Recent results of polarization observables in π^0- and η-photoproduction off the proton

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for the
CBELSA/TAPS and A2 collaboration

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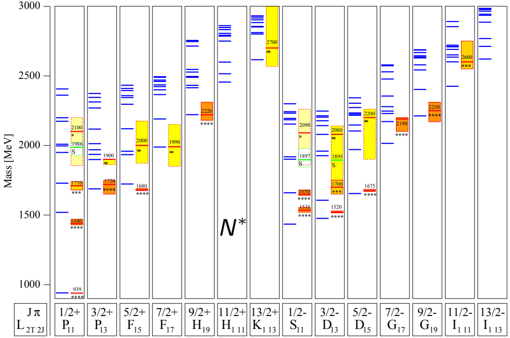
Outline

Why baryon spectroscopy?

Goal: Understanding nucleon excitation spectra
$\leftrightarrow$ Understanding dynamics of the constituents inside the nucleon

- many more resonances expected in quark models or lattice QCD than experimentally observed
- What are the relevant degrees of freedom?
- most resonances observed in πN $\rightarrow$ some resonances might not couple to πN

Quark model vs. experimental data

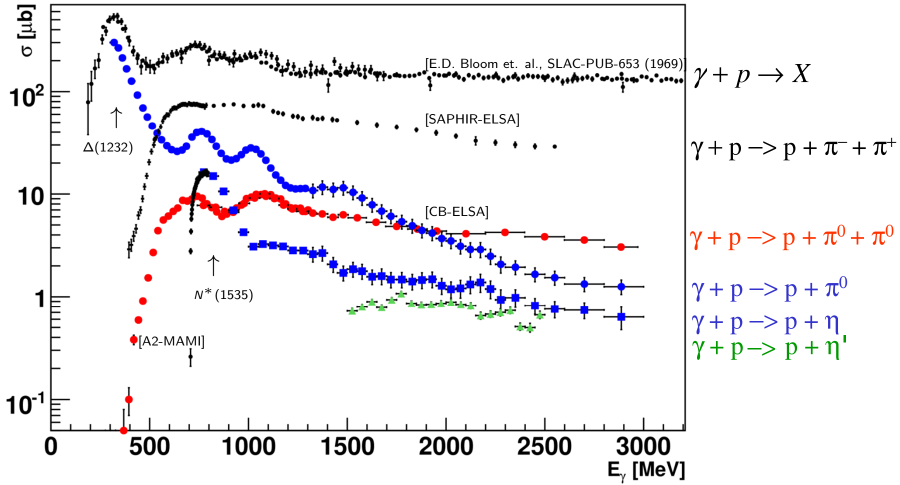


U. Loering, B.C. Metsch, H.R. Petry, Eur.Phys.J.A10:395-446,2001

Photoproduction reactions are excellent tool to probe excitation spectra!

Photoproduction reactions

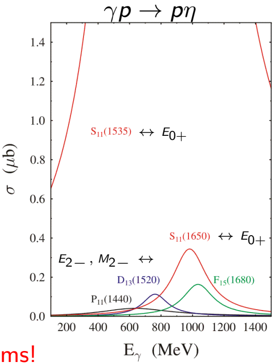
Study of different reaction channels gives access to different resonant structures
$\Rightarrow$ Worldwide effort to get high precision data (ELSA,MAMI, JLab, ...)



Importance of polarization observables

- Scattering amplitude $f \longleftrightarrow$ 4 complex amplitudes (CGLN amplitudes)
  $f(F_1(W, \cos\theta_{cm}), F_2(W, \cos\theta_{cm}), F_3(W, \cos\theta_{cm}), F_4(W, \cos\theta_{cm}))$
- PWA: $F_1 = \sum_{l=0}^{\infty}(lM_{l+} + E_{l+})P'_{l+1} + [(l+1)M_{l-} + E_{l-}]P'_{l-1}$
  - $E_{l\pm}(W), M_{l\pm}(W)$: Multipoles
  - $P'_{l\pm 1}(\cos\theta_{cm})$: Legendre polynomials
- Measurable observables $\longleftrightarrow$ Multipoles $\longleftrightarrow$ Resonance parameters

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	$C_{x'}$	-	$C_{z'}$	-	-	-	-

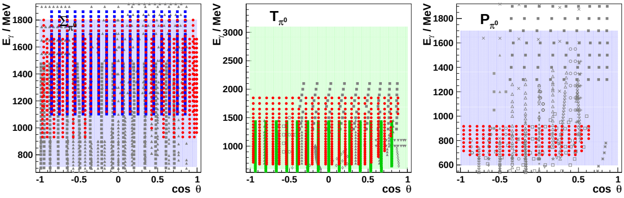


$$\sigma \sim |E_{0+}|^2 + |E_{1+}|^2 + |M_{1+}|^2 + |M_{1-}|^2 + \ldots$$

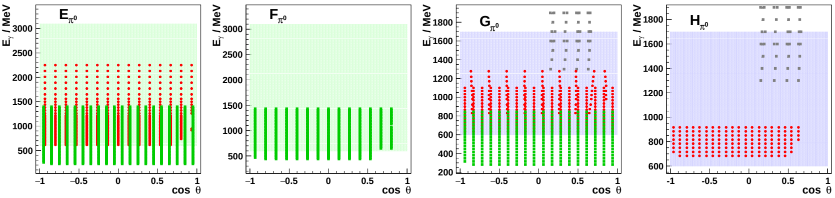
$$\Sigma \sim -2E^*_{0+}E_{2+} + 2E^*_{0+}E_{2-} - 2E^*_{0+}M_{2+} + 2E^*_{0+}M_{2-}\ldots$$

$\Rightarrow$Polarization observables are sensitive to interference terms!

