

Photoproduction of mesons off light nuclei

- the search for η -mesic nuclei -

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



Introduction



Experimental setups

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

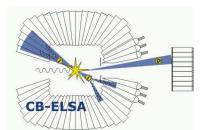


Experimental results

- coherent photoproduction of η -mesons: ${}^3\text{He}(\gamma, \eta){}^3\text{He}$, ${}^7\text{Li}(\gamma, \eta){}^7\text{Li}$
- $\pi^0 - p$ back-to-back emission as signal for ‘bound’ S_{11} -decays?
- other entrance channels: coherent production of $\eta\pi^0$ -pairs?

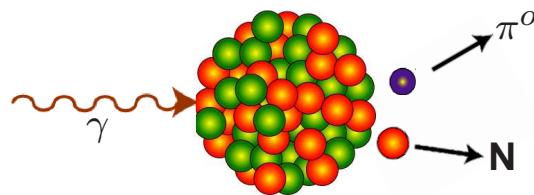


Conclusions



Photoproduction of mesons off nuclei - what can we learn?

● breakup (quasi-free)

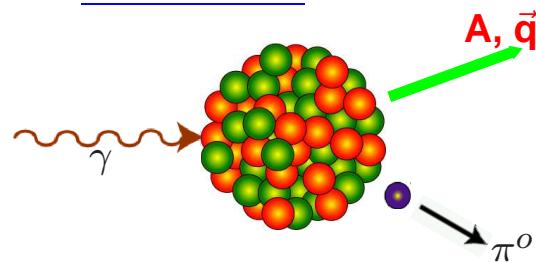


$$\frac{d\sigma}{d\Omega} \propto \sum |\mathcal{A}|^2 \times \dots$$

& nuclear effects & FSI & ...

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

● coherent

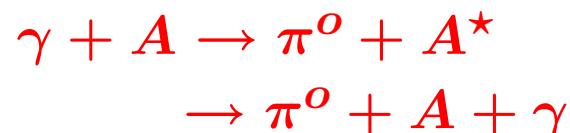
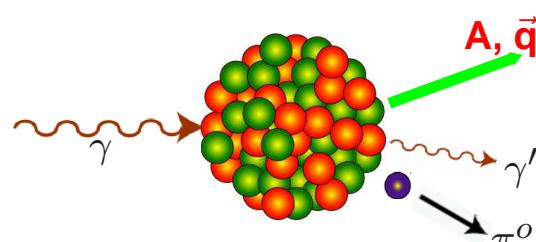


$$\frac{d\sigma}{d\Omega} \propto |\sum \mathcal{A}|^2 \times F^2(q^2) \times \dots$$

& nuclear effects & FSI & ...

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

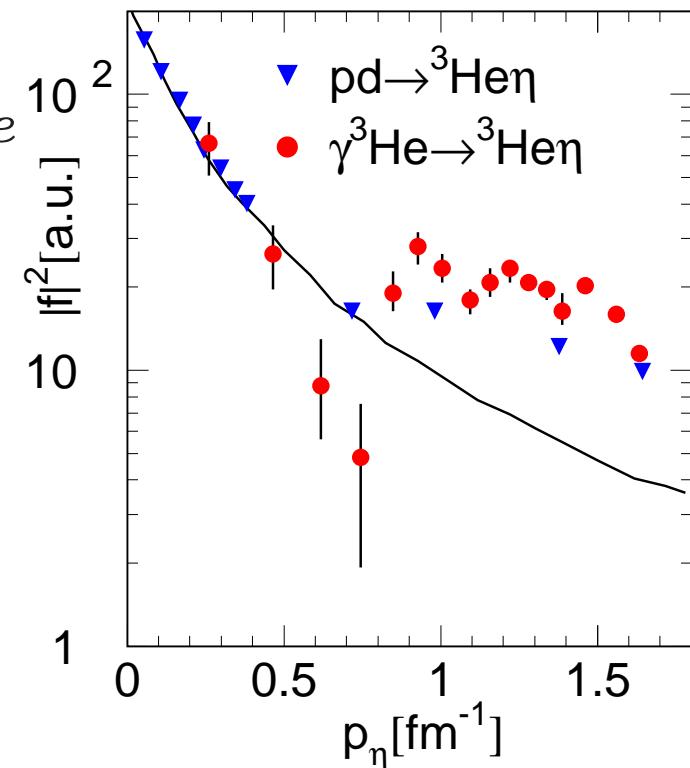
● incoherent



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

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): $\pi^+ + ^{16}O \rightarrow p + _\eta^{15}O$
Johnson et al. (1993): $\pi^+ + ^{18}O \rightarrow \pi^- + _\eta^{18}Ne$
- ◆ **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 2H -, 3H -, 3He -, 4He - η states
- ◆ **experiments:**
threshold behavior of η -production
 $p + d \rightarrow ^3He + \eta$
 $\gamma + ^3He \rightarrow ^3He + \eta$



η -photoproduction off the proton: resonance contributions?

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				

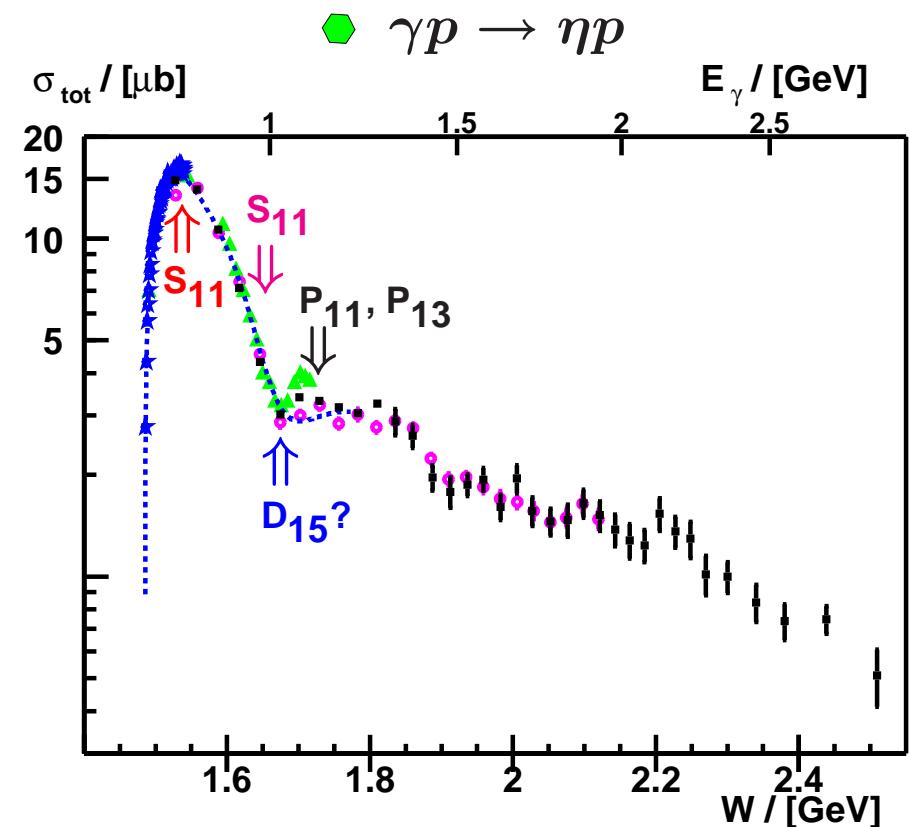
- **$D_{15}(1675)$ has stronger electromagnetic coupling to neutron than to proton**

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?**

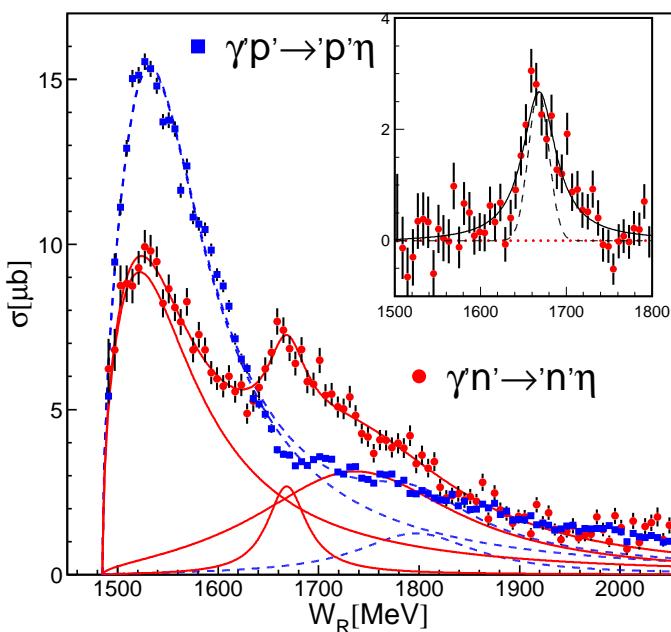


Data:

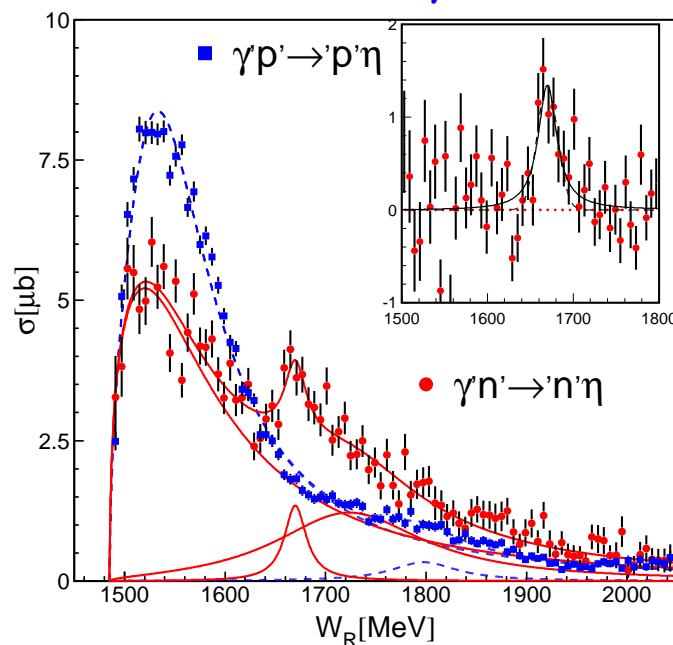
- TAPS: B. Krusche et al., PRL74 (1995) 3736
- GRAAL: F. Renard et al., PLB528 (2002) 215
- CLAS: M. Dugger et al., PRL89 (2002) 222002
- Crystal Barrel: V. Crede et al., PRL94 (2005) 012004

