Single meson photoproduction at CBELSA/TAPS

Annika Thiel

Exotic multi-quark states and baryon spectroscopy workshop

25.06.2024

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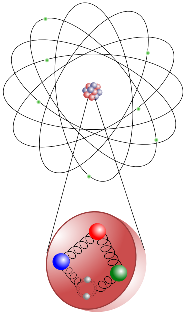
and
School of Physics and Astronomy, University of Glasgow, Scotland, UK

Motivation

Structure of Matter: Spectroscopy

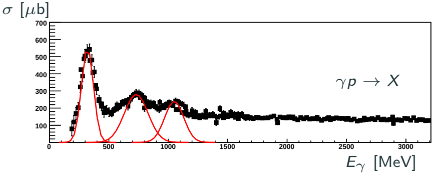
excitation spectrum

Spectroscopy of atoms



$\rightarrow$ information about QED

Spectroscopy of hadrons



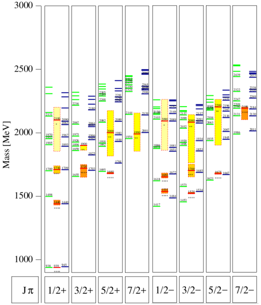
$\rightarrow$ information about QCD

Spectroscopy of Hadrons

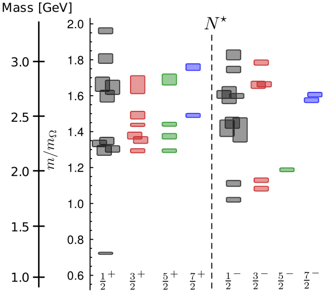
Excitation spectrum gives information about the dynamics inside the nucleon (between quarks and gluons)

Theoretical Predictions

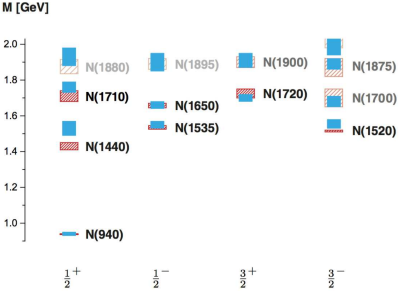
Quark Model



Lattice QCD Calculations



Dyson–Schwinger/Bethe–Salpeter approach



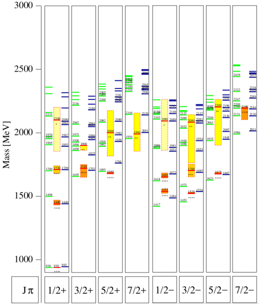
[M. Ronniger et al., Eur.Phys.J.A 47 (2011), 162] [R. Edwards et al., Phys.Rev.D 84 (2011) 07450] [Eichmann, Fischer, Few Body Syst. 60 (2019) 1,2]

Discrepancies between measurement and calculations:

"missing resonances" and level ordering

Theoretical Predictions

Quark Model



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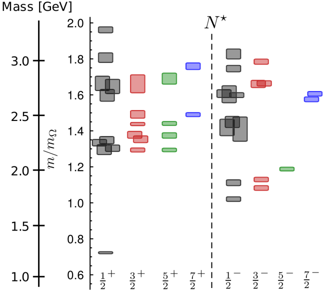

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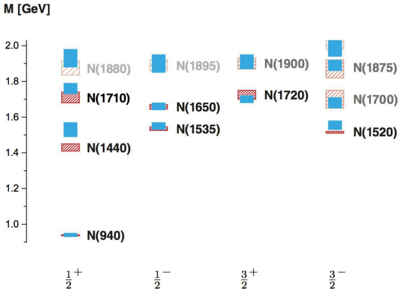

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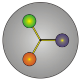
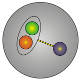
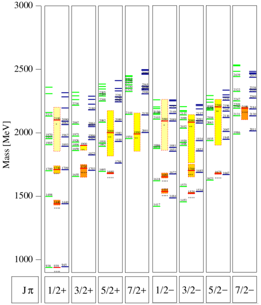
→ What are the relevant degrees of freedom?





