Photoproduction of η-mesons off 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

- η-photoproduction - elementary reactions
- coherent photoproduction of η-mesons: ^{3}He$(\gamma,\eta)^{3}$He, ^{7}Li$(\gamma,\eta)^{7}$Li
- other entrance channels: photoproduction of $\eta\pi^{o}$-pairs

Conclusions

interaction of mesons in nuclear matter

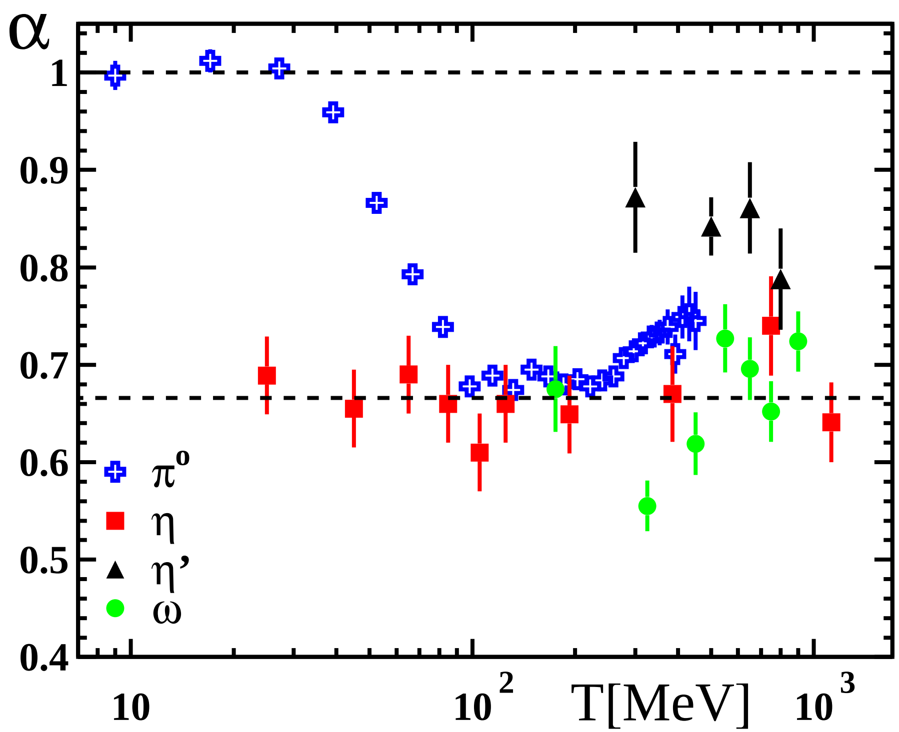
- results from inclusive (quasi-free) meson photoproduction

  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

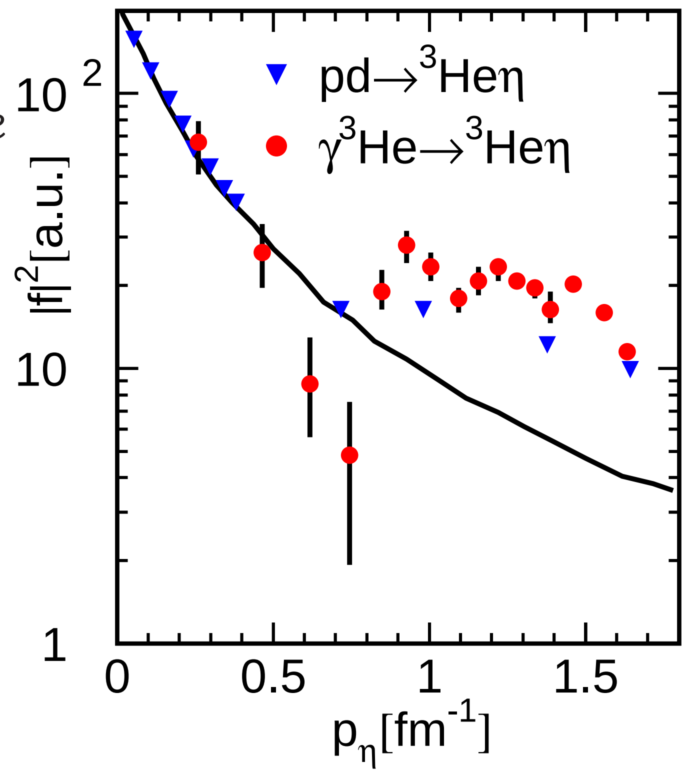


- π^o-mesons: strongly absorbed at energies sufficient to excite Δ; but only weak interaction at small momenta $\longrightarrow$ no bound-states
- η-mesons: strong interaction at small momenta due to s-wave S_{11}(1535) state at threshold $\longrightarrow$ strong enough for bound states?
- ω ,η'-mesons: not much known yet, could be promising

the story of η-mesic nuclei

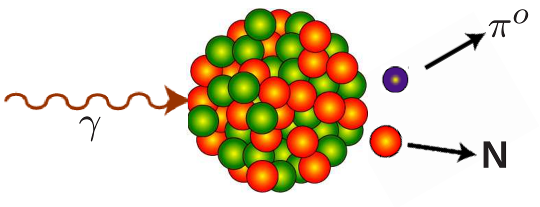
- **1985: Bhalerao & Liu:**
  attractive η-nucleus interaction for A$\geq$12
- **1986: Liu & Haider:**
  suggestion of η-nucleus bound states
- **experiments: inconclusive e.g.:**
  Chrien et al. (1988): $\pi^+ + ^{16}O \rightarrow p + ^{15}_{\eta}O$
  Johnson et al. (1993): $\pi^+ + ^{18}O \rightarrow \pi^- + ^{18}_{\eta}Ne$
- **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**

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



Different entrance channels for photoproduction

- **breakup (quasi-free)**



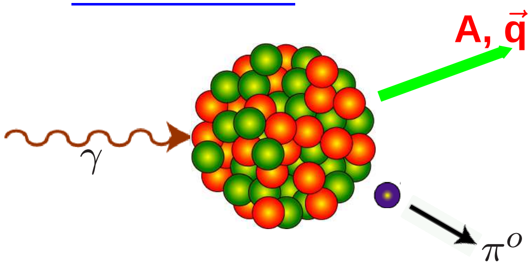
$$\gamma + A \rightarrow \pi^o + A' + N + \ldots$$

$$\frac{d\sigma}{d\Omega} \propto \Sigma|\mathcal{A}|^2 \times \ldots$$

& nuclear effects & FSI & ...

- often dominant (exception low energy π^0)
- select 'magic momentum'
- complicated final states

- **coherent**



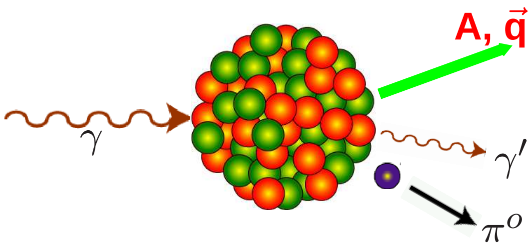
$$\gamma + A \rightarrow \pi^o + A$$

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

& nuclear effects & FSI & ...

- works only close to thresholds
- simple final states
- suppressed by nuclear FF
- spin/iso-spin filter

