# Baryon spectroscopy and properties: Measurement of polarization observables in photoproduction of mesons on nuclei

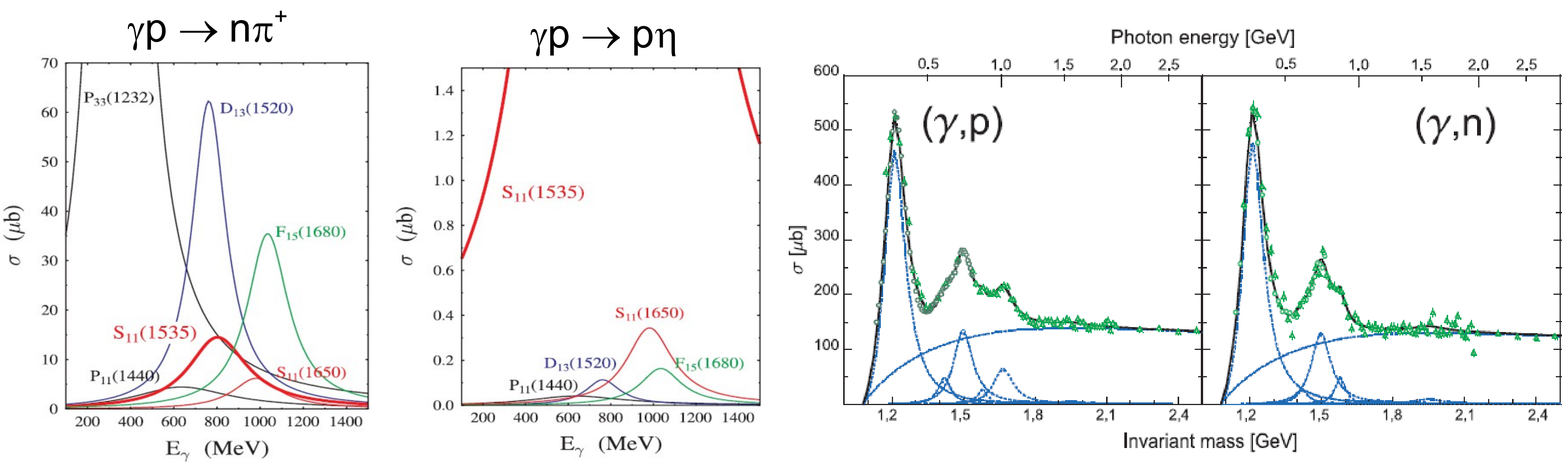
**Vahe Sokhoyan**

**Baryons 2022**
**11.11.2022**

# Baryon resonances

<u>Goal</u>: Gain a good understanding of the spectrum and properties of baryon resonances

Experimentally: Broad overlapping resonances
- Partial Wave Analysis necessary
- Measurement of cross-sections and polarization observables
- Different production channels




- Channels different from $\pi N \rightarrow$ Photoproduction experiments
- Production on the proton (e.g., $\pi^0$, $\eta$, $\eta'$, $2\pi^0$, $\pi^0\eta$, $\omega$,….)
- Production of mesons on light and heavy nuclei:
  baryon spectroscopy and search for in-medium modifications

# Motivation and outline

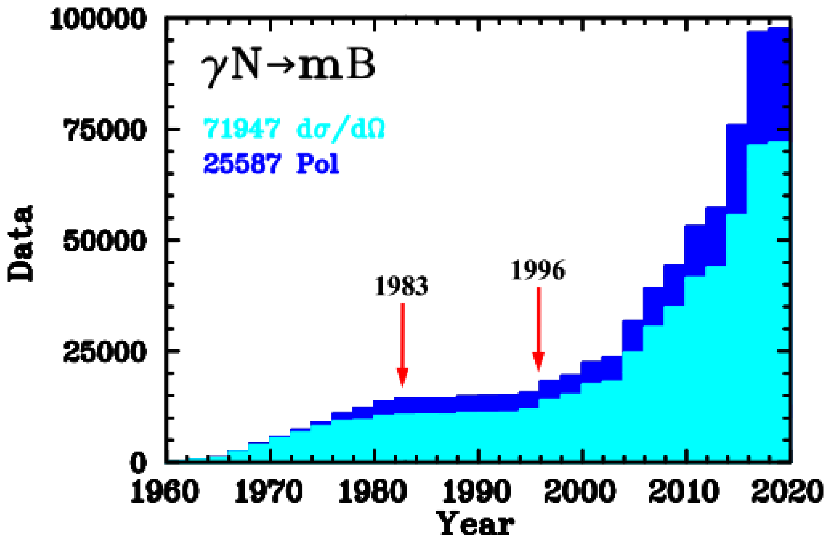
"Complete experiment" for single meson photoproduction: 8 carefully selected observables, 15 observables for double meson final states

- Experiments with polarized beams and targets, measurement of recoil polarization
- Relatively scarce data set for the neutron
- Ongoing effort at ELSA, JLab, MAMI,...

| set | | observables | | | |
|---|---|---|---|---|---|
| single | S | $d\sigma/d\Omega$ | $\Sigma$ | T | P |
| beam-target | BT | G | H | E | F |
| beam-recoil | BR | $O_{x'}$ | $O_{z'}$ | $C_{x'}$ | $C_{z'}$ |
| target-recoil | TR | $T_{x'}$ | $T_{z'}$ | $L_{x'}$ | $L_{z'}$ |

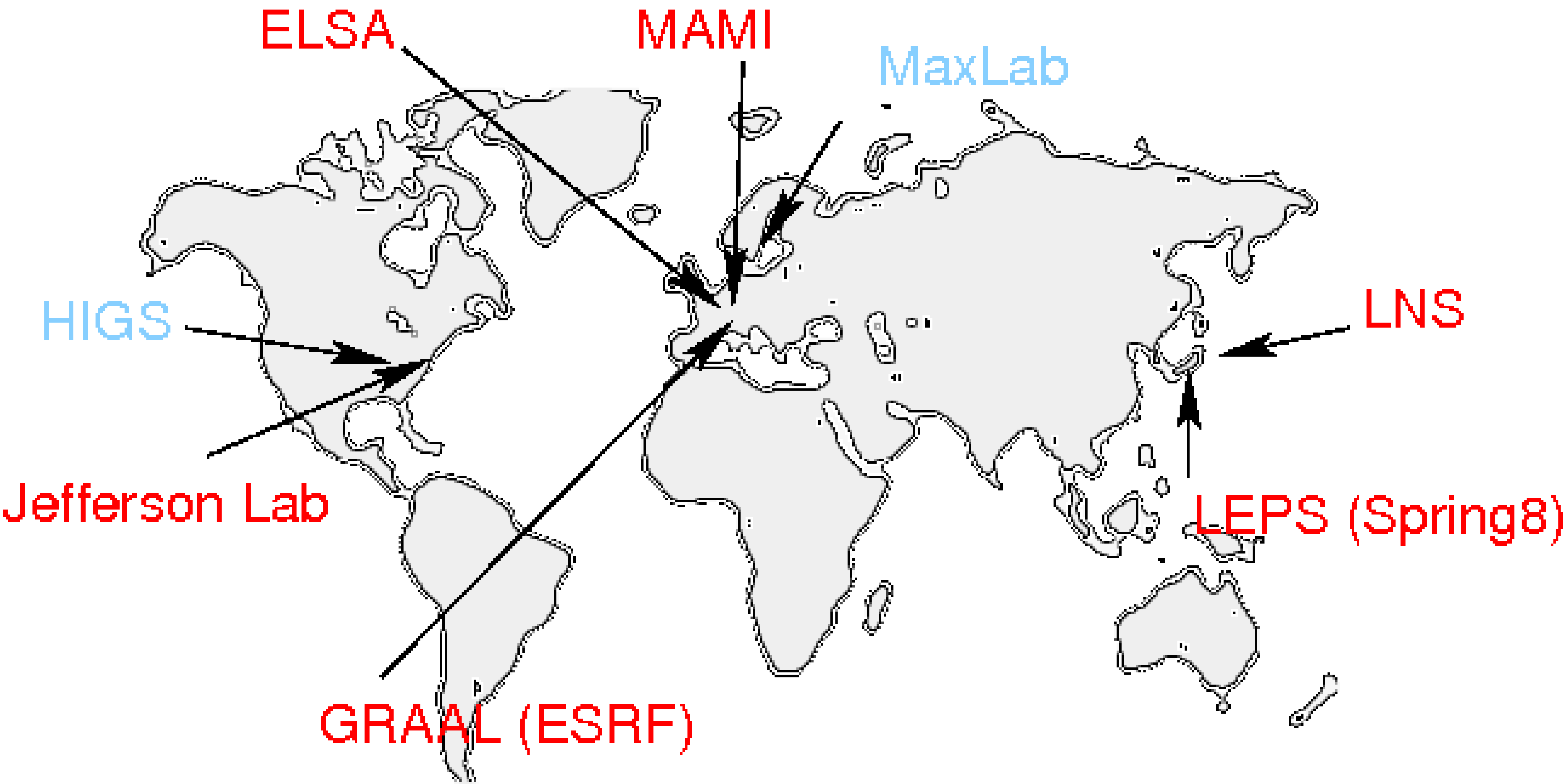
**In this talk:**

- Selected results for the meson photoproduction on the proton and neutron
- Search for d*(2380) → *comprehensively covered in the morning session by Dan Watts (York)*
- Example: Set of measurements for photoproduction of $\pi^0\eta$ pairs from the proton to lead
- Compton scattering on nucleons and nuclei
- New opportunities for the field with active targets




D.G. Ireland, E. Pasyuk and I. Strakovsky
Prog. Part. Nucl. Phys. 111 (2020) 103752

# Experiments

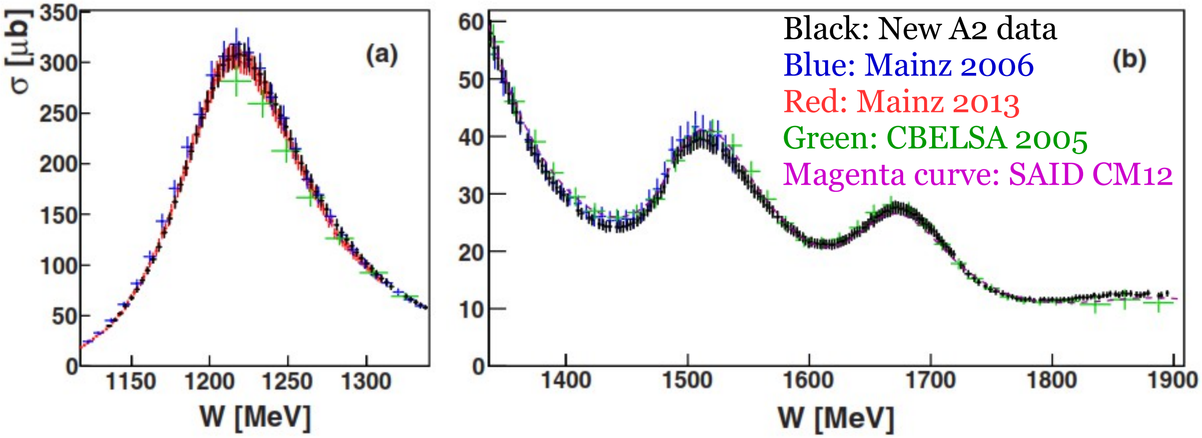


# In memory of Prof. Bernd Krusche

**From whom we had an honor to learn and to work with...**

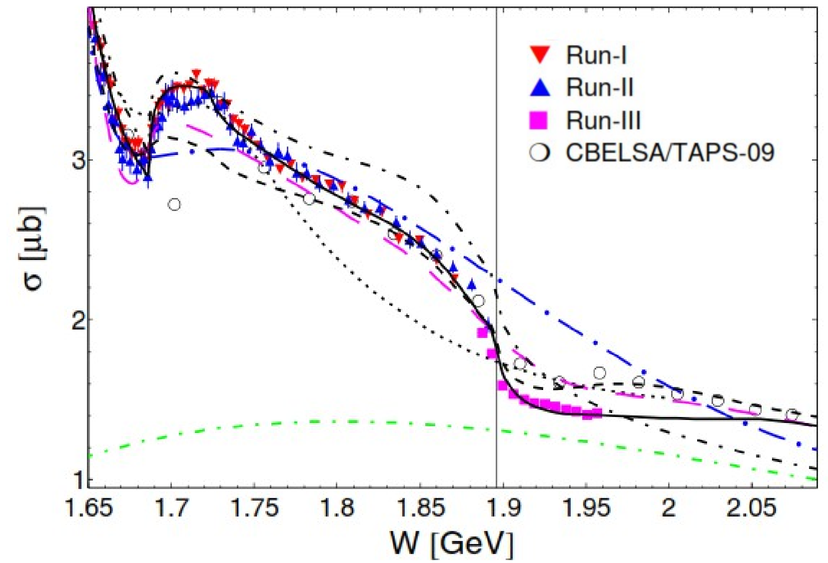
# Selected unpolarized results A2

## $\gamma p \rightarrow p\pi^0$



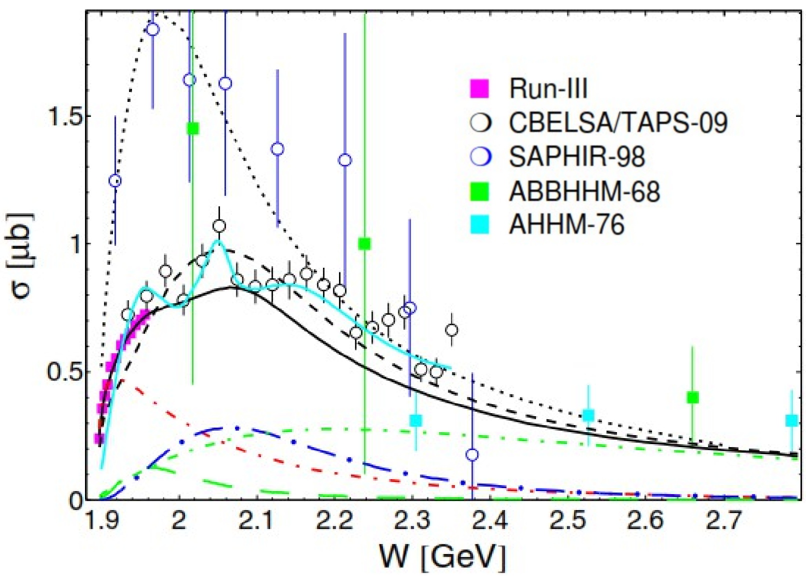

P. Adlarson et al., Phys.Rev. C92, 2 (2015)

## $\gamma p \rightarrow p\eta$



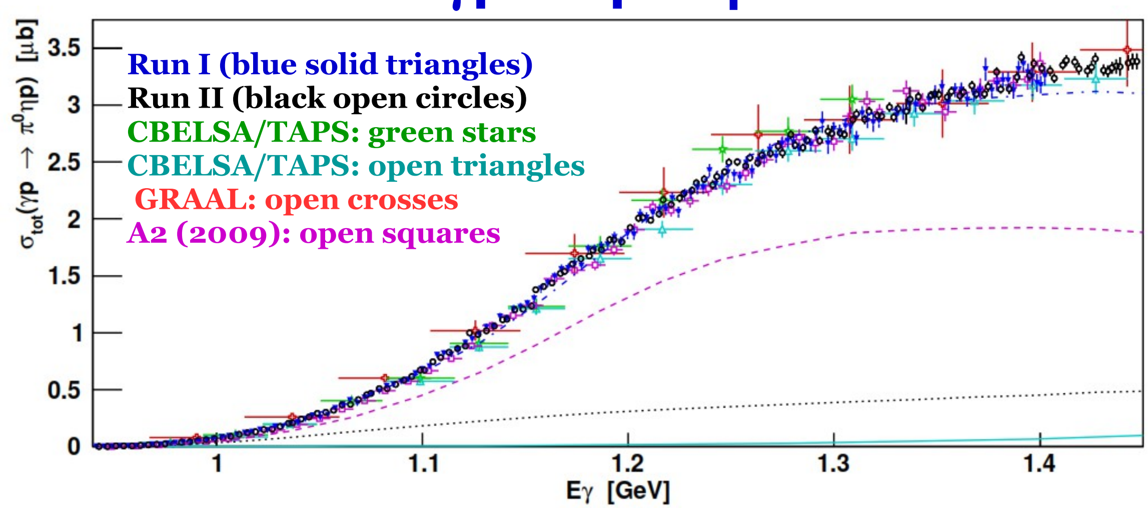

V. Kashevarov et al., Phys.Rev.Lett. 118, 21 (2017)

## $\gamma p \rightarrow p\eta'$



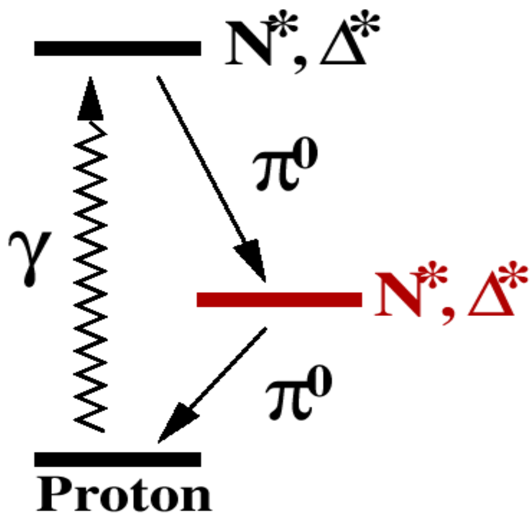

V. Kashevarov et al., Phys.Rev.Lett. 118, 21 (2017)

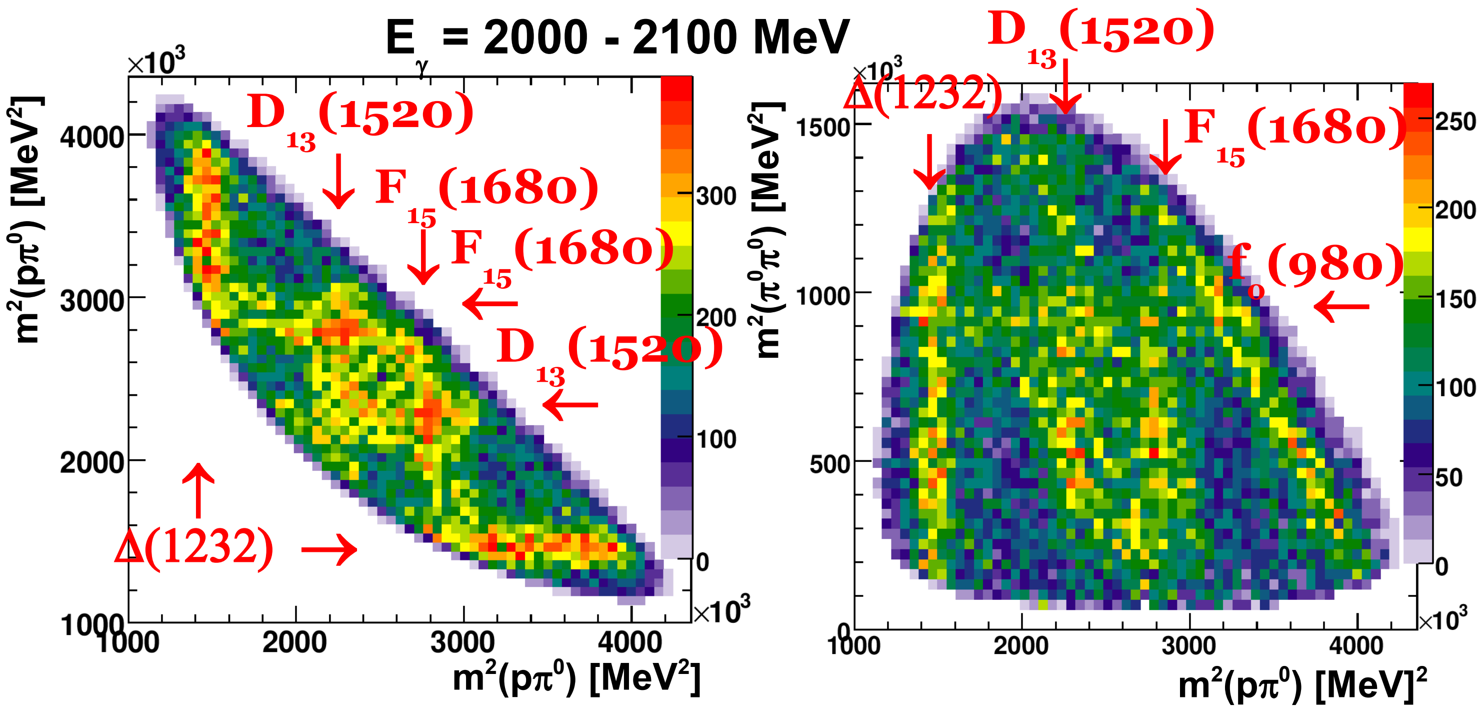
## $\gamma p \rightarrow p\pi^0\eta$

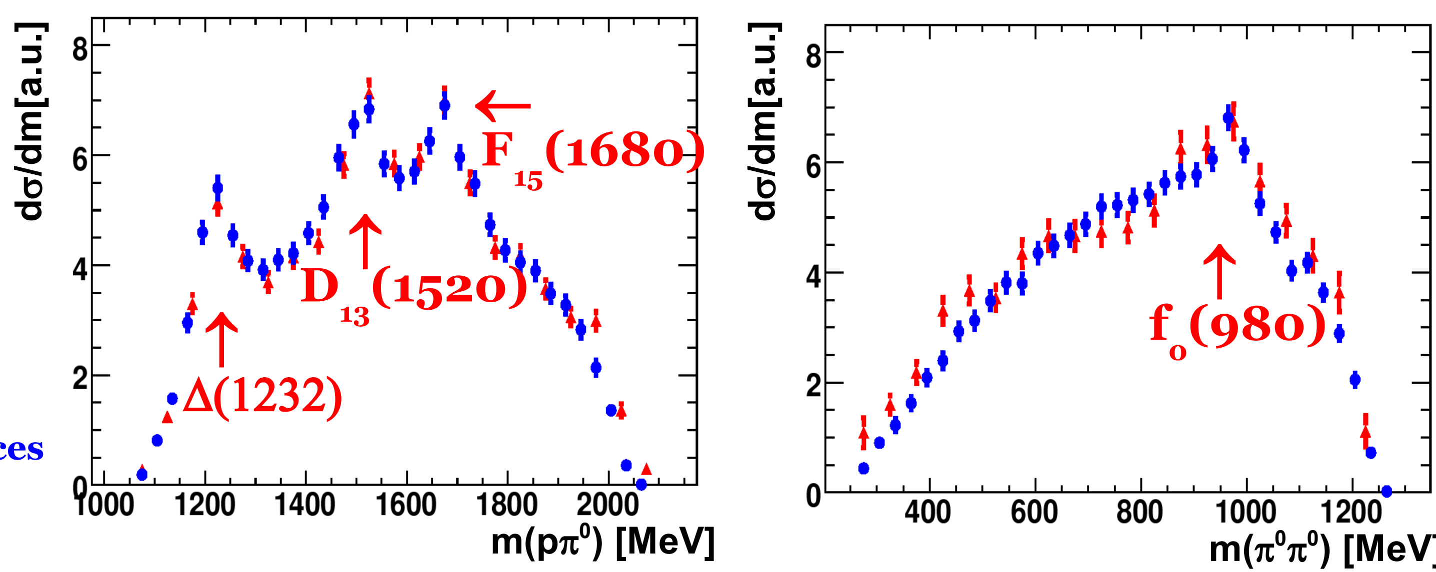



V. Sokhoyan et al., Phys. Rev. C 97, 055212 (2018)

# CBELSA/TAPS: Sequential decays in double $\pi^o$ production




→ Double meson production gains importance at higher energies

→ Contributions of multiple intermediate resonances are clearly visible in the data

→ Partial Wave Analysis needed to identify the resonances and to study their properties

→ Measurement of polarization observables and unpolarized cross section (preferably for the 5D phase space)

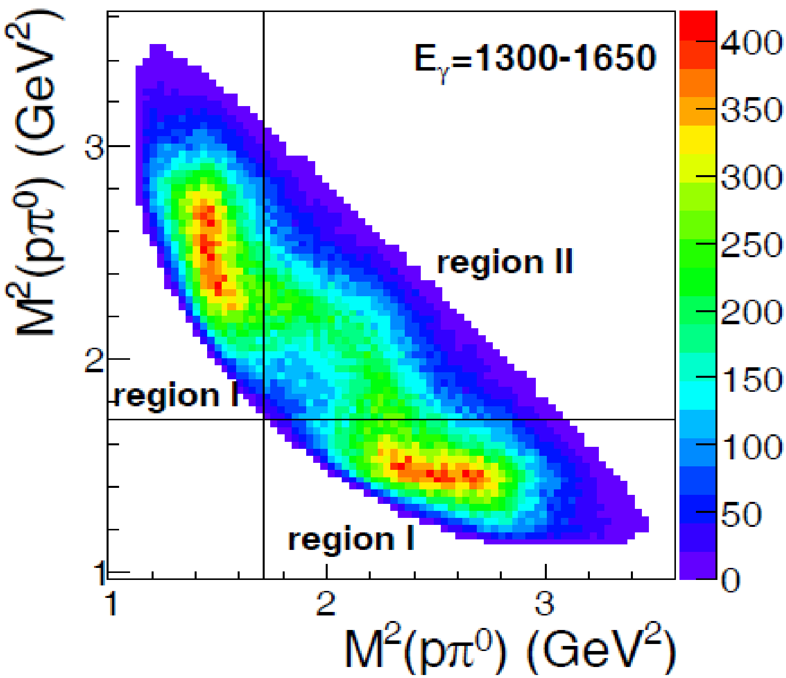
**Clear observation of cascading decays!**

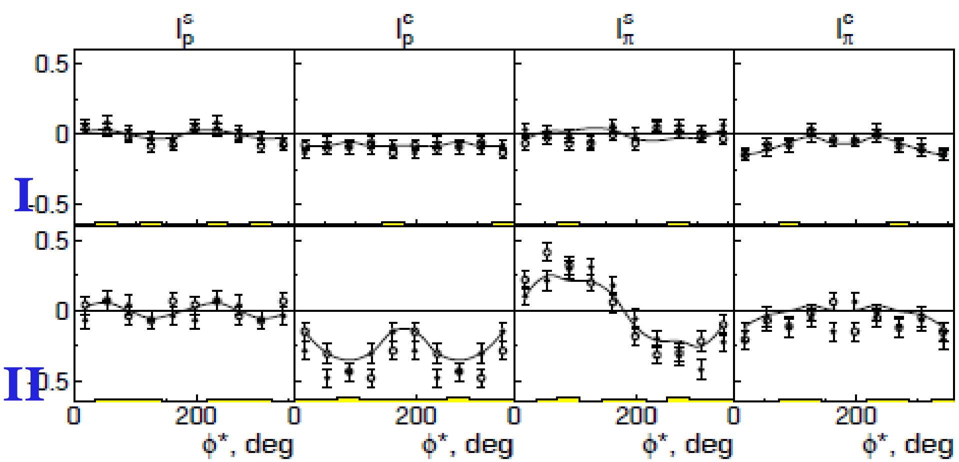
V. Sokhoyan, E. Gutz et al., Eur. Phys. J. A51, 95 (2015)

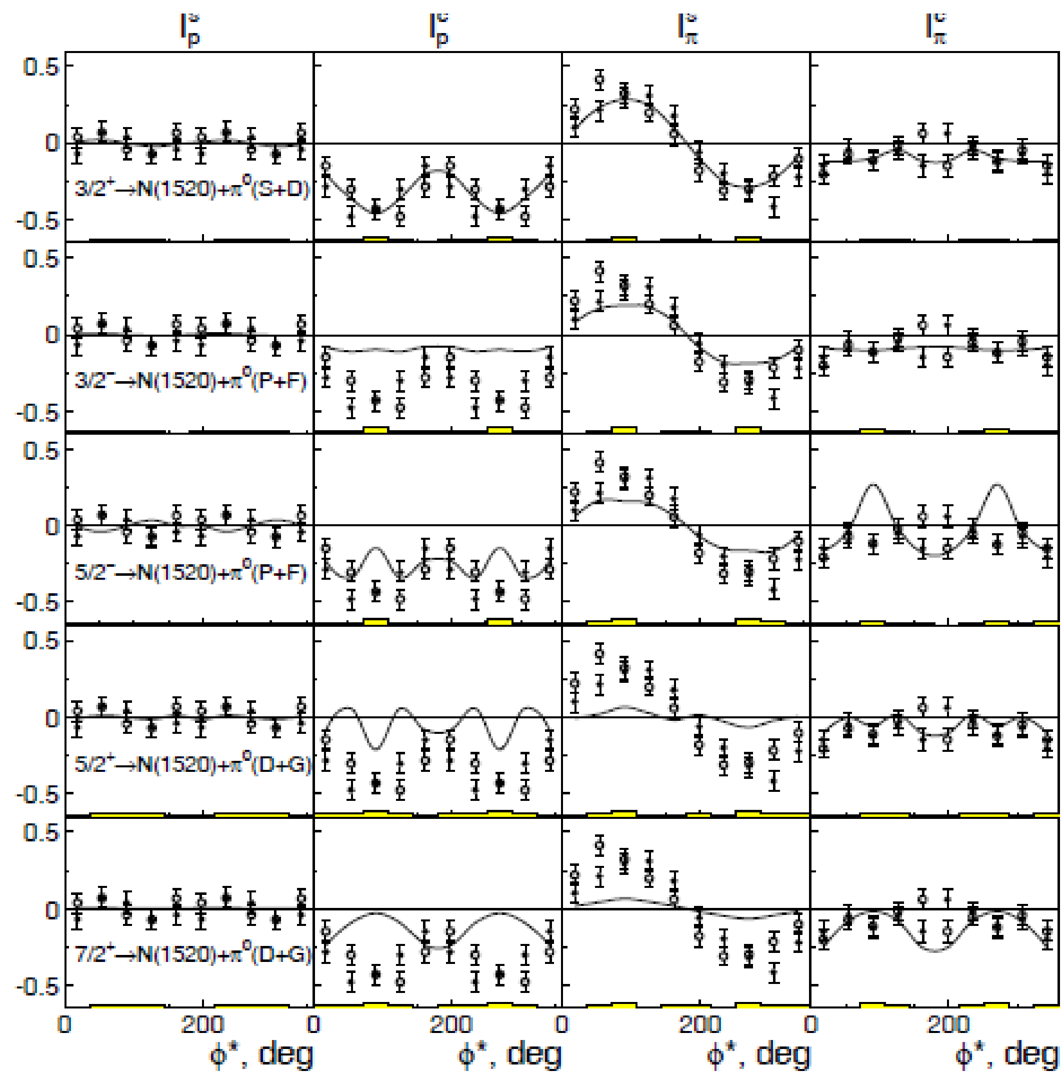
# Example: Accessing reaction mechanisms with polarized photons

## $I^s$ and $I^c$ in $\gamma p \to p\pi^0\pi^0$ and N(1900)3/2$^+$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \{1 + \delta_l[I^s \sin(2\phi) + I^c \cos(2\phi)]\}$$



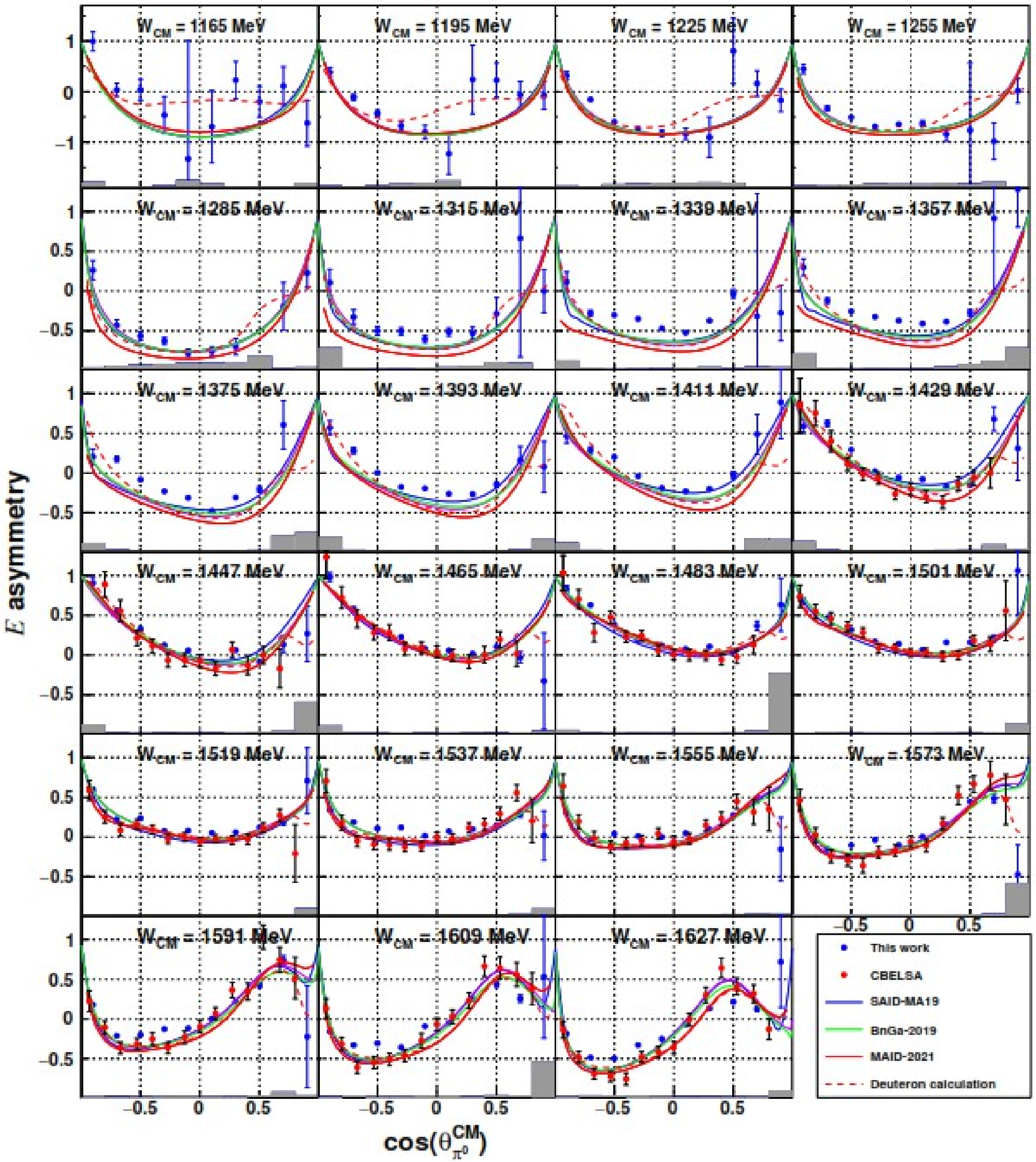

Data from the region I, curves: BnGa PWA: decays via D13(1520)$\pi^0$

**Dominance of the N(1900)3/2$^+$ resonance directly seen in the polarized data**


**V. Sokhoyan et al. [CBELSA/TAPS Collaboration] Phys.Lett. B 746, 127 (2015)**

**V. Sokhoyan et al. [CBELSA/TAPS Collaboration] Eur. Phys. J. A 51, 95 (2015)**

# A2: Single $\pi^0$ photoproduction (deuteron target)




$$\frac{(\sigma_A - \sigma_P)}{(\sigma_A + \sigma_P)}$$

A2: quasi-free proton
CBELSA/TAPS: free proton

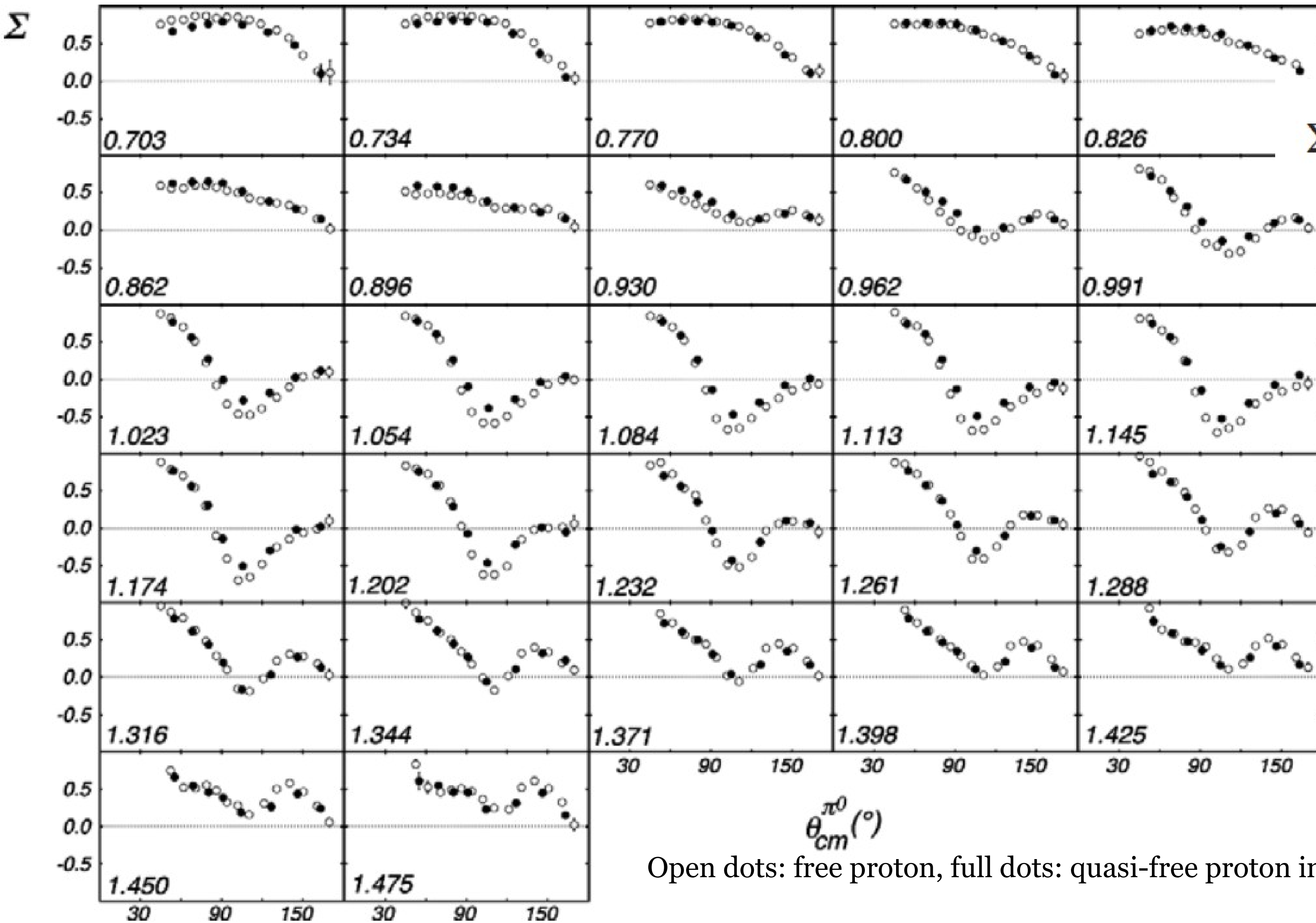
SAID-MA19
MAID-2021
BNGa-2019
} Free proton

Nuclear model (A. Fix)

Generally: agreement between data for the free and quasi-free protons!

