7 February 2018, JINR Laboratory of Nuclear Problems, Dubna, Russia

Polarization experiments at MAMI

V. L. Kashevarov for A2 Collaboration at MAMI
Institut für Kernphysik, Johannes Gutenberg-Universität, Mainz, Germany /
DLNP JINR, Dubna, Russia

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

A2

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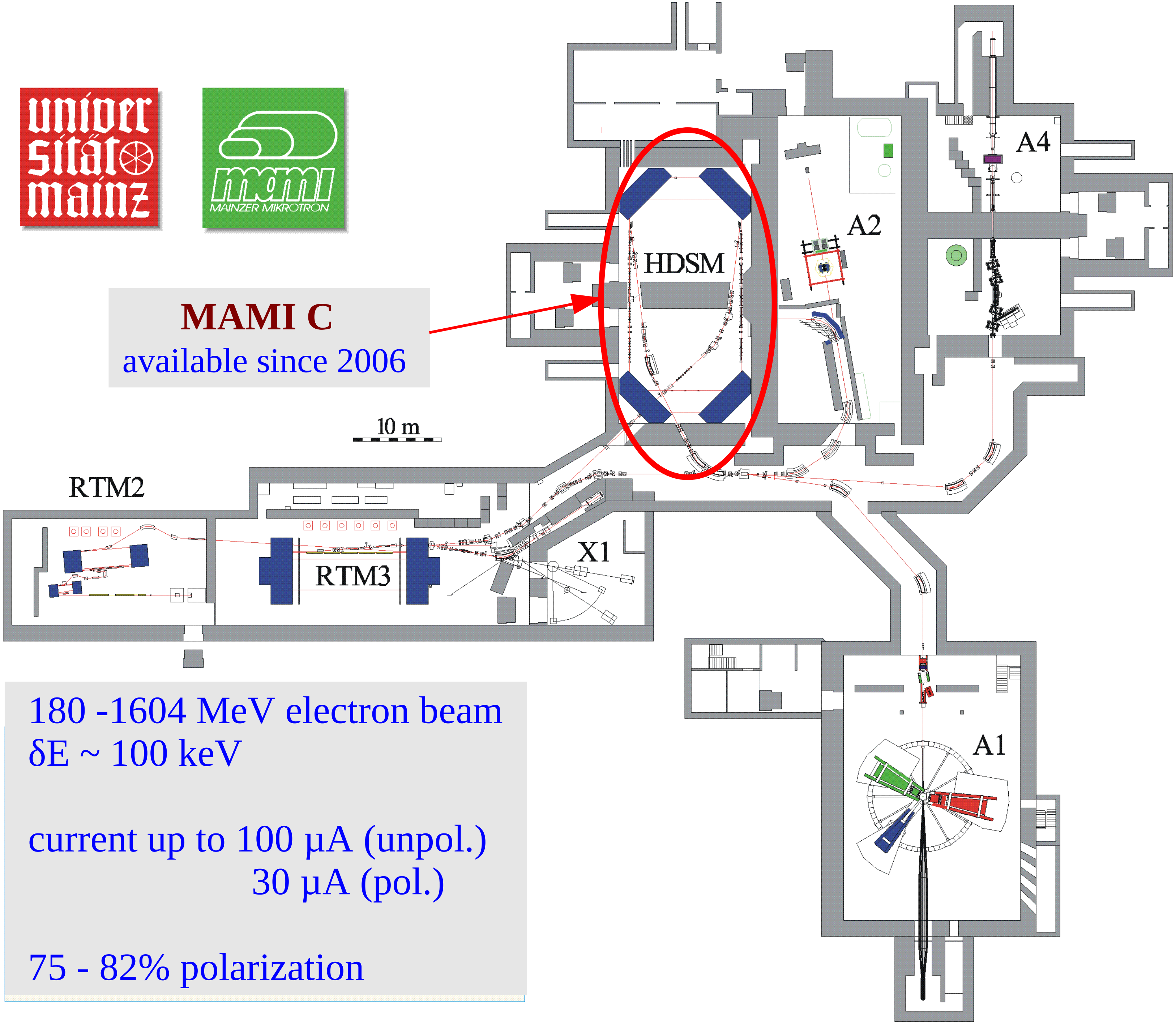
Outline

- Electron accelerator MAMI C
- A2 Collaboration at MAMI
- Meson photoproduction with MAMI C
- Experiments with polarized targets
- Publications
- Summary



180 -1604 MeV electron beam
δE ~ 100 keV

current up to 100 μA (unpol.)
30 μA (pol.)

75 - 82% polarization

A2 Collaboration at MAMI

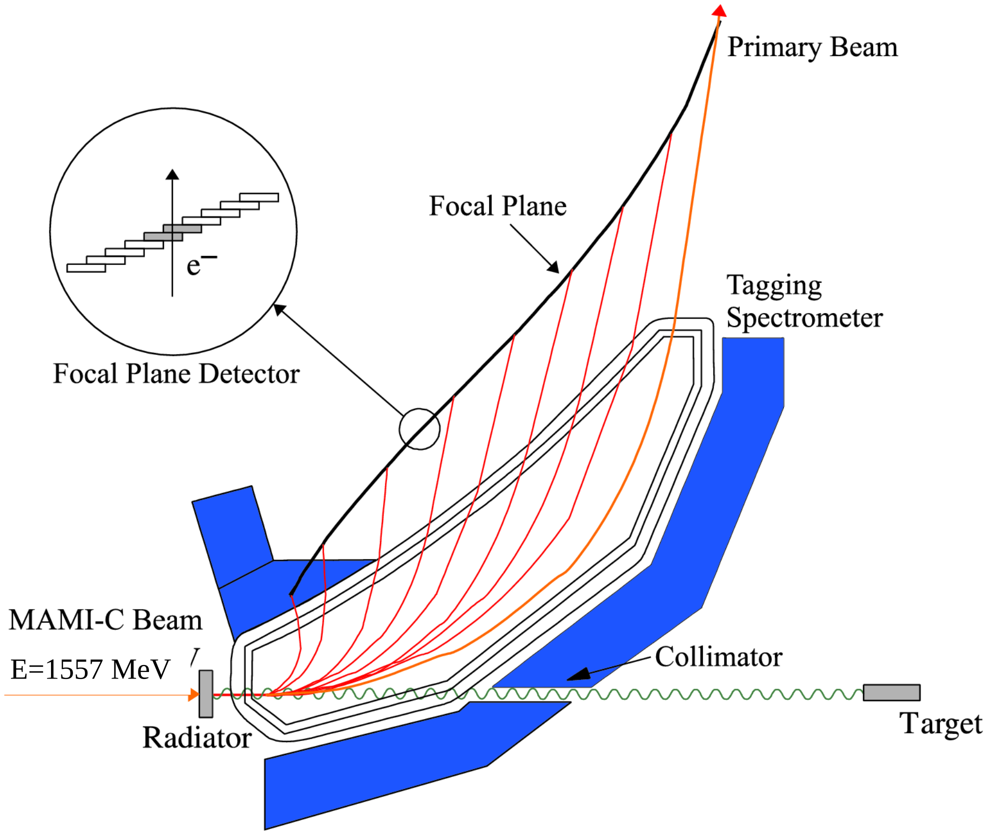
- **Experiments with real photon beam:**
  - meson photoproduction on nucleons and nuclei;
  - Compton scattering on nucleons.

- **International collaboration: ~90 participants, 20 institutes from 9 countries: Canada, Croatia, Germany, Israel, Italy, Russia, Switzerland, United Kingdom, USA.**

- **Russia: INR Moscow, JINR Dubna, LPI Moscow, PNPI Gatchina, TPI Tomsk.**

- **Main experimental set up: Crystal BALL/TAPS.**

Experimental apparatus: photon beam



Tagged photon beam

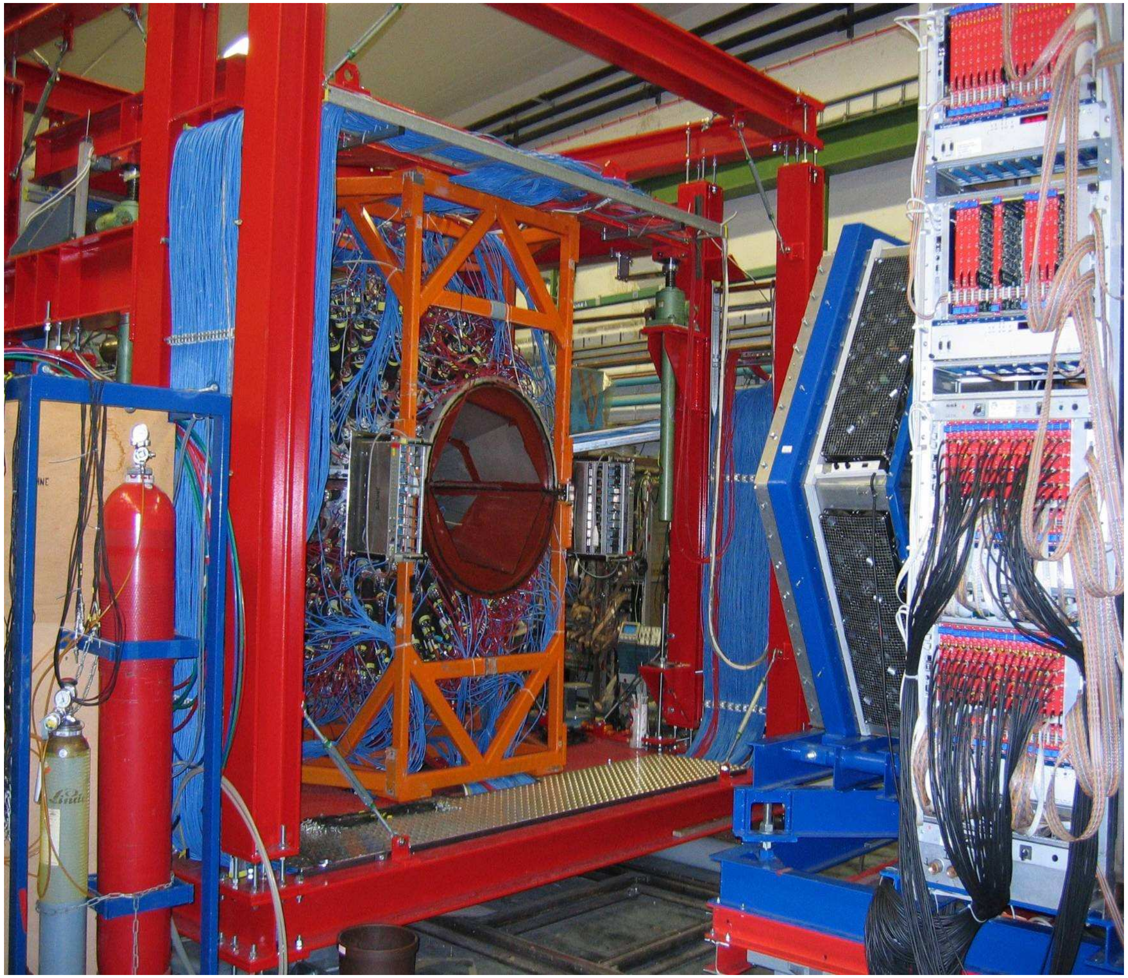
- unpolarized
- circular polarization
- linear polarization