Fermi de-folded proton and neutron data

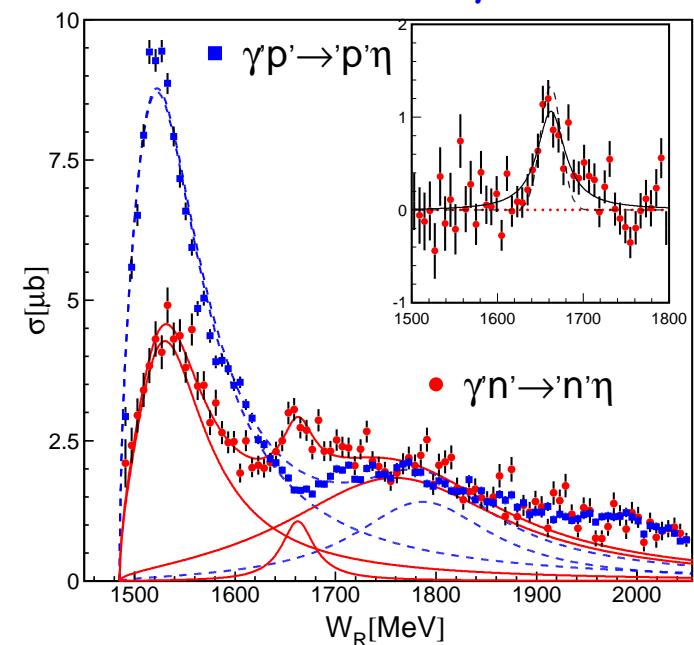
- total cross section



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



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



- 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 ± 4) MeV (total), (1670 ± 3) MeV ($\cos(\Theta_\eta^*) < 0$), (1662 ± 5) MeV ($\cos(\Theta_\eta^*) > 0$)
- width: (48 ± 15) MeV (total), (26 ± 9) MeV ($\cos(\Theta_\eta^*) < 0$), (40 ± 20) MeV ($\cos(\Theta_\eta^*) > 0$)
- experimental resolution for width: ≈ 25 MeV

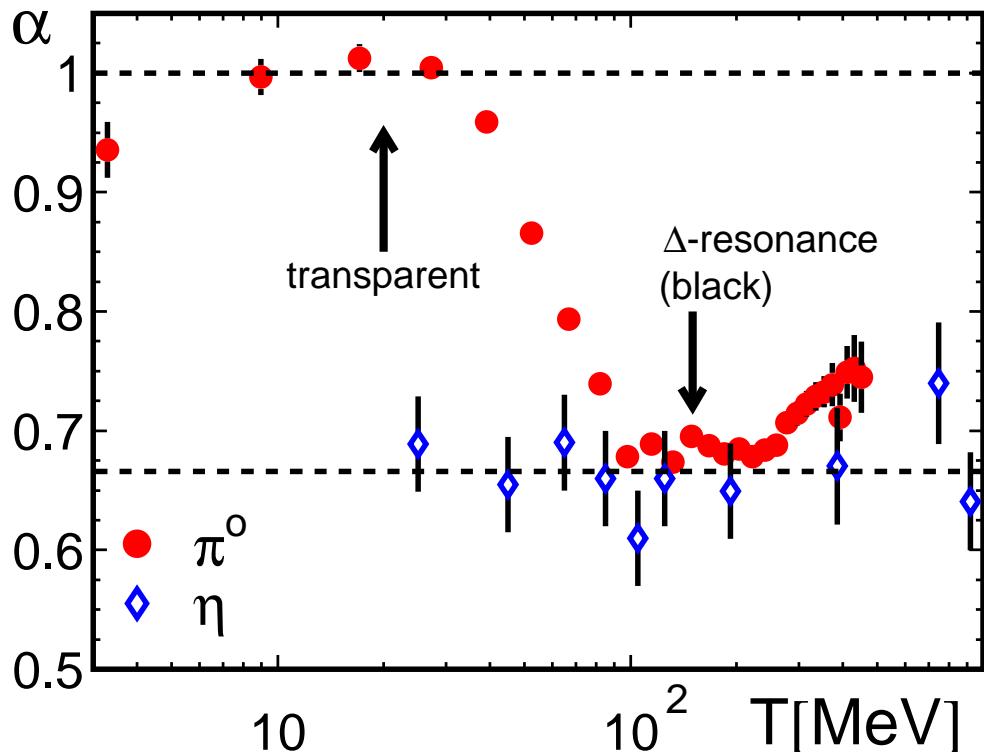
interaction of mesons in nuclear matter

- ◆ 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?

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

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



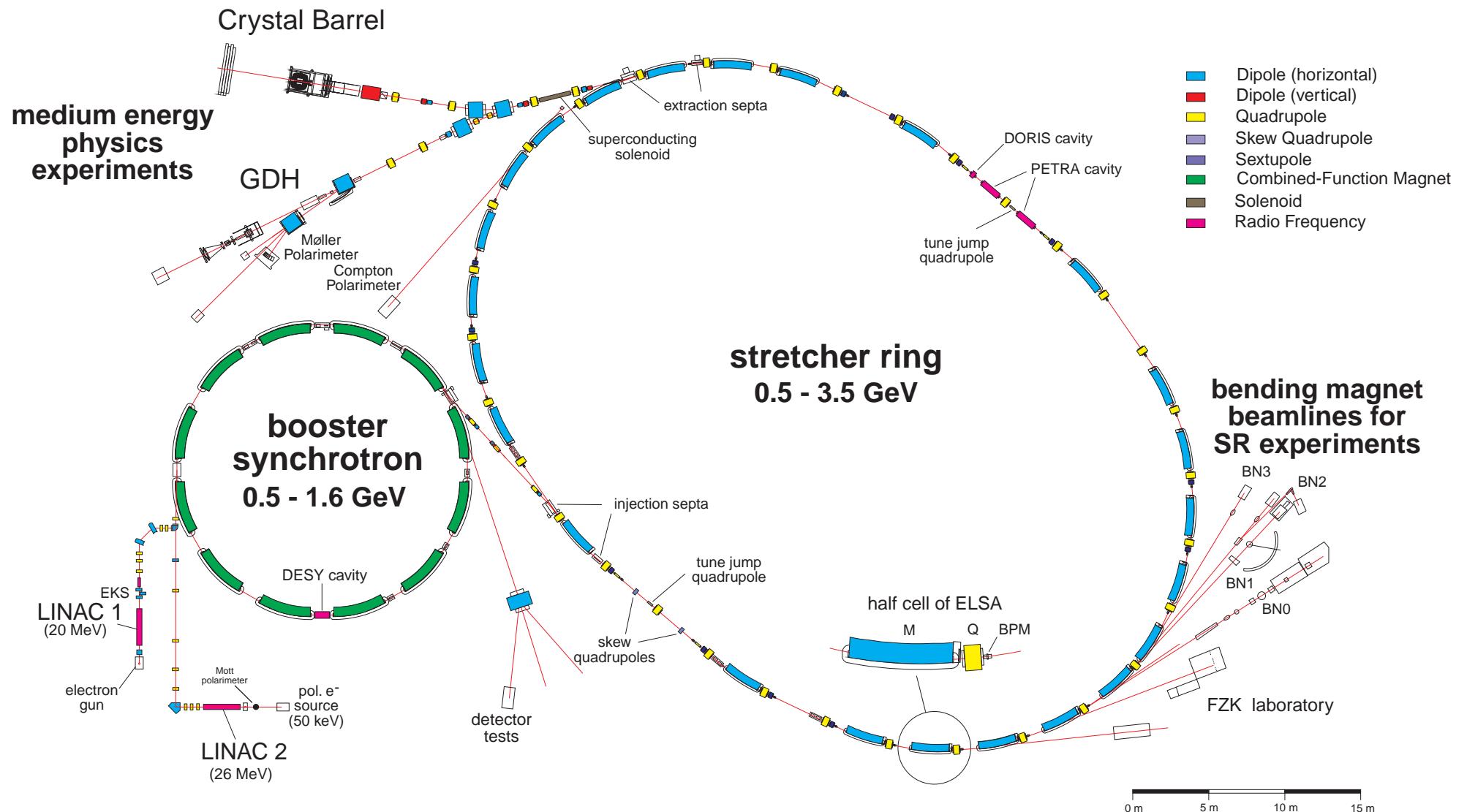
J_z : -1 +1/2 -1/2 -1/2 0 → spin-flip transition

- isospin structure: $A_{1/2}^{IS}/A_{1/2}^p \approx 0.09$ → dominantly isovector

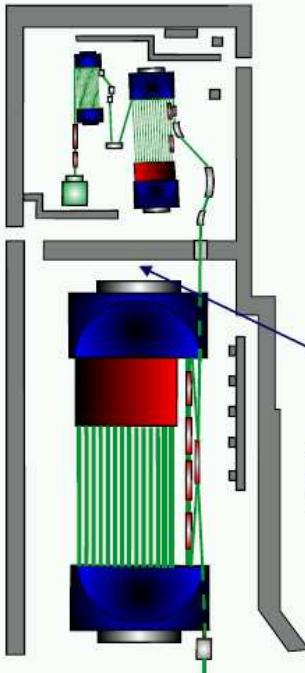
- expectation for light nuclei:

- 1) ^4He : **J=0, I=0, isoscalar, non spin-flip** → very small signal
(not seen, only upper bounds, V. Hejny et al.)
- 2) ^2H : **J=1, I=0, isoscalar, spin-flip** → small signal
(seen, almost in agreement with expectations)
- 3) ^3He : **J=1/2, I=1/2, isovector, spin-flip** → 'large' signal

Electron Stretcher Accelerator (ELSA)



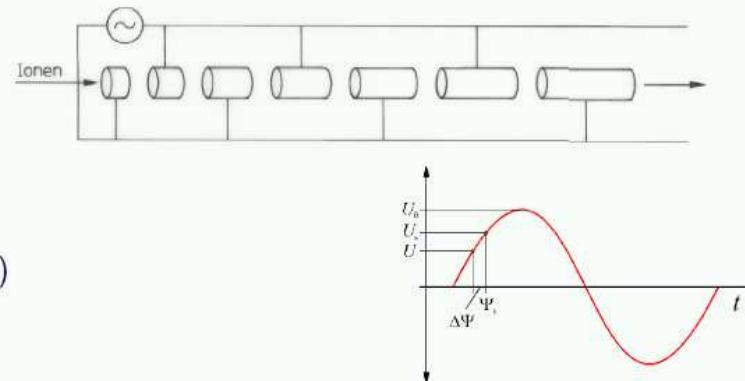
MAMI accelerator in Mainz



Mainz Microtron (MAMI)

continuous wave electron accelerator, max. beam energy 883

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



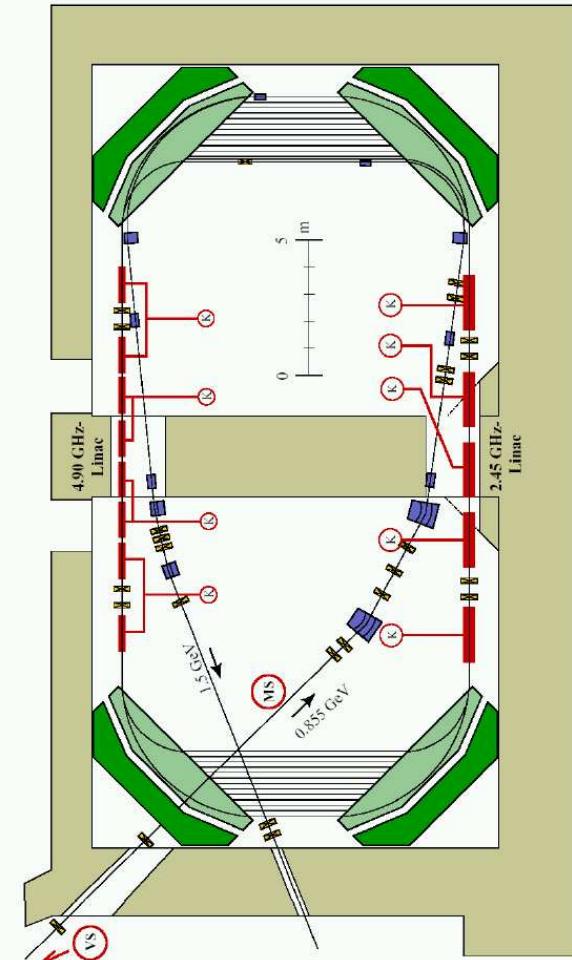
accelerators
(racetrack microtrons)