F. Cividini et al. [A2 Collaboration], EPJA 58 113 (2022)

# GRAAL: Single $\pi^0$ photoproduction on the deuteron




$$\Sigma_3 = \frac{d\sigma_{\parallel} - d\sigma_{\perp}}{d\sigma_{\parallel} + d\sigma_{\perp}}$$

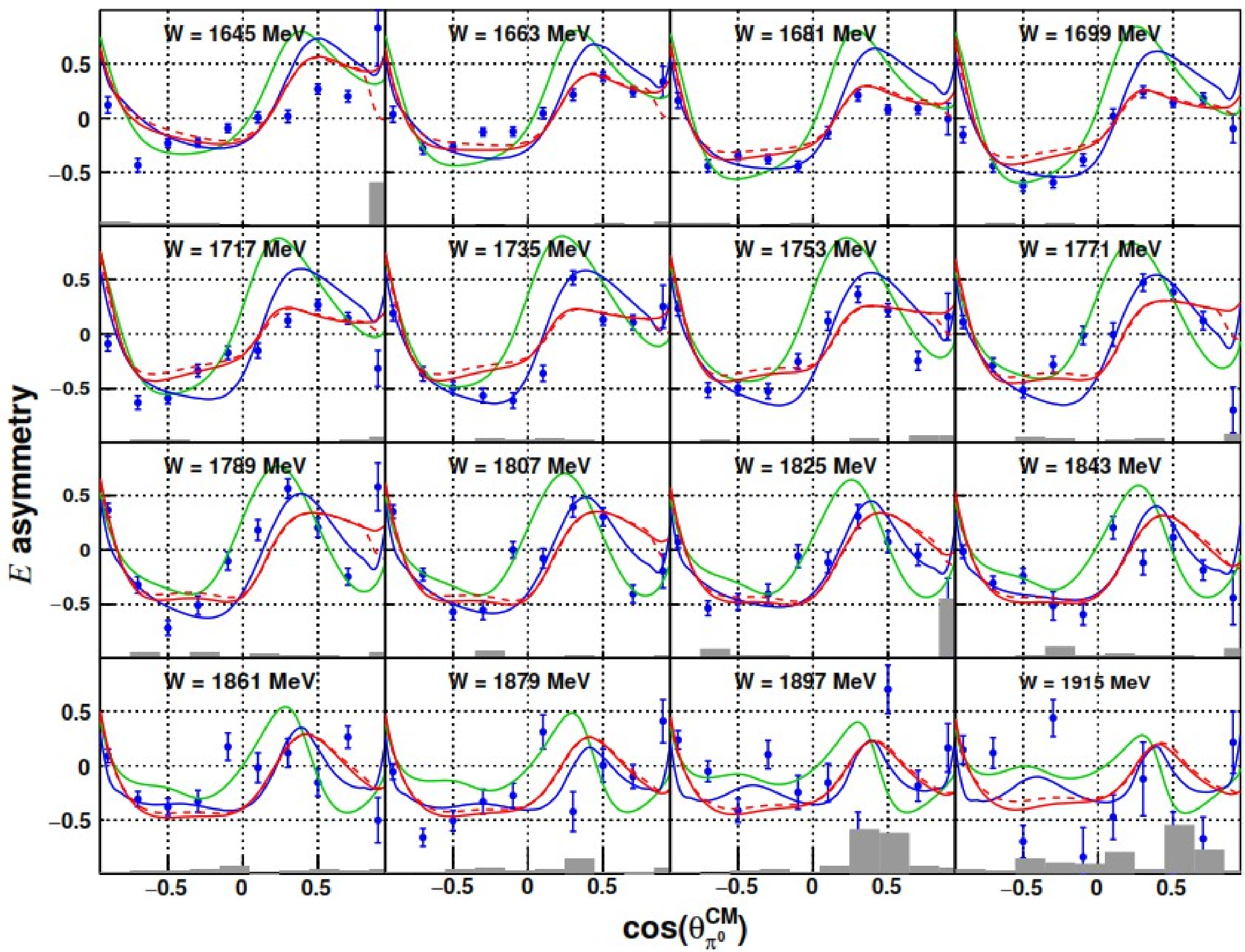
Linearly polarized photons, unpolarized target

Open dots: free proton, full dots: quasi-free proton in the deuteron

Generally: agreement between data for the free and quasi-free protons!

R. Di Salvo et al., Eur. Phys. J. A 42, 151–157 (2009)

# A2: Single $\pi^0$ photoproduction on the neutron (deuteron target)




$$\frac{(\sigma_A - \sigma_P)}{(\sigma_A + \sigma_P)}$$

A2: quasi-free proton
CBELSA/TAPS: free proton

— SAID-MA19
— MAID-2021
— BNGa-2019

Free neutron

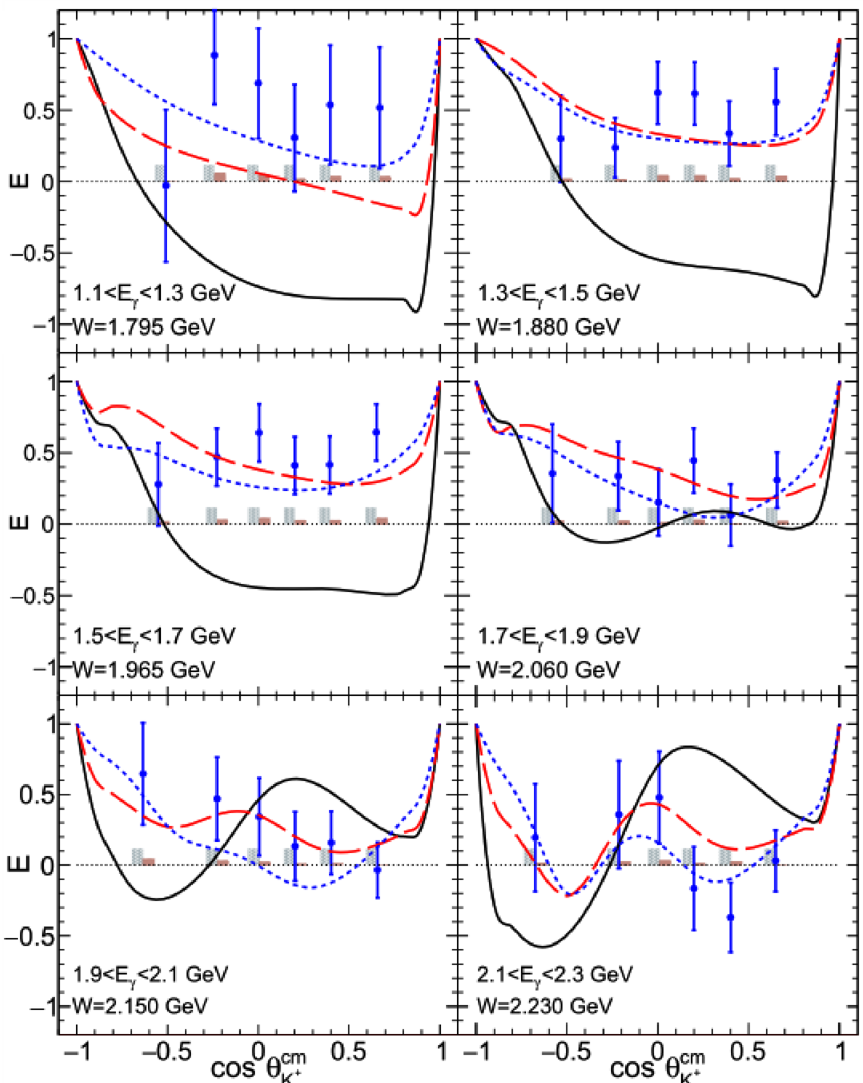
-- Nuclear model (A. Fix)

No previous data!

**F. Cividini et al. [A2 Collaboration], EPJA 58 113 (2022)**

**Many more recent data from CLAS, ELSA, MAMI,...**

# CLAS: E observable for $K^+\Sigma^-$ on the neutron




BnGa-2017 solutions (prediction)
BnGa fit including the new data
BnGa fit including the new data + D13 at 2170 MeV

→ No previous data exists!
→ PWA predictions do not describe the data
→ Significant impact
→ Reduction of $\chi^2$ in the BnGa PWA fit when adding $D_{13}$ at 2170 MeV

→ Stronger improvement in $\chi^2$ of the fits of the existing LEPS data on Σ a with $D_{13}$ resonance

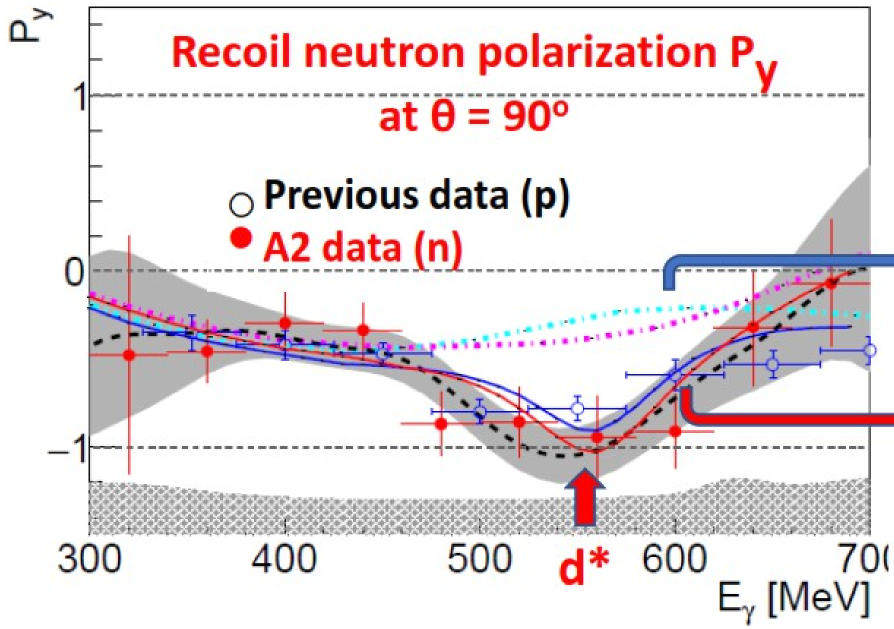
LEPS: H. Kohri et al. Phys. Rev. Lett., 97, 082003 (2006)

*→ Recommendation in N. Zachariou et al. (2020): Obtain new precise data on Σ (!)*

**N. Zachariou et al., Physics Letters B 808, 135662 (2020)**

# A2 and BGO-OD: Measurement of various observables for d*(2380) studies

## A2: Measurement of multiple polarization observables at A2 (Σ, Cx(n), Py(n))



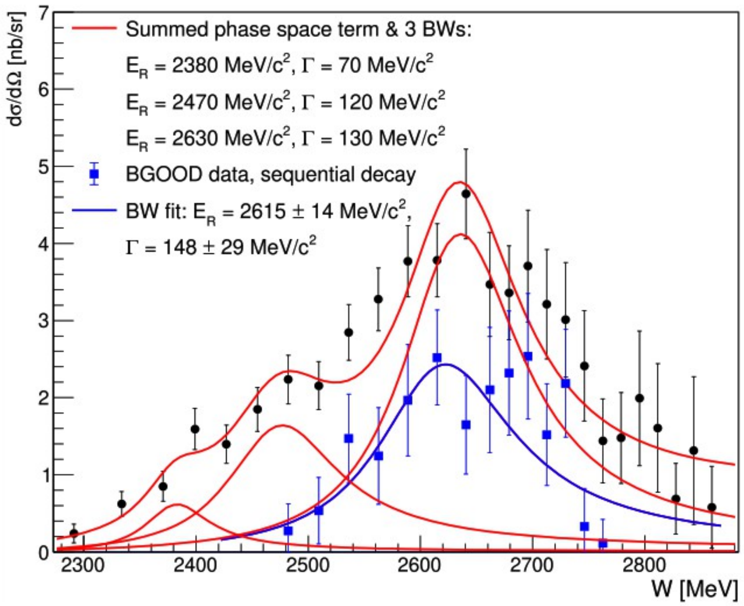

○ I. Ikeda et al., PRL 42 1321 (1979)

● M. Bashkanov et al., PRL 124, 132001 (2020)

Models without d*(2380)

Models with d* (2380)

## BGO-OD: Unpolarized cross section for the coherent $2\pi^0$ production on the deuteron



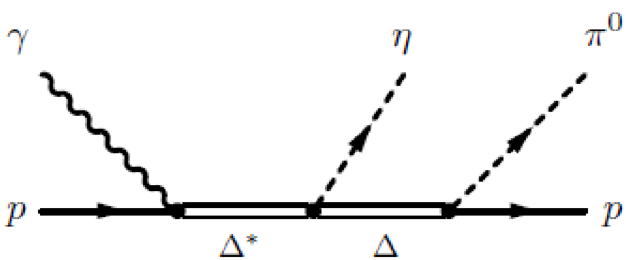

Many more results and discussion

→ Talk of Dan Watts this morning

T. C. Jude et al., Phys. Lett. B 832, 137277 (2022)

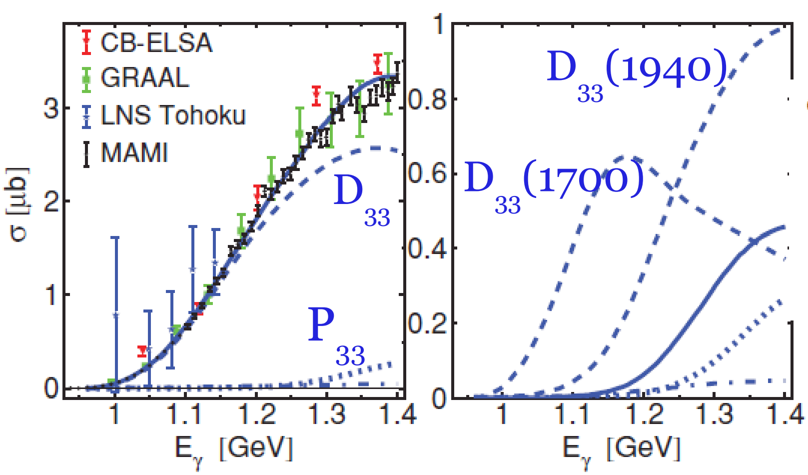
# $\pi^0\eta$ photoproduction: From the free proton to lead

$D_{33}$ dominates at low energies



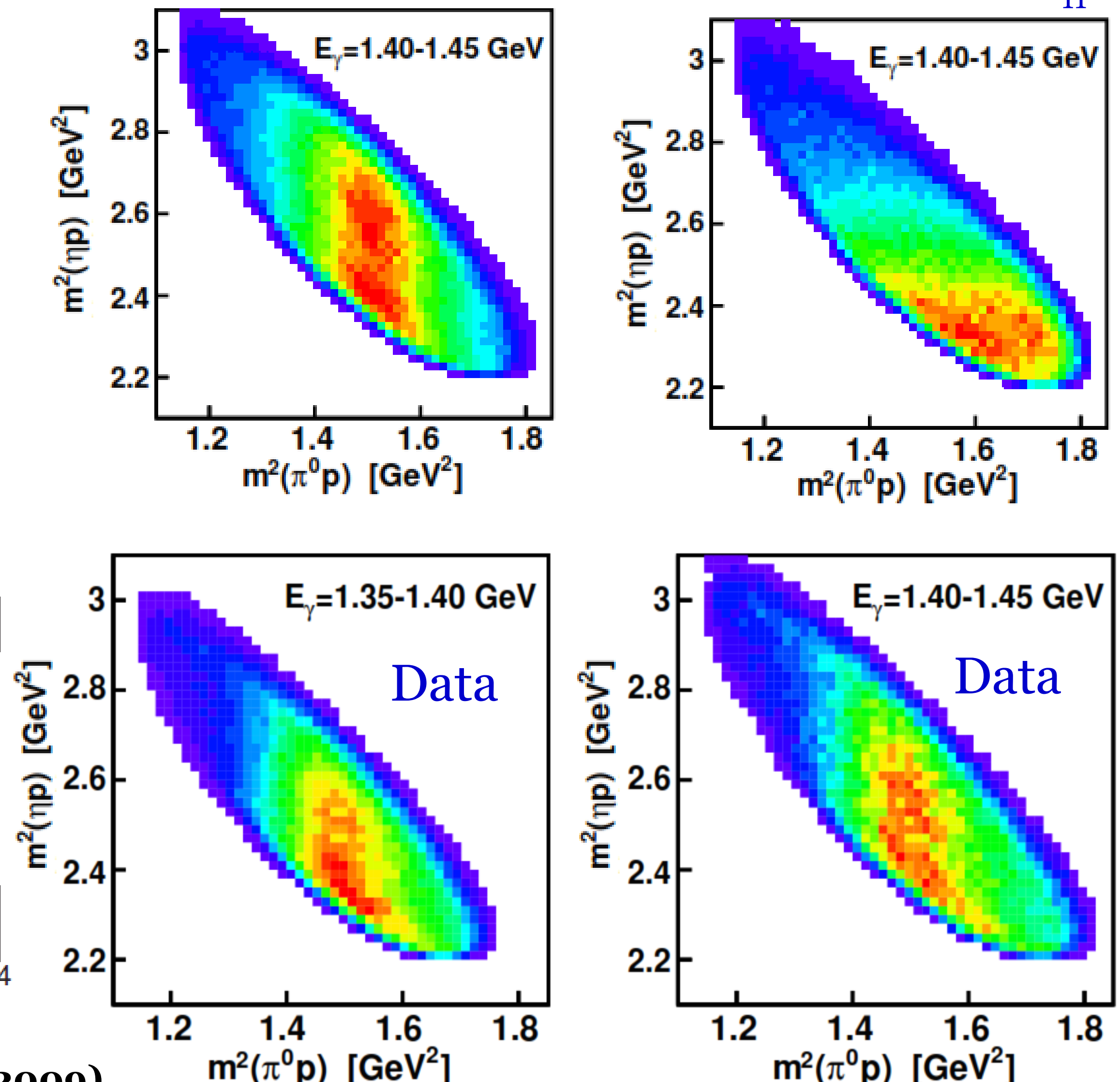

$\eta$ acts as an isospin filter, e.g
$\gamma p \rightarrow D_{33}(1700) \rightarrow \Delta(1232)\eta$

**M. Döring, E. Oset, and D. Strottman, Phys. Rev. C 73, 045209 (2006)**




**V. L. Kashevarov, et al., EPJ A 42, 141 (2009)**

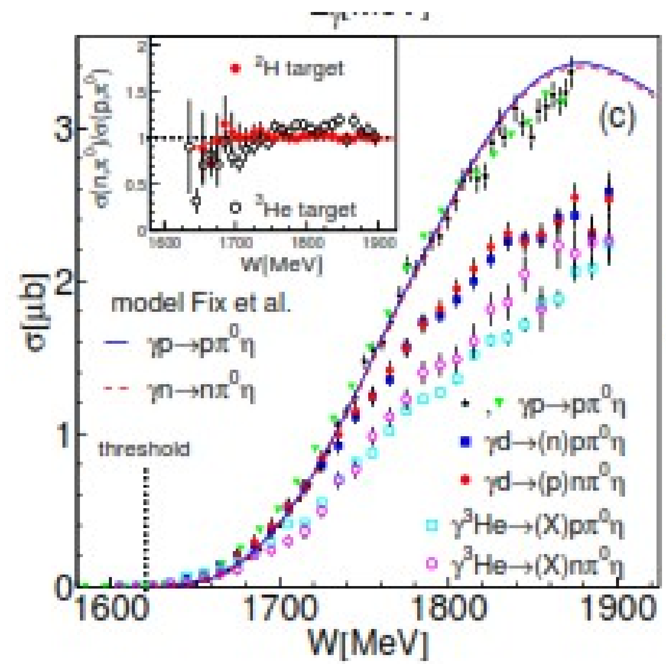
MC for $\gamma p \rightarrow \Delta(1232)\eta$ MC for $\gamma p \rightarrow S_{11}\pi^0$

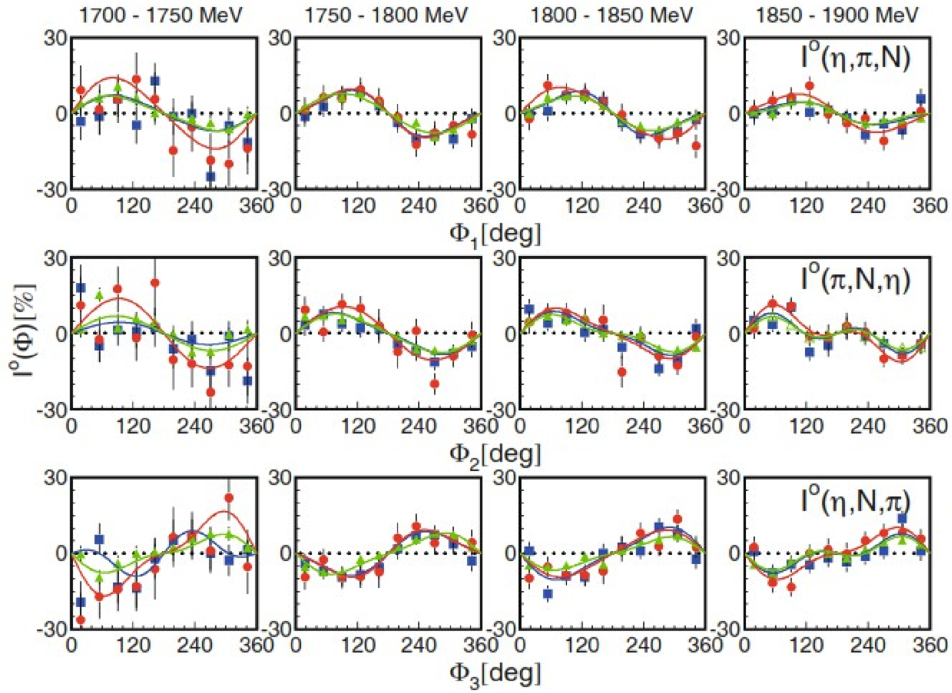



**V. Sokhoyan et al., PRC 97, 055212 (2018)**

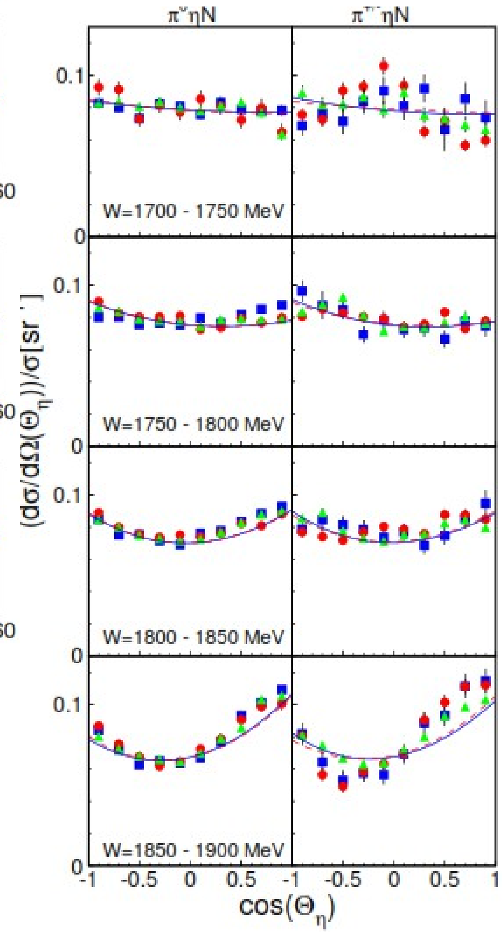
Strong contribution from $\gamma p \rightarrow (D_{33}(1700)) \rightarrow \Delta(1232)\eta \rightarrow p\pi^0\eta$

# FSI and experimental observables (deuteron)




**Free proton**, **quasi-free proton**, **quasi-free neutron**




- Significant reduction in the total cross section
- Agreement between free and quasi-free protons for the beam helicity asymmetry and angular distributions

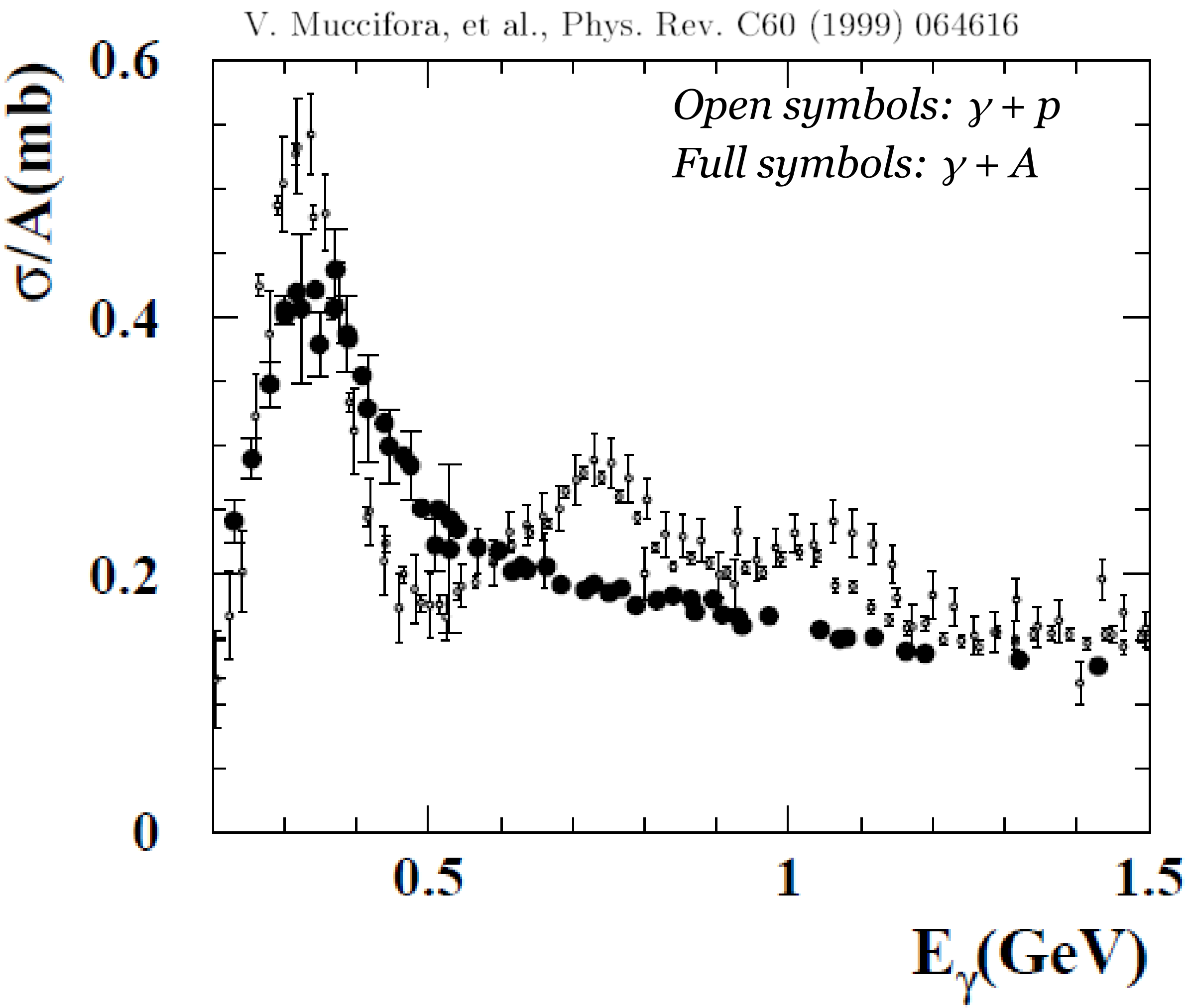
→ Absorptive but not rescattering nature of FSI (?)
→ Polarization observables well-suited for studying in-medium modifications (?)
→ Measurements of polarization observables with heavier targets!?
→ Still … careful case-dependent consideration is vital!

A. Käser et al. [A2Collaboration] Eur.Phys.J.A 52, 9 (2016)

# Photoproduction on heavier nuclei

Goal: Search for in-medium modifications of baryon resonances

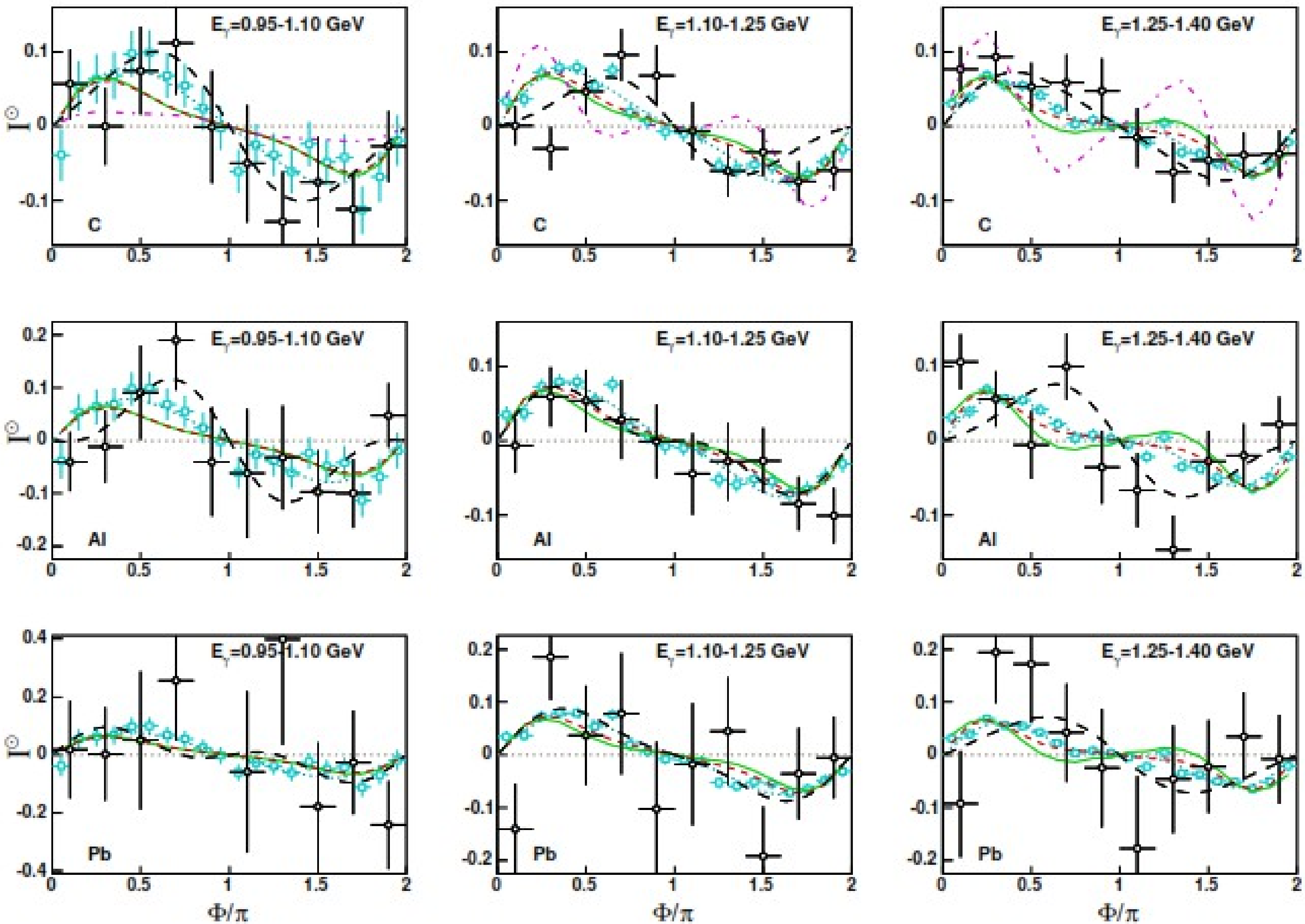
- Pronounced in-medium effect:
  No bump structure in the photoabsorption cross-section measured for $\gamma + A$
  → not fully explained in a model-independent way




→ Second resonance region: No strong experimental indication for significant modifications of $D_{13}(1520)$ or $S_{11}(1535)$

→ Search for modifications of the $D_{33}(1700)$ resonance
→ First measurement of the beam helicity asymmetry for photoproduction on heavy targets

# A2: Beam helicity asymmetry for $\pi^0\eta$ (C. Al, Pb)




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

**Data:**

Solid targets
Hydrogen

**Curves:**

Black: fit of solid target data with sine series
Cyan: fit of the proton Data with sine series

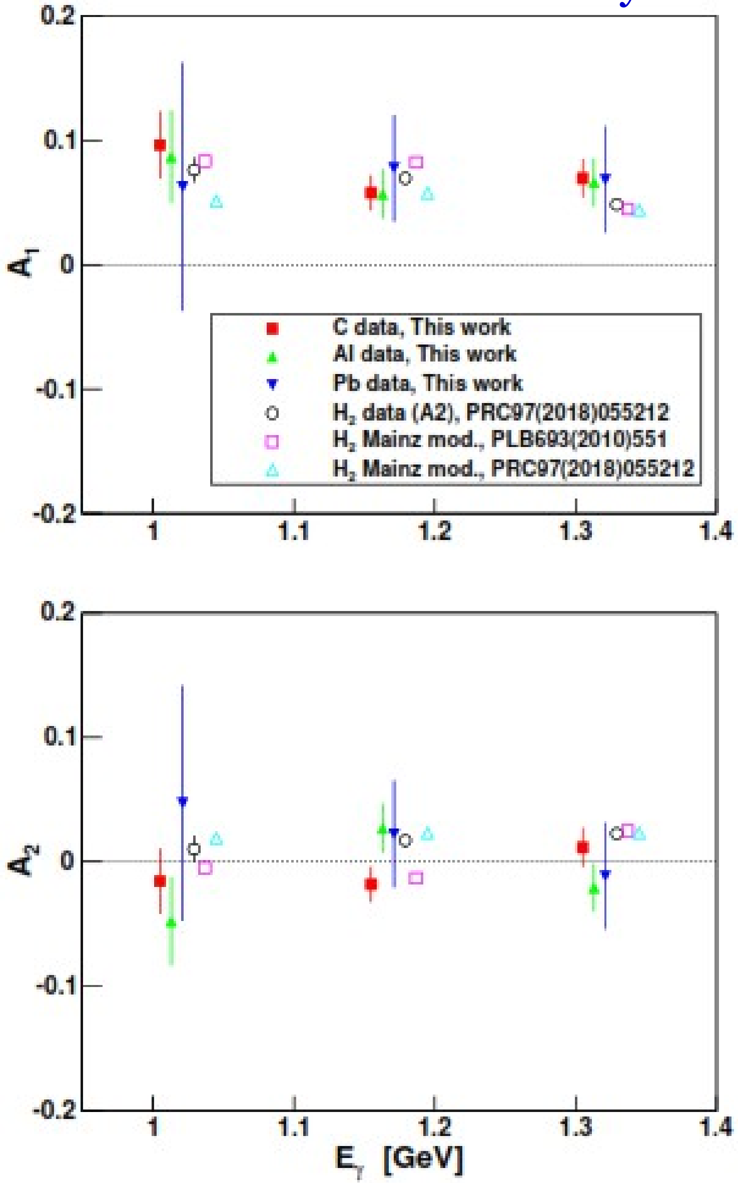
MaTm H2
MaTm (C, Al, Pb) with FSI
MaTm (C, Al, Pb) with FSI without the D33 wave

**V. Sokhoyan et al. [A2 Collaboration], Phys. Lett. B 802, 135243 (2020)**
**V. Sokhoyan et al. [A2 Collaboration], Phys. Rev. C 97, 055212 (2018)**

- Agreement between free proton and solid target data
- Very small differences for the MaTm model with/without FSI
- Removing the $D_{33}$ wave results in very large differences for Carbon (and other nuclei)

# Beam helicity asymmetry for $\pi^0\eta$ (C, Al, Pb) A2

Results of the Fourier analysis




$$I^{\odot}(\Phi_\pi) = A_1 \sin\Phi_\pi + A_2 \sin 2\Phi_\pi$$

A1: contribution of the $D_{33}$ wave

A2: interference with other resonances

- First study of the production of $\pi^0\eta$ pairs on heavy nuclei and of the beam helicity asymmetry with heavy targets
- Agreement between free proton and nuclear targets
- Final State Interaction observed to be small
- Asymmetry signal (absorption but no rescattering!?
- Detailed theory calculations needed!

**The method works!**

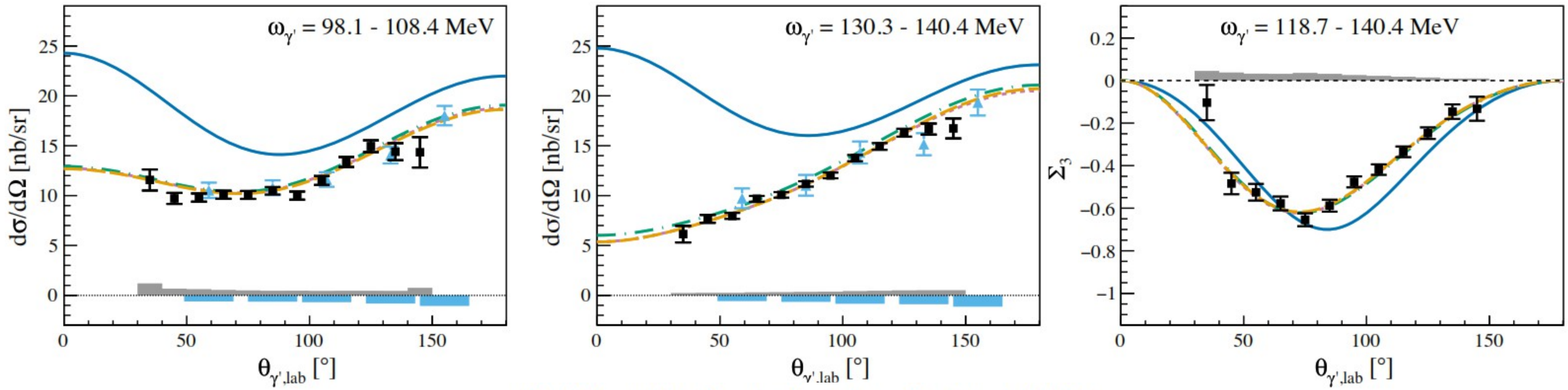
- Alternative approach for studying in-medium effects
- Low FSI effects
- High statistics data sets needed for further confirmation!
- Other possibilities: e.g., use linearly polarized photons or other reactions (dependent on the topic of interest)

**V. Sokhoyan et al. [A2 Collaboration], Phys. Lett. B 802, 135243 (2020)**

# Compton scattering on the proton and light nuclei

Highest statistics data set for Compton scattering on the proton below pion threshold (with linearly polarized photons
→ accurate extraction of the scalar polarizabilities

$$\Sigma_3 = \frac{d\sigma_\parallel - d\sigma_\perp}{d\sigma_\parallel + d\sigma_\perp}$$




$$\alpha_{E1} = 10.99 \pm 0.16 \pm 0.47 \pm 0.17 \pm 0.34$$

$$\beta_{M1} = 3.14 \pm 0.21 \pm 0.24 \pm 0.20 \pm 0.35$$

Extraction only based on this data set!

**E. Mornacchi et al. [A2 Collaboration], Phys. Rev. Lett. 128, 132503 (2022)**

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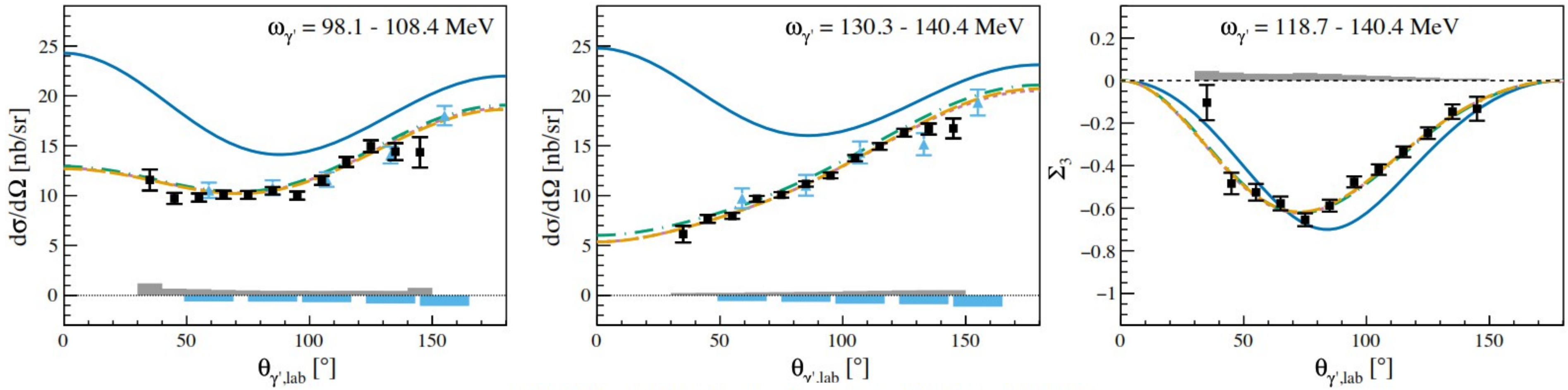


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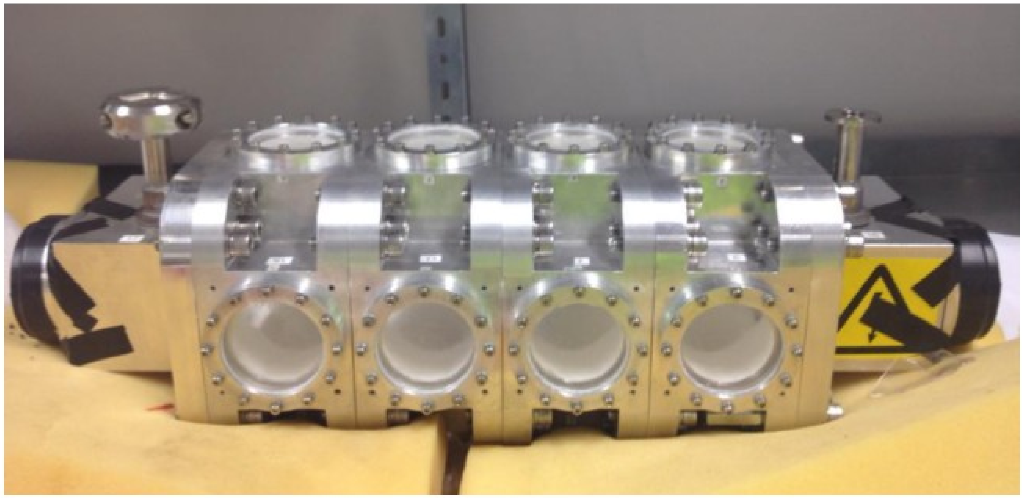
Extraction only based on this data set!