Theoretical Predictions

Quark Model



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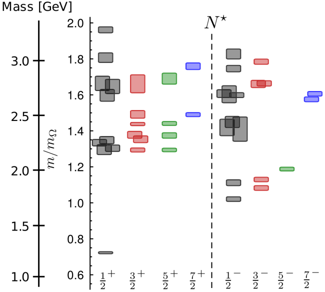

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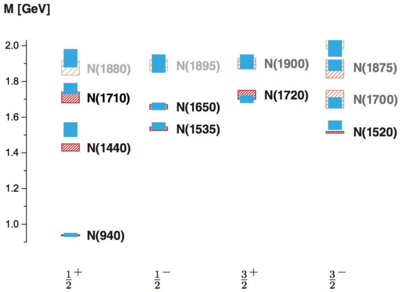

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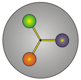
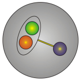
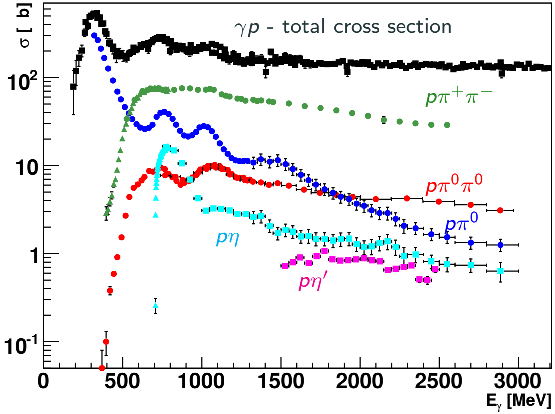




Most resonances observed in πN scattering:

→ Experimental bias?

Resonances

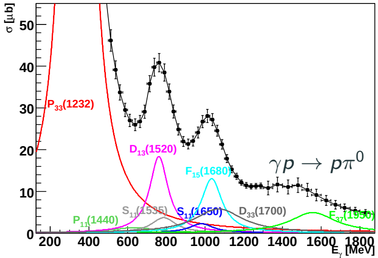


Total cross section sensitive to dominant resonance contributions:

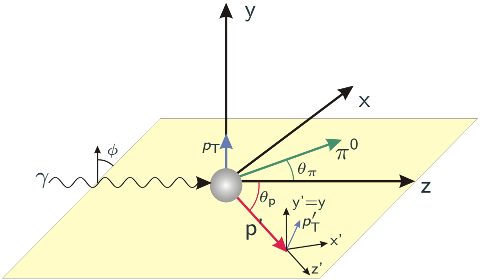
$\sigma \sim |E_{0+}|^2 + |E_{1+}|^2 + |M_{1+}|^2 + |M_{1-}|^2 + \ldots$

Resonances overlap strongly with different strengths and widths

$\rightarrow$ Weak resonance contributions difficult to measure



Polarization Observables



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

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

		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	-$C_{x'}$	–	-$C_{z'}$	–	–	–	–

Complete Experiments

Complete Experiment:

Extraction of the amplitudes without model dependence

For a single pseudoscalar meson at least **well-defined** 8 observables necessary

[Chiang and Tabakin, Phys.Rev.C 55 (1997) 2054-2066]

Complete Experiments

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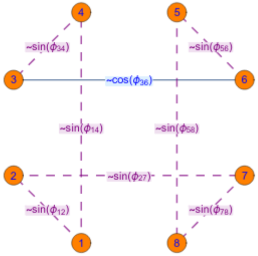
Extraction of complete sets using graph theory:



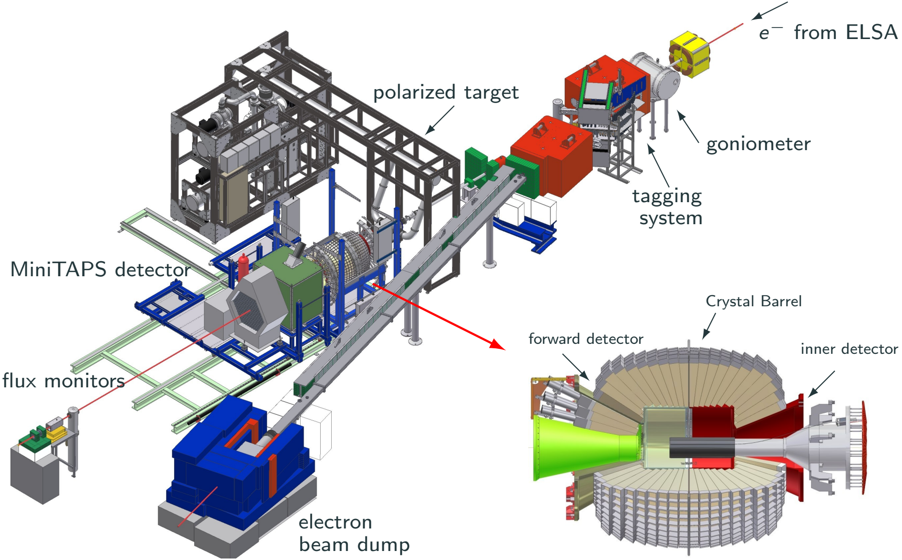
Electroproduction: 13 Observables

[Y. Wunderlich, ... AT, et al., Phys.Rev.C 102 (2020) 3, 034605]