The Glasgow photon tagging spectrometer

352 channels
2 – 5 MeV energy resolution

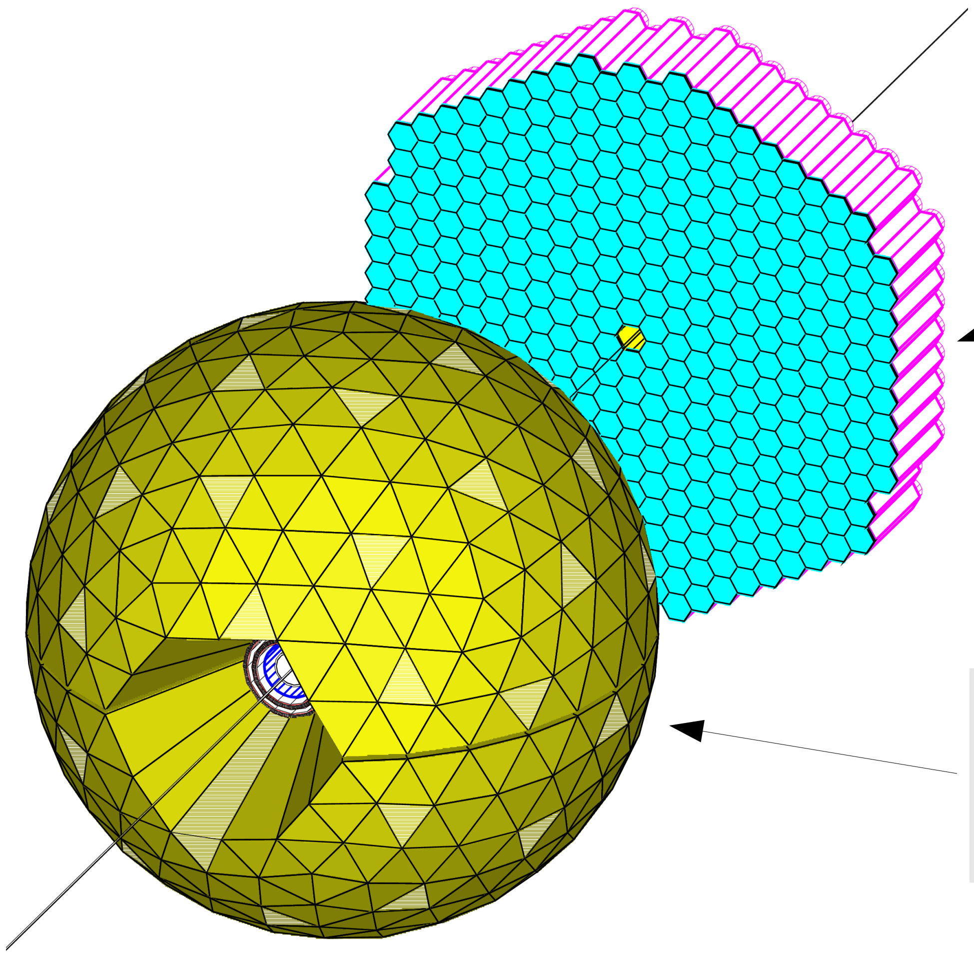
Experimental apparatus: detector system

4π photon spectrometer (97% of 4π)
Detection of neutrons and charged particles is also possible at restricted energy regions



Crystal Ball:
$20^o – 160^o$ (94%)
and
TAPS : $1^o – 20^o$ (3%)

Experimental apparatus: detector system



TAPS (Giessen, Basel)

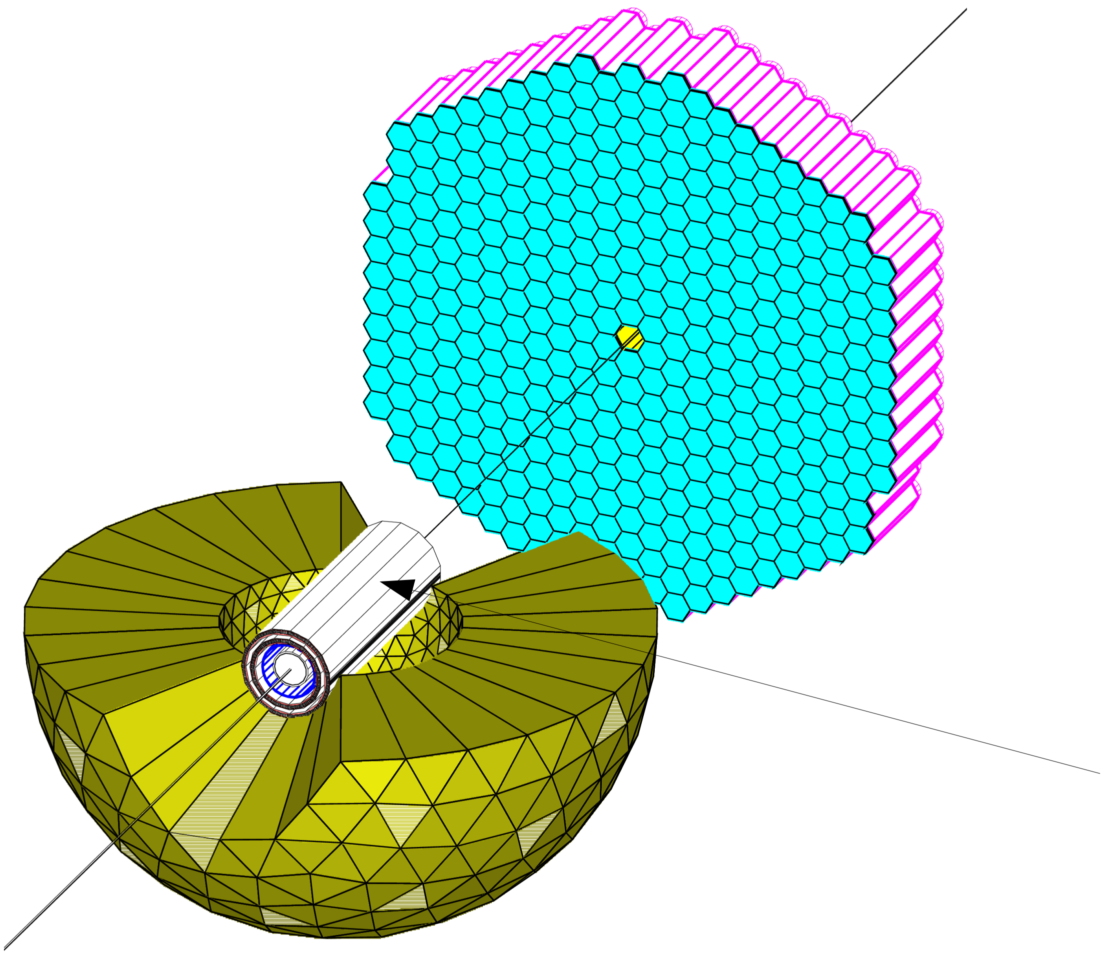
366 BaF_2 crystals
12 radiation lengths

and 5mm plastic scintilator
in front of each module (**VETO**)

Crystal Ball (UCLA, JWU, Mainz)

672 NaI(Tl) crystals
15.7 radiation lengths

Experimental apparatus: detector system

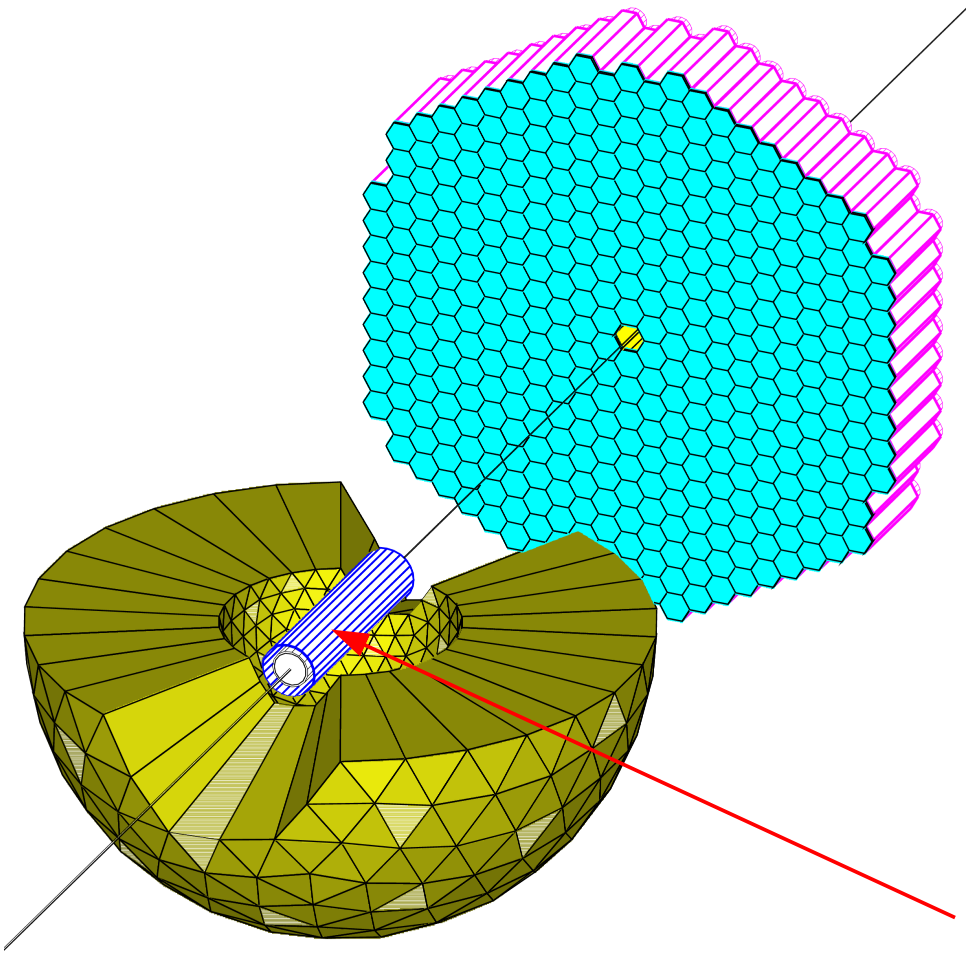


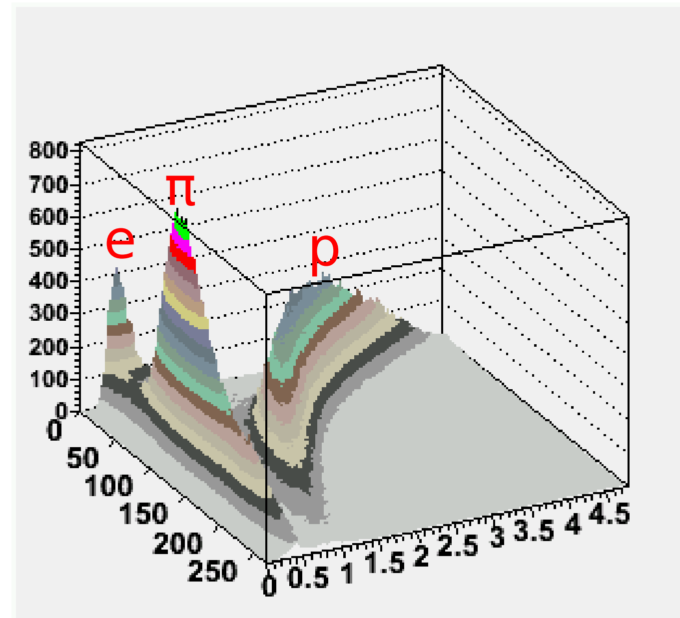
MWPC (Pavia)

2 cylindrical chambers

Vertex reconstruction:
- -target position correction (z),
- -beam position control (x,y),
- -improve angular resolution.