1.-3. Stage: Racetrack Microtrons:

- ◆ microbunches of 0.4ns
- ◆ linear accelerator structures
- ◆ constant B field \Rightarrow varying radii (18, 51, 90 return cycles)
- ◆ very efficient acceleration and continuous mode
- ◆ high current (0.1mA)

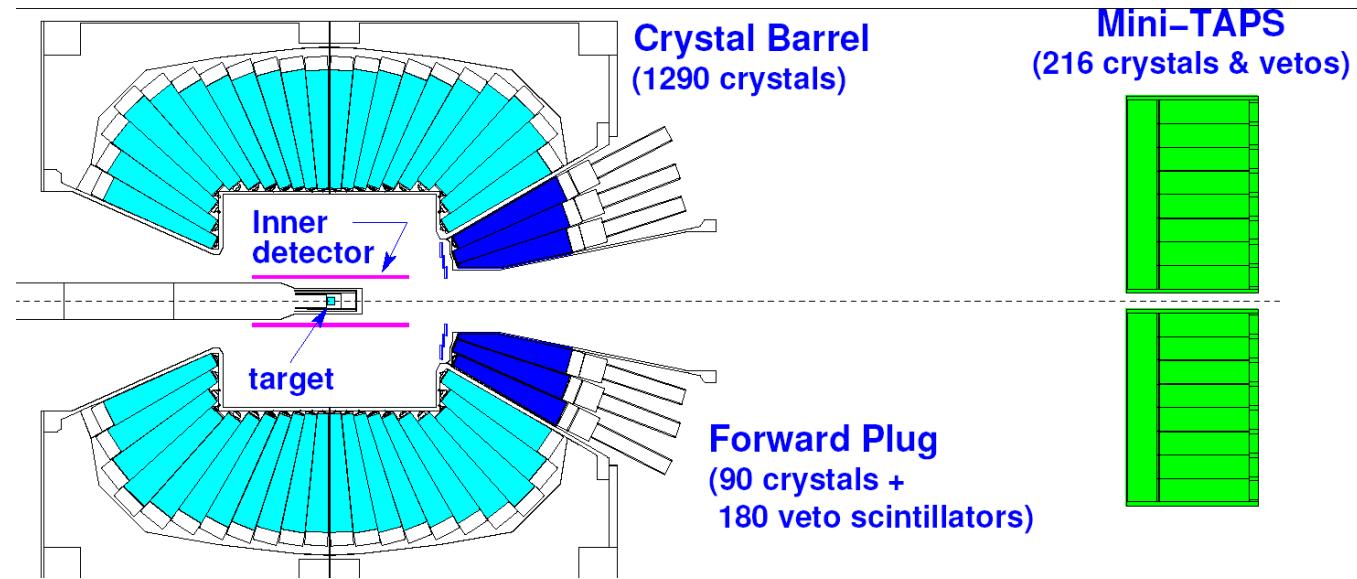
4. Stage: Harmonic Double Sided Microtron

maximum energy: 1.5 GeV

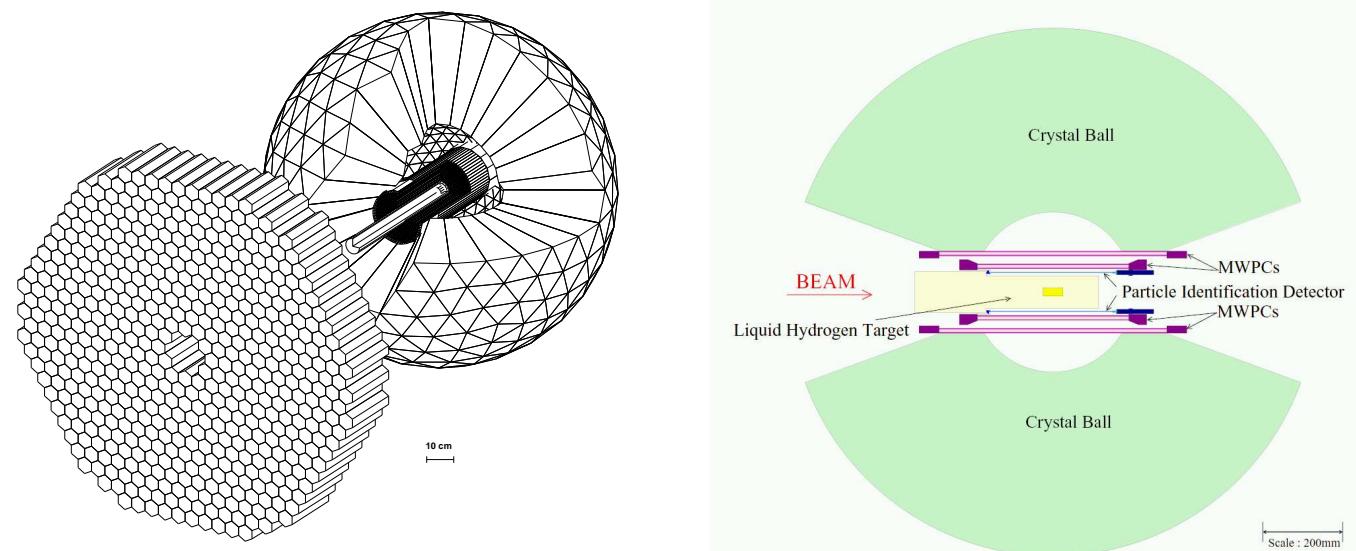


Experiments: Crystal Ball & Crystal Barrel with TAPS

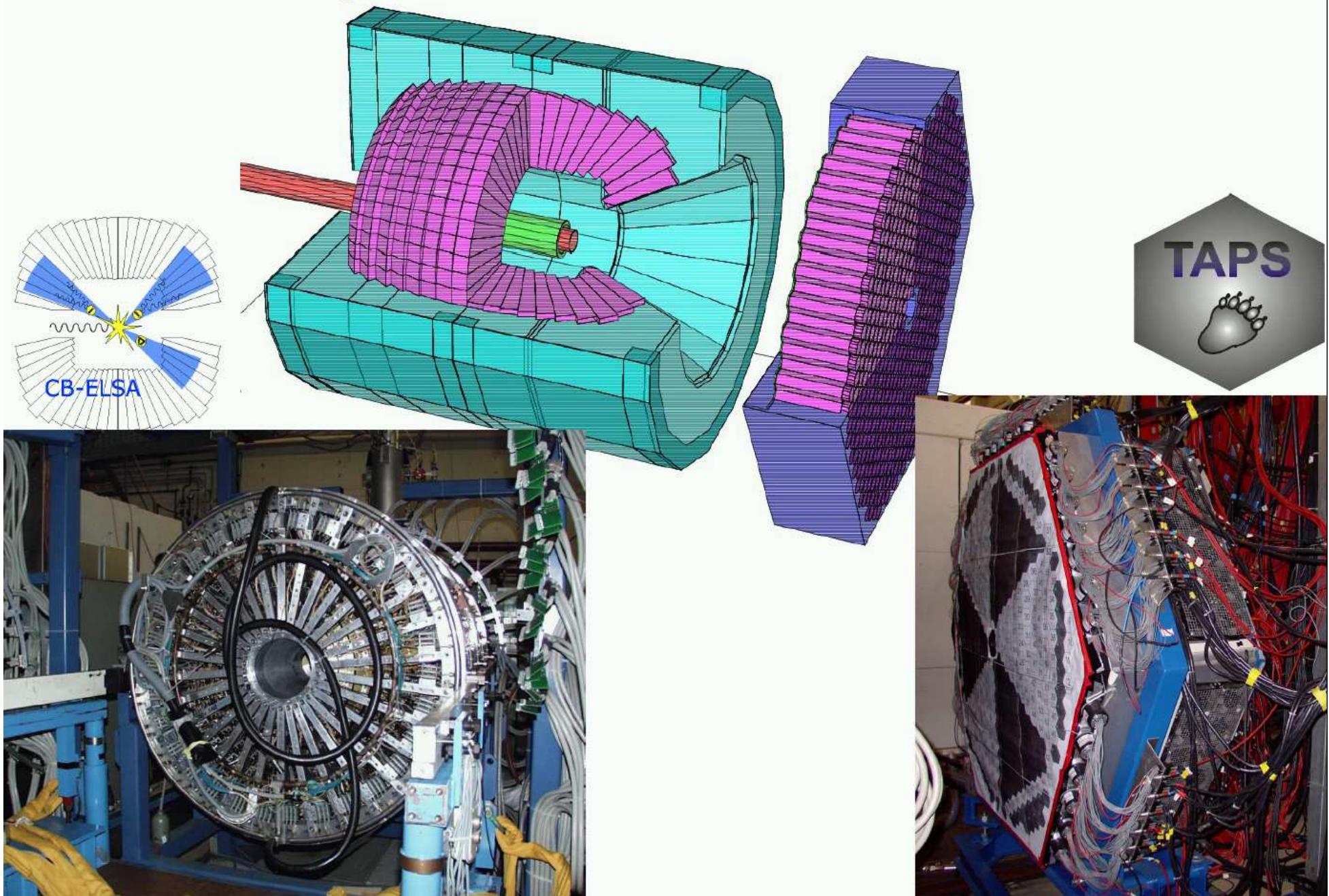
- ◆ **Bonn ELSA accelerator:**
Crystal Barrel (CsI),
TAPS (BaF_2) forward wall,
inner detectors
 $E_\gamma \leq 3.5 \text{ GeV}$,
lin. pol.: available,
circ. pol.: available



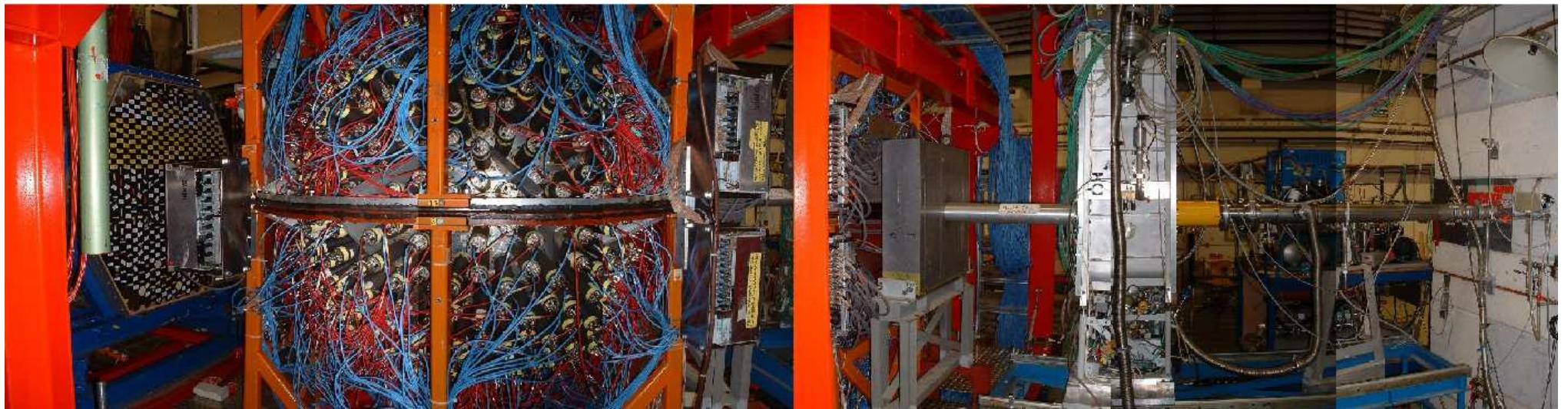
- ◆ **Mainz MAMI accelerator:**
Crystal Ball (NaJ),
TAPS (BaF_2) forward wall,
inner detectors
 $E_\gamma \leq 1.5 \text{ GeV}$,
lin. pol.: available,
circ. pol.: available