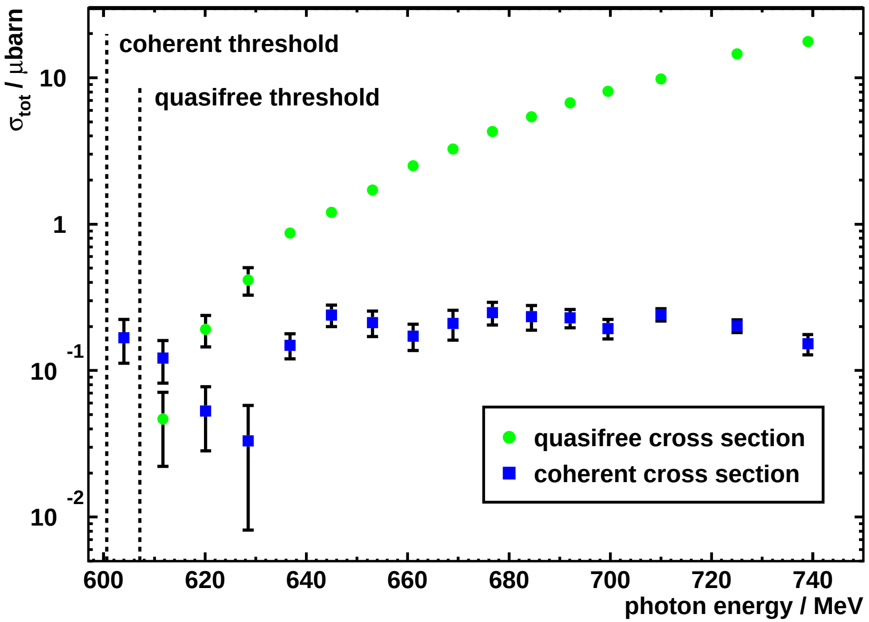
- **incoherent**



$$\gamma + A \rightarrow \pi^o + A^\star$$
$$\rightarrow \pi^o + A + \gamma$$

- similar to coherent
- different FF's
- different spin/iso-spin selection

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

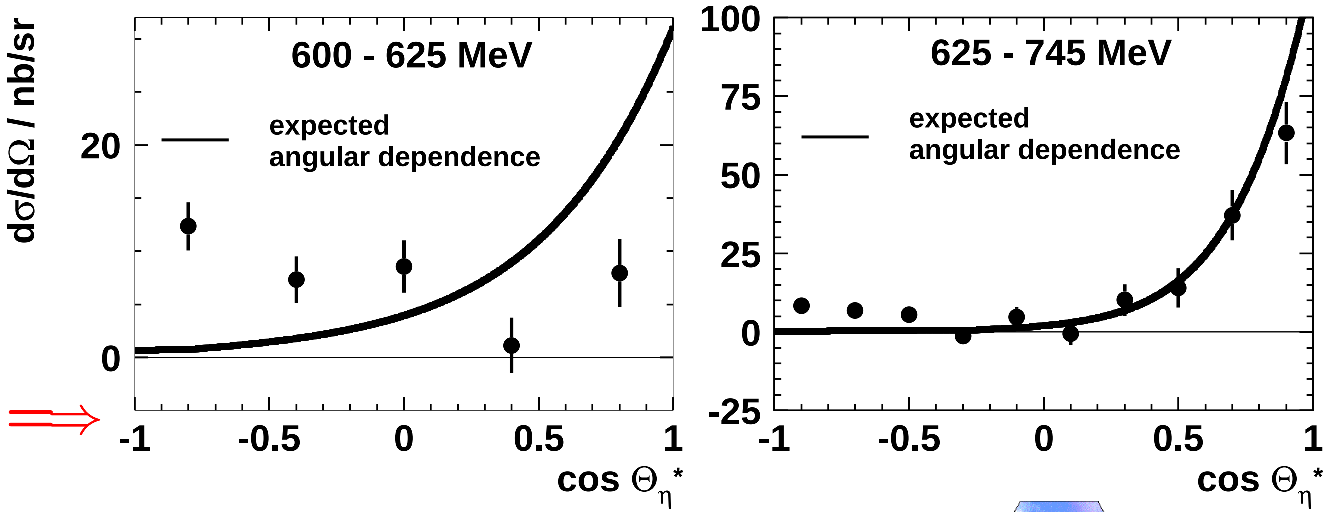


M. Pfeiffer et al., PRL 92 (2005) 252001

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

⇐ **threshold enhancement of coherent part**

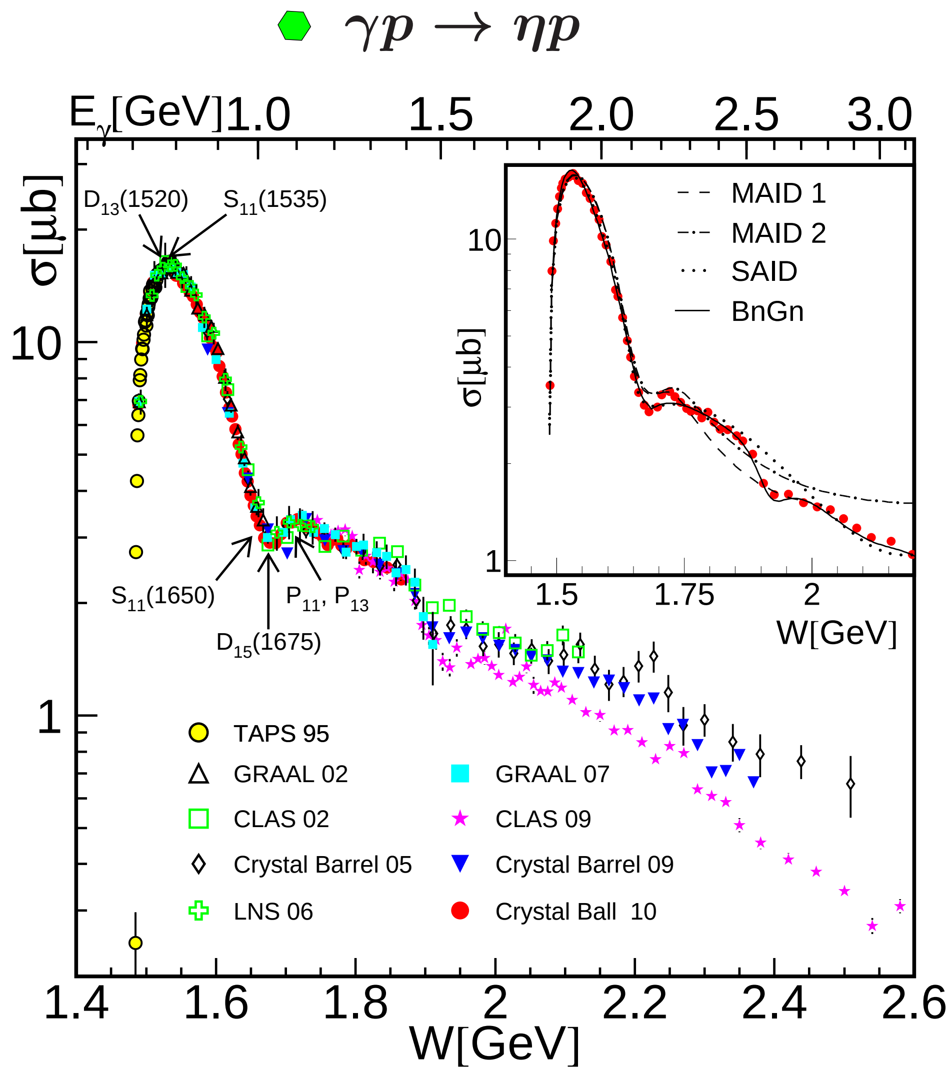
istropic angular distribution of coherent part at threshold ⟹



η-photoproduction off the proton: resonance contributions?

branching ratios and elm. couplings (PDG):

state	b_η [%]	$A^p_{1/2}$	$A^p_{3/2}$	$A^n_{1/2}$	$A^n_{3/2}$
• $D_{13}(1520)$:	0.23±0.04	-24	150	-59	-139
• $S_{11}(1535)$:	42±10	90		-46	
• $S_{11}(1650)$:	5 − 15	53		-15	
• $D_{15}(1675)$:	0±1	19	15	-43	-58
• $F_{15}(1680)$:	0±1	-15	133	29	-33
• $D_{13}(1700)$:	0±1	-18	-2	0±5	-3
• $P_{11}(1710)$:	10 − 30	24		-2	
• $P_{13}(1720)$:	4±1	-10	-19	4	-10

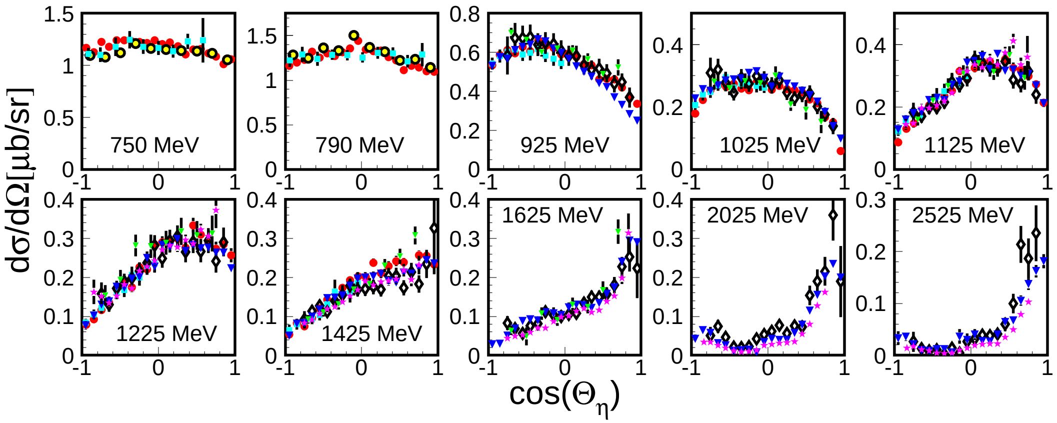


- **dominent contribution from S_{11} states, interference structure?**
- **D_{15}(1675) has stronger electromagnetic coupling to neutron than to proton**
- **complicated pattern around 1.7 GeV**

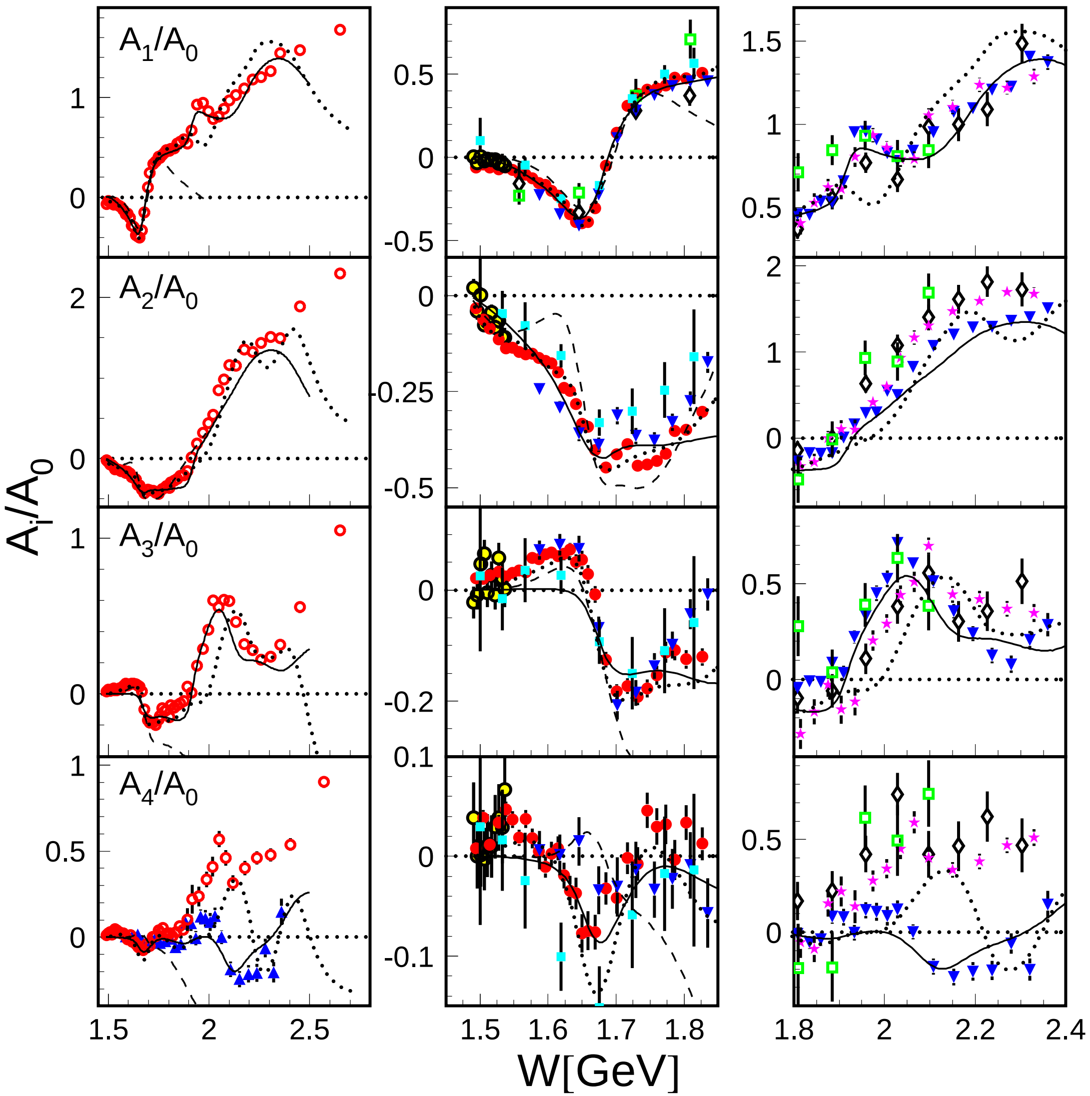
- **PWA's agree excellently with data in S_{11} range, less so at higher energies**

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

- **typical angular distributions**



- **fitted coefficients**



- **fitted with:**

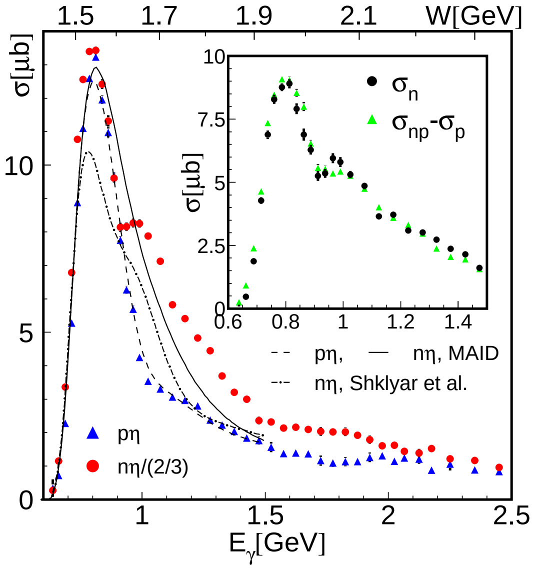
$$\frac{d\sigma}{d\Omega} = \Sigma A_i P_i(\cos(\Theta^\star))$$

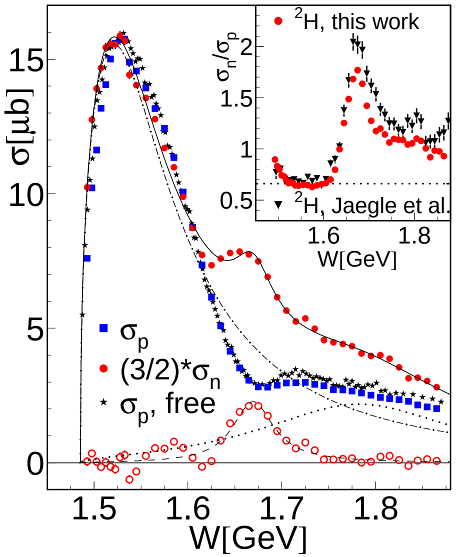
- **typical s-wave behavior at threshold**
- **fast variation - interesting structures around $W \approx$ 1.7 GeV**
- **diffractive (t-channel) at highest energies**

