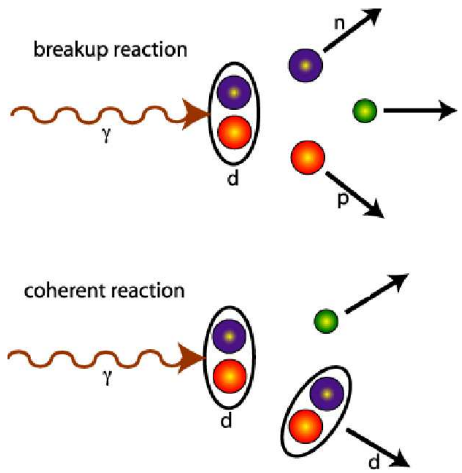
Photoproduction of mesons off light nuclei

- excited states of the neutron and meson - nucleus bound states -

B. Krusche, U. Basel, CBELSA/TAPS, CBALL/TAPS collaborations

Introduction



Experimental setups

- Crystal Barrel & TAPS @ ELSA
- Crystal Ball & TAPS @ MAMI

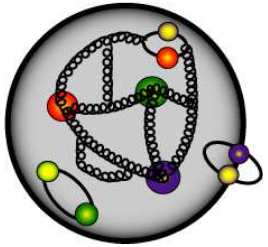
Experimental results

- photoproduction of mesons off quasi-free nucleons: η, η', π^o, $\pi^o\pi^o$, $\pi^o\eta$,...
- coherent photoproduction of mesons off light nuclei: $\pi^o\eta$, $\pi^o\pi^o$, $\pi^o\pi^o\pi^o$
- search for η-mesic nuclei: ^{3}He$(\gamma,\eta)^3$He, ^{7}Li$(\gamma,\eta)^7$Li

Conclusions

Structure of the Nucleon

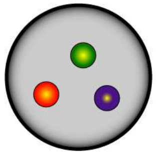
- **complex many body system**



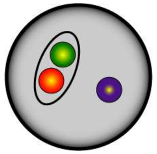
- valence quarks
- sea quarks
- gluons

- **models - effective dof's:**

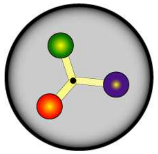
- **3 equivalent constituent quarks**



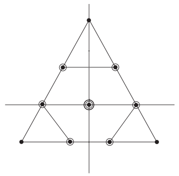
- **quark - diquark models (fewer states)**



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

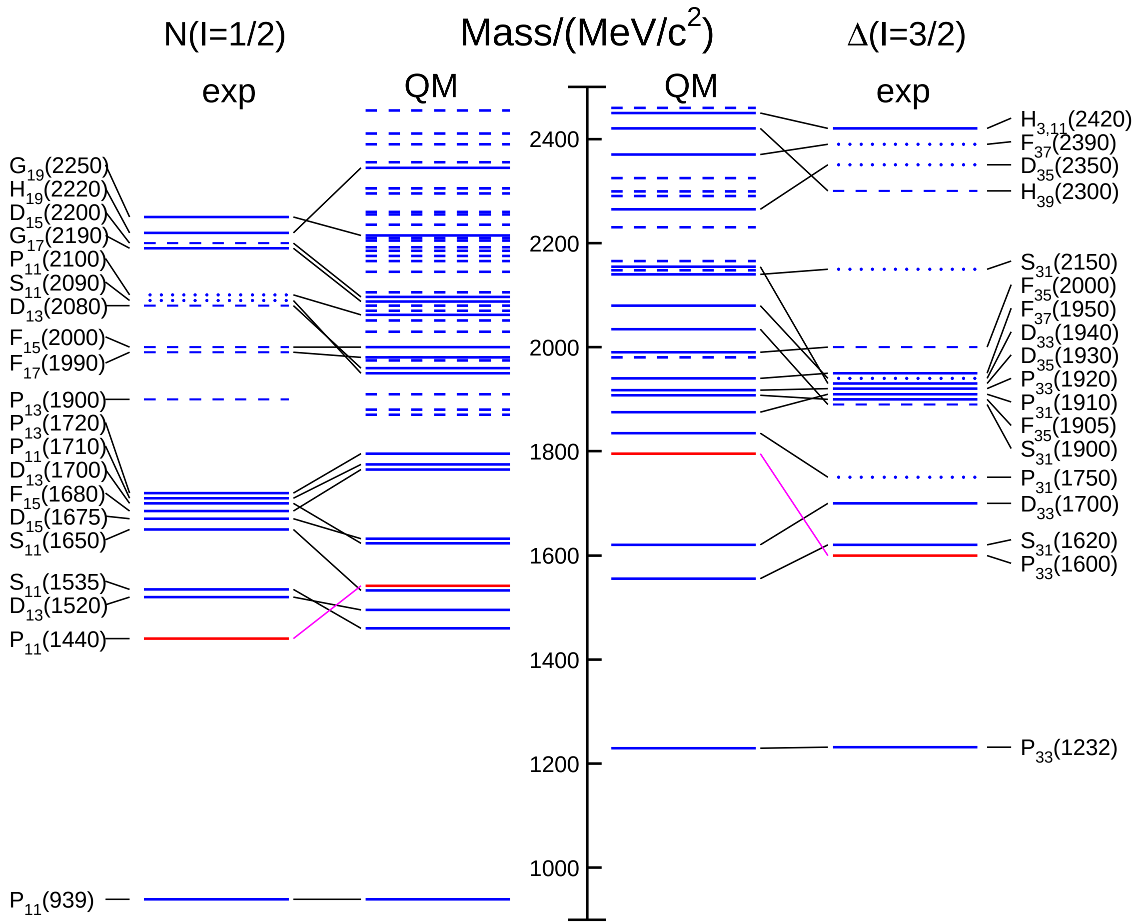


- **chiral soliton models (anti-decuplet states)**



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

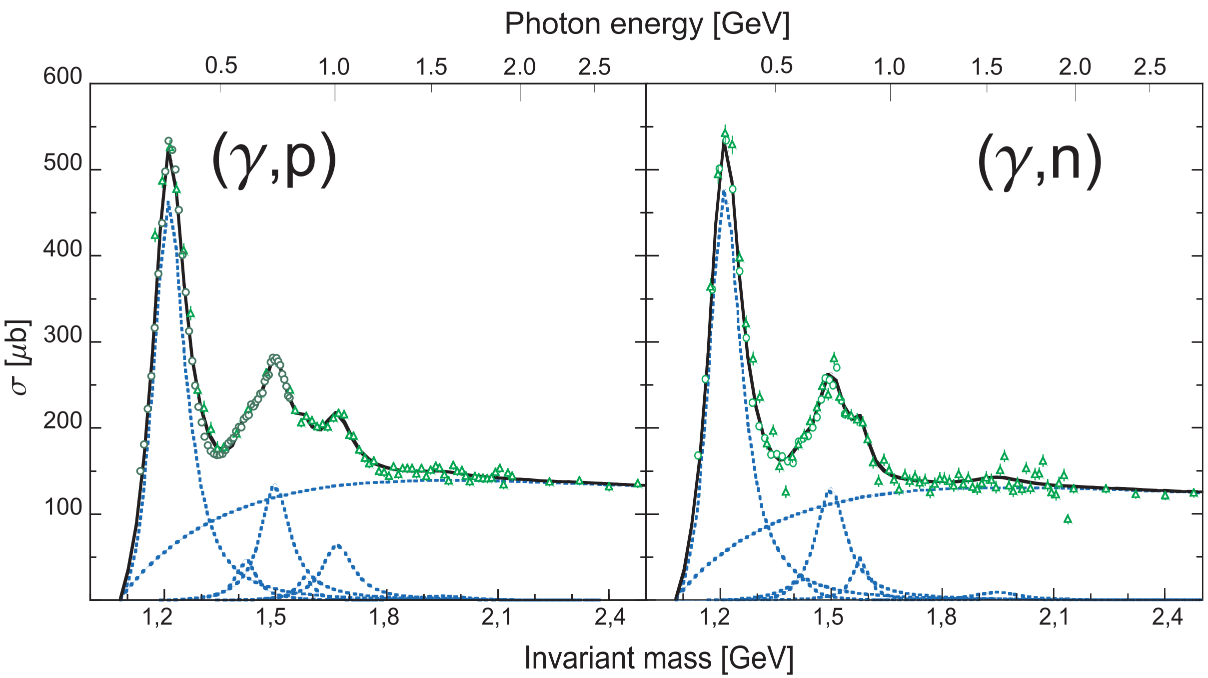
- **comparison: known excited states - constituent quark model** (Capstick & Roberts)



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

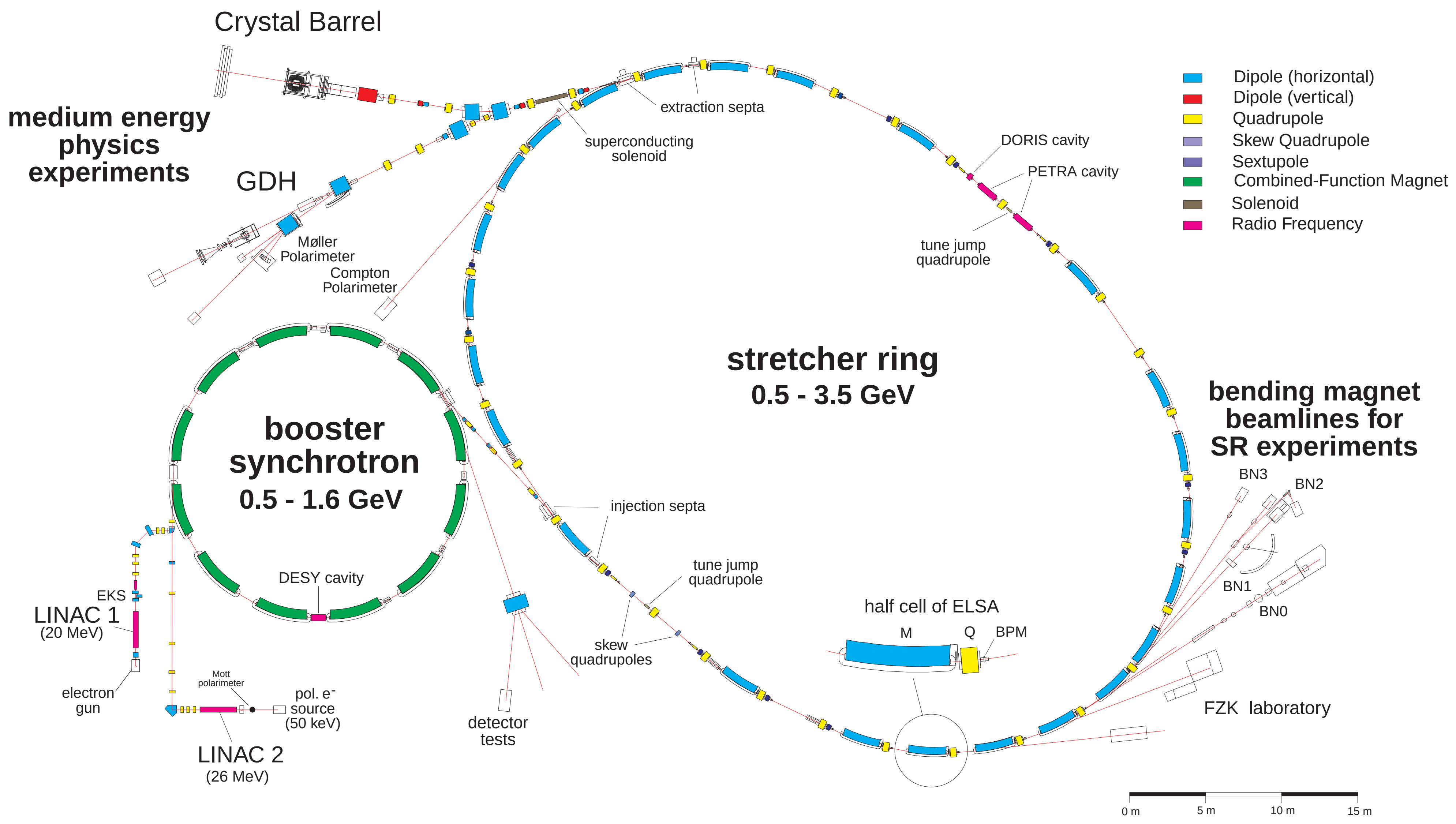
electromagnetic excitations of the neutron

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



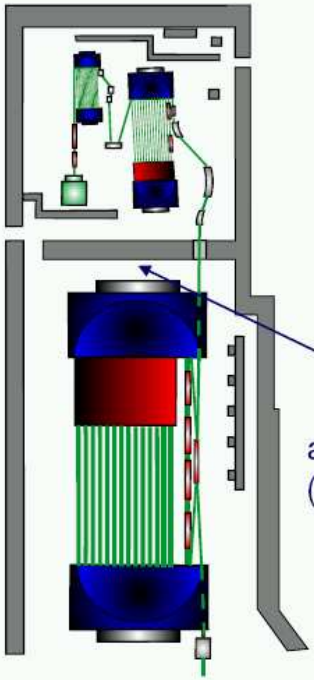
- **complications due to use of nuclear targets (deuteron):**
  - **Fermi motion**
  - **nuclear effects like FSI, re-scattering, coherent contributions**

Electron Stretcher Accelerator (ELSA)



more: V. Crede, Monday, 12:00

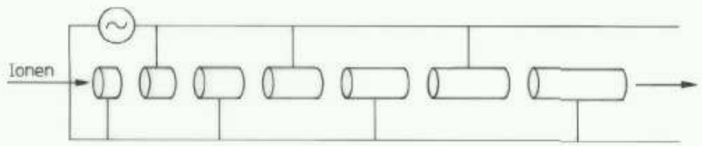
MAMI accelerator in Mainz

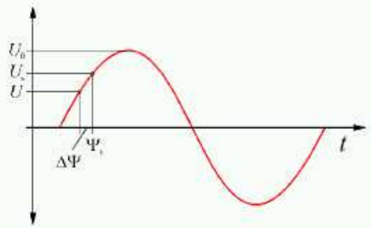


accelerators
(racetrack microtrons)

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

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

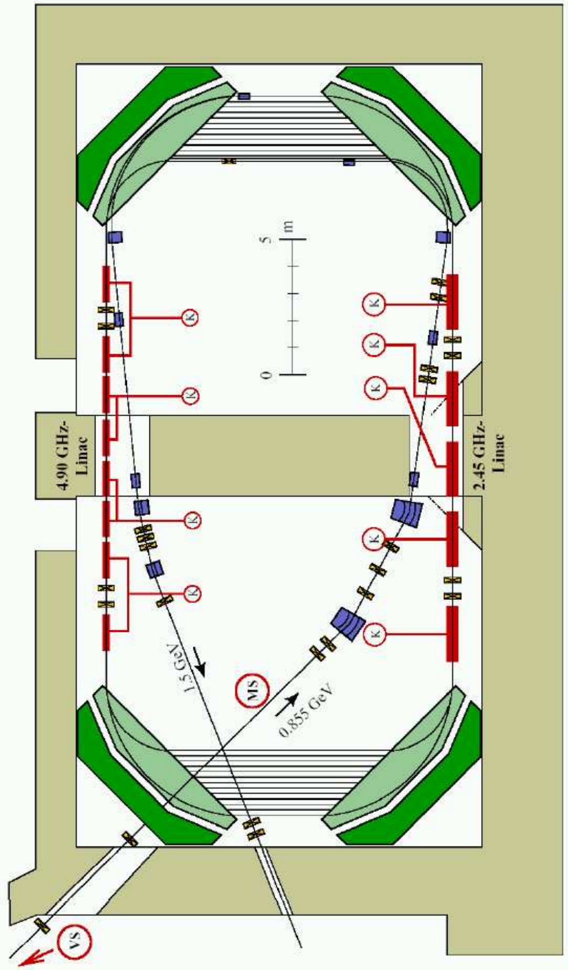




1.-3. Stage: Ractrack Microtrons:

- 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)

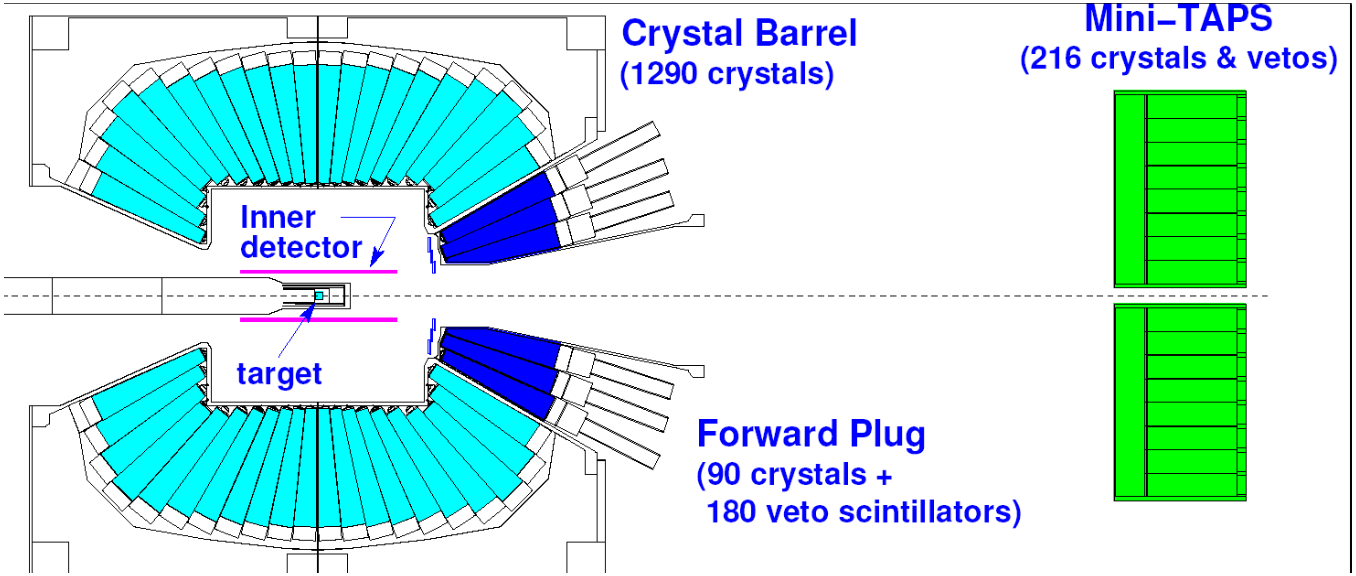
4. Stage: Harmonic Double Sided Microtron
maximum energy: 1.5 GeV



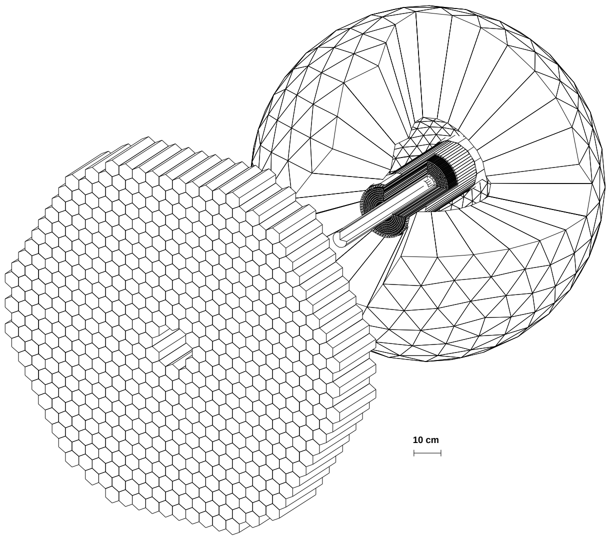
more: B. Briscoe, Monday 15:00

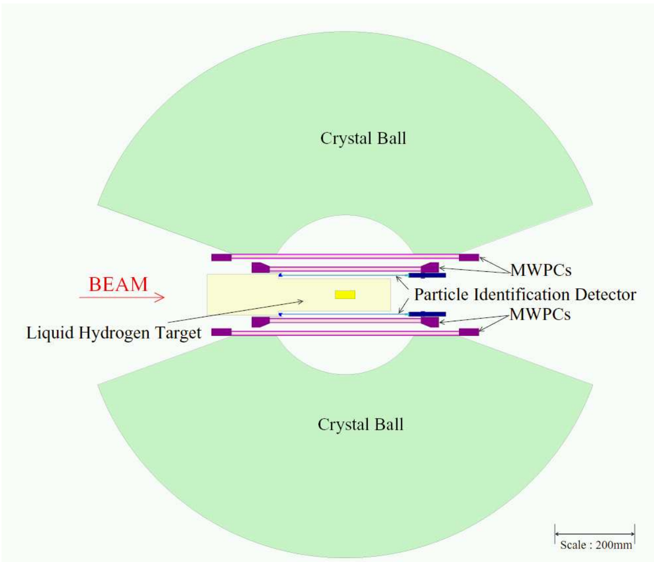
Experiments: Crystal Ball & Crystal Barrel with TAPS

