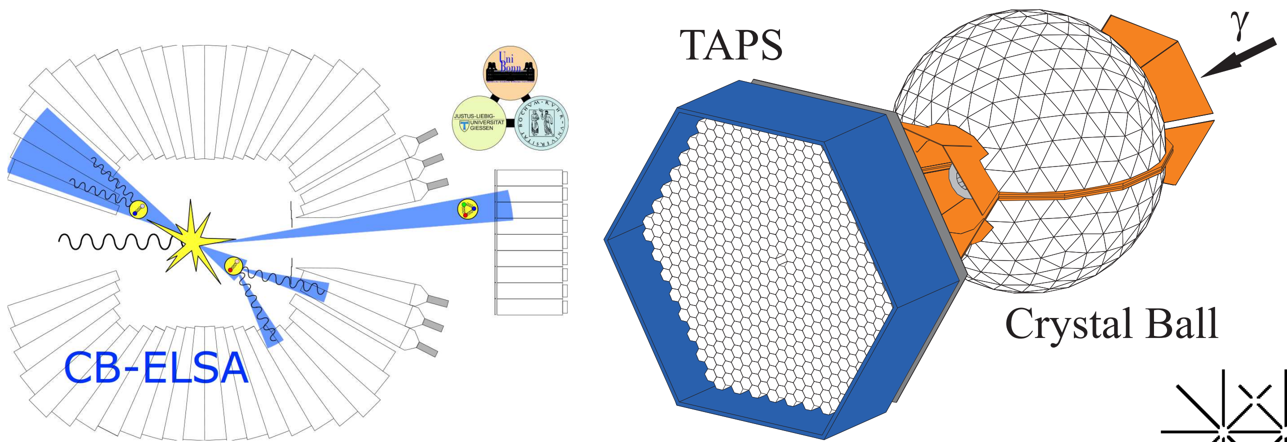
Photoproduction of Mesons of Quasifree Nucleons

- selected results -

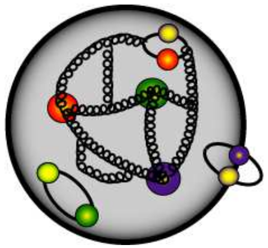
B. Krusche, U. Basel for the CBELSA/TAPS and A2 collaborations

- Introduction
- Experimental setups
- Results
- Conclusions



Structure of the Nucleon

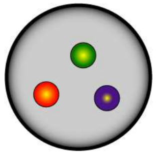
complex many body system



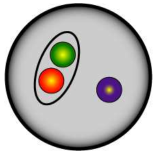
- valence quarks
- sea quarks
- gluons

models - effective dof's:

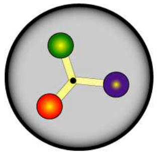
- **3 equivalent constituent quarks**



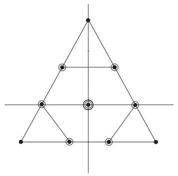
- **quark - diquark models (fewer states)**



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

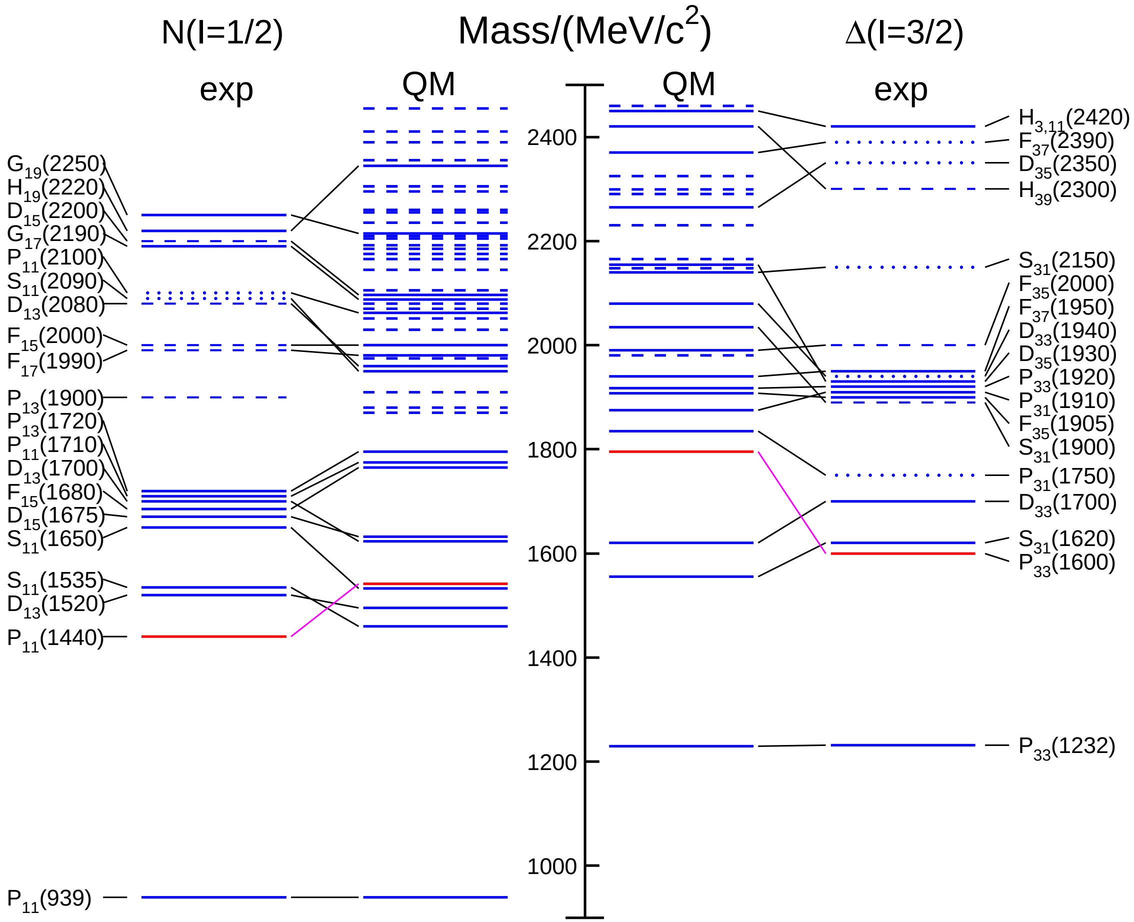


- **chiral soliton models (anti-decuplet states)**



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

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

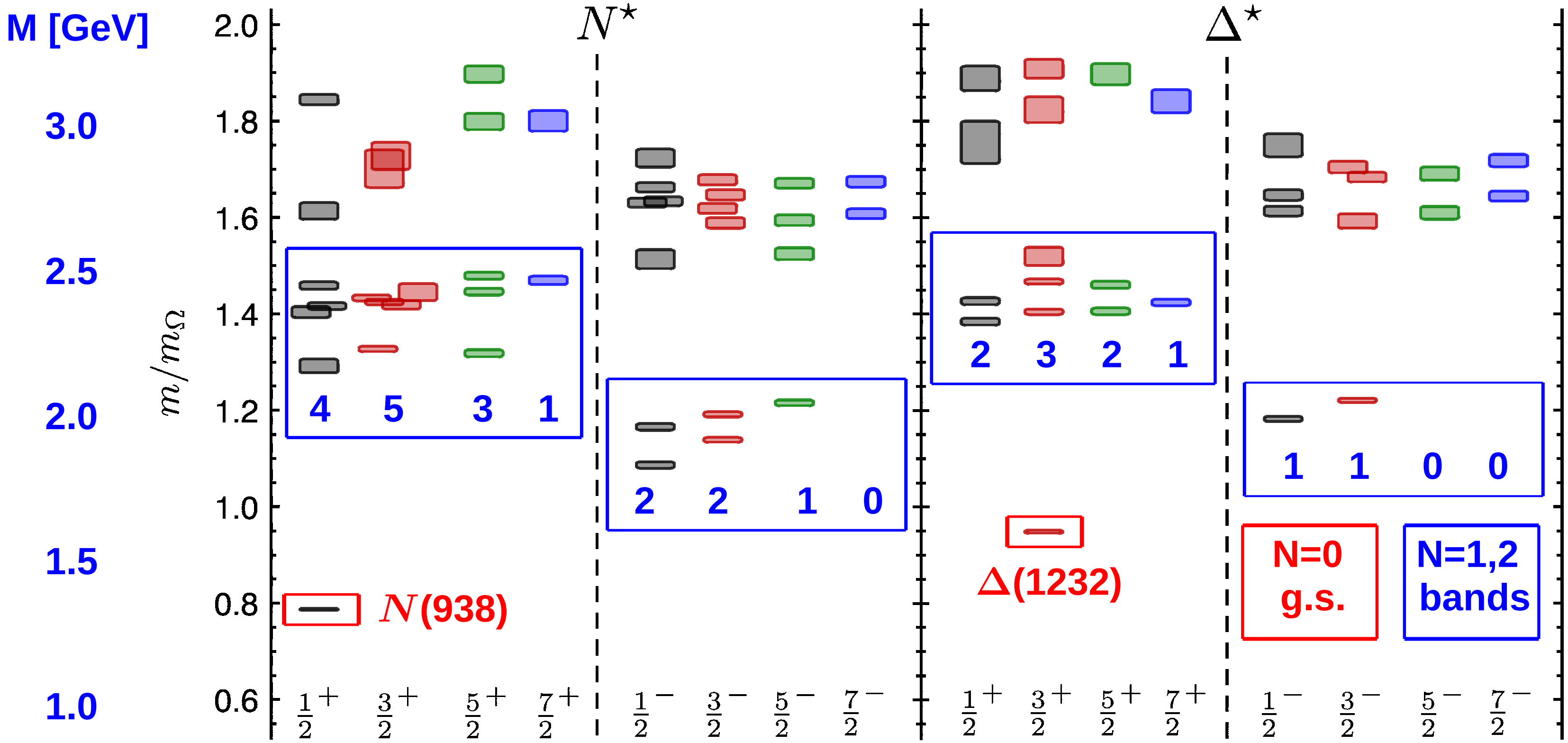


- **ordering of (low-lying) states?**
- **missing resonance problem?**

Progress in Baryon Spectroscopy

Nucleon resonances from Lattice QCD:

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



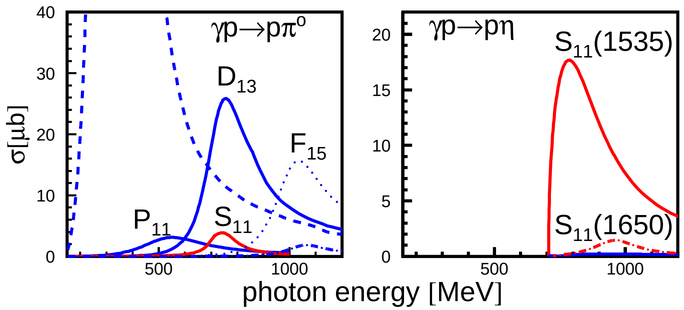
- **Basic features agree with expectations from $SU(3) \otimes O(3)$ symmetry:**
  - **counting of levels consistent with non-relativistic quark model**
  - **Lattice results of course in very early state, m_π =400 MeV...**

Experimental Options:

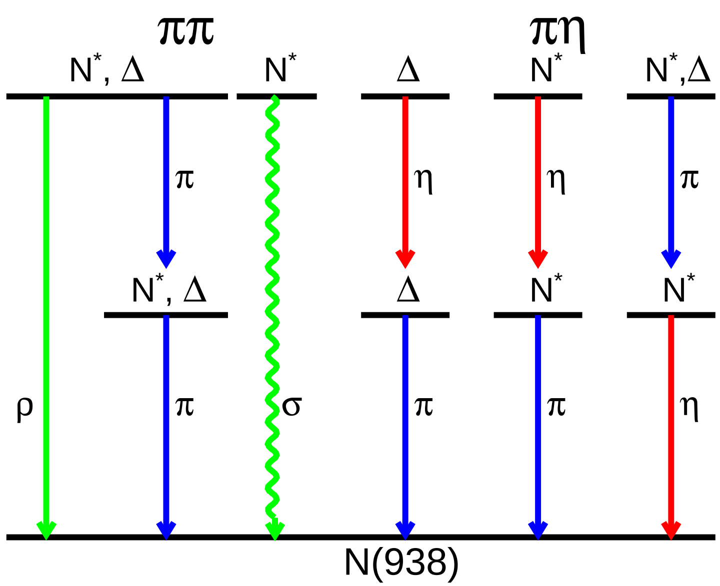
Final states:

- **single meson production:**

$$\gamma p \rightarrow p\pi, \eta, \eta', \omega ...; \Sigma K^{(\star)} ...$$



- **multiple meson production:**



Observables:

- **ang. distributions**

$\longrightarrow \quad d\sigma/d\Omega$

- **Dalitz plots**

$\longrightarrow \quad M(N, m_i), M(m_1, m_2)$

- **polarization dof:**

- linearely pol. beams
- circularly pol. beams
- longitudinally pol. targets
- transversely pol. targets
- recoil polarization

