

Photoproduction of mesons off nuclei

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



Introduction

- excited states of the nucleon
- meson nucleus interactions



Experimental setups

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

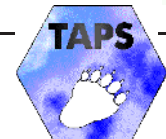
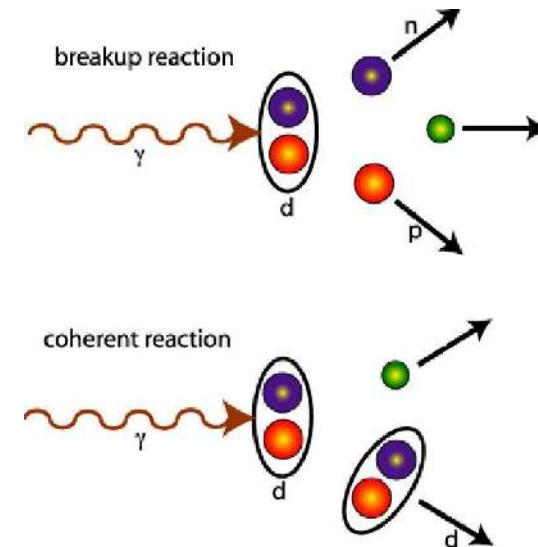


Experimental results

- photoproduction of mesons off quasi-free nucleons: η , η' , $\pi^0\pi^0$, $\pi^0\eta$,...
- coherent photoproduction of mesons off light nuclei: $\pi^0\eta$, $\pi^0\pi^0$, $\pi^0\pi^0\pi^0$
- search for η -mesic nuclei

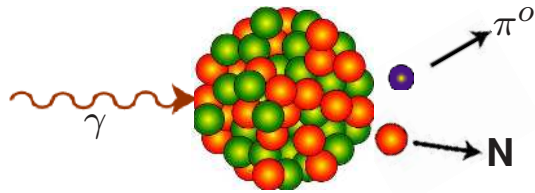


Conclusions



Photoproduction of mesons off nuclei - what can we learn?

◆ breakup (quasi-free)



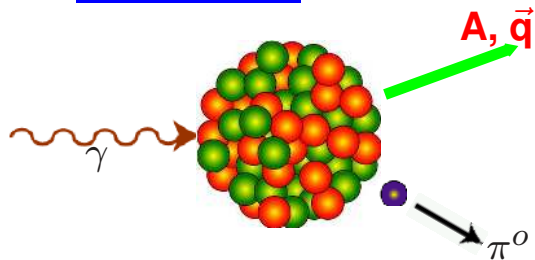
$$\gamma + A \rightarrow \pi^0 + A' + N + \dots$$

$$\frac{d\sigma}{d\Omega} \propto \sum |\mathcal{A}|^2 \times \dots$$

& nuclear effects & FSI & ...

- ◆ **photo-excitation of quasi-free neutrons**
- ◆ **in-medium properties of hadrons, meson FSI...**

◆ coherent



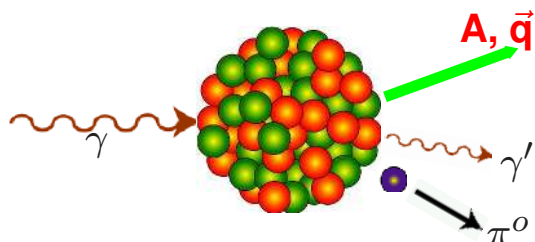
$$\gamma + A \rightarrow \pi^0 + A$$

$$\frac{d\sigma}{d\Omega} \propto |\sum \mathcal{A}|^2 \times F^2(q^2) \times \dots$$

& nuclear effects & FSI & ...

- ◆ **spin/iso-spin filters**
- ◆ **meson - nucleus bound states...**
- ◆ **△ in-medium properties**
- ◆ **nuclear form factors**

◆ incoherent

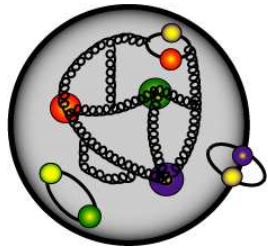


$$\begin{aligned} \gamma + A &\rightarrow \pi^0 + A^* \\ &\rightarrow \pi^0 + A + \gamma \end{aligned}$$

- ◆ **transition form factors**
- ◆ **△ in-medium properties**
- ◆ **spin/iso-spin selection**

Structure of the Nucleon

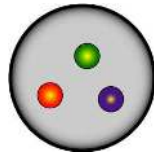
complex many body system



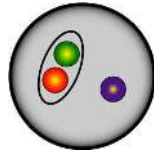
- green hexagon valence quarks
- yellow hexagon sea quarks
- black line gluons

models - effective dof's:

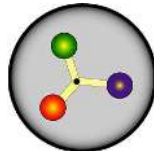
3 equivalent constituent quarks



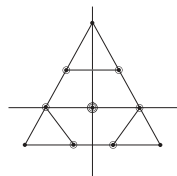
quark - diquark models (fewer states)



quarks - flux tubes etc. (more states)

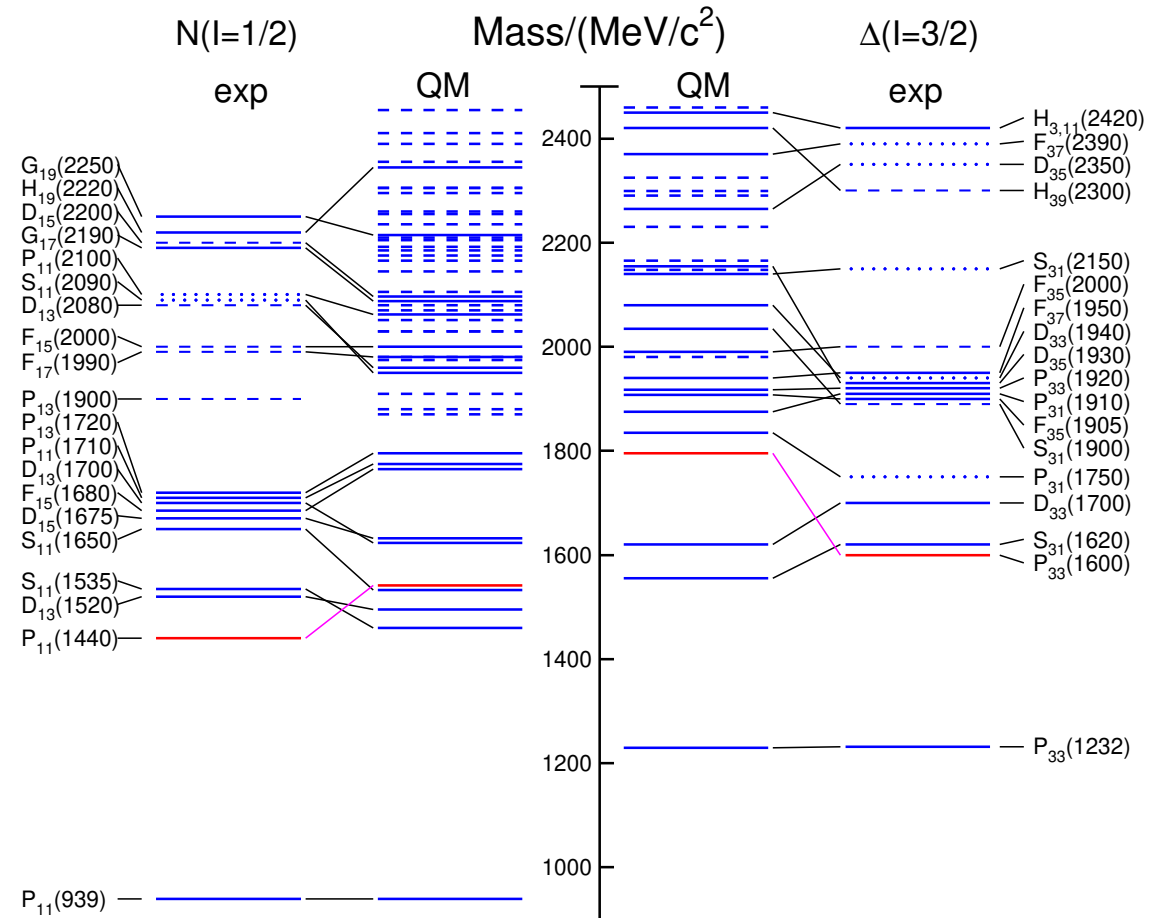


chiral soliton models (anti-decuplet states)



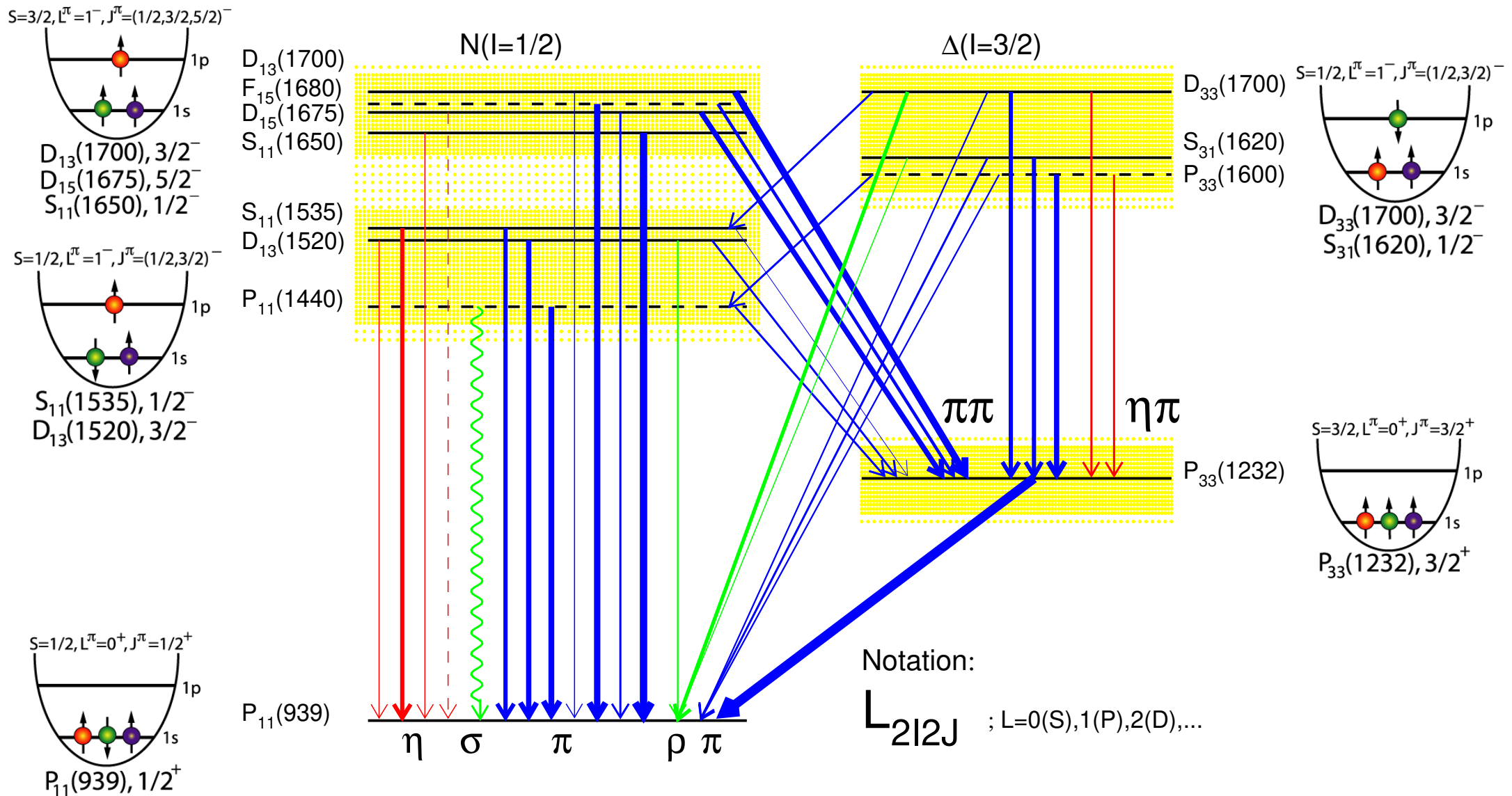
coupled channel dynamics (molecule-like states) ■■■

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



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

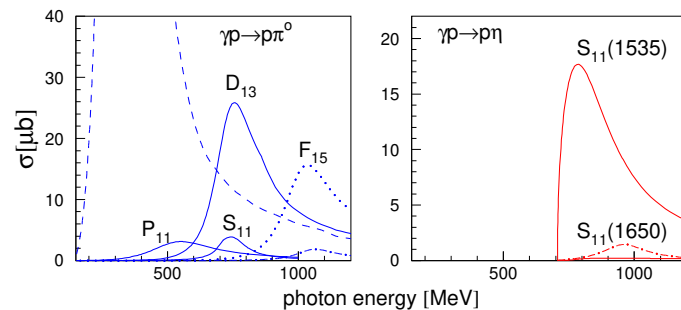
low lying excited states



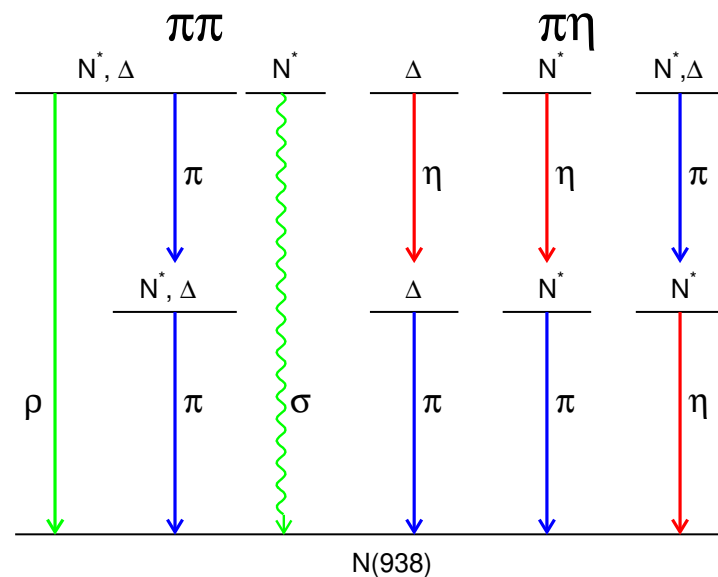
Experimental Options:

Final states:

- single meson production:
 $\gamma p \rightarrow p\pi, \eta, \eta', \omega \dots; \Sigma K^{(*)} \dots$



- multiple meson production:



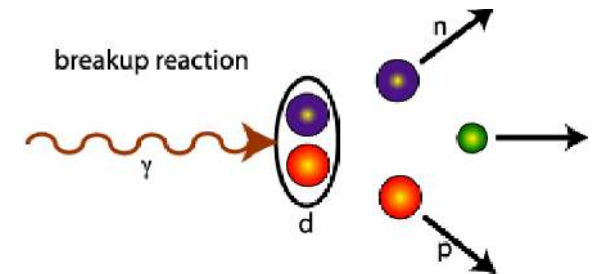
Observables:

- ang. distributions
 $\longrightarrow d\sigma/d\Omega$
- Dalitz plots
 $\longrightarrow M(N, m_i), M(m_1, m_2)$
- polarization dof:
 - linearly pol. beams
 - circularly pol. beams
 - longitudinally pol. targets
 - transversely pol. targets
 - recoil polarization

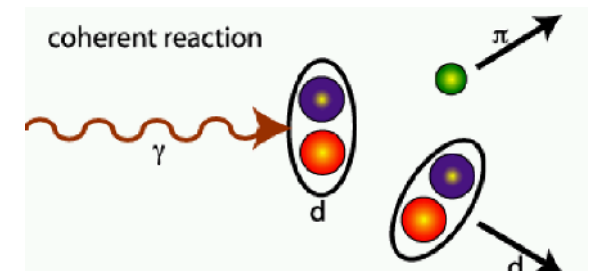
$$\begin{aligned} &\longrightarrow I^\odot \\ &\longrightarrow \Sigma, R, T \\ &\longrightarrow E, G, H, F \\ &\longrightarrow \dots \end{aligned}$$

Isospin: neutron targets

- elm. excitations
isospin dependent
- quasifree off the deuteron



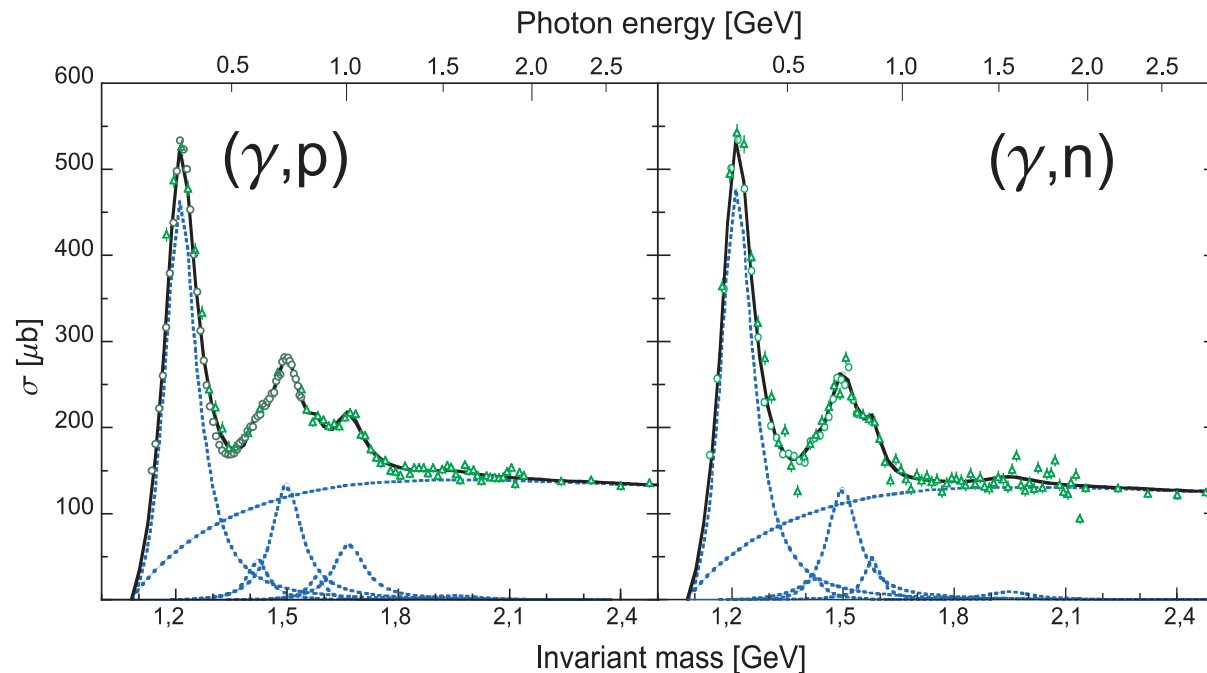
- coherent off the deuteron



electromagnetic excitation off 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

resonance excitations in quasi-free and coherent photoproduction of mesons



motivations:

- ◆ investigate/find resonances that are stronger excited on the neutron than on the proton (Moorehouse rules)
- ◆ investigate spin/iso-spin structure of electromagnetic resonance excitations



tools & status & problems:

- ◆ **quasi-free production processes to investigate neutron excitations**
so far mainly results for pion, η -production for differential cross sections
partly not well understood 'deuteron' effects
- ◆ **coherent production processes as spin/iso-spin filters**
so far almost only for π^0 and sparse results for η
in most cases very small cross sections, difficult to separate from breakup

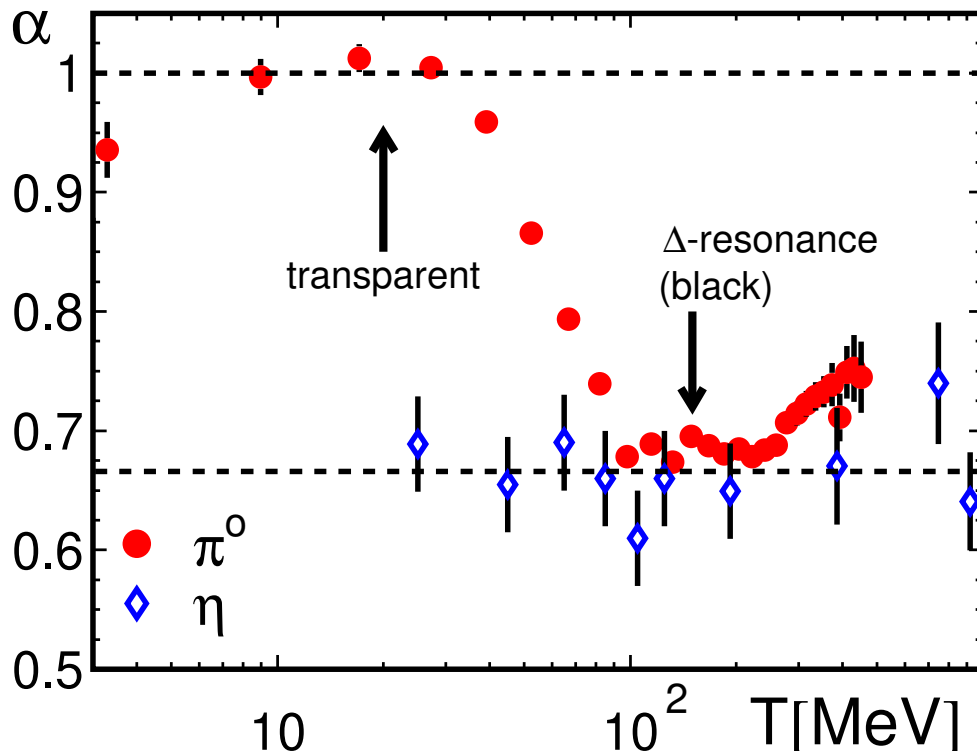
interaction of mesons in nuclear matter

◆ results from inclusive (quasi-free) pion photoproduction

A-scaling of cross sections as function of kinetic energy **T**:

$$\sigma(A) \propto A^{\alpha(T)}$$

$\alpha \approx 1$: 'volume', no absorption
 $\alpha \approx 2/3$: 'surface', strong absorption



◆ **π^0 -mesons**: strongly absorbed at energies sufficient to excite Δ ; but only very weak interaction at small momenta

→ no bound-states possible

◆ **η -mesons**: strong interaction also at very small momenta due to s-wave $S_{11}(1535)$ resonance at threshold

→ strong enough for (quasi)-bound states?