**E. Mornacchi et al. [A2 Collaboration], Phys. Rev. Lett. 128, 132503 (2022)**

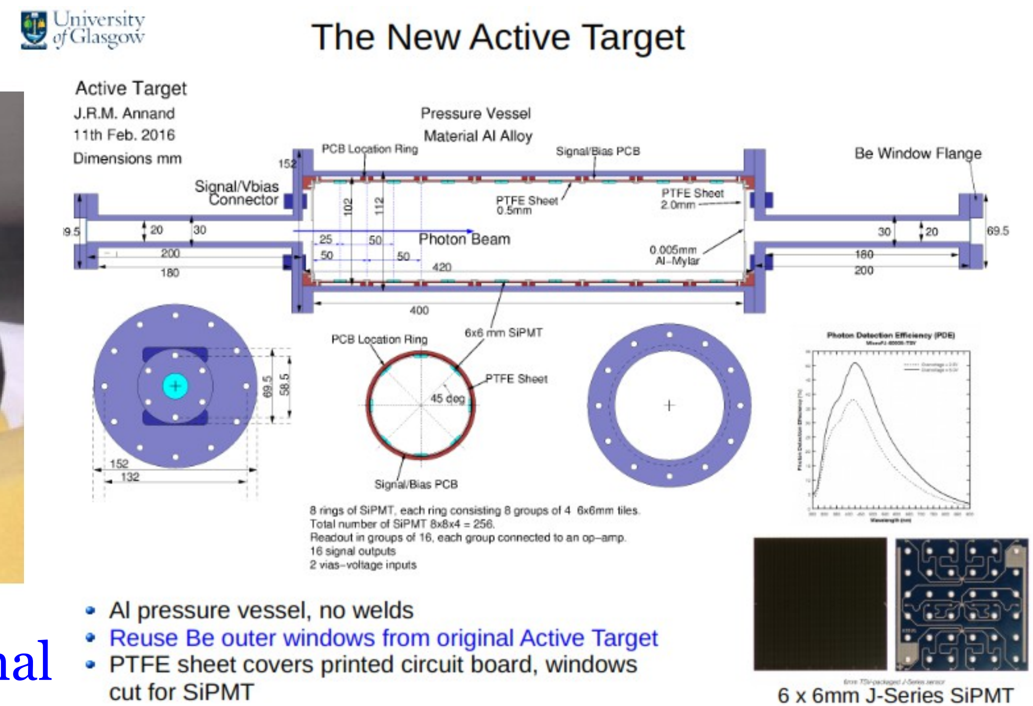
Next step: precise determination of the scalar polarizabilities of the neutron!
(MAMI PAC proposal: P.P. Martel, D. Hornidge, E. Downie)
→ Compton scattering on $^{3,4}$He or deuteron
→ Detection of low-energetic recoil particles needed to separate Compton scattering on $^{3}$He

Further applications of recoil detectors: Measurement of the proton radius via dilepton photoproduction at the low momentum transfer, measurement of the proton radius via elastic electron scattering (PRES experiment at MAMI), applications for meson photoproduction on nuclei, …

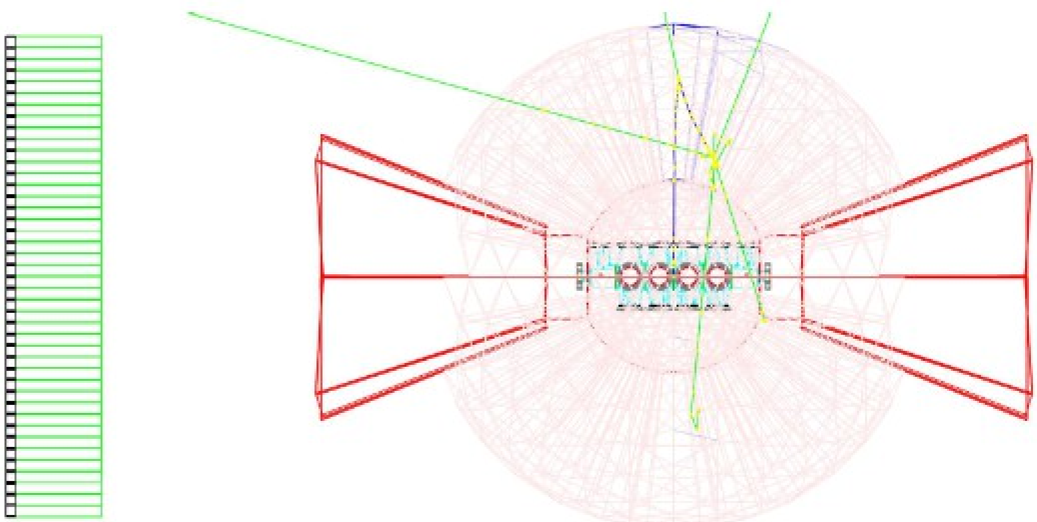
# Ongoing developments with a He active target (scintillation-based)

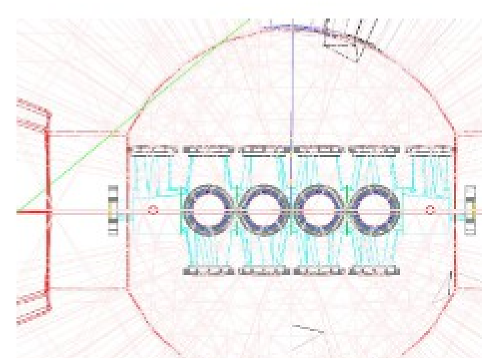


Prototype target from Max-Lab with external PMT readout (in Mainz)




Prototype with SiPMs inside the target

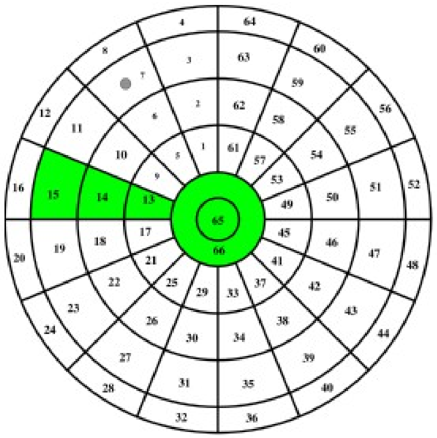


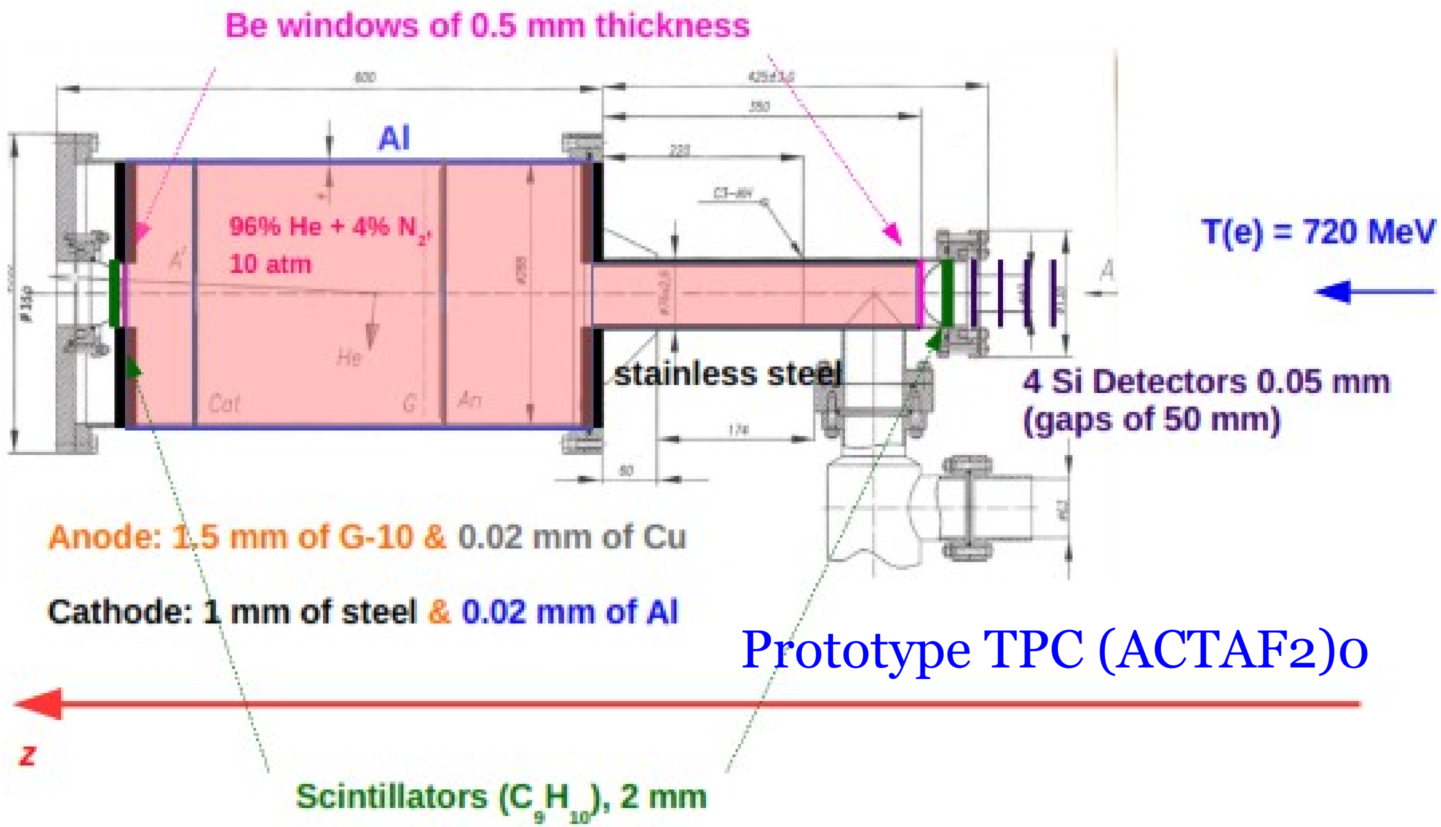


GEANT simulation of the active target in CB (J. Annand et al. )

# Next steps: Detection of low-energy recoil particles with TPC

Segmented anode (?)





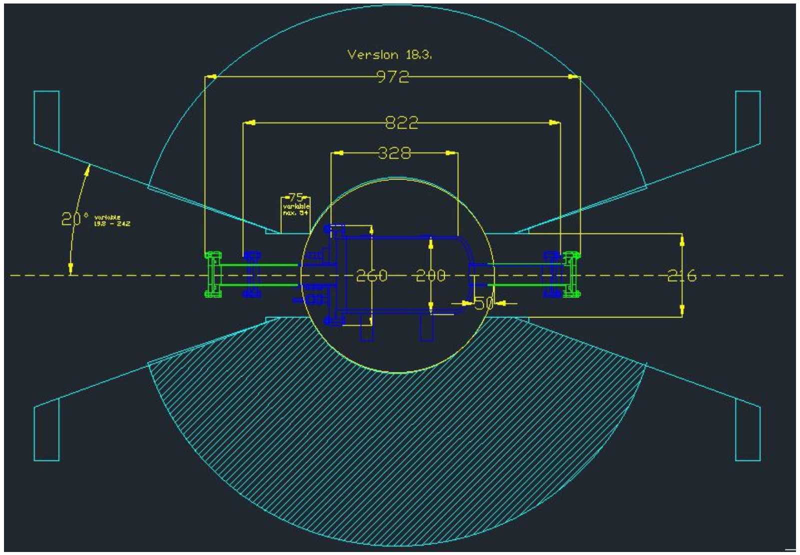

Prototype TPC (ACTAF2)0

**TPC as an active target (developed at PNPI):**

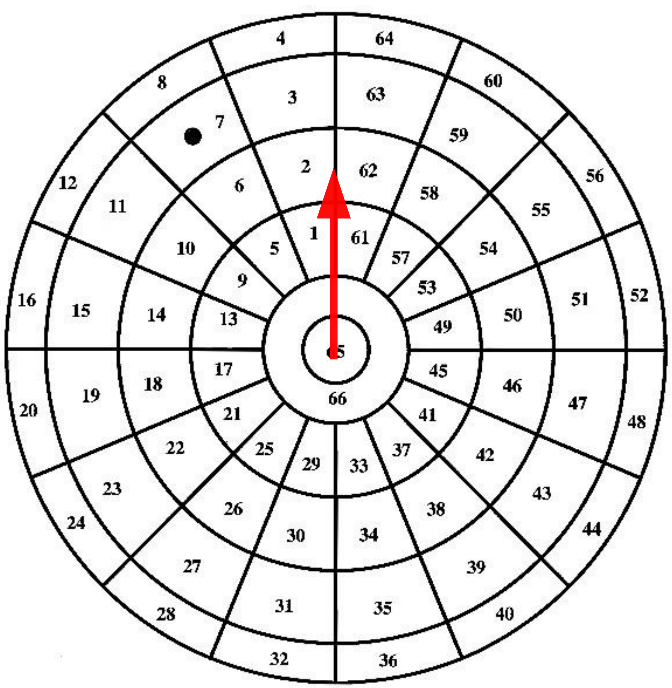
- Pressure up to 25 bar with hydrogen, deuterium, helium, argon, ...
- ΔE~20-30 keV, Δθ~2-3°, φ can be accessed with a segmented anode
- Vertex reconstruction (resolution better than 0.5 mm for Z)
- Small size (diameter = 200 mm) possible, length of the active volume: ~20 cm

→ **Novel experiments with detection of low-energetic recoil particles!**

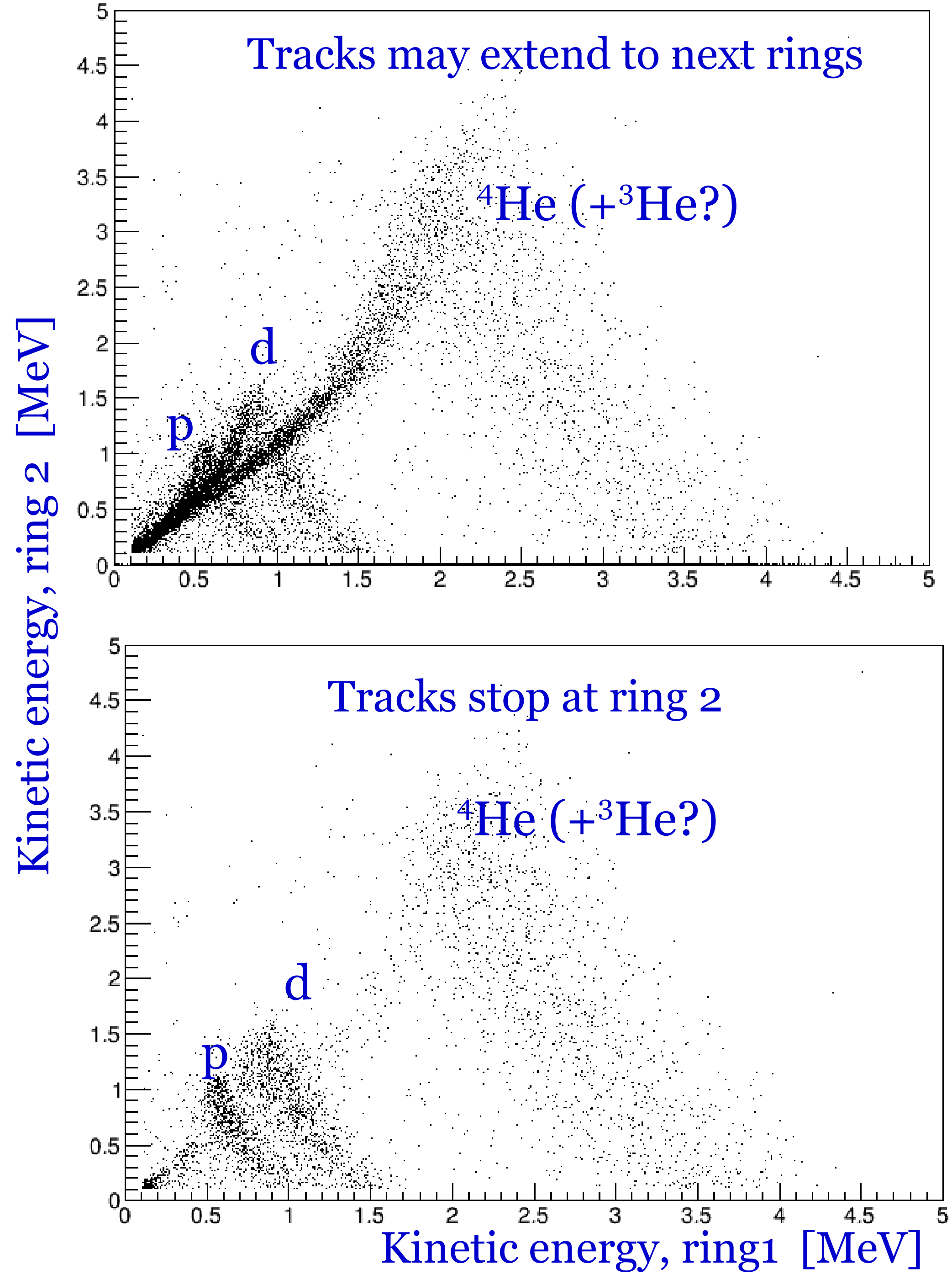
# Separation of recoil particles with TPC (electron beam at MAMI)




**Possible installation in CB**



**Anode structure**



# Summary

- Broad program for the measurement polarized beam/target/recoil asymmetries
- New results of baryon resonances, d*(2380), nucleon polarizabilities,...
- Polarization observables measured on nuclear targets are less affected by FSI compared to unpolarized cross sections
- Recent asymmetry measurements for $\pi^0\eta$ heavy targets open a new path for experiments of this kind
- New approach with detection of low-energy recoil targets with active targets (scintillation-based, TPC, ...) enabling novel experiments in meson and dilepton photoproduction, Compton scattering, electron scattering,...

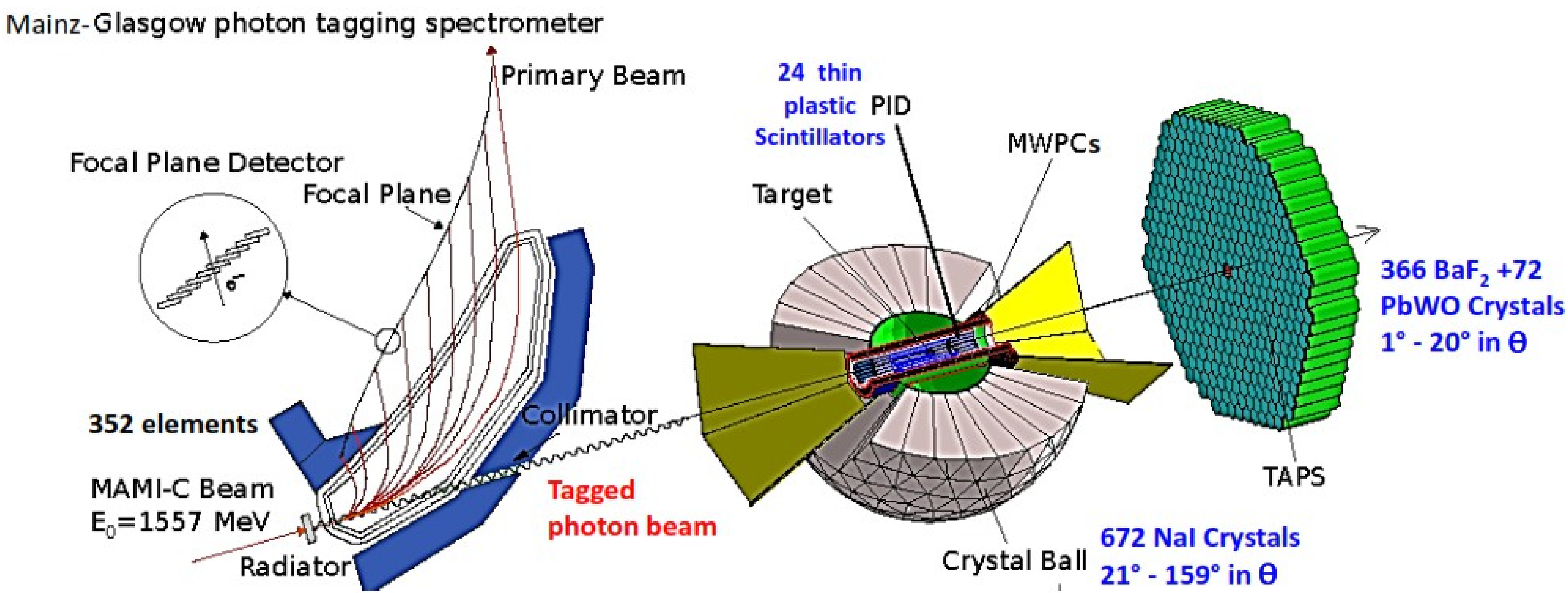
A2 | MAMI MAINZER MIKROTRON | SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL | Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter PRISMA

Carl Zeiss Stiftung

**Thank you for your attention!**

# Backup

# Crystal Ball/TAPS experiment at MAMI (A2)

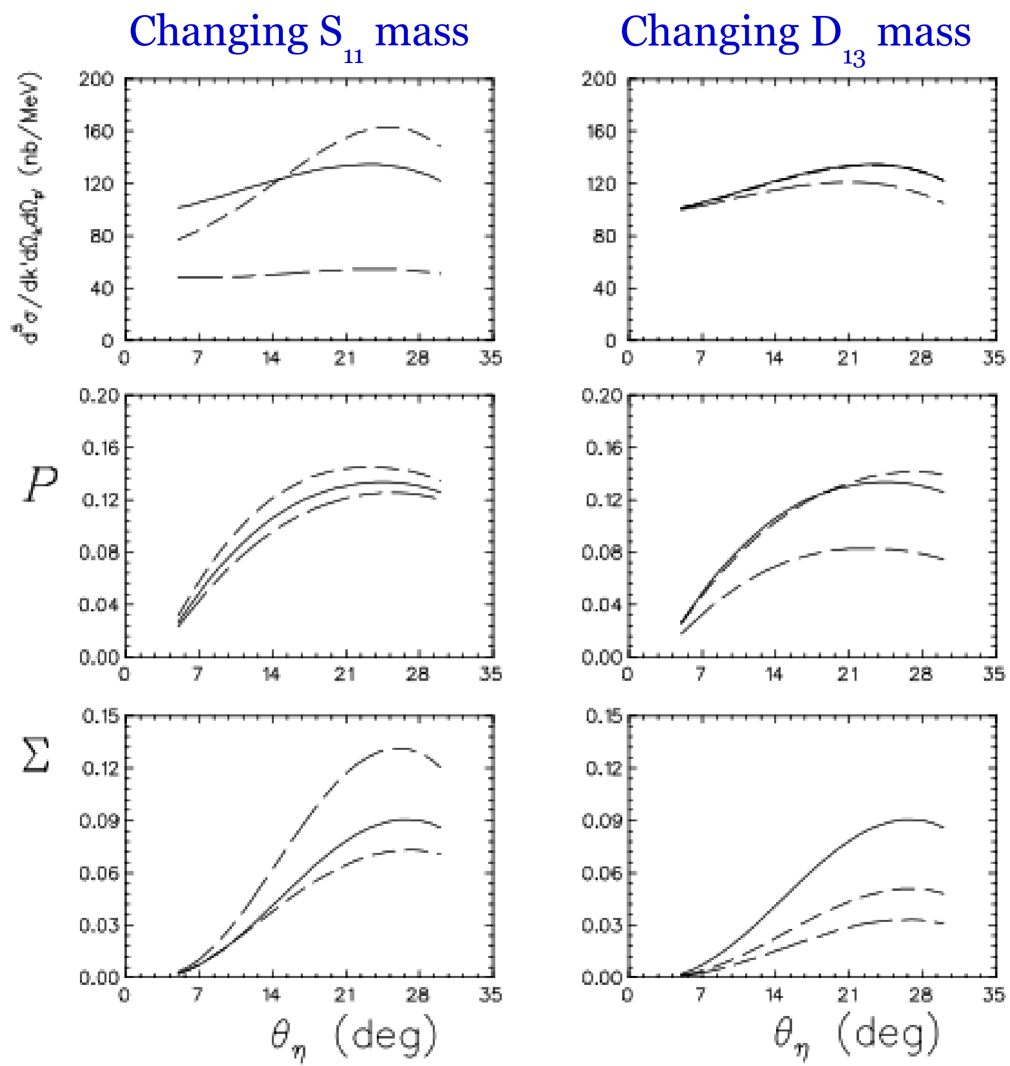



Polarized Butanol/D-Butanol

- High-Flux, Tagged, Bremsstrahlung Photon Beam (unpolarized, linearly or circularly polarized)
- Polarized and unpolarized targets
- Recoil polarimeter
- Further developments: active He gas target, active TPC high pressure TPC,...

# Further ideas: Single η photoproduction of on nuclei

" ...the current experimental work for quasifree scattering has thus far been limited to the measurement of the total and differential cross sections... **polarization show the promise of discerning the subtle dynamics in meson photoproduction processes**."




Carbon target
$E\gamma$ = 750 MeV, $p_{miss}$ = 100 MeV/c

Solid: no mass shift for $D_{13}$(1520) and $S_{11}$(1535)
Long-dash short-dash line: Masses increased by 3%; Dashed: masses decreased by 3%

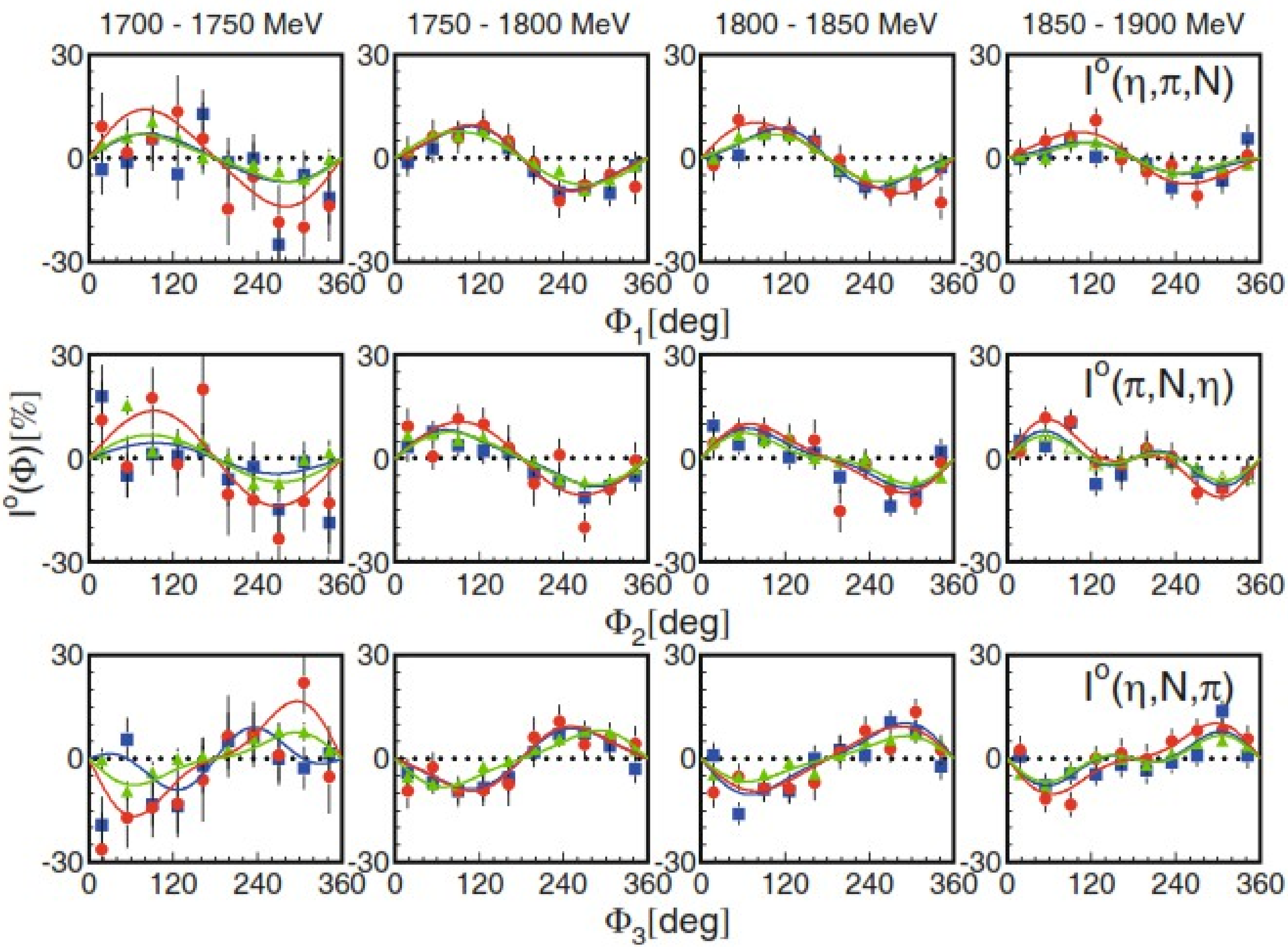
(Calculations with Walecka model)

- **Significant sensitivity to mass changes in many kinematic regions both for $S_{11}$ and $D_{13}$ resonances**
- **FSI effects predicted to be small for asymmetries**

**→ Can be measured with high accuracy, e.g, in A2**

**B.I.S. van der Ventel et al., Phys.Rev.C 68 (2003) 024601**
**In agreement with results from F. X. Lee et al., Nucl.Phys. A 603, 345 (1996)**

# $\pi^0\eta$: Beam helicity asymmetry (deuteron)




free proton
quasifree proton
quasifree neutron

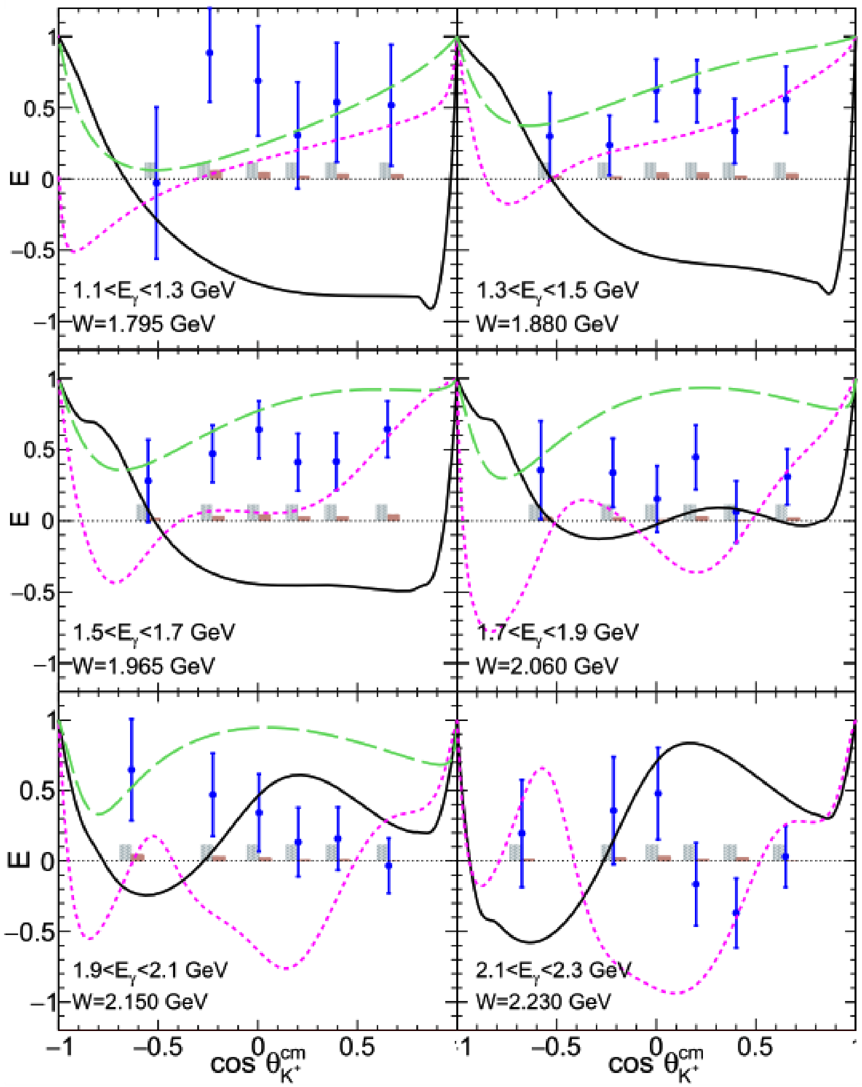
Curves: fit to the data

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

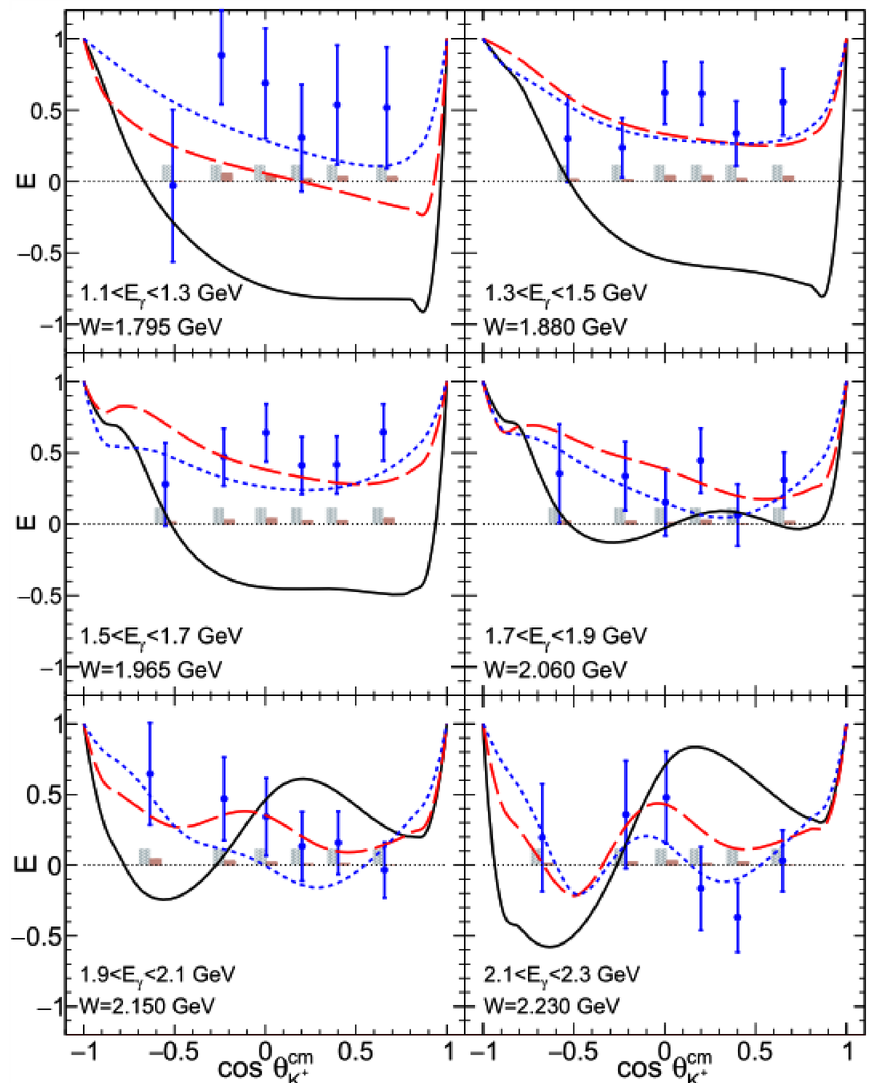
**A. Käser et al., Eur.Phys.J. A52, 272 (2016) [A2 Collaboration]**

**Agreement between free and quasi-free proton data!**

# CLAS: E observable for $K^+\Sigma^-$ on the neutron




Kaon MAID 2000 and 2017
BnGa (predictions)




BnGa-2017 solutions (prediction)
BnGa fit including the new data
BnGa fit including the new data + D13 at 2170 MeV

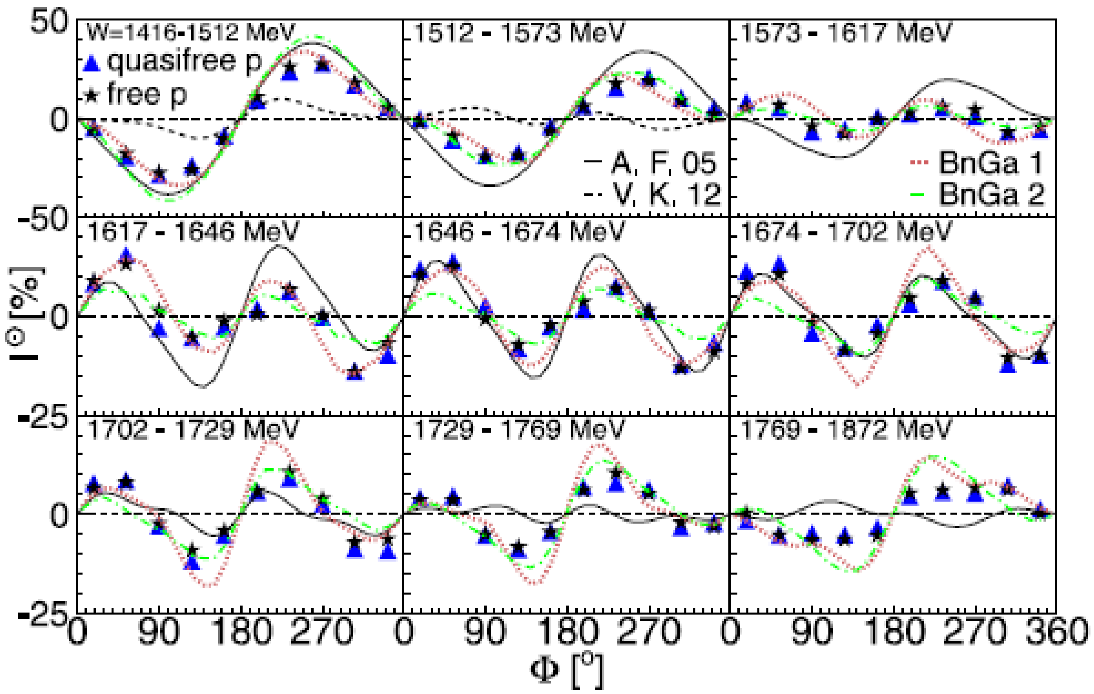
Reduction of $\chi^2$ in the fits of the existing LEPS data on Σ a with a new D13 resonance → **New precise data on Σ**

LEPS: D. Ho, et al., Phys. Rev. Lett. 118, 242002 (2017)

**N. Zachariou et al., Physics Letters B 808, 135662 (2020)**

# Photoproduction of two neutral pions

*Example: Significant reduction of the total cross-section was observed for the deuteron target in several reactions, indicating strong FSI effects, but e.g. for the production of 2 neutral pions, the beam helicity asymmetry is in excellent agreement for the free proton (hydrogen target) and quasi-free proton (deuteron target) data*

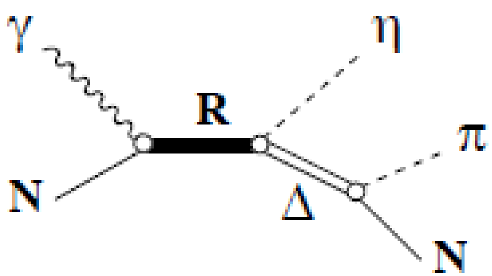



Black: free proton, Blue: quasi-free proton

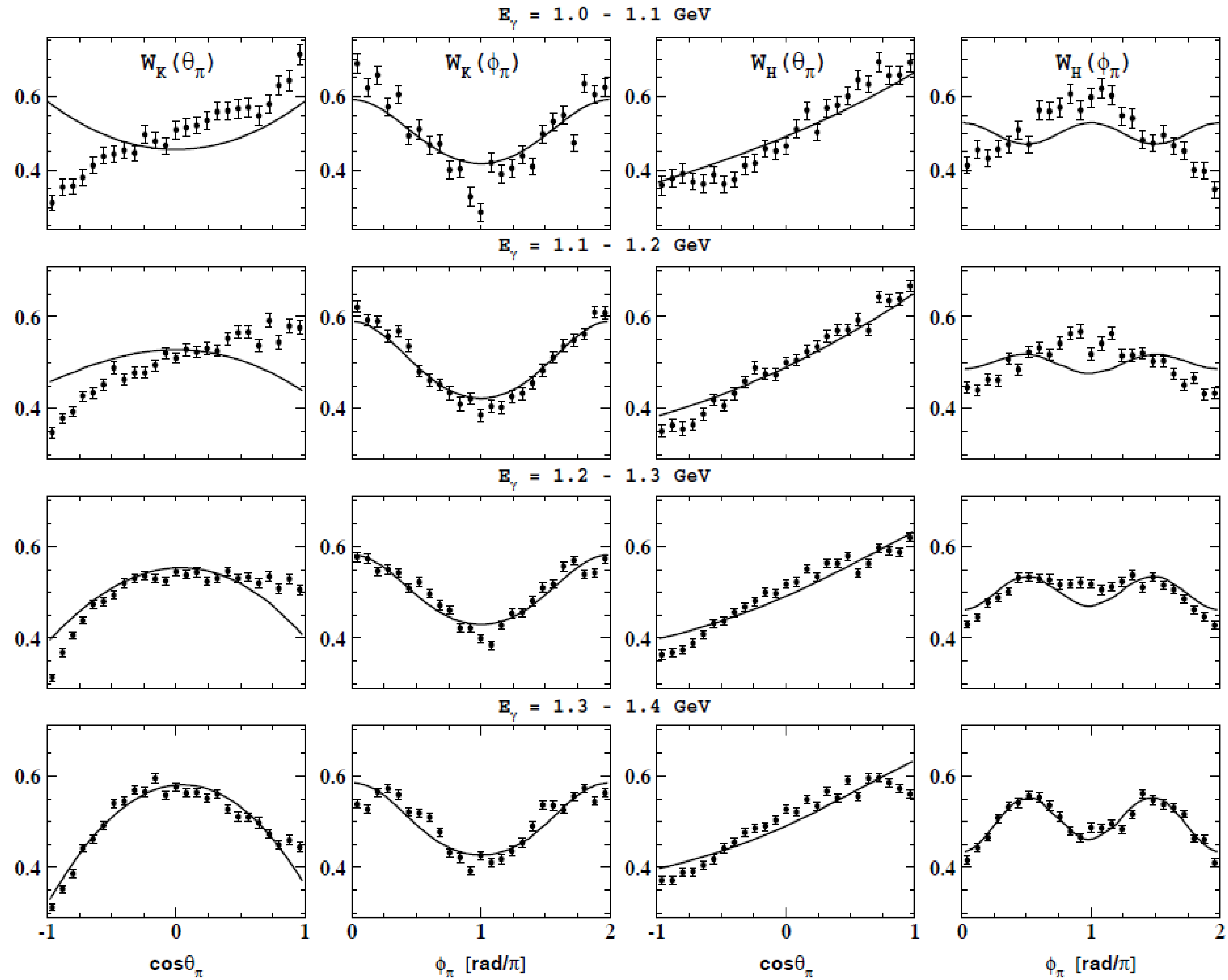
*M. Oberle, B. Krusche et al., Phys.Lett. B721 (2013) 237-243*