Measured single and double polarization in $\gamma p \to p\pi^0$



- data basis until 2007
- CBELSA/TAPS data
- A2 data
- CLAS data



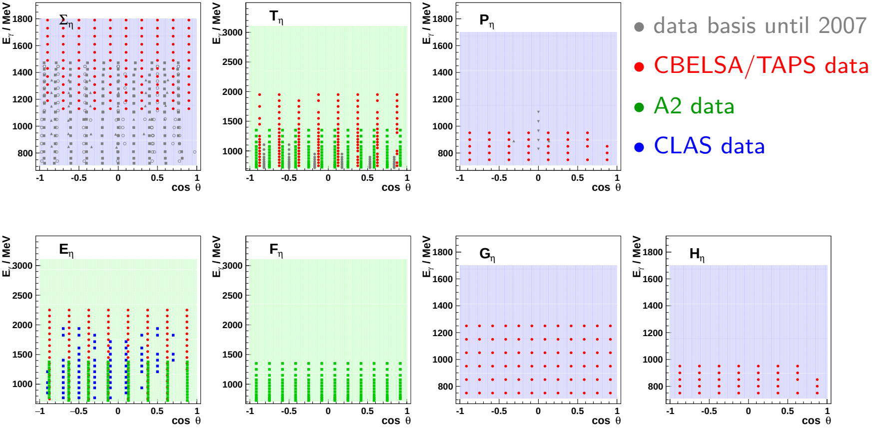
CBELSA/TAPS publications:

G: A.Thiel et al., PRL 109 (2012) 102001
E: M. Gottschall et al., PRL 112 (2014) 012003
T,P,H: J. Hartmann et al., PRL 113 (2014) 062001
Σ: F. Afzal et al. (preliminary)

A2 publications:

σ: P. Adlarson, Phys. Rev. C 92, 024617 (2015)
T,F: J.R.M. Annand et al., Phys. Rev. C 93, 055209 (2016)
E: F. Afzal et al. (preliminary)
G: K. Spieker et al. (preliminary)

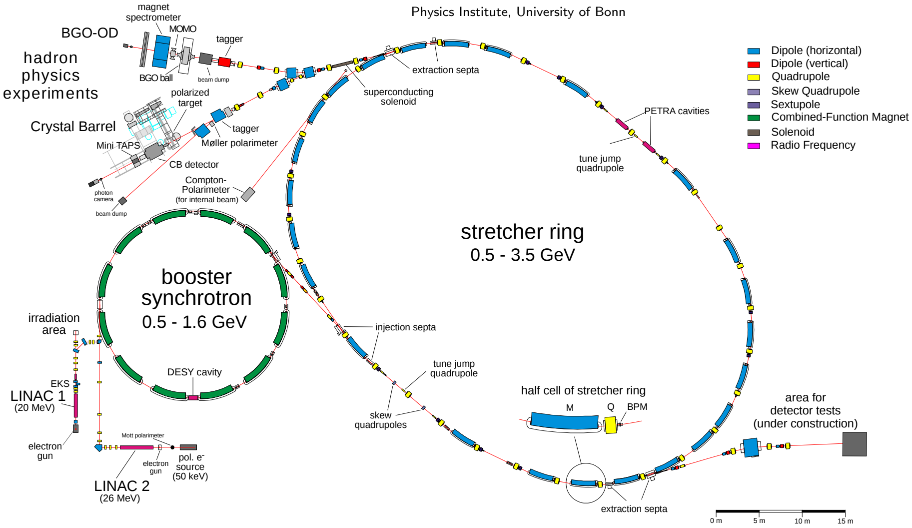
Measured single and double polarization data in $\gamma p \to p\eta$



CBELSA/TAPS publications:
G,E,T,P,H: J. Müller et al., in preparation
Σ: F. Afzal et al. (preliminary)

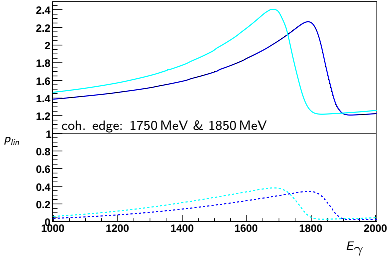
A2 publications:
T,F: C.S. Akondi et al., PRL 113, 102001 (2014)
E: F. Afzal et al. (preliminary)

The Electron Stretcher Accelerator (ELSA)



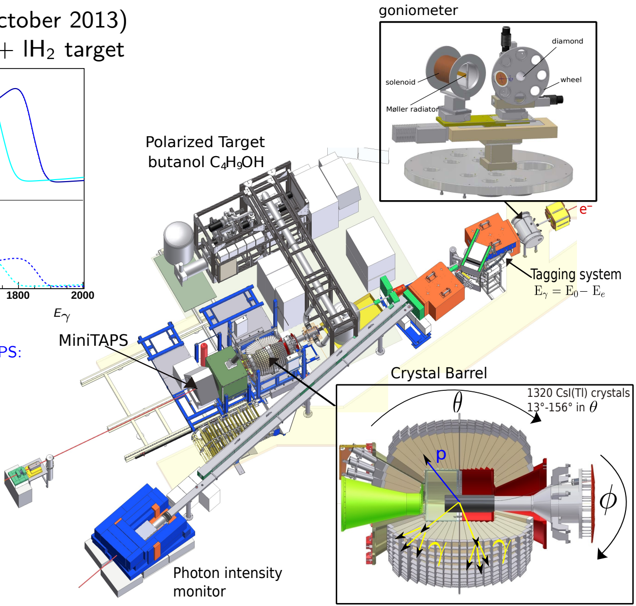
The CBELSA/TAPS experiment at ELSA in Bonn