$\longrightarrow \quad I^{\odot}$

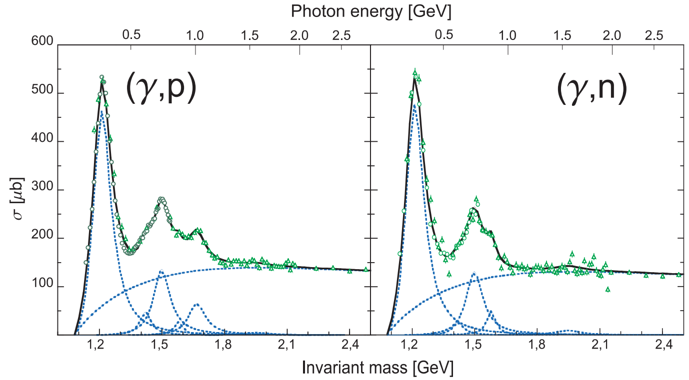
$\longrightarrow \quad \Sigma, P, T$

$\longrightarrow \quad E, G, H, F$

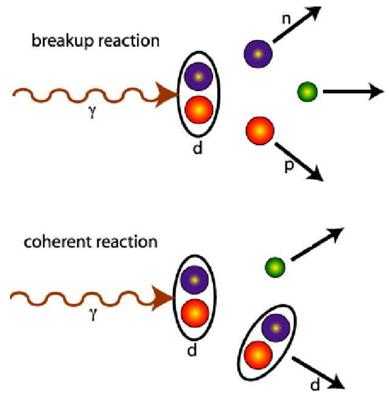
$\longrightarrow \quad ...$

Isospin: neutron targets

- **elm. excitations isospin dependent**

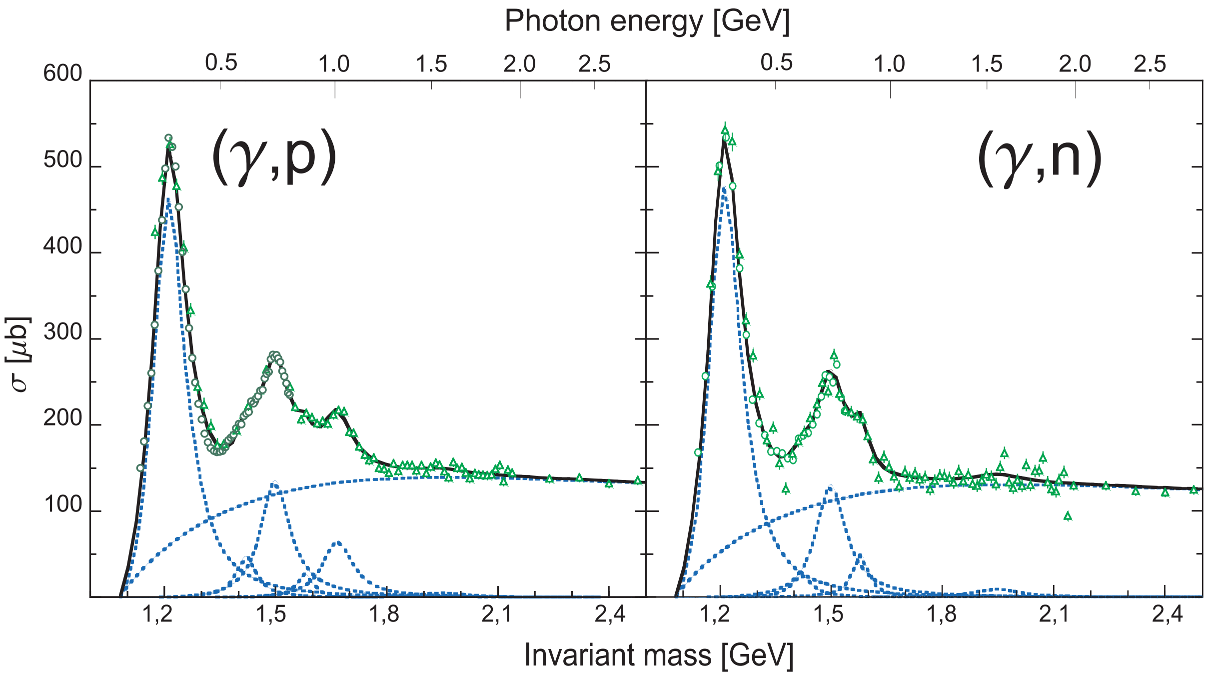


- **quasifree (coherent) off the deuteron**



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

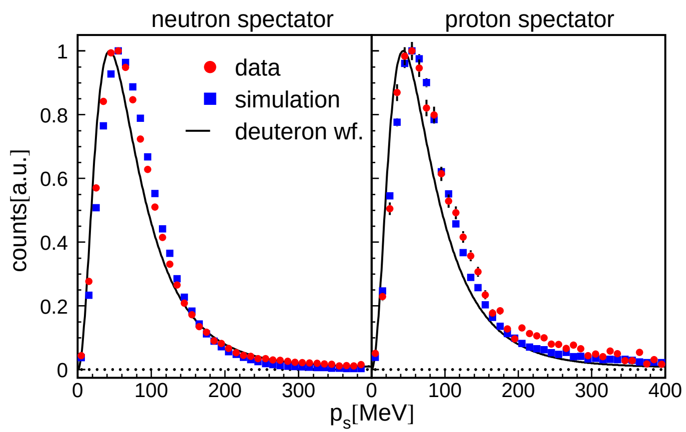
(2) reaction kinematics modified by Fermi motion - smears out all structures

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

Solutions:

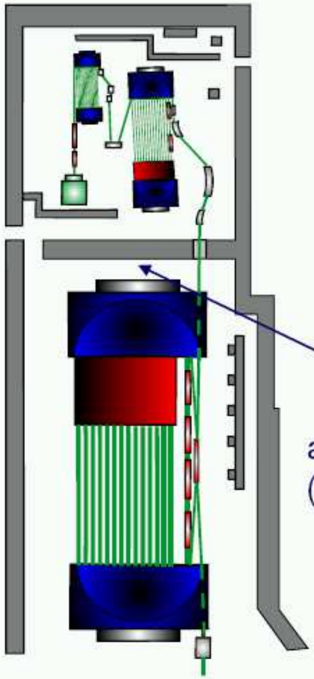
(1,2) Typical neutron detection efficiencies for CB and TAPS in the range 10% - 30%, CB cannot measure energies (TAPS via ToF); but kinematics completely defined:

- initial state: incident photon and deuteron at rest
  known/measured: $E_\gamma, m_d, \vec{p}_d = 0$
- 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

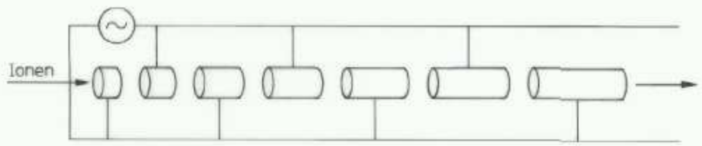
MAMI accelerator in Mainz

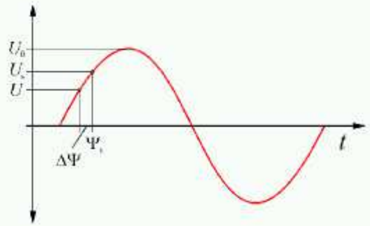


accelerators
(racetrack microtrons)

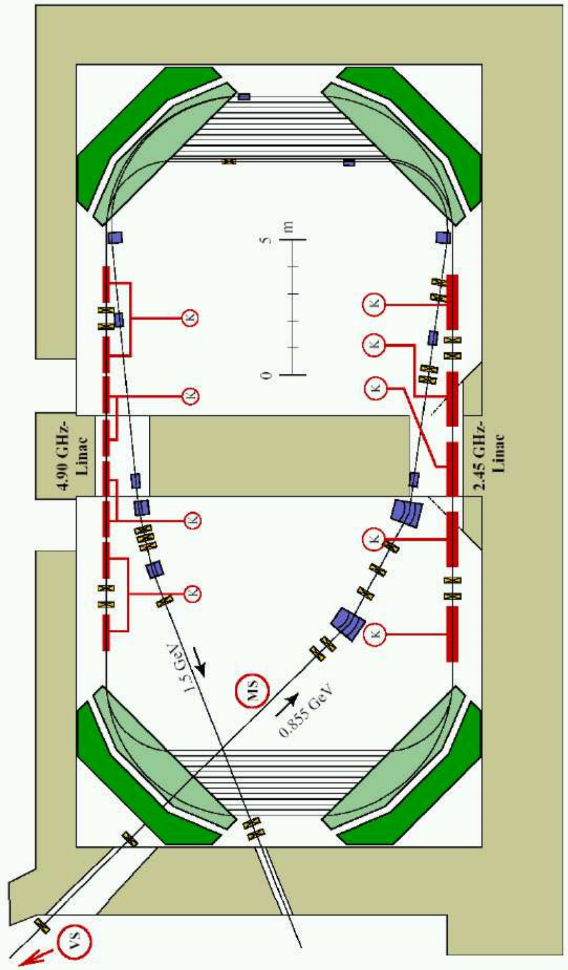
Mainz Microtron (MAMI)
continuous wave electron accelerator, max. beam energy 883

0. Stage: Linac (2.5 GHz, 3.45 MeV)



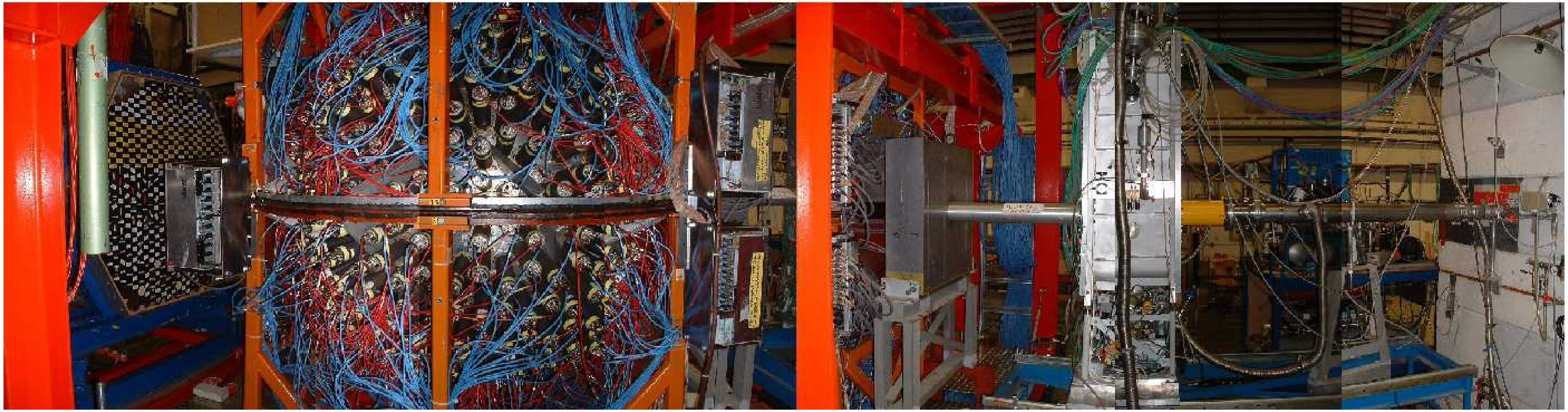


1.-3. Stage: Ractrack Microtrons:
- microbunches of 0.4ns
- linear accelerator structures
- constant B field ⇒ varing radii (18, 51, 90 return cycles)
- very efficient acceleration and continuous mode
- high current (0.1mA)



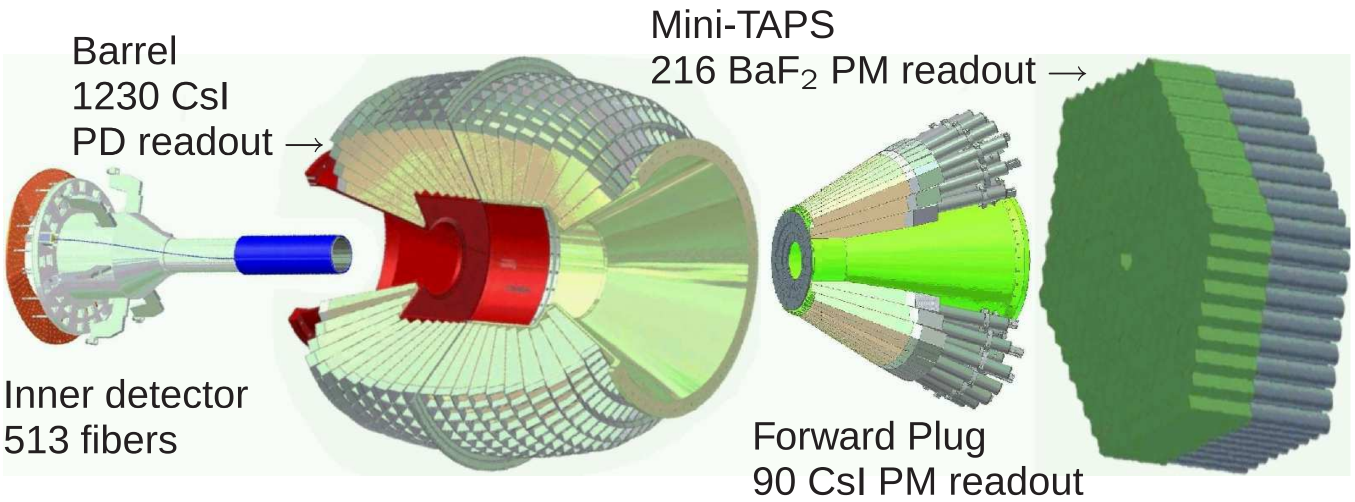
4. Stage: Harmonic Double Sided Microtron
maximum energy: 1.5 GeV

