Photoproduction of baryon resonances - recent results from the A2 collaboration

STRONG 2020 workshop

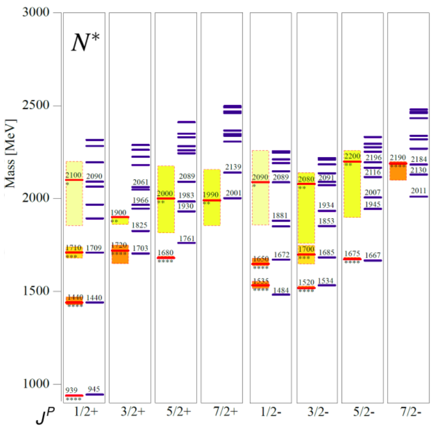
Farah Afzal

September 15^{th}, 2021

University of Bonn

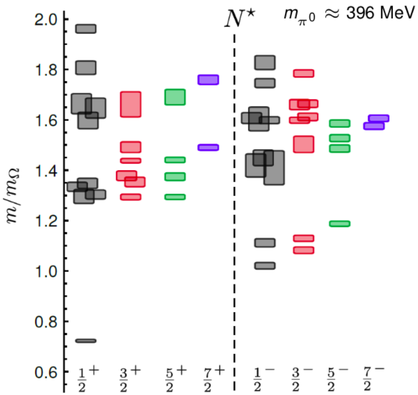
Baryon spectroscopy

Quark model with experimental data



[M. Ronninger and B. Metsch, Eur. Phys. J. A 47 (2011) 162]

Lattice QCD calculations



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

- Discrepancy between theory and experiment: missing resonances, ordering of states

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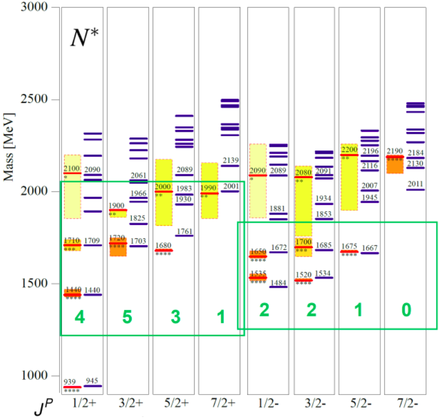

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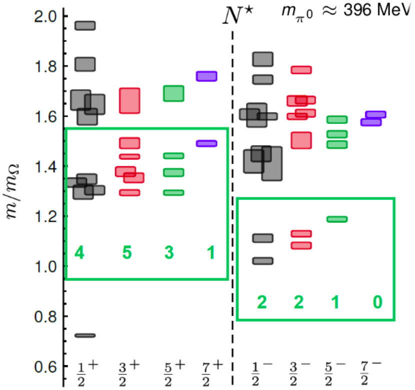
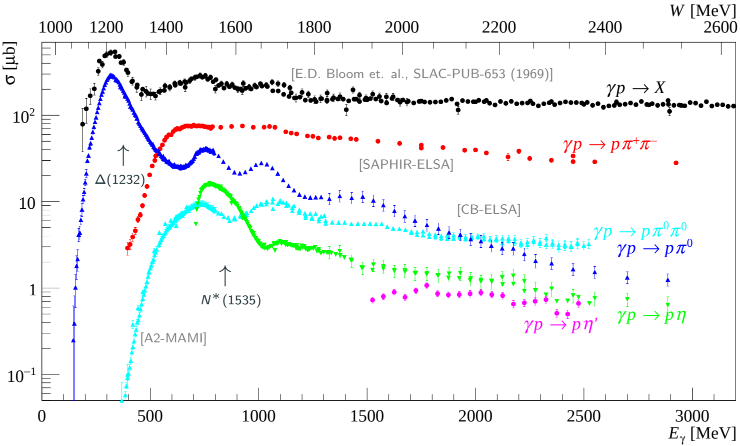


[R. G. Edwards et al., Phys. Rev. D 84 (2011) 074508]

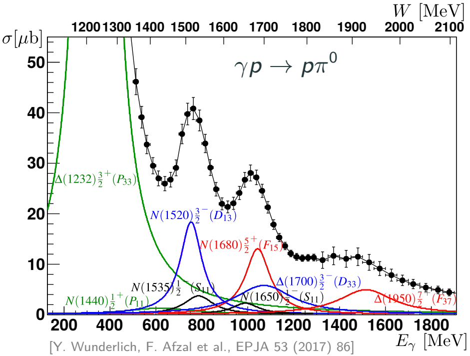
- Discrepancy between theory and experiment: missing resonances, ordering of states
- most resonances observed in πN scattering $\rightarrow$ experimental bias?

Worldwide effort to get high precision data (ELSA, MAMI, JLab, SPring-8, ...)



- Photoproduction reactions are an excellent tool to probe excitation spectra!
- Resonances contribute with different strength to distinct channels
- How can we disentangle contributing resonances?

Unpolarized cross section



[Y. Wunderlich, F. Afzal et al., EPJA 53 (2017) 86]

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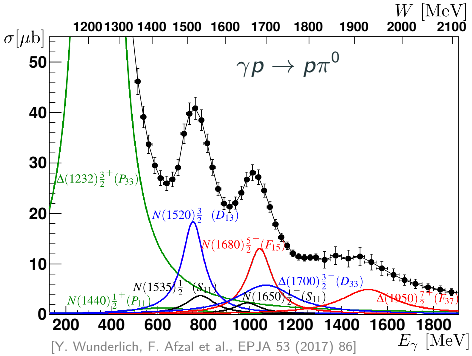
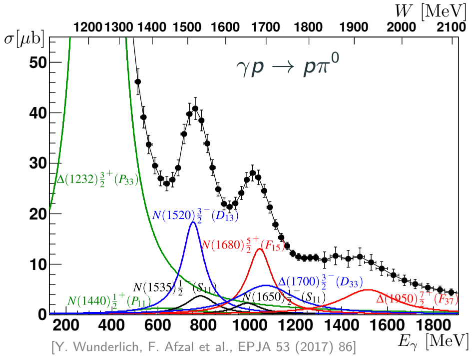


[Y. Wunderlich, F. Afzal et al., EPJA 53 (2017) 86]

$$\frac{d\sigma}{d\Omega}_0(W,\theta) \propto \sum_{\text{spins}} |<f|\mathcal{F}|i>|^2$$

Unpolarized cross section



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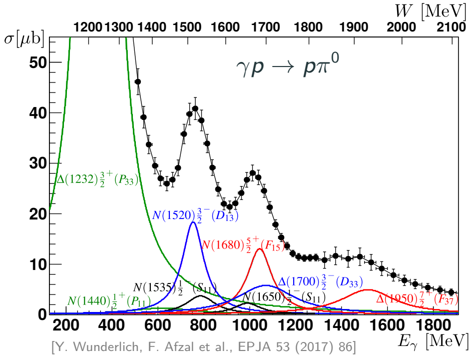
Photoproduction amplitude $\mathcal{F}$

$\leftrightarrow$ 4 complex amplitudes

e.g. CGLN amplitudes: F_1, F_2, F_3, F_4

Unpolarized cross section



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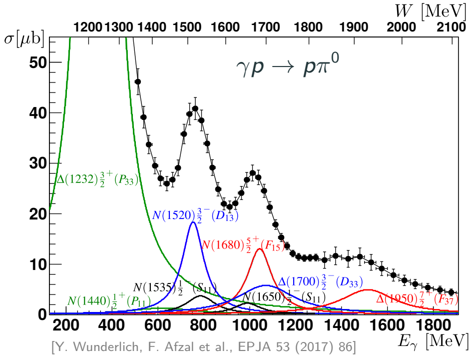
- PWA: e.g. $F_1 = \sum_{l=0}^{\infty}(lM_{l+} + E_{l+})P'_{l+1} + [(l+1)M_{l-} + E_{l-}]P'_{l-1}$
  - $E_{l\pm}(W), M_{l\pm}(W)$: Multipoles
  - $P'_{l\pm1}(\cos\theta_{cm})$: Legendre polynomials



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  - $E_{l\pm}(W), M_{l\pm}(W)$: Multipoles
  - $P'_{l\pm1}(\cos\theta_{cm})$: Legendre polynomials
- $\sigma \sim |E_{0+}|^2 + |E_{1+}|^2 + |M_{1+}|^2 + |M_{1-}|^2 + \ldots$
  $\rightarrow$ unpolarized cross section is sensitive to dominant contributing resonances

