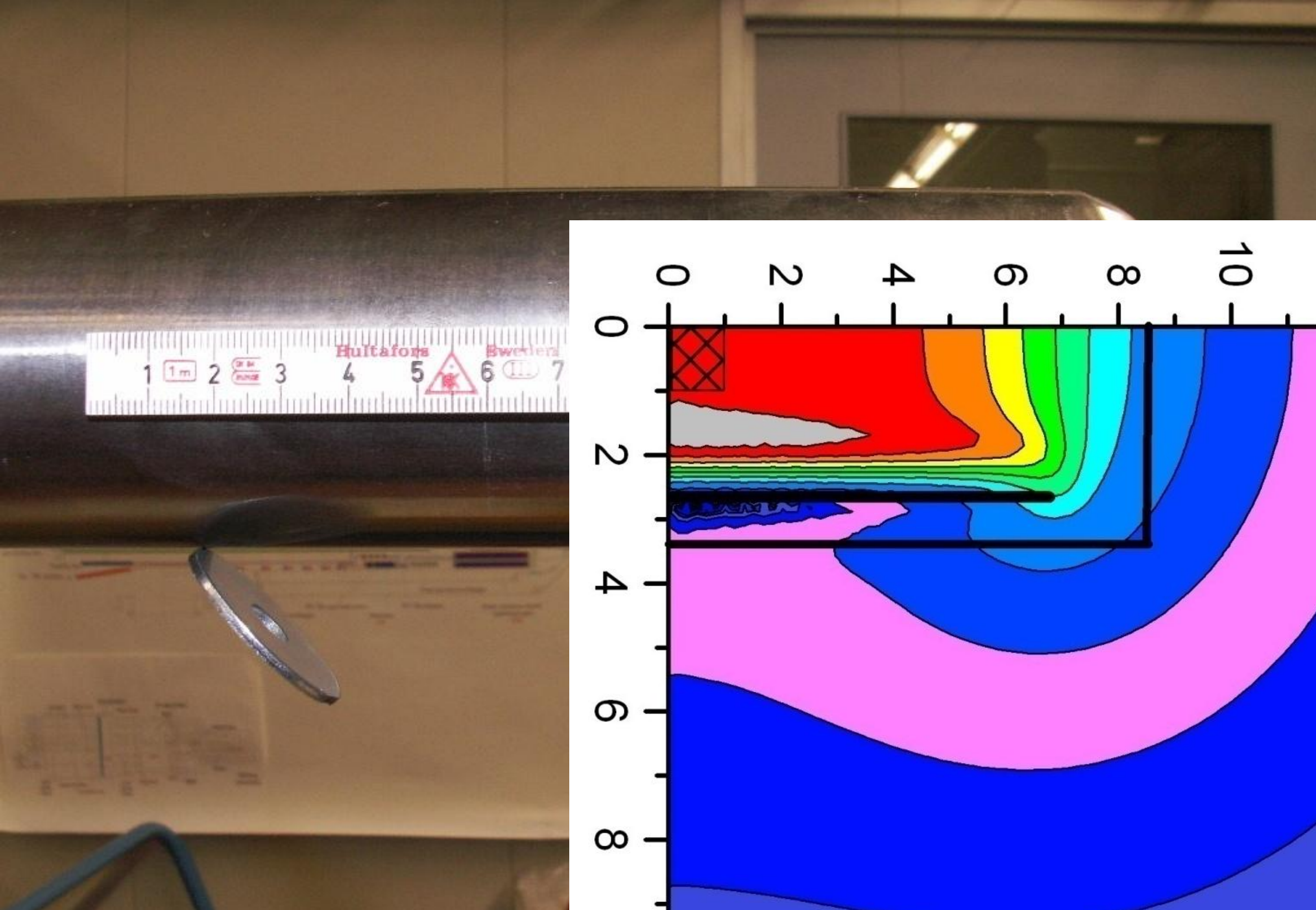


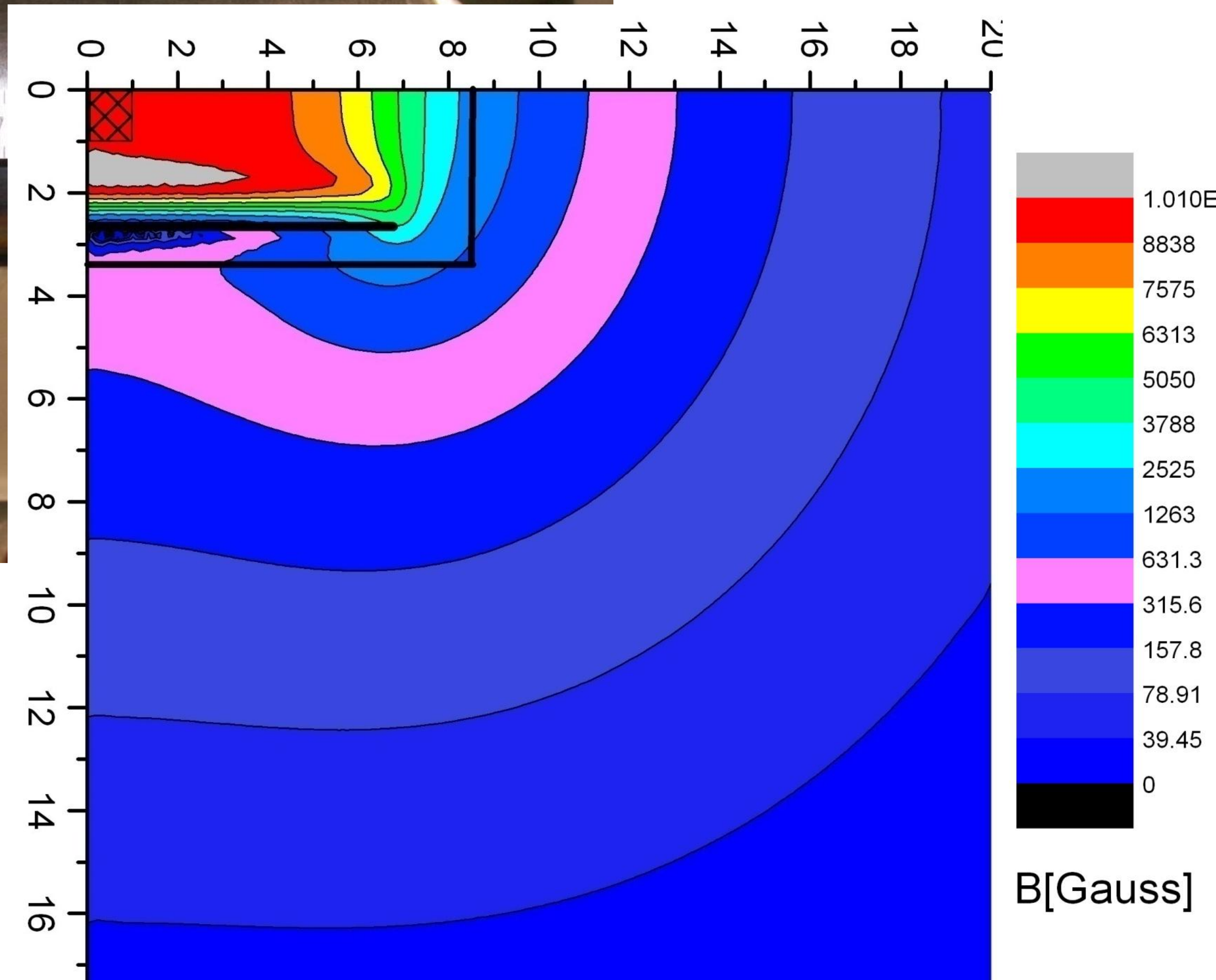


- Copper/scandium wire with 54 Nb-Ti filaments embedded in it.
- Cu:Sc=1.35:1
- Alloy composition: Nb47wt.%Ti
- Diameter=0.222mm
- It achieves currents up to 50A at 4.2K and 1T.

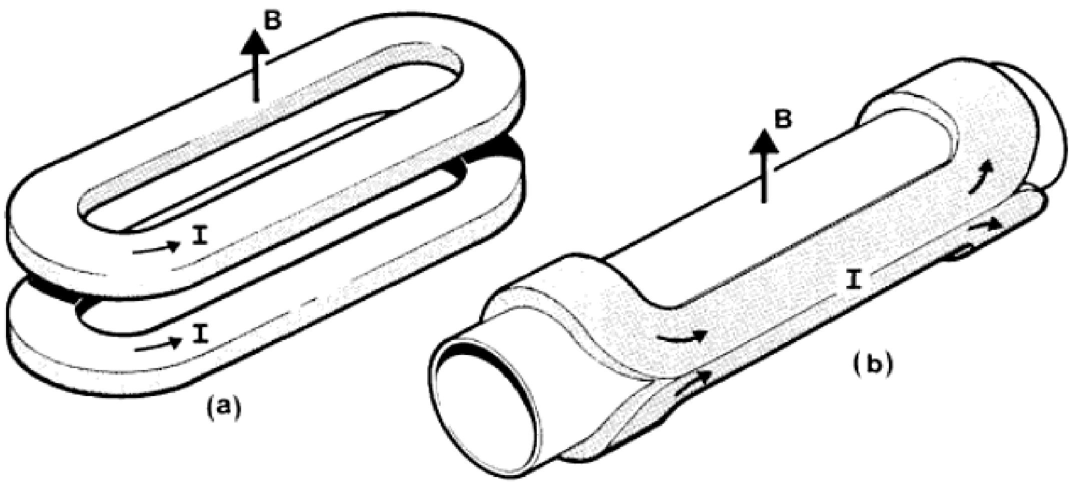
Coil winding in Mainz workshop
Glueing with Epoxy

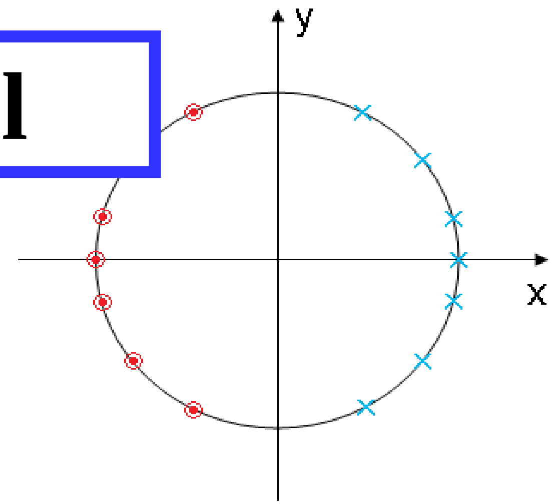
Holding Coil





Internal transverse holding coil



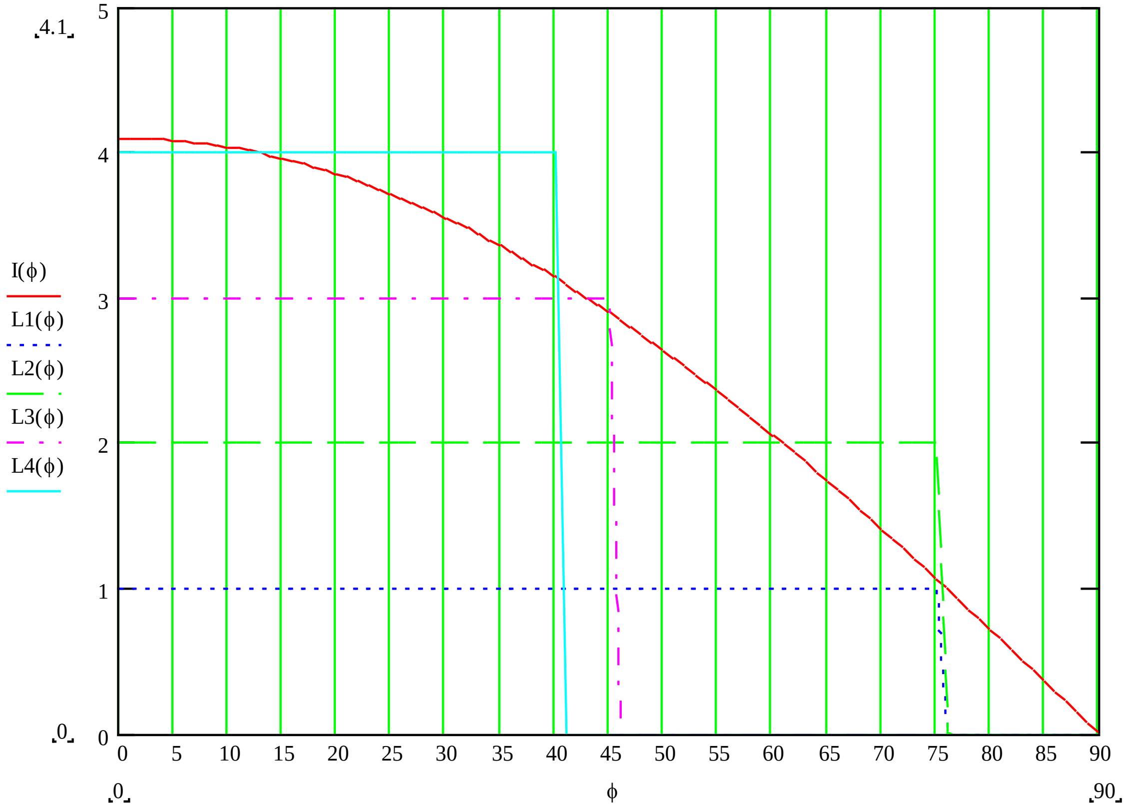


Ideal case for dipole magnet:

$$J(\Phi) \propto \cos\Phi$$

- Calculations done with Opera 3D.
- “Saddle” coil: winding must fit to the so-called overlapping ellipse or “cosine” shape of current distribution.
- Different layers are used to optimize the homogeniety.