Experimental apparatus: detector system





ΔE (PID) vs $E_{cluster}$ (CB) , MeV

PID (Edinburg)

barrel of 24 2-mm-thick plastic scintilator strips;

VETO detector for photons in CB;

ΔE for charged particle identification in CB.

Experimental apparatus: target

Frozen Spin Target (Mainz, Dubna)

available since 05.2010

Butanol or D-Butanol;

3He/4He dilution refrigerator;

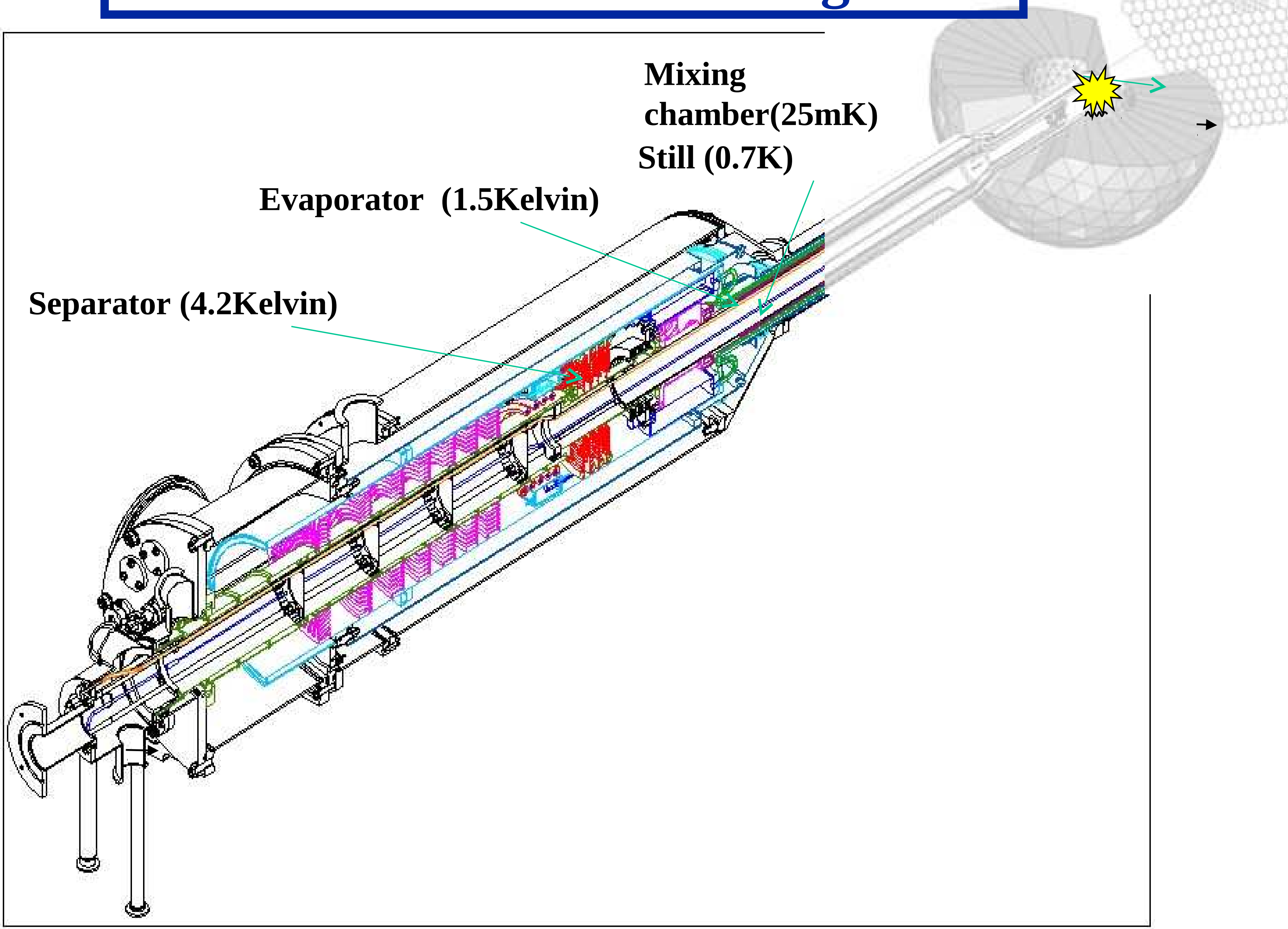
Superconducting holding magnet;

Longitudinal or transverse polarizations are possible;

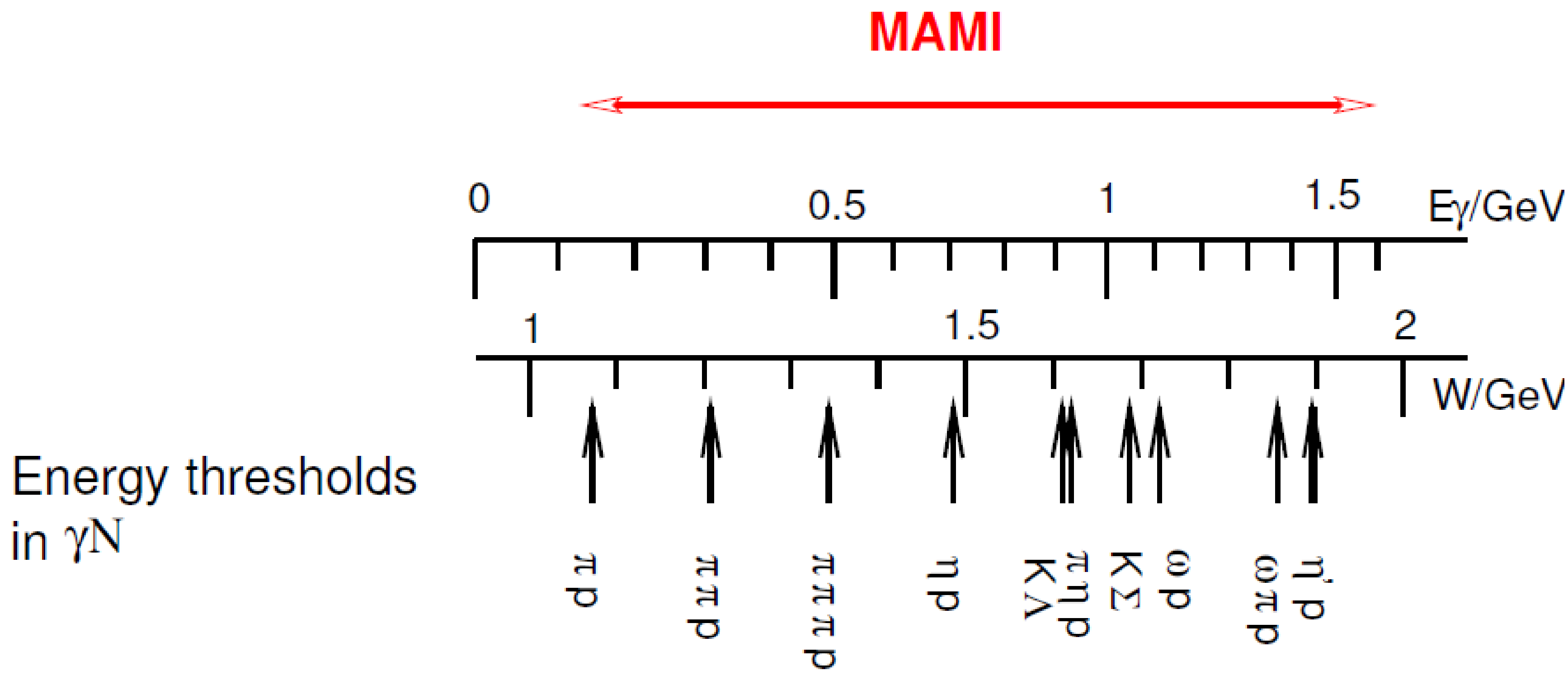
Maximal polarization
for protons ~90%,
for deuterons ~75%;

Relaxation time ~2000 hours

Mainz/Dubna Dilution refrigerator



Meson photoproduction with MAMI C



- For measurement of polarization observables all combination of beam-target, beam-recoil, and target-recoil are possible

Meson photoproduction with MAMI C: experiments with polarized target

1. $\gamma\, p \rightarrow \pi^{o}\, p$
2. $\gamma\, p \rightarrow \pi^{+}\, n$
3. $\gamma\, n \rightarrow \pi^{o}\, n$
4. $\gamma\, p \rightarrow \eta\, p$
5. $\gamma\, n \rightarrow \eta\, n$
6. $\gamma\, p \rightarrow \pi^{o}\, \pi^{o}\, p$
7. $\gamma\, p \rightarrow \pi^{o}\, \eta\, p$

Red – already published

Main goal - complete experiment

Conception of the complete experiment in two body scattering of particles with spin was introduced by L. D. Puzikov, R. M. Ryndin, and Ya. A. Smorodinsky in 1957.