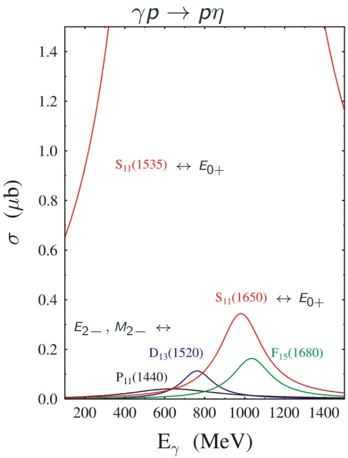
Polarization observables

Polarization observables in the 2-body kinematic system for the photoproduction of a pseudoscalar meson

Photon polarization		Target polarization			Recoil nucleon polarization			Target and recoil polarizations			
		X	Y	Z(beam)	X'	Y'	Z'	X' X	X' Z	Z' X	Z' Z
unpolarized	σ	-	T	-	-	P	-	$T_{x'}$	$L_{x'}$	$T_{z'}$	$L_{z'}$
linear	$-\Sigma$	H	(-P)	-G	$O_{x'}$	(-T)	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(L_{x'})$	$(-T_{x'})$
circular	-	F	-	-E	$C_{x'}$	-	$C_{z'}$	-	-	-	-

$\sigma, \Sigma, T, P + 4$ double pol. observables needed for a unique solution

[W. Chiang and F. Tabakin, Phys. Rev., C55 (1997) 2054-2066]



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Polarization observables in the 2-body kinematic system for the photoproduction of a pseudoscalar meson

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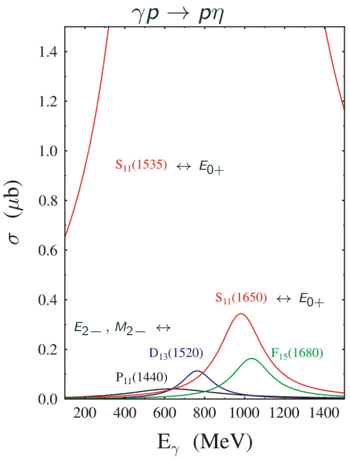
linear	$-\Sigma$	H	(-P)	-G	$O_{x'}$	(-T)	$O_{z'}$	($-L_{z'}$)	($T_{z'}$)	($L_{x'}$)	($-T_{x'}$)
circular	-	F	-	-E	$C_{x'}$	-	$C_{z'}$	-	-	-	-

σ, Σ, T, P + 4 double pol. observables needed for a unique solution

[W. Chiang and F. Tabakin, Phys. Rev., C55 (1997) 2054-2066]

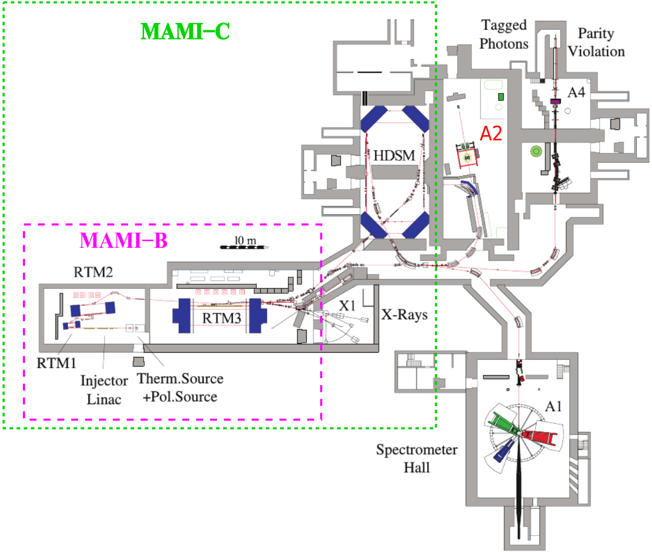
$$\Sigma \sim \underbrace{-2E_{0+}^* E_{2+} + 2E_{0+}^* E_{2-} - 2E_{0+}^* M_{2+} + 2E_{0+}^* M_{2-}}_{< S, D >} + \ldots$$



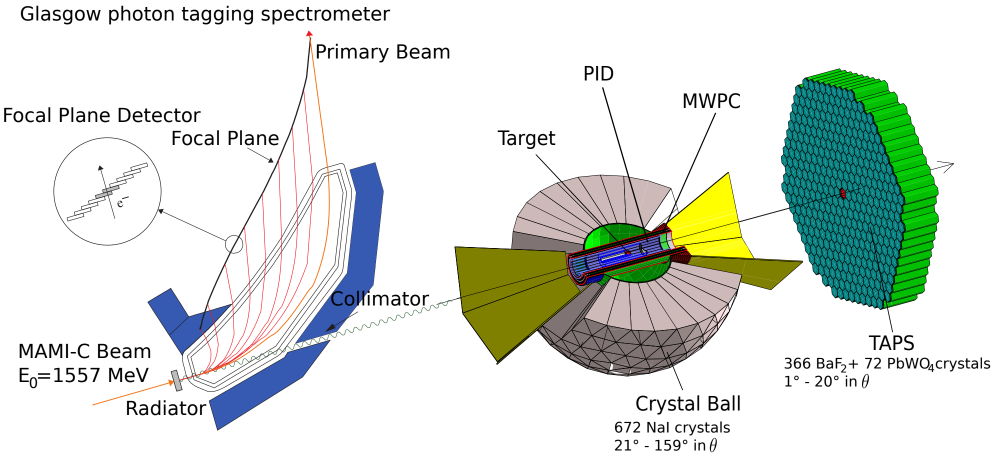
→Polarization observables are sensitive to interference terms!

→Interferences with the dominant S-wave (E_{0+}) important in η photoproduction!

Experimental setup

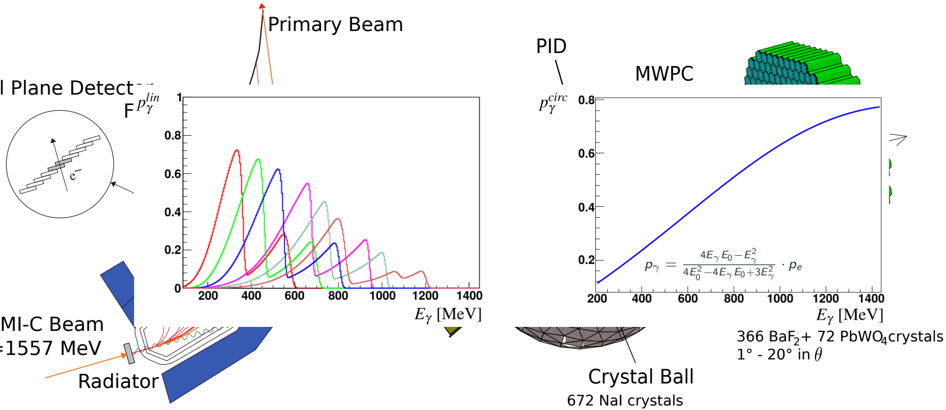


- Unpolarized or longitudinally polarized electrons
- Acceleration in 3 race track microtrons (RTM1-3) to 855 MeV (MAMI-B)
- Acceleration in in harmonic double-sided microtron (HDSM) to 1600 MeV (MAMI-C)



Glasgow photon tagging spectrometer
Primary Beam
Focal Plane Detector
Focal Plane
e⁻
Collimator
MAMI-C Beam
E_0=1557 MeV
Radiator
PID
MWPC
Target
TAPS
366 BaF_2+ 72 $PbWO_4$ crystals
1° - 20° in θ
Crystal Ball
672 NaI crystals
21° - 159° in θ

