

Recent baryon spectroscopy results from the CBELSA/TAPS experiment

Annika Thiel

Menu 2023

16.10.2023

Helmholtz-Institut für Strahlen- und Kernphysik, University of Bonn, Germany

and

School of Physics and Astronomy, University of Glasgow, Scotland



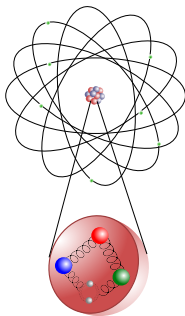
University
of Glasgow



Motivation

Structure of Matter: Spectroscopy

Spectroscopy
of atoms

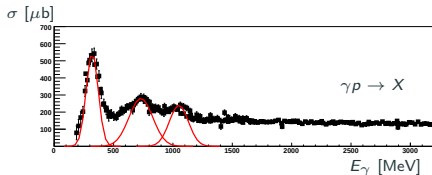


Spectroscopy
of hadrons

excitation spectrum



→ information about QED

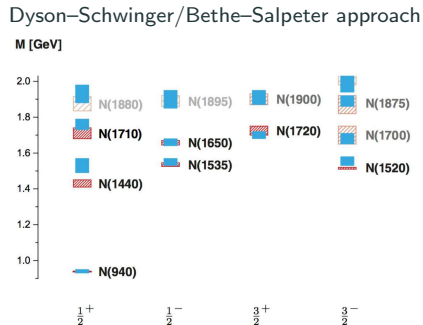
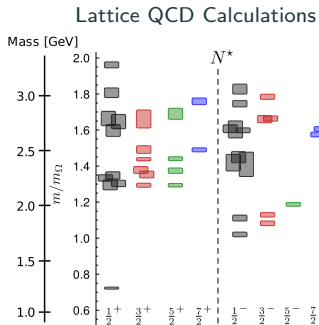
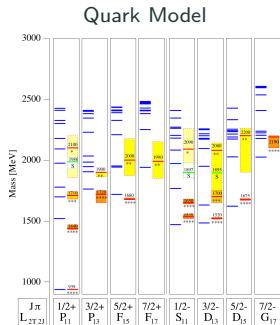


→ information about QCD

Spectroscopy of Hadrons

Excitation spectrum gives information about the dynamics inside the nucleon
(between quarks and gluons)

Theoretical Predictions



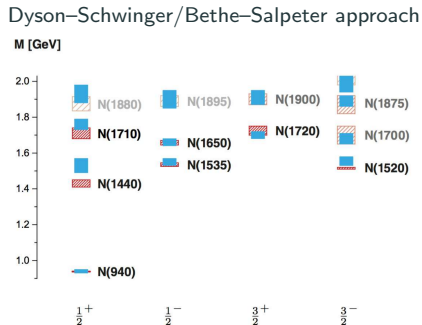
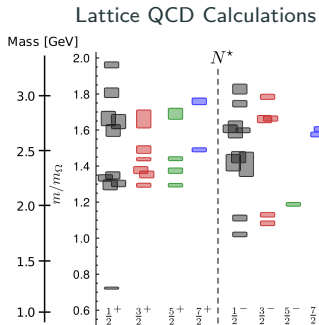
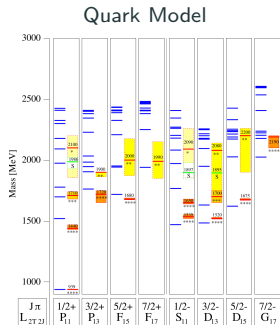
[U. Loering, et al., Eur.Phys.J.A10:395 (2001)]

[R. Edwards et al., Phys.Rev.D 84 (2011) 07450]

[Eichmann, Fischer, Few Body Syst. 60 (2019) 1,2]

Discrepancies between measurement and calculations:
"missing resonances" and level ordering

Theoretical Predictions



[U. Loering, et al., Eur.Phys.J.A10:395 (2001)]

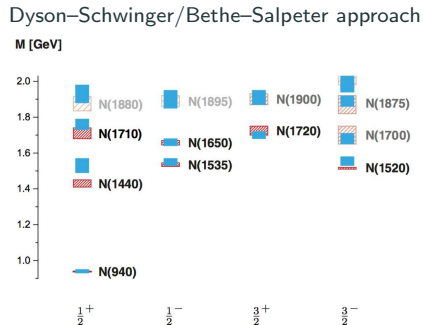
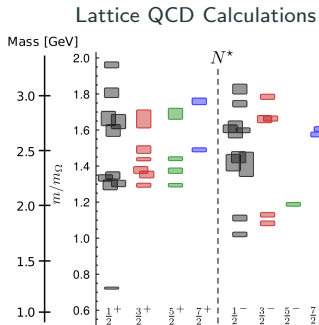
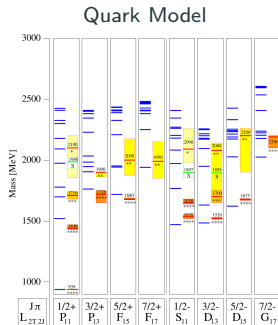
[R. Edwards et al., Phys.Rev.D 84 (2011) 07450]

[Eichmann, Fischer, Few Body Syst. 60 (2019) 1,2]

→ What are the relevant degrees of freedom?



