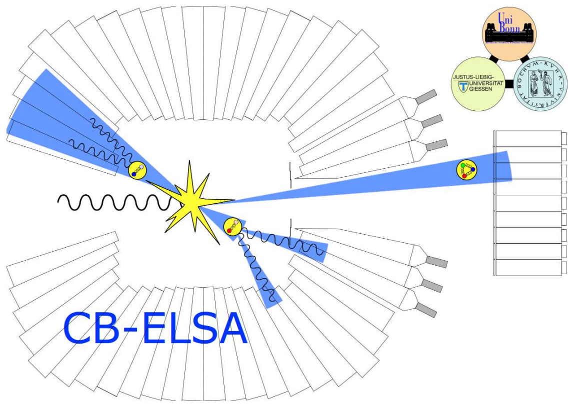
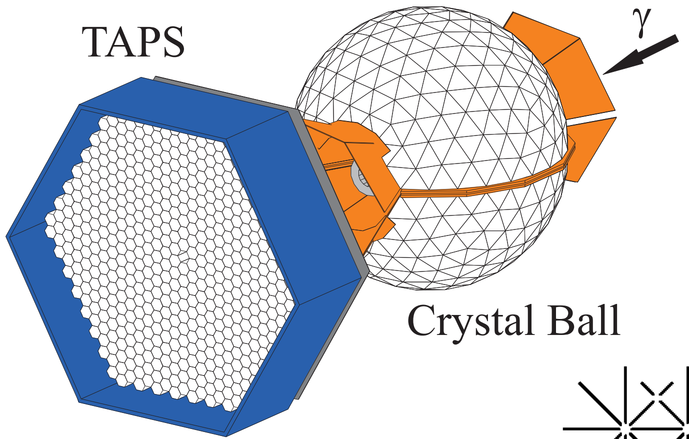
Photoproduction of Mesons of Quasifree Nucleons

- selected results -

B. Krusche, U. Basel for the CBELSA/TAPS and A2 collaborations

- **Introduction**
- **Experimental setups**
- **Results**
- **Conclusions**

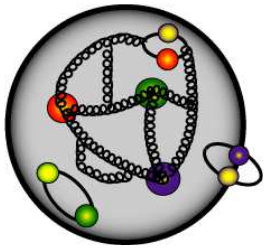




UNI BASEL

Structure of the Nucleon

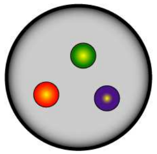
complex many body system



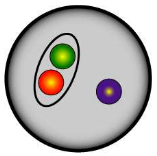
- valence quarks
- sea quarks
- gluons

models - effective dof's:

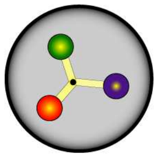
- **3 equivalent constituent quarks**



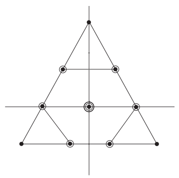
- **quark - diquark models (fewer states)**



- **quarks - flux tubes etc. (more states)**

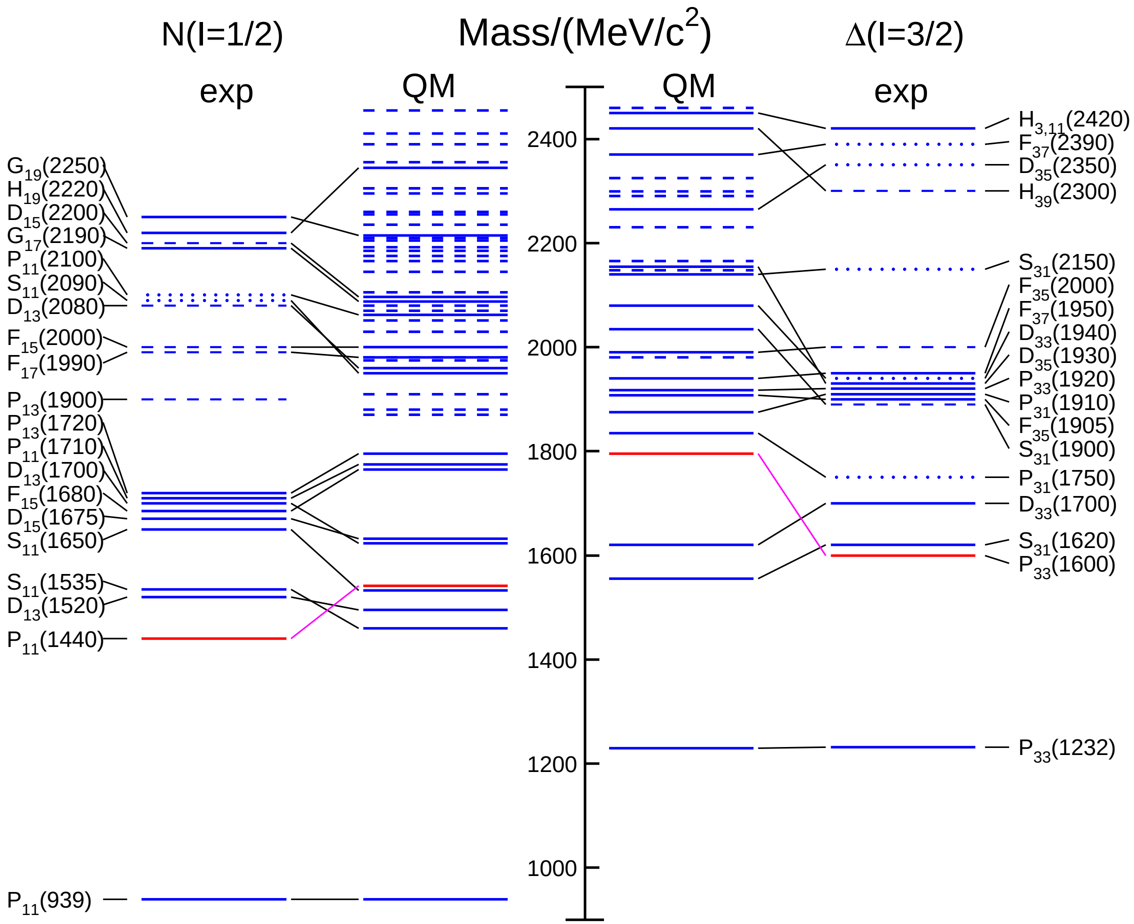


- **chiral soliton models (anti-decuplet states)**



- **coupled channel dynamics (molecule-like states)**

comparison: known excited states - constituent quark model (Capstick & Roberts)

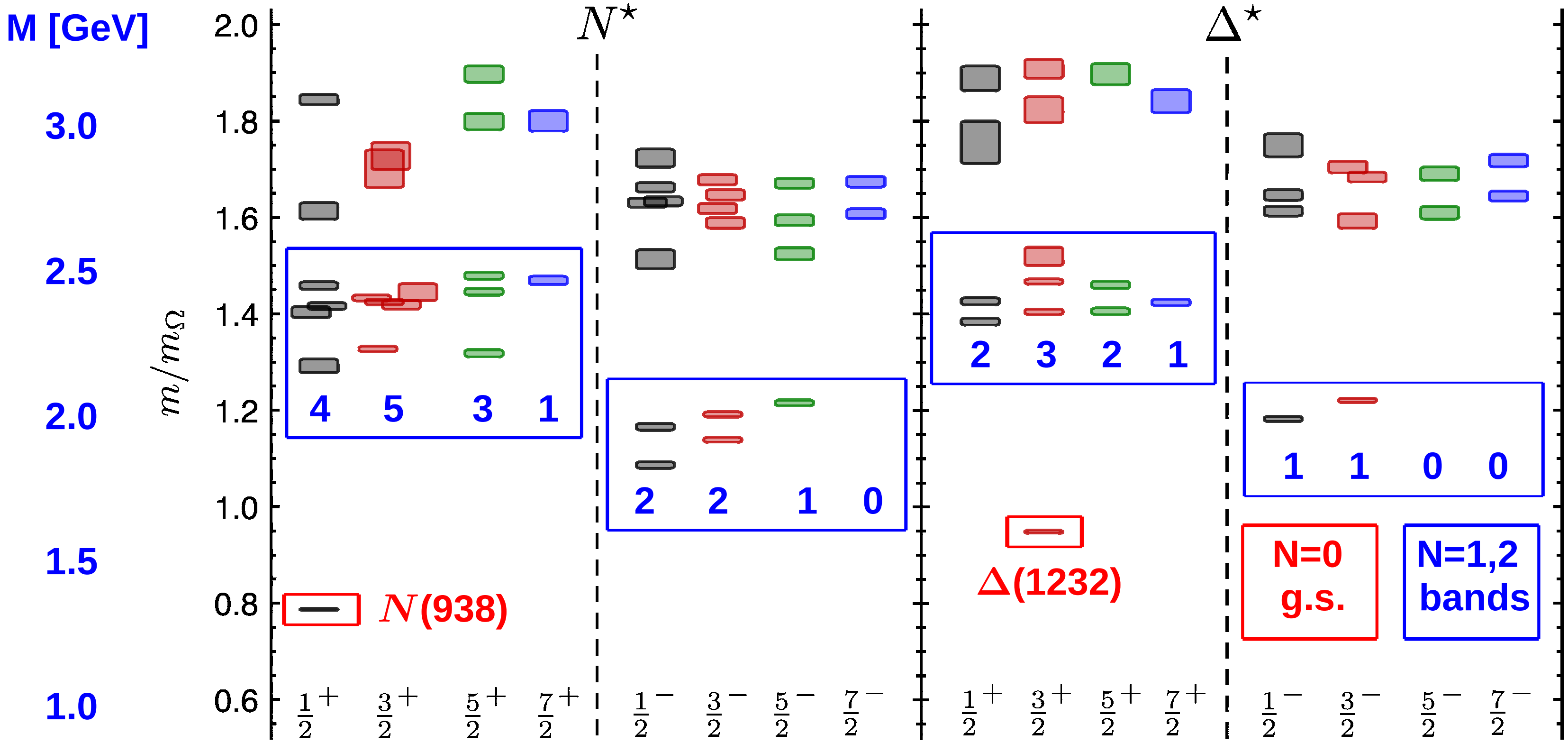


- **ordering of (low-lying) states?**
- **missing resonance problem?**

Progress in Baryon Spectroscopy

Nucleon resonances from Lattice QCD:

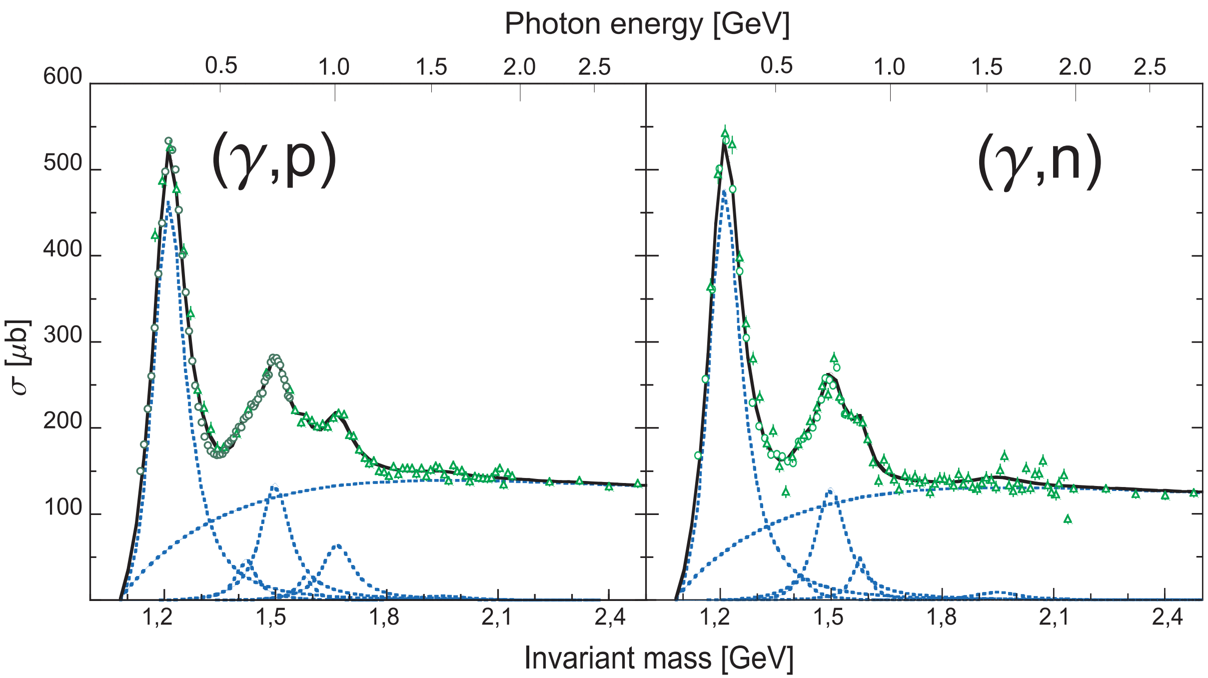
(R.G. Edwards et al., PRD84 (2011) 074508)



- **Basic features agree with expectations from $SU(3) \otimes O(3)$ symmetry:**
  - **counting of levels consistent with non-relativistic quark model**
  - **Lattice results of course in very early state, m_π =400 MeV...**

electromagnetic excitations of the neutron

- **importance of measurements off the neutron:**
  - **different resonance contributions**
  - **needed for extraction of iso-spin composition of elm. couplings**



- **complications due to use of nuclear targets (deuteron):**
  - **coincident detection of recoil nucleons**
  - **Fermi motion, nuclear effects like FSI, coherent contributions**

mesurements off quasifree nucleons bound in the deuteron

Complications:

(1) detection of recoil nucleons mandatory

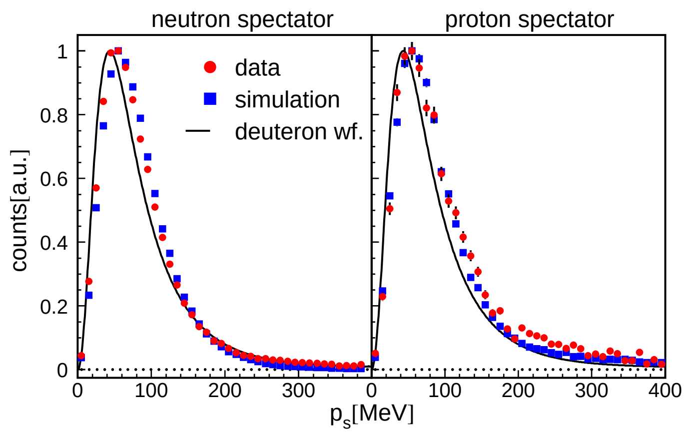
(2) reaction kinematics modified by Fermi motion - smears out all structures

(3) possible influence of meson - nucleon and nucleon-nucleon FSI on cross sections

Solutions:

(1,2) Typical neutron detection efficiencies for CB and TAPS in the range 10% - 30%, CB cannot measure energies (TAPS via ToF); but kinematics completely defined:

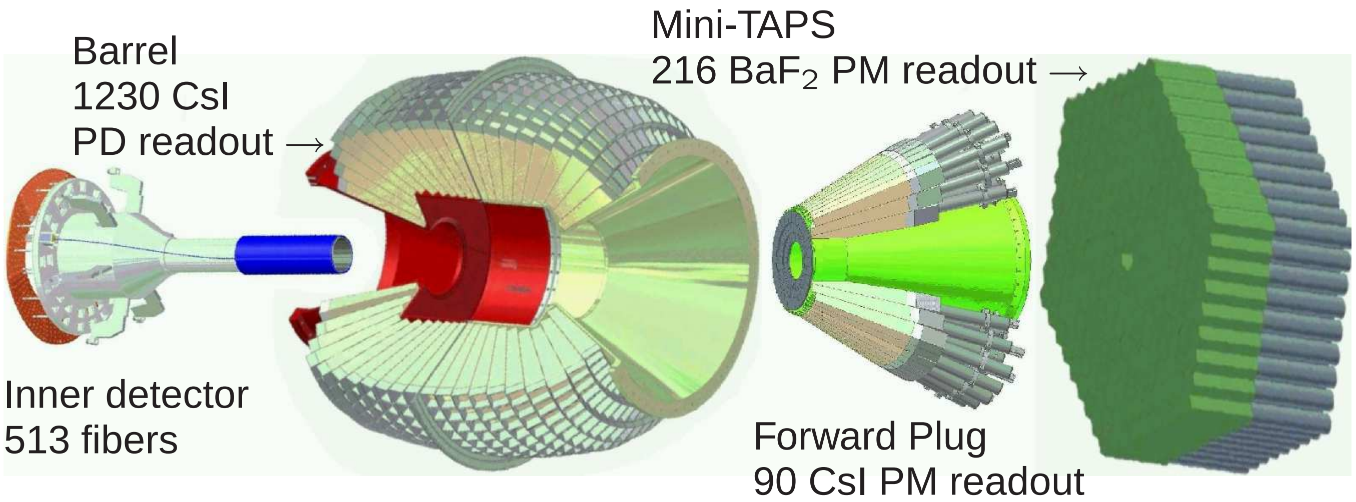
- initial state: incident photon and deuteron at rest
  known/measured: E_γ, m_d, $\vec{p}_d = 0$
- final state: meson, participant, and spectator nucleon
  known/measured: m_s, m_p, Θ_p, Φ_p, m_m, $\vec{p}_m$
  not measured: $T_p, \vec{p}_s$ (four variables)
- four constraints from energy/momentum conservation