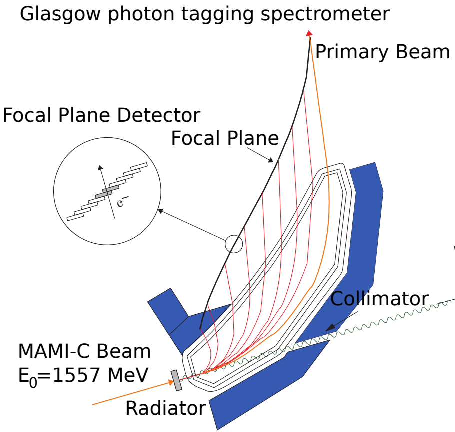
Glasgow photon tagging spectrometer

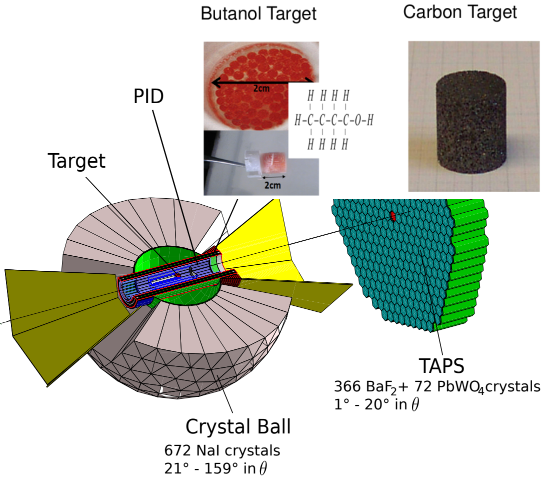


366 BaF_2+ 72 $PbWO_4$ crystals
1° - 20° in θ

672 NaI crystals
21° - 159° in θ

The A2 experiment at MAMI (Mainz)





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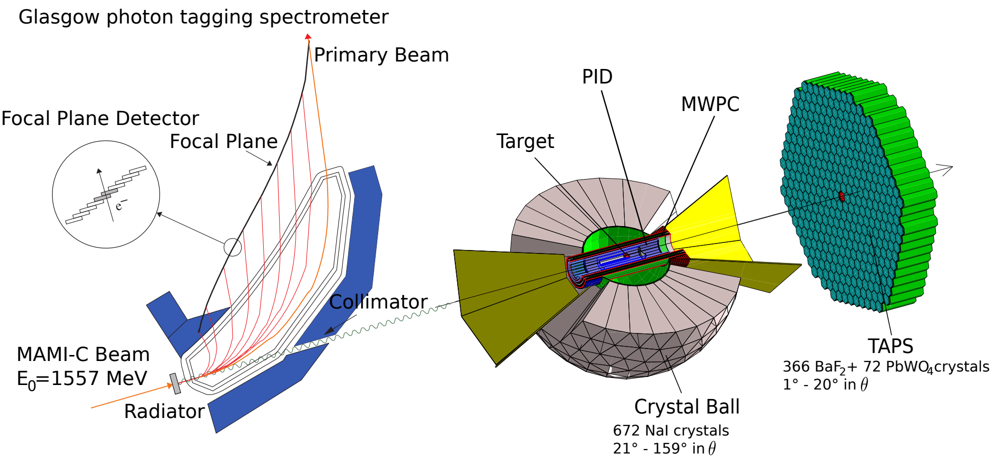
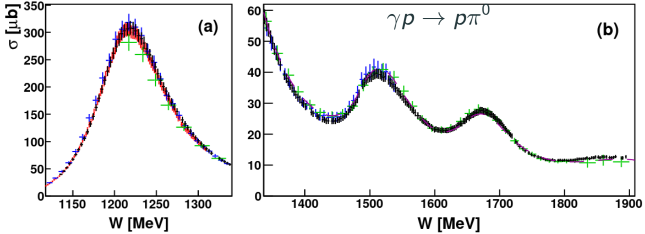


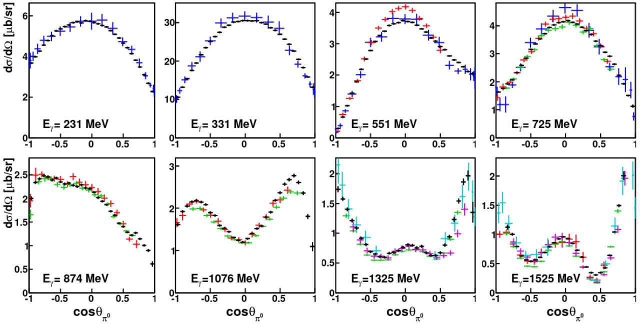
Ideally suited to identify charged and neutral final states!

Measurement of cross sections



P. Adlarson et al., Phys. Rev. C 92.2 (2015), p. 024617

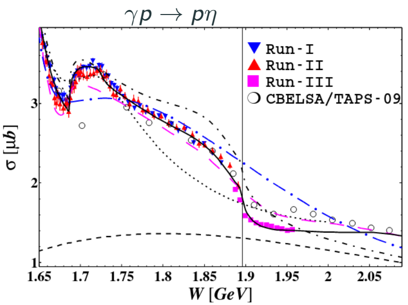
+ other MAMI data, + other MAMI data, + CB-ELSA

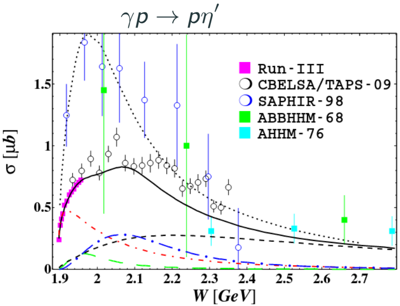


+ other MAMI data + GRAAL + CLAS + CB-ELSA + CBELSA/TAPS

- fine energy binning
- full angular coverage
- increases existing data by 47%

Measurement of cross sections





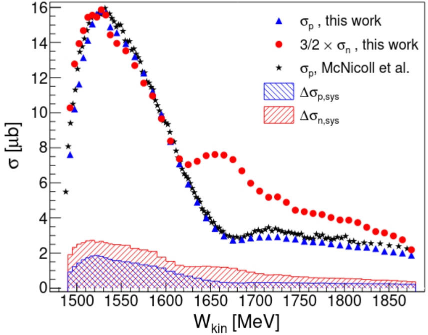
V.L. Kashevarov et al., Phys. Rev. Lett. 118, 21 (2017), p. 212001

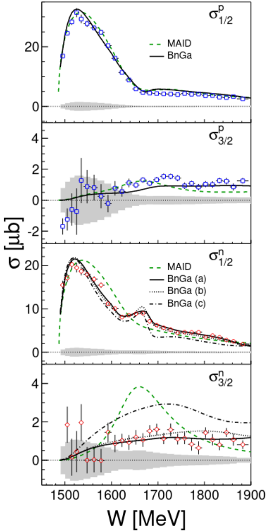
- key role for description: 3 $S-$wave resonances: $N(1535)\frac{1}{2}^-$, $N(1650)\frac{1}{2}^-$ and $N(1895)\frac{1}{2}^-$
- strong $p\eta'$ cusp observed in $p\eta$ cross section
- $N(1895)\frac{1}{2}^-$ needed for description of $p\eta'$ cusp and fast rise of $p\eta'$ cross section

Measurement of cross sections

narrow peak observed in $\gamma n \to n\eta$
at $W = (1670 \pm 5)$ MeV with $\Gamma = 30$ MeV

[D. Werthmüller et al., Phys.Rev. C90 (2014) no.1, 015205]





[L. Witthauer et al., Phys. Rev. Lett. 117, no. 13, 132502 (2016)]

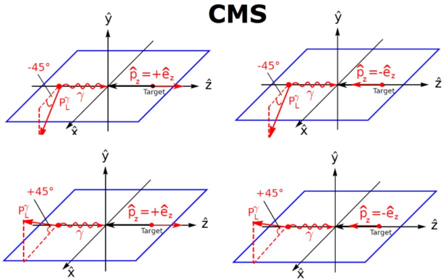
helicity dependend cross sections used to shed further light on this structure

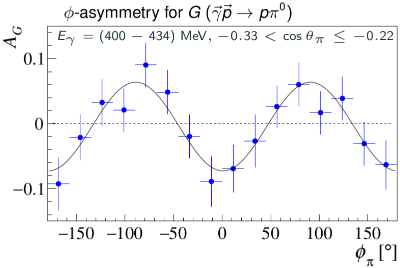
Structure only present in $\sigma^n_{1/2}$!