Theoretical Predictions



[U. Loering, et al., Eur.Phys.J.A10:395 (2001)]

[R. Edwards et al., Phys.Rev.D 84 (2011) 07450]

[Eichmann, Fischer, Few Body Syst. 60 (2019) 1,2]

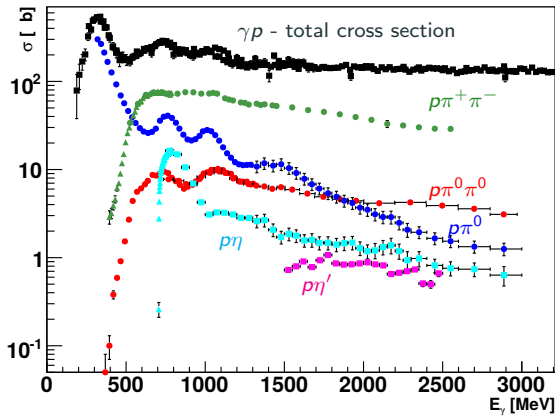
→ What are the relevant degrees of freedom?

Most resonances observed in πN scattering:

→ Experimental bias?



Resonances

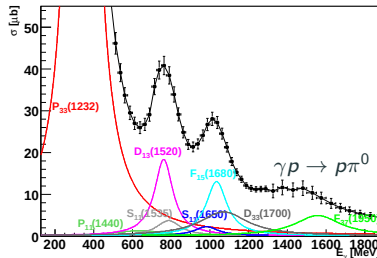


Total cross section sensitive to dominant resonance contributions:

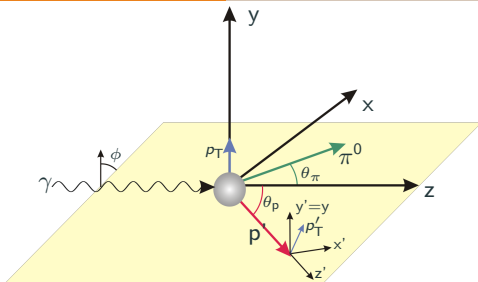
$$\sigma \sim |E_{0+}|^2 + |E_{1+}|^2 + |M_{1+}|^2 + |M_{1-}|^2 + \dots$$

Resonances overlap strongly with different strengths and widths

→ Weak resonance contributions difficult to measure



Polarization Observables

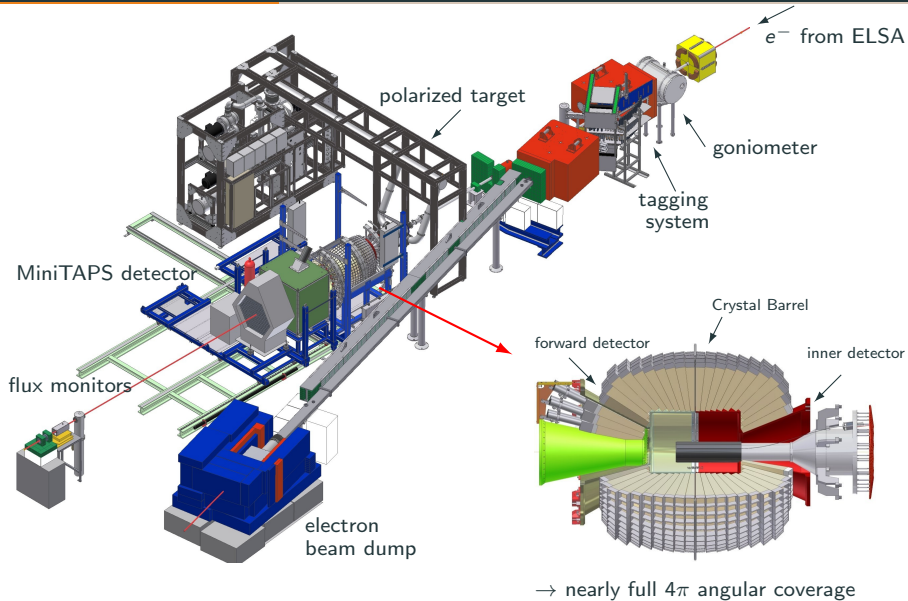


Polarization Observables are a tool to access weak resonance contributions, sensitive to interference terms:

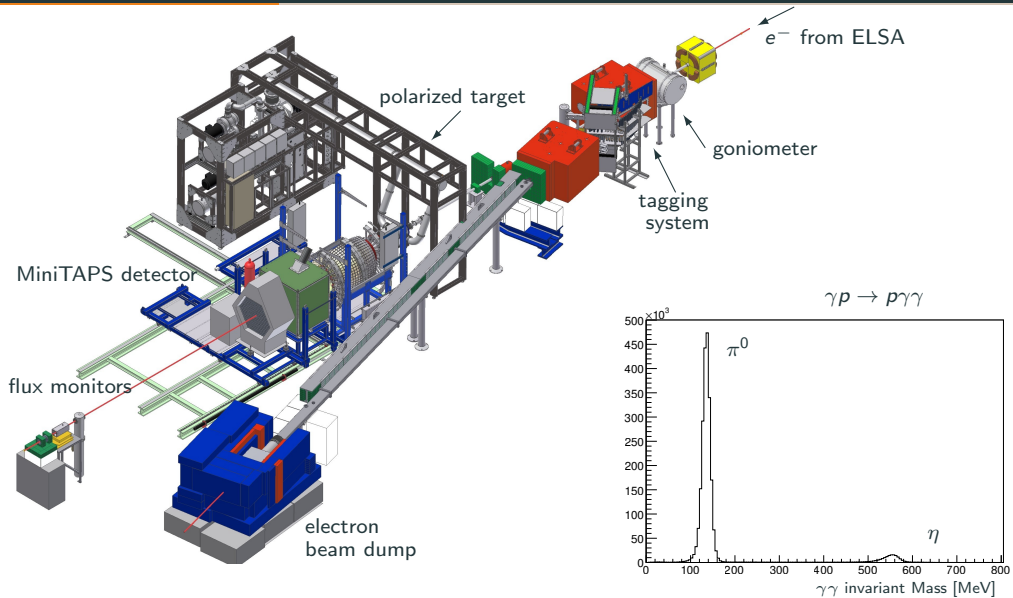
$$\Sigma \sim -2E_{0+}^* E_{2+} + 2E_{0+}^* E_{2-} - 2E_{0+}^* M_{2+} + \dots$$