- **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

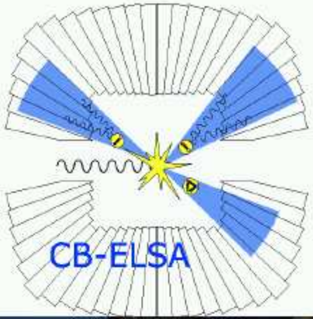


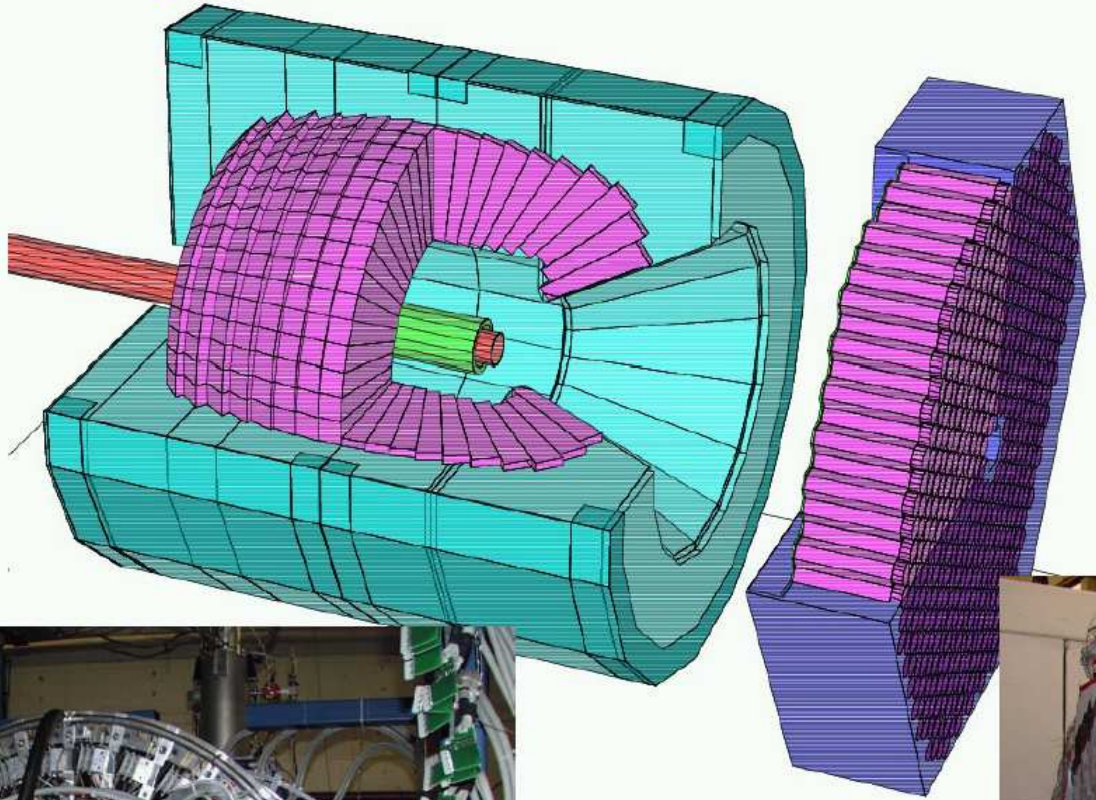
- **Mainz MAMI accelerator:**
  Crystal Ball (NaJ),
  TAPS (BaF_2) forward wall,
  inner detectors
  $E_\gamma \leq$ 1.5 GeV,
  lin. pol.: available,
  circ. pol.: available

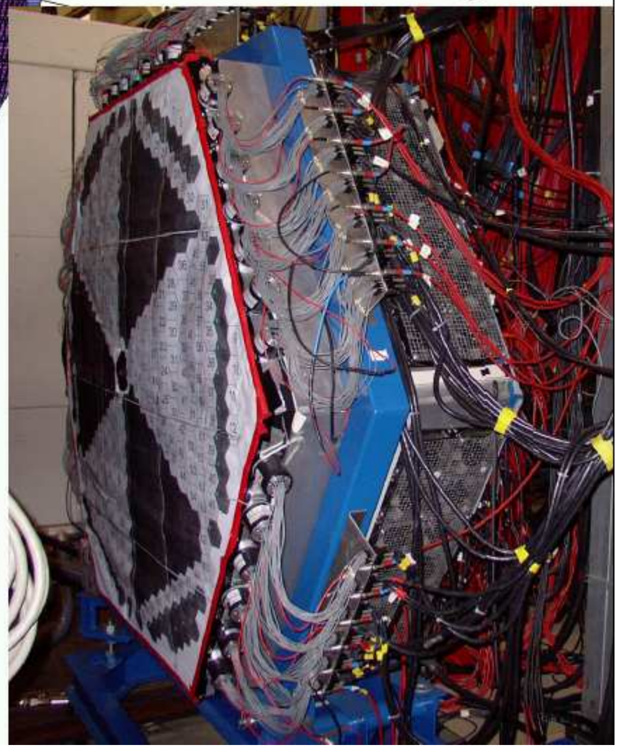




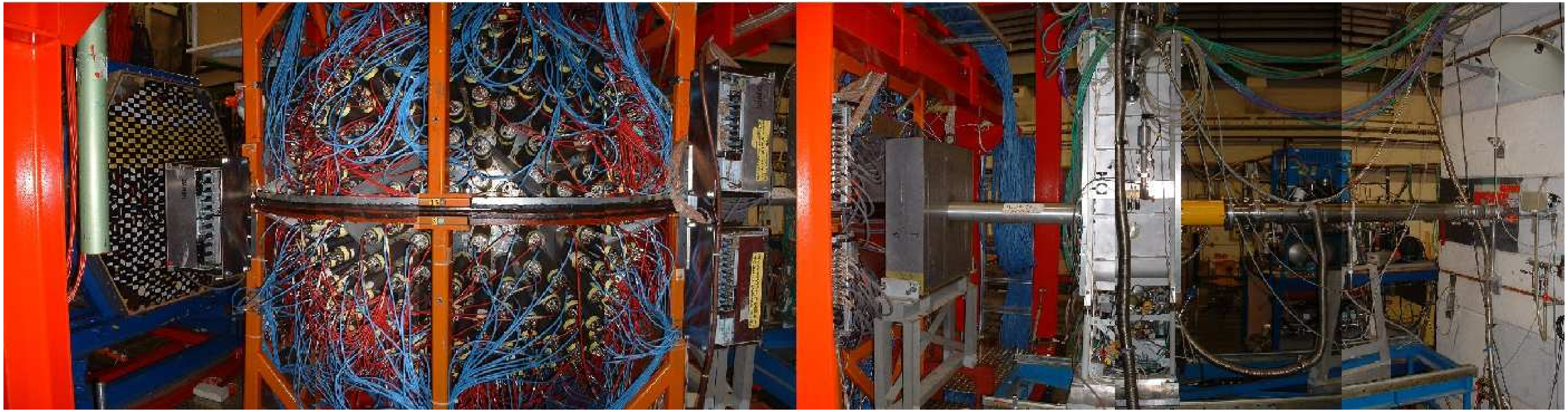
Crystal Barrel and TAPS







TAPS Crystal Ball - at MAMI



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	166	59	139
• $S_{11}(1535)$:	30 - 55	90		-46	
• $S_{11}(1650)$:	3 - 10	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				
• $P_{11}(1710)$:	6.2 ± 1.0				
• $P_{13}(1720)$:	4 ± 1				

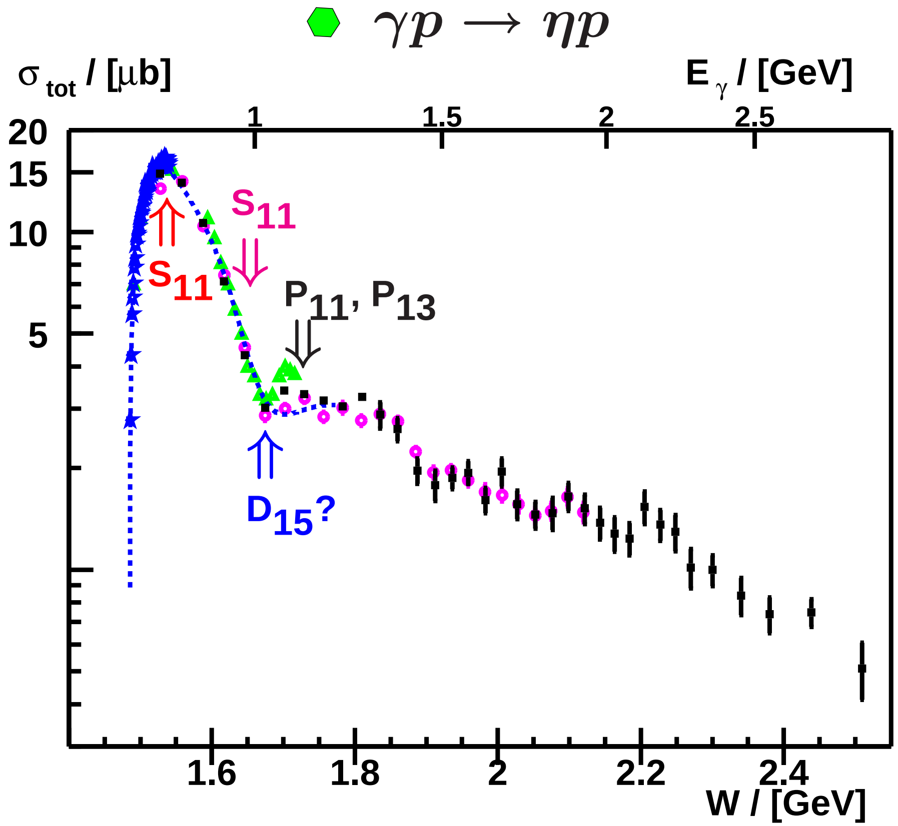
- **$D_{15}(1675)$ has stronger electromagnetic coupling to neutron than to proton**

  but parameters quite uncertain:

  $A^n_{1/2}$=-(21-57), $A^n_{3/2}$=-(30-77)

  b_η=0-1% (PDG), b_η=17% (ETA-MAID, Chiang et al.)

- **interference structure in S_{11}-sector?**

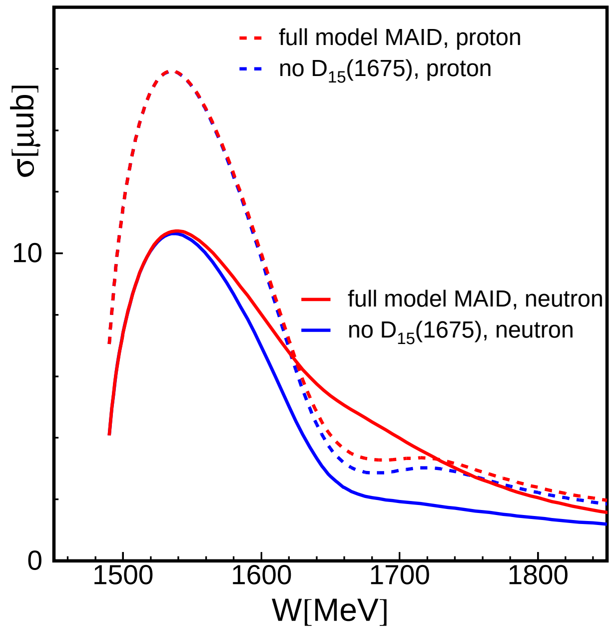


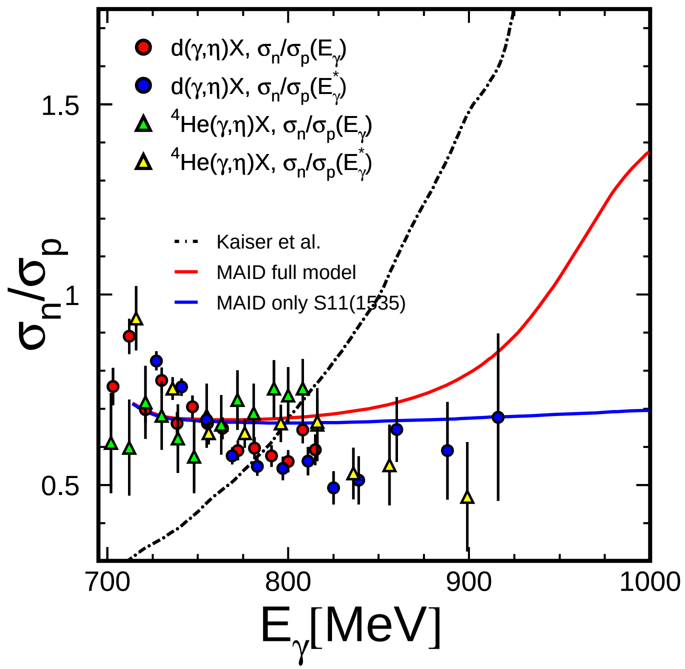
Data:

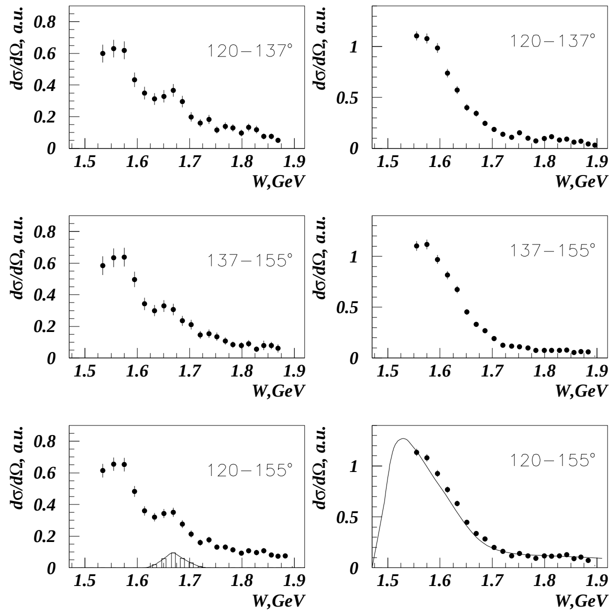
- TAPS: B. Krusche et al., PRL74 (1995) 3736
- GRAAL: F. Renard et al., PLB528 (2002) 215
- CLAS: M. Dugger et al., PRL89 (2002) 222002
- Crystal Barrel: V. Crede et al., PRL94 (2005) 012004

what is expected for $n(\gamma,\eta)n$ - why is it interesting?

- **total cross sections for proton and neutron from MAID model with and without D_{15}(1675))**
- **previous data from MAMI only at lower incident photon energies**
- **GRAAL experiment reported narrow structure in neutron excitation function**







- **predictions from chiral soliton models:** **P_{11}-like state of the anti-decuplet has strong photon-coupling to the neutron and large ηN decay branching ratio**

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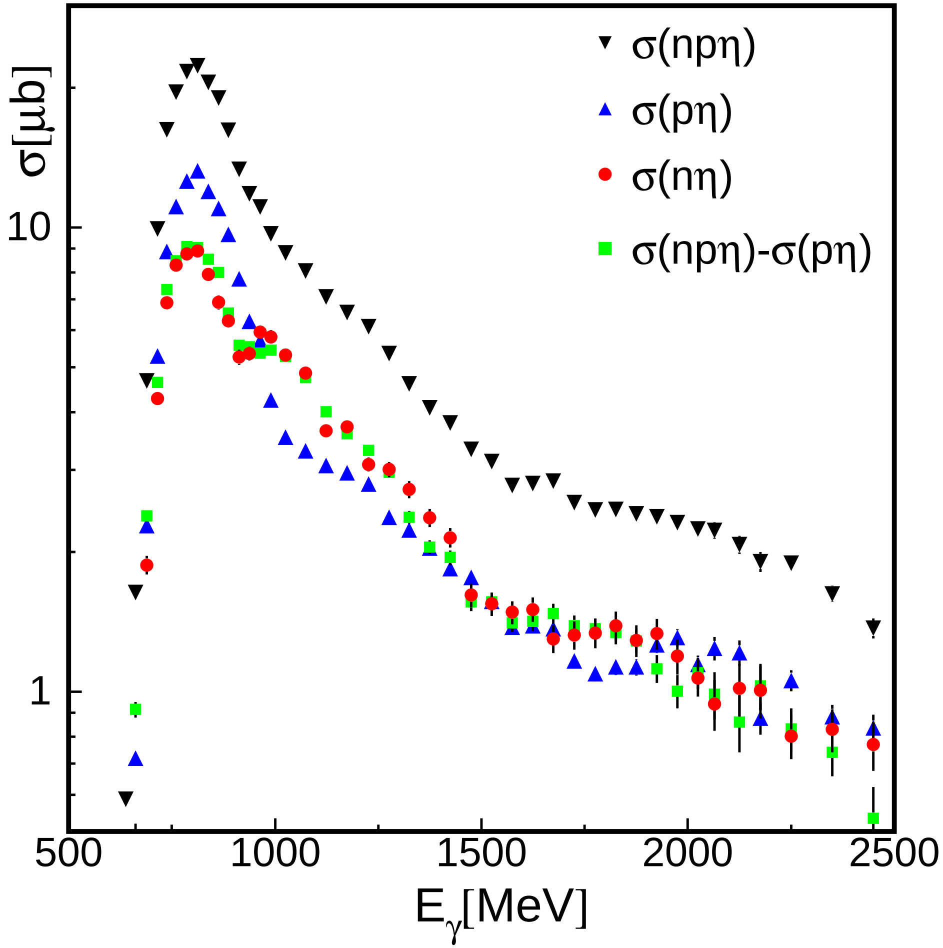
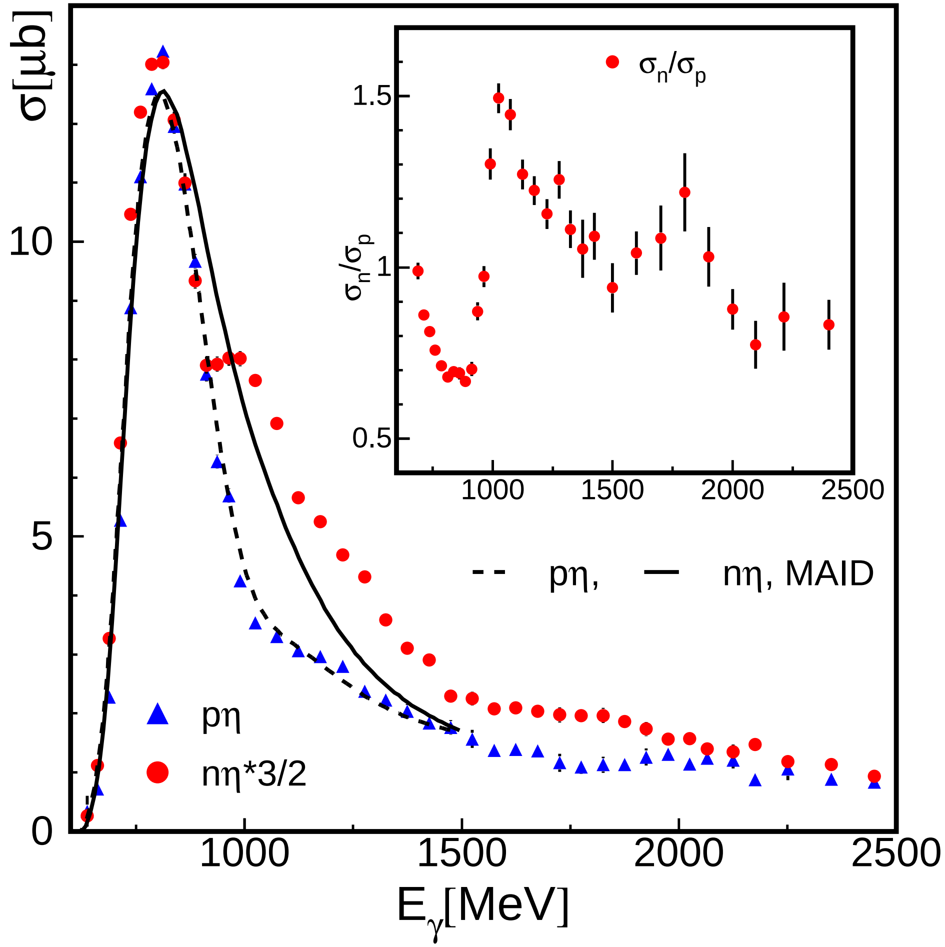
quasifree η-photoproduction off the deuteron

- cross section for $\gamma n \rightarrow \eta n$ from analyses with very different systematics:
  (1) η in coincidence with recoil neutrons
  (2) difference of inclusive data and η in coincidence with recoil protons