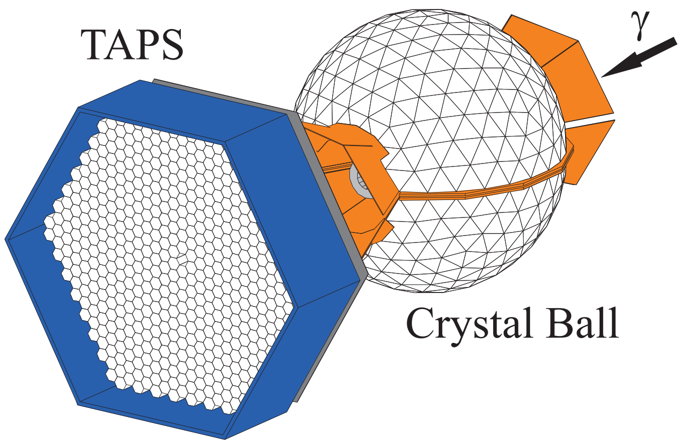
(3) comparison of quasifree production off protons and production off free protons to study FSI effects

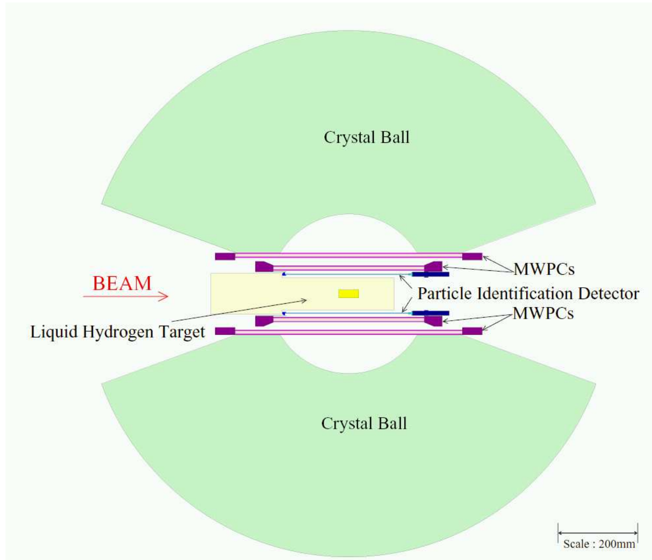
Calorimeters: Crystal Barrel & Crystal Ball with TAPS

- **Bonn ELSA accelerator:**
  Crystal Barrel (CsI),
  TAPS (BaF_2) forward wall,
  inner detectors
  $E_\gamma \leq$ 3.5 GeV,
  lin. pol.: available,
  circ. pol.: available



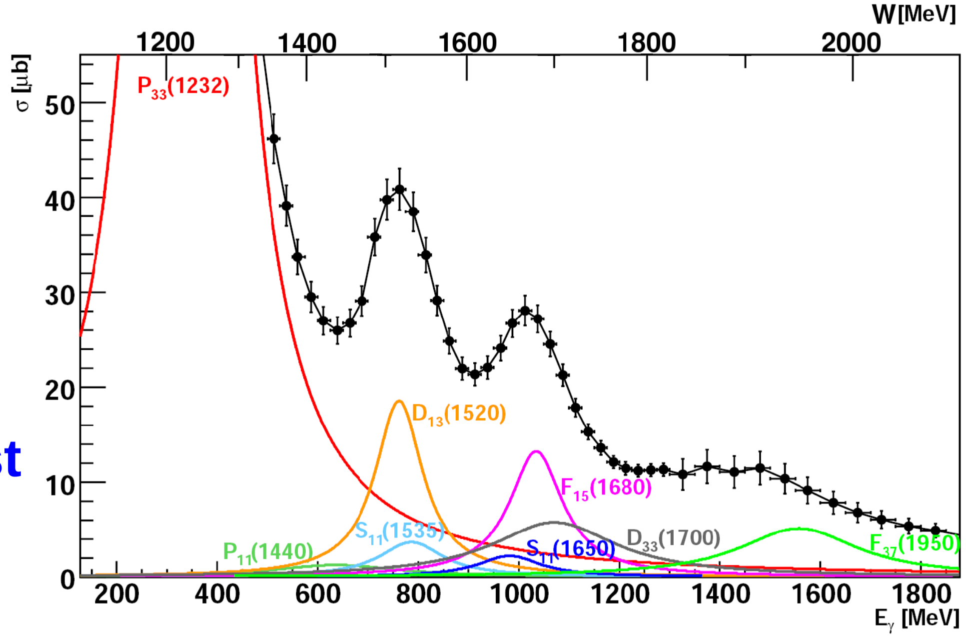
- **Mainz MAMI accelerator:**
  Crystal Ball (NaJ),
  TAPS (BaF_2) forward wall,
  inner detectors
  $E_\gamma \leq$ 1.5 GeV,
  lin. pol.: available,
  circ. pol.: available





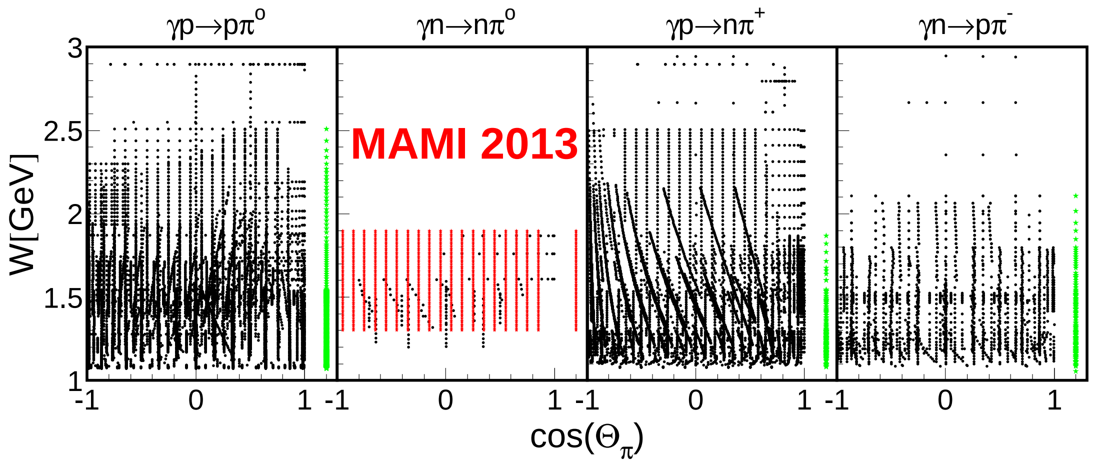
Results - Example I: Photoproduction of π^0-mesons

- photoproduction of single pions one of best studied meson production reactions
- backbone of partial wave analyses like SAID, MAID, BnGn,... for extraction of resonance properties
- reaction with neutral pions of great interest
- impact of π^0-production off the neutron?



- Existing data base/ new results

cross section data for different isospin channels



isospin decompostion of pion photoproduction

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

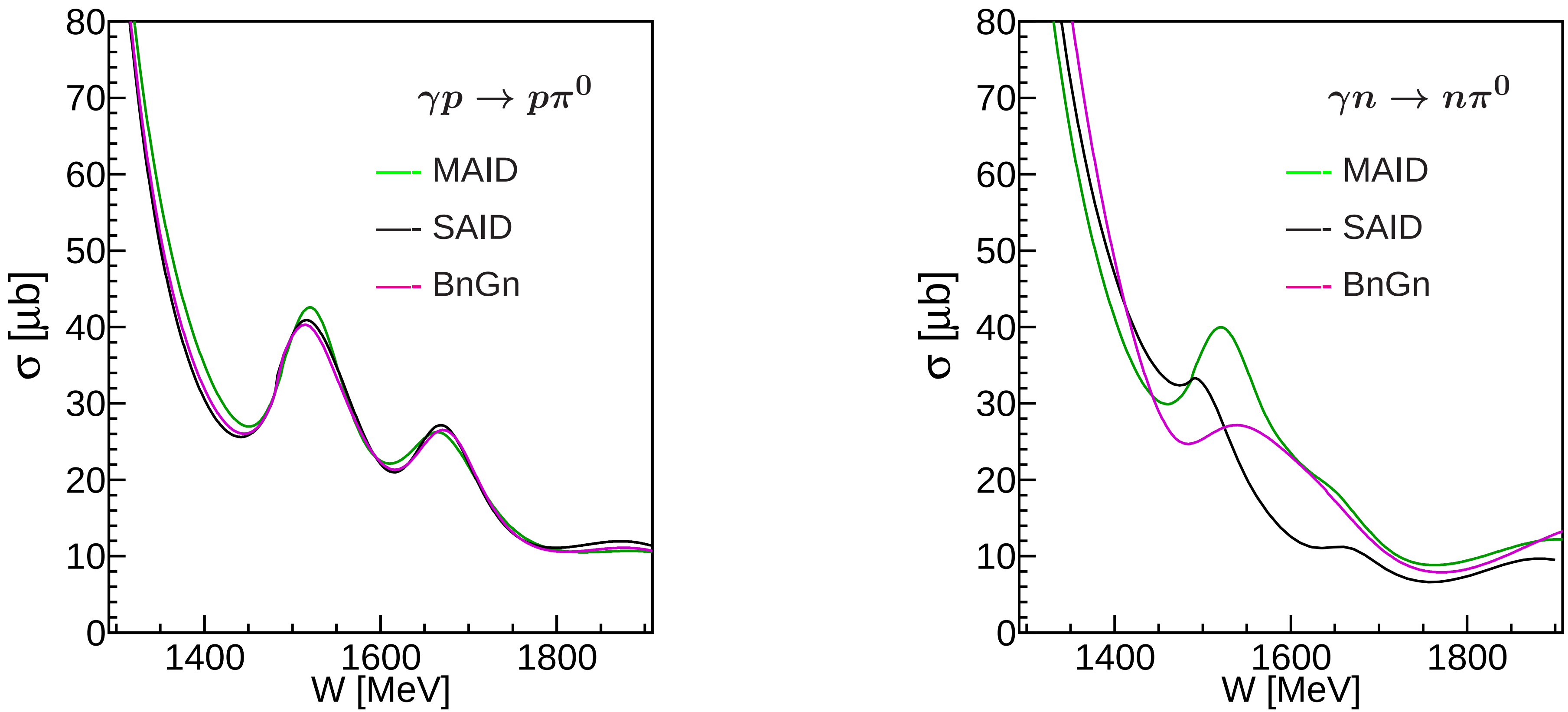
$$A(\gamma p \to \pi^0 p) = -\sqrt{\tfrac{1}{3}}A^{V3} + \sqrt{\tfrac{2}{3}}(A^{IV} - A^{IS})$$

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

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

$\gamma N \rightarrow N\pi^0$ - reaction-model fits, predictions

- **Results from partial wave, reaction models:** — SAID — MAID — BnGa

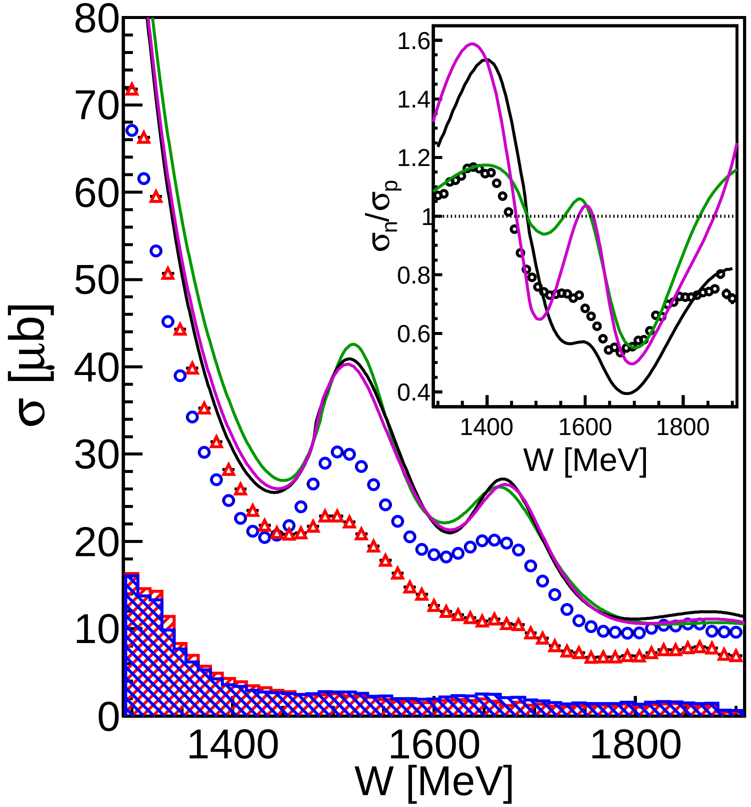


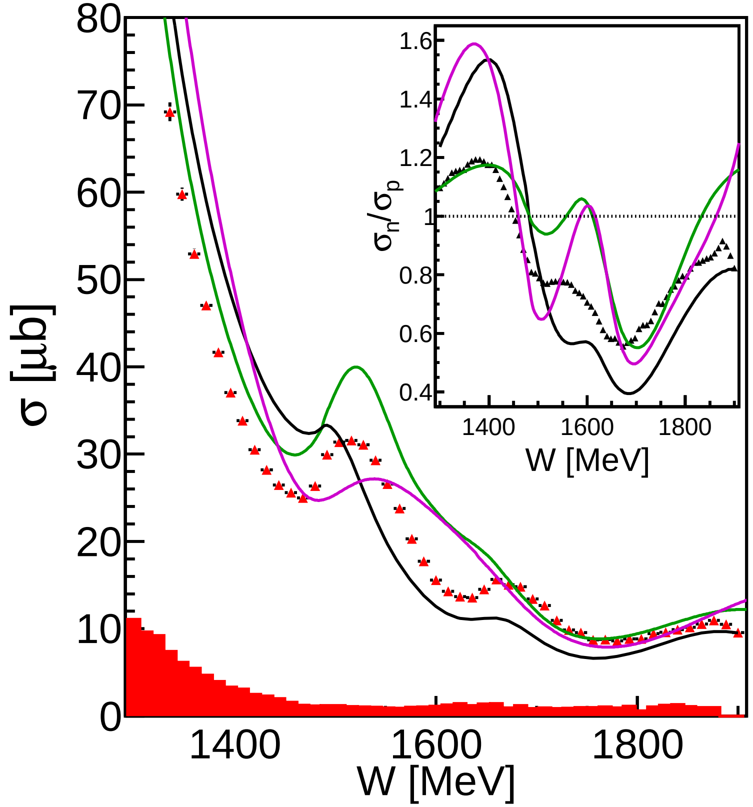
- **results agree for proton target (because fitted to proton data)**
- **predictions for neutron target disagree completely**
- **data from $\gamma n \rightarrow p\pi^-$ do not sufficiently constrain the fits for neutron target (completely different non-resonant backgrounds)**

