Double polarisation observables G and E and helicity dependent cross section for single pi^0 photoproduction off proton and neutron at MAMI

Susanna Costanza

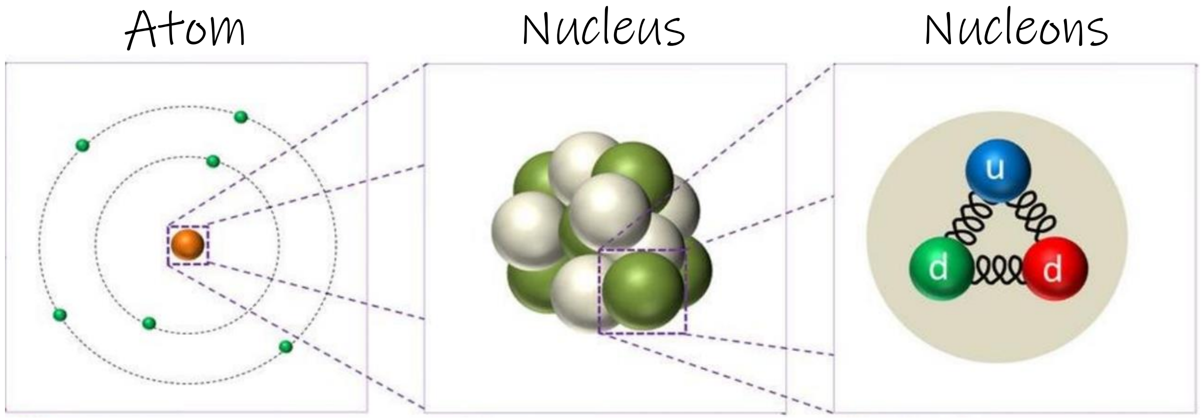
Università degli Studi di Pavia – INFN Pavia

on behalf of the A2 Collaboration @ MAMI

The 5th International Conference on Particle Physics and Astrophysics

Online, 5–9 October 2020

Introduction

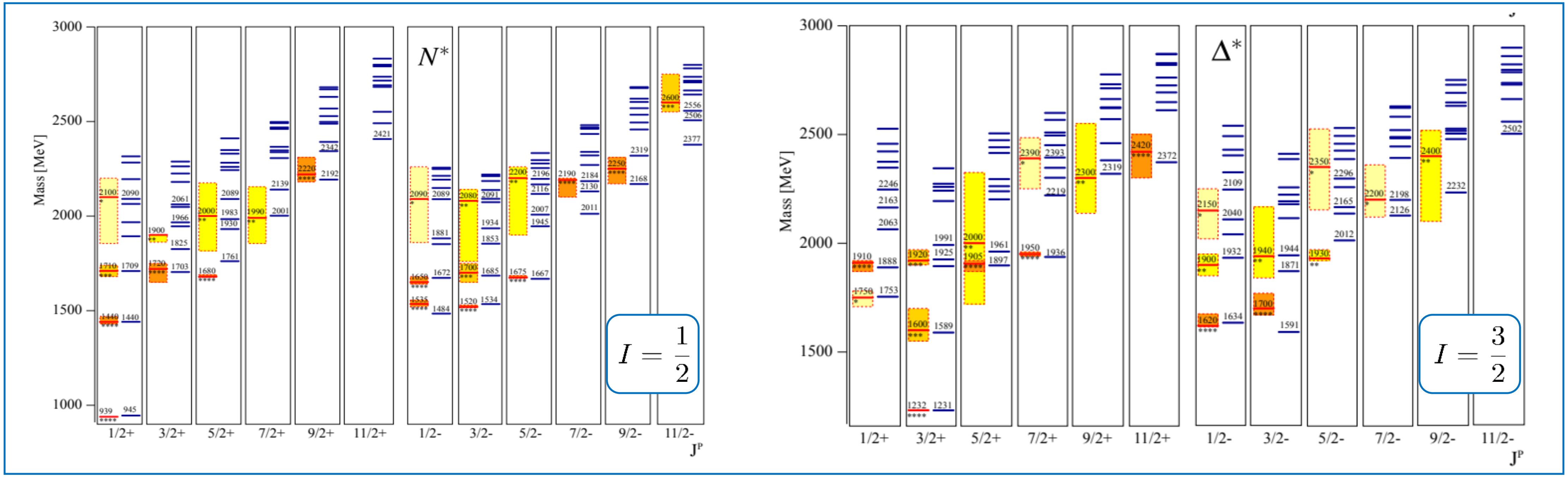


Nowadays, fundamental properties of the proton (nucleon, in general), e.g. the proton radius or spin or its excited states, are still not fully understood.

How can we study the nucleon and its excited states, and predict the baryon mass states?

- **Perturbative QCD** → MEANINGLESS!!
  - Low energy regime ⟷ non perturbative approach
- **Phenomenological Quark Models** → LIMITED SUCCESS
  - Based on internal degrees of freedom
  - Based on residual interactions of the quarks

Looking for missing resonances



Mismatch between experiment and model predictions: where is it rooted?

theory

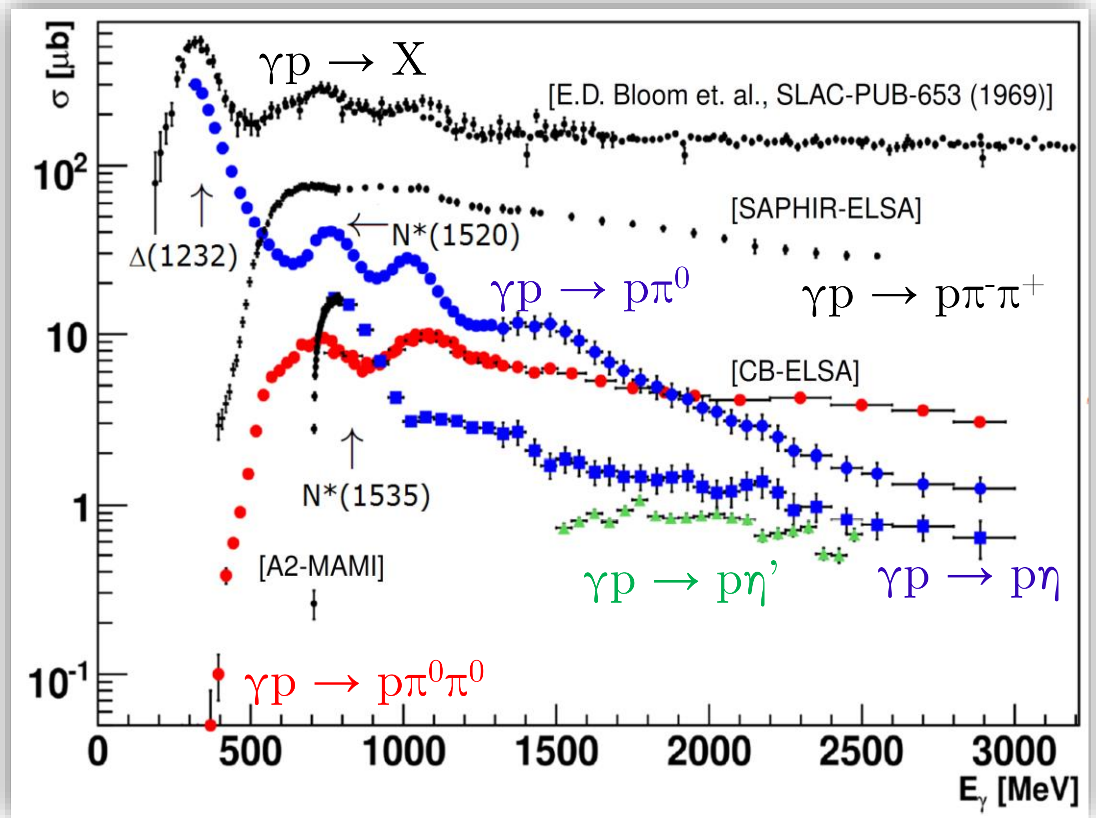
Inappropriate internal degrees of freedom in the models

experiment

Data analyses relying entirely on meson-induced reactions will miss states weakly coupling to $N\pi$