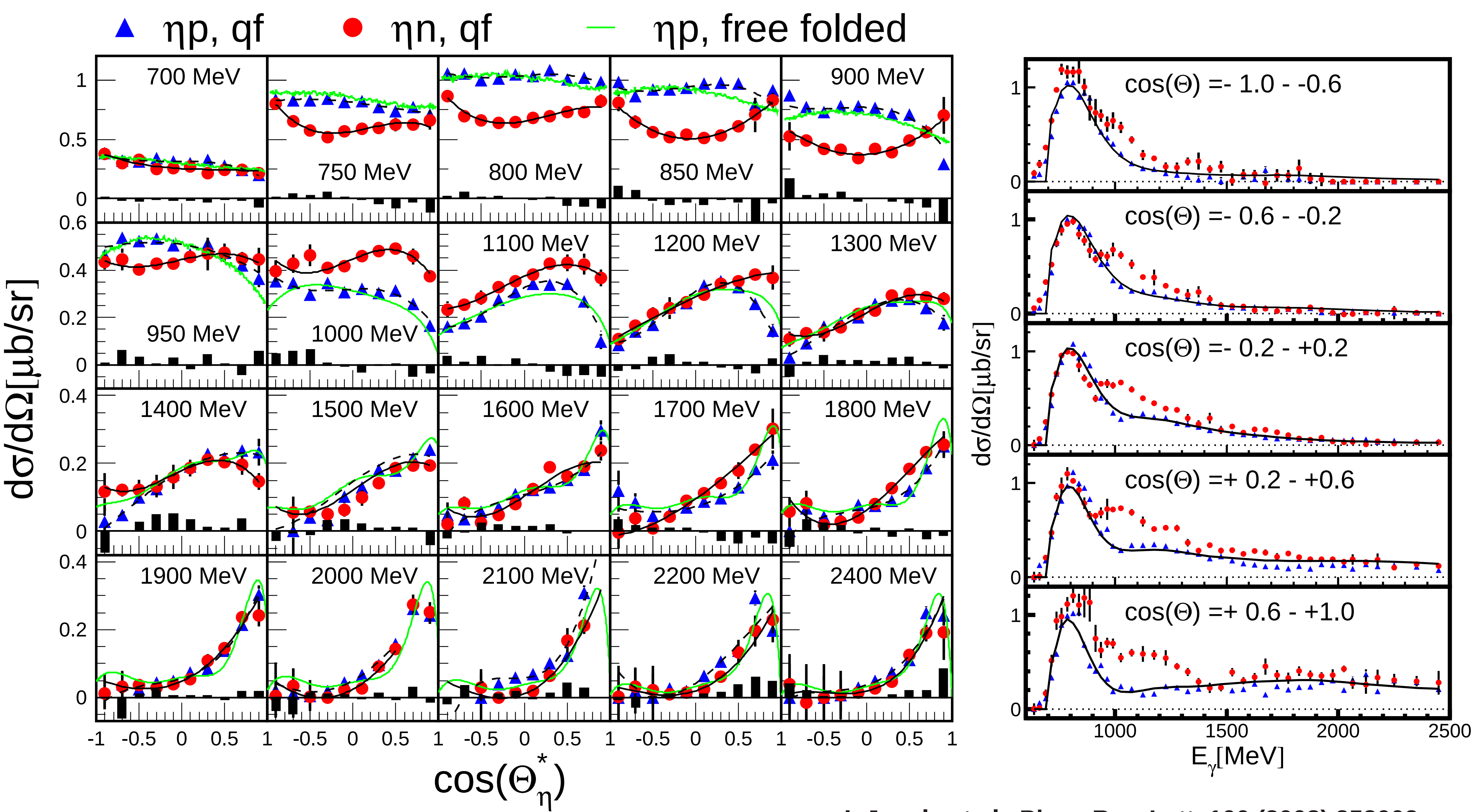




I. Jaegle et al.

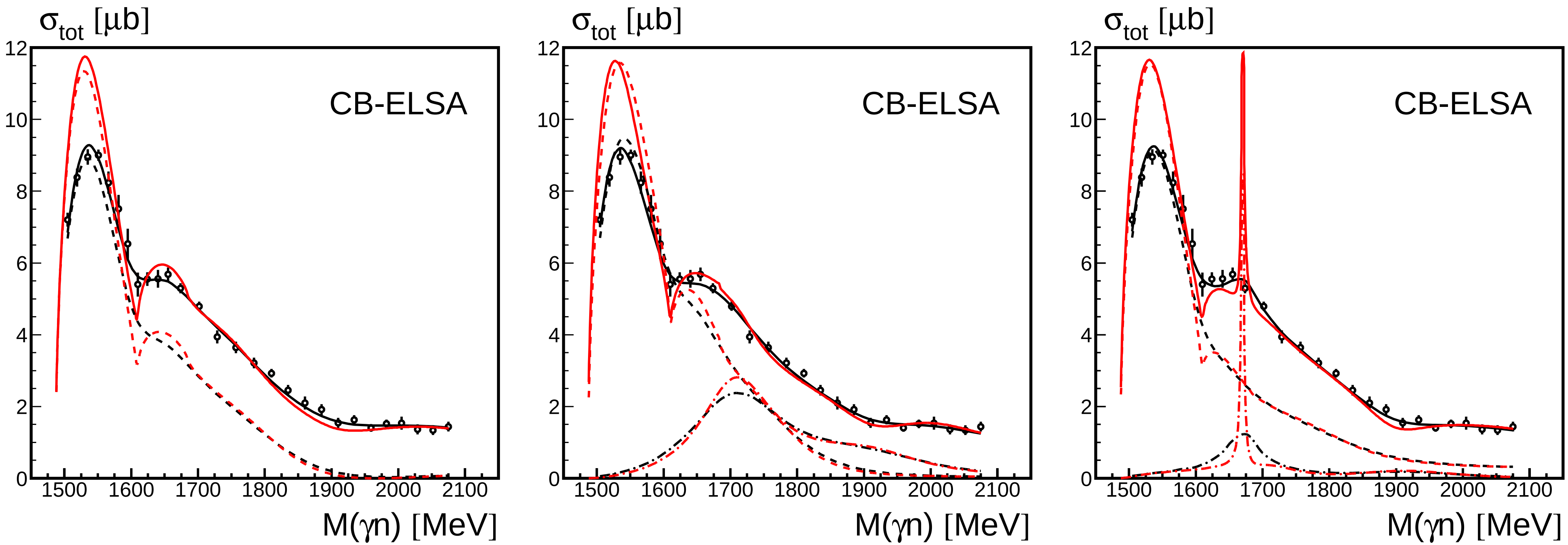
ELSA

quasi-free angular distributions



I. Jaegle et al., Phys. Rev. Lett. 100 (2008) 252002

Bonn-Gatchina-Model analysis



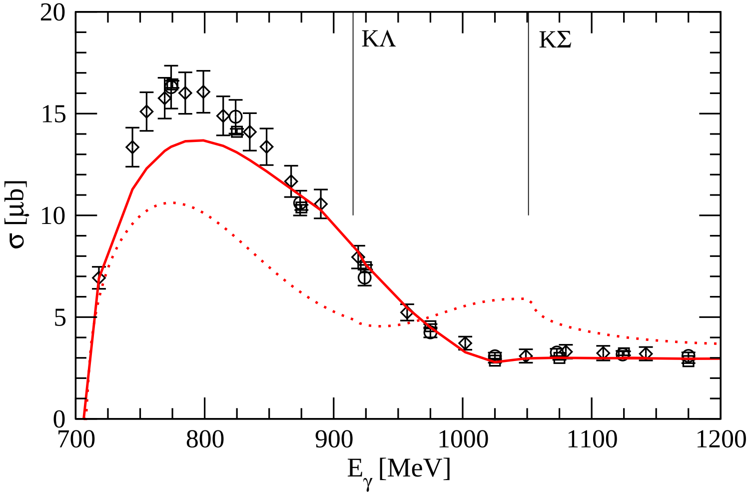
- **different scenarios to reproduce 'bump' structure:**
  - **left: interference in S_{11}-sector: adjusting phases etc.**
  - **center: introduction of conventional (broad) P_{11} resonance**
  - **right: introduction of very narrow P_{11} resonance**

A. Anisovich et al., EPJA 41 (2009) 13

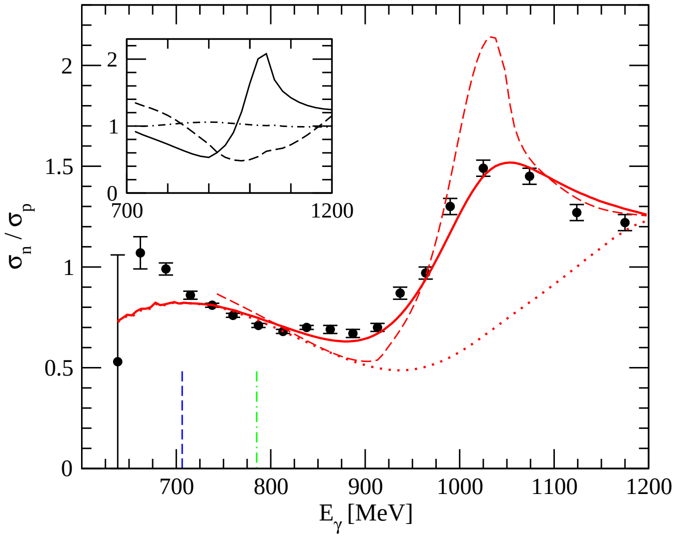
s-wave coupled channel model

- s-wave coupled channel model with dynamical generation of S_{11}(1535) pole

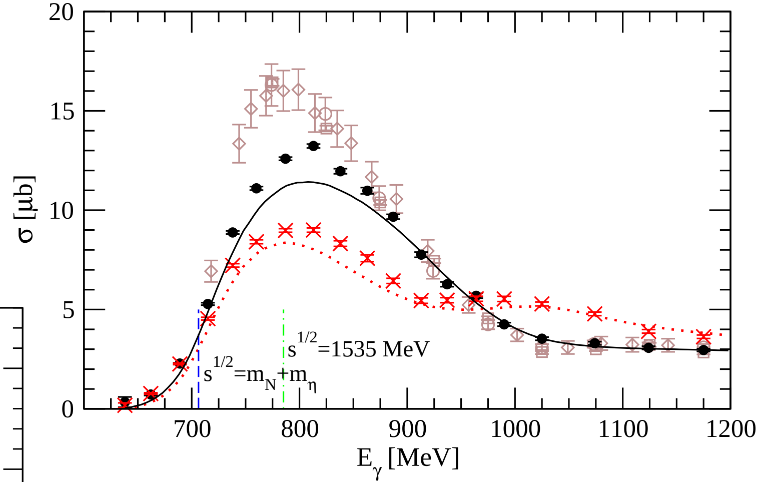
free cross sections



cross section ratio



quasi-free cross sections



- structure in σ_n/σ_p due to KΛ, KΣ threshold effects (intermediate strangeness states in loop-diagrams)

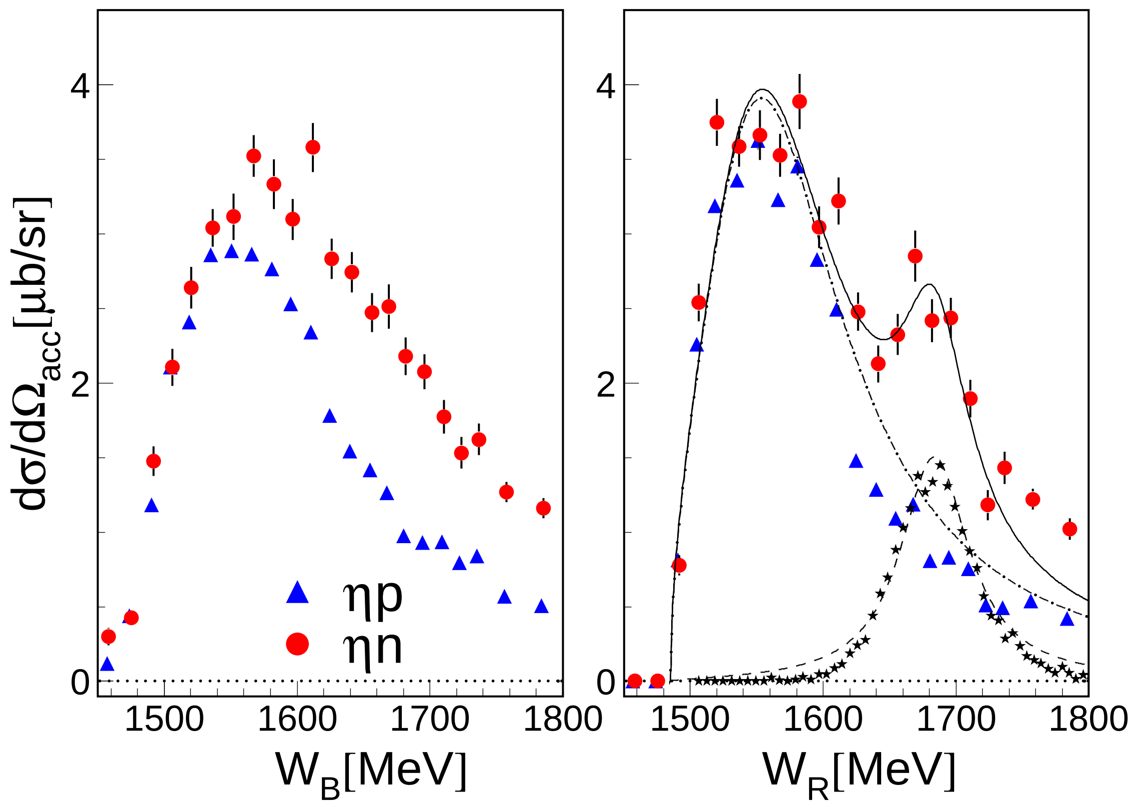
M. Döring. K. Nakayama, nucl-th:0909.3538v1

‘de-folding’ of Fermi motion

- for events with neutron in TAPS ($\cos(\Theta^\star_\eta) <$ -0.1) neutron energy from time-of-flight
- comparsion: W from photon energy (Fermi smeared) - W from nucleon - meson 4-vectors (resolution smeared)
- de-folded proton cross section similar to free proton, de-folded neutron cross section shows structure around 1.7 GeV:

position: W=1683 MeV
width: Γ=60$\pm$10 MeV
(resolution dominated)

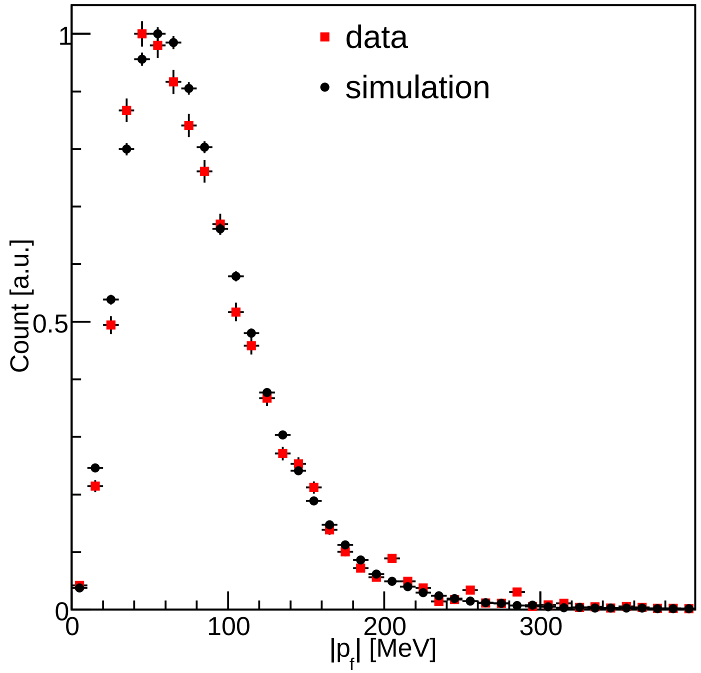
I. Jaegle et al.,
Phys. Rev. Lett. 100 (2008) 252002



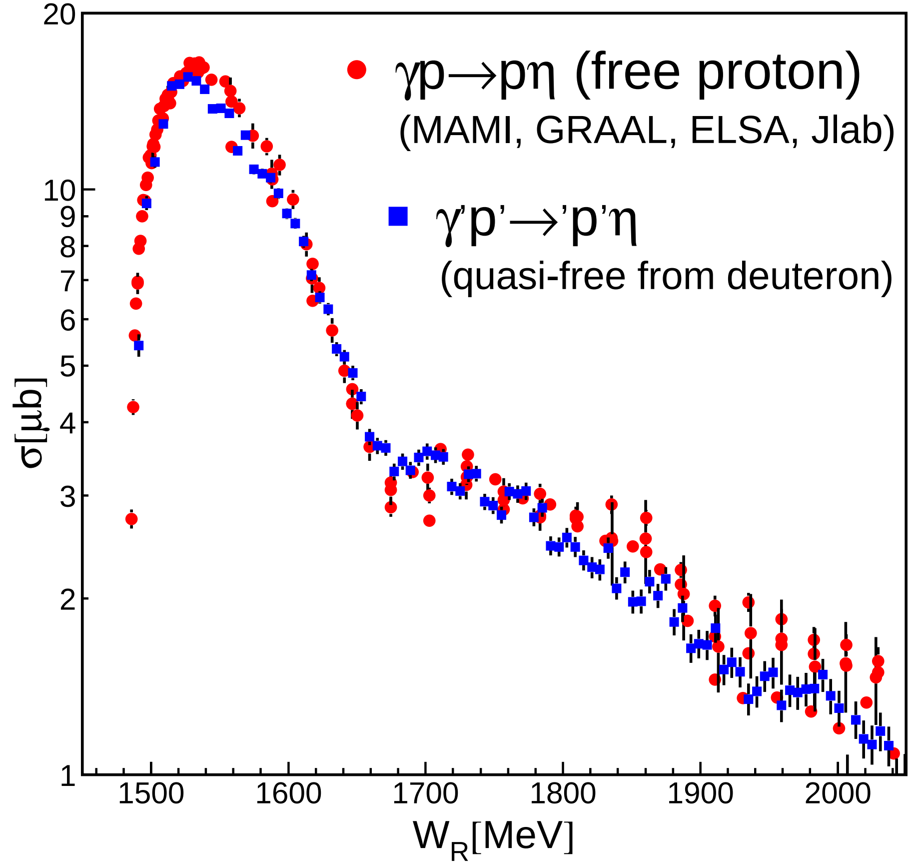
‘de-folding’ of Fermi motion - kinematical re-construction

- **reaction kinematics completely determined even without neutron ToF:**
  - **initial state: incident photon and deuteron at rest**
    known/measured: E_γ, m_d, $p_d = 0$
  - **final state:** η**-meson, participant, and spectator nucleon**
    known/measured: m_s, m_p, Θ_p, Φ_p, m_η, p_η
    not measured: T_p, p_s **(four variables)**
  - **four constraints from energy/momentum conservation**
    →four-vectors of participant and spectator determined

- **spectator momentum in quantitative agreement with deuteron wave function**

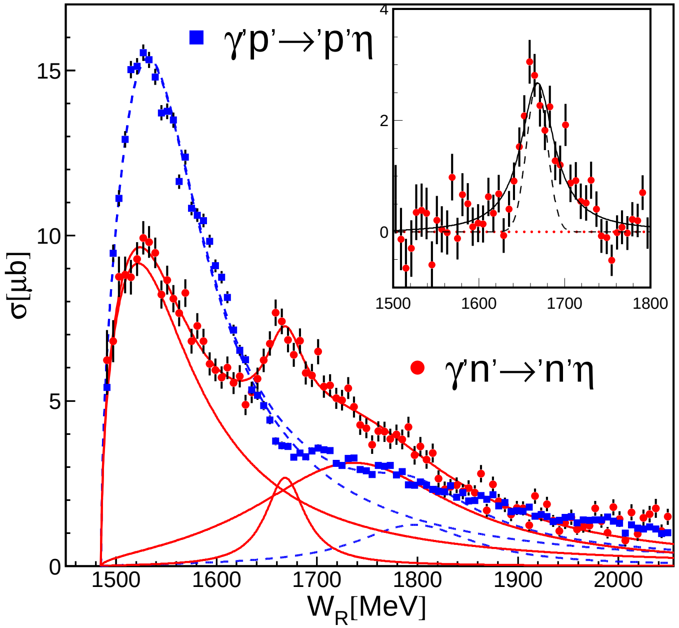


- **proton cross section in quantitative agreement with free proton data**

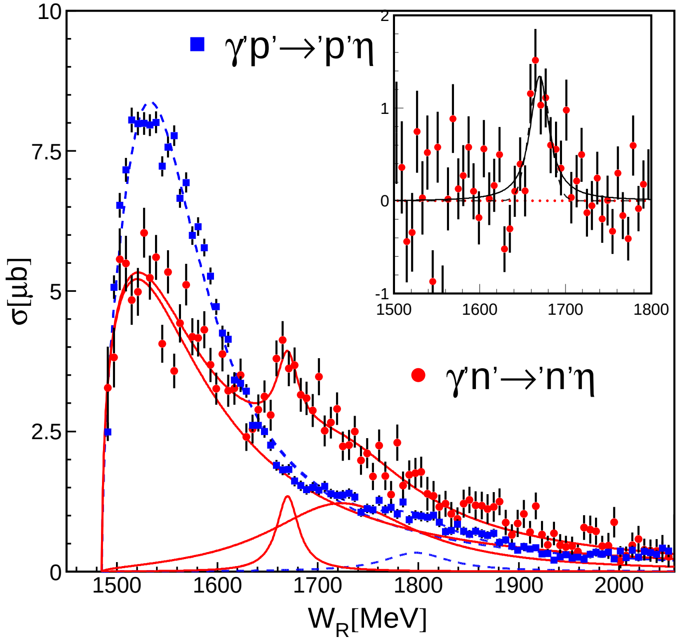


Fermi de-folded proton and neutron data

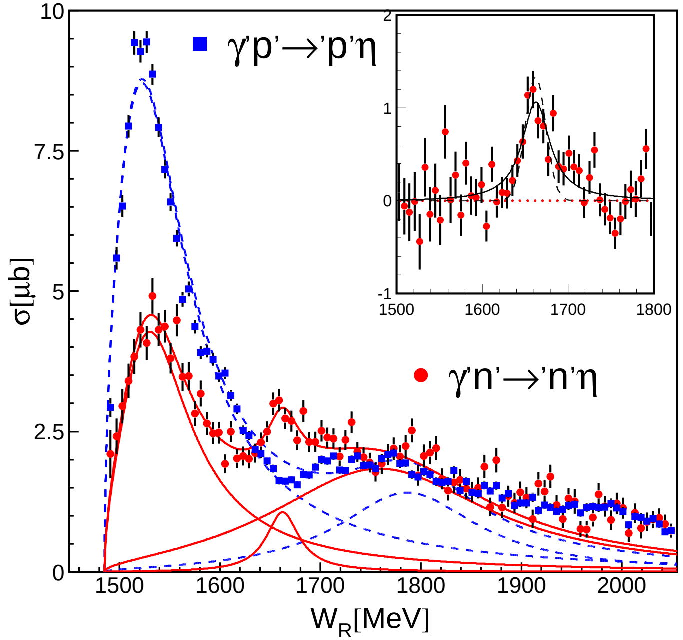
- **total cross section**



- **cos($\Theta_\eta^\star$)$<$0**



- **cos($\Theta_\eta^\star$)$>$0**



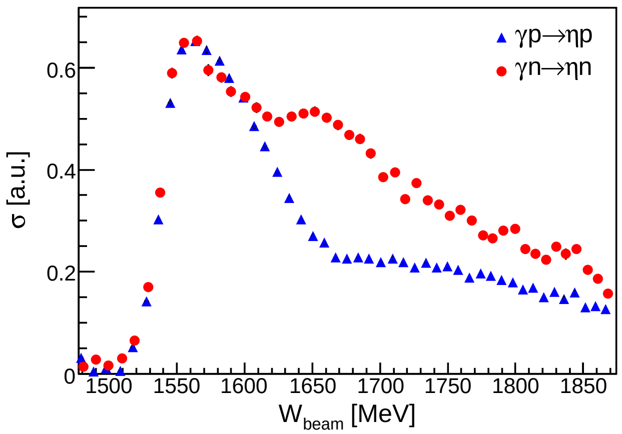
- **phenomenological fit of data with:**
  - **proton:** one Breit-Wigner with energy dep. width for S_{11}, one further BW
  - **neutron:** one Breit-Wigner with energy dep. width for S_{11}, two further BW
- **parameters of narrow neutron Breit-Wigner:**
  - **position:** (1668$\pm$4) MeV (total), (1670$\pm$3) MeV (cos($\Theta_\eta^\star$)$<$0), (1662$\pm$5) MeV (cos($\Theta_\eta^\star$)$>$0)
  - **width:** (48$\pm$15) MeV (total), (26$\pm$9) MeV (cos($\Theta_\eta^\star$)$<$0), (40$\pm$20) MeV (cos($\Theta_\eta^\star$)$>$0)
  - **experimental resolution for width:** $\approx$25 MeV

