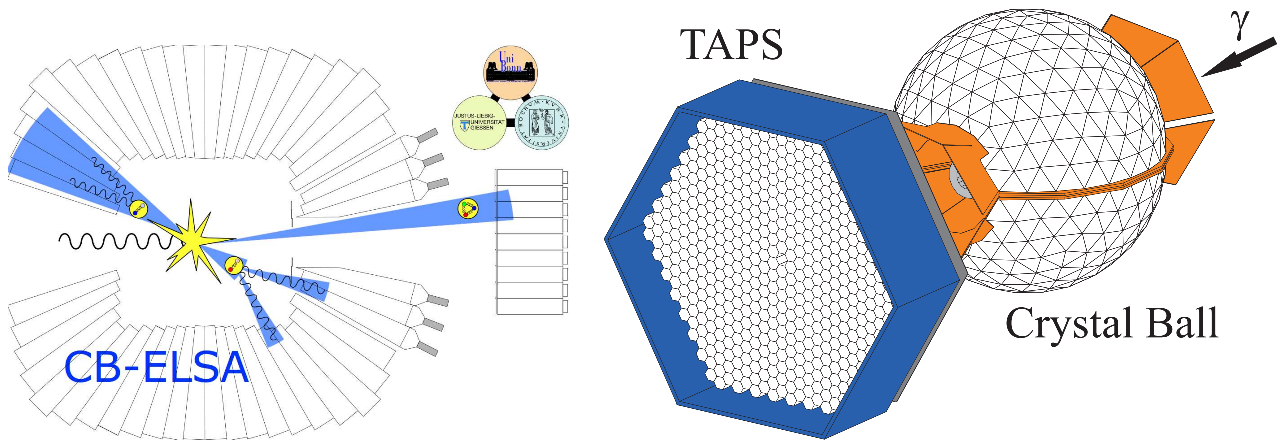
Photoproduction of mesons from quasifree nucleons

B. Krusche, U. Basel

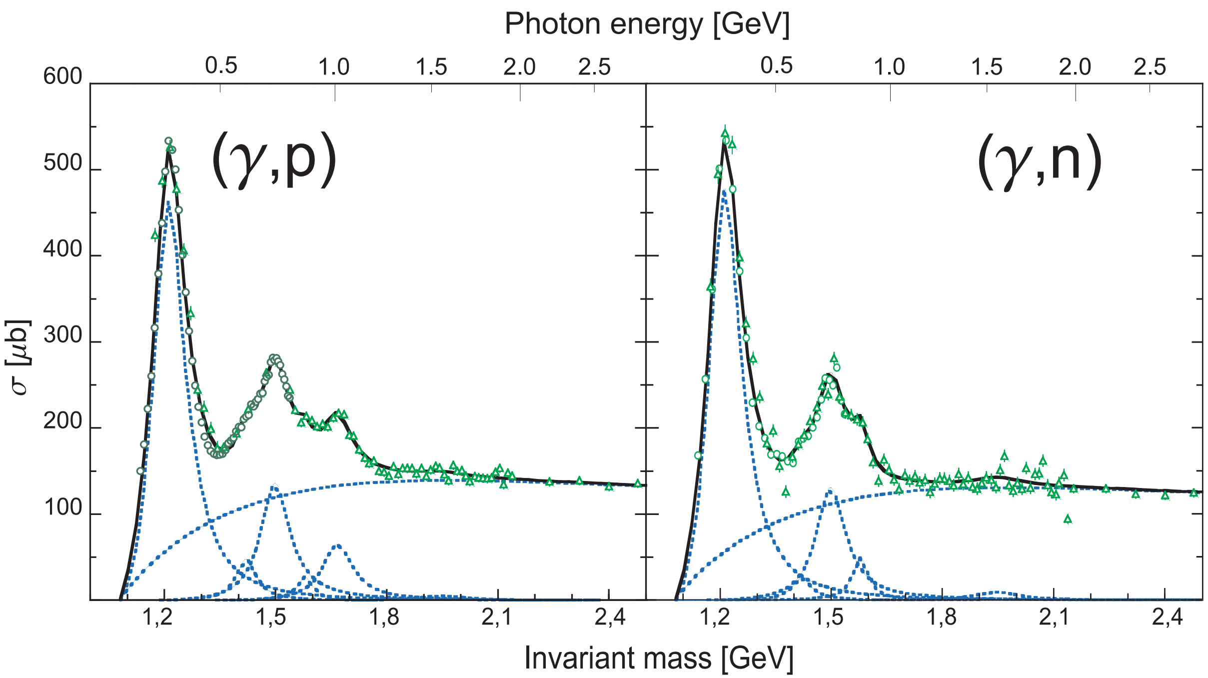
- **Introduction**
- **Experimental setups**
- **Results**
- **Conclusions**



UNI BASEL

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

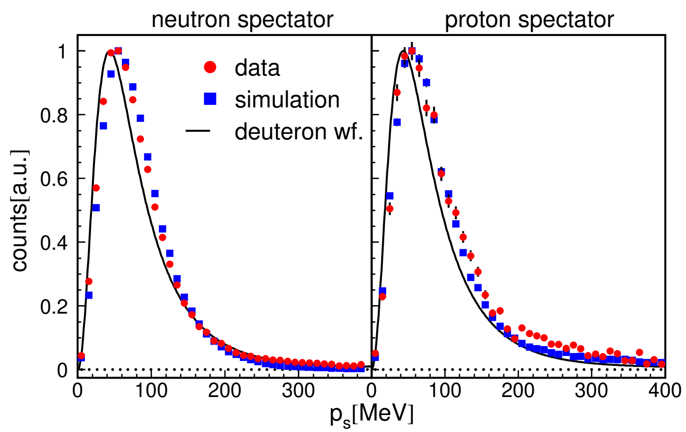
(2) reaction kinematics modified by Fermi motion - smears out all structures

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

Solutions:

(1,2) Typical neutron detection efficiencies for elm. calorimeters in the range 10% - 30%, kinematics completely defined without measurement of recoil neutron energy:

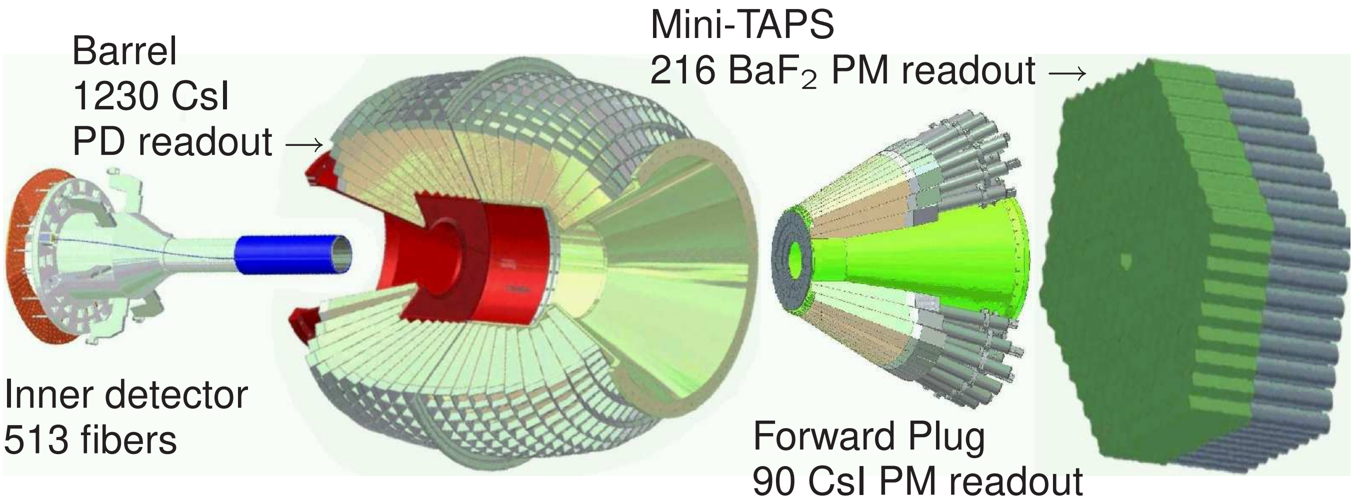
- initial state: incident photon and deuteron at rest
  known/measured: $E_\gamma, m_d, \vec{p}_d = 0$
- final state: meson, participant, and spectator nucleon
  known/measured: $m_s, m_p, \Theta_p, \Phi_p, m_m, \vec{p}_m$
  not measured: $T_p, \vec{p}_s$ (four variables)
- four constraints from energy/momentum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



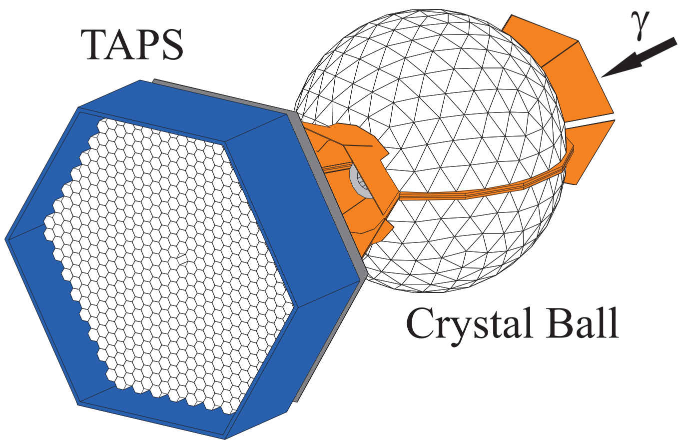
(3) comparison of quasifree production off protons and production off free protons to study FSI effects

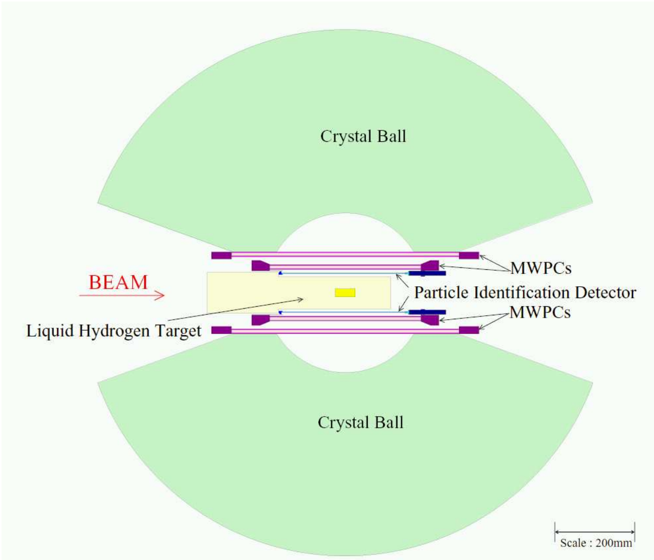
Calorimeters: Crystal Barrel & Crystal Ball with TAPS

- **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



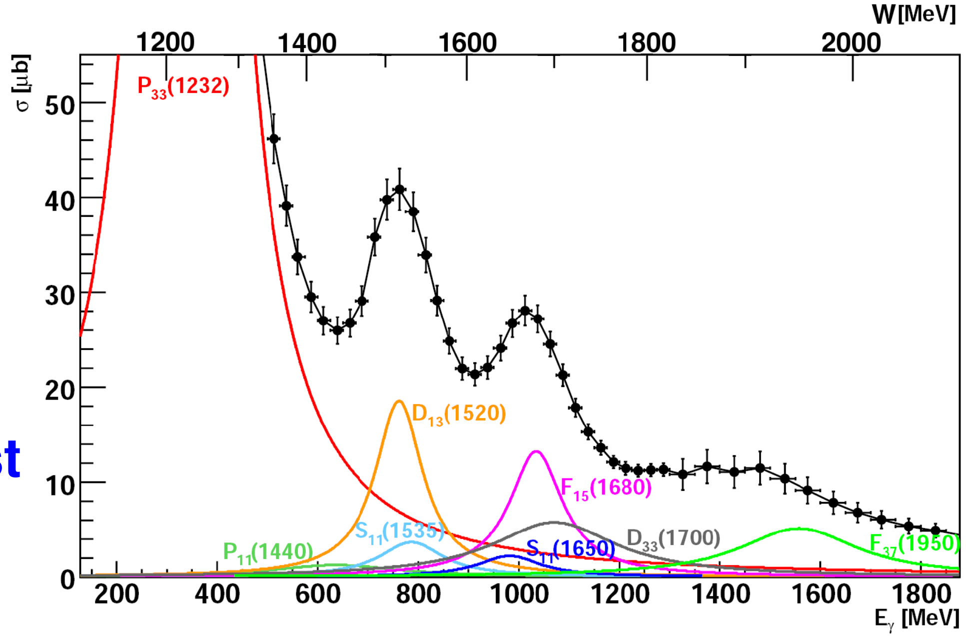
- **Mainz MAMI accelerator:**
  Crystal Ball (NaJ),
  TAPS (BaF_2) forward wall,
  inner detectors
  $E_\gamma \leq$ **1.5 GeV,**
  lin. pol.: available,
  circ. pol.: available





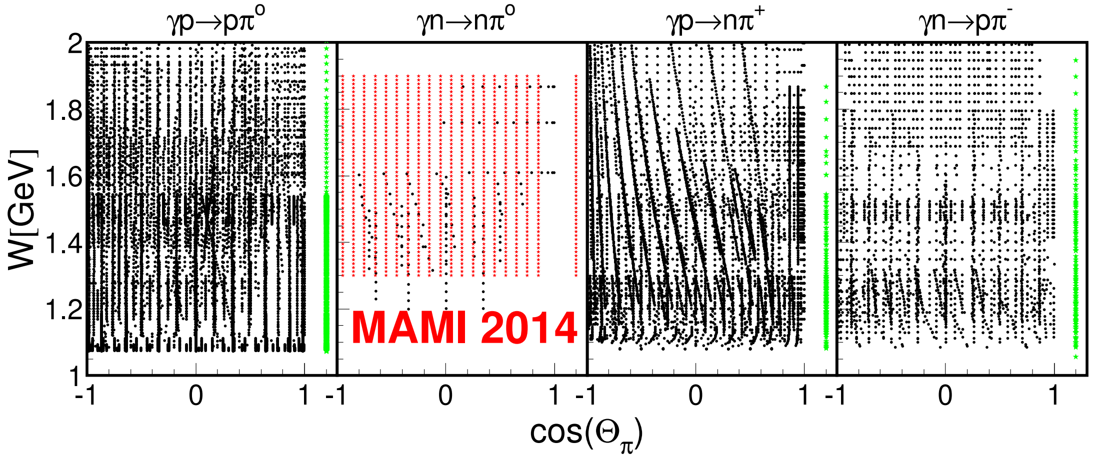
Results - Example I: Photoproduction of π^0-mesons

- 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

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

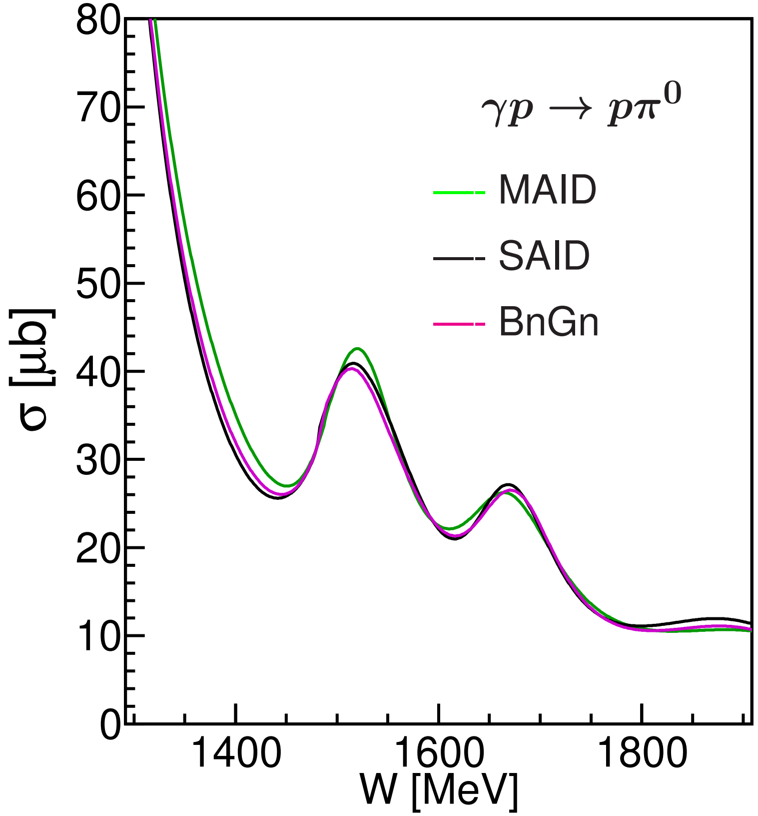
$$A(\gamma p \rightarrow \pi^0 p) = +\sqrt{\tfrac{2}{3}}A^{V3} + \sqrt{\tfrac{1}{3}}(A^{IV} - A^{IS})$$