Single meson photoproduction

- 16 observables for pseudoscalar meson photoproduction
- for complete experiment need 8 of them

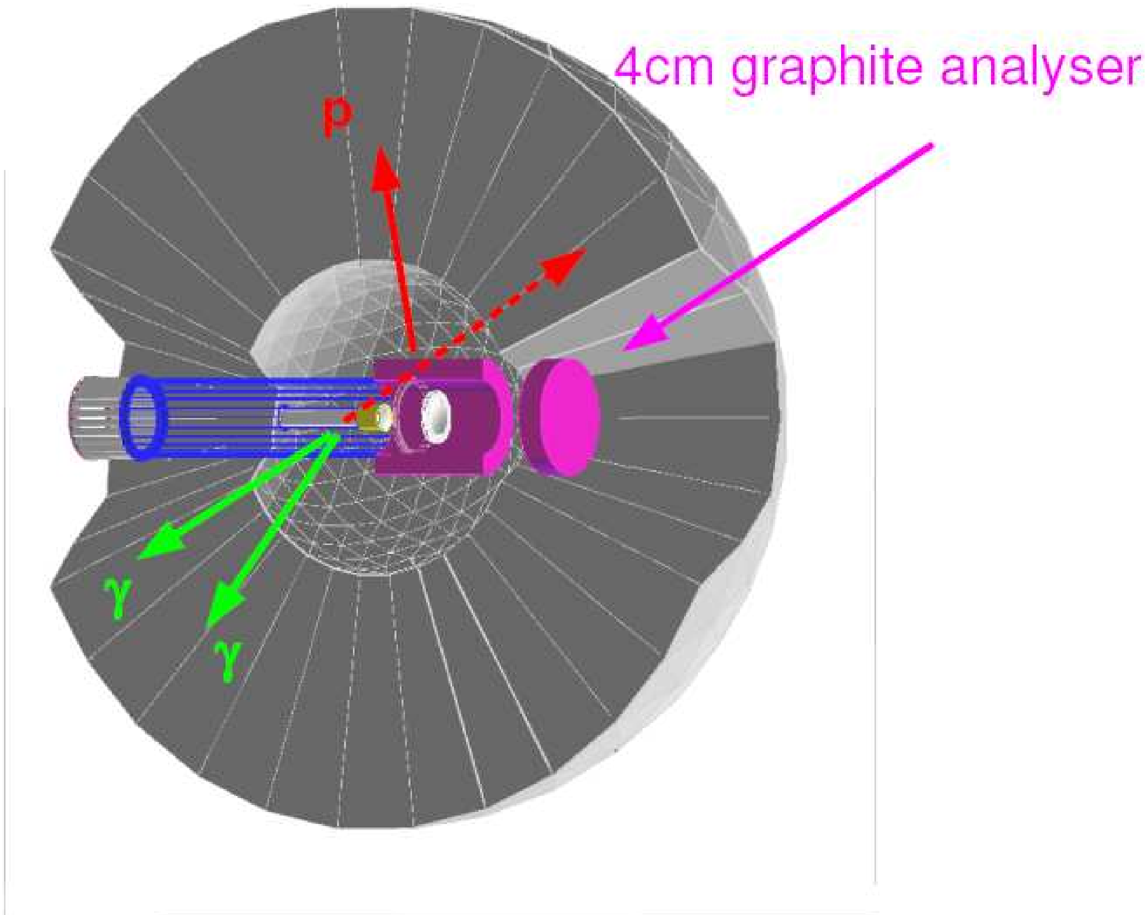
Beam	Target				Recoil			Target + Recoil			
	$-$	$-$	$-$	$-$	x'	y'	z'	x'	x'	z'	z'
	$-$	x	y	z	$-$	$-$	$-$	x	z	x	z
unpolarized	σ_0	0	T	0	0	P	0	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
linear pol.	$-\Sigma$	H	$(-P)$	$-G$	$O_{x'}$	$(-T)$	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(-L_{x'})$	$(-T_{x'})$
circular pol.	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

already done at MAMI C for π^0 photoproduction on proton

The entries in parentheses signify that the same polarization observables also appear elsewhere in the table

Experimental apparatus: Recoil polarimetry

Recoil proton polarimeter (Edinburg)



Method:

detection of proton scattered in the graphite analyzer and comparison its angle with kinematic reconstruction.

definitions from Barker, Donnachie, Storrow, 1975

- polarized photons and polarized target

BT

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{1 - P_T \Sigma \cos 2\varphi + P_x (-P_T H \sin 2\varphi + P_\odot F) + P_y (T - P_T P \cos 2\varphi) + P_z (P_T G \sin 2\varphi - P_\odot E)\}$$

- polarized photons and recoil polarization

BR

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{1 - P_T \Sigma \cos 2\varphi + P_{x'} (-P_T O_{x'} \sin 2\varphi - P_\odot C_{x'}) + P_{y'} (P - P_T T \cos 2\varphi) + P_{z'} (-P_T O_{z'} \sin 2\varphi - P_\odot C_{z'})\}$$

- polarized target and recoil polarization

TR

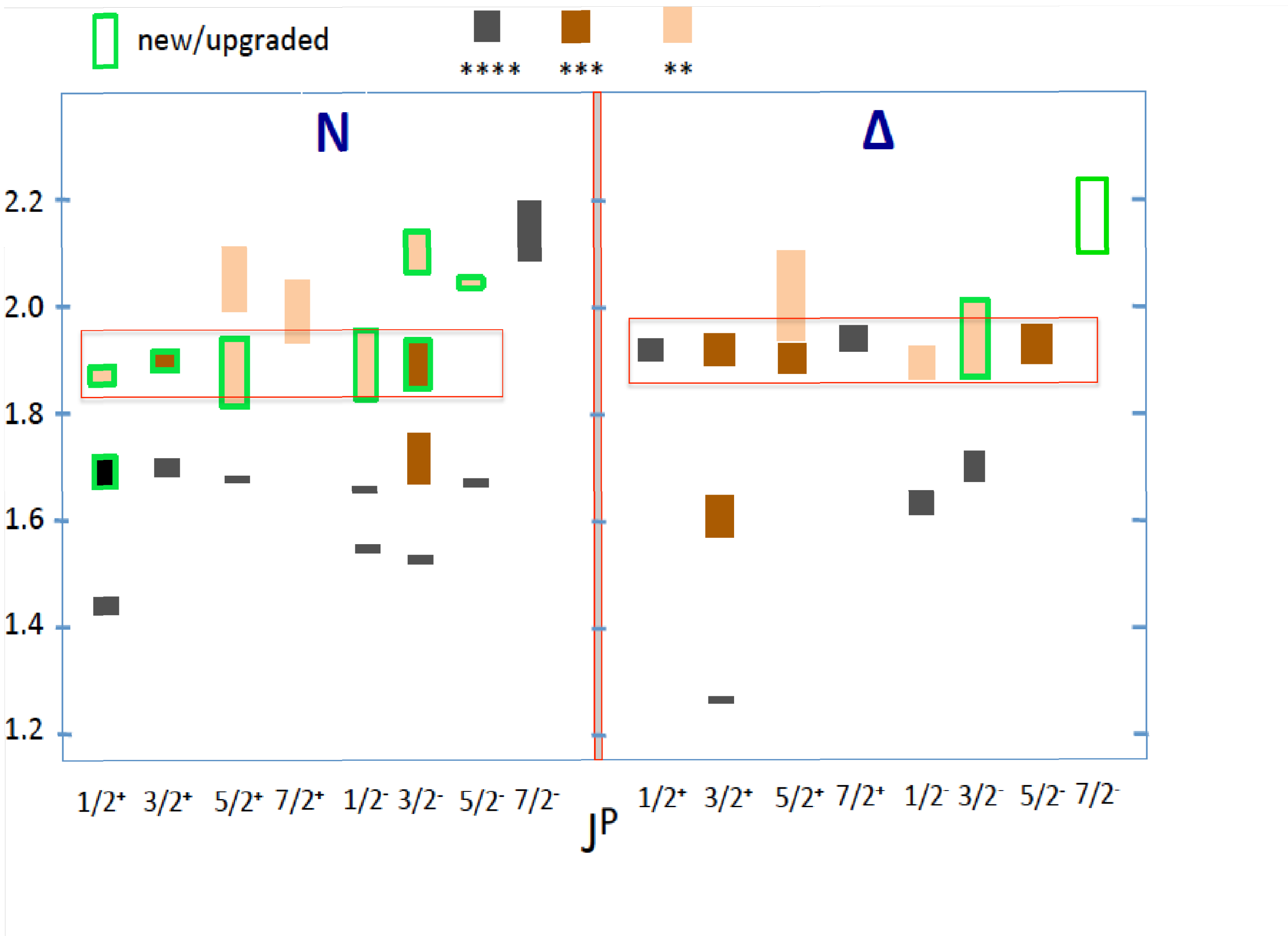
$$\frac{d\sigma}{d\Omega} = \sigma_0 \{1 + P_y T + P_{y'} P + P_{x'} (P_x T_{x'} - P_z L_{x'}) + P_{y'} P_y \Sigma + P_{z'} (P_x T_{z'} + P_z L_{z'})\}$$

Double meson photoproduction

- **64 observables for two pseudoscalar meson photoproduction;**
- **28 relations from consideration of the absolute magnitudes of the helicity or transversity amplitudes;**
- **21 relations from consideration of their phases;**
- **15 independent quantities;**
- **need 8 helicity or transversity amplitudes;**
- **8 observables to obtain the absolute magnitudes of the amplitudes plus 7 for independent phase differences;**
- **each observable depends on 5 kinematic variable !**

W. Roberts and T. Oed, PRC 71, 055201 (2005)

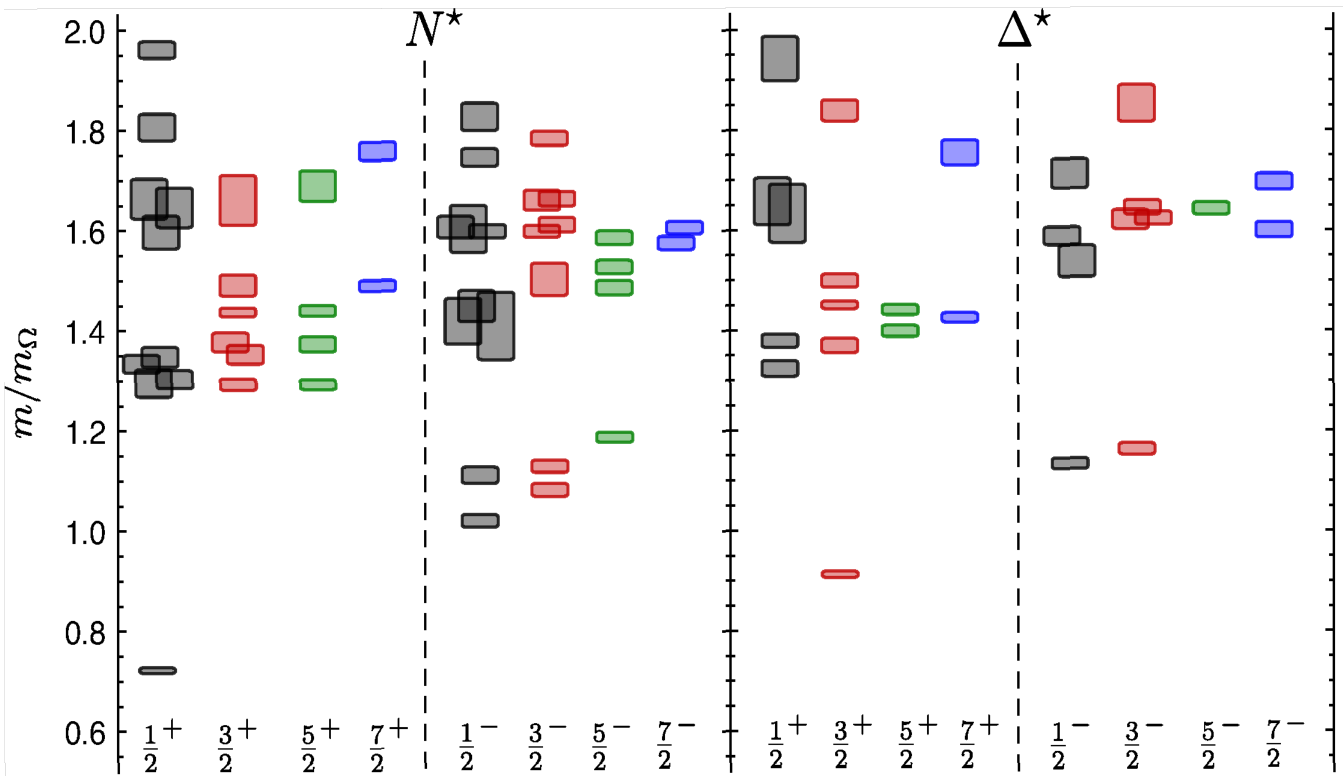
Nucleon and Δ resonances spectrum from PDG-2016



Nucleon and Δ resonances spectrum from lattice theory predictions

Edwards et al. PRD 84 (2011)

New missing resonances problem!