Photoproduction reactions

Experimental alternative:
use of reactions induced by photons



- ✓ The photon is absorbed by the nucleon and interacts with its internal structure

⇨ **excited stated** (**resonances**)

$$\gamma N \to N^* \to N\pi$$ Meson photoproduction

- ✓ Investigation of **different final states** is necessary to disentangle the **resonance contributions**
- ✓ Resonances are accessible via **different production processes**: πN, γN, γ*N, Ψ, Ψ'-decays, pN, ...
- ✓ Measurement of **polarisation observables** and test of Partial Wave Analysis (PWA) models (MAID, SAID, BnGa)

Polarisation observables

Measurable observables ↔ Multipoles ↔ Resonance parameters

- Scattering amplitude $\mathcal{F} \leftrightarrow$ CGLN-amplitudes: 4 complex amplitudes ($\rightarrow$ 16 polarisation observables) governing pseudoscalar meson photoproduction off the nucleons in the GeV energy range
- CGLN-amplitudes $F_i(W, \cos\vartheta_{cm})$ $\rightarrow$ expanded into Legendre polynomials $P'_{l\pm1}(\cos\vartheta_{cm})$ and photoproduction multipoles ($E_{l\pm}(W)$, $M_{l\pm}(W)$)
- Multipoles: information on the resonances and their properties in a given partial wave

photon		target			recoil nucleon			target and recoil			
		x	y	z	-	-	-	x	z	x	z
		-	-	-	x'	y'	z'	x'	x'	z'	z'
-	σ_0	-	T	-	-	P	-	$T_{x'}$	$L_{x'}$	$T_{z'}$	$L_{z'}$
linear	$-\Sigma$	H	$(-P)$	G	$O_{x'}$	$(-T)$	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(L_{x'})$	$(-T_{x'})$
circular		F	-	$-E$	$C_{x'}$	-	$C_{z'}$	-	-	-	-

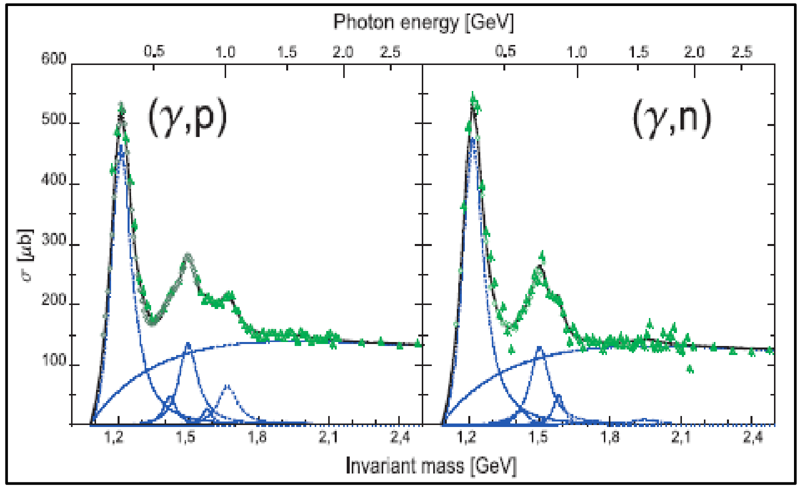
1 unpolarised, 3 single polarised, 12 double polarised measurements

The measurement of 7 (8) properly chosen observables is necessary to unambiguously (in a model independent way) determine the scattering amplitudes ("complete analysis")

Measurements off the neutron

Why are these measurements important?

- **Different resonance contributions**



- **Needed for extraction of isospin composition of elm couplings**

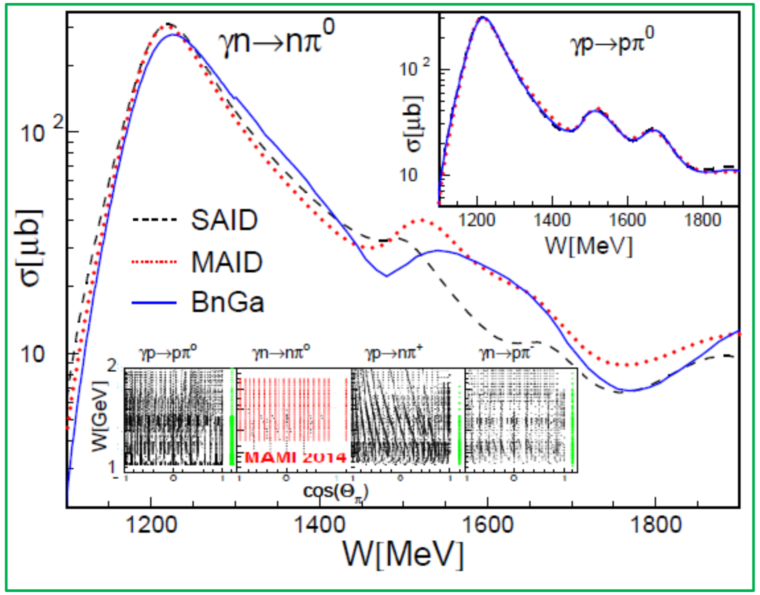
$$A(\gamma p \to \pi^+ n) = -\sqrt{\tfrac{1}{3}}A^{V3} + \sqrt{\tfrac{2}{3}}(A^{IV} - A^{IS})$$

$$A(\gamma p \to \pi^0 p) = +\sqrt{\tfrac{2}{3}}A^{V3} + \sqrt{\tfrac{1}{3}}(A^{IV} - A^{IS})$$

$$A(\gamma n \to \pi^- p) = +\sqrt{\tfrac{1}{3}}A^{V3} - \sqrt{\tfrac{2}{3}}(A^{IV} + A^{IS})$$

$$A(\gamma n \to \pi^0 n) = +\sqrt{\tfrac{2}{3}}A^{V3} + \sqrt{\tfrac{1}{3}}(A^{IV} + A^{IS})$$

- **Disagreement between predictions (results from partial wave, reaction models) for neutron target**
  - agreement only in the $\Delta(1232)$ resonance
  - large discrepancies in the second and third resonance region



M. Dieterle et al, PRL 112 (2014) 142001

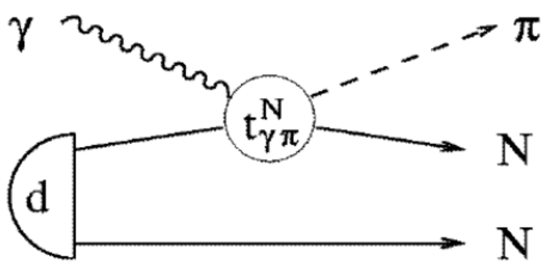
Measurements off the neutron

Measurements off the neutron are complicated by the lack of neutron targets

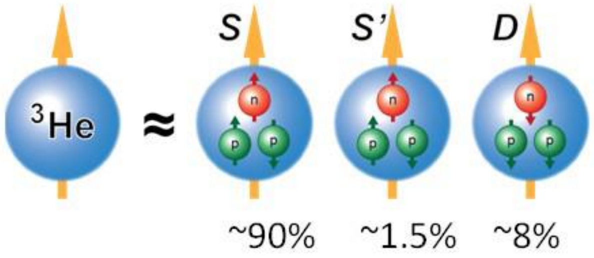
^{2}H: System of one proton and one neutron with paired spins, in relative *s* states (96% probability): $\mu \approx \mu_p + \mu_n$

- **Deuteron** at rest in the lab frame
- The two nucleons have momentum according to the **Fermi motion**
- Rescattering of the spectator nucleon with the pion or the nucleon involved in the reaction: **Final State Interactions (FSI)**

} **Nuclear effects**



^{3}He: System of two protons with spins paired off and an "active" unpaired neutron, in relative *s* states (~90% probability)