Optimisation + Simulation



Ideal case for dipole magnet:

$$J(\theta) \propto \cos\theta$$

4-layer dipole:

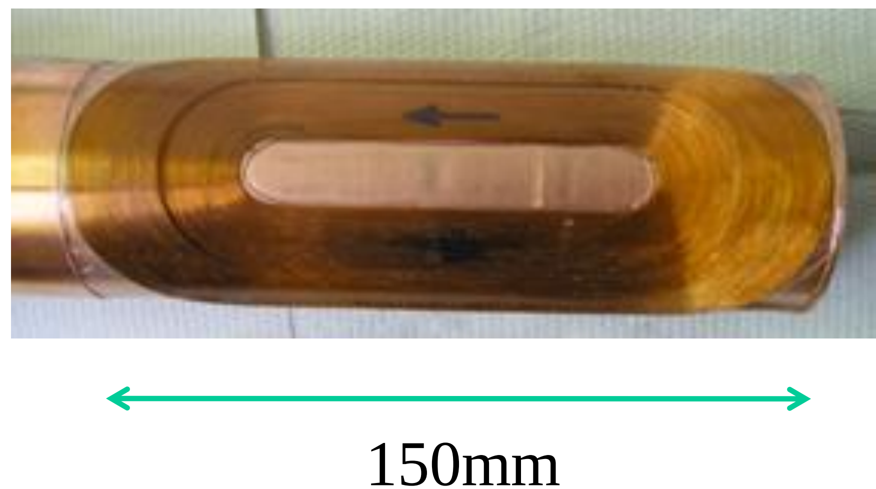
$N_1=N_2=138$

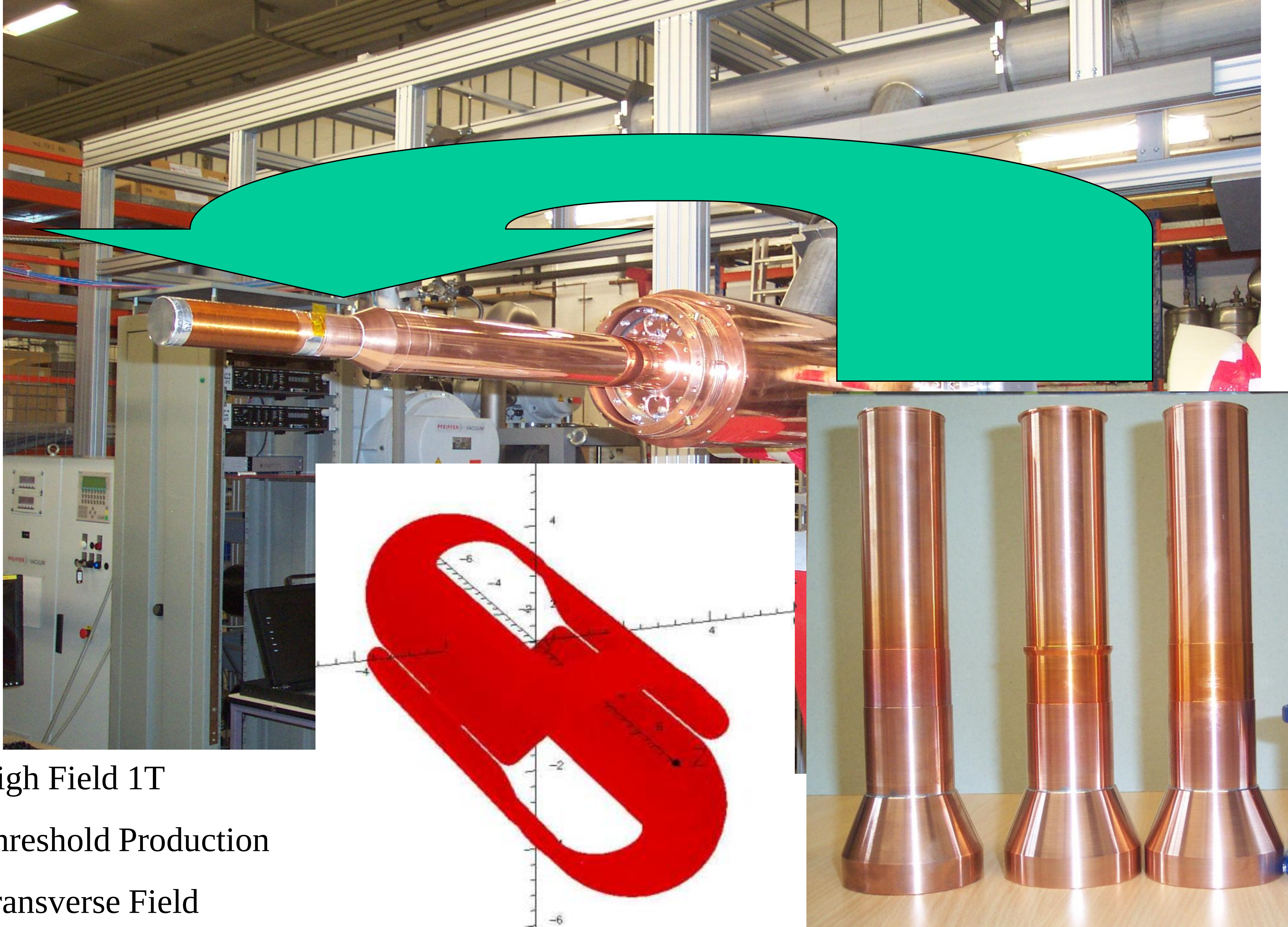
$N_3=N_4=78$

4-layer dipole:

$N_1=N_2=138$

$N_3=N_4=78$



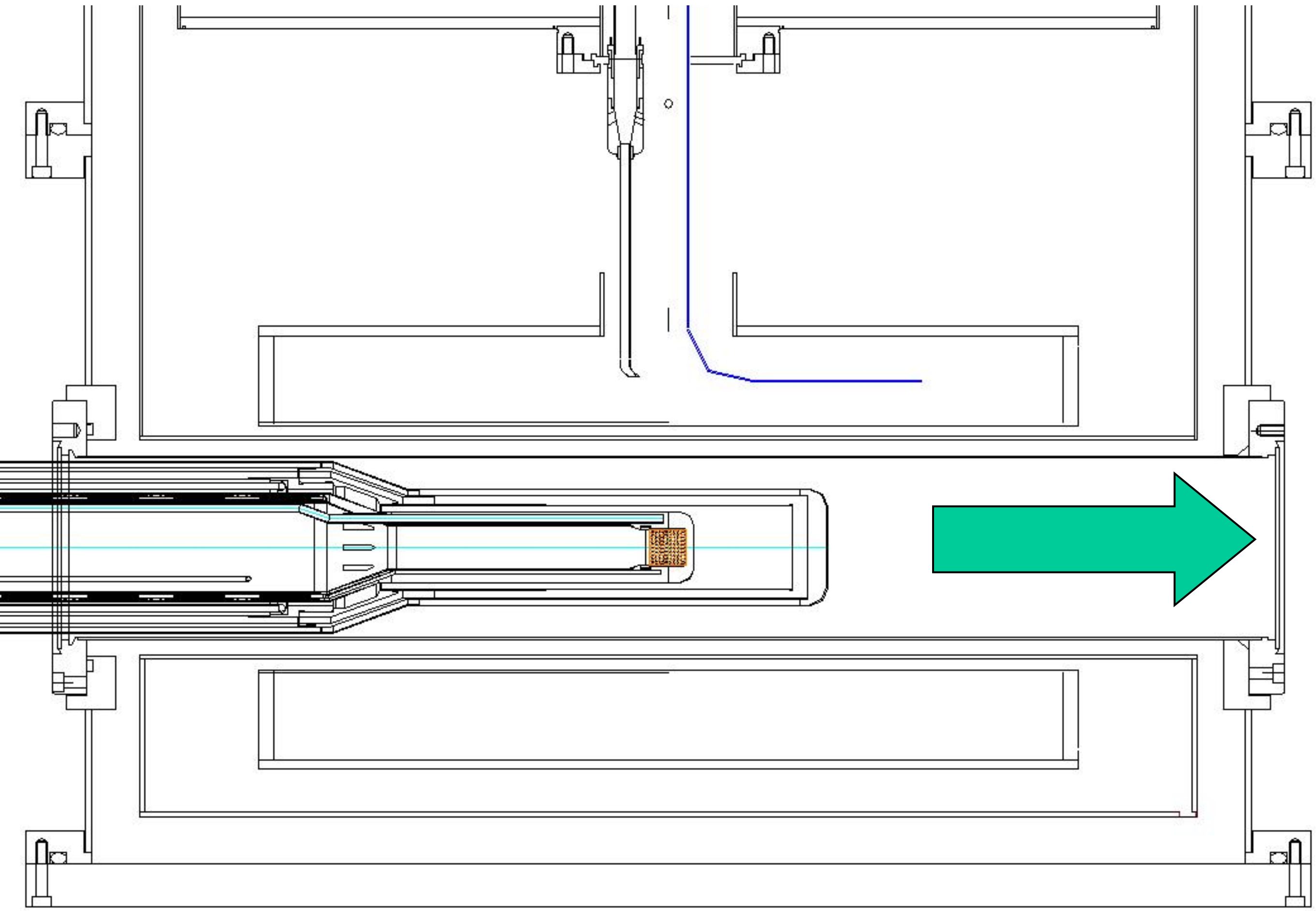


High Field 1T

Threshold Production

Transverse Field

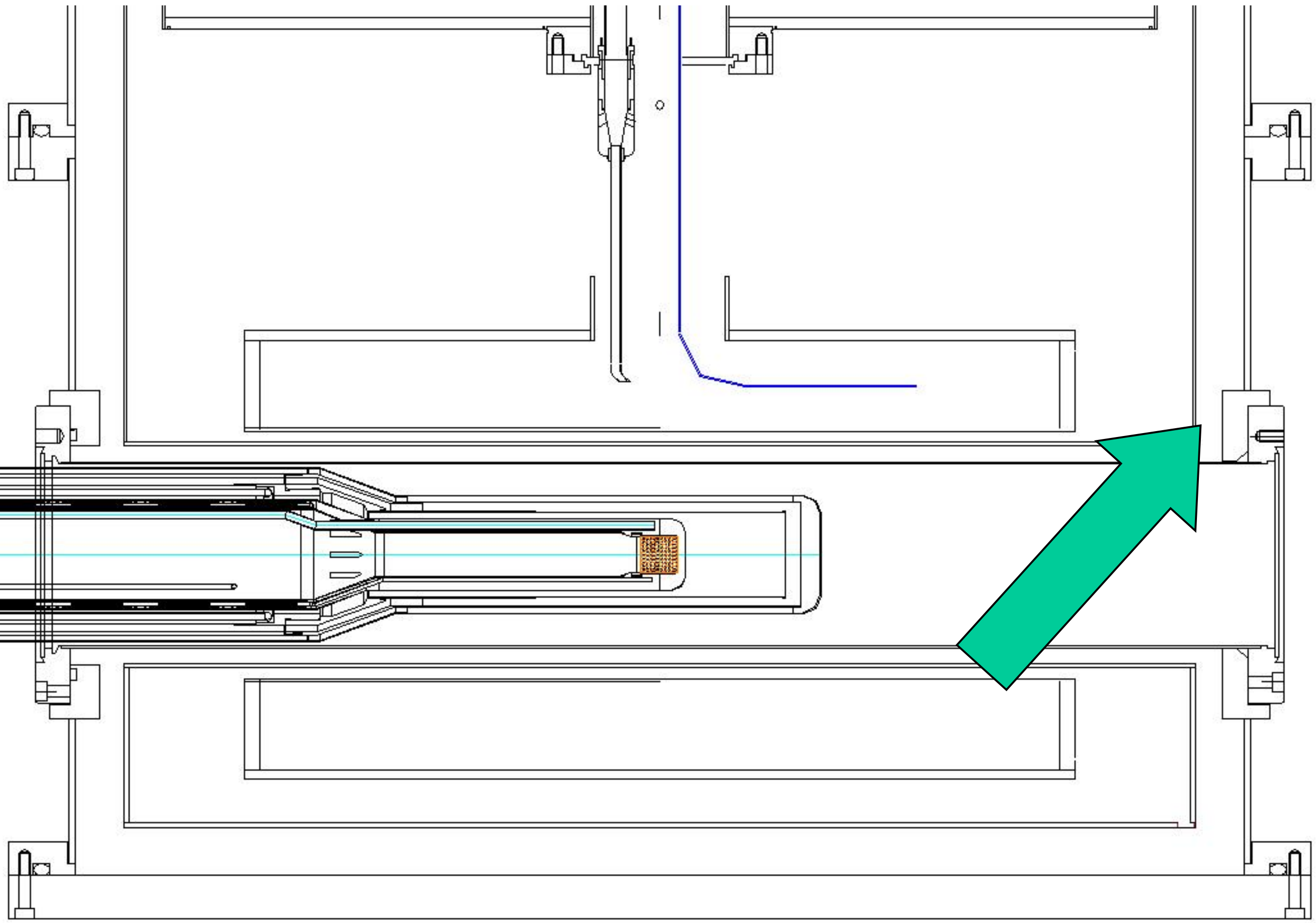
Rotation of the Holding Field



1) B_z=2.5Tesla
2) B_z=0.5Tesla

Superconducting 2.5Tesla Magnet for polarising in z-direction

Rotation of the Holding Field

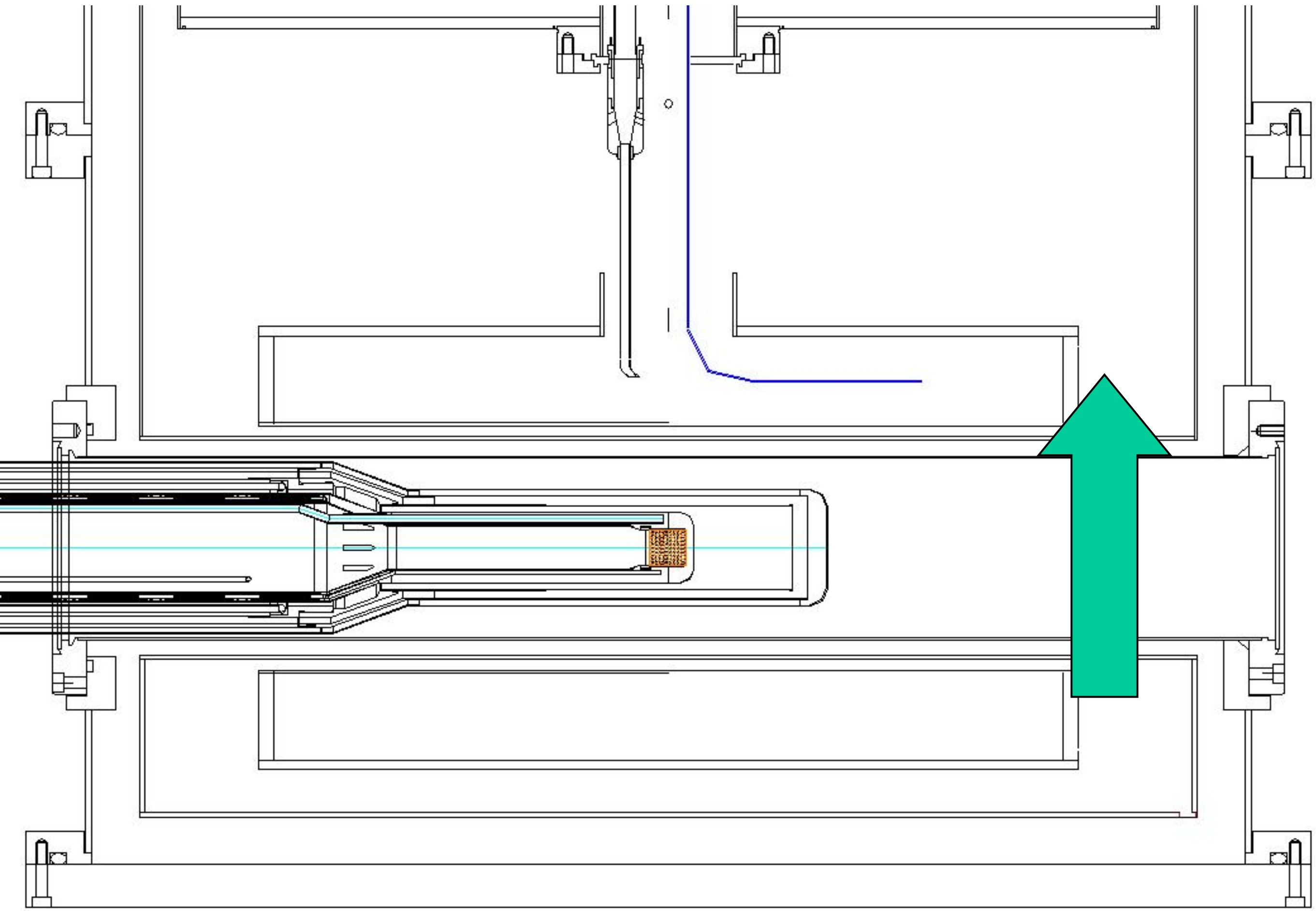


2) B_z=0.5Tesla

3) B_y=0.5Tesla

Superconducting 2.5Tesla Magnet for polarising in z-direction

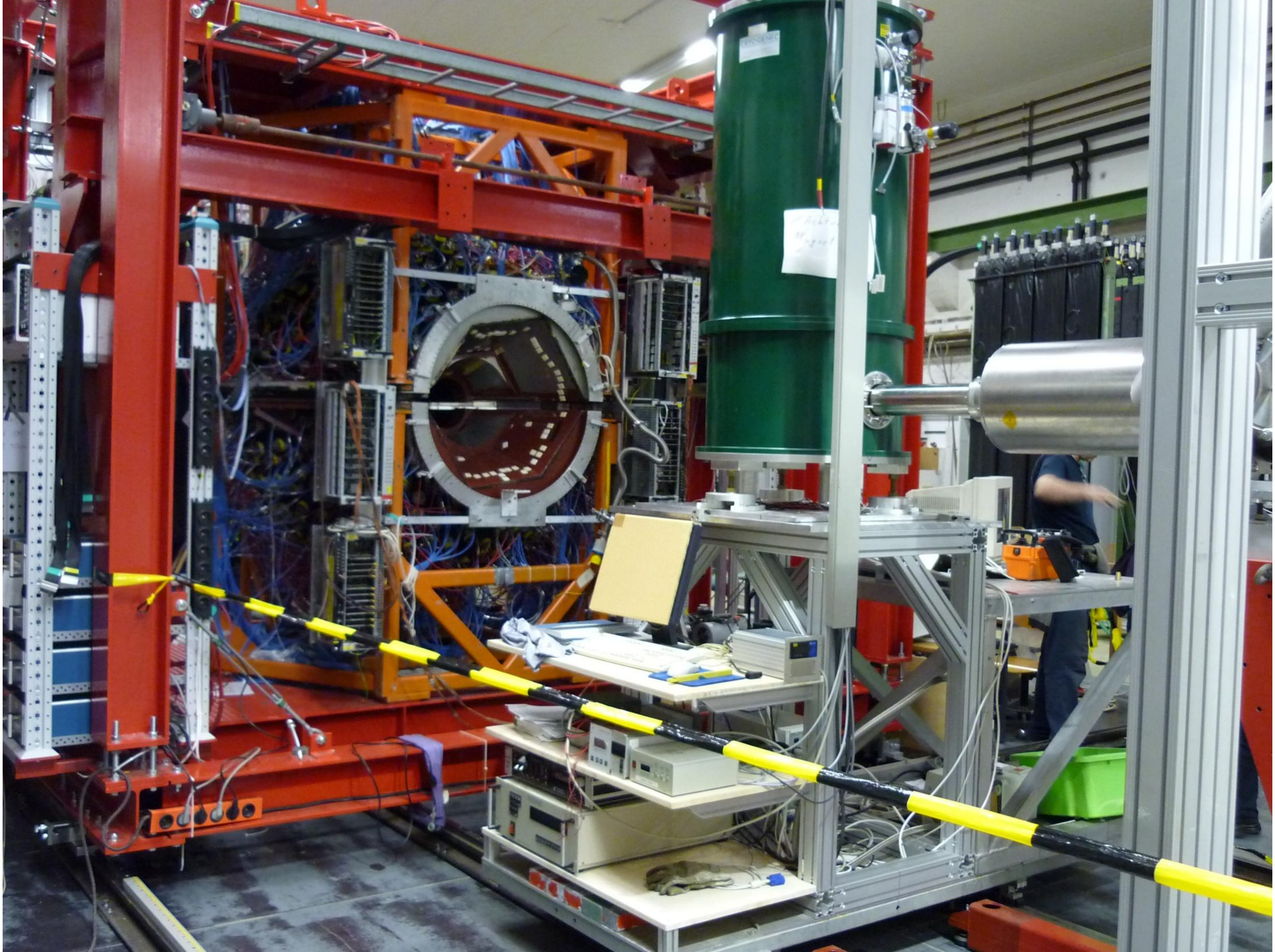
Rotation of the Holding Field



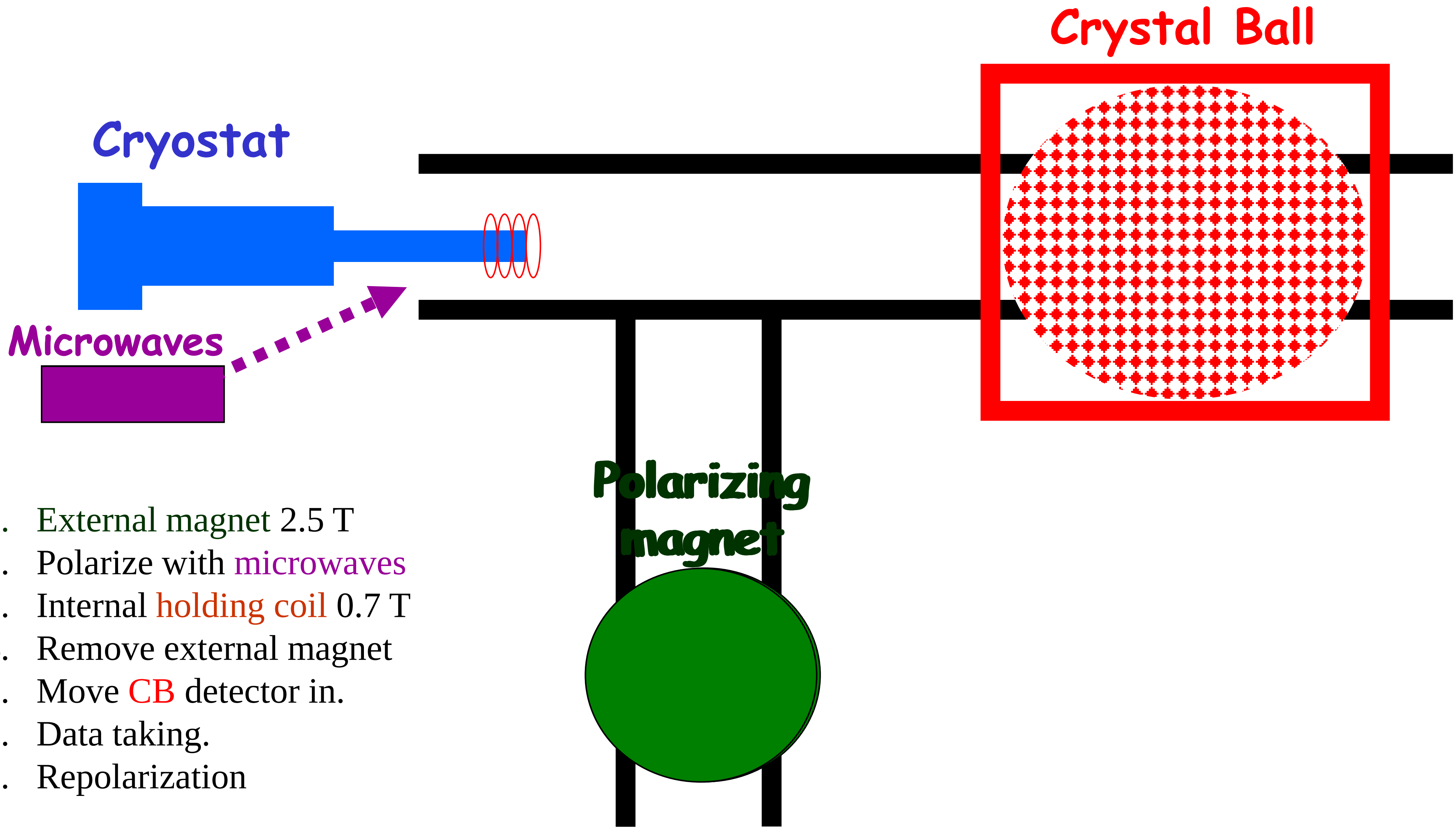
4) B_z=0.0Tesla

B_y=0.5Tesla

Superconducting 2.5Tesla Magnet for polarising in z-direction

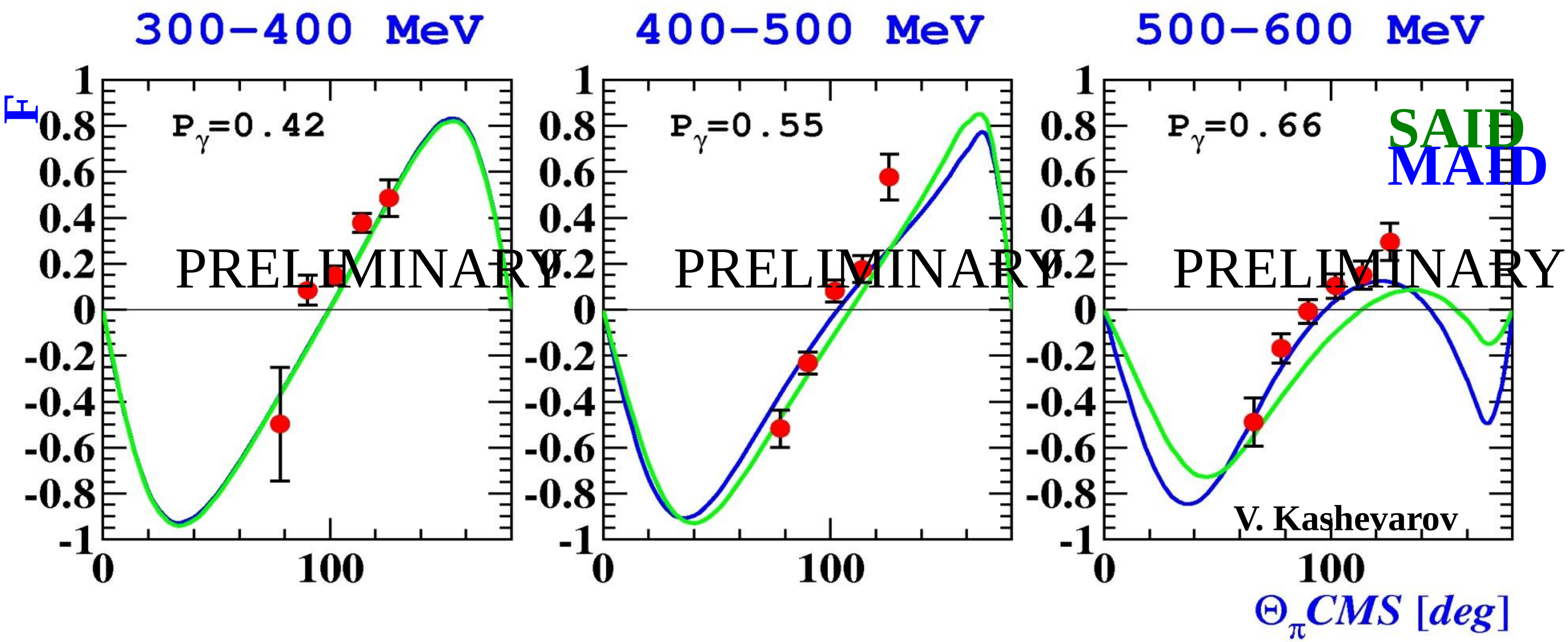


Frozen Spin Target Waltz



1. External magnet 2.5 T
2. Polarize with microwaves
3. Internal holding coil 0.7 T
4. Remove external magnet
5. Move CB detector in.
6. Data taking.
7. Repolarization

First measurement of transverse spin observable F in $\gamma p \to \pi^0 p$



- World first measurement of F – VERY PRELIMINARY!
- Need more work on P_γ (currently standard conditions assumed)
- Need to extend to full solid angle coverage (measure with TAPS)
- P_{targ} from average over time – need event-by-event normalisation
- However – everything works!