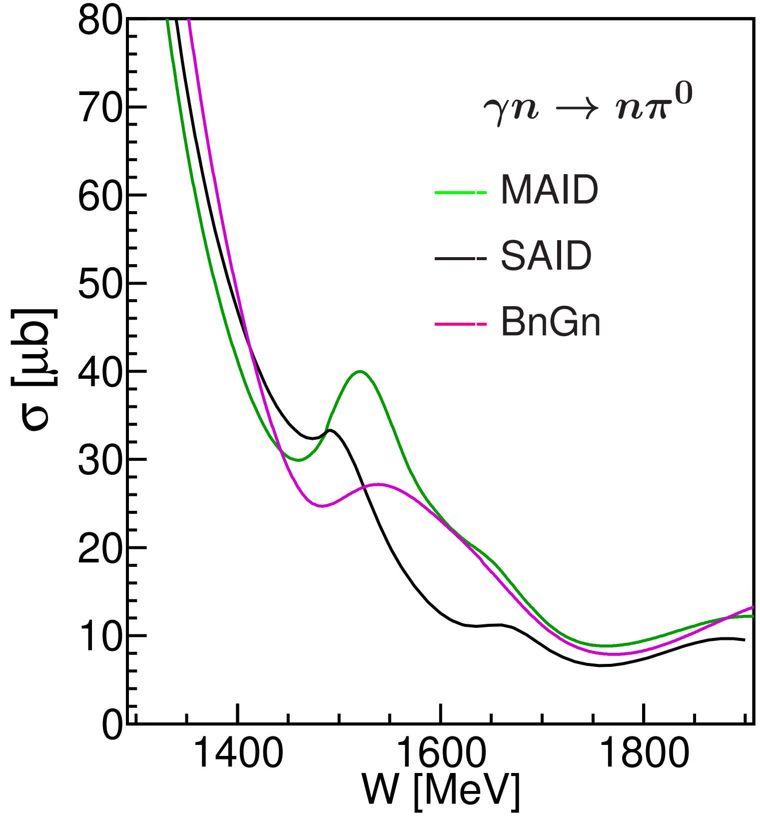
$$A(\gamma n \rightarrow \pi^- p) = +\sqrt{\tfrac{1}{3}}A^{V3} - \sqrt{\tfrac{2}{3}}(A^{IV} + A^{IS})$$

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

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

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



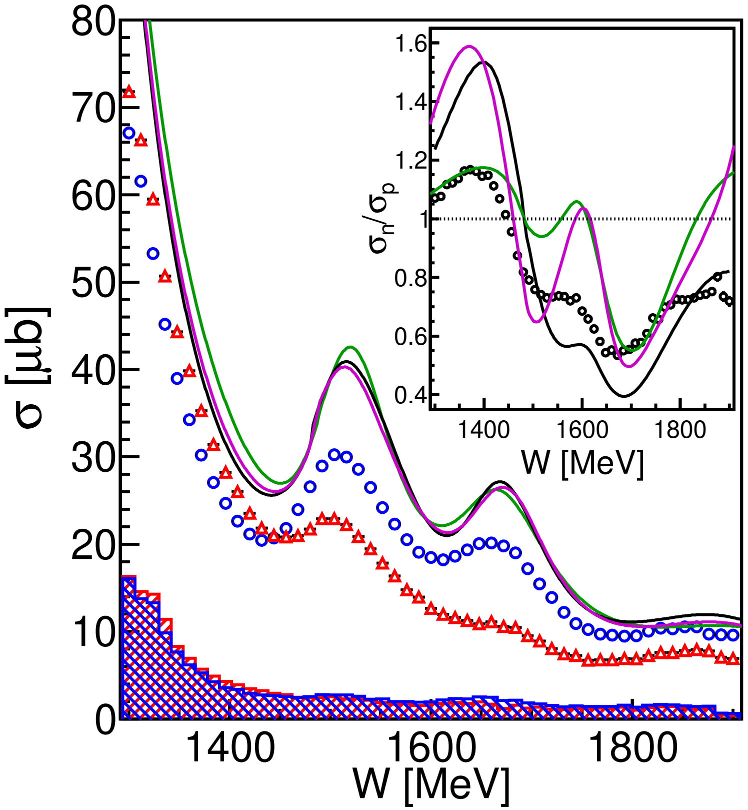


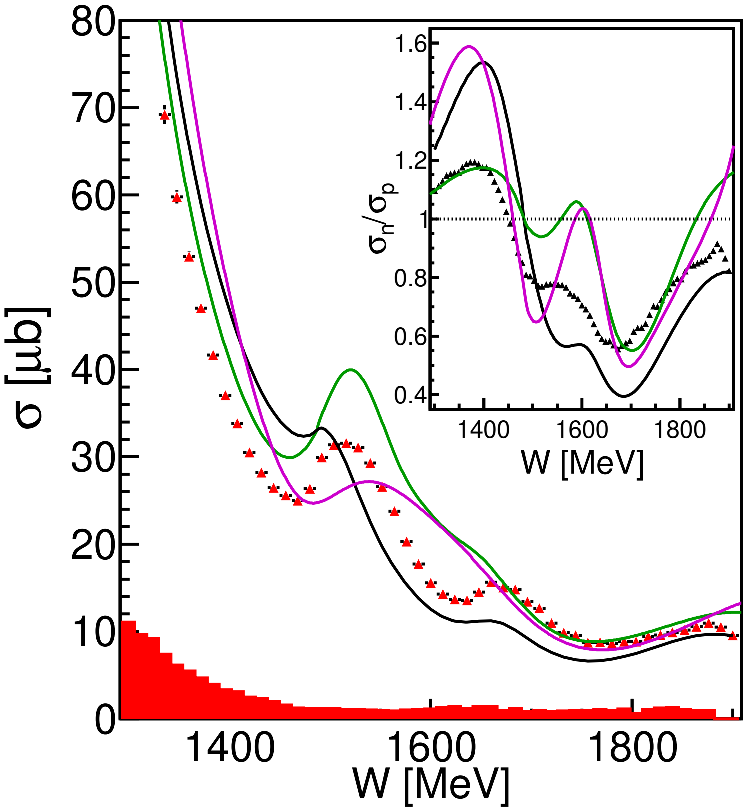
- **results agree for proton target (because fitted to proton data)**
- **predictions for neutron target disagree**
- **data from $\gamma n \to p\pi^-$ do not sufficiently constrain the fits for neutron target (different non-resonant backgrounds)**

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

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

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



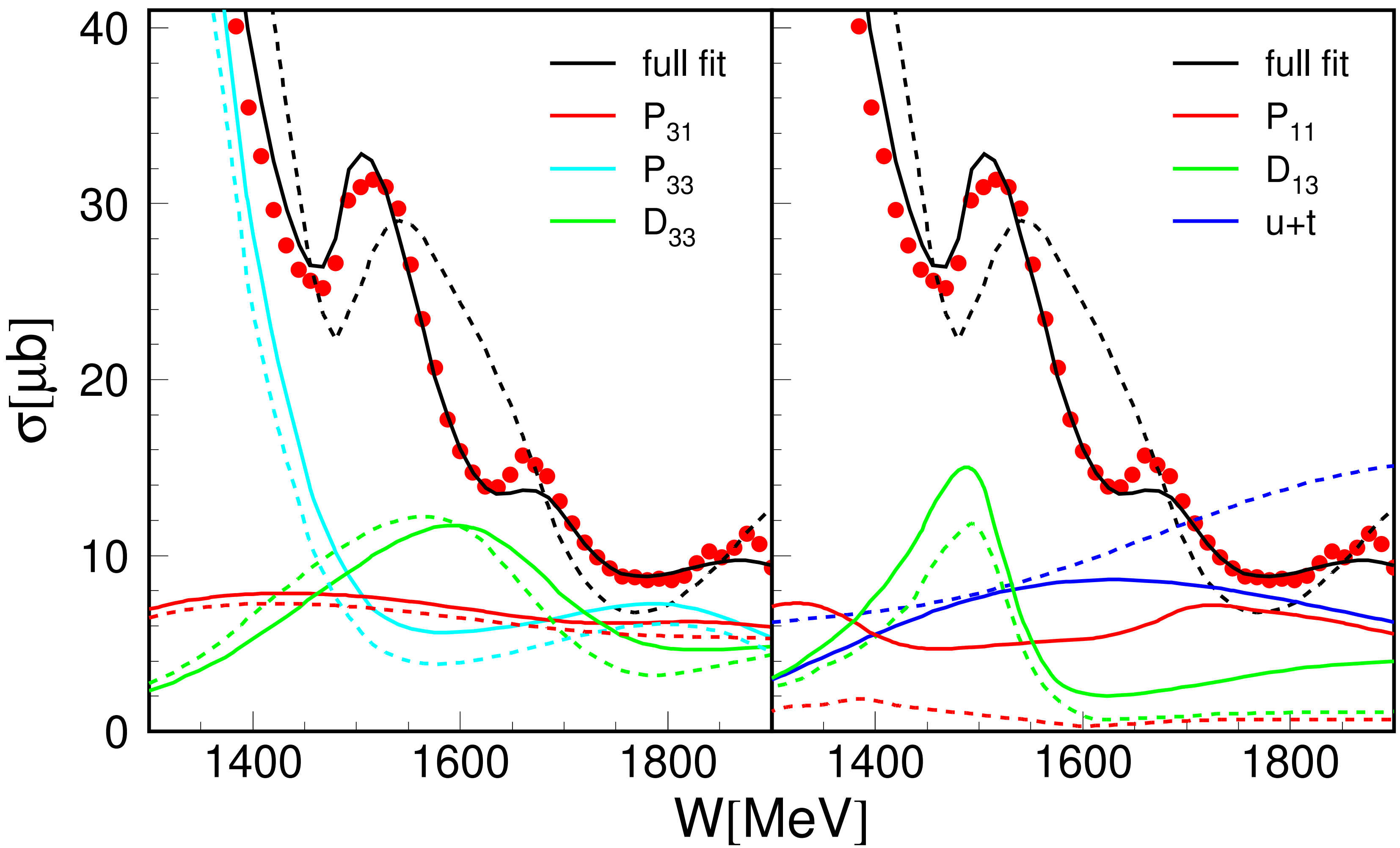


- **significant effects from final state interactions in proton data**
- **neutron data corrected under assumption of identical FSI for both reactions**
- **poor agreement between neutron data and PWA predictions**

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

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

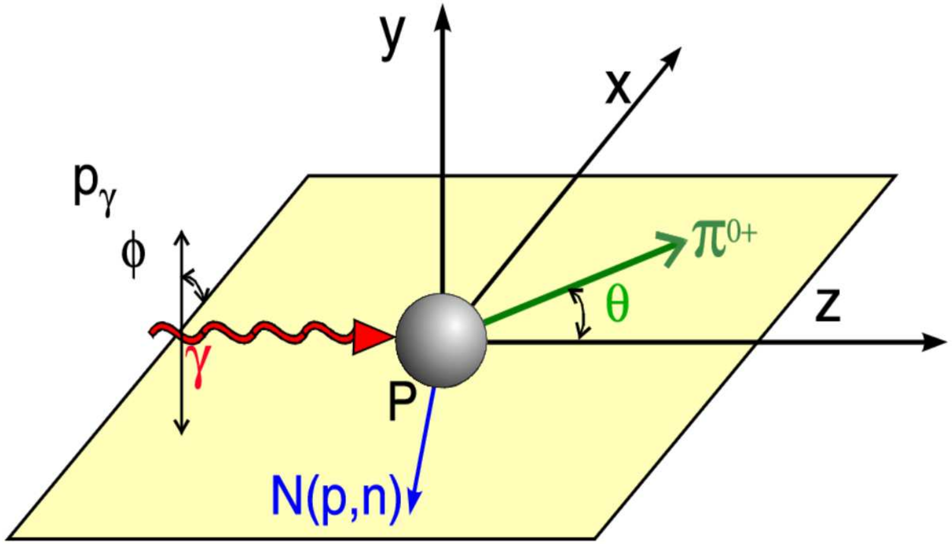
- **Refit of BnGa PWIA:** - - - BnGa original — BnGa refit



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

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**



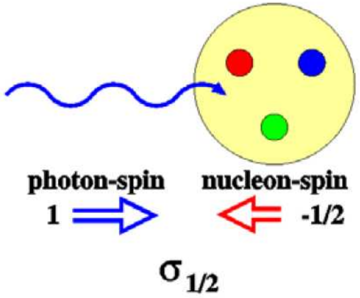
photon polarization	target polarization -	x	y	z
unpolarized	σ	-	T	-
linearly	Σ	H	-P	-G
circularly	-	F	-	-E

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

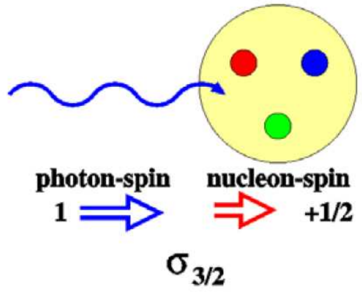
$\gamma N \rightarrow N\pi^o$ - helicity dependent cross sections

(M. Dieterle et al., PLB 779 (2017) 523)

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



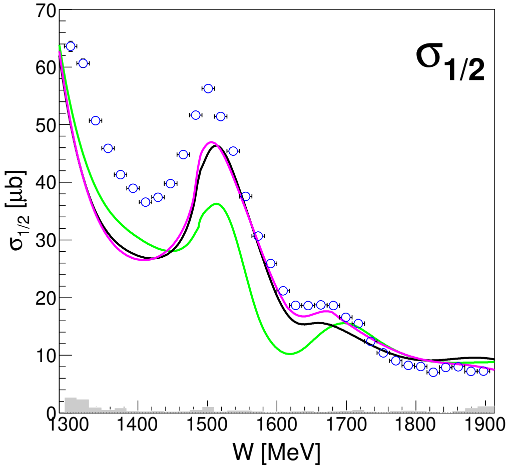
- **helicity component $\sigma_{3/2}$**



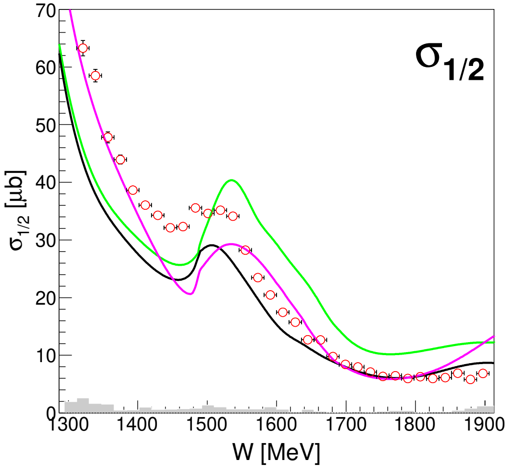
- **circularly pol. beam,**
  longitudinally pol. target (buthanol)

