V. L. Kashevarov and Yu. A. Usov 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

DZHELEPOV LABORATORY OF NUCLEAR PROBLEMS

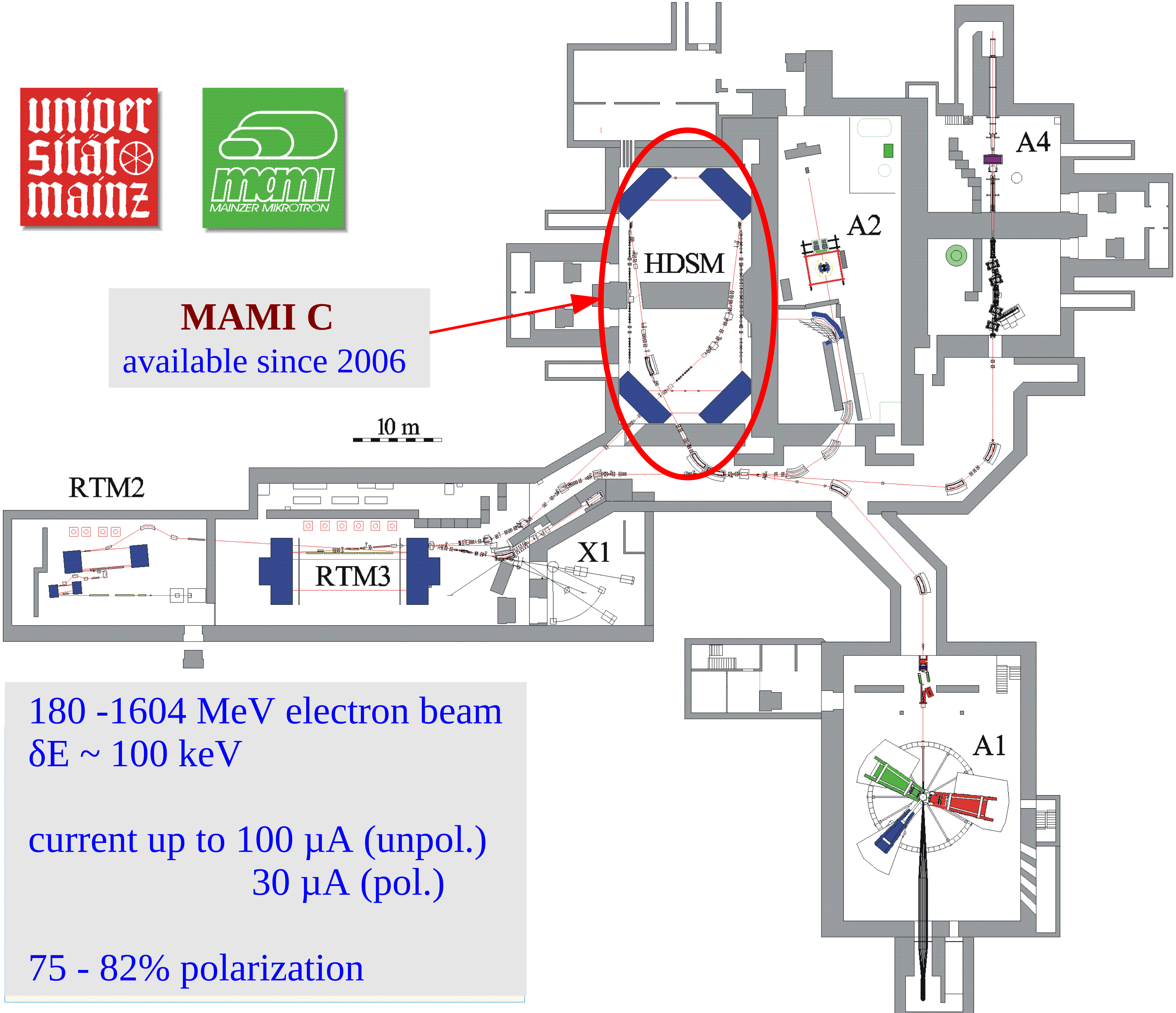
JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

A2

Outline

- Electron accelerator MAMI C
- A2 Collaboration at MAMI
- Scientific program
- Meson photoproduction with MAMI C
- Experiments with polarized targets
- Selected results
- Summary

MAMI C
available since 2006



180 -1604 MeV electron beam
δE ~ 100 keV

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

75 - 82% polarization

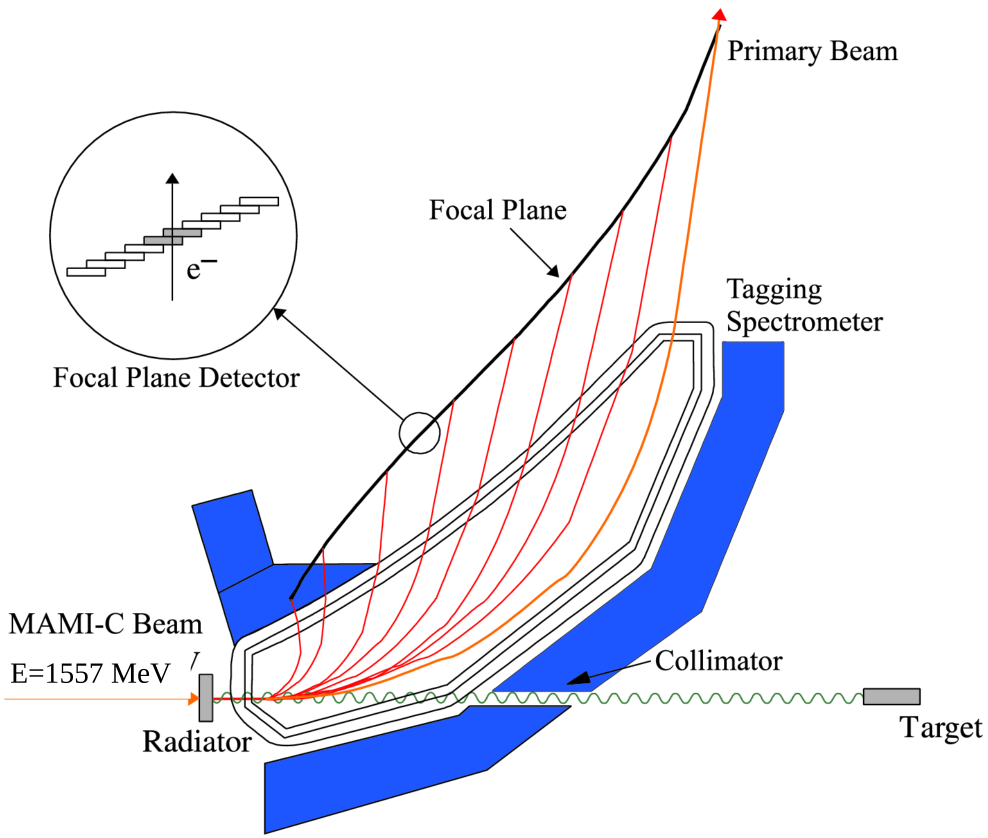
A2 Collaboration at MAMI

- **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.**

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

Experimental apparatus: photon beam



Tagged photon beam

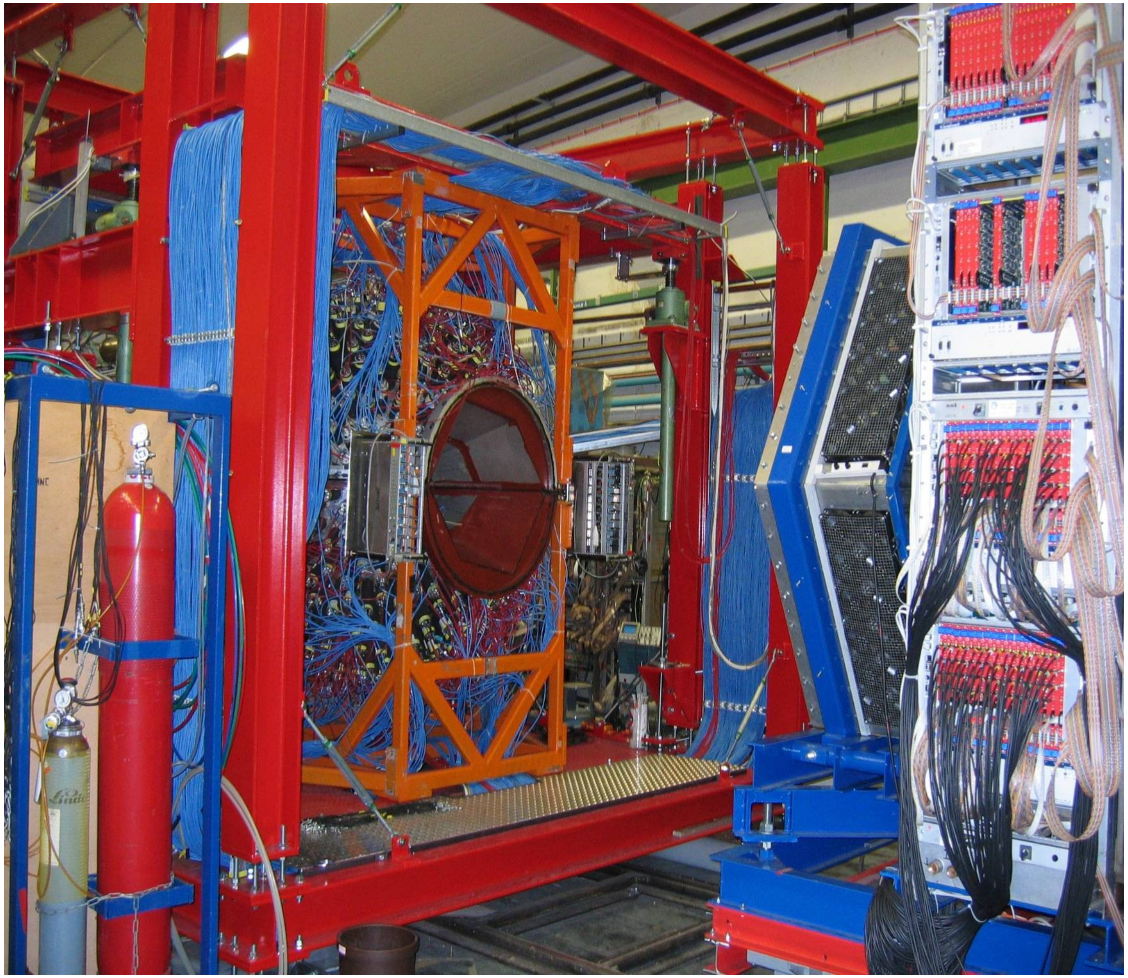
- unpolarized
- circular polarization
- linear polarization

The Glasgow photon tagging spectrometer

352 channels
2 – 5 MeV energy resolution

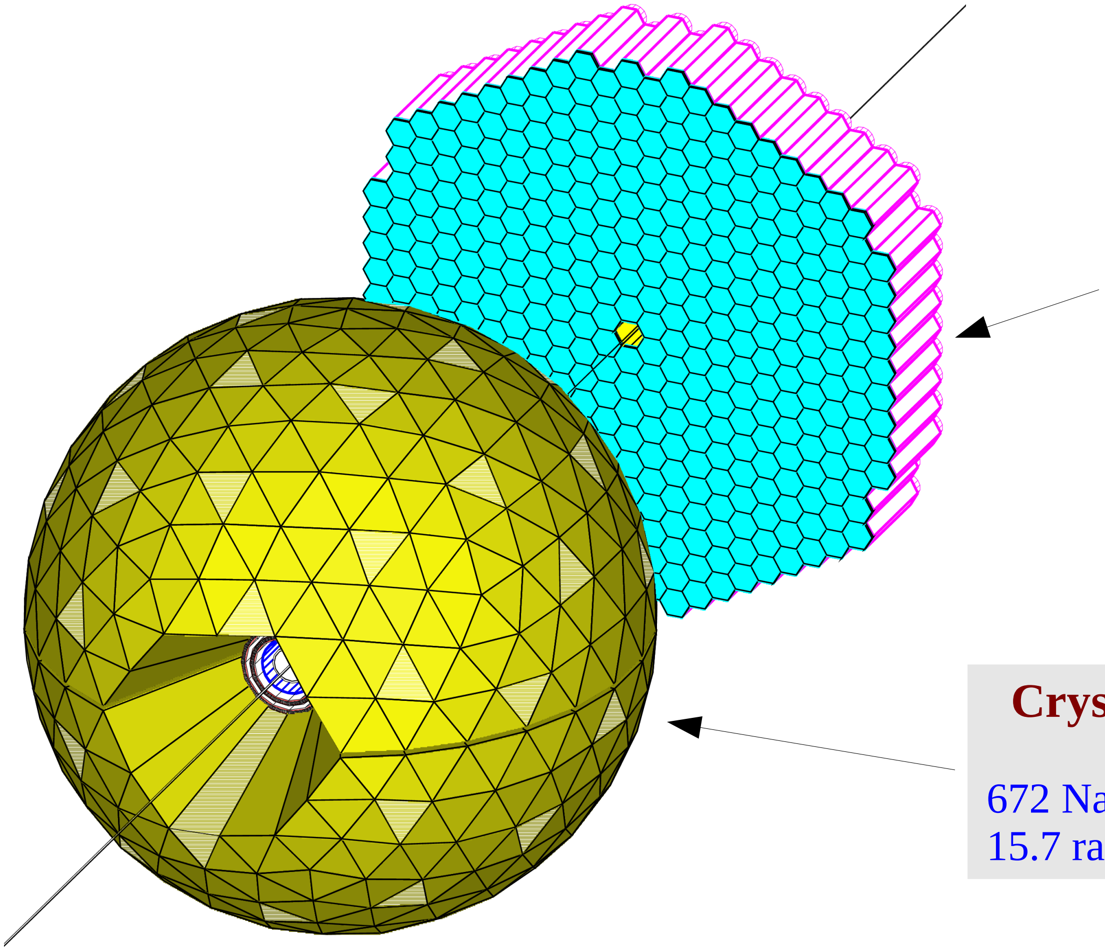
Experimental apparatus: detector system

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)