		Target			Recoil			Target+Recoil			
		-	-	-	x'	y'	z'	x'	x'	z'	z'
Photon		x	y	z	-	-	-	x	z	x	z
unpolarized	σ	-	T	-	-	P	-	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
linearly pol.	Σ	H	(-P)	-G	$O_{x'}$	(-T)	$O_{z'}$	-	-	-	-
circularly pol.	-	F	-	-E	$-C_{x'}$	-	$-C_{z'}$	-	-	-	-

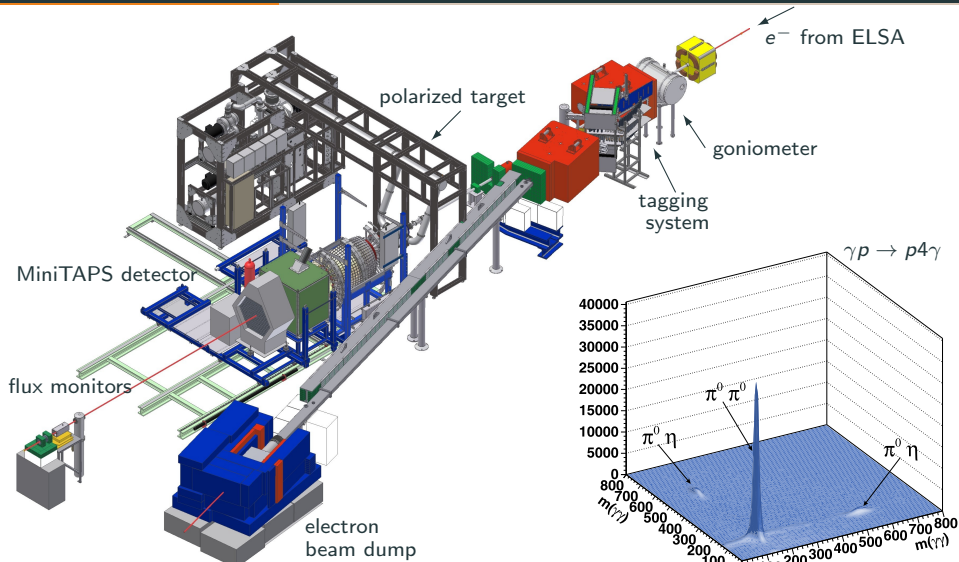
The Setup of the CBELSA/TAPS Experiment



The Setup of the CBELSA/TAPS Experiment

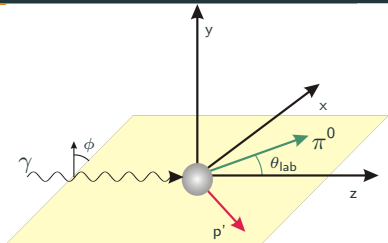


The Setup of the CBELSA/TAPS Experiment



Extraction of the observables

Cross Section with Beam und Target Polarization



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

Photon Polarization		Target Polarization		
		x	y	z
unpolarized	σ	–	T	–
linearly polarized	Σ	H	P	G
circularly polarized	–	F	–	E

π^0 -photoproduction:

G : A.Thiel et al., PRL 109 (2012) 102001

Eur. Phys. J. A53 (2017) 1, 8

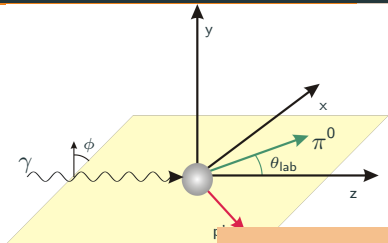
E : M. Gottschall et al., PRL 112 (2014) 012003

Eur. Phys. J. A57 (2021), 1, 40

T, P, H : J. Hartmann et al., PRL 113 (2014) 062001

Phys.Lett. B748 (2015) 212

Cross Section with Beam und Target Polarization



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

See poster presentation by S. Ciupka
on new results for π^0 photoproduction

Photon Polarization		x	y	z
unpolarized	σ	–	T	–
linearly polarized	Σ	H	P	G
circularly polarized	–	F	–	E

π^0 -photoproduction:

G: A.Thiel et al., PRL 109 (2012) 102001

Eur. Phys. J. A53 (2017) 1, 8

E: M. Gottschall et al., PRL 112 (2014) 012003

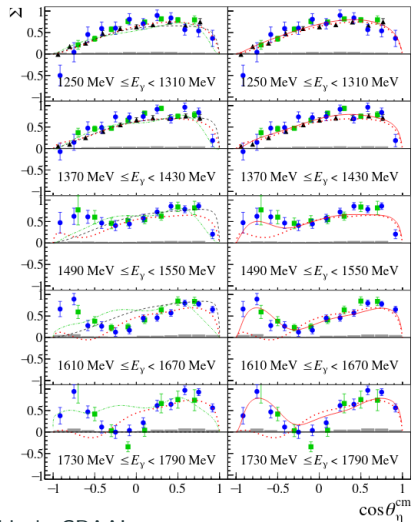
Eur. Phys. J. A57 (2021), 1, 40

T, P, H: J. Hartmann et al., PRL 113 (2014) 062001

Phys.Lett. B748 (2015) 212

Cusp Effect visible in η Photoproduction

High precision measurement of the Beam Asymmetry with high angular coverage



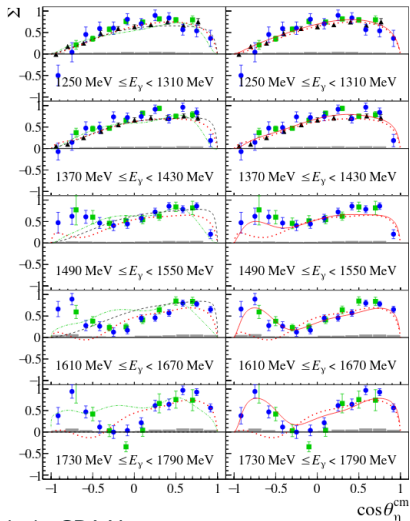
black: GRAAL

green: CLAS blue: CBELSA/TAPS

Cusp Effect visible in η Photoproduction

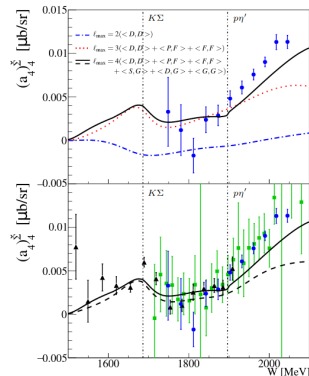
High precision measurement of the Beam Asymmetry with high angular coverage

Cusp effect of the η' threshold visible in the Legendre coefficients



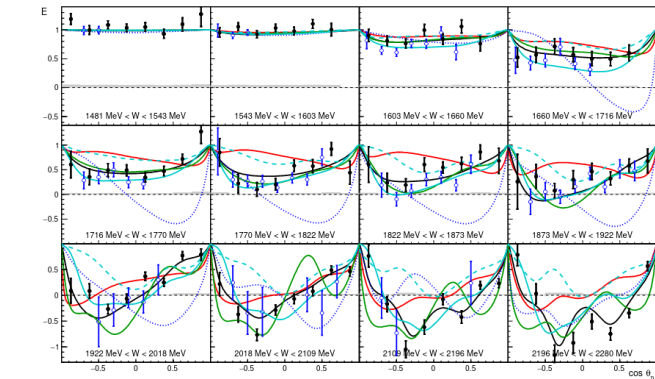
black: GRAAL

green: CLAS blue: CBELSA/TAPS



[F. Afzal et al., Phys.Rev.Lett. 125 (2020) 15, 152002]

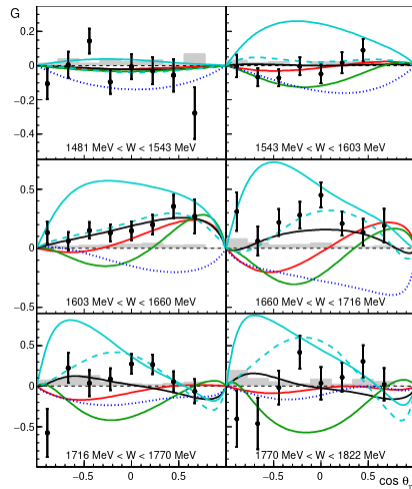
$\gamma p \rightarrow p\eta$: Double Polarization Observable E and G



— BnGa 2011-02
 — BnGa Refit
 — MAID2018
 ... SAID (GE09)
 — JüBo2015
 — JüBo2015-3

Black dots: CBELSA/TAPS

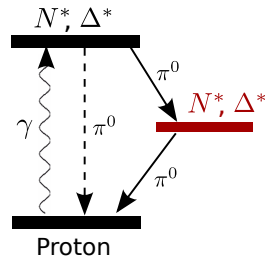
Blue open circles: CLAS



[J. Müller et al., Phys. Lett. B **803**, 135323 (2020)]

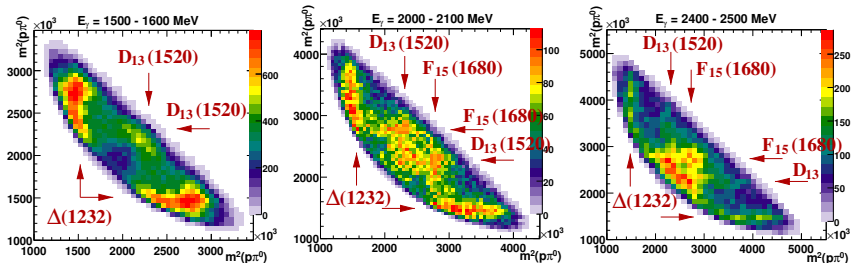
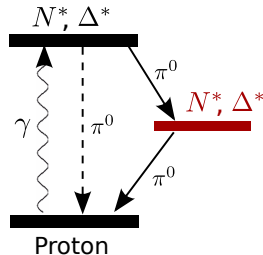
Observables in Multi-Meson Final States