Differential cross section for pseudo-scalar meson photoproduction using **elliptically** polarized photons and longitudinally polarized target:

$$\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}_0(\theta)\left[1 - P_{lin}\boldsymbol{\Sigma}\cos(2(\alpha-\phi)) - P_z\left(-P_{lin}\mathbf{G}\sin(2(\alpha-\phi)) + P_{circ}\mathbf{E}\right)\right]$$

Summing over both helicity states and combining different settings: $A_G = G \cdot \cos(2\phi_\pi)$





Measurement of double polarization observables G, E

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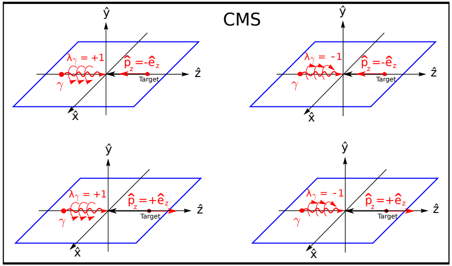
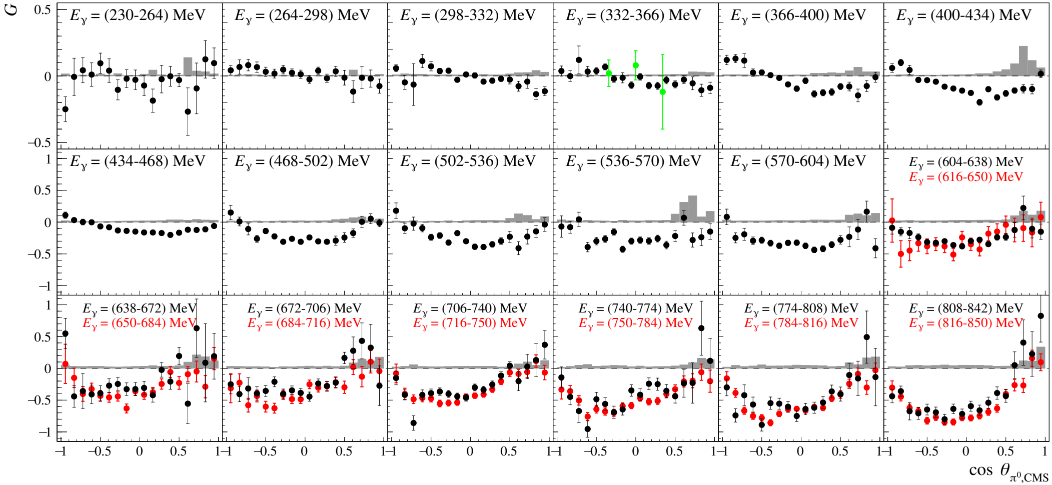
Integrating over ϕ:

$$N_B\Big|_{\pm 1}^{\pm P_z}(\theta) = N_B(\theta)\cdot\left[1 - d\,P_{circ}P_z\mathbf{E}\right]$$



$$\mathrm{E} = \frac{\sigma^{1/2} - \sigma^{3/2}}{\sigma^{1/2} + \sigma^{3/2}} = \frac{N_B^{1/2} - N_B^{3/2}}{N_B^{1/2} + N_B^{3/2}}\cdot\frac{1}{d}\cdot\frac{1}{P_{circ}P_z}$$

Double polarization observable G in $\gamma p \rightarrow p\pi^0$

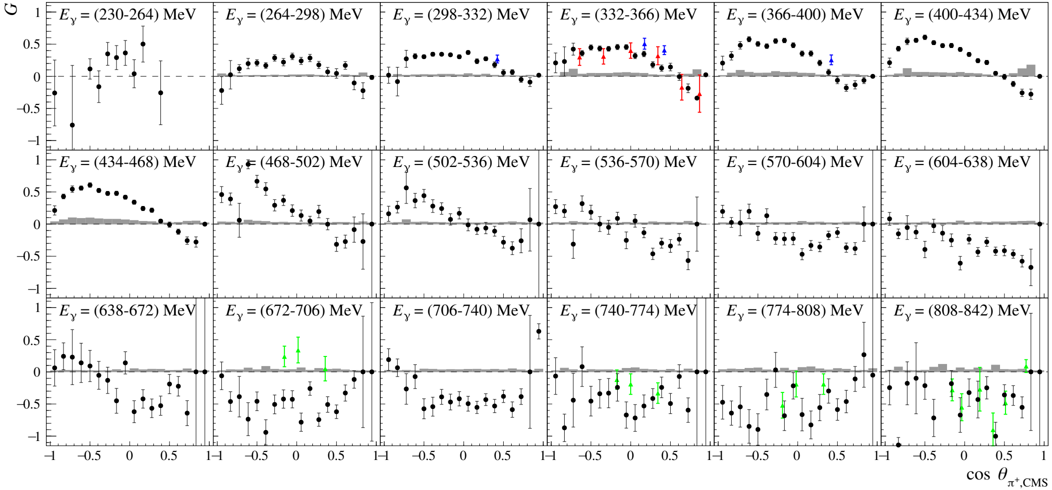


● this work ● A2/GDH [1] ● CBELSA/TAPS [2]

[1] J. Ahrens et al. Eur. Phys. J. A **26** (2005) 135 [2] A. Thiel et al. Eur. Phys. J. A **53** (2017) 8

data: K. Spieker, PhD thesis

Double polarization observable G in $\gamma p \to n\pi^+$

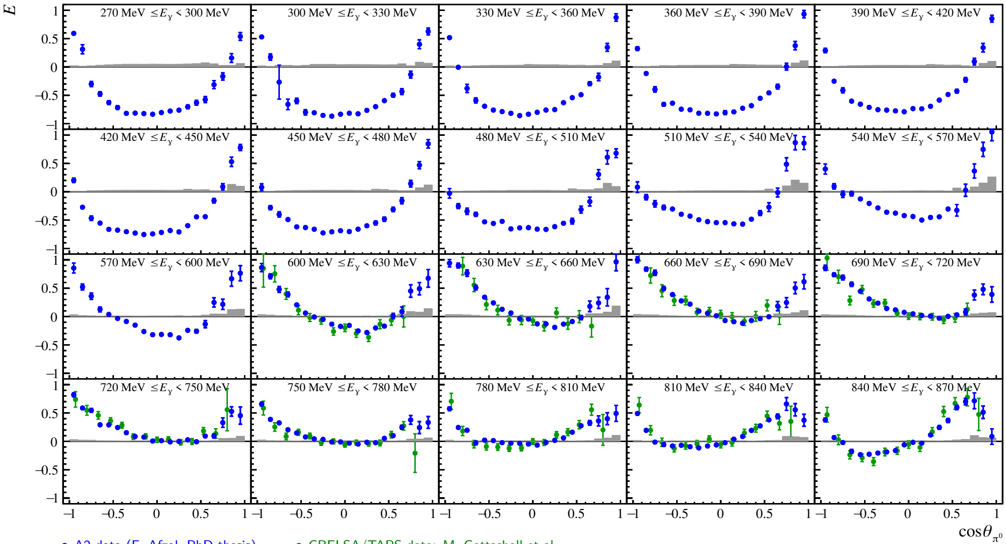


● this work ● A2/GDH [1] ● Belyaev et al. [2] ● Bussey et al. [3]

[1] J. Ahrens et al. Eur. Phys. J. A **26** (2005) 135 [2] A. Belayev et al, Sov. J. Nucl. Phys. **40** (1984) 83 [3] P. J. Bussey et al, Nucl. Phys. B **83** (1980) 403-414

data: K. Spieker, PhD thesis

Double polarization observable E in $\gamma p \to p\pi^0$



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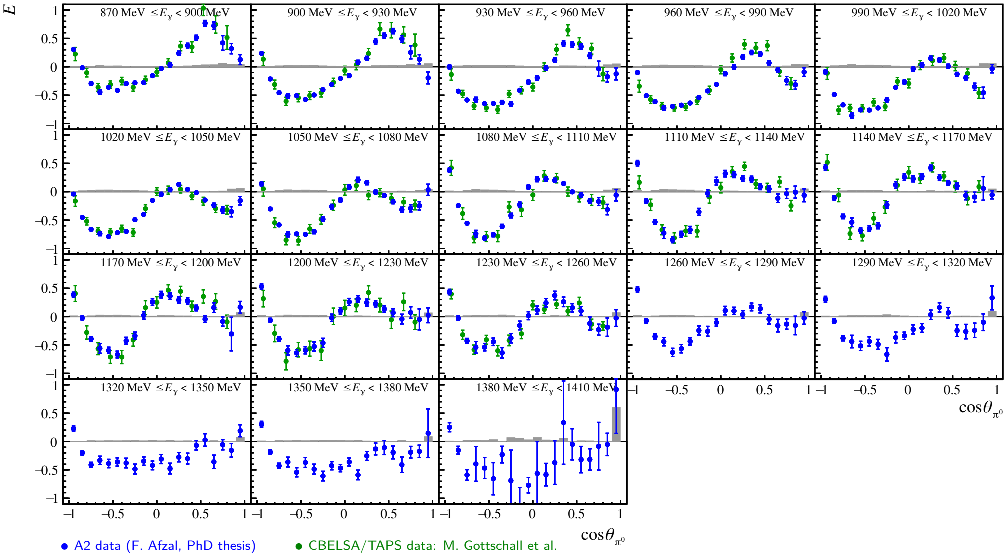
Double polarization observable E in $\gamma p \rightarrow p\pi^0$



• A2 data (F. Afzal, PhD thesis) • CBELSA/TAPS data: M. Gottschall et al.