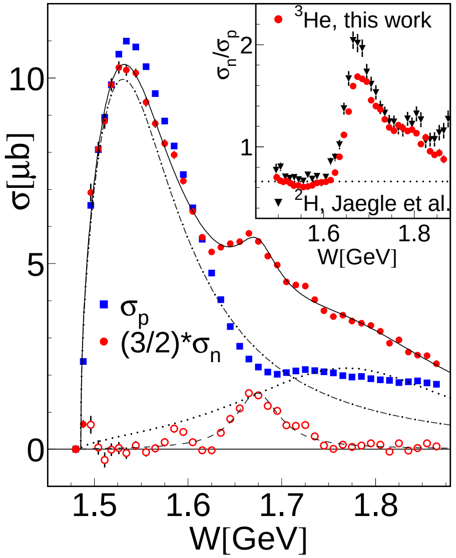
quasifree $\gamma' n' \to n\eta$: more surprises

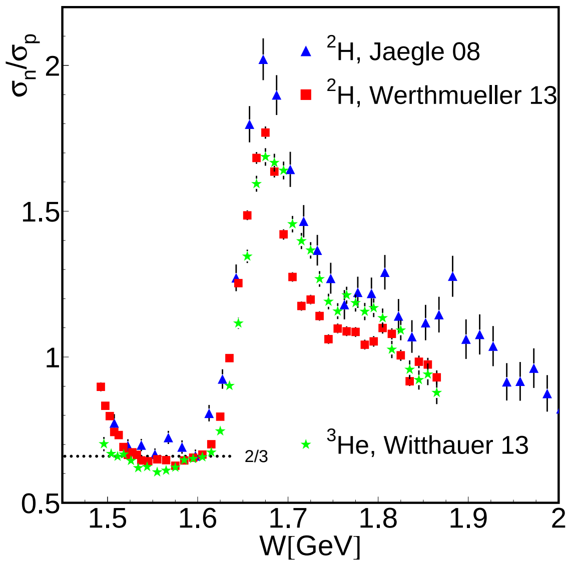
(I. Jaegle et al., D. Werthmüller et al., L. Witthauer et al.)

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







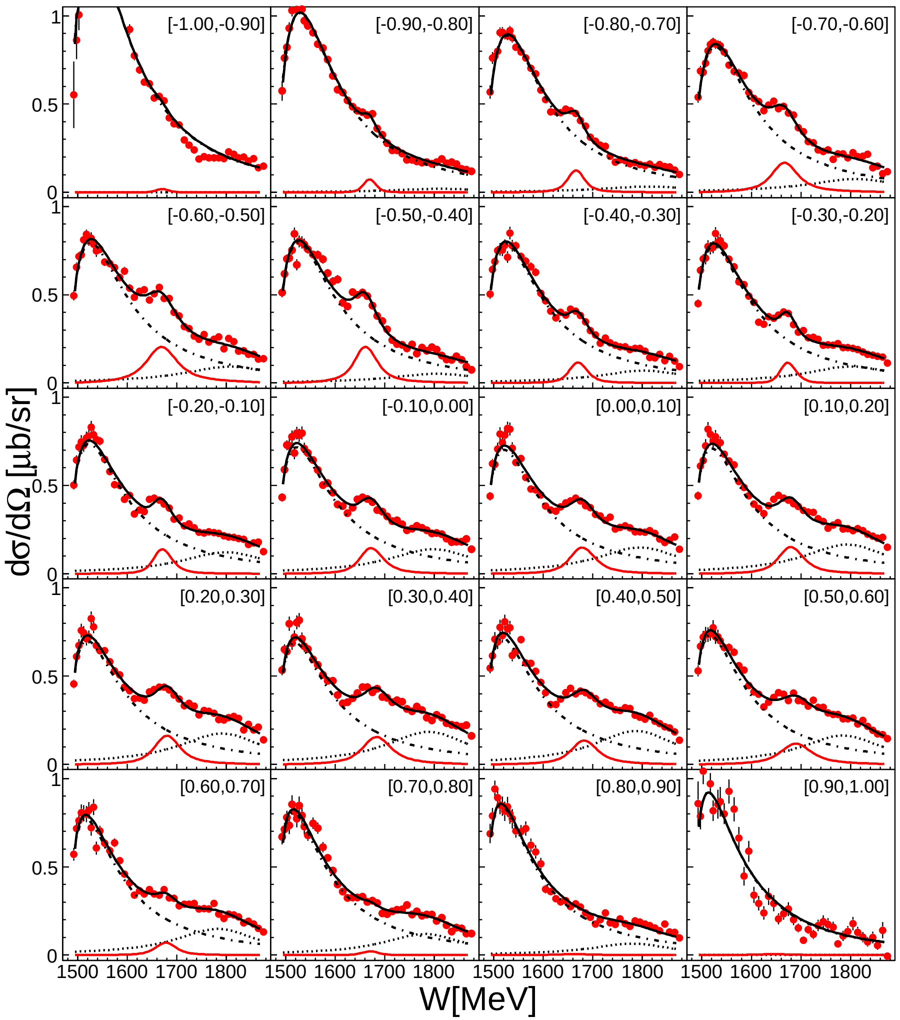


- pronounced, narrow structure in neutron excitation function close at W=1.68 GeV
- width of structure $\approx$ 30 MeV
- neutron/proton ratios in agreement for all measurements:
  - in S_{11}(1535) region 2/3 ratio
  - peak close to 1.7 GeV
  - very close to threshold almost unity, no distinction between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

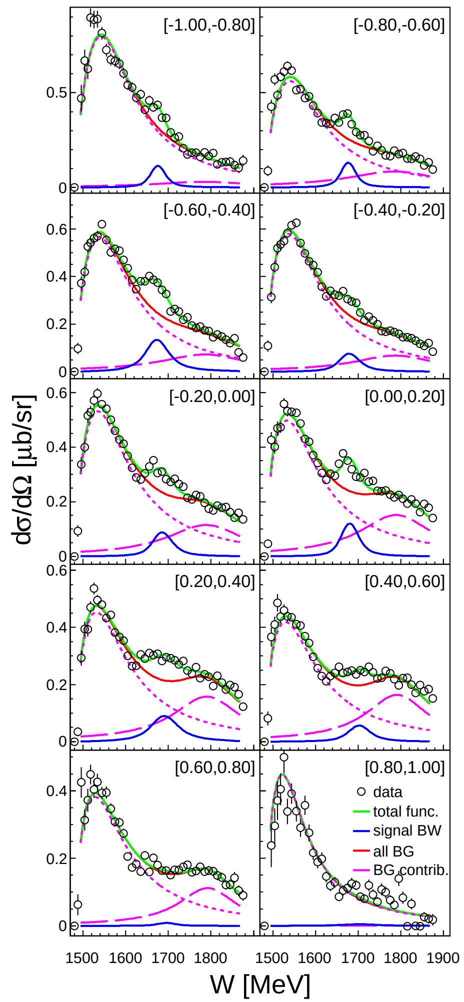
$\gamma n \rightarrow n\eta$ - excitations functions for different angular bins

(D. Werthmüller and L. Witthauer et al., submitted to PRL)

- **deuteron target**



- **^{3}He target**



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

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

$$\gamma(\text{E1}) \;+\; \text{N} \;\rightarrow\; \text{S}_{11} \;\rightarrow\; \text{N} \;+\; \eta$$

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

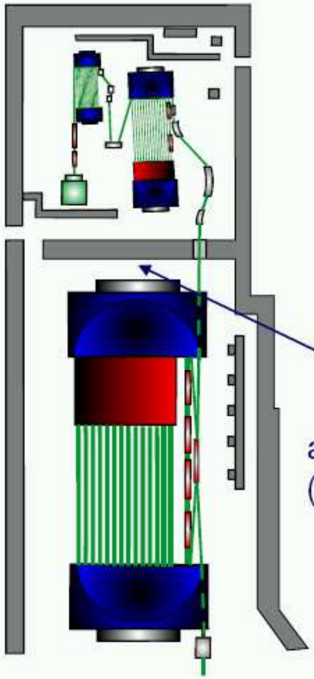
- expectation for light nuclei:

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

2) ^{4}He: J=0, I=0, isoscalar, non spin-flip $\rightarrow$ negligible
(not seen, only upper bounds, V. Hejny et al.)

3) ^{3}He: J=1/2, I=1/2; ^{7}Li: J=3/2, I=1/2,
isovector, spin-flip contributions $\rightarrow$ good candidates

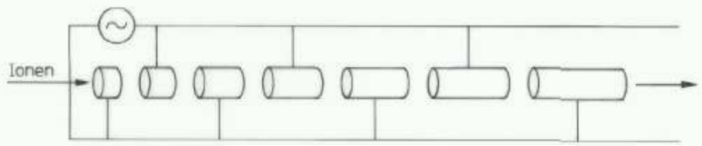
MAMI accelerator in Mainz

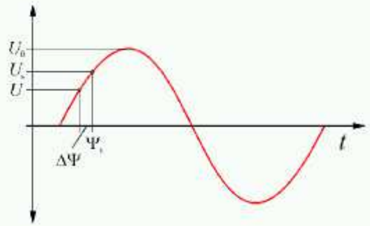


accelerators
(racetrack microtrons)

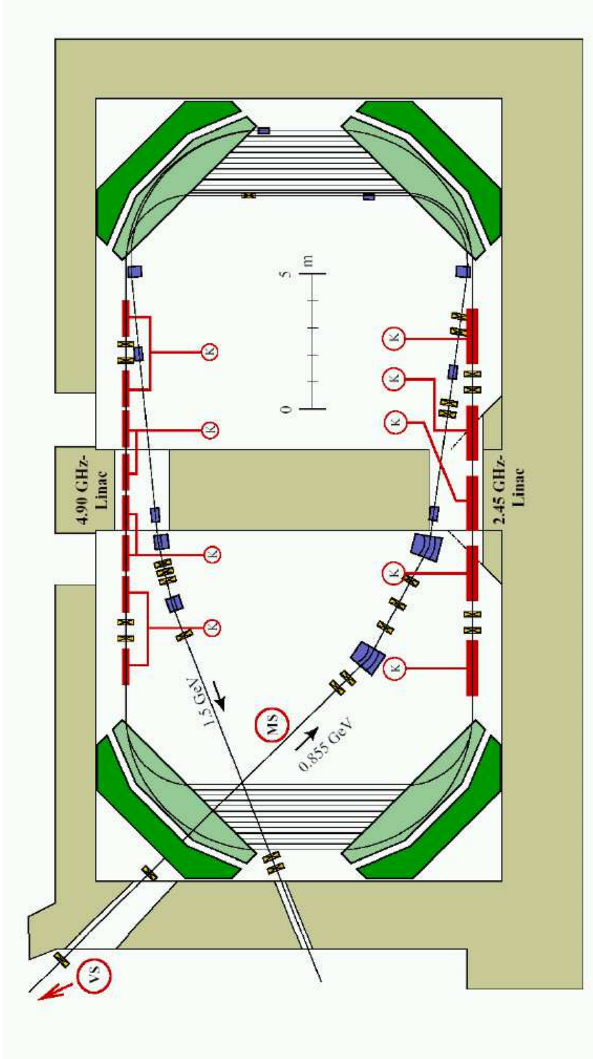
Mainz Microtron (MAMI)
continuous wave electron accelerator, max. beam energy 883