- Multi-meson final states like $\gamma p \rightarrow p\pi^0\pi^0$ or $\pi^0\eta$ preferred at higher energies
- Probes the high mass region, where the missing resonances occur
- Can help to observe cascading decays



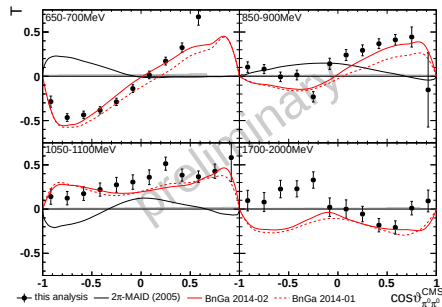
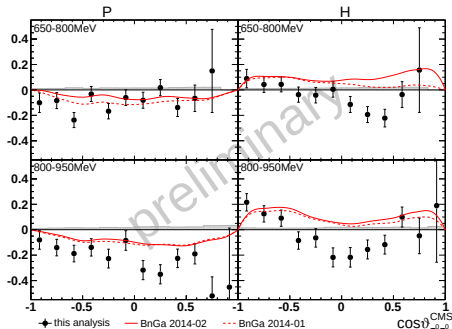
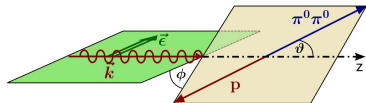
Observables in Multi-Meson Final States

- Multi-meson final states like $\gamma p \rightarrow p\pi^0\pi^0$ or $\pi^0\eta$ preferred at higher energies
- Probes the high mass region, where the missing resonances occur
- Can help to observe cascading decays



$\gamma p \rightarrow p \pi^0 \pi^0$: Polarization Observables T, P, H

Only results shown in quasi two-body kinematics



Observables also extracted for different kinematic variables

Full three-body kinematics allows the measurement of further observables.

[T. Seifen et al., arXiv:2207.01981]

Interpretation

Multipoles and CGLN Amplitudes

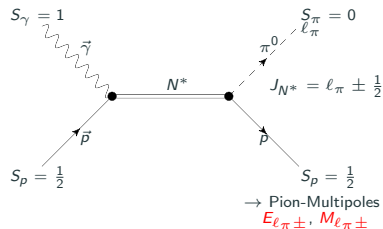
Multipoles give information about the intermediate states, can be combined into four CGLN amplitudes:

$$F_1(W, z) = \sum_{\ell=0}^{\infty} [\ell M_{\ell+} + E_{\ell+}] \cdot P'_{\ell+1}(z) + [(\ell+1)M_{\ell-} + E_{\ell-}] \cdot P'_{\ell-1}(z)$$

$$F_2(W, z) = \sum_{\ell=0}^{\infty} \dots$$

...

with $z = \cos \theta_{\pi}$ and the Legendre polynomials $P_{\ell}(z)$.



Multipoles and CGLN Amplitudes

Multipoles give information about the intermediate states, can be combined into four CGLN amplitudes:

$$F_1(W, z) = \sum_{\ell=0}^{\infty} [\ell M_{\ell+} + E_{\ell+}] \cdot P'_{\ell+1}(z) + [(\ell+1)M_{\ell-} + E_{\ell-}] \cdot P'_{\ell-1}(z)$$

$$F_2(W, z) = \sum_{\ell=0}^{\infty} \dots$$

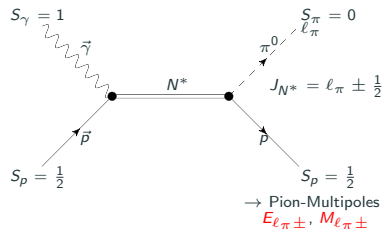
...

with $z = \cos \theta_{\pi}$ and the Legendre polynomials $P_{\ell}(z)$.

All observables can be expressed in CGLN amplitudes, for example:

$$\hat{\Sigma} = \frac{\Sigma \cdot \sigma(\theta_{\pi})}{\rho_0} = -\sin^2 \theta_{\pi} \cdot \text{Re} \left[\frac{1}{2} |F_3|^2 + \frac{1}{2} |F_4|^2 + F_2^* F_3 + F_1^* F_4 + \cos \theta F_3^* F_4 \right] \rho_0$$

with the density of states $\rho_0 = k/q$.



Multipoles and CGLN Amplitudes

Multipoles give information about the intermediate states, can be combined into four CGLN amplitudes:

$$F_1(W, z) = \sum_{\ell=0}^{\ell_{\max}} [\ell M_{\ell+} + E_{\ell+}] \cdot P'_{\ell+1}(z) + [(\ell+1)M_{\ell-} + E_{\ell-}] \cdot P'_{\ell-1}(z)$$

$$F_2(W, z) = \sum_{\ell=0}^{\ell_{\max}} \dots$$

...