Discussion of results

Dominant partial wave contributions in polarization observables

$$\check{\mathrm{E}}(W, \cos\theta) = \mathrm{E}(W, \cos\theta) \cdot \frac{d\sigma}{d\Omega}(W, \cos\theta) = \sum_{k=0}^{2L_{max}} (a_L(W))_k \cdot P_k^0(\cos\theta)$$

Dominant partial wave contributions in polarization observables

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$$\check{E}(W,\cos\theta) = E(W,\cos\theta)\cdot\frac{d\sigma}{d\Omega}(W,\cos\theta) = \sum_{k=0}^{2L_{max}} (a_L(W))_k \cdot P_k^0(\cos\theta)$$

$$(a_2)_2^{\check{E}}(W) = (E_{0+}^*, E_{1+}^*, \ldots, M_{2-}^*) \left(\begin{array}{c|ccc|cccc} 0 & 0 & 0 & 0 & 6 & 1 & 3 & -3 \\ \hline 0 & 6 & 0 & -3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & -1 & 0 & 0 & 0 & 0 \\ 0 & -3 & -1 & 0 & 0 & 0 & 0 & 0 \\ \hline 6 & 0 & 0 & 0 & 12 & \frac{24}{7} & \frac{60}{7} & 0 \\ 1 & 0 & 0 & 0 & \frac{24}{7} & 2 & -\frac{15}{7} & 0 \\ 3 & 0 & 0 & 0 & \frac{60}{7} & -\frac{15}{7} & \frac{12}{7} & -\frac{27}{7} \\ -3 & 0 & 0 & 0 & 0 & 0 & -\frac{27}{7} & 6 \end{array}\right) \begin{pmatrix} E_{0+} \\ E_{1+} \\ M_{1+} \\ M_{1-} \\ E_{2+} \\ E_{2-} \\ M_{2+} \\ M_{2-} \end{pmatrix}$$

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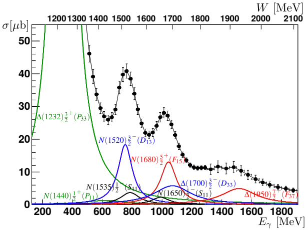
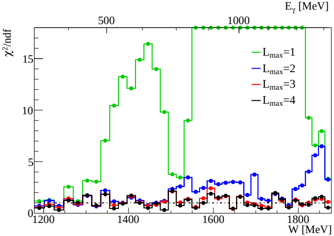
$$= \langle P, P \rangle + \langle S, D \rangle + \langle D, D \rangle$$

Dominant partial wave contributions (E (A2), $\gamma p \rightarrow p\pi^0$)

$$\check{E}(W,\cos\theta) = E(W,\cos\theta)\cdot\frac{d\sigma}{d\Omega}(W,\cos\theta) = \sum_{k=0}^{2L_{max}+1}(a_L(W))_k \cdot P_k^0(\cos\theta)$$



[Y. Wunderlich, F. Afzal et al., EPJA 53 (2017) 86]



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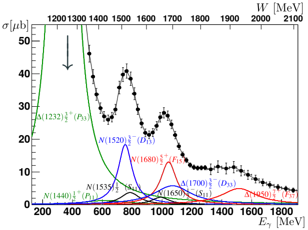

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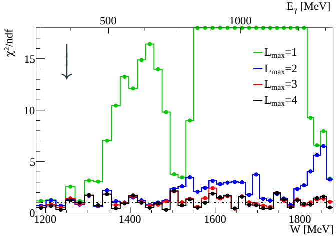
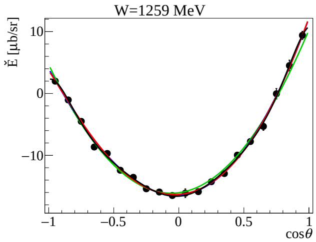
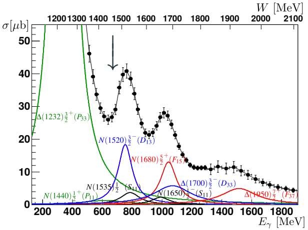


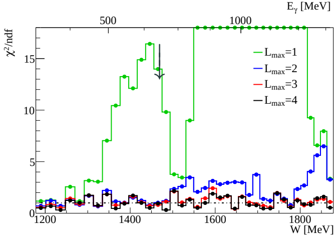


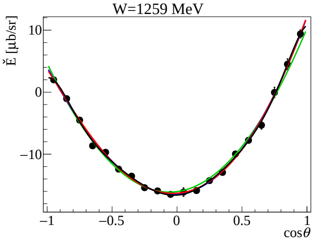
Dominant partial wave contributions (E (A2), $\gamma p \to p\pi^0$)

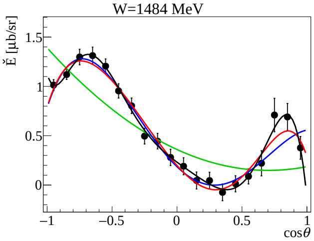
$$\check{E}(W, \cos\theta) = E(W, \cos\theta) \cdot \frac{d\sigma}{d\Omega}(W, \cos\theta) = \sum_{k=0}^{2L_{max}+1} (a_L(W))_k \cdot P_k^0(\cos\theta)$$



[Y. Wunderlich, F. Afzal et al., EPJA 53 (2017) 86]

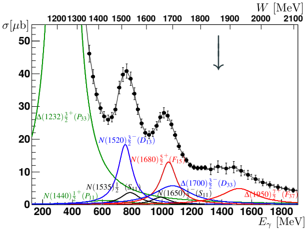




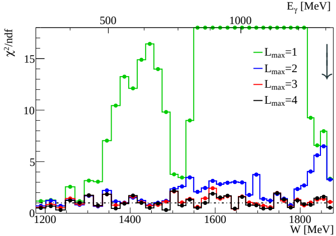


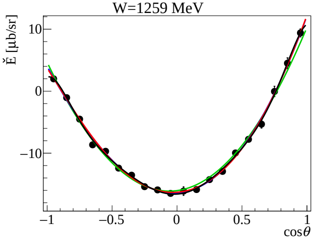
Dominant partial wave contributions (E (A2), $\gamma p \rightarrow p\pi^0$)

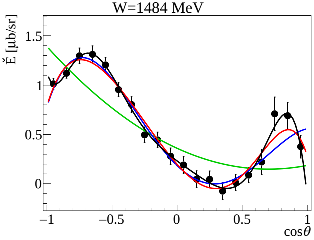
$$\check{E}(W, \cos\theta) = E(W, \cos\theta) \cdot \frac{d\sigma}{d\Omega}(W, \cos\theta) = \sum_{k=0}^{2L_{max}+1} (a_L(W))_k \cdot P_k^0(\cos\theta)$$

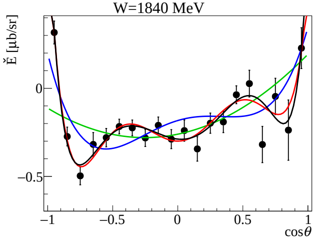


[Y. Wunderlich, F. Afzal et al., EPJA 53 (2017) 86]