PDG 2016 N* resonance table

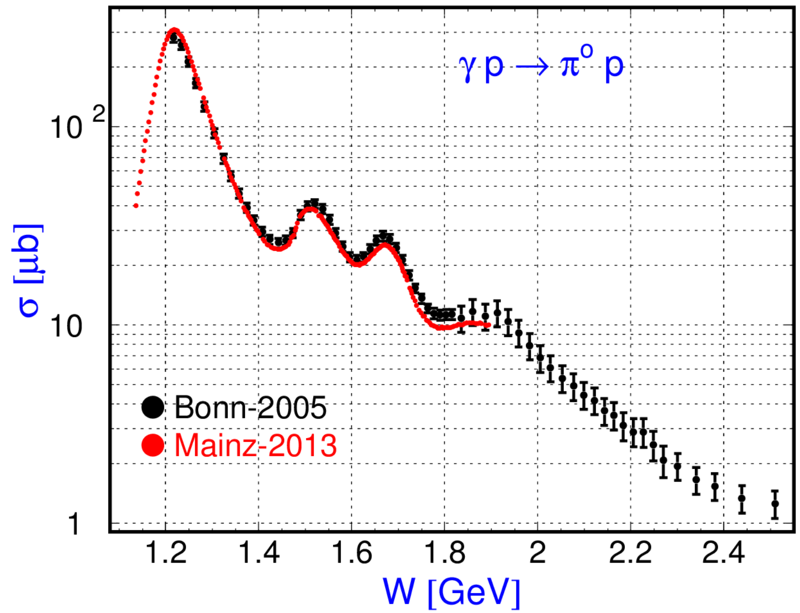
Particle	J^P	overall	$N\gamma$	$N\pi$	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N	$1/2^+$	****									
$N(1440)$	$1/2^+$	****	****	****		***				*	***
$N(1520)$	$3/2^-$	****	****	****	***					***	***
$N(1535)$	$1/2^-$	****	****	****	****					**	*
$N(1650)$	$1/2^-$	****	***	****	***			***	**	**	***
$N(1675)$	$5/2^-$	****	***	****	*			*		*	***
$N(1680)$	$5/2^+$	****	****	****	*	**				***	***
$N(1700)$	$3/2^-$	***	**	***	*			*	*	*	***
$N(1710)$	$1/2^+$	****	****	****	***		**	****	**	*	**
$N(1720)$	$3/2^+$	****	***	****	***			**	**	**	*
$N(1860)$	$5/2^+$	**		**						*	*
$N(1875)$	$3/2^-$	***	***	*			**	***	**		***
$N(1880)$	$1/2^+$	**	*	*		**		*			
$N(1895)$	$1/2^-$	**	**	*	**			**	*		
$N(1900)$	$3/2^+$	***	***	**	**		**	***	**	*	**
$N(1990)$	$7/2^+$	**	**	**					*		
$N(2000)$	$5/2^+$	**	**	*	**			**	*	**	
$N(2040)$	$3/2^+$	*		*	—						
$N(2060)$	$5/2^-$	**	**	**	*				**		
$N(2100)$	$1/2^+$	*		*	—						
$N(2120)$	$3/2^-$	**	*	**				*	*		
$N(2190)$	$7/2^-$	****	***	****			*	**		*	
$N(2220)$	$9/2^+$	****		****	—						
$N(2250)$	$9/2^-$	****		****							
$N(2300)$	$1/2^+$	**		**							
$N(2570)$	$5/2^-$	**		**	—						
$N(2600)$	$11/2^-$	***		***							
$N(2700)$	$13/2^+$	**		**							

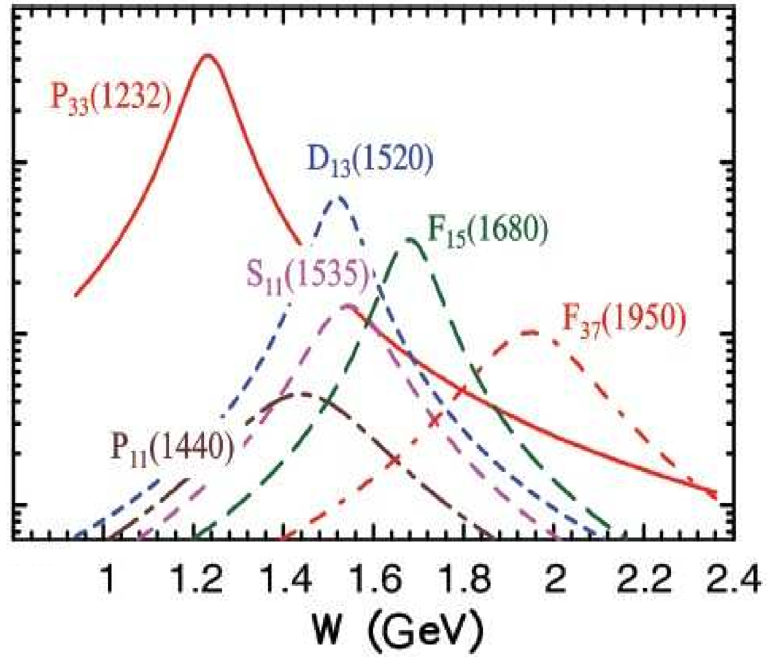
(blue ellipse) 8 N* in 2001/2003

(red ellipse) 15 N* new in 2015/16

— Resonances, where we do not find evidence for γ,η

$\gamma\ p \rightarrow \pi^o\ p$



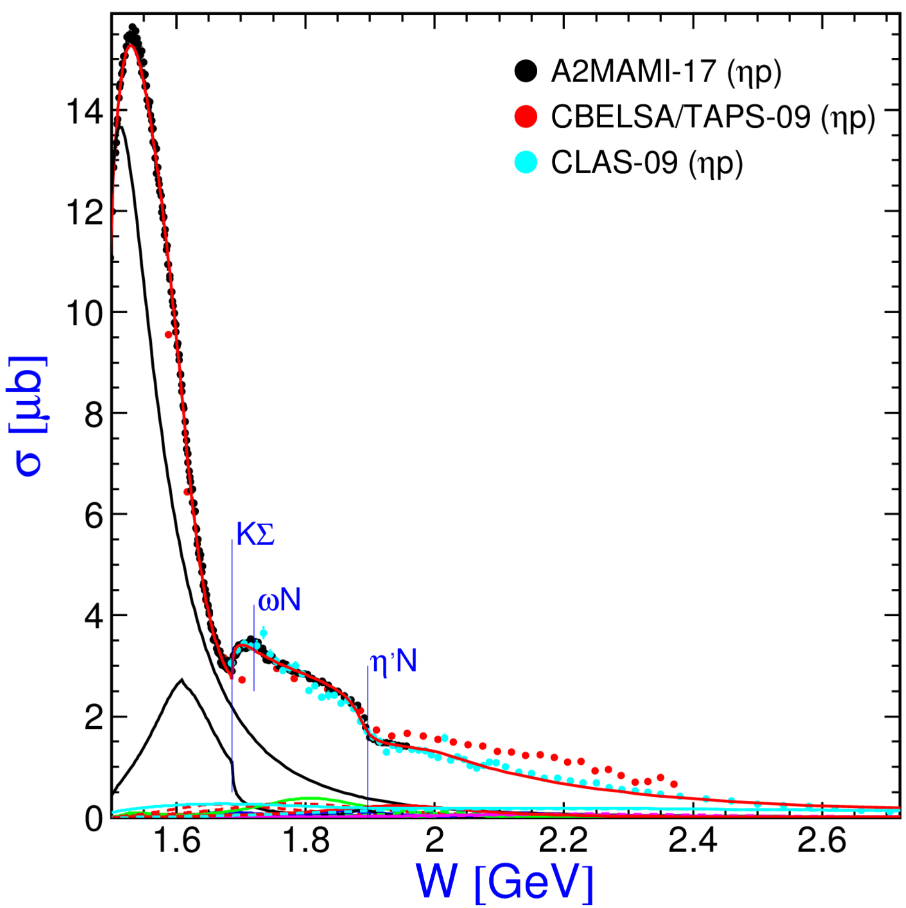


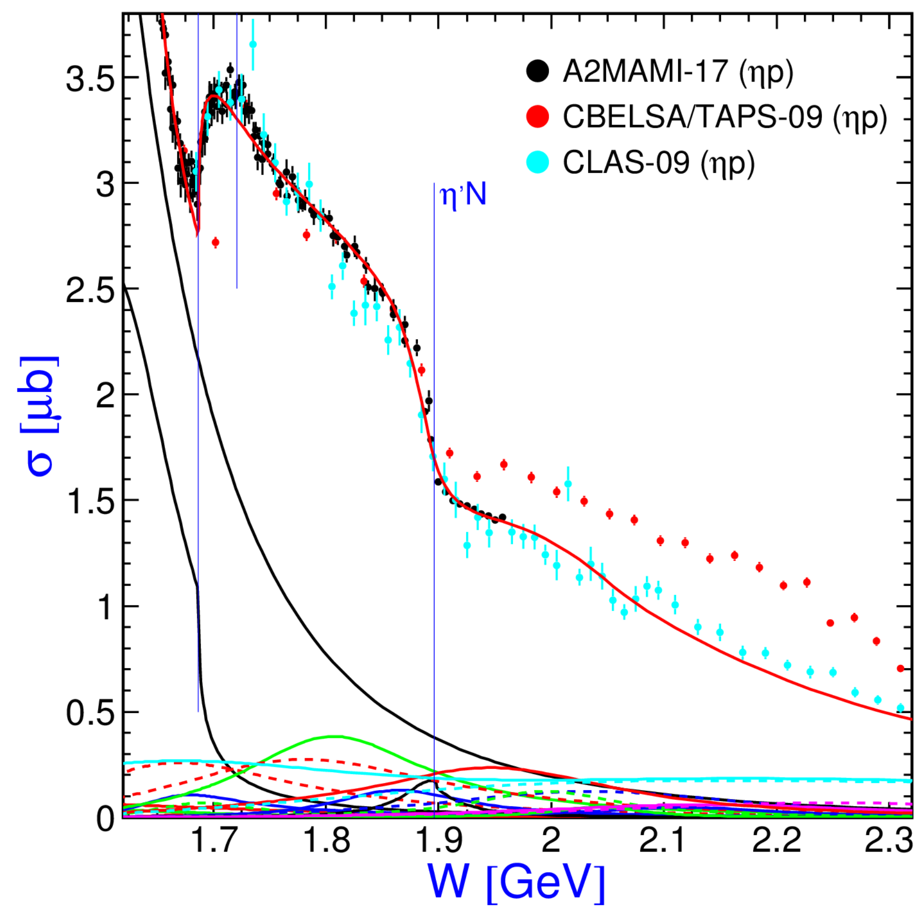
- Only the $P_{33}(1232)$, $D_{13}(1520)$, $F_{15}(1680)$, and perhaps the $F_{37}(1950)$ are directly visible;
- the $P_{11}(1440)$, $S_{11}(1535)$, and many other resonances can only be analyzed in a Partial Wave Analysis.