Truncation at a certain level

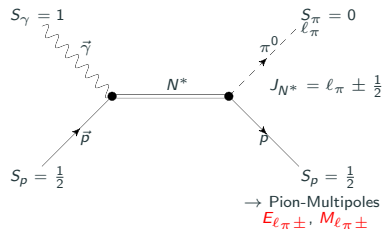
→ Truncated PWA

with $z = \cos \theta_{\pi}$ and the Legendre polynomials $P_{\ell}(z)$.

All observables can be expressed in CGLN amplitudes, for example:

$$\hat{\Sigma} = \frac{\Sigma \cdot \sigma(\theta_{\pi})}{\rho_0} = -\sin^2 \theta_{\pi} \cdot \text{Re} \left[\frac{1}{2} |F_3|^2 + \frac{1}{2} |F_4|^2 + F_2^* F_3 + F_1^* F_4 + \cos \theta F_3^* F_4 \right] \rho_0$$

with the density of states $\rho_0 = k/q$.



Example of a Truncated Partial Wave Analysis

Observable described by

$$\check{T} = T \cdot \sigma = \frac{q}{k} \sin \theta \left[\sum_{h=0}^{2L_{\max}-1} A_h (\cos \theta)^h \right]$$

- using S- and P-waves ($L_{\max} = 1$):

$$\check{T} = \frac{q}{k} \sin \theta [A_0 + A_1 \cdot \cos \theta]$$

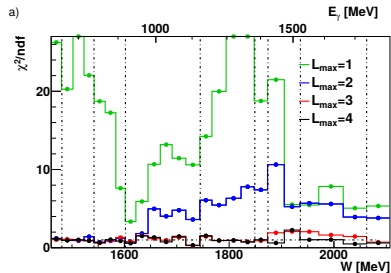
- using S-, P- and D-waves ($L_{\max} = 2$):

$$\check{T} = \frac{q}{k} \sin \theta [A_0 + A_1 \cdot \cos \theta + A_2 \cdot \cos^2 \theta + A_3 \cdot \cos^3 \theta]$$

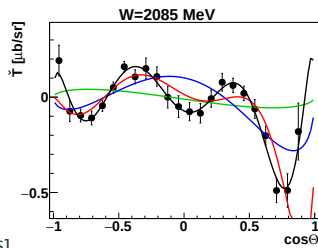
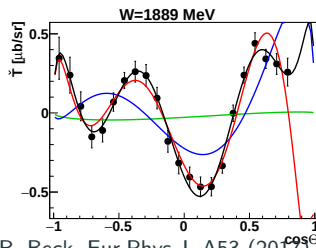
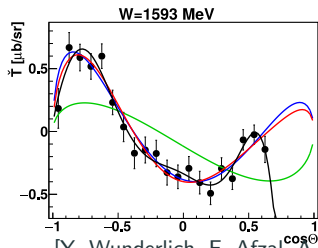
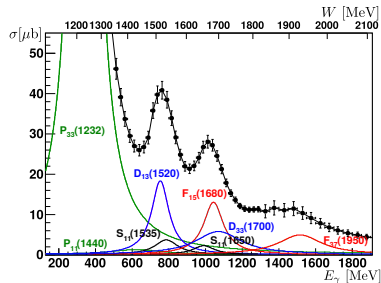
- using S-, P-, D- and F-waves ($L_{\max} = 3$):

$$\begin{aligned} \check{T} = \frac{q}{k} \sin \theta [& A_0 + A_1 \cdot \cos \theta + A_2 \cdot \cos^2 \theta + A_3 \cdot \cos^3 \theta \\ & + A_4 \cdot \cos^4 \theta + A_5 \cdot \cos^5 \theta] \end{aligned}$$

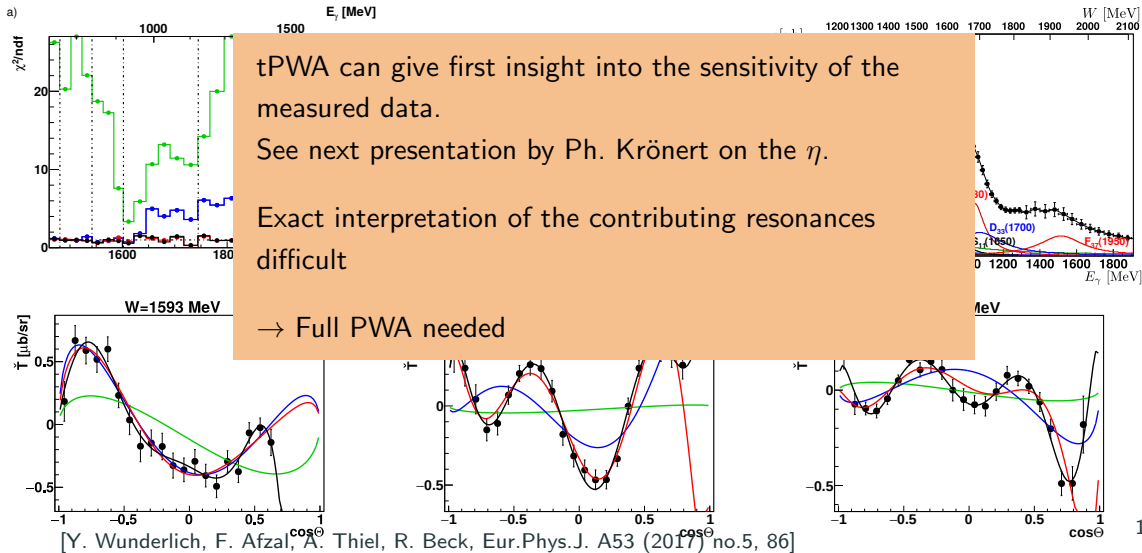
First Interpretation with a Truncated Partial Wave Analysis



Fits with different L_{max} reveal sensitivity of the data!