$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

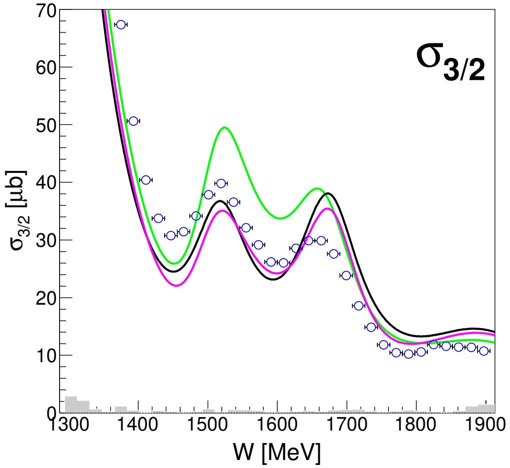
- **proton - $\sigma_{1/2}$**



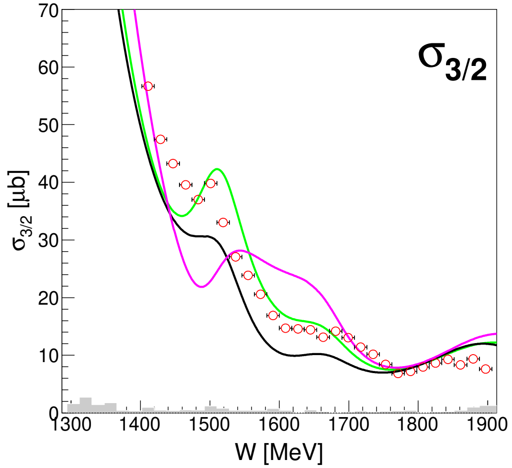
- **neutron - $\sigma_{1/2}$**



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



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



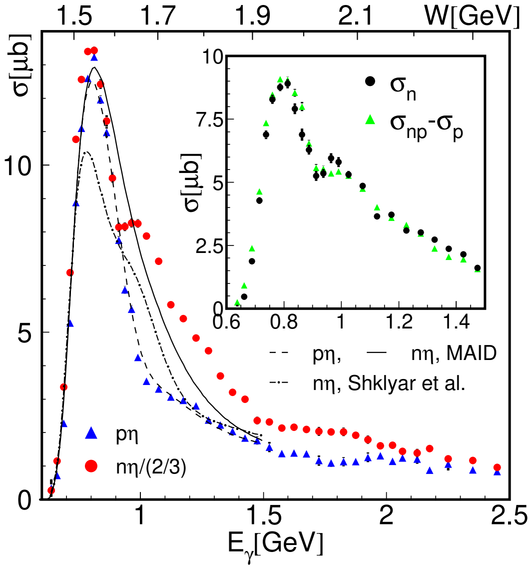
- **Total cross sections compared to PWA results:** — SAID — MAID — BnGa
- **New PWA will be much better constrained for neutron target!**

quasifree $\gamma n \to n\eta$: unexpected structure

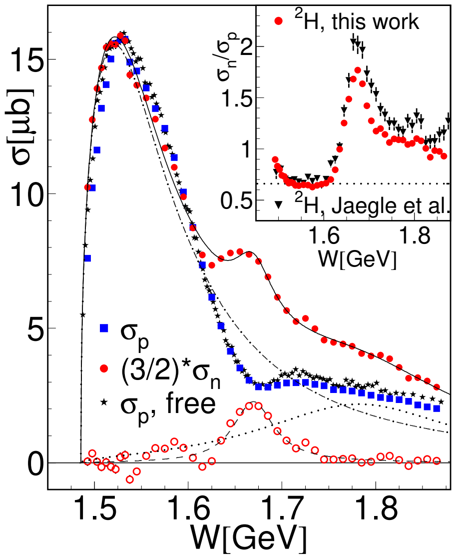
(I. Jaegle et al., D. Werthmüller et al., L. Witthauer et al.)

- **ELSA:**
- **MAMI:**
- **neutron/proton ratio**

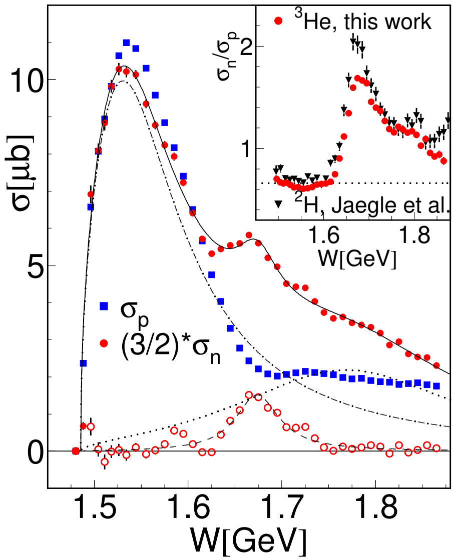
$\gamma d \to (n)(p)\eta$

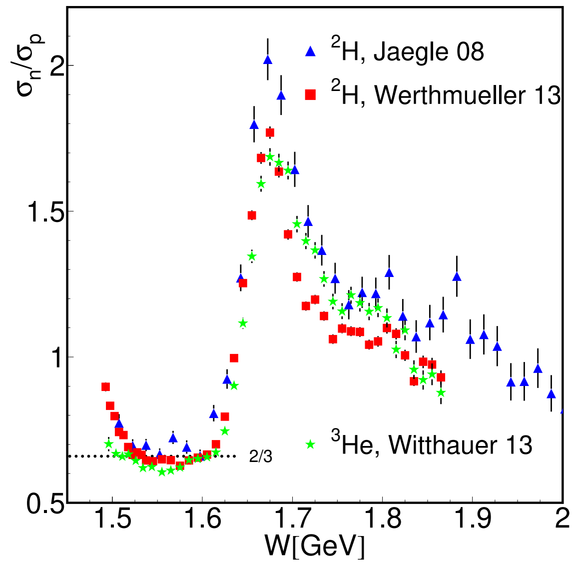


$\gamma d \to (n)(p)\eta$



γ^3He $\to X(n)(p)\eta$



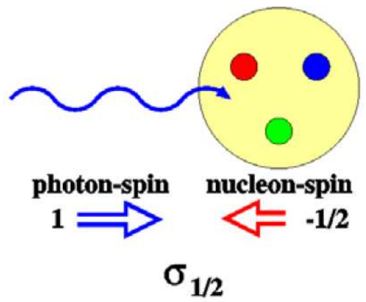


- **pronounced, narrow structure in neutron excitation function close to W=1.68 GeV**
- **width of structure $\approx$ 30 MeV**
- **observed for deuterium (several experiments) and 3-helium targets**
- **many different potential explanations:**
  - **interference effects in S_{11}-wave**
  - **more complicated coupled channel effects**
  - **intrinsic narrow resonances (P_{11}-like pentaquark)**

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

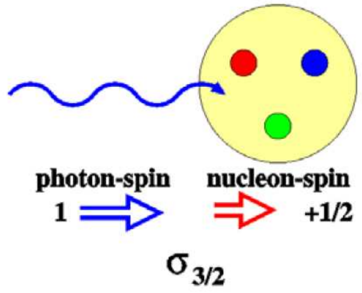
(L. Witthauer et al., PRL 117 (2016) 132502)

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

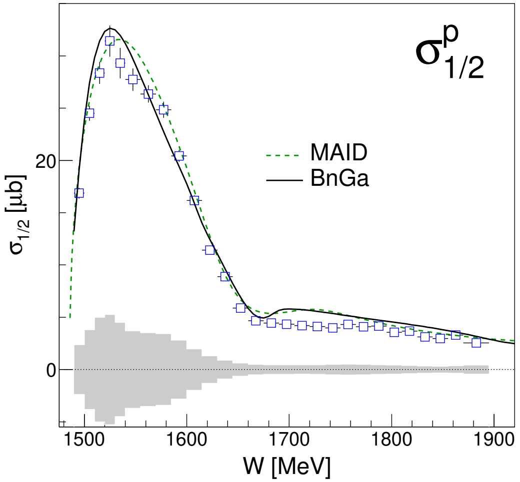


- circularly pol. beam,
  longitudinally pol. target (buthanol)

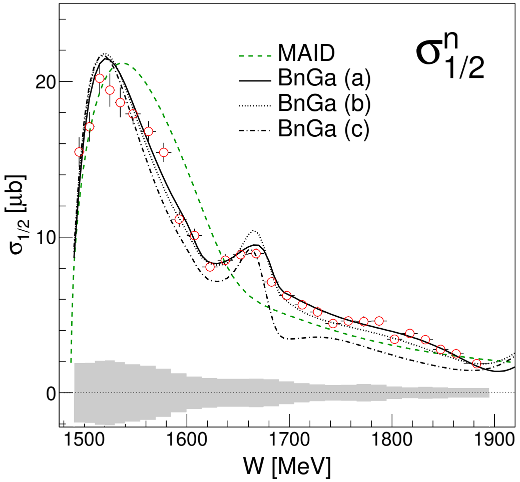
$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$



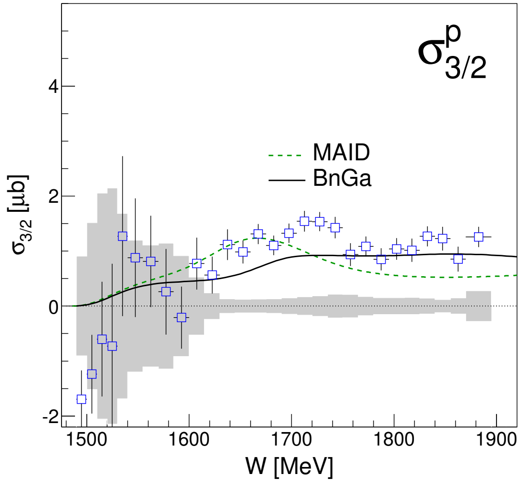
- proton - $\sigma_{1/2}$



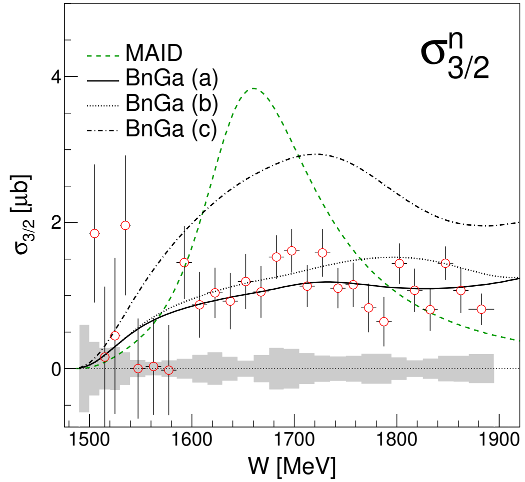
- neutron - $\sigma_{1/2}$



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



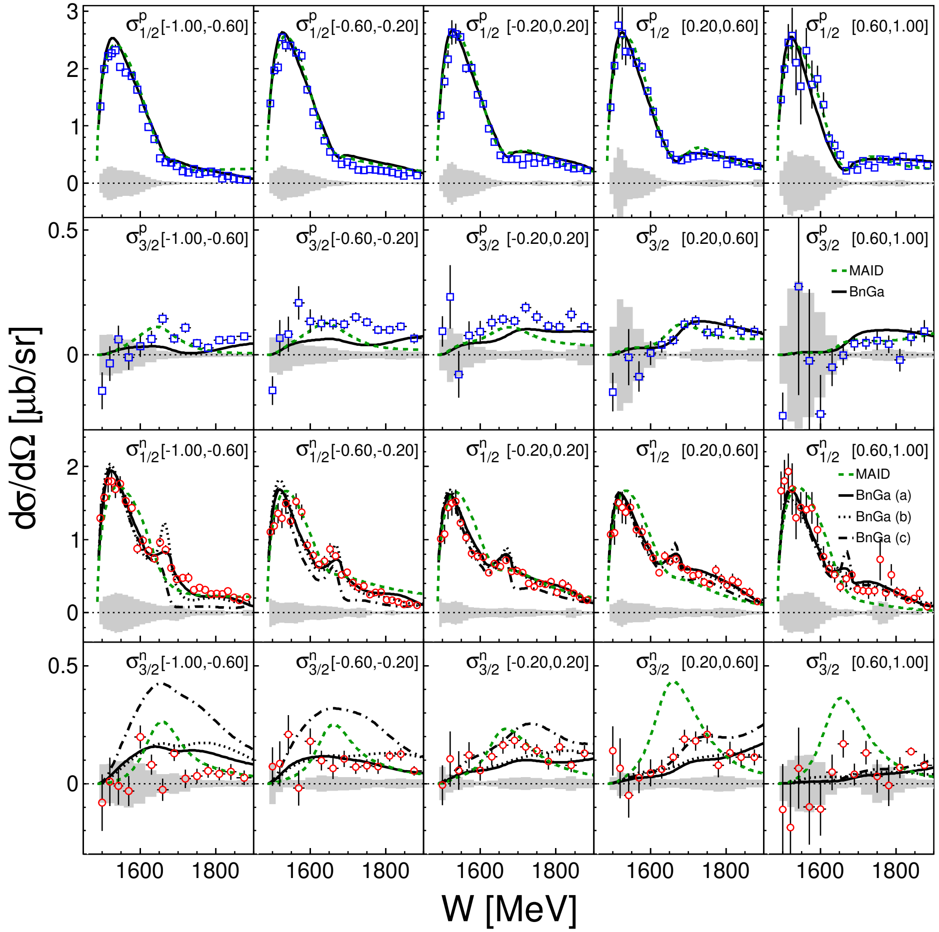
- neutron - $\sigma_{3/2}$



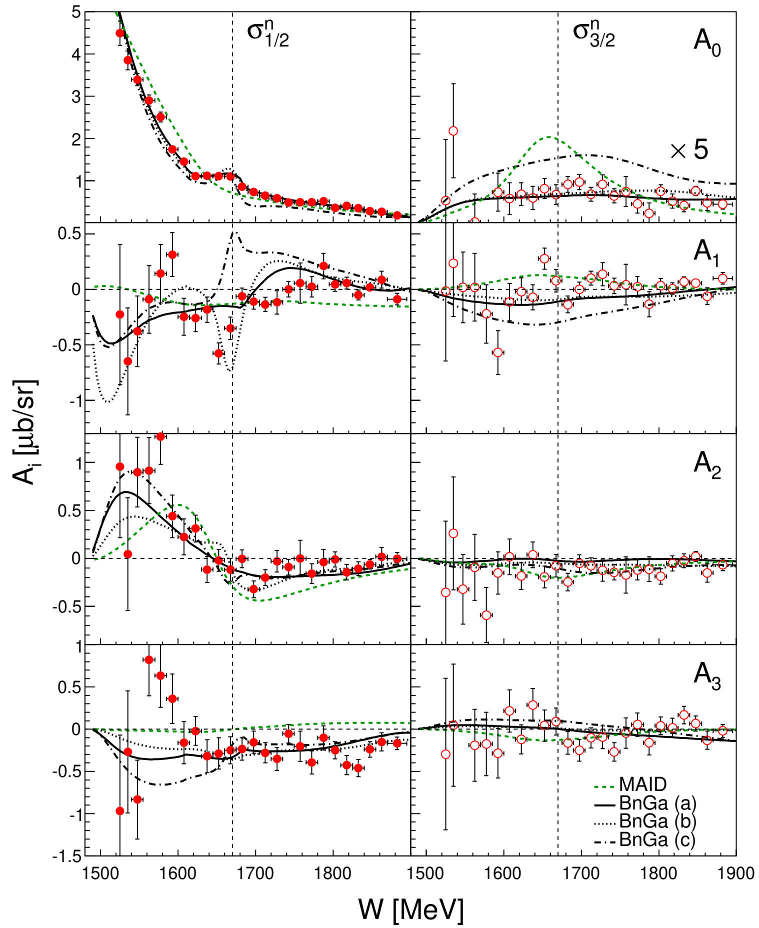
- structure in neutron excitation function is in $\sigma_{1/2}$ part!
- for proton and neutron very small contributions from $\sigma_{3/2}$
- for proton possibly indication for contribution from $P_{13}(1720)$ state