$\gamma n \rightarrow n\pi^0$ - quasifree π^0-production off neutrons

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

- **Total cross sections compared to PWA results:** — SAID — MAID — BnGa



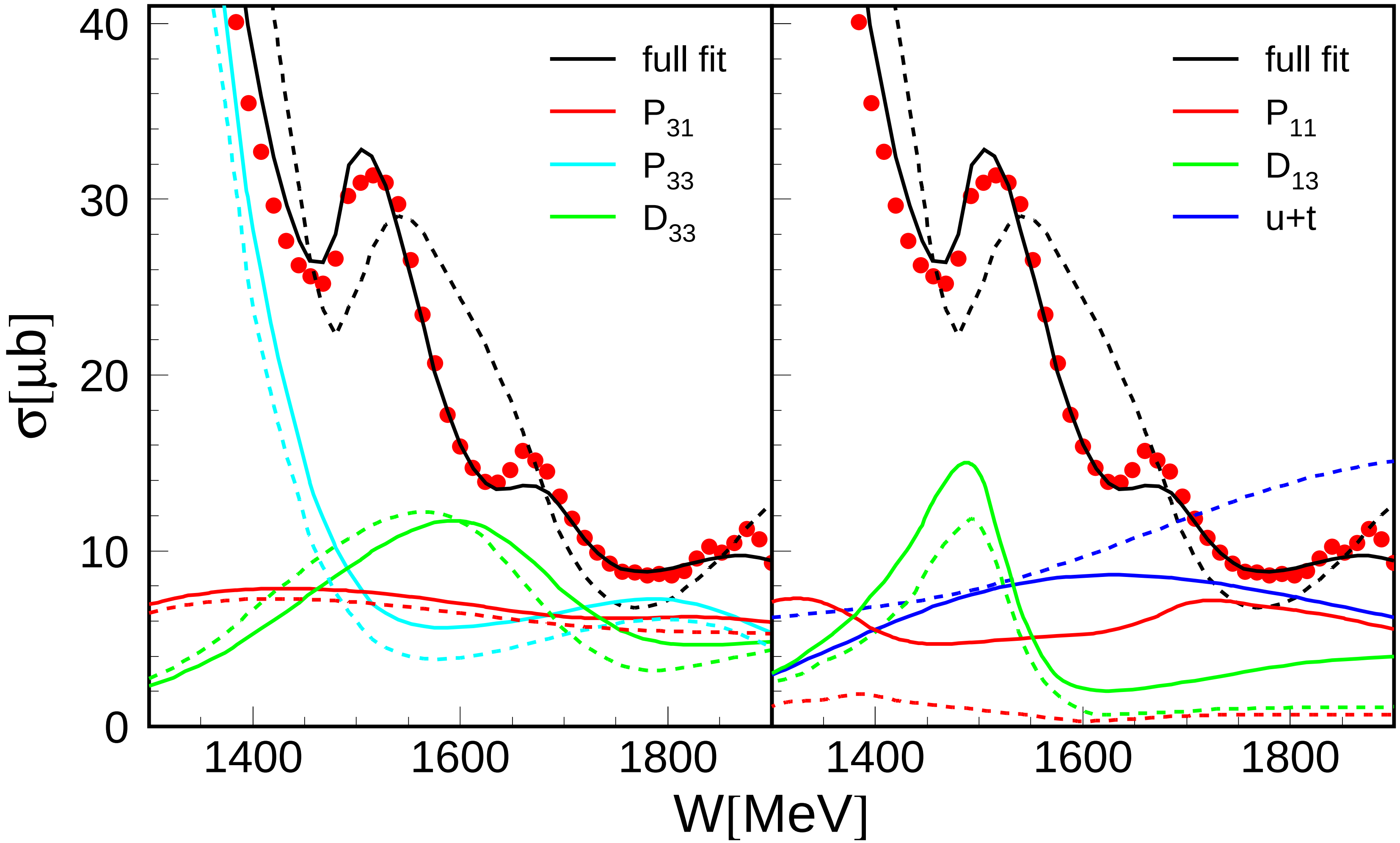


- **significant effects from final state interactions in proton data**
- **neutron data corrected under assumption of identical FSI for both reactions**
- **poor agreement between neutron data and PWA predictions**

$\gamma n \to n\pi^0$ - quasifree π^0-production off neutrons

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

- **Refit of BnGa PWIA:** — BnGa original - - - BnGa refit

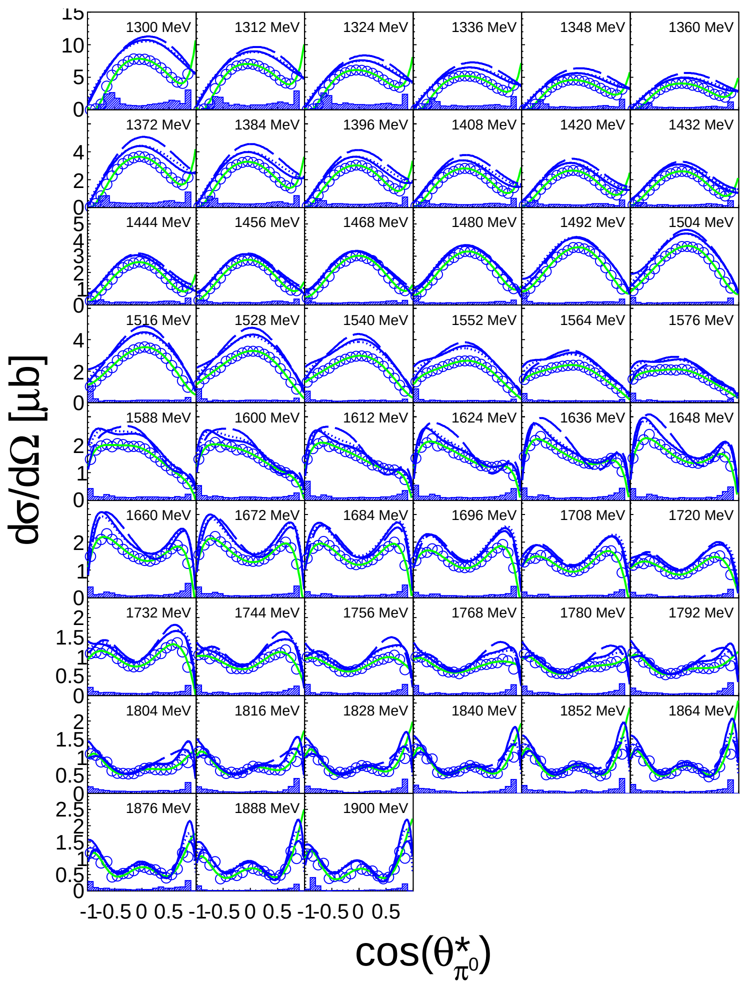


- **only small effects for $I = 3/2$ (Δ-states) partial waves**
- **large effects for $I = 1/2$ ($N^\star$) partial waves and background**

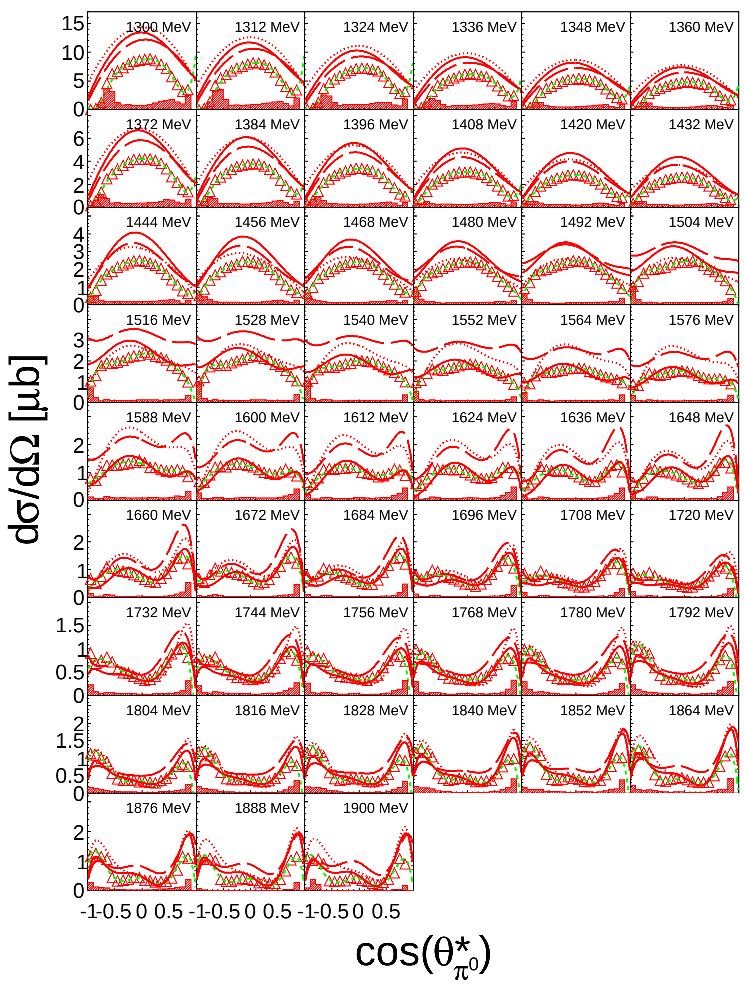
$\gamma N \rightarrow N\pi^0$ - angular distributions

(M. Dieterle et al.)

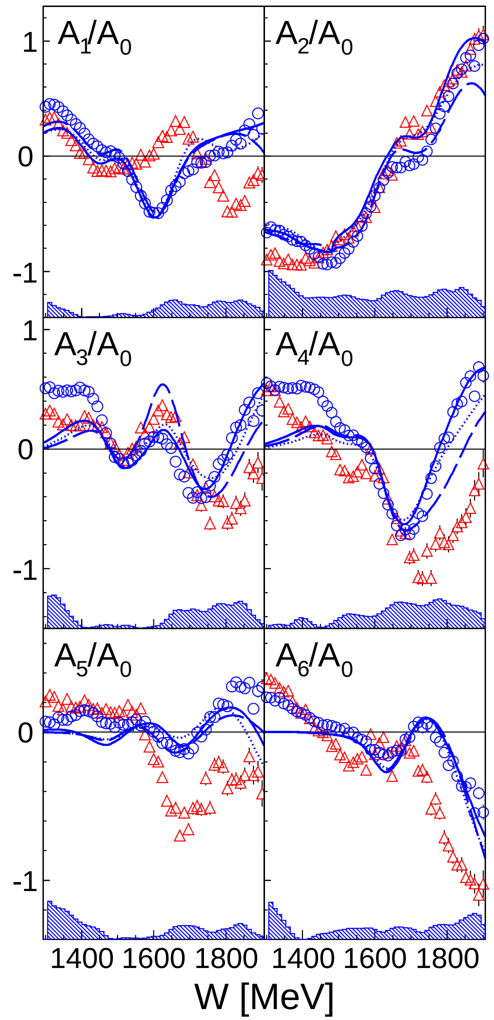
$\gamma' p' \rightarrow p\pi^0$



$\gamma' n' \rightarrow n\pi^0$



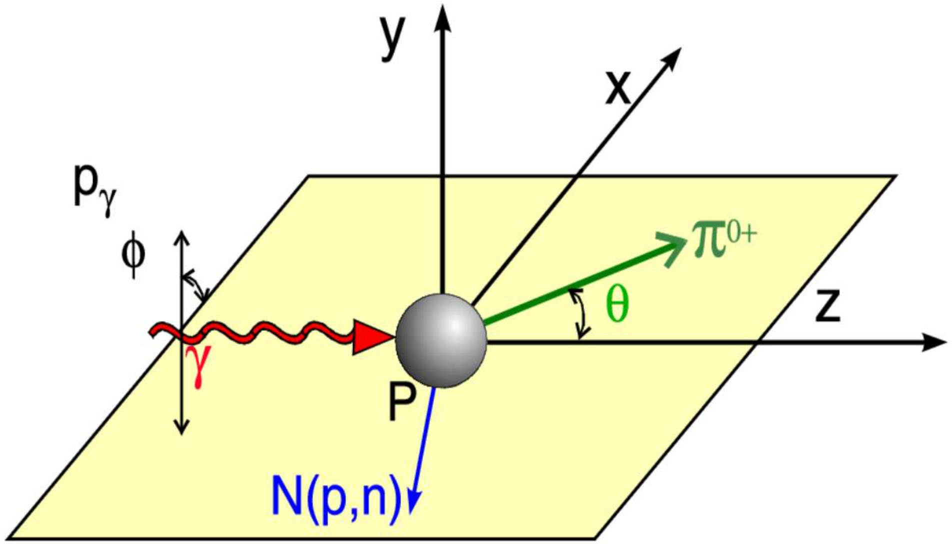
coefficients



Coefficients of Legendre polynomials from $\frac{d\sigma}{d\Omega} = \Sigma A_i P_i(\cos(\Theta^\star))$

polarization observables - beam - target

- **completely model independent multipole analysis requires measurement of:**
  - **4 single polarization observables (σ, Σ, T, P)** — **Chiang & Tabakin PRC 55 (1997)**
  - **4 carefully chosen double polarization observables**



photon polarization	target polarization -	x	y	z
unpolarized	σ	-	T	-
linearly	Σ	H	-P	-G
circularly	-	F	-	-E

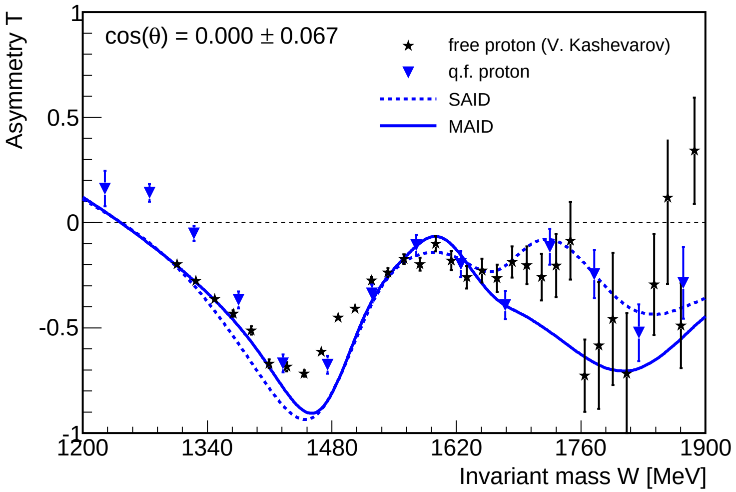
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \{1 - P_l \Sigma \cos(2\phi) \\ + P_x [-P_l H \sin(2\phi) + P_c F] \\ - P_y [-T + P_l P \cos(2\phi)] \\ - P_z [-P_l G \sin(2\phi) + P_c E] \}$$

polarization observables for $\gamma n \to n\pi^0$

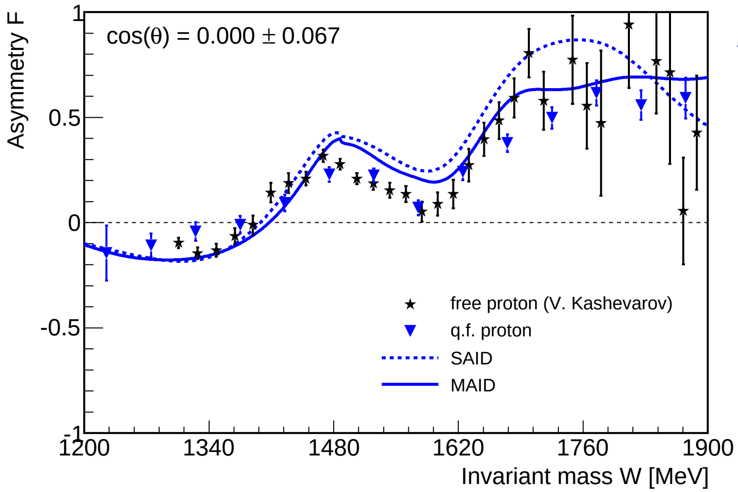
(Th. Strub et al., very preliminary)

- **first, preliminary results for T (target asym.) and F (trans. pol. target, circ. pol. beam)**

$T : \gamma p \to p\pi^0$ (blue: qf. p, black: free p)

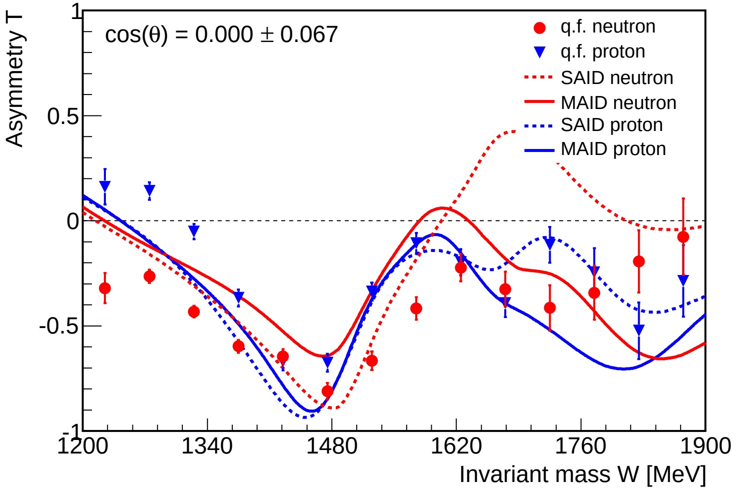


$F : \gamma p \to p\pi^0$ (blue: qf. p, black: free p)