Bonn-2005: O. Bartholomy et al., PRL 94 (2005) 0122003
Mainz-2013: P. Adlarson et al., PRC 92(2015) 024617

P33(1232)
P11(1440)
D13(1520)
S11(1535)
S31(1620)
S11(1650)
D15(1675)
F15(1680)
D33(1700)
P13(1720)
F35(1905)
P31(1910)
F37(1950)

$\gamma\ p \to \eta\ p$ Partial contributions to the total cross sections



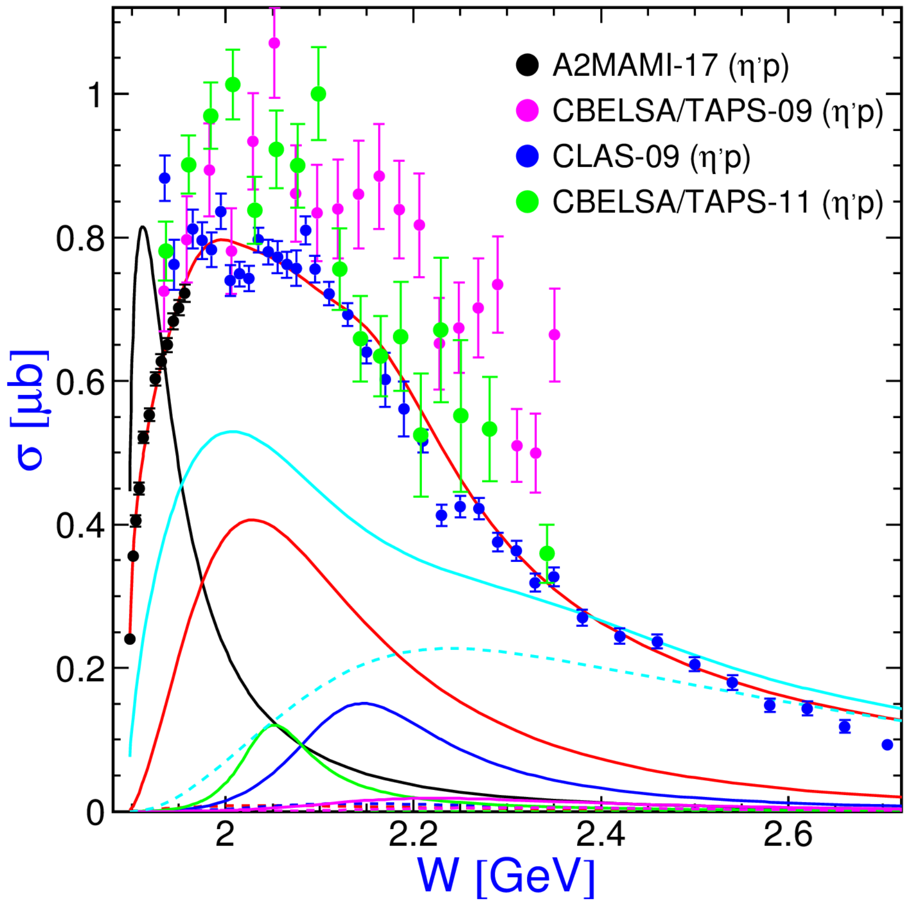


S11 – black solid;
P11 – red solid; P13 – red dashed
D13 – green solid; D15 – green dashed
F15 – blue solid; F17 – blue dashed
G17 – magenta solid; G19 – magenta dashed

Background - cyan

$\gamma\ p \rightarrow\ \eta'\ p$

Partial contributions to the total cross sections



S11 – black solid;

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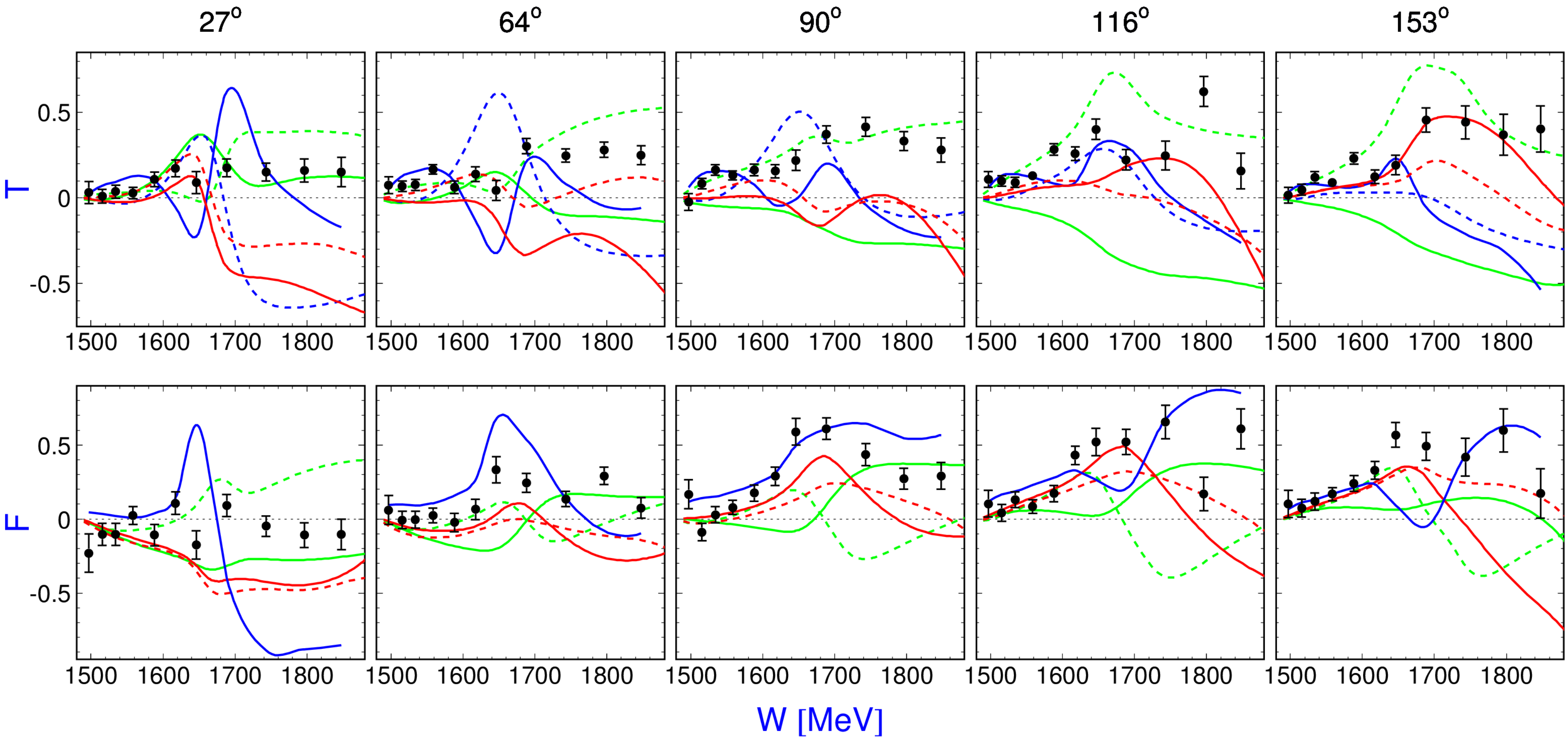
G17 – magenta solid; G19 – magenta dashed

Background - cyan

γ p → η p

Data: A2MAMI, PRL 113 (2014)
1th publication from A2 with FST !



dashed green line: MAID 2003 Isobar Model
solid green line:MAID 2003 Reggezed Isobar Model
solid blue line: SAID GE09; dashed: SAID E429;
solid reded line: BG2011-02; dashed: BG20010-02

$\gamma\ p \rightarrow \eta\ p$

A.V. Anisovich, E. Klempt, V. Nikonov, A. Sarantsev, U. Thoma, arXiv:1402.7164v1

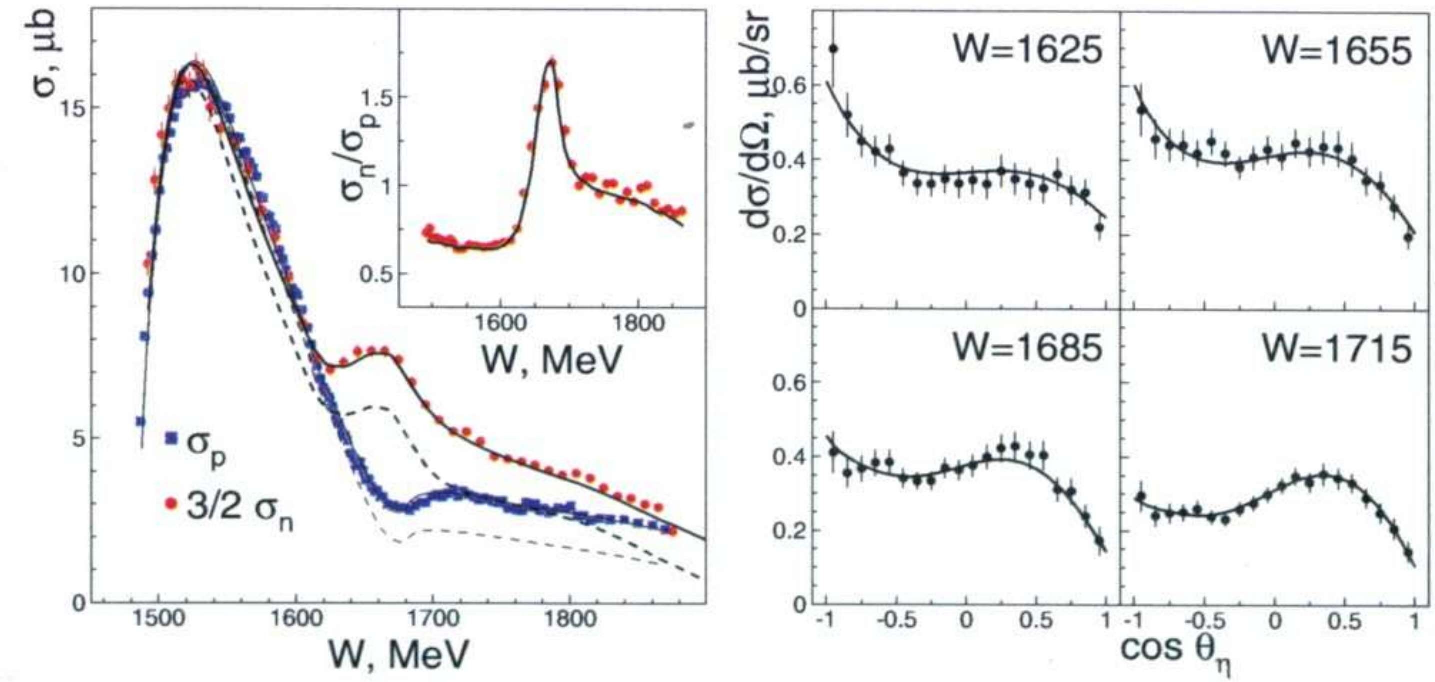


FIG. 1. (Color online) Left: The total cross section for $\gamma n \to \eta n$ (multiplied by 3/2), $\gamma p \to \eta p$, and their ratio (as inset). The solid curves represent our fit folded with the experimental resolution (thick ηn, thin ηp), the dashed curves the contributions from the S_{11} waves. Right: Selected differential cross section for $\gamma n \to \eta n$ in the region of the narrow structure