'history' of η -mesic nuclei

● **1985: Bhalerao & Liu:**
attractive η -nucleus interaction for $A \geq 12$

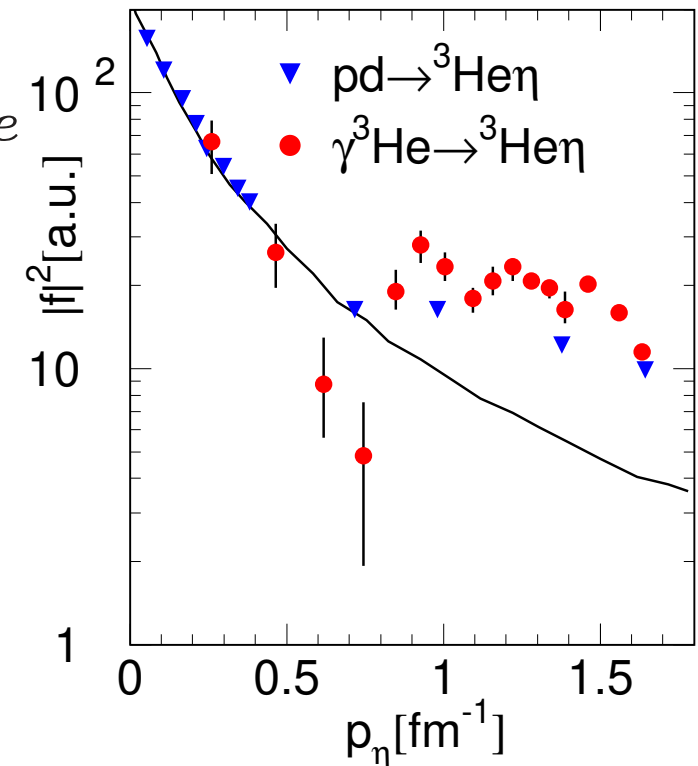
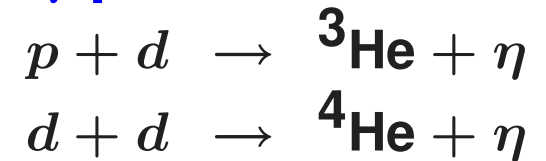
● **1986: Liu & Haider:**
suggestion of η -nucleus bound states

● **experiments: inconclusive e.g.:**
Chrien et al. (1988): $\pi^+ + {}^{16}\text{O} \rightarrow p + {}^{15}_{\eta}\text{O}$
Johnson et al. (1993): $\pi^+ + {}^{18}\text{O} \rightarrow \pi^- + {}^{18}_{\eta}\text{Ne}$

● **1993 - 2002: analysis of new
 η -production data from the proton:**
larger η N-scattering lengths

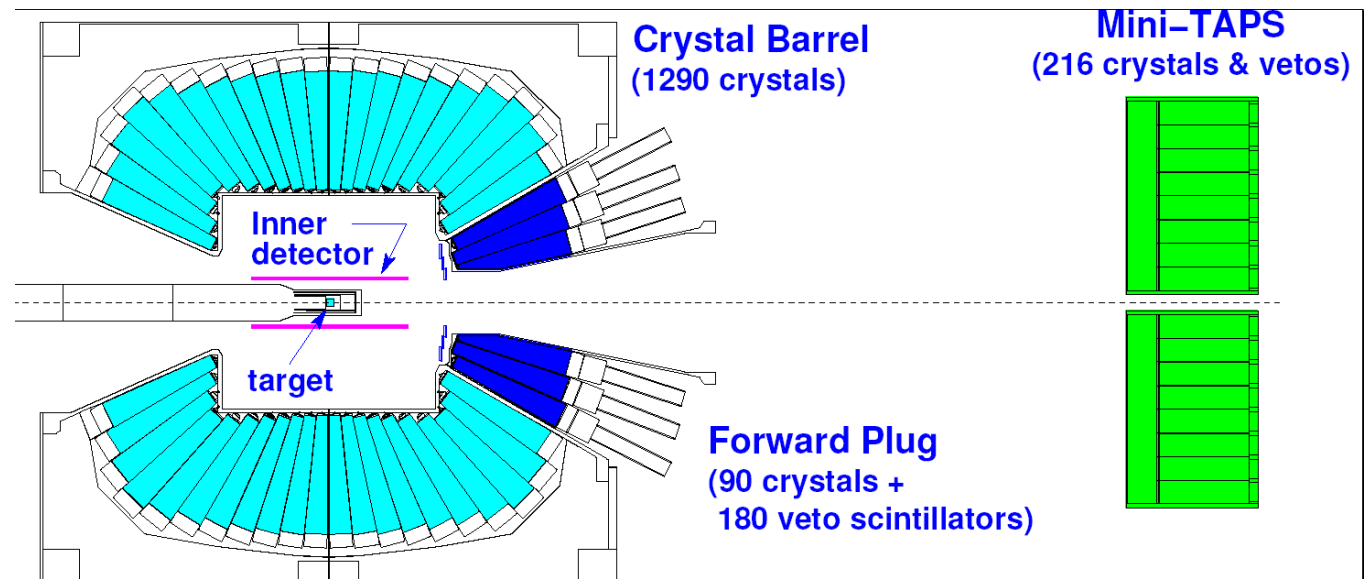
● **1991 - 2002: T. Ueda, C. Wilkin,
S.A. Rakityanski and others:**
suggestions of bound
 ${}^2\text{H-}$, ${}^3\text{H-}$, ${}^3\text{He-}$, ${}^4\text{He-}\eta$ states

● **experiments:
threshold behavior
of η -production**

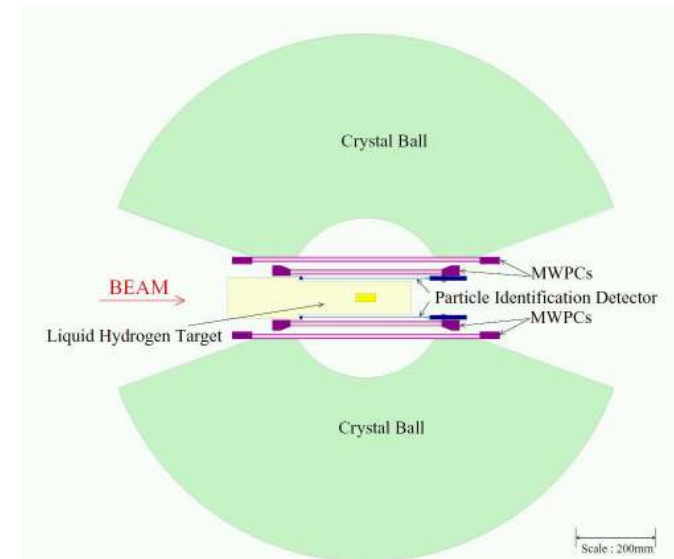
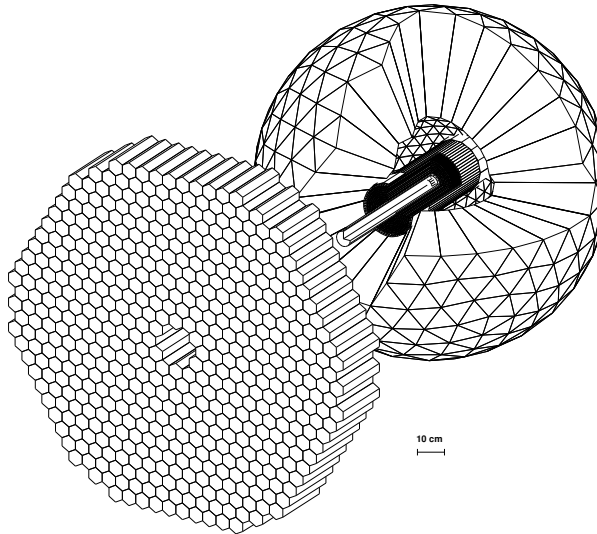


experiments: Crystal Ball & Crystal Barrel with TAPS

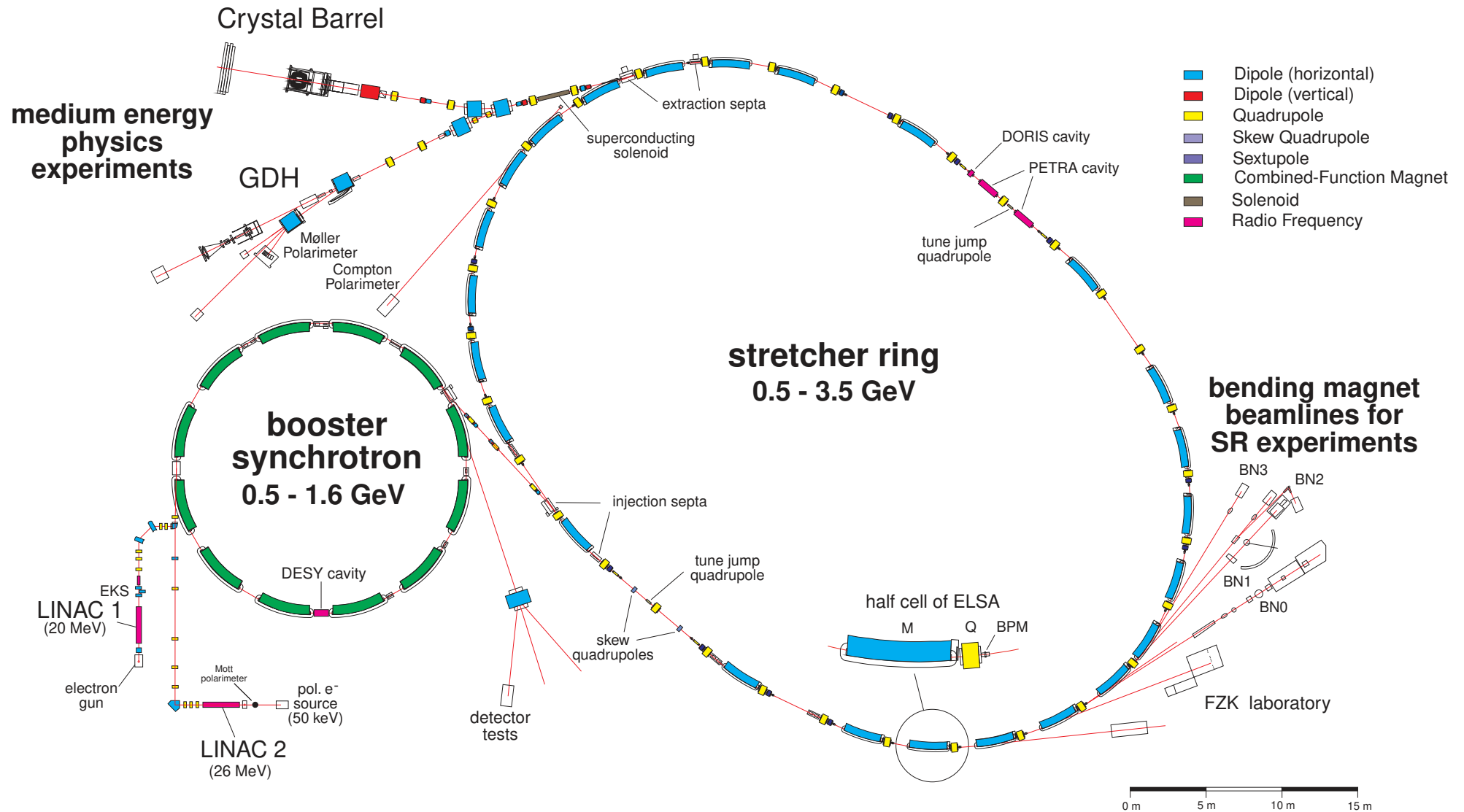
- ◆ **Bonn ELSA accelerator:**
Crystal Barrel (CsI),
TAPS (BaF₂) forward wall,
inner detectors
 $E_\gamma \leq 3.5$ GeV,
lin. pol.: available,
circ. pol.: available



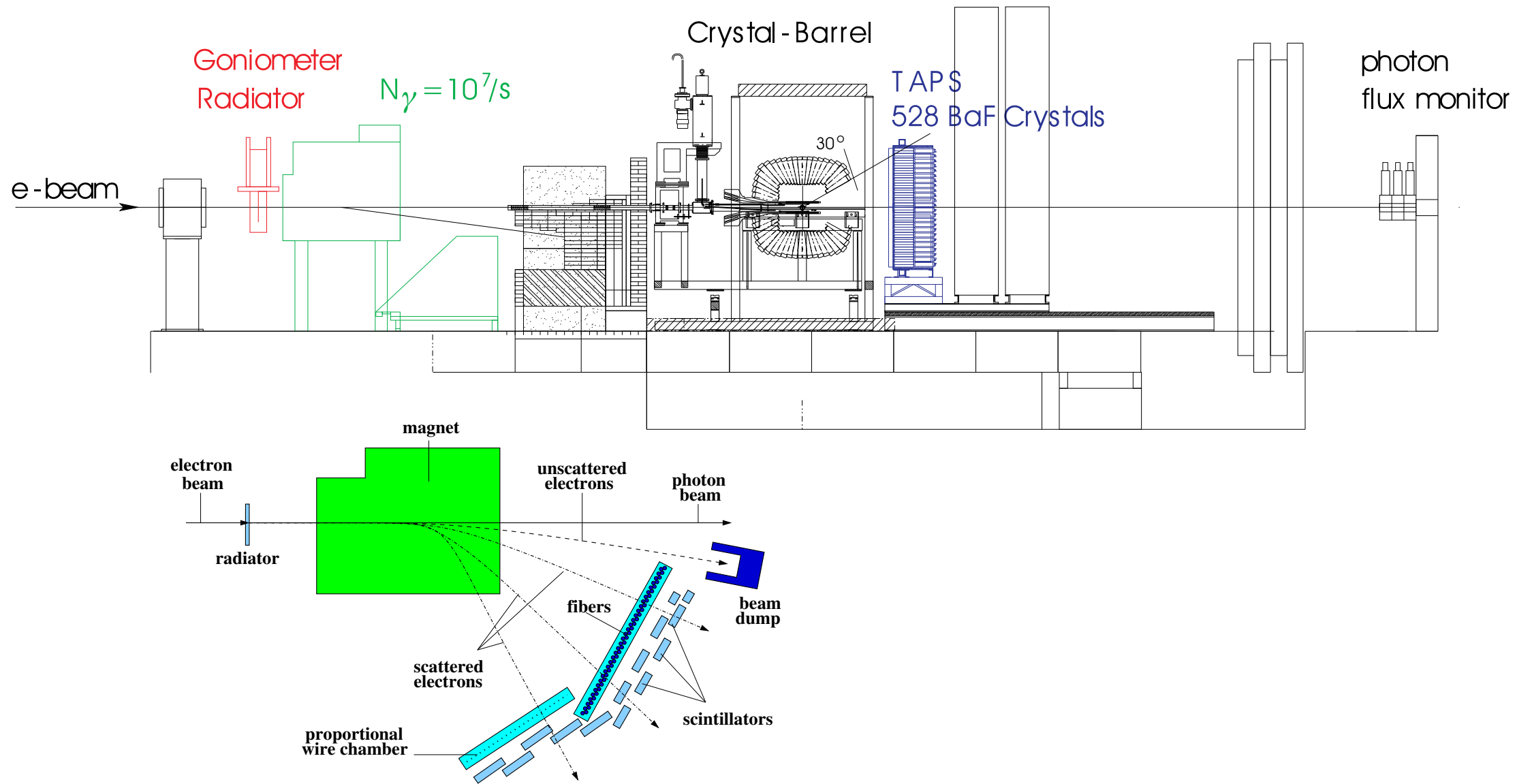
- ◆ **Mainz MAMI accelerator:**
Crystal Ball (NaJ),
TAPS (BaF₂) forward wall,
inner detectors
 $E_\gamma \leq 0.8$ (1.5) GeV,
lin. pol.: available,
circ. pol.: available



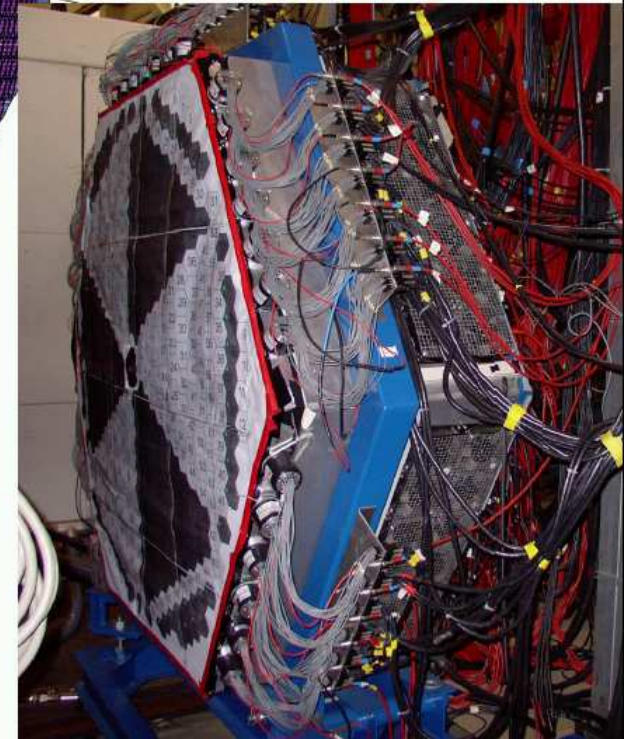
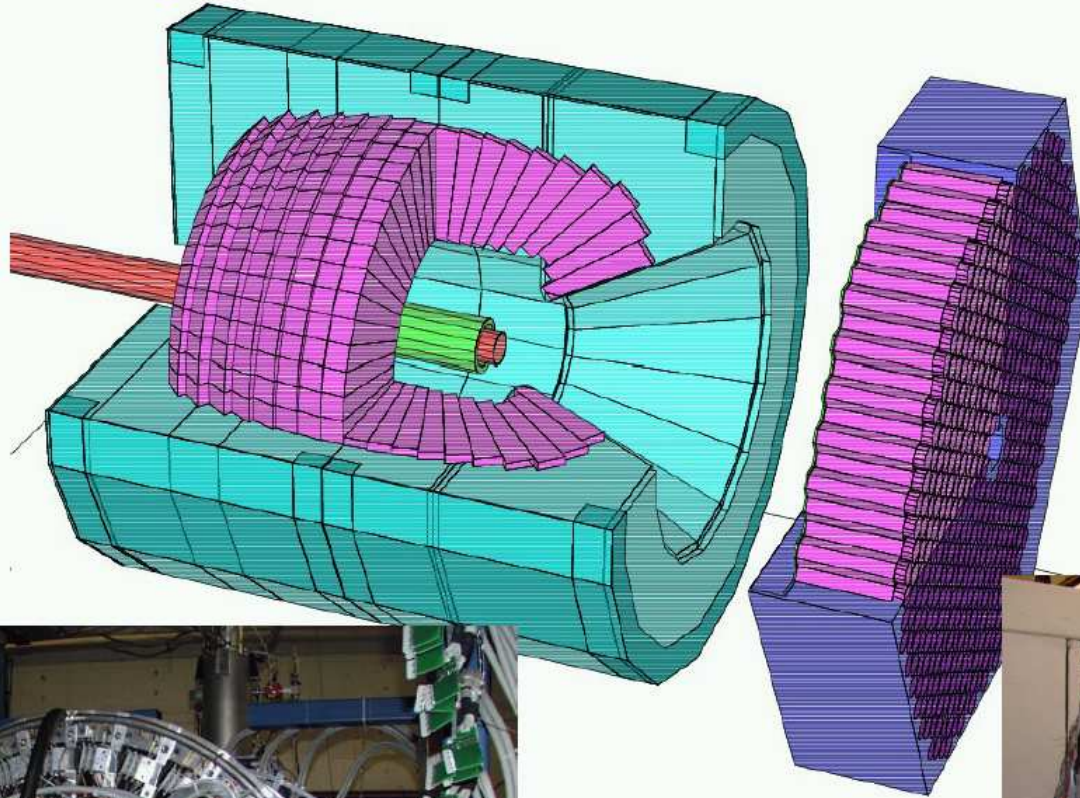
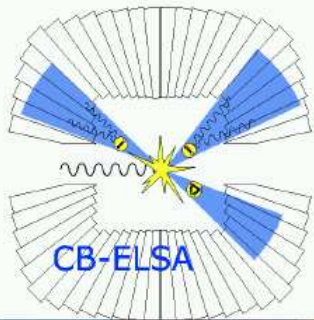
Electron Stretcher Accelerator (ELSA)



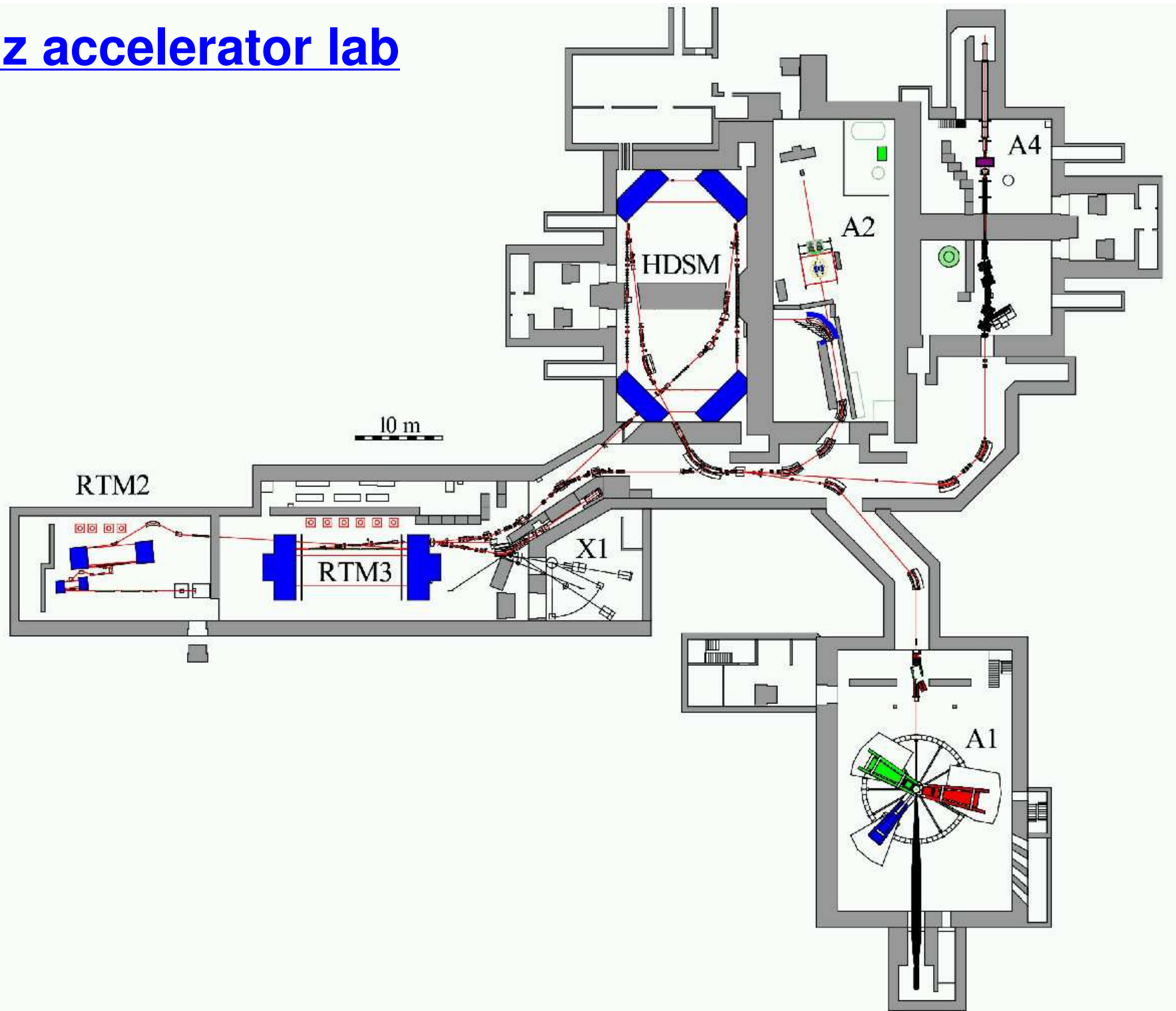
Experimental setup: Crystal Barrel and TAPS



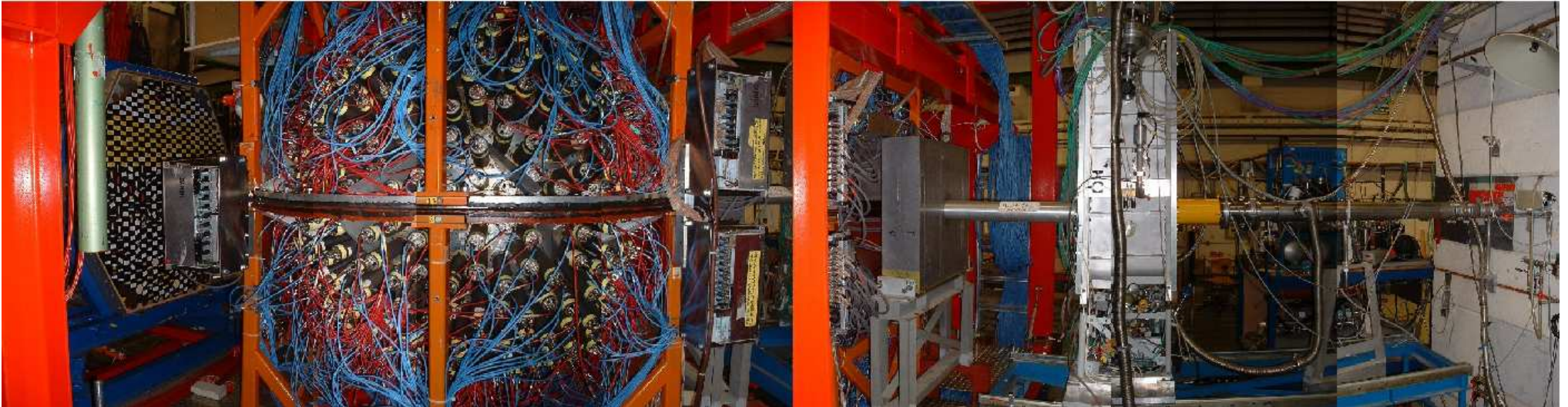
Crystal Barrel and TAPS



Mainz accelerator lab



TAPS Crystal Ball - at MAMI



resonances coupling to η photoproduction off the proton

branching ratios and elm. couplings (PDG):

state	b_η [%]	$A_{1/2}^p$	$A_{3/2}^p$	$A_{1/2}^n$	$A_{3/2}^n$
• $D_{13}(1520)$:	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				

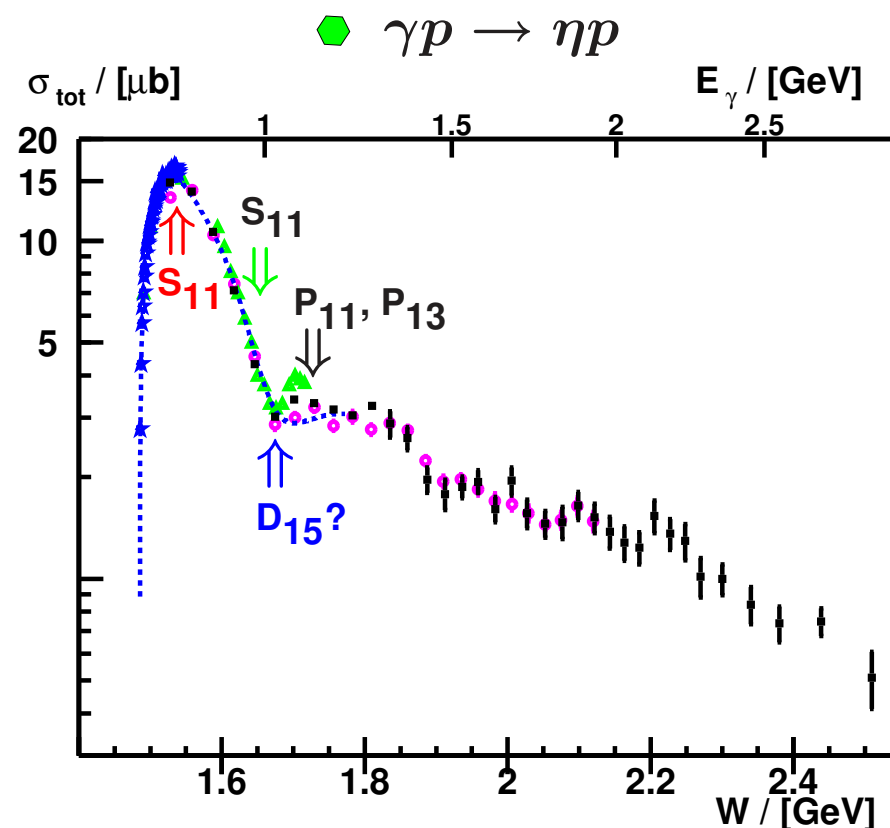
- $D_{15}(1675)$ has stronger electromagnetic coupling to neutron than to proton

but parameters quite uncertain:

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

$$b_\eta = 0-1\% \text{ (PDG)}, b_\eta = 17\% \text{ (ETA-MAID, Chiang et al.)}$$

- interference structure in S_{11} -sector?