Two meson photoproduction: 16 Observables

[P. Kroenert, ... AT, et al., Phys.Rev.C 103 (2021) 1, 014607]

The Setup of the CBELSA/TAPS Experiment



$\rightarrow$ nearly full 4π angular coverage

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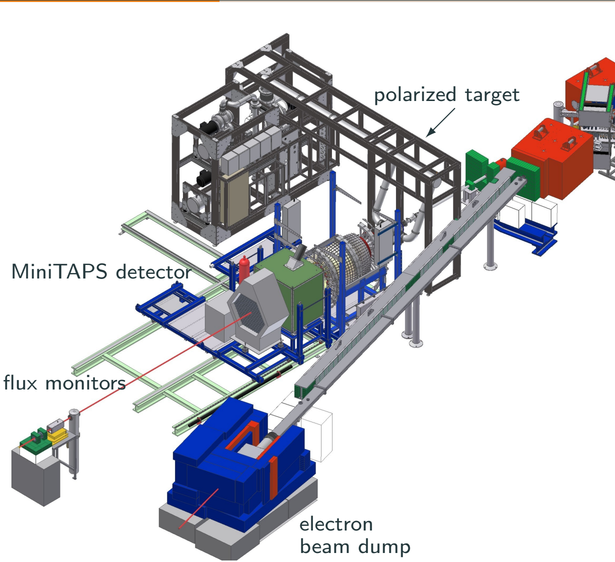

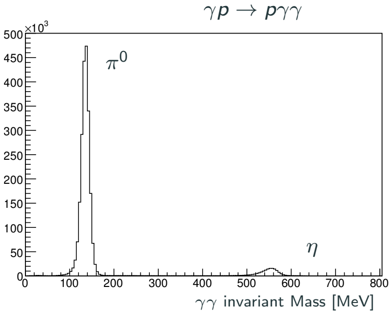

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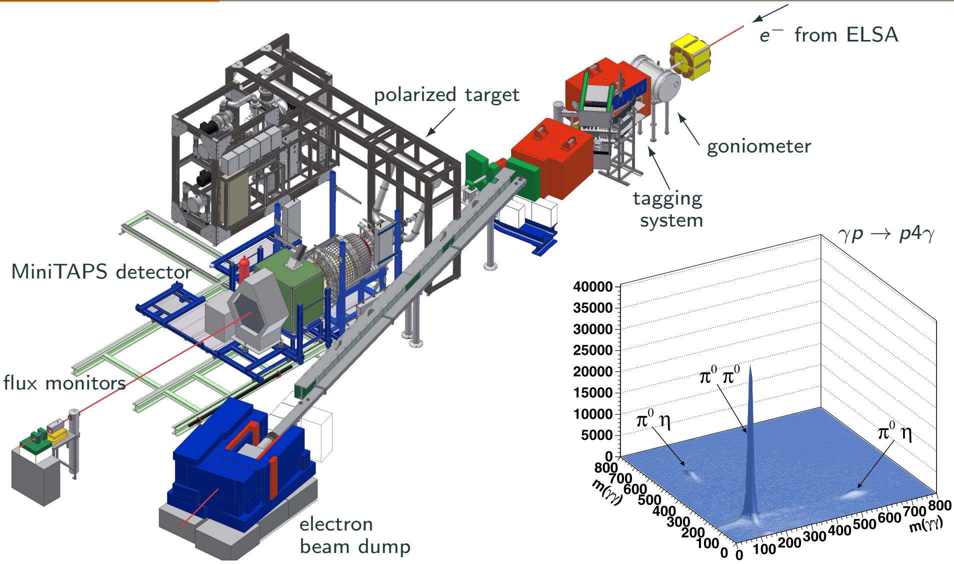