Measurement of Σ (July-October 2013)
Linearly polarized photons + lH_2 target



More talks/posters from CBELSA/TAPS:

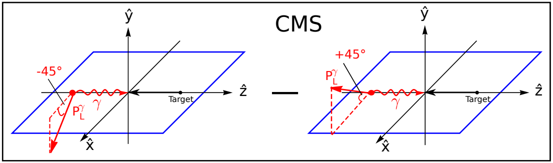
- M. Nanova, Di, 12:00 HK 11.5
- M. Nanova, Do, 15:30 HK 38.6
- J. Ottnad, Mo, 18:00 HK 8.5
- P. Bielefeldt, Mo, 18:15 HK 8.6
- N. Stausberg, Di, 16:45 HK 27.5
- B. Salisbury, Di, 16:45 HK 27.6
- S. Ciupka, Di, 16:45 HK 27.11
- D. Schaab, Di, 16:45 HK 27.49

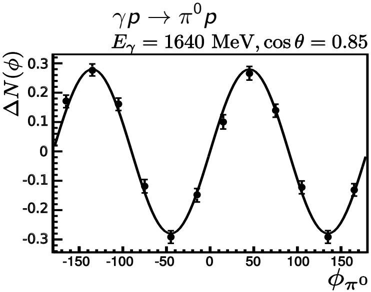


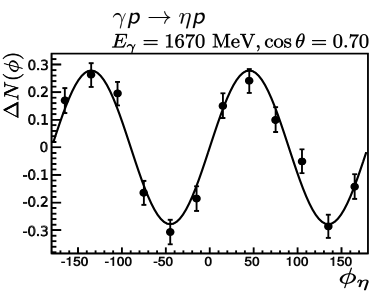
Determination of the beam asymmetry Σ

- linearly polarized beam, unpolarized liquid hydrogen target

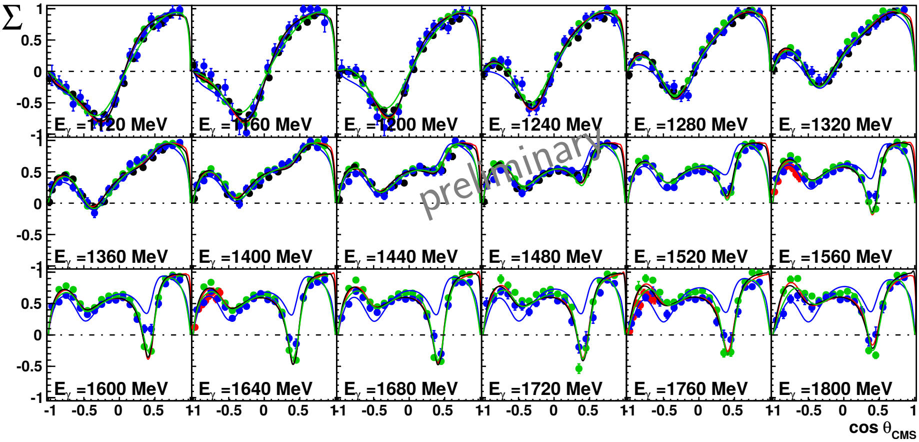
$$\Delta N = \frac{N_{-45^\circ} - N_{+45^\circ}}{N_{-45^\circ} + N_{+45^\circ}} = p_\gamma^{lin} \Sigma \sin(2\phi)$$







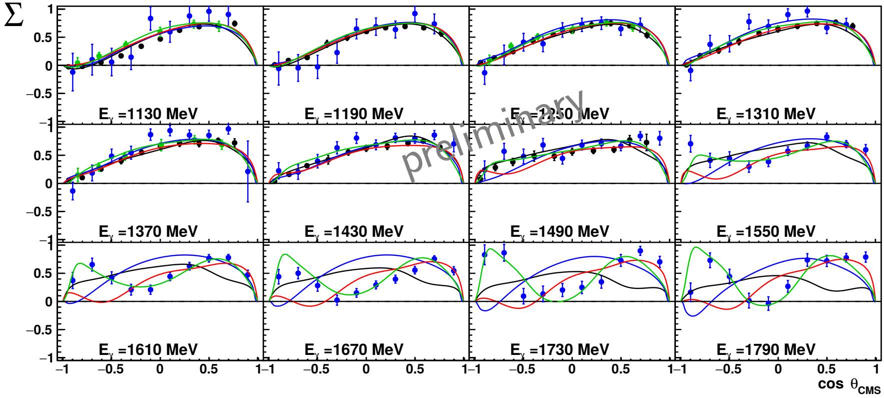
The beam asymmetry Σ in π^0-photoproduction



- this work
- CLAS data (M.Dugger et al., Phys.Rev.C 88, 2013)
- GRAAL data (O. Bartalini et al., Eur.Phys.J.A26, 399, 2005)
- LEPS data (M.Sumihama et al., PLB657, 32, 2007)