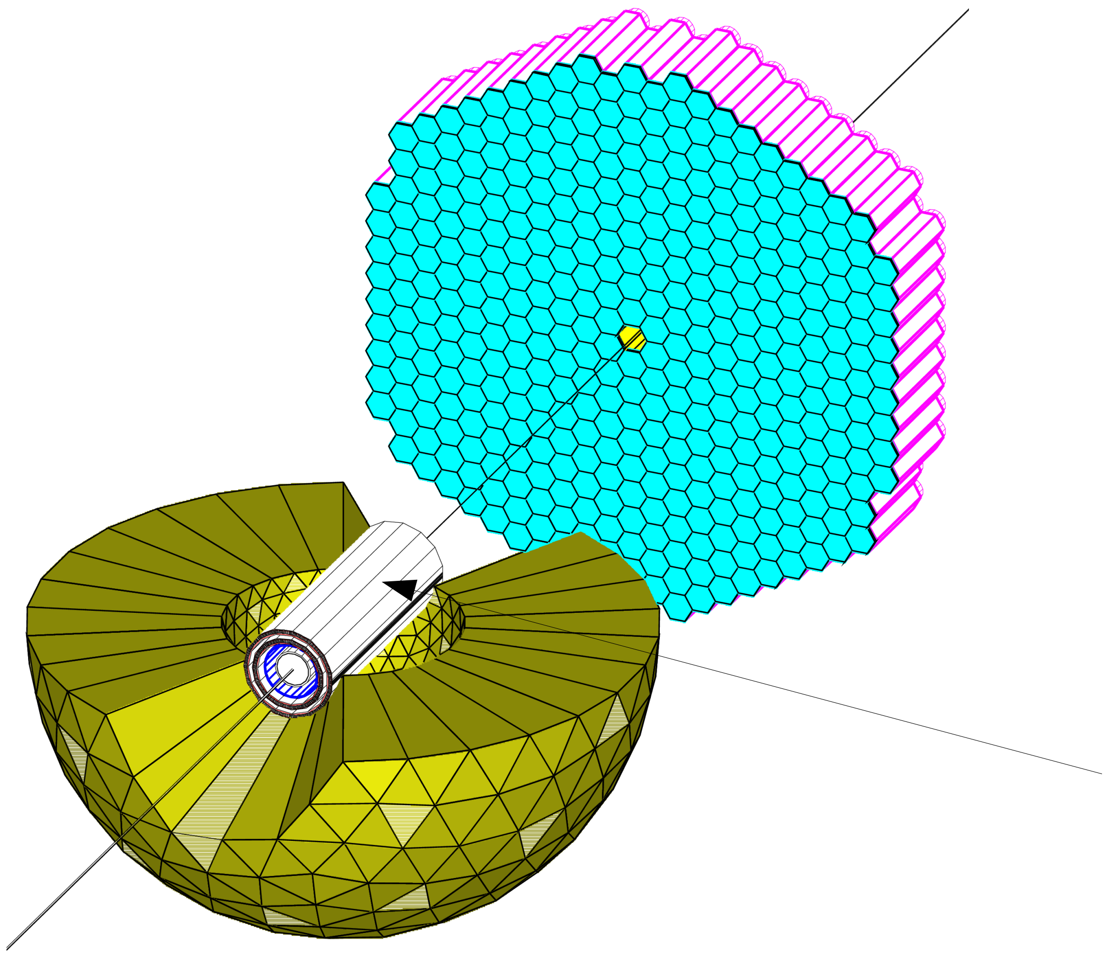
366 BaF_2 crystals
12 radiation lengths

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

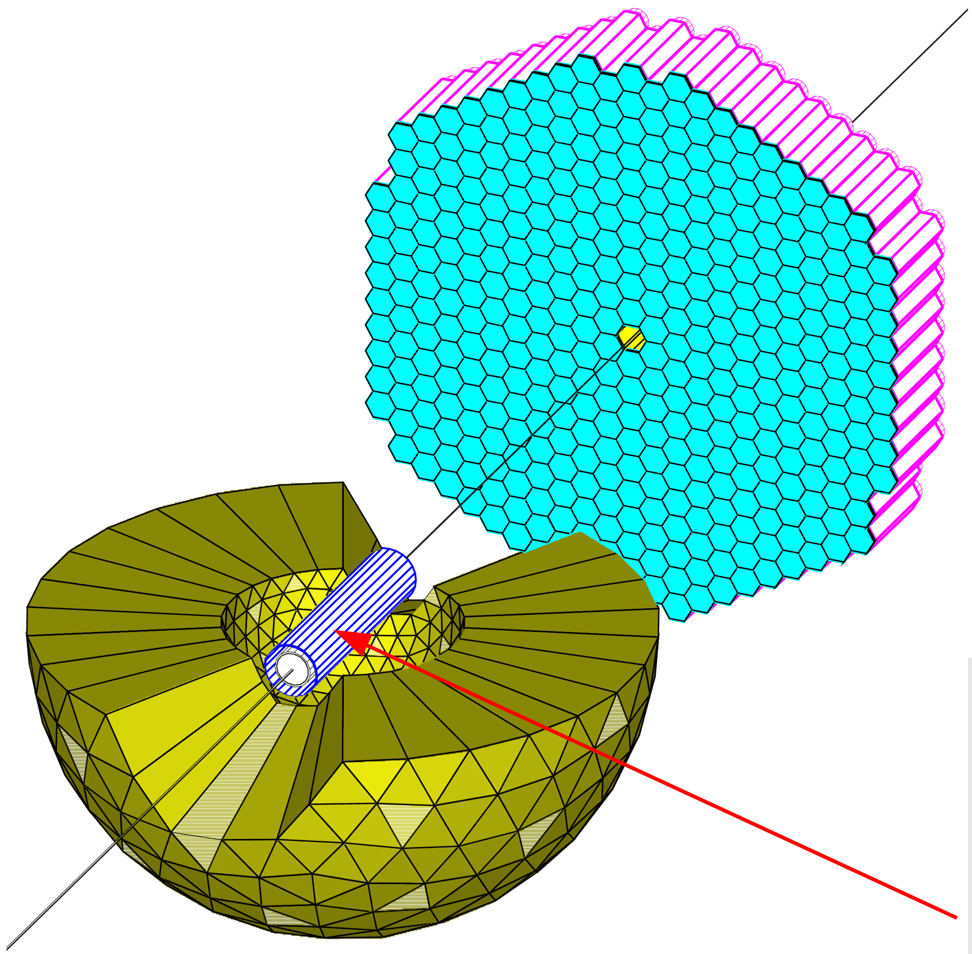


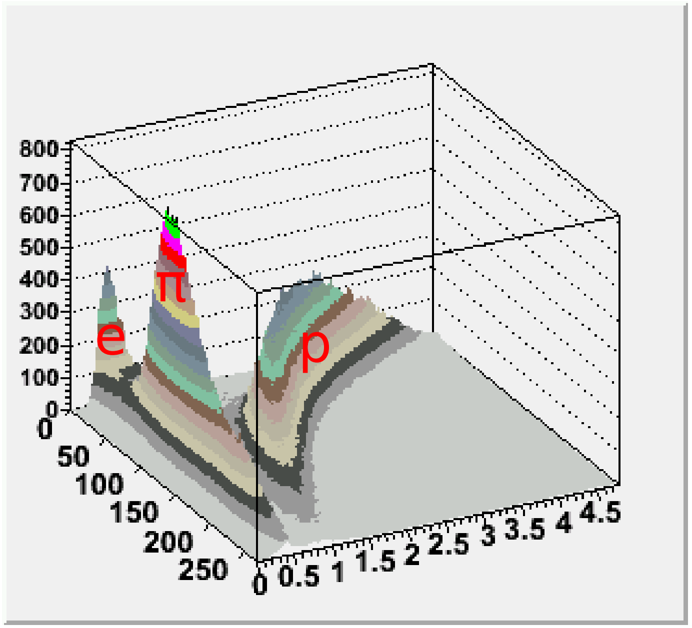
MWPC (Pavia)

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;

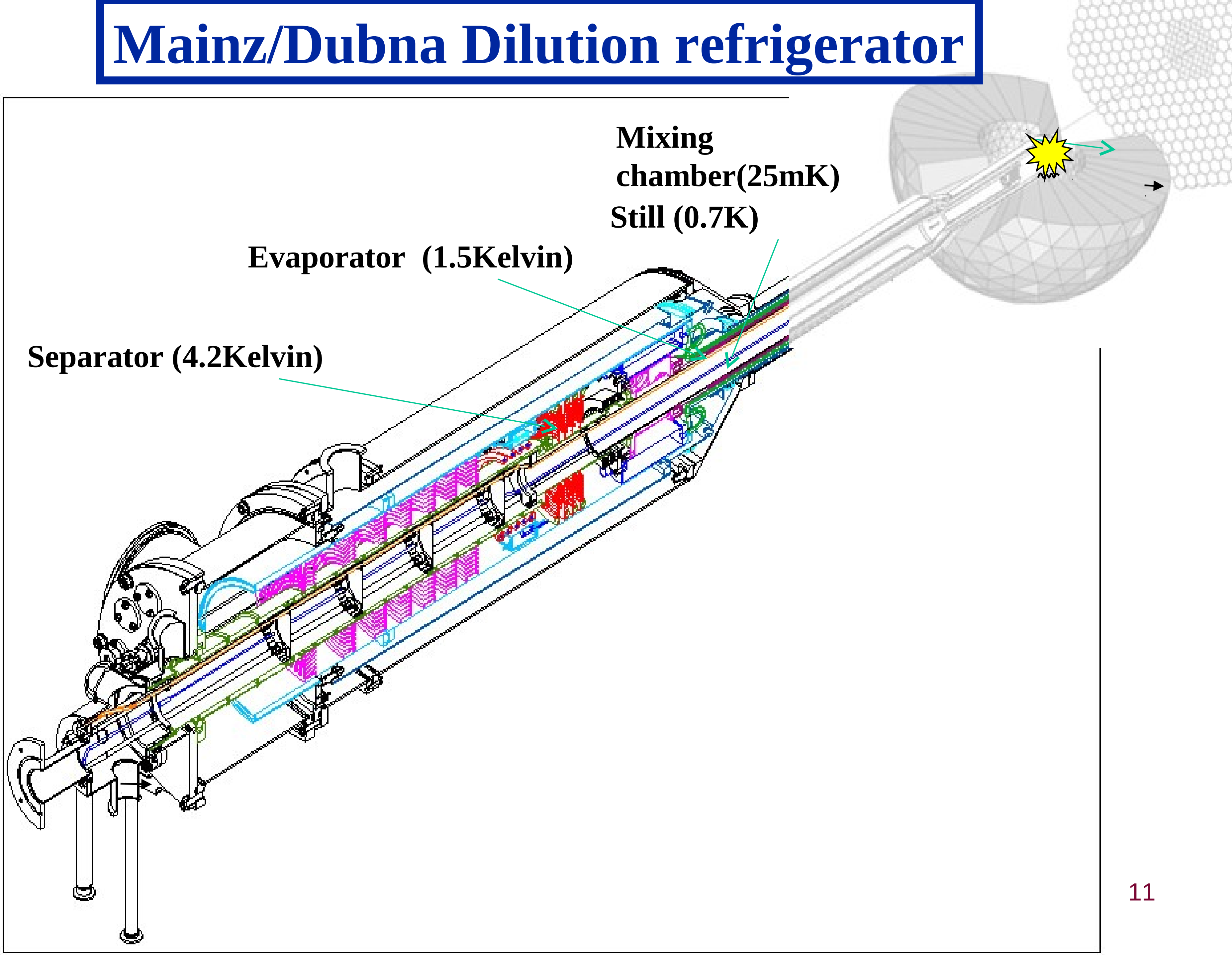
Superconducting holding magnet;

Longitudinal or transverse polarizations are possible;

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

Relaxation time ~2000 hours

Mainz/Dubna Dilution refrigerator



Scientific program

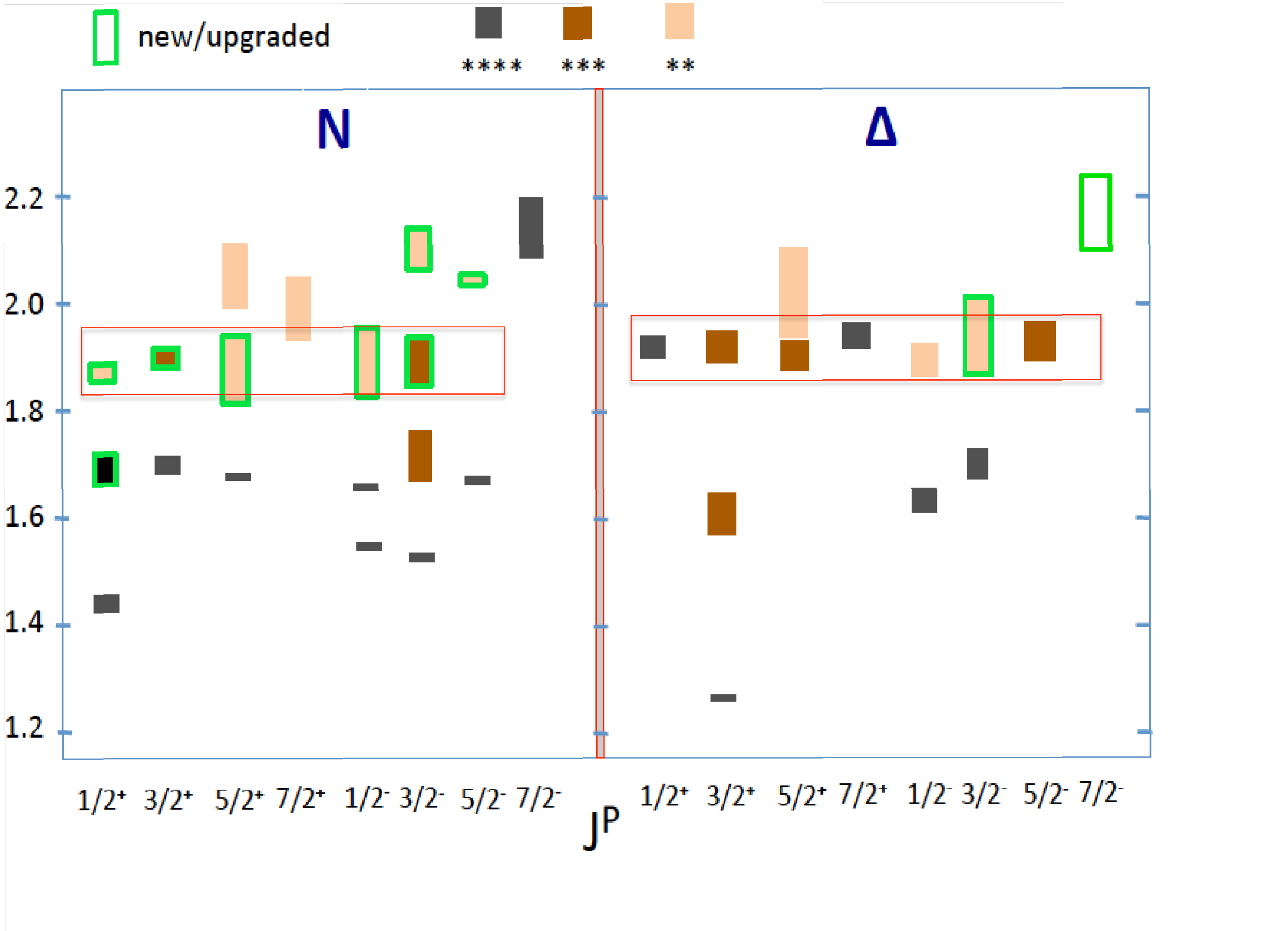
- **Photoproduction of mesons on nucleons:**
  - reaction mechanism (FST)
  - baryon spectroscopy (FST)