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





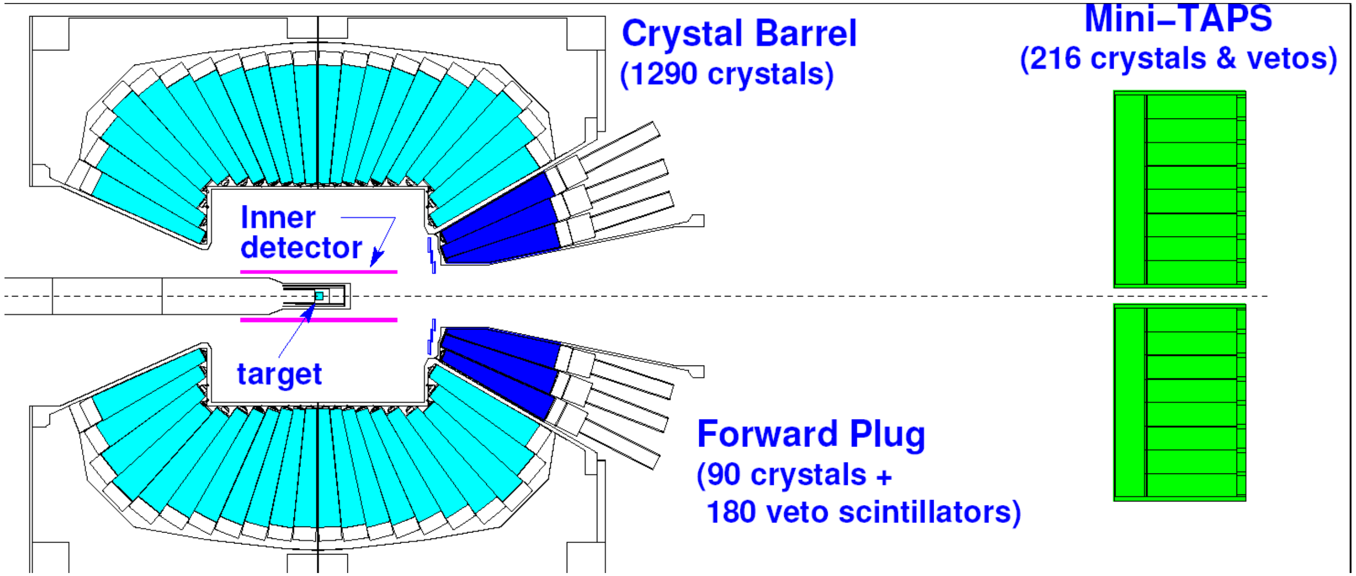
1.-3. Stage: Ractrack Microtrons:
- microbunches of 0.4ns
- linear accelerator structures
- constant B field ⇒ varing radii (18, 51, 90 return cycles)
- very efficient acceleration and continuous mode
- high current (0.1mA)



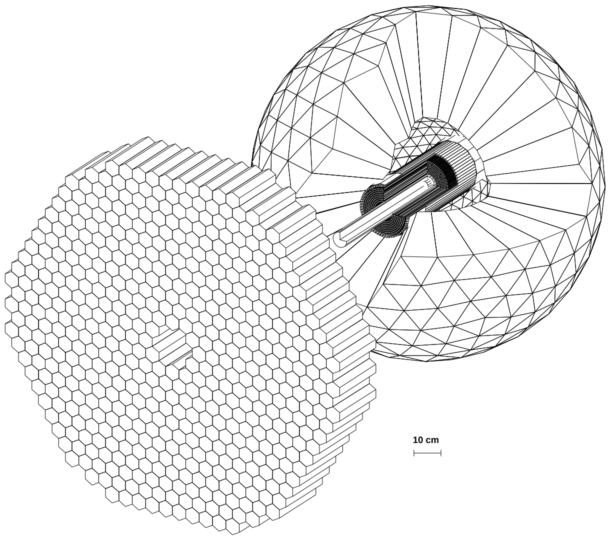
4. Stage: Harmonic Double Sided Microtron
maximum energy: 1.5 GeV

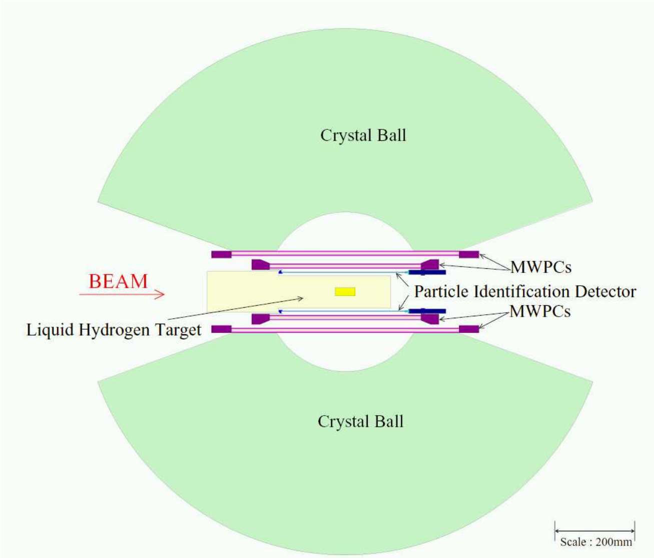
Experiments: Crystal Ball & Crystal Barrel with TAPS

- **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

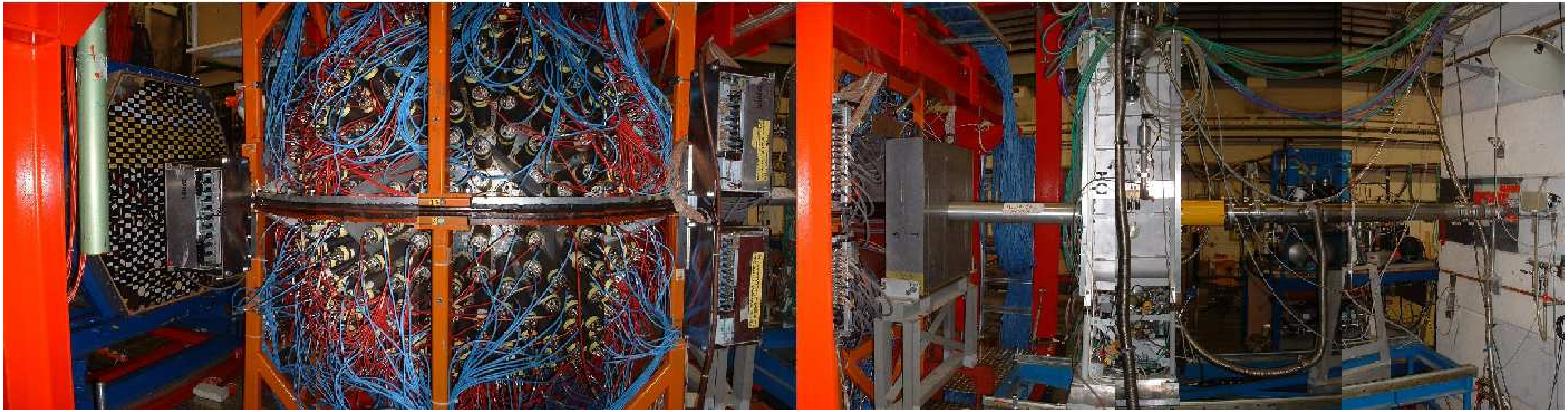


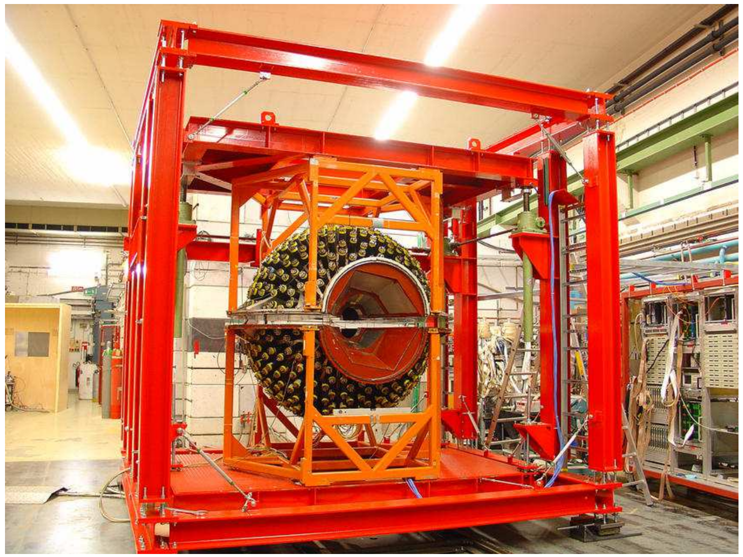
- **Mainz MAMI accelerator:**
  Crystal Ball (NaJ),
  TAPS (BaF_2) forward wall,
  inner detectors
  $E_\gamma \leq$ **1.5 GeV,**
  lin. pol.: available,
  circ. pol.: available





TAPS Crystal Ball - at MAMI





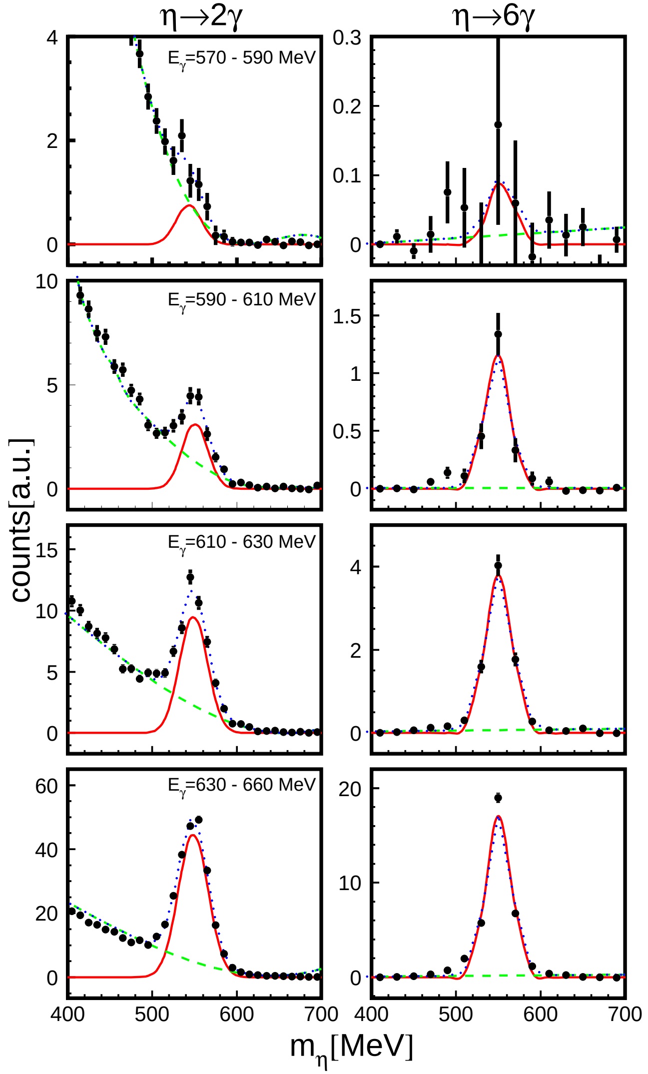
Experiments at MAMI

- γ^3He$\rightarrow \eta^3$He
  liquid ^{3}He target (0.073 nuclei/barn),
  E_γ =0.45 GeV - 1.4 GeV
  F. Pheron et. al., Phys. Lett. B 709 (2012) 21

- γ^7Li$\rightarrow \eta^7$Li
  solid ^{7}Li target (0.264 nuclei/barn),
  E_γ =0.14 GeV - 0.81 GeV
  Y. Maghrbi et. al., Eur. Phys. J. A 49 (2013) 38