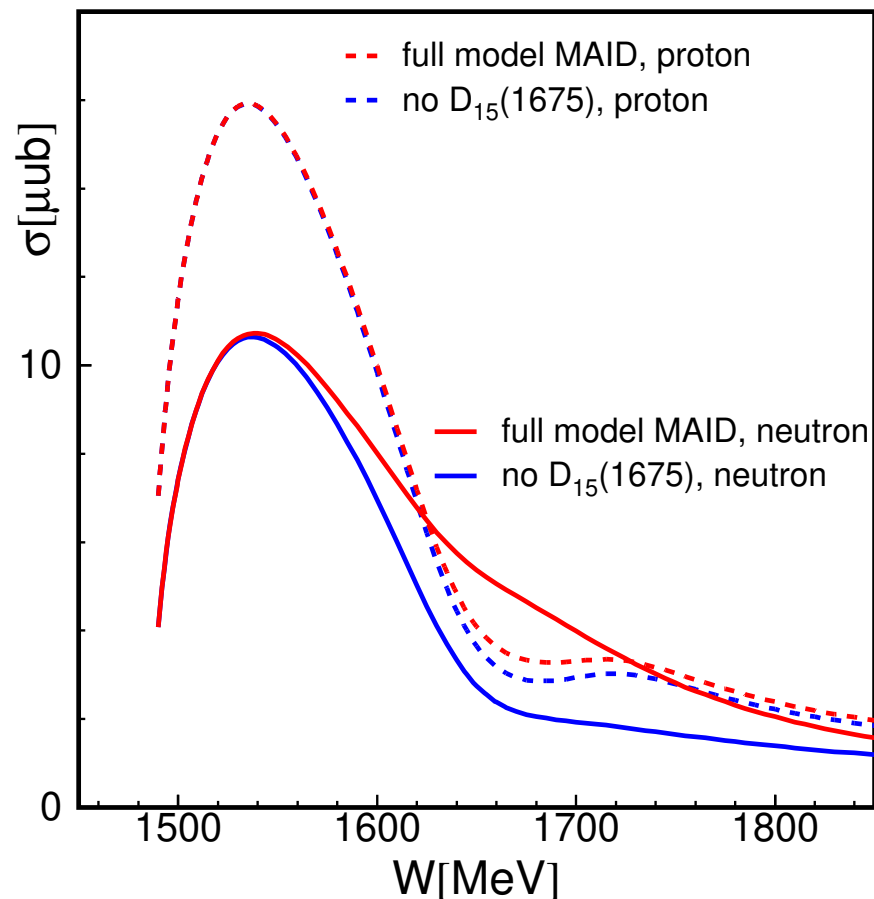


Data:

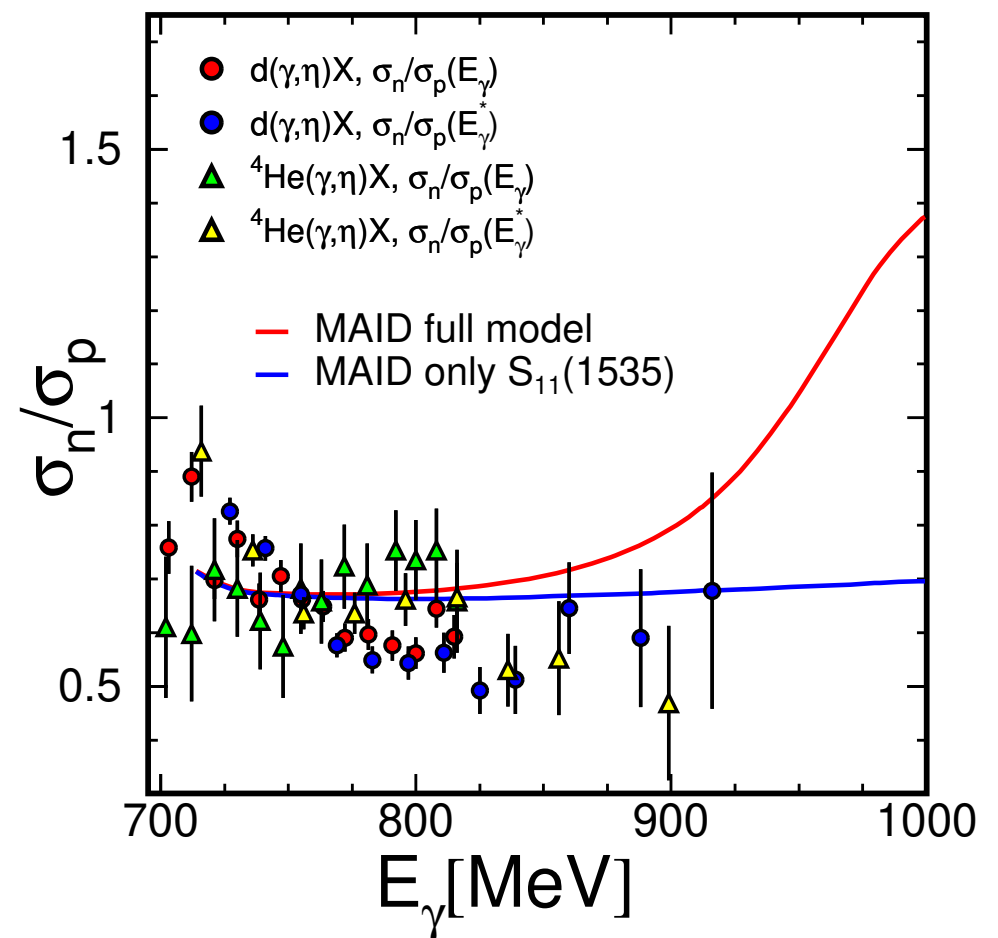
- TAPS: B. Krusche et al., PRL74 (1995) 3736
- GRAAL: F. Renard et al., PLB528 (2002) 215
- CLAS: M. Dugger et al., PRL89 (2002) 222002
- Crystal Barrel: V. Crede et al., PRL94 (2005) 012004

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

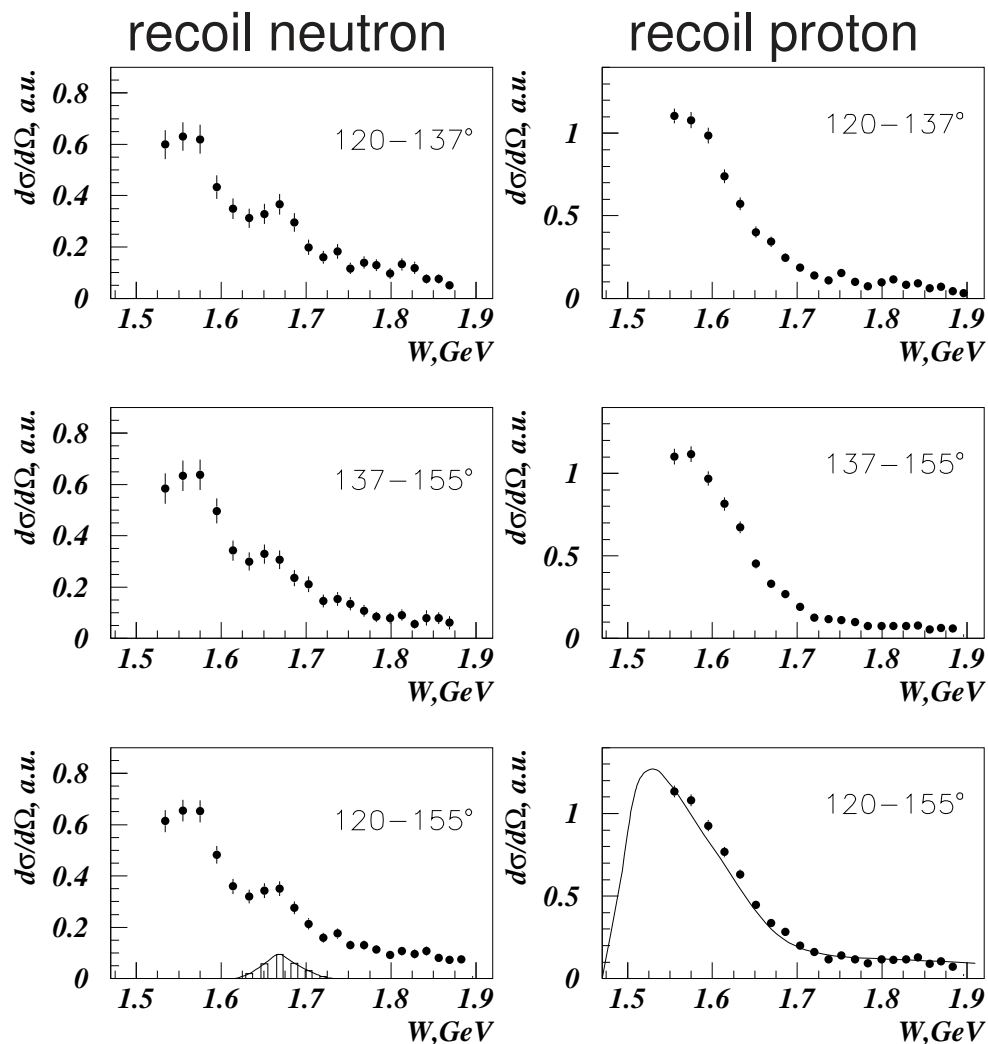
- total cross sections for proton and neutron from MAID model with and without $D_{15}(1675)$
(Eta-MAID, W.T. Chiang et al., NPA 700 (2002) 429)



- previous data from MAMI only at lower incident photon energies

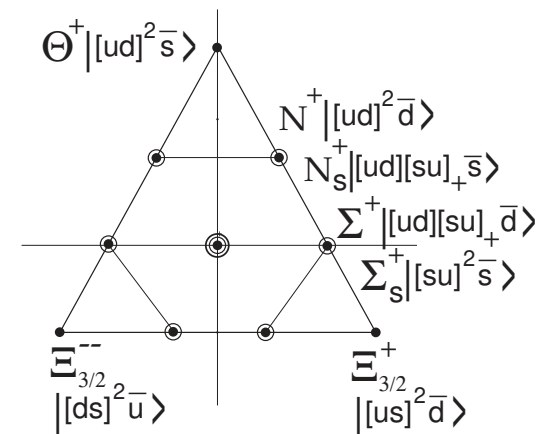


quasifree eta photoproduction from p,n: results from GRAAL



V. Kouznetsov for the GRAAL collaboration,
proceedings NSTAR 2004, page 197

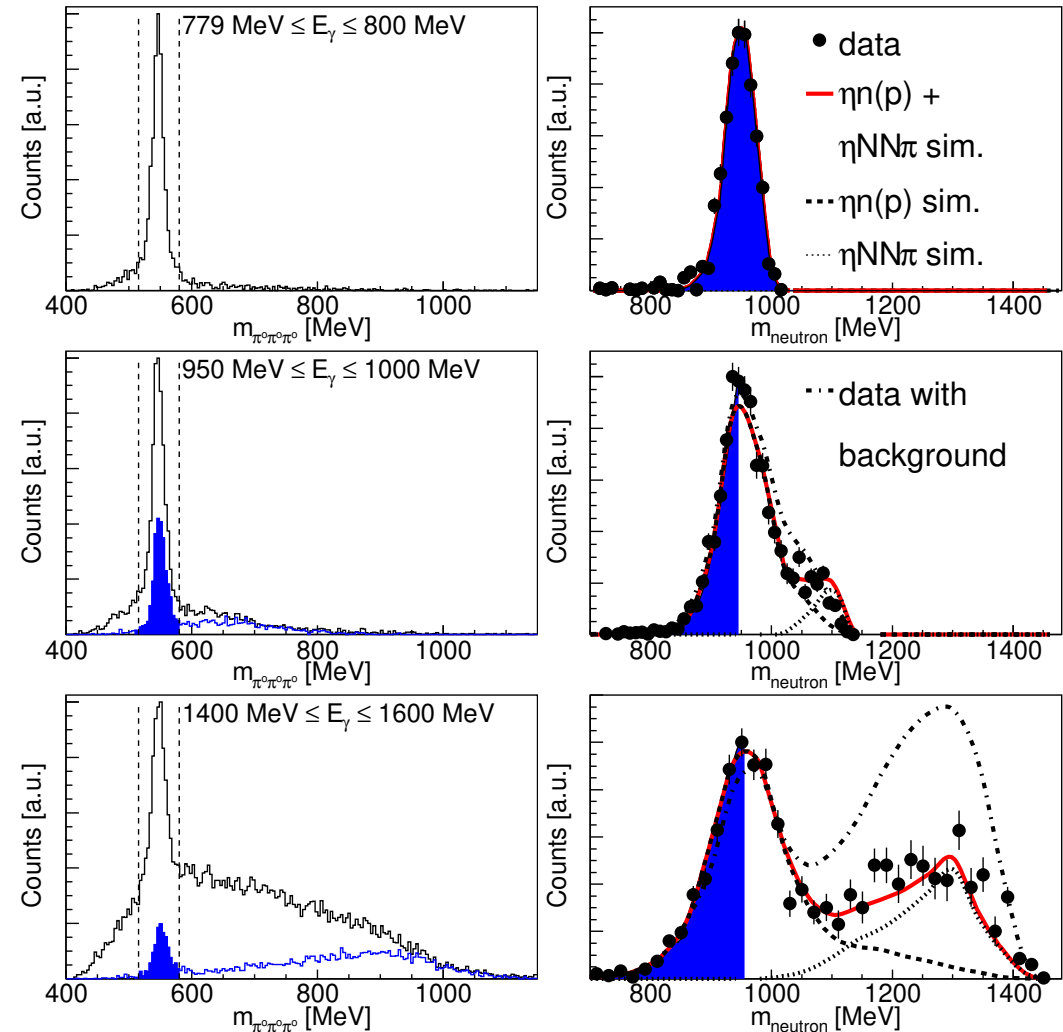
- **proton cross section in agreement with free proton results**
- **narrow structure in quasifree neutron cross section at $W=1675$, width $\Gamma \approx 40$ MeV**
- **predicted properties of nucleon-like pentaquark**



identification of η -meson production (exclusive)

- ◆ **decay channel:** $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$
- ◆ select events with 7 hits
- ◆ invariant mass off all photon pairs
- ◆ cut on π^0 invariant mass
- ◆ select best combination of 6γ to $3\pi^0$ by χ^2 -test
- ◆ use π^0 mass as constraint, construct $3\pi^0$ invariant mass
- ◆ cut on $3\pi^0$ invariant mass
- ◆ missing mass analysis to remove $\eta\pi$ final states etc.
treat recoil nucleon as missing particle:

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

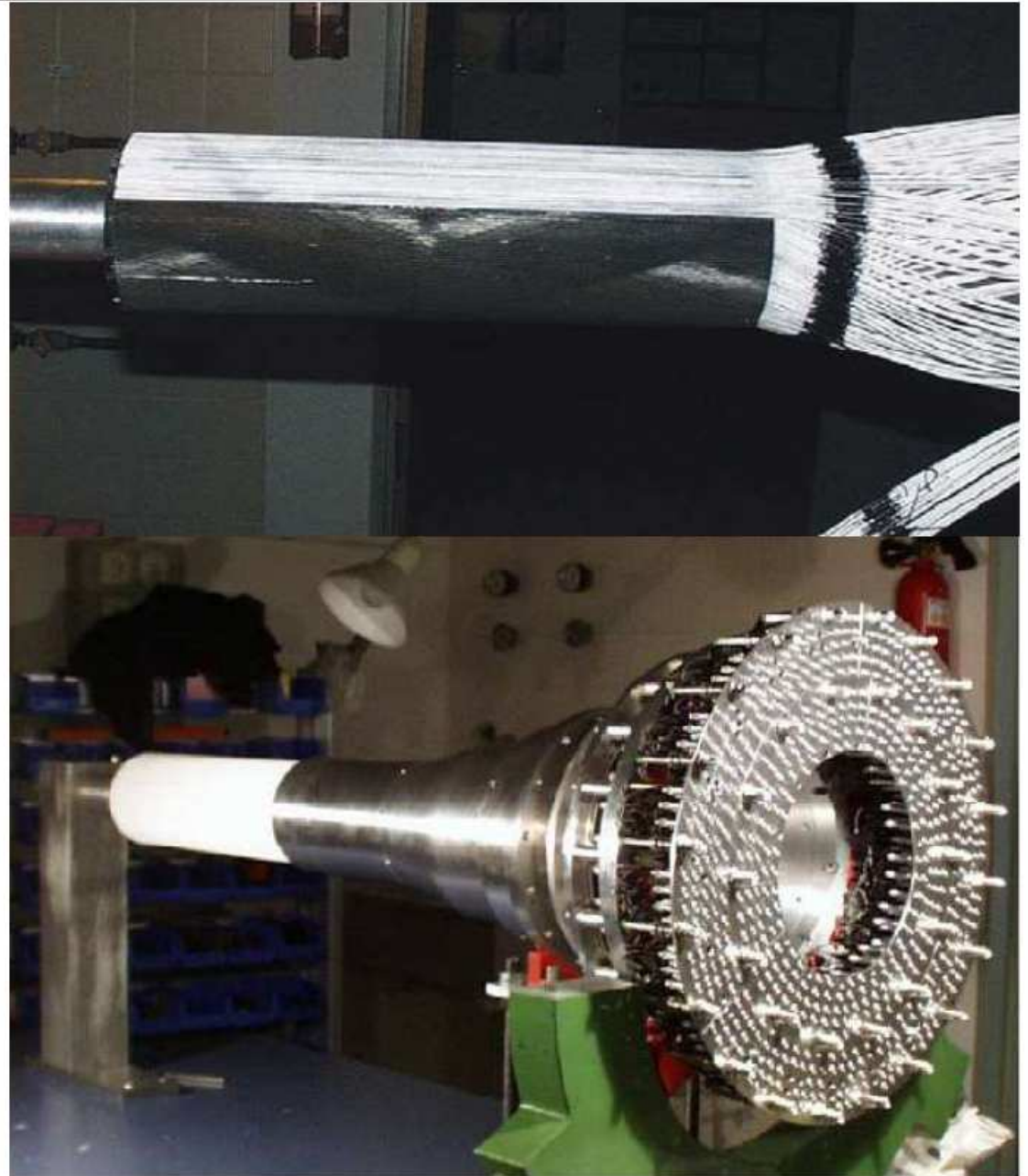
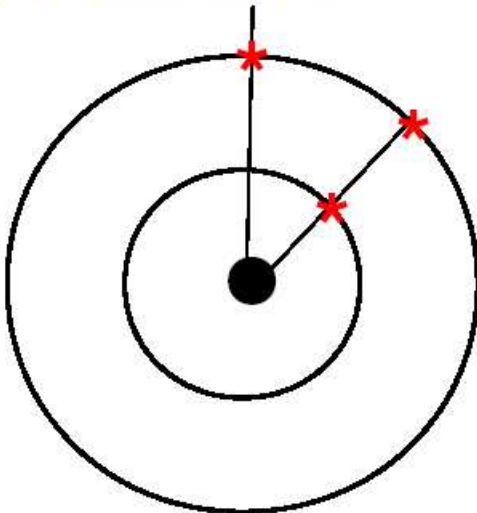




Nucleon Identification CB

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:

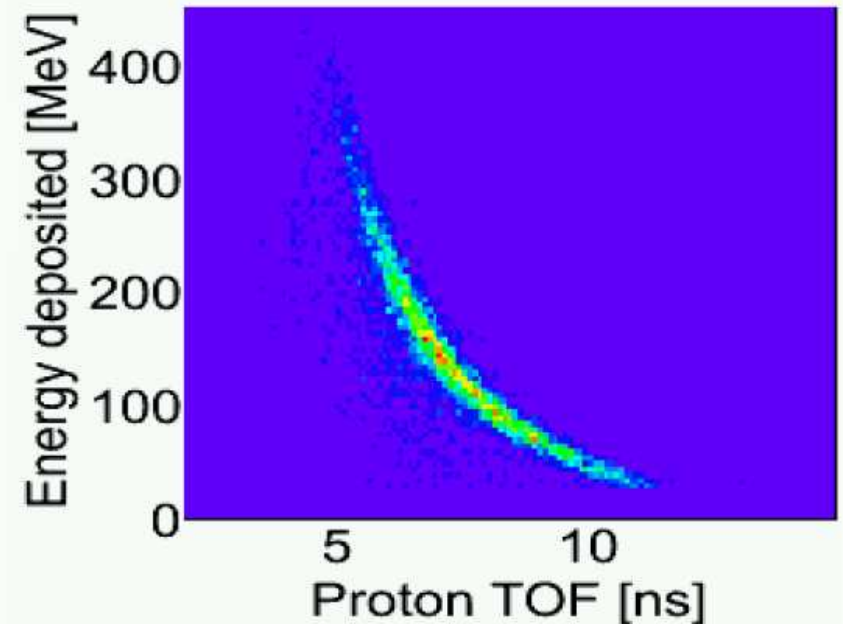
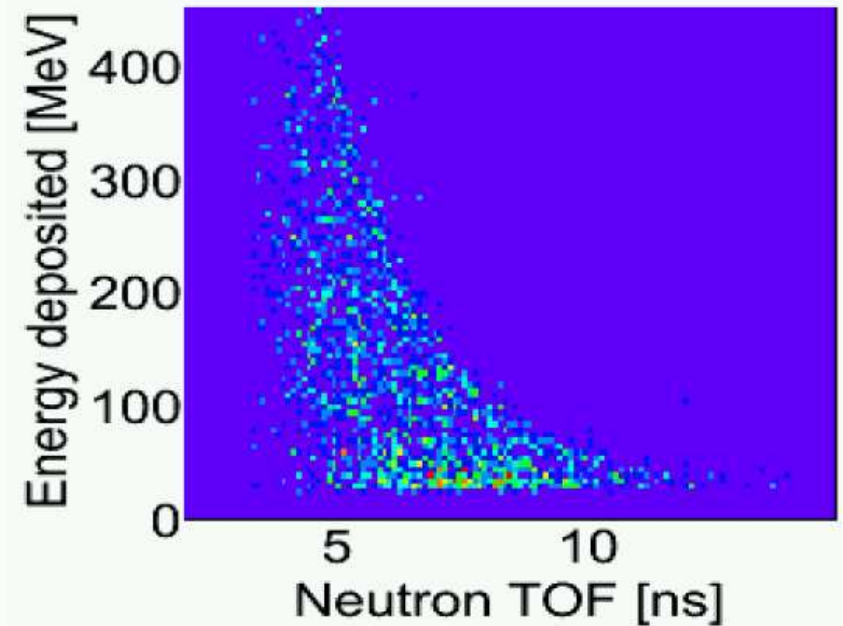
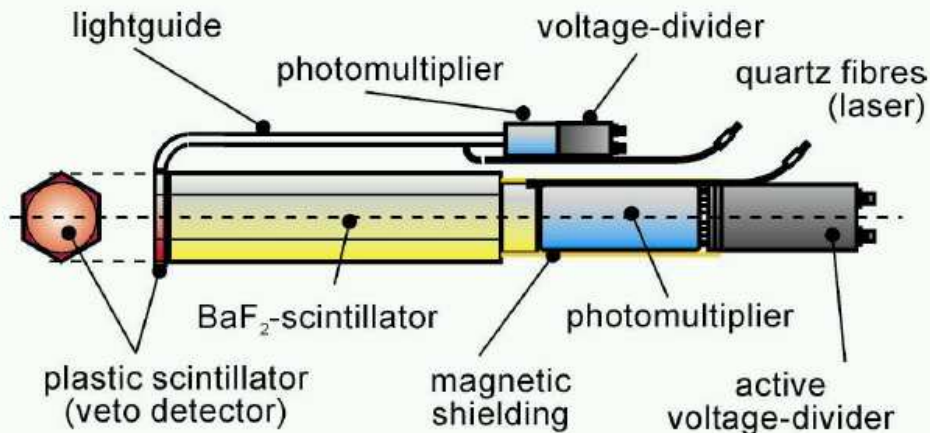
- ▶ 5 mm plastic scintillator
- ▶ individual for each BaF_2 crystal

proton:

veto hit in front of BaF_2 crystal
+ E vs TOF

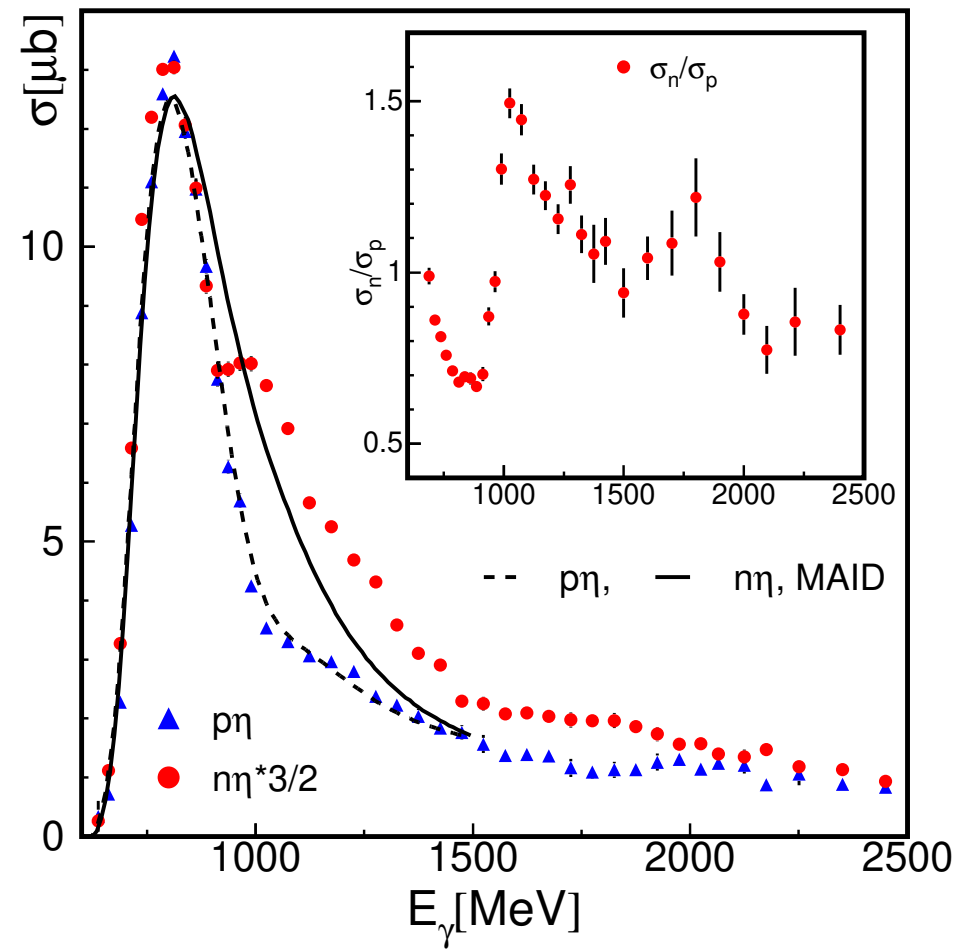
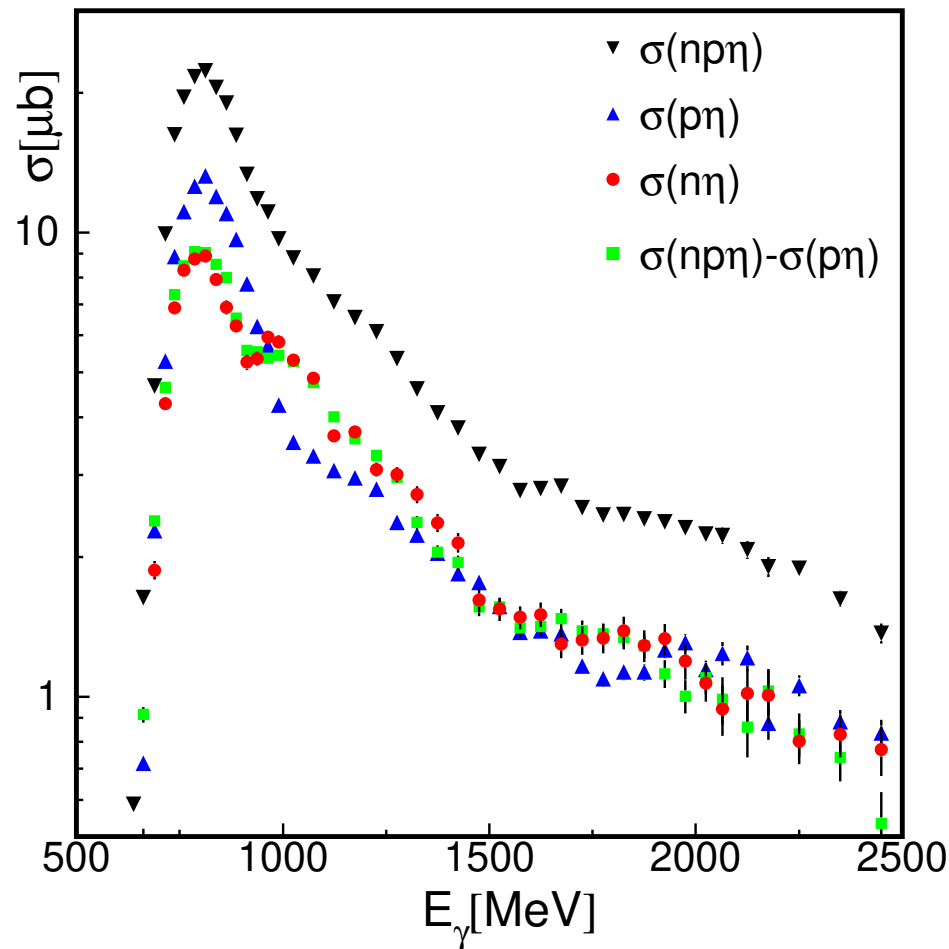
neutron:

no veto hit in front of BaF_2 crystal
+ E vs TOF



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



comparison of free and quasi-free cross sections

quasi-free total cross sections 'corrected' for Fermi smearing

(correction factors from folding
ETA-MAID model with momentum
distribution of bound nucleons)

result:

- in $S_{11}(1535)$ peak below 0.9 GeV perfect agreement between free and quasi-free proton data and quasi-free neutron data scaled by 2/3

Fit parameters for S_{11} Breit-Wigner:

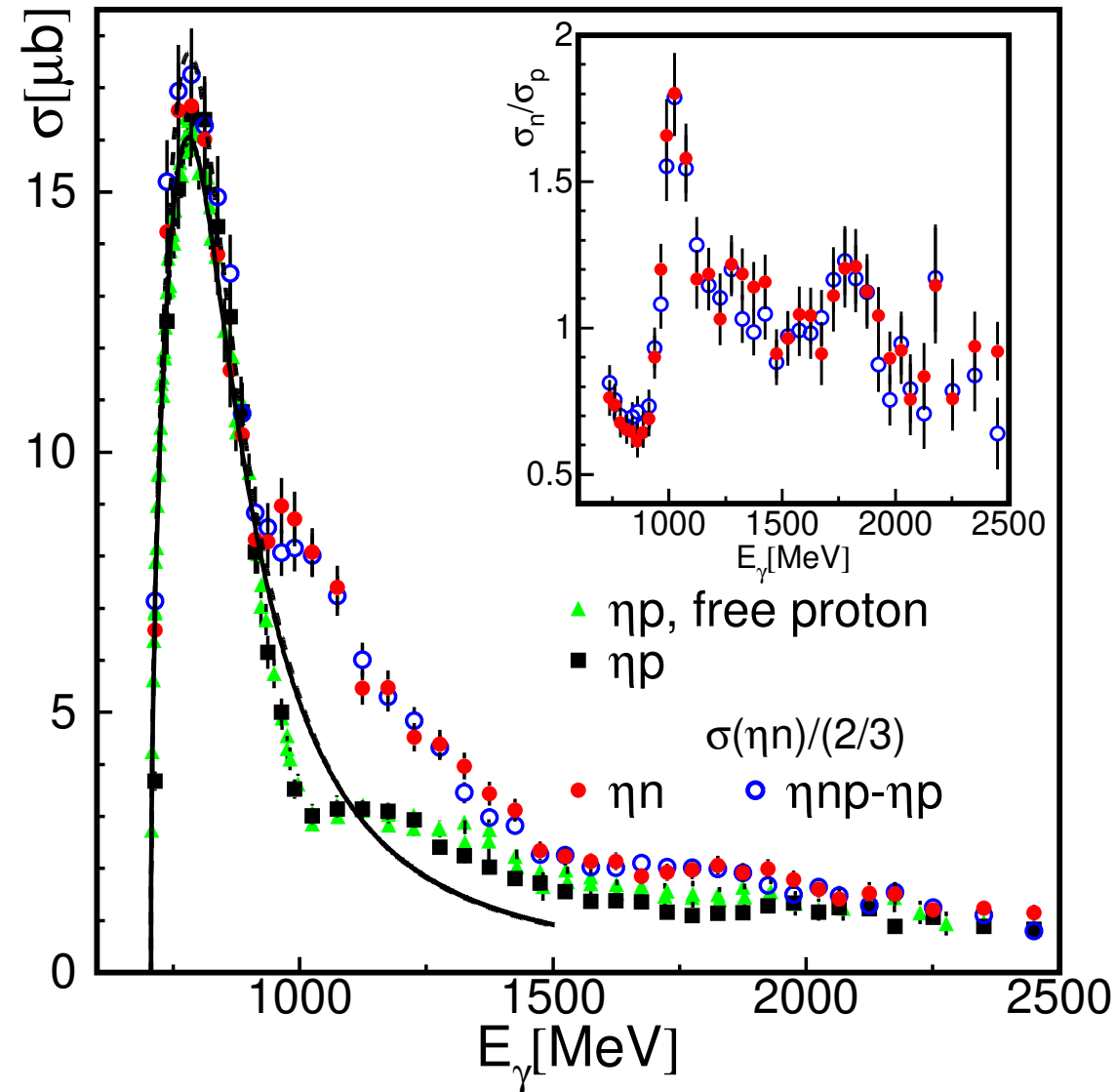
proton:

$W=1538$ MeV, $\Gamma=157$ MeV, $A_{1/2}^p=103$

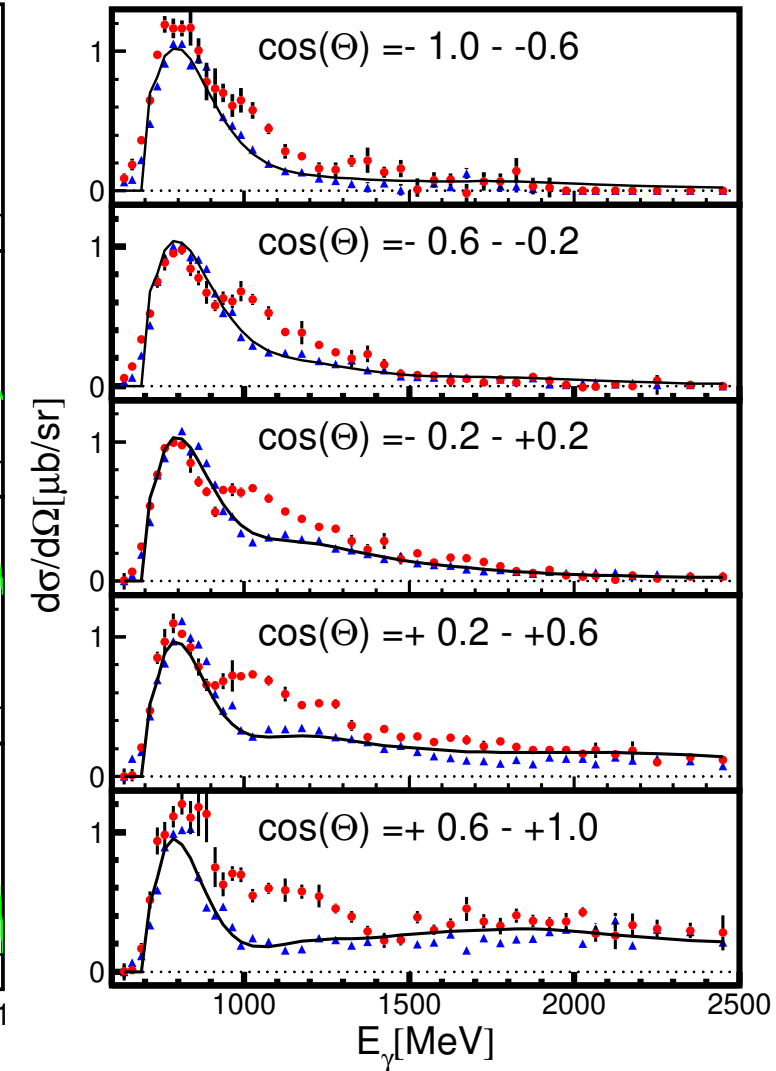
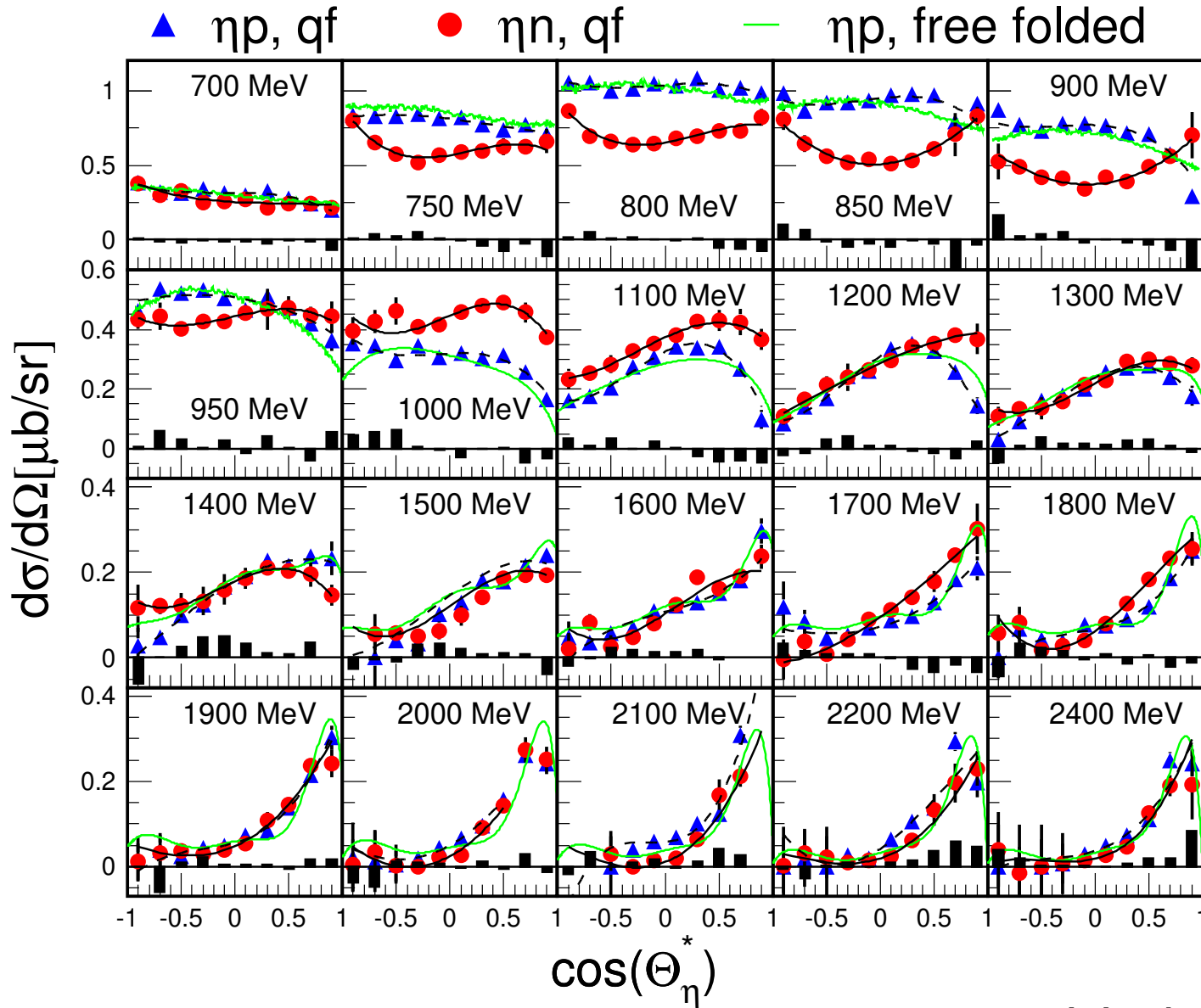
neutron:

$W=1538$ MeV, $\Gamma=148$ MeV, $A_{1/2}^n=85$

- narrow structure around 1 GeV in neutron/proton ratio, width is only upper bound



quasi-free angular distributions



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

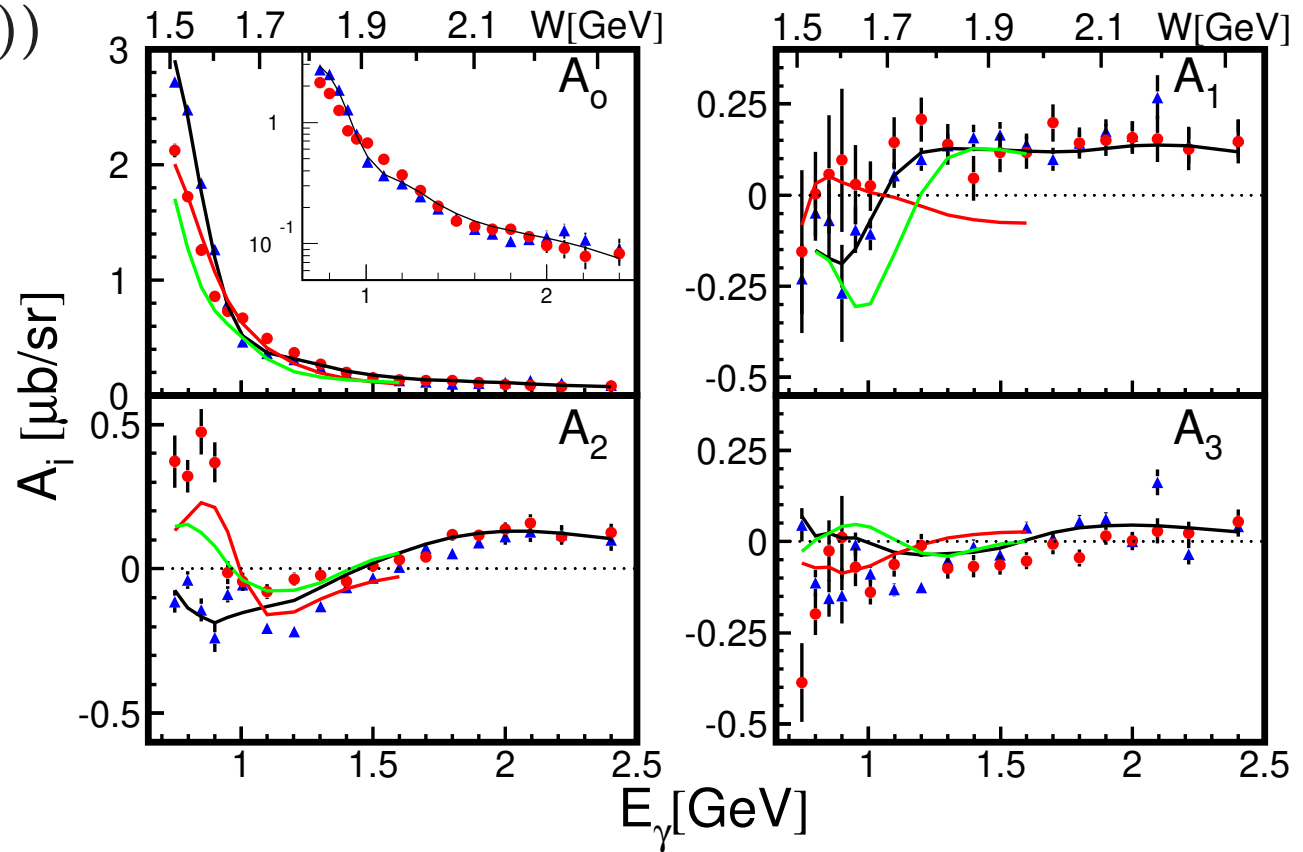
fit of angular distributions

fit with:

$$\frac{d\sigma}{d\Omega} = \frac{q^*}{k^*} \times \sum A_i P_i(\cos(\Theta^*))$$

result:

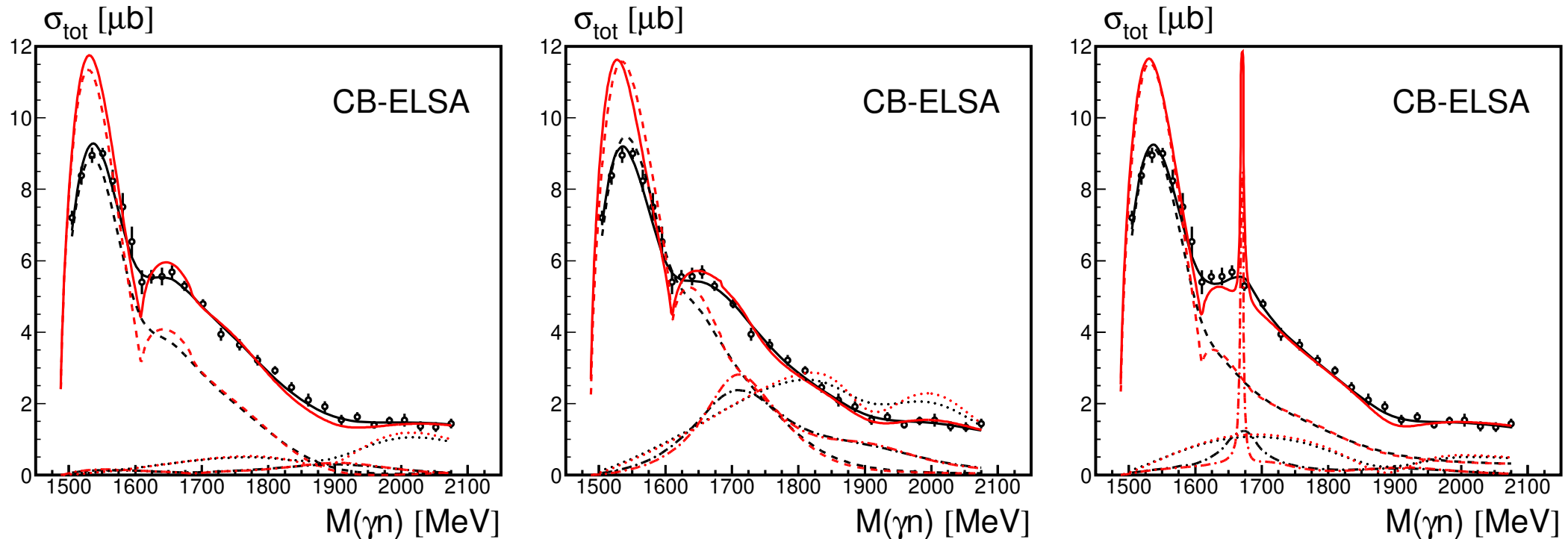
- all coefficients similar for proton and neutron above 1.25 GeV
- A_0 coefficient: dominance of S_{11} resonances, for neutron small shoulder around 1 GeV
- A_1 coefficient: interference S_{11} , P_{11} ?
- A_2 coefficient: interference S_{11} - D_{13} resonance



- quasifree neutron ● quasifree proton — free proton (Ff)
- q.f. neutron (Maid) — q.f. neutron (Shklyar et al.)