$\gamma\ p \to \eta\ p$

A.V.Anisovich et al., PLB 719, 89, 2013
Coupled channel isobar model
Fit to the total and differential cross sections

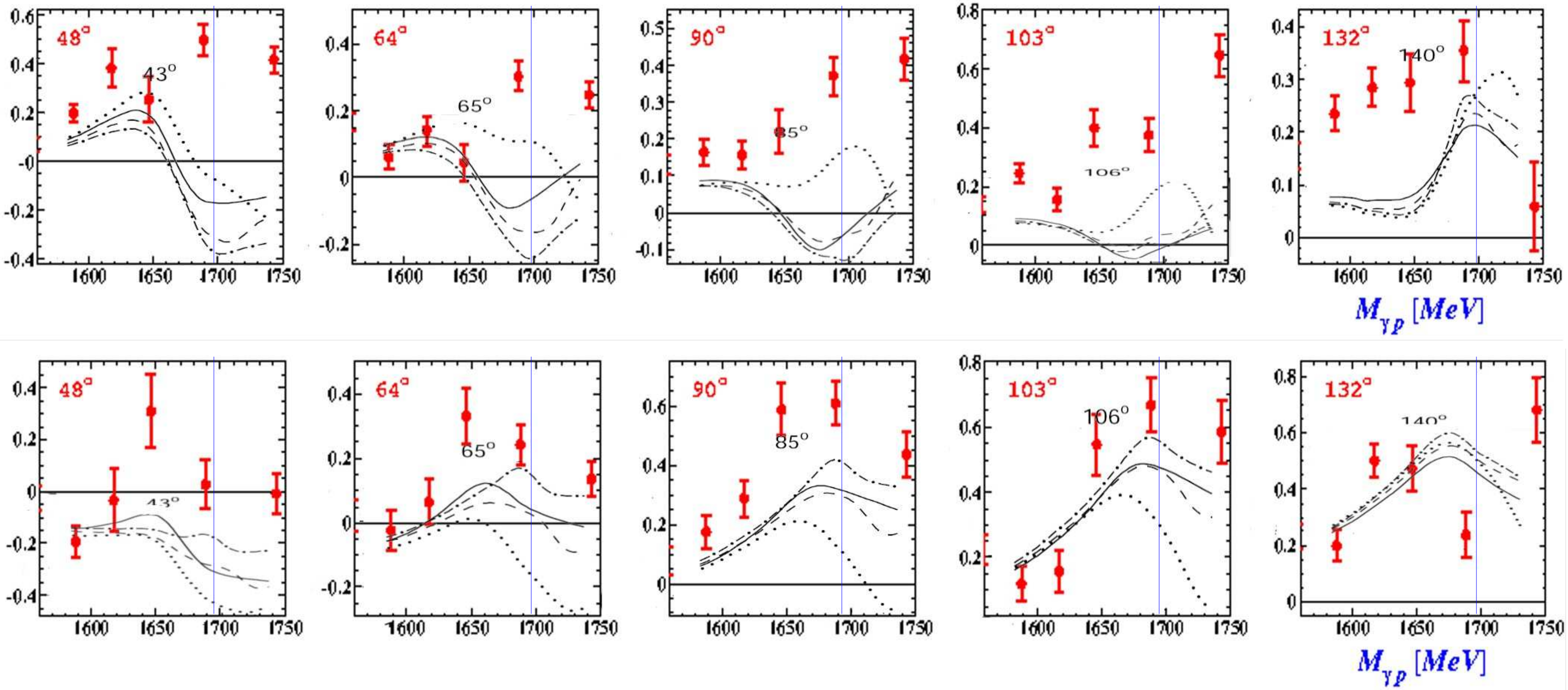
Data: A2MAMI, PRL 113 (2014)
1th publication from A2 with FST !

Predictions for T and F asymmetries

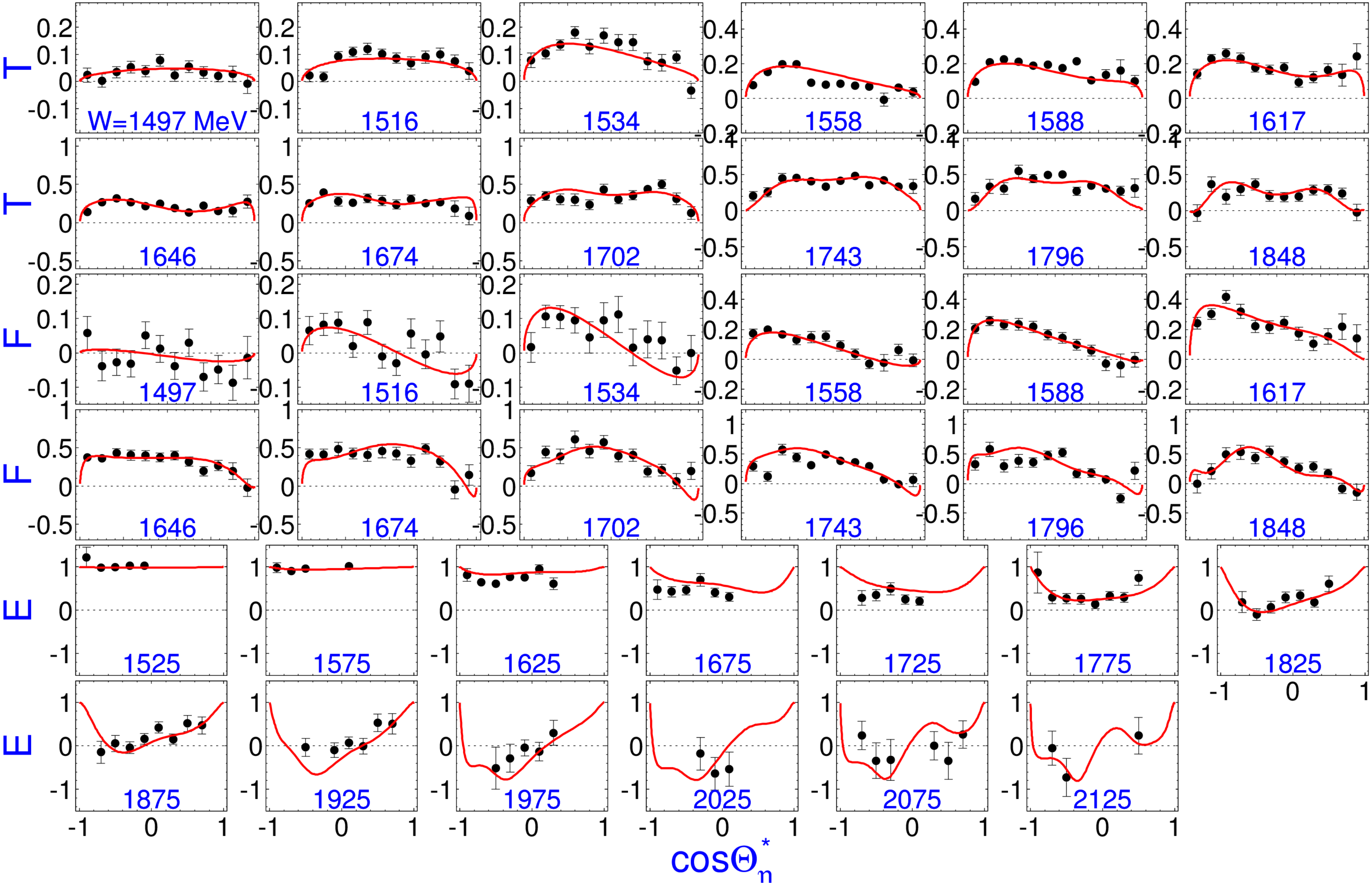
Solid curves: ωp channel included to S11 partial wave
Dashed: P11(1719)+ solution
Dashed-dotted: P11(1694)- solution
Dotted: P13(1696) solution

T

F



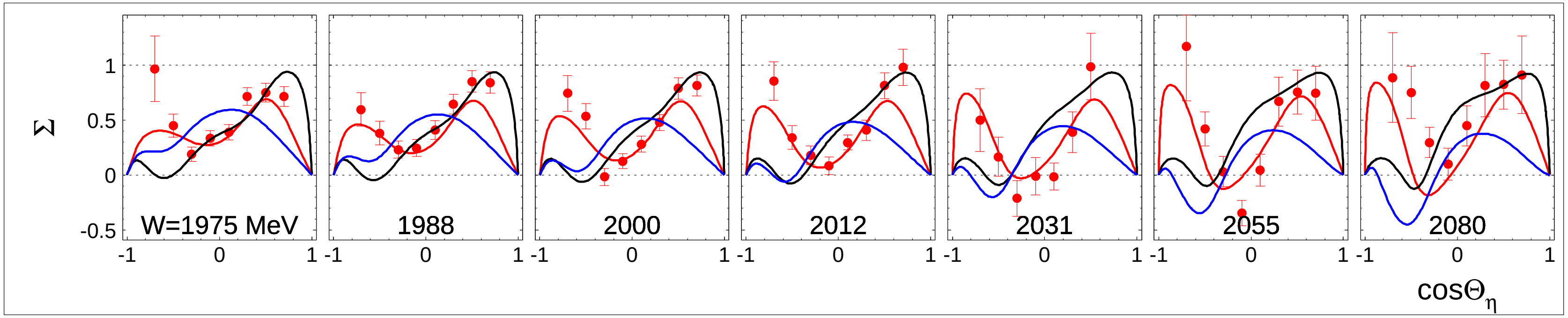
$\gamma\ p \rightarrow\ \eta\ p$ Polarization observables



Data: A2MAMI-14 (T and F), CLAS-15 (E);
Lines: red – EtaMAID-2018 (preliminary)

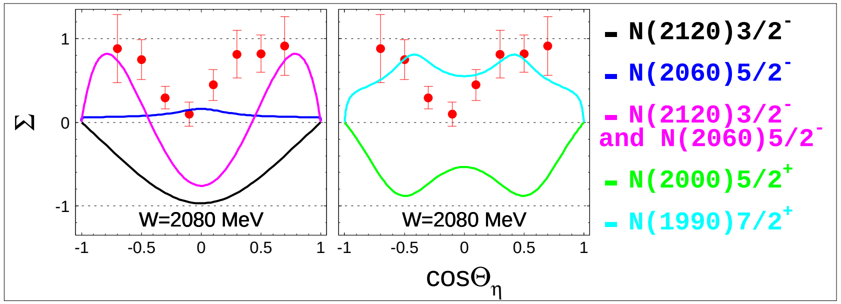
Selected fit results

Σ for $\gamma p \to \eta p$



Red lines - full solution, black - refit without $N(2120)3/2^-$, blue - refit without $N(2060)5/2^-$.