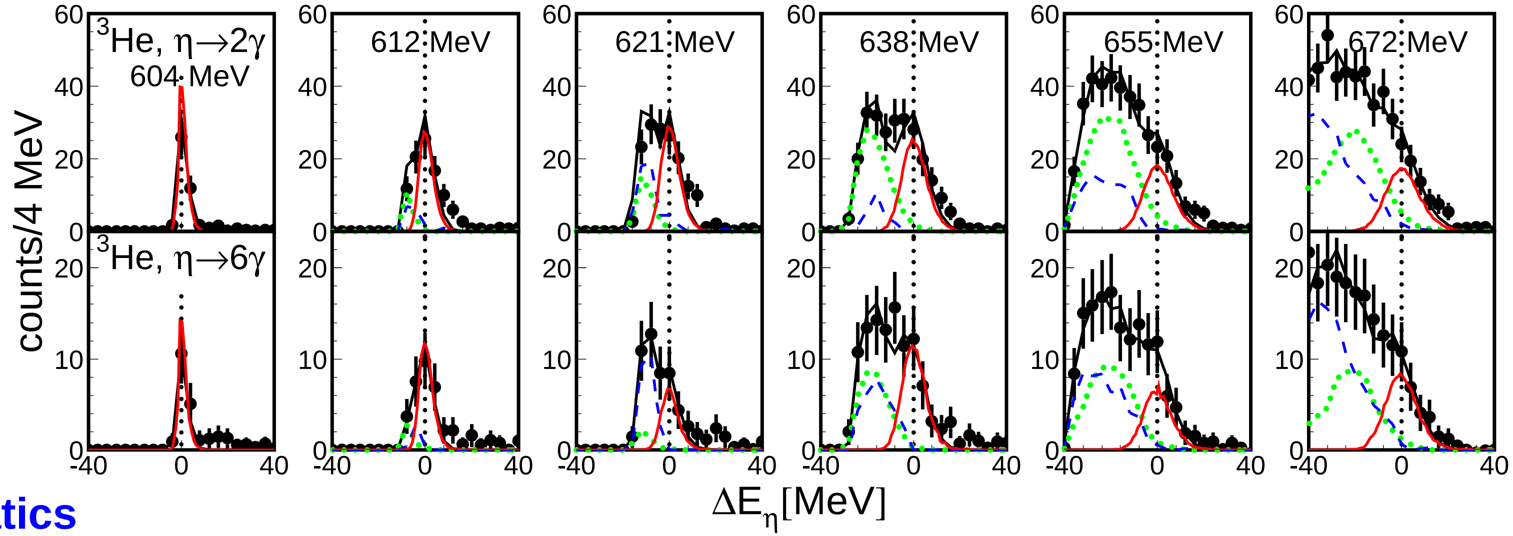
- analysis:
  identification of η-mesons from 2γ and 6γ decays with invariant mass analysis,
  identification of coherent kinematics with missing energy analysis

- invariant mass spectra for ^{7}Li target

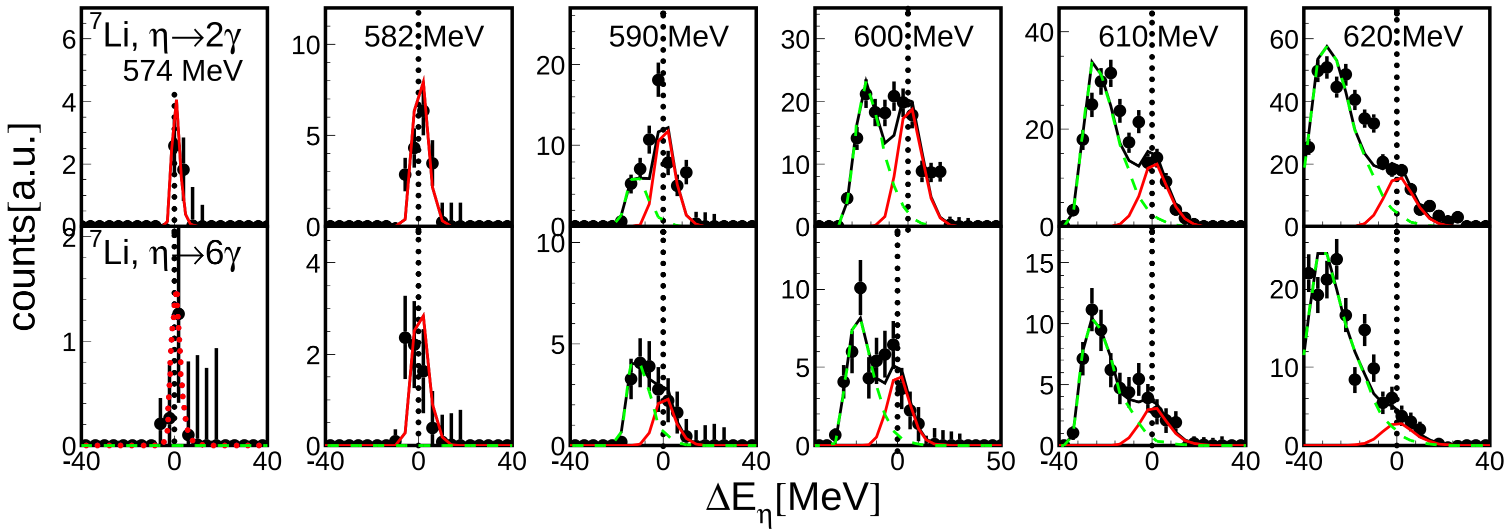


reaction identification - missing energy analysis

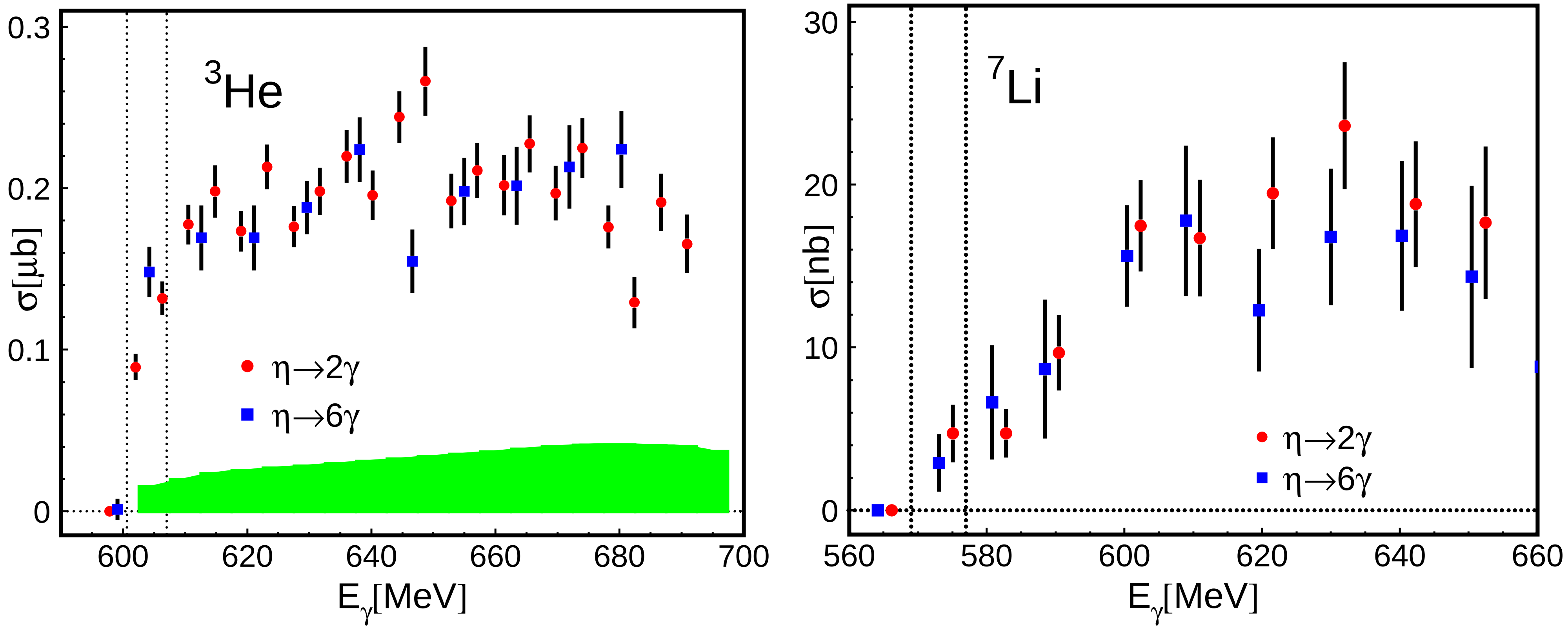
separation of breakup and coherent reaction:



- no additional hit in detector
- overdetermined kinematics compare η kinetic cm-energy from incident photon energy to measured η-energy; MC simulations for signal shapes
- background from breakup reactions rises fast with incident photon energy



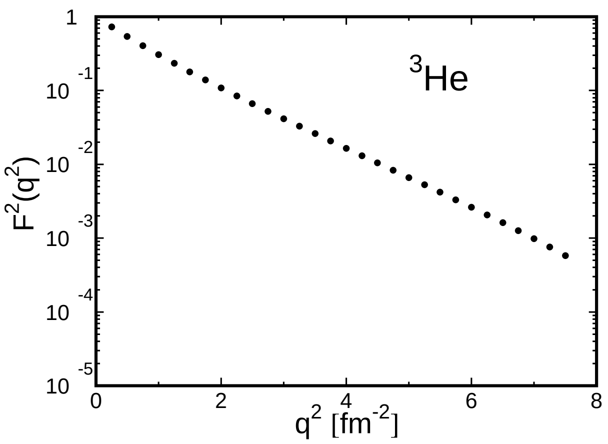
results: threshold behavior of coherent reaction

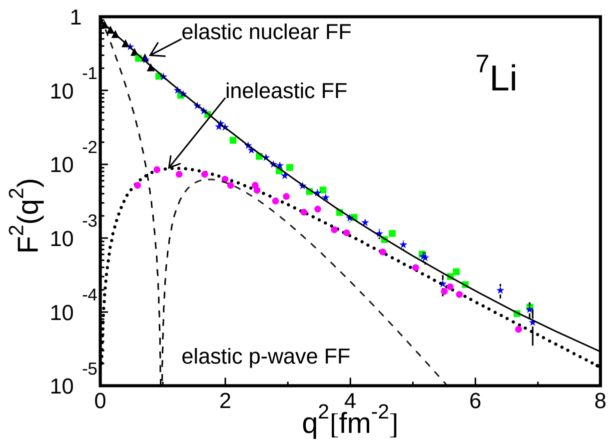


- **good agreement between 2γ and 6γ results**
- **^{3}He cross section in magnitude one order of magnitude larger than ^{7}Li**
- **much steeper rise of ^{3}He cross section at threshold**

plane wave impulse approximation for coherent reaction

- **elementary amplitude:** E_{0+} **spin-flip**
- **nuclear structure:** **for ^{3}He dominant from unpaired $1s_{1/2}$ neutron;**
  for ^{7}Li from unpaired $1p_{3/2}$ proton and from $1p_{3/2} \rightarrow 1p_{1/2}$ excitation.
- **nuclear (mass) form factors:** **(charge FF corrected for proton radius)**