PWA solutions: —BnGa(2014_01) —BnGa(2014_02) —SAID(CM12) —JüBo2015 Fit B

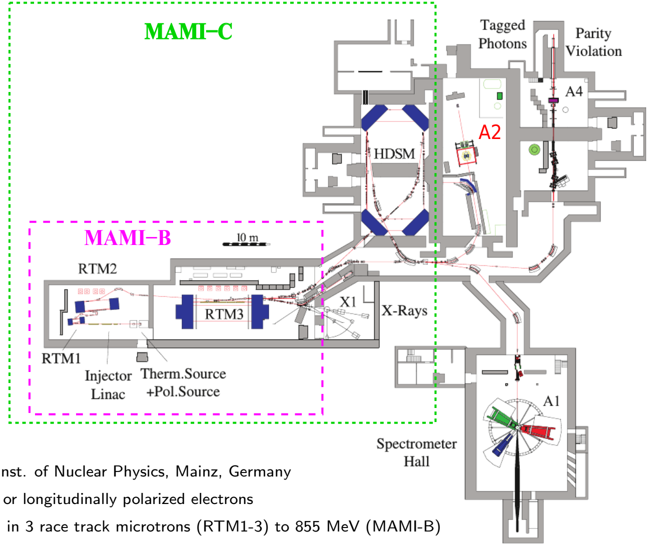
The beam asymmetry Σ in η-photoproduction



- **this work**
- **GRAAL data (O.Bartalini et al., Eur.Phys.J. A33, 169, 2007)**
- **CB-ELSA (D.Elsner et al., Eur.Phys.J. A33, 147, 2007)**

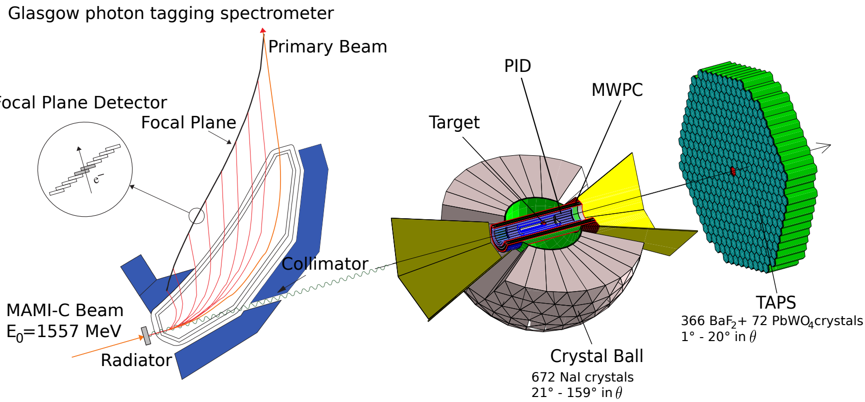
PWA solutions: —η−MAID —BnGa(2016) —SAID(GE09) —JüBo2016-3.1

MAinz MIcrotron MAMI



- Located at Inst. of Nuclear Physics, Mainz, Germany
- Unpolarized or longitudinally polarized electrons
- Acceleration in 3 race track microtrons (RTM1-3) to 855 MeV (MAMI-B)
- Acceleration in harmonic double-sided microtron (HDSM) to 1600 MeV (MAMI-C)

The Crystal Ball experiment at MAMI in Mainz



More talks from A2:

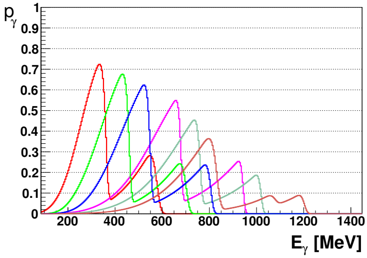
- K. Spieker, Do 14:30 HK 38.2
- S. Lutterer, Do 14:45 HK 38.3
- S. Abt, Do 15:00 HK 38.4
- M. Wolfes, Do 15:45 HK 38.7
- M. S. Günther, Do 16:00 HK 38.8
- P. Adlarson, Fr 14:30 HK 57.2
- A. Neiser, Fr 15:30 HK 57.5

Polarized e^- beam on diamond radiator

First experimental attempt to measure E and G with longitudinally polarized electron beam in combination with a diamond crystal $\rightarrow$ using linearly and circularly polarized photons within same beam time!

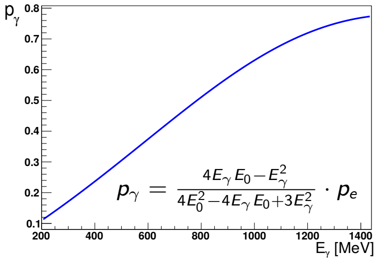
Linearly polarized photons

- diamond radiator needed
- coherent bremsstrahlung
- coherent edges at: 350 MeV, 450 MeV, 550 MeV, 650 MeV, 750 MeV and 850 MeV



Circularly polarized photons

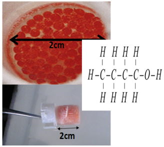
- longitudinally polarized electrons needed
- helicity transfer to photons
- Mott/Møller measurement: $p_e \approx 75\% - 78\%$



Dubna-Mainz frozen spin polarized target

- polarization via Dynamic Nuclear Polarization DNP
- 70 GHz microwave irradiation at 2.5 T is used to transfer the electrons polarization to protons
- $^3He/^4He$ dilution cryostat with 25 mK holding coil and 0.63 T
- relaxation time $\tau \approx 2000$ h
- $9 \cdot 10^{22}$ pol. protons per cm^2 in the target cell
- p_T up to 90%
- carbon target needed for background studies