Bonn-Gatchina model analysis

- ◆ **basis: coupled channel isobar analysis with background terms**



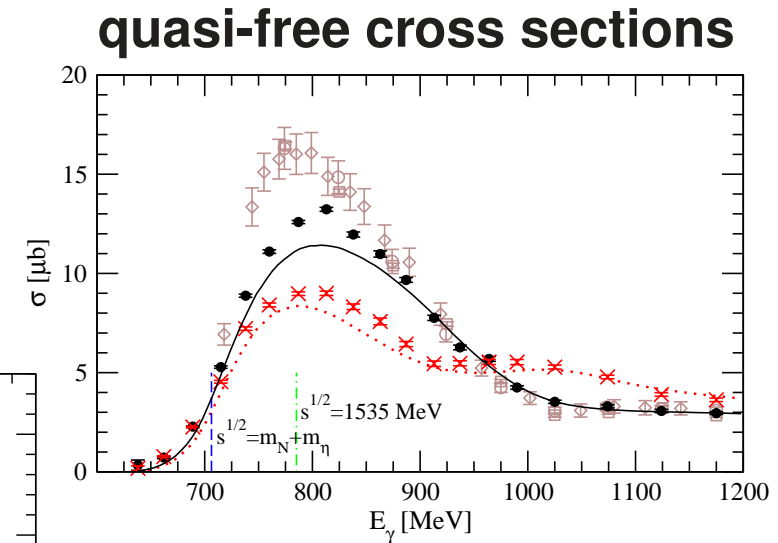
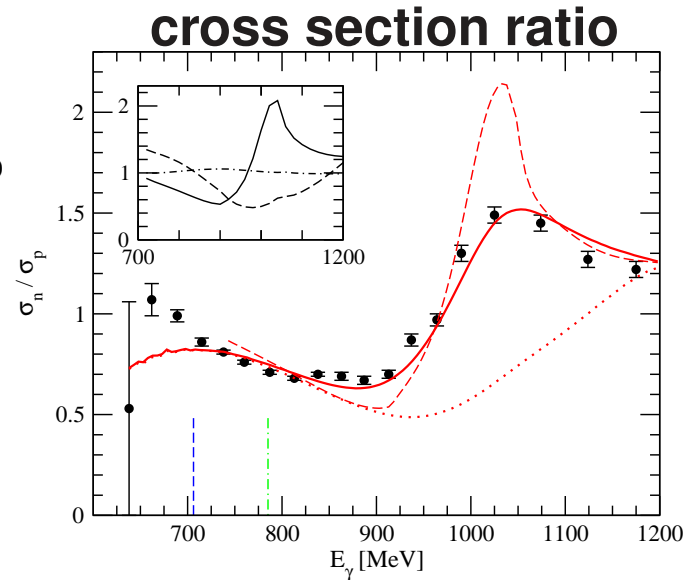
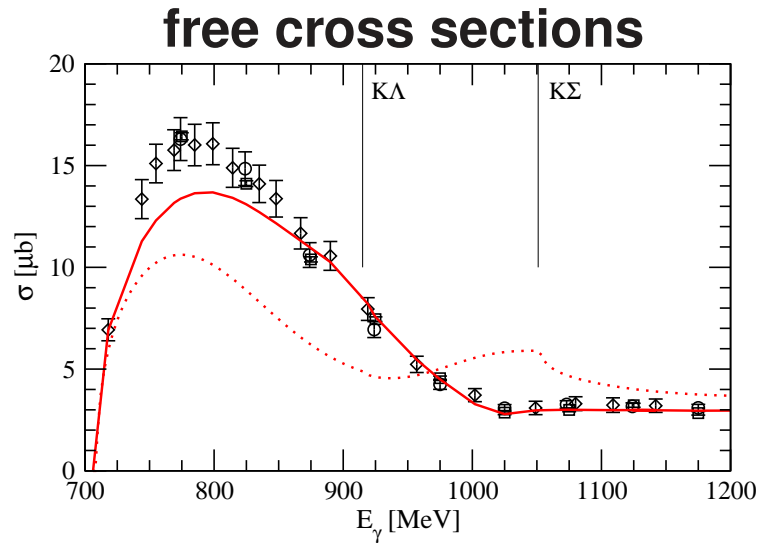
- ◆ **different scenarios to reproduce 'bump' structure:**

- ◆ **left: interference in S_{11} -sector: adjusting phases etc.**
- ◆ **middle: 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



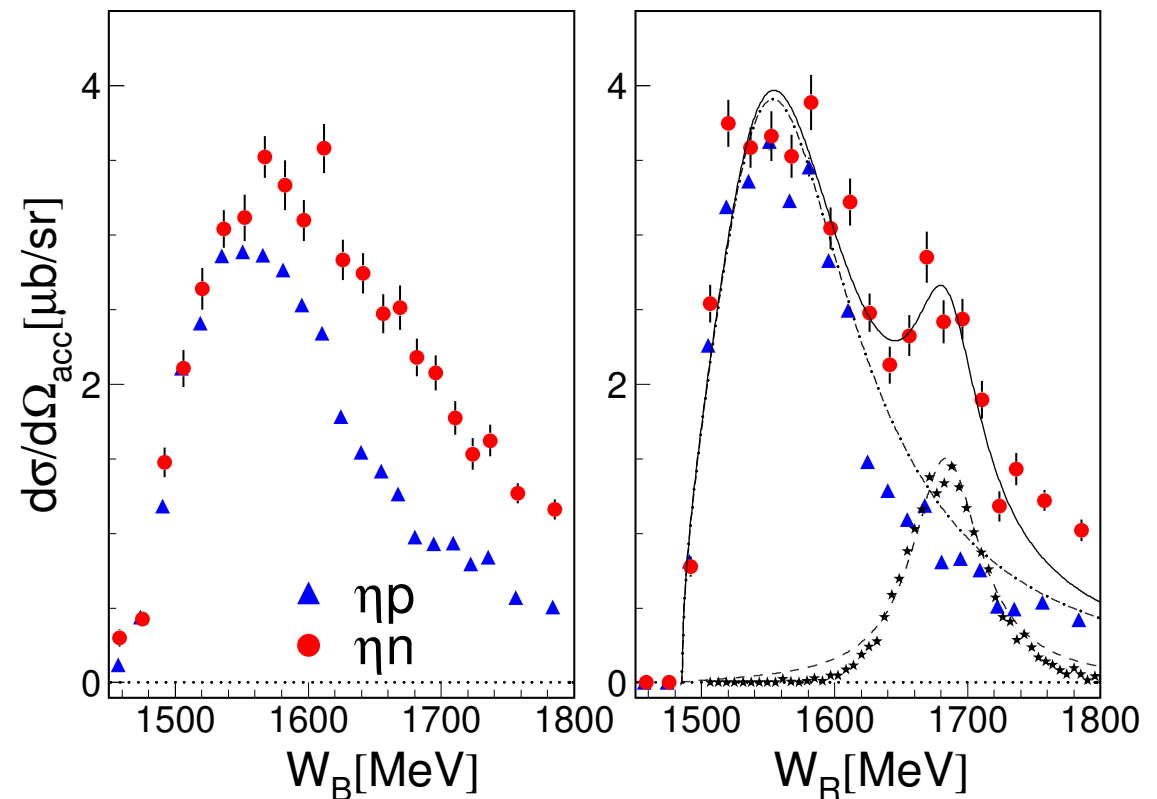
- ◆ structure in σ_n / σ_p due to $K\Lambda$, $K\Sigma$ threshold effects (intermediate strangeness states in loop-diagrams)

'de-folding' of Fermi smearing

- for events with neutron in TAPS
($\cos(\Theta_{\eta}^{\star}) < -0.1$)
neutron energy from time-of-flight
- comparision: 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:

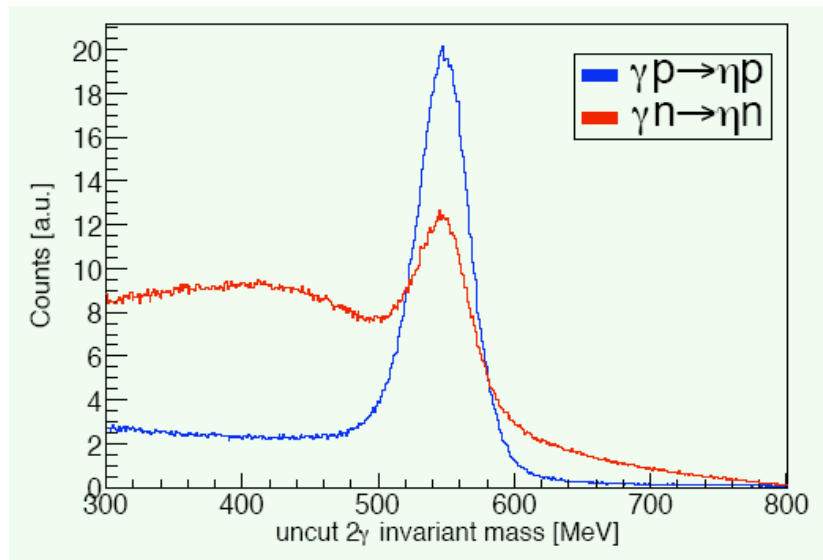
position: $W=1683$ MeV
width: $\Gamma=60\pm 10$ MeV
(resolution dominated)

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

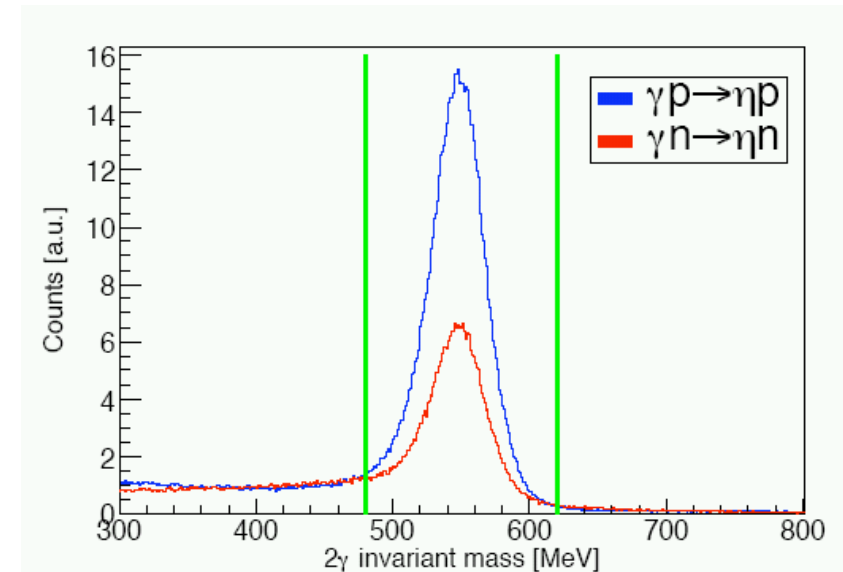


new preliminary results from MAMI C: reaction identification

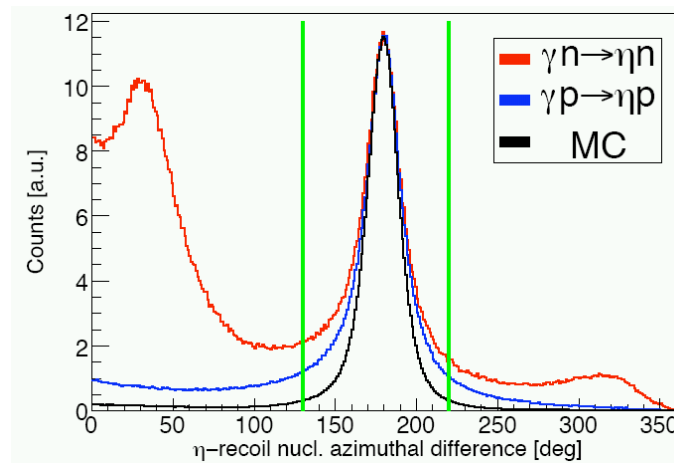
◆ raw invariant mass



◆ cut on co-planarity

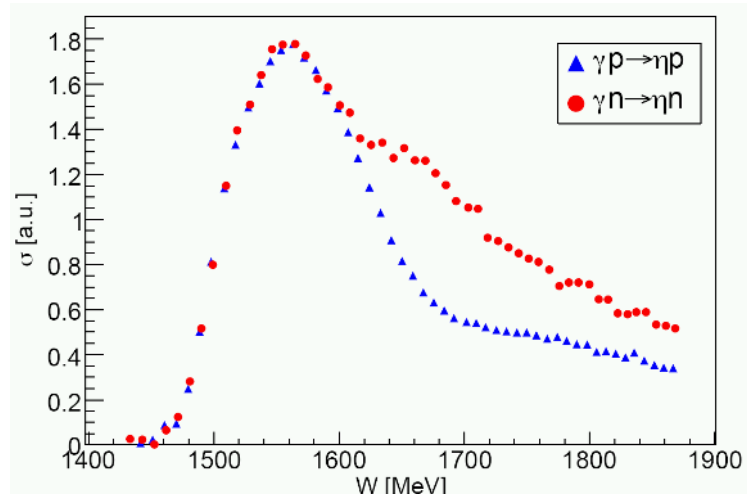


◆ co-planarity

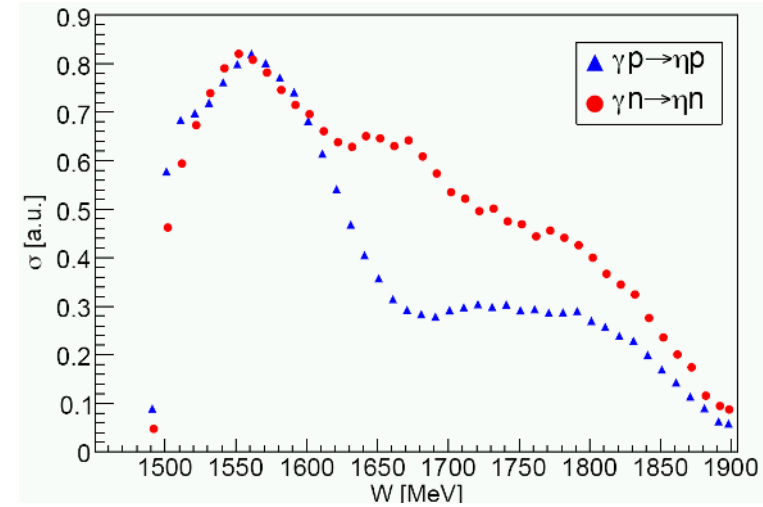


preliminary excitation functions

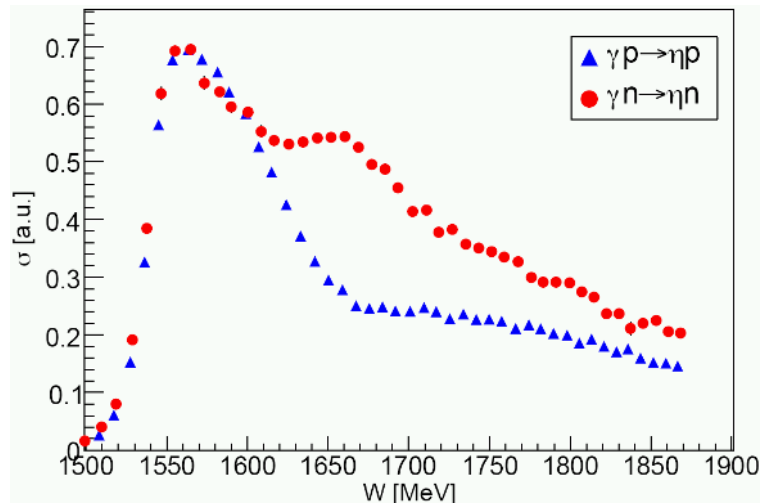
◆ $W = f(E_\gamma), 130 < \Delta\Phi < 220$



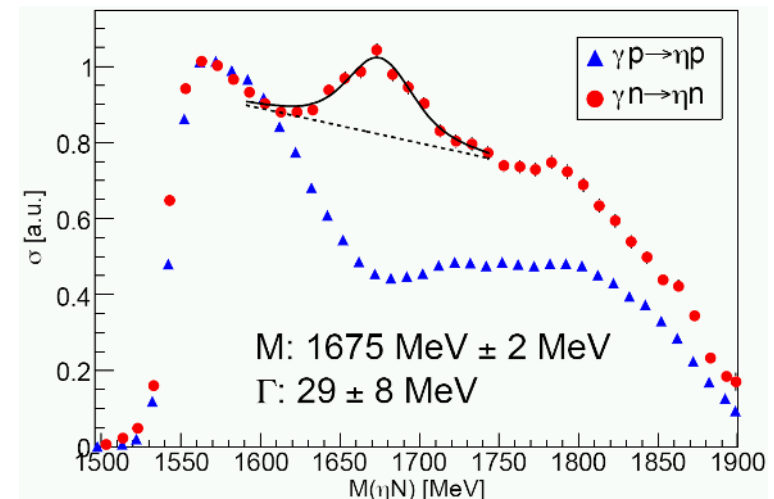
◆ $W = f(n, \eta), 130 < \Delta\Phi < 220$



◆ $W = f(E_\gamma), 170 < \Delta\Phi < 190$

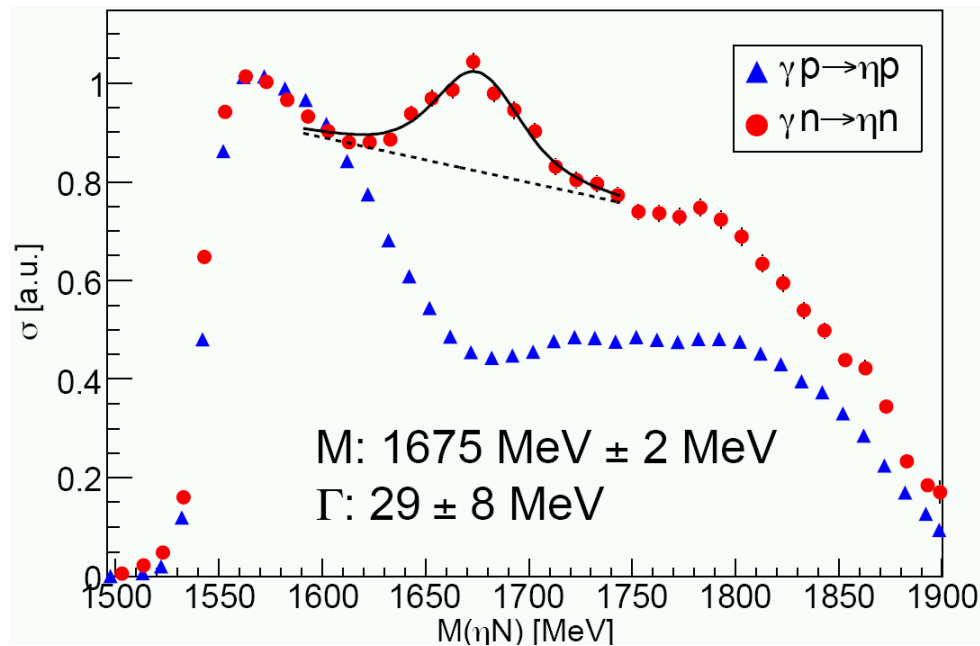


◆ $W = f(n, \eta), 170 < \Delta\Phi < 190$

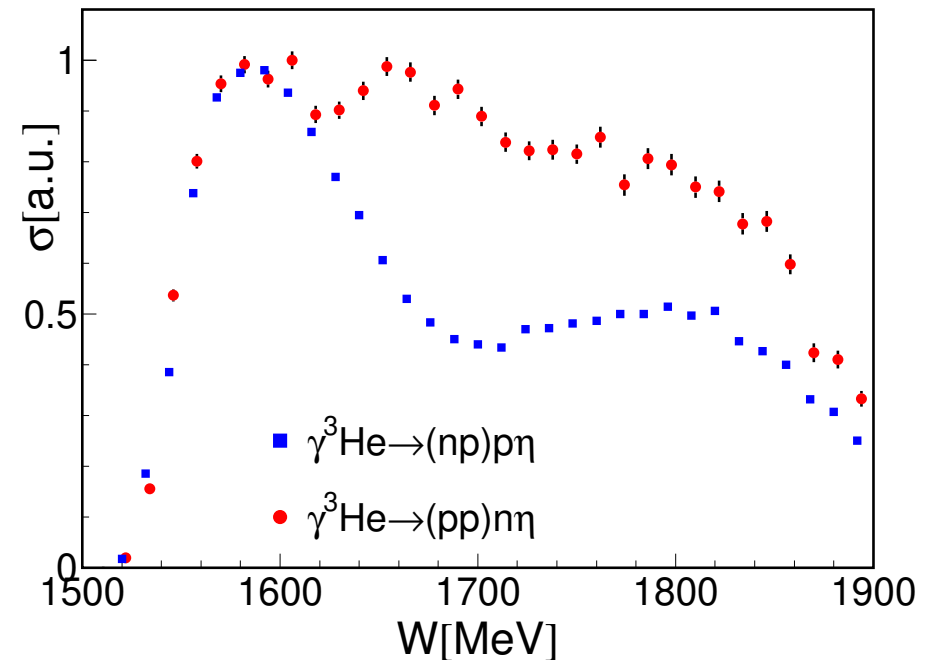


structure also seen for ^3He target nuclei

◆ nucleons bound in deuteron



◆ nucleons bound in ^3He



Summary

- ◆ narrow structure in excitation function of $\gamma n \rightarrow n\eta$:
- ◆ **GRAAL:** $W \approx 1680 \text{ MeV}, \Gamma < 30 \text{ MeV}$
- ◆ **Tohoku-LNS:** $W \approx 1666 \text{ MeV}, \Gamma < 40 \text{ MeV}$
- ◆ **ELSA:** $W \approx 1685 \text{ MeV}, \Gamma < 60 \text{ MeV}$
- ◆ **MAMI-C:** $W \approx 1675 \text{ MeV}, \Gamma < 40 \text{ MeV}$
- ◆ **so far no information about quantum numbers of possible resonance or whatever nature of the structure**

coherent η -photoproduction: search for light η -mesic nuclei

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



J_z : -1 +1/2 -1/2 -1/2 0 \rightarrow **spin-flip transition**

- isospin structure: $A_{1/2}^{IS}/A_{1/2}^P \approx 0.09$ \rightarrow **dominantly isovector**

- **expectation for light nuclei:**

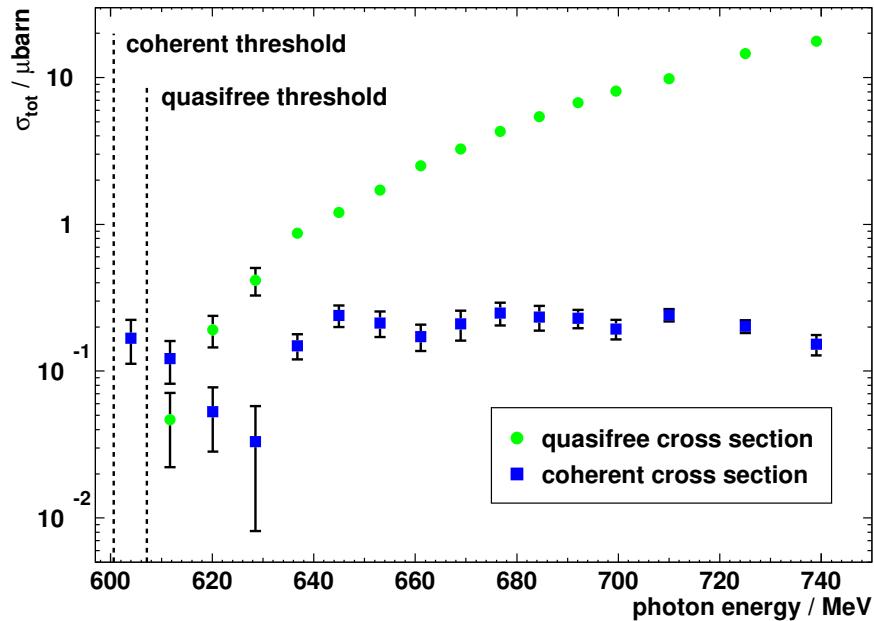
1) ^4He : $J=0, l=0$, isoscalar, non spin-flip \rightarrow **very small signal**
(not seen, only upper bounds, V. Hejny et al.)

2) ^2H : $J=1, l=0$, isoscalar, spin-flip \rightarrow **small signal**
(seen, almost in agreement with expectations)

3) ^3He : $J=1/2, l=1/2$, isovector, spin-flip \rightarrow **'large' signal**



η -photoproduction from ^3He - threshold behavior

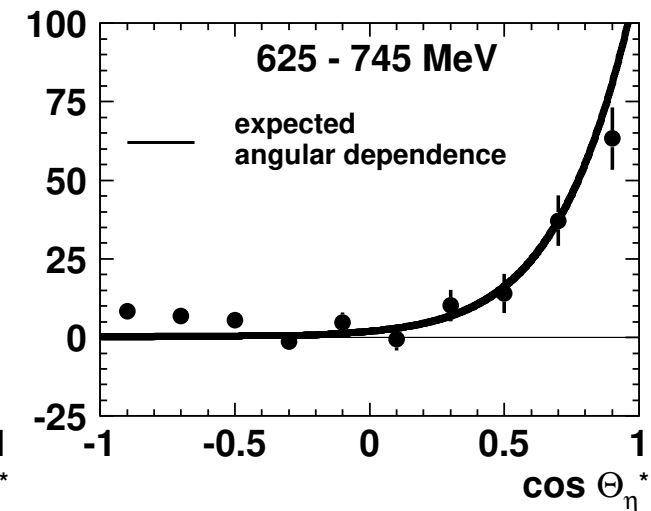
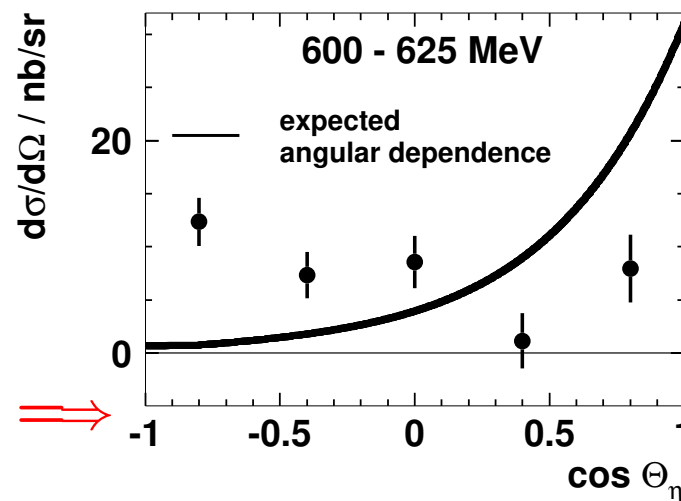