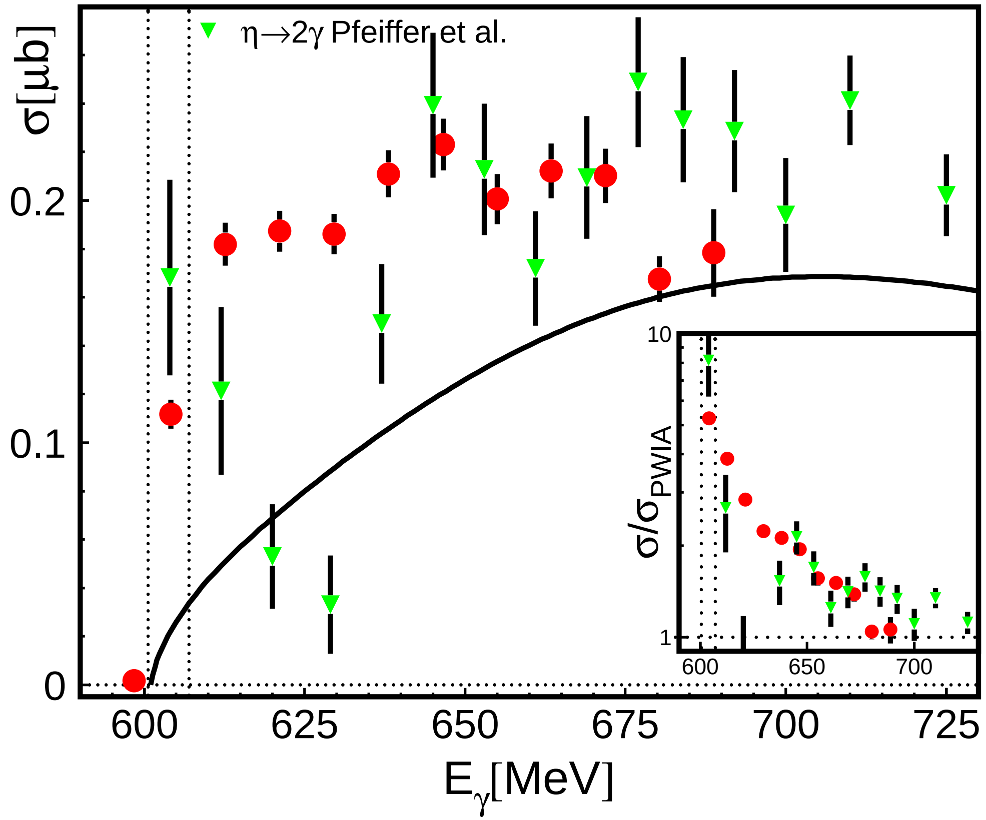


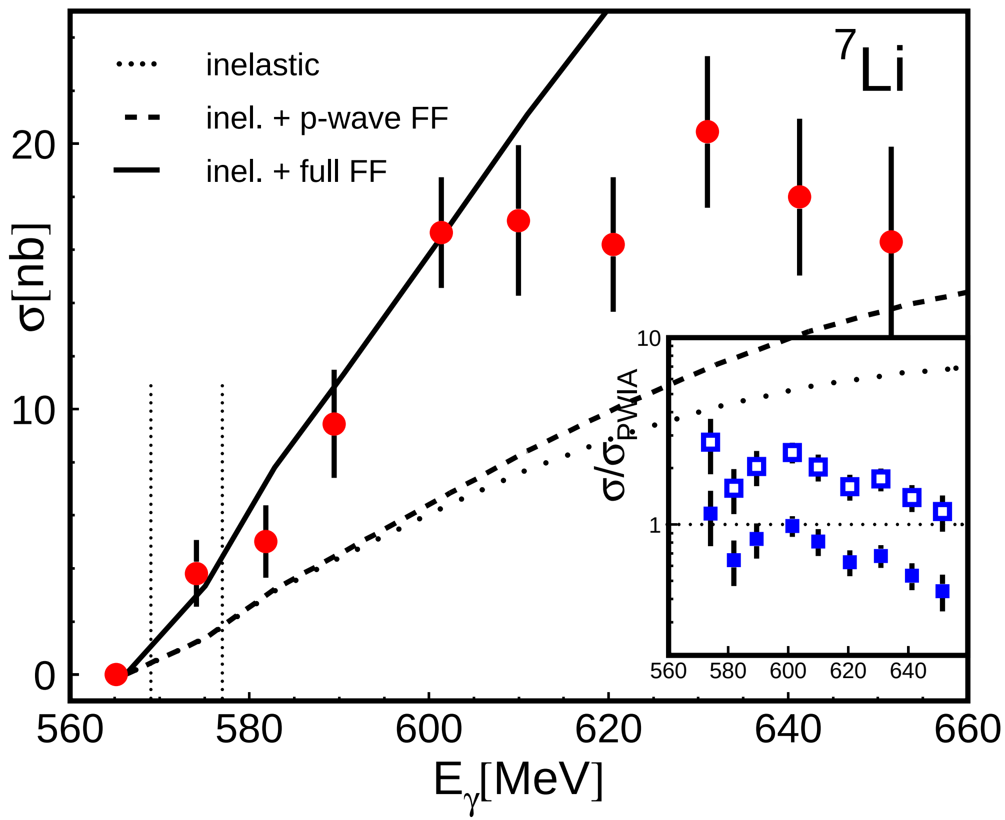


- **cross section approximation:**

$$\frac{d\sigma_{\eta A}}{d\Omega} = \left(\frac{q_\eta^{(A)}}{k_\gamma^{(A)}}\frac{k_\gamma^{(N)}}{q_\eta^{(N)}}\right)\frac{d\sigma_{\text{elem}}}{d\Omega}\left(F_{C*}^2(q^2) + F_{Cx*}^2(q^2)\right)$$

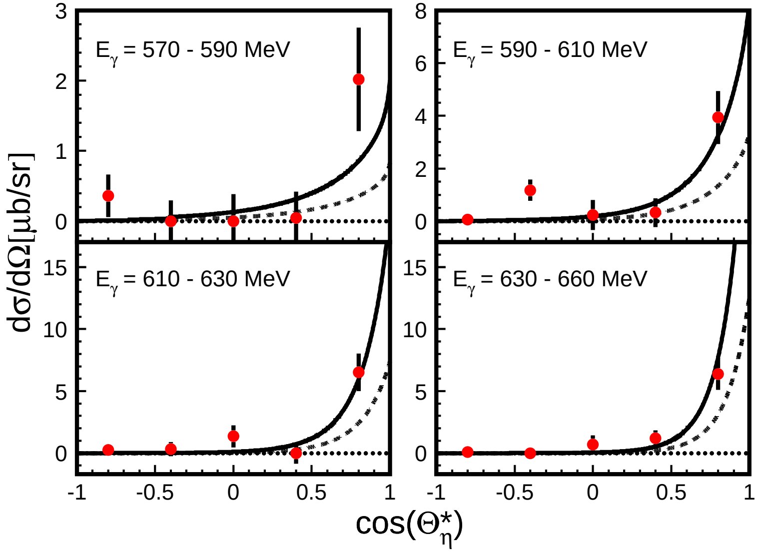
total cross sections compared to PWIA



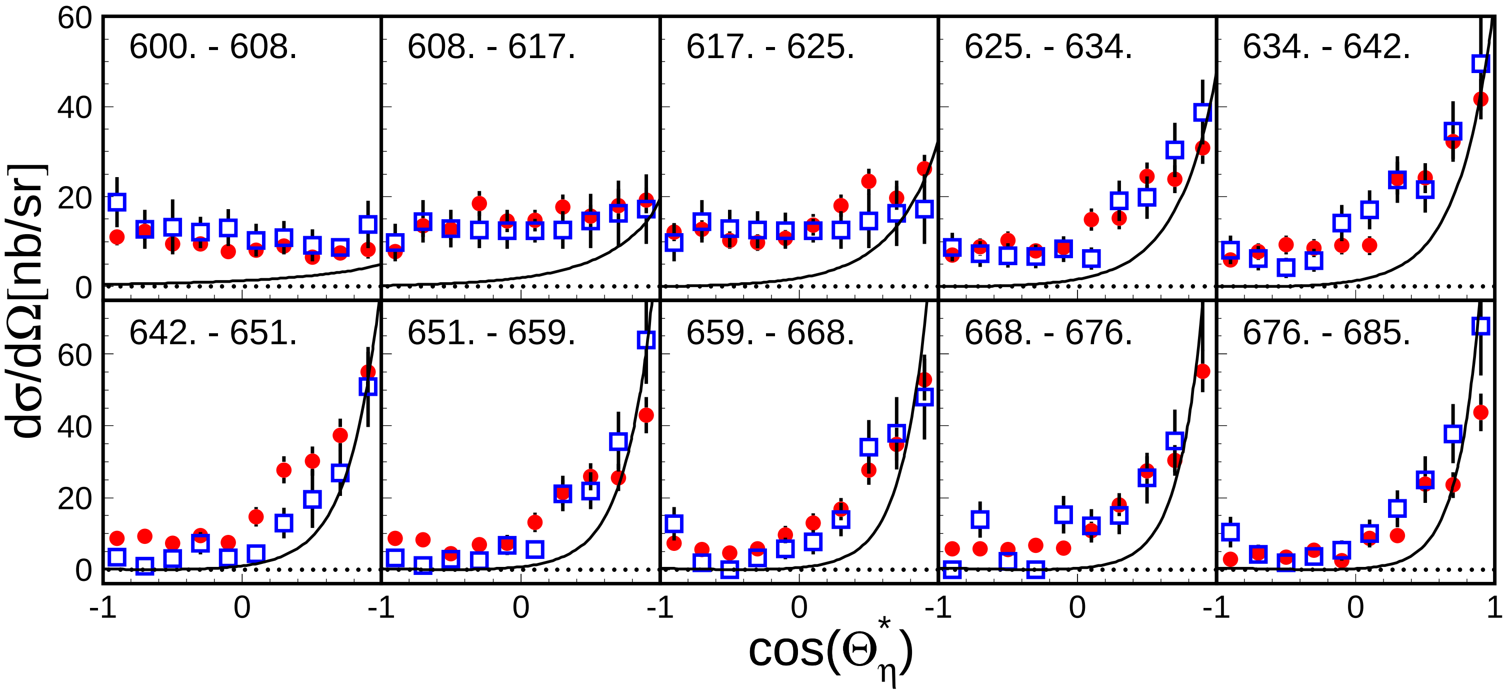


- **most simple PWIA approximation agrees overall within factors of ≈2**
- **much steeper rise of cross section at threshold for ^{3}He, large enhancement with respect to PWIA**

angular distributions

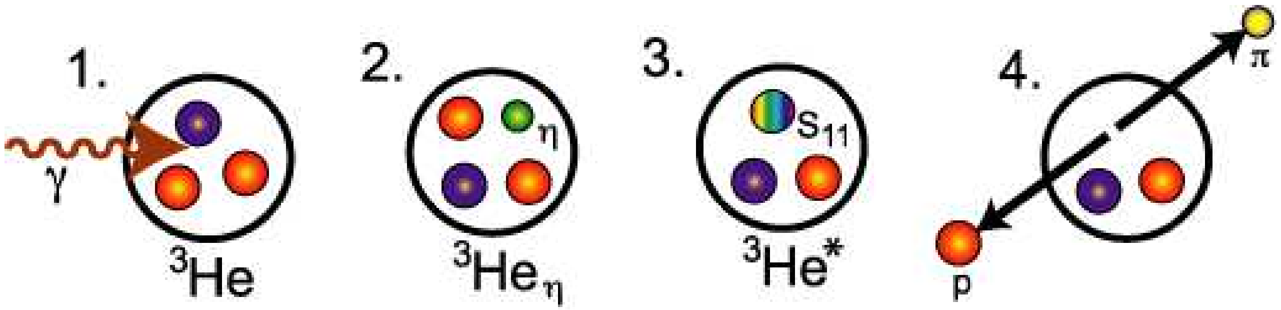


- ^{7}Li strong forward peaking, dominated by form factor dependence
- ^{3}He almost isotropic at threshold, form factor behavior ony at higher energies