Butanol Target



Carbon Target

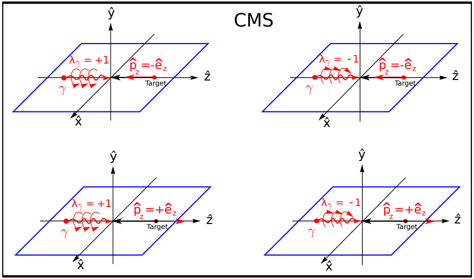
Determination of E and G

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

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

Integrating over ϕ:

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

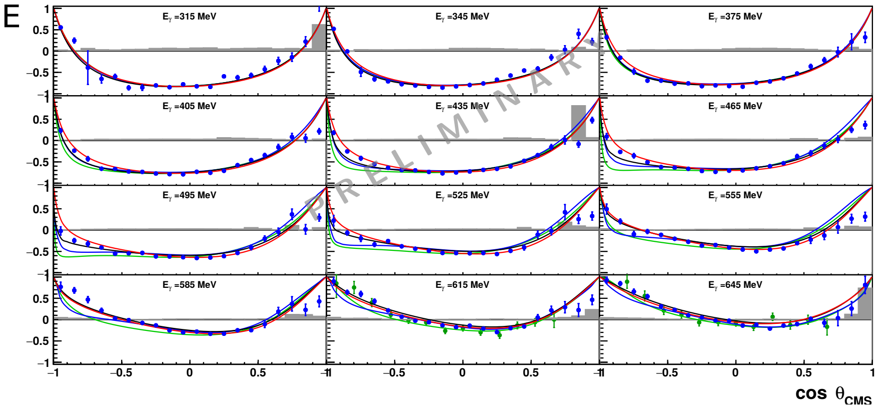


$$\mathrm{E} = \frac{\sigma^{1/2}-\sigma^{3/2}}{\sigma^{1/2}+\sigma^{3/2}} = \frac{N_B^{1/2}-N_B^{3/2}}{N_B^{1/2}+N_B^{3/2}}\cdot\frac{1}{d}\cdot\frac{1}{P_{circ}P_z}$$

Results for E in π^0-photoproduction (315 MeV - 645MeV)

- **this work (longitudinally polarized electrons + diamond radiator → elliptically polarized photons)**
- **CBELSA/TAPS data (taken with amorphous radiator, M. Gottschall et al., Phys. Rev. Lett. 112 (2014) 012003)**

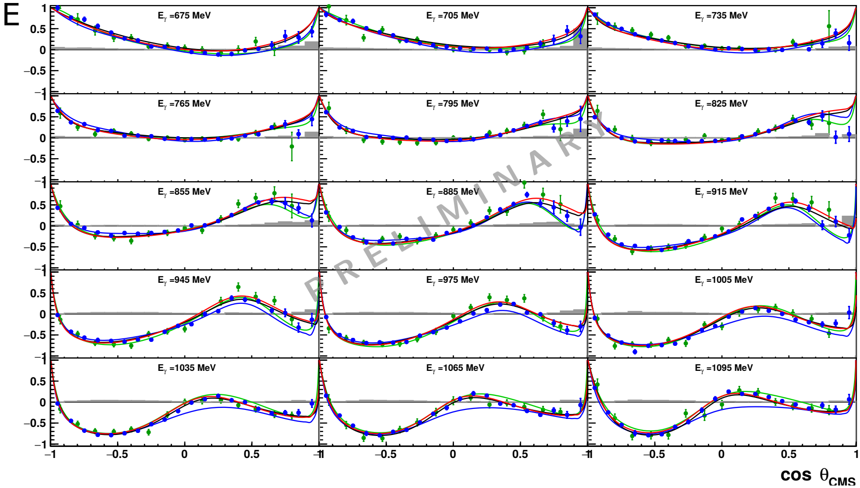
— **BnGa_2014_02 (PWA pred.)** — **BnGa_2014_01 (PWA pred.)** — **JüBo2016-3.1 (PWA pred.)**
— **SAID-CM12 (PWA pred.)**



Results for E in π^0-photoproduction (675 MeV - 1095 MeV)

- this work (longitudinally polarized electrons + diamond radiator → elliptically polarized photons)
- CBELSA/TAPS data (taken with amorphous radiator, M. Gottschall et al., Phys. Rev. Lett. 112 (2014) 012003)

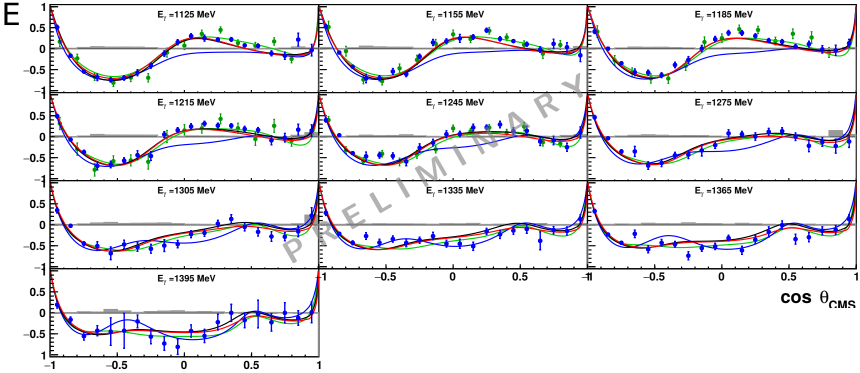
— BnGa_2014_02 (PWA fit) — BnGa_2014_01 (PWA fit) — JüBo2016-3.1 (PWA fit) — SAID-CM12 (PWA pred.)