*[A2 Collaboration]*

# $\pi^o\eta$ differential cross-sections (proton target)



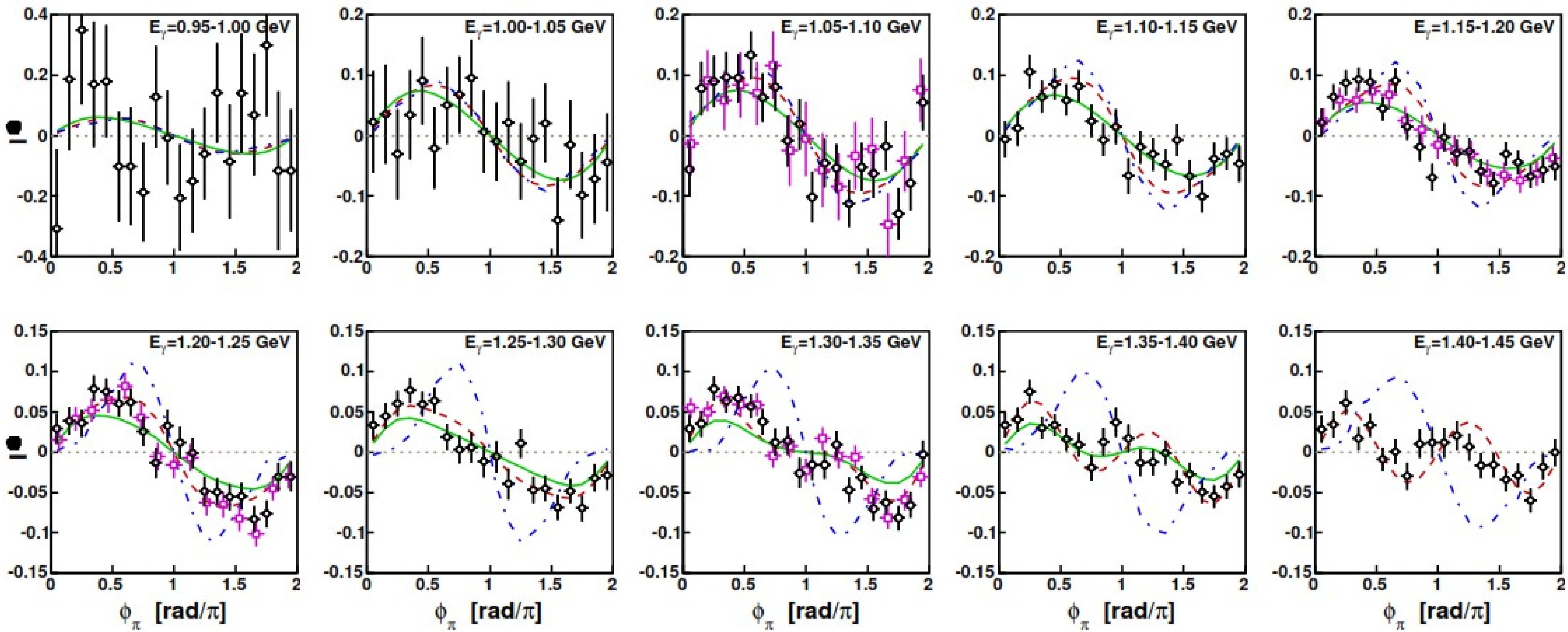

**R = $D_{33}$**




Angular distributions: Reasonable agreement with a model including only the $D_{33}$ amplitude

V. L. Kashevarov, A. Fix et al., Eur. Phys., J. A 42, 141 (2009)
[A2 Collaboration]

# $\pi^0\eta$: Beam helicity asymmetry (proton)




Run I and Run II (open circles)

Predictions:
BnGa PWA (2014): blue dash-dotted line
MaTm model: red dashed line

Fit of MaTm model to the present data: solid green line

- Significant differences at high energies between data and BnGa PWA
- High impact fpor PWA can be expected

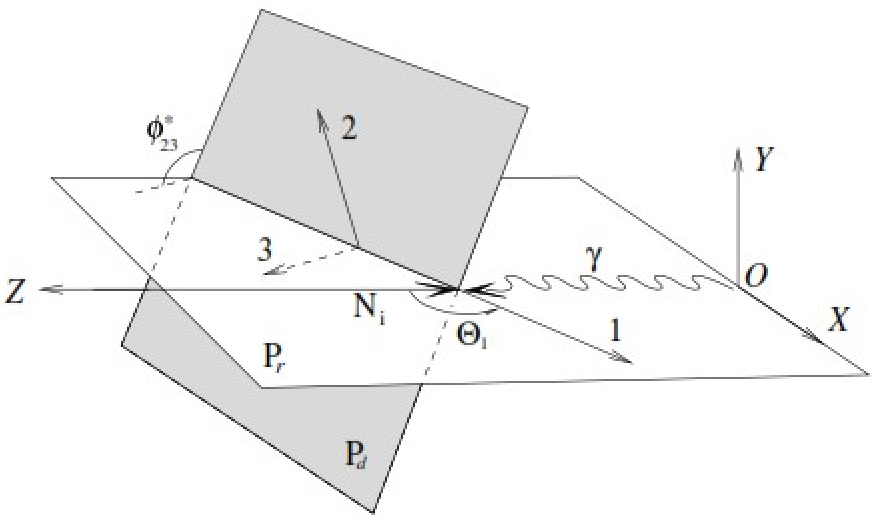
.... + add a reference to the existing data

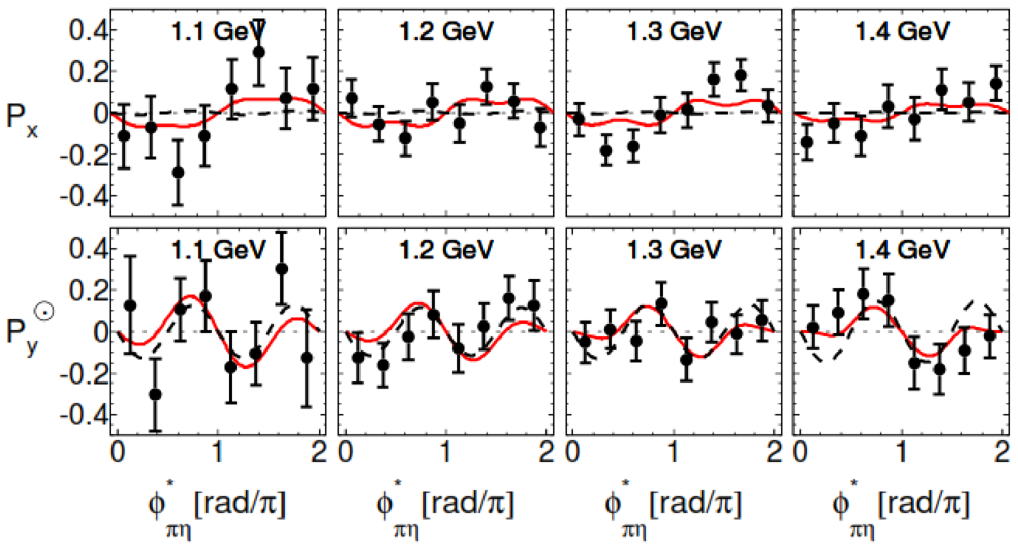
**V. Sokhoyan et al., Phys. Rev. C 97, 055212 (2018)**

# A2: $\pi^0\eta$ production, double polarization observables

$$\frac{d\sigma}{d\Omega_1 dM_{23} d\Omega^*_{23}} = \frac{d\sigma_0}{d\Omega_1 dM_{23} d\Omega^*_{23}} \Big\{ 1 + h P_\odot I^\odot + \frac{1}{\sqrt{2}} P_T [P_x \cos\phi - P_y \sin\phi + h P_\odot (P_x^\odot \cos\phi - P_y^\odot \sin\phi)] \Big\}$$

| Beam | Target | |
|---|---|---|
| | $x$ | $y$ |
| – | $P_x$ | $P_y$ |
| $c$ | $P_x^\odot$ | $P_y^\odot$ |



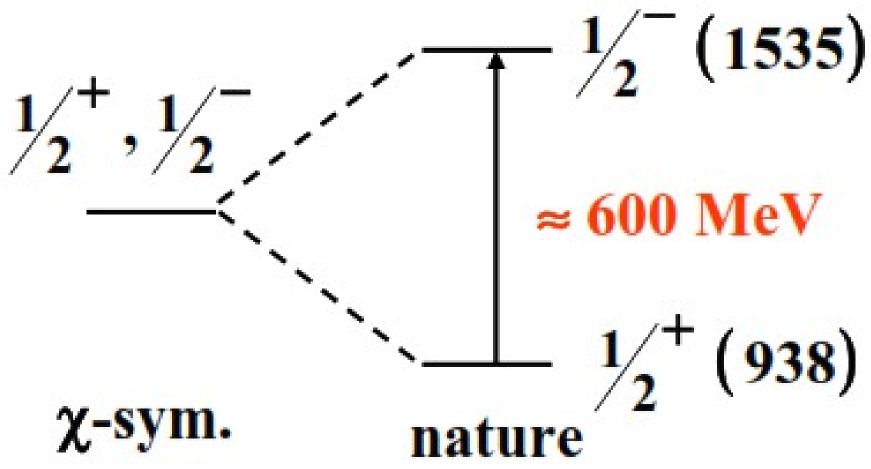

Dashed: only $D_{33}$ wave, solid: A. Fix model, dashed-dotted BnGa PWA

J. R. M. Annand et al., Phys.Rev. C91, no.5, 055208 (2015)

# Photoproduction of η on nuclei

**Are baryon resonances modified in the nuclear medium?**

- Which mechanisms are involved?
- What can we learn about the origin of mass?
- Can chiral symmetry be partially restored in the nuclear medium?




*"… in particular how N degenerates with its chiral partner, the N*(1, 535). An ambitious goal would therefore be to measure N*(1, 535) decays, e.g., in the Nη channel." (The CBM Physics Book)*

# interaction of mesons in nuclear matter

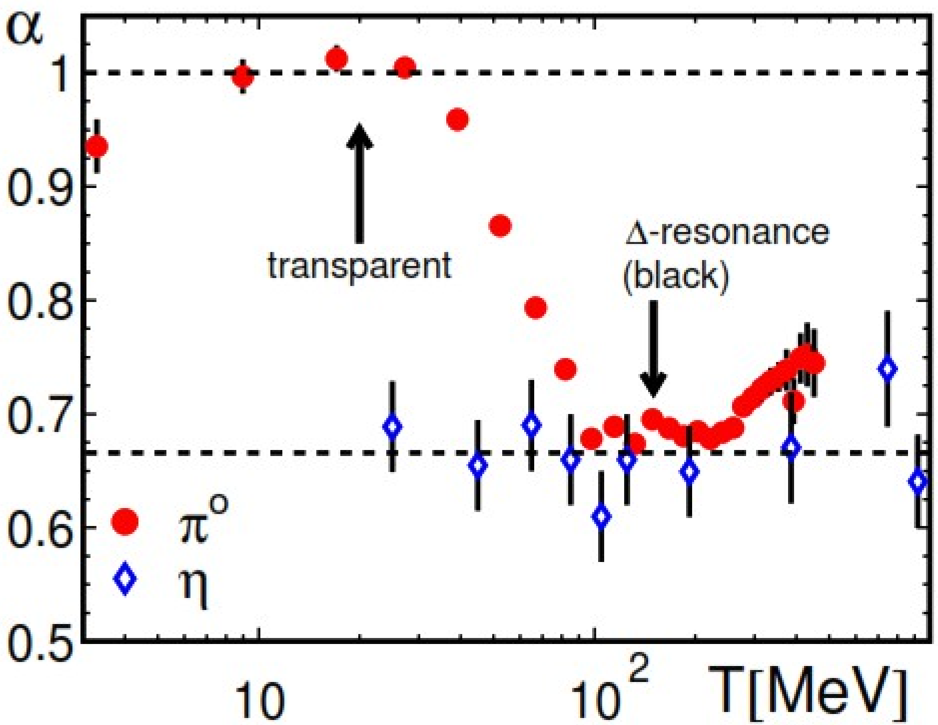
- results from inclusive (quasi-free) pion photoproduction

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

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

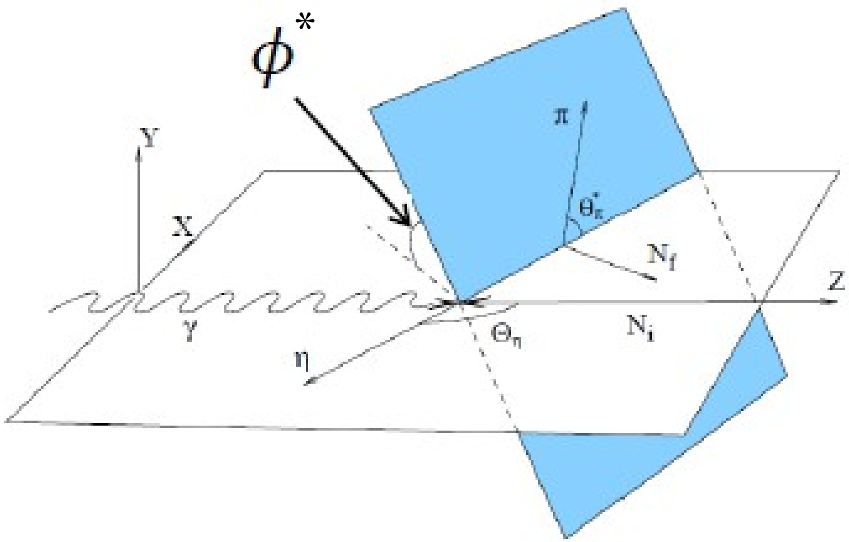
$\alpha \approx 1$: 'volume', no absorption

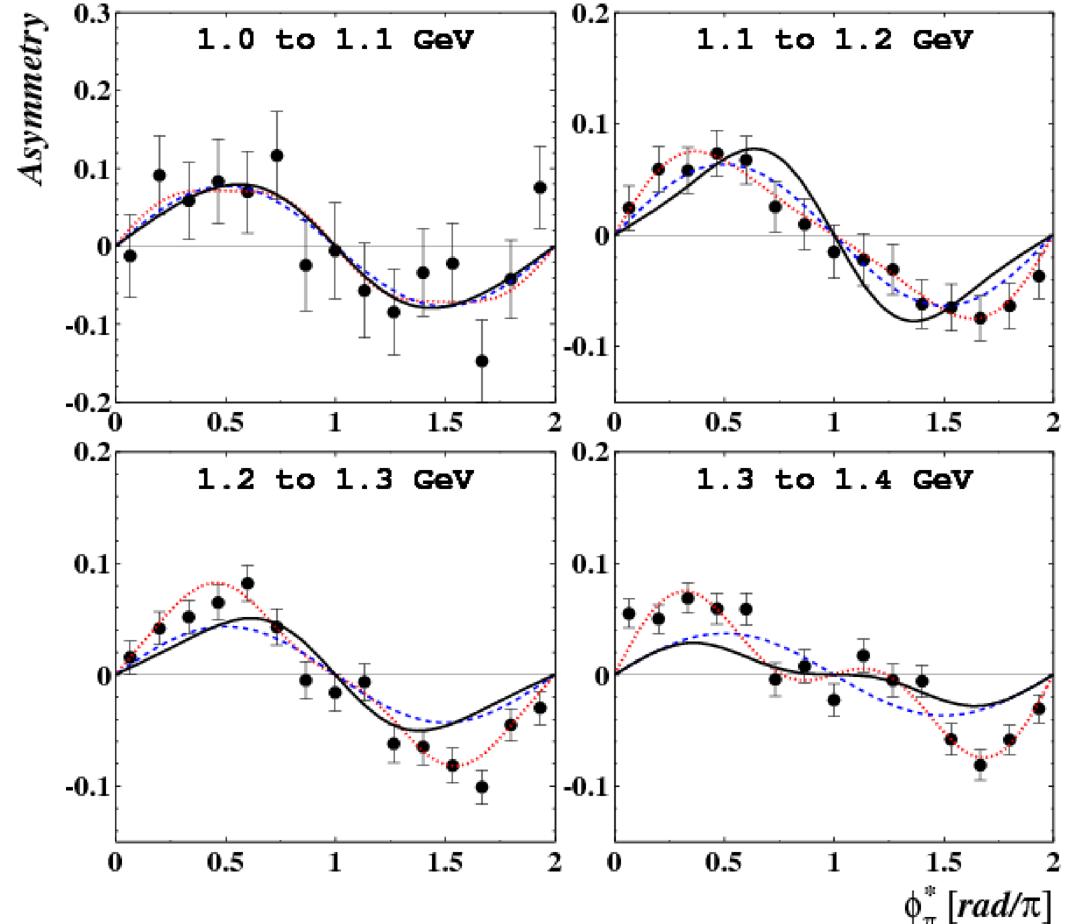
$\alpha \approx 2/3$: 'surface', strong absorption




- $\pi^o$-mesons: strongly absorbed at energies sufficient to excite $\Delta$; but only very weak interaction at small momenta
  $\longrightarrow$ no bound-states possible
- $\eta$-mesons: strong interaction also at very small momenta due to s-wave $S_{11}(1535)$ resonance at threshold
  $\longrightarrow$ strong enough for (quasi)-bound states?

# $\pi^0\eta$: Beam helicity asymmetry (proton target)




Beam helicity asymmetry:

$$W^c(\phi) \sim \sigma^+(\phi) - \sigma^-(\phi)$$

$W^c(\phi)$ can be expanded as:

$$W^c(\phi) = \sum_{n=1}^{n_{max}} A_n \sin n\phi$$

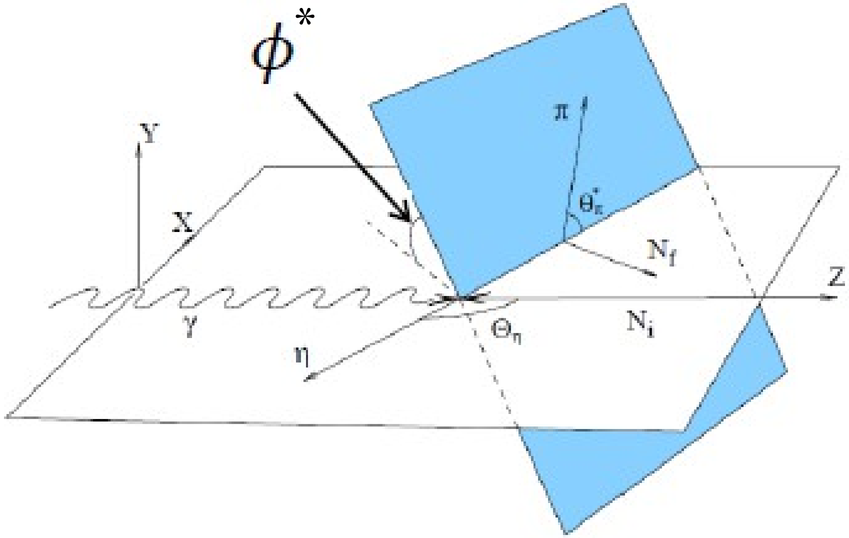
Dotted line: fit with the first 3 terms of the sine expansion (A1, A2, A3)
Solid line: isobar model with 6 resonances
Dashed line: only D33 wave

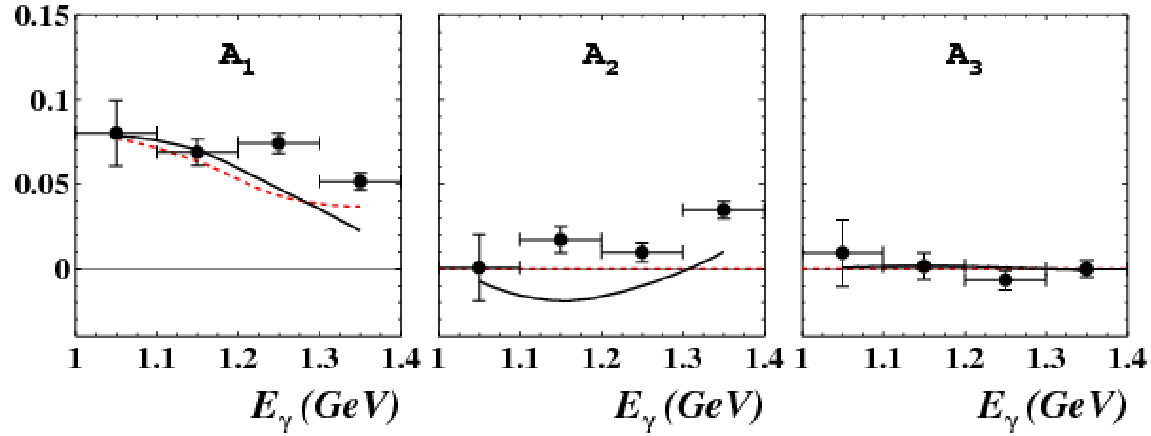
**V. L. Kashevarov, et al., Phys. Lett. B 693, 551 (2010)**

**[A2 Collaboration]**

**Both unpolarized and polarized data indicate the dominance of the $D_{33}$ wave at energies $E_\gamma$ < 1.2 GeV**

# Beam helicity asymmetry (proton target)




Coefficients of the sine expansion
Solid line : full model prediction
Dashed line: only the *D*33 amplitude.

**V. L. Kashevarov, et al., Phys. Lett. B 693, 551 (2010)**

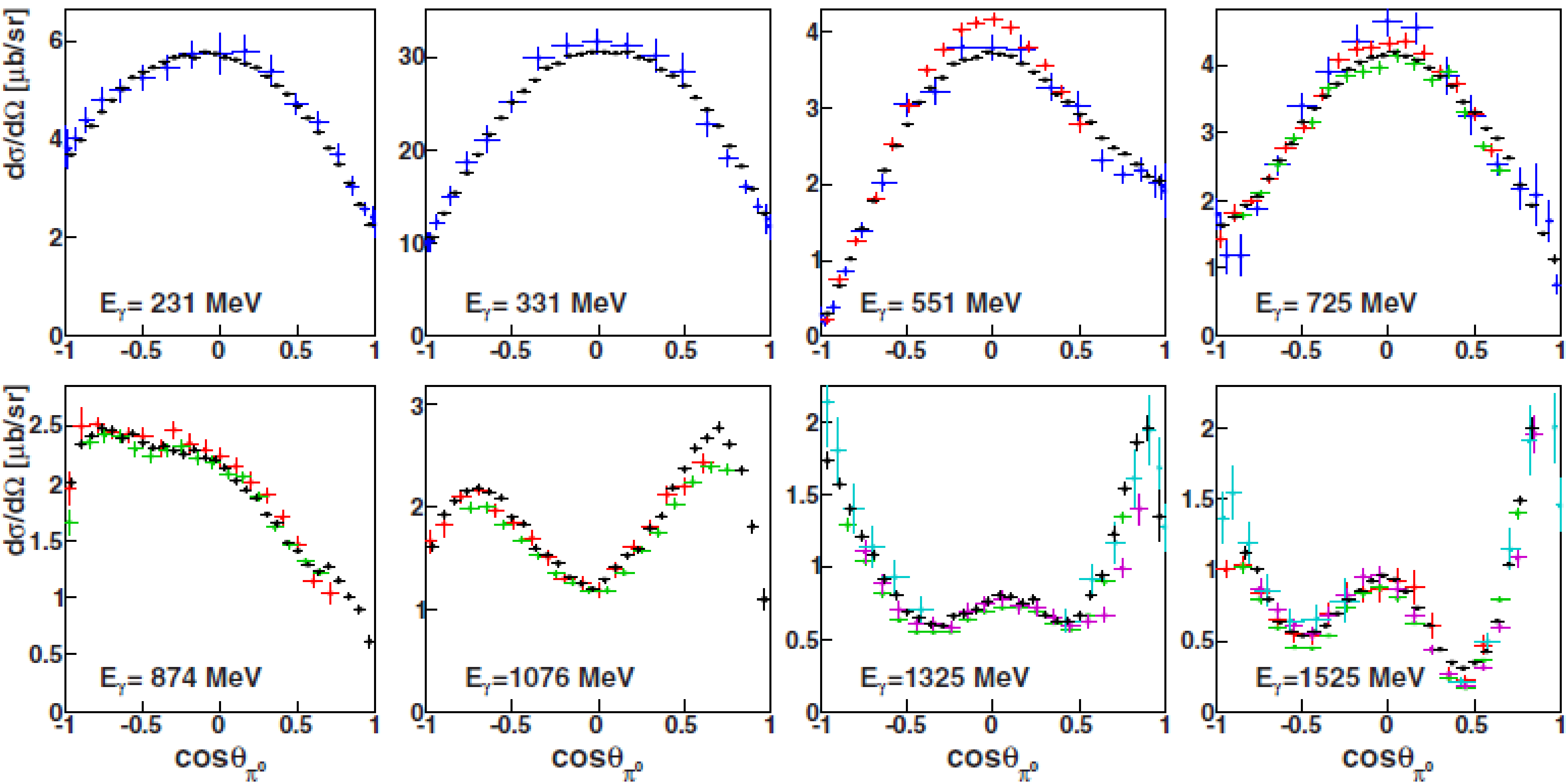
$W^c(\phi)$ can be expanded as:

$$W^c(\phi) = \sum_{n=1}^{n_{max}} A_n \sin n\phi$$

**A1 represents purely the contribution of the $D_{33}$ wave**
**A2 is sensitive to interference terms**
**A3 is negligible**

**Both unpolarized and polarized data indicate the dominance of the $D_{33}$ wave at energies $E_\gamma$ < 1.2 GeV**

# Single $\pi^o$ production




P. Adlarson et al., Phys.Rev. C92 (2015) no.2, 024617

MAMI 2006: R. Beck, R. Leukel, and A. Schmidt, Acta Phys. Pol. B 33, 813 (2002); R. Beck, Eur. Phys. J. A 28, 173(2006)

CBELSA/TAPS: V. Crede et al., Phys. Rev. C 84, 055203 (2011)

CLAS: M. Dugger et al., Phys. Rev. C 76, 025211 (2007)

GRAAL: O. Bartalini et al., Eur. Phys. J. A 26, 399 (2005)

- **Interpretation within further partial wave analyses**

# FSI in mixed pion channels

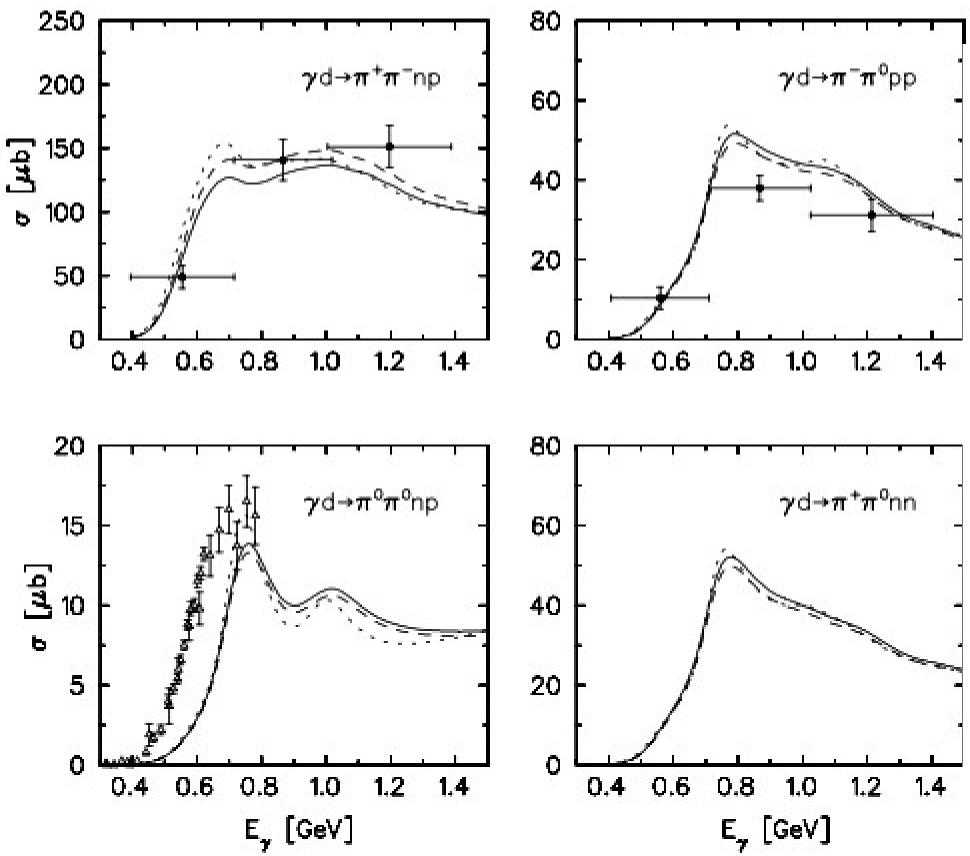


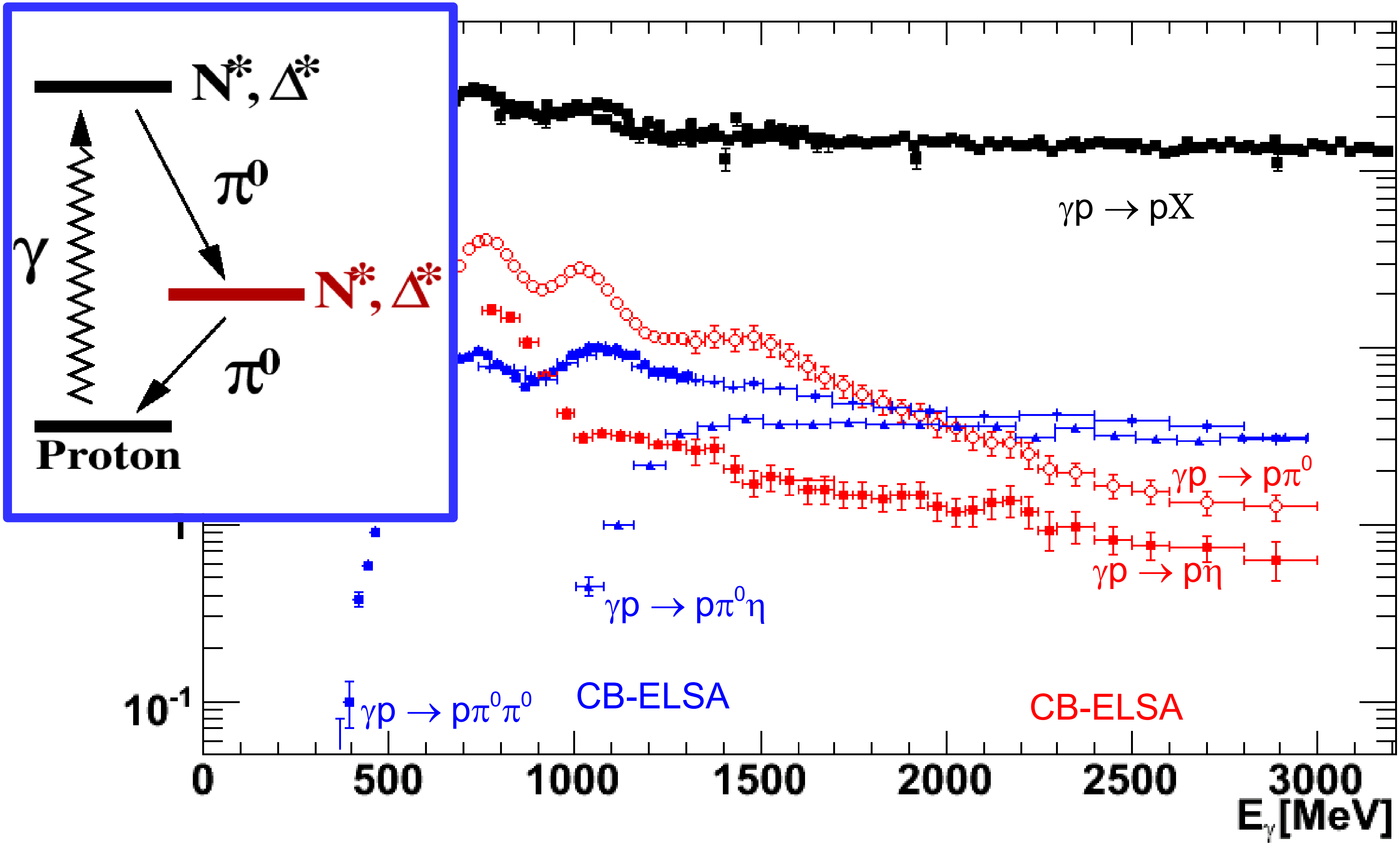

**Fig. 11.** Total cross section for incoherent double-pion photo production on a deuteron for different charge channels. Soli and dashed curves are obtained with and without final N interaction. Dotted curves show the corresponding elementar cross sections. In $\pi^+\pi^-$ and $\pi^0\pi^0$ channels they are calculated as a sum of the cross sections on a proton and a neutron. The data are from ref. [38] (circles) and ref. [39] (triangles).

This feature is easily explained by the relatively large momentum transfer associated with the production of two pions. Firstly, it leads to a reduction of the region of small distances between the nucleons, where the $NN$ interaction is sizeable. Furthermore, more importantly in the neutral channel where also the coherent transition (without deuteron break up) is possible, is the nonorthogonality of the initial and final $NN$ wave functions in IA. As a consequence, the IA contains part of the coherent reaction. The size of this "nonorthogonal contribution" is roughly given by the coherent cross section (see, *e.g.*, [40]) and depends strongly on the momentum transfer to the $NN$ subsystem (in the extreme case when the momentum transfer goes to zero, the IA contains it completely). In particular, this effect leads to a large role of $NN$ FSI in the single $\pi^0$ photoproduction on the deuteron where the coherent channel turns out to be quite sizeable. Again, the role of orthogonality in the $\pi\pi$ reactions is reduced because of a significantly increased momentum transfer. Comparison with the available data in fig. 11 shows that the agreement in the $\pi^+\pi^-$ and $\pi^-\pi^0$ channels is quite satisfactory. Deviation from the $\pi^0\pi^0$ data should arise from the same origin as that discussed above for the corresponding elementary reaction.

A. Fix and H. Arenhövel, Eur. Phys. J. A 25, 115{135 (2005)

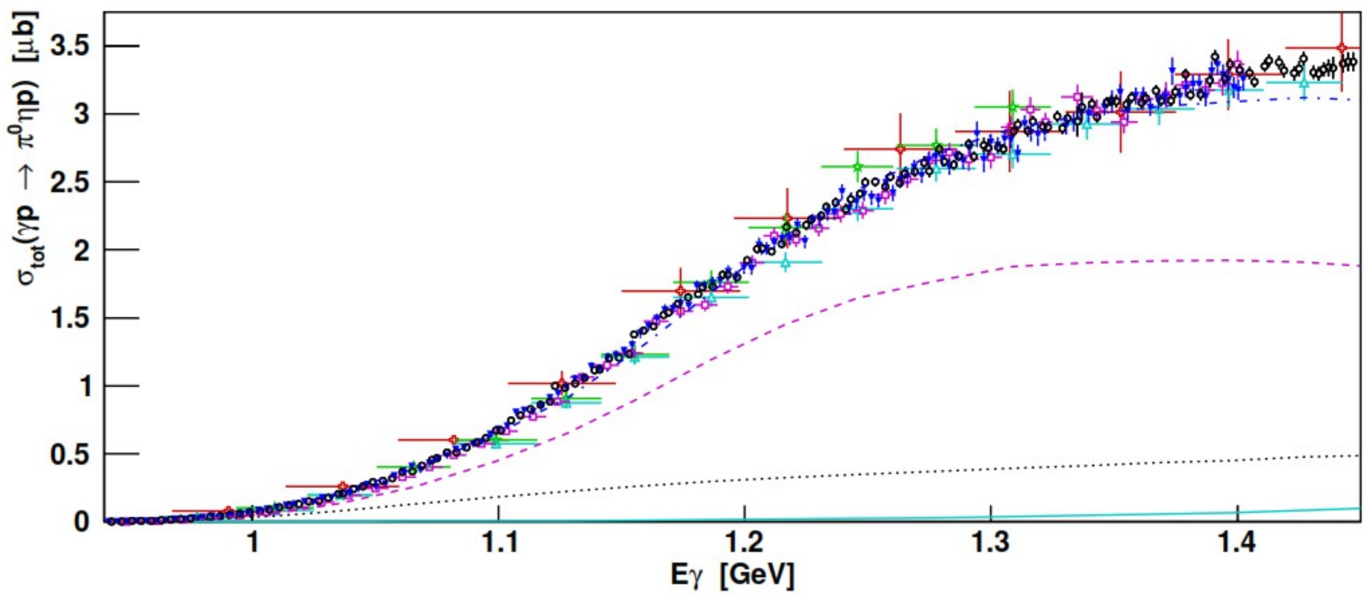
# Double meson photoproduction

Goal: Gain a good understanding of the spectrum and properties of baryon resonances




- At high energies: Multi-meson final states play a role of increasing importance!
- Access to resonances with cascading decays

# $\pi^0\eta$ production off the proton




Run I (blue solid triangles)
Run II (black open circles)
CBELSA/TAPS: green stars
CBELSA/TAPS: cyan open triangles
GRAAL: red open crosses
A2 (2009): magenta open squares

BnGA PWA: blue dash-dotted line
$\gamma p \to \Delta(1232)\eta$: magenta dashed
$\gamma p \to S11(1535)\pi^0$: black dotted
$\gamma p \to a_0(980)p$: cyan solid

New data set:

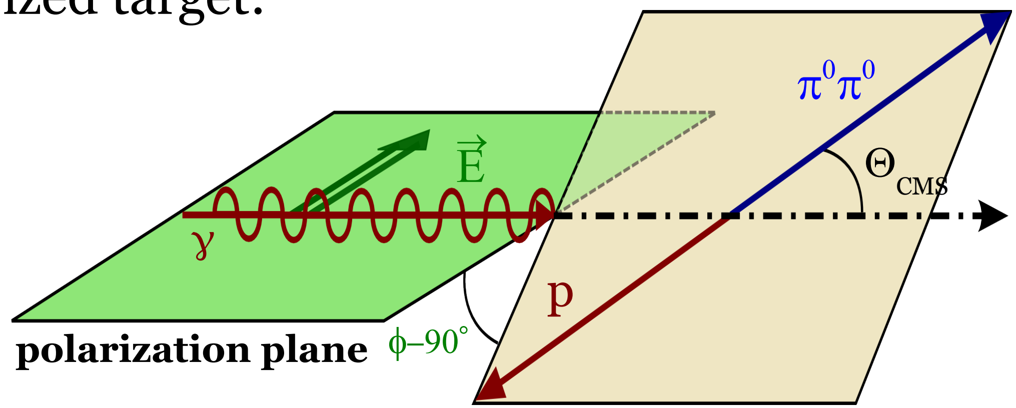
- Improved statistics: More than 1.500.000 events for the unpolarized cross-section and more than 1.000.000 events in the polarized sample
- Kinematic fit applied
- Event-based data (5D) sample obtained
- Finer binning and extension of the energy coverage to the threshold region
- Total cross-section, angular distributions, Dalitz plots and beam helicity asymmetry extracted → input for PWA with a potentially high impact

# Double pion production ($I^s$ and $I^c$)

Linearly polarized photon beam, unpolarized target:

Quasi two-body consideration:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 [1 + \delta_l \Sigma \cos(2\phi)]$$

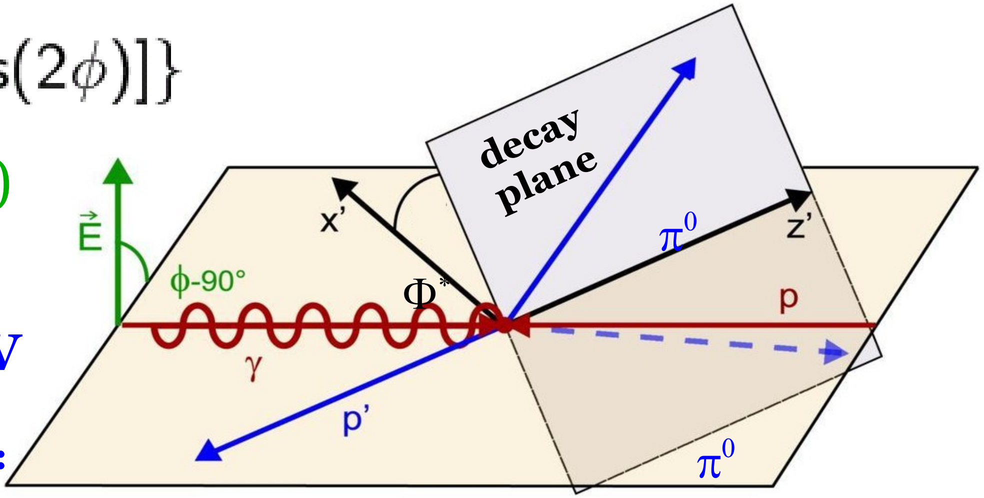



- Three-particle final state: additional plane!
- Additional polarization observables!