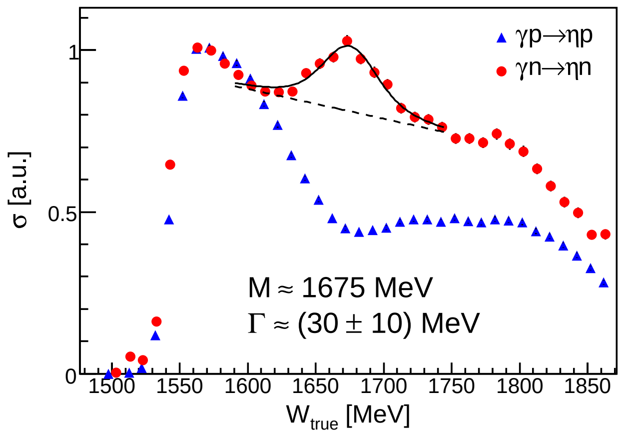
New high statistics measurement at MAMI C

Very preliminary analysis, less than 50 % of data, no efficiency corrections, fit with Breit-Wigner folded with experimental resolution: $\Gamma(BW) \approx$ **30 MeV**

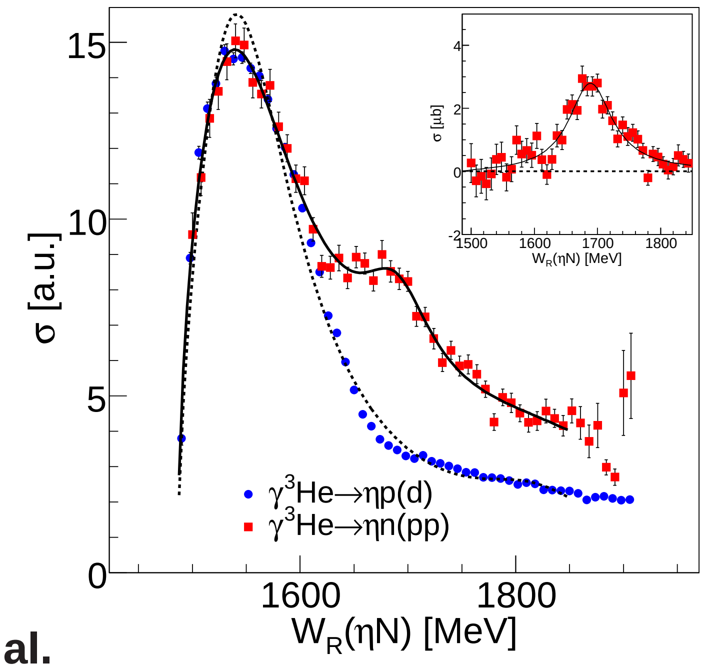
D. Werthmüller et al.

- $W = f(E_\gamma)$
- $W = f(P_n, P_\eta)$





- **just for completeness: structure also seen in quasi-free η-production off ^{3}He:**



L. Witthauer et al.

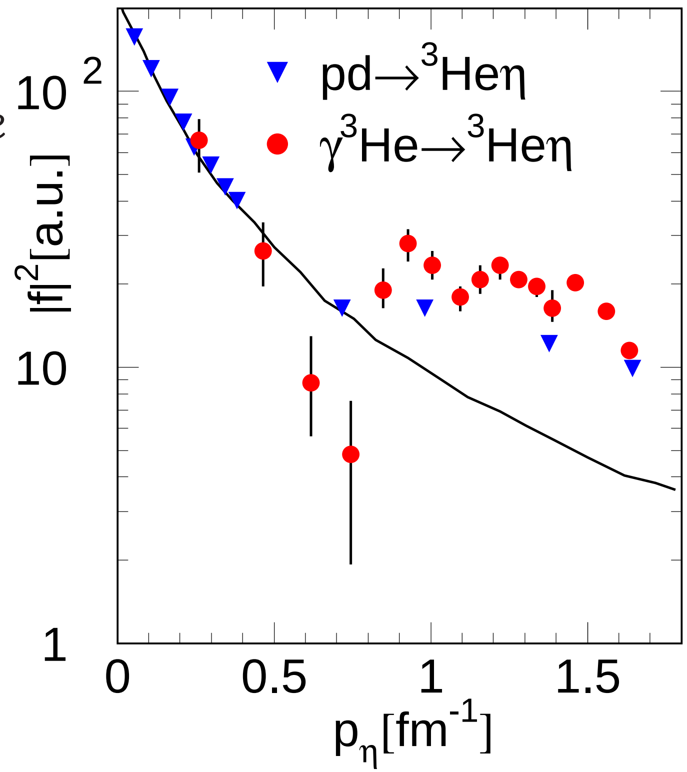
Summary

- narrow structure in excitation function of $\gamma n \rightarrow n\eta$:
- GRAAL: $W \approx$ 1680 MeV, $\Gamma <$30 MeV
- Tohoku-LNS: $W \approx$ 1666 MeV, $\Gamma <$40 MeV
- ELSA: $W \approx$ 1685 MeV, $\Gamma <$50 MeV
- MAMI-C: $W \approx$ 1675 MeV, $\Gamma <$40 MeV
- so far no information about quantum numbers of possible resonance or whatever nature of the structure

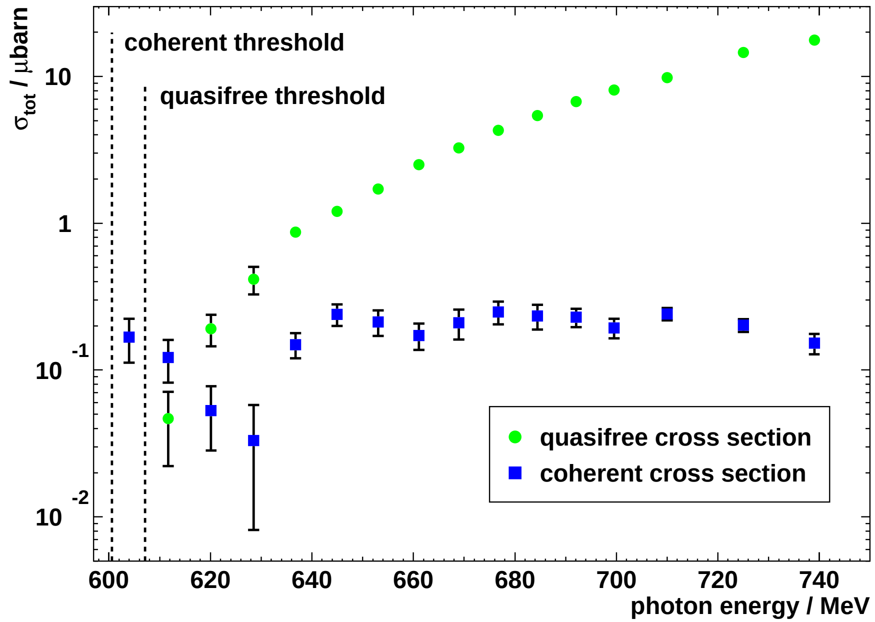
the story of η-mesic nuclei

- **1985: Bhalerao & Liu:**
  attractive η-nucleus interaction for A$\geq$12
- **1986: Liu & Haider:**
  suggestion of η-nucleus bound states
- **experiments: inconclusive e.g.:**
  Chrien et al. (1988): $\pi^+ + ^{16}O \rightarrow p + ^{15}_{\eta}O$
  Johnson et al. (1993): $\pi^+ + ^{18}O \rightarrow \pi^- + ^{18}_{\eta}Ne$
- **1993 - 2002: analysis of new η-production data from the proton:**
  larger ηN-scattering lengths
- **1991 - 2002: T. Ueda, C. Wilkin, S.A. Rakityanski and others:**
  suggestions of bound ^{2}H-, ^{3}H-, ^{3}He-, ^{4}He-η states
- **experiments: threshold behavior of η-production**

$$p + d \rightarrow {}^3\text{He} + \eta$$
$$\gamma + {}^3\text{He} \rightarrow {}^3\text{He} + \eta$$



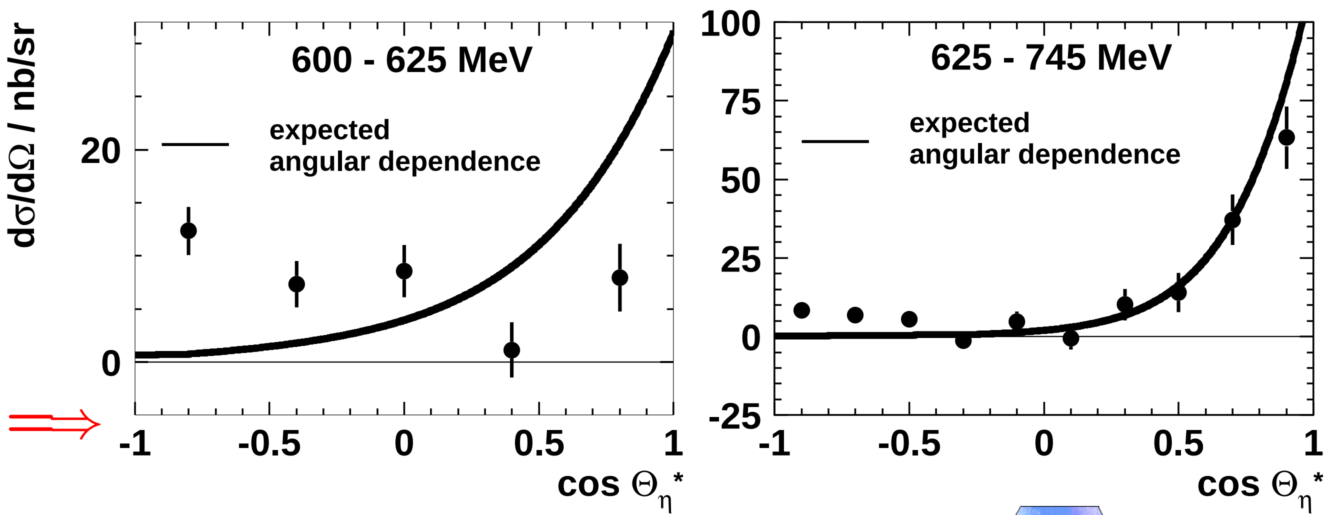
η-photoproduction from ^{3}He - threshold behavior



M. Pfeiffer et al., PRL 92 (2005) 252001

- **evidence for strong final state interaction of the η-meson**

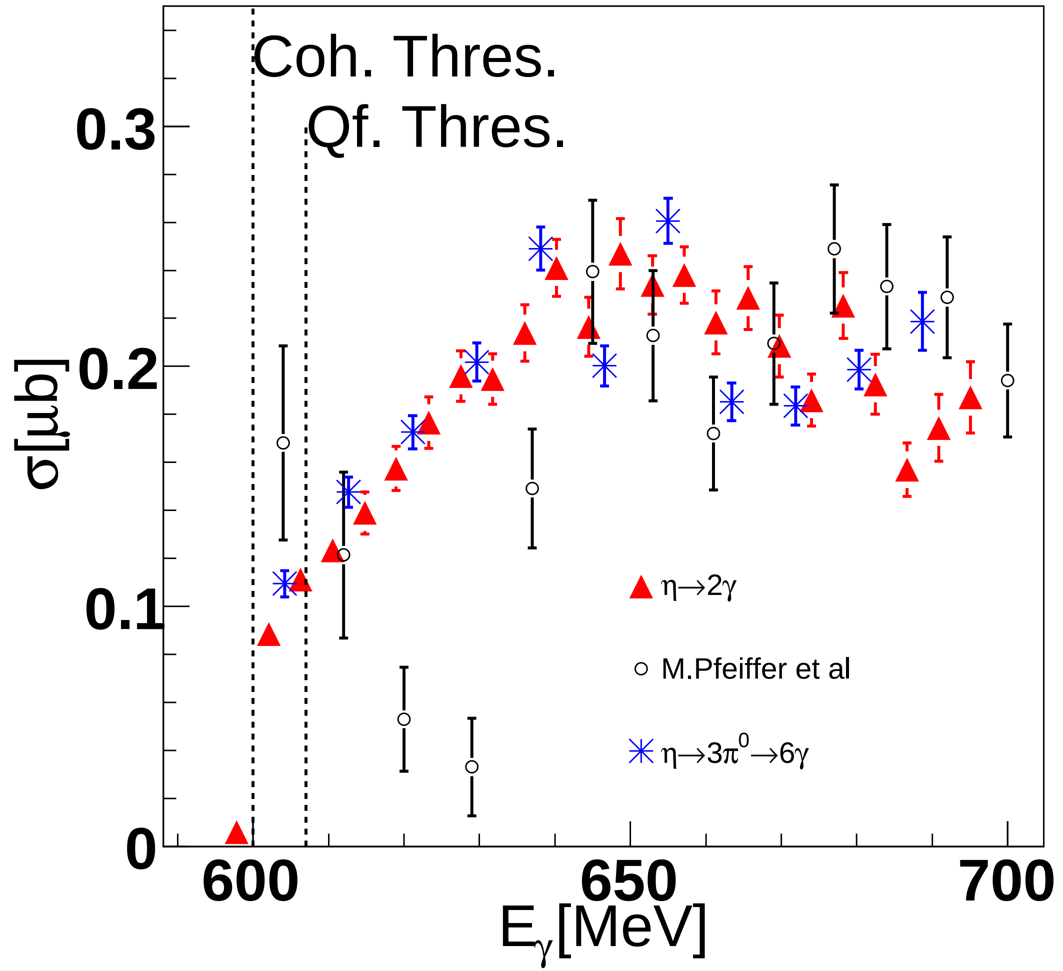
$\Leftarrow$ **threshold enhancement of coherent part**

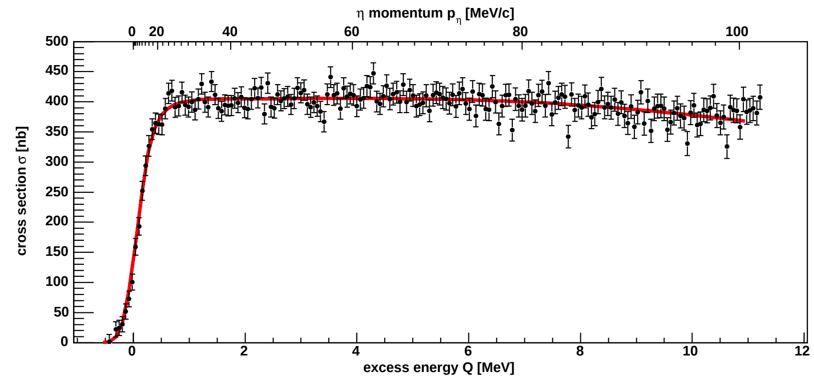


istropic angular distribution of coherent part at threshold $\Rightarrow$

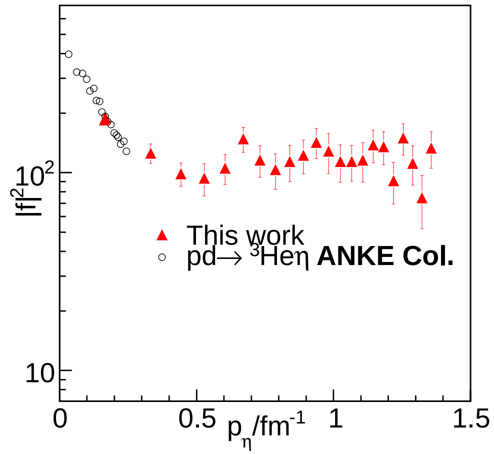
new ^{3}He experiment - coherent η-production

- **very steep rise of total cross section at threshold confirmed; similar to hadron induced reaction: $pd \longrightarrow {}^3\mathrm{He}\eta$ (T. Mersmann et al., PRL 98 (2007) 242301)**





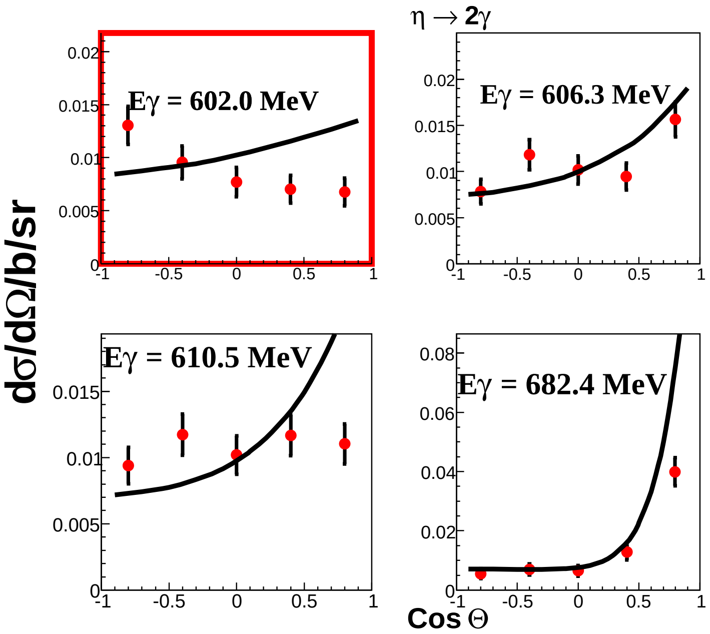
- phase space reduced amplitudes:



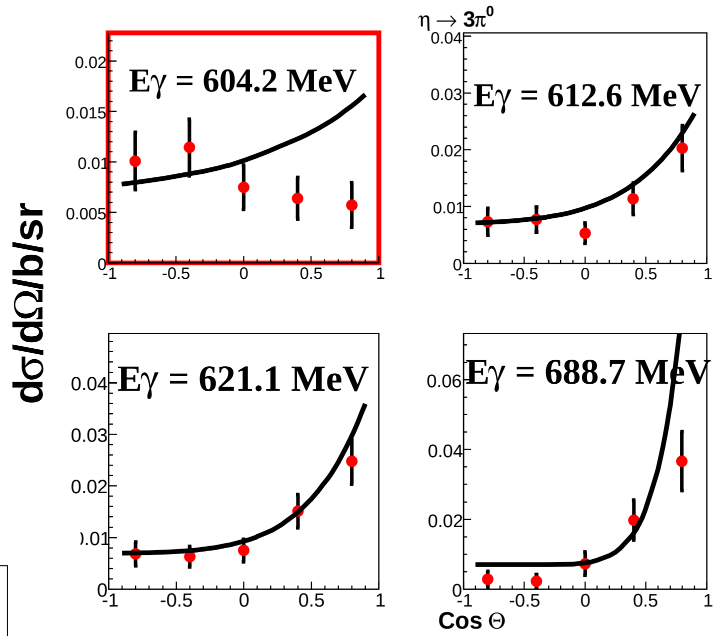
F. Pheron et al.