Double Polarised Experiments

Excitation Spectrum

1.- Longitudinal PT: a) Helicity Dependence E of Meson Photoproduction
b) Measurement of the G in single pion production

2.- Transverse PT: a) Transverse asymmetries T and F in η–photoproduction in the $S_{11}(1535)$ region
b) Spin observables in $\pi\eta$ photoproduction in the $D_{33}(1700)$ region

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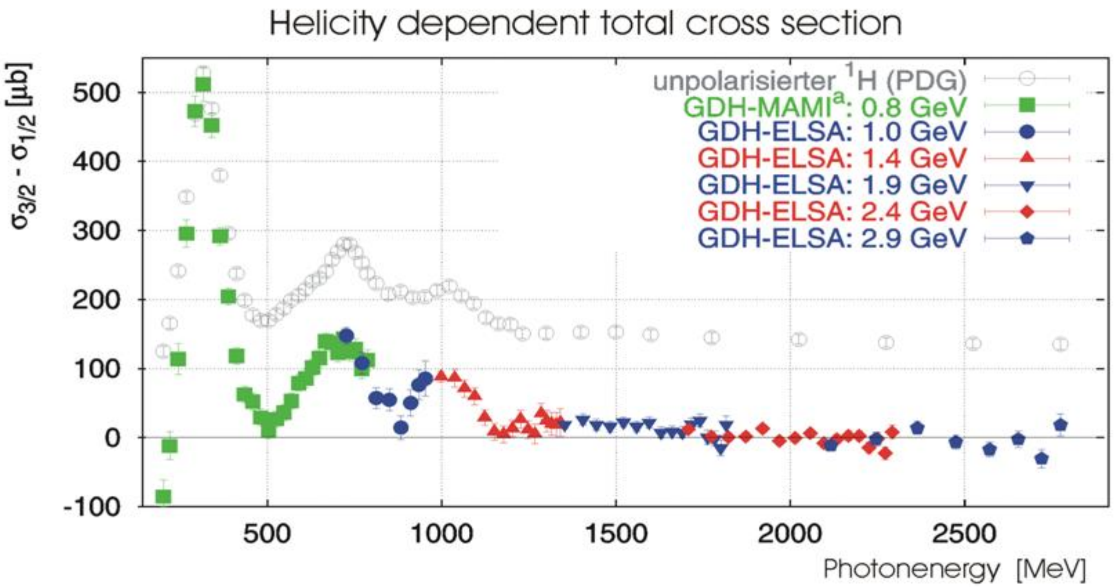
Fundamental Properties

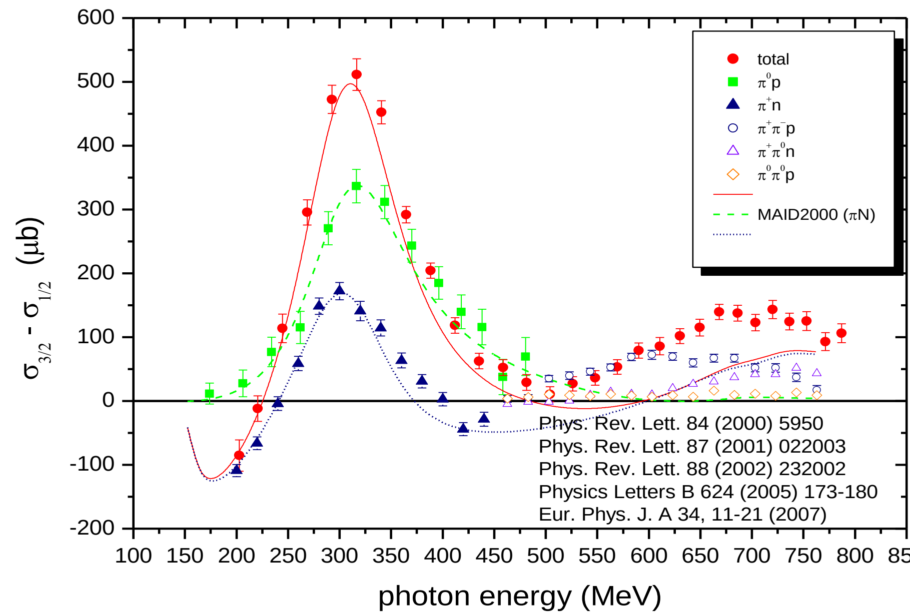
1.- Long. and trans. PT: Spin Polarisibilities

2.- Transverse PT: Transverse asymmetries T and F in π–photoproduction in the threshold region → $m_u - m_d$

A2-06-07/09: Helicity Dependence E of Meson Photoproduction on the Proton

650hours + 800hours





Published data: GDH-Experiment at ELSA and MAMI (DAPHNE).

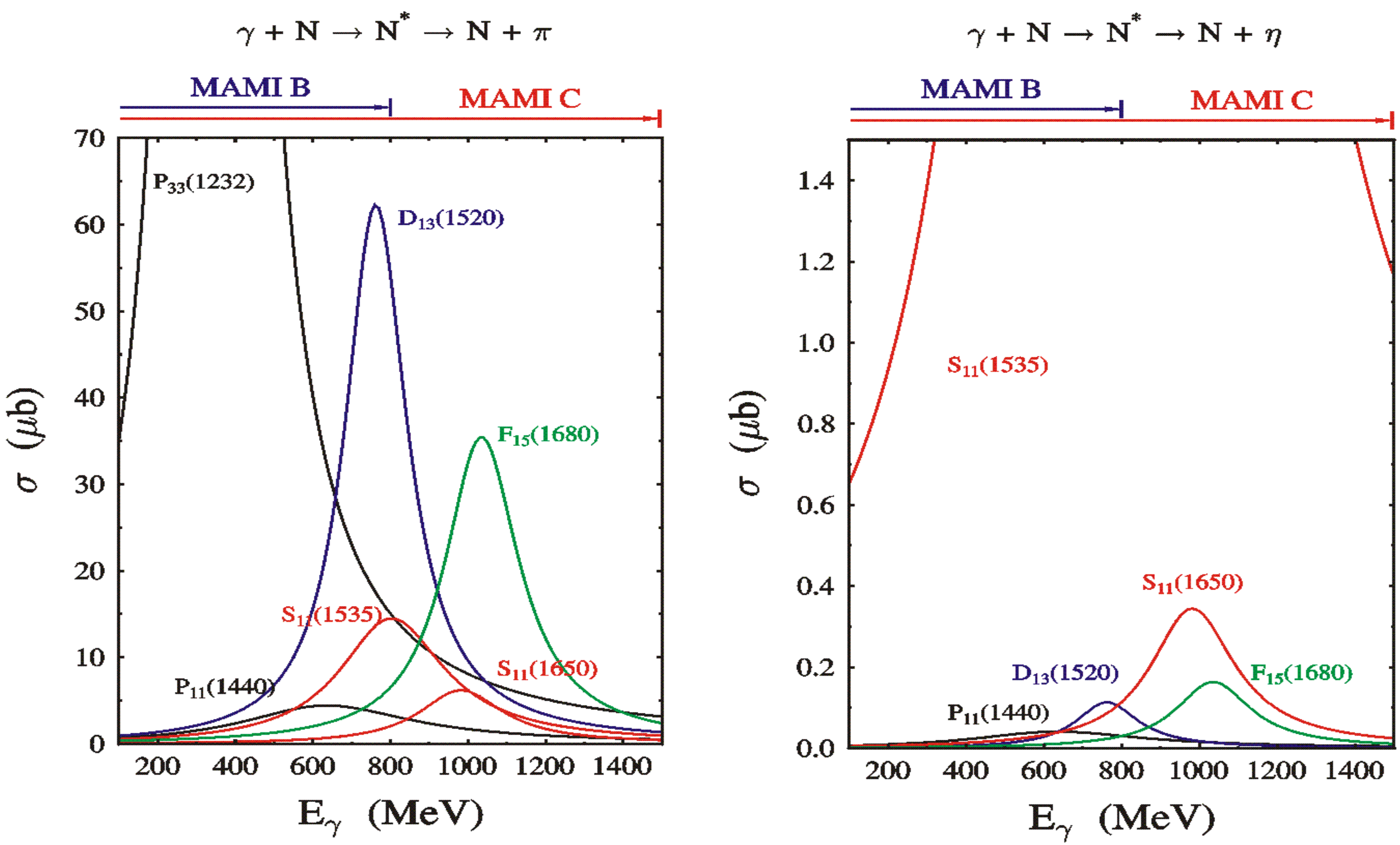
Preliminary results: 'Crystal Barrel ' and 'CLAS' for E > 500 MeV.

'LEGS experiment at BNL Brookhaven' in the $P_{33}(1232)$ region.

Our proposals: Precise measurement of helicity asymmetry in meson photoproduction .

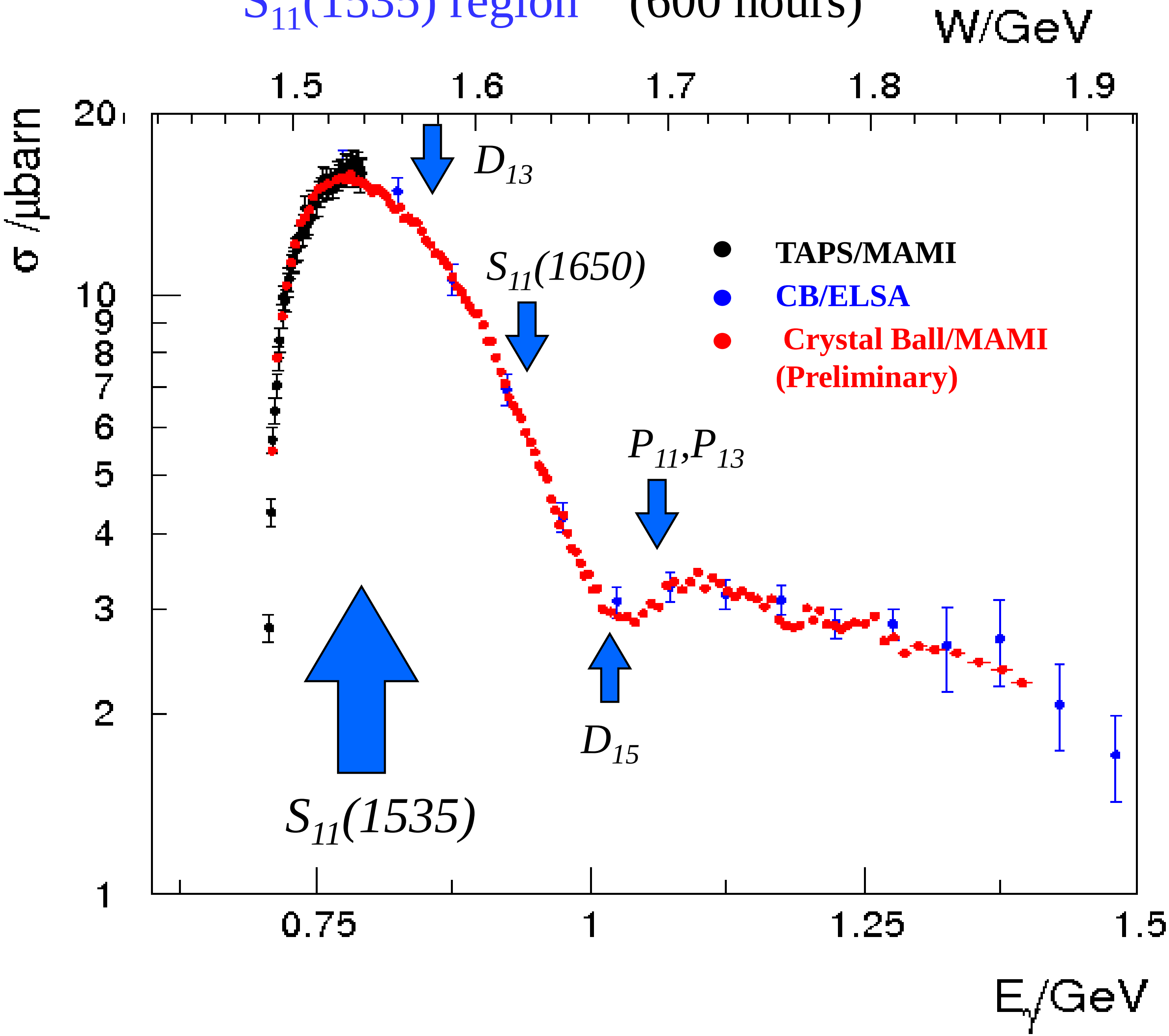
- π^0 production: strongly sensitive to $D_{13}(1520)$, $F_{15}(1680)$.
- η production: investigation of $P_{11}(1710)$, $S_{11}(1650)$, and $F_{15}(1680)$.
- G-Asymmetry: Determination of M_{1-} partial wave (sensitive to Roper-resonance $P_{11}(1440)$).