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \{1 + \delta_l [I^s \sin(2\phi) + I^c \cos(2\phi)]\}$$

$$I^c(\Phi^*) = I^c(2\pi - \Phi^*),\ I^s(\Phi^*) = -I^s(2\pi - \Phi^*)$$

**First measurement of $I^s$ and $I^c$**
**in $\vec{\gamma} p \rightarrow p\pi^0\pi^0$ at energies below ~700 MeV**

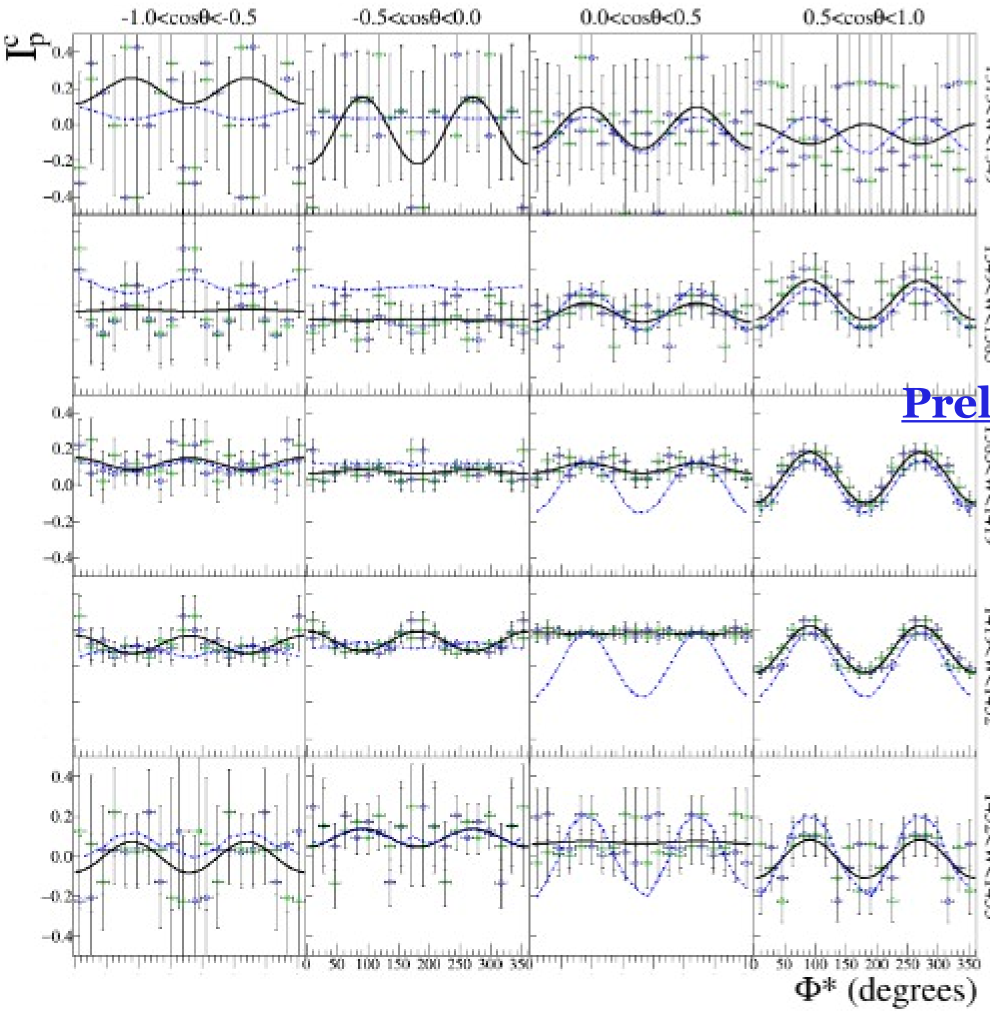



**Data from CBELSA/TAPS above 1 GeV had a high impact on PWA:**

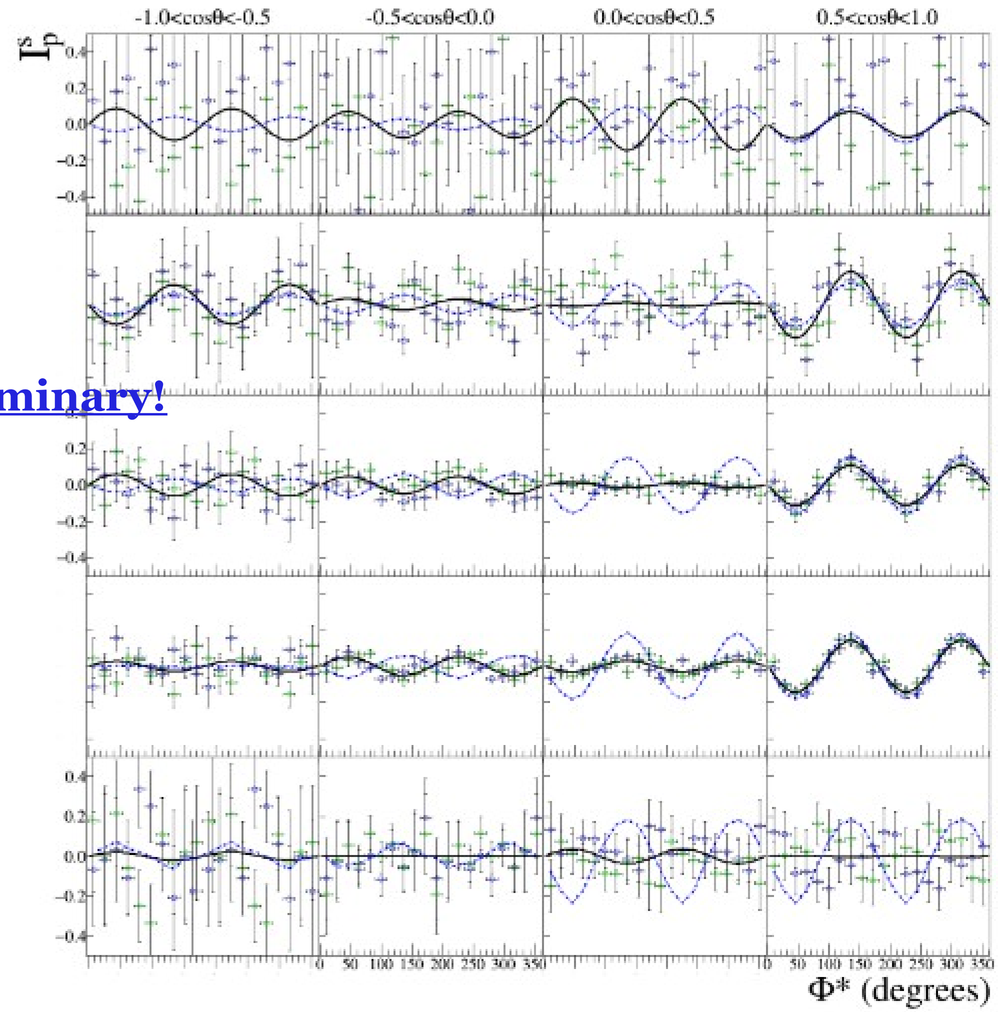

V. S. , E. Gutz, H. Pee, et al., Phys.Lett. B746 (2015) 127-131
V. S. , E. Gutz , V. Crede , H. Pee, et al., Eur.Phys.J. A51 (2015) no.8, 95

# Double pion production ($I^s$ and $I^c$)

$I^c(\Phi^*) = I^c(2\pi - \Phi^*)$




$I^s(\Phi^*) = -I^s(2\pi - \Phi^*)$

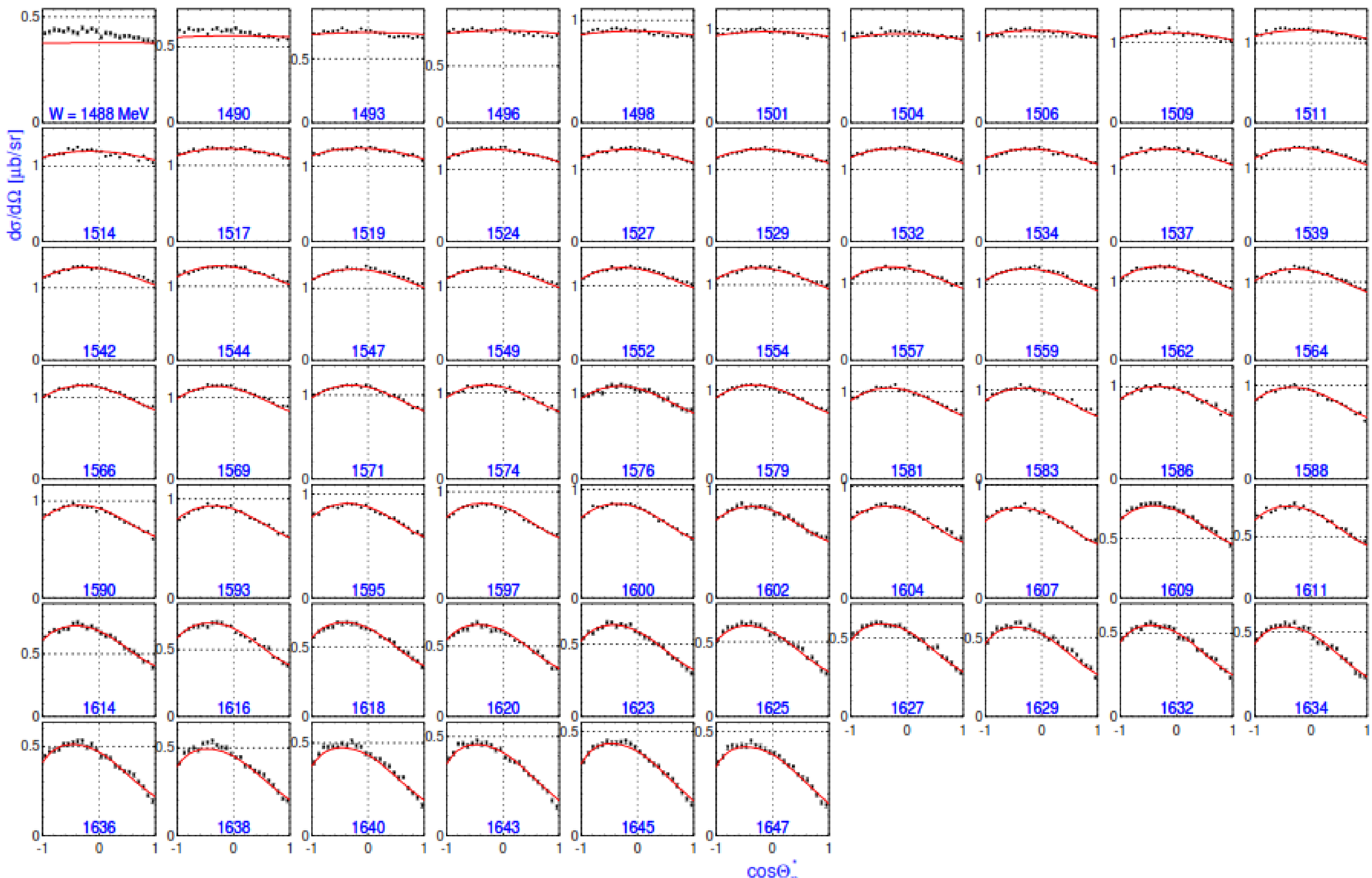



**Preliminary!**

**Solid curve: fit to the data with third order cosine/sine series,**
**dashed curve: BnGa PWA 2014 from (E. Gutz , V. Crede, V. S., H. van Pee, et al., Eur.Phys.J. A50 (2014) 74)**

**Significant differences between data and BnGa PWA predictions!**

# Single η production



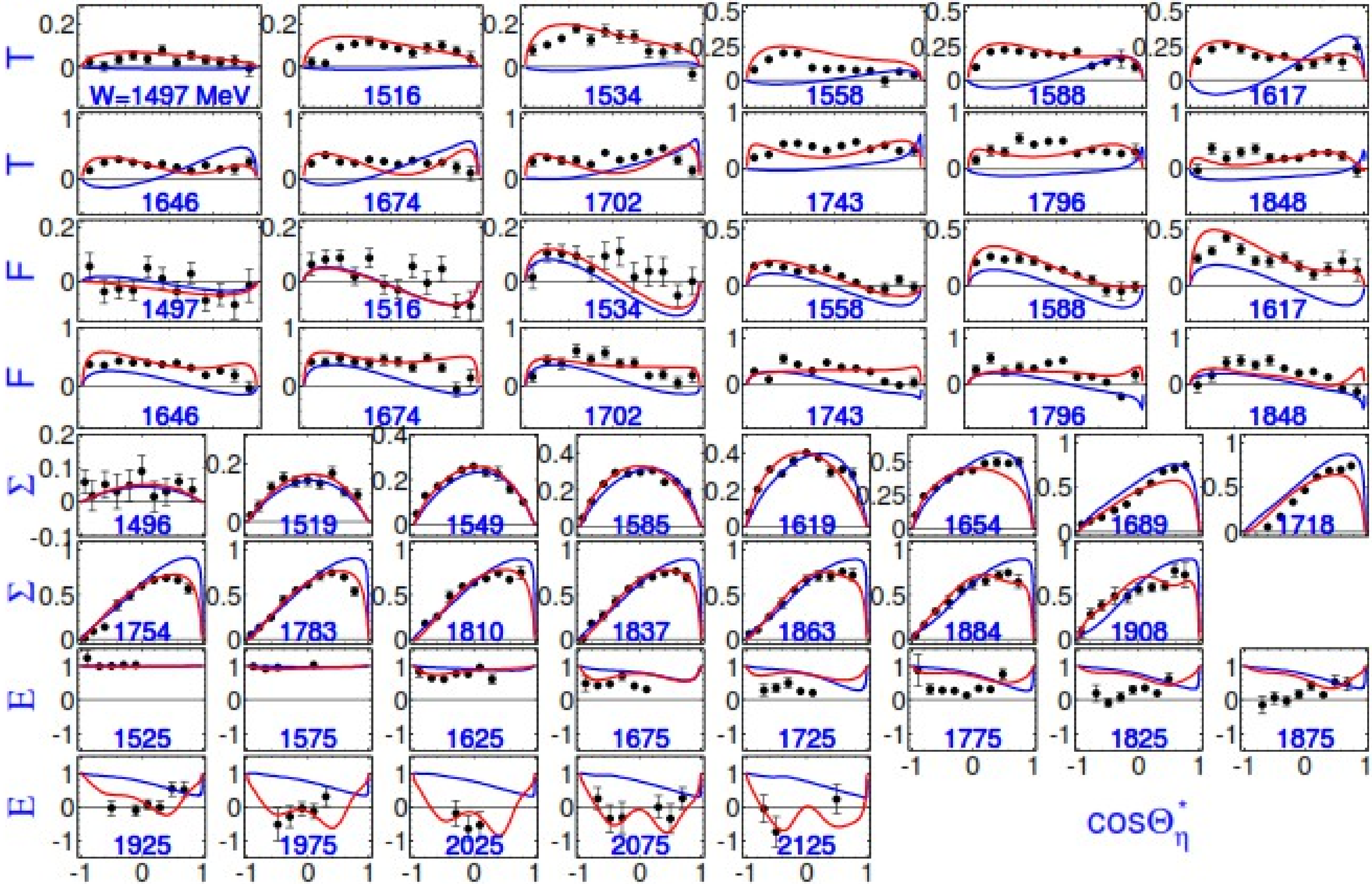

**Data and ηMAID full solution**

V. Kashevarov et al., Phys.Rev.Lett. 118 (2017) no.21, 212001v

# Single η production

T, F, Σ , and E for $\gamma p \rightarrow \eta p$

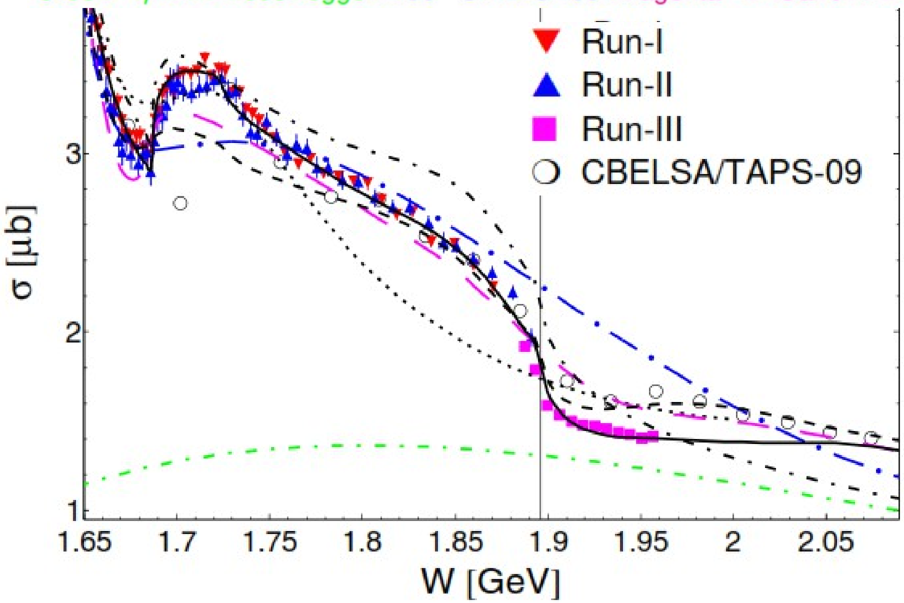
Data: A2MAMI-15 (T,F), GRAAL-07 (Σ), CLAS-15 (E). Red - full solution, - ηMAID03.



# Single η and η' production

Black lines: full solution (solid), background (dashed), $S_{11} + bg$ (dash-dotted).

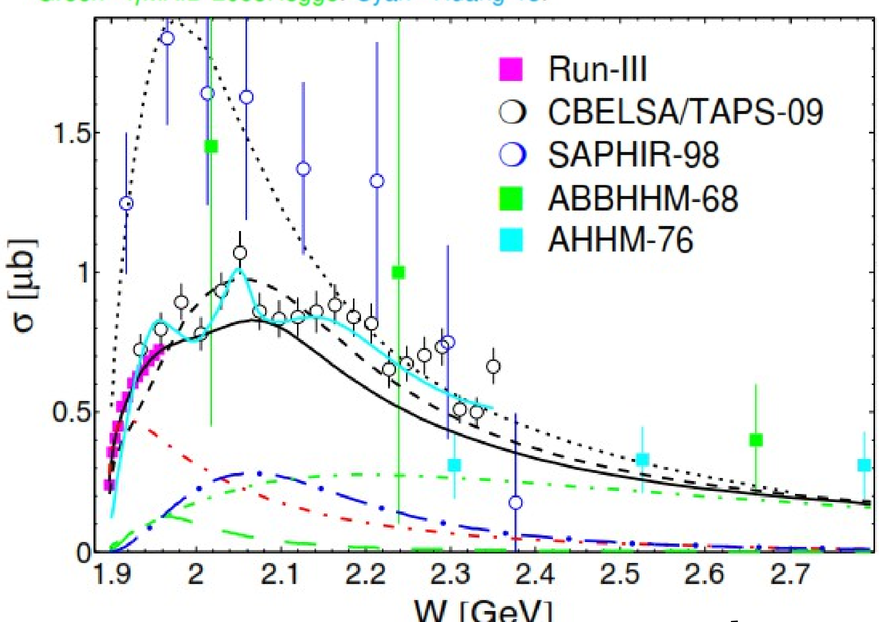
Green - ηMAID-2003Regge. Blue - SAID-GE09. Magenta - BnGa2014-2.




η

Black lines: full solution (solid), background (dashed), $N(1895)1/2^-$ (dash-dotted).

Green - ηMAID-2003Regge. Cyan - Huang-13.

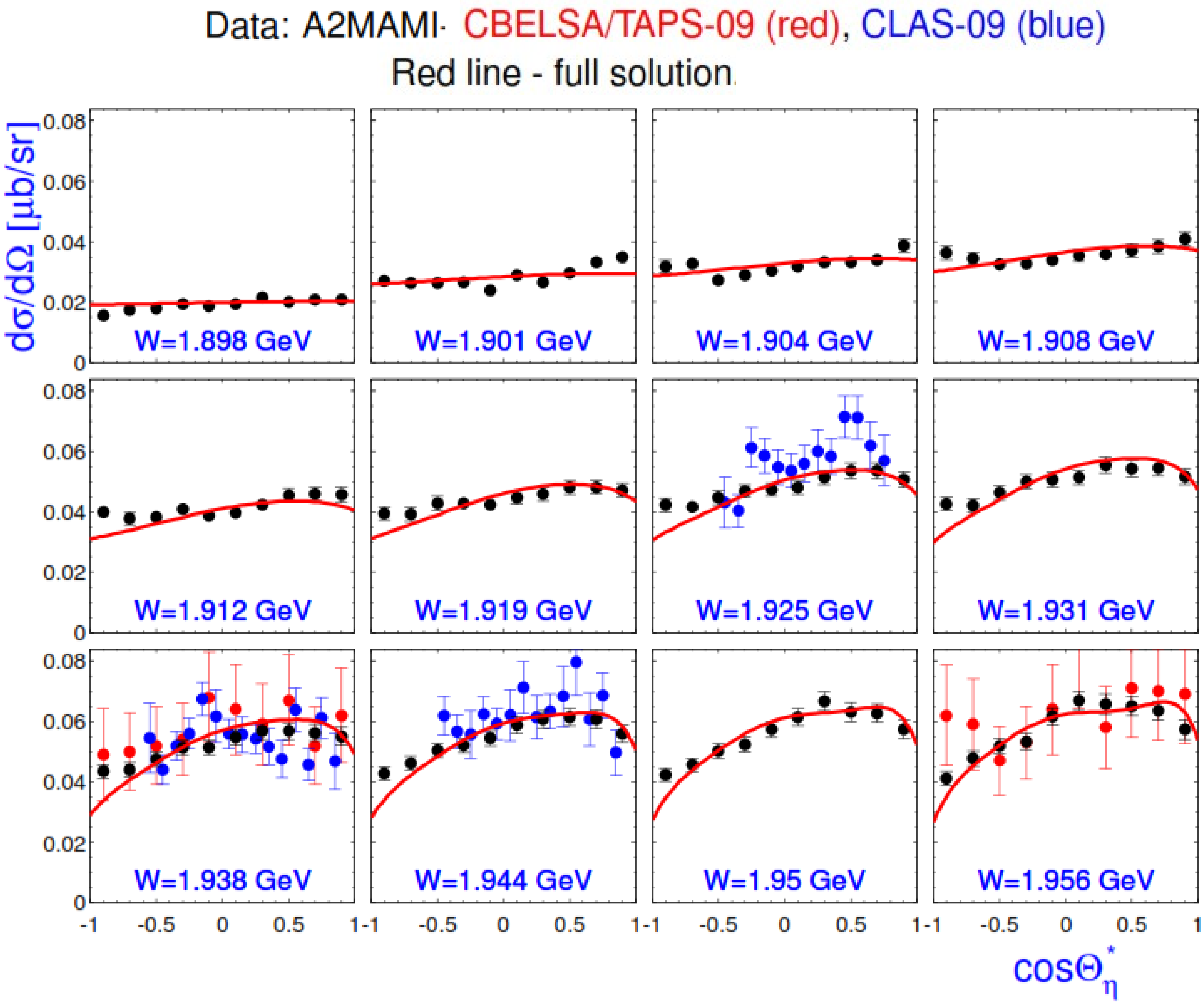



η'

| Particle $J^P$ | overall | $N\gamma$ | $N\pi$ | $N\eta$ | $N\sigma$ | $N\omega$ | $\Lambda K$ | $\Sigma K$ | $N\rho$ | $\Delta\pi$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $N$ $1/2^+$ | **** | | | | | | | | | |
| $N(1440)\ 1/2^+$ | **** | **** | **** | | *** | | | | * | *** |
| $N(1520)\ 3/2^-$ | **** | **** | **** | *** | | | | | *** | *** |
| $N(1535)\ 1/2^-$ | **** | **** | **** | **** | | | | | ** | * |
| $N(1650)\ 1/2^-$ | **** | *** | **** | *** | | | *** | ** | ** | *** |
| $N(1675)\ 5/2^-$ | **** | *** | **** | * | | | * | | * | *** |
| $N(1680)\ 5/2^+$ | **** | **** | **** | * | ** | | | | *** | *** |
| $N(1700)\ 3/2^-$ | *** | ** | *** | * | | | * | * | * | *** |
| $N(1710)\ 1/2^+$ | **** | **** | **** | *** | | ** | **** | ** | * | ** |
| $N(1720)\ 3/2^+$ | **** | *** | **** | *** | | | ** | ** | ** | * |
| $N(1860)\ 5/2^+$ | ** | | ** | | | | | | * | * |
| $N(1875)\ 3/2^-$ | *** | *** | * | | | ** | *** | ** | | *** |
| $N(1880)\ 1/2^+$ | ** | * | * | | ** | | * | | | |
| $N(1895)\ 1/2^-$ | ** | ** | * | ** | | | ** | * | | |
| $N(1900)\ 3/2^+$ | *** | *** | ** | ** | | ** | *** | ** | * | ** |
| $N(1990)\ 7/2^+$ | ** | ** | ** | | | | | * | | |
| $N(2000)\ 5/2^+$ | ** | ** | * | ** | | | ** | * | ** | |
| $N(2040)\ 3/2^+$ | * | | * | | | | | | | |
| $N(2060)\ 5/2^-$ | ** | ** | ** | * | | | | ** | | |
| $N(2100)\ 1/2^+$ | * | | * | | | | | | | |
| $N(2120)\ 3/2^-$ | ** | * | ** | | | | * | * | | |
| $N(2190)\ 7/2^-$ | **** | *** | **** | | | * | ** | | * | |
| $N(2220)\ 9/2^+$ | **** | | **** | | | | | | | |
| $N(2250)\ 9/2^-$ | **** | | **** | | | | | | | |
| $N(2300)\ 1/2^+$ | ** | | ** | | | | | | | |
| $N(2570)\ 5/2^-$ | ** | | ** | | | | | | | |
| $N(2600)\ 11/2^-$ | *** | | *** | | | | | | | |
| $N(2700)\ 13/2^+$ | ** | | ** | | | | | | | |

V. Kashevarov et al., Phys.Rev.Lett. 118 (2017) no.21, 212001v

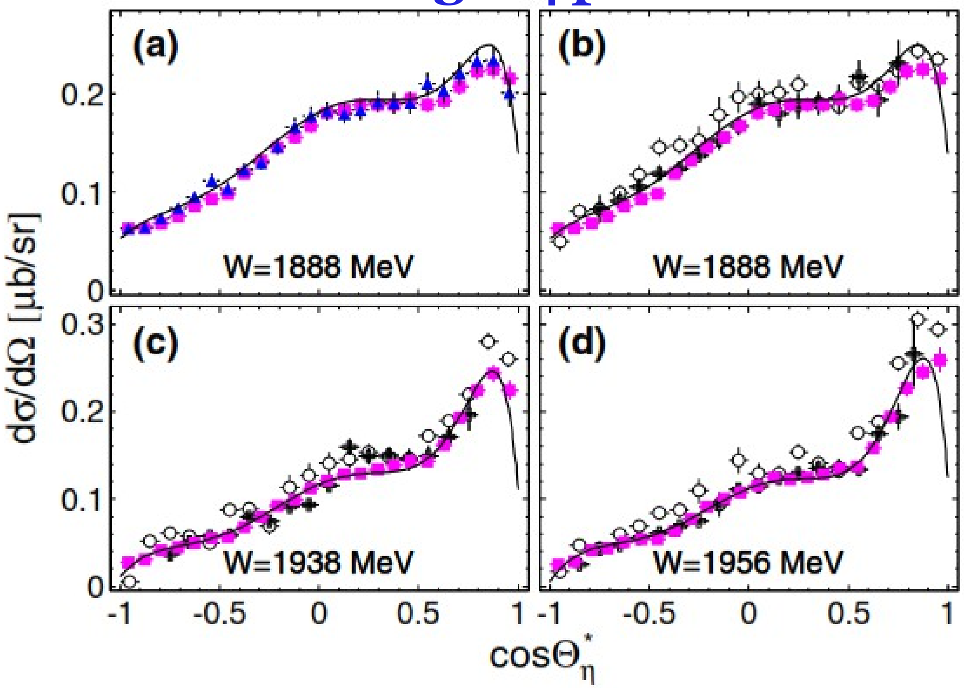
# Single η' production



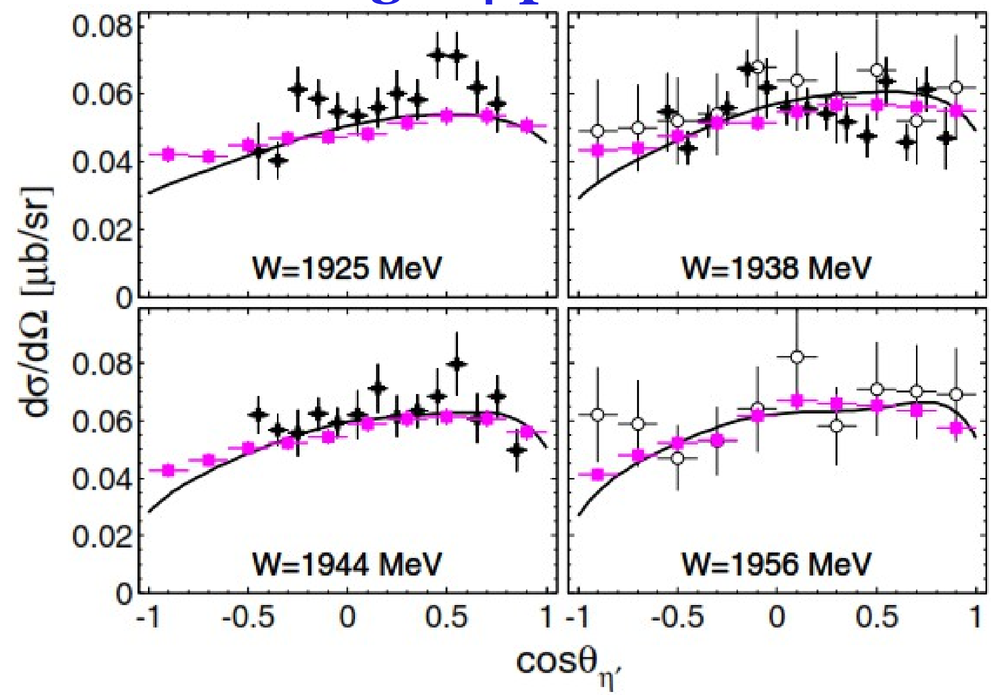

V. Kashevarov et al., Phys.Rev.Lett. 118 (2017) no.21, 212001v

# Single η and η' production

## Single η production




## Single η' production




V. Kashevarov et al., Phys.Rev.Lett. 118 (2017) no.21, 212001v

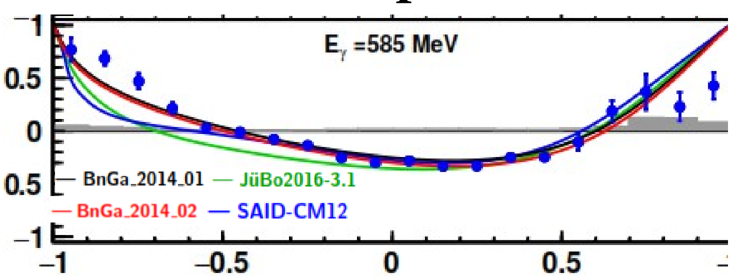
- **Overall: Good agreements with CLAS and CBELSA/TAPS data**
- **In some bins systematic discrepancies (upto 10%) with CBELSA/TAPS data**

# Single meson production: data on polarization observables

| Photon Polarization | | Target Polarization x | y | z |
|---|---|---|---|---|
| unpolarized | $\sigma$ | – | T | – |
| linearly polarized | $\Sigma$ | H | P | G |
| circularly polarized | – | F | – | E |

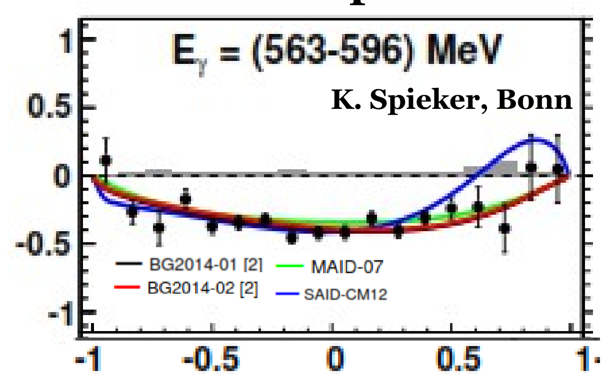
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}(\theta)\cdot\Big[1 - p_\gamma^{lin}\Sigma\cos(2\phi) + p_x(-p_\gamma^{lin}H\sin(2\phi) + p_\gamma^{circ}F) - p_y(-T + p_\gamma^{lin}P\cos(2\phi)) - p_z(-p_\gamma^{lin}G\sin(2\phi) + p_\gamma^{circ}E)\Big]$$

**E for p$\pi^o$**

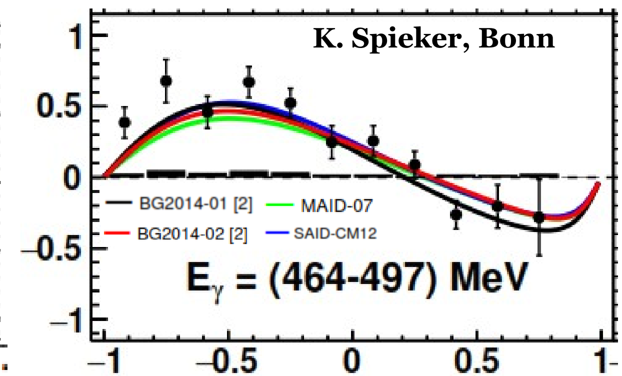



F. Afzal, Bonn

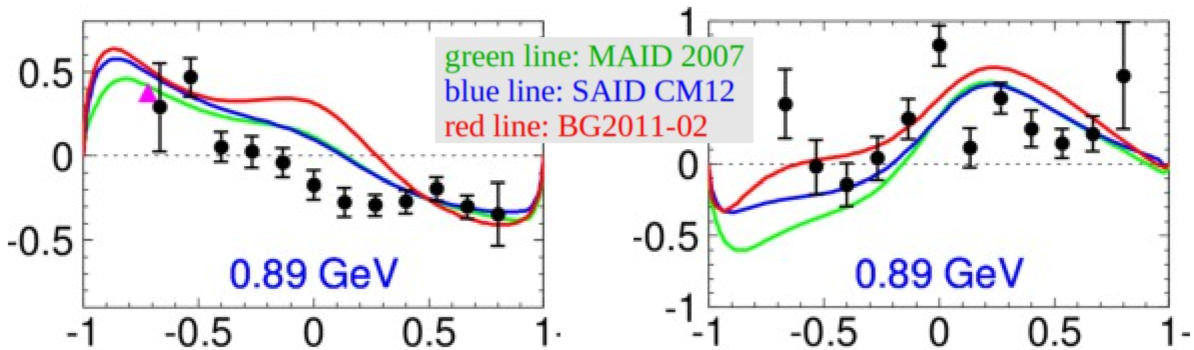
**G for p$\pi^o$**




**G for n$\pi^+$**

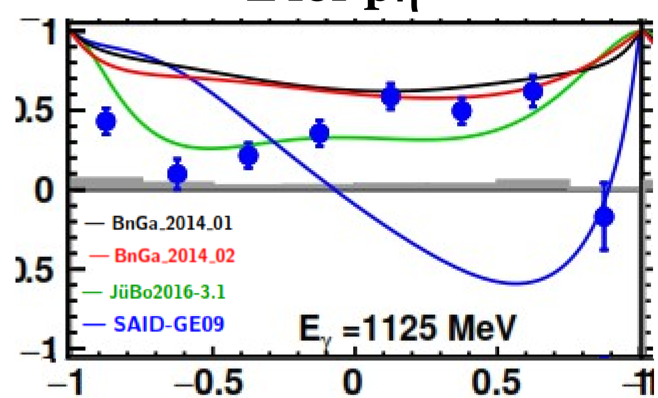



**T for n$\pi^+$** **F for n$\pi^+$**




F. Afzal, Bonn

**E for p$\eta$**




F. Afzal, Bonn

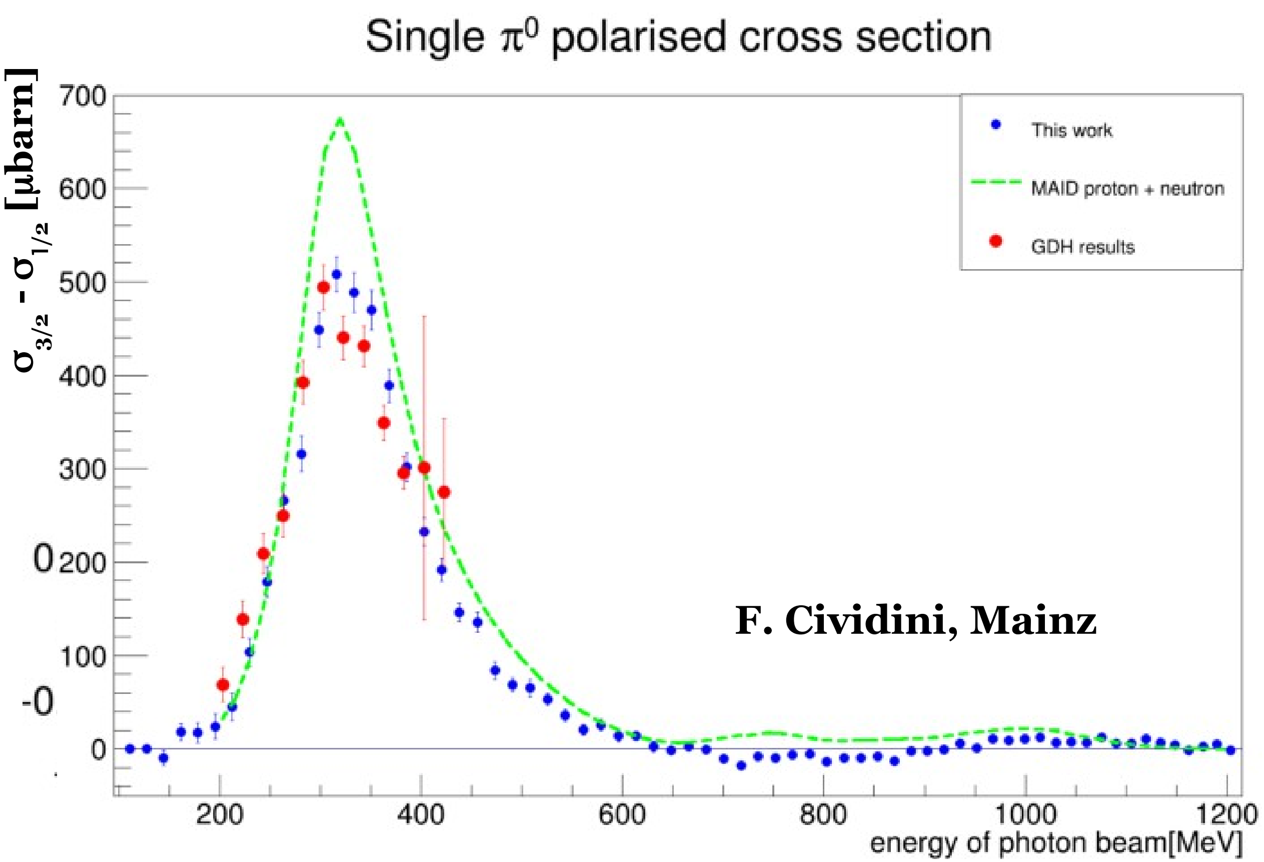
- **See talk of Natalie Walford for further results: 22.08.2017, Parallel Session (A2), 14:30**
- Data on beam asymmetry $\Sigma$ published for 1214 < W < 1450 MeV (S. Gardner et al., Eur.Phys.J. A52 (2016) no.11, 333)
- New data taken on $\Sigma$ for single $\pi^o$ for determination of E2/M1 ratio with improved systematics

# Single meson production: data on polarization observables

| Photon Polarization | | Target Polarization x | y | z |
|---|---|---|---|---|
| unpolarized | $\sigma$ | – | T | – |
| linearly polarized | $\Sigma$ | H | P | G |
| circularly polarized | – | F | – | E |