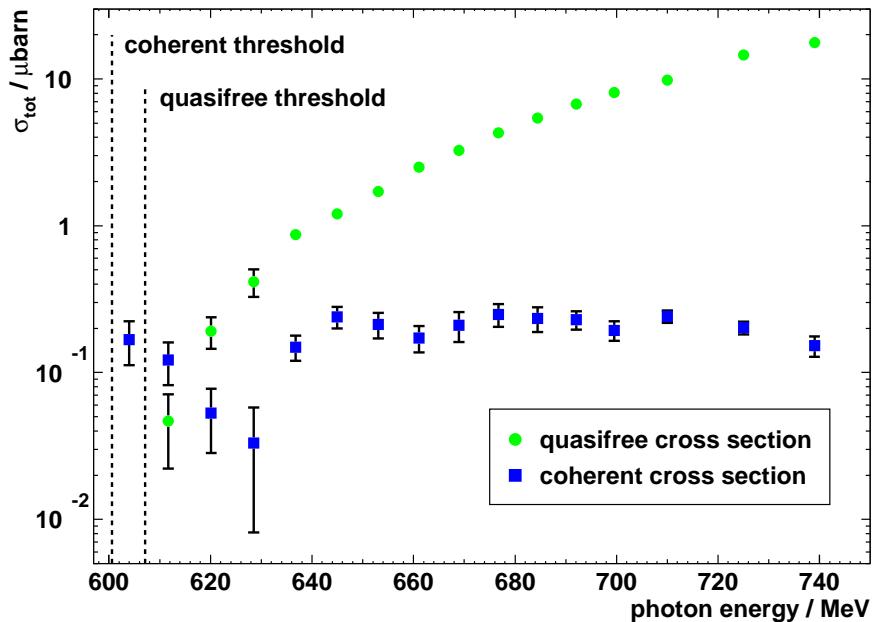
Crystal Barrel and TAPS



TAPS Crystal Ball - at MAMI



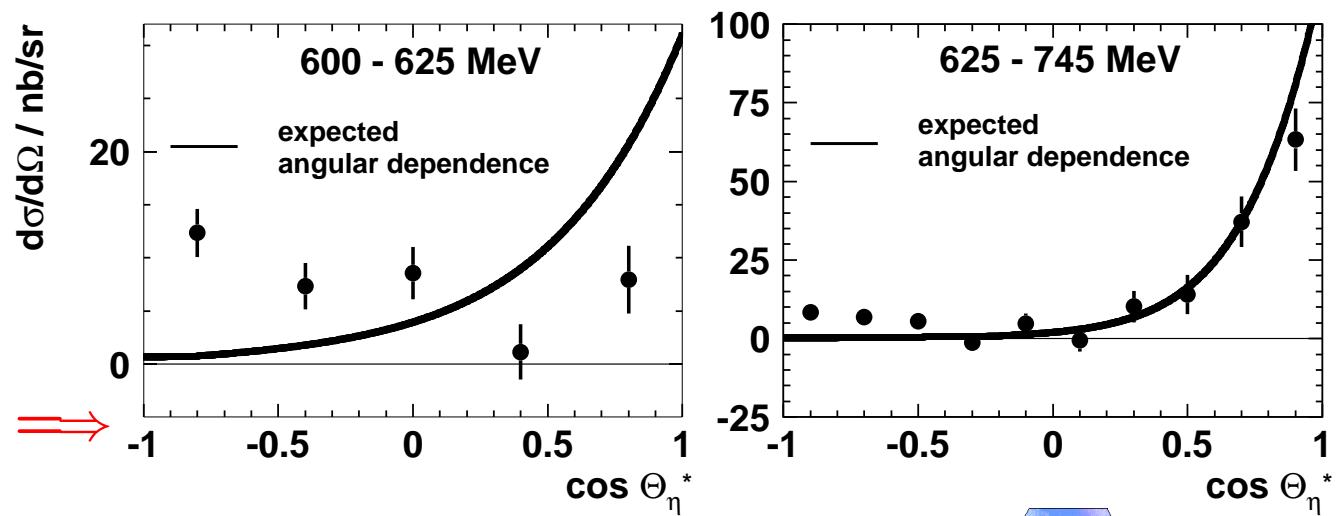
η -photoproduction from ${}^3\text{He}$ - threshold behavior



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

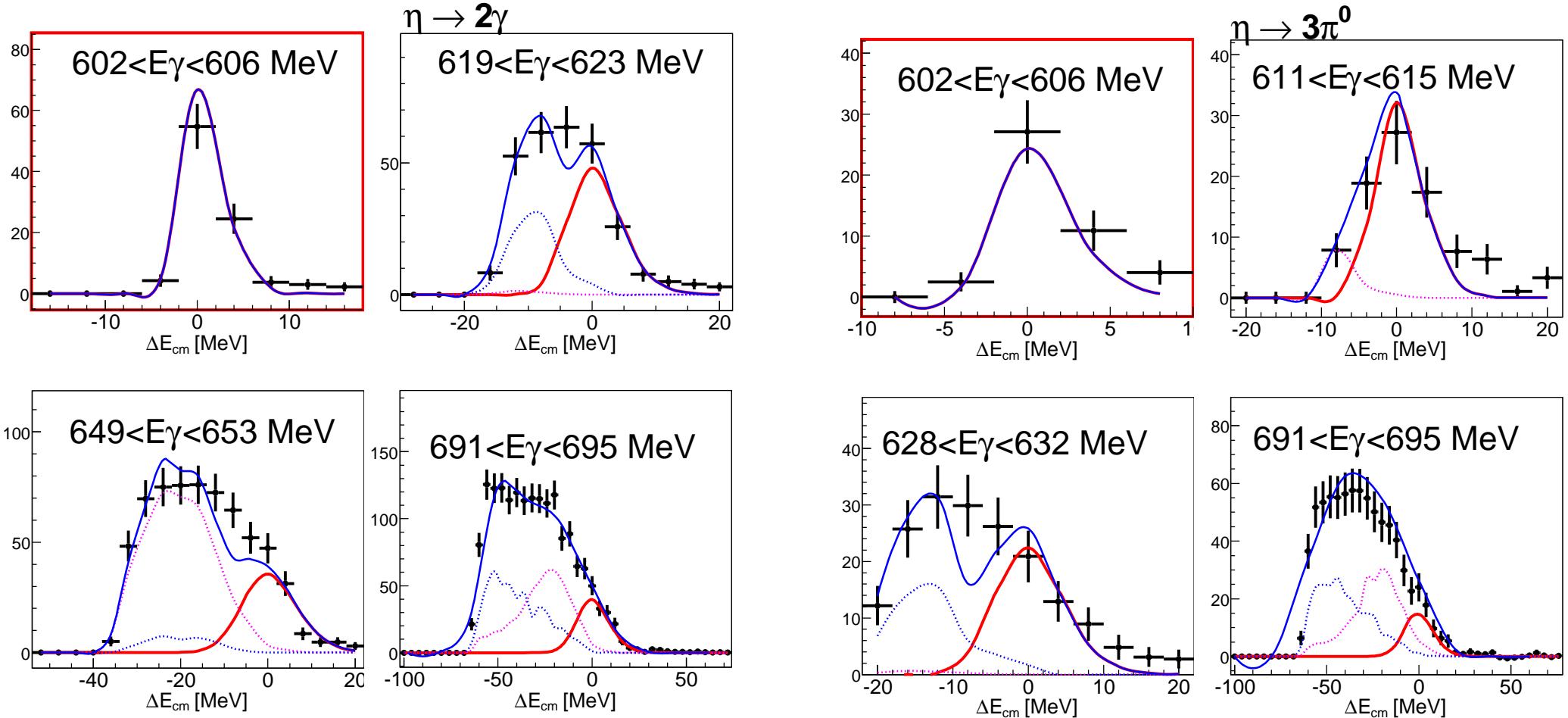


new ^3He experiment - improved statistics

reaction identification:

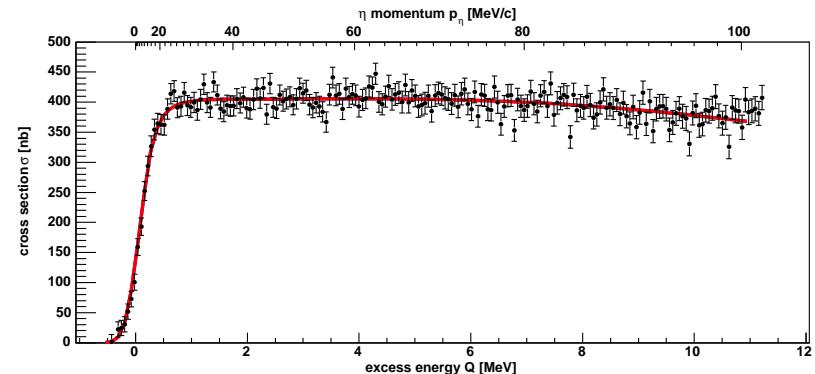
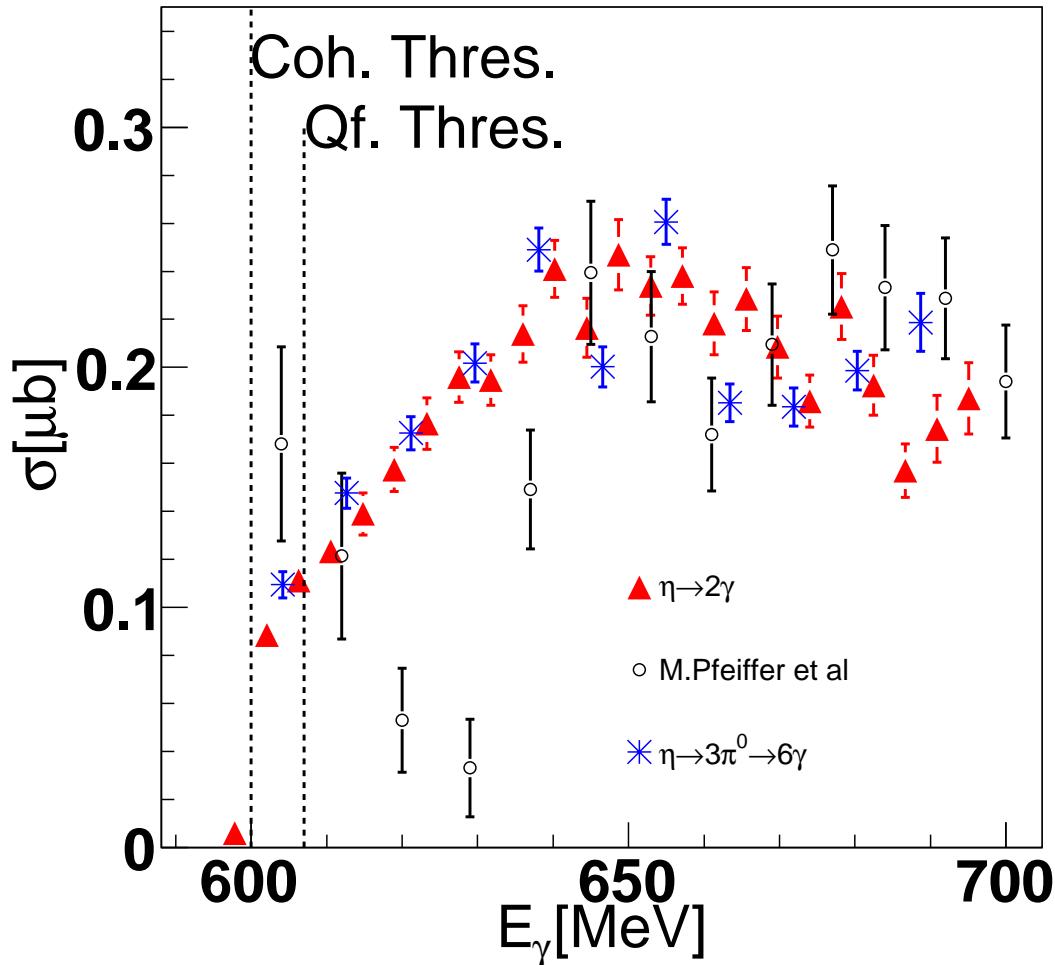
PhD thesis F. Pheron