Pion Production | Eta Production



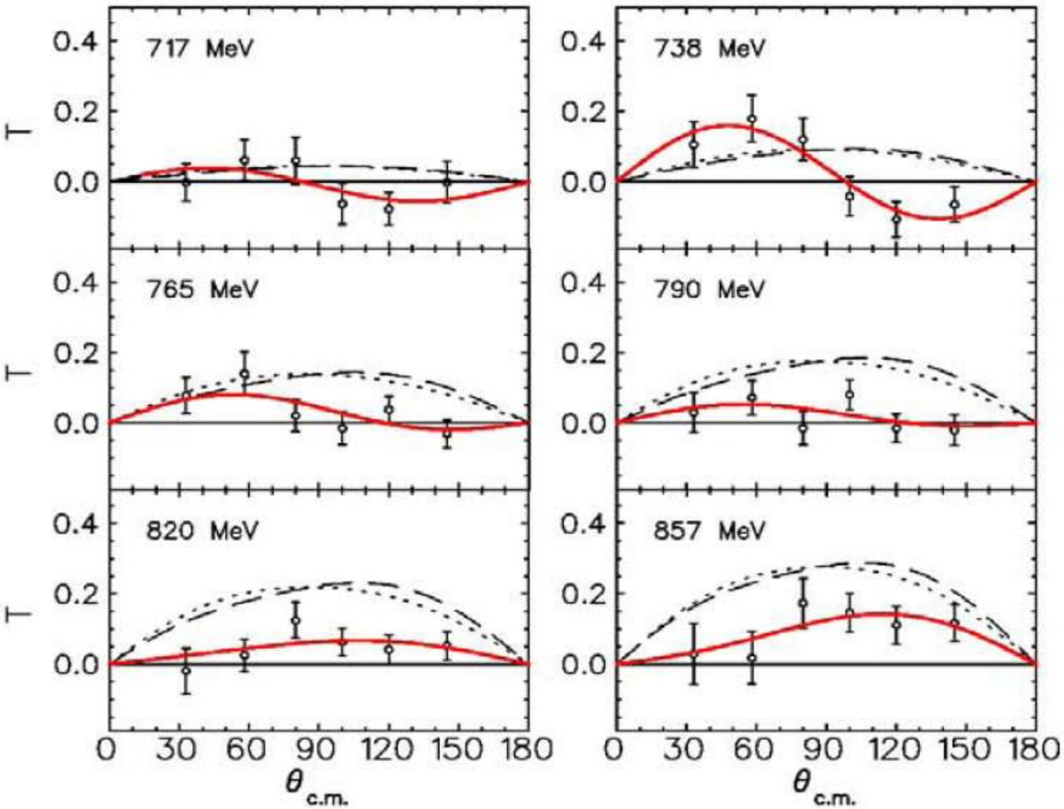
➡ polarisation observables and different channels essential

A2-08/09: Transverse asymmetries T and F in η−photoproduction in the $S_{11}(1535)$ region (600 hours)



GRAAL/ESRF
Beam asym. data Σ
CLAS/Jlab PT data
CBarrel/ELSA PT data

Narrow structure
(Γ<30MeV) in N-Data

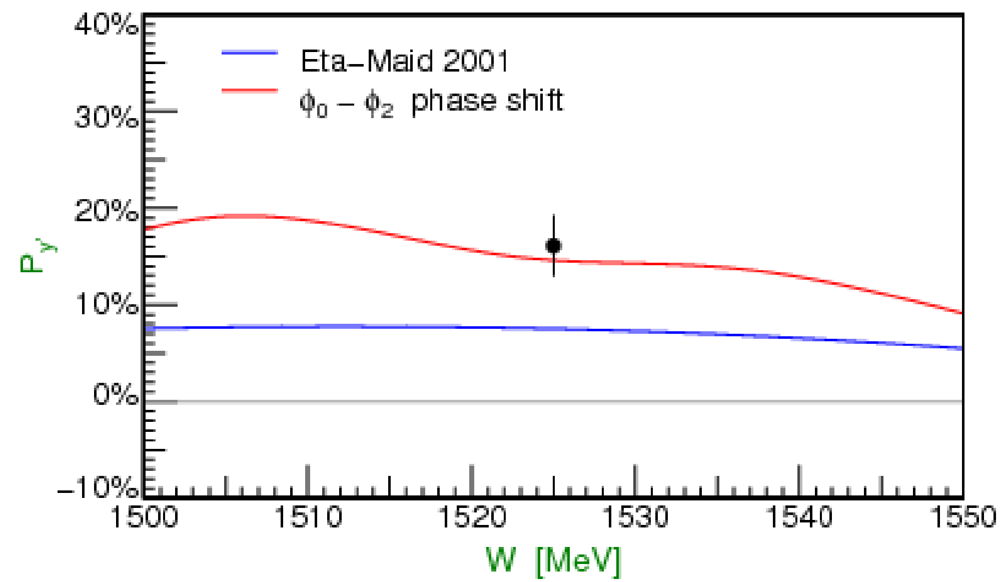


16 polarization observables
in photoproduction of pseudoscalar mesons π,η,η', K

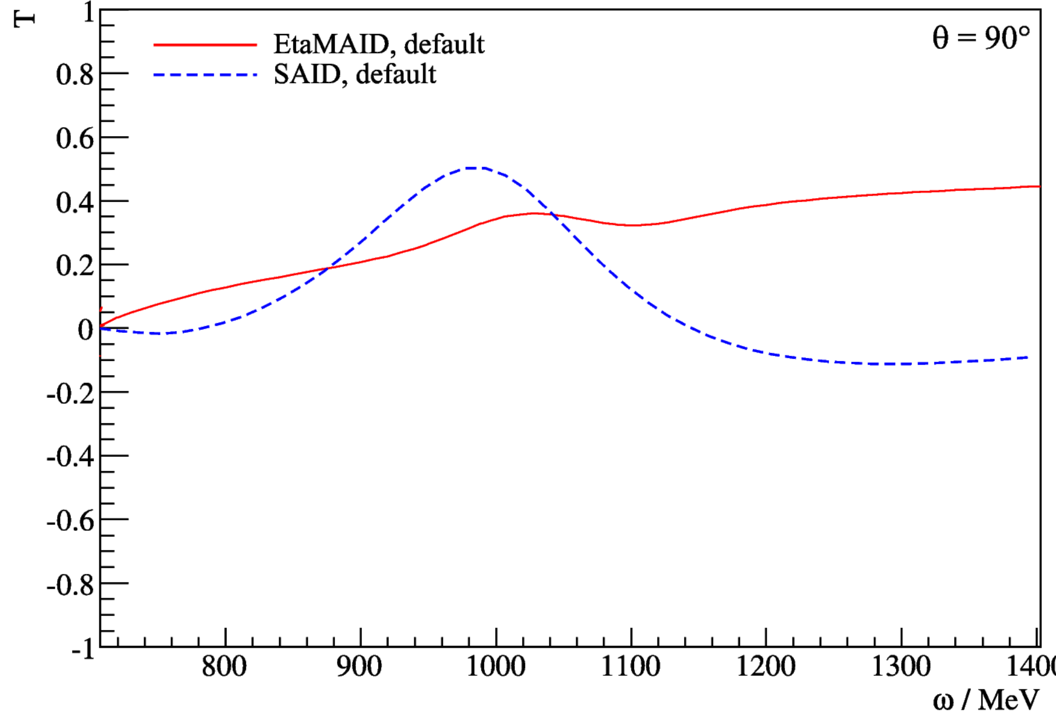
Photon		Target			Recoil			Target – Recoil			
	–	–	–	–	x'	y'	z'	x'	x'	z'	z'
	–	x	y	z	–	–	–	x	z	x	z
unpolarized	σ	0	T	0	0	P	0	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
linear polariz.	$-\Sigma$	H	$(-P)$	$-G$	$O_{x'}$	$(-T)$	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(-L_{x'})$	$(-T_{x'})$
circular polariz.	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

Red curves: **Multipole analysis based on S11 dominance and data from dσ/dΩ, S and T**
(strong phase change between E_{0+} and B_{2-})
L.Tiator *et al.*, Phys. Rev. C60 035210 (1999)

Recoil polarization and beam-recoil double polarization measurement of η electroproduction on the proton in the region of the S11(1535) res.
H. Merkel *et al.*, . **Phys. Rev. Lett. 99, 132301 (2007)**

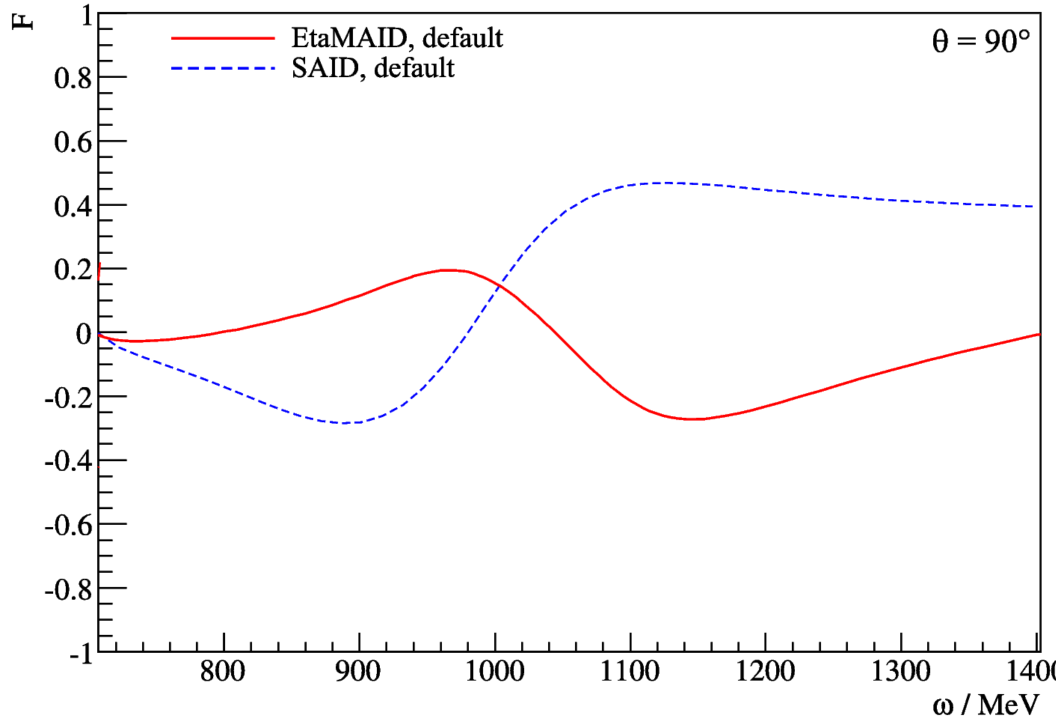


Discrepancies between SAID and EtaMAID predictions for T and F.

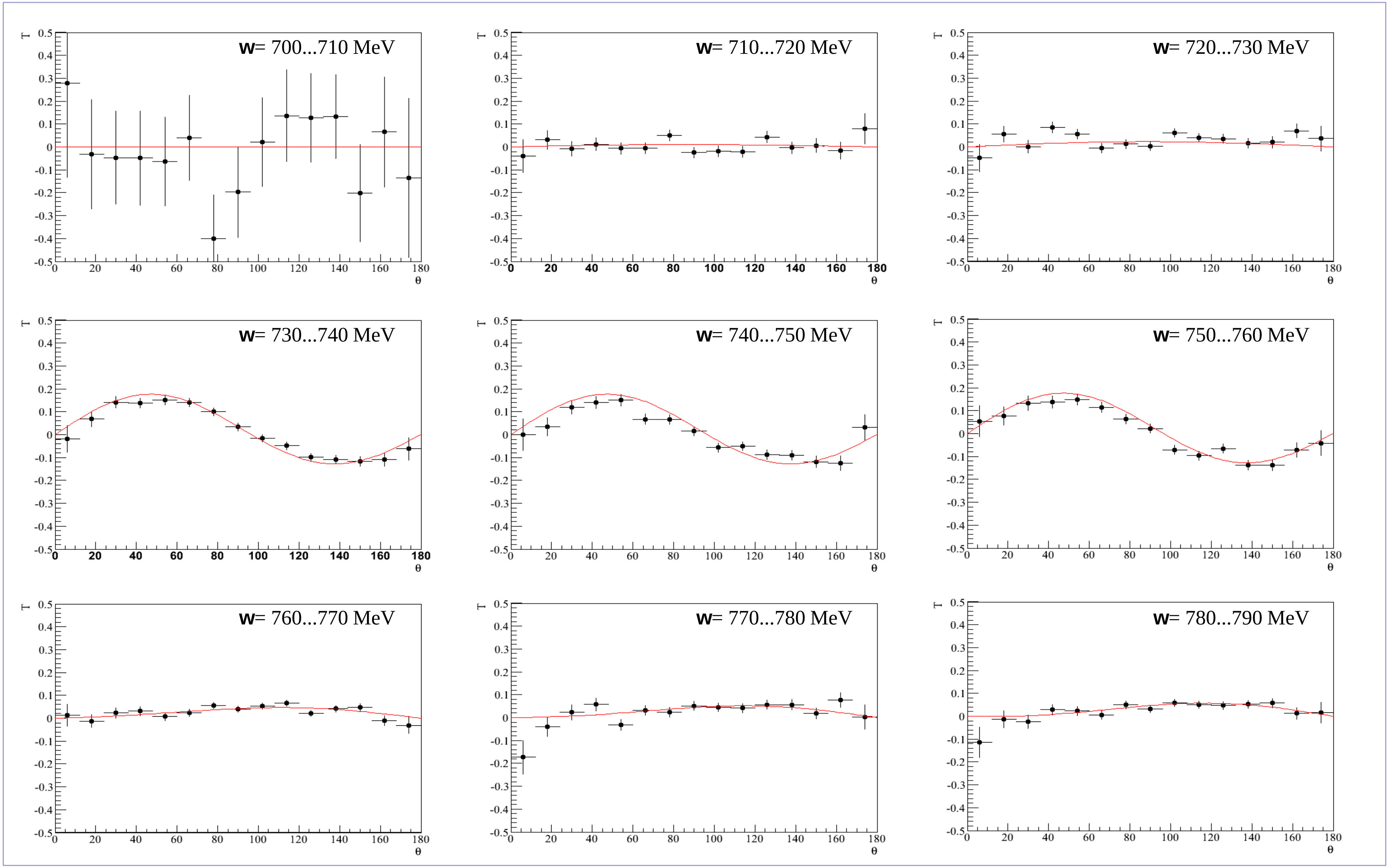


- Measurement of T and F at MAMI:

- Investigate S-D-phase rotation.
- High accuracy and energy/angular resolution up to 1400 MeV.
- F for free (circularly pol. photons).