TAPS Crystal Ball - at MAMI

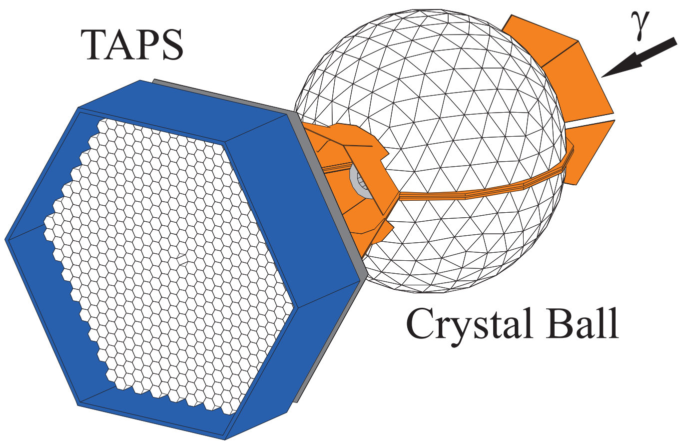


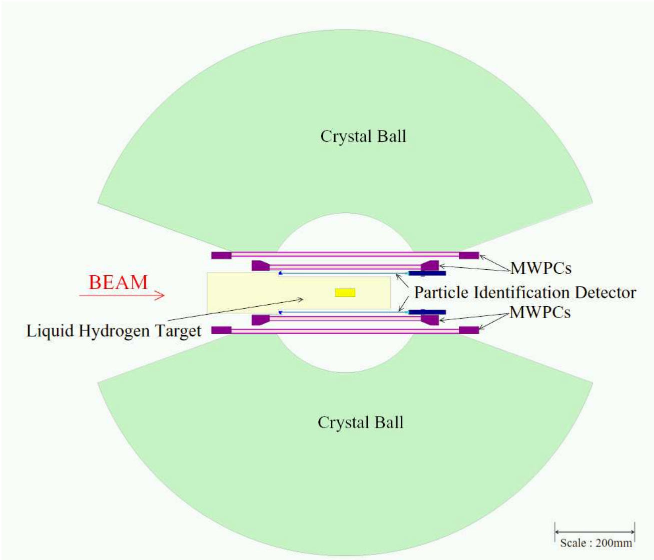
Calorimeters: Crystal Barrel & Crystal Ball with TAPS

- **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



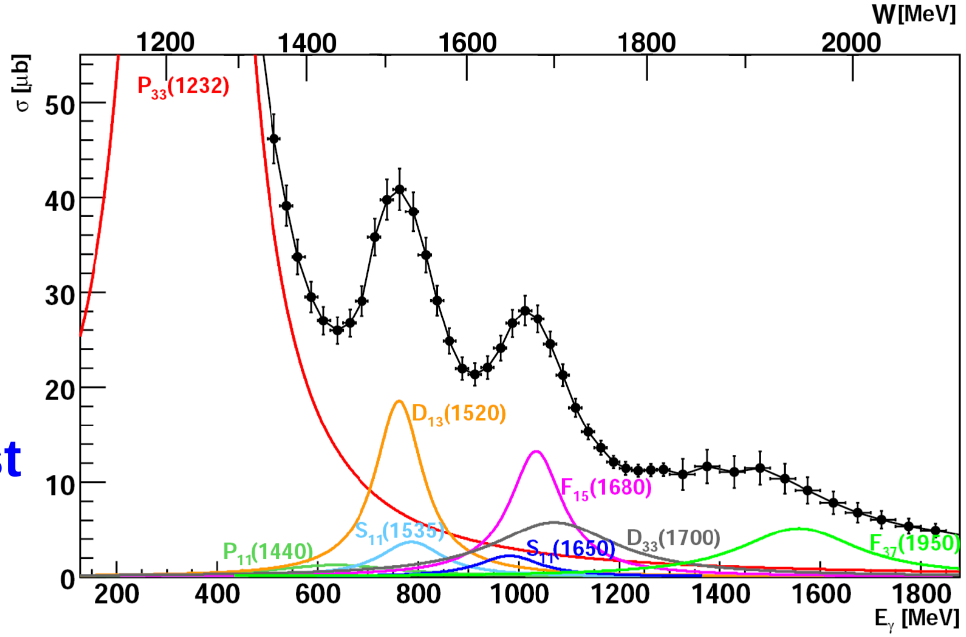
- **Mainz MAMI accelerator:**
  Crystal Ball (NaJ),
  TAPS (BaF_2) forward wall,
  inner detectors
  $E_\gamma \leq$ **1.5 GeV,**
  lin. pol.: available,
  circ. pol.: available





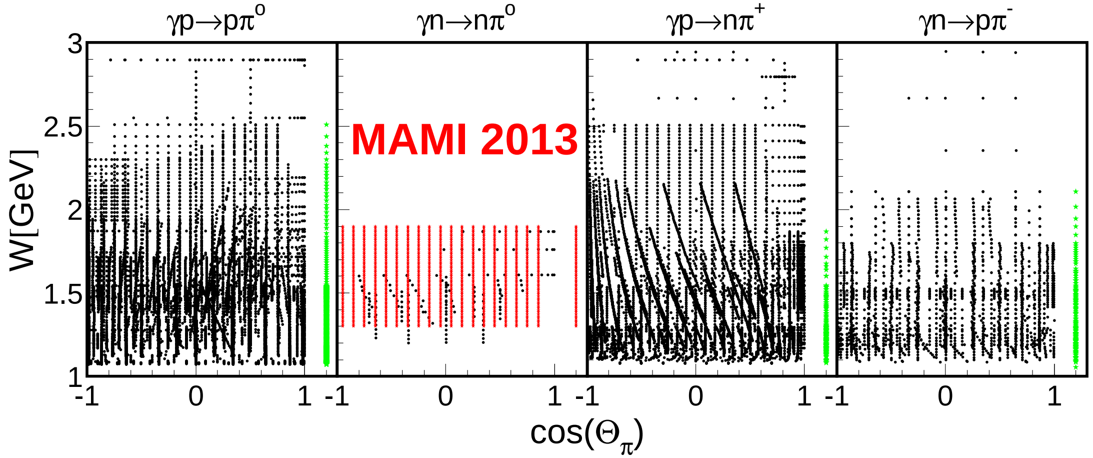
Results - Example I: Photoproduction of π^0-mesons

- 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

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

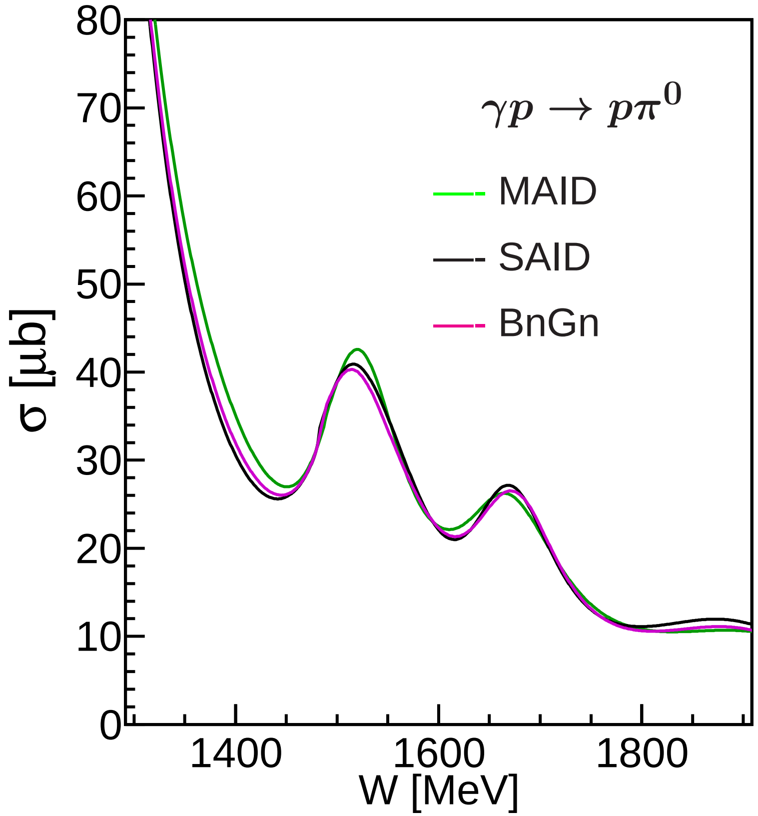
$$A(\gamma p \to \pi^0 p) = -\sqrt{\tfrac{1}{3}}A^{V3} + \sqrt{\tfrac{2}{3}}(A^{IV} - A^{IS})$$

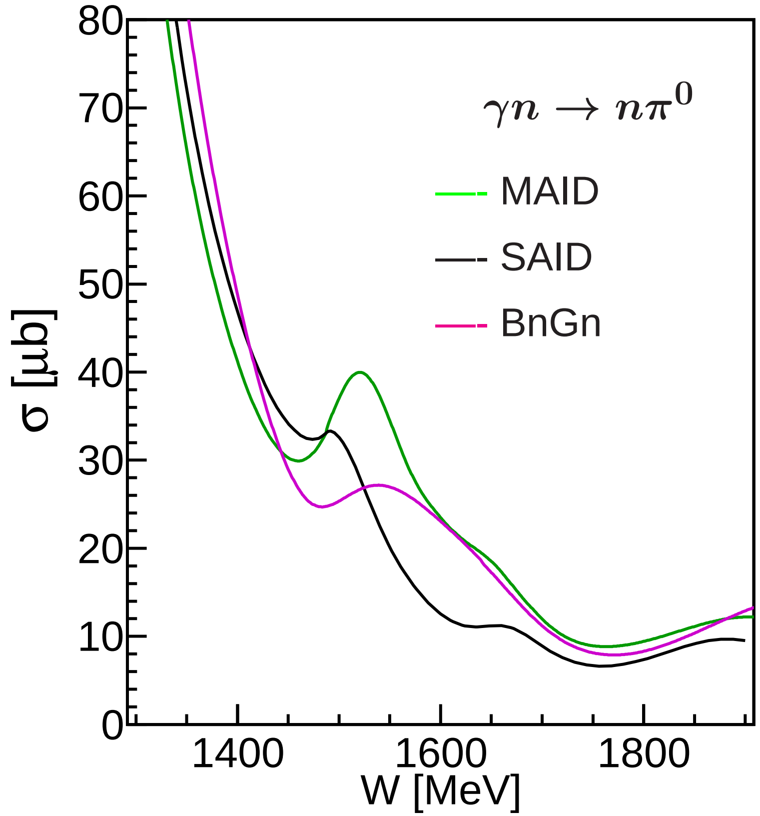
$$A(\gamma n \to \pi^- p) = +\sqrt{\tfrac{1}{3}}A^{V3} - \sqrt{\tfrac{2}{3}}(A^{IV} + A^{IS})$$

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

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

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



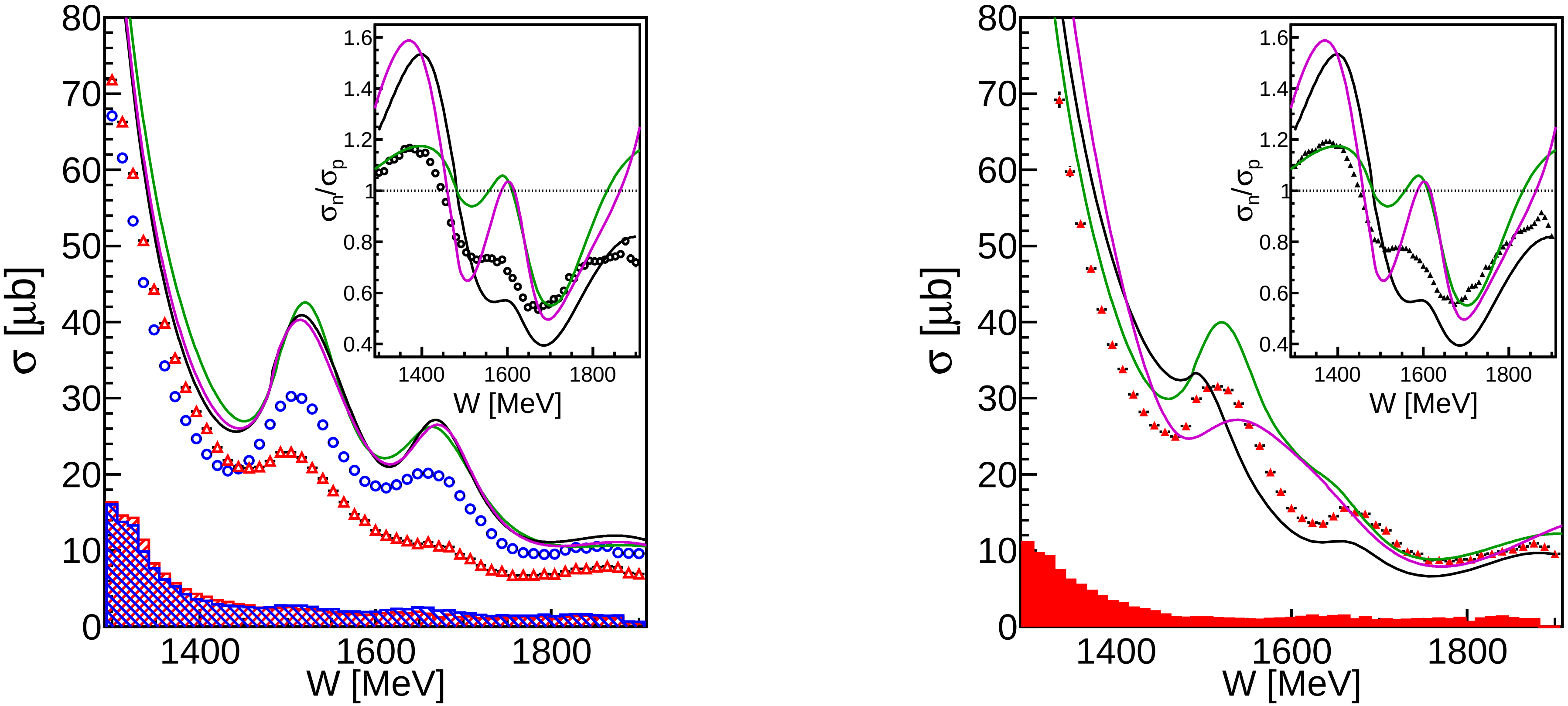


- **results agree for proton target (because fitted to proton data)**
- **predictions for neutron target disagree completely**
- **data from $\gamma n \rightarrow p\pi^-$ do not sufficiently constrain the fits for neutron target (completely different non-resonant backgrounds)**