- **Photoproduction of mesons on nuclei:**
  - neutron skin
  - eta-mesic and eta'-mesic nuclei
  - dibaryons (FST)

- **Compton scattering on nucleons:**
  - scalar polarizabilities
  - spin polarizabilies (FST)

- **Rare decays of mesons**

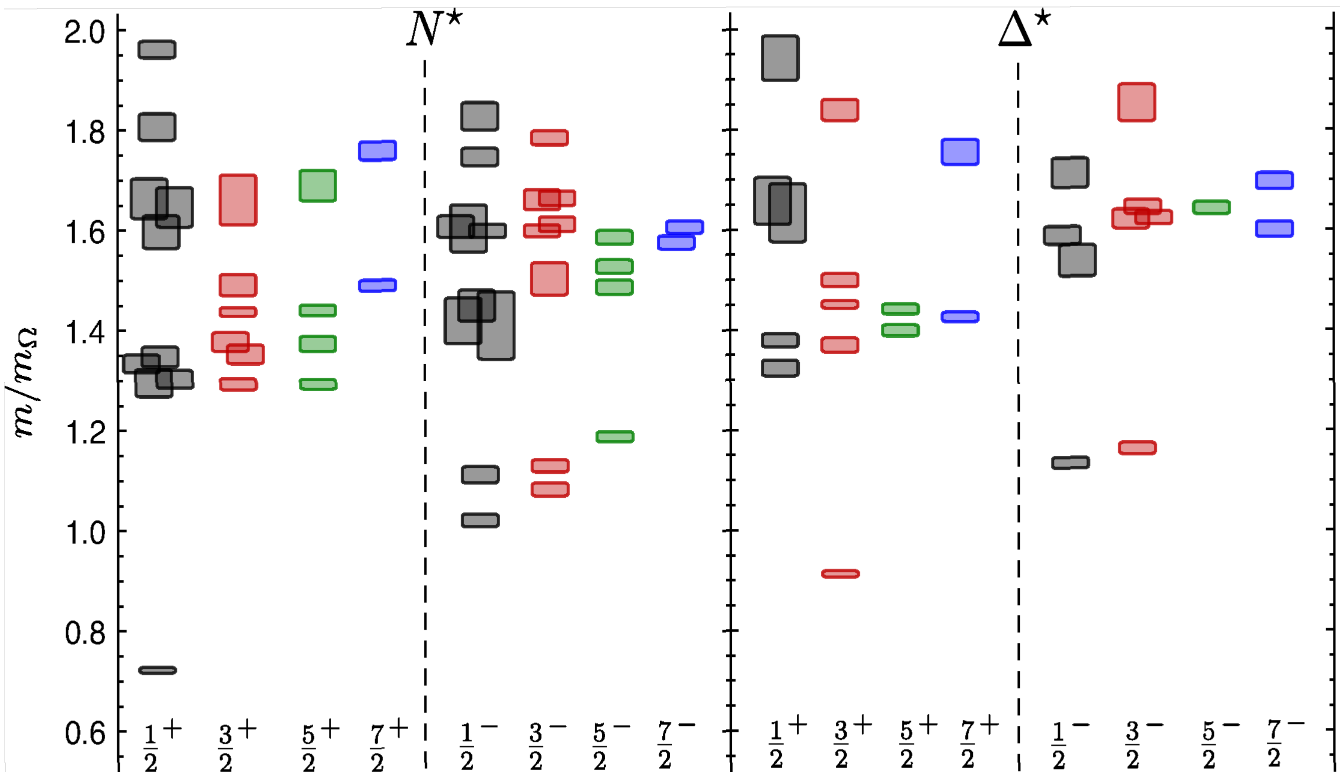
Nucleon and Δ resonances spectrum from PDG-2016



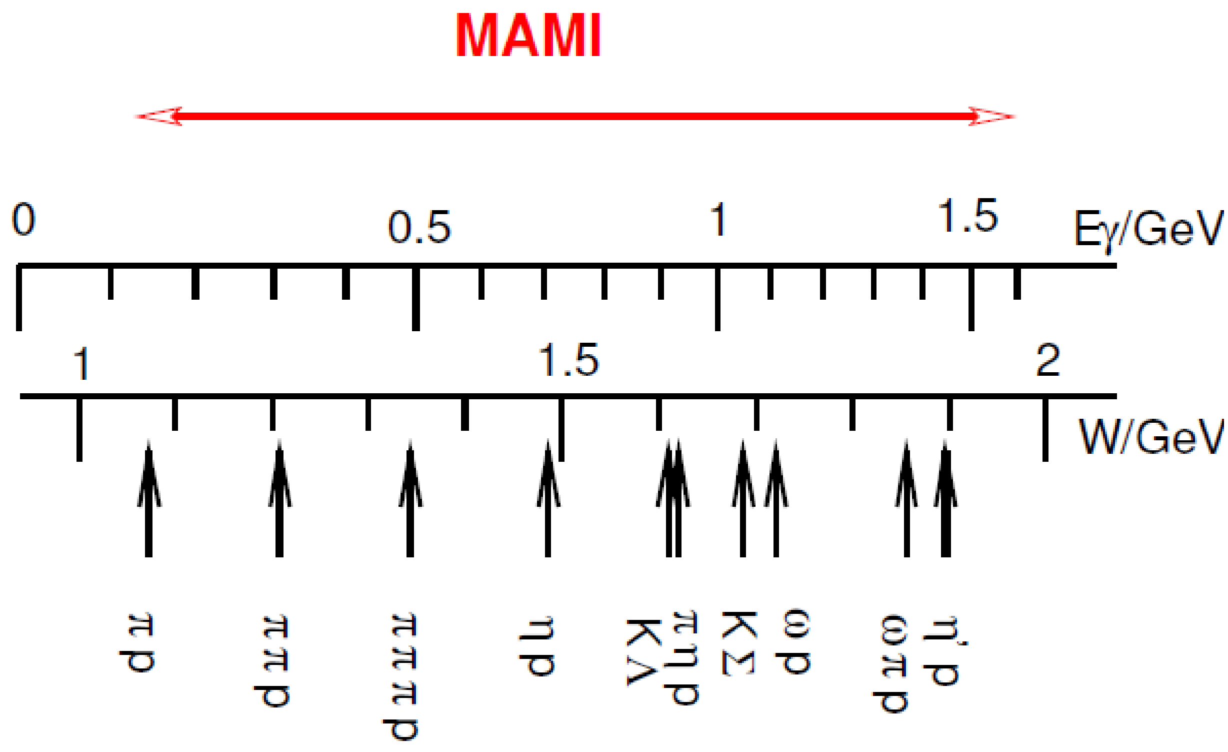
Nucleon and Δ resonances spectrum from lattice theory predictions

Edwards et al. PRD 84 (2011)

New missing resonances problem!



Meson photoproduction with MAMI C



Energy thresholds in γN

- 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. $\gamma\ p \rightarrow \pi^o\ \eta\ p$
8. $\gamma\ p \rightarrow \pi^o\ \pi^o\ n$
9. $\gamma\ p \rightarrow \pi^o\ \eta\ n$
10. $\gamma\ p \rightarrow \eta'\ p$ (plan for 2019)

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

(circled) 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

definitions from Barker, Donnachie, Storrow, 1975

- polarized photons and polarized target

BT

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

- polarized photons and recoil polarization

BR

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

- polarized target and recoil polarization

TR

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

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)

Analisys of data

- **Main specific of analysis of raw data is background subtraction**
- **Main tool for analysis of obtained observables – PWA**

Target asymmetry T

Target asymmetry T is defined for transverse polarized target ($\theta_T = 90^o$):

$$T(E_\gamma, \Theta_\pi, \phi = 0^o) = \frac{1}{P_T} \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \qquad (1)$$

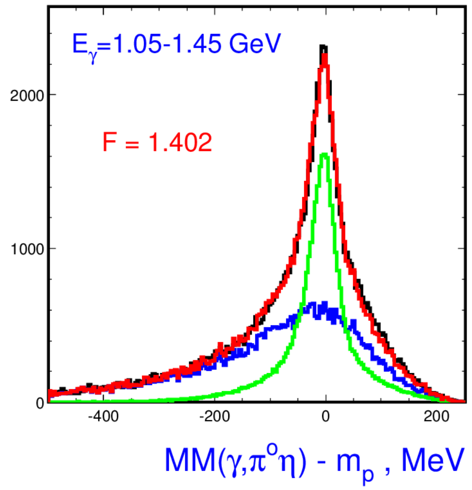
where $d\sigma^+ (d\sigma^-)$ denote the differential cross sections for +(-) proton spin direction, ϕ is angle between proton spin direction and reaction plane, P_T is target polarisation degree.

If $\phi_T = 90^o$:

$$T(E_\gamma, \Theta_\pi) = \frac{1}{P_T} \frac{d\sigma(\phi_\pi = 0^o) - d\sigma(\phi_\pi = 180^o)}{d\sigma(\phi_\pi = 0^o) + d\sigma(\phi_\pi = 180^o)} \qquad (2)$$

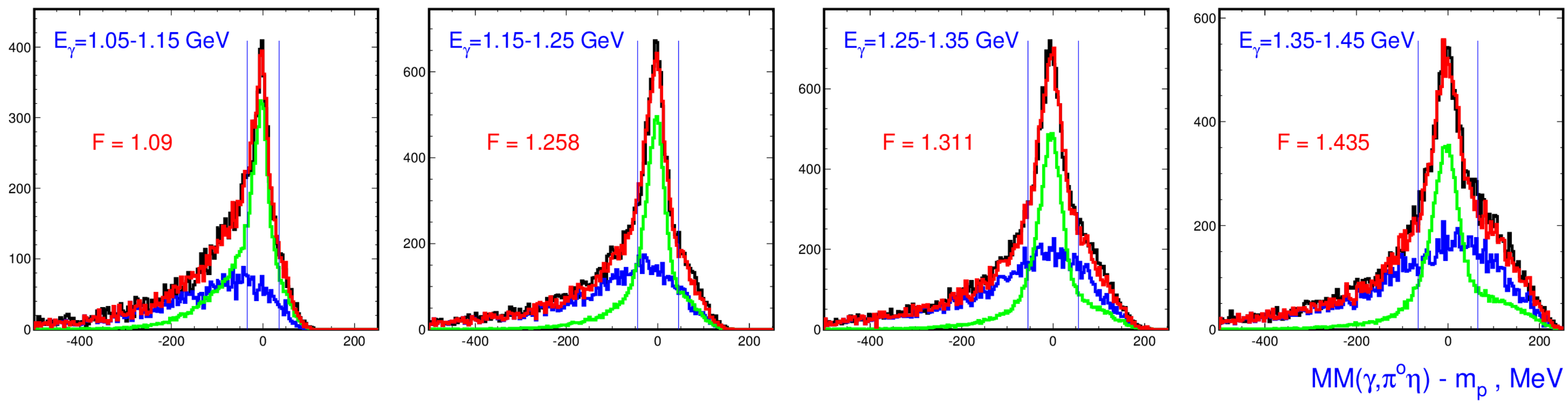
$$T(E_\gamma, \Theta_\pi) = \frac{1}{P_T} \frac{1}{sin\phi_\pi} \frac{d\sigma(\phi_\pi) - d\sigma(\phi_\pi + 180^o)}{d\sigma(\phi_\pi) + d\sigma(\phi_\pi + 180^o)} \qquad (3)$$