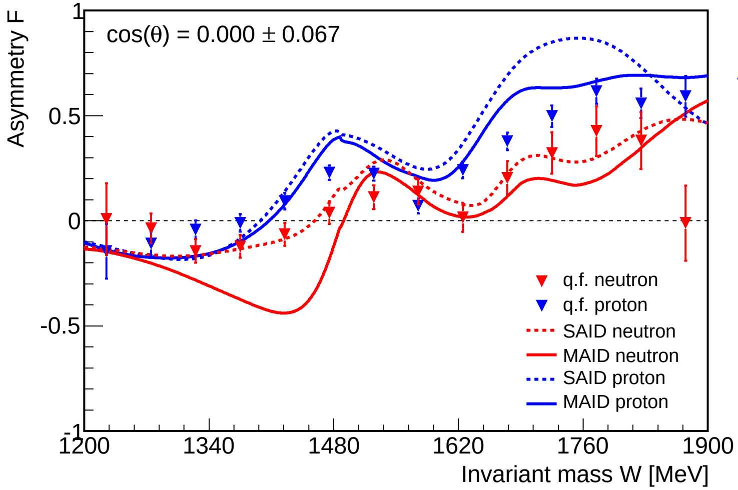


- **asymmetries for free and quasi-free protons agree!**

$T : \gamma n \to n\pi^0$ (blue: qf. p, red: qf. n)



$F : \gamma n \to n\pi^0$ (blue: qf. p, red: qf. n)



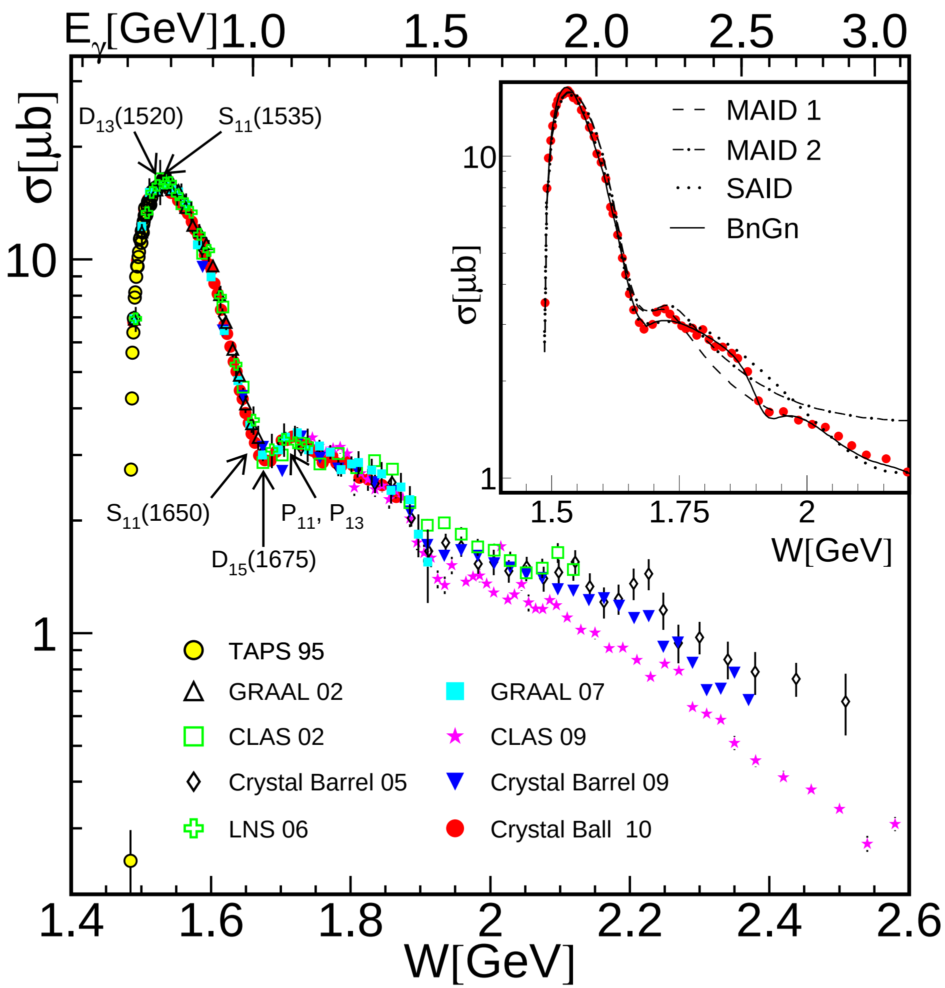
- **significant deviations between PWA predictions and neutron data**

η-photoproduction off the proton: resonance contributions?

branching ratios and elm. couplings (PDG):

state	b_η [%]	$A^p_{1/2}$	$A^p_{3/2}$	$A^n_{1/2}$	$A^n_{3/2}$
• $D_{13}(1520)$:	0.23 ± 0.04	-24	150	-59	-139
• $S_{11}(1535)$:	42 ± 10	90		-46	
• $S_{11}(1650)$:	$5-15$	53		-15	
• $D_{15}(1675)$:	0 ± 1	19	15	-43	-58
• $F_{15}(1680)$:	0 ± 1	-15	133	29	-33
• $D_{13}(1700)$:	0 ± 1	-18	-2	0 ± 5	-3
• $P_{11}(1710)$:	$10-30$	24		-2	
• $P_{13}(1720)$:	4 ± 1	-10	-19	4	-10

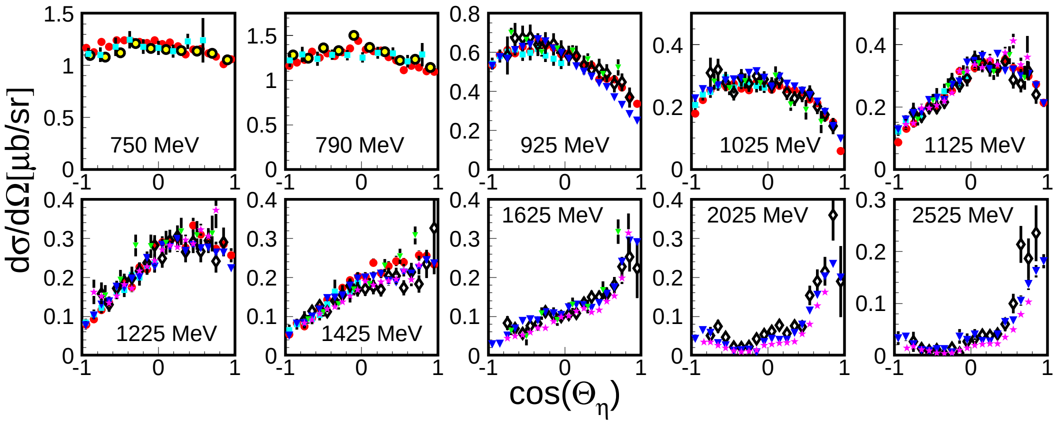
$\gamma p \rightarrow \eta p$



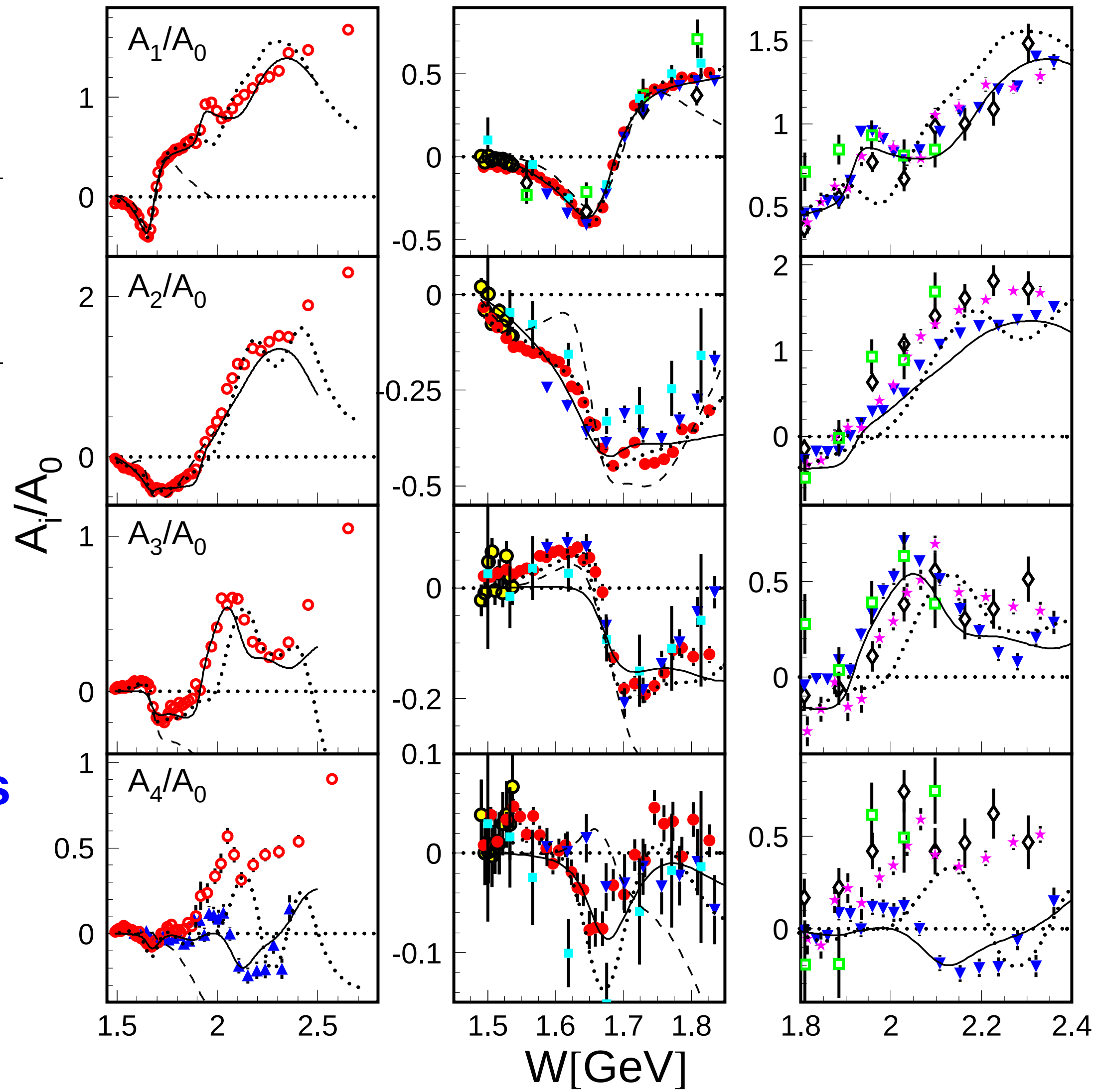
- dominent contribution from S_{11} states, interference structure?
- $D_{15}(1675)$ has stronger electromagnetic coupling to neutron than to proton
- complicated pattern around 1.7 GeV
- PWA's agree excellently with data in S_{11} range, less so at higher energies

angular distributions for $\gamma p \rightarrow p\eta$

- **typical angular distributions**



- **fitted coefficients**



- **fitted with:**

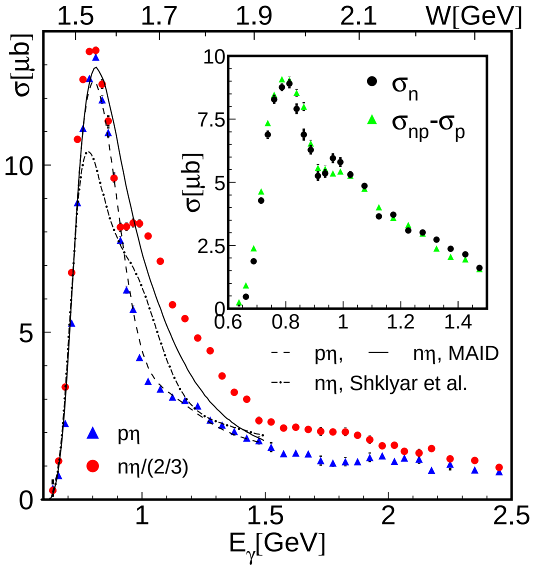
$$\frac{d\sigma}{d\Omega} = \Sigma A_i P_i(\cos(\Theta^\star))$$

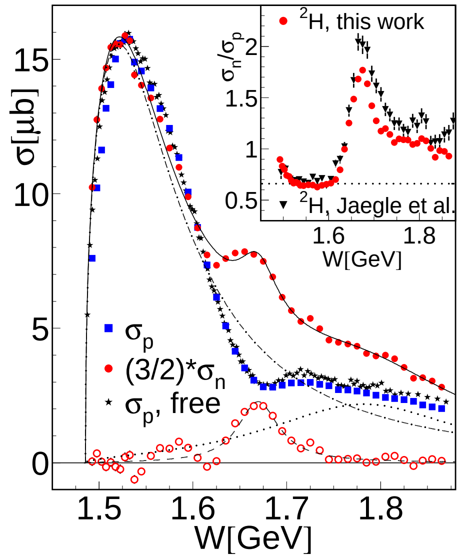
- **typical s-wave behavior at threshold**
- **fast variation - interesting structures around $W \approx$ 1.7 GeV**
- **diffractive (t-channel) at highest energies**

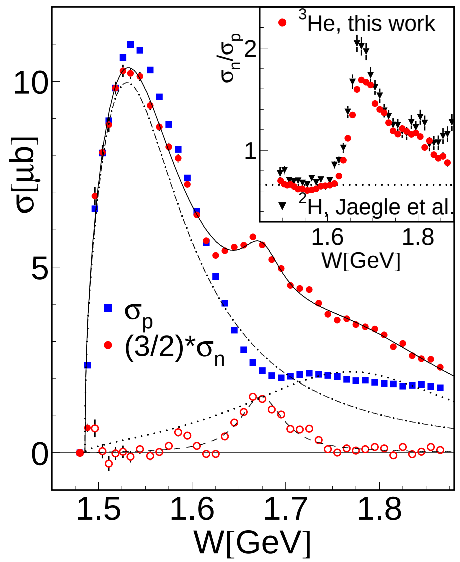
quasifree $\gamma n \rightarrow n\eta$: more surprises

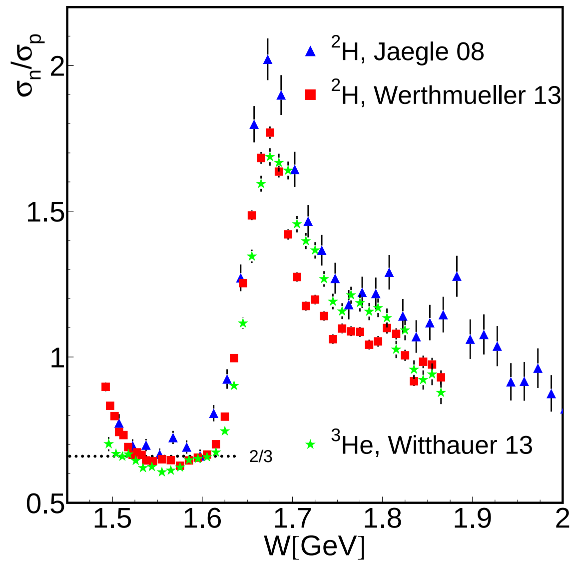
(I. Jaegle et al., D. Werthmüller et al., L. Witthauer et al.)