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

(M. Dieterle et al., submitted to PRL)

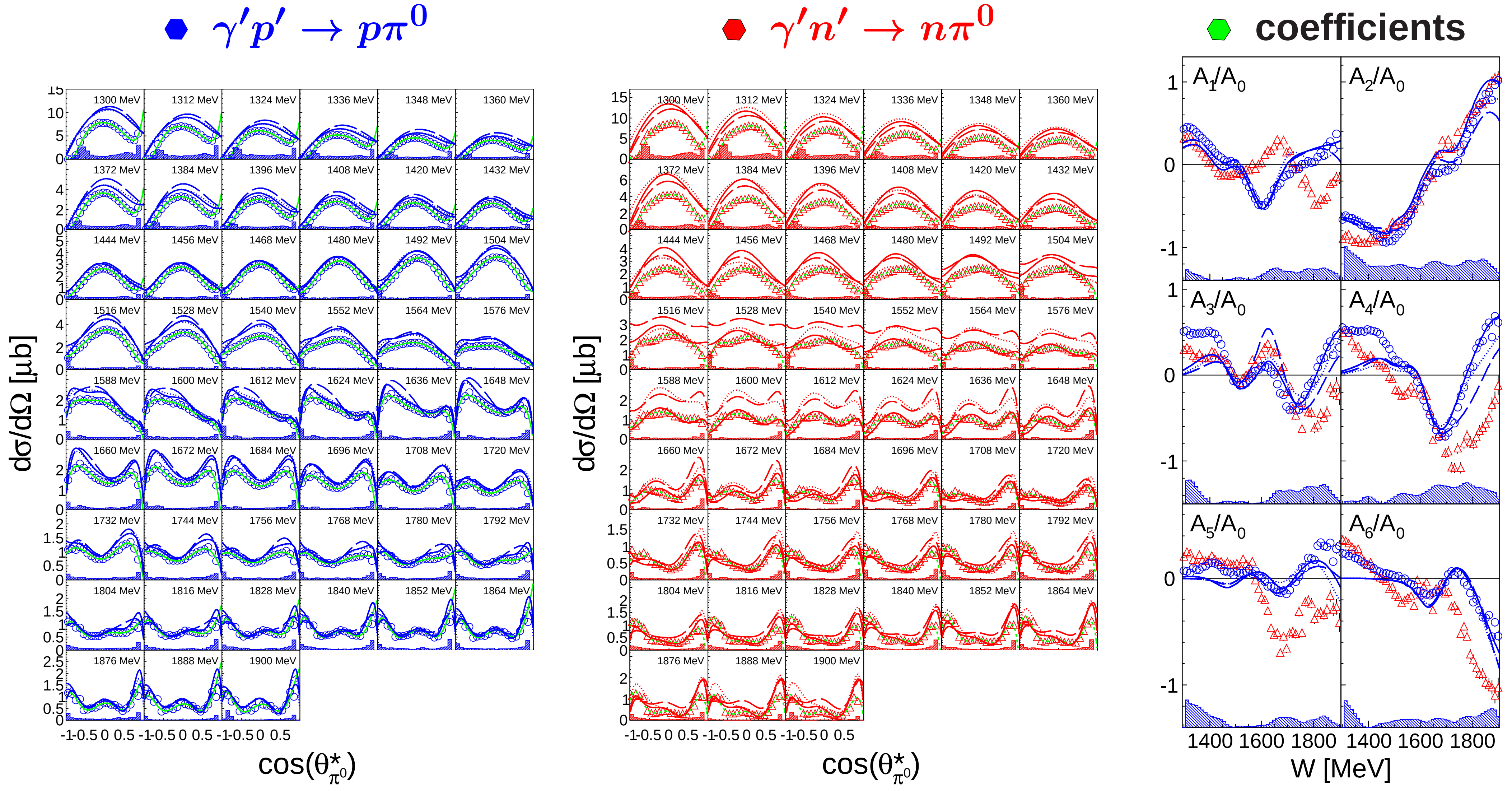
- **Total cross sections compared to PWA results:** — SAID — MAID — BnGa



- **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**

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

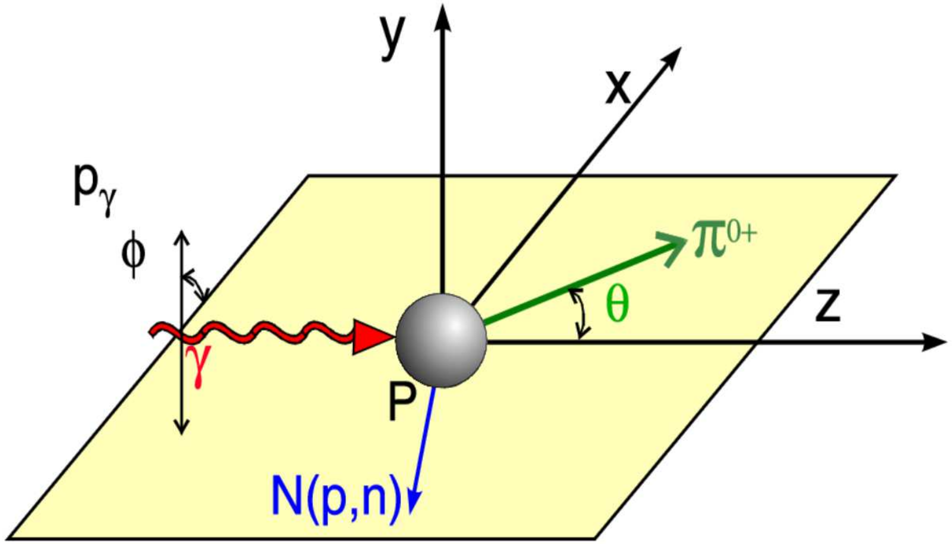
(M. Dieterle et al.)



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

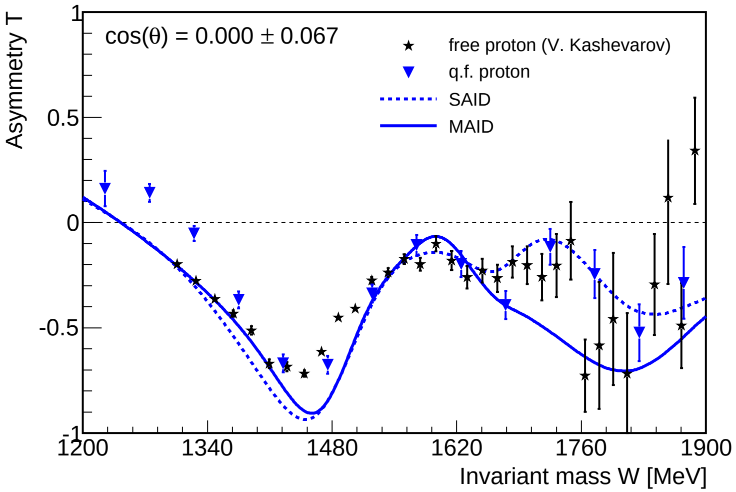
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \{1 - P_l\Sigma\cos(2\phi)$$
$$+P_x\left[-P_l H\sin(2\phi) + P_c F\right]$$
$$-P_y\left[-T + P_l P\cos(2\phi)\right]$$
$$-P_z\left[-P_l G\sin(2\phi) + P_c E\right]\}$$

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

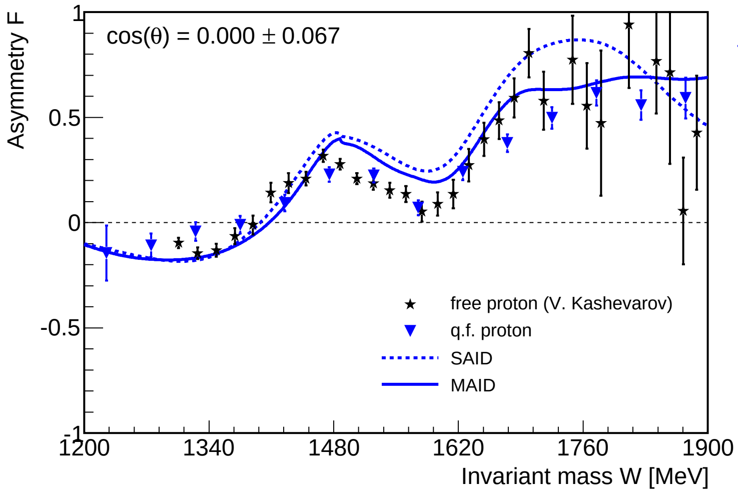
(Th. Strub et al., very preliminary)

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

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

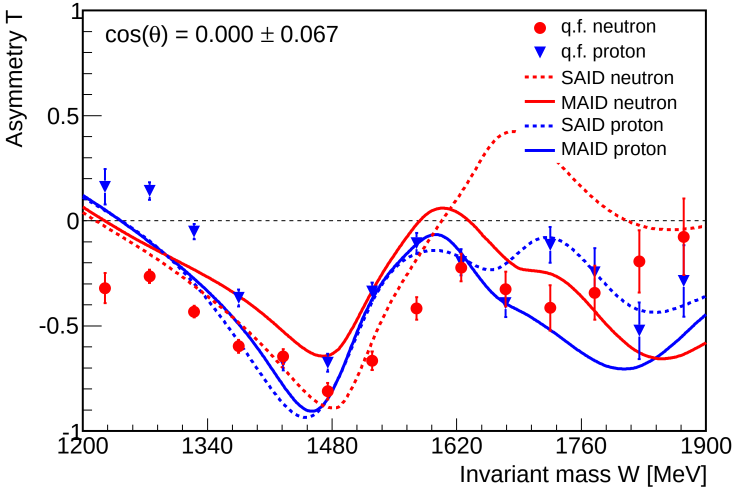


$F : \gamma p \rightarrow p\pi^0$ (blue: qf. p, black: free p)

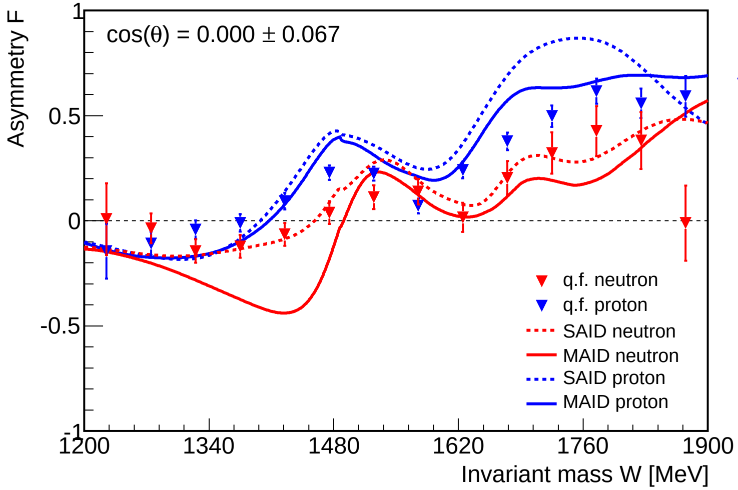


- asymmetries for free and quasi-free protons agree!