$\gamma\ p \rightarrow \pi^o \eta\ p$ *Data analysis: background subtraction*



Butanol C_4H_9OH

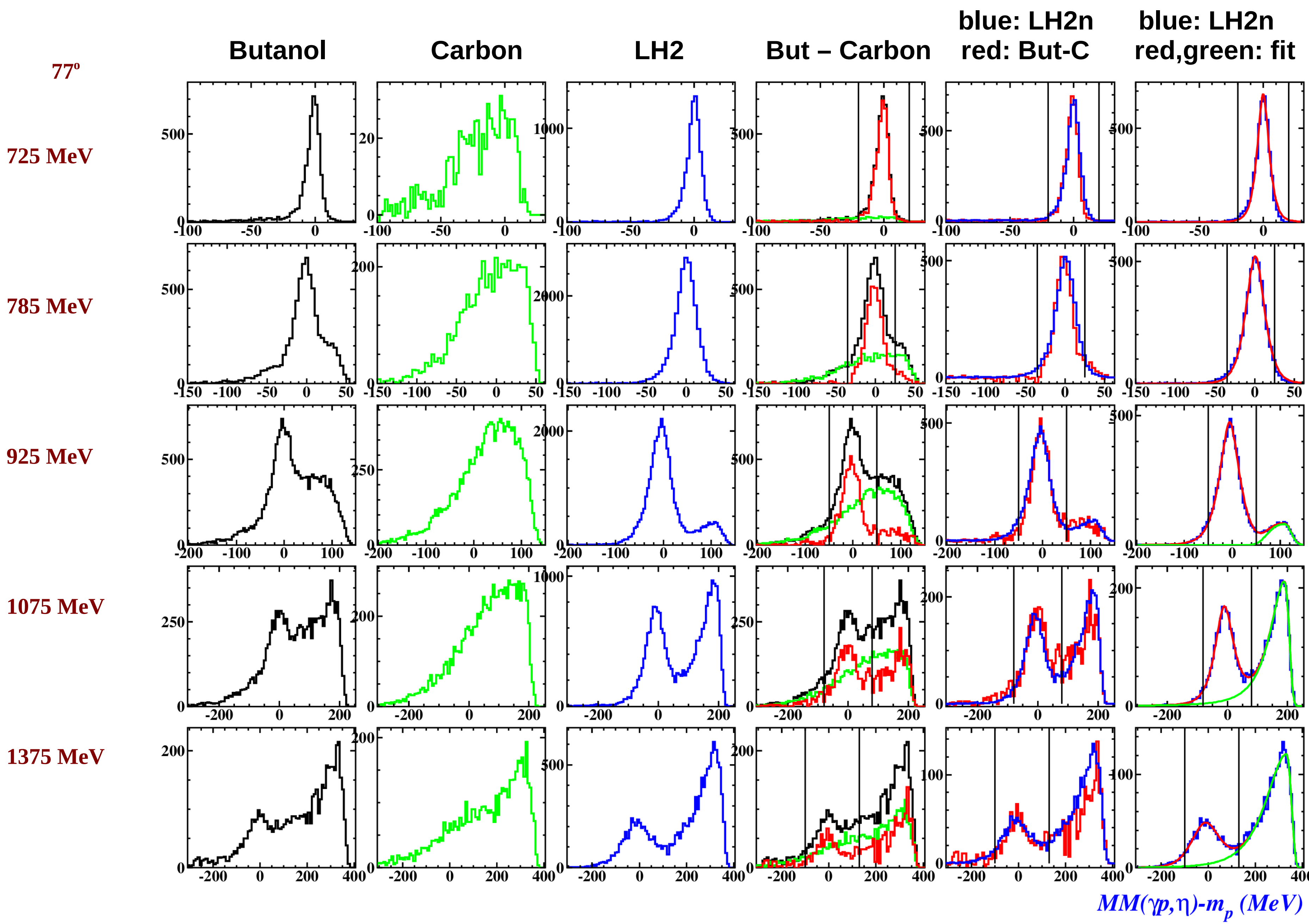
butanol = F*carbon + C*hydrogen



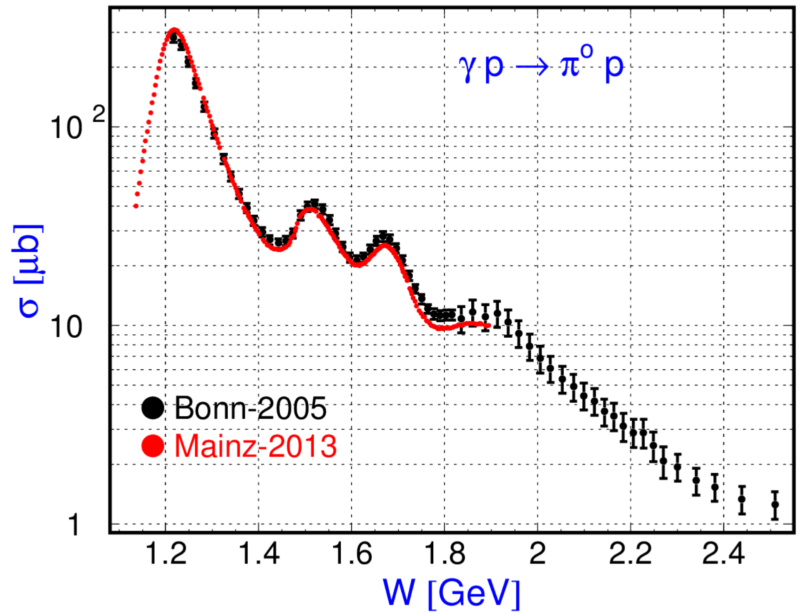
Black histogram:	butanol target (April 2011)
Blue:	carbon target (Aug2010 + Aug2011)
Green:	liquid hydrogen target (July 2007)
Red:	best fit (carbon + hydrogen)

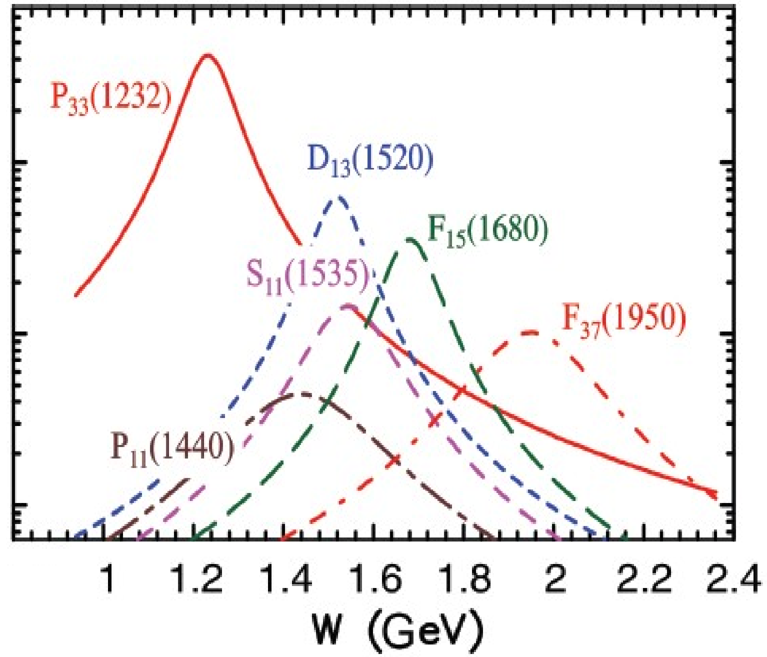
$\gamma\ p \rightarrow \eta\ p$

Backround subtraction



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





- 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)

https://maid.kph.uni-mainz.de

M A I D

Photo- and Electroproduction of Pions, Etas and Kaons on the Nucleon

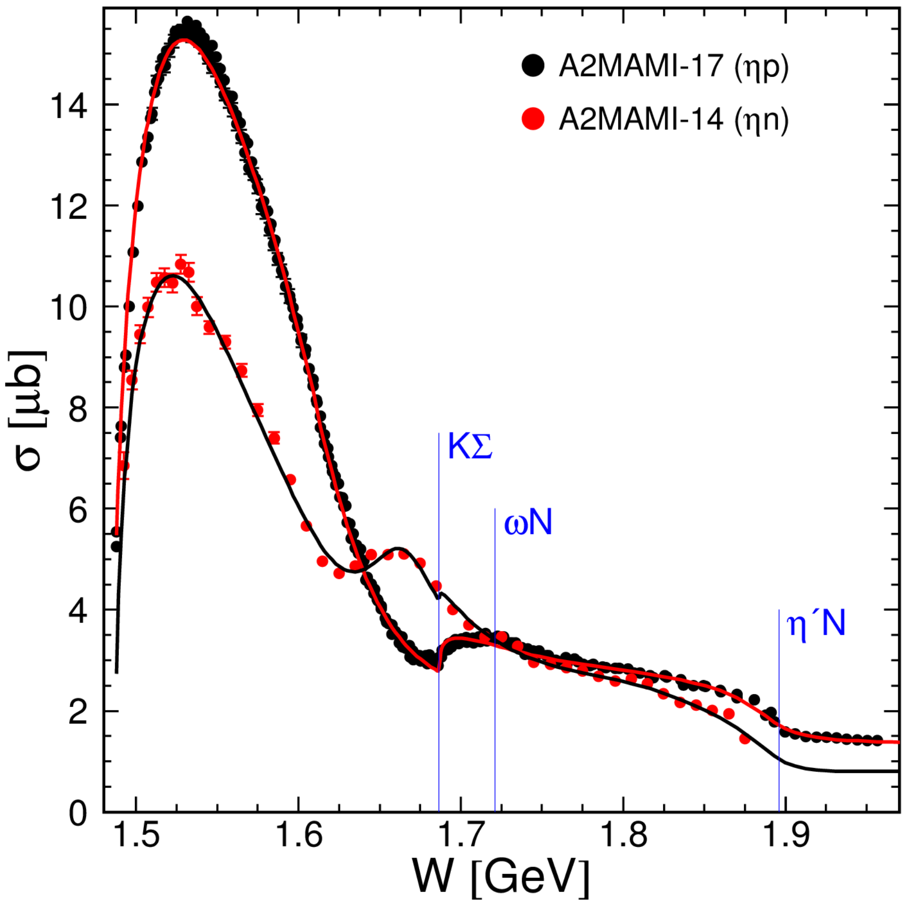
Institut für Kernphysik, Universität Mainz

Mainz, Germany

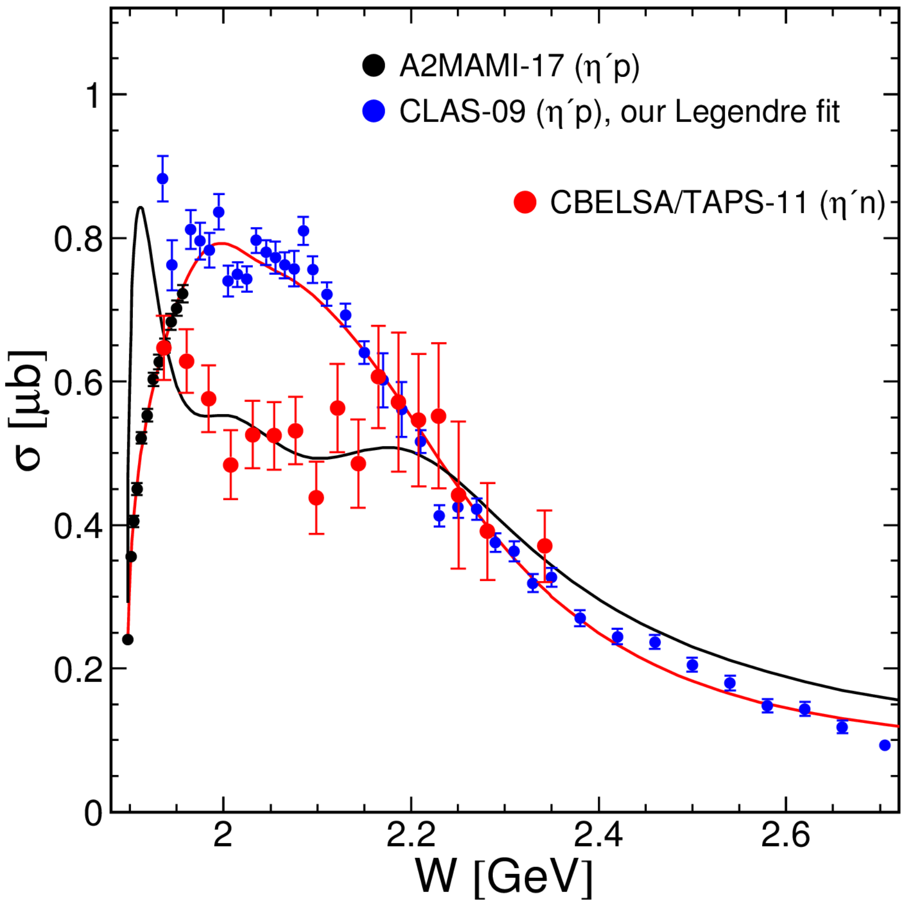
MAID2007	unitary isobar model for (e,e'π)
DMT2001	dynamical model for (e,e'π)
KAON-MAID	isobar model for (e,e'K)
ETA-MAID	isobar model for (e,e'η) reggeized isobar model for (γ,η)
Chiral MAID NEW	chiral perturbation theory approach for (e,e'π)
2-PION-MAID	isobar model for (γ,ππ)
archive	MAID2000 MAID2003 DMT2001original ETAprime2003

Total cross sections

γ N → η N



γ N → η' N



Lines: full EtaMAID2018 solution for γp (red) and γn (black) channels.