Results for E in π^0-photoproduction (1125 MeV - 1395 MeV)

- **this work (longitudinally polarized electrons + diamond radiator → elliptically polarized photons)**
- **CBELSA/TAPS data (taken with amorphous radiator, M. Gottschall et al., Phys. Rev. Lett. 112 (2014) 012003)**

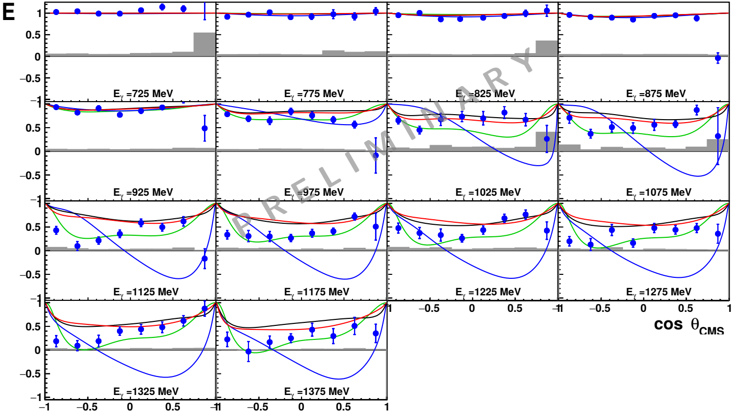
— BnGa_2014_02 (PWA fit) — BnGa_2014_01 (PWA fit) — JüBo2016-3.1 (PWA fit) — SAID-CM12 (PWA pred.)



Results for E in η-photoproduction

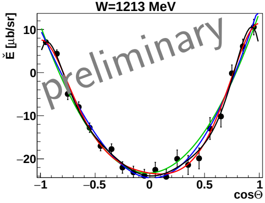
- **this work (longitudinally polarized electrons + diamond radiator $\rightarrow$ elliptically polarized photons)**

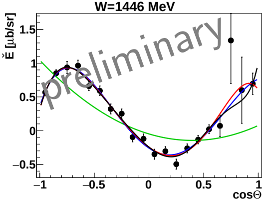
— BnGa_2014_02 (PWA pred.) — BnGa_2014_01 (PWA pred.) — JüBo2016-3.1 (PWA fit)
— SAID-GE09 (PWA pred.)

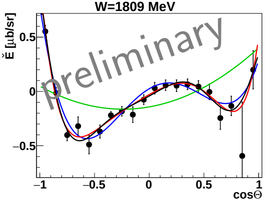


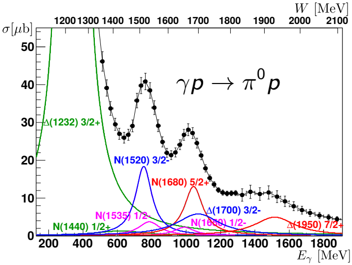
Truncated PWA (which L_{max} is seen in the data?)

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









four-star resonances listed in PDG

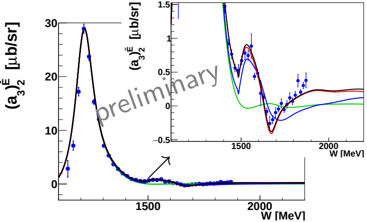
$L_{max} = 0$ S-wave	$L_{max} = 1$ P-wave	$L_{max} = 2$ D-wave
N(1535) 1/2- N(1650) 1/2- Δ(1620) 1/2-	N(1440) 1/2+ N(1720) 3/2+ Δ(1232) 3/2+	N(1520) 3/2- N(1675) 5/2- Δ(1700) 3/2-

$L_{max} = 3$ F-wave	$L_{max} = 4$ G-wave
N(1680) 5/2+ Δ(1905) 5/2+ Δ(1950) 7/2+	N(2190) 7/2-

Y. Wunderlich, F. Afzal, A. Thiel and R. Beck, accepted in EPJA

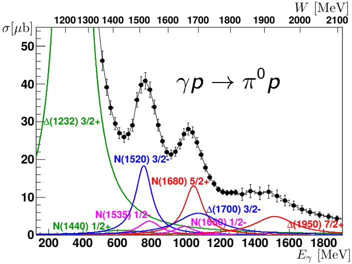
Truncated PWA (which L_{max} is seen in the data?)

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



BnGa_2014 PWA:
- S+P waves
- S+P+D waves
- S+P+D+F waves
- S+P+D+F+G waves

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



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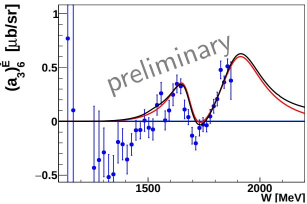

BnGa_2014 PWA:

- S+P waves
- S+P+D waves
- S+P+D+F waves
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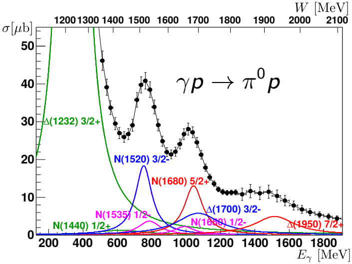
$$(a_4)_6^{\check{E}} = \langle F, F\rangle + \langle D, G\rangle + \langle G, G\rangle$$



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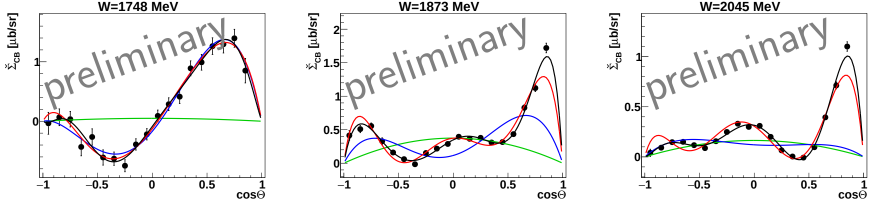