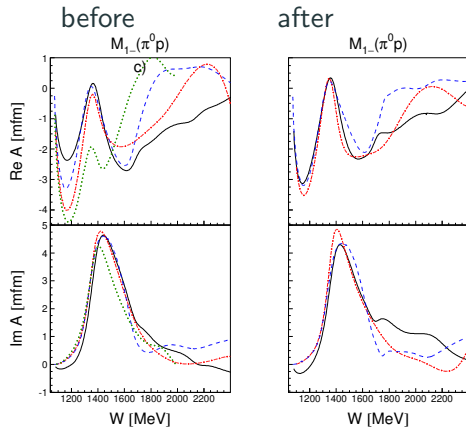
First Interpretation with a Truncated Partial Wave Analysis



New Fits from different Analyses

New observables for $p\pi^0$ have been included in the analyses of the groups:

- BnGa (black)
- JüBo (red)
- SAID (blue)



For all other multipoles see:

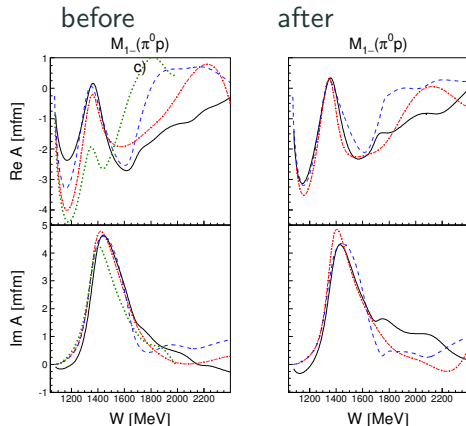
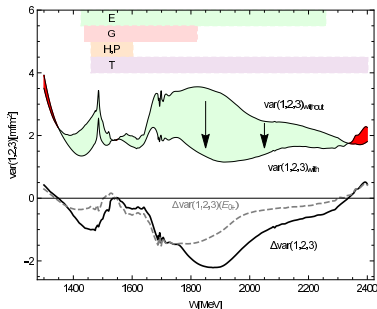
[Anisovich et al., Eur.Phys.J. A52 (2016) no.9, 284]

New Fits from different Analyses

New observables for $p\pi^0$ have been included in the analyses of the groups:

- BnGa (black)
- JüBo (red)
- SAID (blue)

Variance between the different analyses decreases!



For all other multipoles see:
[Anisovich et al., Eur.Phys.J. A52 (2016) no.9, 284]

Comparison between PDG values

- Until 2010: almost only results from pion nucleon scattering used in the PDG, only few pion photoproduction data used
- PWA groups include photoproduction data with different final states from several experiments
- Now: new values from the fits are entering the PDG

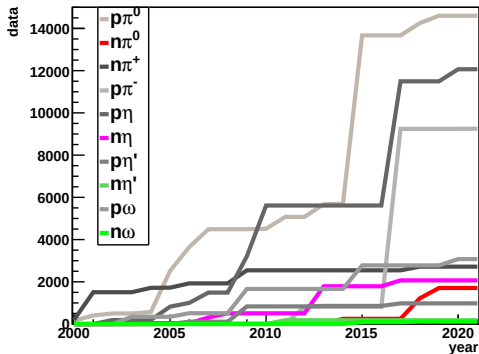
Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	***	***	***	***	-			-		
$N(1520)$	$3/2^-$	****	***	***	***	**	****			- - -		
$N(1535)$	$1/2^-$	****	***	***	***	*	****			- -		
$N(1650)$	$1/2^-$	****	***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

[A. T., et al., PNP 125 (2022) 103949]

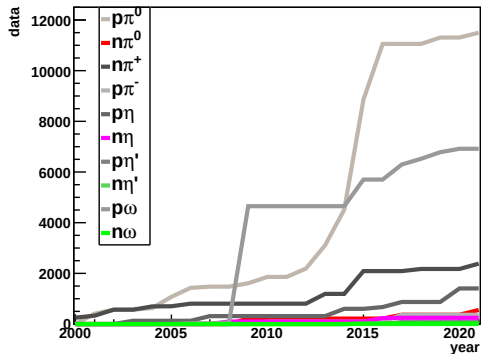
Large improvement, but still lot of work to be done!

Measurements off Neutrons

Unpolarized cross section



Polarization observables



[A. T., et al., PPNP 125 (2022) 103949]

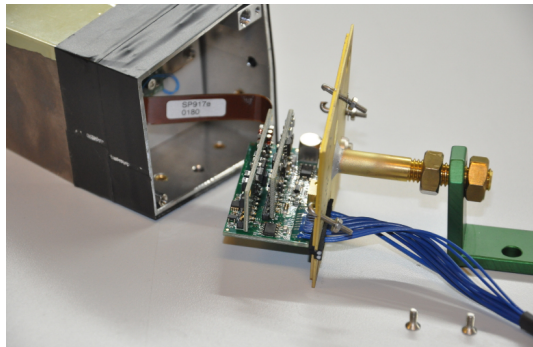
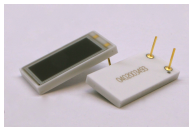
Database sparse for completely neutral final states like $\gamma n \rightarrow n\pi^0$

→ Readout of the CBELSA/TAPS experiment upgraded

Recent Developments

- Crystal Barrel calorimeter does not provide a fast trigger signal
→ Trigger on neutrons not possible!