EtaMAID 2018: https://maid.kph.uni-mainz.de/eta2018/etamaid2018.html
L. Tiator et all, arXiv:1807.04525

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

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

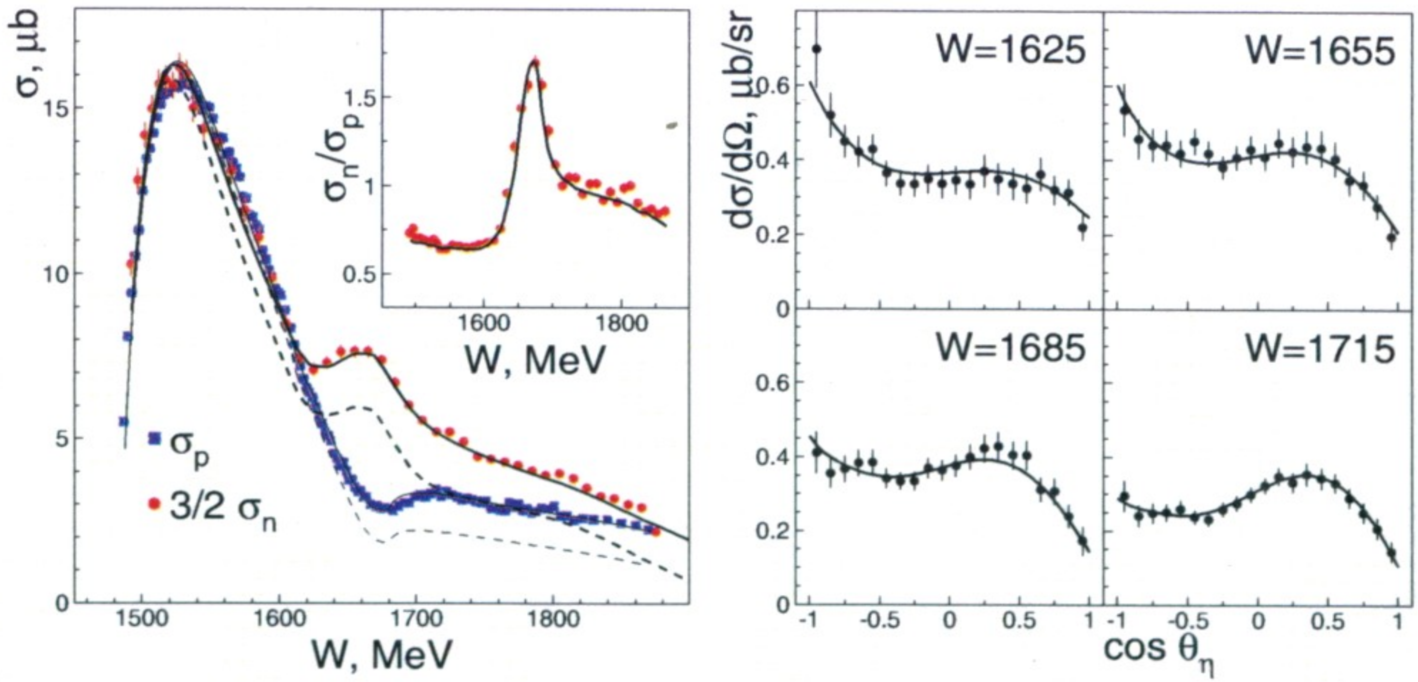


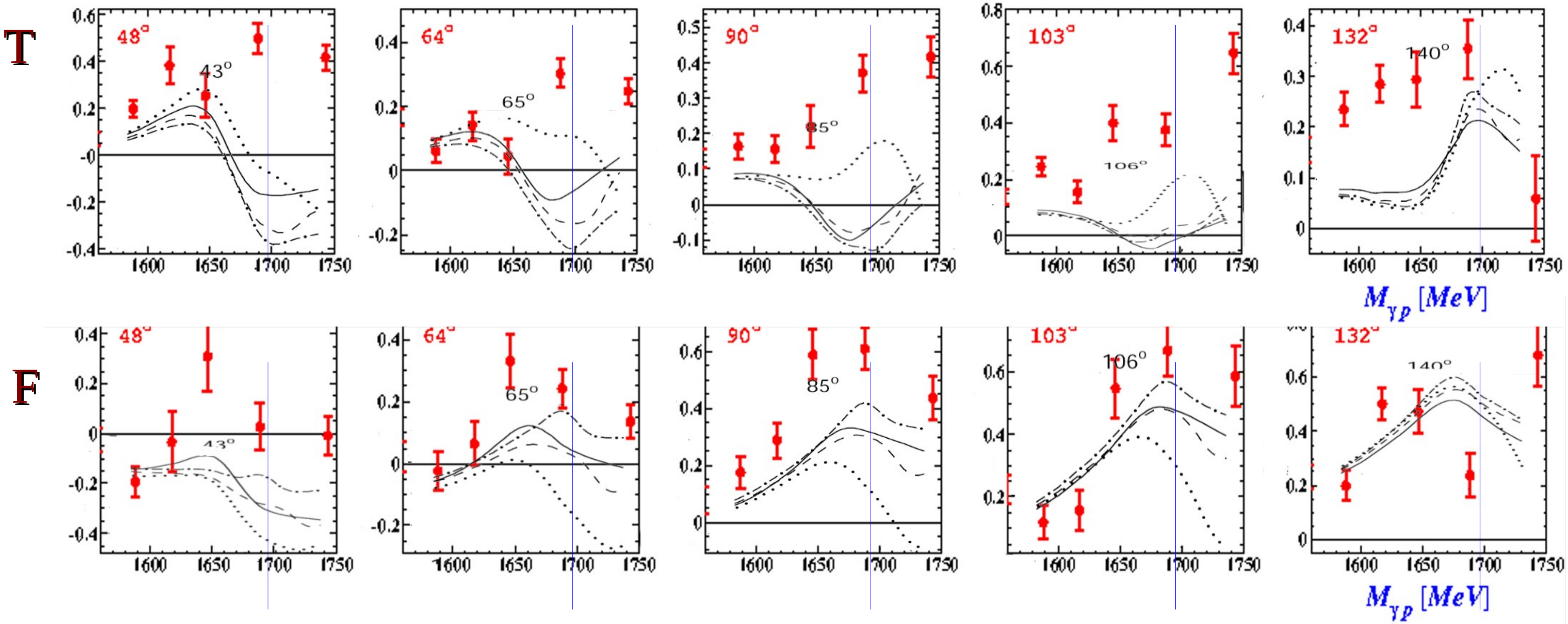
FIG. 1. (Color online) Left: The total cross section for $\gamma n \to \eta n$ (multiplied by 3/2), $\gamma p \to \eta p$, and their ratio (as inset). The solid curves represent our fit folded with the experimental resolution (thick ηn, thin ηp), the dashed curves the contributions from the S_{11} waves.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

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

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

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

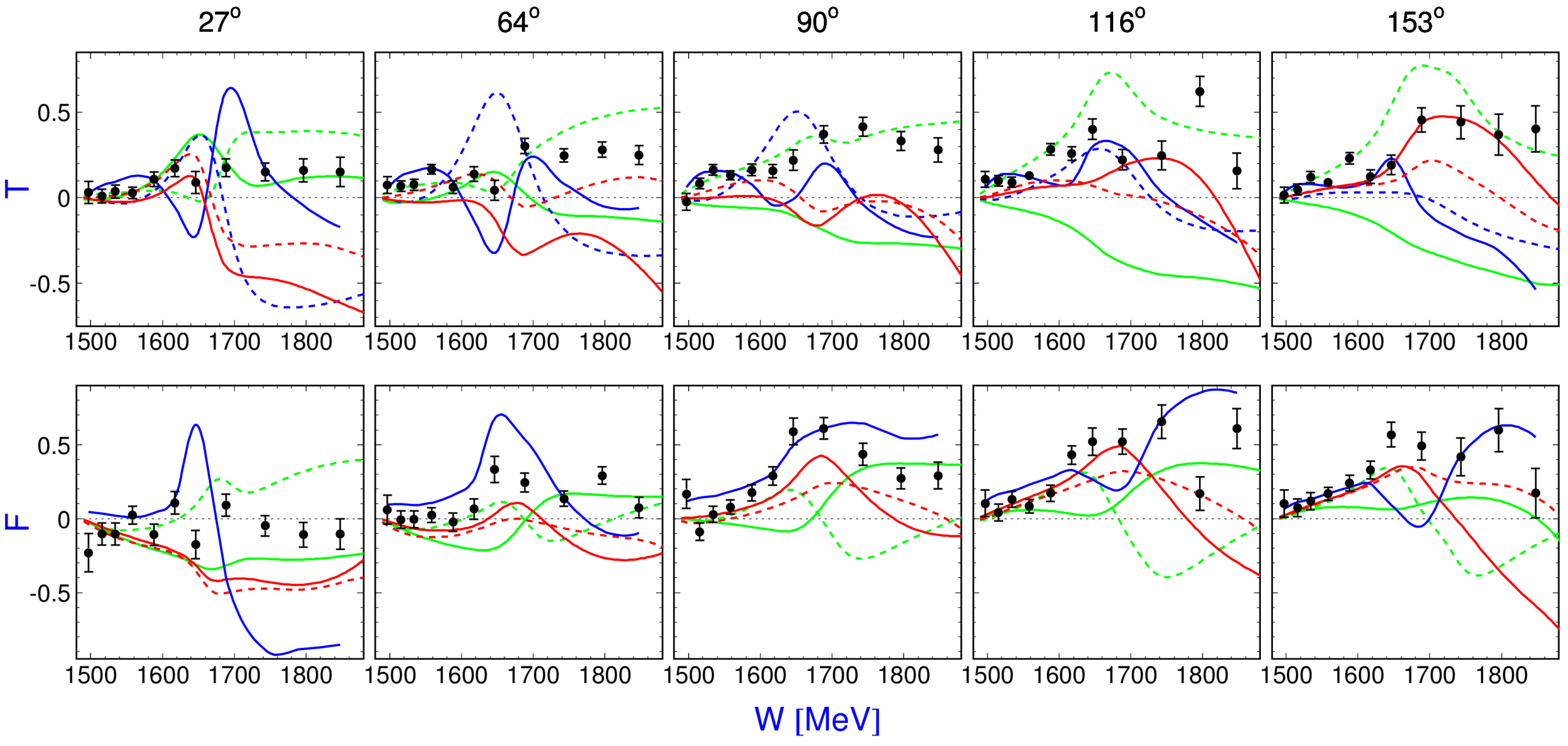
Predictions for T and F asymmetries
Solid curves: ωp channel included to S11 partial wave
Dashed: P11(1719)+ solution
Dashed-dotted: P11(1694)- solution
Dotted: P13(1696) solution



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

Data: A2MAMI, PRL 113 (2014)

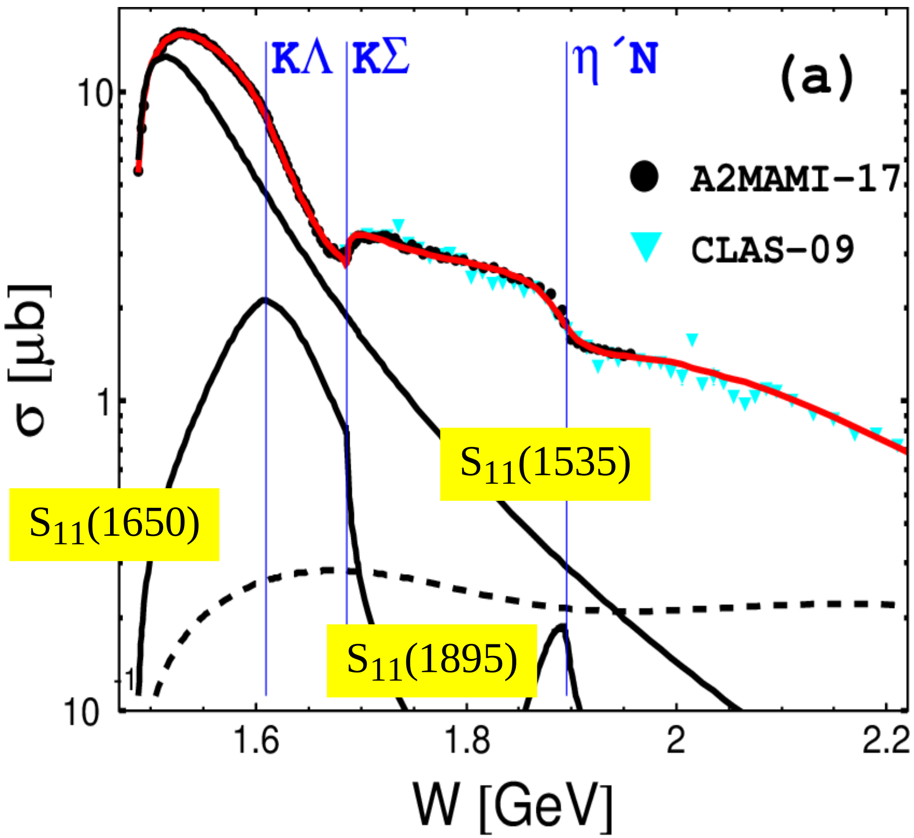
1th publication from A2 with FST !



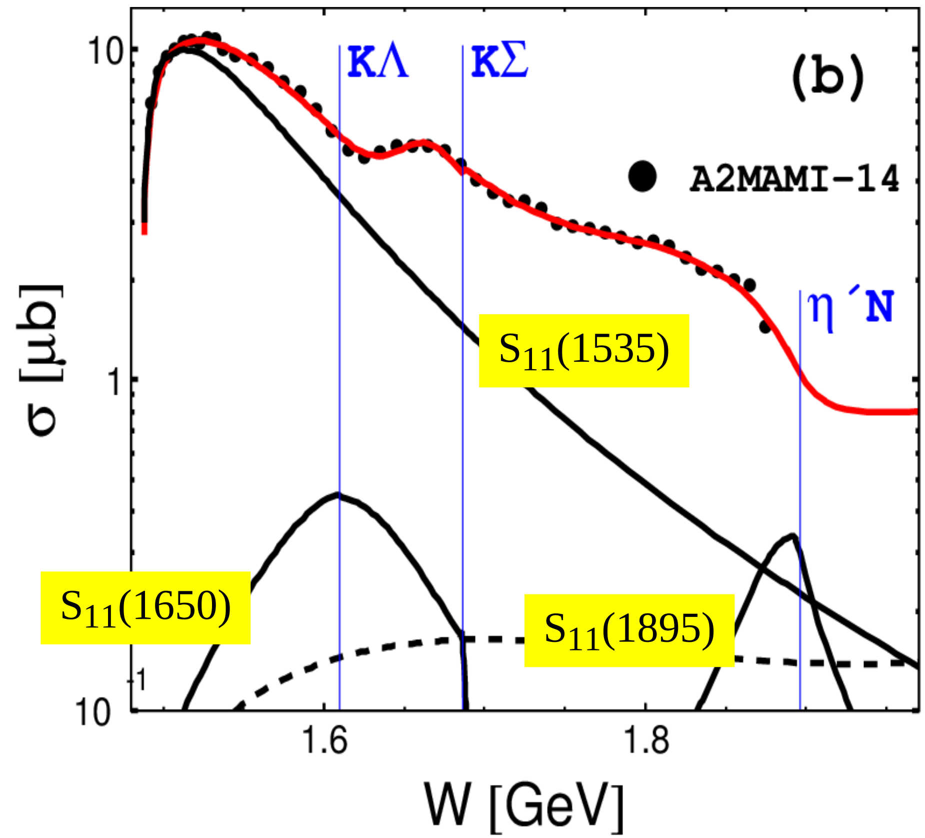
dashed green line: MAID 2003 Isobar Model
solid green line:MAID 2003 Reggezed Isobar Model
solid blue line: SAID GE09; dashed: SAID E429;
solid reded line: BG2011-02; dashed: BG20010-02