M. Pfeiffer et al., PRL 92 (2005) 252001

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

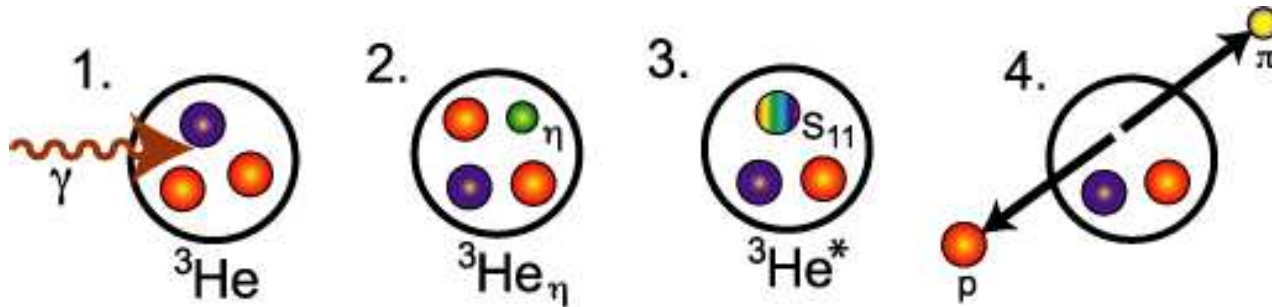
⇐ threshold enhancement of coherent part

isotropic angular distribution of coherent part at threshold ⇐



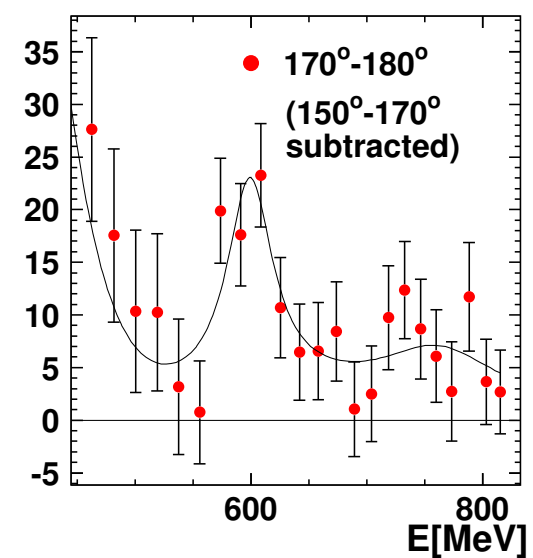
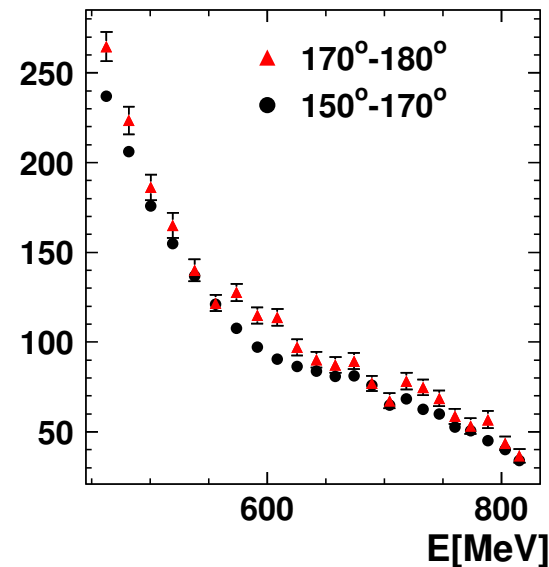
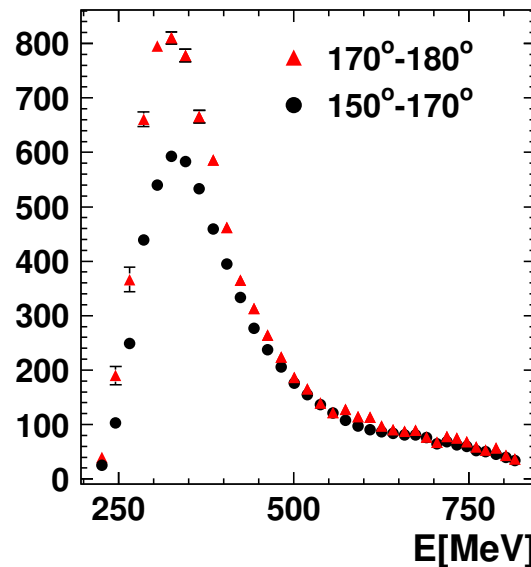
search for η -mesic nuclei

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



→ search for back-to-back π^0 - p pairs

- ◆ excess of π^0 -p back-to-back emission at the η -threshold (3.5σ)



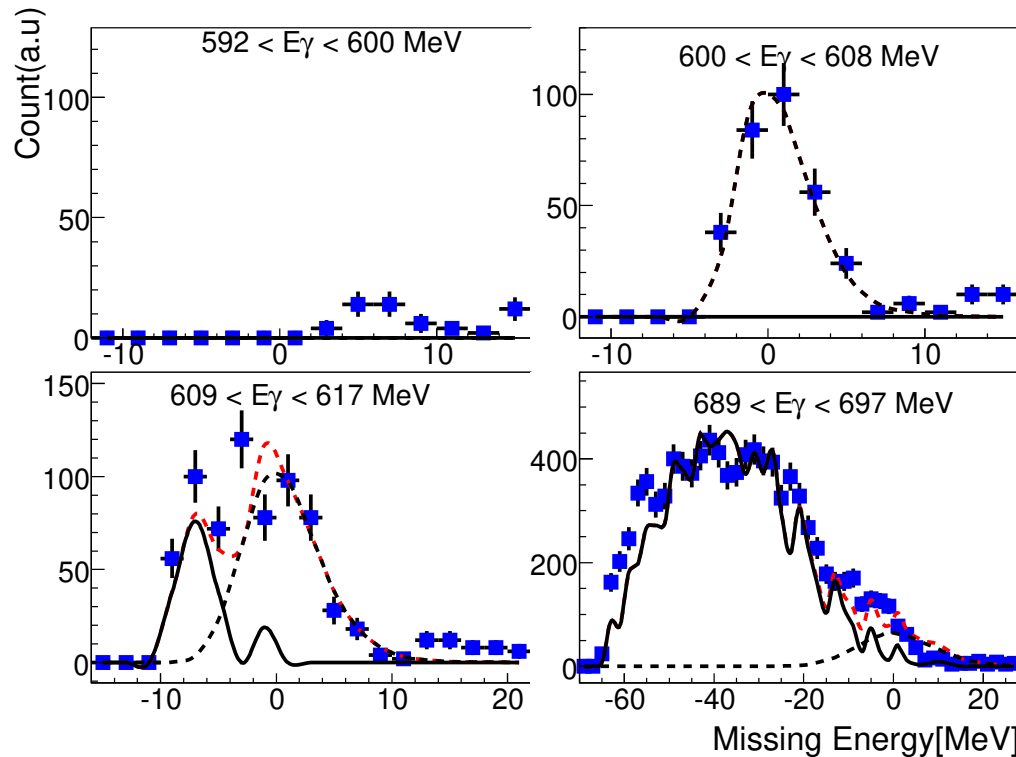
new ^3He experiment - improved statistics

PhD thesis F. Pheron

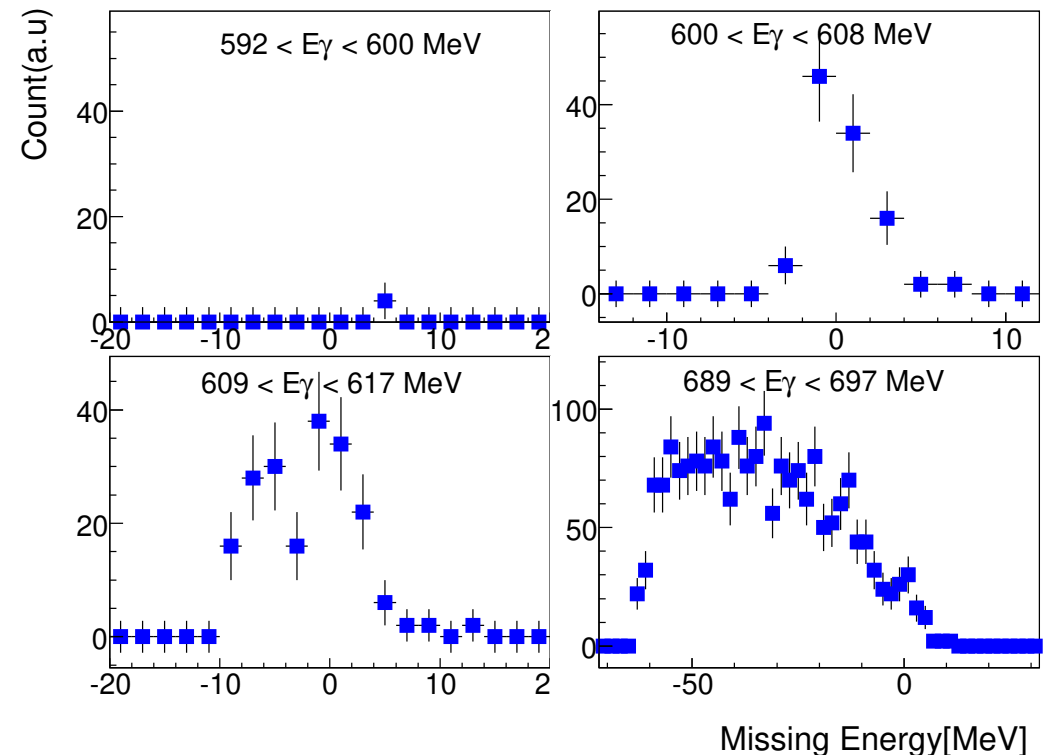
reaction identification:

- ◆ invariant mass analyses for $\eta \rightarrow 2\gamma$ and $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$
- ◆ missing energy analysis for coherent kinematics:

$\eta \rightarrow 2\gamma$



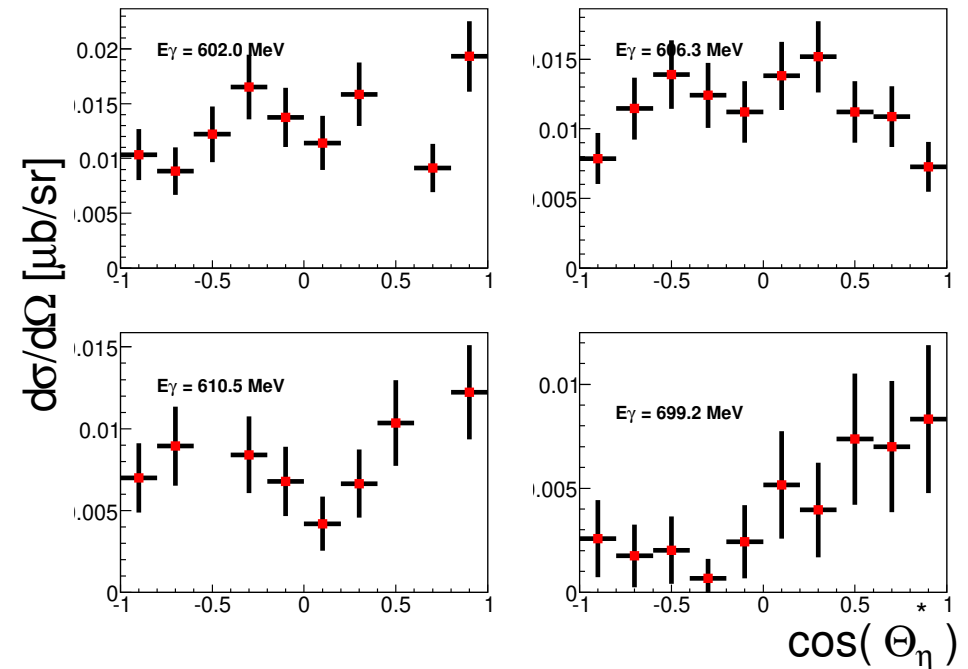
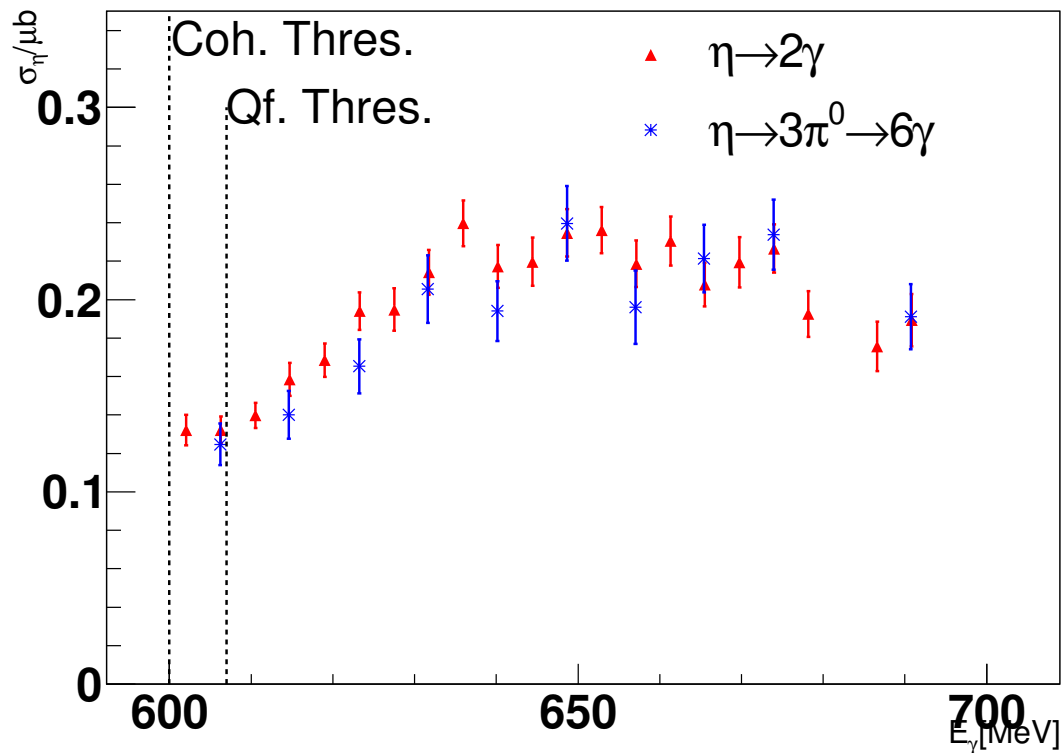
$\eta \rightarrow 6\gamma$



new ^3He experiment - coherent η -production

preliminary cross sections:

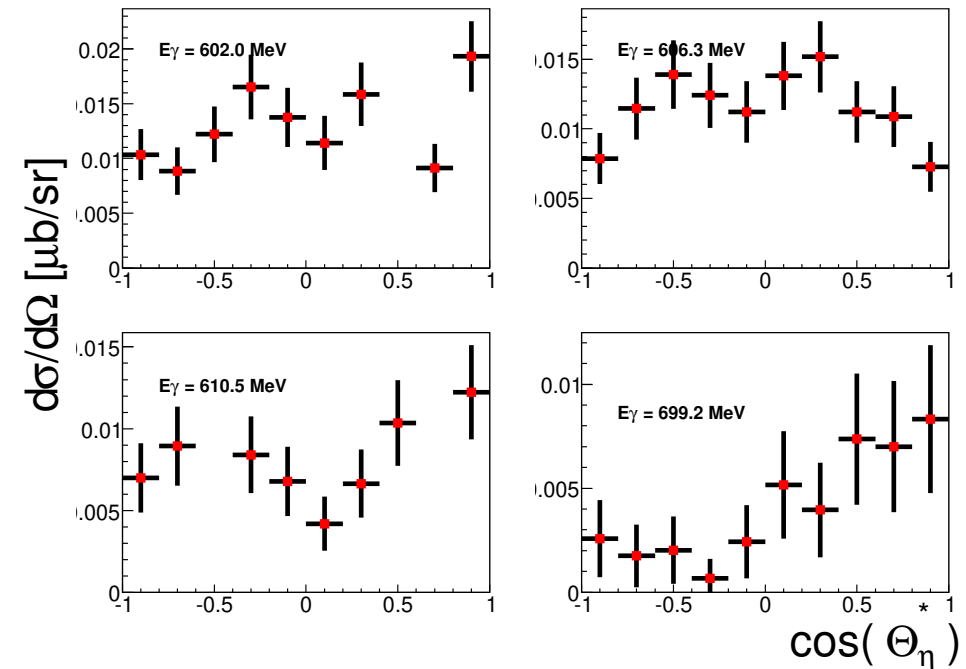
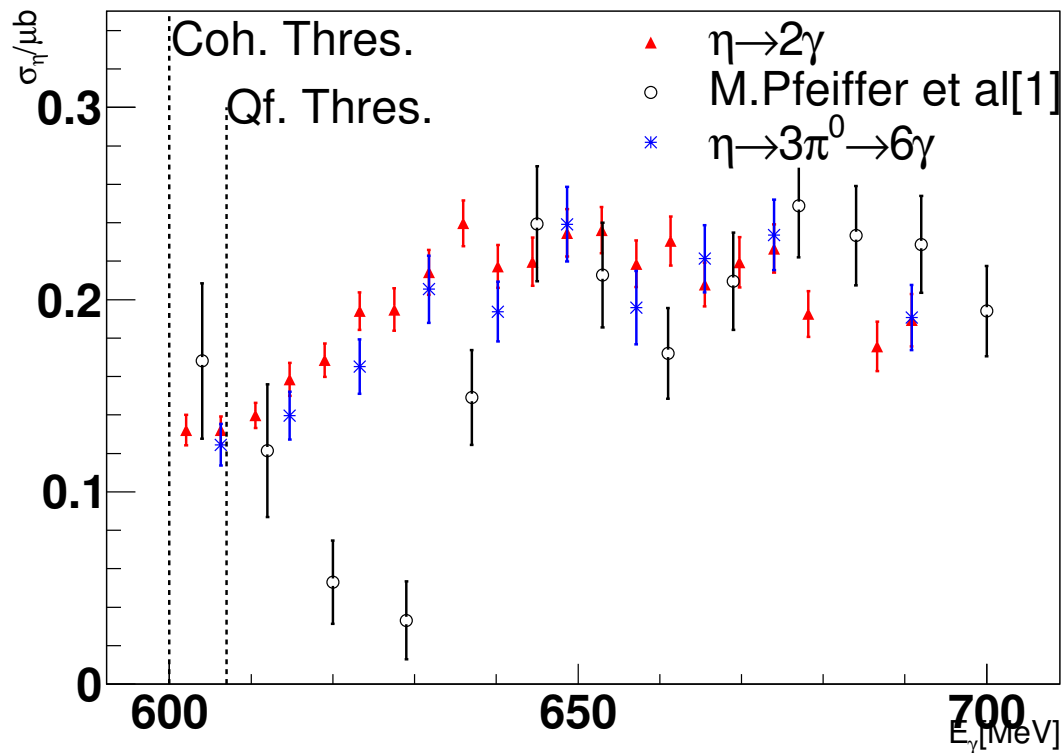
- very steep rise of total cross section at threshold confirmed
- rather flat angular distributions at threshold



new ^3He experiment - coherent η -production

preliminary cross sections:

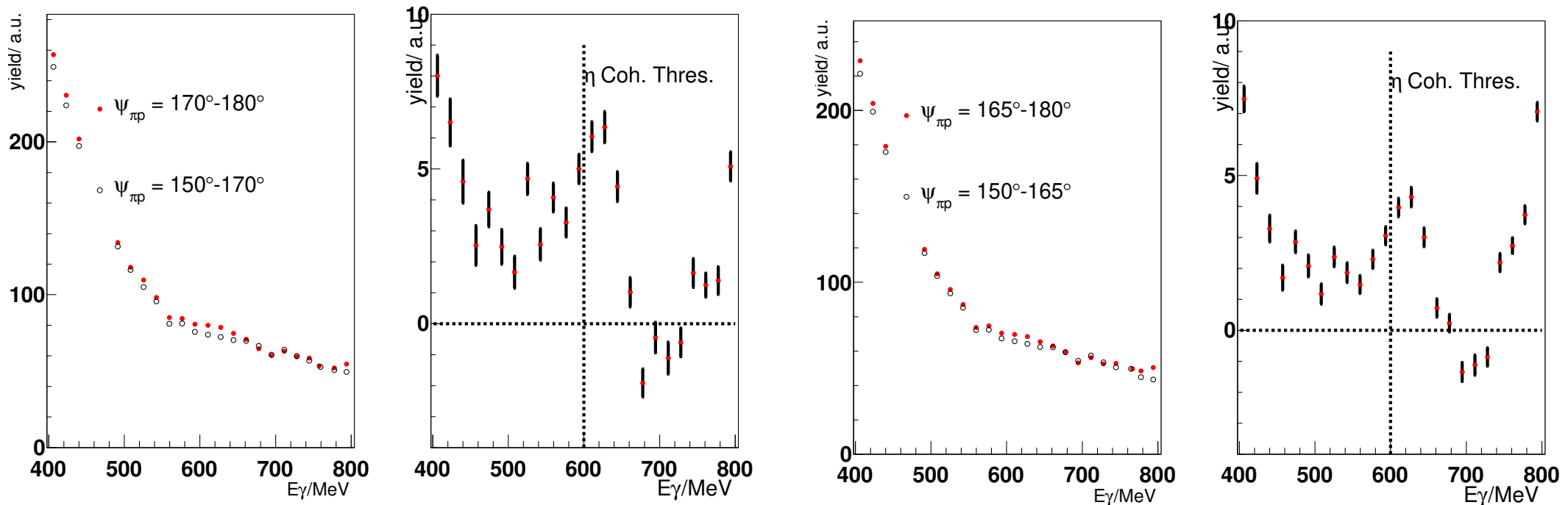
- very steep rise of total cross section at threshold confirmed
- rather flat angular distributions at threshold



new ^3He experiment

π^0 -p back-to-back pairs:

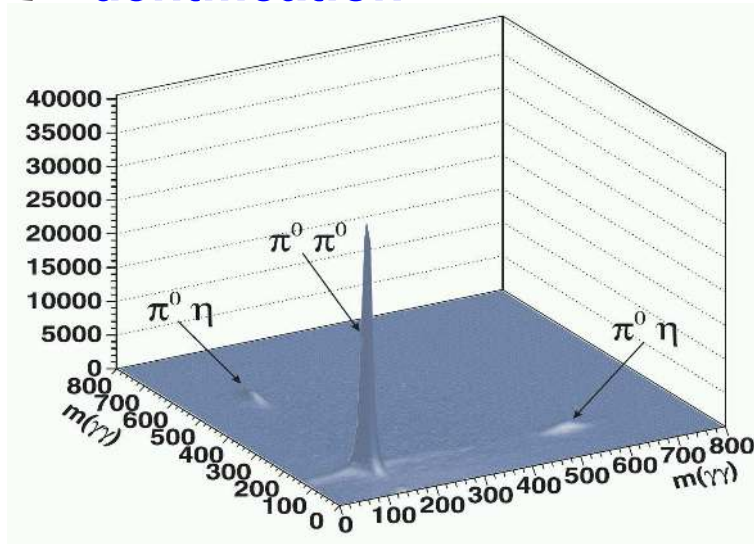
- ◆ peak structure at coherent threshold also confirmed



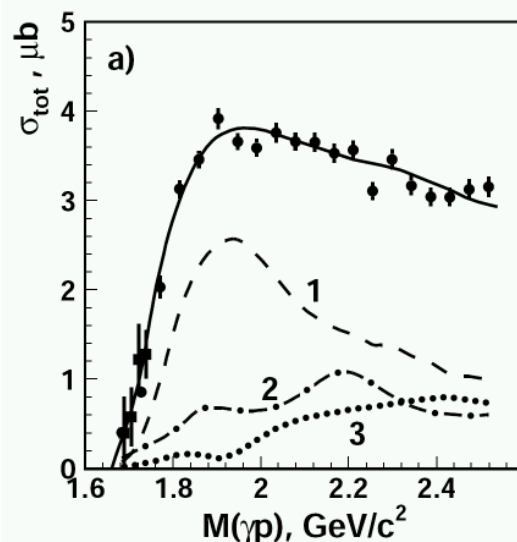
Summary: new data confirm previous results with much better statistics - further analysis under way

the reaction $\gamma p \rightarrow \pi^0 \eta p$ - $\pi^0 \eta$ -pairs off the proton

Identification

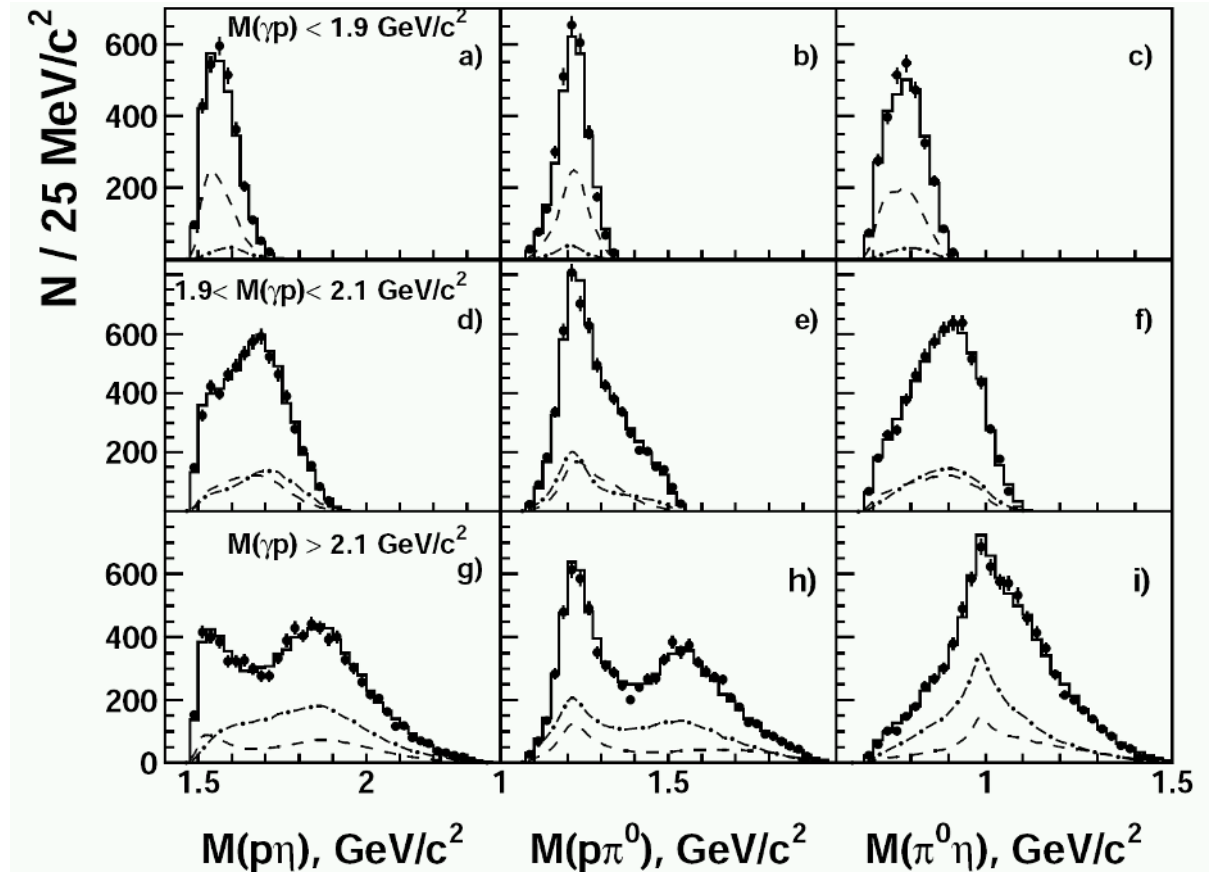


Total cross section



Invariant mass distributions

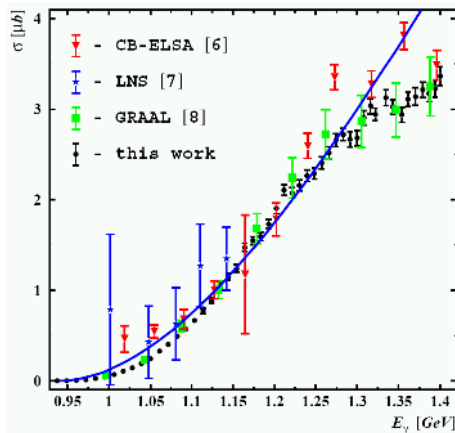
I. Horn et al. (ELSA)