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



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



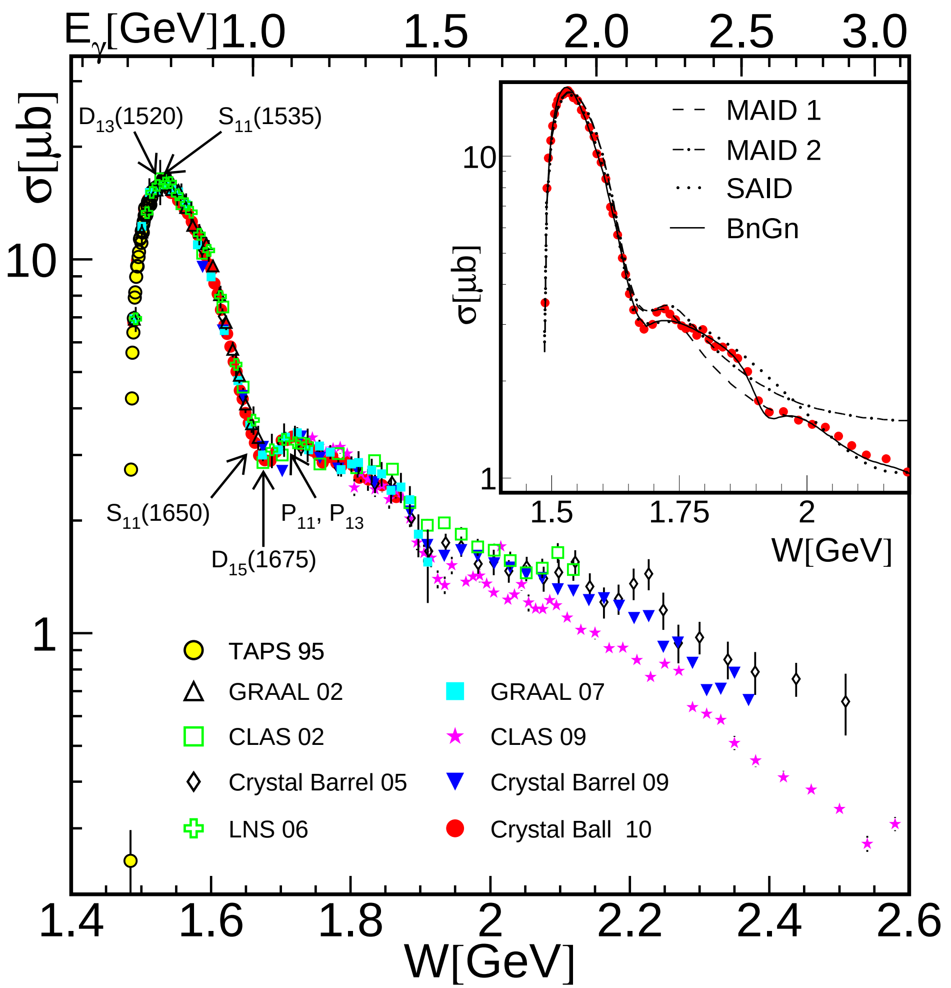
- significant deviations between PWA predictions and neutron data

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

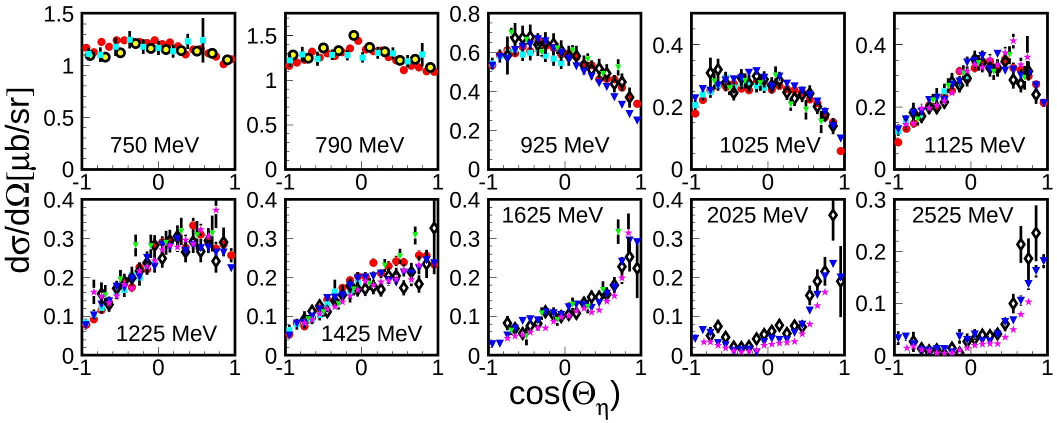
$\gamma p \rightarrow \eta p$



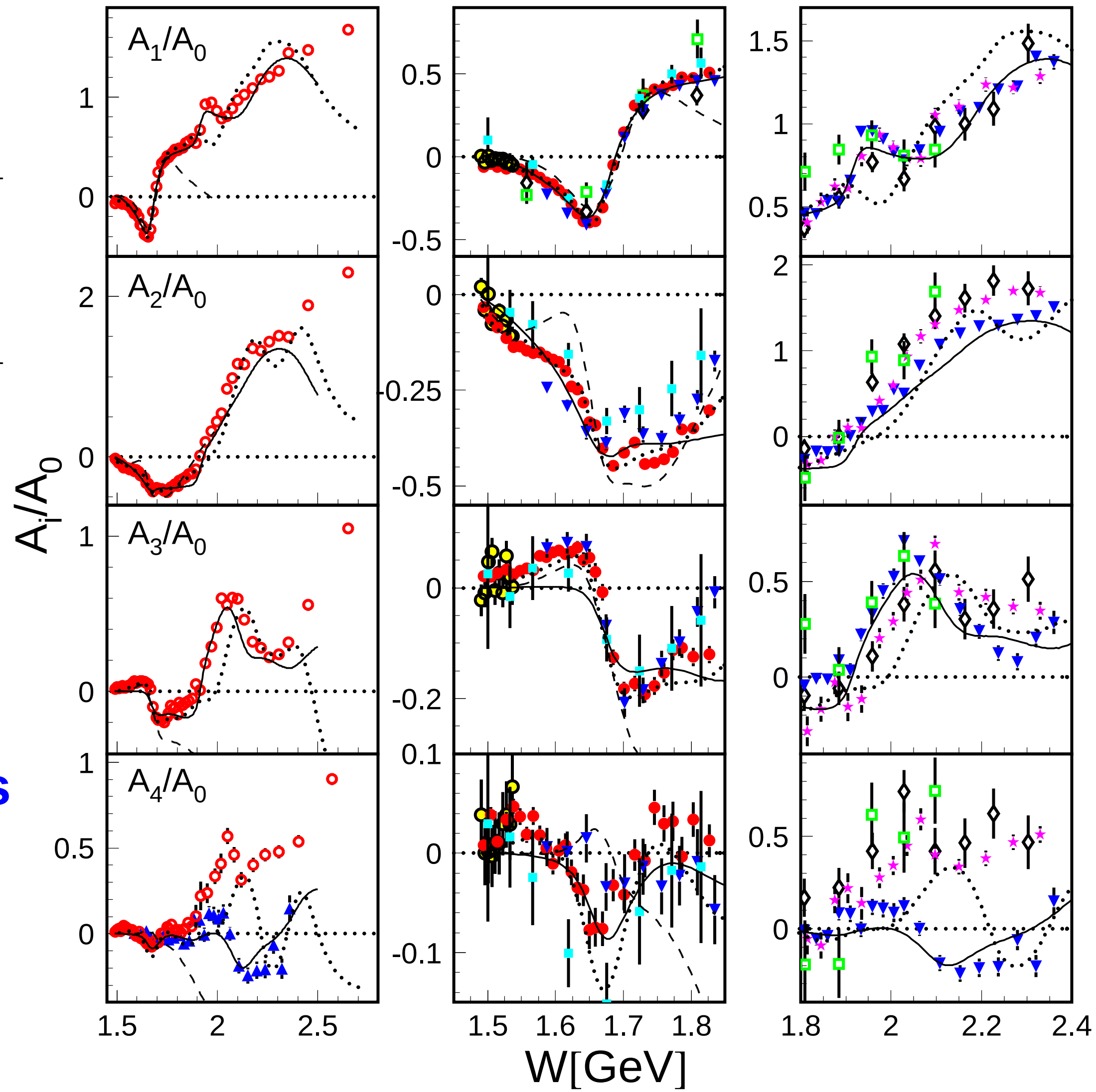
- **dominent contribution from S_{11} states, interference structure?**
- **$D_{15}(1675)$ has stronger electromagnetic coupling to neutron than to proton**
- **complicated pattern around 1.7 GeV**
- **PWA's agree excellently with data in S_{11} range, less so at higher energies**

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

- **typical angular distributions**



- **fitted coefficients**



- **fitted with:**

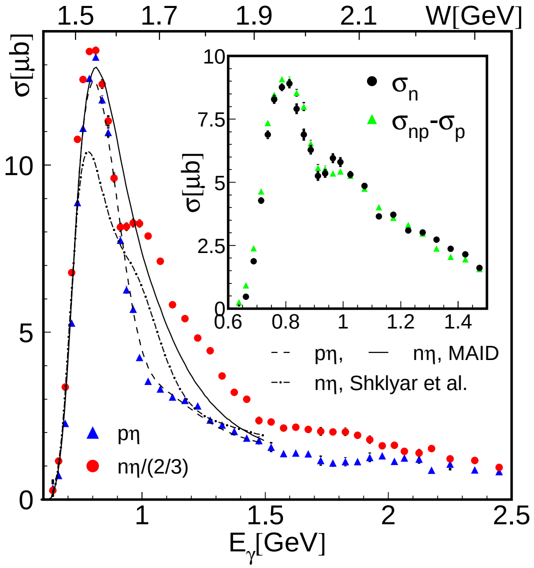
$$\frac{d\sigma}{d\Omega} = \sum A_i P_i(\cos(\Theta^\star))$$

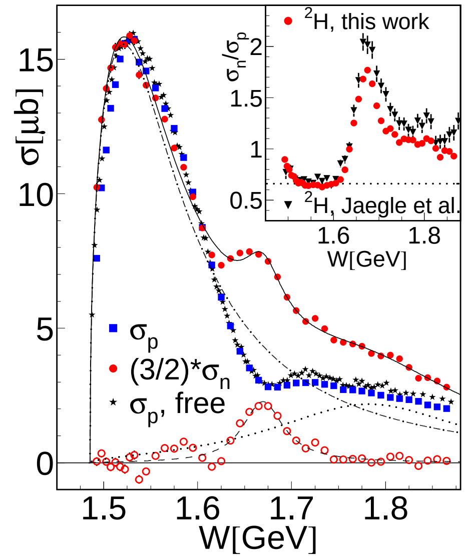
- **typical s-wave behavior at threshold**
- **fast variation - interesting structures around $W \approx$ 1.7 GeV**
- **diffractive (t-channel) at highest energies**

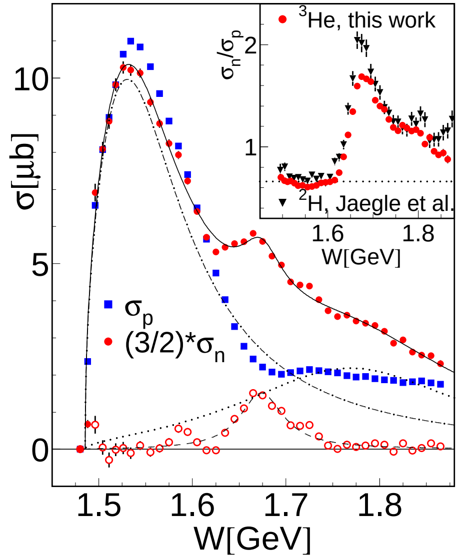
quasifree $\gamma n \to n\eta$: more surprises

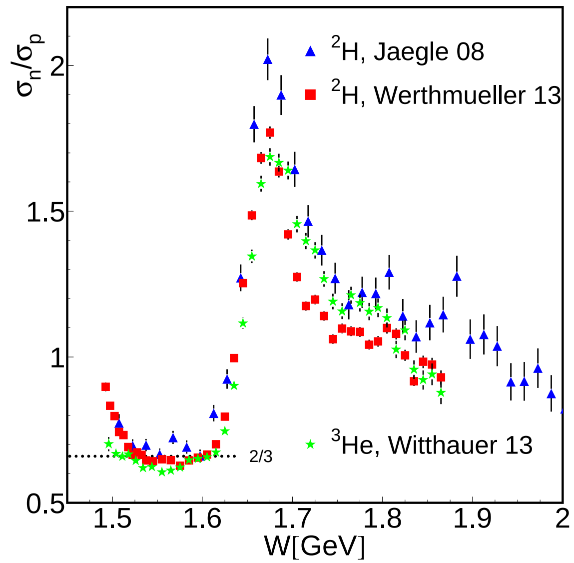
(I. Jaegle et al., D. Werthmüller et al., L. Witthauer et al.)

- **ELSA:** $\gamma d \to (n)(p)\eta$
- **MAMI:** $\gamma d \to (n)(p)\eta$ $\quad$ γ^3He $\to X(n)(p)\eta$
- **neutron/proton ratio**