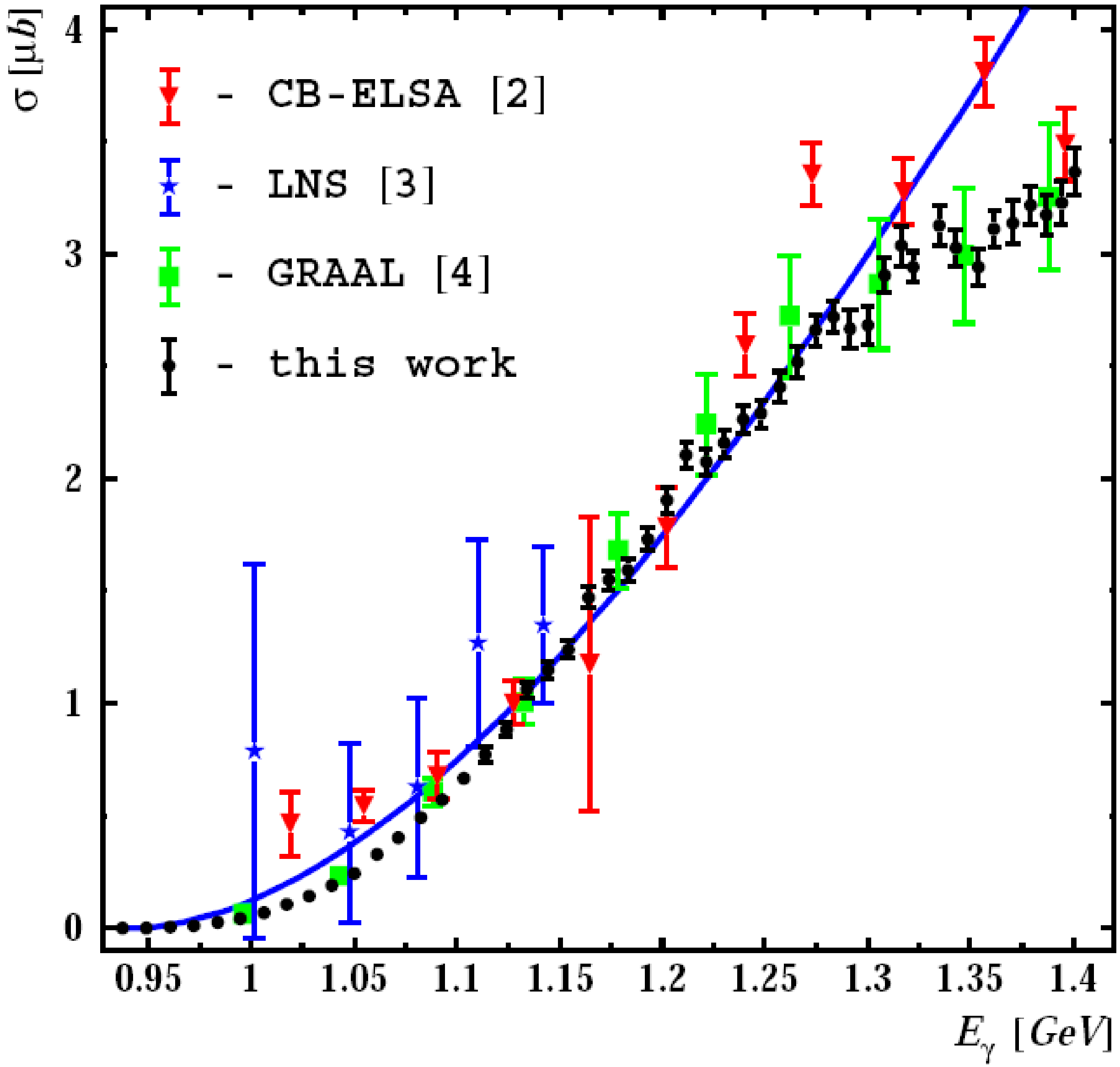


T simulations (EtaMAID) at ~ 600 h



A2-09/09: Spin observables in πη photoproduction in the $D_{33}(1700)$ region

(600 hours parallel with **A2-08/09**)

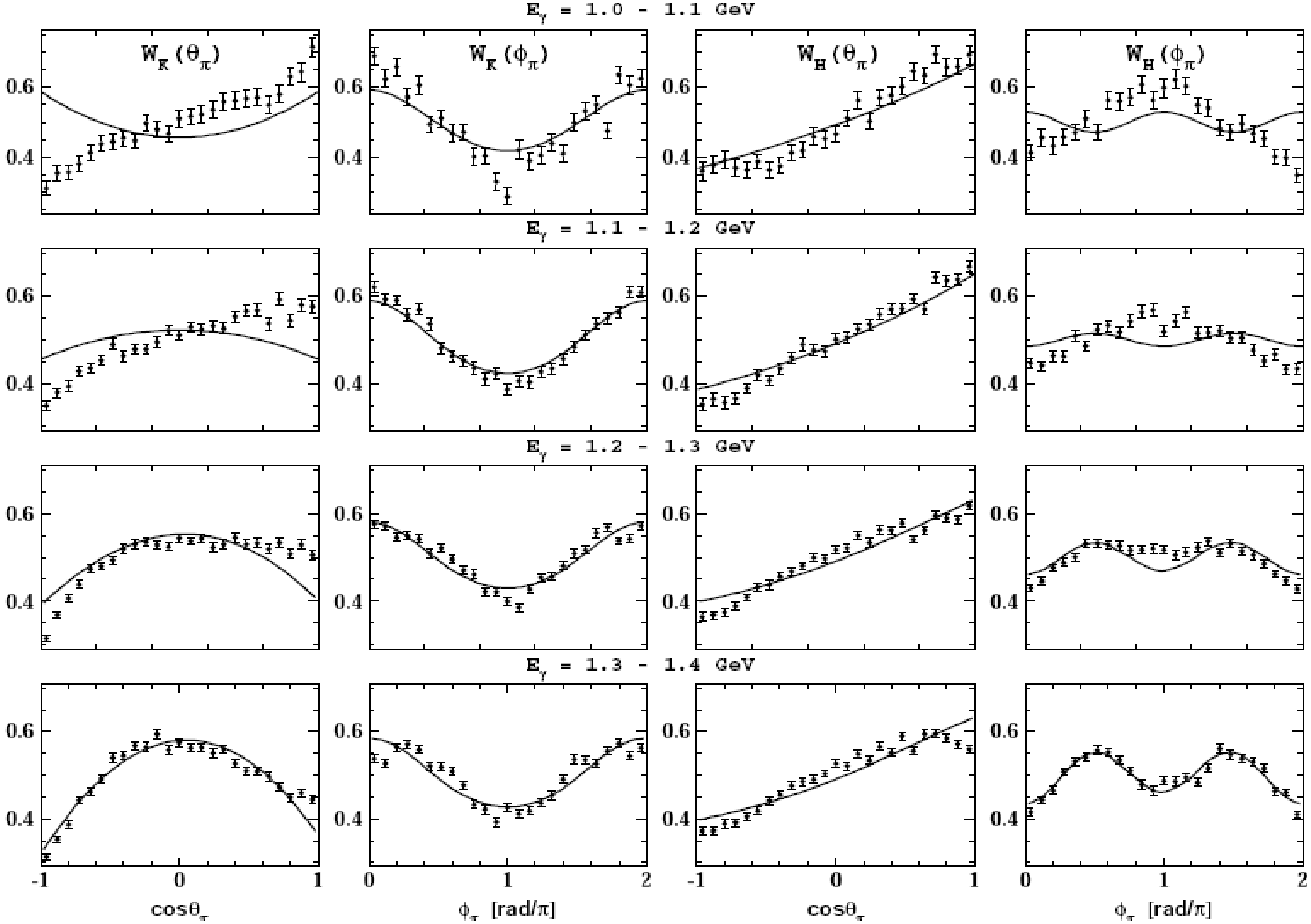


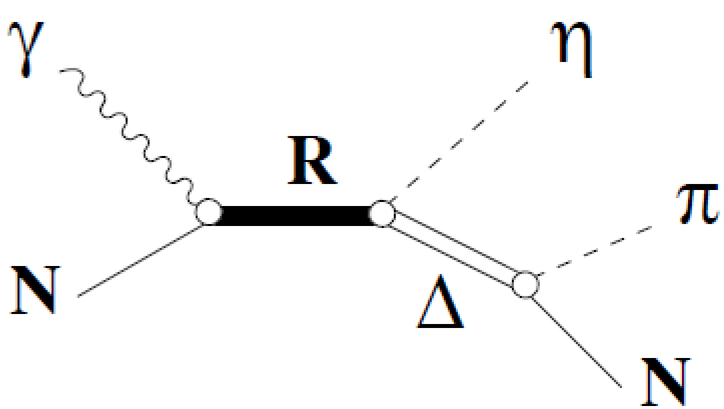
$\gamma p \rightarrow p\pi^0\eta$

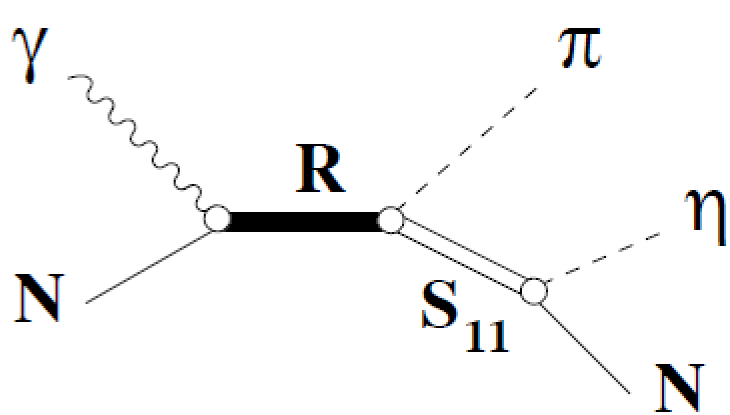
A.Fix, Ostrick, Tiator
EPJ. A36, 61-72, (2008)

Data:
V.Kashevarov et al.
EPJ. A 72,141,(2009)

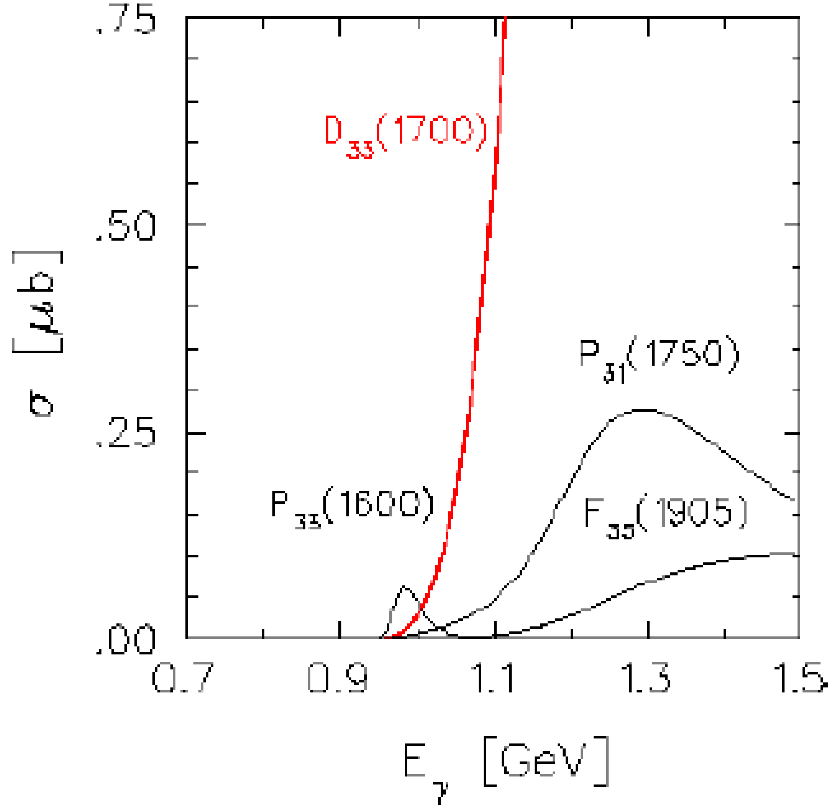
Model A. Fix
$\Delta_{33}(1700)$ dominance