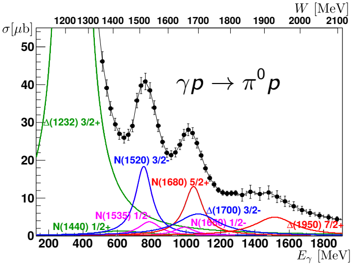

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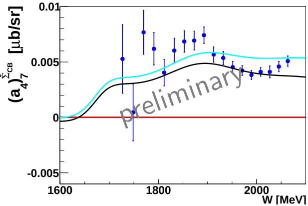

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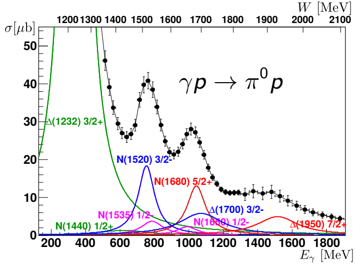
- S+P+D waves
- S+P+D+F waves
- S+P+D+F+G waves
- S+P+D+F+G+H waves

$$(a_5)_7^{\check{\Sigma}} = \langle F, G \rangle + \langle D, H \rangle + \langle G, H \rangle$$

A.V. Anisovich et al. find evidence for the one-star resonance Δ(2200)7/2- [arXiv:1503.05774]



four-star resonances listed in PDG

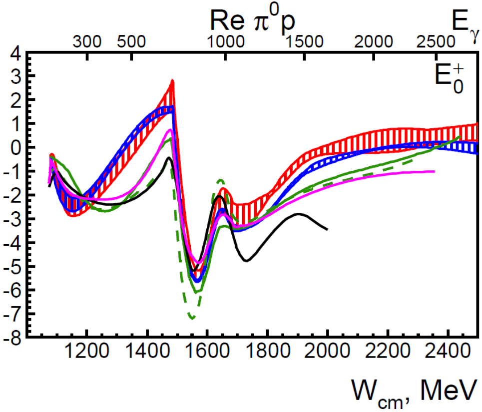
$L_{max} = 0$ S-wave	$L_{max} = 1$ P-wave	$L_{max} = 2$ D-wave
N(1535) 1/2- N(1650) 1/2- Δ(1620) 1/2-	N(1440) 1/2+ N(1720) 3/2+ Δ(1232) 3/2+	N(1520) 3/2- N(1675) 5/2- Δ(1700) 3/2-

$L_{max} = 3$ F-wave	$L_{max} = 4$ G-wave
N(1680) 5/2+ Δ(1905) 5/2+ Δ(1950) 7/2+	N(2190) 7/2-

Y. Wunderlich, F. Afzal, A. Thiel and R. Beck, accepted in EPJA

Impact of polarization data

- Fit error bars get smaller when including new polarization data (BnGa_2014)
- Differences between the different PW analyses exist
  → Inclusion of more polarization observables will converge all analyses to the same solution



—BnGa_2011
—BnGa_2014 with new pol. data
—SAID_SN11
—SAID_CM12
—JüBn_2014
—MAID2007

Summary and Outlook

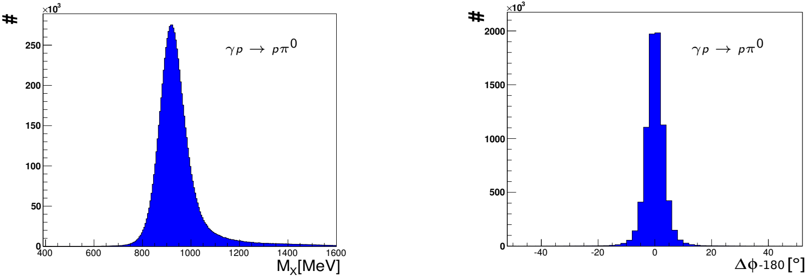
- The beam asymmetry Σ has been measured in π^0- and η-photoproduction by the CBELSA/TAPS collaboration for E_γ =1100 MeV - 1800 MeV with high precision
  $\rightarrow$ data shows sensitivity to G-wave
- The double polarization observables E and G were measured at the Crystal Ball experiment at MAMI within the same beam time using longitudinally polarized electrons on a diamond radiator
  $\rightarrow$ successful first attempt to measure E and G simultaneously
  $\rightarrow$ data covers energy range down to $\Delta(1232)$ resonance region
  $\rightarrow$ complementary to CBELSA/TAPS and CLAS data
- Outlook:
  - Crystal Barrel detector has been upgraded for a higher detection efficiency, especially for photoproduction off the neutron
  - Soon new polarization data (T,P,H) will be taken.

Thank you!