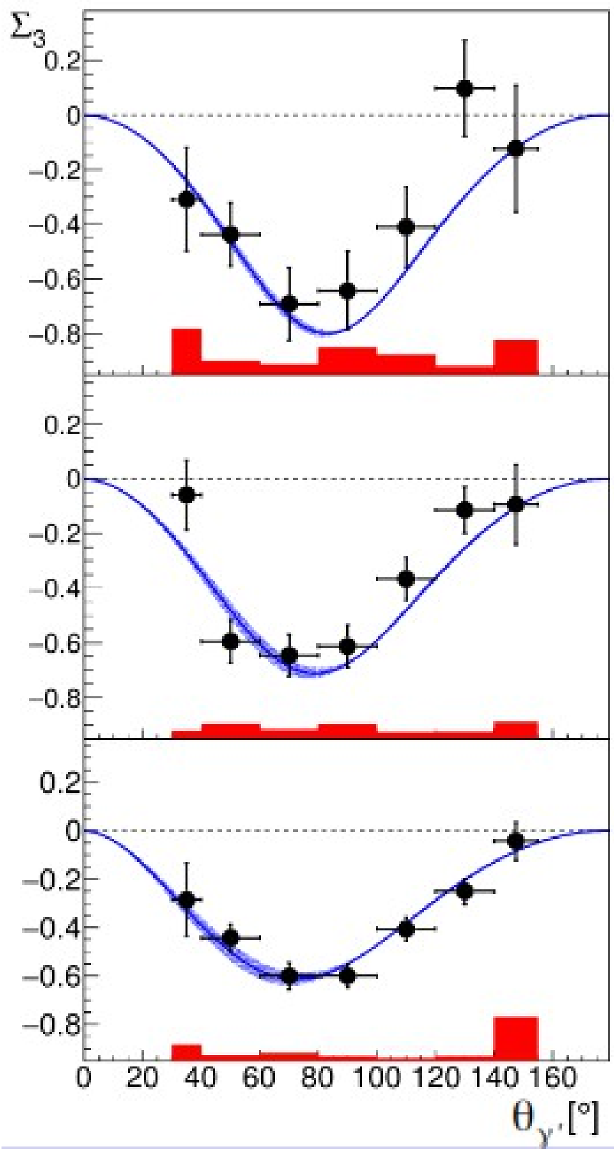
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}(\theta)\cdot\Big[1 - p_\gamma^{lin}\Sigma\cos(2\phi) + p_x(-p_\gamma^{lin}H\sin(2\phi) + p_\gamma^{circ}F) - p_y(-T + p_\gamma^{lin}P\cos(2\phi)) - p_z(-p_\gamma^{lin}G\sin(2\phi) + p_\gamma^{circ}E)\Big]$$

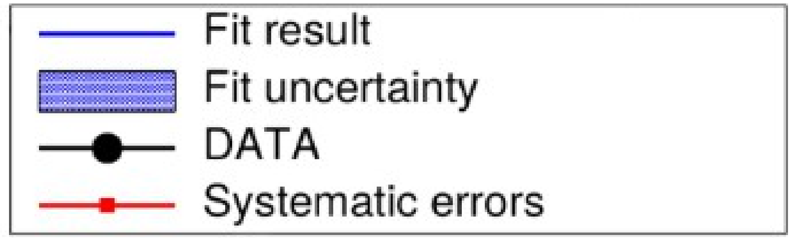
- Extraction of E for nucleons bound in deuteron in progress
- Total inclusive polarized cross-section extracted for $\pi^0$ production




- **See talk of Natalie Walford for further results: 22.08.2017, Parallel Session (A2), 14:30**

# Below pion threhold: Compton scattering




Fit on our $\Sigma_3$ results using Baldin sum rule constraint gives:

**BChPT framework:**

$\beta_{M1} = 2.8^{+2.3}_{-2.1} \times 10^{-4}\ \mathrm{fm}^3$

$\chi^2/\mathrm{ndf} = 19.2/20$

**HBChPT framework:**

$\beta_{M1} = 3.7^{+2.5}_{-2.3} \times 10^{-4}\ \mathrm{fm}^3$

$\chi^2/\mathrm{ndf} = 17.1/20$

At low energy, the measurement of the beam asymmetry $\Sigma_3$ provides an alternative way to extract $\beta_{M1}$:

$$\frac{d\sigma}{d\Omega}(\theta,\phi)=\frac{d\sigma}{d\Omega}(\theta)[1+p_\gamma \Sigma_3 \cos(2\phi)] \quad \text{where} \quad \Sigma_3=\frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}$$

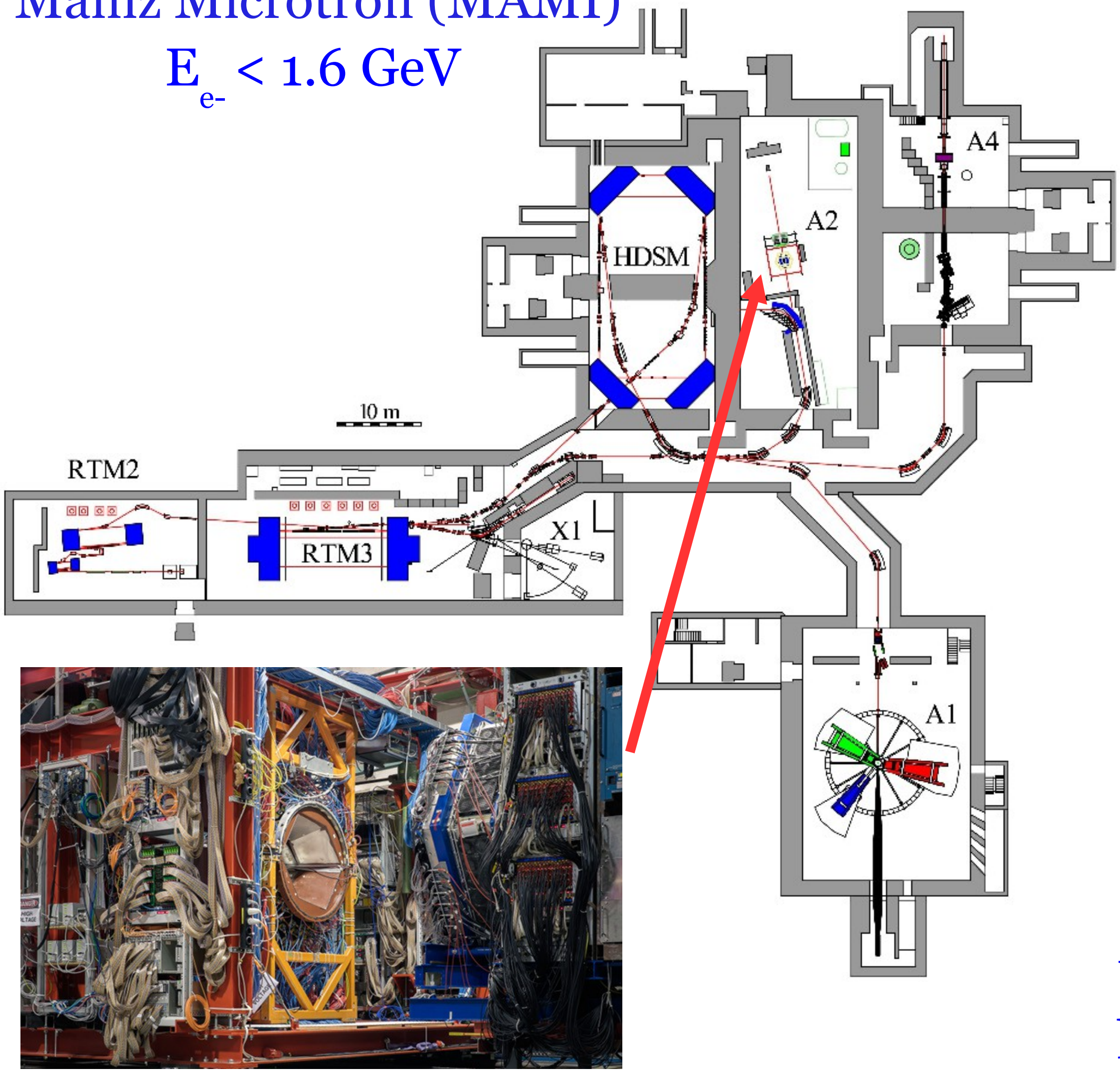
V. S., E.J. Downie, E. Mornacchi, J.A. McGovern, N. Krupina,Eur.Phys.J. A53 (2017) no.1, 14

High-precision measurements of the beam asymmetry and unpolarized cross-section planned in the end of 2017!

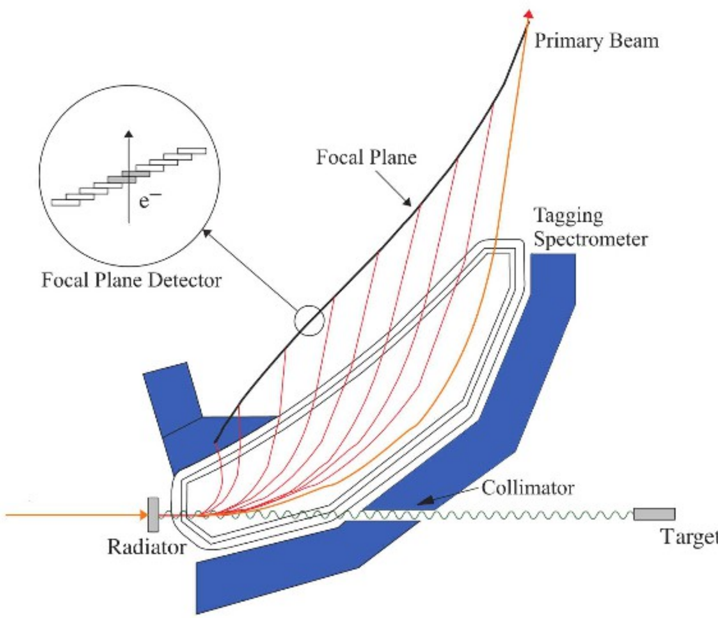
# Experimental setup

Mainz Microtron (MAMI)

$E_{e-} < 1.6$ GeV




Tagger/End point tagger




$$E_\gamma = E_{e-} - E_{tagg}$$

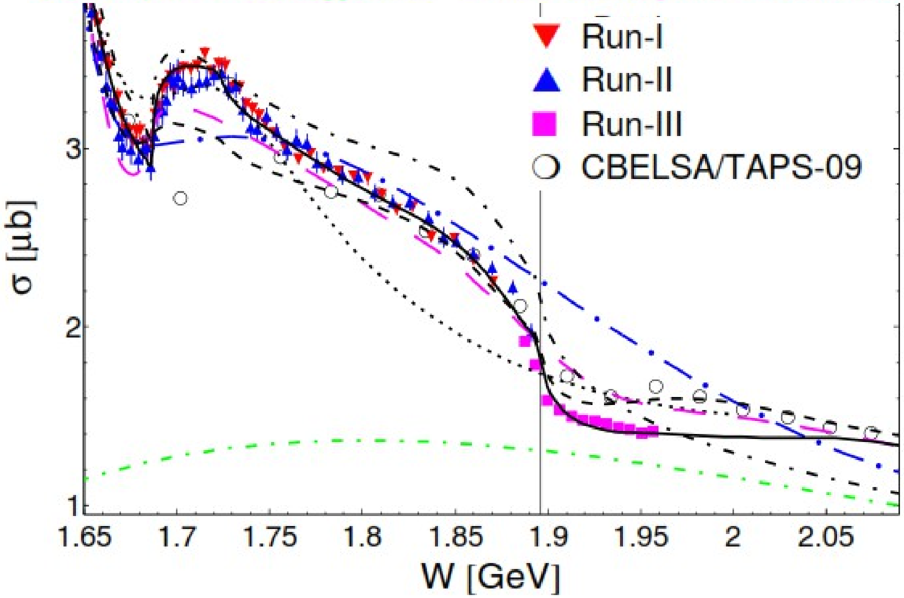
Upgrade → experiments with ~4 times higher rates will be possible!

- High-Flux, Tagged, Bremsstrahlung Photon Beam: Unpolarized, Linear, and Circular
- Polarized and Unpolarized Targets
- Recoil polarimeter
- ➔ Development of an active He gas target in progress

# Single η and η' production

Black lines: full solution (solid), background (dashed), $S_{11} + bg$ (dash-dotted).

Green - ηMAID-2003Regge. Blue - SAID-GE09. Magenta - BnGa2014-2.

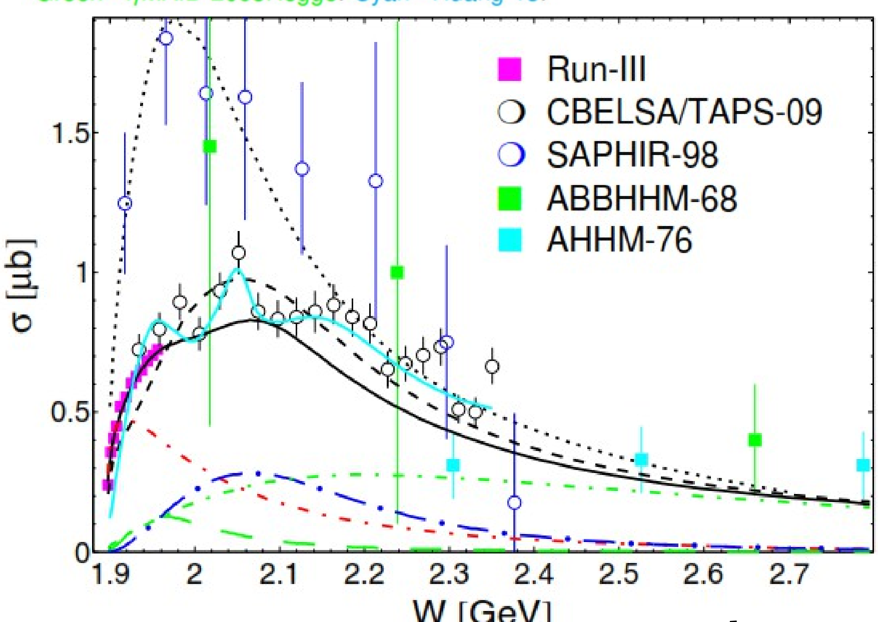



η

| Particle | $J^P$ | overall | $N\gamma$ | $N\pi$ | $N\eta$ | $N\sigma$ | $N\omega$ | $\Lambda K$ | $\Sigma K$ | $N\rho$ | $\Delta\pi$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $N$ | $1/2^+$ | **** | | | | | | | | | |
| $N(1440)$ | $1/2^+$ | **** | **** | **** | | *** | | | | * | *** |
| $N(1520)$ | $3/2^-$ | **** | **** | **** | *** | | | | | *** | *** |
| $N(1535)$ | $1/2^-$ | **** | **** | **** | **** | | | | | ** | * |
| $N(1650)$ | $1/2^-$ | **** | *** | **** | *** | | | *** | ** | ** | *** |
| $N(1675)$ | $5/2^-$ | **** | *** | **** | * | | | * | | * | *** |
| $N(1680)$ | $5/2^+$ | **** | **** | **** | * | ** | | | | *** | *** |
| $N(1700)$ | $3/2^-$ | *** | ** | *** | * | | | * | * | * | *** |
| $N(1710)$ | $1/2^+$ | **** | **** | **** | *** | | ** | **** | ** | * | ** |
| $N(1720)$ | $3/2^+$ | **** | *** | **** | *** | | | ** | ** | ** | * |
| $N(1860)$ | $5/2^+$ | ** | | ** | | | | | | * | * |
| $N(1875)$ | $3/2^-$ | *** | *** | * | | | ** | *** | ** | | *** |
| $N(1880)$ | $1/2^+$ | ** | * | * | | ** | | * | | | |
| $N(1895)$ | $1/2^-$ | ** | ** | * | ** | | | ** | * | | |

Black lines: full solution (solid), background (dashed), $N(1895)1/2^-$ (dash-dotted).

Green - ηMAID-2003Regge. Cyan - Huang-13.

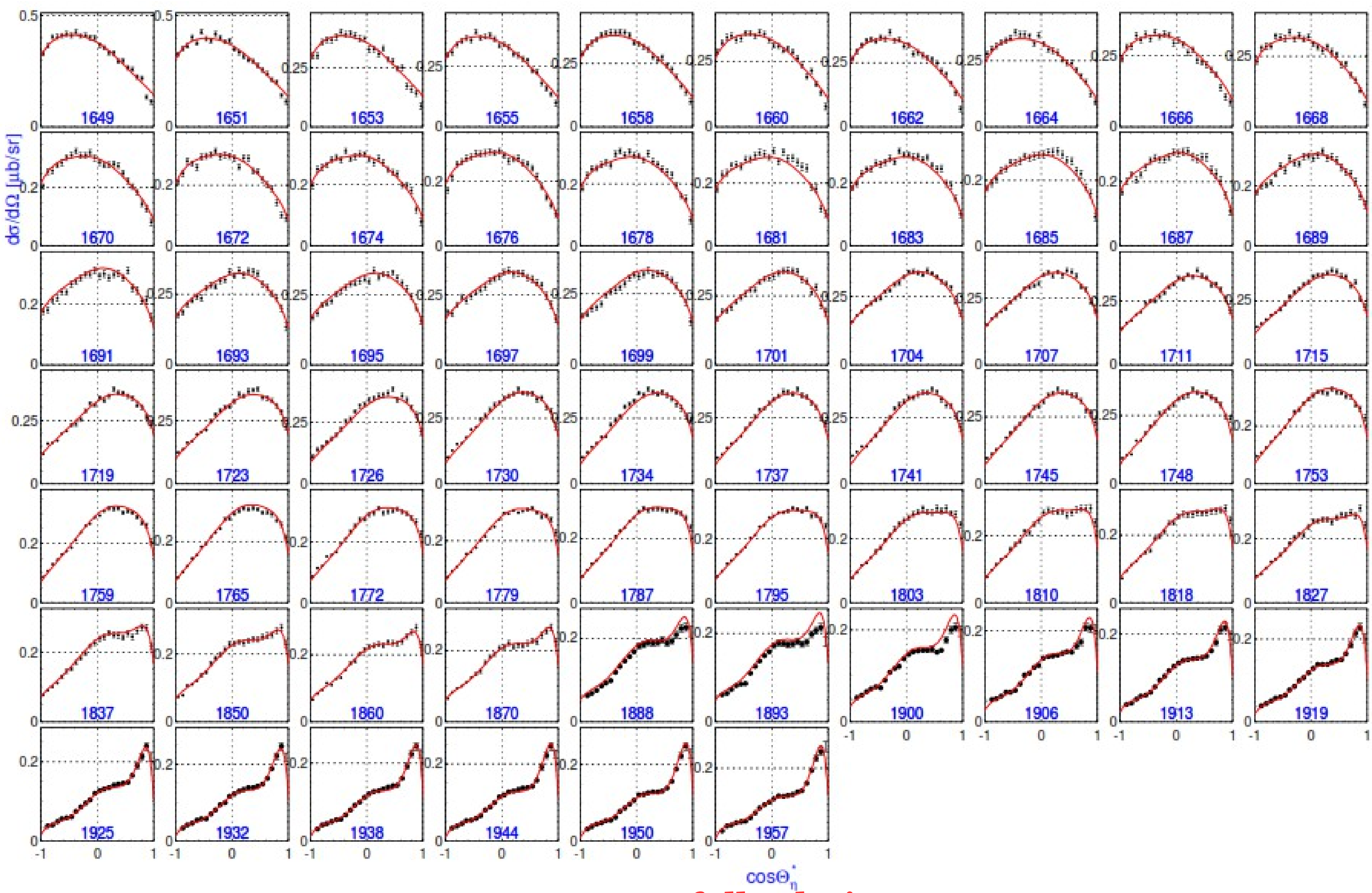



η'

| Resonance $J^P$ | $M_{BW}$ [MeV] | $\Gamma_{BW}$ [MeV] | $\beta_{\eta N}$ [%] | $A_{1/2}$ |
|---|---|---|---|---|
| $N(1535)1/2^-$ | $1528 \pm 6$ | $163 \pm 25$ | $41 \pm 4$ | $+115$ |
| **** | $1535 \pm 10$ | $150 \pm 25$ | $42 \pm 10$ | $+115 \pm 15$ |
| $N(1650)1/2^-$ | $1634 \pm 5$ | $128 \pm 16$ | $28 \pm 11$ | $+45$ |
| **** | $1655^{+15}_{-10}$ | $140 \pm 30$ | 14–22 | $+45 \pm 10$ |
| $N(1895)1/2^-$ | $1890^{+9}_{-23}$ | $150 \pm 57$ | $20 \pm 6$ | $-30$ |
| ** | | | | |

V. Kashevarov et al., Phys.Rev.Lett. 118 (2017) no.21, 212001v

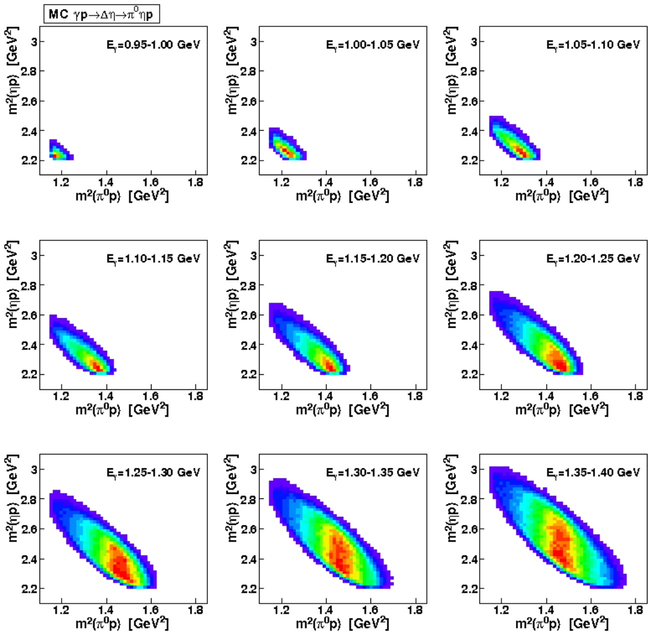
# Single η production

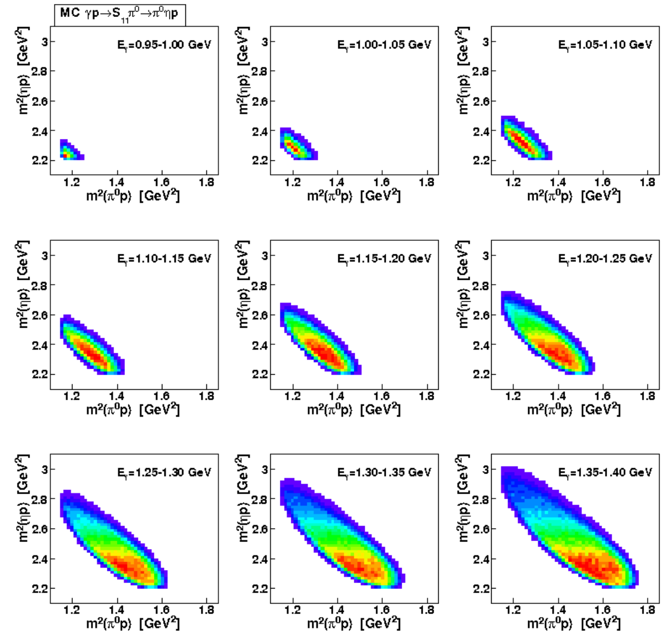


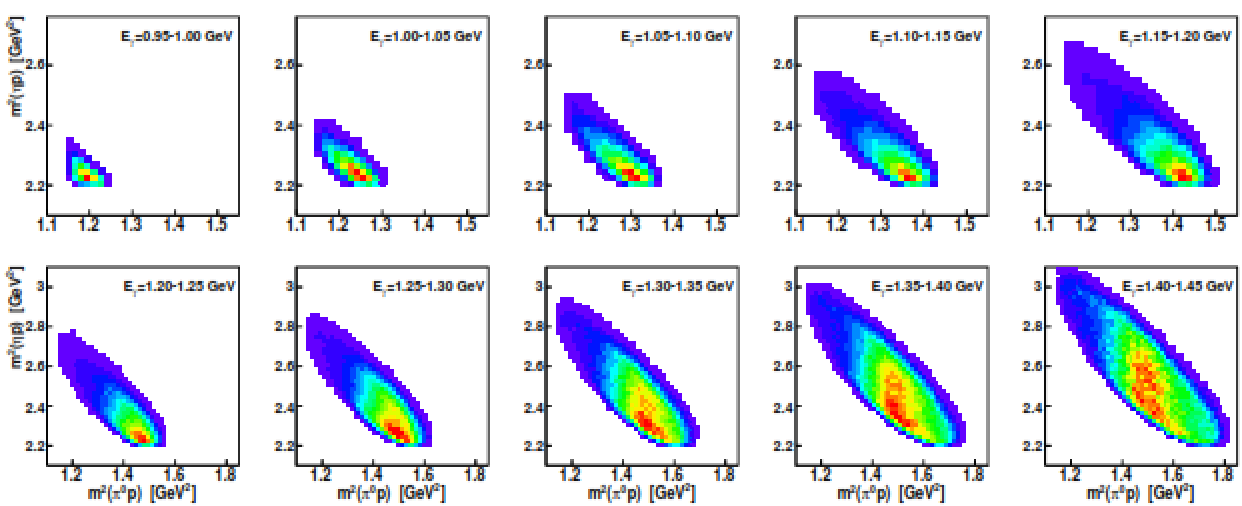

**Data and ηMAID full solution**

V. Kashevarov et al., Phys.Rev.Lett. 118 (2017) no.21, 212001v

# $\pi^0\eta$ production



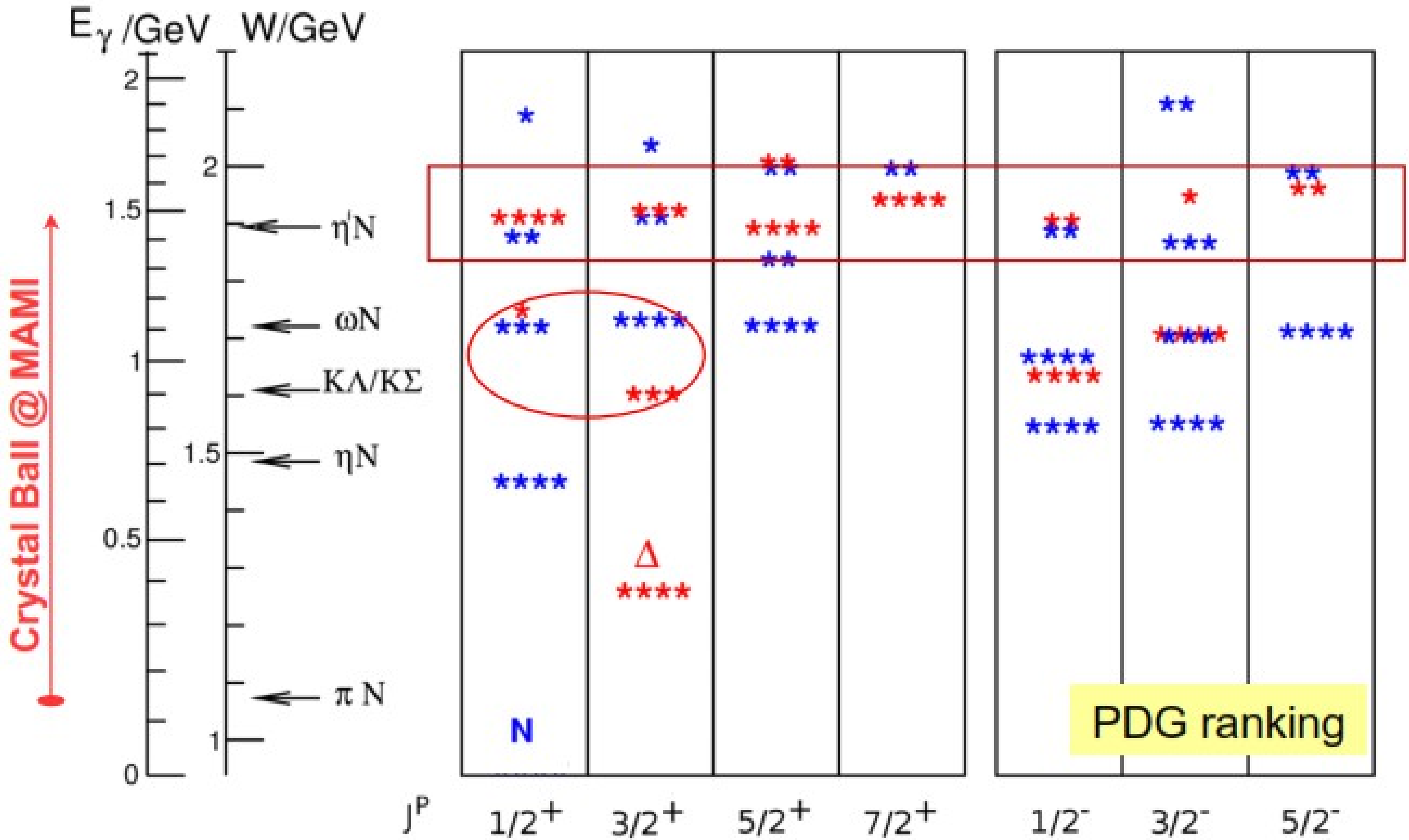



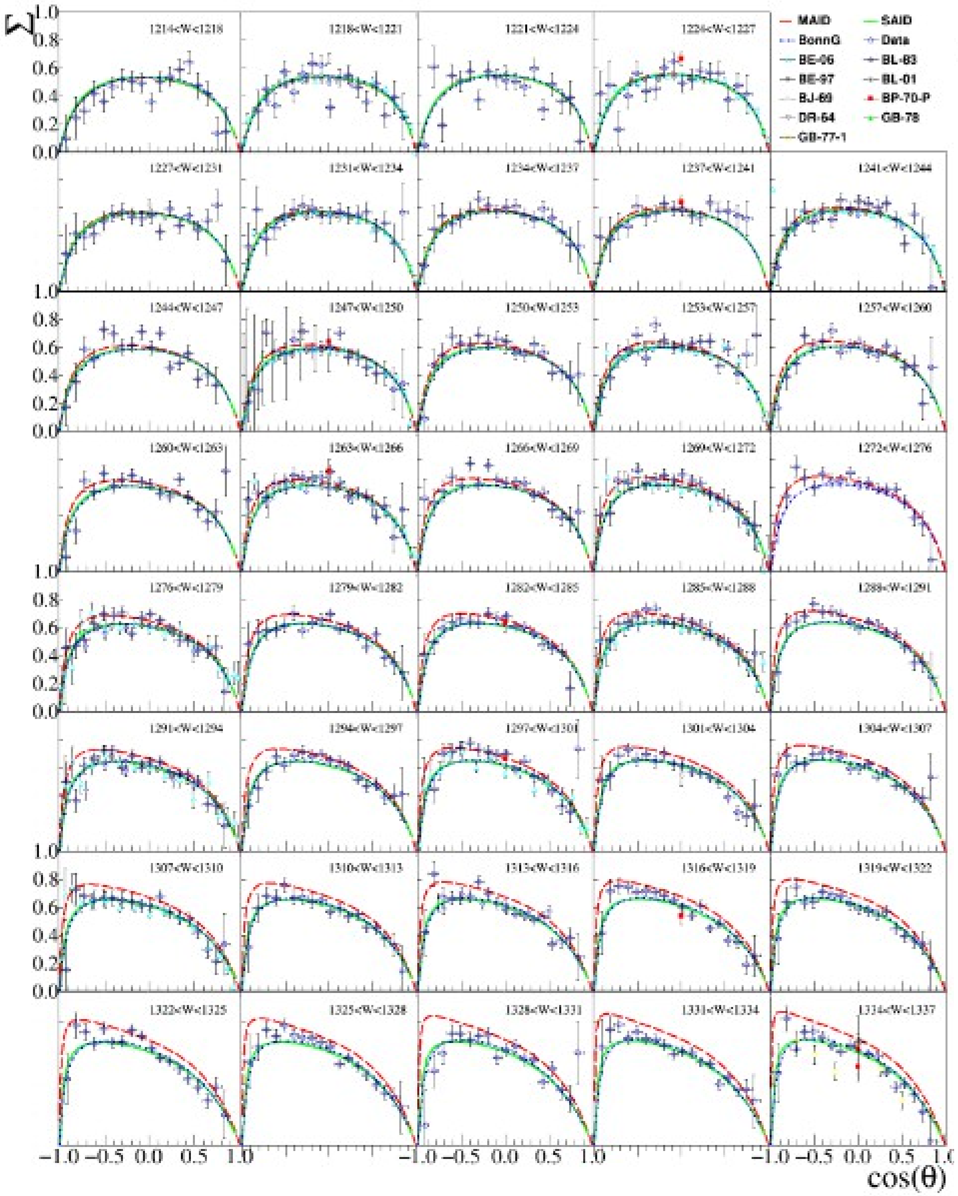

Strong contribution from $\gamma p \to (D_{33}(1700)) \to \Delta(1232)\eta \to p\pi^0\eta$

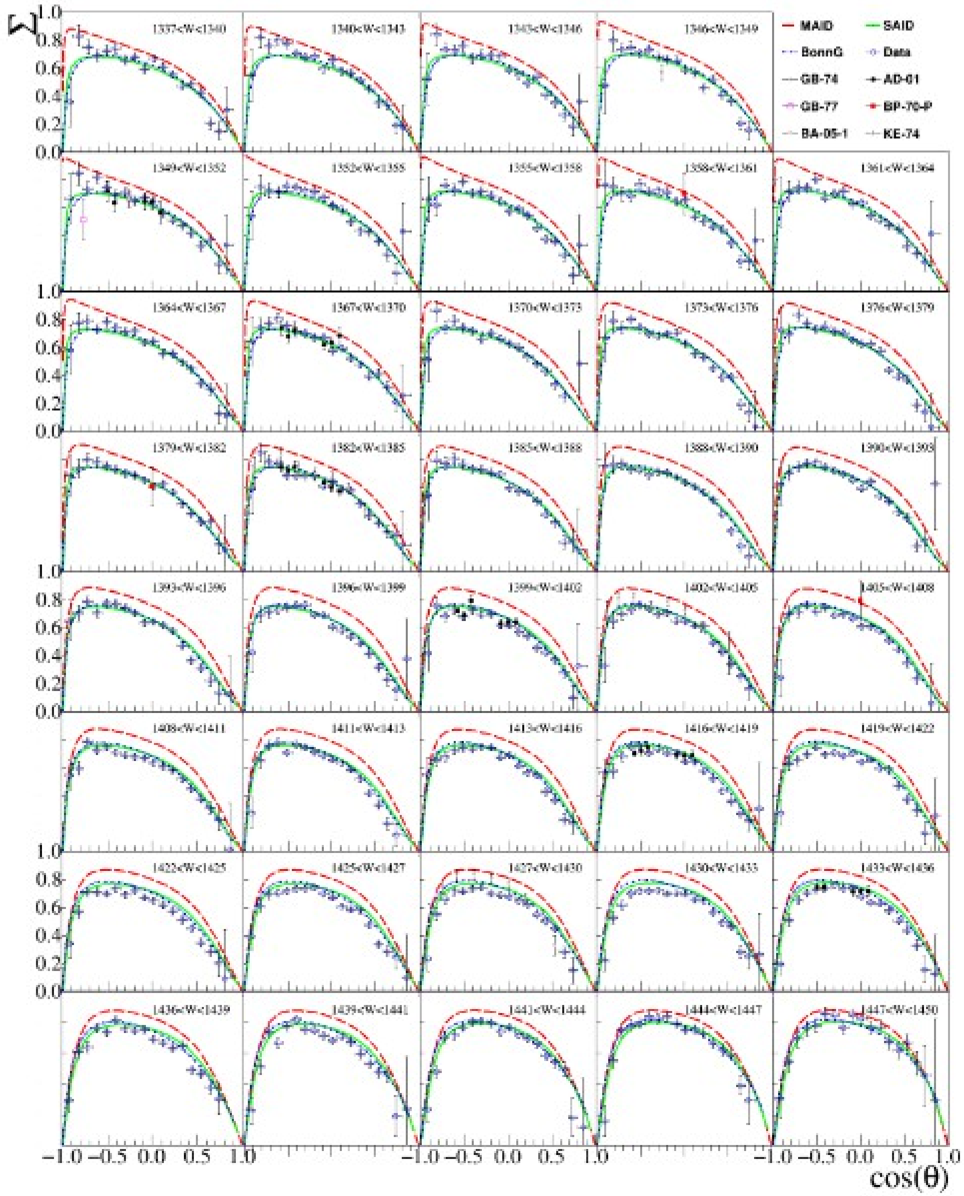
# Baryon resonances

Goal: Gain a good understanding of the spectrum and properties of baryon resonances



# Single $\pi^o$ production: beam asymmetry

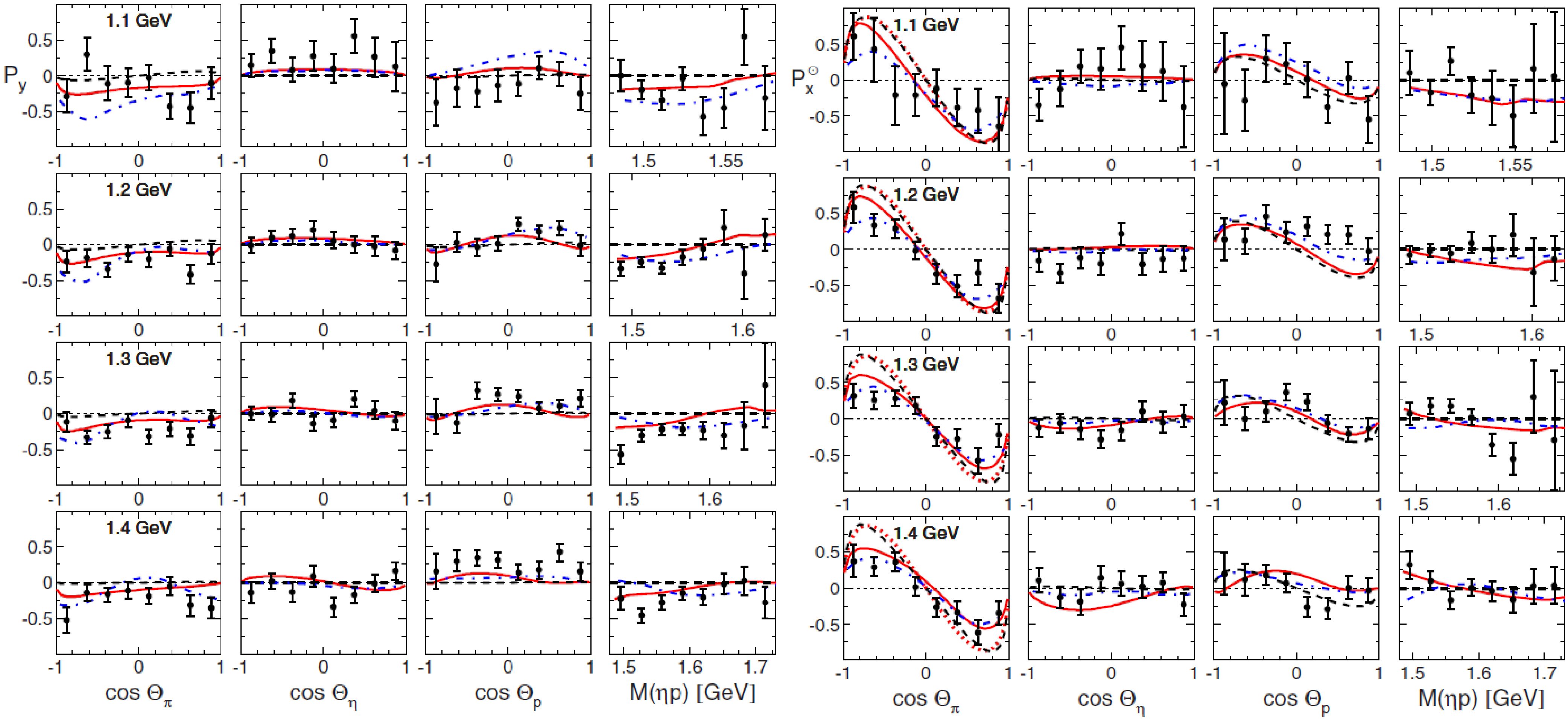



**Text and references will be added**

- **Interpretation within further partial wave analyses**

# $\pi^0\eta$ production, single and double polarization



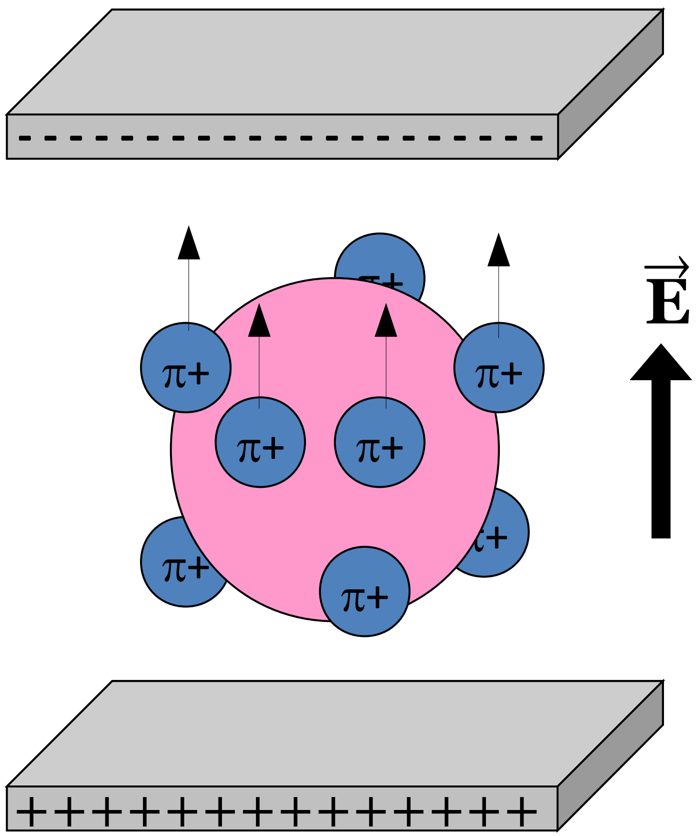

(Data are shown in a quasi two-boy approach)