- **ELSA:** $\gamma d \rightarrow (n)(p)\eta$
- **MAMI:** $\gamma d \rightarrow (n)(p)\eta$ $\quad \gamma^3\text{He} \rightarrow X(n)(p)\eta$
- **neutron/proton ratio**







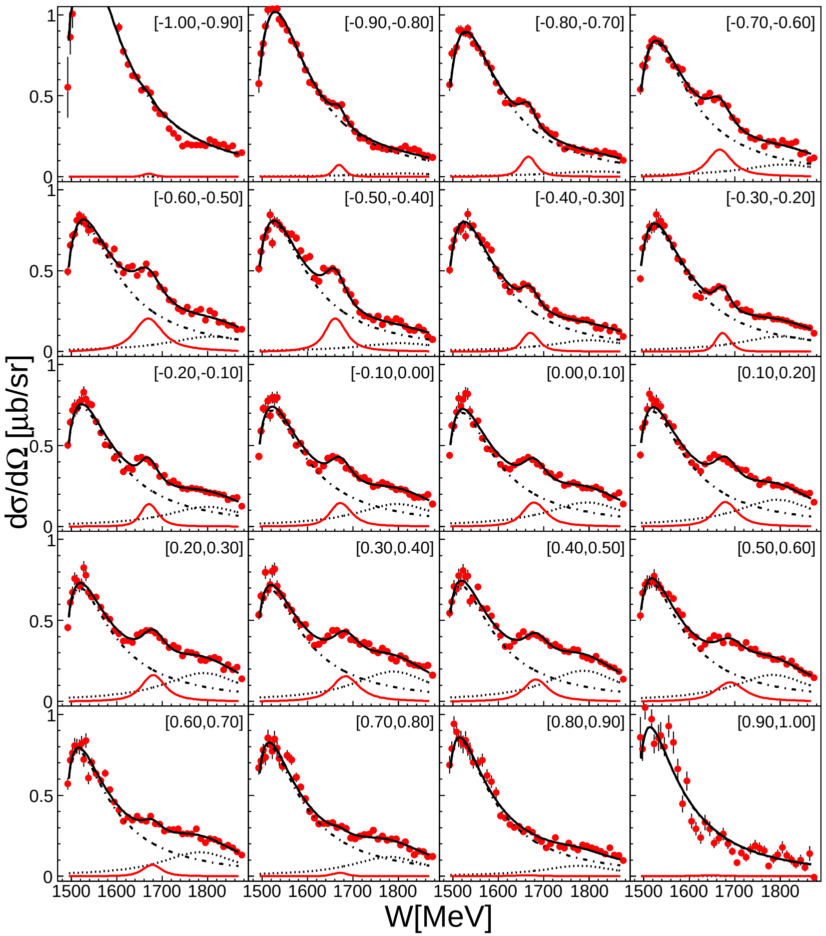


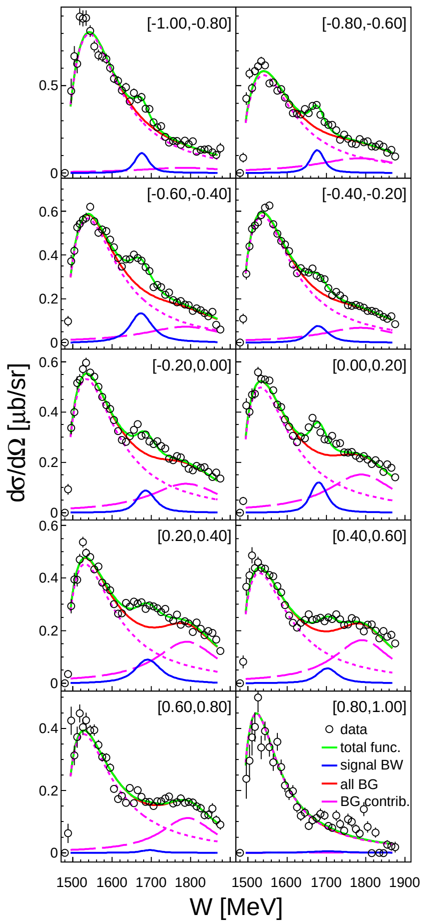
- **pronounced, narrow structure in neutron excitation function close to W=1.68 GeV**
- **width of structure $\approx$ 30 MeV**
- **neutron/proton ratios in agreement for all measurements:**
  - in S_{11}(1535) region 2/3 ratio
  - peak close to 1.7 GeV
  - very close to threshold almost unity, no distinction between participant and spectator
- **free and deuteron quasifree proton data agree;**
  quasifree ^{3}He data suppressed by $\approx$ 25%

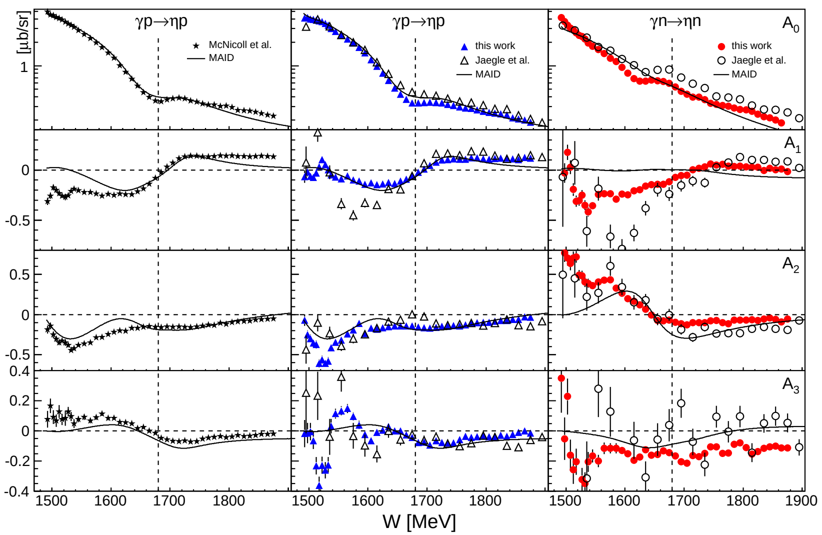
$\gamma n \rightarrow n\eta$ - excitations functions for different angular bins

(D. Werthmüller and L. Witthauer et al., Phys. Rev. Lett. 111 (2013) 232001; EPJA 49 (2013) 154; PRC 90 (2014) 015205)

- **deuteron target**
- **^{3}He target**
- **Legendre coefficients**





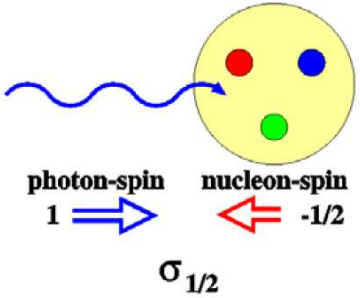


- **non-trivial angular dependence observed**

$\gamma N \rightarrow N\eta$ - helicity dependent cross sections

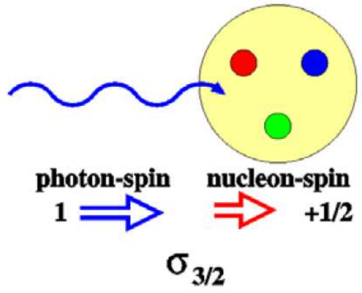
(L. Witthauer et al., very preliminary)

- **helicity component $\sigma_{1/2}$**

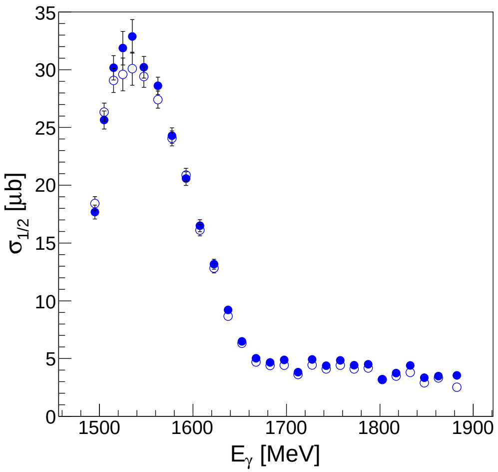


- **double polarization:**
  circularly pol. beam,
  longitudinally pol. target (buthanol)

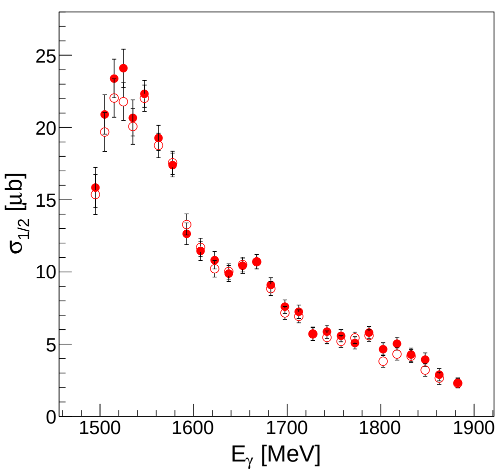
- **helicity component $\sigma_{3/2}$**



- **proton - $\sigma_{1/2}$**



- **neutron - $\sigma_{1/2}$**



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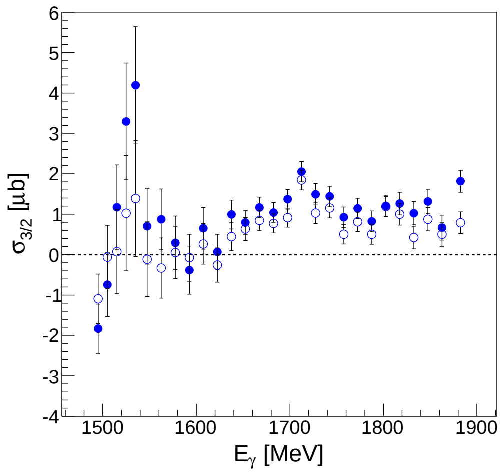
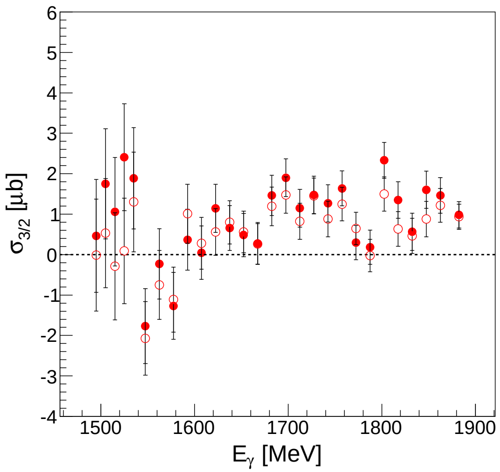


- **neutron - $\sigma_{3/2}$**

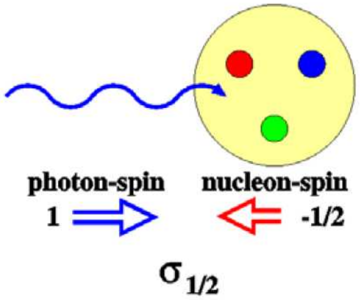


- **structure in neutron excitation function is in $\sigma_{1/2}$ part!**

$\gamma N \rightarrow N\eta$ - helicity dependent cross sections

(L. Witthauer et al., very preliminary)

- **helicity component $\sigma_{1/2}$**



- **double polarization:**
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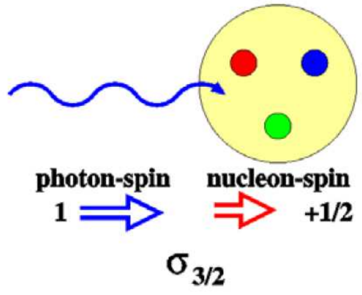
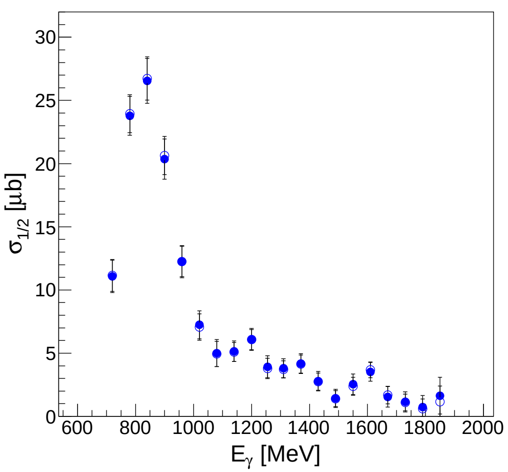
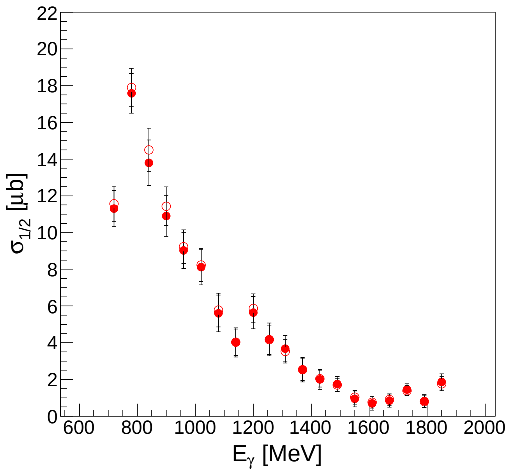
- **helicity component $\sigma_{3/2}$**



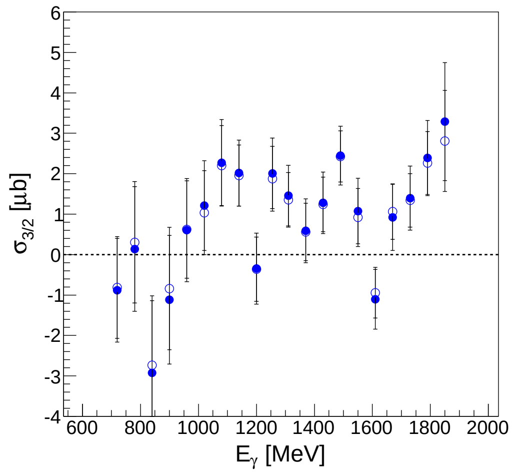
- **proton - $\sigma_{1/2}$**



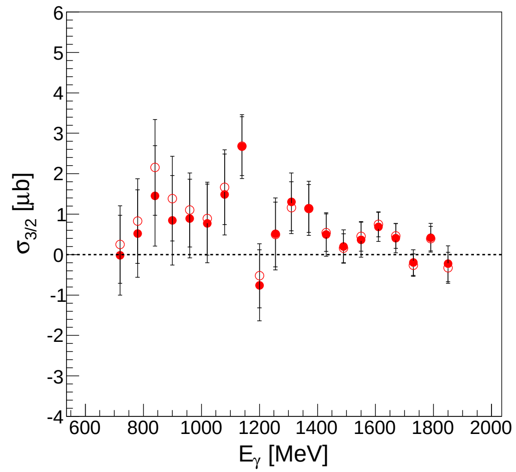
- **neutron - $\sigma_{1/2}$**



- **proton - $\sigma_{3/2}$**



- **neutron - $\sigma_{3/2}$**



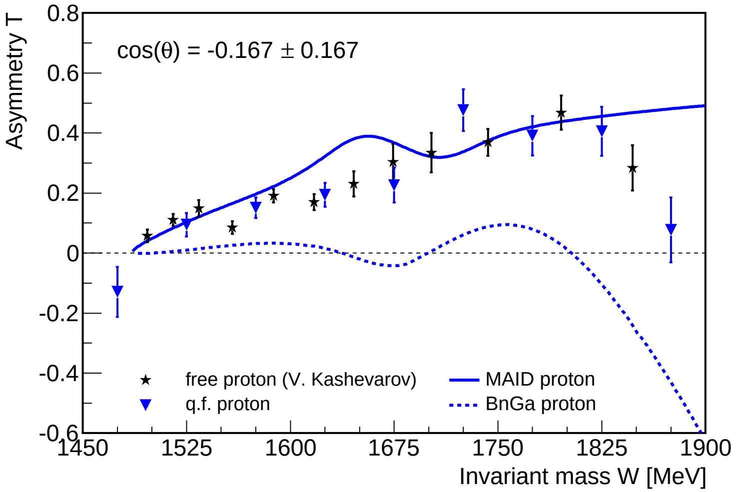
- **structure in neutron excitation function is in $\sigma_{1/2}$ part!**

polarization observables for $\gamma n \rightarrow n\eta$

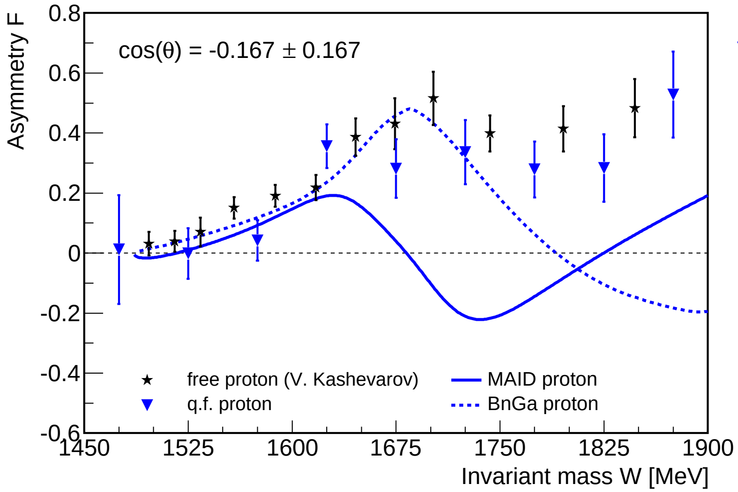
(Th. Strub et al., very preliminary)

- first, preliminary results for T (target asym.) and F (trans. pol. target, circ. pol. beam)

$T: \gamma p \rightarrow p\eta$ (blue: qf. p, black: free p)