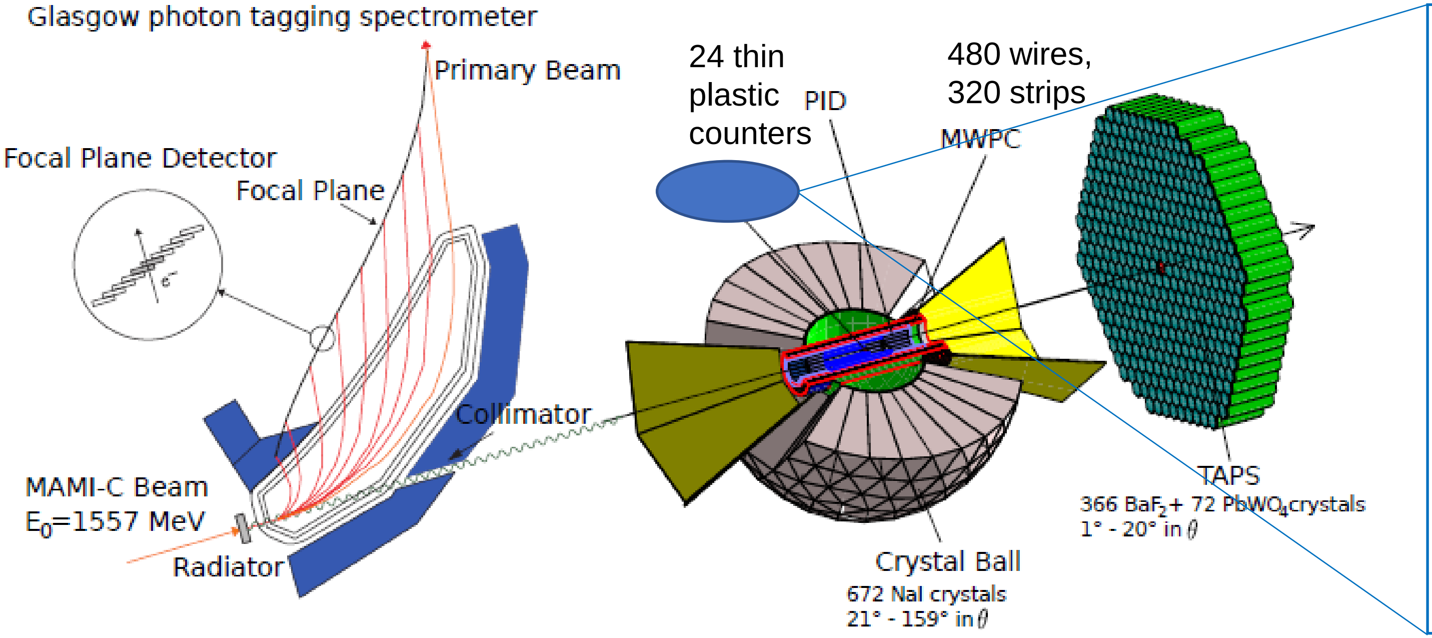


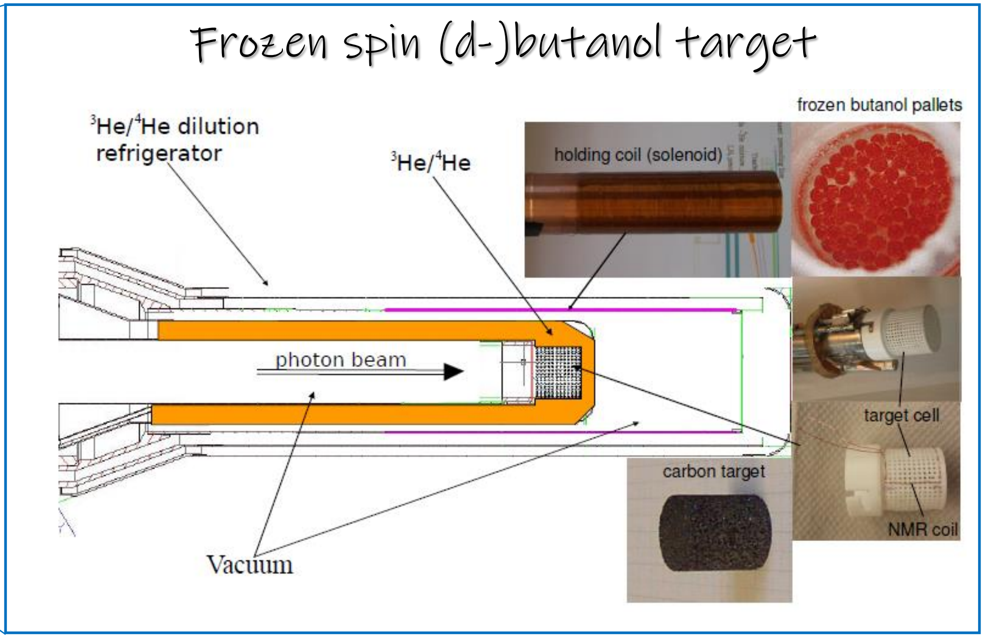
The proton contribution is small: $\mu \approx \mu_n$

Allows direct access to the free neutron cross section prevented by nuclear structure effects and FSI

A2@MAMI: detector overview

Location: MAMI Accelerator (Mainz)





Beam:

- photon beam produced by bremsstrahlung process and tagged by the magnetic spectrometer
- $E_\gamma < 1.5$ GeV, $\Delta E_\gamma = 2$ - 4 MeV
- Linear and circular polarisations available

Target:

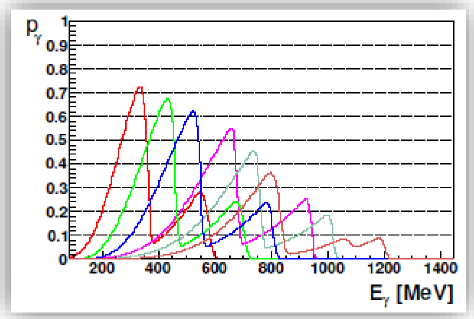
- high relaxation time ($\approx$ 1000 h)
- $9{\cdot}10^{22}$ polarised protons per cm^2 in the target cell
- p_T close to 90%
- Carbon target needed for background studies

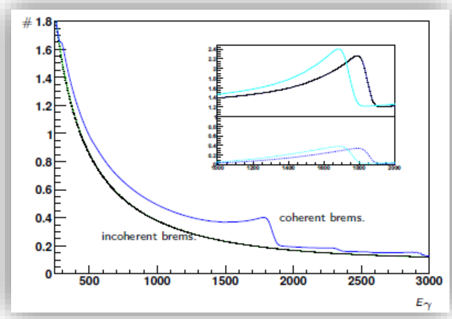
Double polarisation observables G and E

First experimental attempt to measure G and E with longitudinally polarised electron beam incident on a diamond crystal with a longitudinally polarised **butanol** target
(→ **using linearly and circularly polarised photons at the same time!**)

Linearly polarised photons

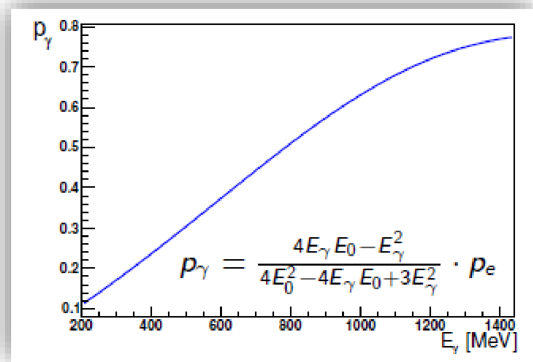
- Diamond radiator needed
- Coherent bremsstrahlung: preferred plane between incoming electron and outgoing photon → orientation of the field vector of the photon
- Coherent edges: 350 … 850 MeV





Circularly polarised photons

- Longitudinally polarised electrons needed
- Helicity transfer from electrons to photons → circularly polarised photons
- Mott/Moeller measurement of polarisation degree: $p_e \approx$ 75-78%



Double polarisation observables G and E

Differential cross section for pseudo-scalar meson photoproduction using elliptically polarised photons in combination with a longitudinally polarised target:

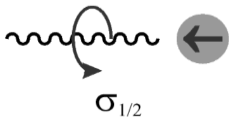
$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}_0(\theta)\left[1 - P_{lin}\mathbf{\Sigma}\cos(2(\alpha-\phi)) - P_z\left(-P_{lin}\mathbf{G}\sin(2(\alpha-\phi)) + P_{circ}\mathbf{E}\right)\right]$$

Integrating over $\phi \rightarrow$ E:

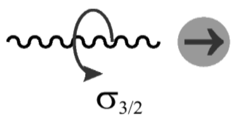
$$N_B\Big|_{\pm 1}^{\pm P_z}(\theta) = N_B(\theta)\cdot\left[1 - d\,P_{circ}P_z\mathbf{E}\right]$$

$$\mathrm{E} = \frac{\sigma^{1/2}-\sigma^{3/2}}{\sigma^{1/2}+\sigma^{3/2}} = \frac{N_B^{1/2}-N_B^{3/2}}{N_B^{1/2}+N_B^{3/2}}\cdot\frac{1}{d}\cdot\frac{1}{P_{circ}P_z}$$

Photon spin = +1
Baryon spin = -½



Photon spin = +1
Baryon spin = +½



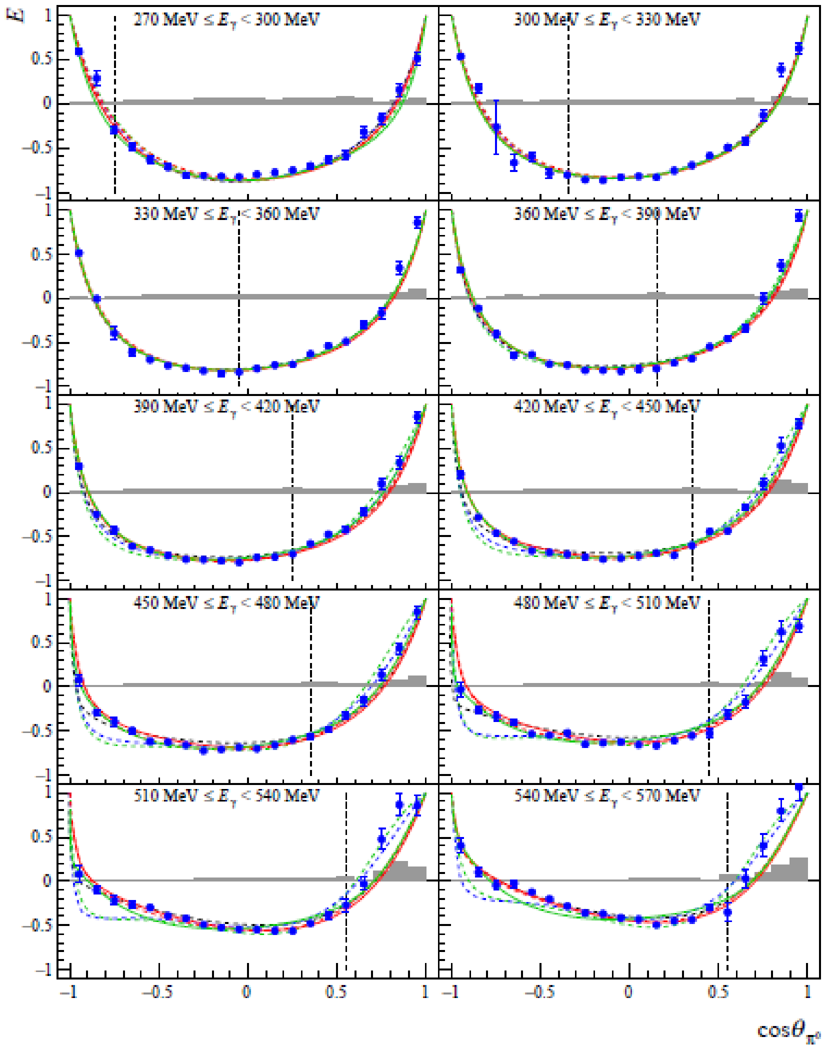
d = **dilution factor** = amount of polarisable protons in the data $\quad d = 1 - s_c\cdot\frac{N_C}{N_B}$

s_c = **scaling factor** for flux and acceptance difference between carbon and butanol beamtimes

Integrating over all possible helicity states $\rightarrow$ **G**:

$$N_B\Big|_{\pm\alpha}^{\pm P_z}(\theta,\phi) = N_B(\theta)\cdot\left[1 - P_{lin}\mathbf{\Sigma_B}\cos(2(\alpha-\phi)) + d\,P_{lin}P_z\mathbf{G}\sin(2(\alpha-\phi))\right]$$

E observable off the proton

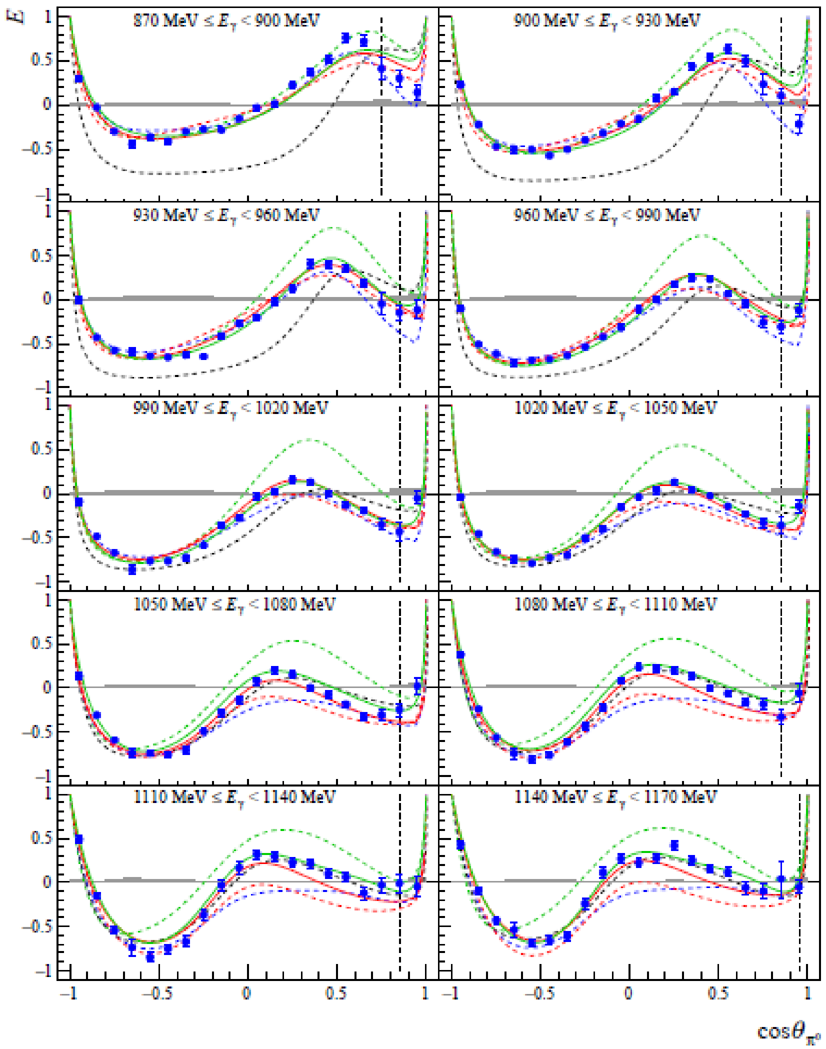


$\gamma p \rightarrow \pi^0 p$

Blue points: A2 data from F. Afzal

PWA solutions:

- BnGa-2011-02 (red dashed line)
- BnGa-2017 (red solid line)
- JüBo-2015-FitB (green dashed line)
- JüBo-2017 (green solid line)
- SAID-CM12 (blue dashed line)
- MAID2007 (black dashed line)



Dominant partial wave contribution

Profile function expressed in a truncated PWA:

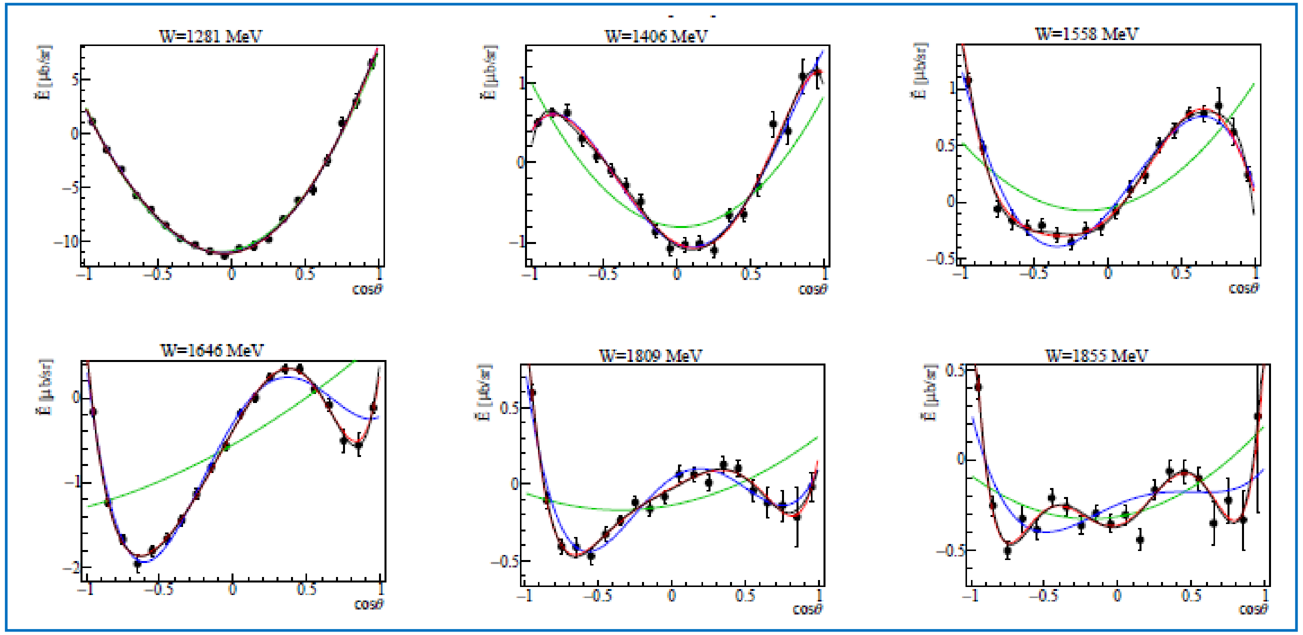
$$\breve{E}(W,\theta) = E(W,\theta)\cdot\frac{d\sigma}{d\Omega}(W,\theta) = \rho\sum_{l=0}^{2L_{max}}(a_{L_{max}})_l^{\breve{E}}(W)P_l(\cos\theta)$$

Legendre polynomials

Helicity asymmetry

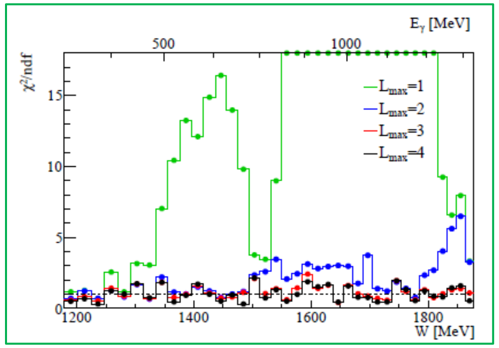
BnGa-2014-02 PWA solution

Legendre coefficients for a given truncation at $L_{\max}$



$L_{\max} = 1$ $L_{\max} = 3$
$L_{\max} = 2$ $L_{\max} = 4$

χ^2/ndf



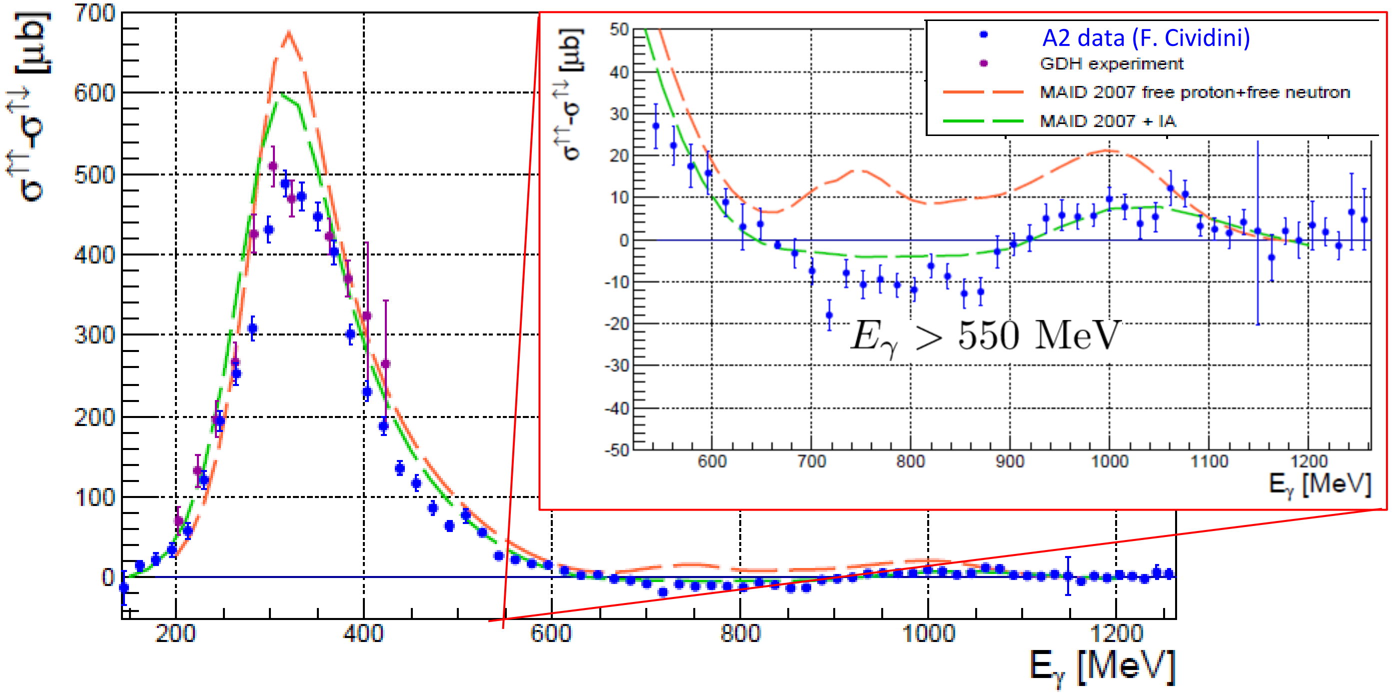
- $W = 1281$ MeV: $L_{\max} = 1$
- From $W = 1350$ MeV until $W = 1550$ MeV (second resonance region): $L_{\max} = 2$
- From $W = 1600$ MeV to 2250 MeV (third and fourth resonance regions): $L_{\max} = 3$
- Within the statistical precision of the E data, no indications for G-waves or higher order partial wave contributions

Single pi0 production on the deuteron

Helicity dependent cross section of inclusive single π^0 photoproduction on the deuteron:

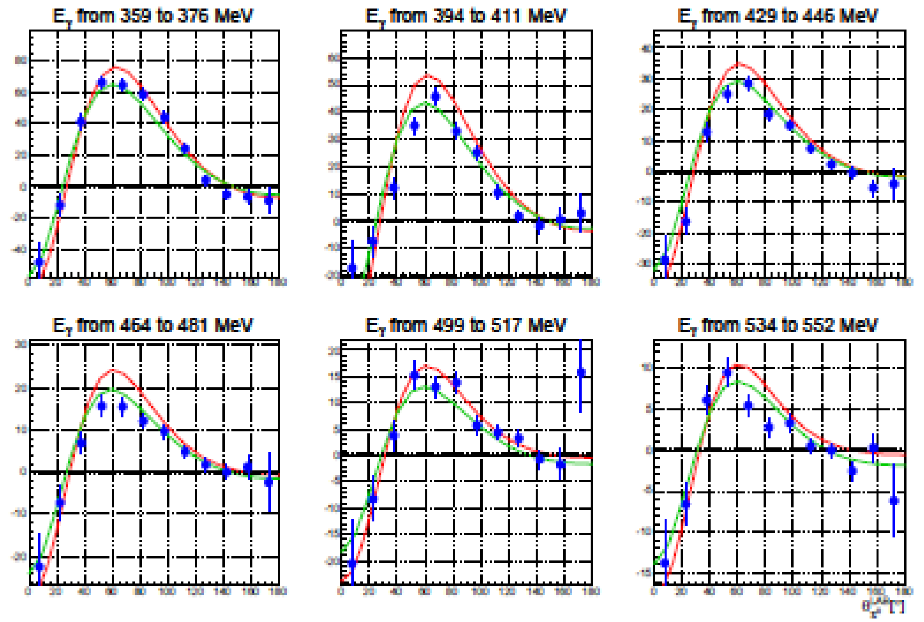
$$\frac{d\overrightarrow{\sigma}}{d\Omega}(E_\gamma) = \frac{d\sigma^{\uparrow\uparrow}}{d\Omega}(E_\gamma) - \frac{d\sigma^{\uparrow\downarrow}}{d\Omega}(E_\gamma) = 2 \cdot \frac{N^{\uparrow\uparrow}(E_\gamma,\theta) - N^{\uparrow\downarrow}(E_\gamma,\theta)}{N_\gamma(E_\gamma)\cdot\epsilon_{REC}(E_\gamma,\theta)\cdot\Delta\Omega\cdot d} \cdot \frac{1}{P_\odot^\gamma} \cdot \frac{1}{P_z^T}$$

Total cross section $\gamma d \to \pi^0 X$

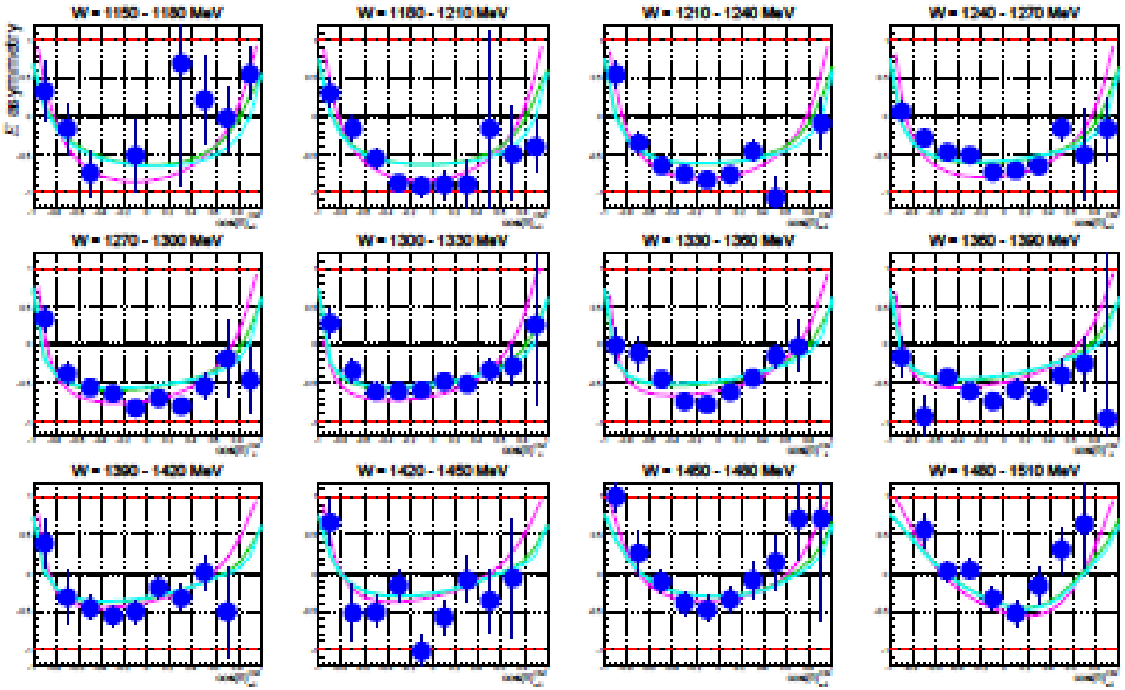


Differential cross section

359 MeV < E_γ < 552 MeV

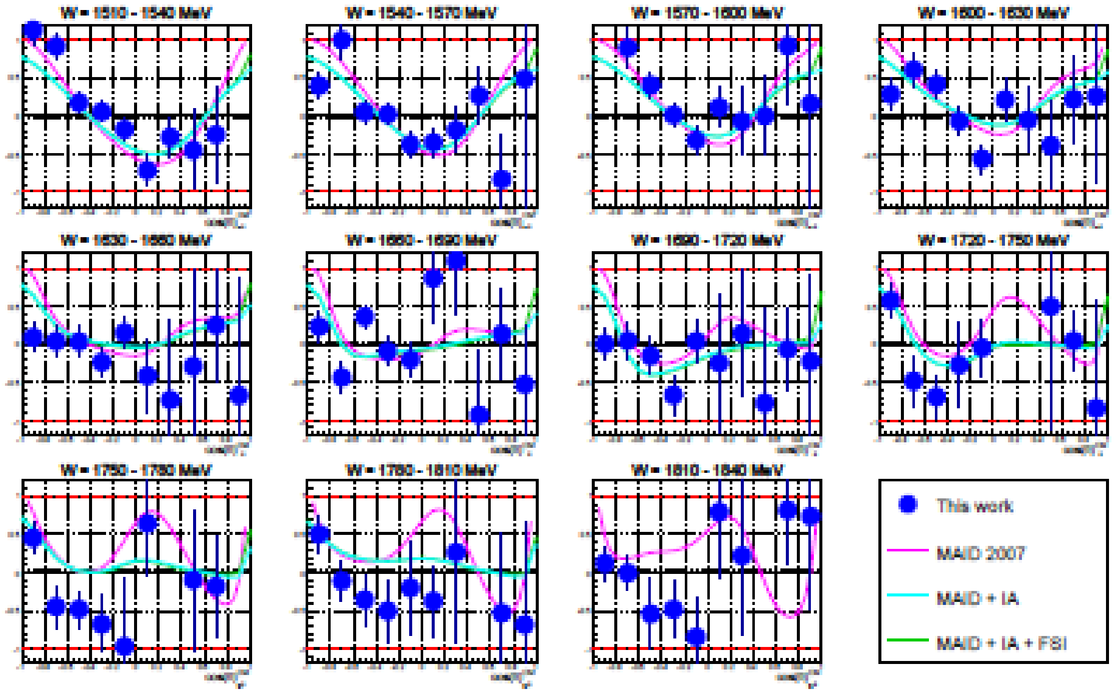


E observable off the neutron



$\gamma \mathbf{n} \rightarrow \pi^0 \mathbf{n}$

The data for $W_{CM} < 1350$ MeV were acquired for the first time and offer the first description of the π^0-E observable off the neutron in the Δ-resonance region.



As for the proton target, the effect of FSI on the E observable is marginal. Therefore the study of observables which lead to a better understanding of the nucleon is feasible even without the availability of a free neutron target.