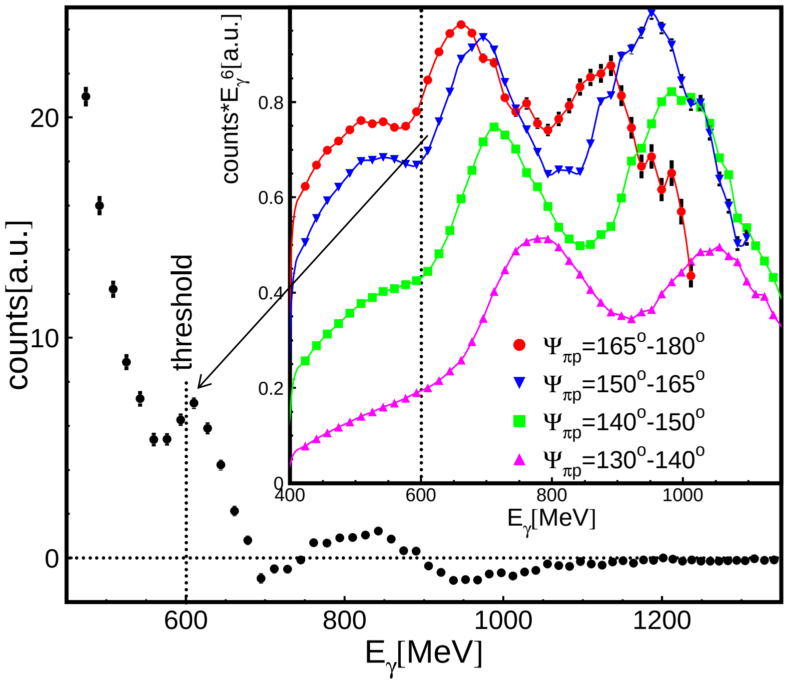
search for η-mesic nuclei in other reaction channels

- 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 seen in previous experiment



- but: complicated structures from nucleon resonance excitations obscure all possible signals

Conclusions

coherent photoproduction of η-mesons:

- ‘coherent’ photoproduction identified for ^{3}He and ^{7}Li
- total cross section one order of magnitude larger for ^{3}He than for ^{7}Li; for both reactions absolute magnitude roughly in agreement with expectations from PWIA modelling
- strong threshold enhancement for $\gamma +^3$ He $\rightarrow \eta +^3$ He similar like in hadron induced reactions $\rightarrow$ final state property
- fast variation of shape of angular distributions at threshold; different from PWIA expectation
- for ^{7}Li threshold behavior (absolute magnitude and shape of angular distributions) similar to PWIA expections. No indication for unusual FSI effects

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

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

what about η-mesic ^{4}He?

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

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

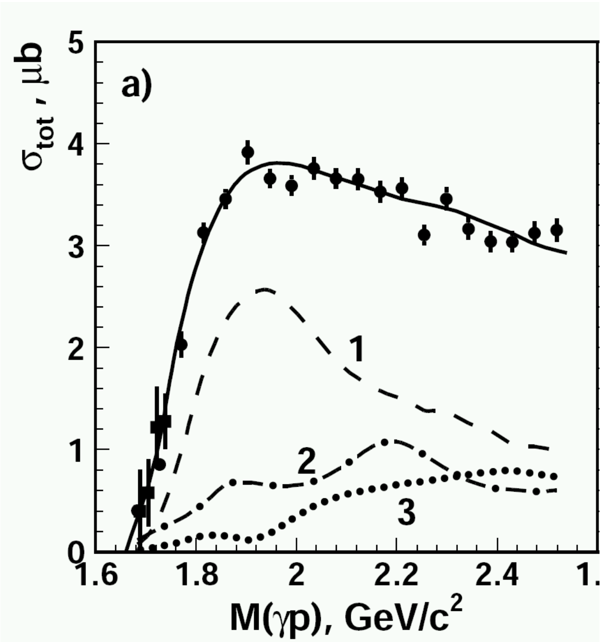
  J_z: -1 +1/2 -1/2 -1/2 0 $\Rightarrow$ spin-flip transition

- 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



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

dominant process close to threshold:

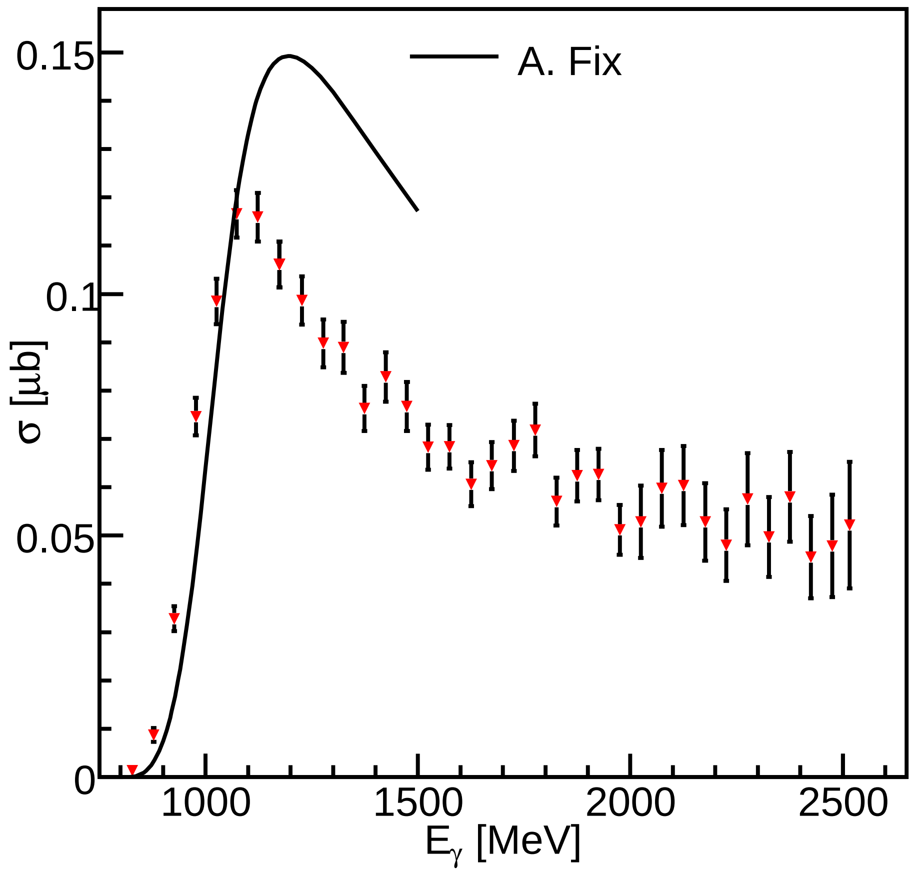
γp $\rightarrow$$D_{33}(1700)\rightarrow$ ηP_{33}(1232) $\rightarrow$ $\eta\pi^o$p

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

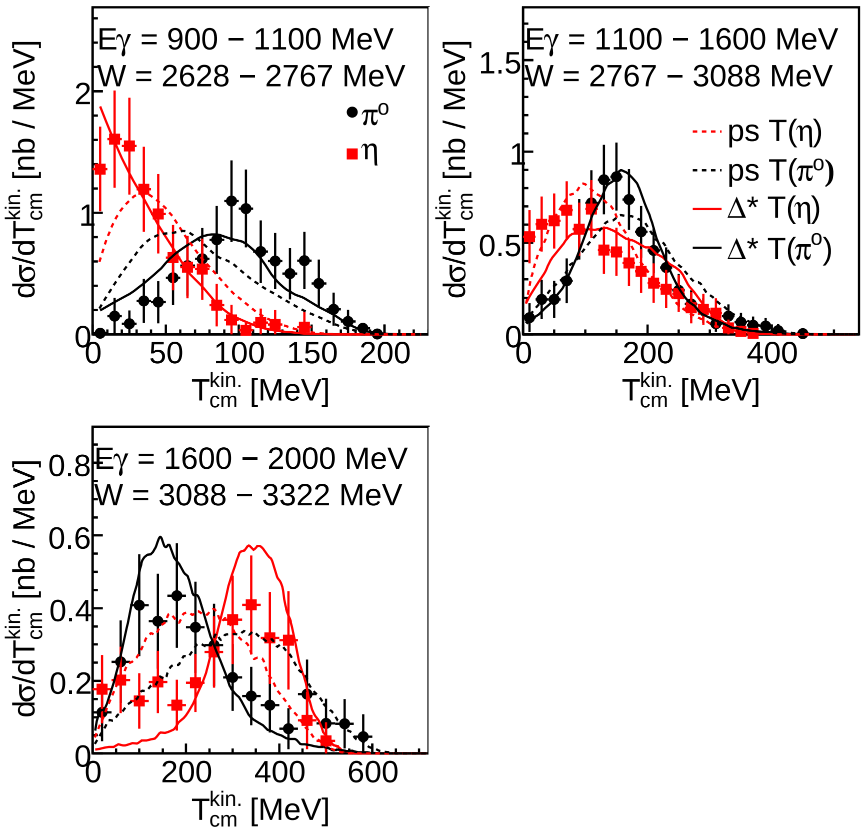
$\Rightarrow$no spin-flip,
identical amplitude for p, n
$\Rightarrow$ideal entrance channel

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

- total cross section



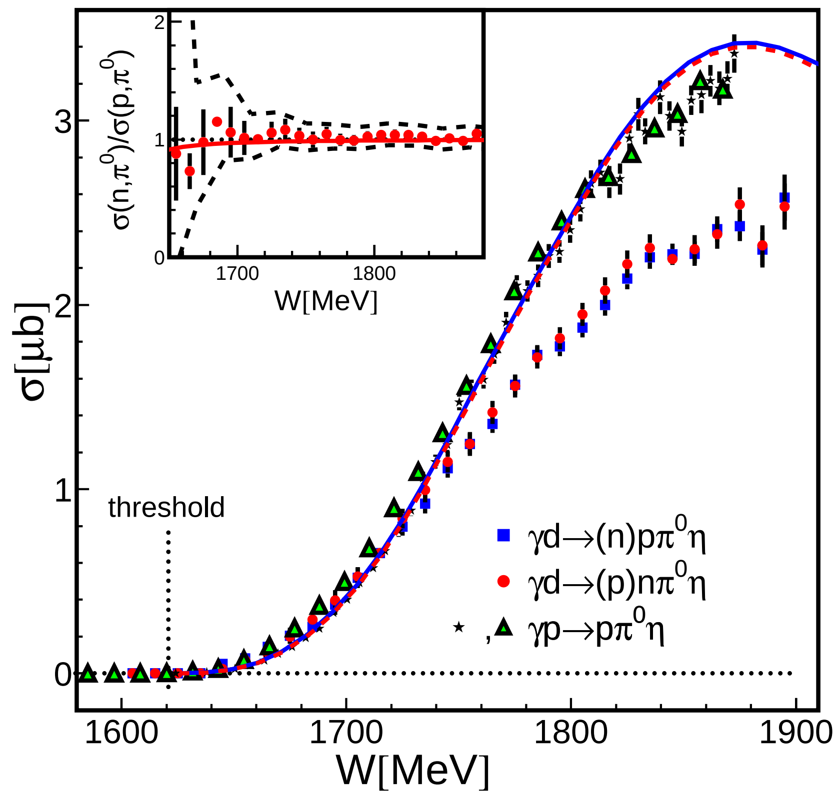
- kinetic energy

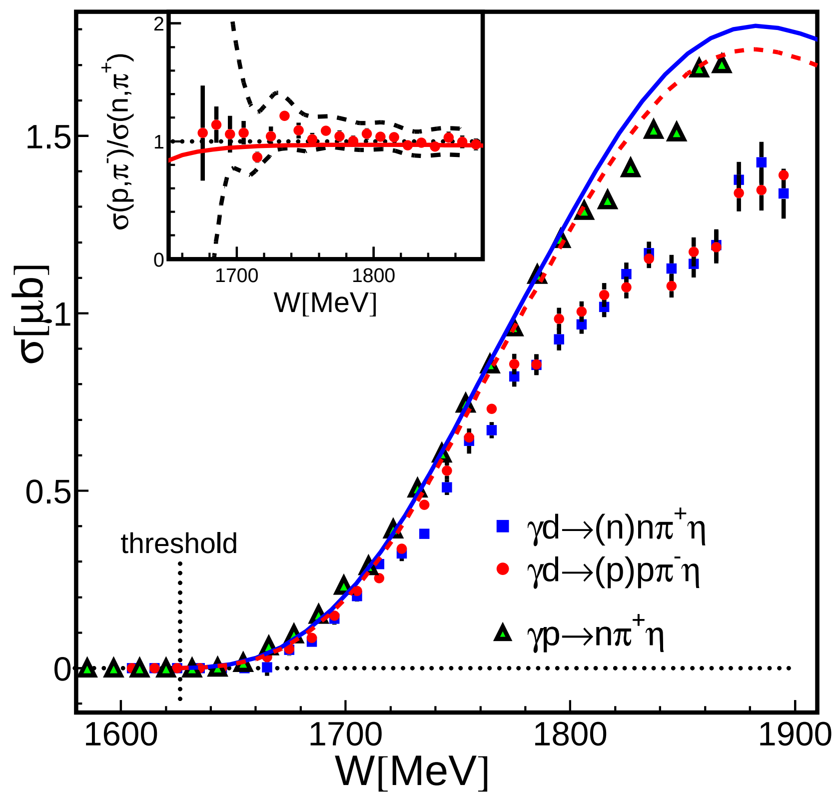


- total cross section in reasonable agreement with predictions
- T distributions support dominant $\Delta^\star \rightarrow \Delta(1232)\eta \rightarrow N\eta\pi^o$ contribution: $T(\pi^o)$ peaks around 100 MeV ($\Delta(1232) \rightarrow N\pi$), $T(\eta)$ rises with E_γ