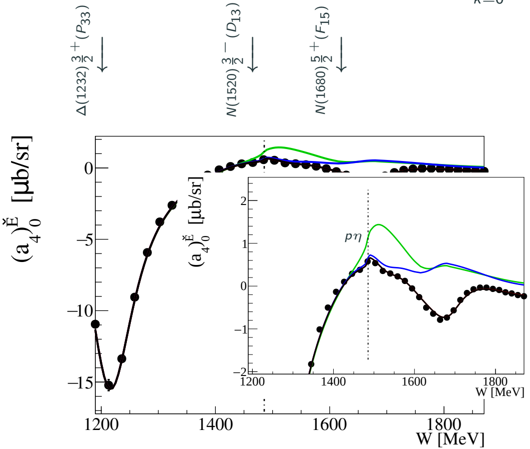








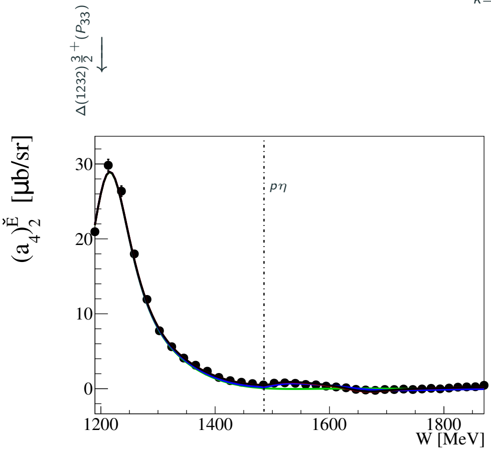
$$\check{E}(W, \cos\theta) = E(W, \cos\theta) \cdot \frac{d\sigma}{d\Omega}(W, \cos\theta) = \sum_{k=0}^{2L_{max}+1} (a_L(W))_k \cdot P_k^0(\cos\theta)$$



$$(a_4)_0^{\check{E}} = \langle S, S\rangle + \langle P, P\rangle$$
$$+ \langle D, D\rangle$$
$$+ \langle F, F\rangle$$
$$+ \langle G, G\rangle$$

Only interference terms of the same L. Similar to differential cross section.

$$\check{E}(W,\cos\theta) = E(W,\cos\theta)\cdot\frac{d\sigma}{d\Omega}(W,\cos\theta) = \sum_{k=0}^{2L_{max}+1}(a_L(W))_k \cdot P_k^0(\cos\theta)$$

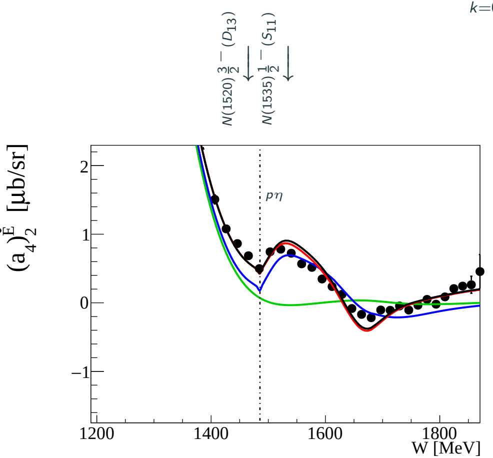


$$(a_4)_2^{\check{E}} = \langle P,P\rangle + \langle S,D\rangle + \langle D,D\rangle + \langle P,F\rangle + \langle F,F\rangle + \langle D,G\rangle + \langle G,G\rangle$$

$p\eta$ cusp is well visible in the data and BnGa-2014-02 PWA ($< S, D >$).

Dominant partial wave contributions (E (A2), $\gamma p \to p\pi^0$)

$$\check{E}(W,\cos\theta) = E(W,\cos\theta)\cdot\frac{d\sigma}{d\Omega}(W,\cos\theta) = \sum_{k=0}^{2L_{max}+1}(a_L(W))_k \cdot P_k^0(\cos\theta)$$



$$(a_4)_2^{\check{E}} = \langle P,P\rangle$$ (green)

$$+\langle S,D\rangle + \langle D,D\rangle$$ (blue)

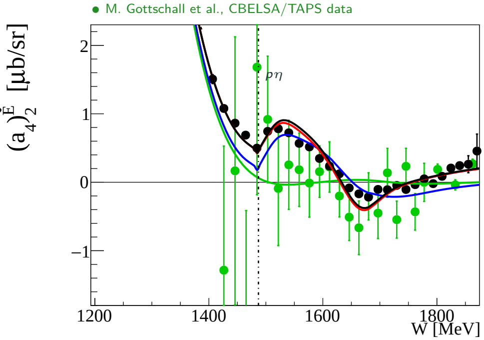
$$+\langle P,F\rangle + \langle F,F\rangle$$ (red)

$$+\langle D,G\rangle + \langle G,G\rangle$$ (black)

$p\eta$ cusp is well visible in the data and BnGa-2014-02 PWA ($< S, D >$).

Dominant partial wave contributions (E (A2), $\gamma p \to p\pi^0$)

$$\check{E}(W,\cos\theta) = E(W,\cos\theta)\cdot\frac{d\sigma}{d\Omega}(W,\cos\theta) = \sum_{k=0}^{2L_{max}+1} (a_L(W))_k \cdot P_k^0(\cos\theta)$$



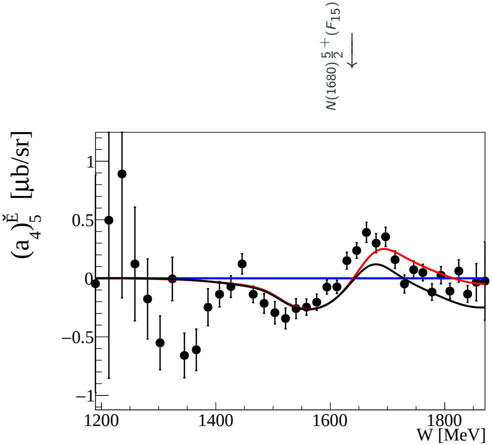
$$(a_4)_2^{\check{E}} = \langle P, P\rangle$$
$$+\langle S, D\rangle + \langle D, D\rangle$$
$$+\langle P, F\rangle + \langle F, F\rangle$$
$$+\langle D, G\rangle + \langle G, G\rangle$$

Very precise new A2 data shows the $p\eta$ cusp.

It is important to cover the entire angular range.

Dominant partial wave contributions (E (A2), $\gamma p \to p\pi^0$)

$$\check{E}(W, \cos\theta) = E(W, \cos\theta) \cdot \frac{d\sigma}{d\Omega}(W, \cos\theta) = \sum_{k=0}^{2L_{max}+1} (a_L(W))_k \cdot P_k^0(\cos\theta)$$



$$(a_4)_5^{\check{E}} = \langle D, F \rangle$$ (red line)

$$+ \langle P, G \rangle + \langle F, G \rangle$$ (black line)

$<D, F>$-term not well described by BnGa-2014-02 PWA.

Conclusion and Outlook

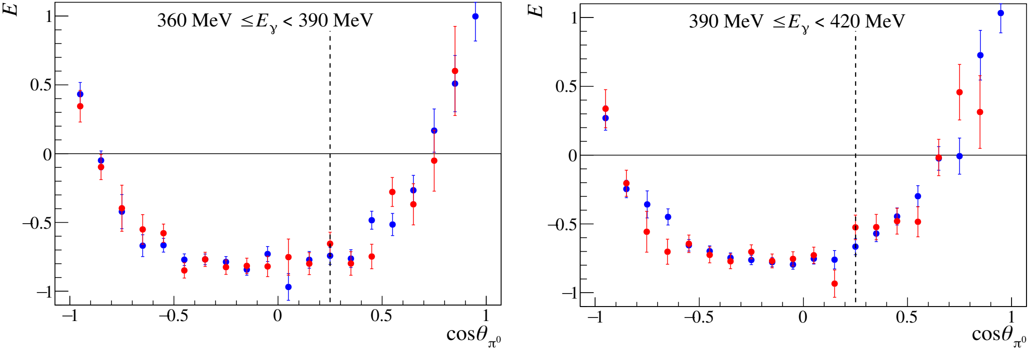
- A2 collaboration have measured many high-precision data for the unpolarized cross section as well as several double polarization observables in various different final states
  $\rightarrow$ Existence of third S-wave resonance $N(1895)\frac{1}{2}^{-}(S_{11})$ has been confirmed in $p\eta$ cross section data
  $\rightarrow$ Full angular coverage and very fine energy binning provided
  $\rightarrow$ First simultaneous measurement of G and E with elliptically polarized photon beam
  $\rightarrow$ Observation of $p\eta$ cusp in $p\pi^0$-E-data
- Outlook: More measurements are planned
  $\rightarrow$ more data to be expected for T, P, H and F
- New polarization data will help to understand the resonance spectrum and will provide an experimental basis for comparison with constituent quark models, lattice QCD or other methods

Thank you for your attention!