Partial contributions of resonances:



$N(2120)3/2^-$ and $N(2060)5/2^-$ interference explains the shape of the angular distributions. Both resonances have an overall status of ** in PDG-2017. Status for ηN: 0 and *, respectively.

Should be updated!

Excluding $N(2000)5/2^+$ or $N(1990)7/2^+$ from the fit practically does not affect the quality of Σ description.

Data: CLAS-17 (red).

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..?

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:

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

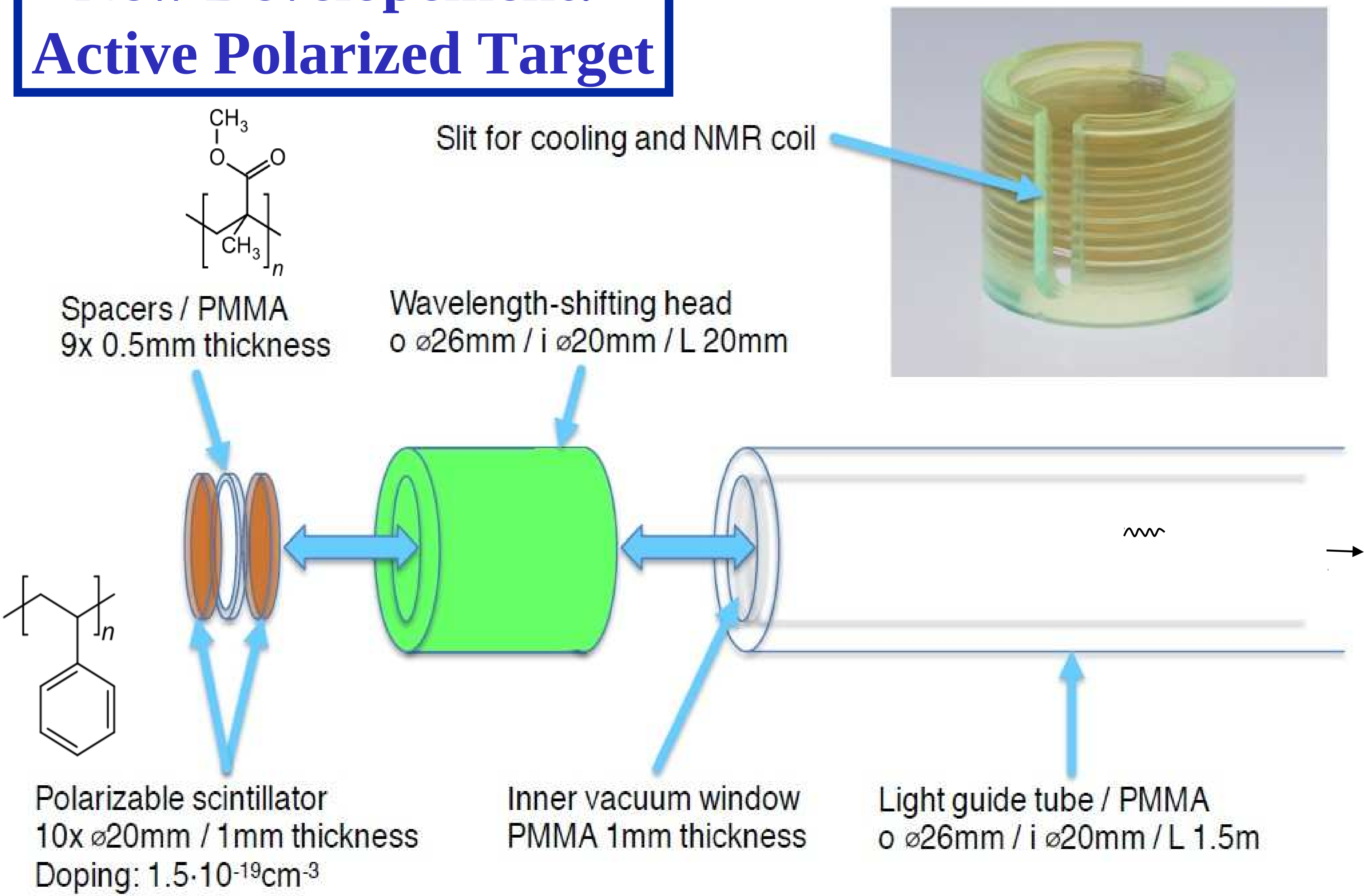
$$\gamma_\pi = -\gamma_{E1E1} + \gamma_{M1M1} - \gamma_{E1M2} + \gamma_{M1E2} = 8.0 \pm 1.8 \times 10^{-4} fm^4$$

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).]

New Developement: Active Polarized Target



Summary

- **A2 Collaboration performs a broad program of the polarization experiments since 2010;**
- **Experiments are carried out with high intensity unpolarized, linearly or circularly polarized photons and transversely or longitudinally polarized nucleons;**
- **Scientific program includes the study of the spectrum and properties of baryon resonances and the internal structure of the nucleons;**
- **Measurements will continue in 2017/18 in Bonn together with CBELSA/TAPS Collaboration.**

A2 publications with JINR (N. Borisov, A. Lazarev, A. Neganov, Yu. A. Usov)

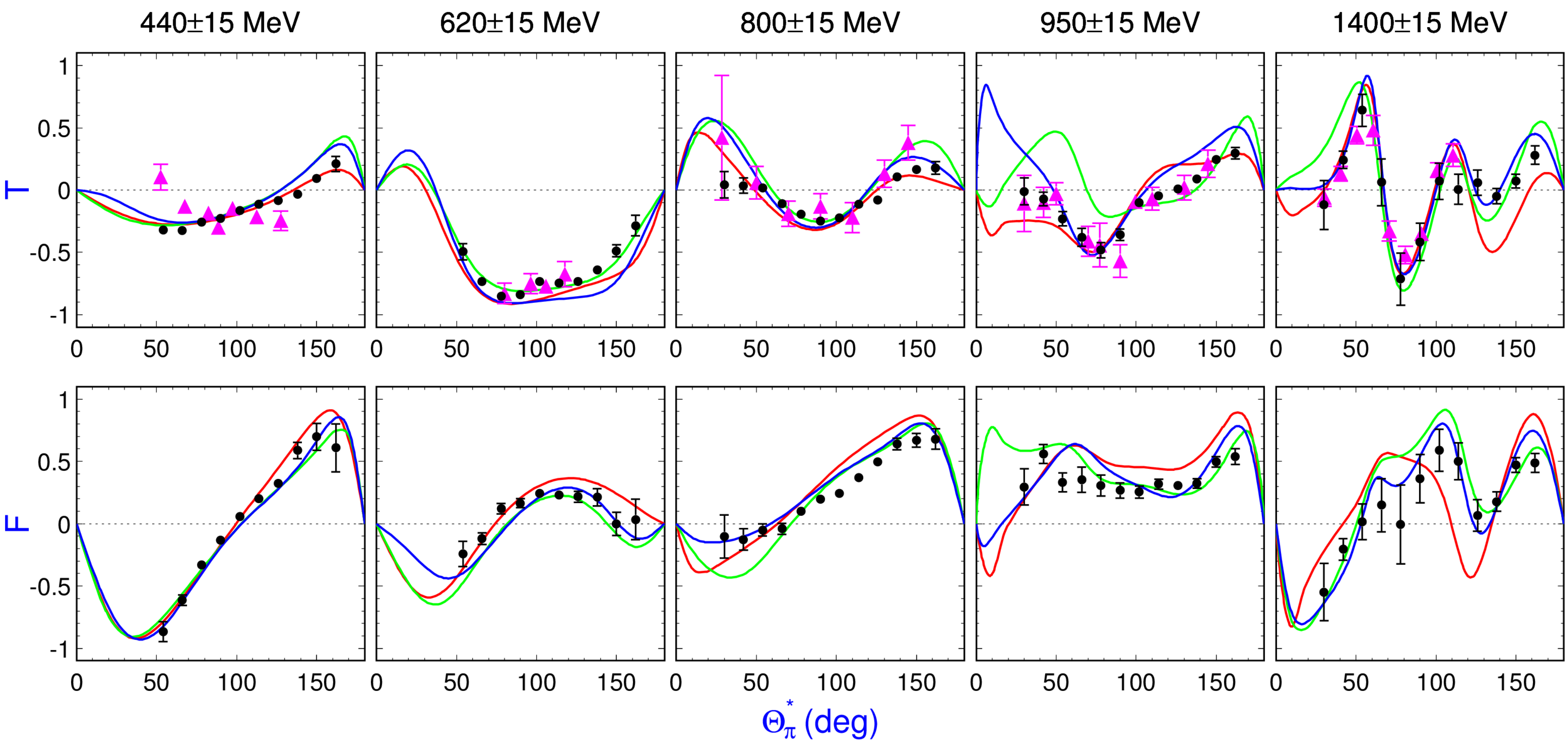
1. Measurement of the Transverse Target and Beam-Target Asymmetriesin η Meson Photoproduction at MAMI,
   PRL 113 (2014) 102001.
2. First measurement of target and beam-target asymmetries in the ɣ p → pi0 eta p reaction,
   PRC 91 (2015) 055208.
3. Measurements of Double-Polarized Compton Scattering Asymmetries
   and Extraction of the Proton Spin Polarizabilities,
   PRL 114 (2015) 112501.
4. Measurement of pi0 photoproduction on the proton at MAMI C,
   PRC 92 (2015) 024617.
5. Threshold π0 photoproduction on transverse polarised protons at MAMI,
   PLB 750 (2015) 252.
6. T and F asymmetries in pi0 photoproduction on the proton
   PRC 93 (2016) 055209.
7. Photon asymmetry measurements of ɣp → pi0 p for Eg=320-650 MeV,
   EPJA 52 (2016) 333.
8. Insight into the Narrow Structure in η Photoproduction on the Neutron from Helicity-Dependent Cross Sections,
   PRL 117 (2016) 132502.
9. Measurement of the omega→e+e- and eta→e+e-g Dalitz decays with the A2 setup at MAMI,
   PRC 95 (2017) 035208.
10. Measurement of the π0→e+e−γ Dalitz decay at the Mainz Microtron,
    PRC 95 (2017) 025202.
11. First measurement of the polarization observable E and helicity-dependent
    cross sections in single π0 photoproduction from quasi-free nucleons,
    PLB 770 (2017) 523.
12. Helicity-dependent cross sections and double-polarization observable
    E in η photoproduction from quasifree protons and neutrons,
    PRC 95 (2017) 055201.

A2 Collaboration at MAMI

25th International A2 Collaboration Meeting, Dubna, Russia, September 2014

$\gamma\ p \rightarrow \pi^o\ p$

T and F asymmetries, selected energy bins



black circles: A2MAMI data, PRC 93 (2016)
magenta triangles: world data (before 2000)

green line: MAID 2007
blue line: SAID CM12
red line: BG2011-02