Selection process of $\gamma p \to \gamma\gamma p$

Selected events had to fulfill kinematic constraints:

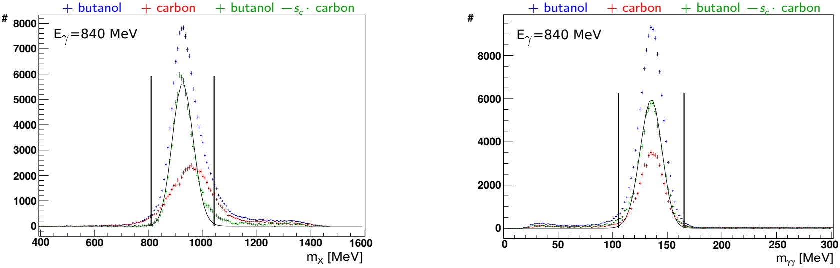
- 3 hits in calorimeters (p+2γ)
- Proton: calculated as missing particle of $\gamma p \to \gamma\gamma X$
- Angular-cuts:
  - Agreement of missing mass and measured charged particle in θ
  - Coplanarity-cut: $\Delta\Phi = |\Phi_{\gamma\gamma} - \Phi_p| = 180^\circ$ within 2.5σ
- Beam photon: $E_\gamma > E_{prod.threshold}$ and time coincidence with reaction products



Selection process of $\gamma p \to \gamma\gamma p$

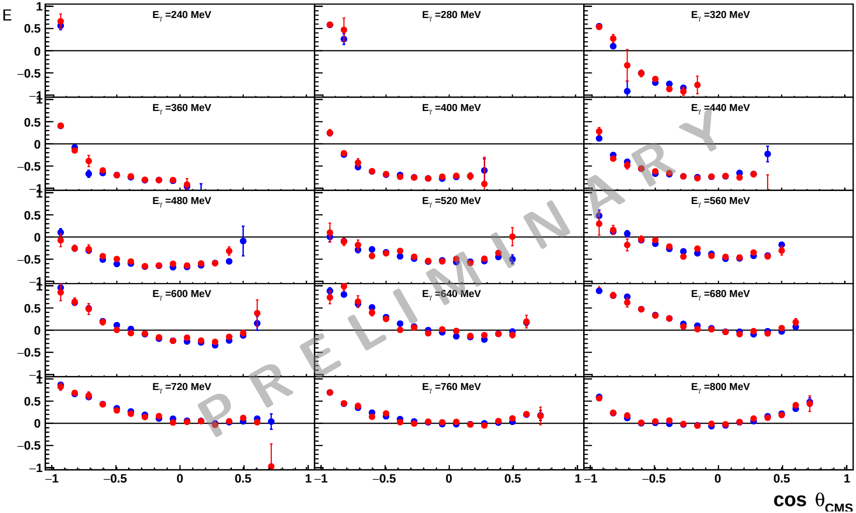
Selected events had to fulfill kinematic constraints:

- 3 hits in calorimeters (p+2γ)
- Time coincidence of beam photons and final state meson
- Energy dependent 3σ-cuts:
  - Proton: Calculated as missing particle of $\gamma p \to \gamma\gamma X$
  - Invariant mass of $\gamma\gamma$
  - Agreement of missing mass and measured charged particle in θ
  - Coplanarity-cut: $\Delta\Phi = |\Phi_{\gamma\gamma} - \Phi_p| = 180^\circ$



Results for E in π^0-photoproduction (240 MeV - 800 MeV)

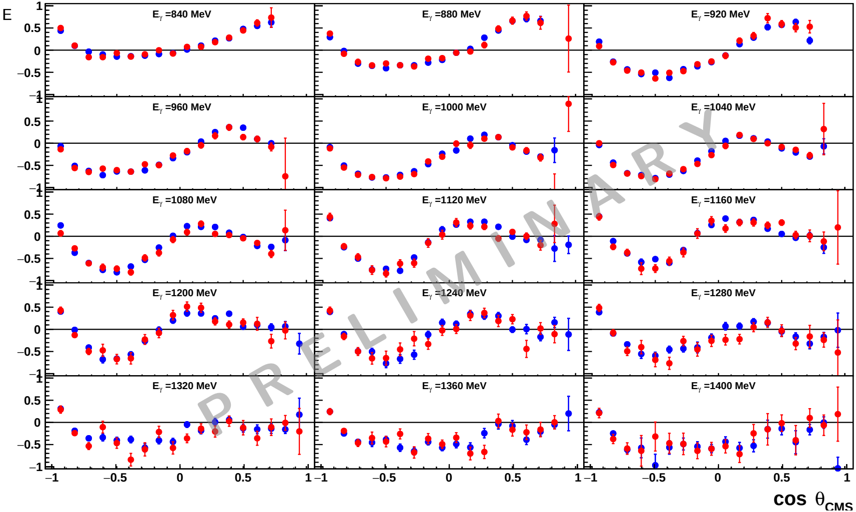
- **this work (longitudinally polarized electrons + diamond radiator → elliptically polarized photons)**
- **this work (longitudinally polarized electrons + amorphous radiator → only circularly polarized photons)**



Very good agreement between data obtained with a diamond and an amorphous radiator!

Results for E in π^0-photoproduction (840 MeV - 1400 MeV)

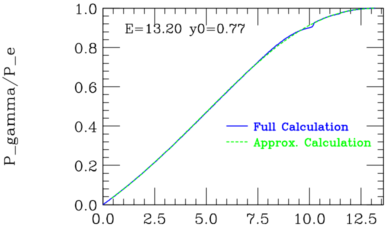
- **this work (longitudinally polarized electrons + diamond radiator $\rightarrow$ elliptically polarized photons)**
- **this work (longitudinally polarized electrons + amorphous radiator $\rightarrow$ only circularly polarized photons)**

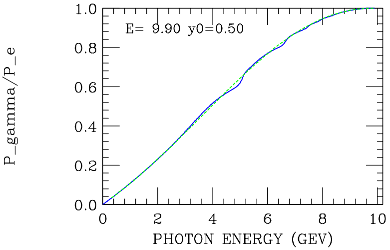


Very good agreement between data obtained with a diamond and an amorphous radiator!

Circular polarization degree in crystals

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)

Impact of polarization observables