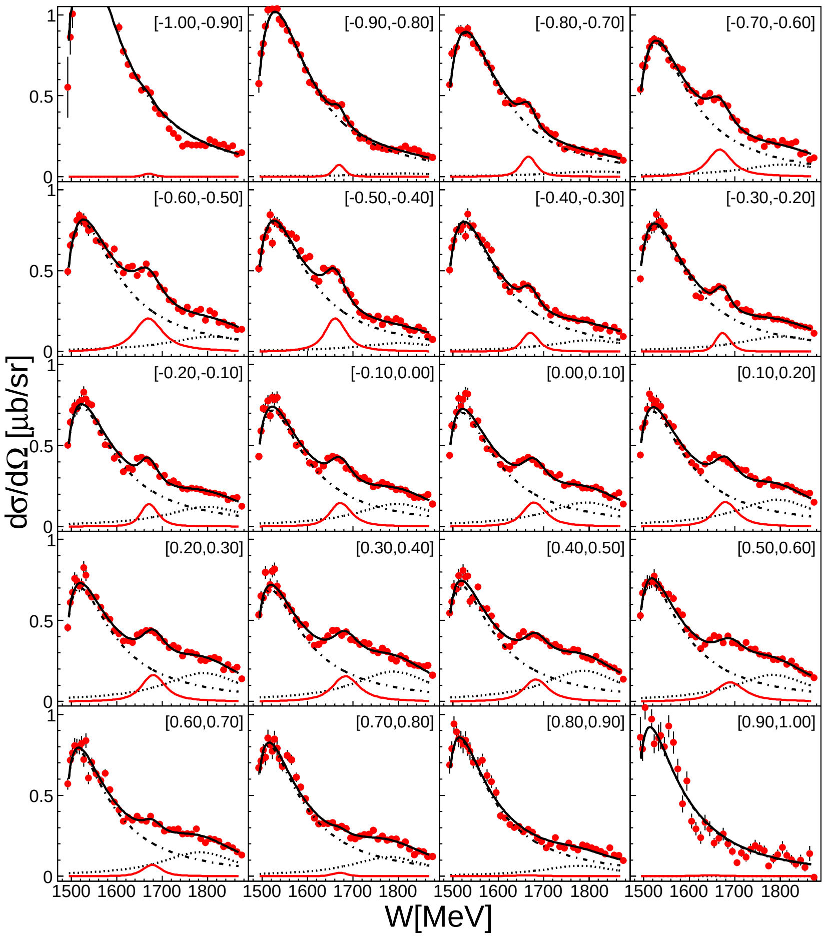


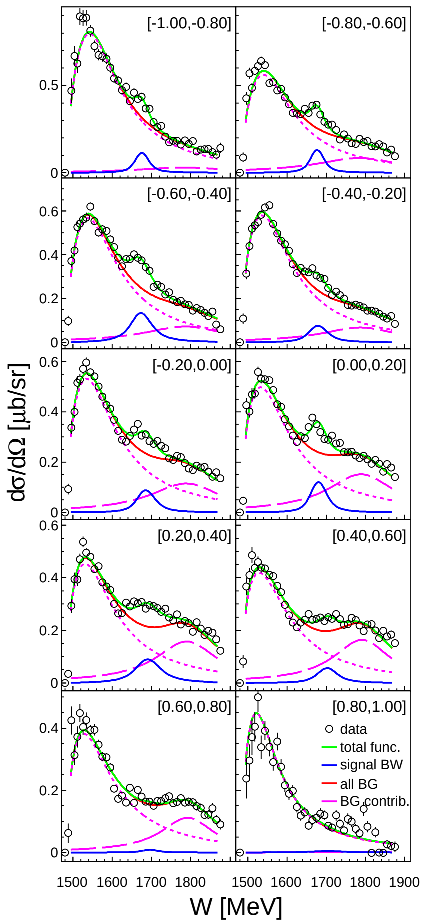
- **pronounced, narrow structure in neutron excitation function close to W=1.68 GeV**
- **width of structure $\approx$ 30 MeV**
- **neutron/proton ratios in agreement for all measurements:**
  - in S_{11}(1535) region 2/3 ratio
  - peak close to 1.7 GeV
  - very close to threshold almost unity, no distinction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

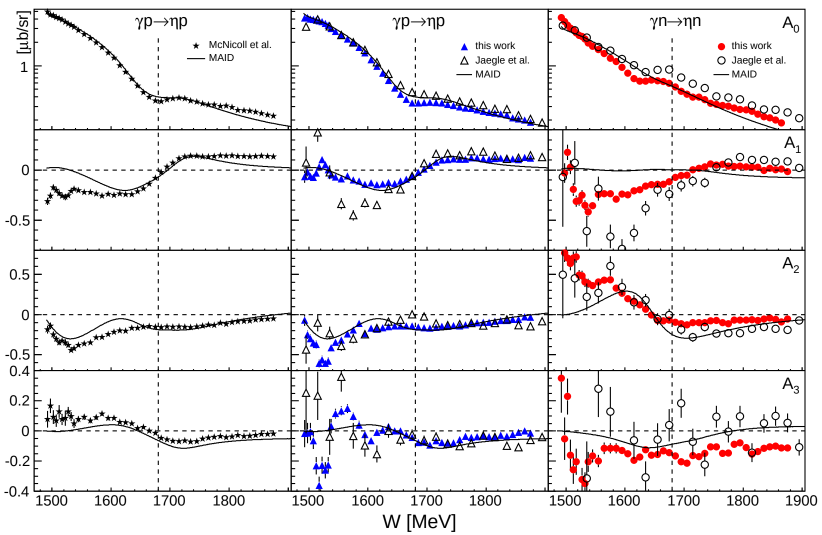
$\gamma n \rightarrow n\eta$ - excitations functions for different angular bins

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

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



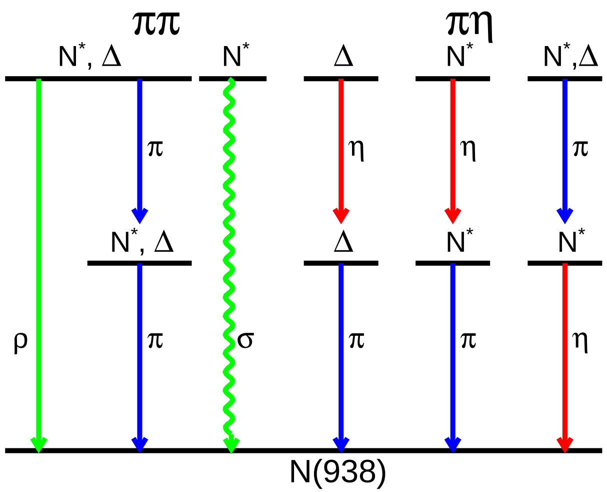




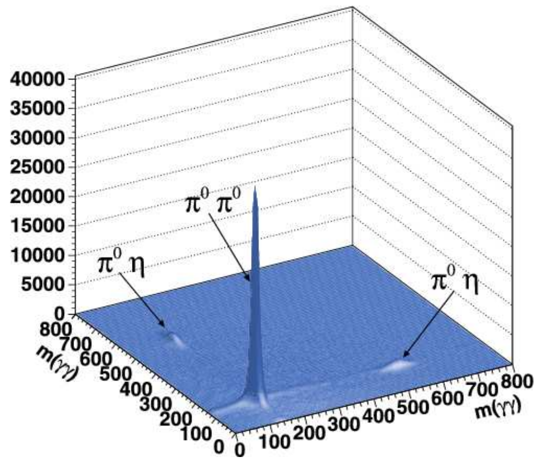
- **non-trivial angular dependence observed**

photoproduction of meson pairs

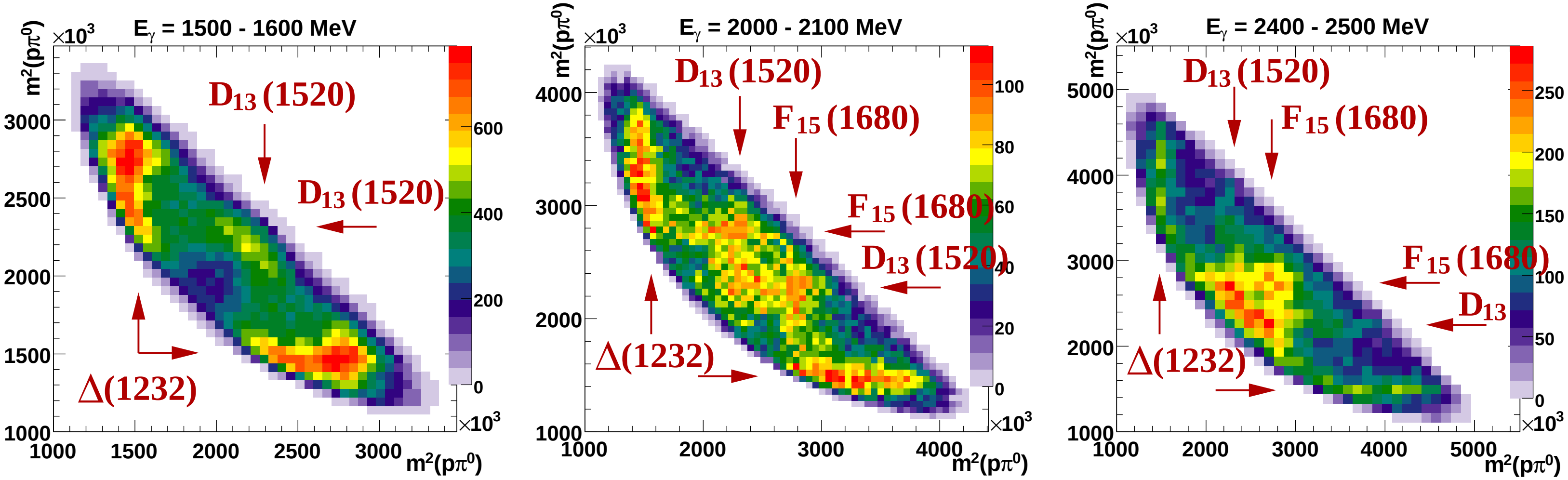
- $\pi\pi$- & $\pi\eta$-pairs:
  access to cascade decays



- clean reaction identification
  in invariant mass spectra



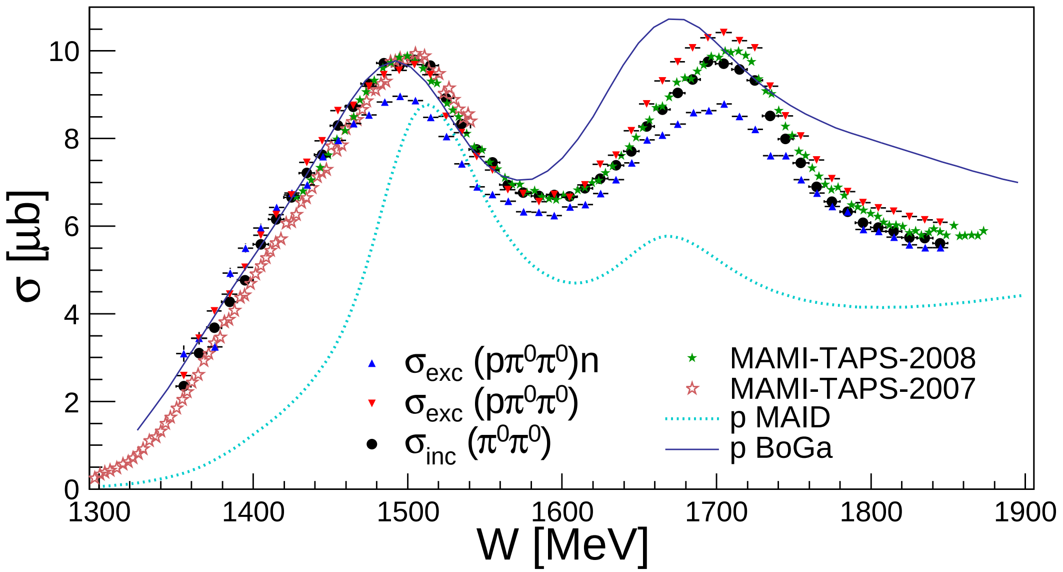
- Dalitz-plot analysis of $\pi^0\pi^0$-pairs



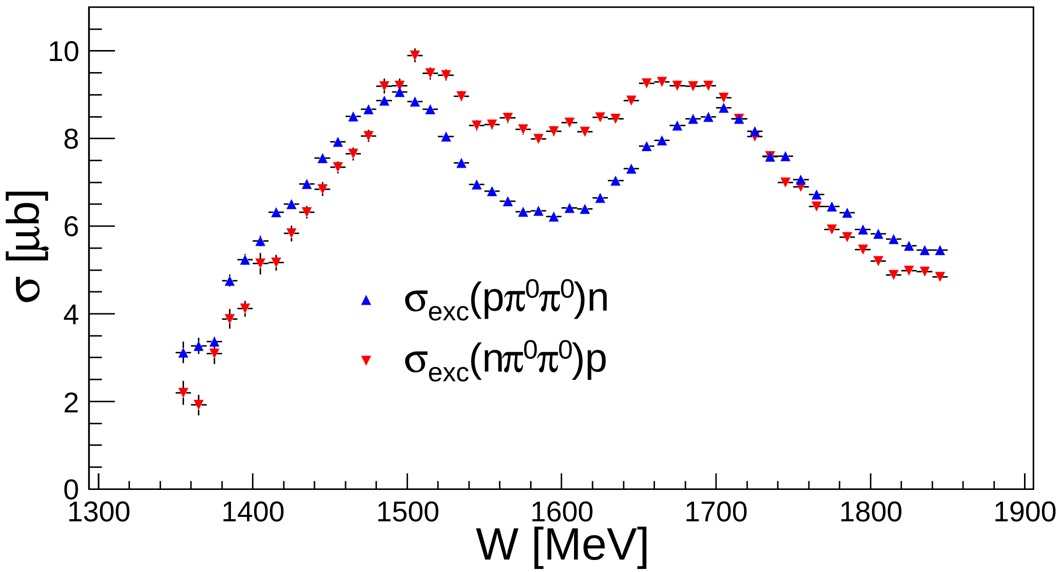
$\gamma N \rightarrow N\pi^o\pi^o$ - total cross sections

(M. Oberle et al., preliminary)