Partial contributions of the resonances to the total cross sections

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



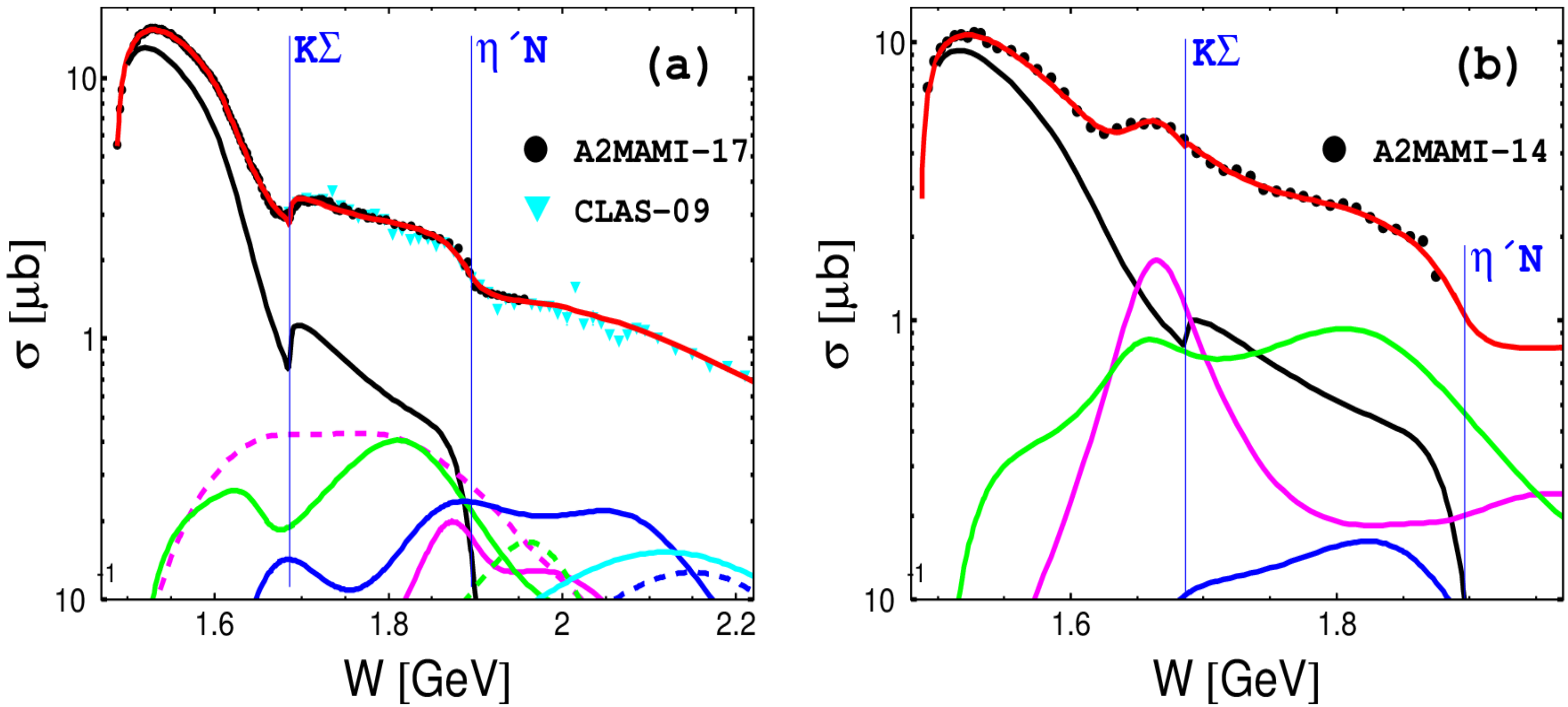
$\gamma\ n \rightarrow \eta\ n$



Black dashed line – Regge + Bonrn contribution

Resonance contributions of partial waves to the total cross sections

$\gamma\ p \to\ \eta\ p$ $\qquad$ $\gamma\ n \to\ \eta\ n$



S_{11} – black solid;

P_{11} – magenta solid; P_{13} – magenta dashed

D_{13} – green solid; D_{15} – green dashed

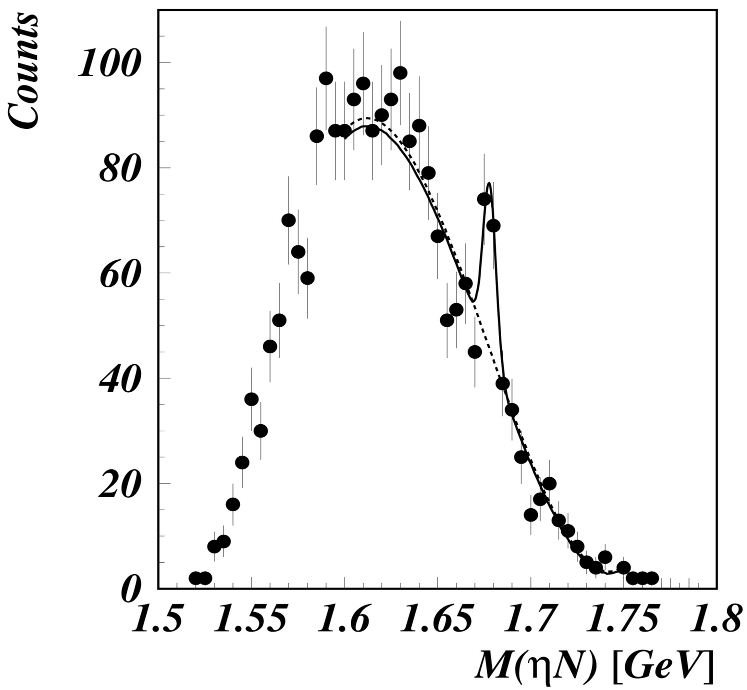
F_{15} – blue solid; F_{17} – blue dashed

G_{17} – cyan solid

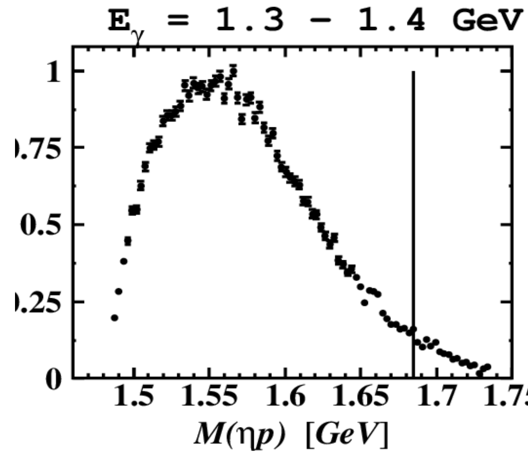
$\gamma\ p \rightarrow \pi^0\ \eta\ p$

GRAAL data: Eγ = 1.4 – 1.5 GeV
$m(\pi^0 N)$ < 1.2 GeV

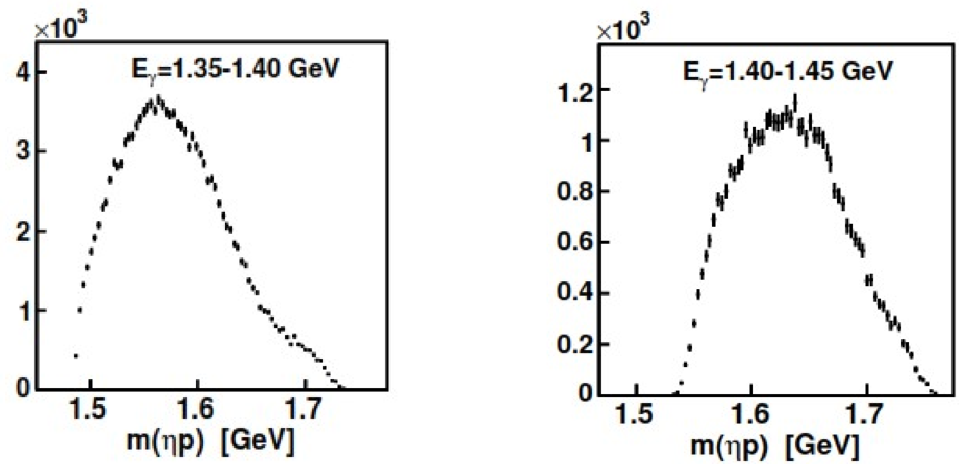
V. Kuznetsov et al., JETP Lett. 106 (2017)



A2 data for $\pi^0\eta$ (no $m(\pi^0 N)$ cut)
V.L.Kashevarov et al., EPJA 42 (2009)



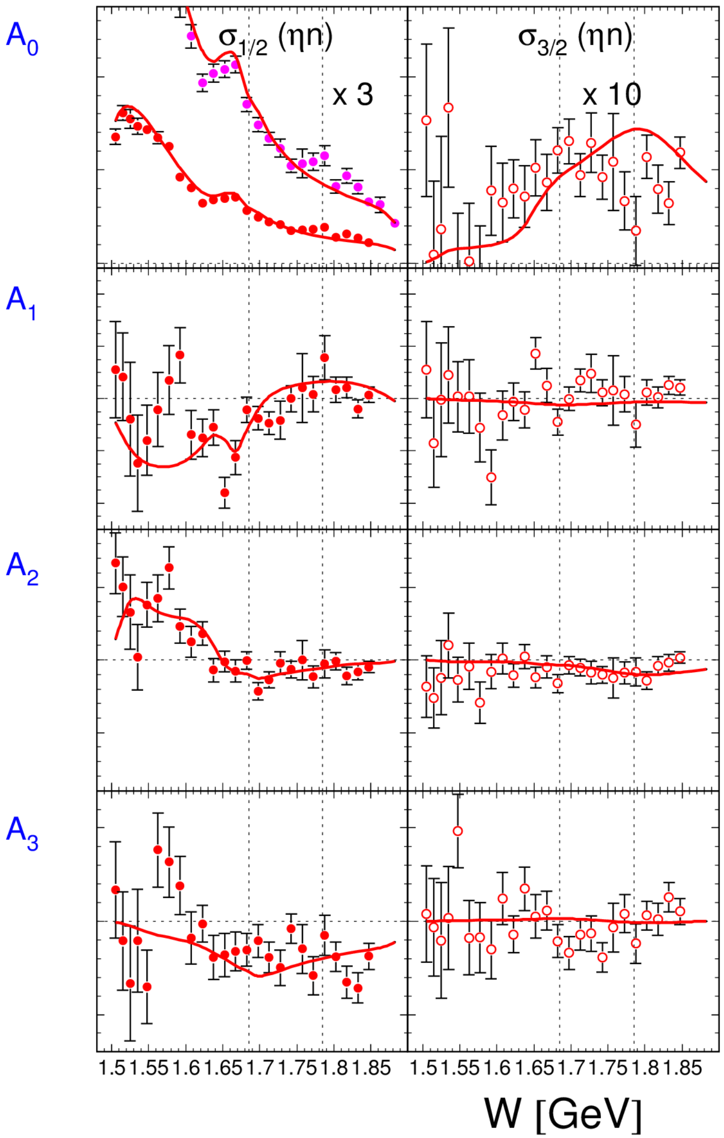
A2 data for $\pi^0\eta$ ($m(\pi^0 N)$ < 1.2 GeV)
V.Sokhoyan et al., PRC 97 (2018)



No signature of narrow N(1685) resonance in the A2 data!

Second narrow resonance in γ n → η n?

L. Witthauer et al, Phys. Rev. C**95** (2017) 055201



1. Narrow structure at W=1680 appears only in $\sigma_{1/2}$ and is thus related to S_{11} and/or P_{11} (in good agreement with our solution)

2. The second narrow structure at W=1726 MeV (second vertical line) is discused in V. Kuznetsov et al, JETP Lett. 105 (2017) 625. One of explanation is ωn production cusp.