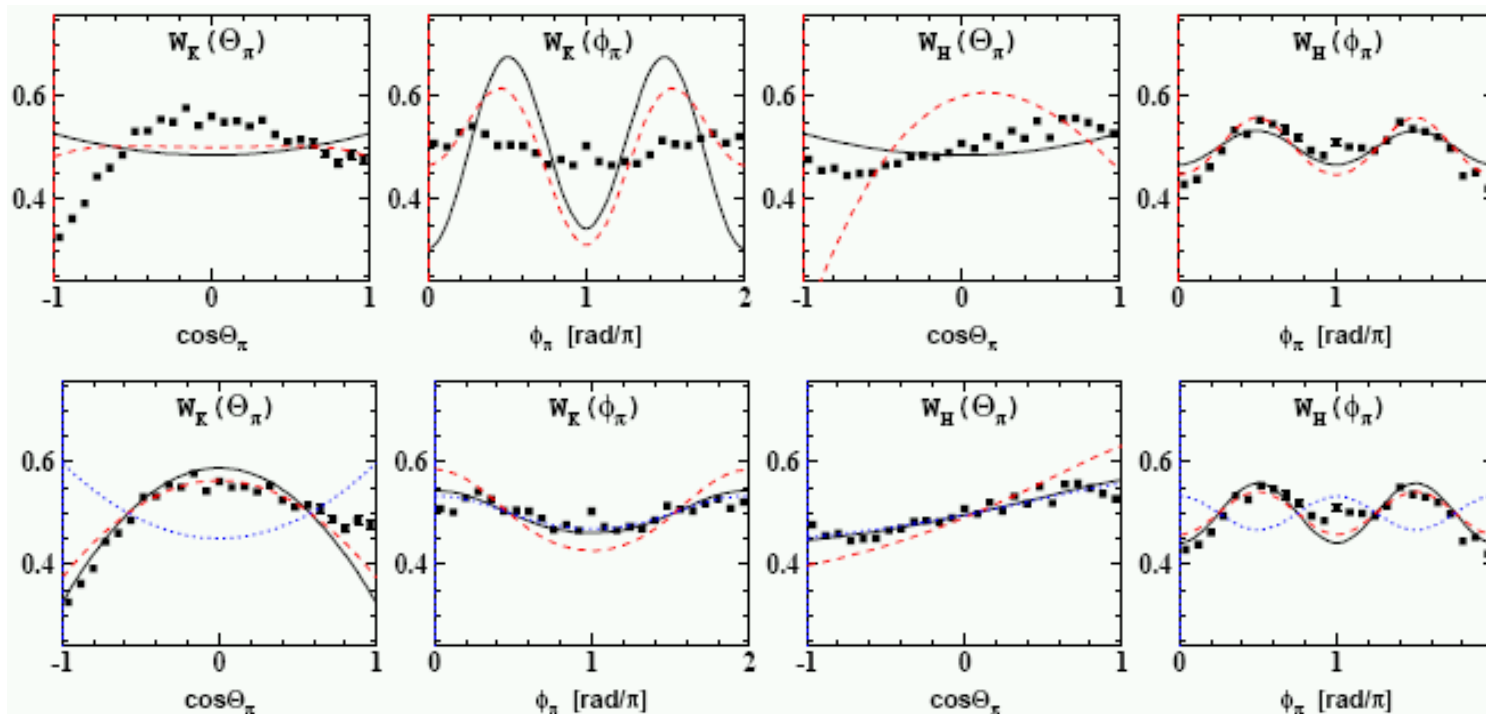
← **dominant final states:**
 — $\Delta(1232)\eta$, — . — $N(1535)\pi$, ... $pa_o(980)$

threshold region of $\pi^0\eta$ dominated by $D_{33}(1700)$

V. Kashevarov et al. (MAMI)



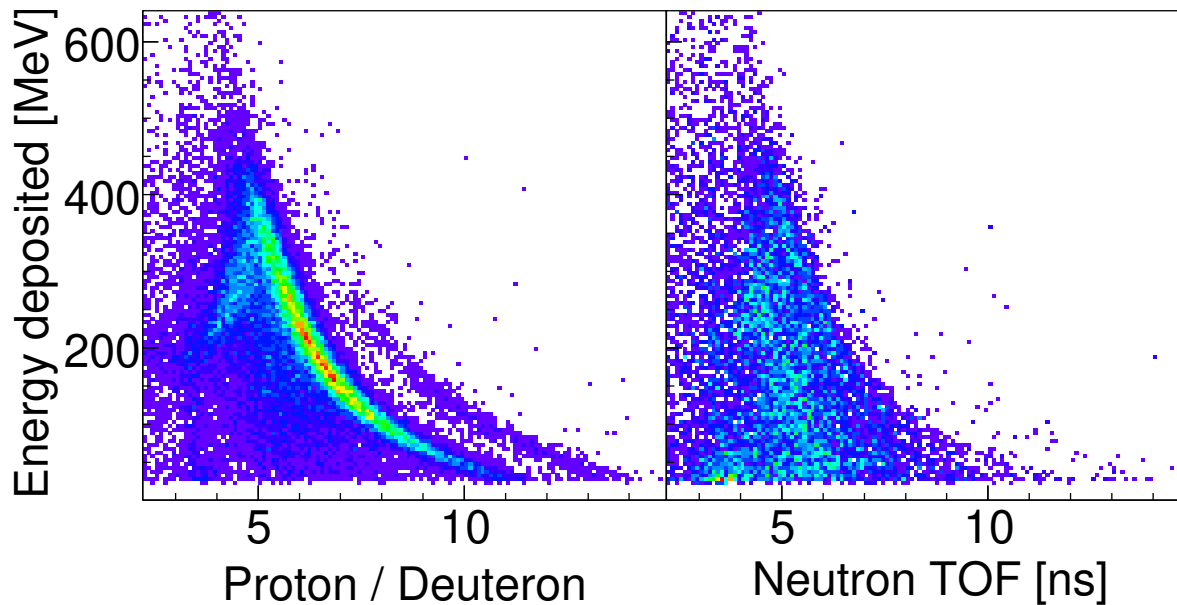
- analysis of threshold region in terms of isobar model (Fix et al.) indicates strong dominance of $D_{33}(1700)$
- extracted amplitudes allow specific predictions for coherent production of $\pi^0\eta$ -pairs of light nuclei (Fix et al.)



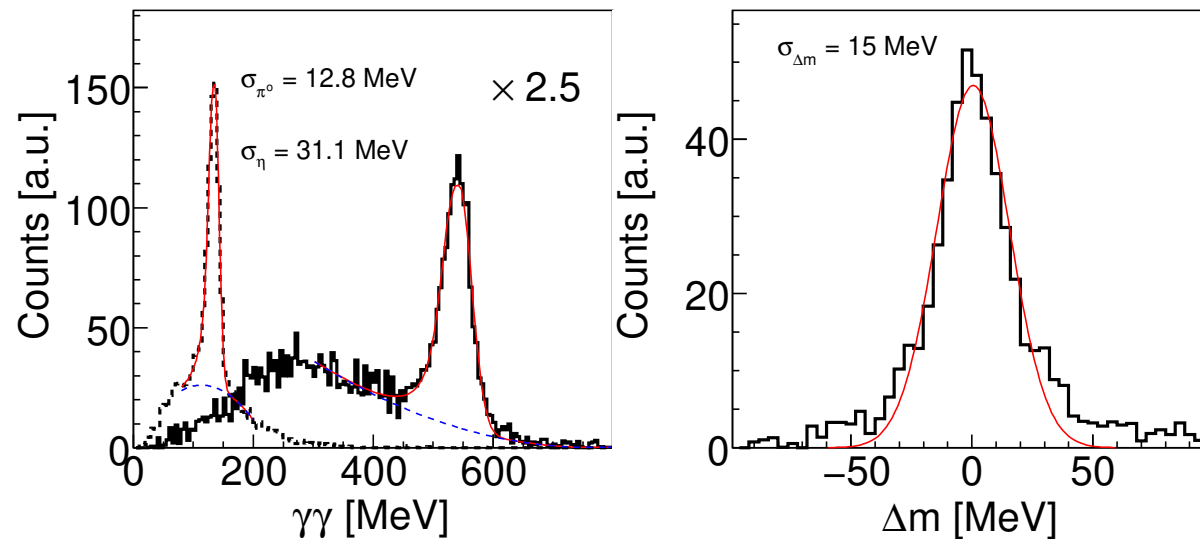
⇐ best model fits
for P_{33} or D_{35} isobars

⇐ model fits
for D_{33} isobar

coherent photoproduction of $\pi^0\eta$ -pairs: $d(\gamma, \eta\pi^0)d$



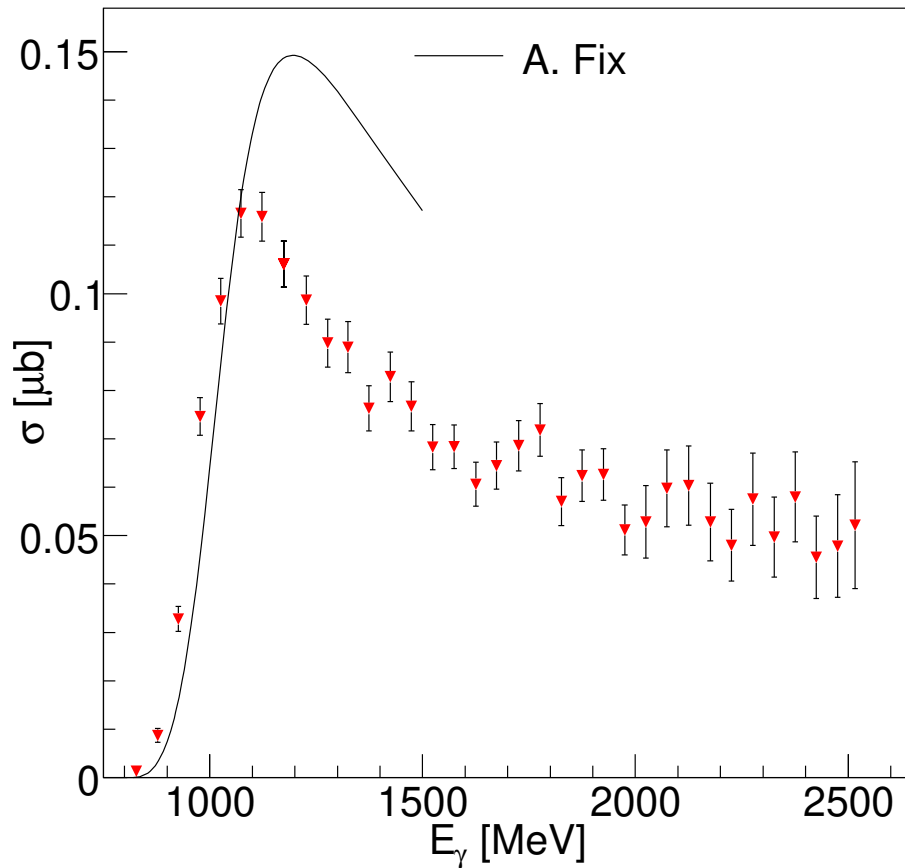
time-of-flight versus energy for deuteron identification



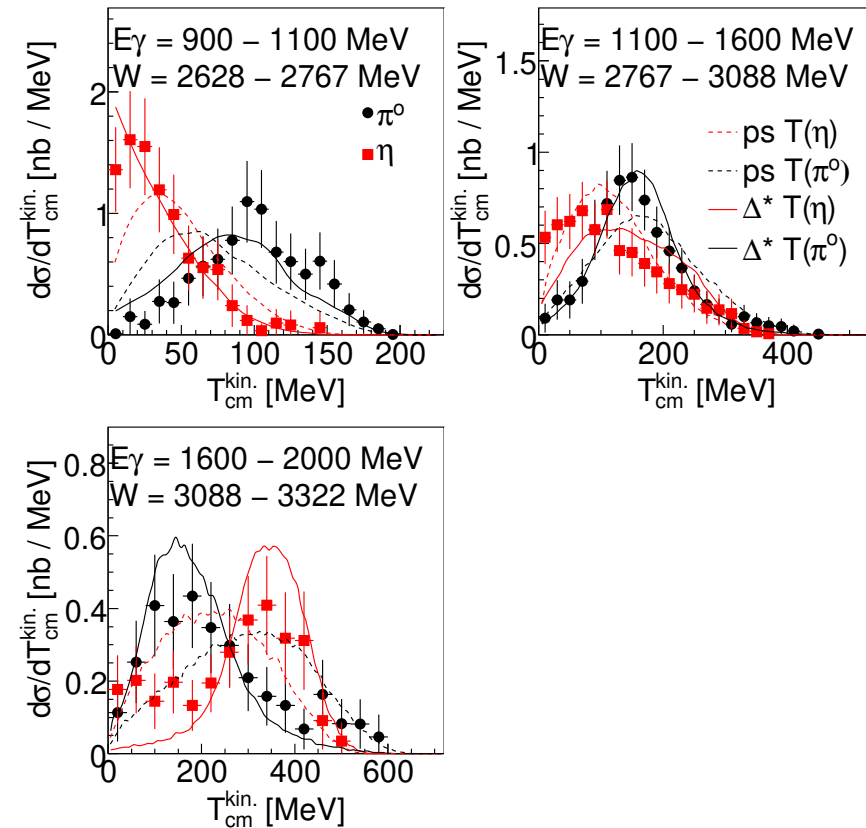
invariant mass (two-photon) for reaction identification and missing mass (deuteron treated as missing particle) for verification of coherent kinematics

$d(\gamma, \eta\pi^0)d$: total cross section, kinetic energy distributions

◆ total cross section



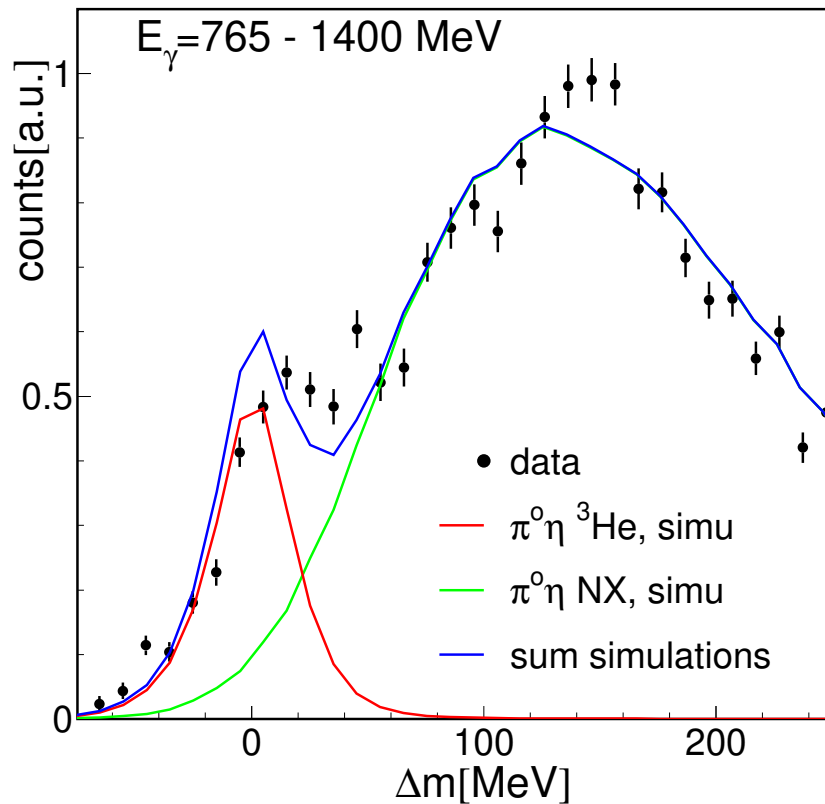
◆ kinetic energy



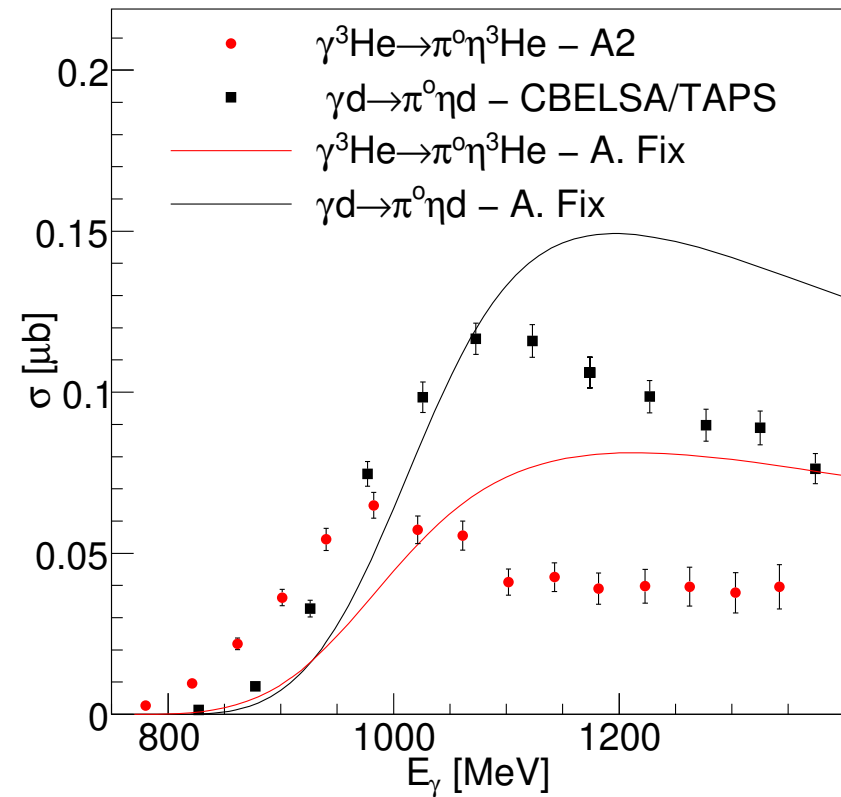
- ◆ total cross section in reasonable agreement with predictions
- ◆ T distributions support dominant $\Delta^* \rightarrow \Delta(1232)\eta \rightarrow N\eta\pi^0$ contribution:
 $T(\pi^0)$ peaks around 100 MeV ($\Delta(1232) \rightarrow N\pi$), $T(\eta)$ rises with E_γ

very preliminary: $^3\text{He}(\gamma, \eta\pi^0)^3\text{He}$

◆ identification via missing mass



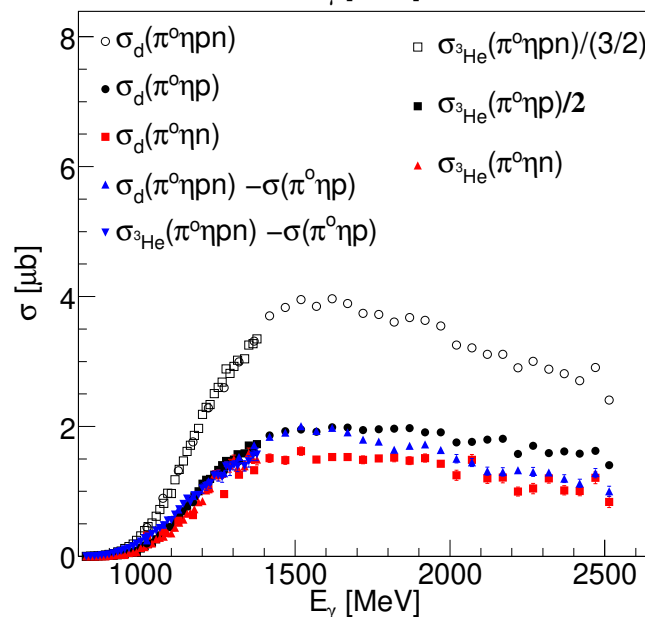
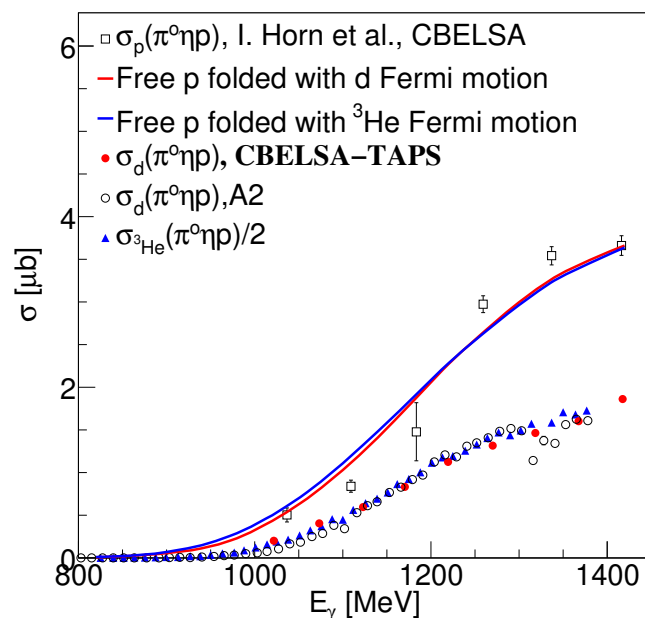
◆ preliminary total cross section



◆ qualitative agreement with isotope dependence from Fix's model

quasi-free photoproduction of $\pi^0\eta$ pairs

...preliminary results

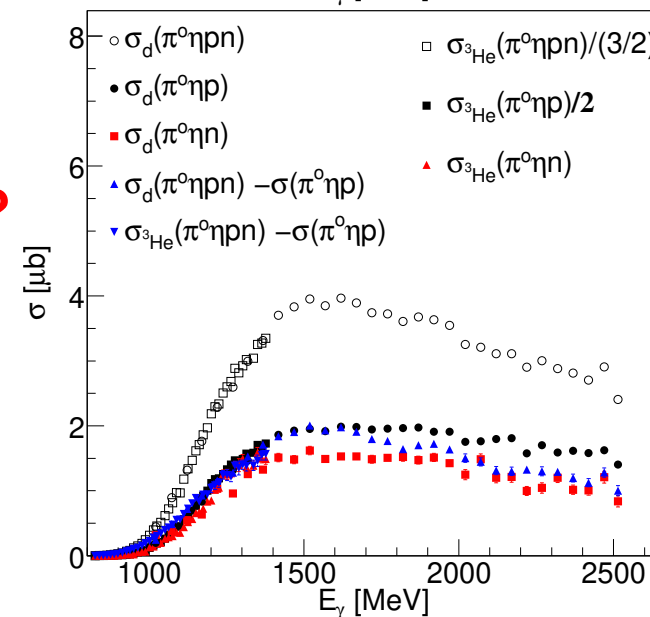
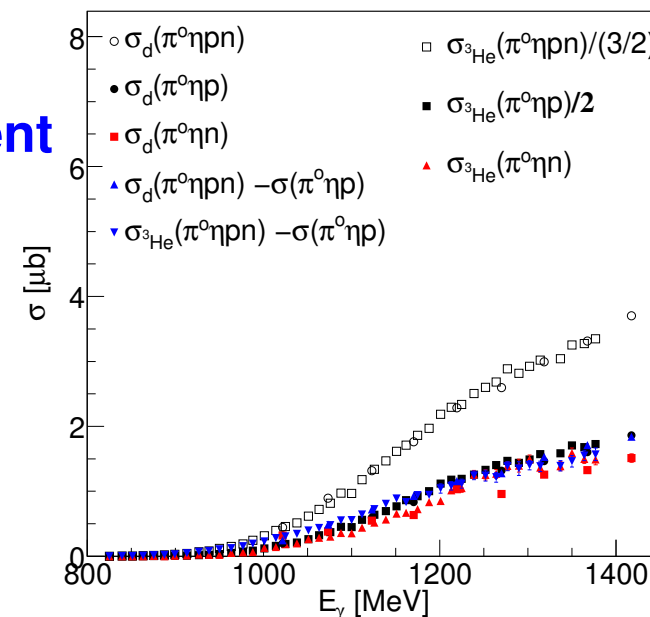


deuteron results from MAMI and ELSA consistent

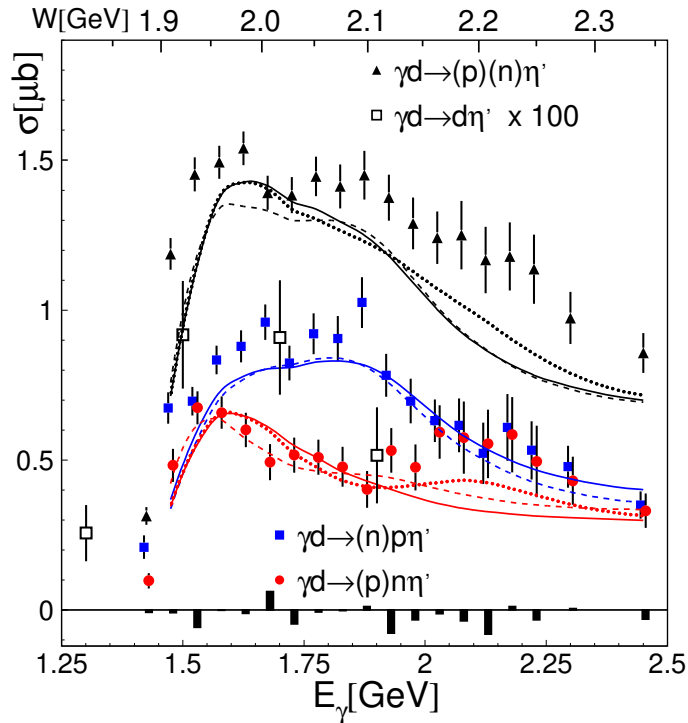
quasi-free proton and neutron results from deuteron and ^3He consistent

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

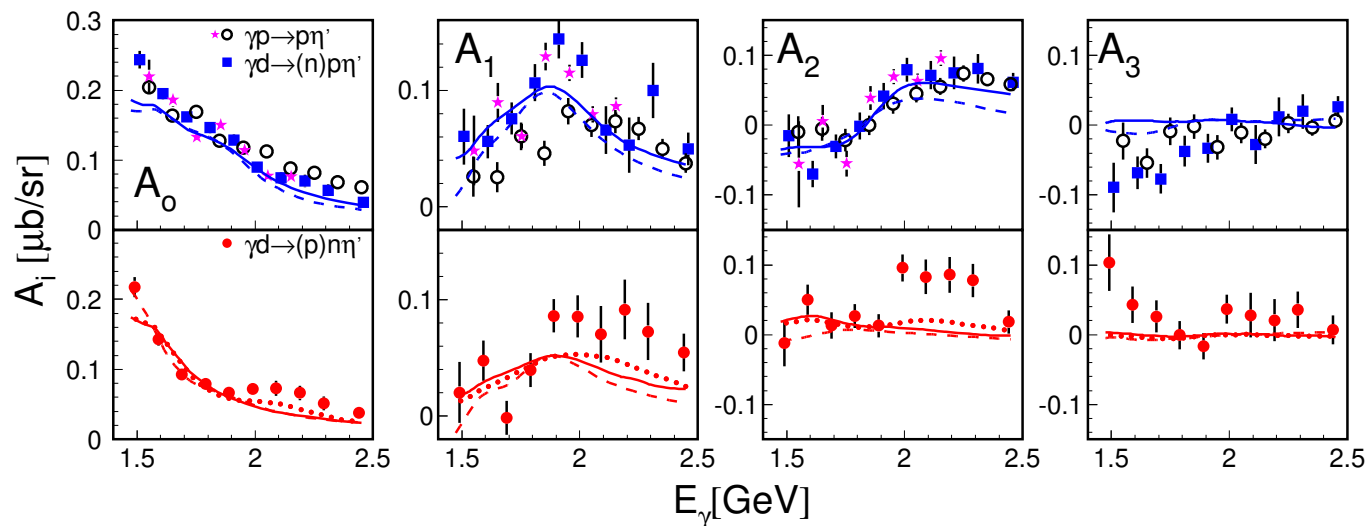


results for many more channels, e.g. quasi-free η'



⇐ total cross sections,
model calculations
K. Nakayama et al.