- **free & quasi-free proton**



- **quasi-free proton & neutron**

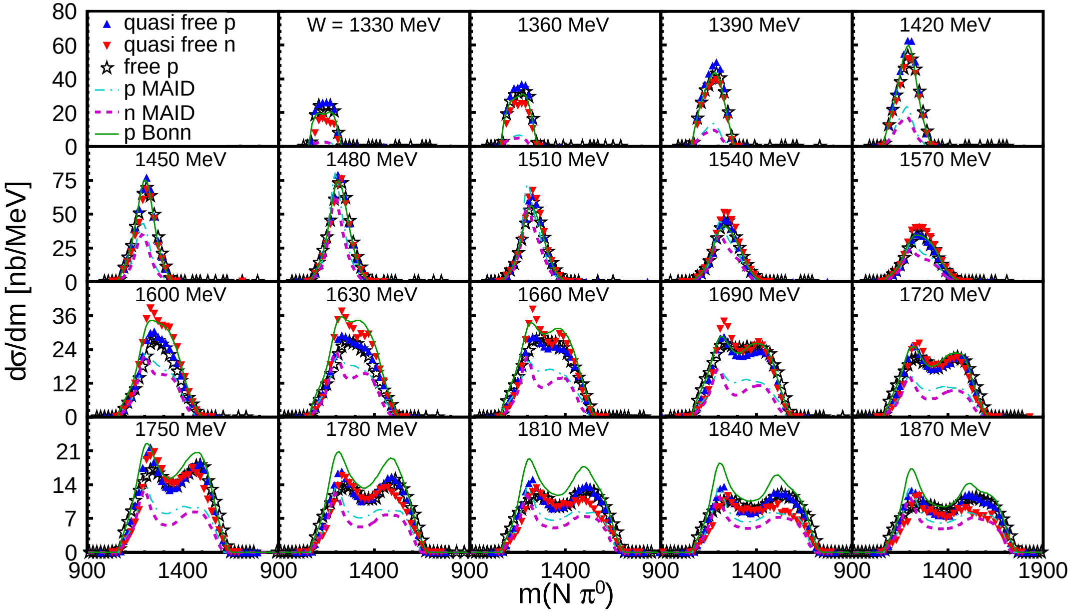


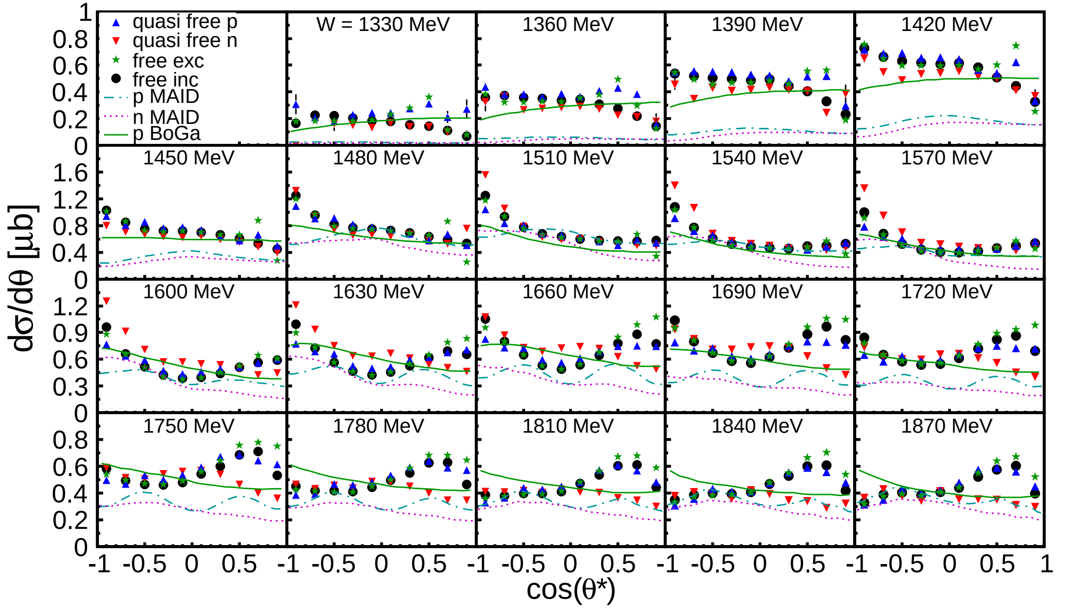
- **moderate FSI effects found for quasi-free proton cross section**
- **proton & neutron excitation functions similar,**
  largest differences around W=1600 MeV between resonance peaks

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

(M. Oberle et al., preliminary)

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





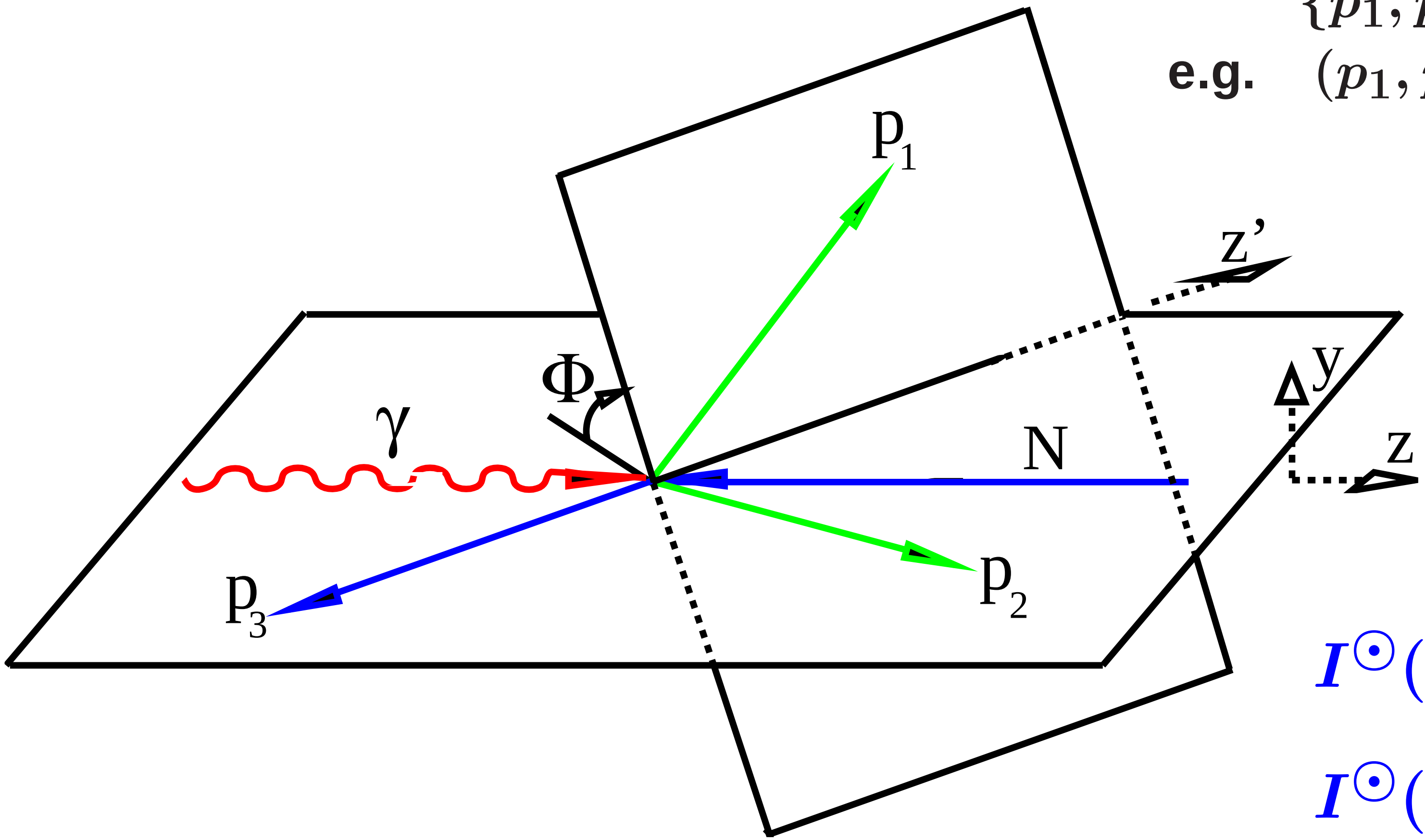
- **invariant mass distributions show contributions from $\Delta^\star, N^\star \rightarrow \pi\Delta(1232)$ & $\Delta^\star, N^\star \rightarrow \pi D_{13}(1520)$; very similar for p & n**
- **proton & neutron angular distributions different for large W $\rightarrow$ different resonance contributions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

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



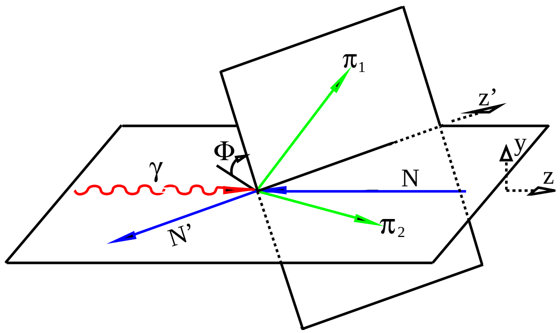
$$I^{\odot}(\Phi) \equiv \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

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

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

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

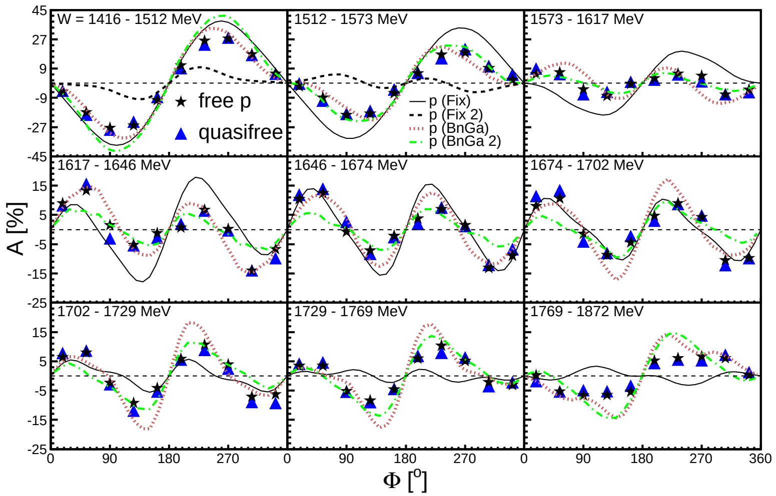
M. Oberle et al., PLB 721(2013) 237, M. Oberle et al., submitted to EPJA



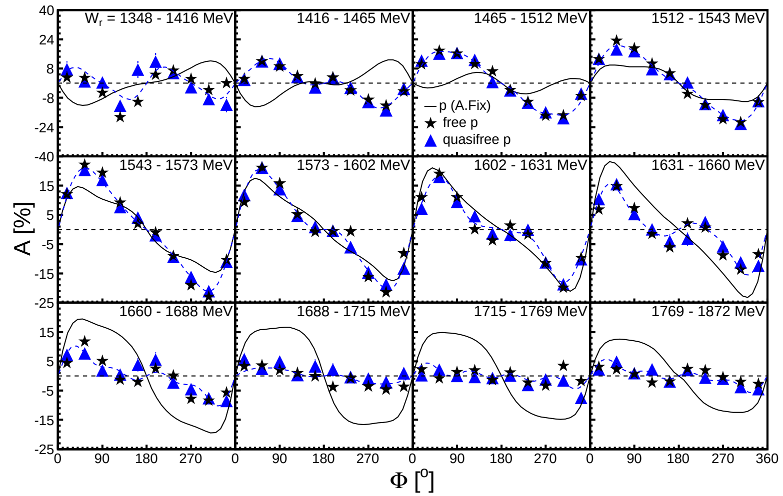
pions ordered by invariant mass:

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

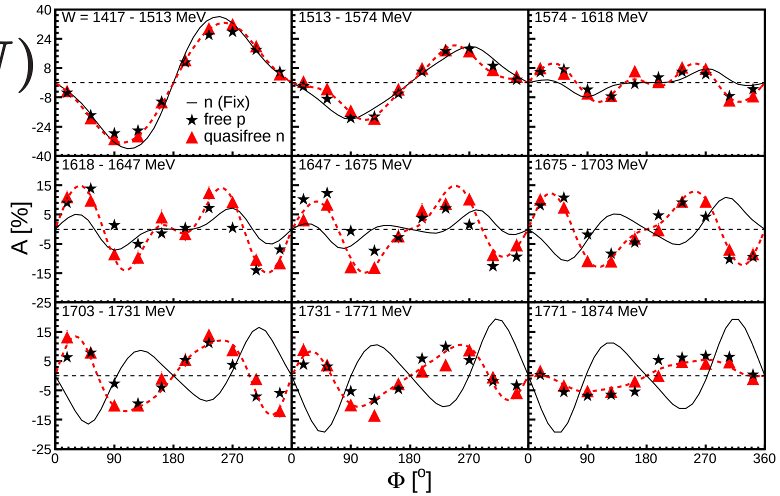
- $\gamma p \rightarrow p\pi^0\pi^0$ (blue: qf. p, black: free p)



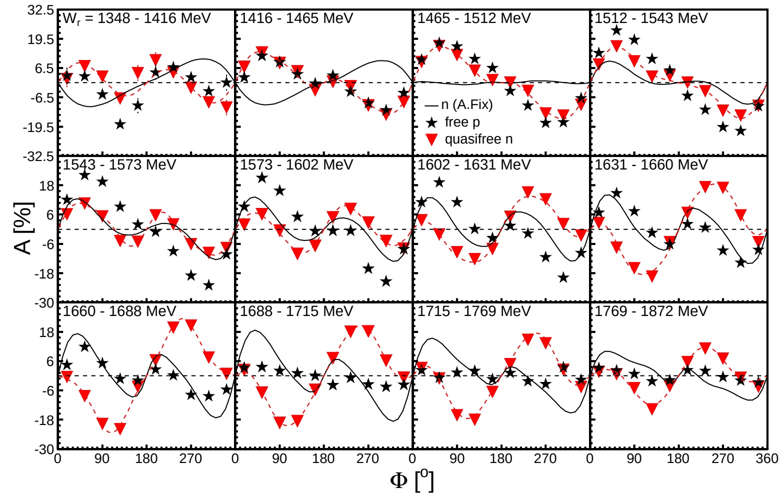
- $\gamma p \rightarrow n\pi^0\pi^+$ (blue: qf. p, black: free p)