Dashed: only $D_{33}$ wave, solid: A. Fix model, dashed-dotted BnGa PWA

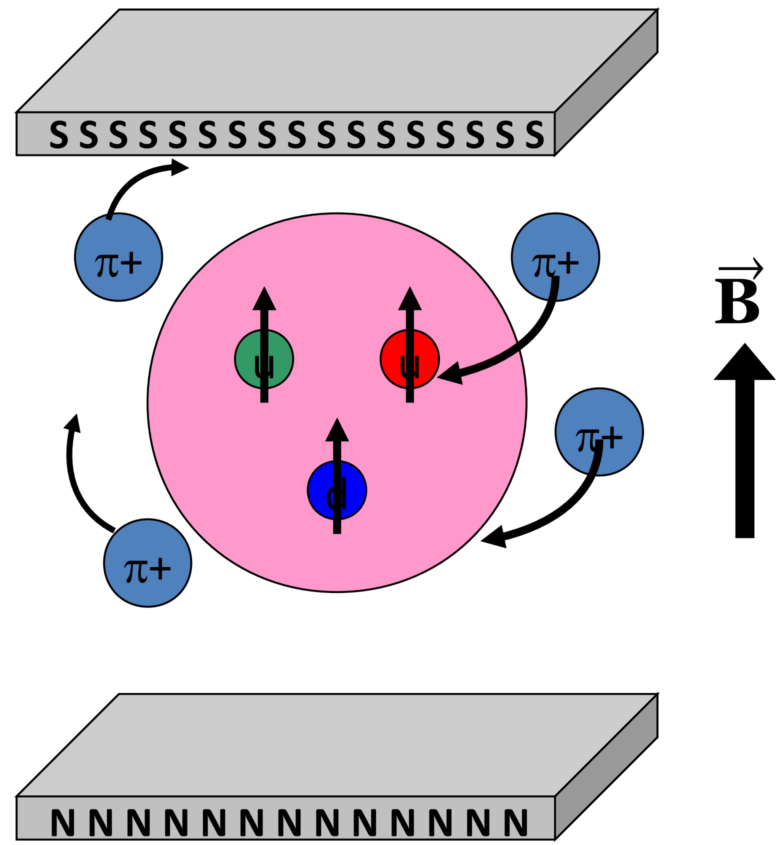
J. R. M. Annand et al., Phys.Rev. C91, no.5, 055208 (2015)

# Scalar polarizabilities

## Proton Electric Polarizability



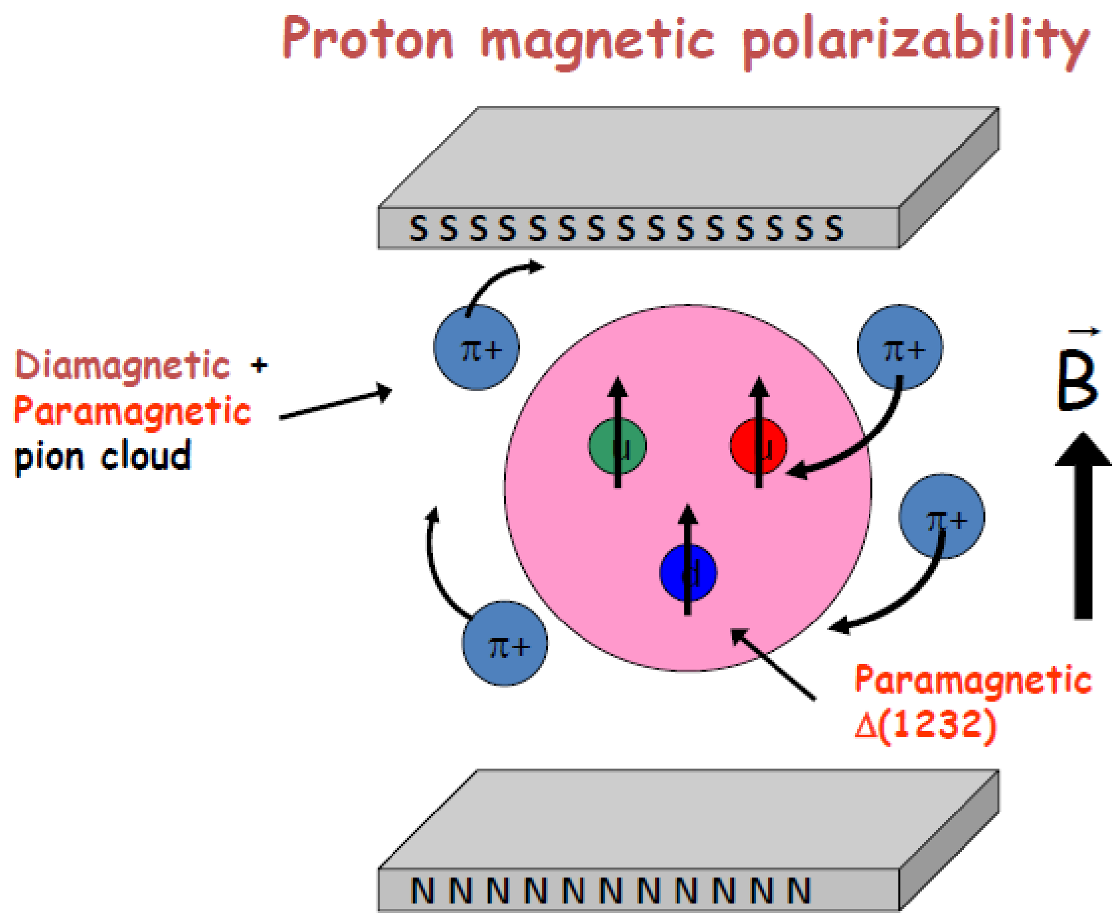

## Proton Magnetic Polarizability




- α: electric polarizabilty
- Proton between charged parallel plates: "stretchability"

- β: magnetic polarizability
- Proton between poles of a magnet: "alignability"

# First look in December 2012 data




Magnetic polarizability: proton between poles of a magnetic

Rory Miskimen (Bosen 2009)

# Measurement of α and β

$$\Sigma_3 = \Sigma_3^{(\mathrm{B})} - \frac{4M\omega^2 \cos\theta \sin^2\theta}{\alpha_{em}(1+\cos^2\theta)^2}\,\beta_{M1} + O(\omega^4), \qquad (6)$$

where $\Sigma_3^{(\mathrm{B})}$ is the pure Born contribution, while

$$\omega = \frac{s - M^2 + \frac{1}{2}t}{\sqrt{4M^2 - t}}, \quad \theta = \arccos\left(1 + \frac{t}{2\omega^2}\right) \qquad (7)$$

are the photon energy and scattering angle in the Breit (brick-wall) reference frame. In fact, to this order in the LEX the formula is valid for $\omega$ and $\theta$ being the energy and angle in the lab or center-of-mass frame.

| Beam | Target | | | | Recoil | | | Target + Recoil | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $-$ | $-$ | $-$ | $-$ | $x'$ | $y'$ | $z'$ | $x'$ | $x'$ | $z'$ | $z'$ |
| | $-$ | $x$ | $y$ | $z$ | $-$ | $-$ | $-$ | $x$ | $z$ | $x$ | $z$ |
| unpolarized | $\sigma_0$ | 0 | $T$ | 0 | 0 | $P$ | 0 | $T_{x'}$ | $-L_{x'}$ | $T_{z'}$ | $L_{z'}$ |
| linear pol. | $-\Sigma$ | $H$ | $(-P)$ | $-G$ | $O_{x'}$ | $(-T)$ | $O_{z'}$ | $(-L_{z'})$ | $(T_{z'})$ | $(-L_{x'})$ | $(-T_{x'})$ |
| circular pol. | 0 | $F$ | 0 | $-E$ | $-C_{x'}$ | 0 | $-C_{z'}$ | 0 | 0 | 0 | 0 |

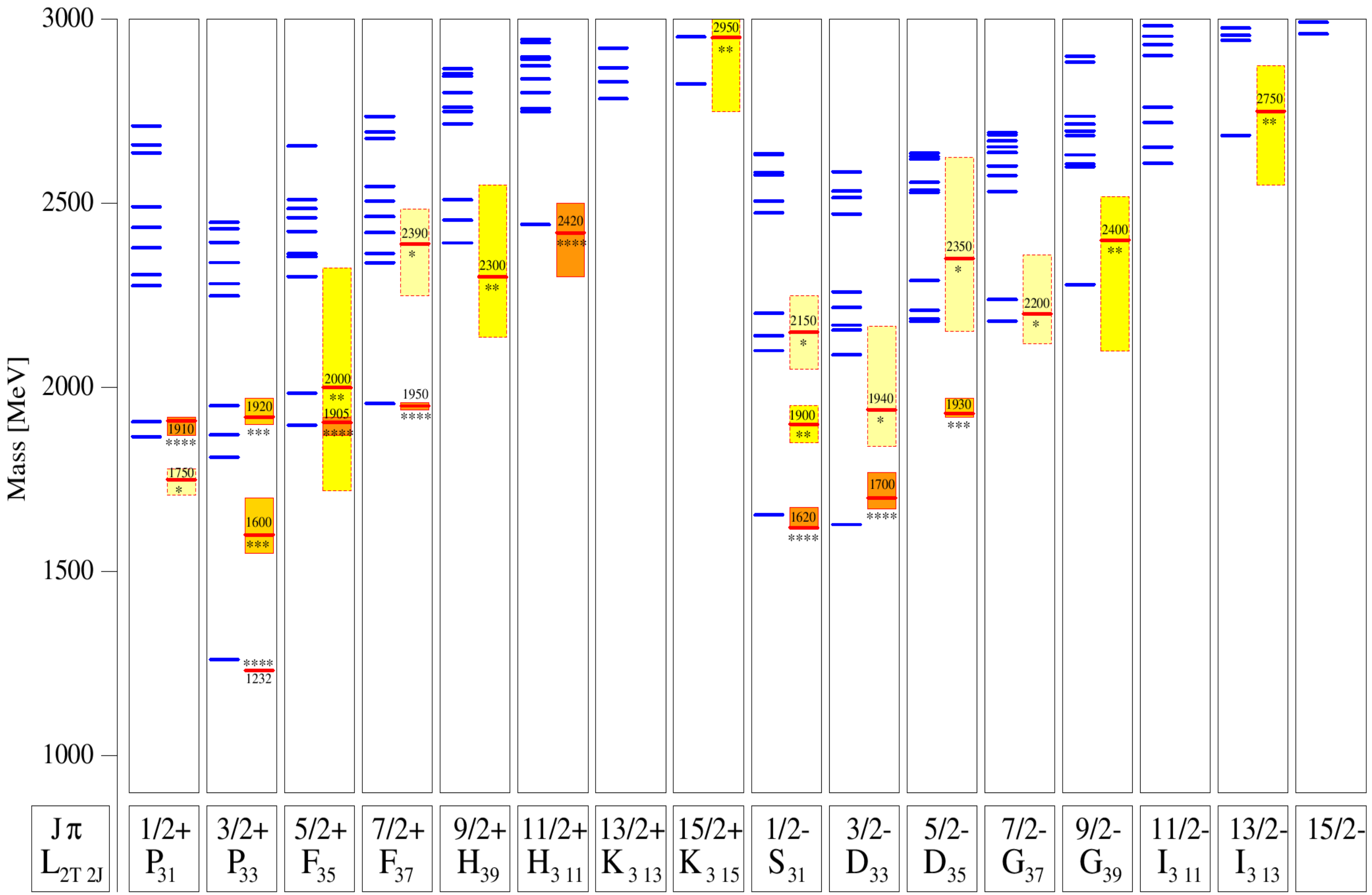
# Baryon resonances

| | | | |
|---|---|---|---|
| 56 | S=1/2;L=0;N=0 | $N_{1/2^+}(939)$ | 939 MeV |
| | S=3/2;L=0;N=0 | $\Delta_{3/2^+}(1232)$ | 1232 MeV |
| 70 | S=1/2;L=1;N=0 | $N_{1/2^-}(1535)$ $N_{3/2^-}(1520)$ | 1530 MeV |
| | S=3/2;L=1;N=0 | $N_{1/2^-}(1650)$ $N_{3/2^-}(1700)$ $N_{5/2^-}(1675)$ | 1631 MeV |
| | S=1/2;L=1;N=0 | $\Delta_{1/2^-}(1620)$ $\Delta_{3/2^-}(1700)$ | 1631 MeV |
| 70 | S=1/2;L=1;N=2 | $N_{1/2^-}(2090)$ $N_{3/2^-}(2080)$ | 2151 MeV |
| | S=3/2;L=1;N=2 | $N_{1/2^-}$ $N_{3/2^-}$ $N_{5/2^-}$ | 2223 MeV |
| | S=1/2;L=1;N=2 | $\Delta_{1/2^-}(2150)$ $\Delta_{3/2^-}$ | 2223 MeV |
| 56 | S=1/2;L=1;N=1 | $N_{1/2^-}$ $N_{3/2^-}$ | 1779 MeV |
| | S=3/2;L=1;N=1 | $\Delta_{1/2^-}(1900)$ $\Delta_{3/2^-}(1940)$ $\Delta_{5/2^-}(1930)$ | 1950 MeV |
| 56 | S=1/2;L=2;N=0 | $N_{3/2^+}(1720)$ $N_{5/2^+}(1620)$ | 1779 MeV |
| | S=3/2;L=2;N=0 | $\Delta_{1/2^+}(1910)$ $\Delta_{3/2^+}(1920)$ $\Delta_{5/2^+}(1905)$ $\Delta_{7/2^+}(1950)$ | 1950 MeV |
| 70 | S=1/2;L=2;N=0 | $N_{3/2^+}$ $N_{5/2^+}$ | 1866 MeV |
| | S=3/2;L=2;N=0 | $N_{1/2^+}$ $N_{3/2^+}(1900)$ $N_{5/2^+}(2000)$ $N_{7/2^+}(1990)$ | 1950 MeV |
| | S=1/2;L=2;N=0 | $\Delta_{3/2^+}$ $\Delta_{5/2^+}$ | 1950 MeV |
| 70 | S=1/2;L=3;N=0 | $N_{5/2^-}$ $N_{7/2^-}$ | 2151 MeV |
| | S=3/2;L=3;N=0 | $N_{3/2^-}$ $N_{5/2^-}(2200)$ $N_{7/2^-}(2190)$ $N_{9/2^-}(2250)$ | 2223 MeV |
| | S=1/2;L=3;N=0 | $\Delta_{5/2^-}$ $\Delta_{7/2^-}(2200)$ | 2223 MeV |
| 56 | S=1/2;L=3;N=1 | $N_{5/2^-}$ $N_{7/2^-}$ | 2334 MeV |
| | S=3/2;L=3;N=1 | $\Delta_{3/2^-}$ $\Delta_{5/2^-}(2350)$ $\Delta_{7/2^-}$ $\Delta_{9/2^-}(2400)$ | 2467 MeV |
| 56 | S=1/2;L=4;N=0 | $N_{7/2^+}$ $N_{9/2^+}(2220)$ | 2334 MeV |
| | S=3/2;L=4;N=0 | $\Delta_{5/2^+}$ $\Delta_{7/2^+}(2390)$ $\Delta_{9/2^+}(2300)$ $\Delta_{11/2^+}(2420)$ | 2467 MeV |
| 70 | S=1/2;L=5;N=0 | $N_{9/2^-}$ $N_{11/2^-}(2600)$ | 2629 MeV |
| 56 | S=3/2;L=5;N=1 | $\Delta_{7/2^-}$ $\Delta_{9/2^-}$ $\Delta_{11/2^-}$ $\Delta_{13/2^-}(2750)$ | 2893 MeV |
| 56 | S=1/2;L=6;N=0 | $N_{11/2^+}$ $N_{13/2^+}(2700)$ | 2781 MeV |
| | S=3/2;L=6;N=0 | $\Delta_{9/2^+}$ $\Delta_{11/2^+}$ $\Delta_{13/2^+}$ $\Delta_{15/2^+}(2950)$ | 2893 MeV |
| 70 | S=1/2;L=7;N=0 | $N_{13/2^-}$ $N_{15/2^-}$ | 3033 MeV |
| 56 | S=3/2;L=7;N=1 | $\Delta_{11/2^-}$ $\Delta_{13/2^-}$ $\Delta_{15/2^-}$ $\Delta_{17/2^-}$ | 3264 MeV |
| 56 | S=1/2;L=8;N=0 | $N_{15/2^+}$ $N_{17/2^+}$ | 3165 MeV |
| | S=3/2;L=8;N=0 | $\Delta_{13/2^+}$ $\Delta_{15/2^+}$ $\Delta_{17/2^+}$ $\Delta_{19/2^+}$ | 3264 MeV |

Table 20: Multiplet structure of nucleon and $\Delta$ resonances. The table contains all known resonances except radial excitations of the $N_{1/2^+}(939)$ and $\Delta_{3/2^+}(1232)$.

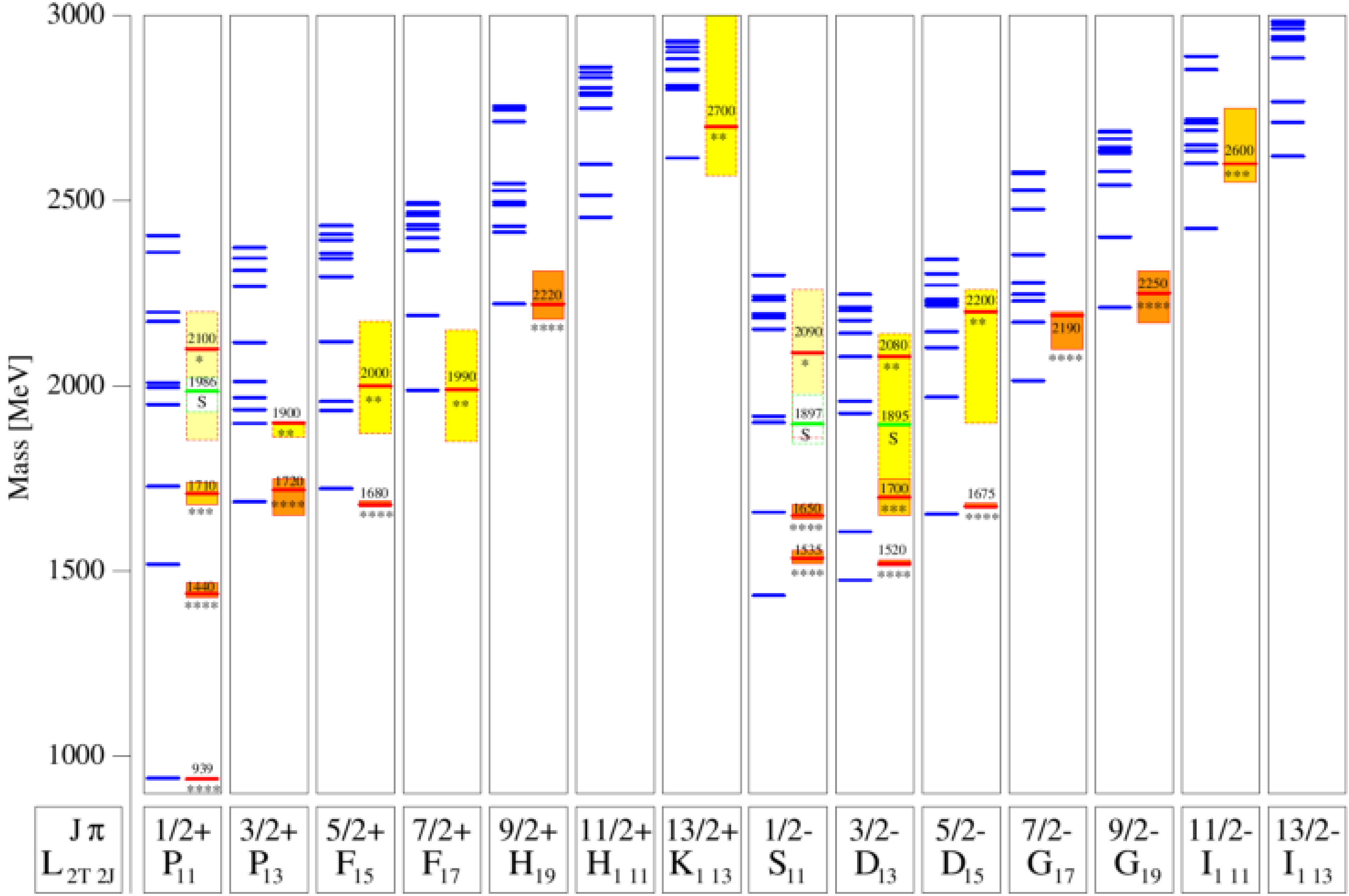
# Introduction

<u>Goal</u>: Gain a good understanding of the spectrum and properties of baryon resonances



# Introduction

<u>Goal</u>: Gain a good understanding of the spectrum and properties of baryon resonances

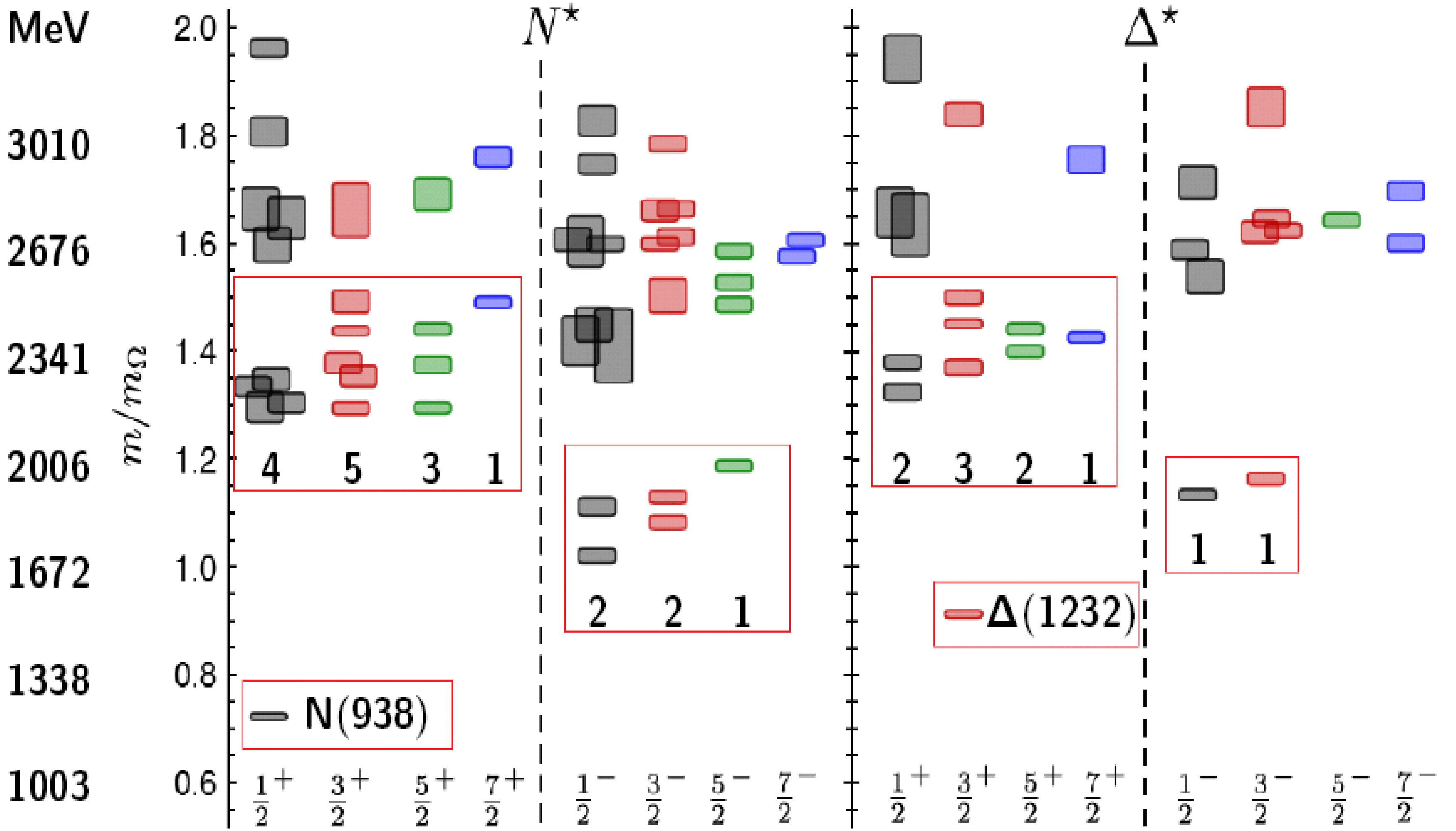


# Introduction

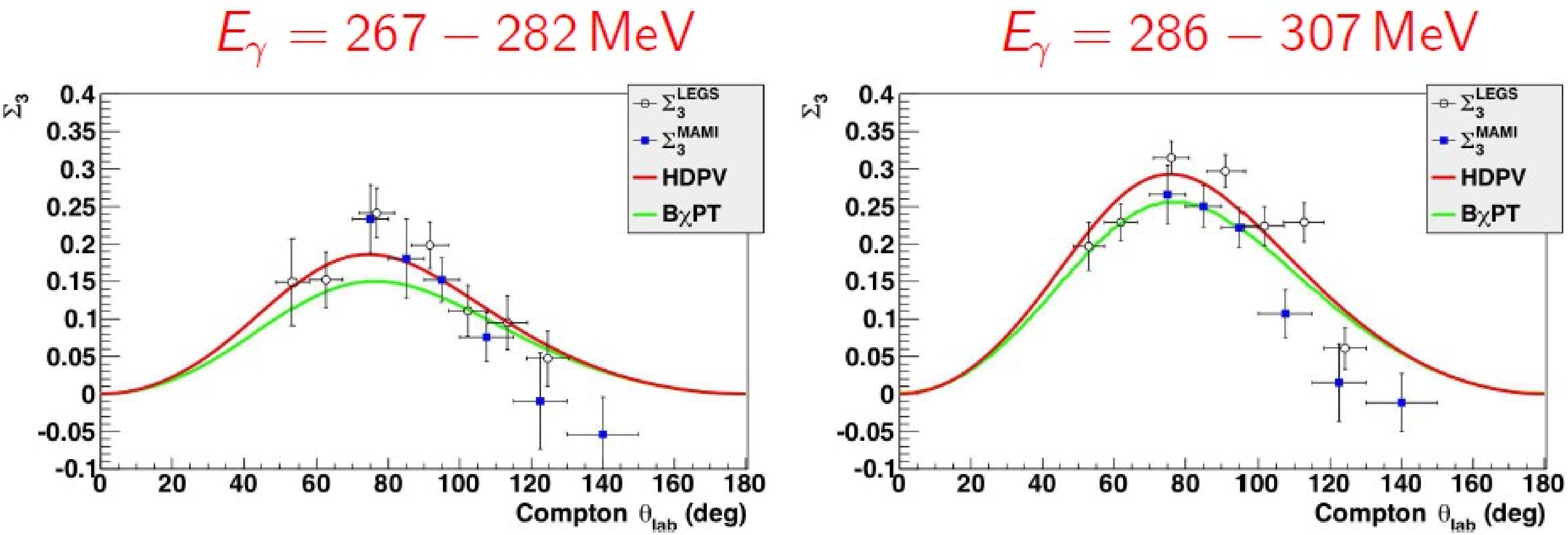
<u>Goal</u>: Gain a good understanding of the spectrum and properties of baryon resonances

$m_\pi = 396$ MeV

**R. G. Edwards et al., Phys. Rev. D 84, 074508 (2011)**



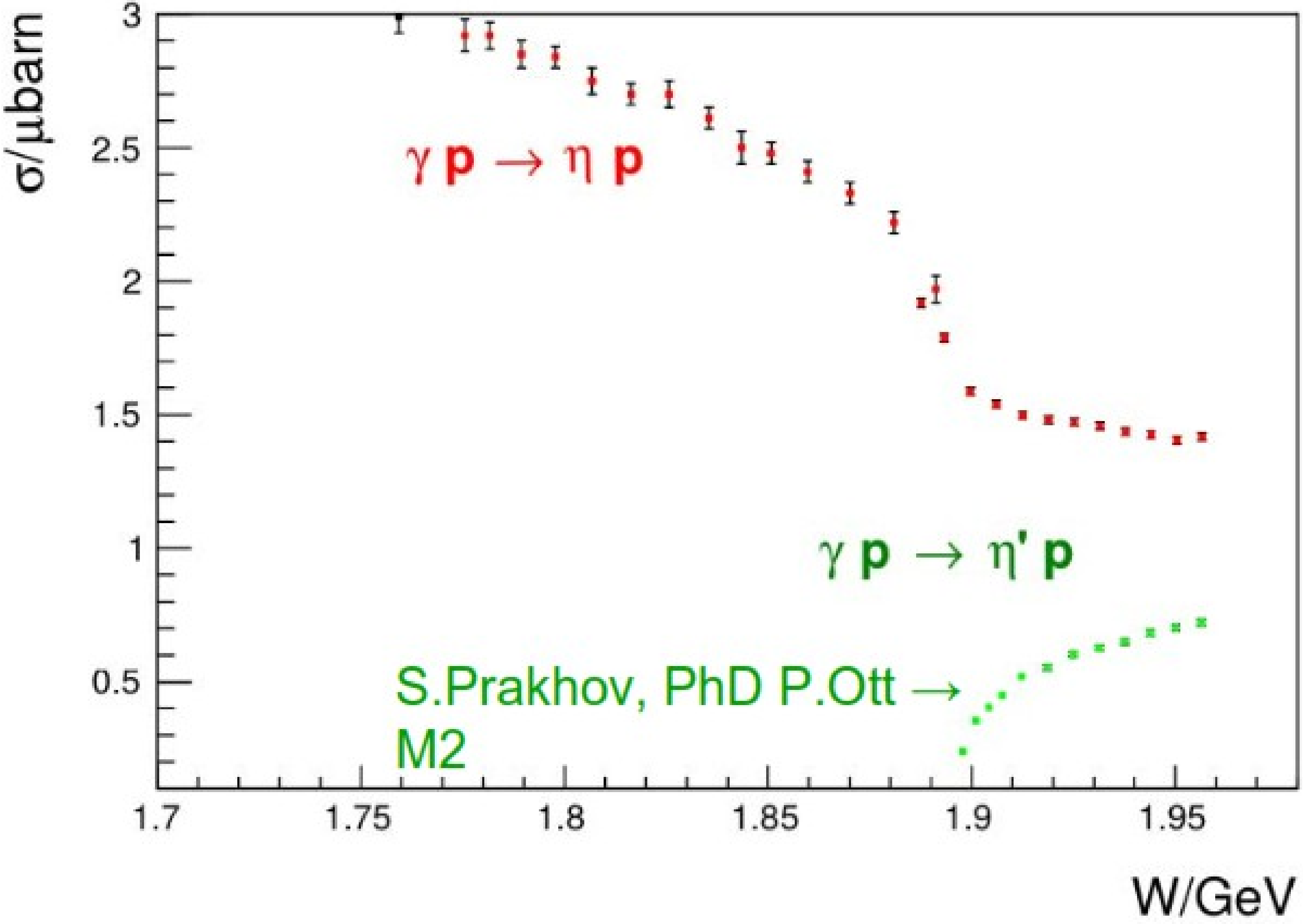
# Spin polarizabilites




- Recent data (MAMI) and older data (LEGS) are shown along with Dispersion Relation (HDPV) and ChPT (B$\chi$PT) predictions.

G. M. Huber, C. Collicott, arXiv:1508.07919 (2015)

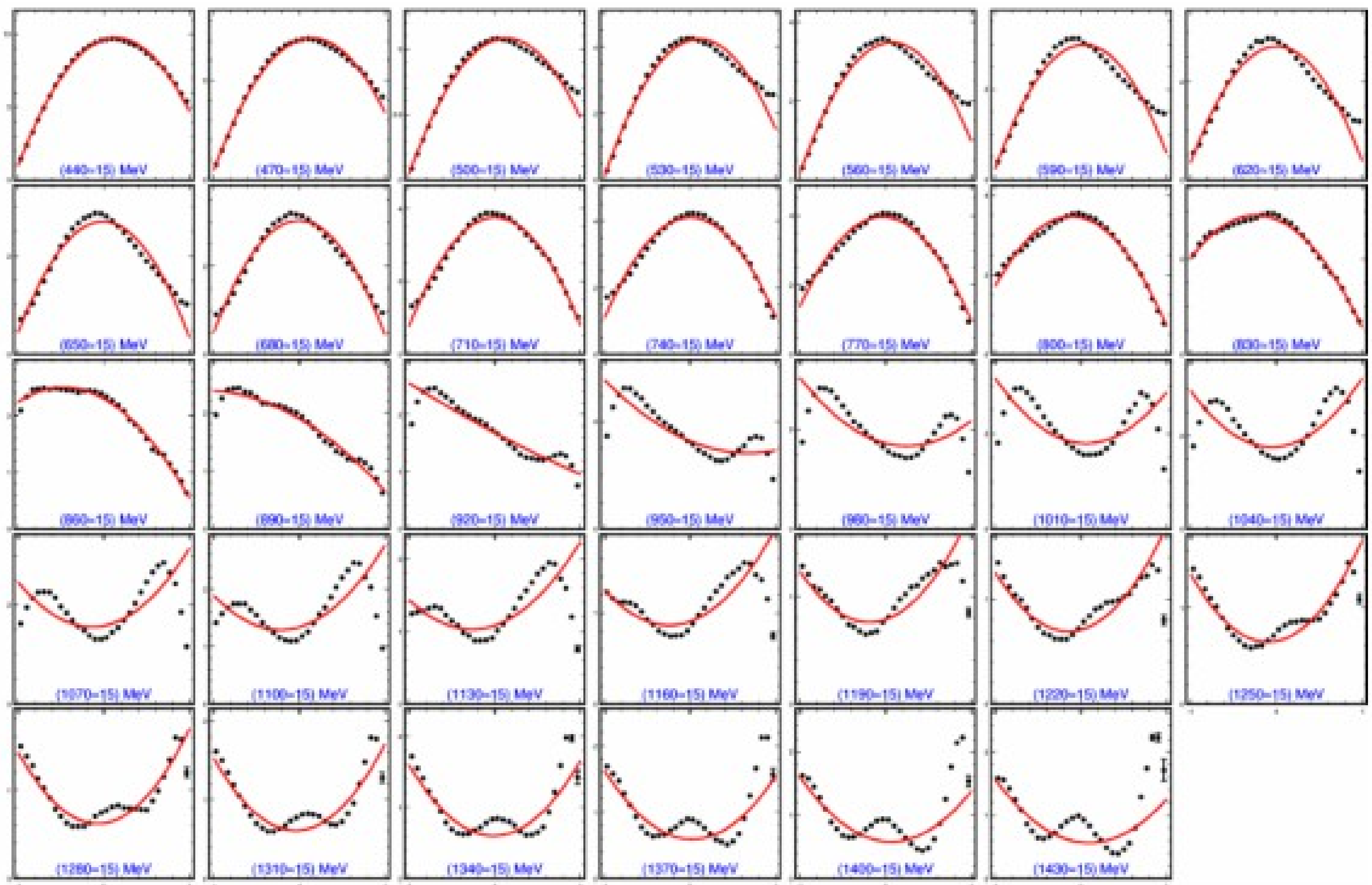
# N(1895)1/2-


σ/μbarn
3
2.5
2
1.5
1
0.5
γ p → η p
γ p → η' p
S.Prakhov, PhD P.Ott →
M2
1.7
1.75
1.8
1.85
1.9
1.95
W/GeV

# Single pion production

## Legendre expansion of the diff. cross section

$$\frac{d\sigma}{d\Omega} = \sum_{k=0}^{2\ell_{max}} A_k^{\sigma}(W)\, P_k(\cos\theta) \qquad \ell max = 1$$

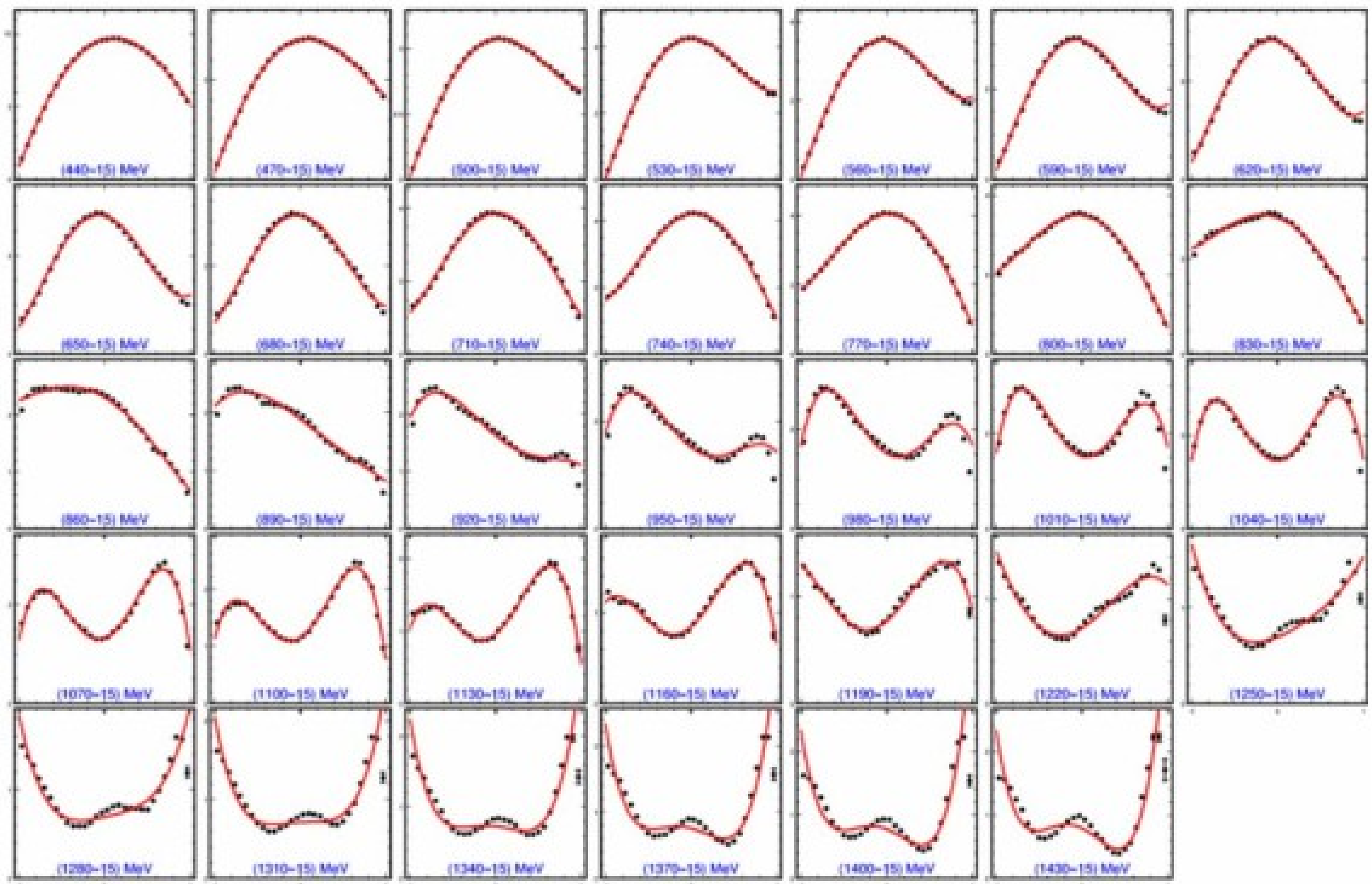



S+P waves are only good up to about 400 MeV

# Single pion production

Legendre expansion of the diff. cross section

$$\frac{d\sigma}{d\Omega} = \sum_{k=0}^{2\ell_{max}} A_k^{\sigma}(W) P_k(\cos\theta) \qquad \ell max = 2$$