$\gamma n \rightarrow n\eta$ - angular dependence of helicity decomposition

helicity dependent cross section for different angular bins



coefficient of Legendre fits of angular distributions

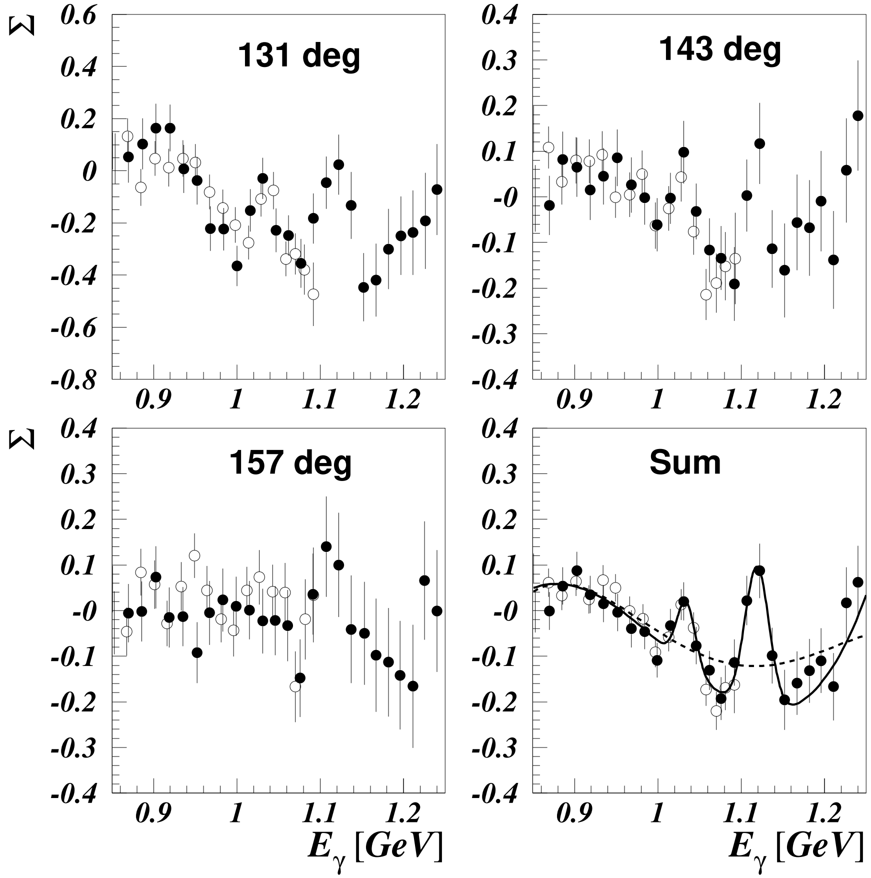


- A_1 **coefficient: best agreement with BnGa fit with narrow** P_{11} **(pos. interference)**

$\gamma n \rightarrow n\eta$ - more structure, more surprizes

Recent result from GRAAL experiment: V.A. Kuznetsov et al., PRC 91 (2015) 042201(R)

Narrow structures in beam asymmetry for Compton scattering off proton:



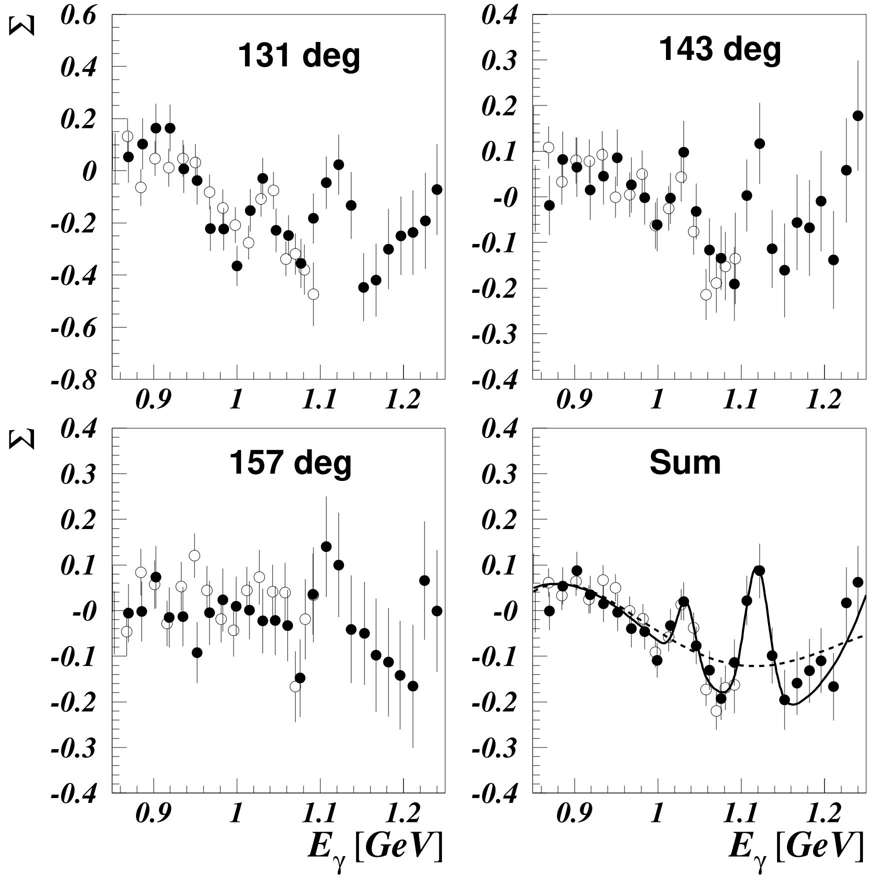
MAMI

$\gamma n \rightarrow n\eta$ - more structure, more surprizes

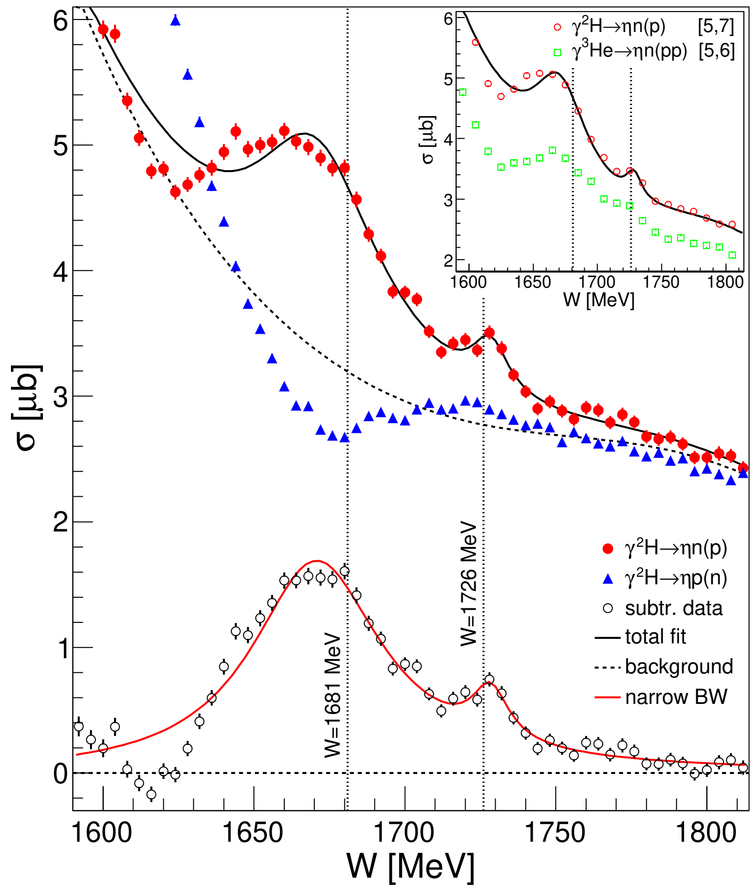
Recent result from GRAAL experiment: V.A. Kuznetsov et al., PRC 91 (2015) 042201(R)

Recent result from A2 MAMI experiment: D. Werthmüller et al., PRC 92 (2015) 069801

Narrow structures in beam asymmetry for Compton scattering off proton:

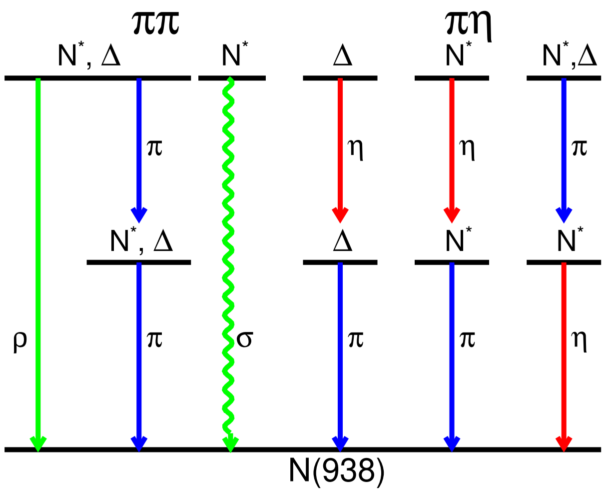


Relation to $\gamma n \rightarrow n\eta$? peak at same W significant

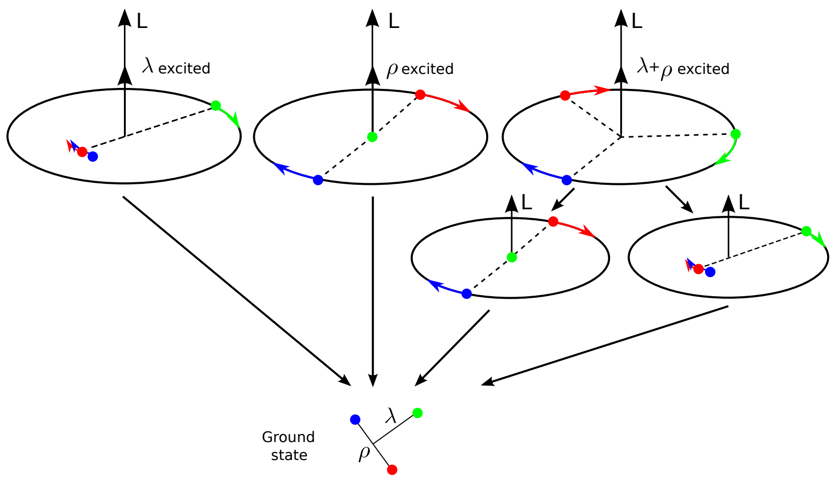


photoproduction of meson pairs

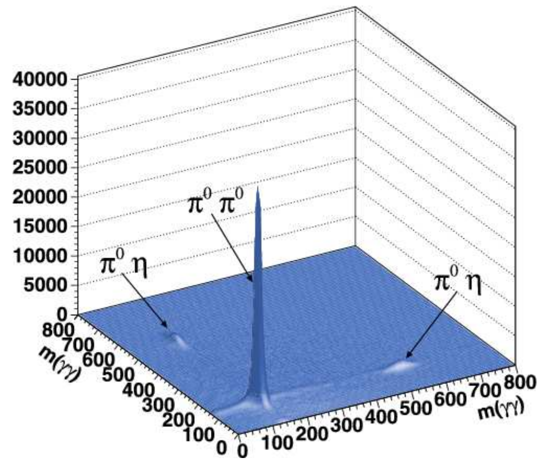
- $\pi\pi$- & $\pi\eta$-pairs: cascade decays



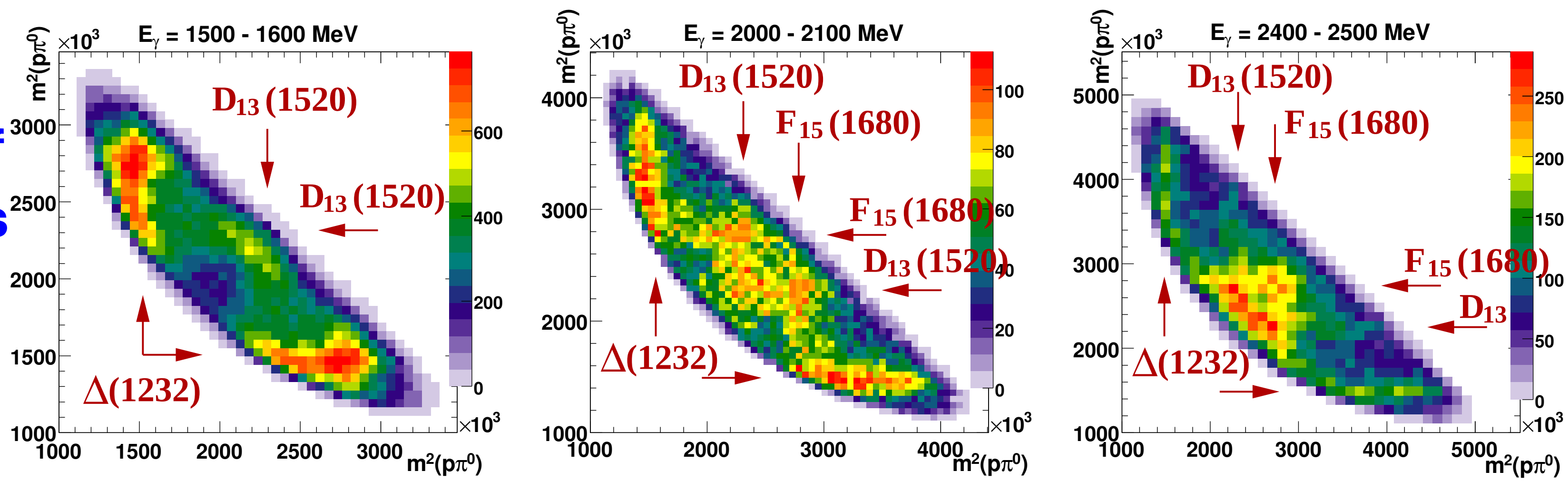
- important for specific nucleonic excitations:



- clean identification in invariant mass

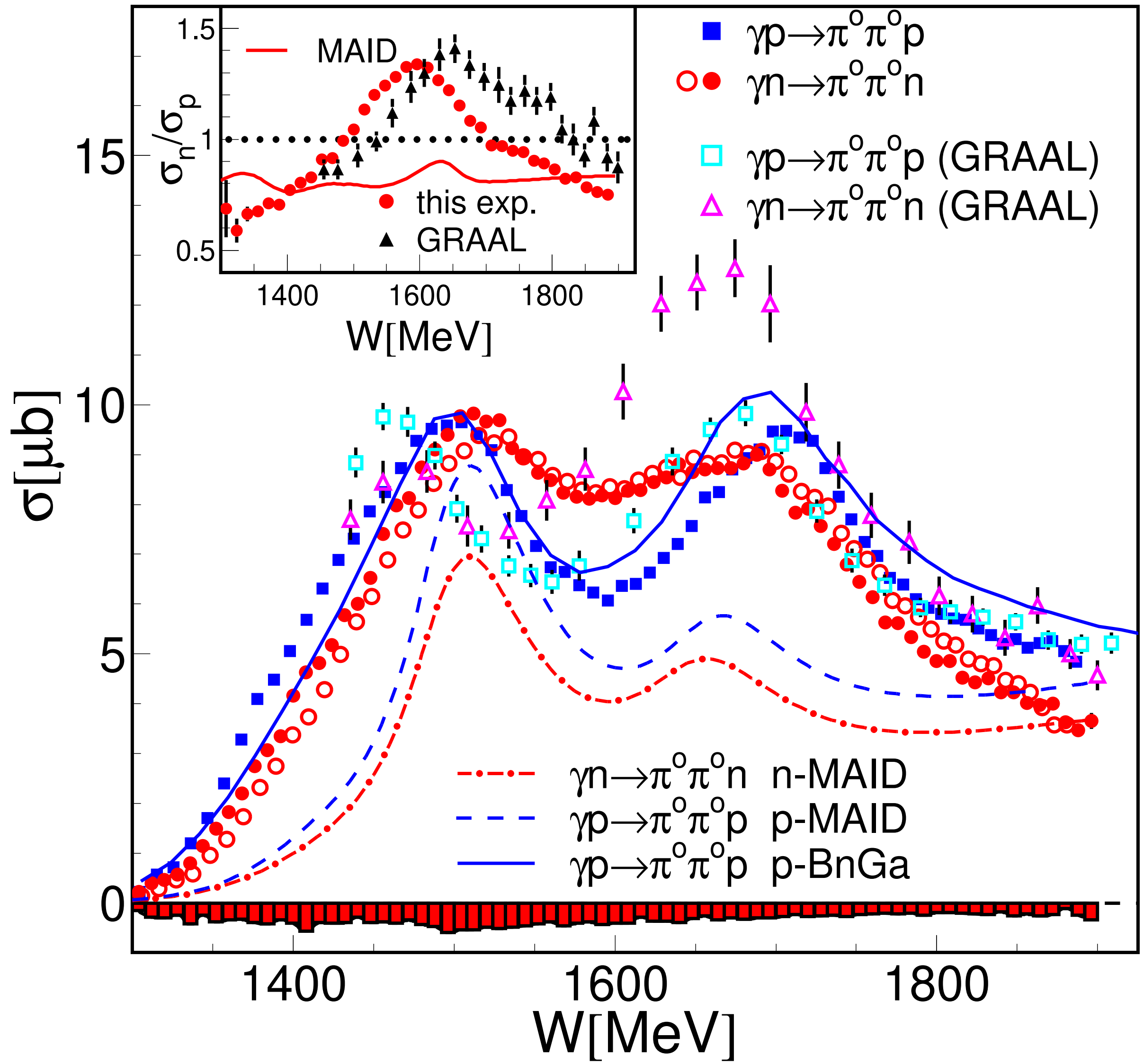


- Dalitz-plot analysis of $\pi^0\pi^0$-pairs



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

(M. Dieterle, M. Oberle et al., EPJA 51(2015) 142)

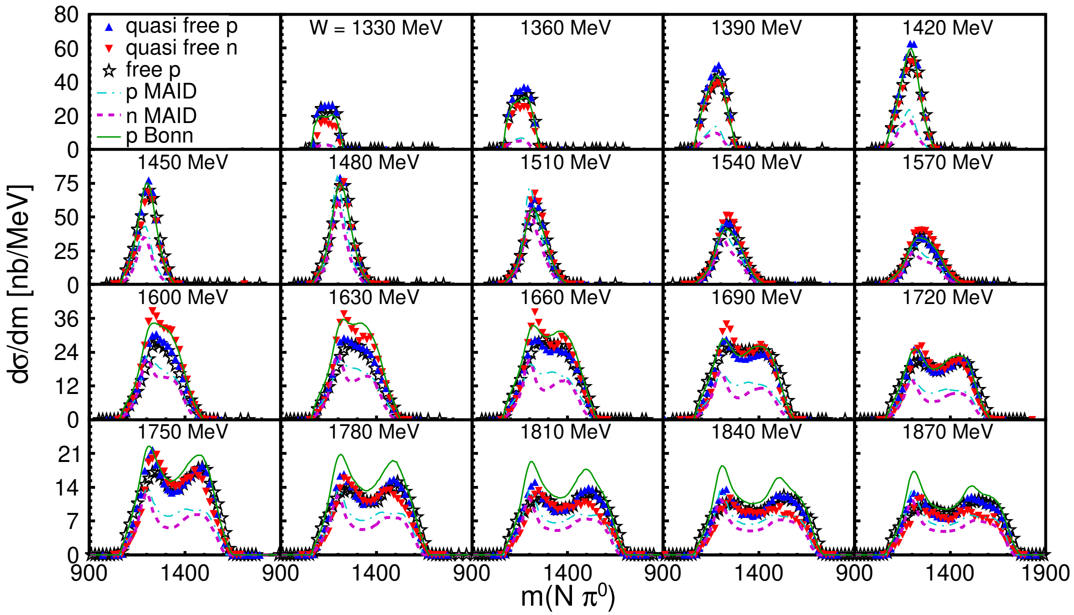


- **moderate FSI effects (≈15%)**
- **large discrepancy with GRAAL neutron data**
- **so far no reasonable model for neutron data**

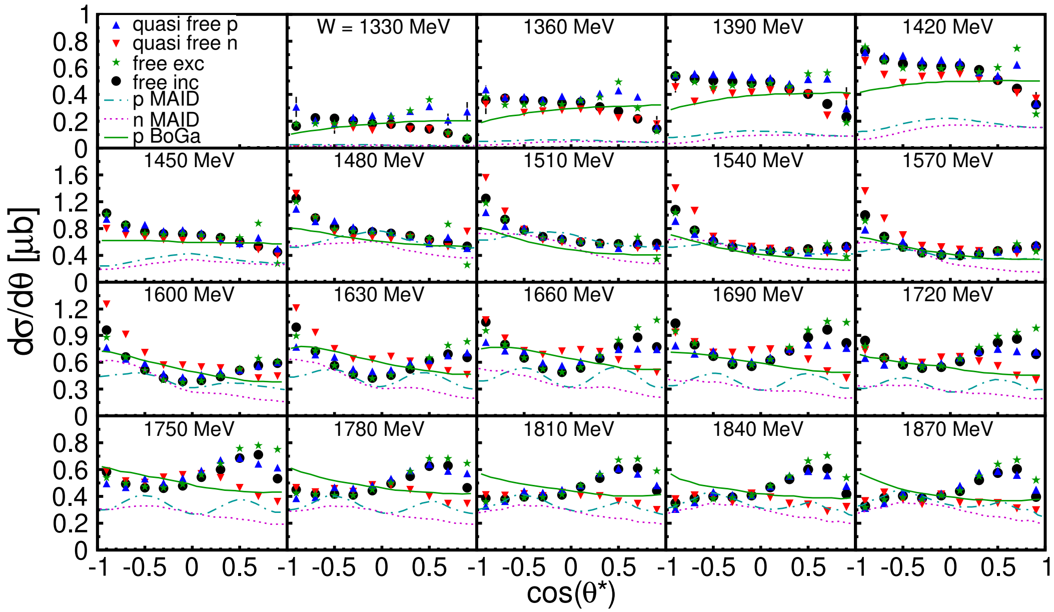
$\gamma N \to N\pi^o\pi^o$ - invariant mass & angular distributions

(M. Dieterle, M. Oberle et al., EPJA 51 (2015) 142)

- **pion -nucleon invariant mass**



- **angular distr. - $\Theta^\star$ polar angle of $\pi\pi$-system**

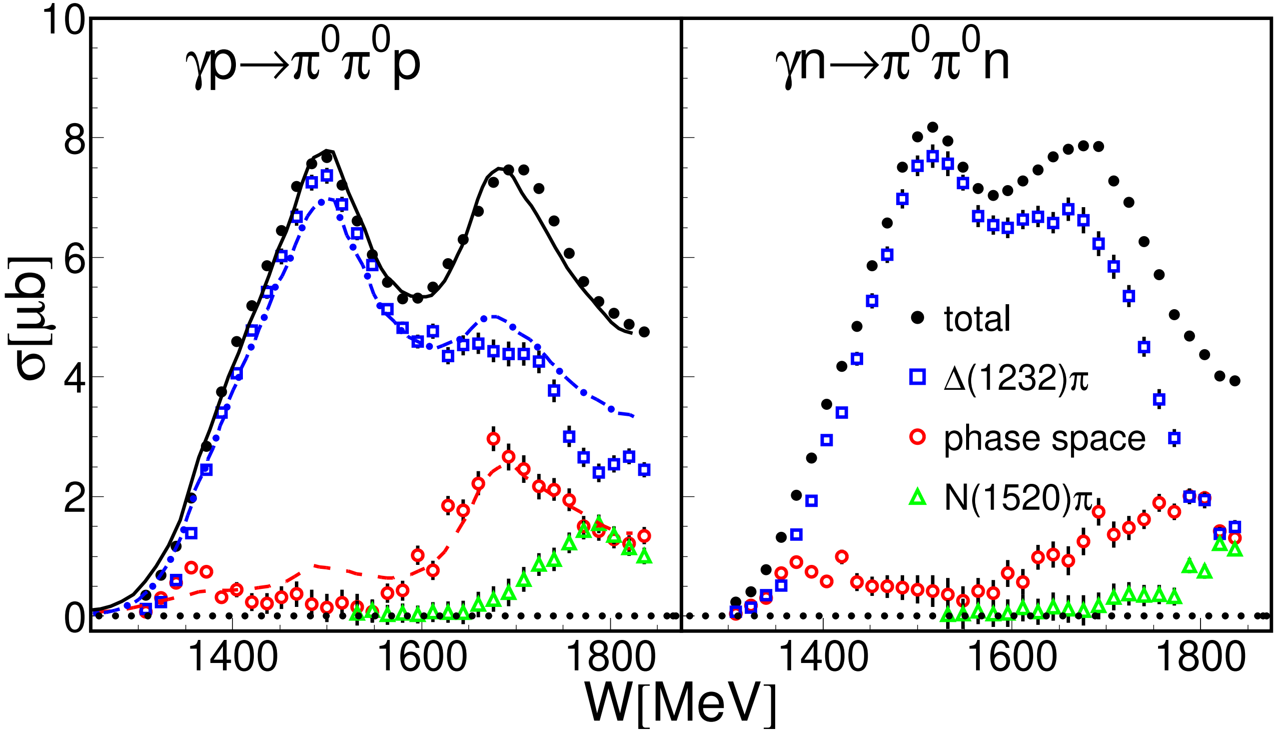


- **invariant mass distributions show contributions from $\Delta^\star, N^\star \to \pi\Delta(1232)$ & $\Delta^\star, N^\star \to \pi D_{13}(1520)$ for p & n**
- **proton & neutron angular distributions different for large W $\to$ different resonance contributions for $\Delta^\star, N^\star \to \pi D_{13}(1520)$?**

contributions to $\gamma N \rightarrow N\pi^o\pi^o$ invariant mass spectra

(M. Dieterle, M. Oberle et al., EPJA 51 (2015) 142)

- simultaneous fit of $\pi\pi$ and πN invariant mass spectra with simulated line shapes

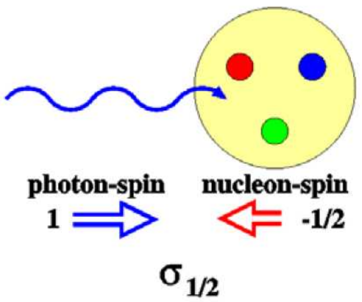


- second resonance bump dominated by $\pi\Delta(1232)$ intermediate state for p and n
- third bump has stronger 'phase-space' contributions for p
- results for quasi-free proton agree with BnGa PWA of free proton data

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

(M. Dieterle et al., preliminary)

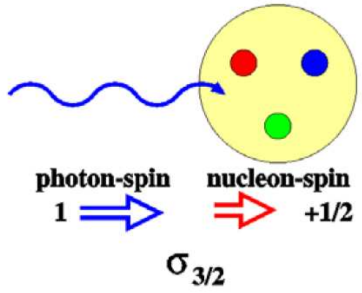
- helicity component $\sigma_{1/2}$



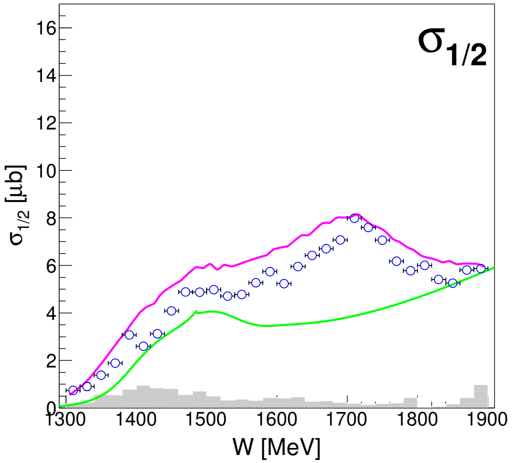
- circularly pol. beam,
  longitudinally pol. target (buthanol)

$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

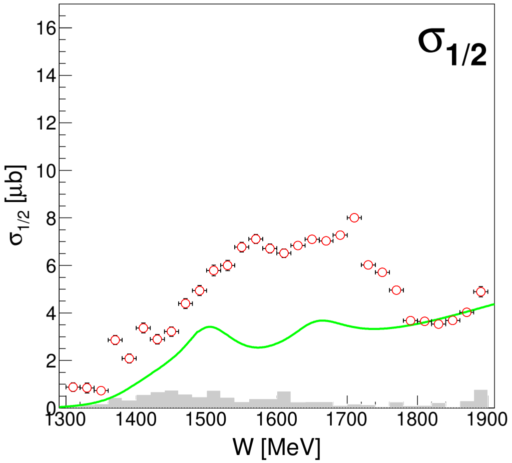
- helicity component $\sigma_{3/2}$



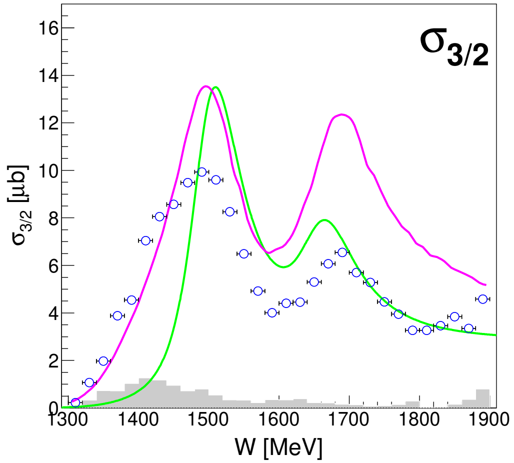
- proton - $\sigma_{1/2}$



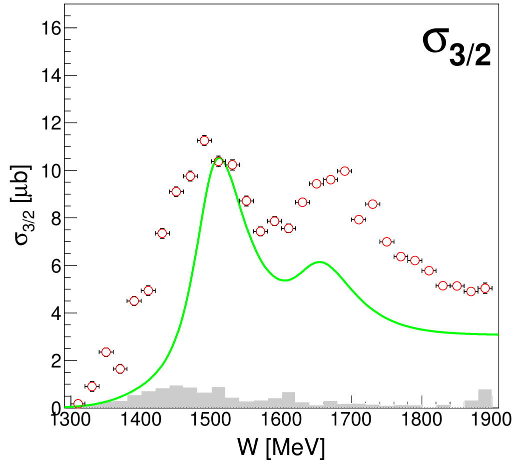
- neutron - $\sigma_{1/2}$



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



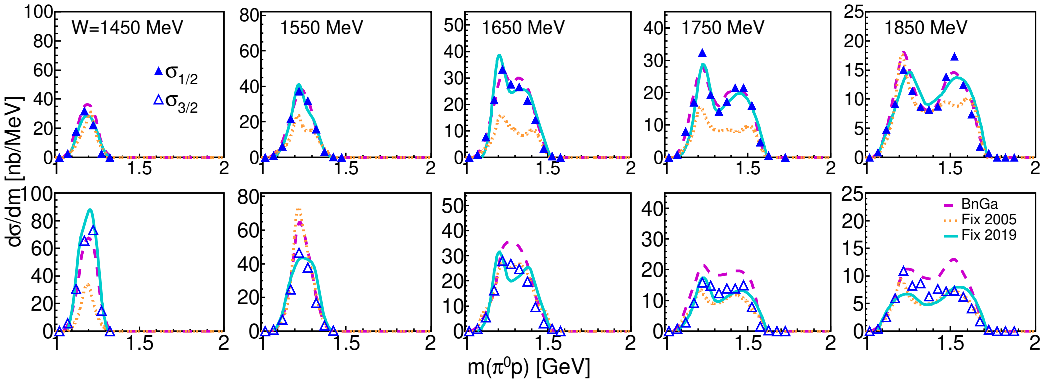
- neutron - $\sigma_{3/2}$



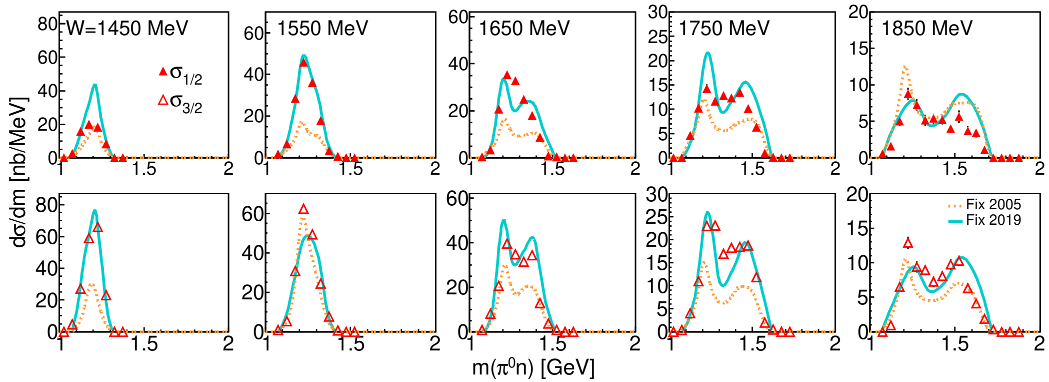
- 2nd resonance peak dominated by $D_{13}(1520)$ (large $A_{3/2}$ for n and p)
- 3rd peak for neutron: $D_{15}(1675)$ (similar large $A_{1/2}$, $A_{3/2}$ for n, small for p)
- 3rd peak for proton: $F_{15}(1680)$, should be dominantly $A_{3/2}$???