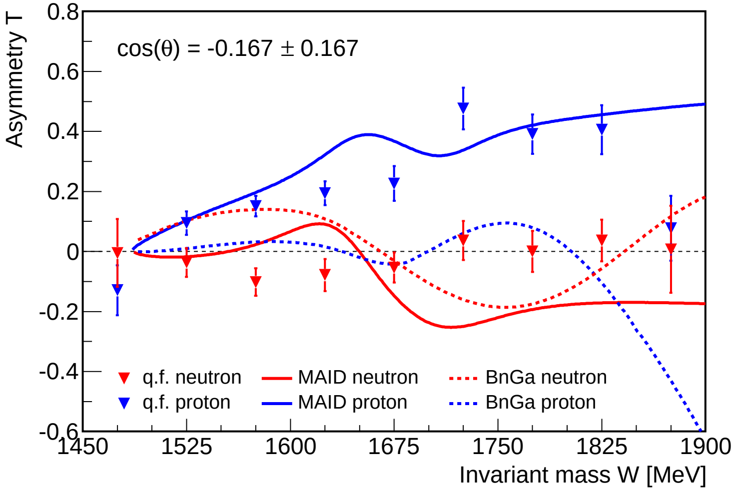


$F: \gamma p \rightarrow p\eta$ (blue: qf. p, black: free p)

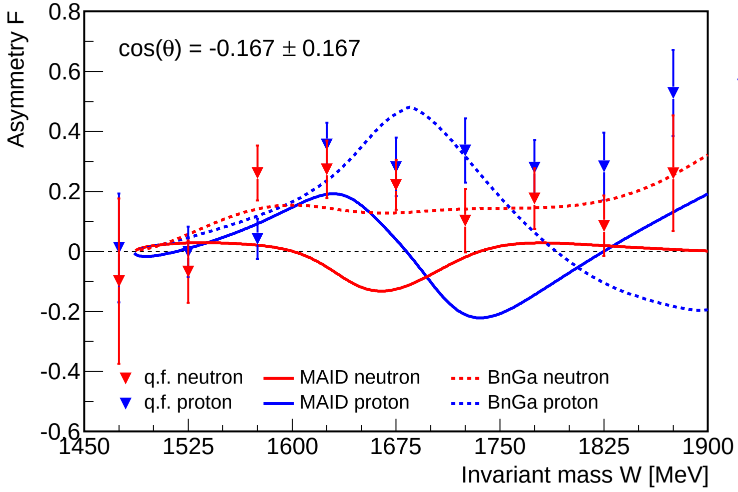


- **asymmetries for free and quasi-free protons agree!**

$T: \gamma n \rightarrow n\eta$ (blue: qf. p, red: qf. n)



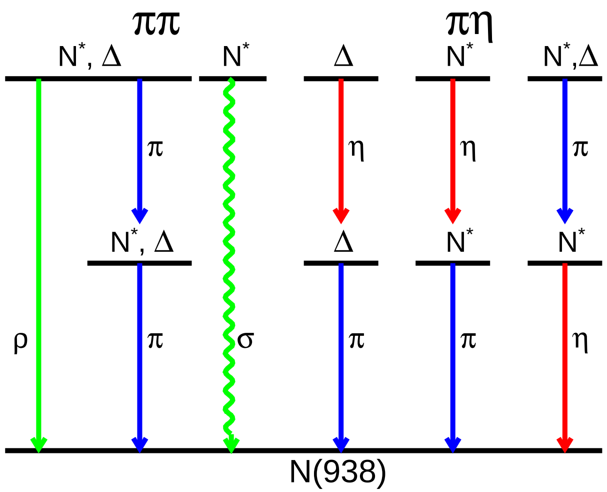
$F: \gamma n \rightarrow n\eta$ (blue: qf. p, red: qf. n)



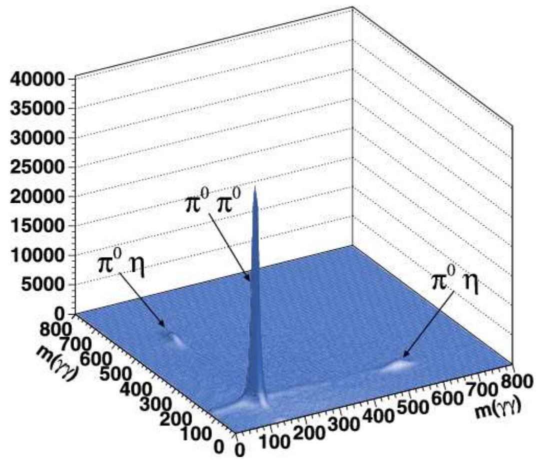
- **significant deviations between PWA predictions**

photoproduction of meson pairs

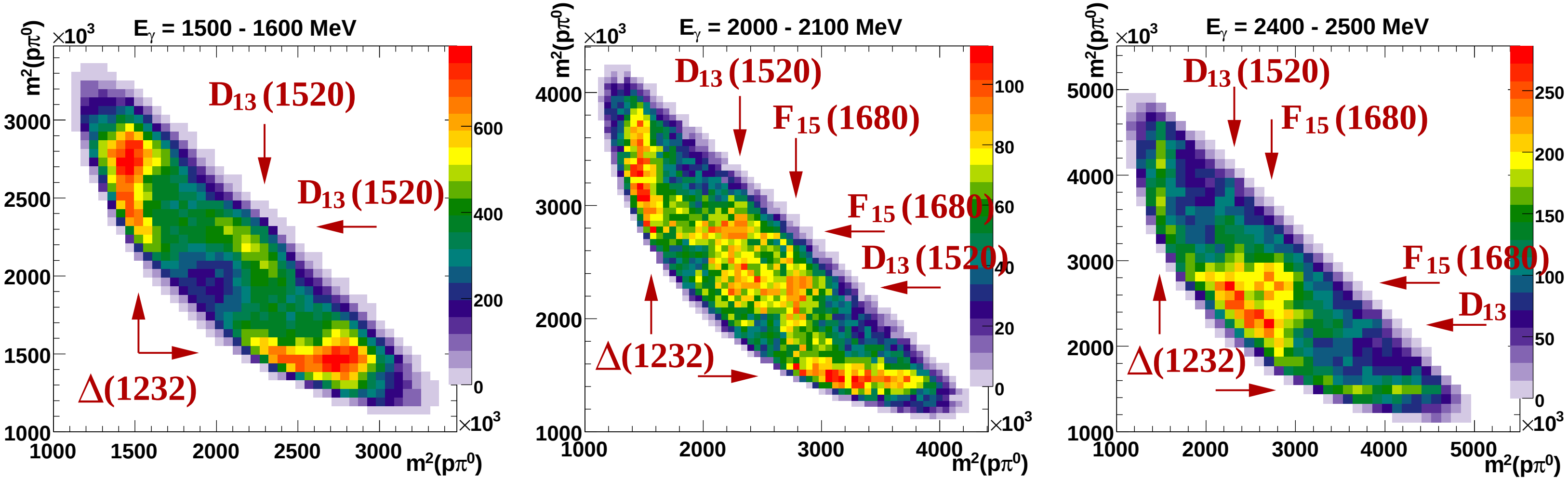
- $\pi\pi$- & $\pi\eta$-pairs:
  access to cascade decays



- clean reaction identification
  in invariant mass spectra



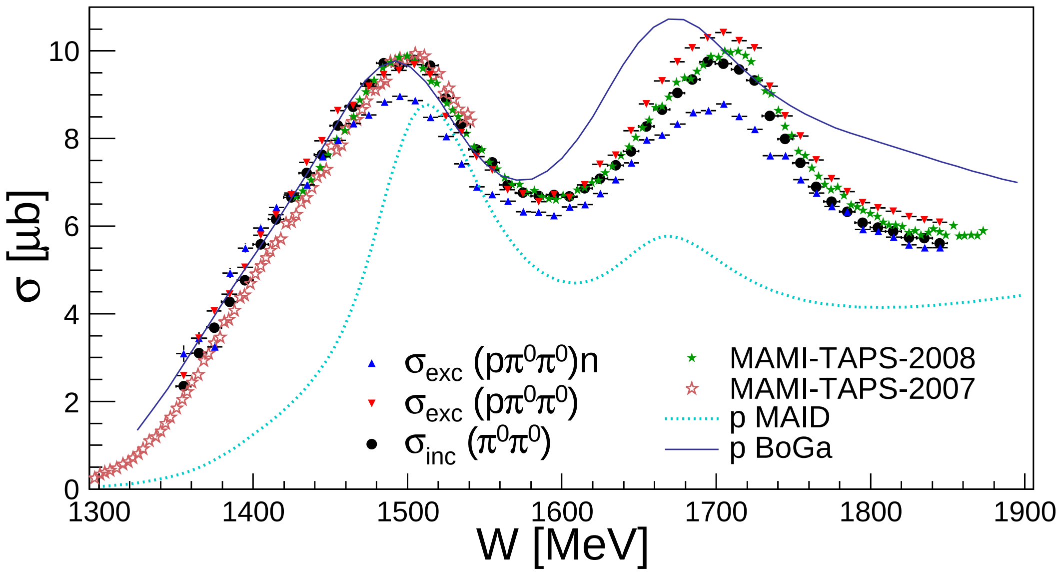
- Dalitz-plot analysis of $\pi^0\pi^0$-pairs

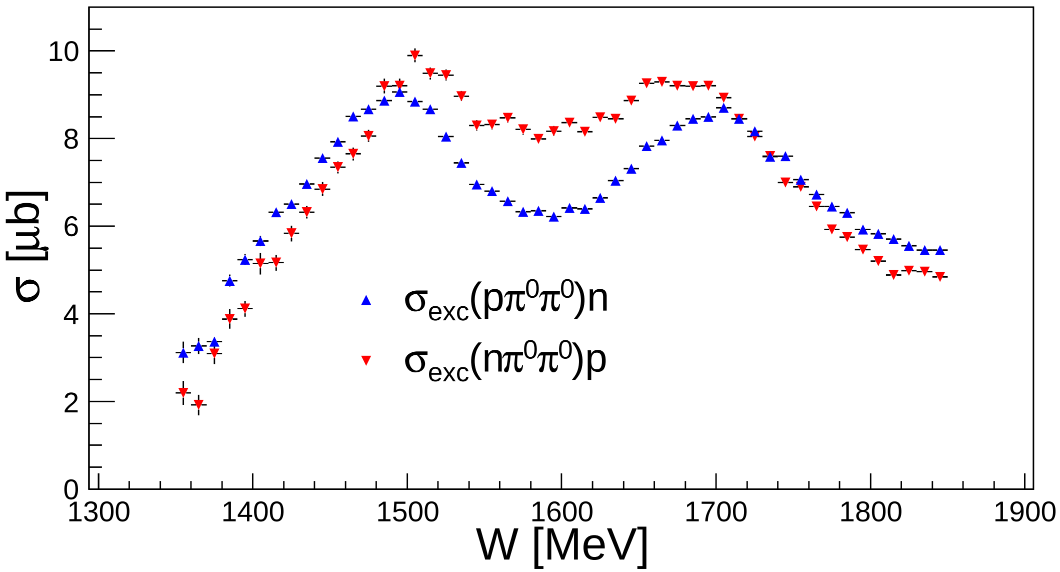


$\gamma N \rightarrow N\pi^o\pi^o$ - total cross sections

(M. Oberle et al., preliminary)

- **free & quasi-free proton**
- **quasi-free proton & neutron**



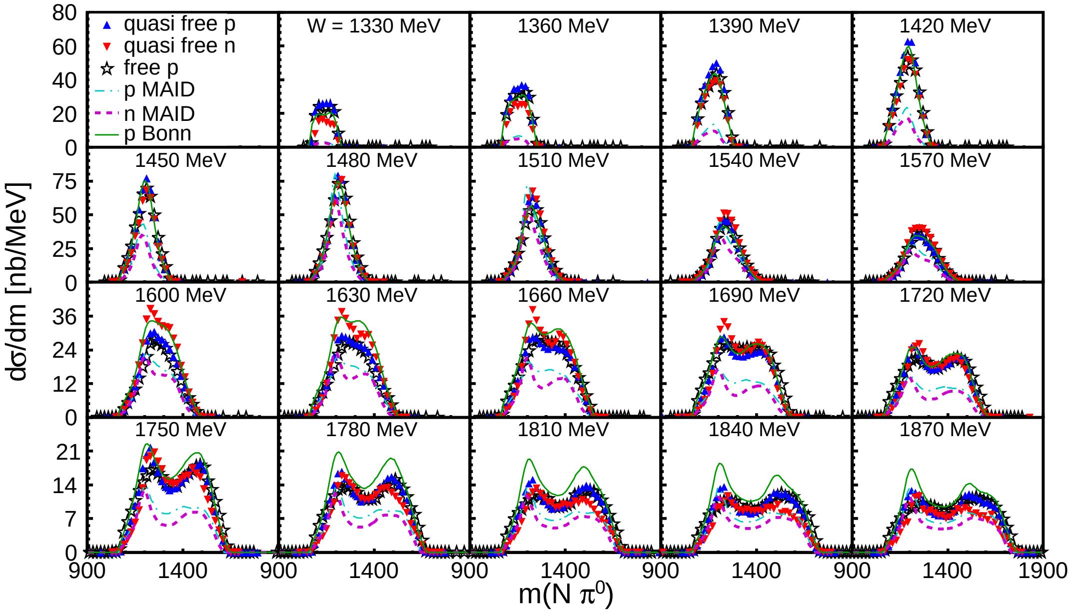


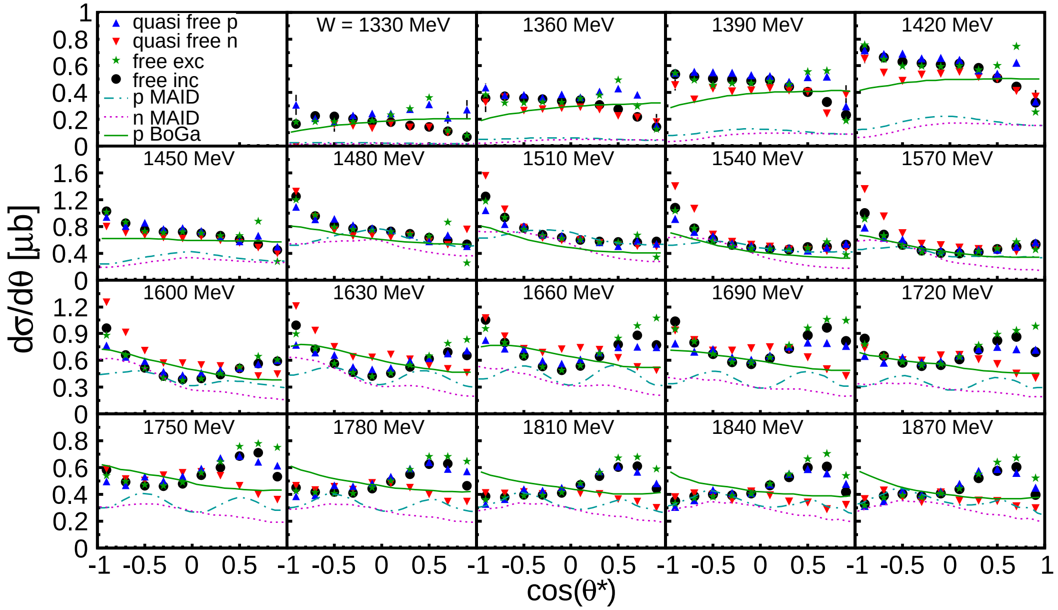
- **moderate FSI effects found for quasi-free proton cross section**
- **proton & neutron excitation functions similar,**
  largest differences around W=1600 MeV between resonance peaks

$\gamma N \to N\pi^o\pi^o$ - invariant mass & angular distributions

(M. Oberle et al., preliminary)

- **pion -nucleon invariant mass**
- **angular distr. - $\Theta^\star$ polar angle of $\pi\pi$-system**



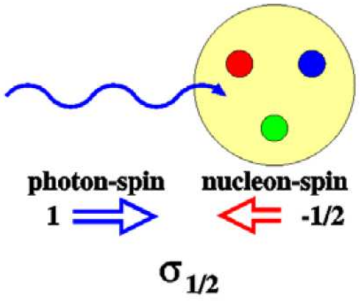


- **invariant mass distributions show contributions from $\Delta^\star, N^\star \to \pi\Delta(1232)$ & $\Delta^\star, N^\star \to \pi D_{13}(1520)$; very similar for p & n**
- **proton & neutron angular distributions different for large W**
  $\to$ different resonance contributions for $\Delta^\star, N^\star \to \pi D_{13}(1520)$?