Conclusions & Outlook

- ✓ An overview was given on recent results from the photoproduction of mesons from nucleons and nuclei at A2@MAMI

- ✓ Measurement of:
  - – inclusive polarised single π^0 photoproduction on the deuteron
  - – exclusive E asymmetry for π^0 from quasi-free proton and quasi-free neutron
  - – extraction of Legendre parameters

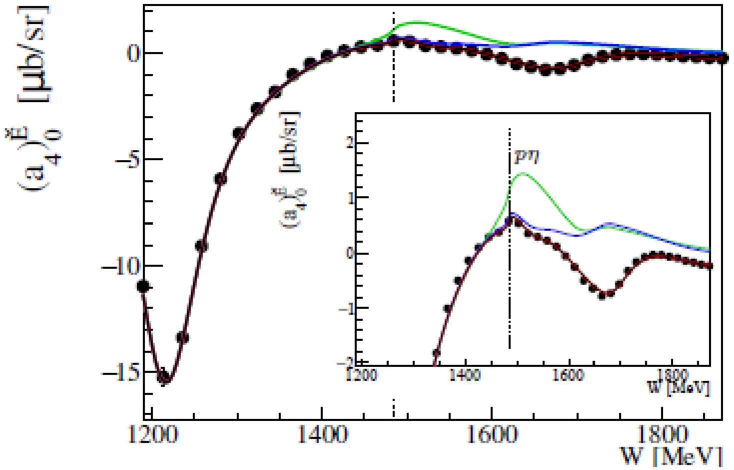
- ✓ E asymmetry:
  - – extended energy range
  - – small contribution of the FSI

- ✓ New input for PWA for π^0 off the neutron

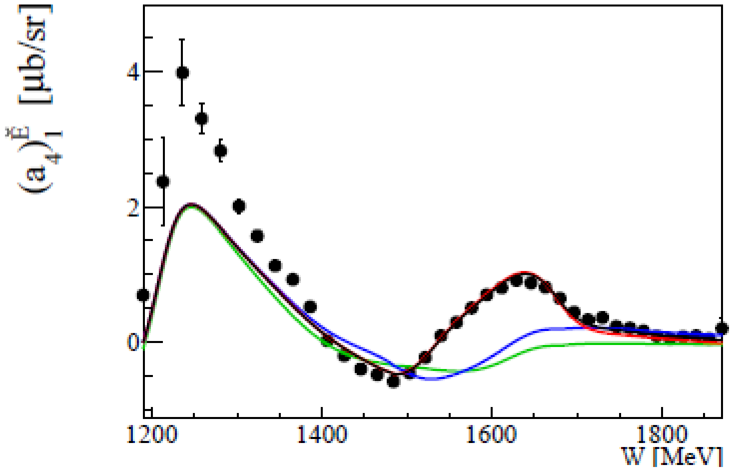
- ✓ A2 can contribute to get a more precise estimation of the properties of baryonic resonances

Additional material

Dominant partial wave contribution - proton



$$(a_4)_0^{\check{E}} = \langle S,S\rangle + \langle P,P\rangle$$
$$+\langle D,D\rangle$$
$$+\langle F,F\rangle$$
$$+\langle G,G\rangle$$

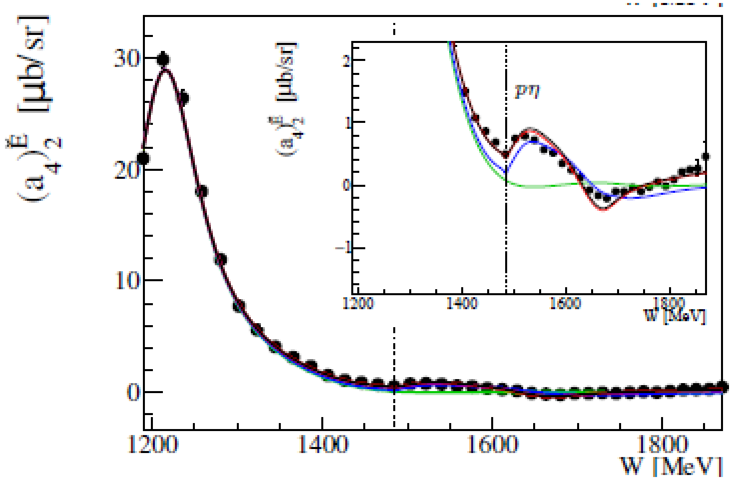


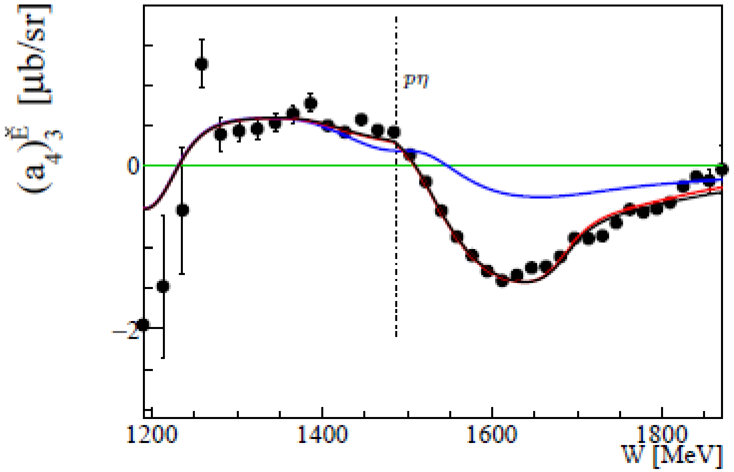
$$(a_4)_1^{\check{E}} = \langle S,P\rangle$$
$$+\langle P,D\rangle$$
$$+\langle D,F\rangle$$
$$+\langle F,G\rangle$$

- Sensitive exclusively to interference terms of the same l
- Sensitive to the absolute value squared of the multipoles
- $\langle P,P\rangle$ dominates until $W = 1350$ MeV due to the $\Delta(1232)$
- $p\eta$ cusp-effect visible due to the interference term $\langle S,S\rangle$

- Deviation from the BnGa-2014-02 PWA solution below $W = 1400$ MeV: energy not covered by any double polarisation observables for the $p\pi^0$ final state until now

Dominant partial wave contribution - proton





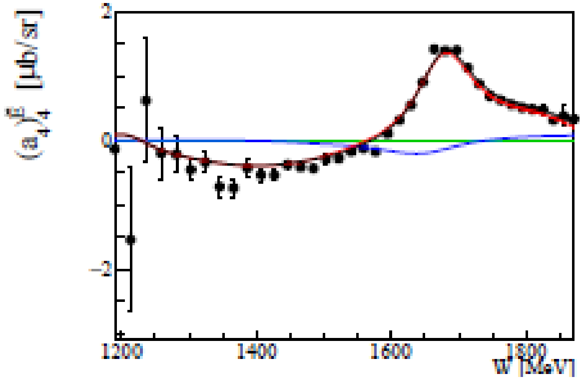
$$(a_4)_2^{\check{E}} = \langle P, P \rangle$$
$$+ \langle S, D \rangle + \langle D, D \rangle$$
$$+ \langle P, F \rangle + \langle F, F \rangle$$
$$+ \langle D, G \rangle + \langle G, G \rangle$$

- $p\eta$ cusp-effect more evident because of the interference term

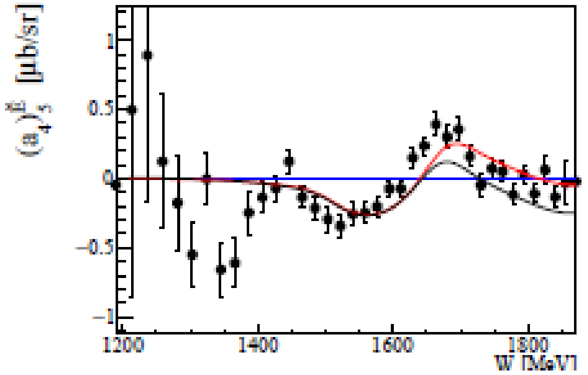
$$(a_4)_3^{\check{E}} = \langle P, D \rangle$$
$$+ \langle S, F \rangle + \langle D, F \rangle$$
$$+ \langle P, G \rangle + \langle F, G \rangle$$

- Pure S-wave and/or P-wave interference terms do not contribute anymore
- Sensitive to the interference term until $W =$ 1500 MeV and later to the and the interference terms