invariant mass distributions for $\gamma N \rightarrow N\pi^{o}\pi^{o}$, $\sigma_{1/2}$,$\sigma_{3/2}$

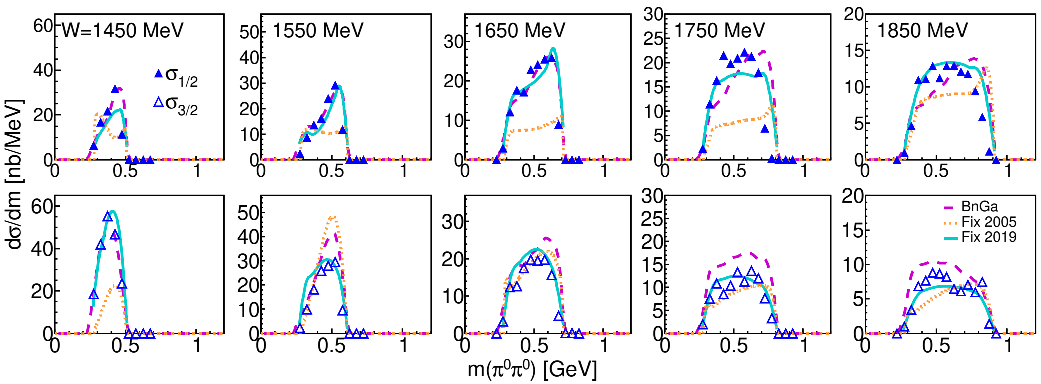
$\gamma p \rightarrow p\pi^0\pi^0$ ($m(p,\pi^0)$)



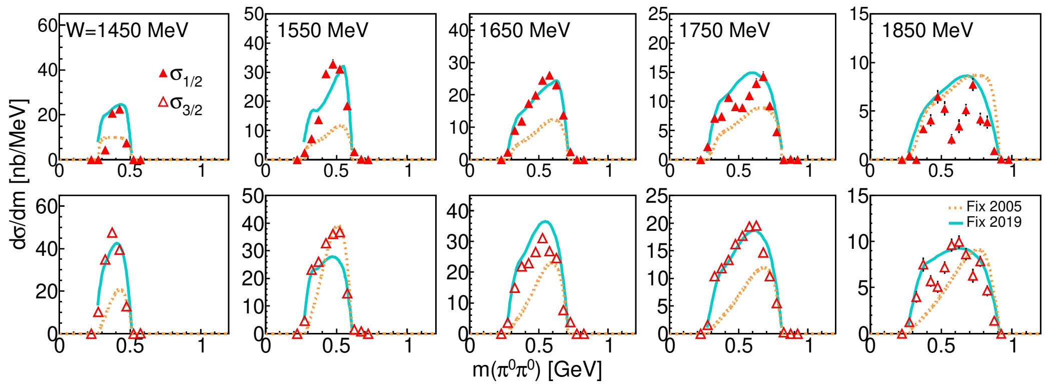
$\gamma n \rightarrow n\pi^0\pi^0$ ($m(n,\pi^0)$)



$\gamma p \rightarrow p\pi^0\pi^0$ ($m(\pi^0,\pi^0)$)

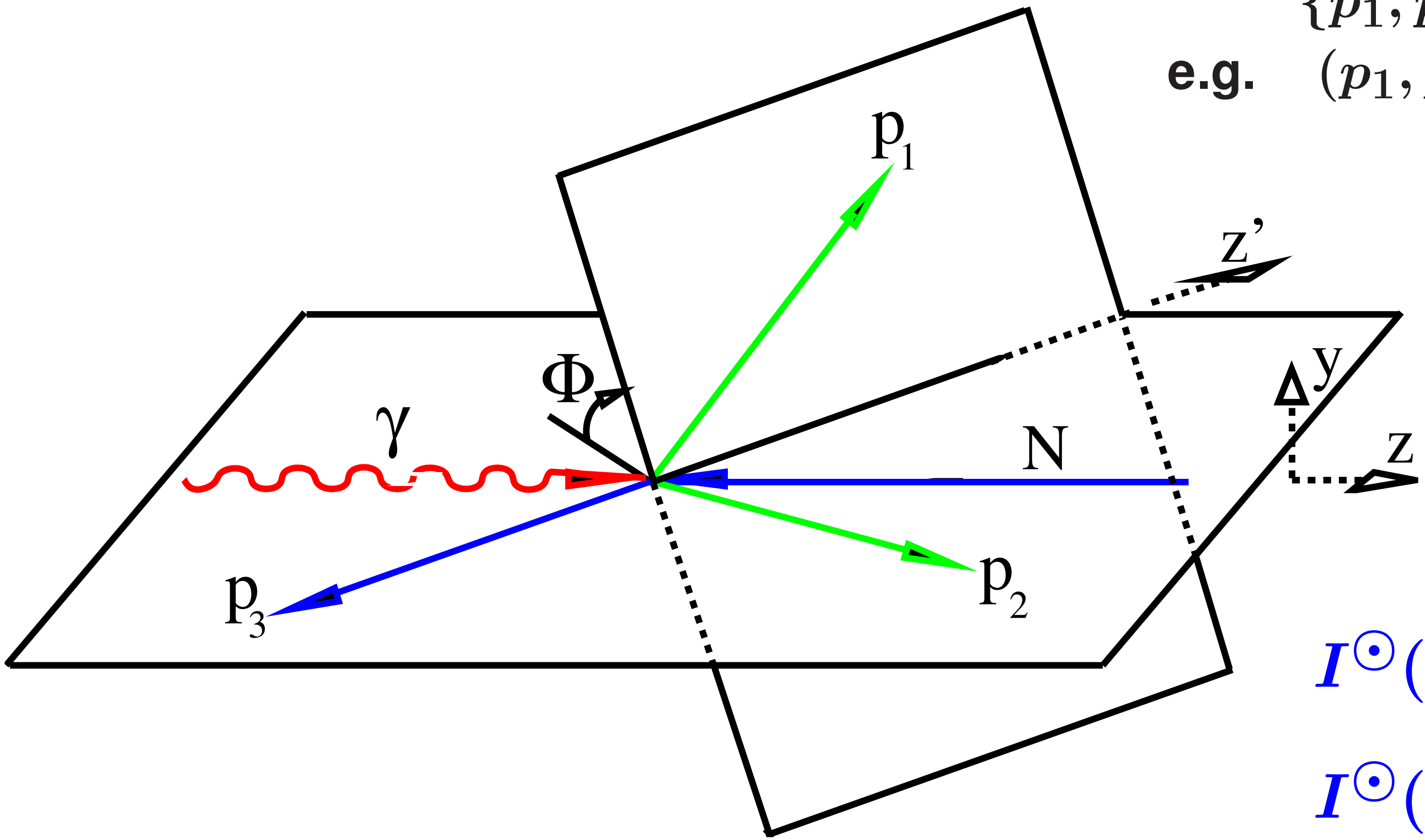


$\gamma n \rightarrow n\pi^0\pi^0$ ($m(\pi^0,\pi^0)$)



additional asymmetries for three-particle final states

beam-helicity asymmetries - circularly polarized beam, unpolarized target



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

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

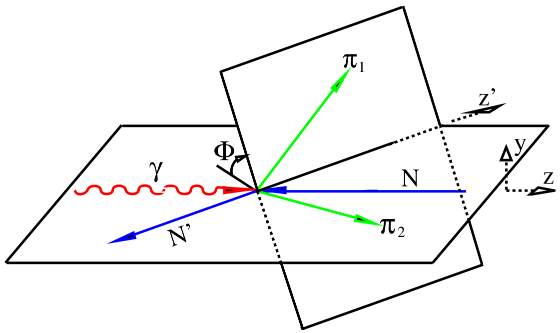
$$I^{\odot}(\Phi) \equiv \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

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

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

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

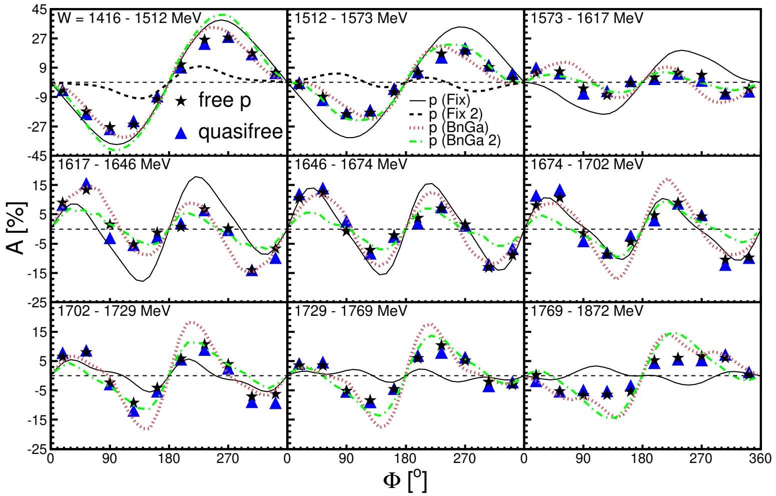
M. Oberle et al., PLB 721(2013) 237, M. Oberle et al., EPJA 50 (2014) 54



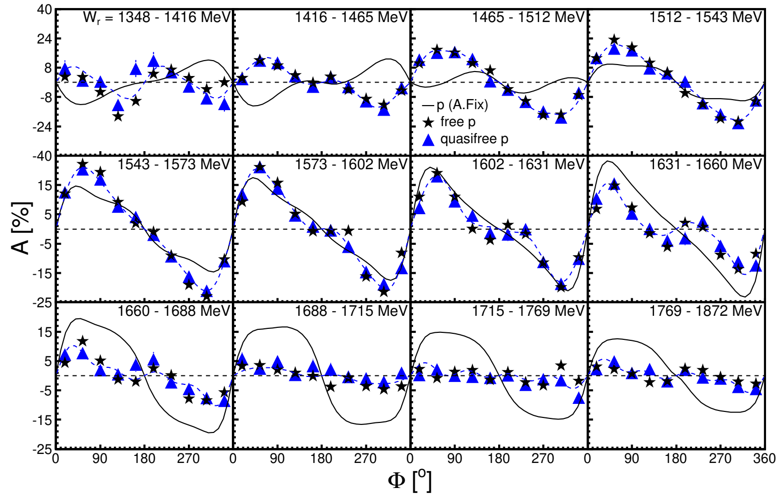
pions ordered by invariant mass:

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

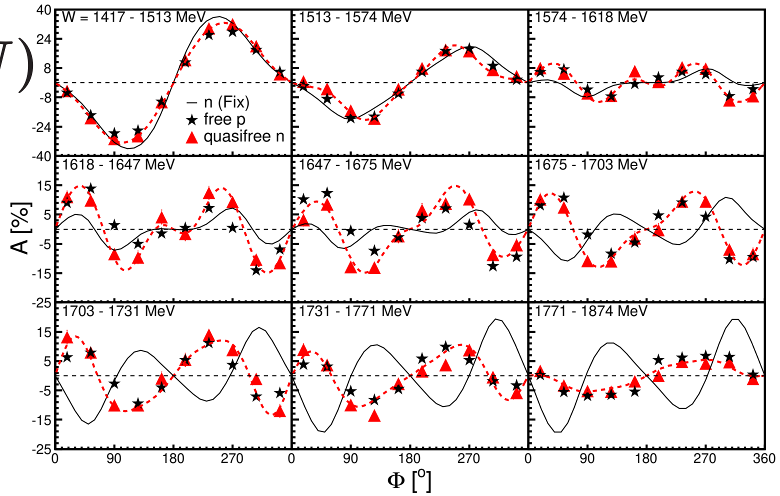
- $\gamma p \rightarrow p\pi^0\pi^0$ (blue: qf. p, black: free p)



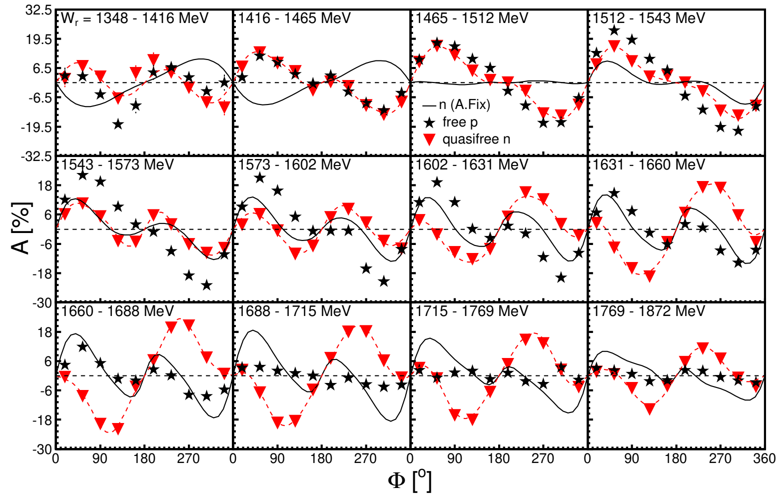
- $\gamma p \rightarrow n\pi^0\pi^+$ (blue: qf. p, black: free p)



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



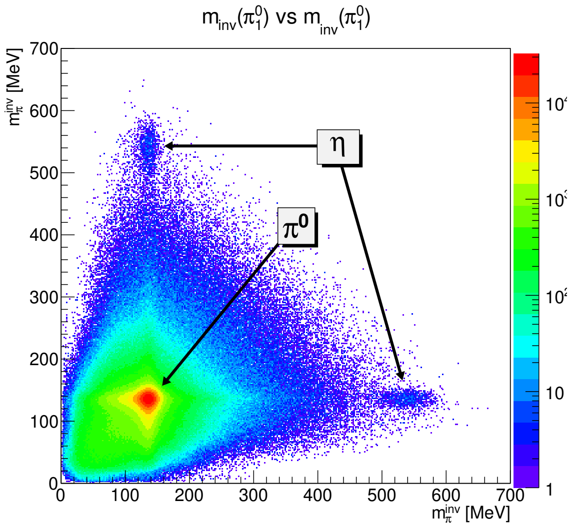
- $\gamma n \rightarrow p\pi^0\pi^-$ (red: qf. n, black: free p)