Data: A2MAMI-17;
Red lines: full solution

Observables in Legendre series

The Legendre expansion can be formulated in terms of associated Legendre polynomials $\{P_\ell^0(x), P_\ell^1(x), P_\ell^2(x)\}$ with the following relations

$$\begin{aligned} P_\ell^0(cos\theta) &= P_\ell(cos\theta)\,, \\ P_\ell^1(cos\theta) &= -sin\theta\ P_\ell^{'}(cos\theta)\,, \\ P_\ell^2(cos\theta) &= sin^2\theta\ P_\ell^{''}(cos\theta)\,. \end{aligned}$$

In particular we can find an expansion

$$\begin{aligned} O_i(W,\theta) &= \sum_{k=0}^{2\ell_{max}} A_k^i(W)\ P_k^0(cos\theta),\ \text{for } O_i = \{\sigma_0, \hat{E}\} \\ O_i(W,\theta) &= \sum_{k=1}^{2\ell_{max}} A_k^i(W)\ P_k^1(cos\theta),\ \text{for } O_i = \{\hat{T}, \hat{P}, \hat{F}, \hat{H}\} \\ O_i(W,\theta) &= \sum_{k=2}^{2\ell_{max}} A_k^i(W)\ P_k^2(cos\theta),\ \text{for } O_i = \{\hat{\Sigma}, \hat{G}\} \end{aligned}$$

Partial wave content of Legendre coefficients, $l_{max} = 3$

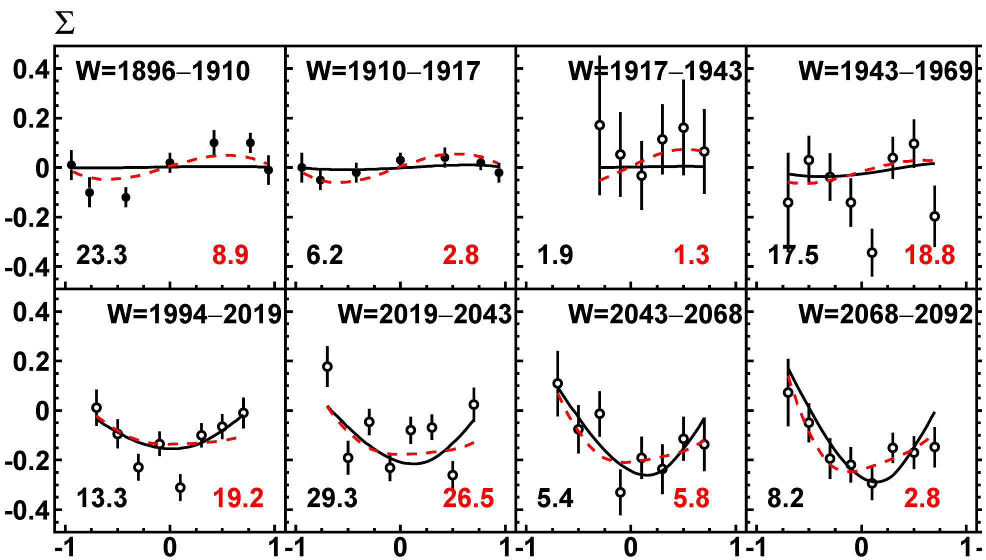
$$
\begin{aligned}
A_0 &= SS + PP + SD + DD + PF + FF \\
A_1 &= SP + PD + SF + DF \\
A_2 &= PP + SD + DD + PF + FF \\
A_3 &= PD + SF + DF \\
A_4 &= DD + PF + FF \\
A_5 &= DF \\
A_6 &= FF
\end{aligned}
$$

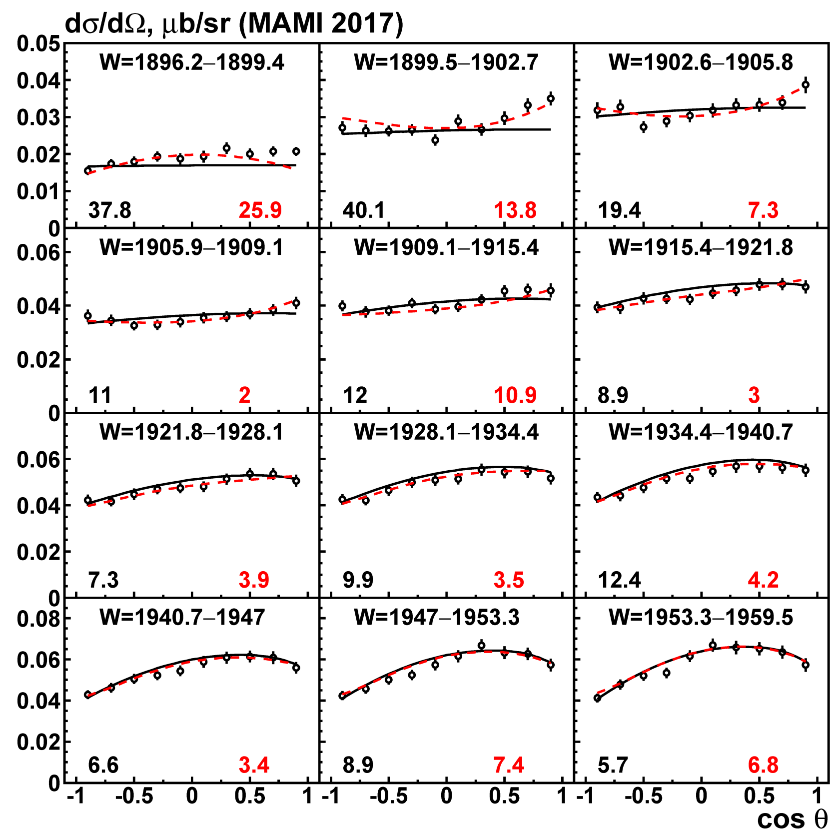
Narrow resonance in η´ photoproduction?

Anisovich, Burkert, Dugger, Klempt, Nikonov, Ritchie, Sarantsev, Thoma, arXiv:1803.06814 (2018)

——— BnGa-2017 solution without narrow resonance

- - - - - BnGa2018 solution with a narrow D_{13} : M_R = 1900 ± 1 MeV, Γ < 3 MeV

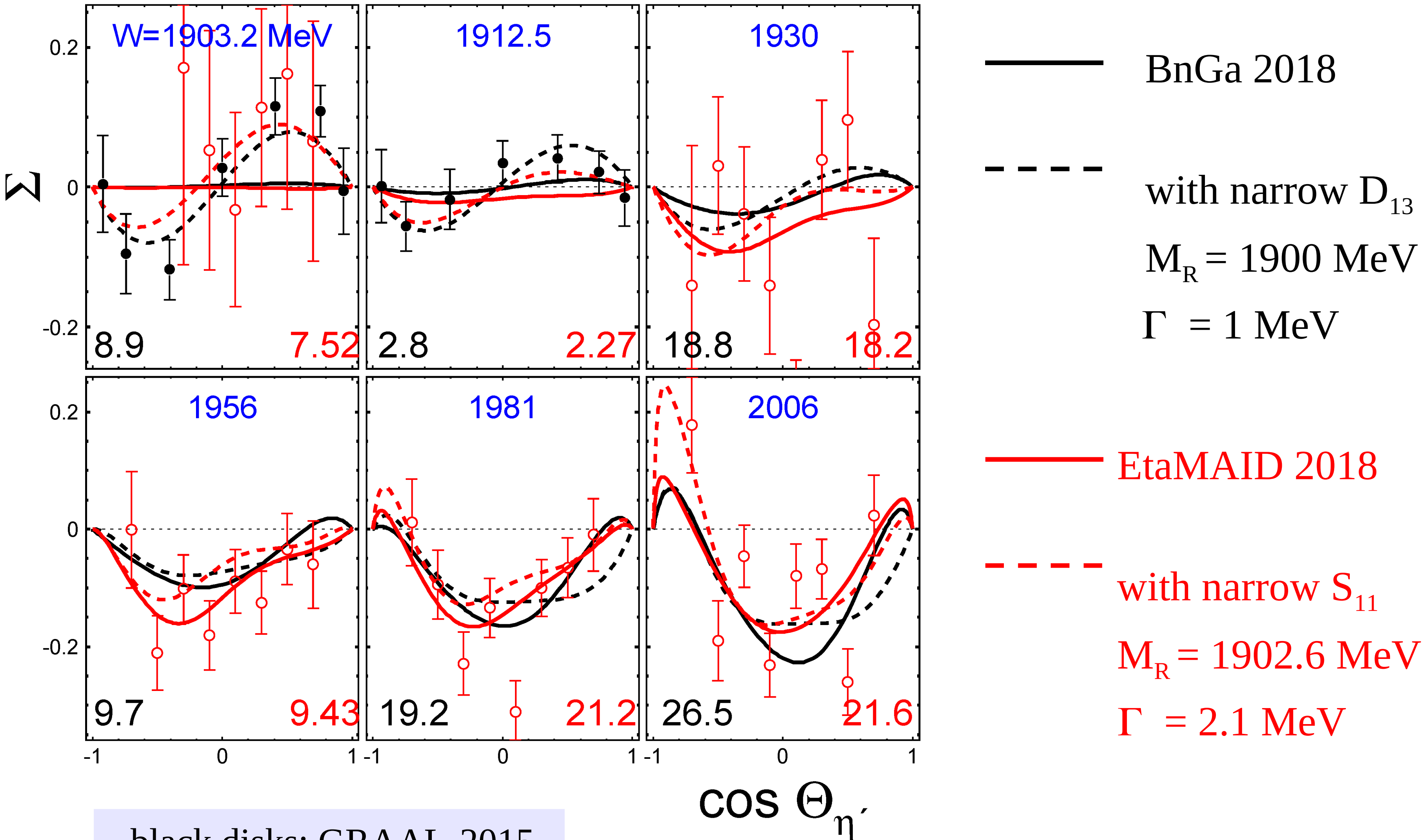




beam asymmetry Σ:
black disks: GRAAL-2015
red circles: CLAS-2017

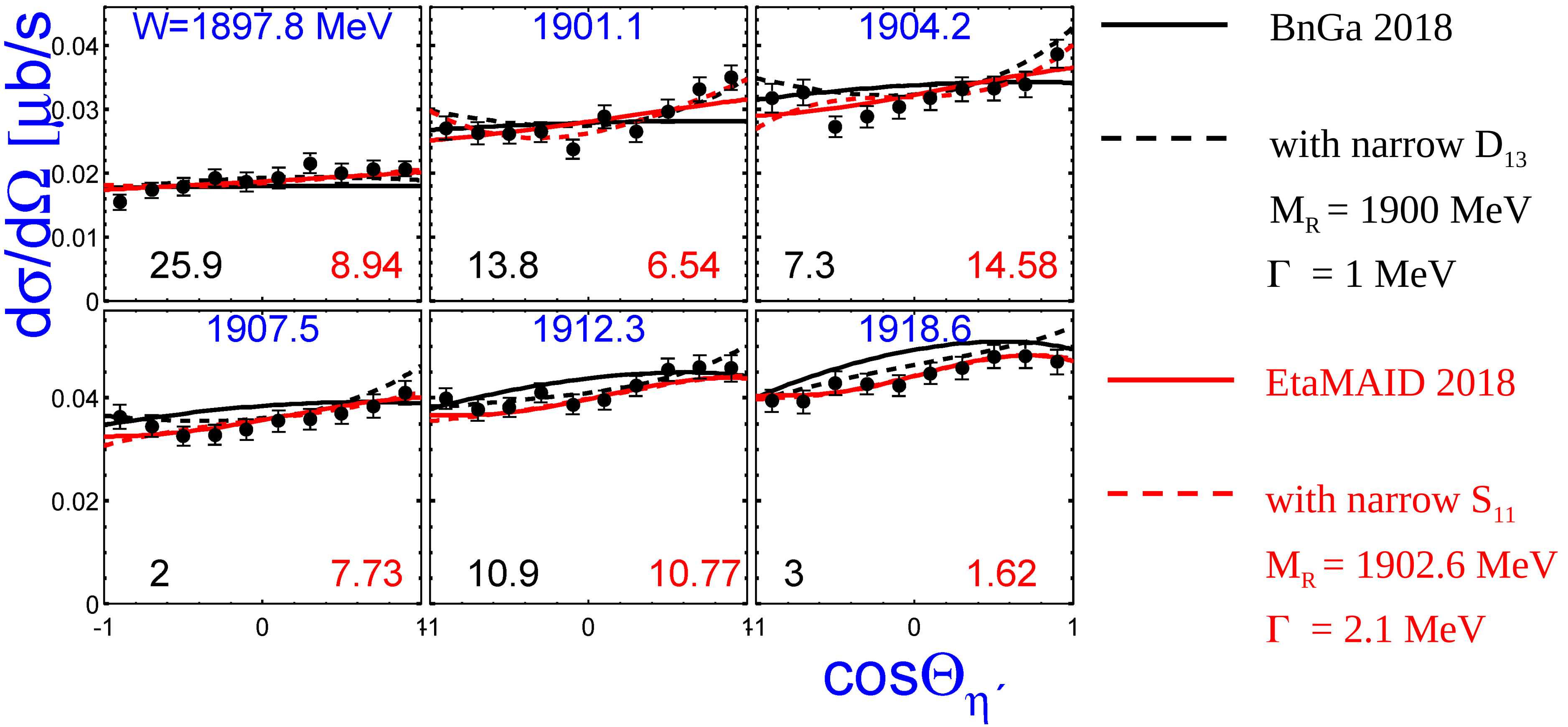
diff. cross sect. dσ/dΩ:
A2MAMI-2017

Narrow resonance S_{11}/D_{13} in $p(\gamma,\eta')p$
EtaMAID vs. BNGA



black disks: GRAAL-2015
red circles: CLAS-2017

Narrow resonance S_{11}/D_{13} in $p(\gamma,\eta')p$
EtaMAID vs. BNGA

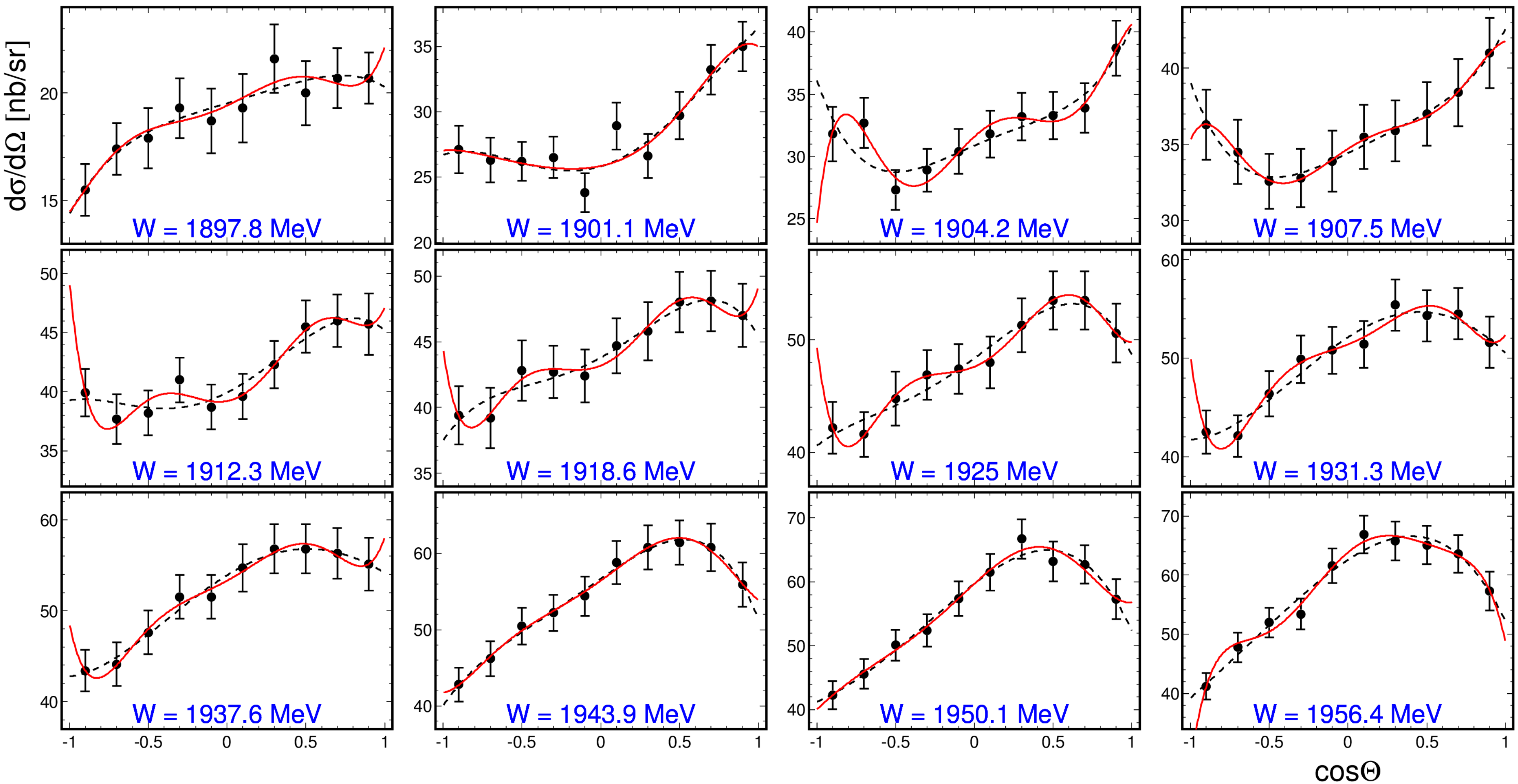


Σ and dσ/dΩ data can well be fitted with a very narrow resonance at W_R=1900 MeV.
In the total c.s. such a resonance is invisible.
It shows up in interferences between *S-F* or *P-D* resonances.