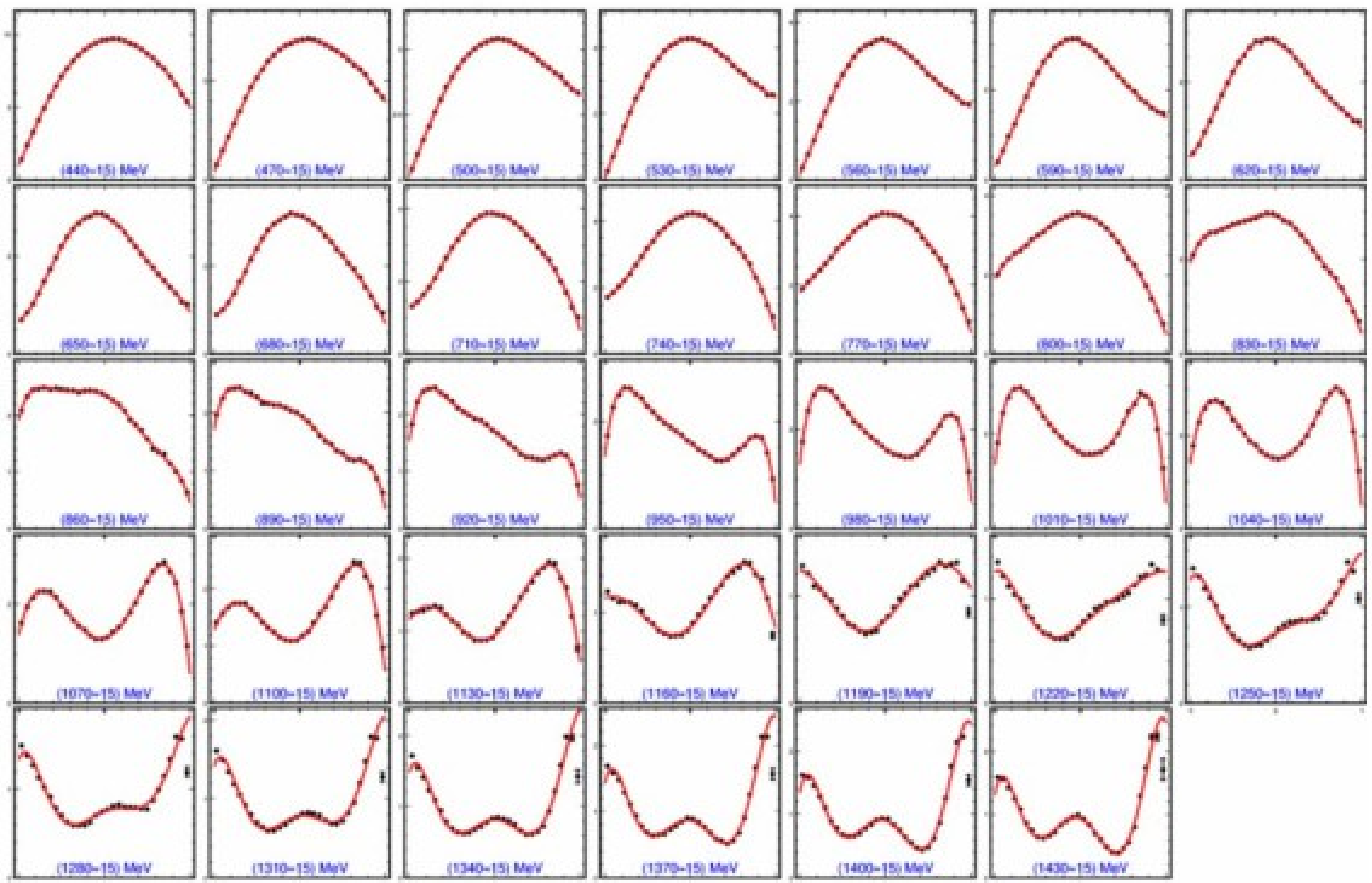


S+P+D waves are good up to about 850 MeV

# Single pion production

## Legendre expansion of the diff. cross section

$$\frac{d\sigma}{d\Omega} = \sum_{k=0}^{2\ell_{max}} A_k^{\sigma}(W)\, P_k(\cos\theta) \qquad \ell max = 3$$

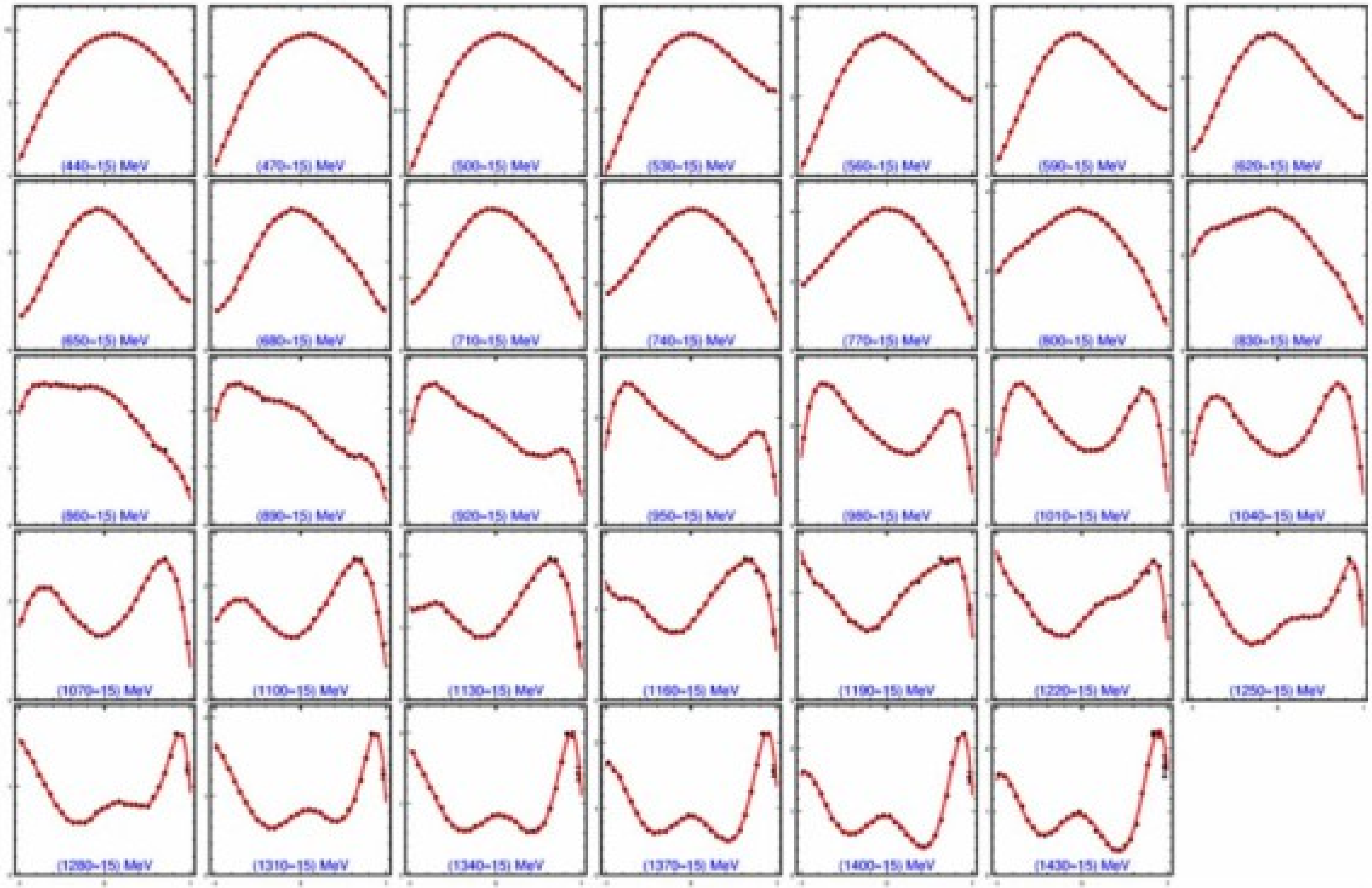


F waves become important around 1 GeV

# Single pion production

## Legendre expansion of the diff. cross section

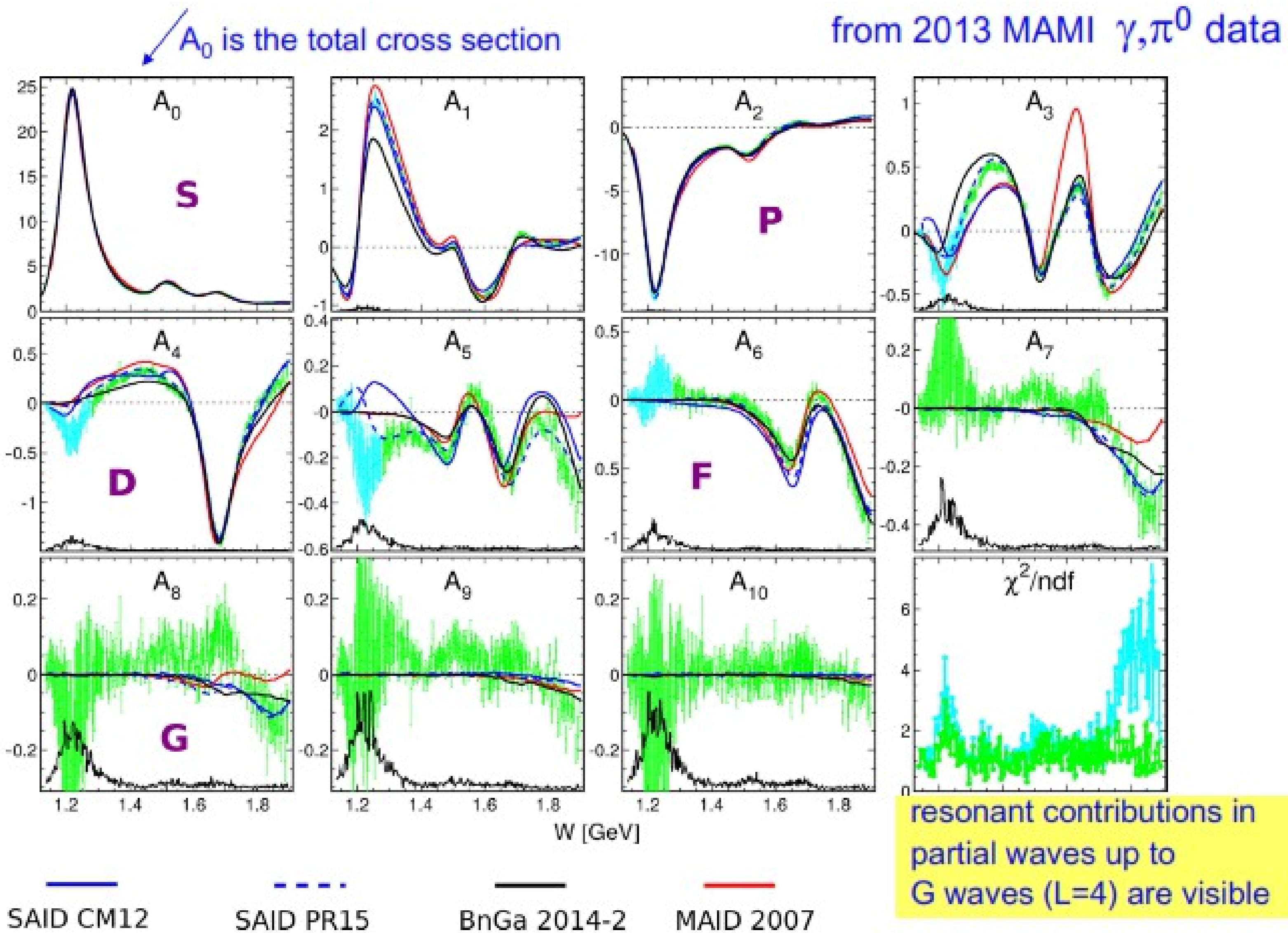
$$\frac{d\sigma}{d\Omega} = \sum_{k=0}^{2\ell_{max}} A_k^{\sigma}(W)\, P_k(\cos\theta) \qquad \ell max = 4$$




around 1.2 GeV also G waves become clearly visible in forward direction

# Single pion production

Legendre expansion of differential cross section




resonant contributions in partial waves up to G waves (L=4) are visible

# Polarized target (slide taken from R. Miskimen)

**Frozen spin target**

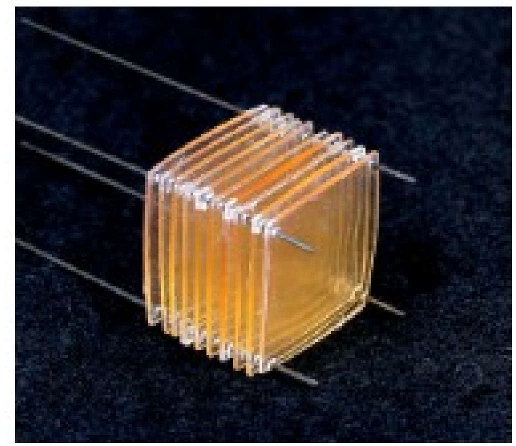
- 2 cm butanol
- target polarized at 25 mK
- 0.6 T holding field
- P ~ 90%
- > 1000 hours relaxation time

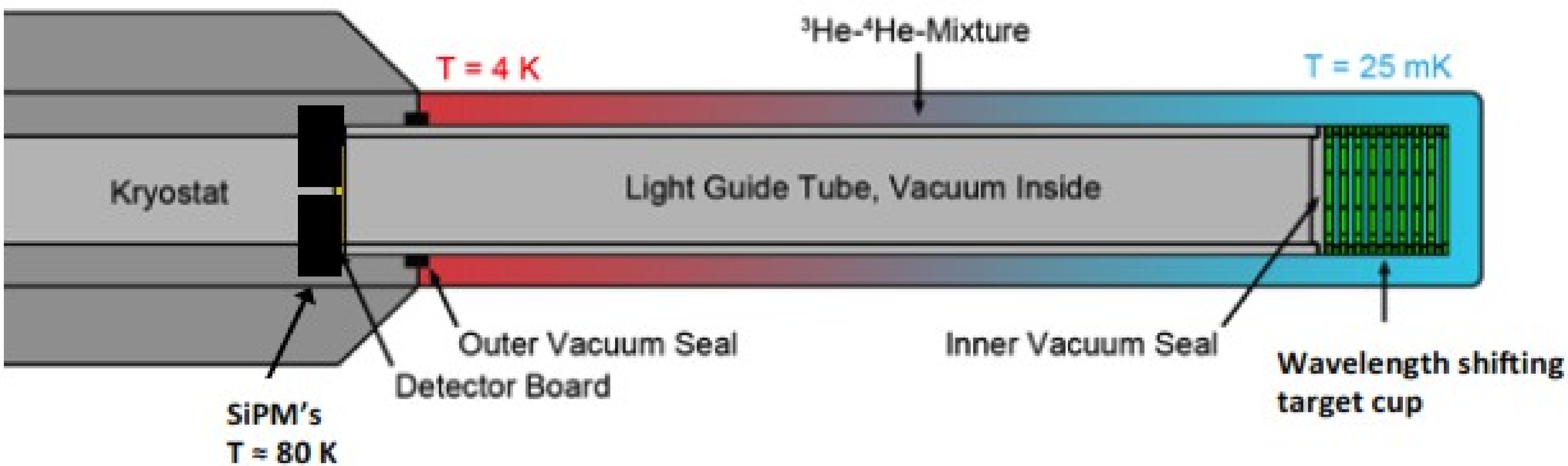
# Polarized active target (slide taken from R. Miskimen)

## Development of a scintillating polarized target for Mainz

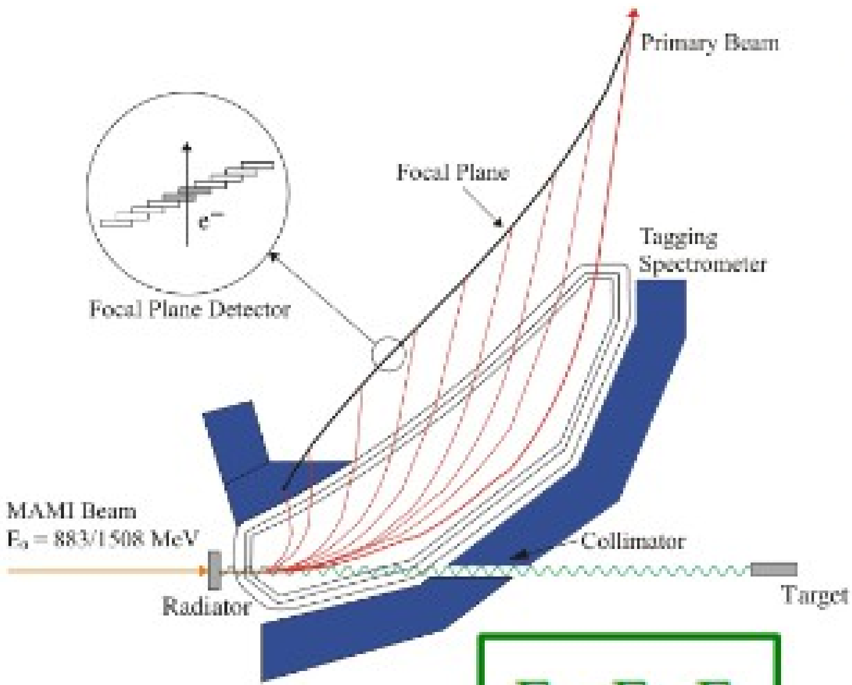
Needed for double-polarized Compton scattering measurements near pion threshold

- **Polarizable scintillator developed at UMass**
- ✓ Proton polarization ≈ 70%
- ✓ Relaxation time ≈ 22 hours
- ✓ Light output ≈ 30% of standard plastic scintillator
- ✓ High clarity for thicknesses up to 1 mm

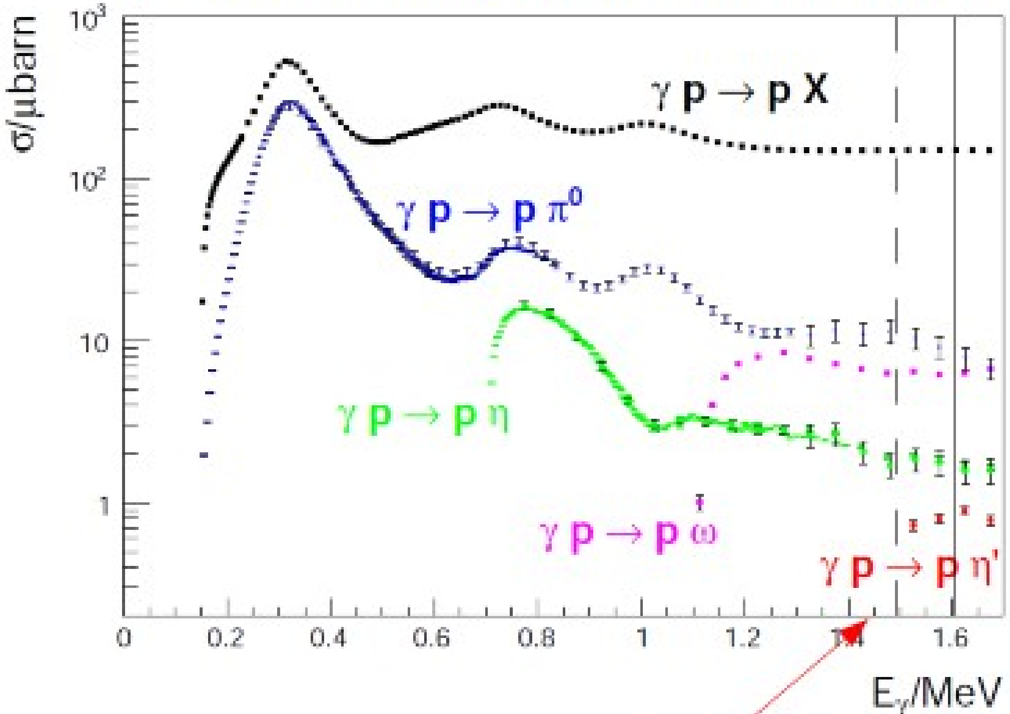




# Polarized active target (slide taken from M. Unverzagt)




$E_\gamma = E_0 - E_{e-}$




*High energy resolution:* $\Delta E_\gamma \approx 2$MeV at $E_{e-} = 883$ MeV

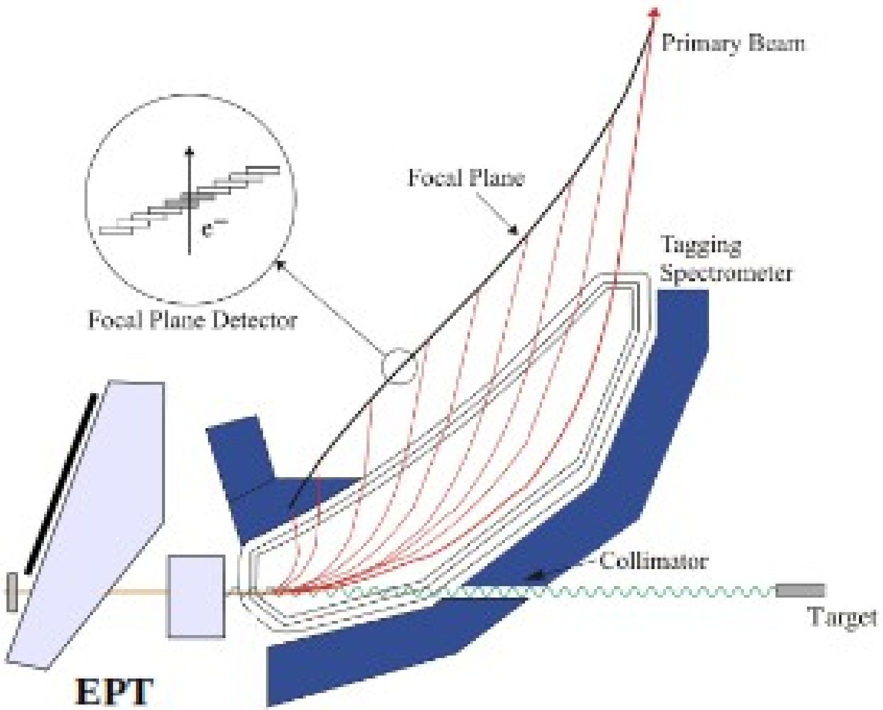
$\Delta E_\gamma \approx 4$MeV at $E_{e-} = 1558$ MeV

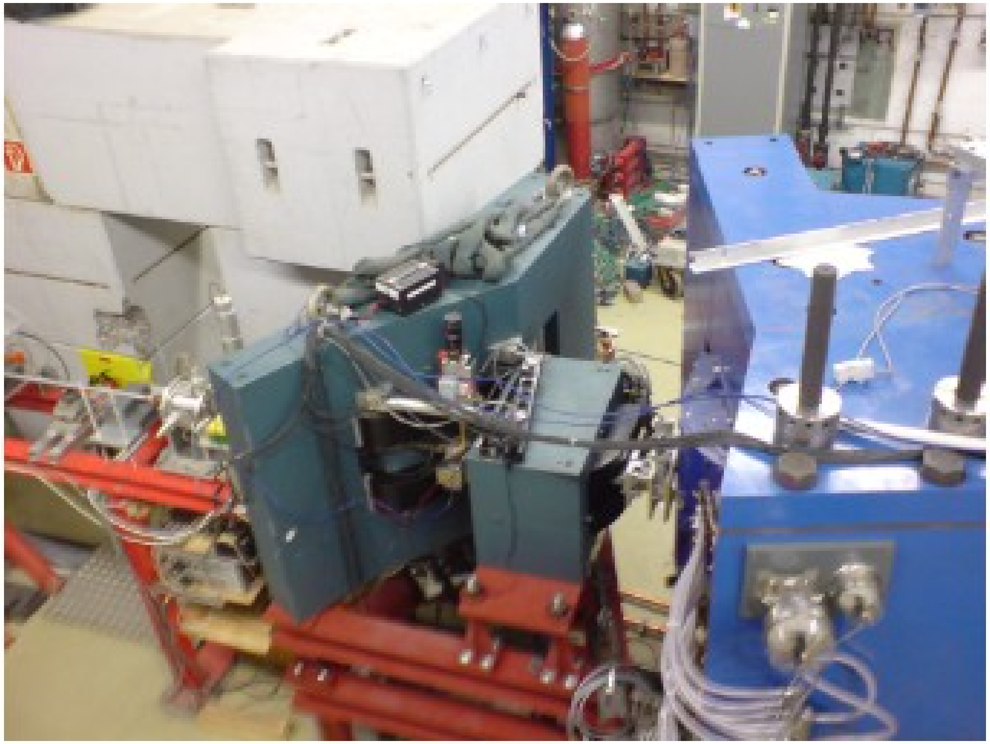
Linearly and circularly polarised photon-beam

Tagging range: 5.1 to 93% of $E_\gamma$ → Maximum energy tagged for $E_0 = 1604$ MeV is 1491 MeV

# EPT (slide taken from M. Unverzagt)

- Installation of EPT during 2012



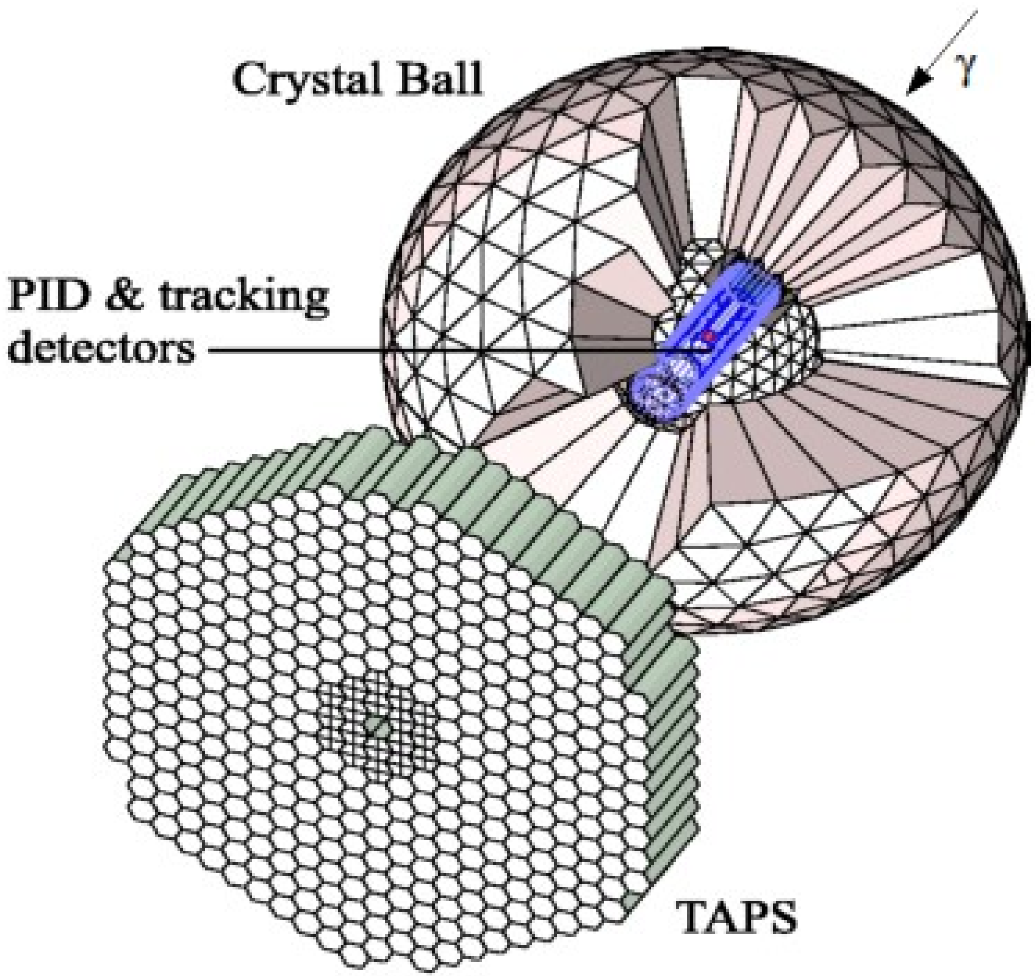
Same working principle as main tagging spectrometer

$E_\gamma \approx 1445\text{-}1595$ MeV

$\Delta E_\gamma \approx 2.5$MeV

Non-permanent installation infront of main Tagger

# Crystal Ball/TAPS (slide taken from M. Unverzagt)




<u>Crystal Ball:</u>

672 NaI(Tl) crystals

93,3% of total solid angle

Each crystal equipped with PMT

$$\frac{\sigma}{E_\gamma} = \frac{2\%}{(E_\gamma / GeV)^{0.25}} \qquad \sigma(\theta) = 2^\circ \ldots 3^\circ$$

$$\Delta t = 2.5 \text{ ns FWHM} \qquad \sigma(\phi) = \frac{2^\circ \ldots 3^\circ}{\sin(\theta)}$$

<u>TAPS:</u>

Up to 510 $BaF_2$ crystals

Polar acceptance: 4-20°

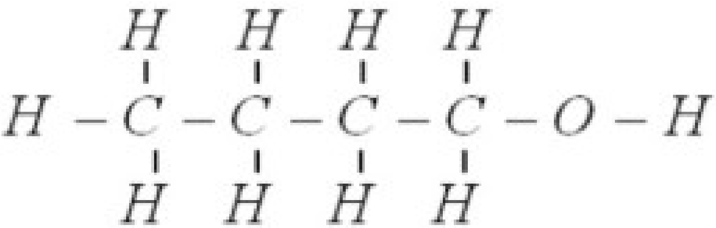
$\Delta t = 0.5$ ns FWHM

$$\frac{\sigma}{E_\gamma} = \frac{0{,}79\%}{\sqrt{E_\gamma / GeV}} + 1{,}8\%$$

# Targets (slide taken from M. Unverzagt)

- $LH_2$/$lD_2$ used for high rate meson production (η/η')
  - Length: 3cm, 5cm, 10cm

- $l^3He$/$l^4He$

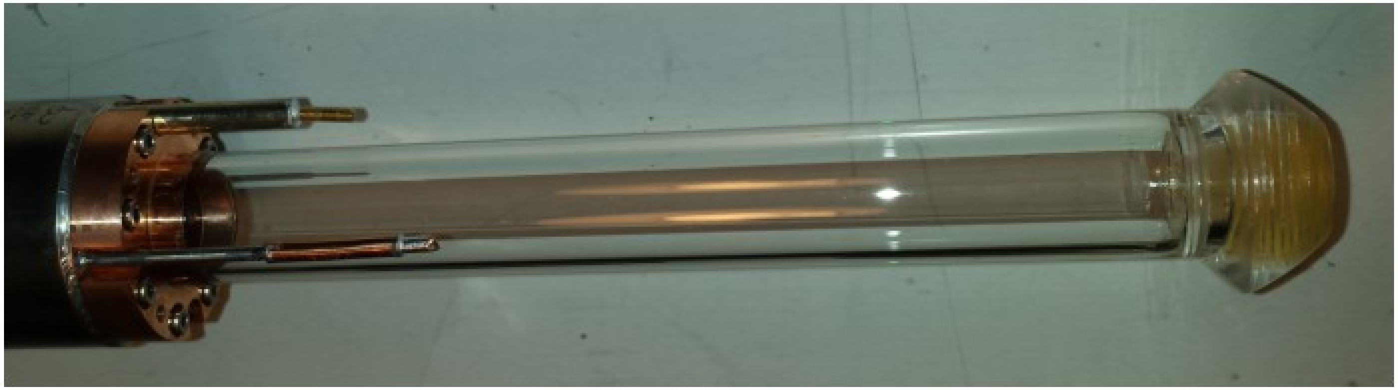



- Polarised Butanol/D-Butanol
  - Transverse and longitudinal polarisation
  - Lenght: 2 cm
  - Dynamic Nuclean Polarisation
  - Max. Polarisation: 90%
  - Holding filed: 0.44 T
  - Relaxation time: τ~1000h

- Solid Targets

# Polarized active target (slide taken from R. Miskimen)

Target assembly



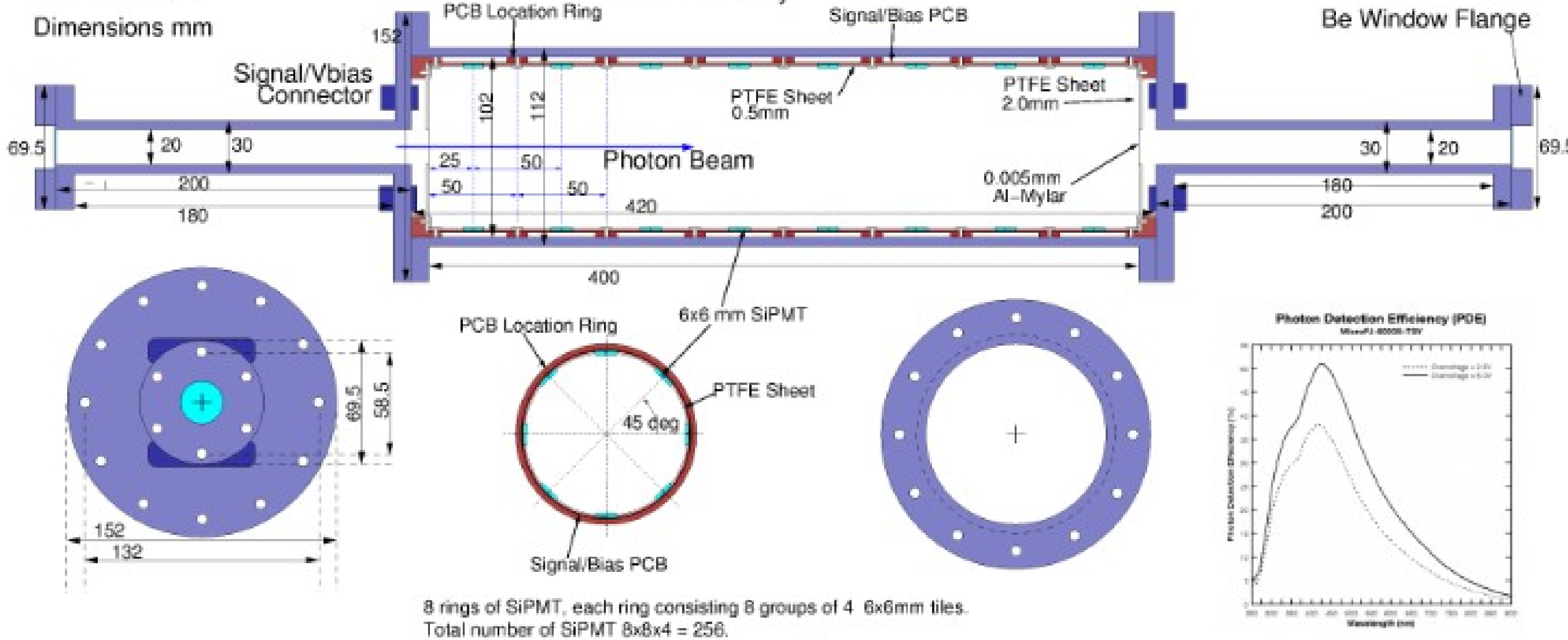
PhD, Maik Biroth, Mainz

# He gas active target

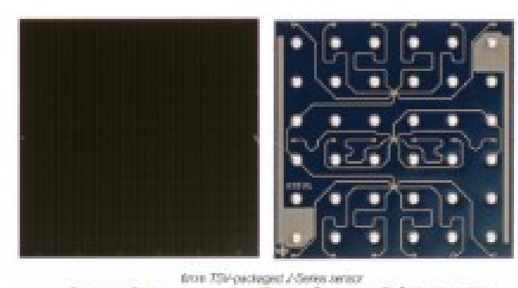
University of Glasgow

## The New Active Target

Active Target
J.R.M. Annand
11th Feb. 2016
Dimensions mm




8 rings of SiPMT, each ring consisting 8 groups of 4 6x6mm tiles.
Total number of SiPMT 8x8x4 = 256.
Readout in groups of 16, each group connected to an op–amp.
16 signal outputs
2 vias–voltage inputs



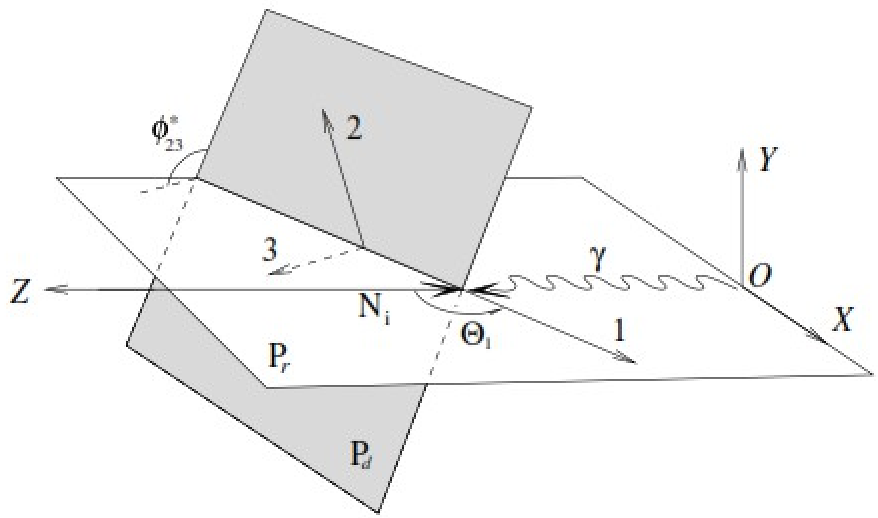
6 x 6mm J-Series SiPMT

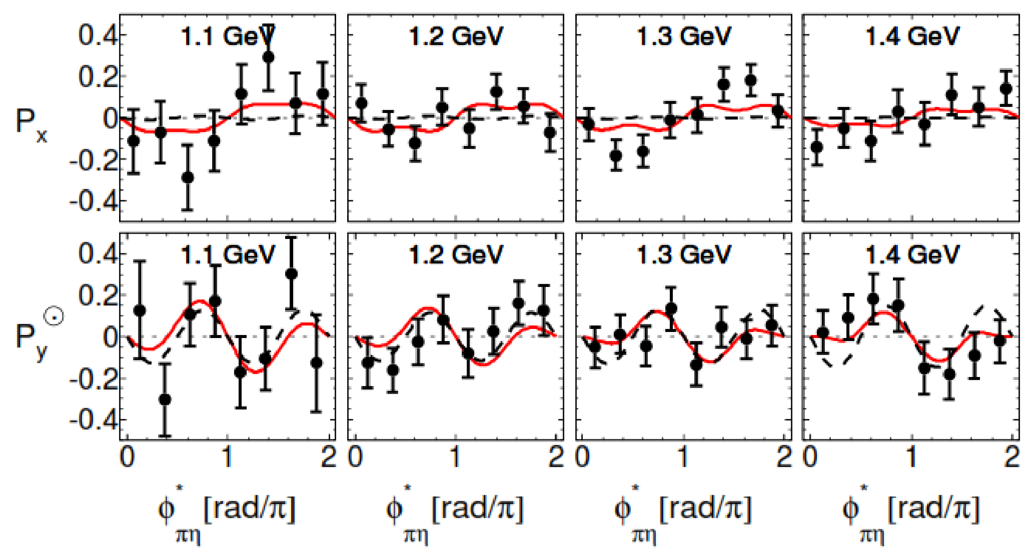
- Al pressure vessel, no welds
- Reuse Be outer windows from original Active Target
- PTFE sheet covers printed circuit board, windows cut for SiPMT

# $\pi^0\eta$ production, double polarization observables

$$\frac{d\sigma}{d\Omega_1 dM_{23} d\Omega^*_{23}} = \frac{d\sigma_0}{d\Omega_1 dM_{23} d\Omega^*_{23}} \Big\{ 1 + h P_\odot I^\odot + \frac{1}{\sqrt{2}} P_T [P_x \cos\phi - P_y \sin\phi] + h P_\odot (P_x^\odot \cos\phi - P_y^\odot \sin\phi)] \Big\}$$

| Beam | Target | |
|---|---|---|
| | $x$ | $y$ |
| – | $P_x$ | $P_y$ |
| $c$ | $P_x^\odot$ | $P_y^\odot$ |



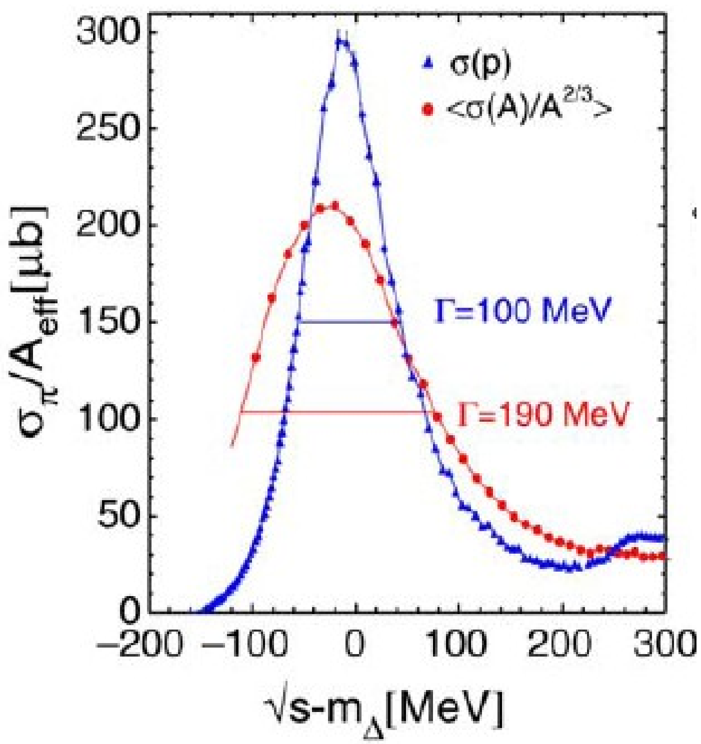




Dashed: only $D_{33}$ wave, solid: A. Fix model, dashed-dotted BnGa PWA

J. R. M. Annand et al., Phys.Rev. C91, no.5, 055208 (2015)

# Motivation

- The width for $\Delta(1232)$ is changed in the nuclear medium from 100 MeV to ~190 MeV in good agreement with the BUU model (University Gießen) calculations




B. Krusche, Progress in Particle and Nuclear Physics 55 (2005) 46–70
M. Post, J. Lehr, U. Mosel, Nuclear Phys. A 741 (2004) 81

- Second resonance region: No strong experimental indication for significant modifications of $D_{13}(1520)$ or $S_{11}(1535)$