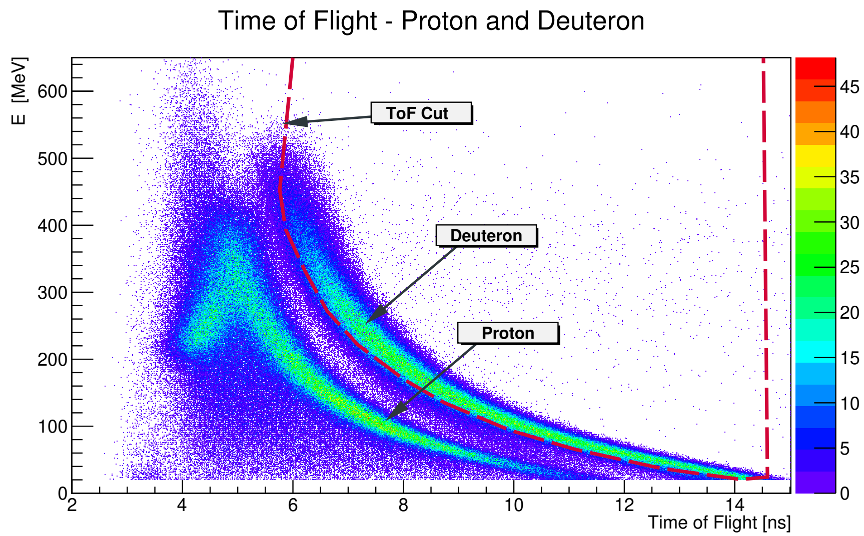
$\gamma d \rightarrow d\pi^0\pi^0$ - coherent $2\pi^0$-production off deuterons

(M. Günther et al., preliminary)

- **Invariant mass**

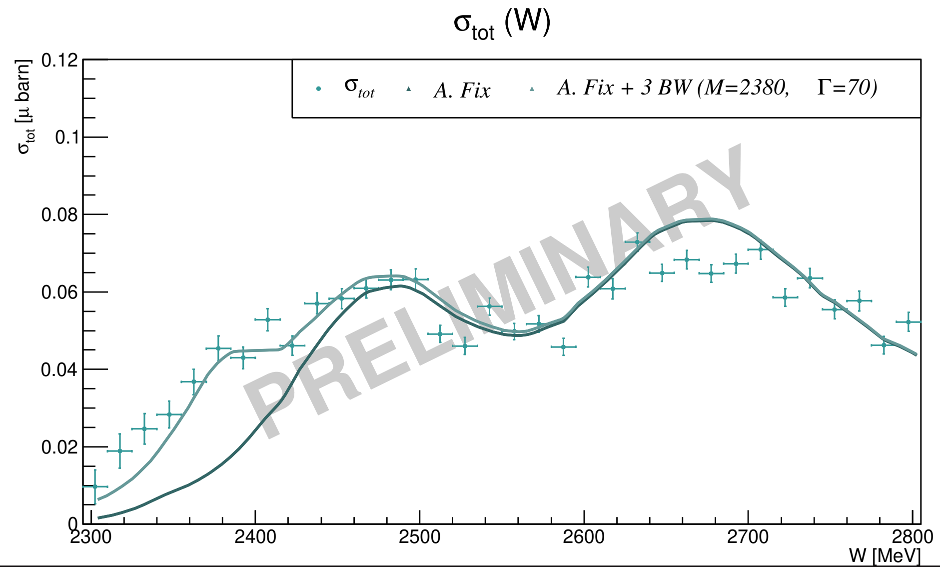


- **Deuteron identification**



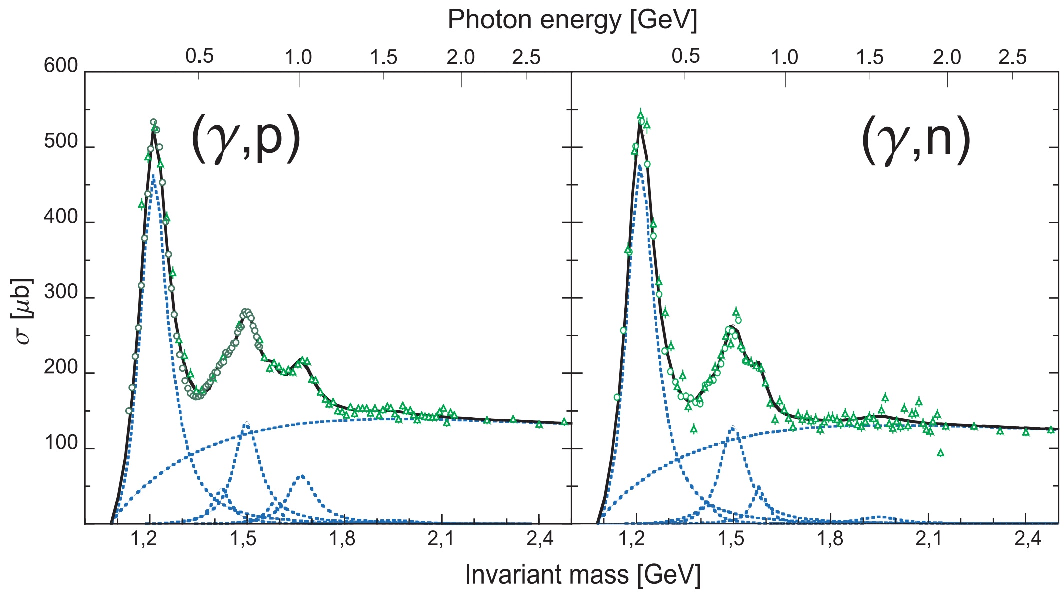
- **total cross section**

- **structure at 2380 MeV?**

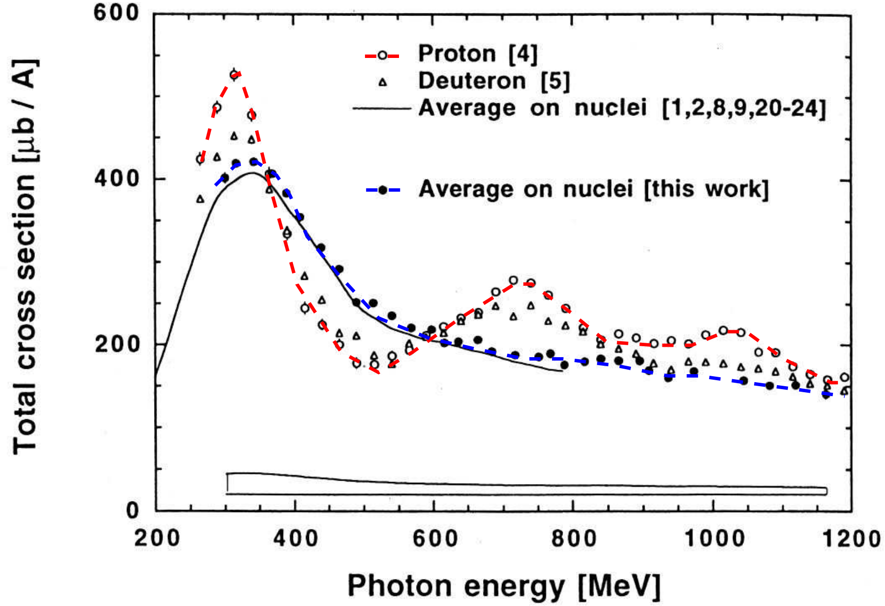


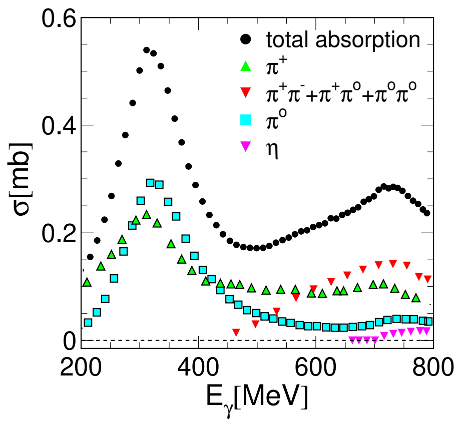
nucleon resonances - total photoabsorption

- the reaction $\gamma N \rightarrow X$



- ... compared to $\gamma A \rightarrow X$



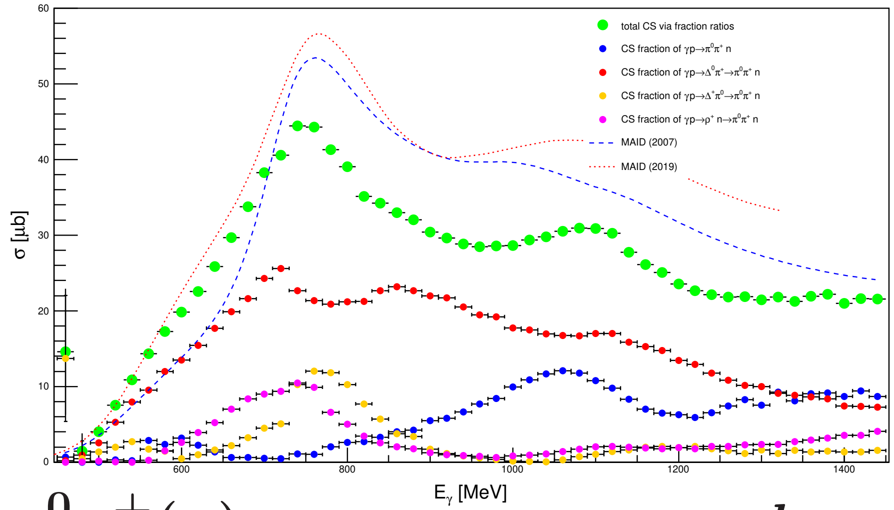


- no signal for higher lying resonances in nuclear excitation function but: second resonance bump has complicated structure already for nucleon

Photoproduction of mixed charge $\pi^0\pi^+$, $\pi^0\pi^-$ pion pairs

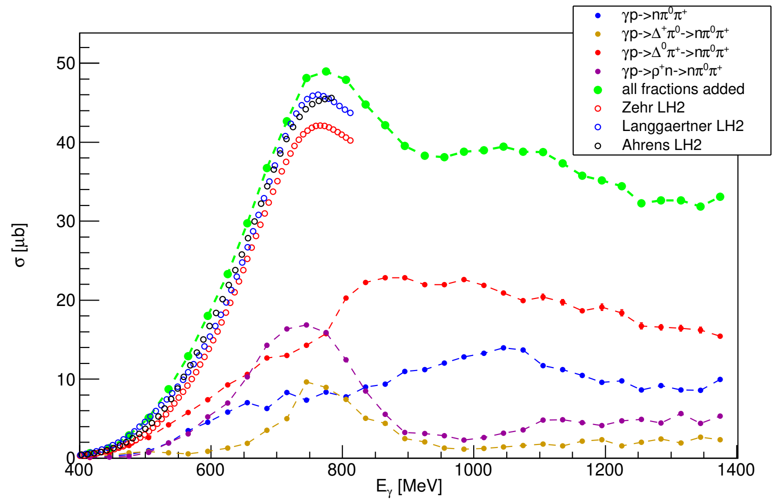
(S. Abt, S. Lutterer, preliminary)

- the reaction $\gamma p \rightarrow n\pi^0\pi^+$ (free proton)

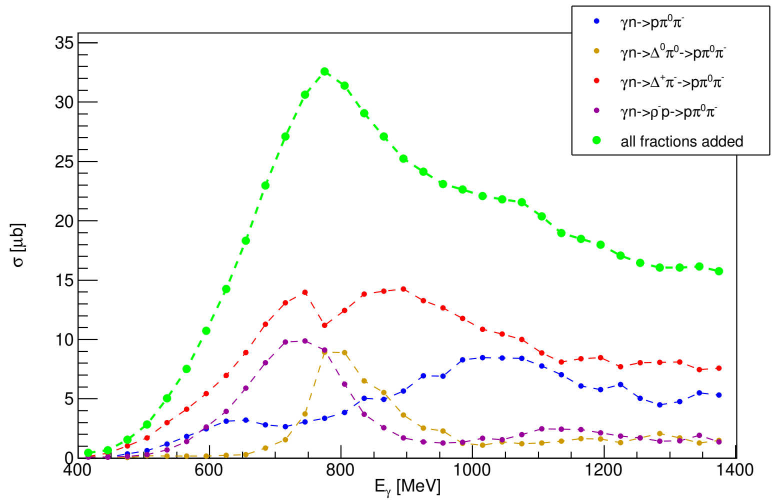


- second resonance peak mainly due to
  $N^\star \rightarrow \Delta\pi^0 \rightarrow N\pi^0\pi^\pm$
  and
  $N^\star \rightarrow N\rho \rightarrow N\pi^0\pi^\pm$

- $\gamma d \rightarrow n\pi^0\pi^+(n)$



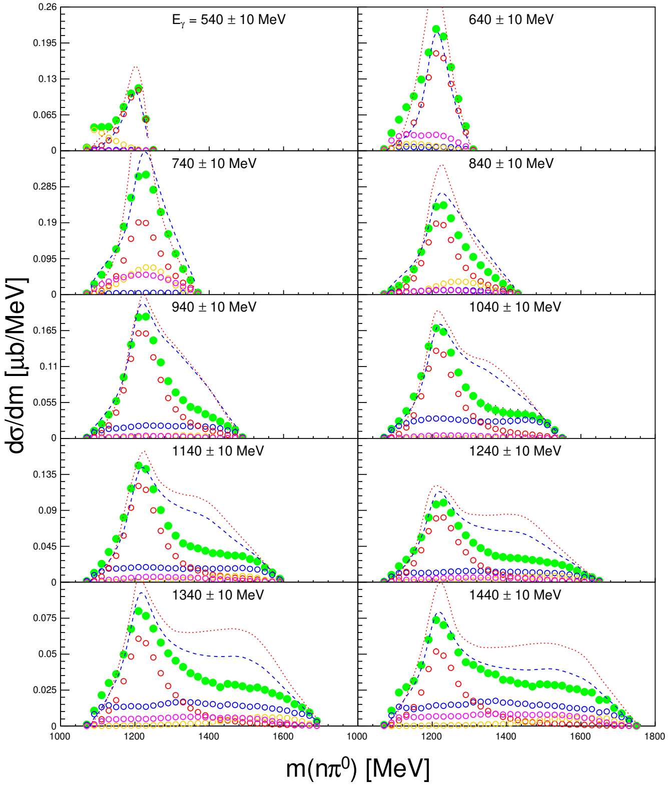
- $\gamma d \rightarrow p\pi^0\pi^-(p)$

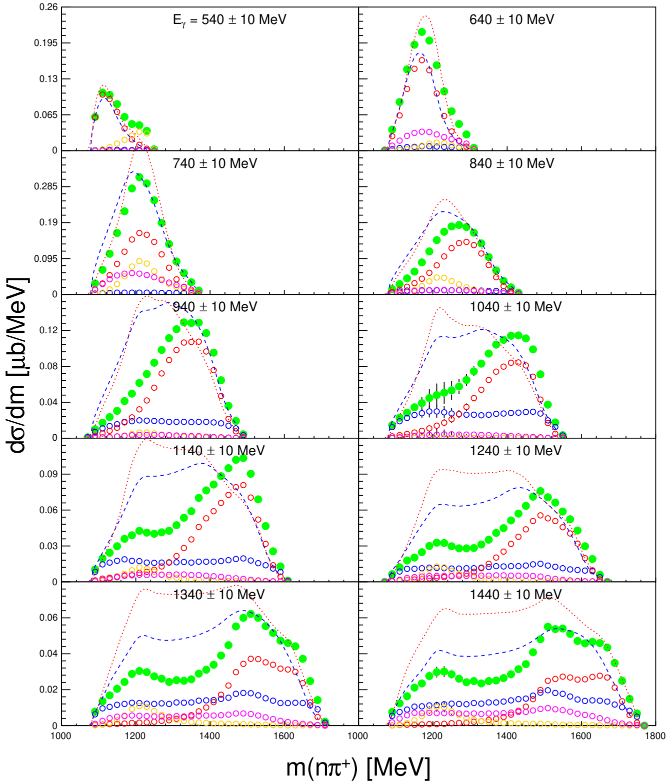


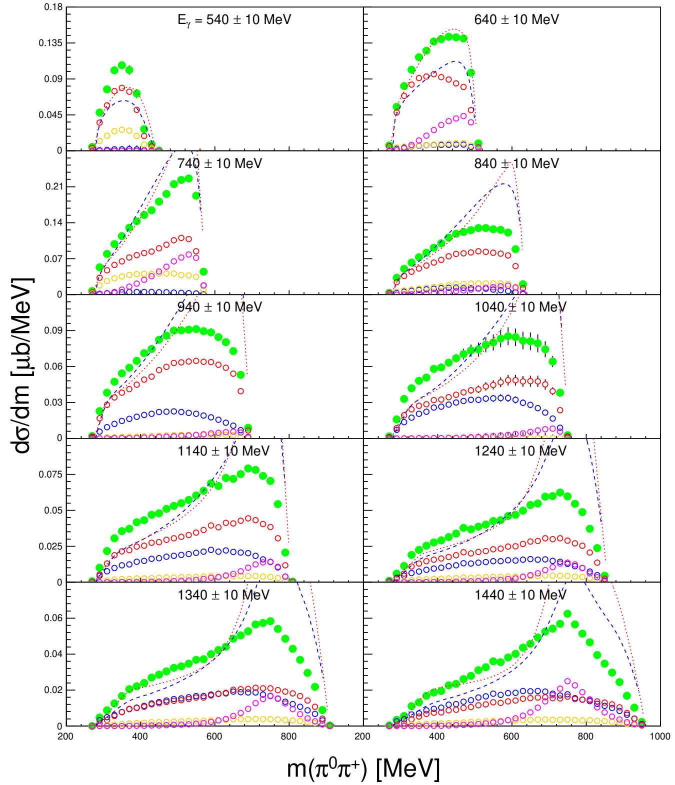
$\gamma p \rightarrow n\pi^0\pi^+$ - invariant mass distributions