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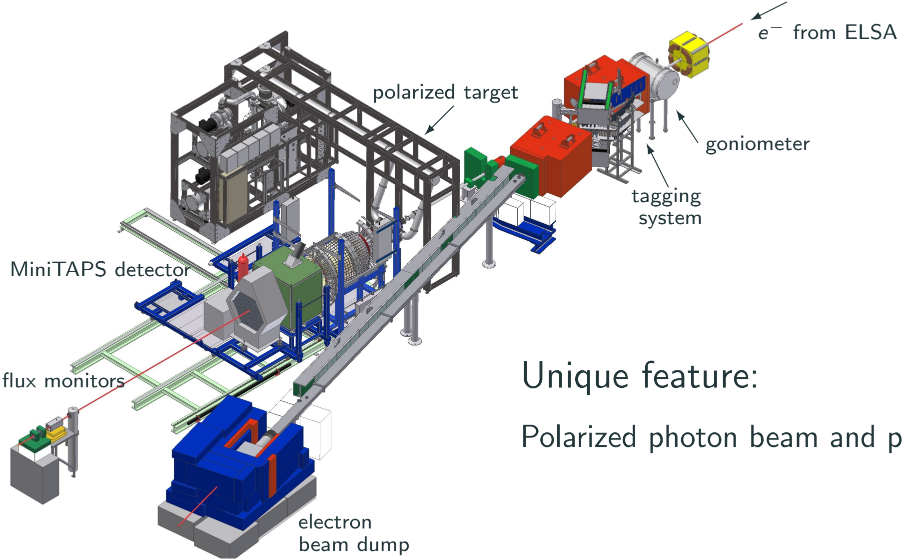
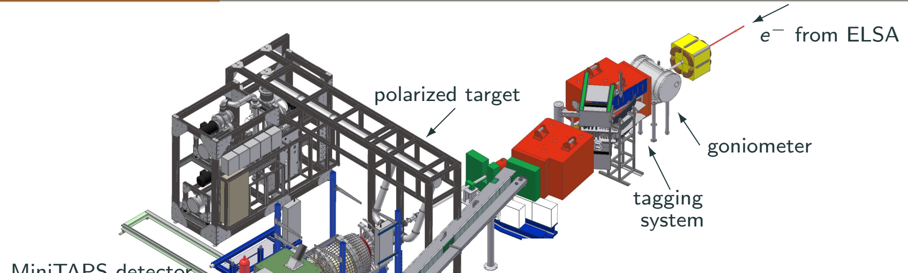
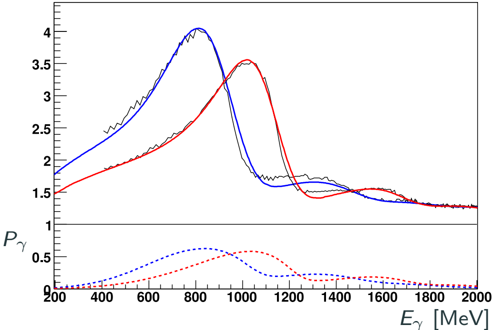


Unique feature:

Polarized photon beam and polarized target!

The Setup of the CBELSA/TAPS Experiment





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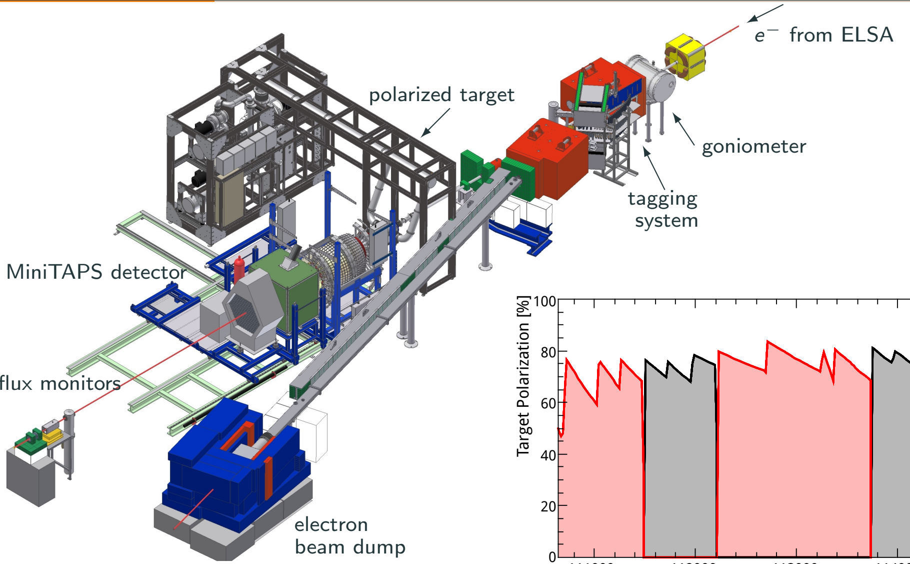
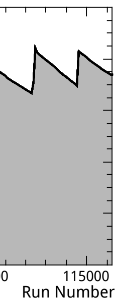
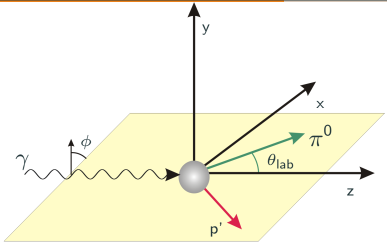