Backup Slides

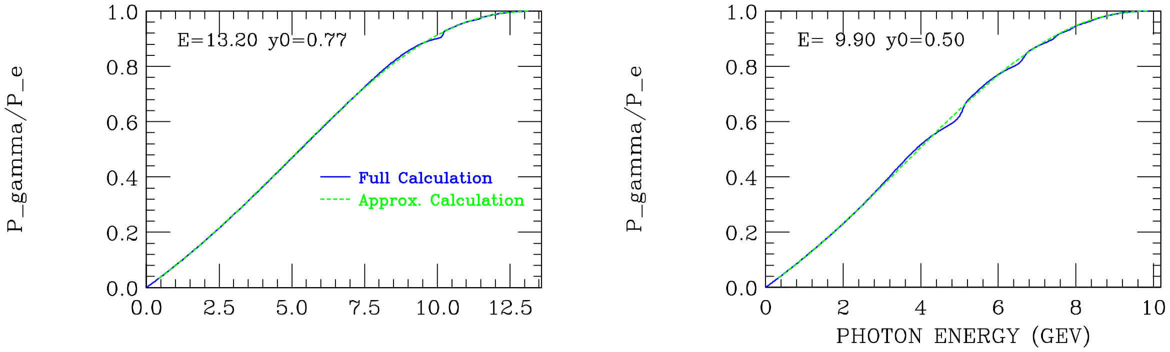
Comparison of diamond and amorphous data

- diamond runs with coherent edge at 450 MeV (elliptically polarized photons)
- Møller runs (amorphous radiator with circularly polarized photons)



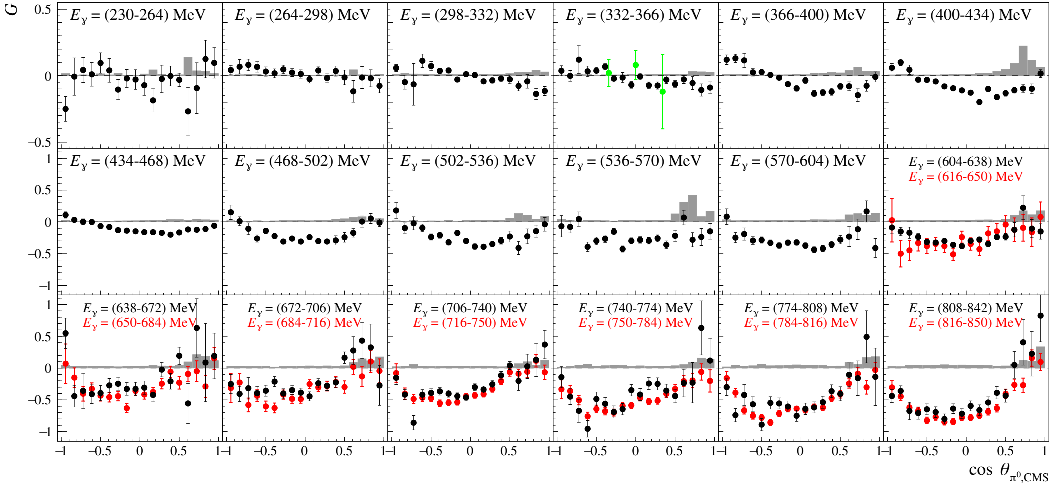
- first experimental evidence that the degree of circular polarization can be calculated in the same way for a diamond radiator as it is done for an amorphous radiator in a first approximation within 3%
- E and G can be determined using longitudinally polarized electrons and a diamond radiator

- Calculation of photon circular polarization degree in crystals by
  I. M. Nadzhafov, Bull. Acad. Sci. USSR, Phys. Ser. Vol. 14, No. 10, p. 2248 (1976).



Bosted et al. (SLAC)

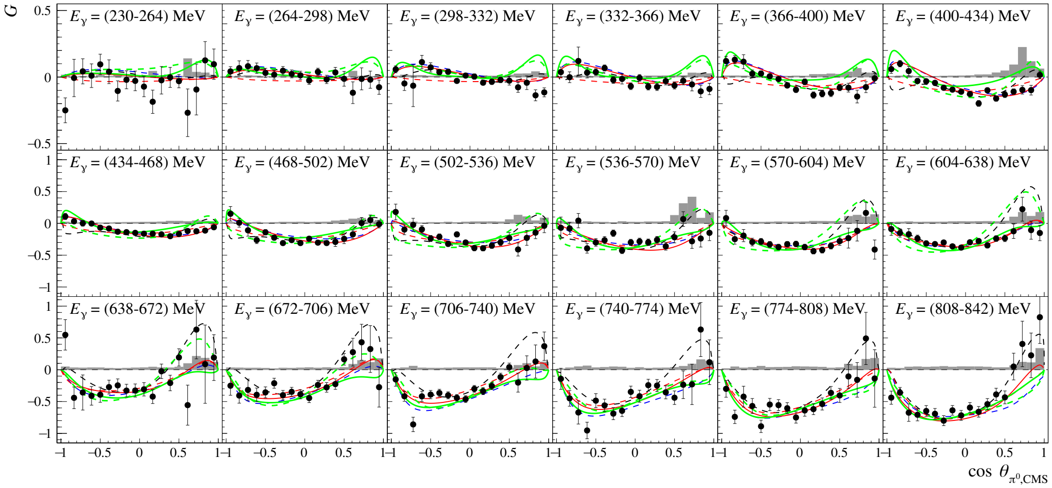
Double polarization observable G in $\gamma p \to p\pi^0$



● this work ● A2/GDH [1] ● CBELSA/TAPS [2]

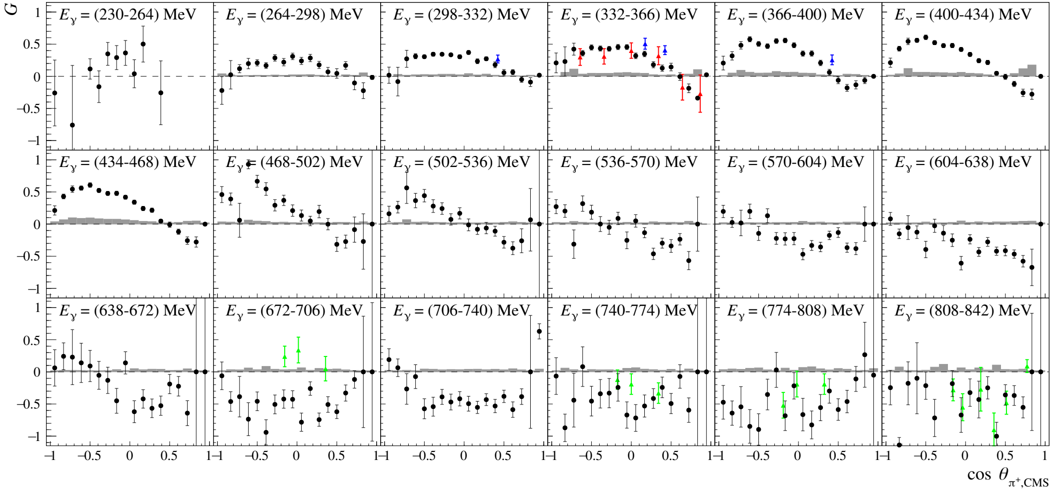
[1] J. Ahrens et al. Eur. Phys. J. A **26** (2005) 135 [2] A. Thiel et al. Eur. Phys. J. A **53** (2017) 8

Double polarization observable G in $\gamma p \to p\pi^0$



[1] A. V. Anisovich et al., Eur. Phys. J. **A** 48 (2012) 15 [2] A. V. Anisovich et al., Phys. Lett. B **785** (2018) 626â“630 [3] D. Rönchen et al.„ Eur. Phys. J. A **50** (2014) 101
[4] D. Rönchen, et al., Eur. Phys. J. A **54** (2018) 110 [5] D. Drechsel et al., Eur. Phys. J. A **34**, (2007) 69-97 [6] R. Workman et al, Phys. Rev. C **86**, (2012) 015202