(S. Abt, preliminary)

- $\pi^0 n$-invariant mass
- $\pi^+ n$-invariant mass
- $\pi^+\pi^0$-invariant mass





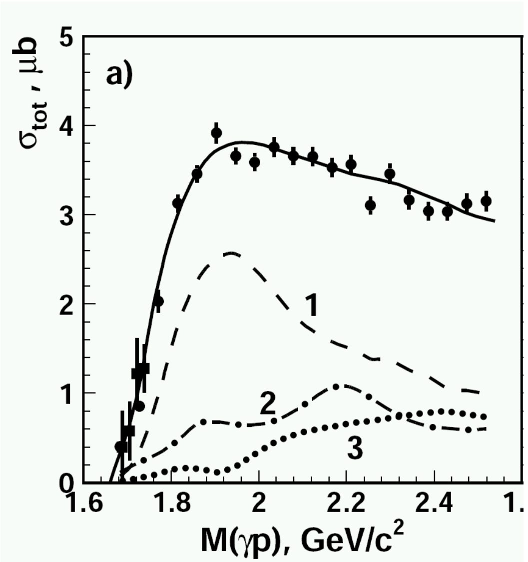


- **dominant contributions from Δ-Kroll-Ruderman term at all incident energies**
- **significant contributions from sequential resonance decays and ρ-meson in second resonance region**

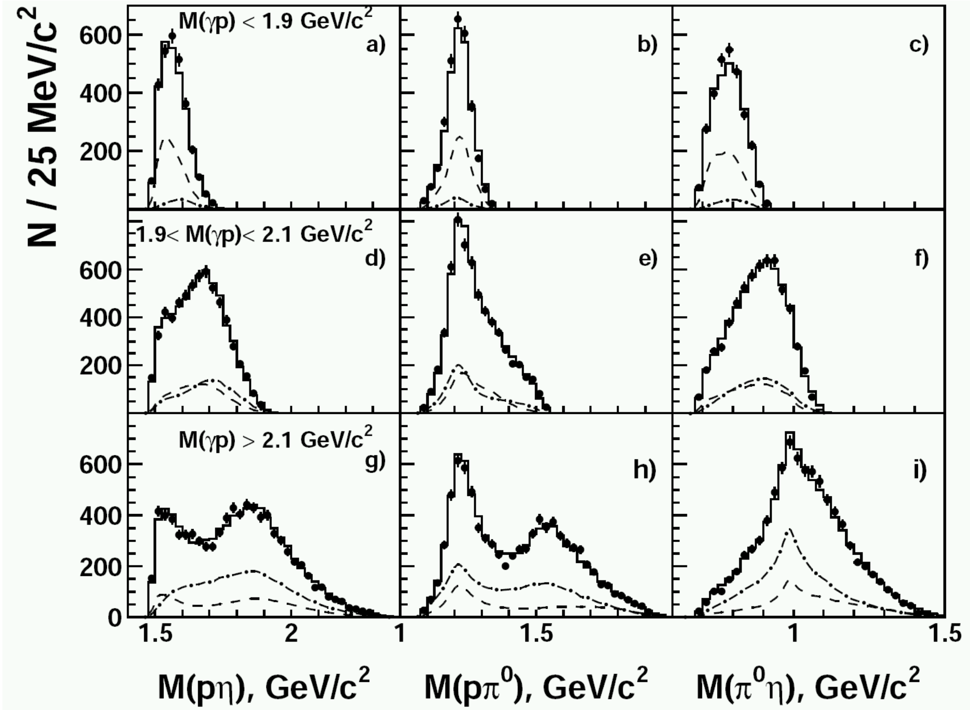
resonance contributions to photoproduction of $\pi\eta$-pairs

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

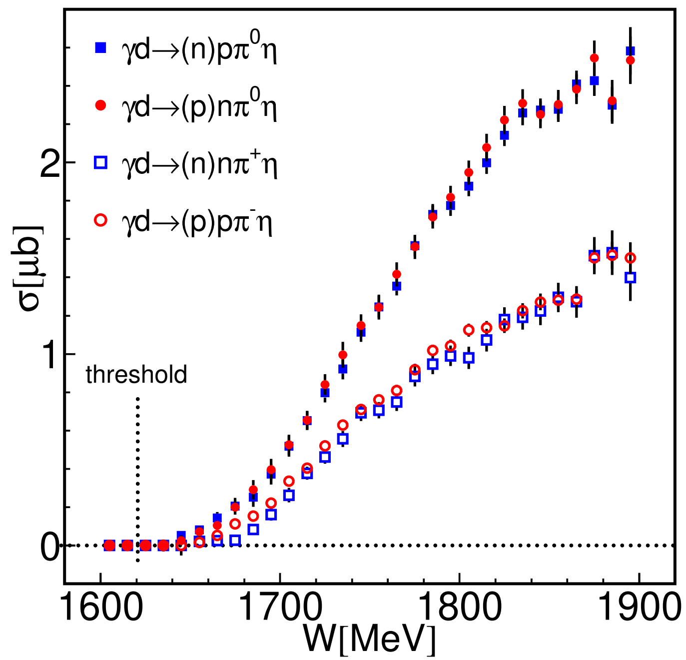


- **dominant final states:** $--\ \Delta(1232)\eta$, $-.-\ N(1535)\pi$, ... $pa_o(980)$
- **dominant process close to threshold:** $\gamma p \rightarrow$ D$_{33}$(1700)$\rightarrow$ ηP$_{33}$(1232) $\rightarrow$ $\eta\pi^o$p

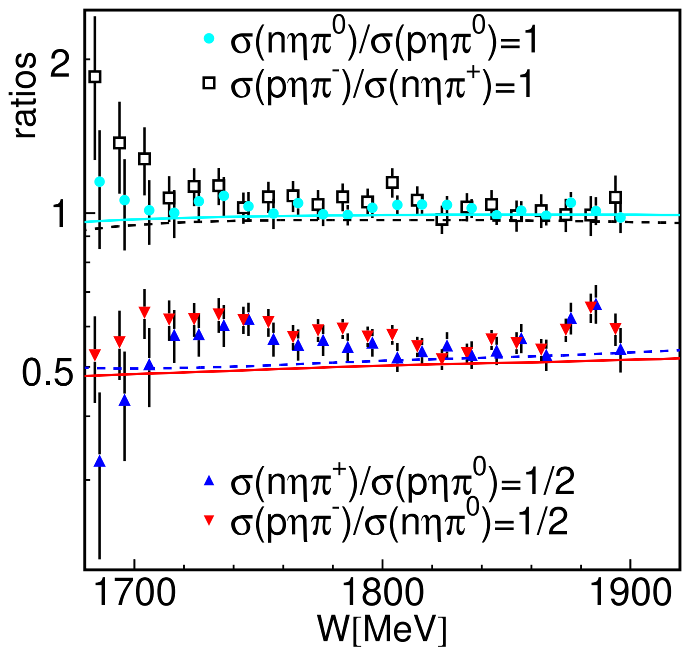
isospin decomposition of $\pi\eta$-photoproduction

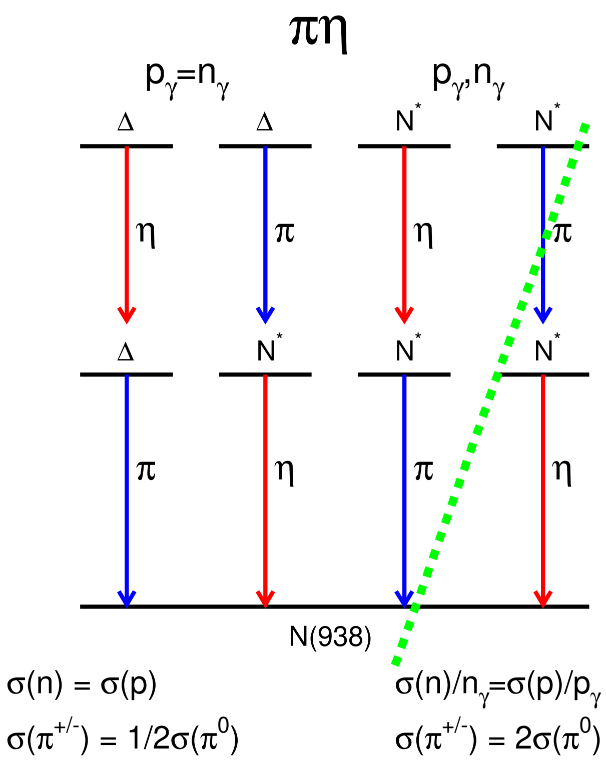
(A. Käser et al., Phys. Lett. B748 (2015) 244)

- **total cross sections**



- **cross section ratios**



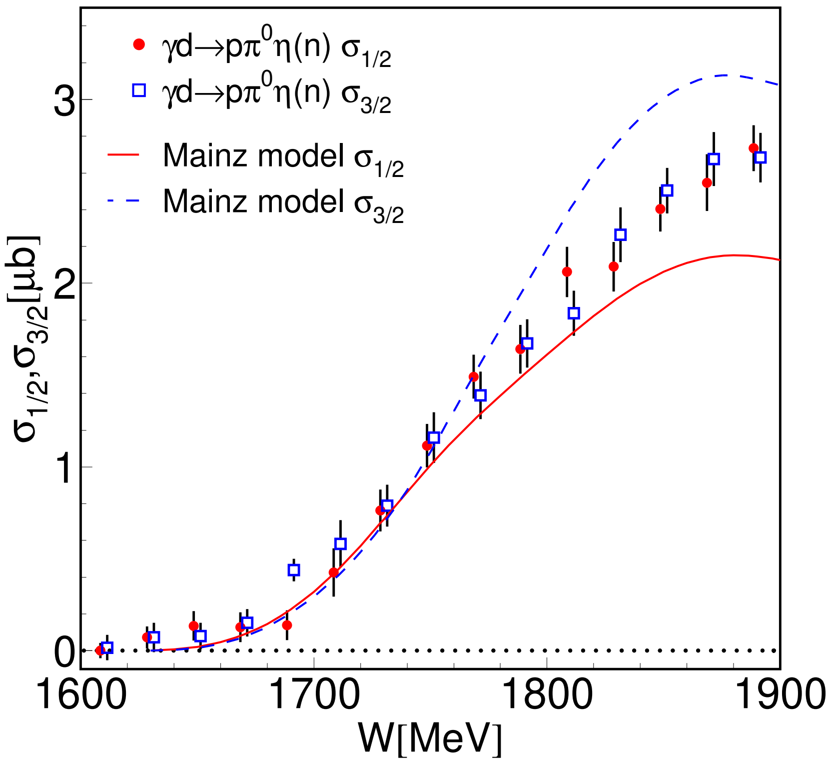


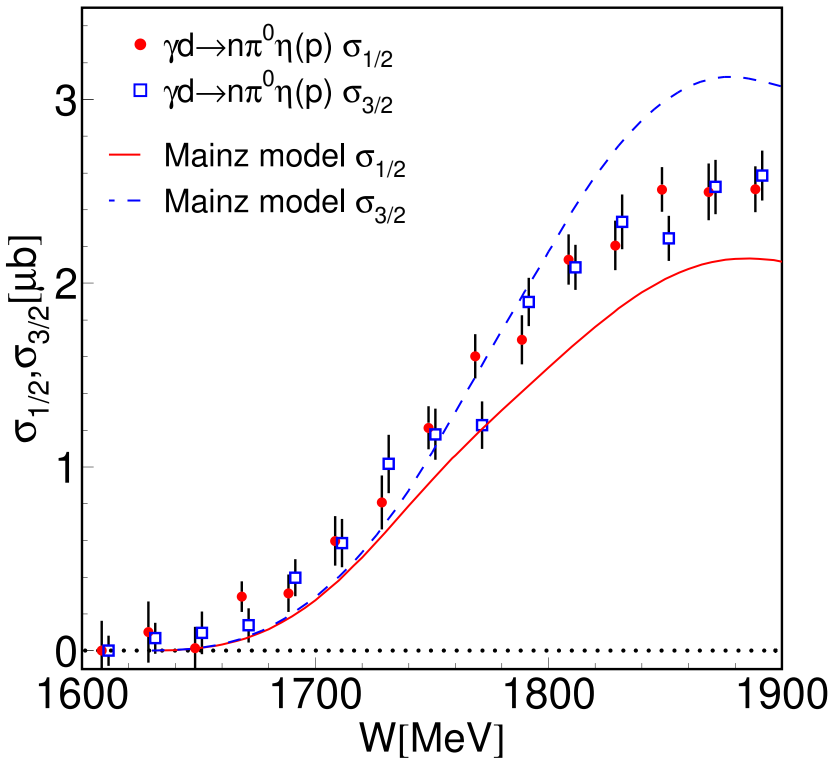
- **cross section ratios agree with $\gamma N \rightarrow \Delta^\star \rightarrow \eta\Delta \rightarrow \eta\pi N$ reaction chain**
- **invariant mass and angular distributions very similar for protons and neutrons, analysis of polarization observables under way**

$\gamma N \rightarrow N\pi^o\eta$ - helicity dependence of cross section

(A. Käser et al., PLB 786 (2018) 305)

- **quasifree proton target**
- **quasifree neutron target**





- **longitudinally polarized target, circularly polarized beam $\rightarrow \sigma_{1/2}, \sigma_{3/2}$**
- **dominating Δ-resonances must have almost equal $A_{1/2}$,$A_{3/2}$ couplings, fits with D_{33}(1700), D_{33}(1940) states**

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
  - development 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 less important for polarization observables than for cross sections
- much progress with intriguing structures in $\gamma n \rightarrow n\eta$ reaction, but no final conclusions