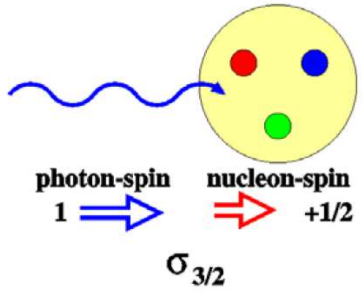
$\gamma N \rightarrow N\pi^o\pi^o$ - helicity dependent cross sections

(M. Dieterle et al., very preliminary)

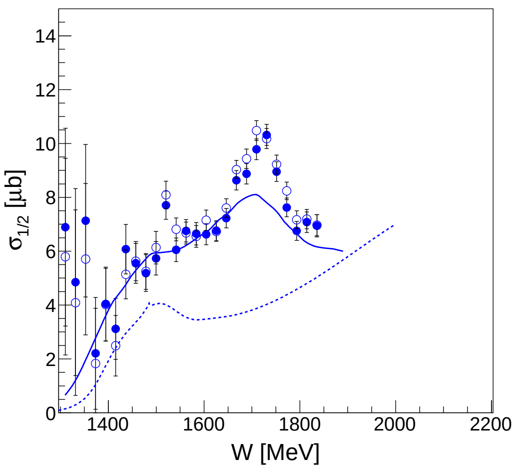
- **helicity component $\sigma_{1/2}$**
- **helicity component $\sigma_{3/2}$**



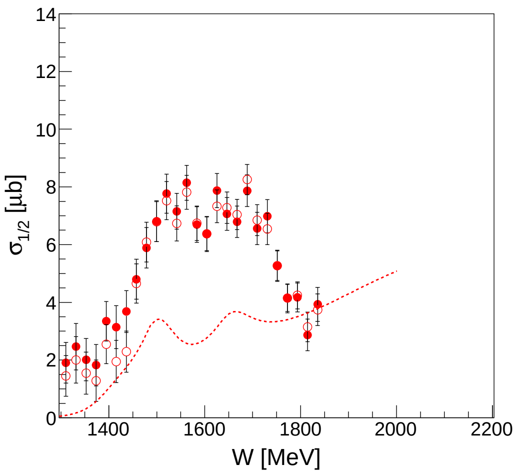
- **double polarization:**
  circularly pol. beam,
  longitudinally pol. target (buthanol)



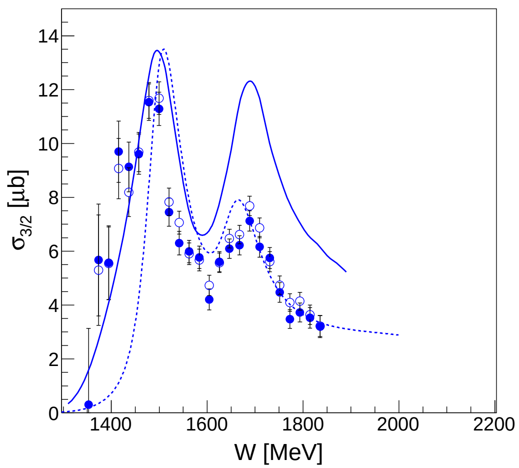
- **proton - $\sigma_{1/2}$**



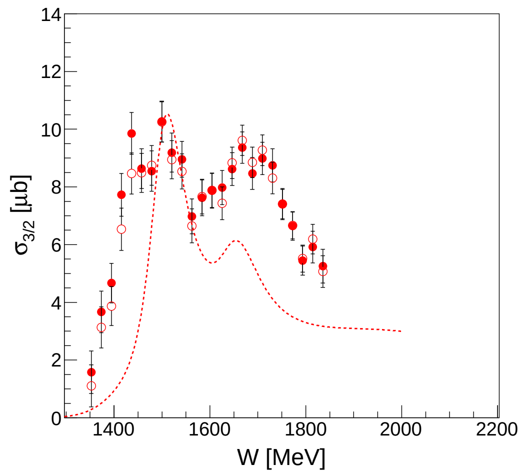
- **neutron - $\sigma_{1/2}$**



- **proton - $\sigma_{3/2}$**



- **neutron - $\sigma_{3/2}$**

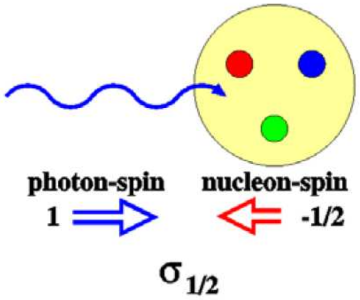


- **2nd resonance peak dominated by $D_{13}(1520)$ (large $A_{3/2}$ for n and p)**
- **3rd peak for neutron: $D_{15}(1675)$ (similar large $A_{1/2}$, $A_{3/2}$ for n, small for p)**
- **3rd peak for proton: $F_{15}(1680)$, should be dominantly $A_{3/2}$???**

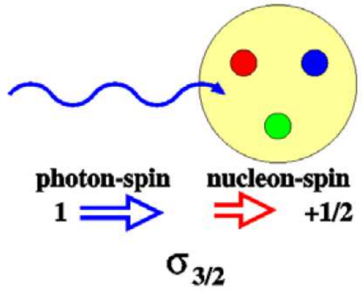
$\gamma N \rightarrow N\pi^o\pi^o$ - helicity dependent cross sections

(M. Dieterle et al., very preliminary)

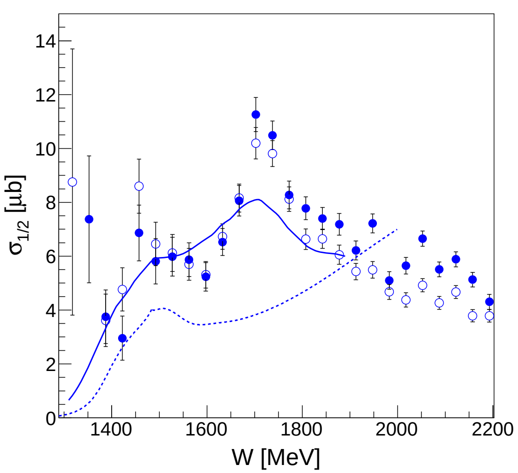
- helicity component $\sigma_{1/2}$
- helicity component $\sigma_{3/2}$



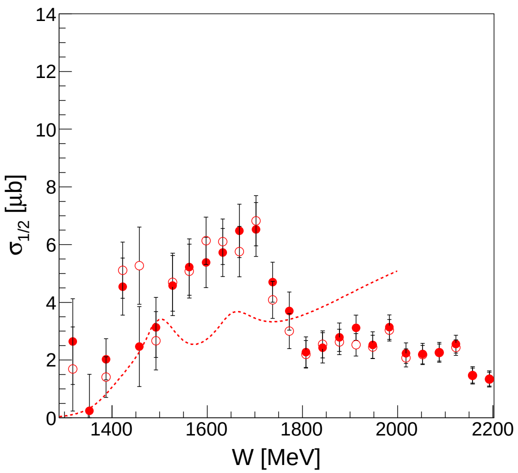
- double polarization:
  circularly pol. beam,
  longitudinally pol. target (buthanol)



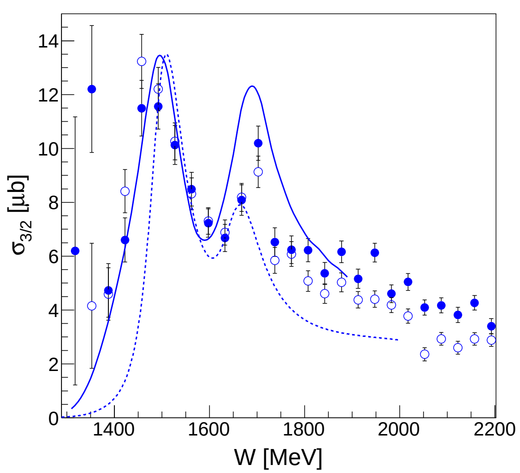
- proton - $\sigma_{1/2}$



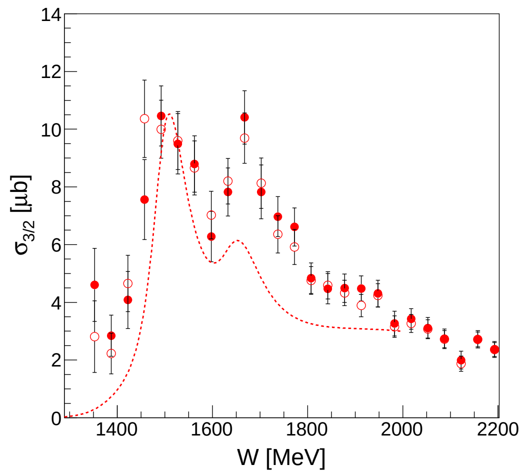
- neutron - $\sigma_{1/2}$



- proton - $\sigma_{3/2}$



- neutron - $\sigma_{3/2}$



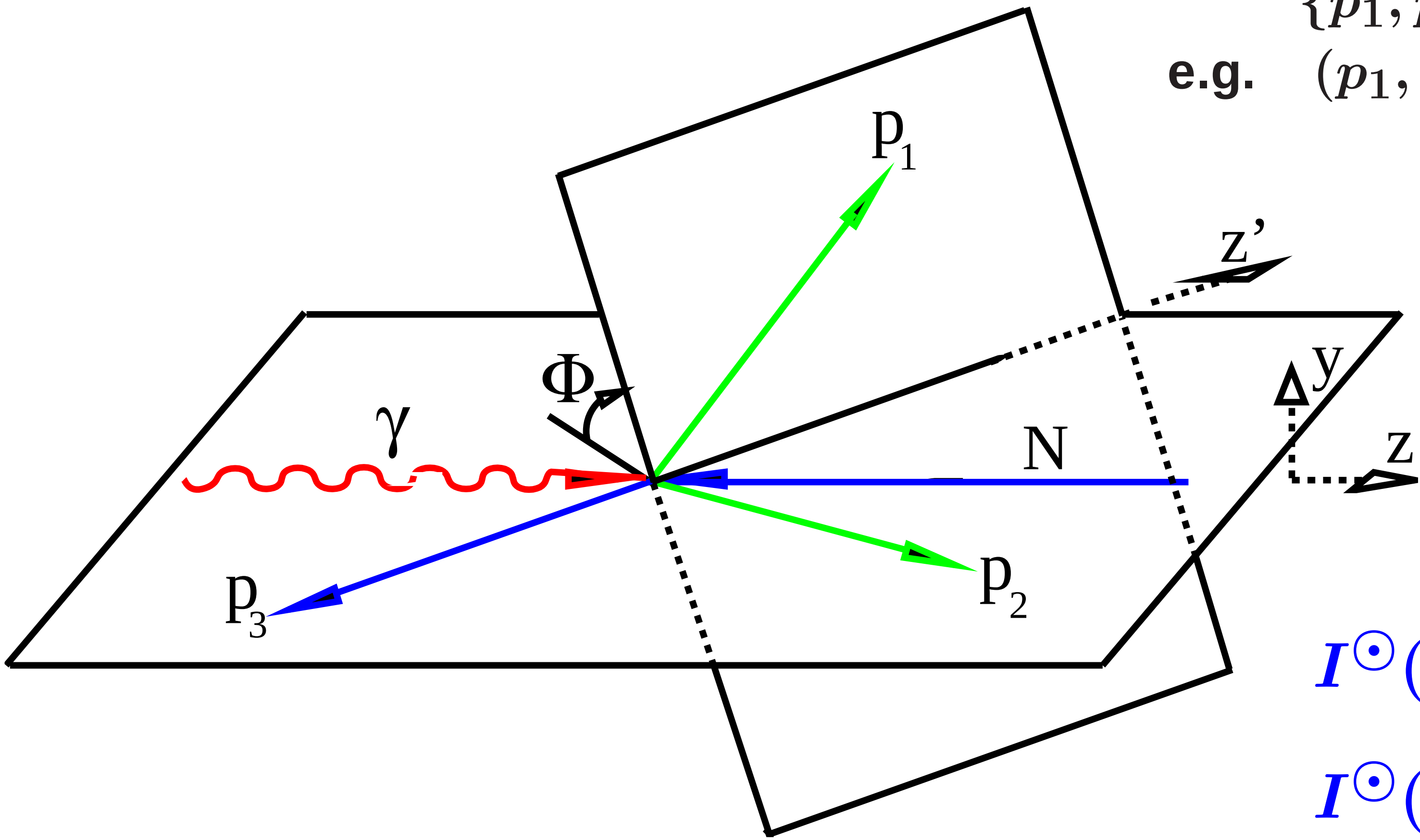
- 2nd resonance peak dominated by $D_{13}(1520)$ (large $A_{3/2}$ for n and p)
- 3rd peak for neutron: $D_{15}(1675)$ (similar large $A_{1/2}$, $A_{3/2}$ for n, small for p)
- 3rd peak for proton: $F_{15}(1680)$, should be dominantly $A_{3/2}$???

example for polarization observables for pion-pairs

beam-helicity asymmetries - circularly polarized beam, unpolarized target

$$\{p_1, p_2, p_3\} = \{\pi_1, \pi_2, N'\}$$

e.g. $(p_1, p_2, p_3) = (\pi^+, \pi^o, n)$



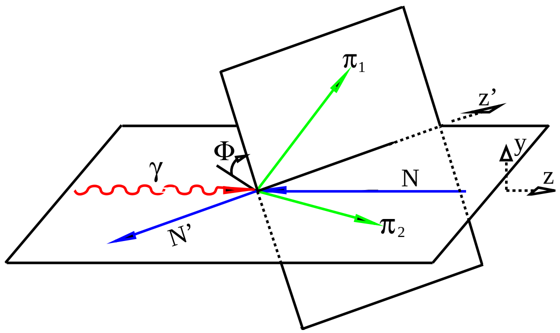
$$I^{\odot}(\Phi) \equiv \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

$$I^{\odot}(\Phi) = -I^{\odot}(2\pi - \Phi)$$

$$I^{\odot}(\Phi) = \Sigma_{n=1}^{\infty} A_n \sin(n\Phi)$$

beam-helicity asym. for $\gamma N \rightarrow N\pi^o\pi^o$ & $\gamma N \rightarrow N\pi^o\pi^\pm$

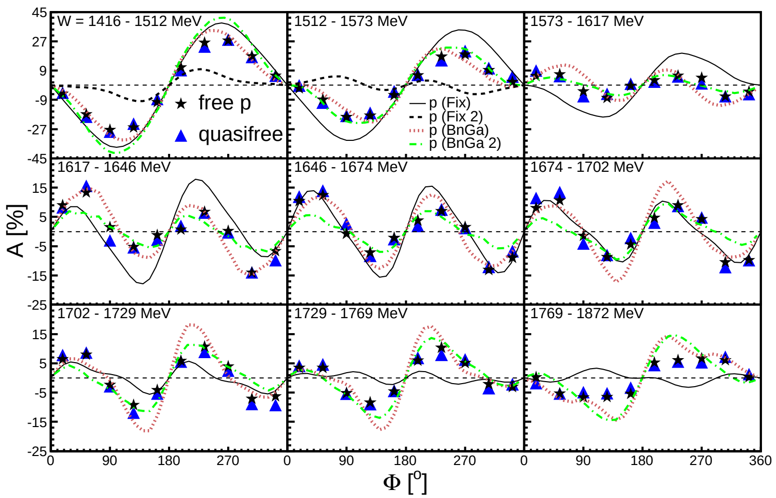
M. Oberle et al., PLB 721(2013) 237, M. Oberle et al., EPJA 50 (2014) 54



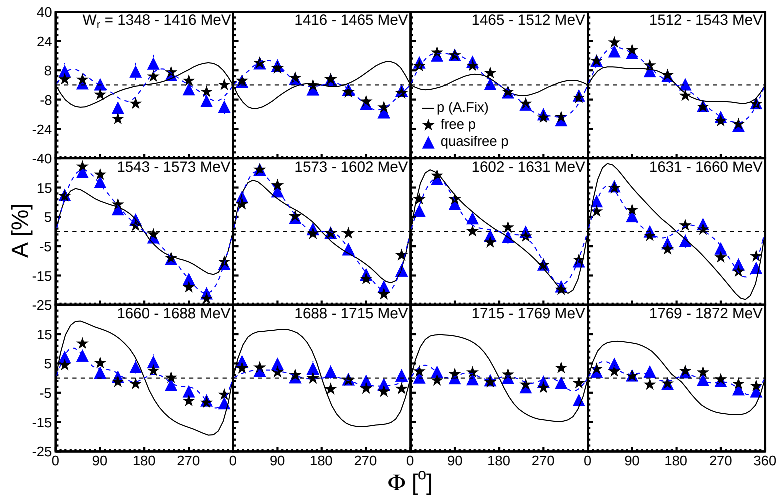
pions ordered by invariant mass:

$$m(\pi_1, N) \geq m(\pi_2, N)$$

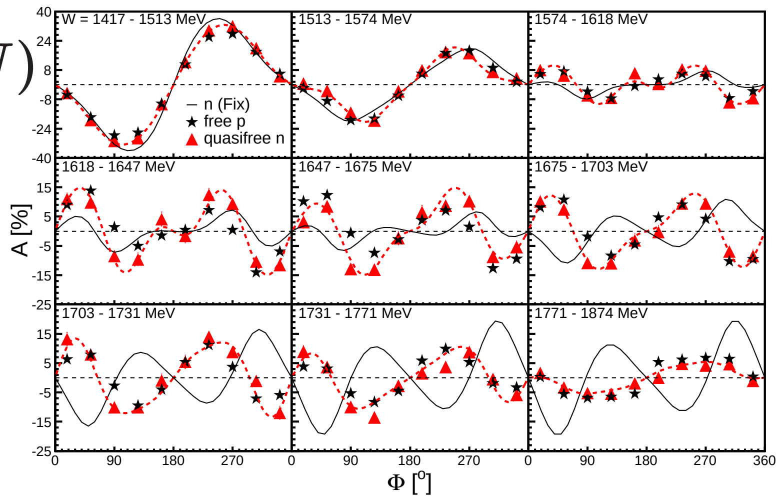
- $\gamma p \rightarrow p\pi^0\pi^0$ (blue: qf. p, black: free p)