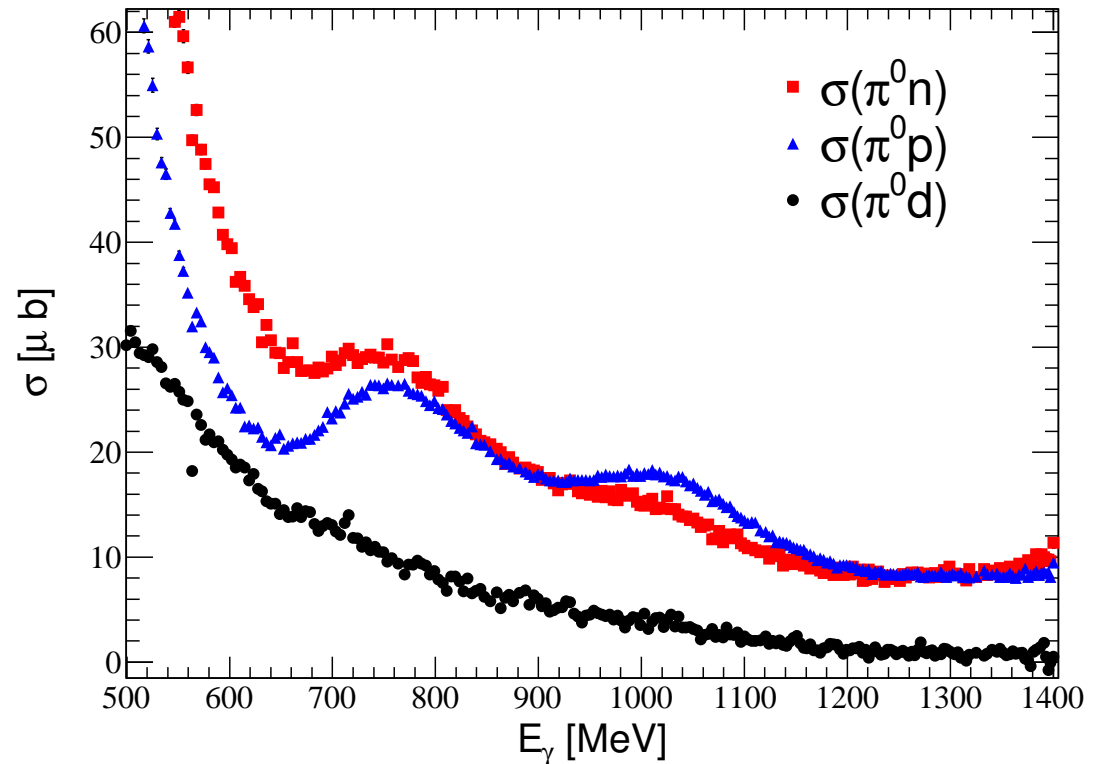
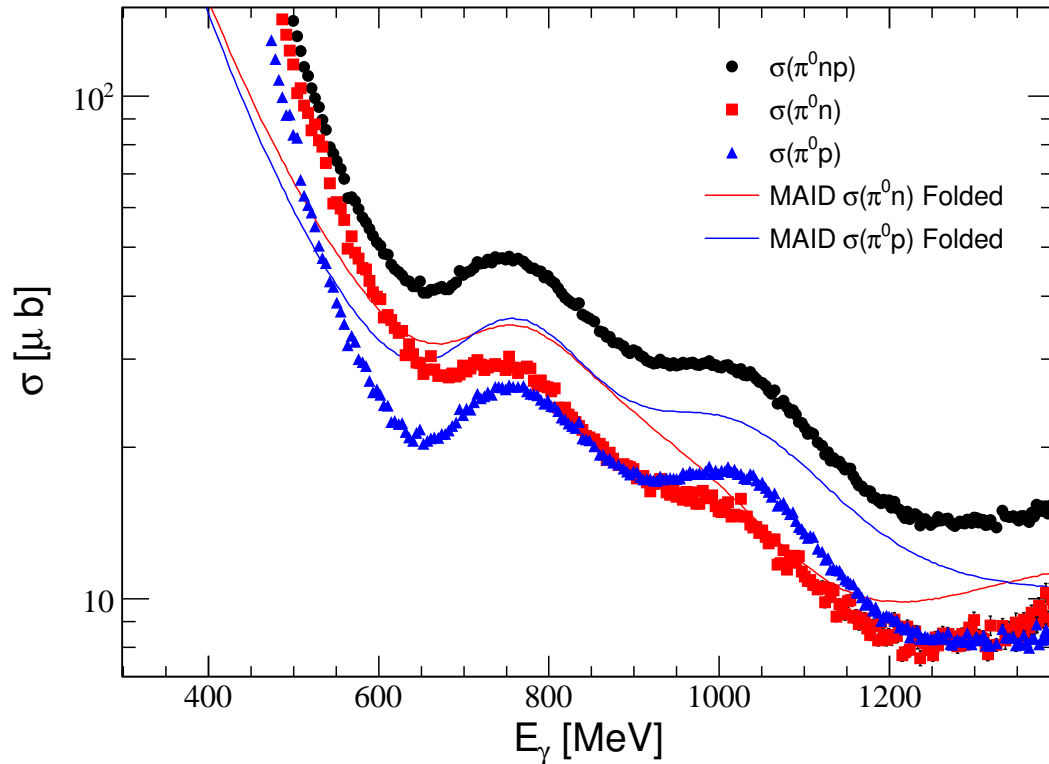
Legendre coefficients
of angular distributions ↓



- 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 $2.0 \text{ GeV} < W < 2.5 \text{ GeV}$ which is less pronounced for proton

...and single π^0 quasi-free and coherent...

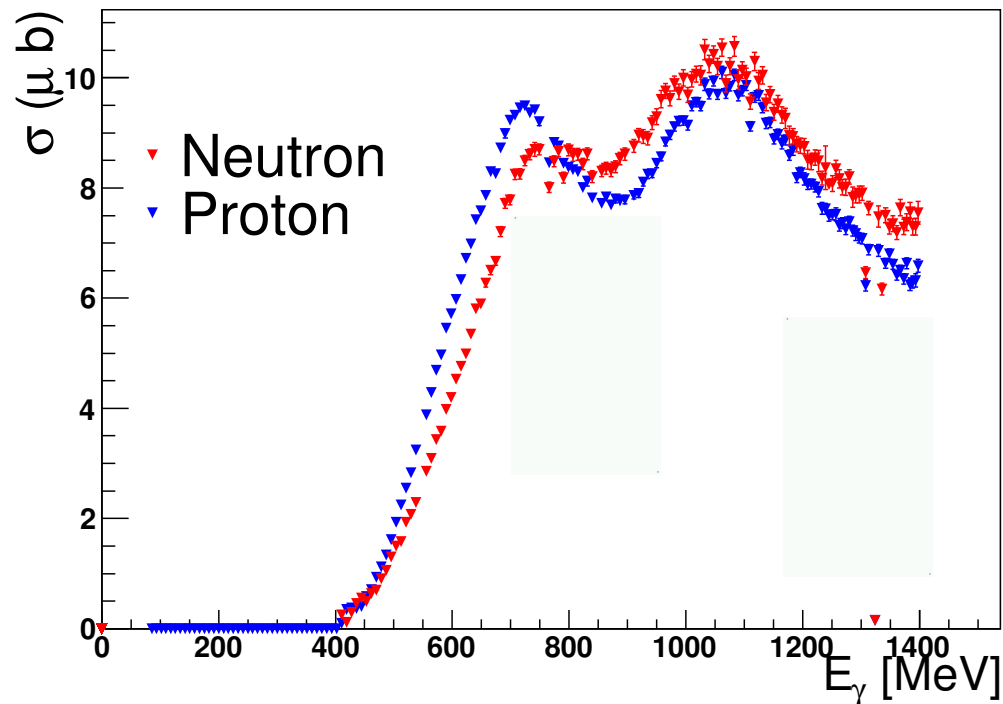
◆ total cross sections



- ◆ quasi-free off proton and neutron: contributions from different N^* -resonances
- ◆ coherent off deuteron:
only Δ -resonances, N^* forbidden due to isospin conservation

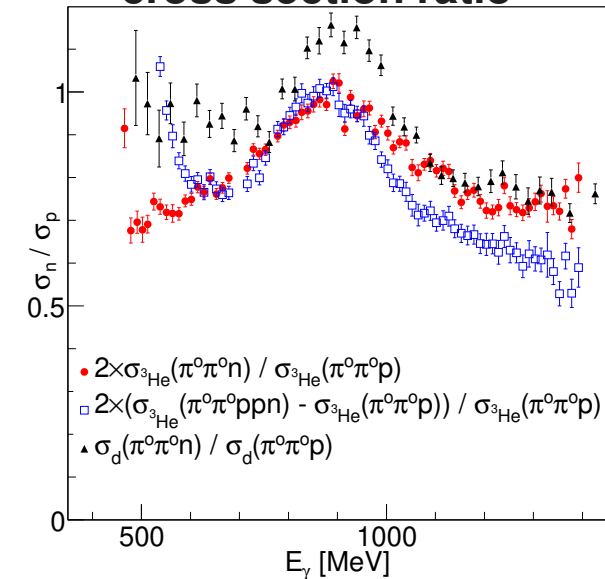
... double π^0 quasi-free and coherent...

• total cross sections

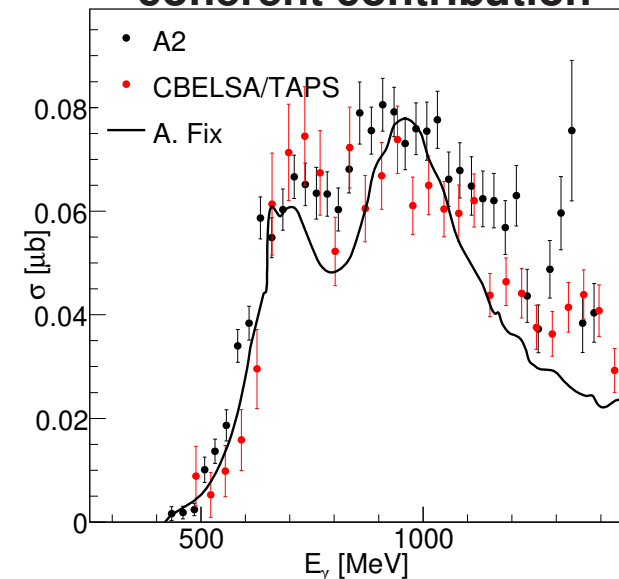


- quasi-free off proton and neutron:
some difference in resonance bump structure
- coherent off deuteron:
only N^* -resonances, Δ -resonances forbidden
due to isospin conservation

cross section ratio

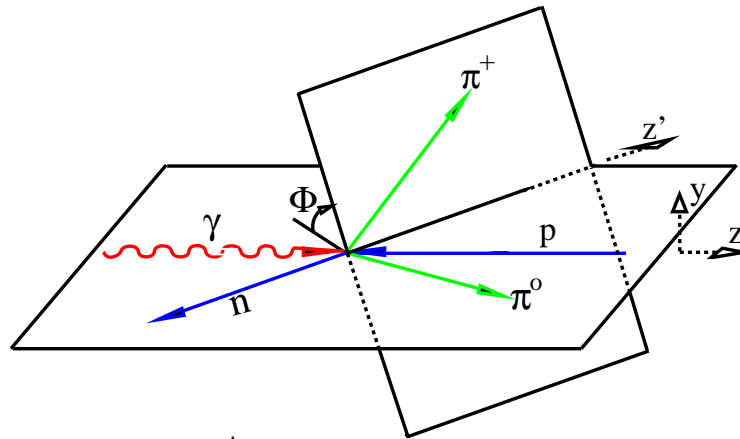


coherent contribution

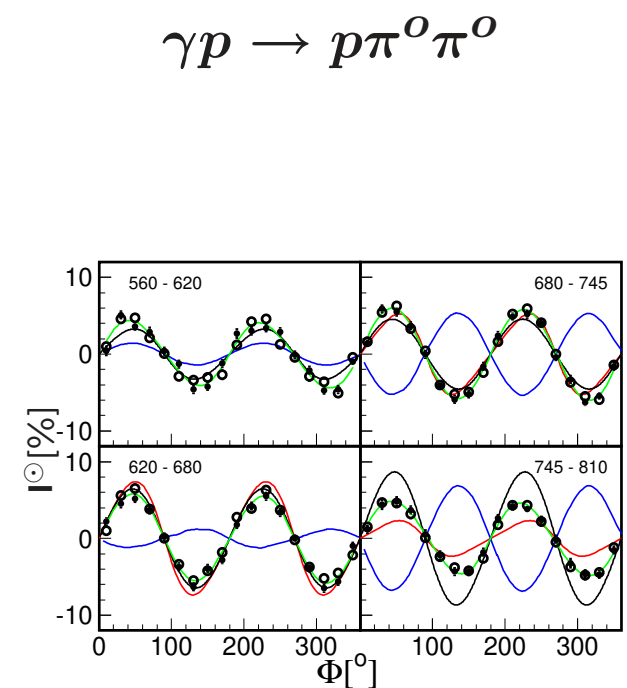
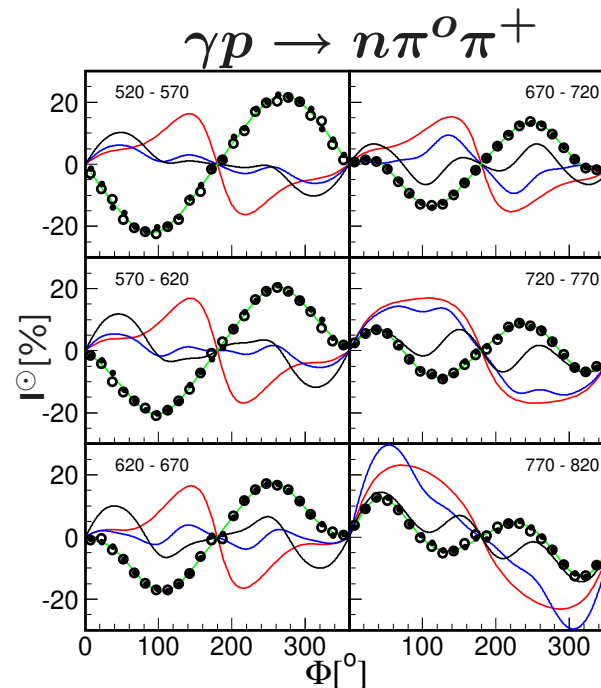
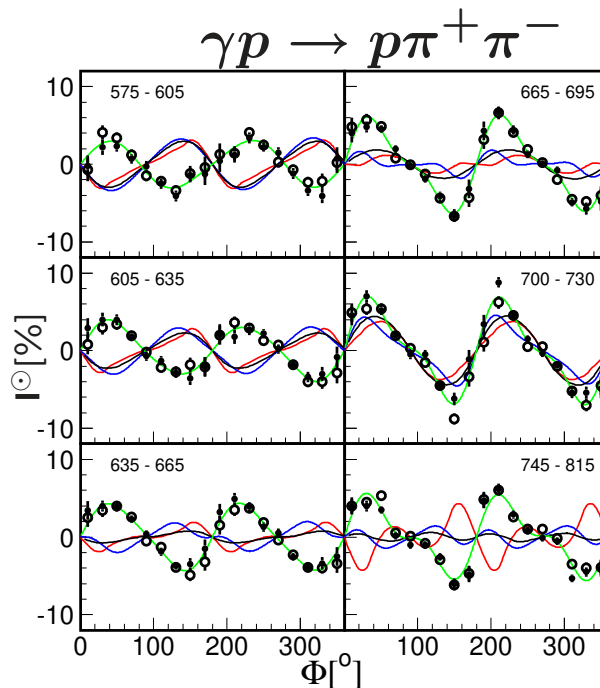


polarization observables - example: beam-helicity for 2π

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



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

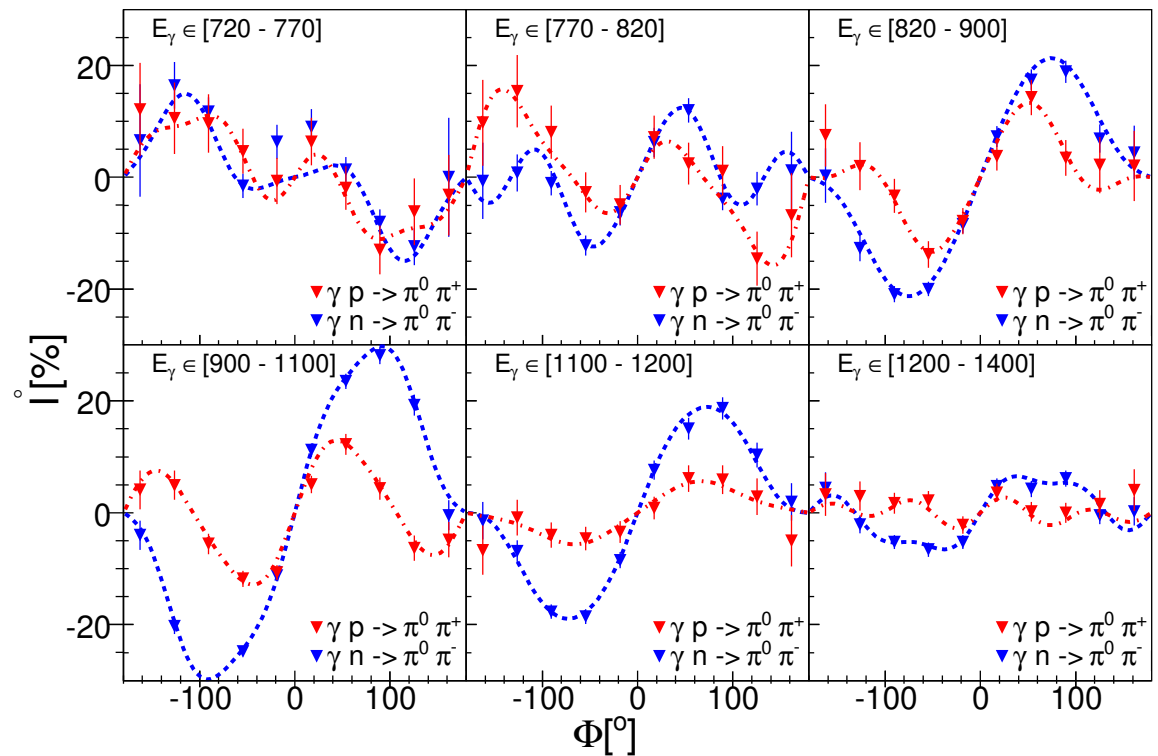
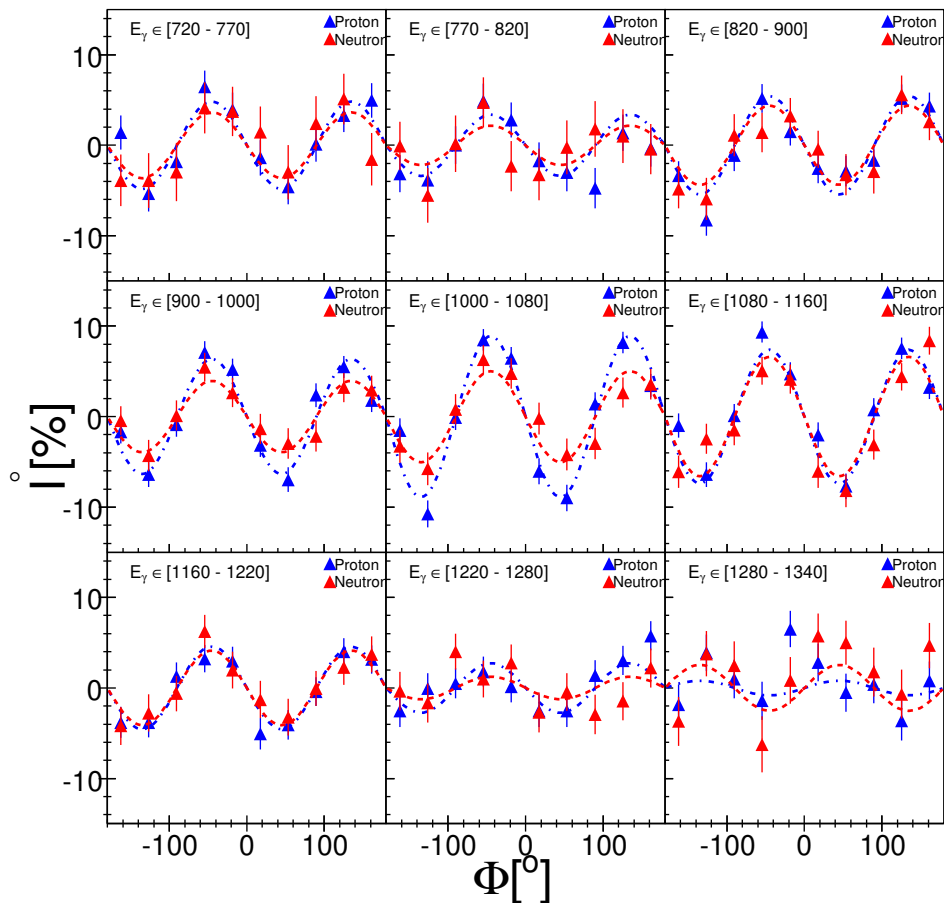


proton results so far not understood!

...quasi-free off the deuteron...

- almost identical results for $\gamma p \rightarrow p\pi^0\pi^0$ and $\gamma n \rightarrow n\pi^0\pi^0$

- less similarities for $\gamma p \rightarrow n\pi^0\pi^+$ and $\gamma n \rightarrow p\pi^0\pi^-$



Conclusions


Systematic investigation of meson production

off ^2H and ^3He :

-  **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 ^3He :**
- ◆ 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
D. Werthmüller
F. Pheron
F. Zehr
M. Dieterle
M. Oberle
L. Witthauer