differential cross section

- $\eta \longrightarrow 2\gamma$

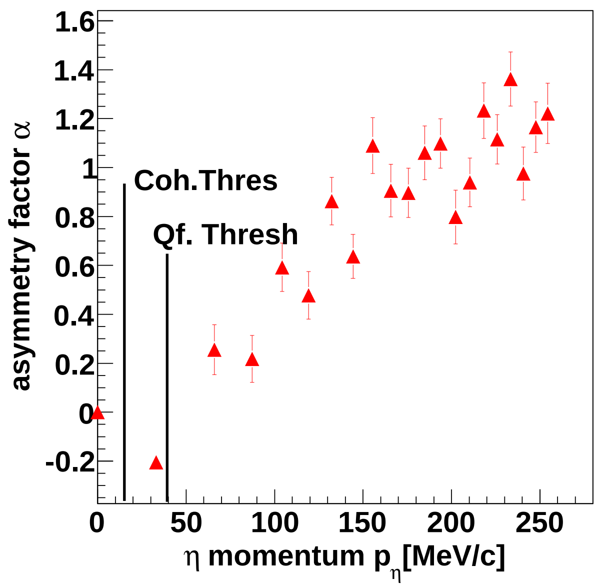


- $\eta \longrightarrow 6\gamma$



- **black lines:**

angular dependence of ^{3}He form factor



distributions fitted with:

$$\frac{d\sigma}{d\Omega} = a + b \cdot \cos(\Theta) + c \cdot \cos^2(\Theta)$$

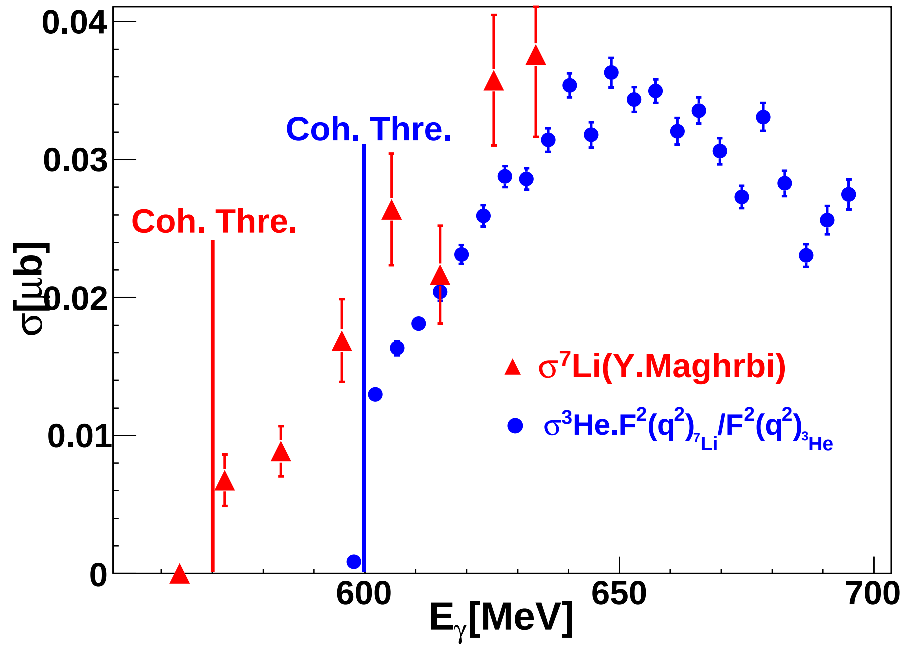
$$\alpha = b/a$$

threshold angular distributions do not behave as expected from form factor dependence

summary: coherent η-photoproduction off light nuclei

- strong threshold enhancement for γ^3He $\rightarrow ^3$He η confirmed
- angular distributions close to threshold different from form factor expectation
- first preliminary results also for γ^7Li $\rightarrow ^7$Li η
- cross section for γ^7Li $\rightarrow ^7$Li η smaller by roughly one order of magnitude (corresponds to ratio of form factors)
- threshold enhancement for γ^7Li $\rightarrow ^7$Li η less pronounced
- what about ^{4}He?

- comparison: γ^3He $\rightarrow ^3$He η and γ^7Li $\rightarrow ^7$Li η



Details:
talks by F. Pheron and Y. Maghrbi

what about η-mesic ^{4}He?

- η-photoproduction dominated by excitation of $S_{11}(1535)$:

  γ(E1) + N $\longrightarrow$ S_{11} $\longrightarrow$ N + η

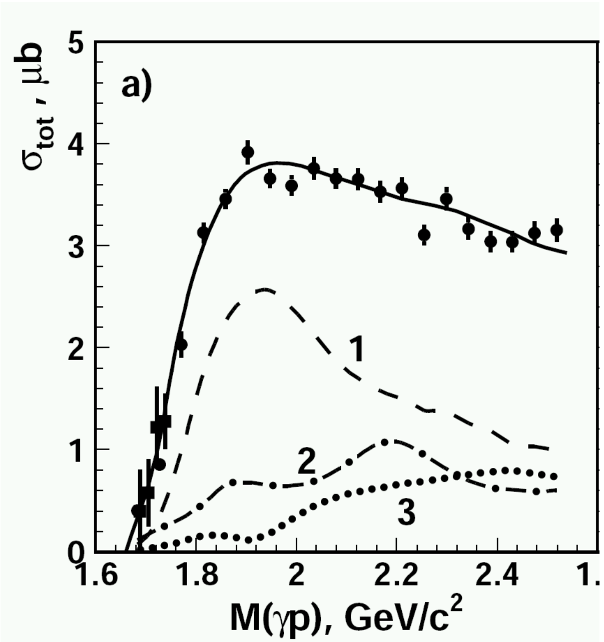
  J_z: -1 +1/2 -1/2 -1/2 0 $\Rightarrow$ spin-flip transition

- isospin structure: $A^{IS}_{1/2}/A^{p}_{1/2} \approx$0.09 $\Rightarrow$ dominantly isovector

- $\Rightarrow$ coherent η-photoproduction ruled out for I=J=0 nuclei

---

- possible way out: coherent photoproduction of $\eta\pi^o$-pairs



$\gamma p \longrightarrow \eta\pi^o p$:
dominant final states
$--$ $\Delta(1232)\eta$
$-.-$ $N(1535)\pi$,
.... $pa_o(980)$

dominant process close to threshold:

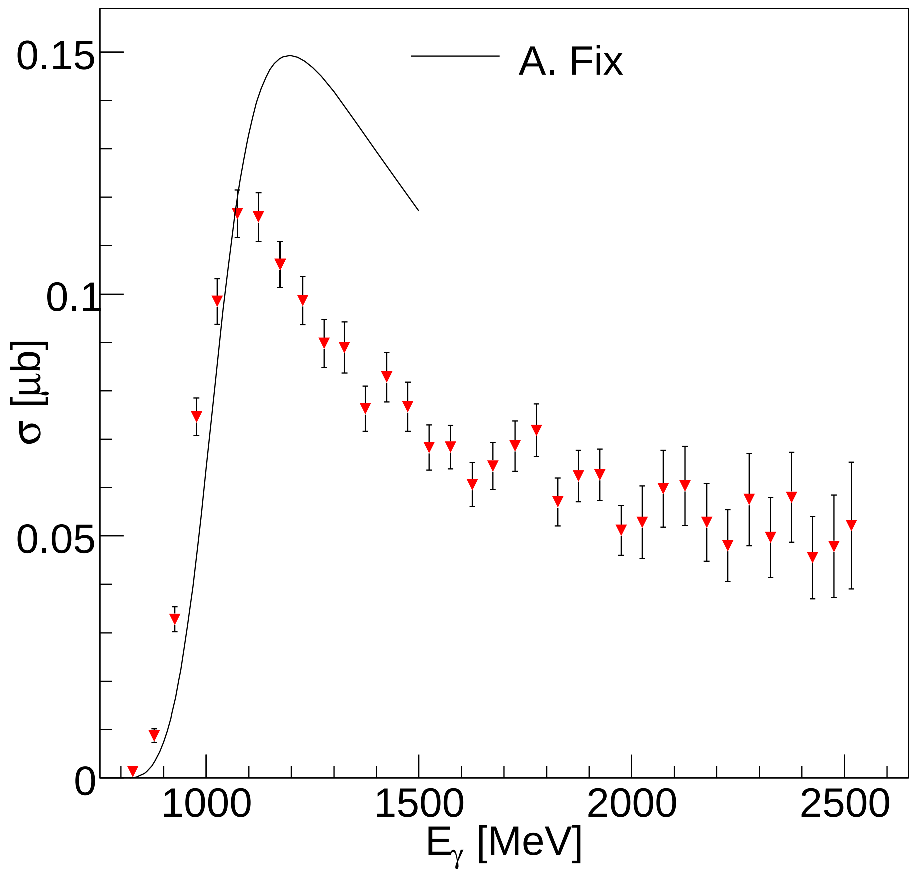
γp $\longrightarrow$$D_{33}(1700)\longrightarrow$ ηP_{33}(1232) $\longrightarrow$ $\eta\pi^o$p

I. Horn et al., PRL 101, EPJA 38 (2008)
V. Kashevarov et al., EPJA (2009)

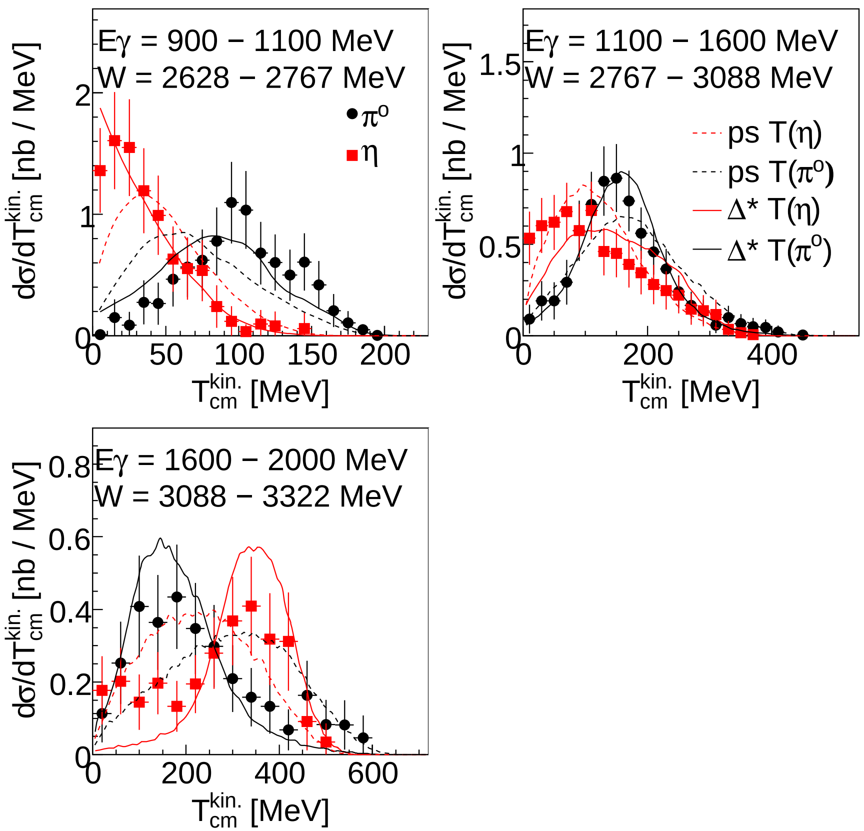
$\Rightarrow$no spin-flip,
identical amplitude for p, n
$\Rightarrow$ideal entrance channel

$d(\gamma,\eta\pi^o)d$: total cross section, kinetic energy distributions

- **total cross section**



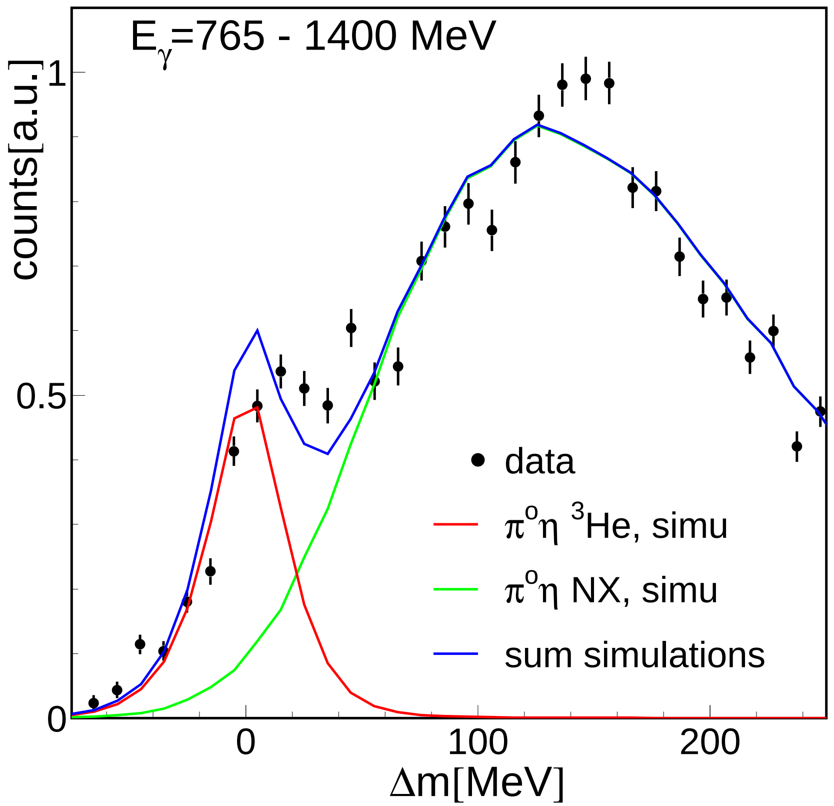
- **kinetic energy**



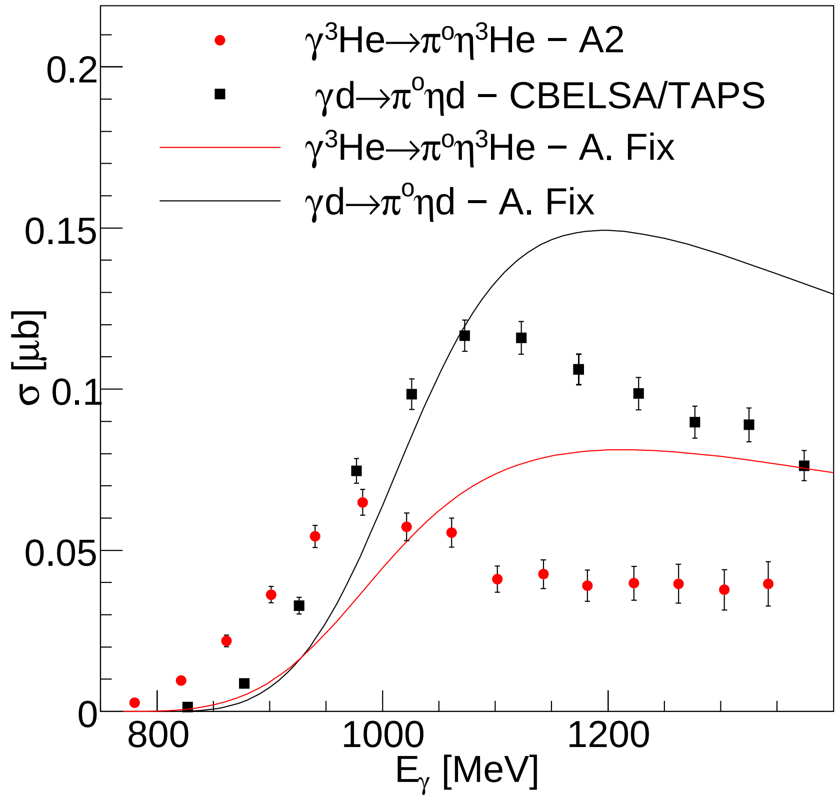
- **total cross section in reasonable agreement with predictions**
- **T distributions support dominant $\Delta^\star \rightarrow \Delta(1232)\eta \rightarrow N\eta\pi^o$ contribution: $T(\pi^o)$ peaks around 100 MeV ($\Delta(1232) \rightarrow N\pi$), $T(\eta)$ rises with E_γ**

very preliminary: $^3\text{He}(\gamma, \eta\pi^o)^3\text{He}$

- identification via missing mass

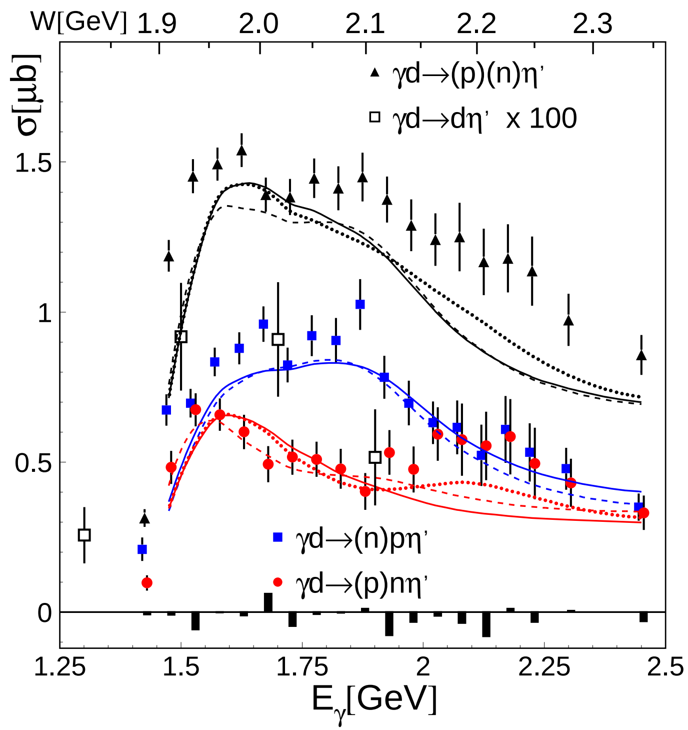


- preliminary total cross section



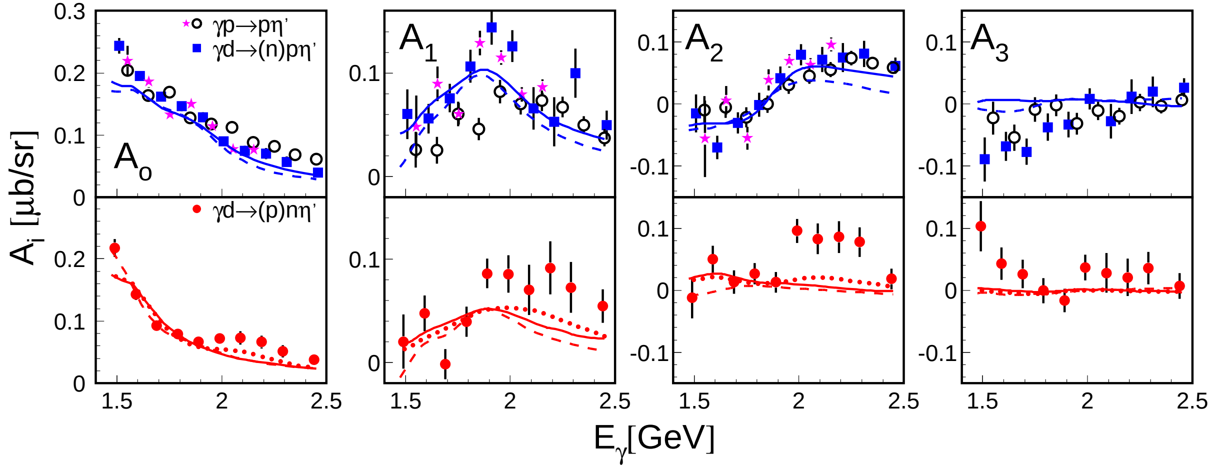
- **qualitative agreement with isotope dependence from Fix' model**

results for many more channels, e.g. quasi-free η'



$\Leftarrow$ **total cross sections, model calculations K. Nakayama et al.**

Legendre coefficients of angular distributions $\Downarrow$



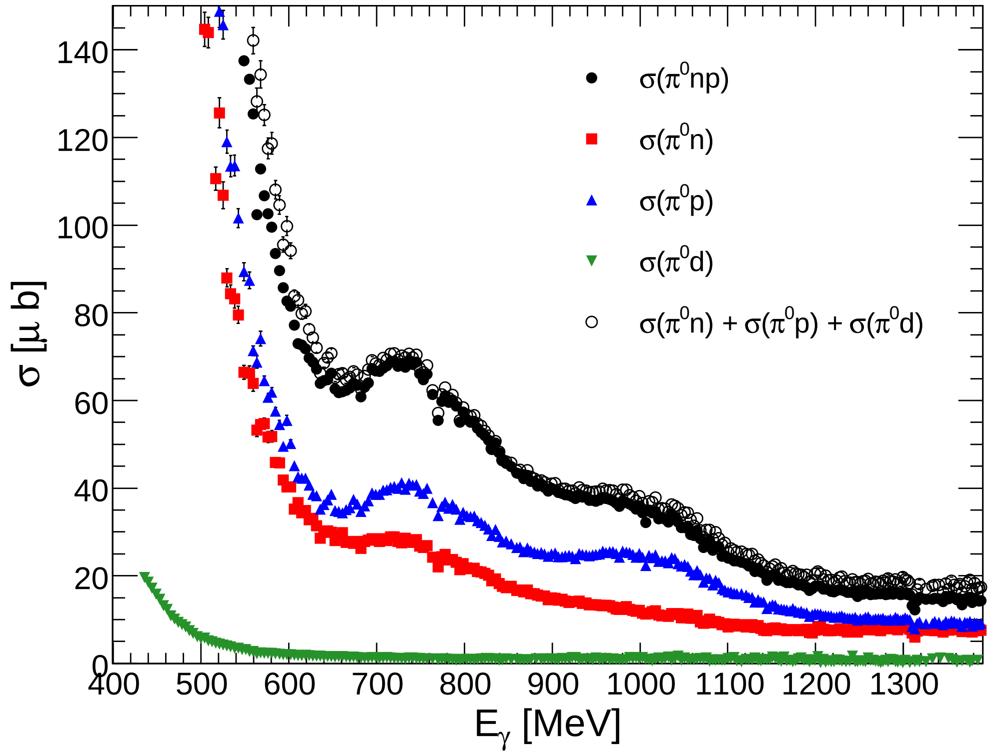
- **very good agreement between quasi-free and free proton cross section**
- **angular distributions dominated by s-waves**
- **reasonable agreement with model calculations**
- **broad structure in neutron cross section between 2.0 GeV$< W <$ 2.5 GeV which is less pronounced for proton**

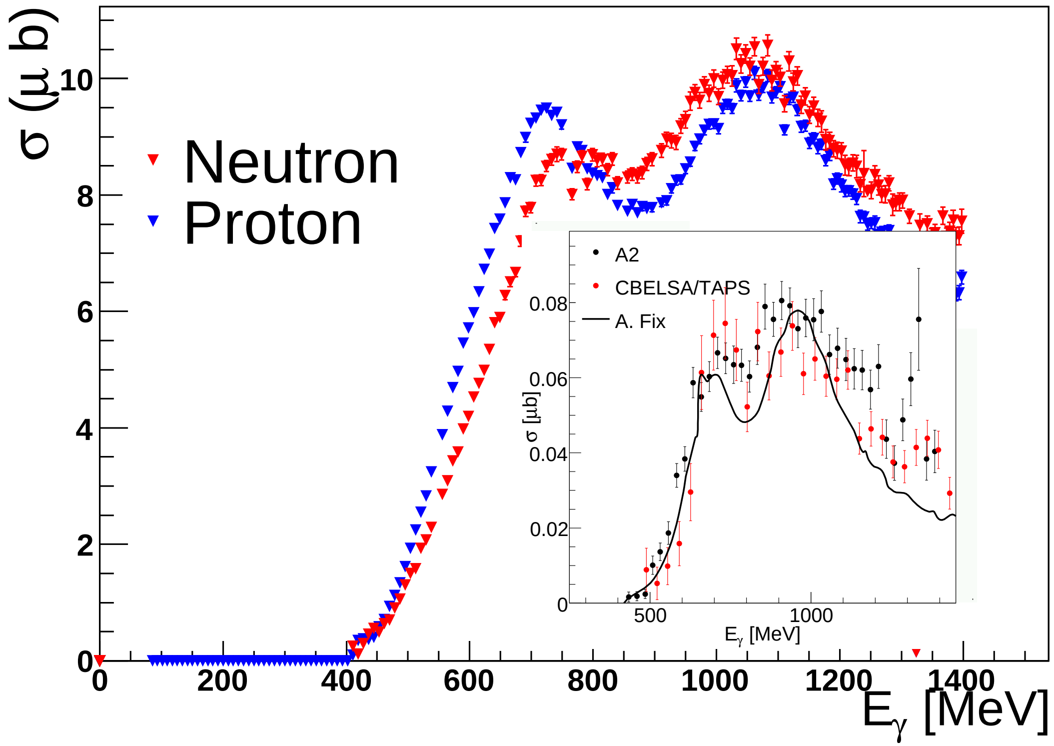
I. Jaegle et al.

single π^o, double π^o...