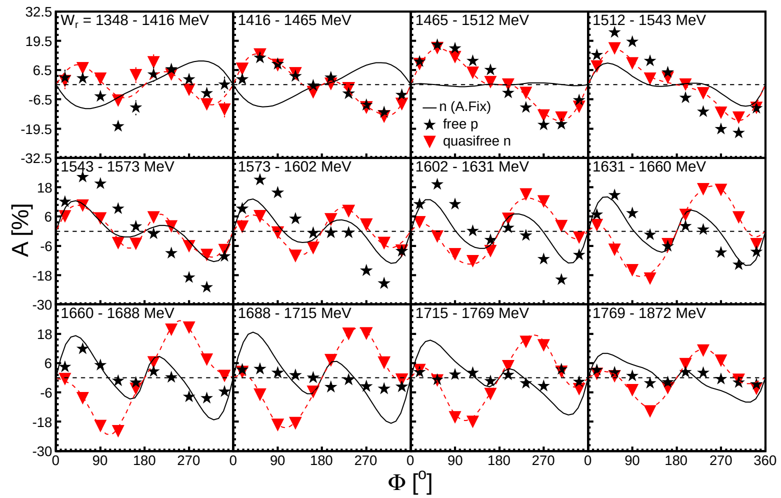
- $\gamma p \rightarrow n\pi^0\pi^+$ (blue: qf. p, black: free p)



- $\gamma n \rightarrow n\pi^0\pi^0$ (red: qf. n, black: free p)



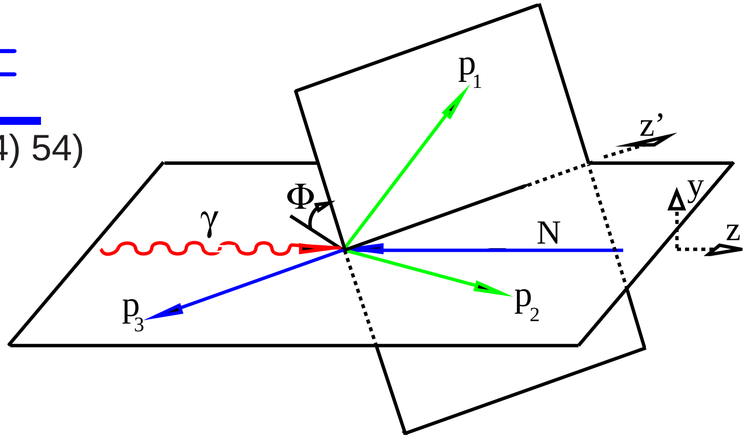
- $\gamma n \rightarrow p\pi^0\pi^-$ (red: qf. n, black: free p)



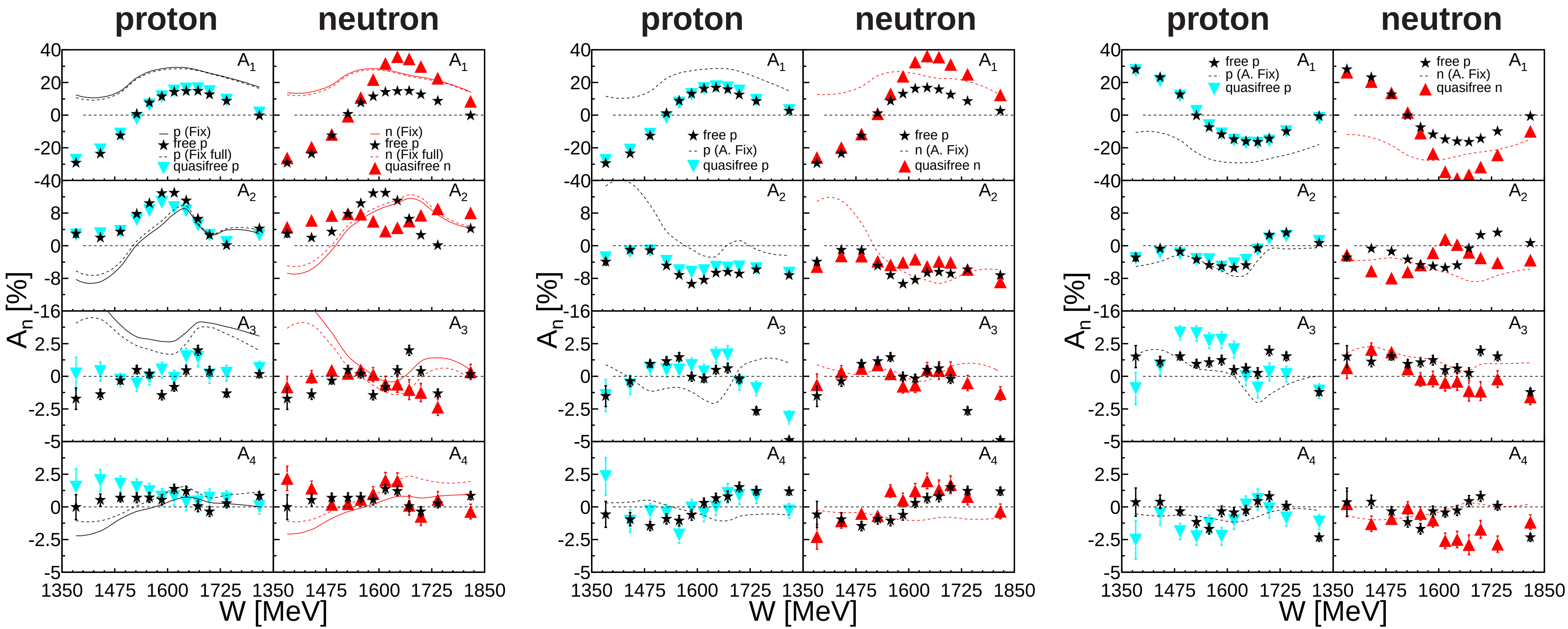
'charge ordered' asym.: $\gamma N \rightarrow N\pi^o\pi^{\pm}$

(M. Oberle et al., EPJA 50 (2014) 54)

- coefficients of sine-series compared to Fix model
- large discrepancies for second resonance region
- excellent agreement between free and quasi-free proton data, no FSI effects



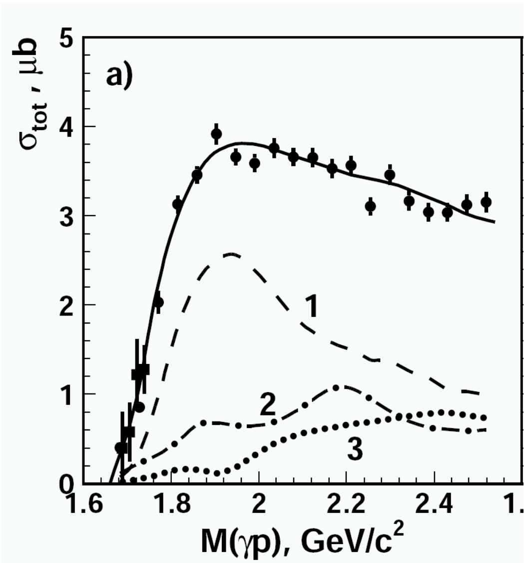
$(p_1, p_2, p_3) = (\pi^{\pm}, \pi^o, N)$ $(p_1, p_2, p_3) = (\pi^o, N, \pi^{\pm})$ $(p_1, p_2, p_3) = (\pi^{\pm}, N, \pi^o)$

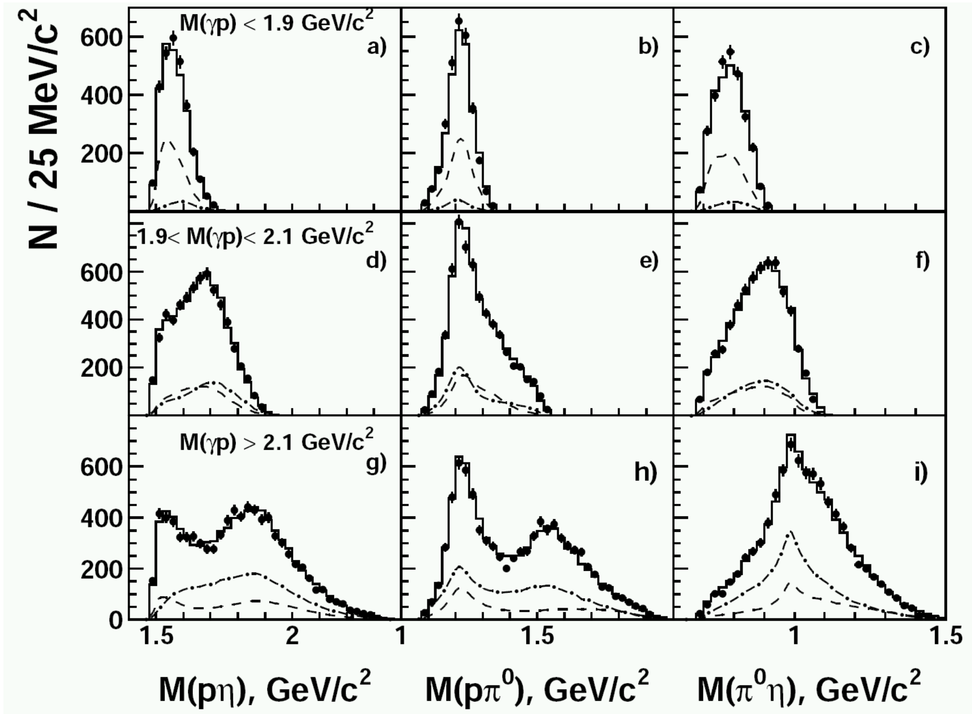


resonance contributions to photoproduction of $\pi\eta$-pairs

I. Horn et al., PRL 101 (2008) 202002; EPJA 38 (2008) 173, V. Kashevarov et al., EPJA 42 (2009) 141; PLB 693 (2010) 551

- **total cross section**
- **Invariant mass distributions**



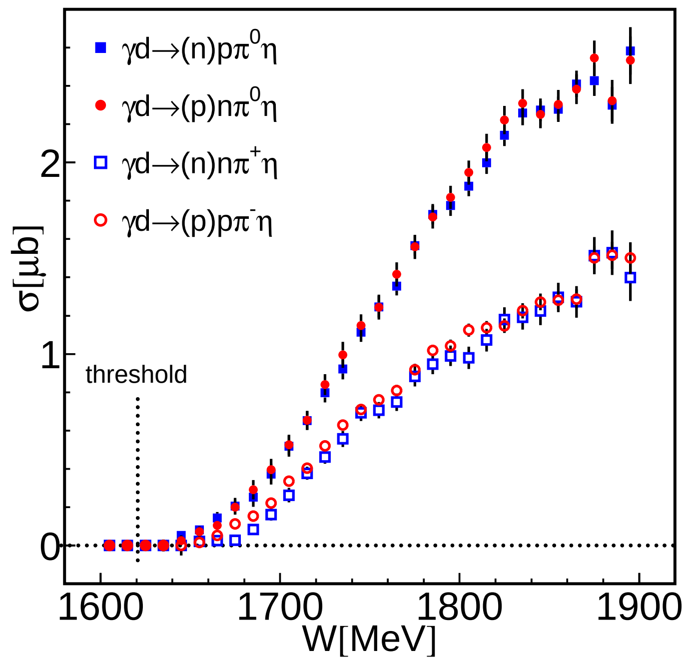


- **dominant final states:** $--\ \Delta(1232)\eta$, $-.-\ N(1535)\pi$, ... $pa_o(980)$
- **dominant process close to threshold:** $\gamma p \rightarrow$ **D**$_{33}$**(1700)**$\rightarrow$ η**P**$_{33}$**(1232)** $\rightarrow$ $\eta\pi^o$**p**

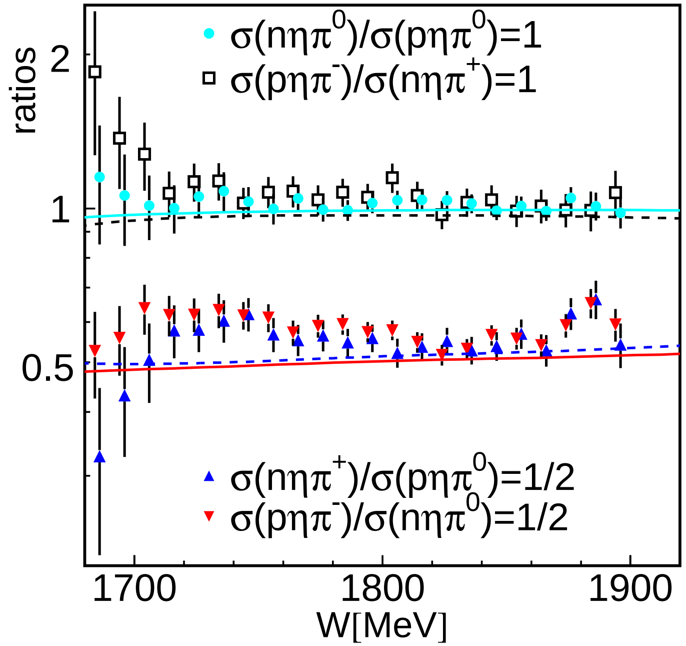
isospin decomposition of $\pi\eta$-photoproduction

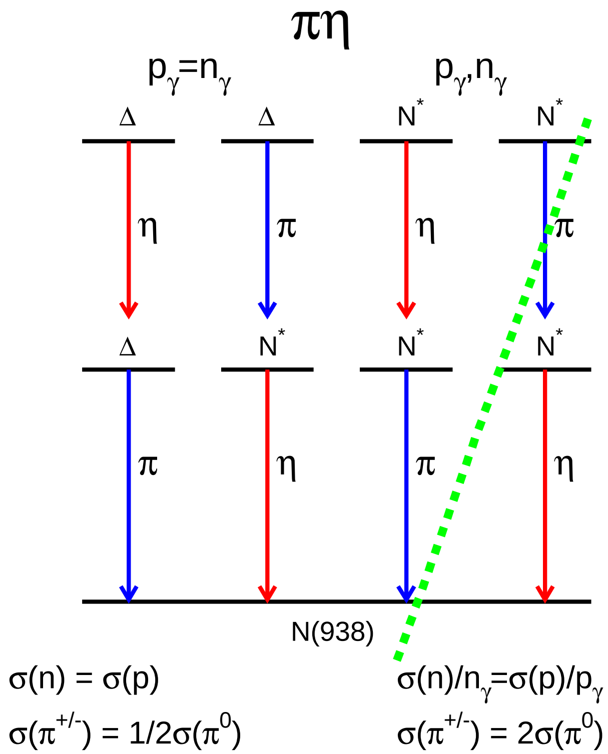
(A. Kaeser et al., preliminary)

- **total cross sections**



- **cross section ratios**





- **cross section ratios agree with $\gamma N \rightarrow \Delta^\star \rightarrow \eta\Delta \rightarrow \eta\pi N$ reaction chain**
- **analysis of invariant mass distributions and polarization observables for all isospin channels under way**

Summary

- measurement of final states with coincident neutrons, in particular 'all neutral' final states like $n\pi^0$, $n\eta$, $n\eta'$, $n\pi^o\pi^o$... mandatory for analysis of $N^\star$ properties
- effects from Fermi motion under control via kinematic reconstruction
- effects from FSI:
  - experimental access via comparison of free and quasi-free proton results
  - develpment of models for FSI in progress
  - FSI effects strongly channel dependent, e.g. small/negligible for η, η', moderate for $\pi^o\pi^o$, substantial for $\pi^o, \eta\pi$
  - for channels so far investigated FSI effects seem to be much less important for polarization observables than for cross sections
- experiments at MAMI taking data or are under analysis, expriments at ELSA will start after detector upgrade