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

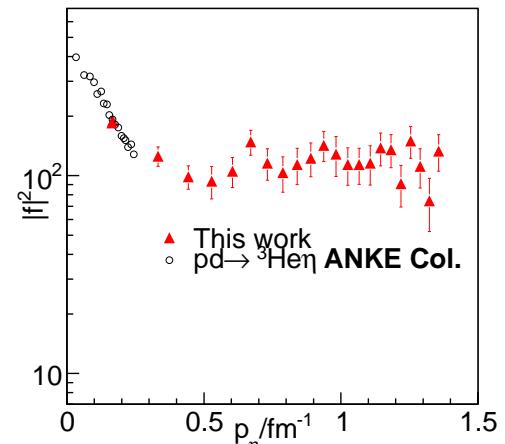


new ^3He experiment - coherent η -production

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



- phase space reduced amplitudes:

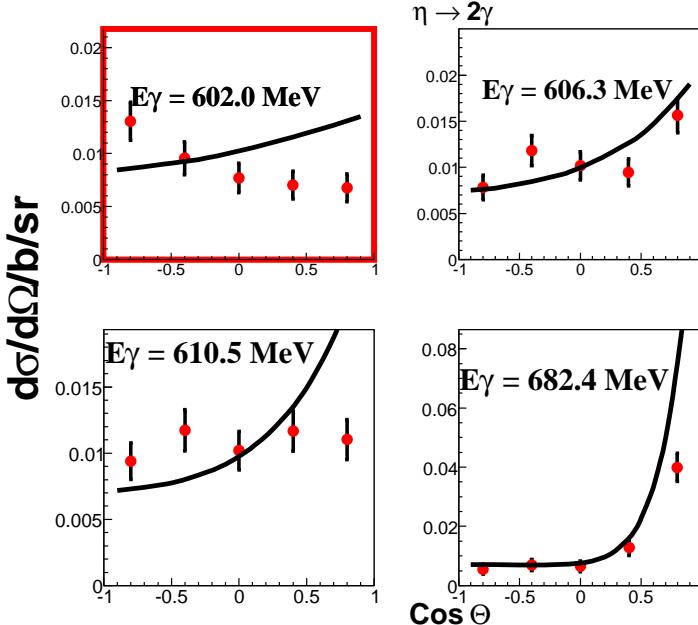


F. Pheron et al.

MAMI

differential cross section

◆ $\eta \rightarrow 2\gamma$



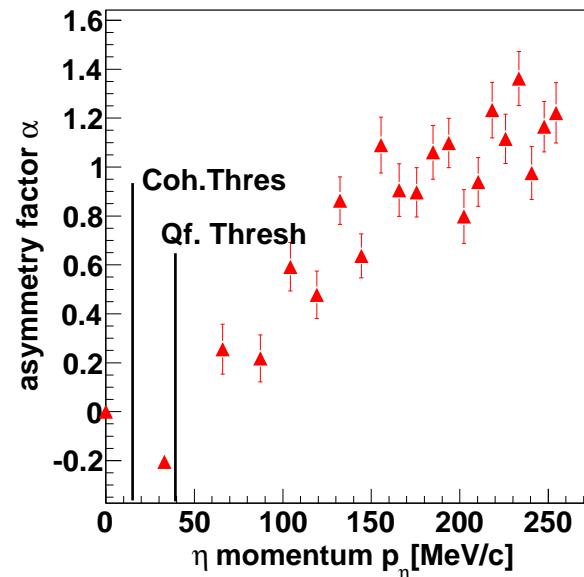
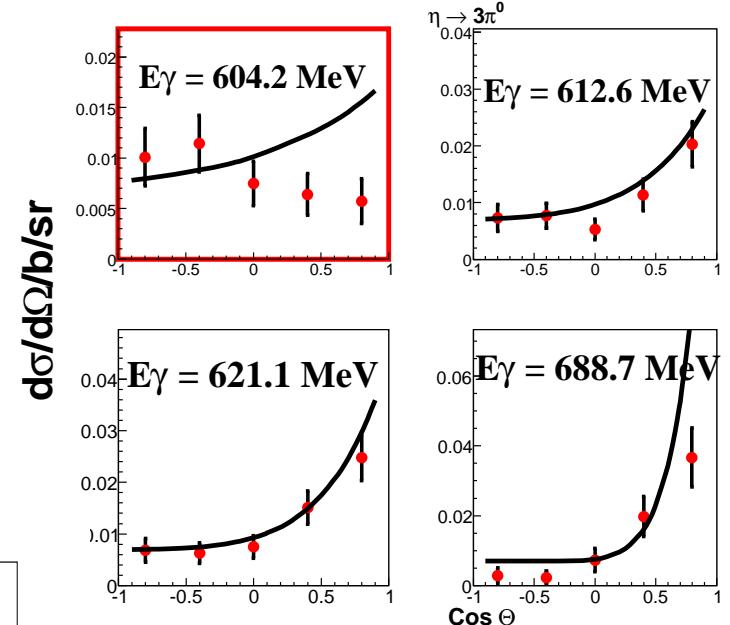
distributions fitted with:

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

$$\alpha = b/a$$

◆ black lines:
angular dependence
of ^3He form factor

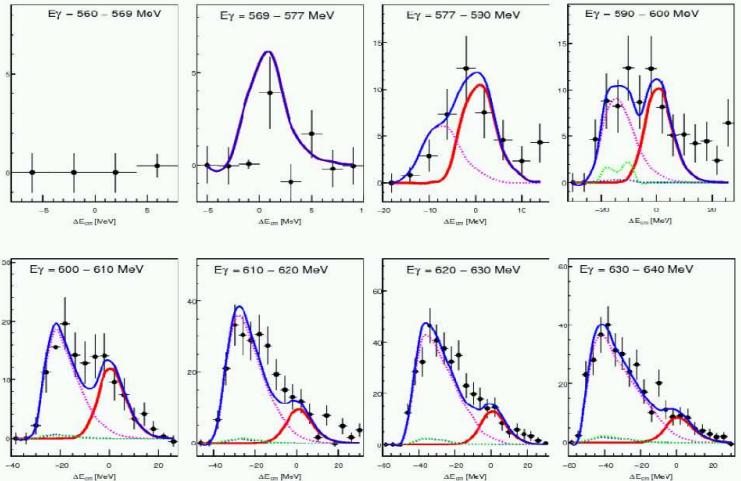
◆ $\eta \rightarrow 6\gamma$



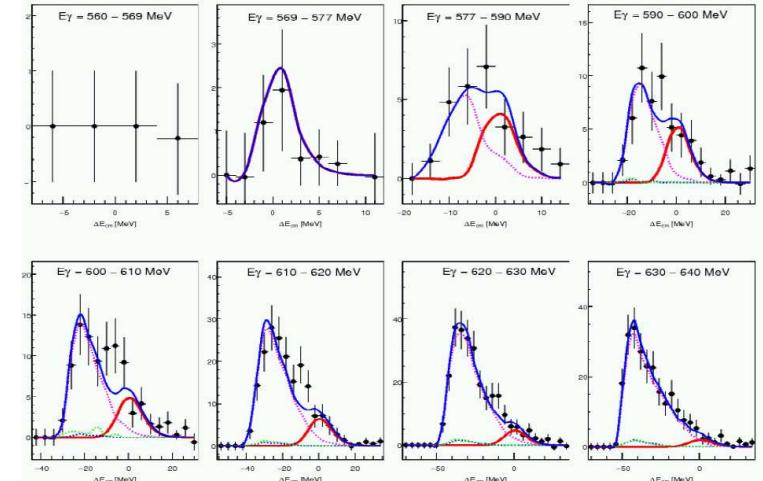
threshold angular distributions
do not behave as expected from
form factor dependence:

coherent η -photoproduction off ${}^7\text{Li}$

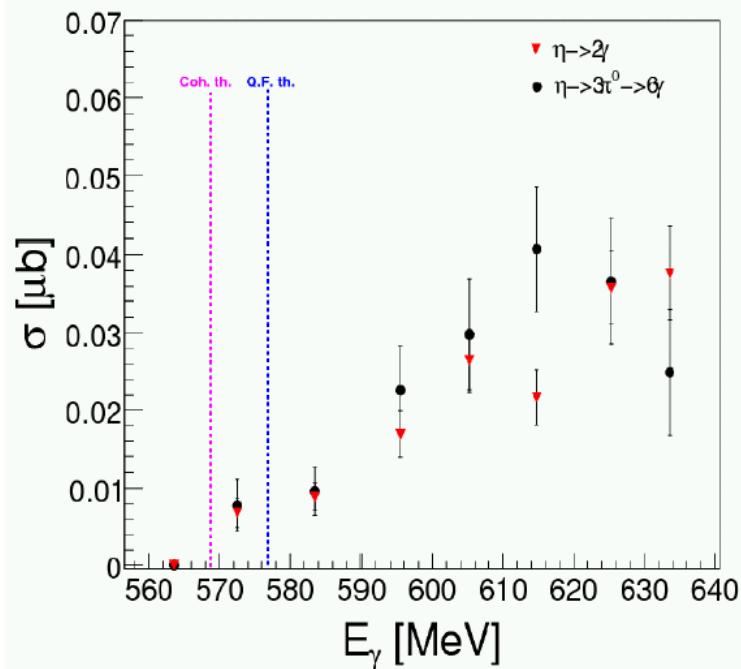
◆ $\eta \rightarrow 2\gamma$



◆ $\eta \rightarrow 6\gamma$

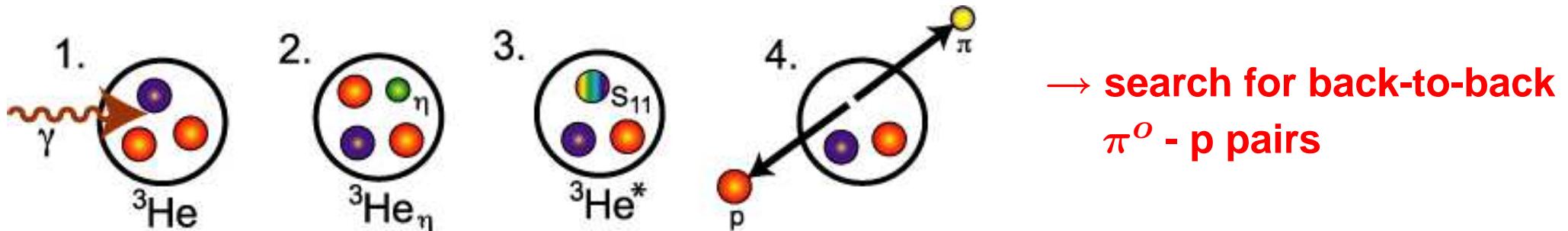


total cross section
for coherent channel:

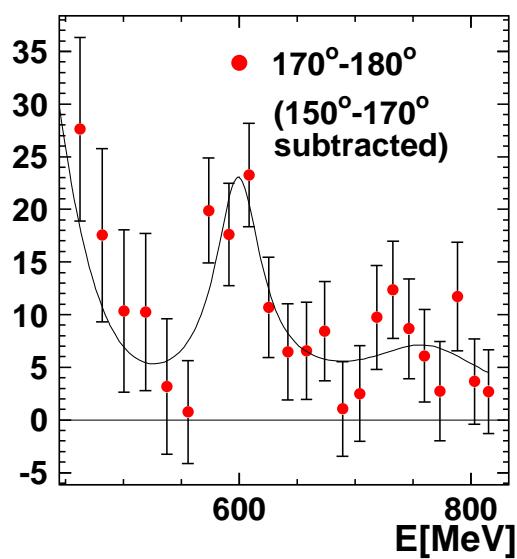
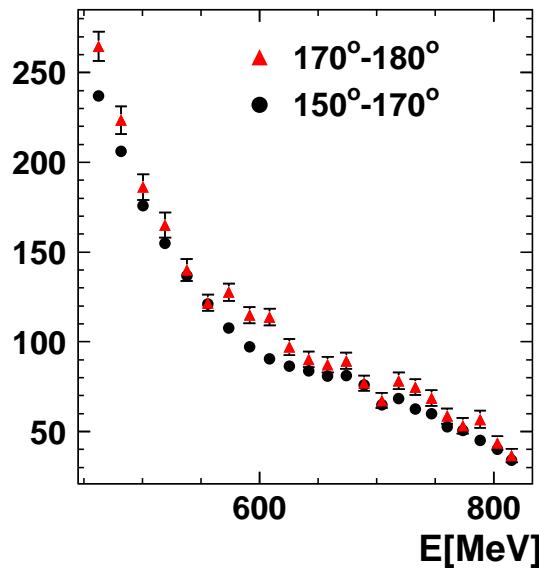
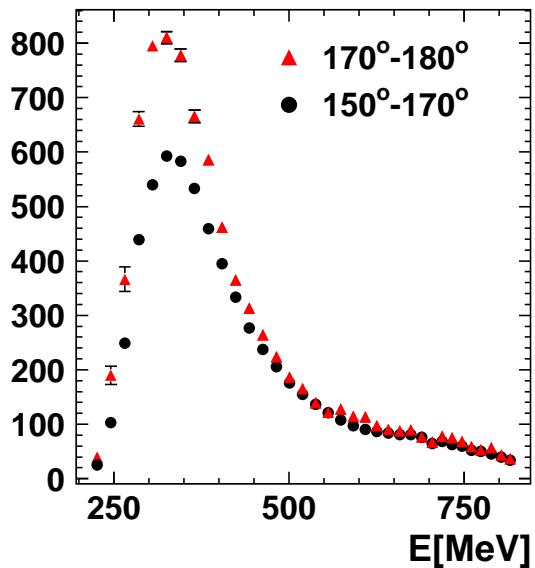


search for η -mesic nuclei

- 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 3He :



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

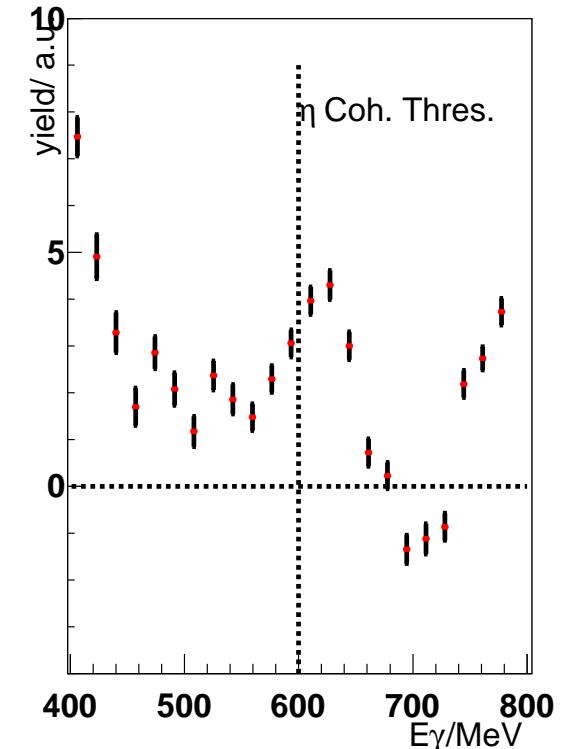
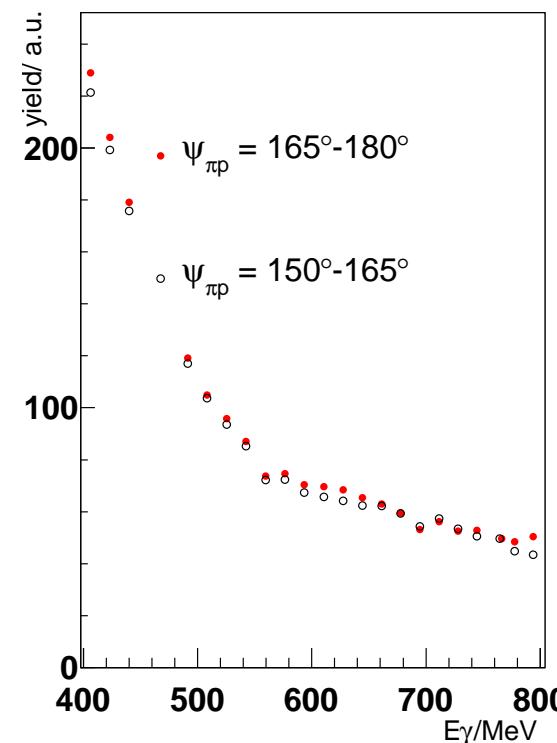
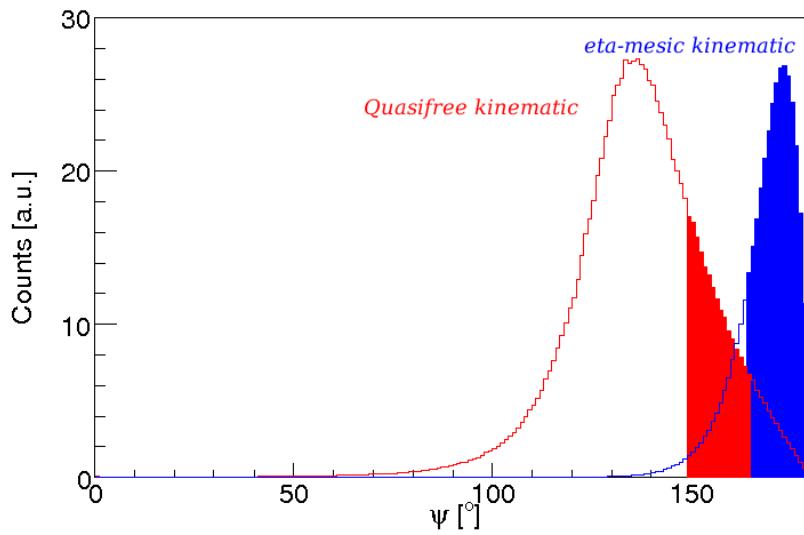


new ^3He experiment: π^0 - p back-to-back pairs

π^0 - p back-to-back pairs:

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

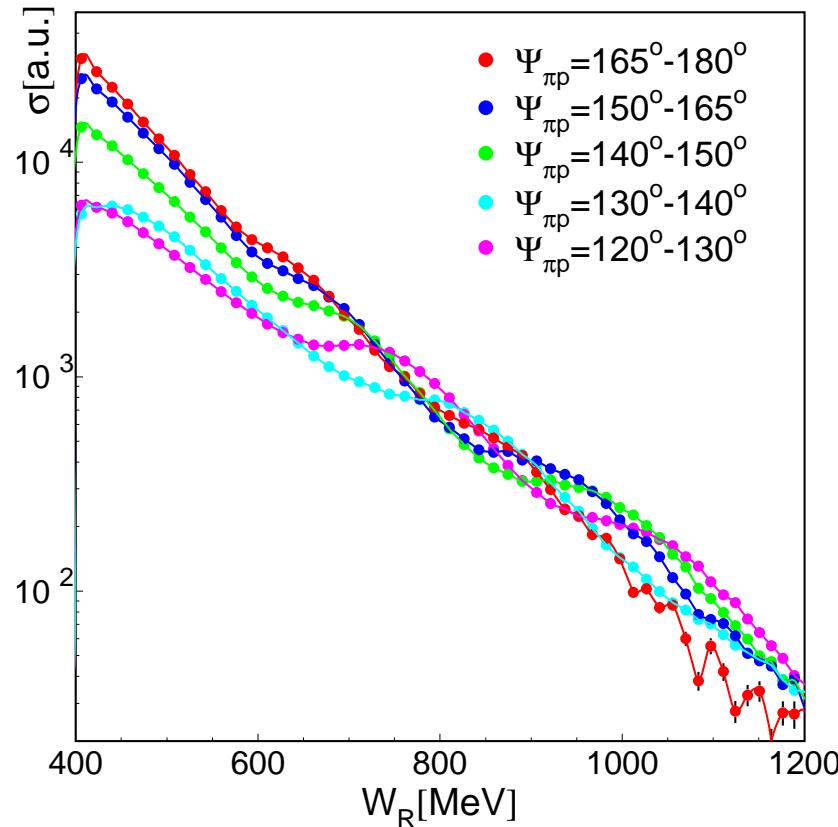
simulation of opening angle behavior
for quasi-free π^0 production
and η -mesic state