- $p\pi^o, n\pi^o, d\pi^o$
  M. Dieterle et al.

- $p\pi^o\pi^o, n\pi^o\pi^o, d\pi^o\pi^o$
  M. Oberle et al.





- **quasi-free off proton and neutron: contriutions from different N*-resonancs**
- **coherent off deuteron (isospin): only Δ-resonances for single π^o,**
  only N*-resonances for double π^o

Conclusions

Systematic investigation of meson production off ^{2}H and ^{3}He:

η-photoproduction off deuteron:

- large difference for resonance contributions to $p(\gamma,\eta)p$ and $n(\gamma,\eta)n$
- narrow structure in excitation function off neutron

η-photoproduction off ^{3}He:

- evidence for (quasi)-bound η-nucleus state

other channels:

- iso-spin dependence of the elm. nucleon excitation

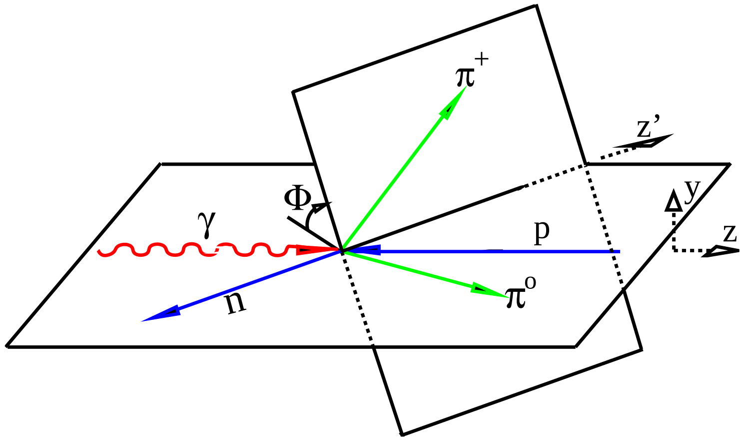
outlook:

- upcoming program to measure quasi-free (double) polarization observables

I. Jaegle
I. Keshelashvili
T. Rostomyan
F. Pheron
Y. Maghrbi
D. Werthmüller
Th. Challand
R. Trojer
M. Dieterle
M. Oberle
L. Witthauer

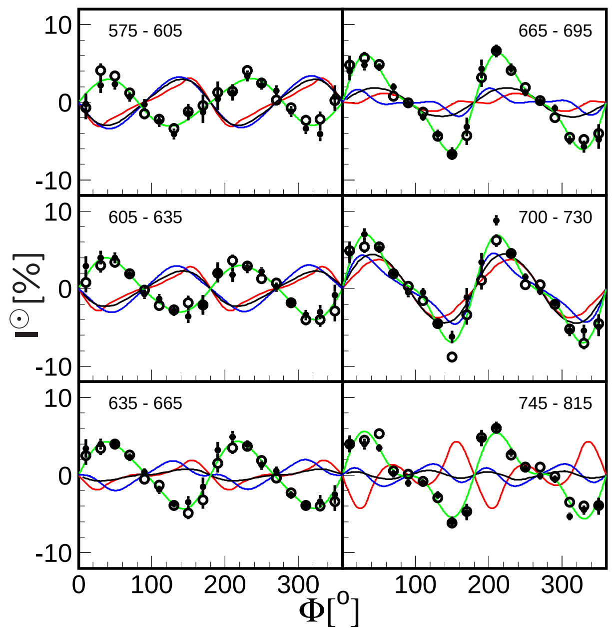
polarization observables - example: beam-helicity for 2π

- **beam-helicity asymmetry (circularly polarized beam, unpolarized target)**

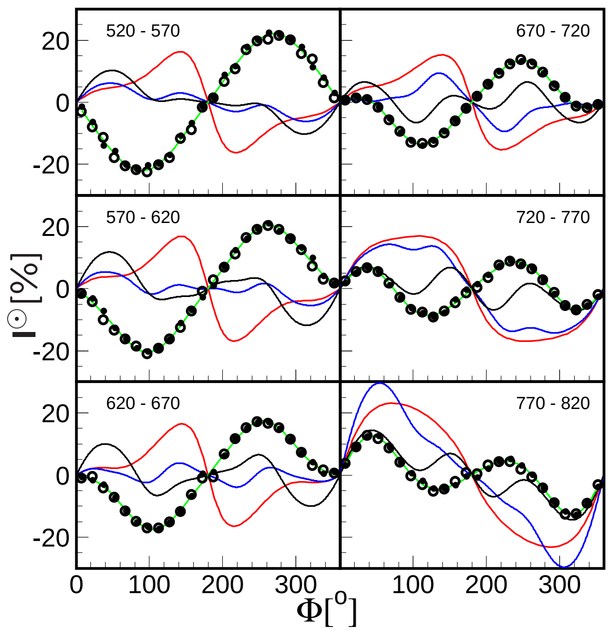


$$I^{\odot}(\Phi) \equiv \frac{d\sigma^{+} - d\sigma^{-}}{d\sigma^{+} + d\sigma^{-}}$$

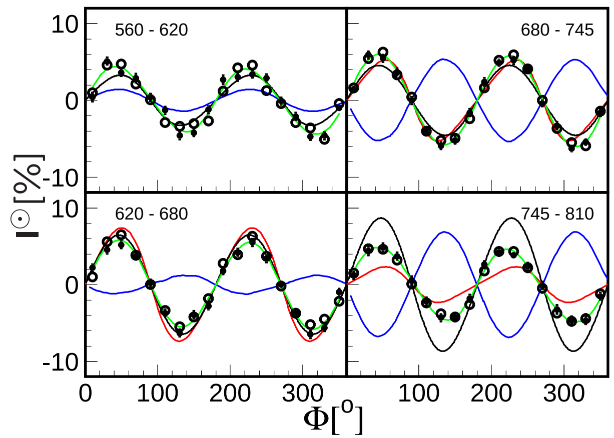
$$\gamma p \rightarrow p\pi^{+}\pi^{-}$$



$$\gamma p \rightarrow n\pi^{o}\pi^{+}$$



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

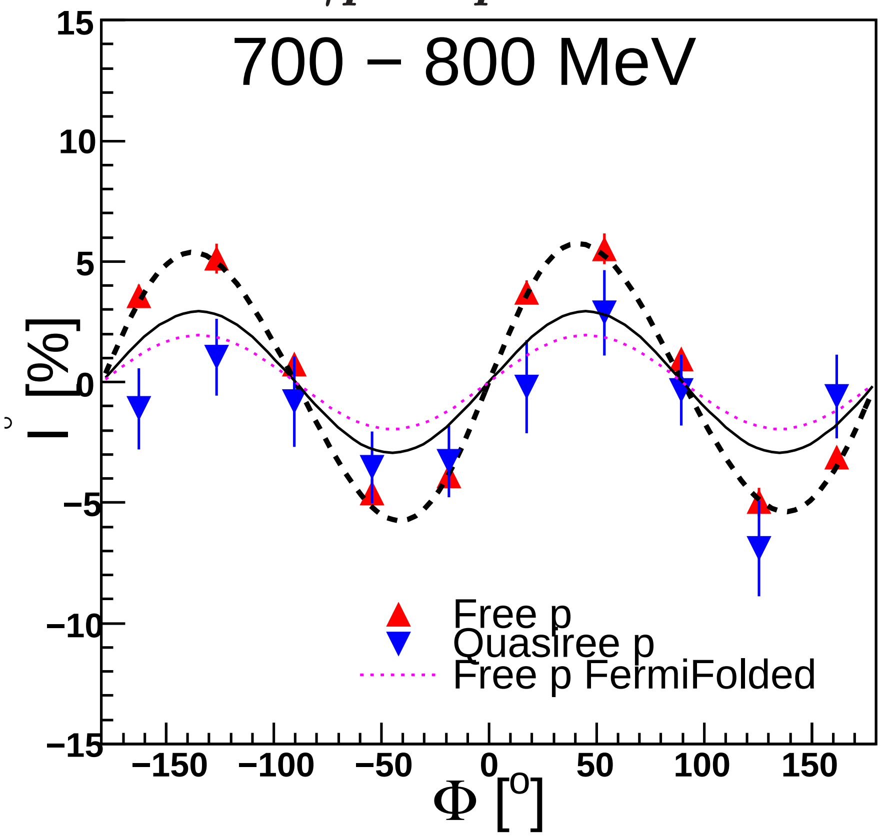


D. Krambrich, F. Zehr et al., PRL 103 (2009) 052002

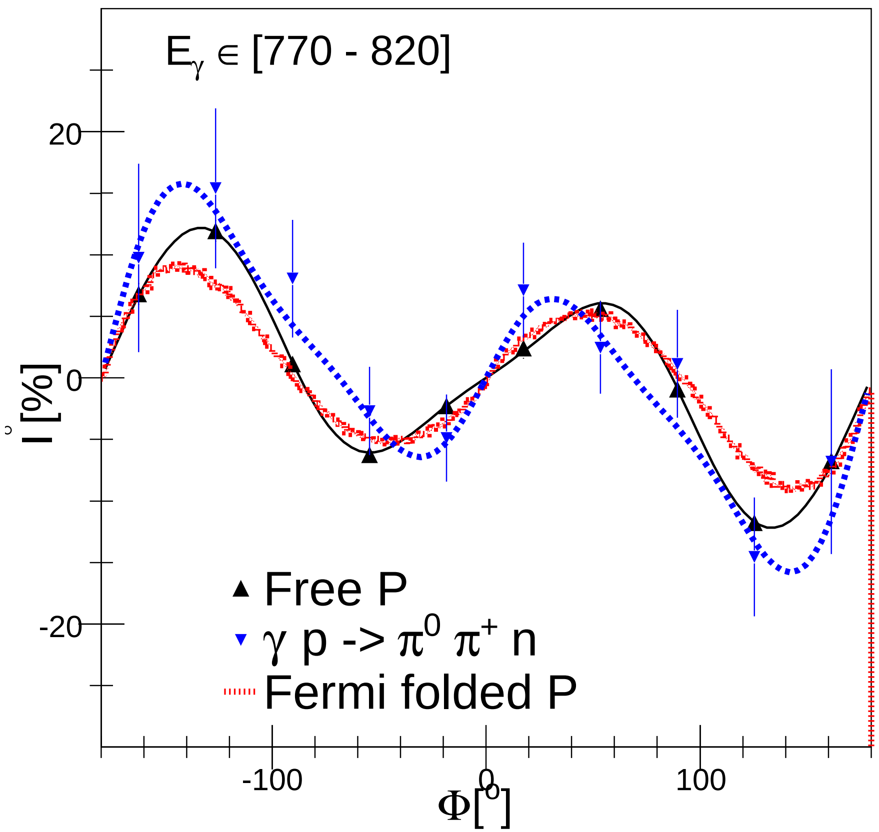
...free and quasi-free (off deuteron) proton results...

- preliminary quasi-free data from protons bound in deuteron already in good agreement with free proton data

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



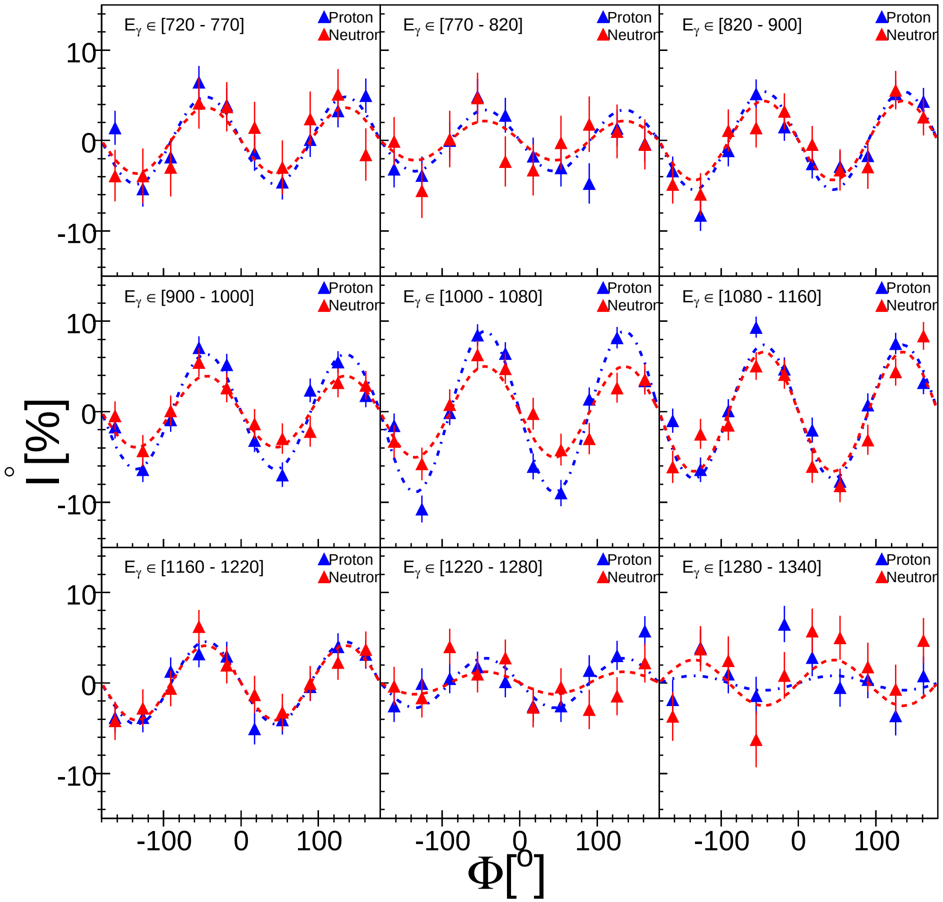
$\gamma p \rightarrow n\pi^o\pi^+$

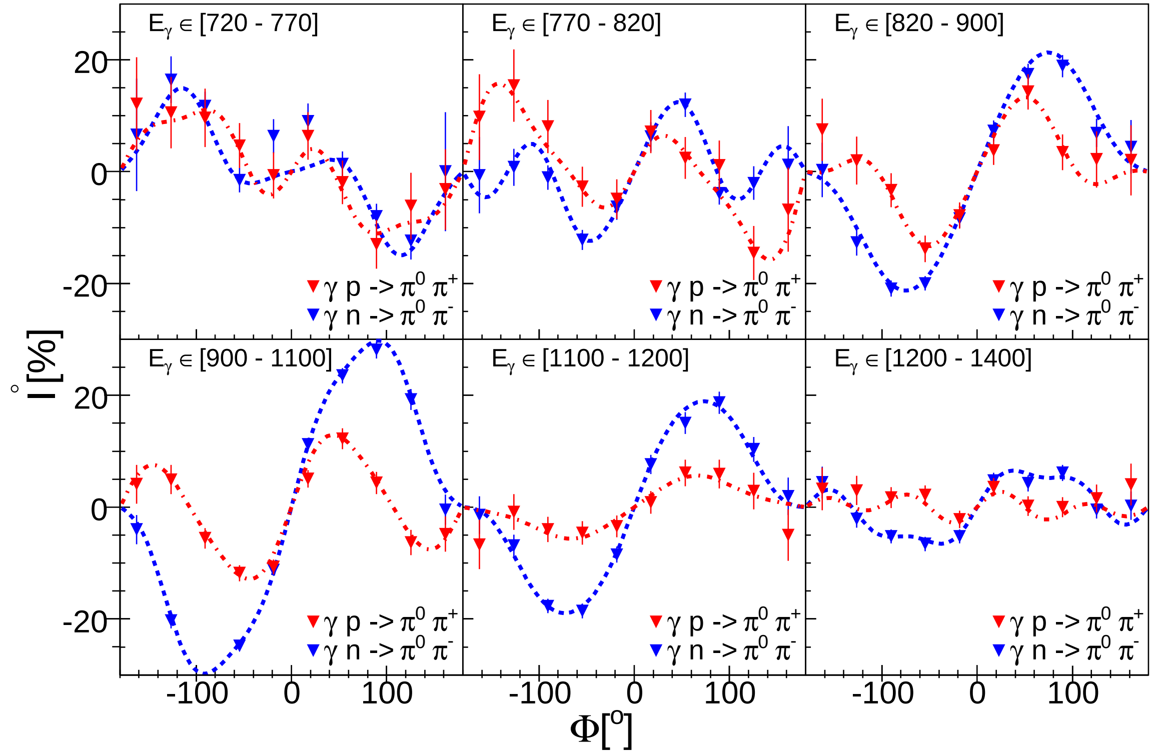


M. Oberle et al.

...quasi-free proton and quasi-free neutron...