Narrow resonance in η´ photoproduction?

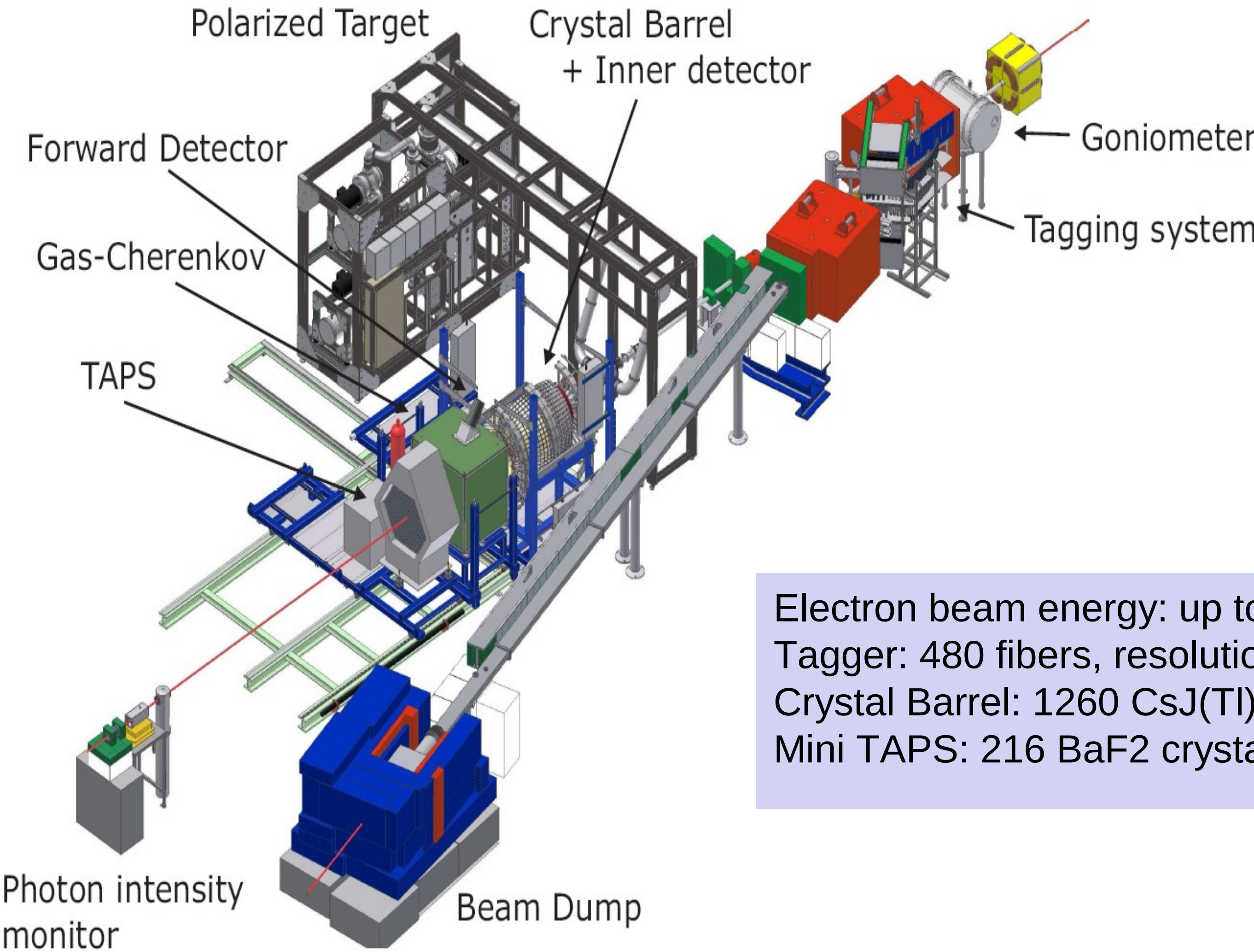
diff. cross sect. dσ/dΩ:
A2MAMI-2017

Legendre fit:
with l_{max} = 2 (D wave) – black dashed
with l_{max} = 3 (F wave) – red solid



CBELSA/TAPS Experiment at ELSA

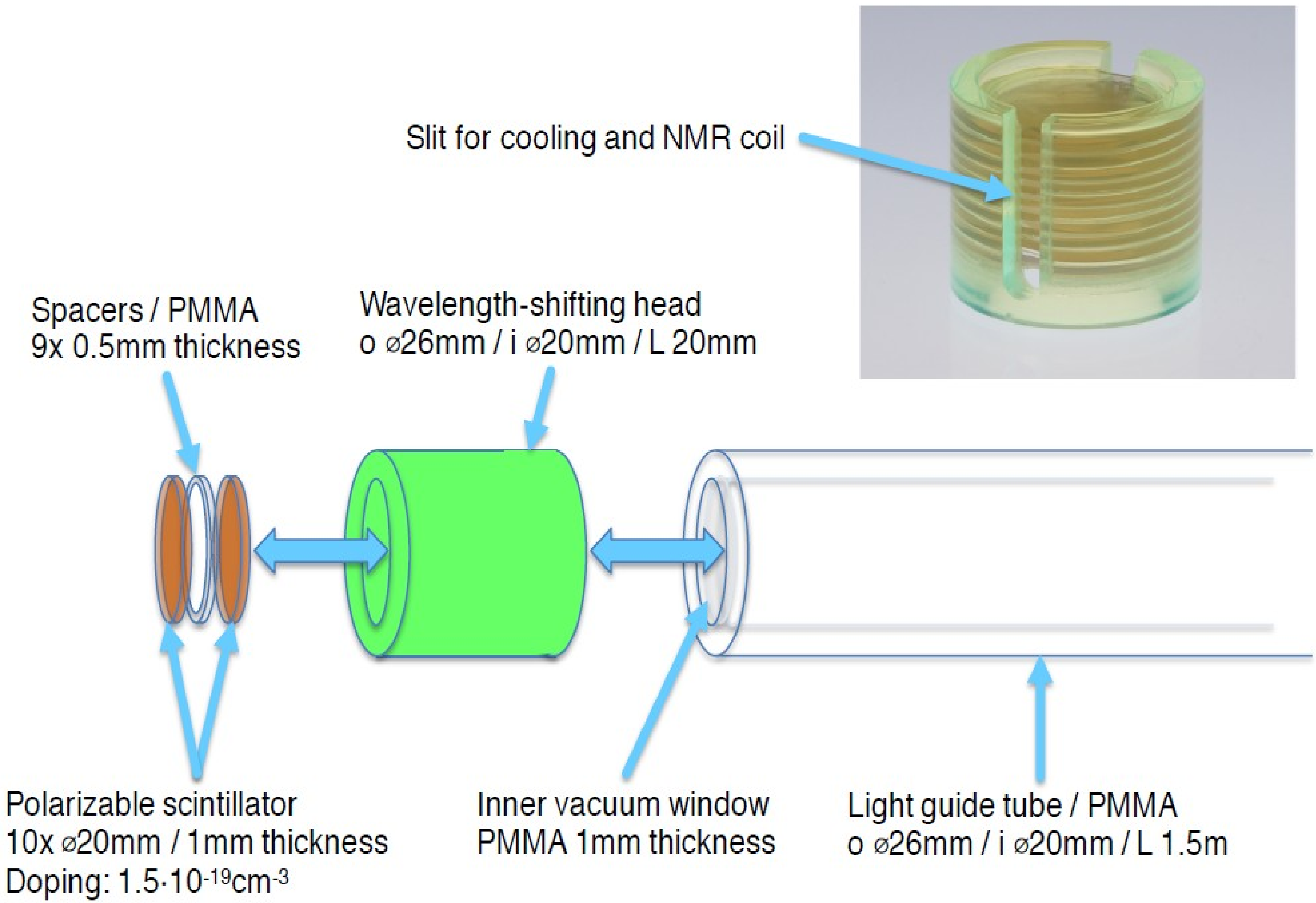
Polarized target for Bonn in talk of I. Gorodnov (Dubna)



Electron beam energy: up to 3.5 GeV
Tagger: 480 fibers, resolution 2 – 25 MeV
Crystal Barrel: 1260 CsJ(Tl) crystals (12 – 156 deg)
Mini TAPS: 216 BaF2 crystals (2 – 12 deg)

New Developement: Active Polarized Target

More details in talk of A. Thomas (Mainz)



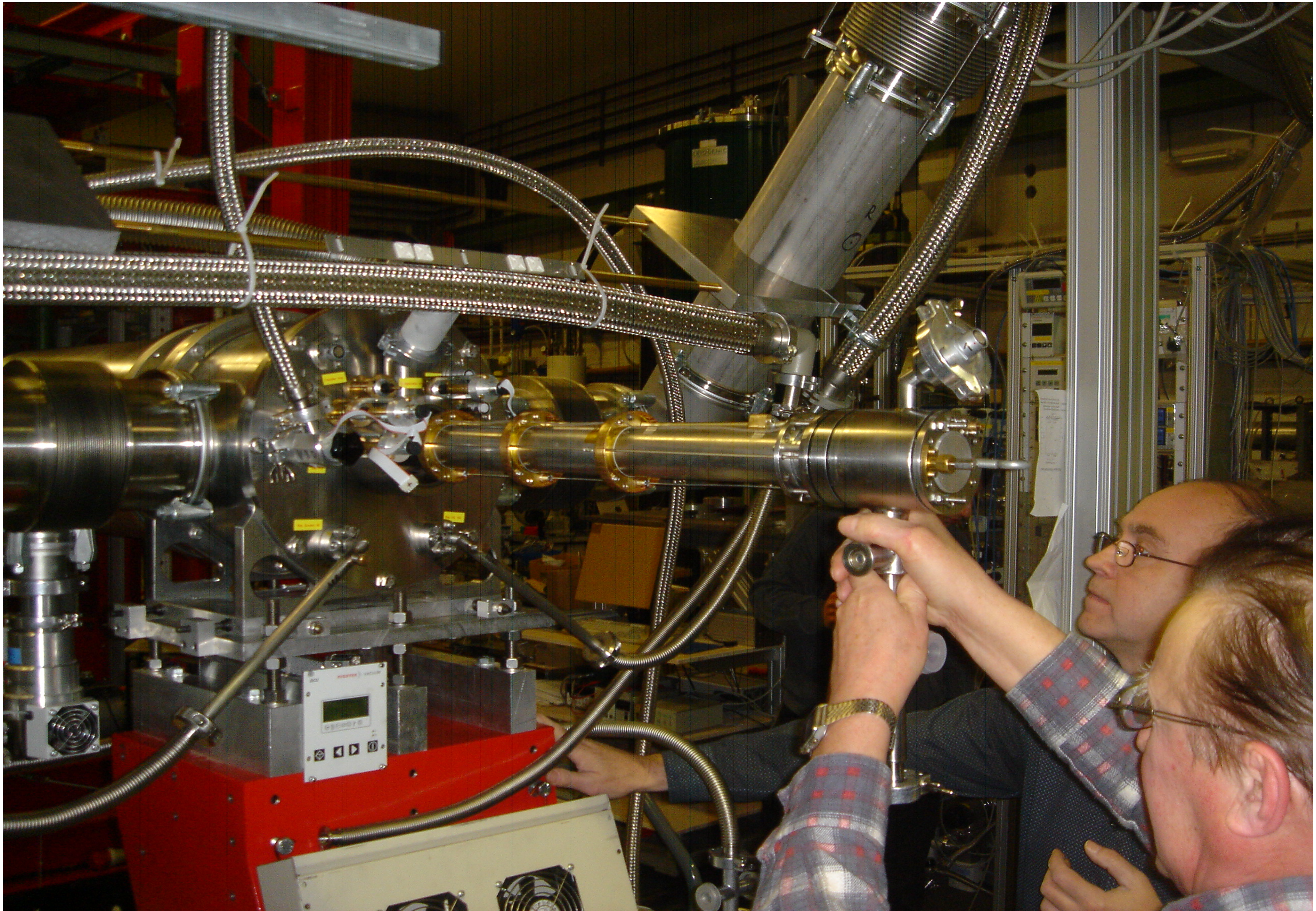
Summary

- 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 2018/19 in Bonn together with CBELSA/TAPS Collaboration.

A2 Collaboration at MAMI

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

Dubna-Mainz FST in Mainz



Dubna-Mainz FST in Bonn