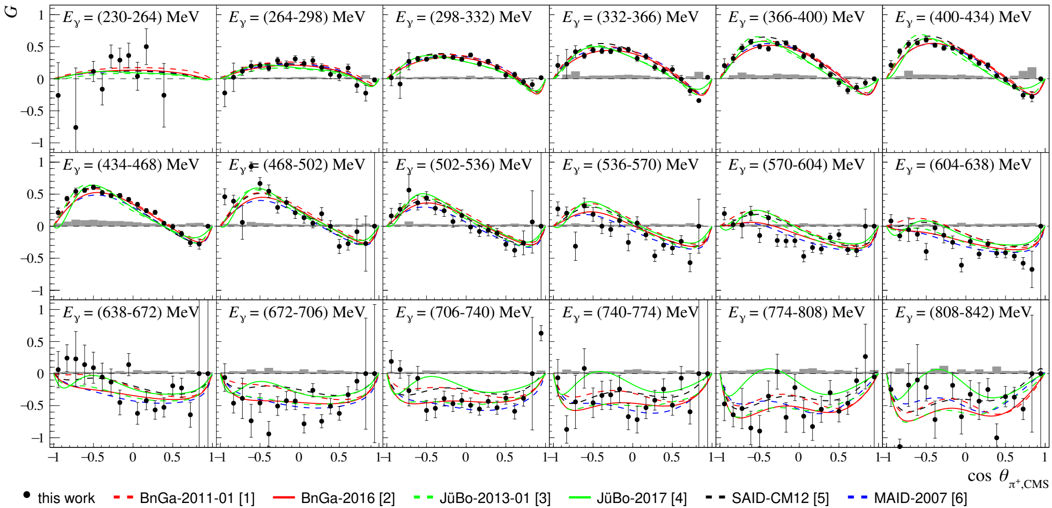
Double polarization observable G in $\gamma p \to n\pi^+$



● this work ● A2/GDH [1] ● Belyaev et al. [2] ● Bussey et al. [3]

[1] J. Ahrens et al. Eur. Phys. J. A **26** (2005) 135 [2] A. Belayev et al, Sov. J. Nucl. Phys. **40** (1984) 83 [3] P. J. Bussey et al, Nucl. Phys. B **83** (1980) 403-414

Double polarization observable G in $\gamma p \rightarrow n\pi^+$



[1] A. V. Anisovich et al., Eur. Phys. J. **A** 48 (2012) 15 [2] A. V. Anisovich et al., Phys. Lett. B **785** (2018) 626â“630 [3] D. Rönchen et al.„ Eur. Phys. J. A **50** (2014) 101
[4] D. Rönchen, et al., Eur. Phys. J. A **54** (2018) 110 [5] D. Drechsel et al., Eur. Phys. J. A **34**, (2007) 69-97 [6] R. Workman et al, Phys. Rev. C **86**,(2012)015202

The helicity asymmetry E in π^0 photoproduction

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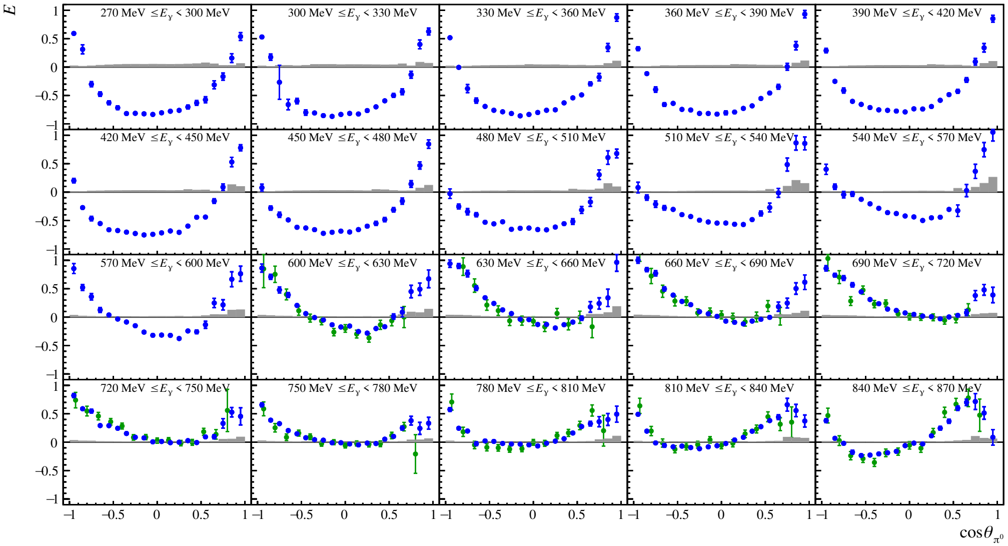
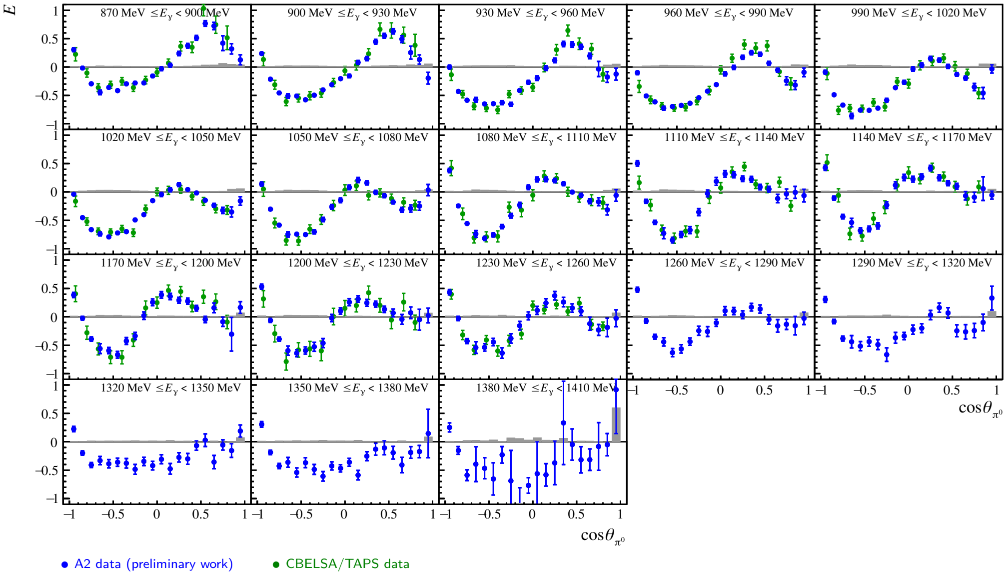


● A2 data (preliminary work) ● CBELSA/TAPS data

The helicity asymmetry E in π^0 photoproduction



The helicity asymmetry E in π^0 photoproduction

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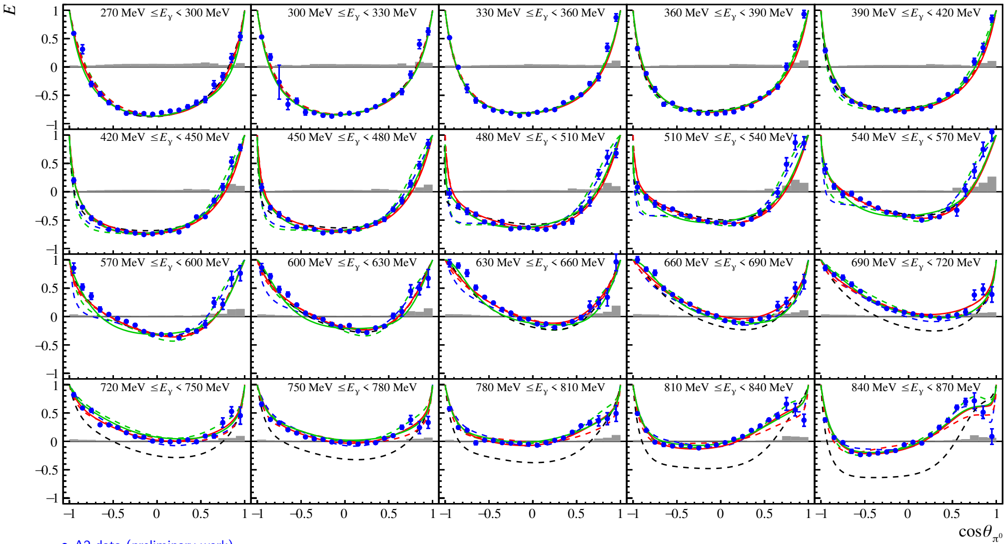

● A2 data (preliminary work)

BnGa-2011-02 — BnGa-2019 — JüBo-2015-FitB — JüBo-2017 — SAID-CM12 — MAID2007

The helicity asymmetry E in π^0 photoproduction