- almost identical results for $\gamma p \rightarrow p\pi^o\pi^o$ and $\gamma n \rightarrow n\pi^o\pi^o$
- less similarities for $\gamma p \rightarrow n\pi^o\pi^+$ and $\gamma n \rightarrow p\pi^o\pi^-$

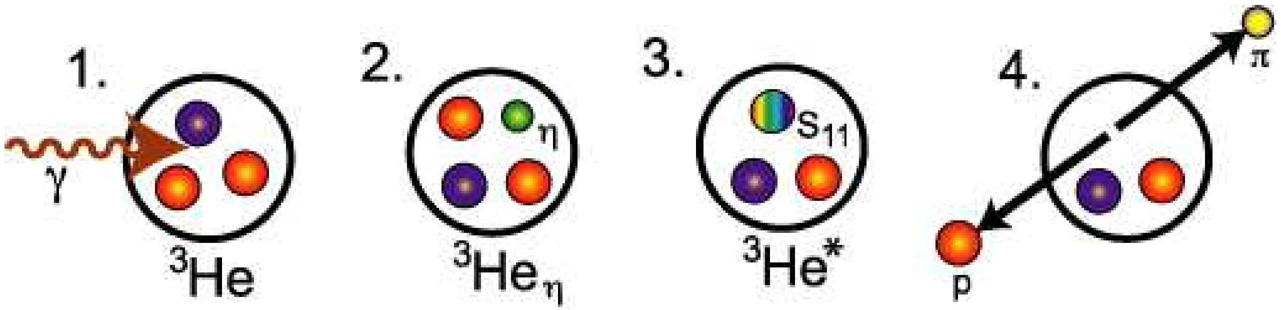




M. Oberle et al.

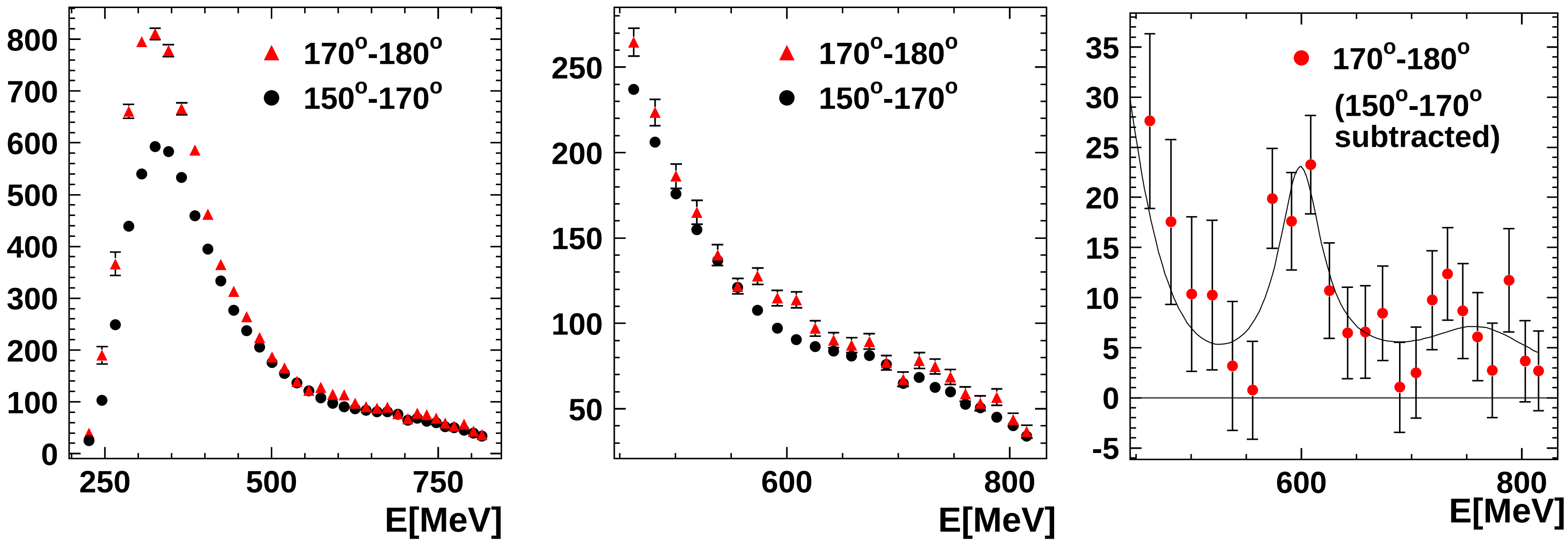
search for η-mesic nuclei

- G. Sokol et al., search in: $\gamma +^{12} C \rightarrow N +_{\eta} (A-1) \rightarrow N + \pi^{+} + n + (A-2)$
- similar principle for photoproduction from ^{3}He:



$\rightarrow$ search for back-to-back π^o - p pairs

- excess of π^o-p back-to-back emission at the η-threshold (3.5σ)



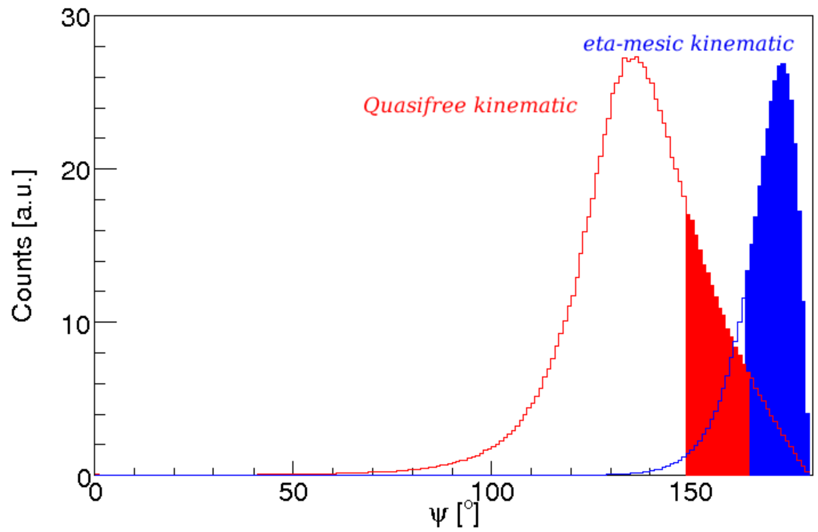
TAPS

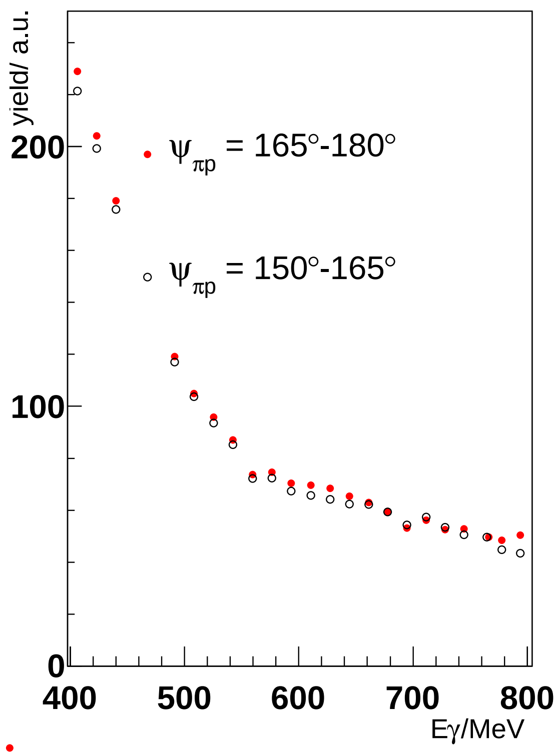
new ^{3}He experiment: π^o-p back-to-back pairs

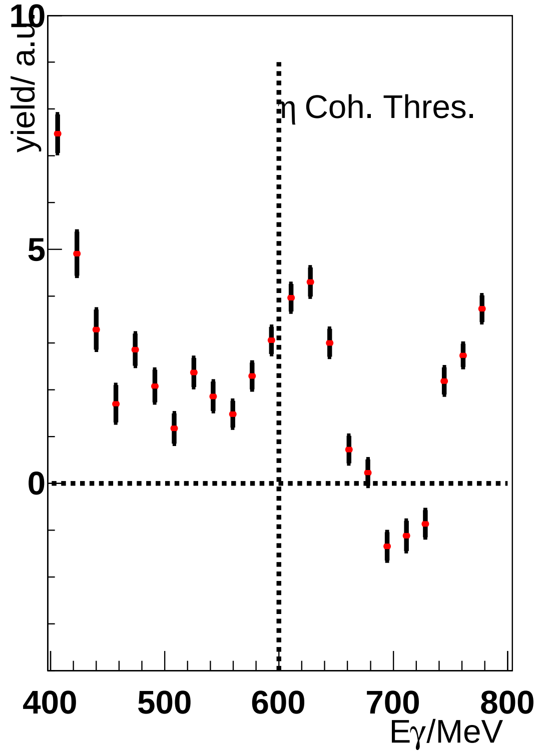
π^o-p back-to-back pairs:

- peak structure at coherent threshold is statistically significant...

simulation of opening angle behavior for quasi-free π^o production and η-mesic state



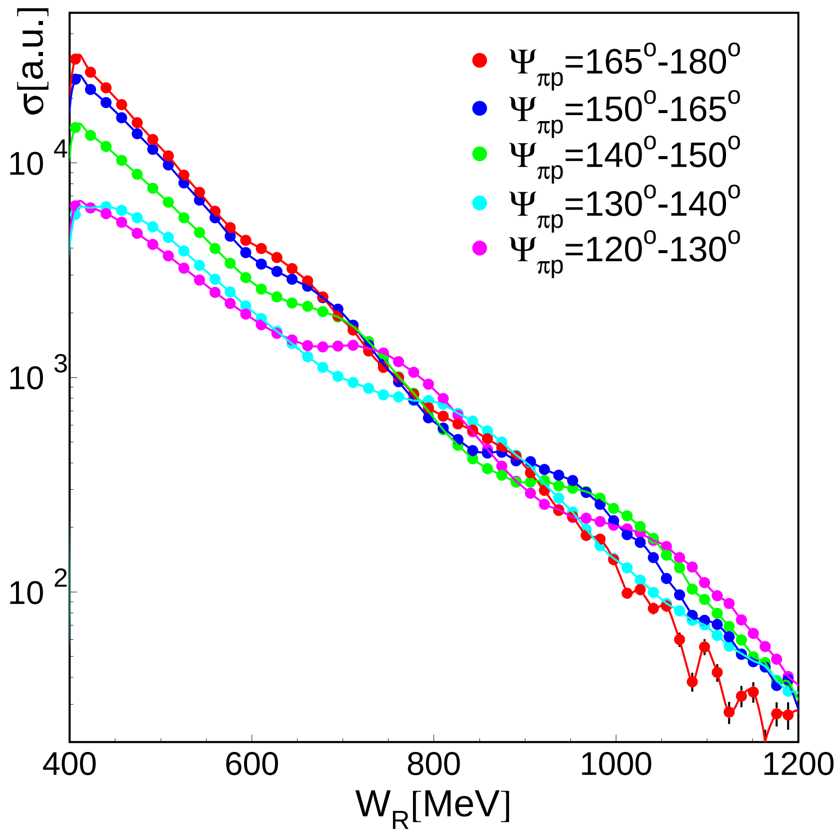




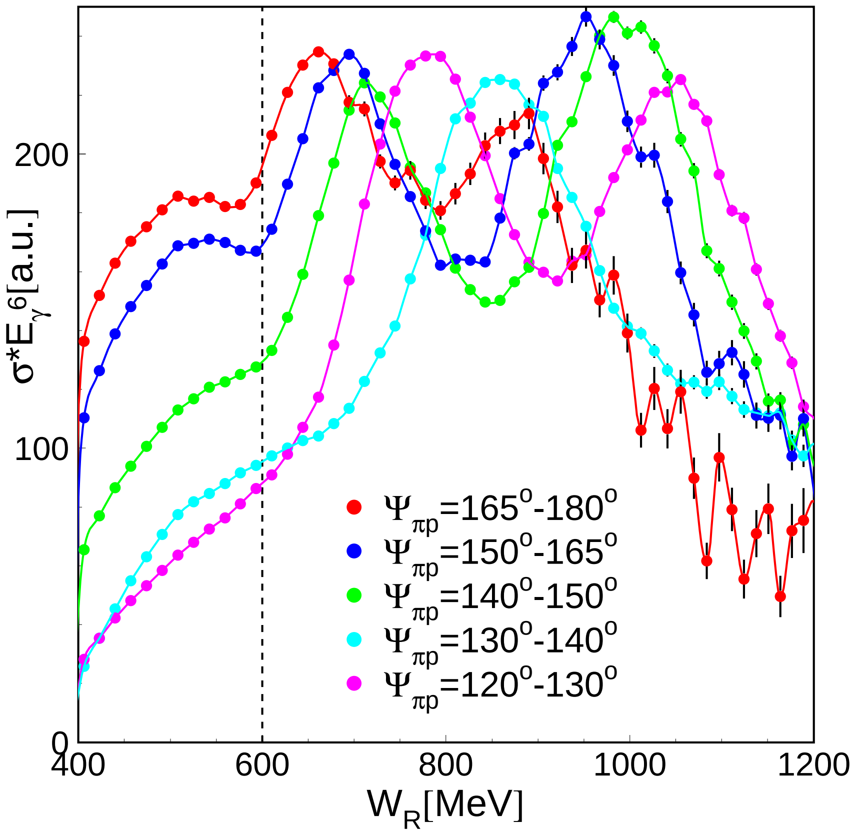
<u>But:</u> behavior of background from single π^o production via nucleon resonances highly non-trivial $\longrightarrow$

Dependence of $\pi^o - p$ excitation functions on opening angle

- **excitation functions - arbitraly scaled**



- **excitation functions $\times E_\gamma^6$**



- **nucleon resonances produce opening angle dependent structures in excitation functions**
- **subtraction of excitation functions for different opening angles can produce artificial structures almost everywhere**
- **basically no hope to isolate tiny structure from η-mesic state in this complicated landscape!**

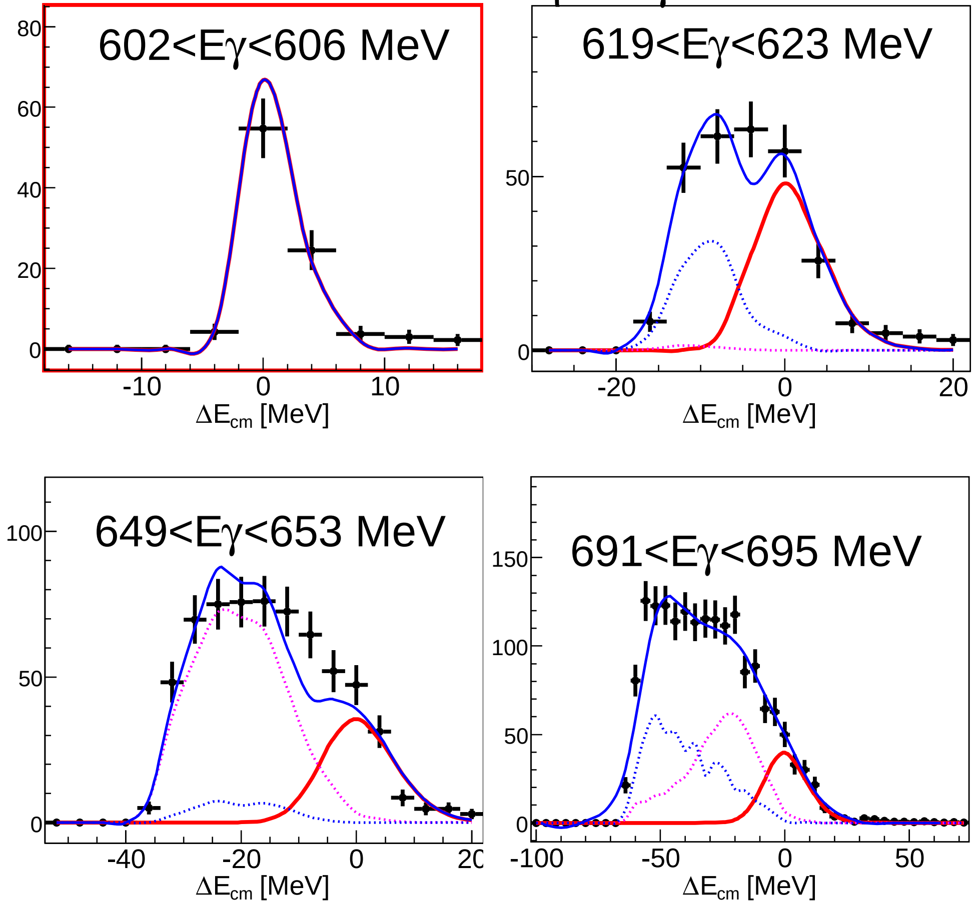
new ^{3}He experiment - improved statistics

PhD thesis F. Pheron

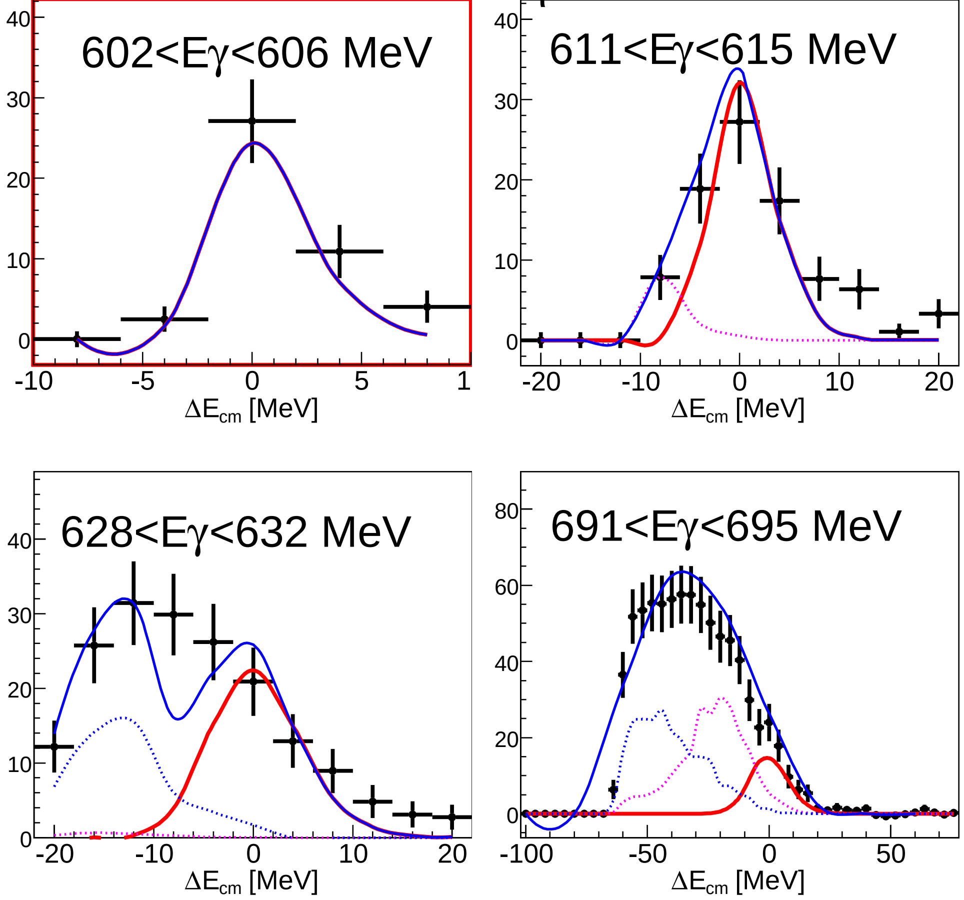
reaction identification:

- invariant mass analyses for $\eta \rightarrow 2\gamma$ and $\eta \rightarrow 3\pi^o \rightarrow 6\gamma$
- missing energy analysis for coherent kinematics:

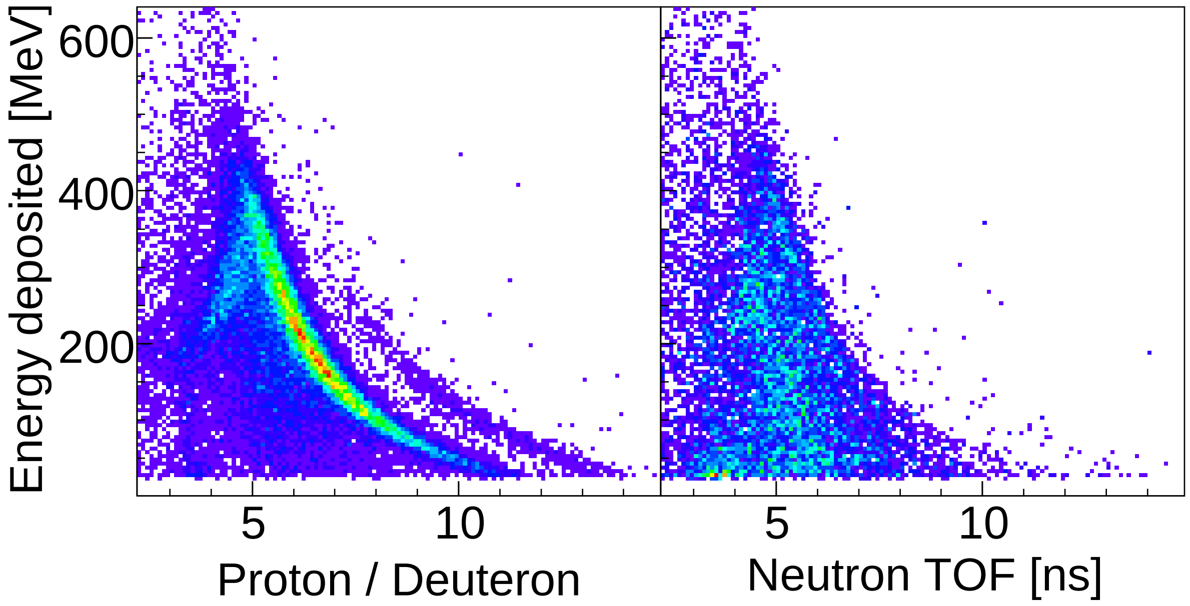
$\eta \rightarrow 2\gamma$



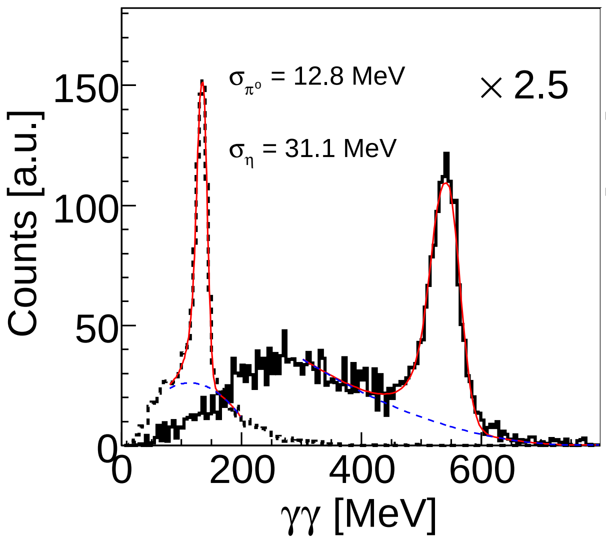
$\eta \rightarrow 3\pi^0$

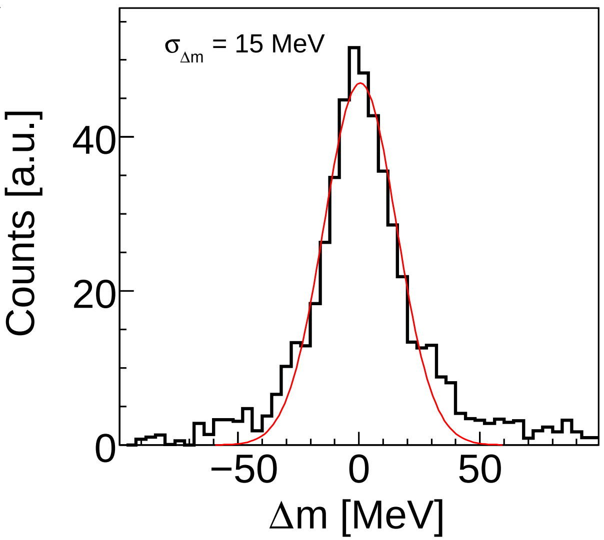


coherent photoproduction of $\pi^o\eta$-pairs: $d(\gamma,\eta\pi^o)d$



- time-of-flight versus energy for deuteron identification





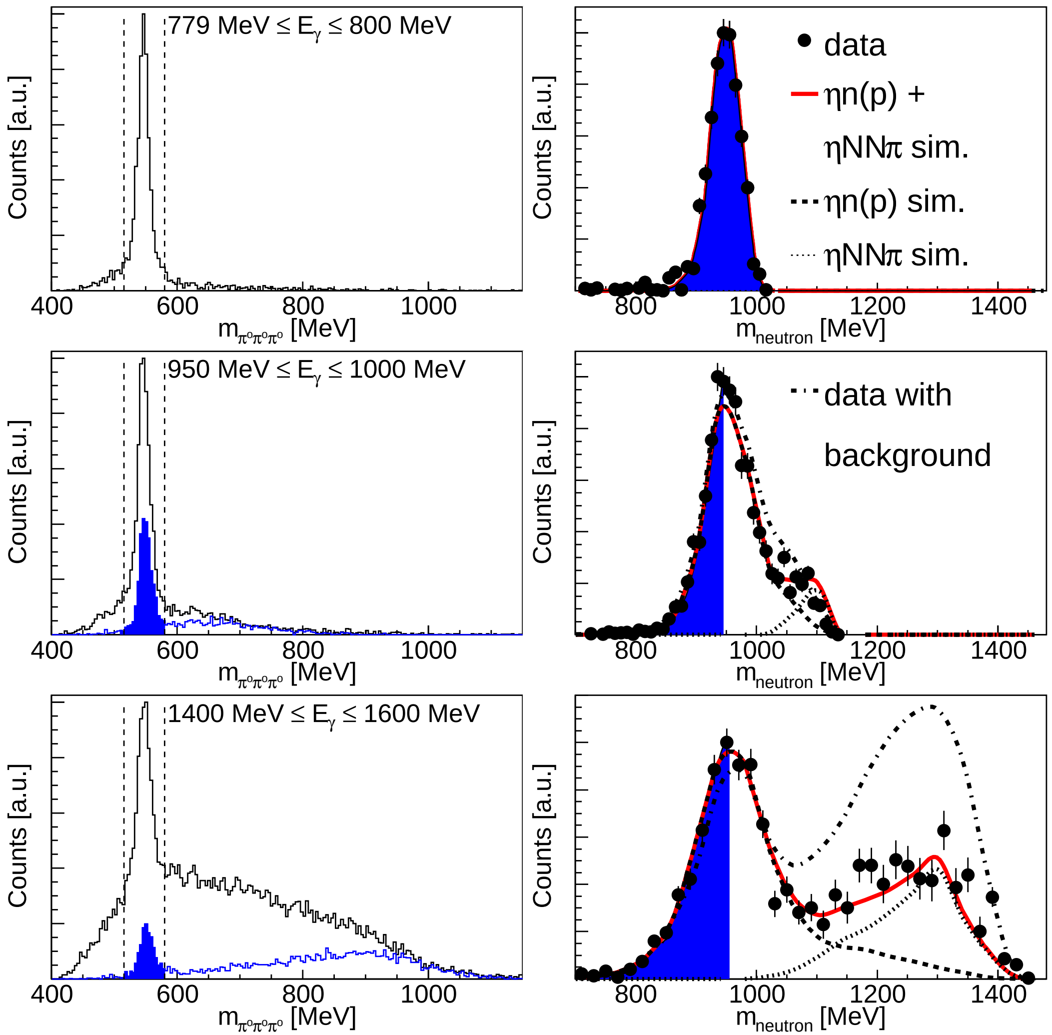
- invariant mass (two-photon) for reaction identification and missing mass (deuteron treated as missing particle) for verification of coherent kinematics

I. Jaegle et al.

identification of η-meson production (exclusive)

- **decay channel: $\eta \rightarrow 3\pi^o \rightarrow 6\gamma$**
- **select events with 7 hits**
- **invariant mass off all photon pairs**
- **cut on π^o invariant mass**
- **select best combination of 6γ to $3\pi^o$ by χ^2-test**
- **use π^o mass as constraint, construct $3\pi^o$ invariant mass**
- **cut on $3\pi^o$ invariant mass**
- **missing mass analysis to remove $\eta\pi$ final states etc. treat recoil nucleon as missing particle:**

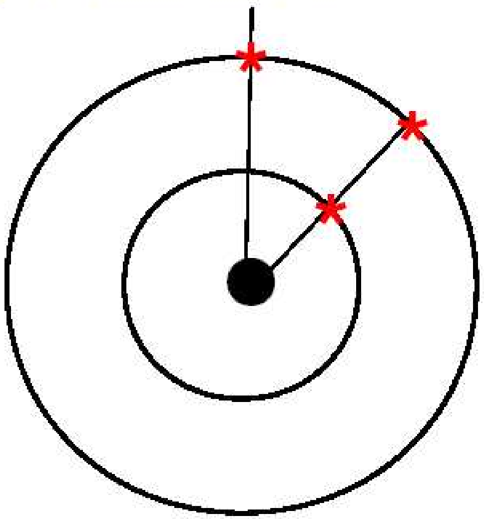
$$m^2 = (\mathbf{P}_\gamma + \mathbf{P}_N - \mathbf{P}_\eta)^2$$

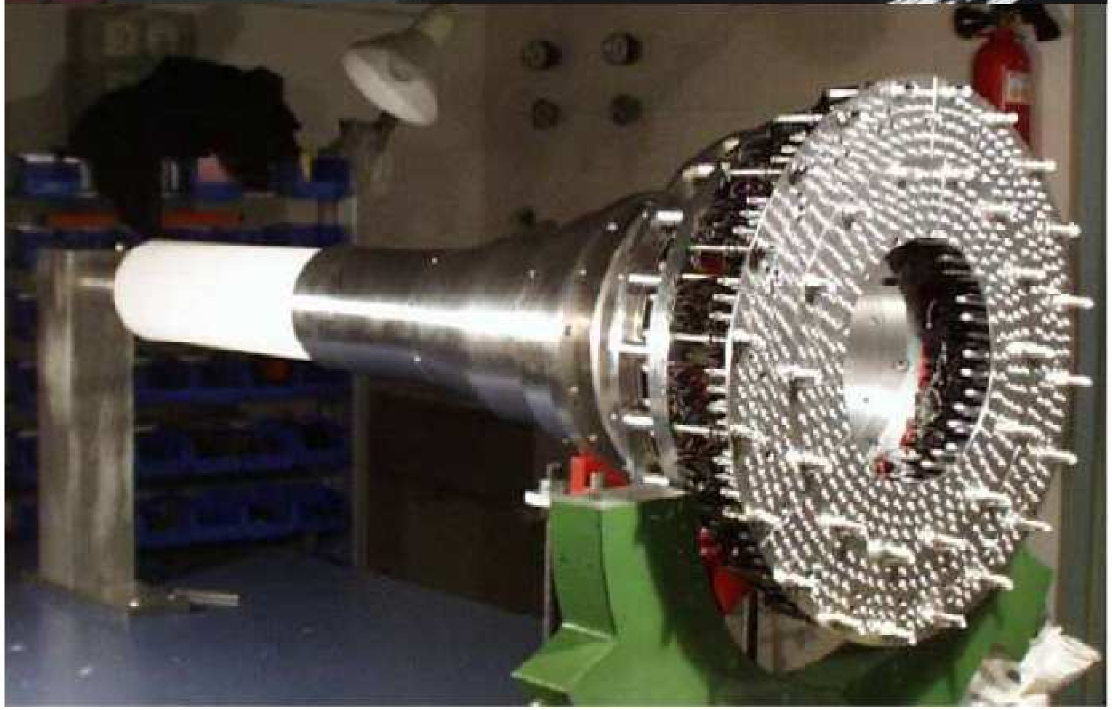


Nucleon Identification CB

inner detector:

- 3 layers of scintillating fibers
- cylindrical shape
- proton:
2 or 3 layers match a hit in the CB
-neutron:
no layer has fired





Nucleon Identification TAPS

taps veto detector:

- **5 mm plastic scintillator**
- **individual for each BaF_2 crystal**

proton:

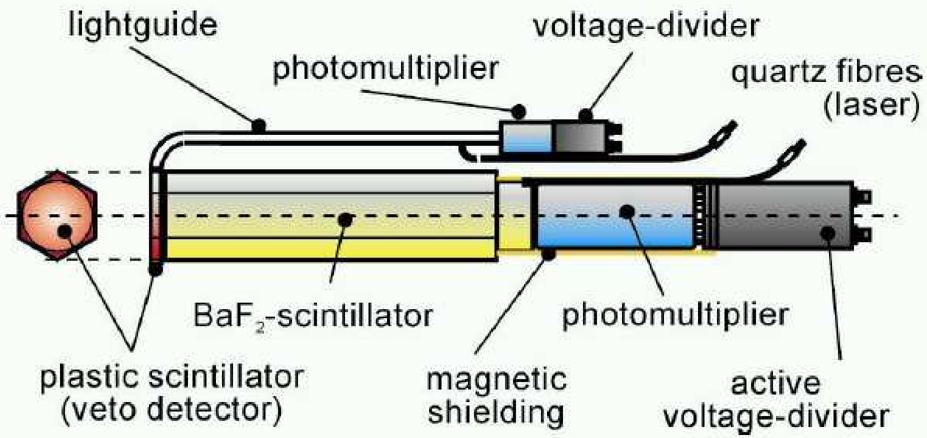
veto hit in front of BaF_2 crystal

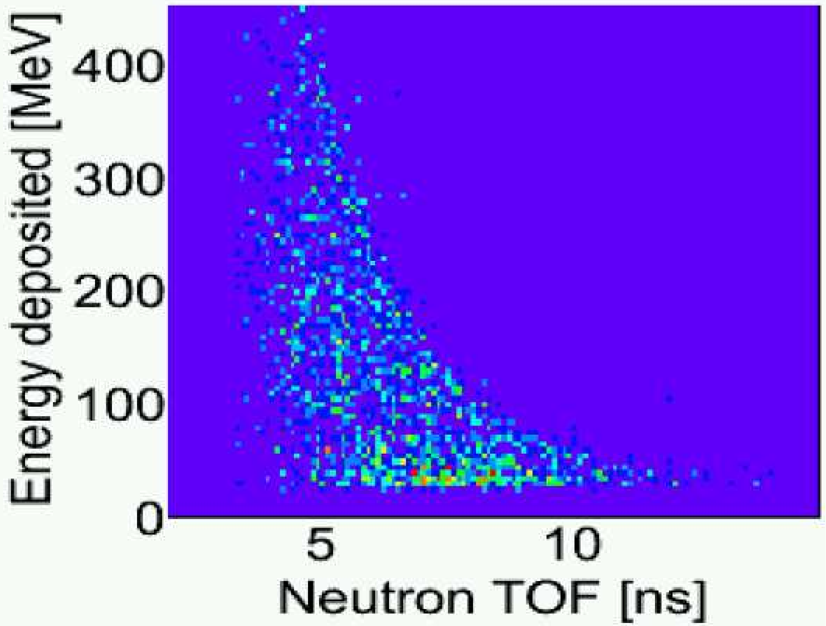
+ E vs TOF

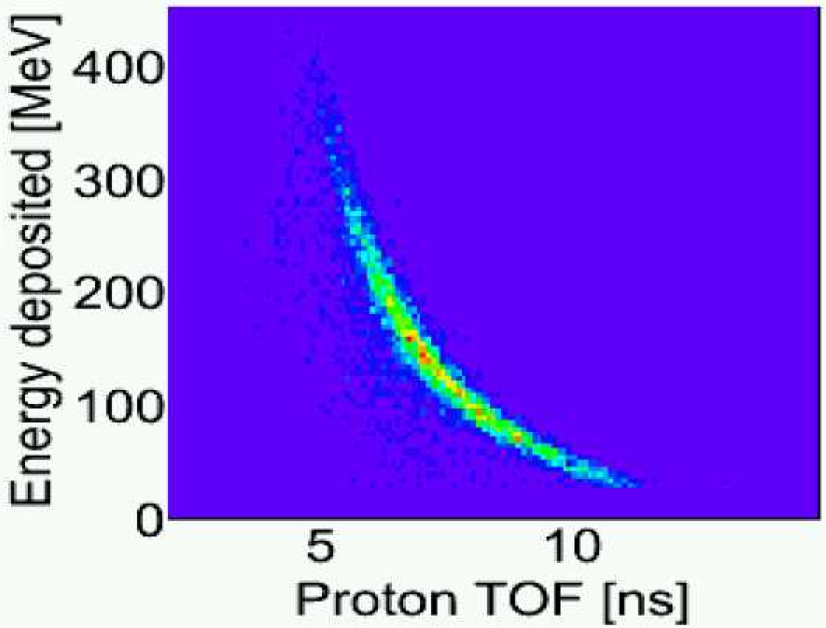
neutron:

no veto hit in front of BaF_2 crystal

+ E vs TOF



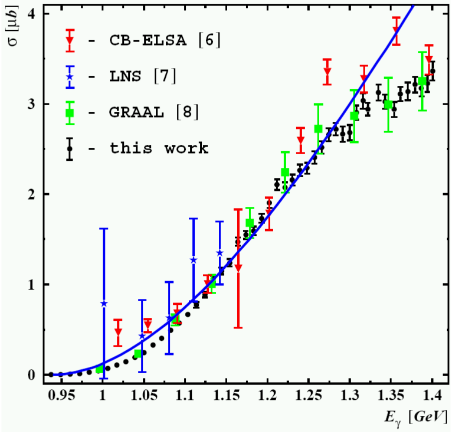




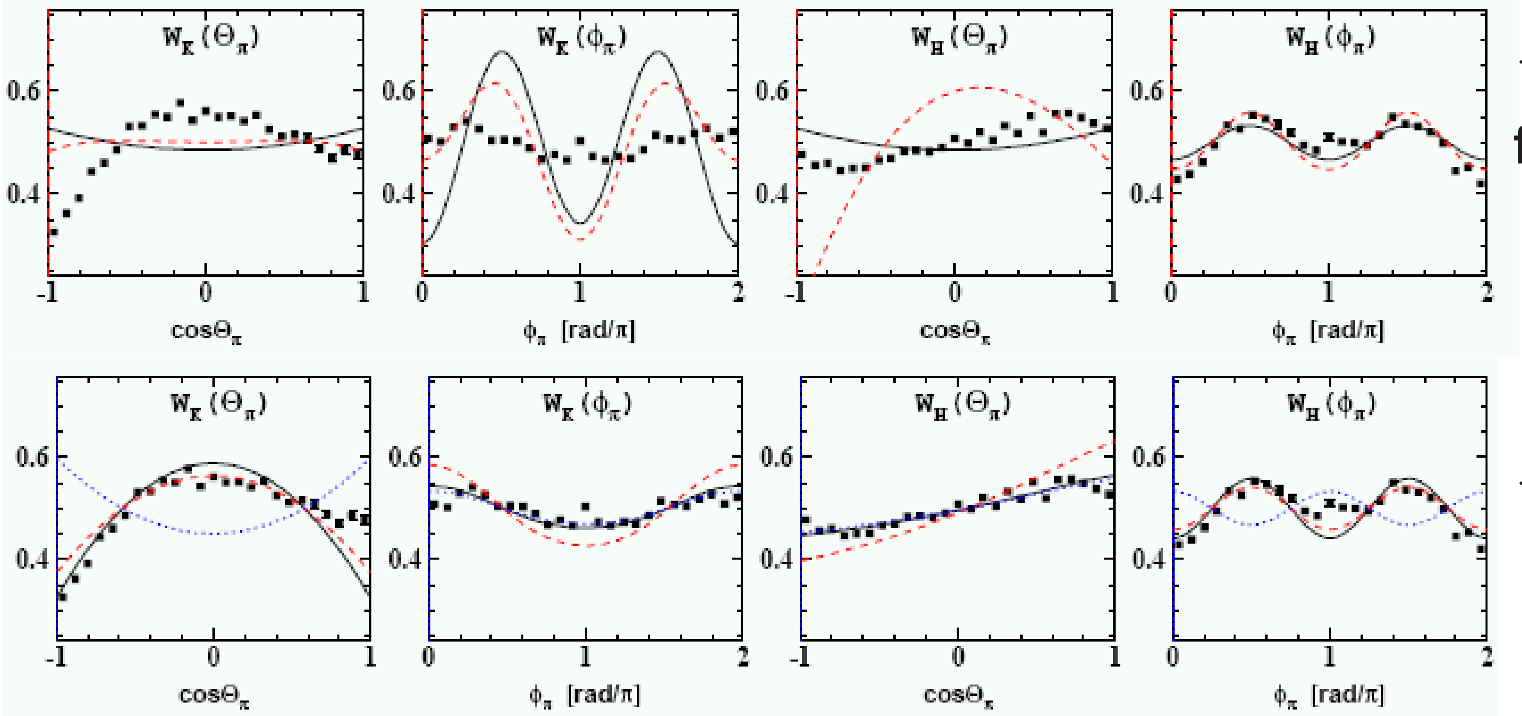
B. Krusche, MESON2010, Cracow, June 2010

threshold region of $\pi^o\eta$ dominated by $D_{33}(1700)$

V. Kashevarov et al. (MAMI)



- analysis of threshold region in terms of isobar model (Fix et al.) indicates strong dominance of $D_{33}(1700)$
- extracted amplitudes allow specific predictions for coherent production of $\pi^o\eta$-pairs of light nuclei (Fix et al.)

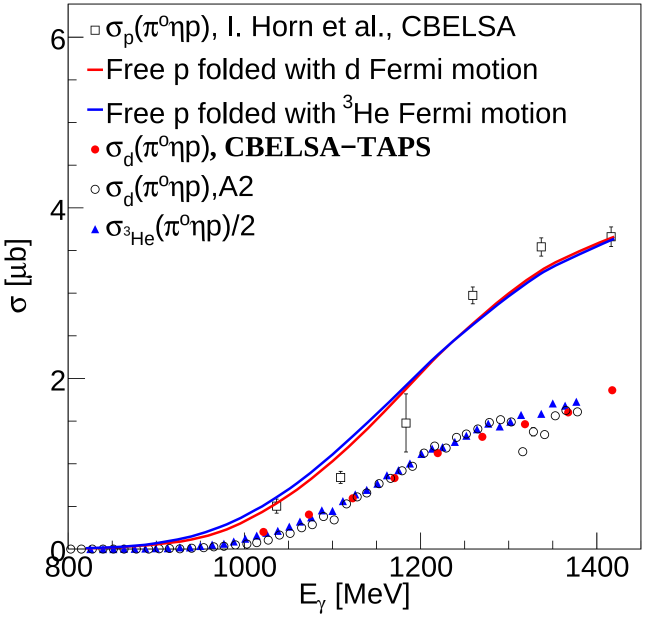


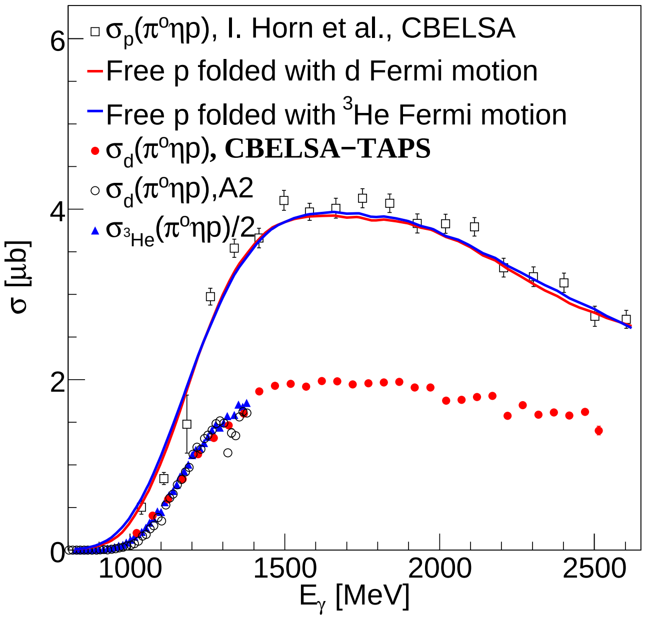
⇐ best model fits for P_{33} or D_{35} isobars

⇐ model fits for D_{33} isobar

quasi-free photoproduction of $\pi^o\eta$ pairs

- ...preliminary results





- deuteron results from MAMI and ELSA consistent
- quasi-free proton and neutron results from deuteron and ^{3}He consistent
- quasi-free proton cross section roughly 50 % smaller than free proton cross section. Not yet understood. FSI ?
- quasi-free proton and neutron cross sections very similar as expected