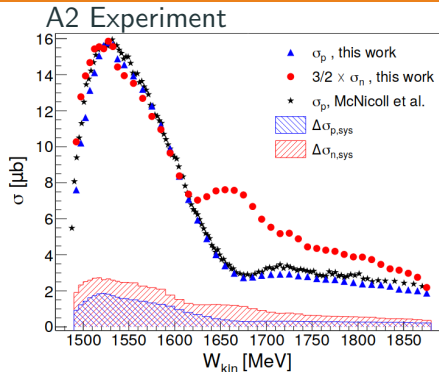
Calorimeters were completely dismantled and read out replaced for higher rates, trigger and time determination



[C. Honisch, et al. arXiv:2212.12364]

→ New high-statistics data sets for completely neutral final states possible!

Measurements off (polarized) Neutrons

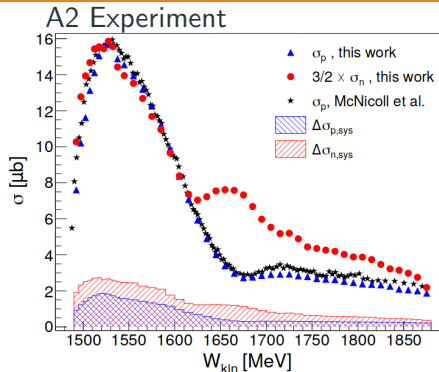


Narrow peak observed in η photoproduction

Polarization observables used to shed
further light on this structure

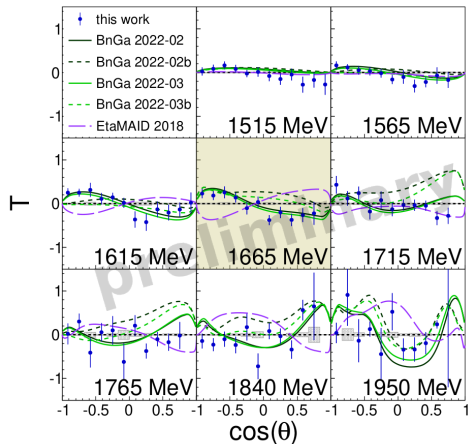
[D. Werthmüller et al., Phys.Rev. C90 (2014) 1,
015205]

Measurements off (polarized) Neutrons



Narrow peak observed in η photoproduction
Polarization observables used to shed
further light on this structure

[D. Werthmüller et al., Phys.Rev. C90 (2014) 1, 015205]



[N. Jermann, accepted for publication in EPJA]

Summary

Conclusion

- Reactions like $\gamma p \rightarrow p\pi^0$, $p\eta$, $p\eta'$, $p\pi^0\pi^0$, ... have been measured with polarized photons and protons with the CBELSA/TAPS experiment
- Data for the observables Σ , G , E , T , P and H has been published for π^0 and η photoproduction, other channels will follow soon
- Data is included in the different partial wave analyses and the multipoles are converging
- Crystal Barrel detector was upgraded for a higher detection efficiency for photoproduction off the neutron
- 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

Future Perspectives: Strangeness Measurements at Bonn

Up to now mostly measurements of non-strange baryons (N^* , Δ^*)

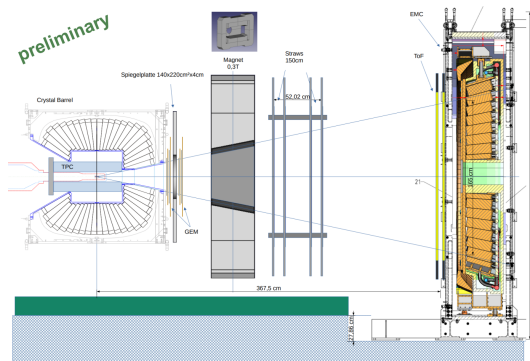
→ Extension to the strange sector (Λ^* , Σ^*) planned

Experimental Upgrade:

Additional forward spectrometer

Strangeness measurements with a polarized beam and a polarized target possible!

Crucial input in the search for exotic states!



Future Perspectives: Strangeness Measurements at Bonn

Up to now mostly measurements of non-strange baryons (N^* , Δ^*)

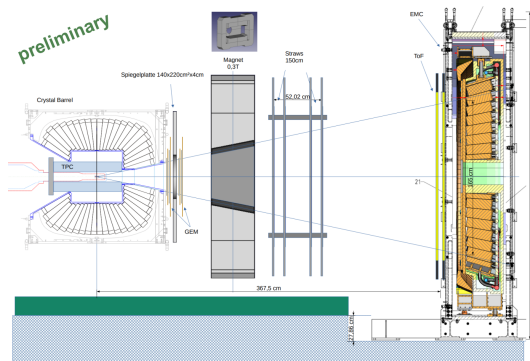
→ Extension to the strange sector (Λ^* , Σ^*) planned

Experimental Upgrade:

Additional forward spectrometer

Strangeness measurements with a polarized beam and a polarized target possible!

Crucial input in the search for exotic states!



Thank you for your attention!