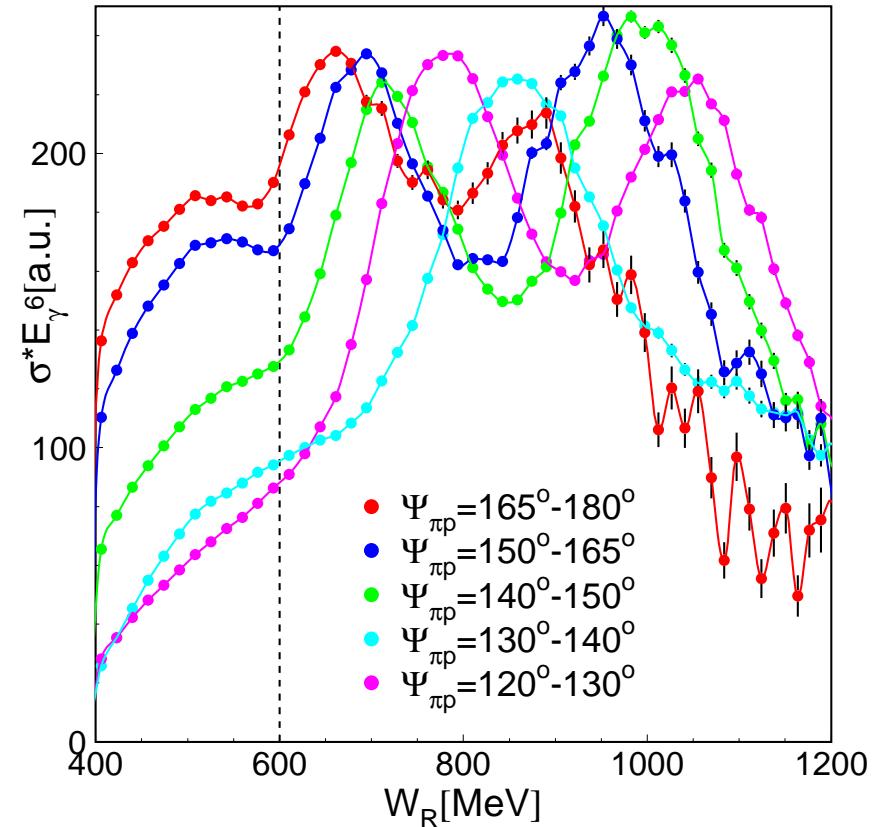
But: behavior of background from single π^0 production via nucleon resonances highly non-trivial →

Dependence of $\pi^0 - p$ excitation functions on opening angle

- excitation functions - arbitraly scaled



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

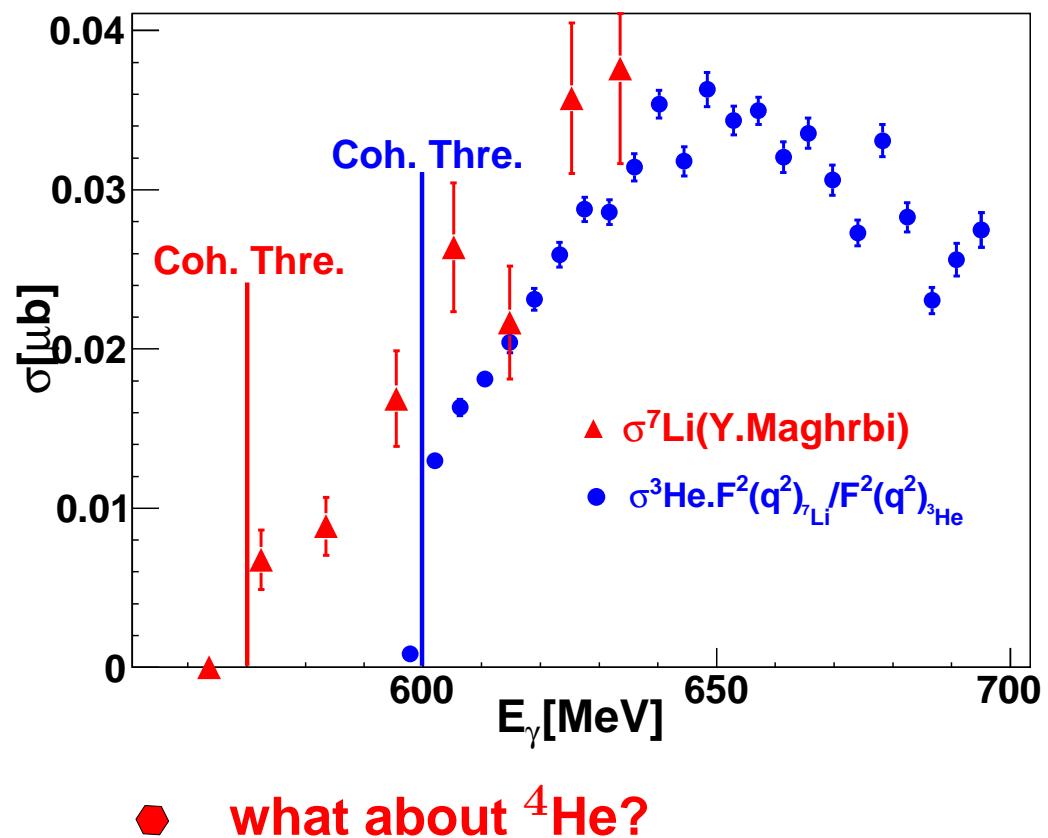


- nucleon resonances produce opening angle dependent structures in excitation functions
- subtraction of excitation functions for different opening angles can produce artificial structures almost everywhere
- basically no hope to isolate tiny structure from η -mesic state in this complicated landscape!

summary: coherent η -photoproduction off light nuclei

- strong threshold enhancement for $\gamma^3\text{He} \rightarrow {}^3\text{He} \eta$ confirmed
- angular distributions close to threshold different from form factor expectation
- structure in $\pi^0 - p$ pairs obscured by background from resonance contributions to quasi-free π^0 production
- first preliminary results also for $\gamma^7\text{Li} \rightarrow {}^7\text{Li} \eta$
- cross section for $\gamma^7\text{Li} \rightarrow {}^7\text{Li} \eta$ smaller by roughly one order of magnitude (corresponds to ratio of form factors)

- threshold enhancement for $\gamma^7\text{Li} \rightarrow {}^7\text{Li} \eta$ less pronounced
- comparison: $\gamma^3\text{He} \rightarrow {}^3\text{He} \eta$ and $\gamma^7\text{Li} \rightarrow {}^7\text{Li} \eta$



what about η -mesic ${}^4\text{He}$?

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



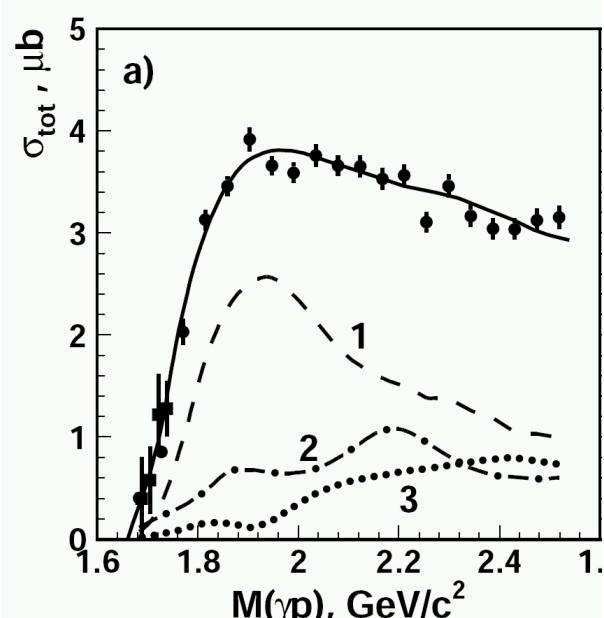
J_z : -1 +1/2 -1/2 -1/2 0

⇒ spin-flip transition

- isospin structure: $A_{1/2}^{IS}/A_{1/2}^p \approx 0.09$ ⇒ dominantly isovector

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

- ## • possible way out: coherent photoproduction of $\eta\pi^0$ -pairs



$\gamma p \rightarrow \eta\pi^0 p$:
dominant final states

- — $\Delta(1232)\eta$
- . — $N(1535)\pi$,
- $p\alpha_0(980)$

dominant process close to threshold:

$\gamma p \rightarrow D_{33}(1700) \rightarrow \eta P_{33}(1232) \rightarrow \eta \pi^0 p$

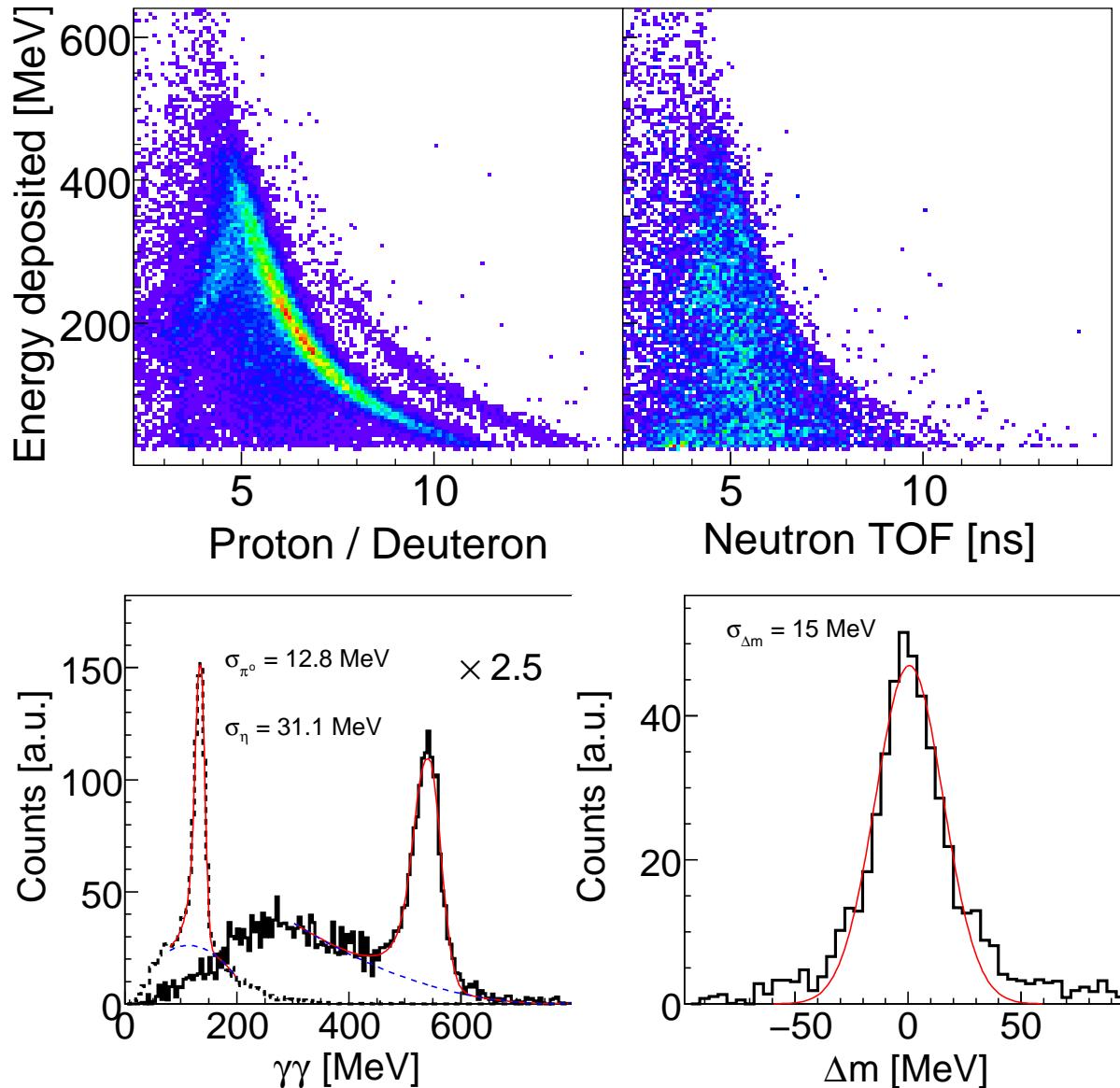
J. Horn et al., PRL 101, EPJA 38 (2008)