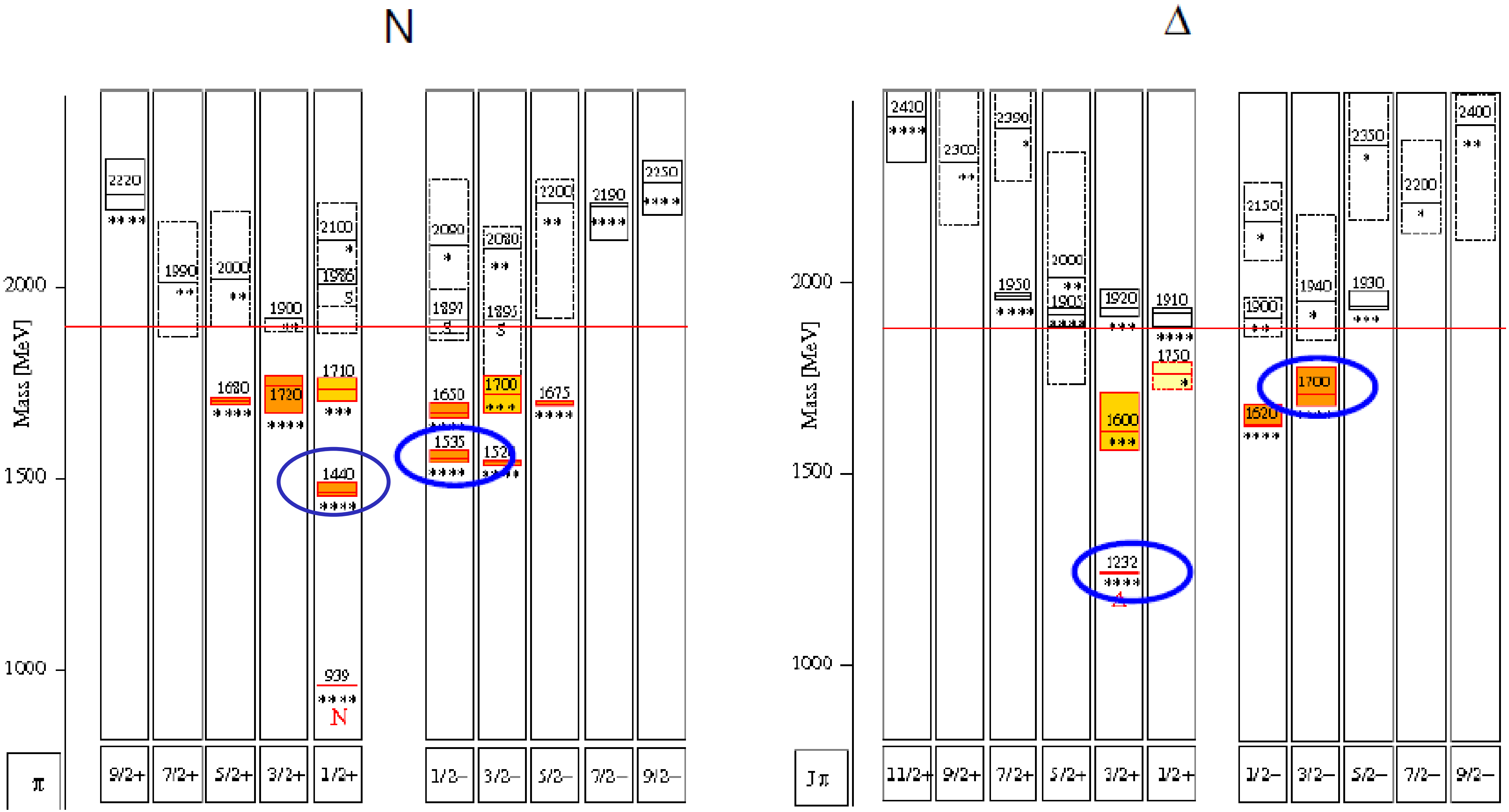
$\gamma p \rightarrow p\pi^0\eta$



Dominated by
single D_{33} resonance
analog S_{11} in $\boldsymbol{\eta}$ prod.
and P_{33} in $\boldsymbol{\pi}$ prod.

Systematic analysis of contributions from p-wave amplitudes:

- angular distributions
- polarisation observables (E,T,F)



Spin observables with focus to P_{11}(1440), S_{11}(1535), and D_{33}(1700) resonance regions.

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).] :

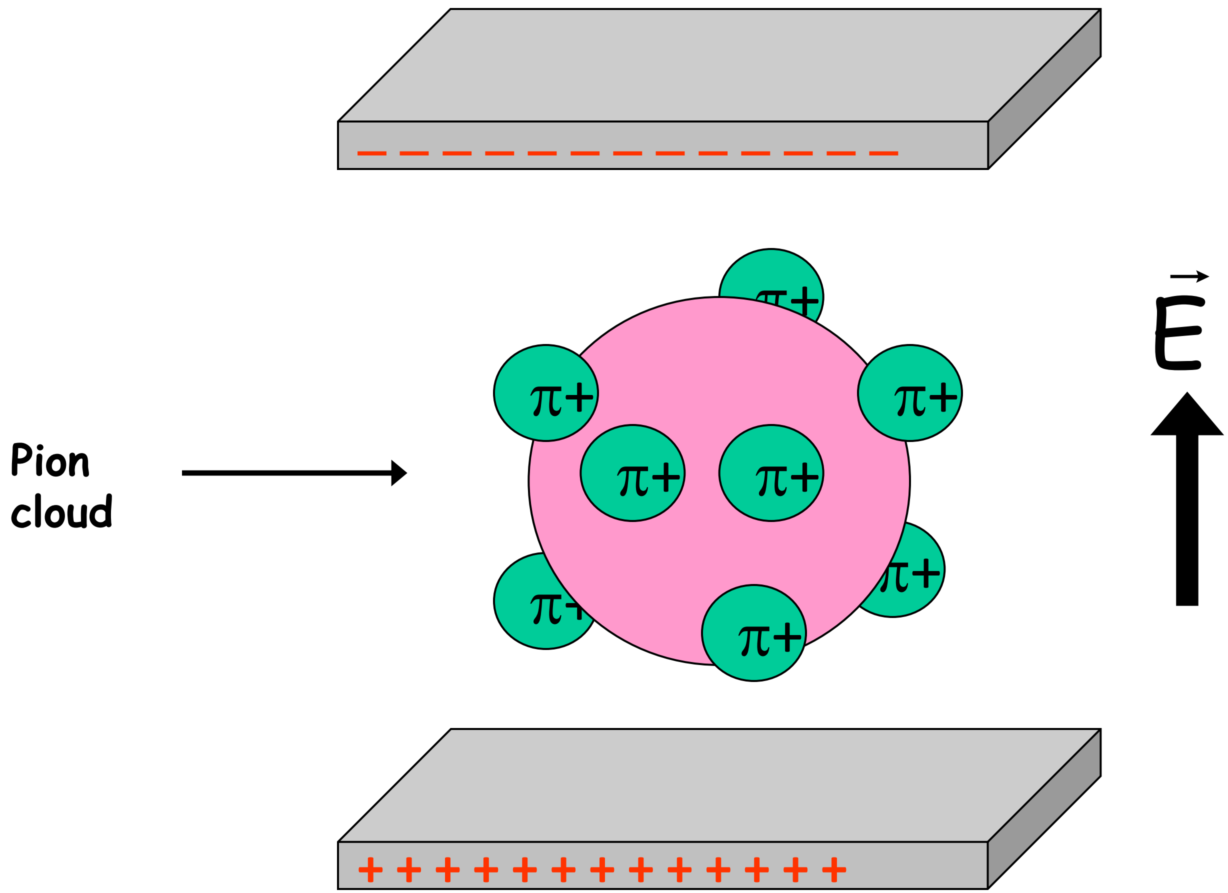
$$\frac{d\sigma}{d\Omega}(\omega,\theta) = \frac{d\sigma}{d\Omega}^{B}(\omega,\theta) - \frac{e^2}{4\pi M}\left(\frac{\omega'}{\omega}\right)^2 (\omega\omega')\left[\frac{\alpha+\beta}{2}(1+\cos\theta)^2 + \frac{\alpha-\beta}{2}(1-\cos\theta)^2\right]$$

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

Real compton scattering with polarized beam and polarized target

$\alpha, \beta, \gamma_1, \gamma_2, \gamma_3, \gamma_4$ ⟷ Dispersion relation, χPT, lattice QCD..?

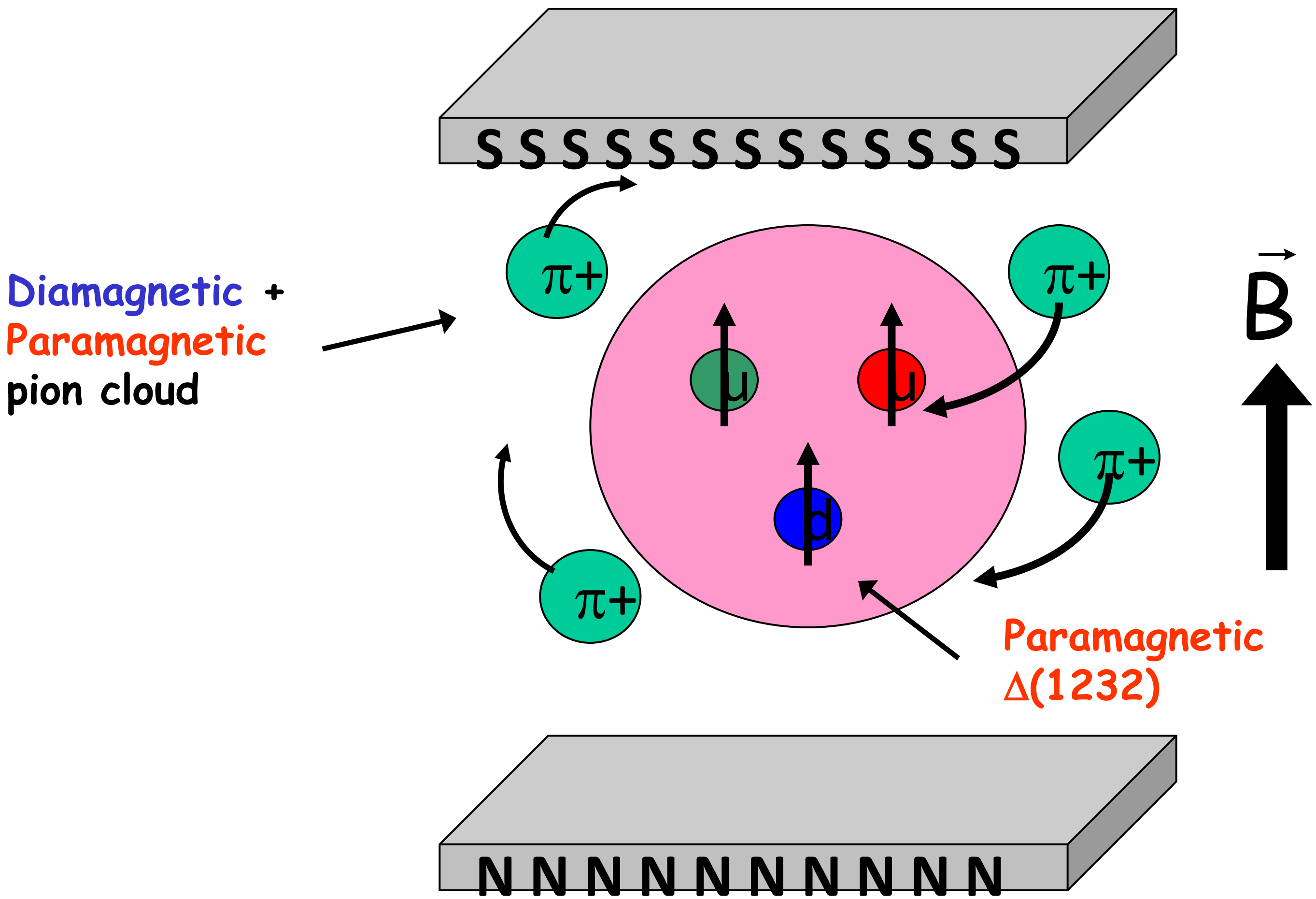
Proton electric polarizability



Electric polarizability: proton between charged parallel plates

[Courtesy of Rory Miskimen]

Proton magnetic polarizability



Magnetic polarizability: proton between poles of a magnetic

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

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

- 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

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).

Proton Spin Polarizabilities

- Linearly polarised photons, parallel and perpendicular to the scattering plane, unpolarised target

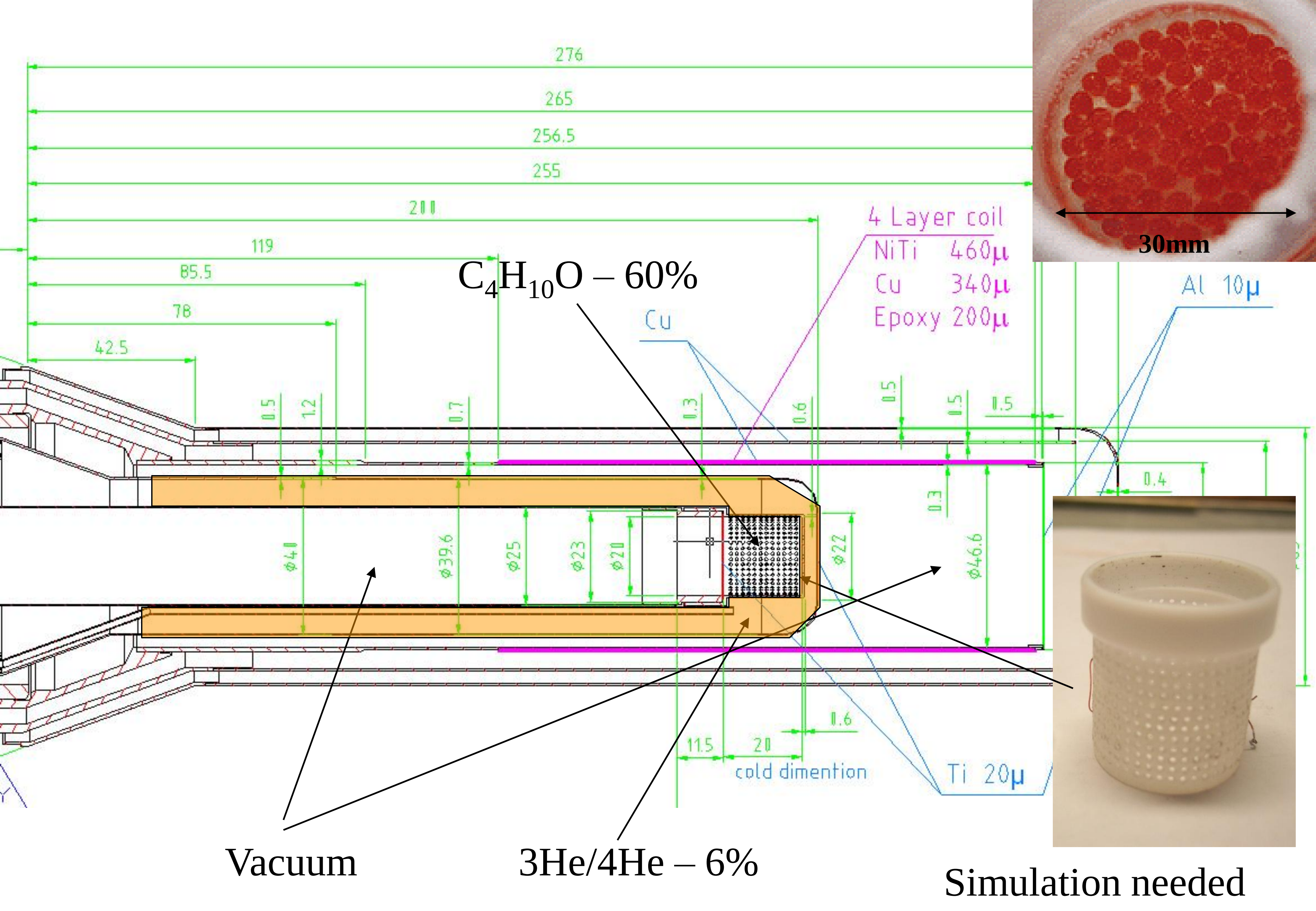
$$\Sigma_3 = \frac{\sigma^{\parallel} - \sigma^{\perp}}{\sigma^{\parallel} + \sigma^{\perp}}$$