isospin decomposition of $\pi\eta$-photoproduction

- $\gamma N \rightarrow N\pi^0\eta$
- $\gamma N \rightarrow N'\pi^\pm\eta$

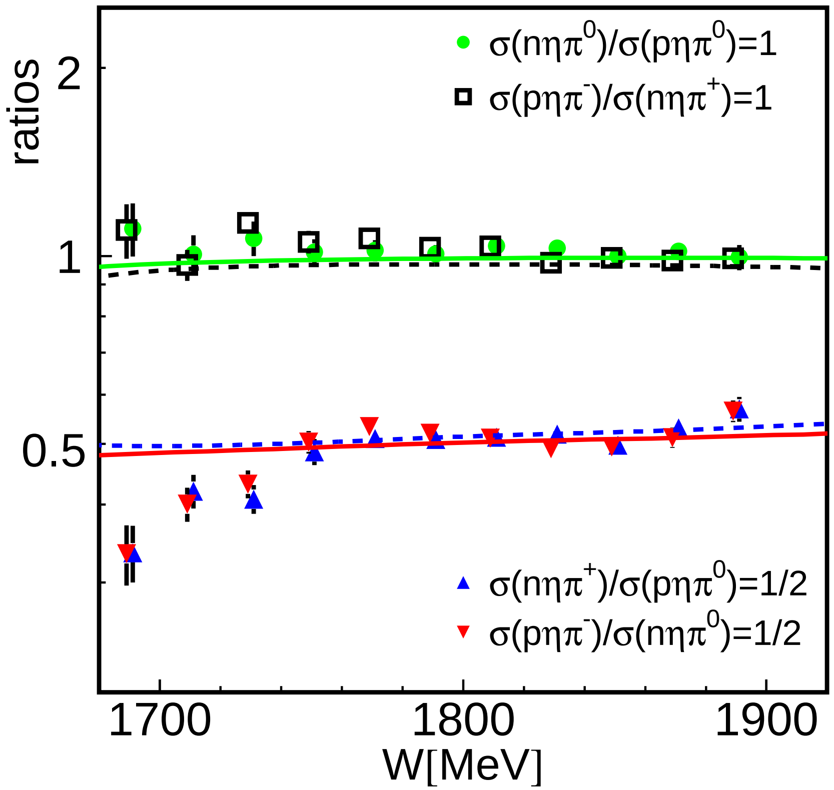


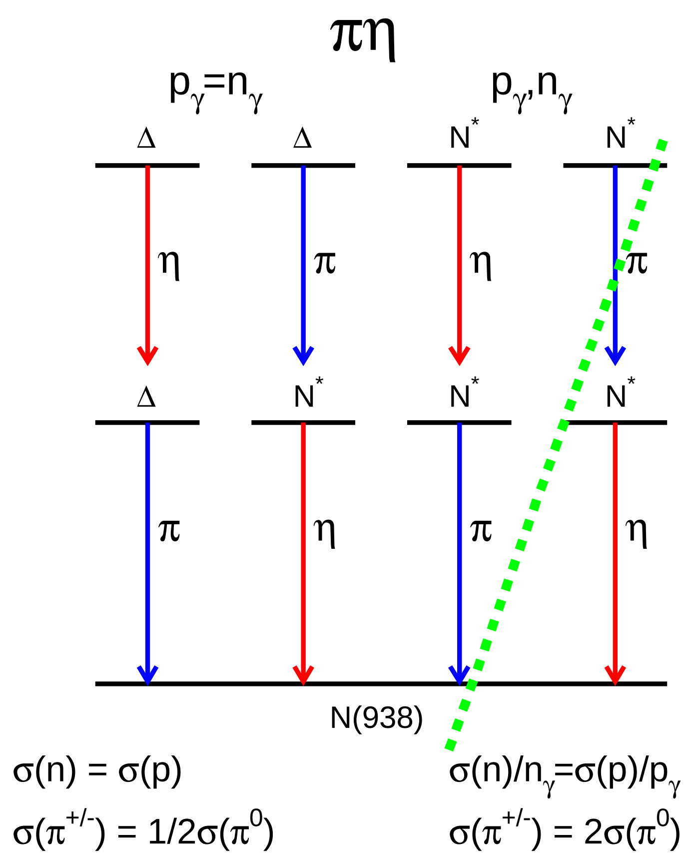


- neutron/proton cross section ratios for neutral and charged pions unity
- charged/neutral pion ratios for same nucleon close to 1/2
- quasi-free off deuteron suppressed by ≈25% compared to free nucleon

isospin decomposition of $\pi\eta$-photoproduction

- **cross section ratios**

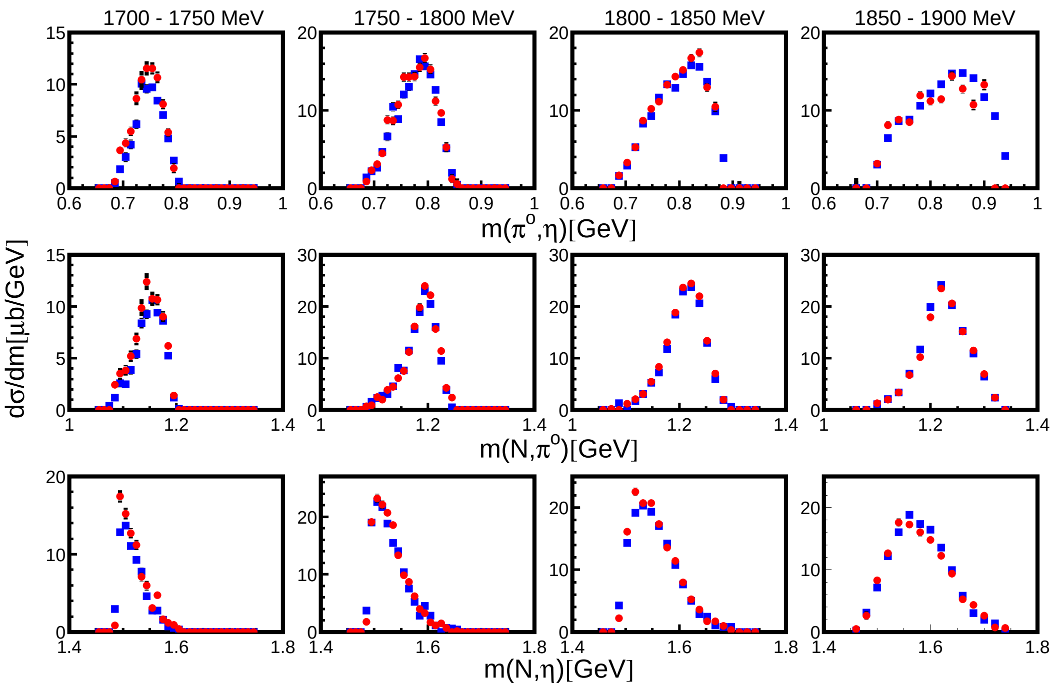




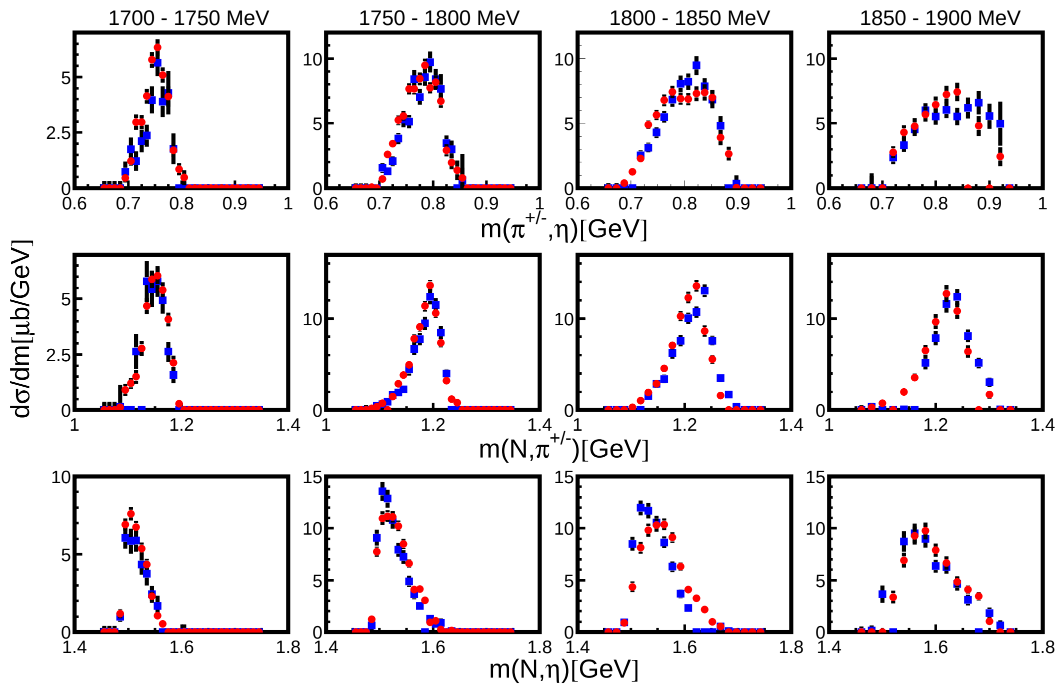
- **cross section ratios agree with $\gamma N \rightarrow \Delta^\star \rightarrow \eta\Delta \rightarrow \eta\pi N$ reaction chain**
- **only alternative would be: $\gamma N \rightarrow \Delta^\star \rightarrow \pi N^\star \rightarrow \pi\eta N$**
- **$\Longrightarrow$ analyze invariant mass distributions**

invariant mass distributions for $\pi\eta$-photoproduction

- $\gamma N \rightarrow N\pi^0\eta$



- $\gamma N \rightarrow N'\pi^{\pm}\eta$



- **shape of invariant mass distributions for all isospin channels practically identical**
- **clear signal for $\Delta(1232) \rightarrow N\pi$-decay**

Outlook

coherent photoproduction of η-mesons:

- ^{3}He so far best candidate for η-mesic state,
  very suggestive but no ‘smoking gun’
- no other nuclei promising targets due to selection rules

quasi-free production (magic momentum transfers)

- perhaps alternative for medium heavy nuclei, so far basically not explored

coherent photoproduction of $\eta\pi^0$-pairs

- seems to be most promising approach to search for ^{4}He$_\eta$;
  experiment proposal accepted, challenging due to small cross sections,
  but much recent progress in achievable data rates for CB/TAPS at MAMI