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

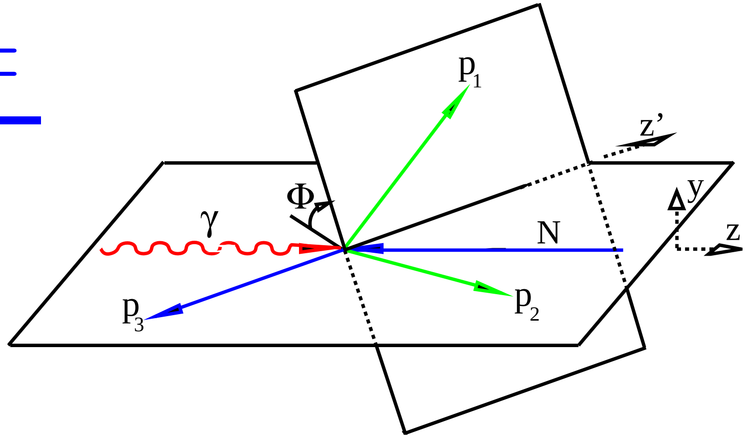


- $\gamma n \rightarrow p\pi^0\pi^-$ (red: qf. n, black: free p)



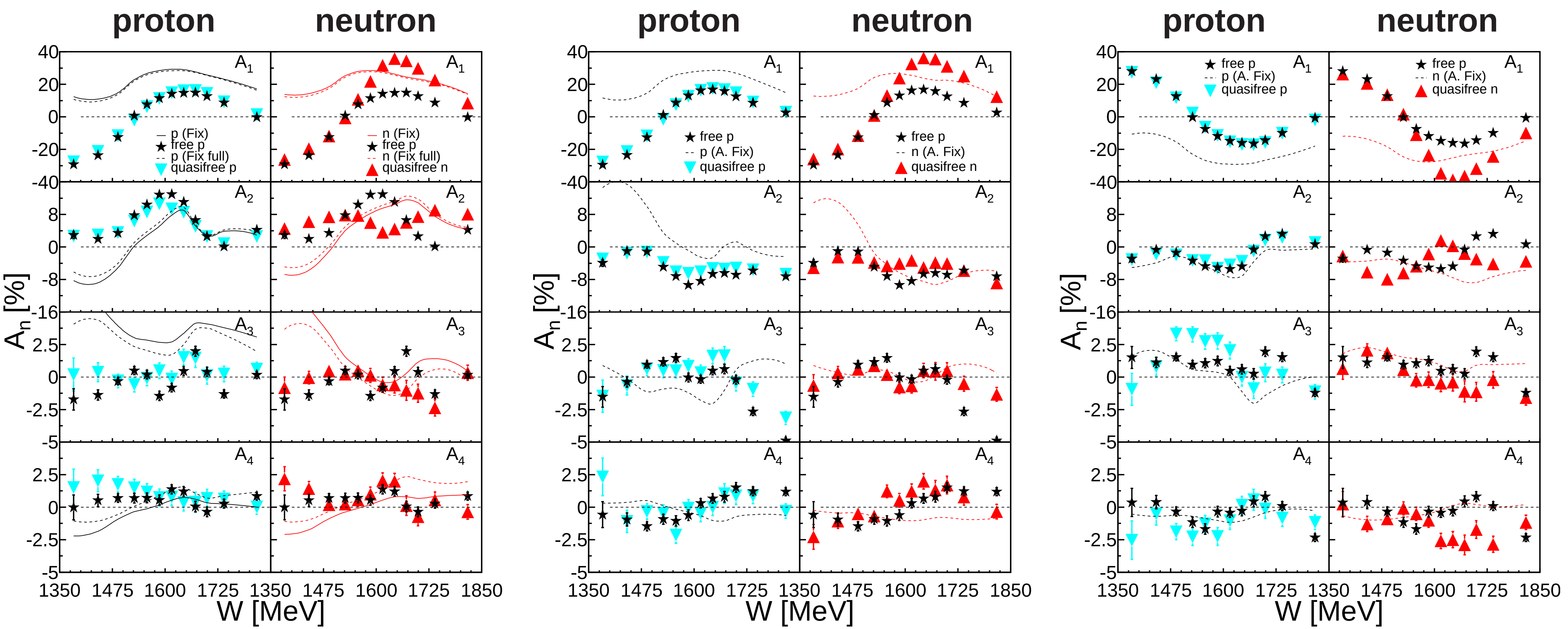
‘charge ordered’ asym.: $\gamma N \rightarrow N\pi^o\pi^\pm$

(M. Oberle et al., preliminary)



- 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

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

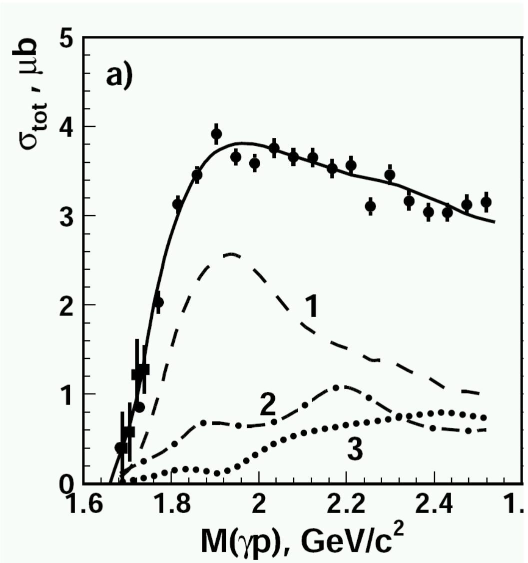


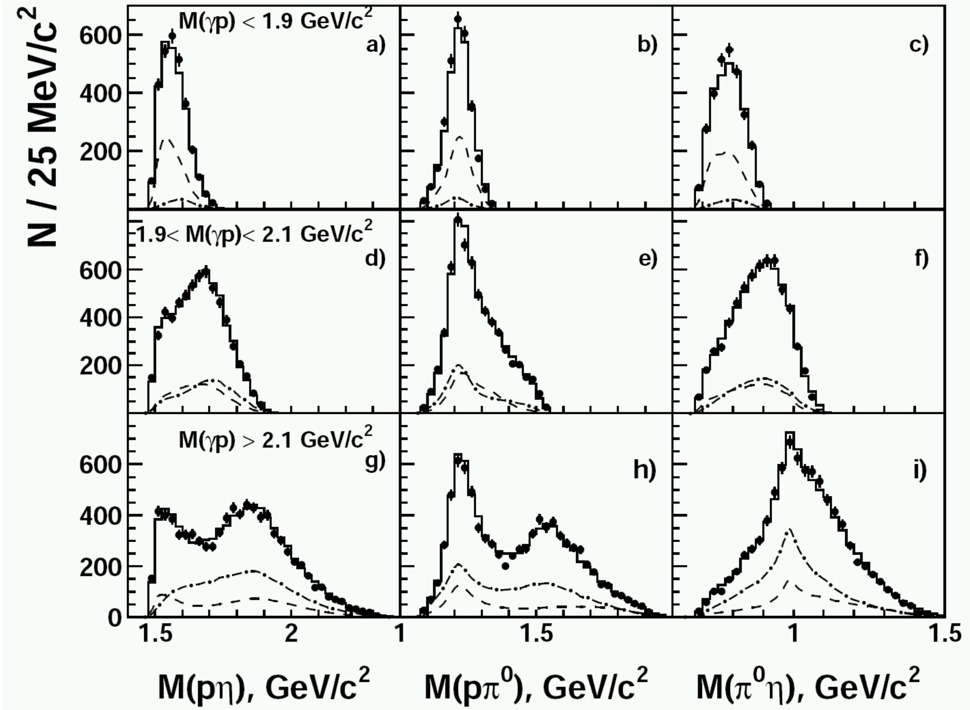
MAMI

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



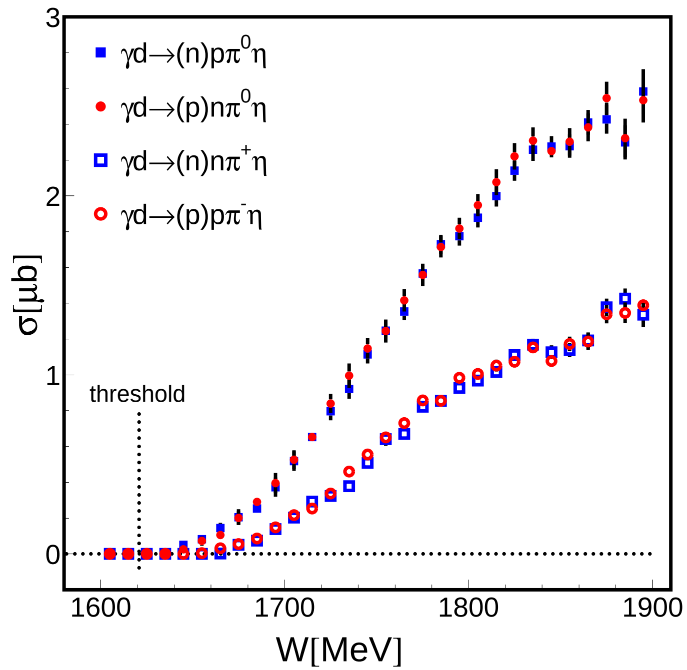


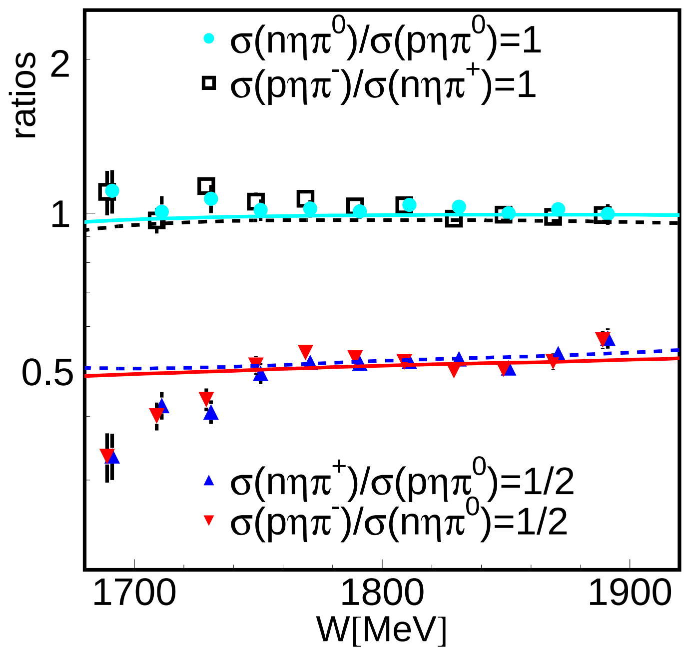
- dominant final states: $--\ \Delta(1232)\eta$, $-.-\ N(1535)\pi$, ... $pa_o(980)$
- dominant process close to threshold: $\gamma p \rightarrow$D$_{33}$(1700)$\rightarrow\ \eta$P$_{33}$(1232)$\ \rightarrow\ \eta\pi^o$p

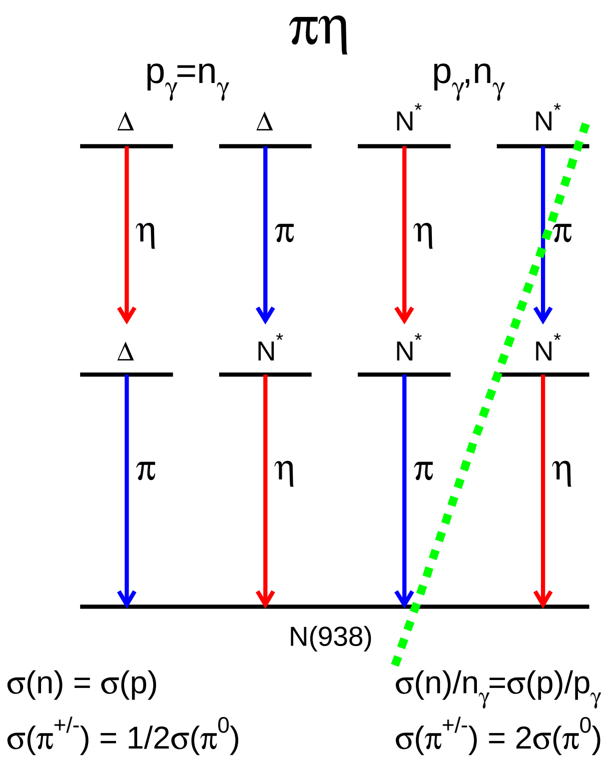
isospin decomposition of $\pi\eta$-photoproduction

(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 import-ant for polarization observables than for cross sections
- experiments at MAMI taking data or are under analysis, expriments at ELSA will start after detector upgrade

Conclusions

- excitation spectrum of nucleons is one of the most important testing grounds of non-perturbative QCD, but not yet understood
- progress on theory side from lattice expected, but still in very early state
- progress in experiment currently mainly from photoproduction of mesons resting on three pillars:
  - exploraration of polarization observables (beam, target, recoil) to establish a data base allowing almost model independent analyses
  - investigation of different final states including multi-meson production so that coupled channel analyses can identify excited states decoupled from dominant decays like π^0 emission to the nucleon ground-state
  - investigation of reactions off quasi-free neutrons to establish also the photocouplings for neutron resonances
- first impact is demonstrated, resonance listings in PDG (so far strongly biased to elastic pion reactions) become more and more influenced by results from the photon induced reactions