- Circularly polarised photons (left-handed (L) and right-handed (R)), longitudinally polarised target

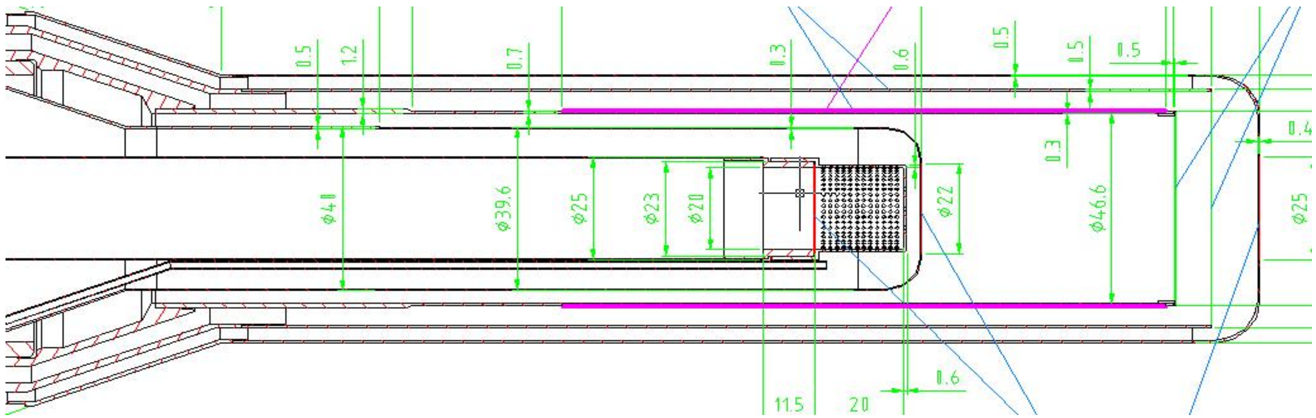
$$\Sigma_{2z} = \frac{\sigma^R_{+z} - \sigma^L_{+z}}{\sigma^R_{+z} + \sigma^L_{+z}} = \frac{\sigma^R_{+z} - \sigma^R_{-z}}{\sigma^R_{+z} + \sigma^R_{-z}}$$

- Circularly polarised photons (left-handed (L) and right-handed (R)), transversely polarised target

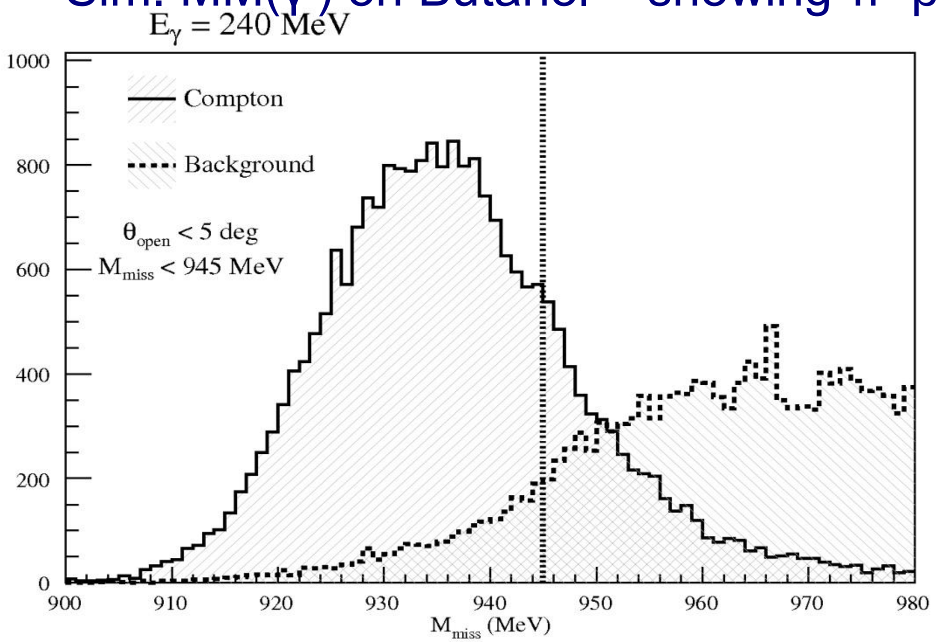
$$\Sigma_{2x} = \frac{\sigma^R_{+x} - \sigma^L_{+x}}{\sigma^R_{+x} + \sigma^L_{+x}} = \frac{\sigma^R_{+x} - \sigma^R_{-x}}{\sigma^R_{+x} + \sigma^R_{-x}}$$

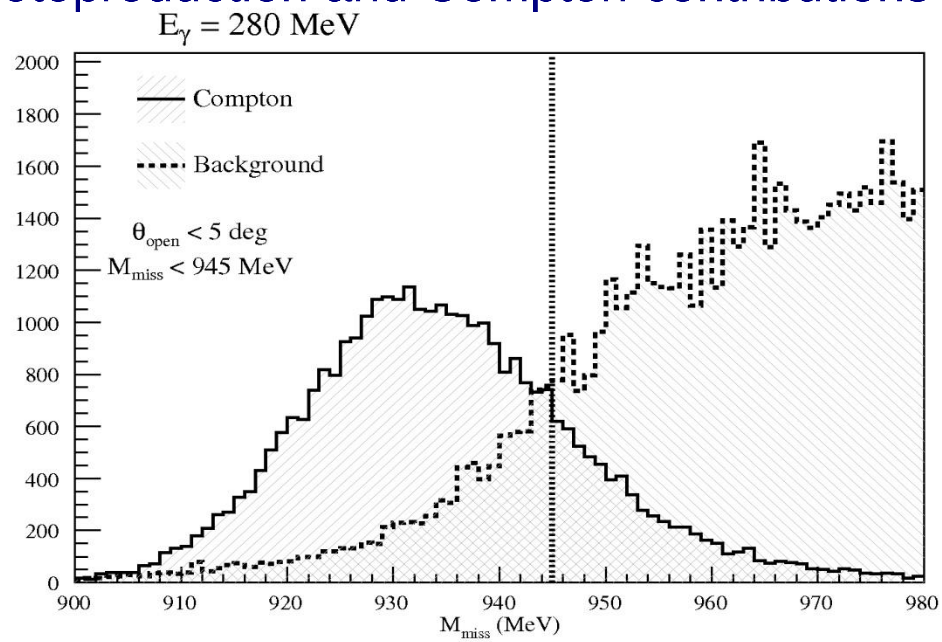

276
265
256.5
255
119
85.5
78
42.5
4 Layer coil
NiTi 460μ
Cu 340μ
Epoxy 200μ
Cu
Al 10μ
Ti 20μ
30mm
C4H10O – 60%
ϕ40
ϕ39.6
ϕ25
ϕ23
ϕ20
ϕ22
ϕ46.6
11.5
cold dimention
Vacuum
3He/4He – 6%
Simulation needed

Nucleon Vector Spin Polarizabilities

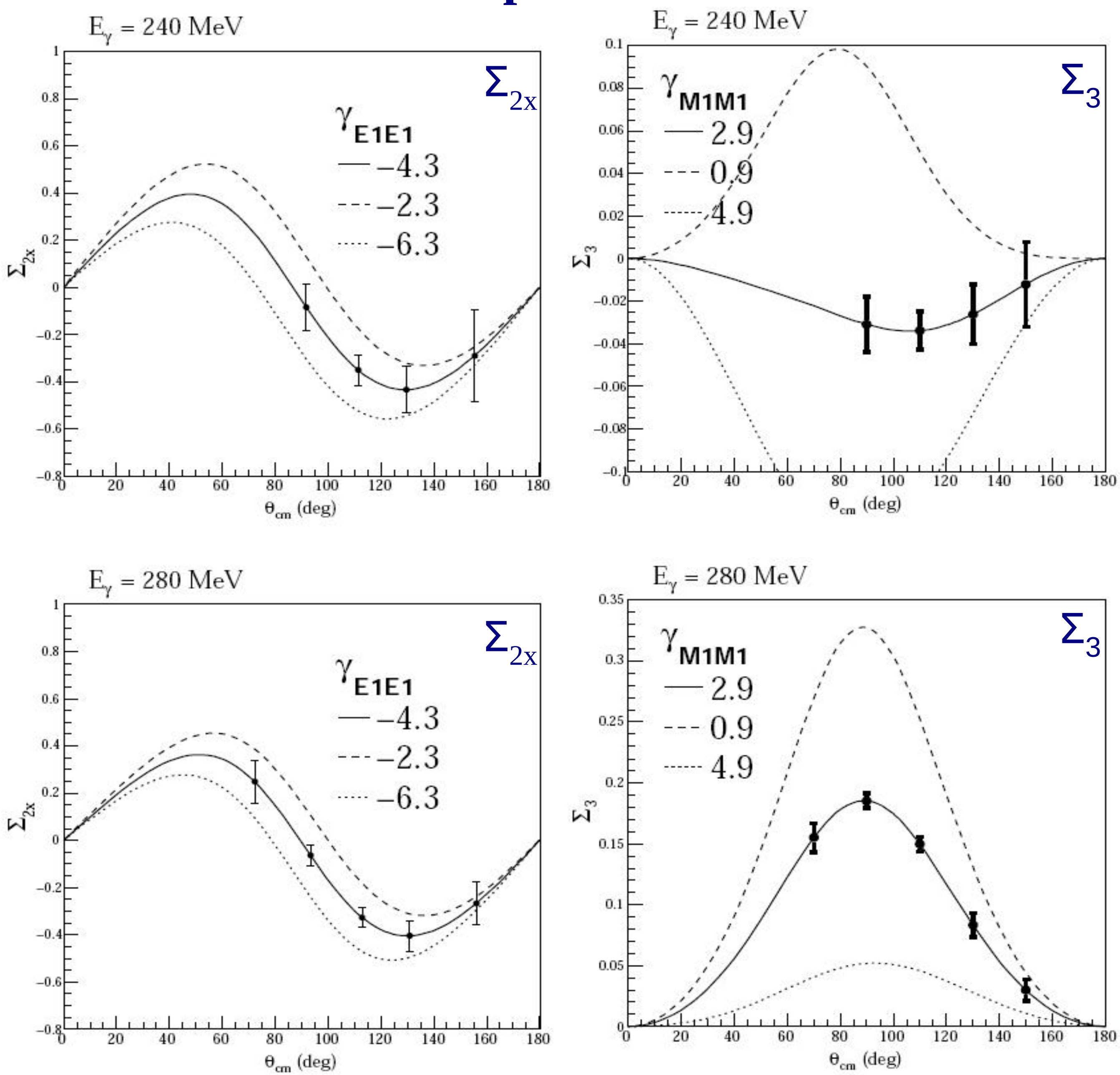


Sim. MM(γ') on Butanol – showing π^0 photoproduction and Compton contributions





Nucleon Vector Spin Polarizabilities



- Σ_3 100 hours measurement
- Σ_{2x} 300 hours measurement
- Curves from:-

B. Pasquini, D. Drechsel, M. Vanderhaeghen,
Phys. Rev. C **76** 015203 (2007)

B. Pasquini, D. Drechsel, M. Vanderhaeghen,
Phys. Rept. **378** 99 (2003)

Conclusions

- MAMI C routinely delivers polarised beam of up to1558 MeV. On average **2500 hours** per year for A2 Real Photon Facility. High Quality data set for η Production exists.
- **New Frozen Spin Target** ready. All directions of polarization.

  Data taking with **CBall TAPS detector system started** February 2010.

- **Spin observables with focus to P_{11}(1440), S_{11}(1535), and D_{33}(1700) resonance regions. Complete Experiments.**
- **First Measurement of 4 Vector Spin Polarisabilities and T in π-threshold region planned.**

Outlook

- **Production of an internal polarising coil avoids FST waltz. FoM better.**
- **R&D for polarised active szintillator target for threshold production.**
- **Improved η- and η'- Factory:** 250000 η/hour + 25000 η'/hour