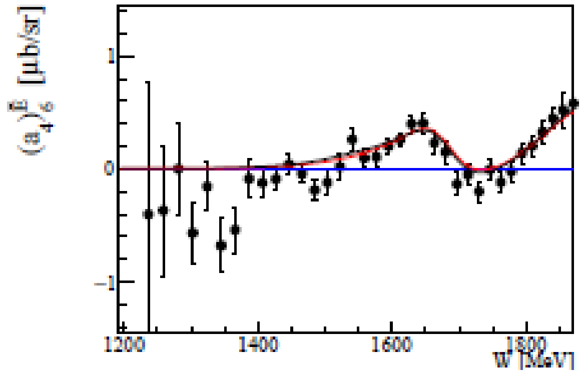
Dominant partial wave contribution - proton



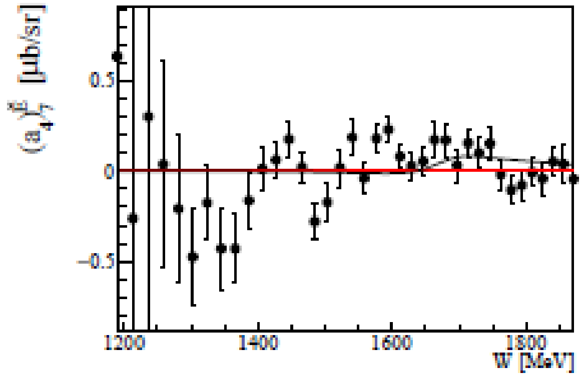
$$
\begin{aligned}
(a_4)_4^{\check{E}} &= \langle D,D\rangle \\
&+ \langle P,F\rangle + \langle F,F\rangle \\
&+ \langle S,G\rangle + \langle D,G\rangle + \langle G,G\rangle
\end{aligned}
$$



$$
\begin{aligned}
(a_4)_5^{\check{E}} &= \langle D,F\rangle \\
&+ \langle P,G\rangle + \langle F,G\rangle
\end{aligned}
$$



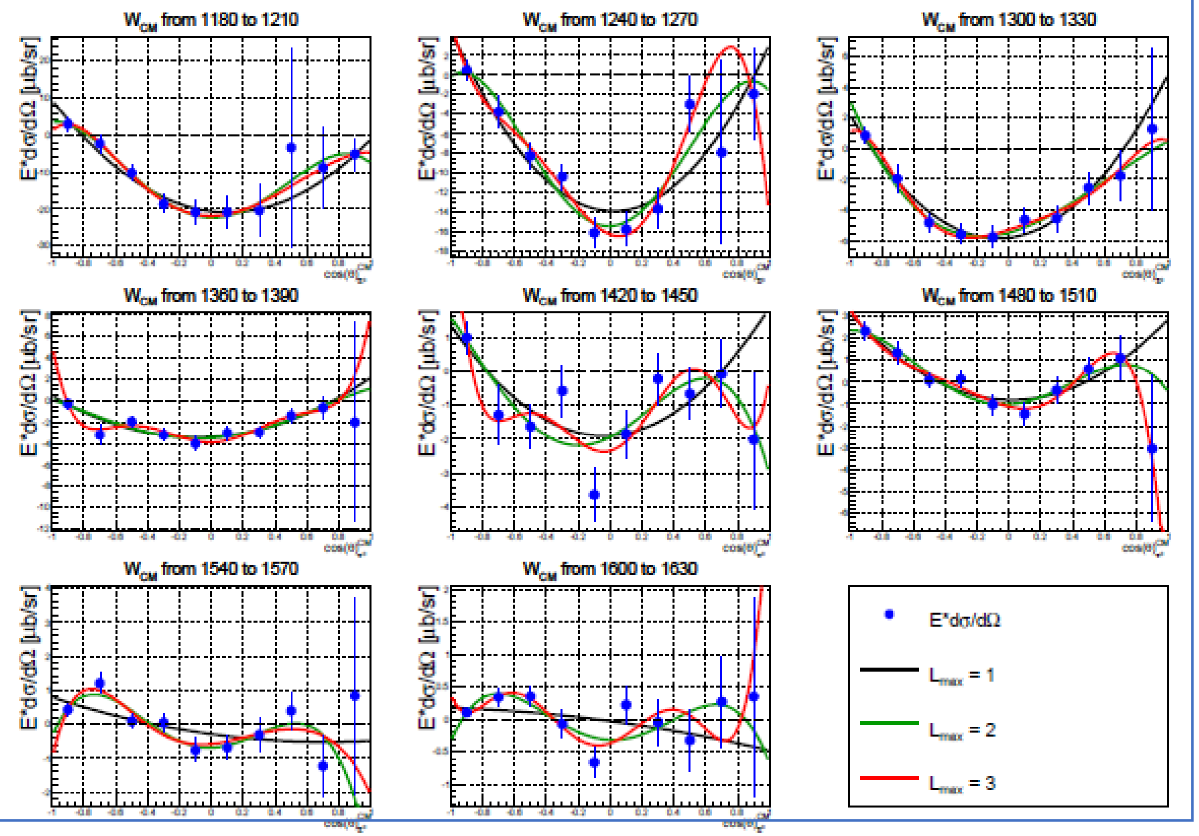
$$
\begin{aligned}
(a_4)_6^{\check{E}} &= \langle F,F\rangle \\
&+ \langle D,G\rangle + \langle G,G\rangle
\end{aligned}
$$



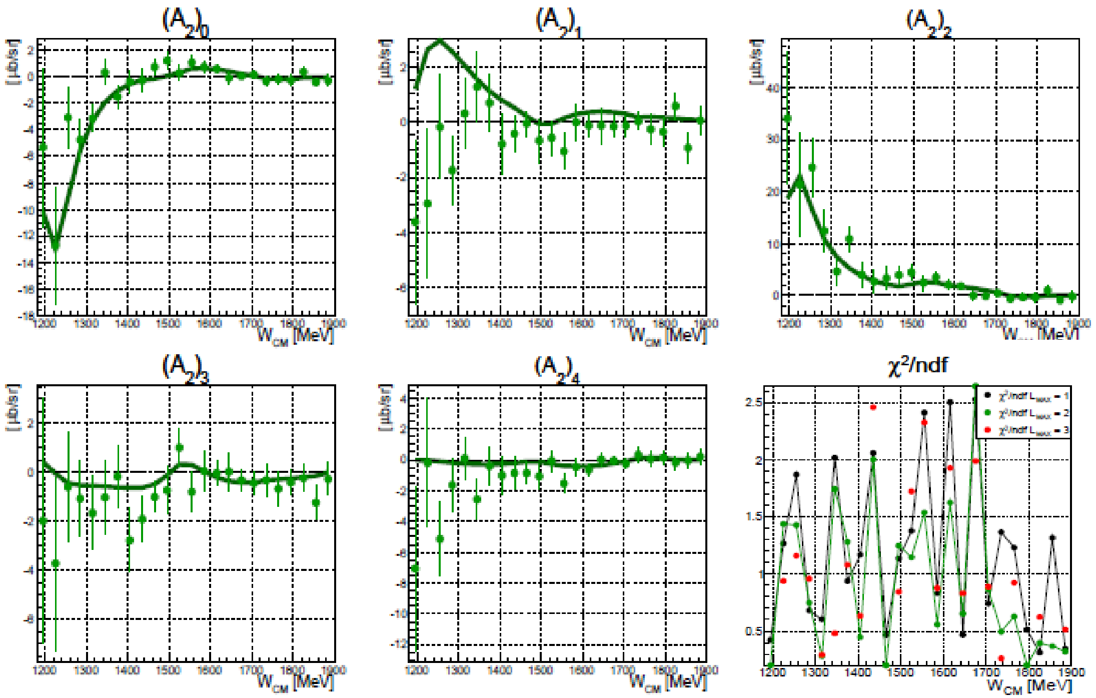
$$(a_4)_7^{\check{E}} = \langle F,G\rangle$$

Dominant partial wave contribution - neutron

$$\breve{E}(W,\theta) = E(W,\theta)\cdot\frac{d\sigma}{d\Omega}(W,\theta) = \rho\sum_{l=0}^{2L_{max}}(a_{L_{max}})_l^{\breve{E}}(W)P_l(\cos\theta)$$



A_k coefficients of the Legendre polynomials from the fit, with $L_{max} = 2$



Green line: Legendre coefficients derived from the SAID model