V. Kashevarov et al., EPJA (2009)

⇒ no spin-flip,
identical amplitude for p, n
→ ideal entrance channel

⇒ ideal entrance channel

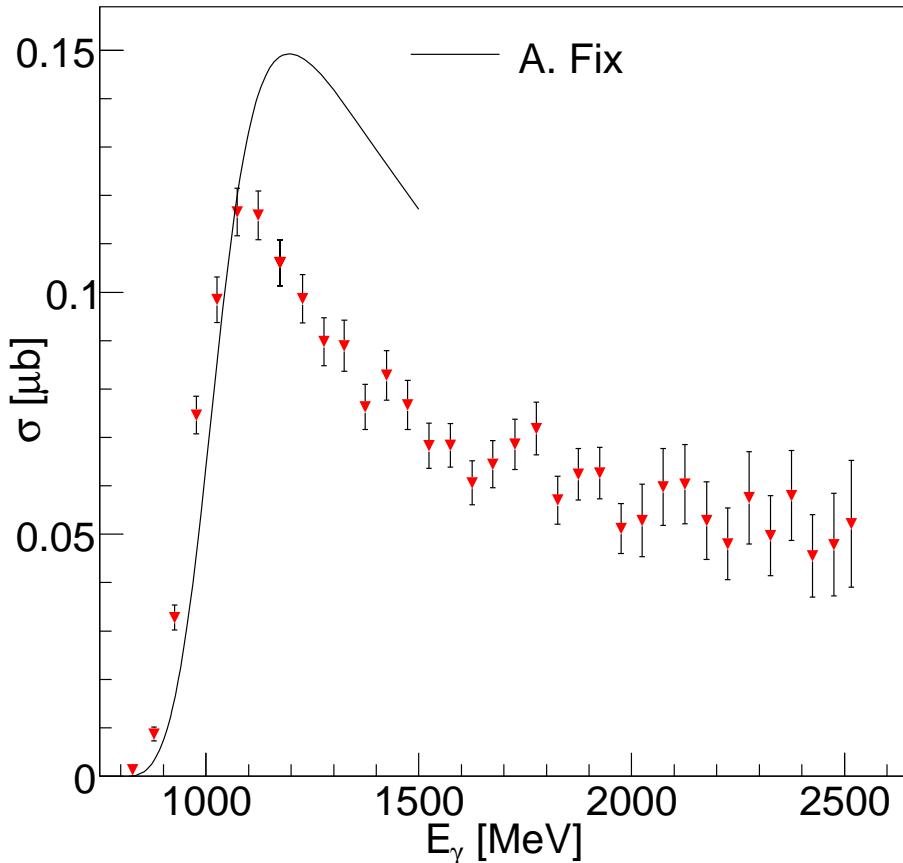
coherent photoproduction of $\pi^0\eta$ -pairs: $d(\gamma, \eta\pi^0)d$



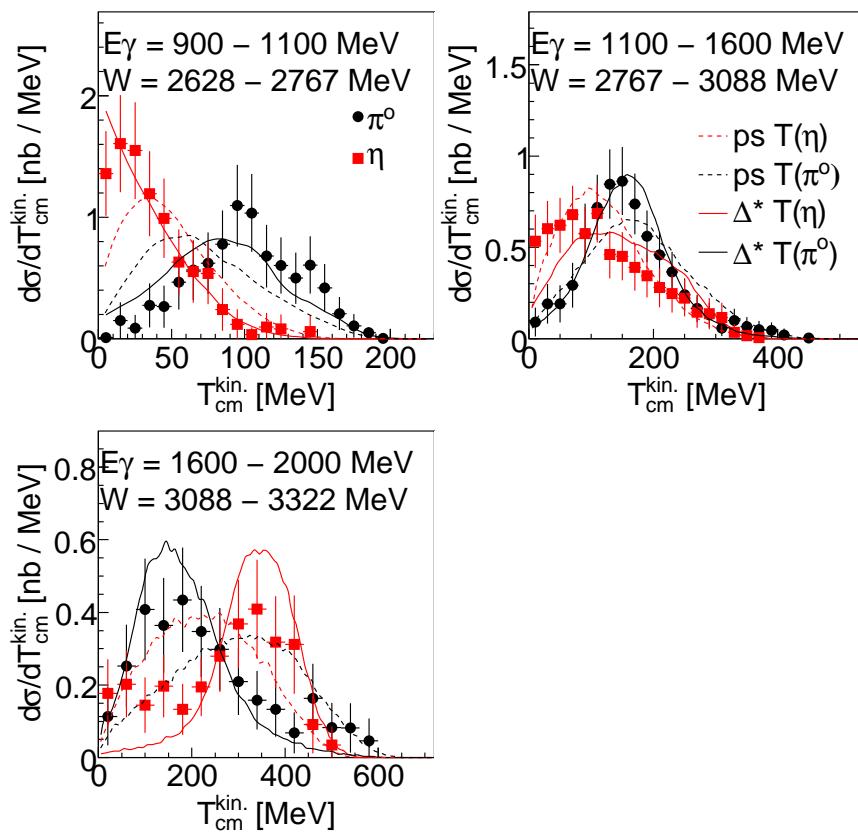
- ◆ time-of-flight versus energy for deuteron identification
- ◆ invariant mass (two-photon) for reaction identification and missing mass (deuteron treated as missing particle) for verification of coherent kinematics

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

◆ total cross section



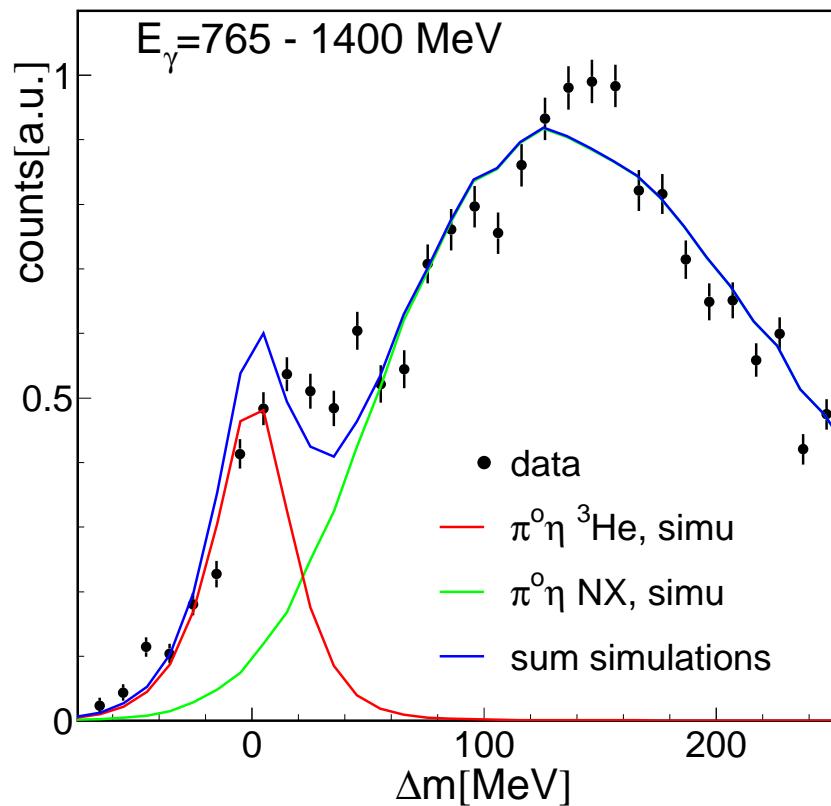
◆ kinetic energy



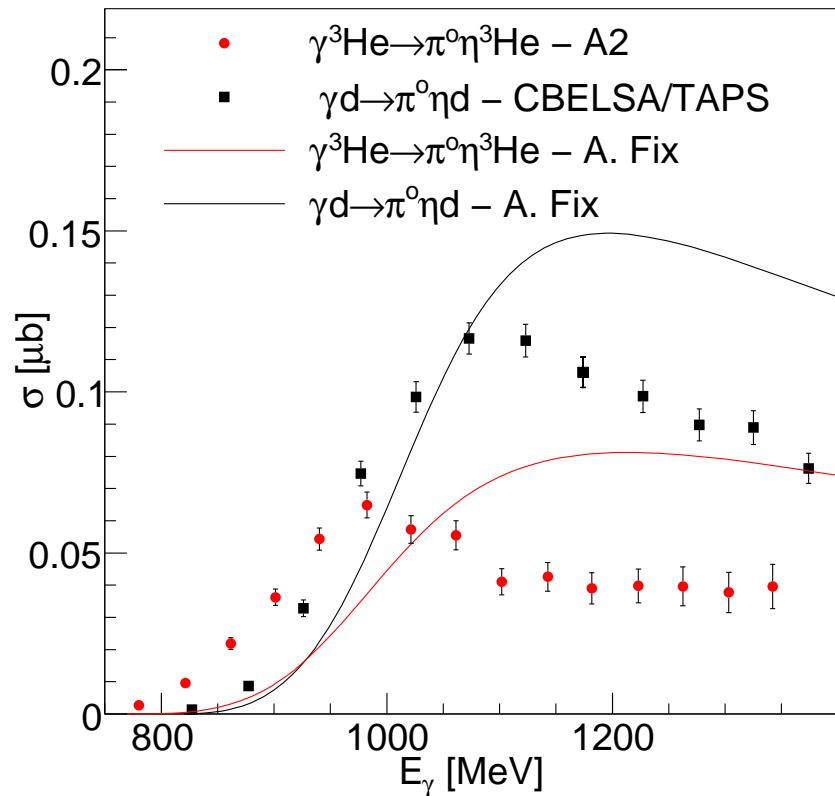
- ◆ total cross section in reasonable agreement with predictions
- ◆ T distributions support dominant $\Delta^* \rightarrow \Delta(1232)\eta \rightarrow N\eta\pi^0$ contribution:
 $T(\pi^0)$ peaks around 100 MeV ($\Delta(1232) \rightarrow N\pi$), $T(\eta)$ rises with E_γ

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' model proposal to measure $\gamma + {}^4\text{He} \rightarrow {}^4\text{He} + \pi^0\eta$ accepted for MAMI

Conclusions



coherent photoproduction of η -mesons:

- strong threshold enhancement for $\gamma + {}^3\text{He} \rightarrow \eta + {}^3\text{He}$
similar like in hadron induced reactions → final state property
- fast variation of shape of angular distributions at threshold
- coherent η -photoproduction off ${}^7\text{Li}$ identified for the first time, magnitude smaller by one order of magnitude, threshold enhancement less pronounced



$\pi^0 - p$ back-to-back pairs:

- possible signal obscured by background from quasi-free single π^0 -production through nucleon resonances



other channels:

- detailed study of coherent photoproduction of $\pi^0\eta$ -pairs under way