Extraction of the observables

Cross Section with Beam und Target Polarization



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

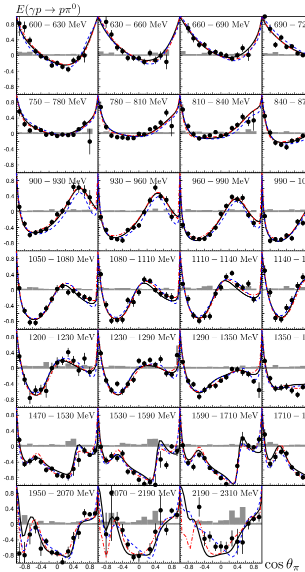
		Target Polarization		
Photon Polarization		x	y	z
unpolarized	σ	–	T	–
linearly polarized	Σ	H	P	G
circularly polarized	–	F	–	E

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

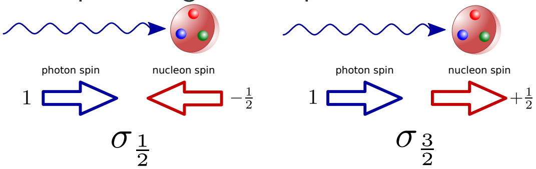
T, **P**, **H**: J. Hartmann et al., PRL 113 (2014) 062001
Phys.Lett. B748 (2015) 212

$\gamma p \to p\pi^0$: Double Polarization Observable E



E is a helicity asymmetry:

Two spin configurations possible

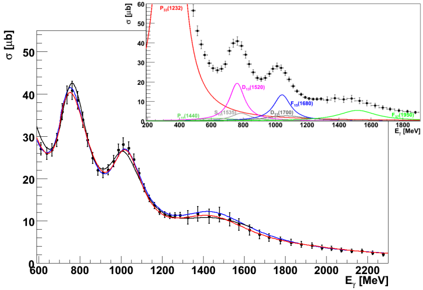


$$E(\theta, E_\gamma) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

Fits to the data:
BnGa11-02
MAID07
SAID CM12
JüBo15-B

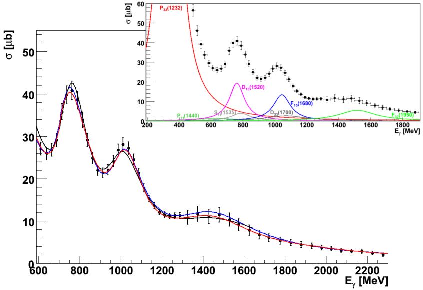
M. Gottschall et al.,
Phys. Rev. Lett. 112, 012003 (2014)
Eur. Phys. J. A **57**, no.1, 40 (2021)

$\gamma p \to p\pi^0$: $\sigma_{1/2}$ vs. $\sigma_{3/2}$

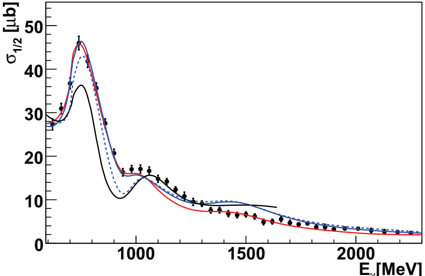


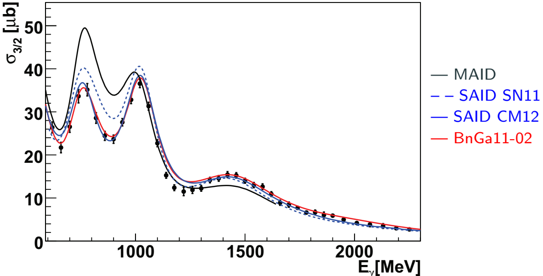
- Different models show good description of the cross section
- Spin dependent cross section can be extracted: $\sigma^{1/2(3/2)} = \sigma_0 \cdot (1 \pm E)$

$\gamma p \rightarrow p\pi^0$: $\sigma_{1/2}$ vs. $\sigma_{3/2}$



- Different models show good description of the cross section
- Spin dependent cross section can be extracted: $\sigma^{1/2(3/2)} = \sigma_0 \cdot (1 \pm E)$
- Large differences occur in $\sigma^{1/2}$ and $\sigma^{3/2}$ cross sections





Cross Section with Beam und Target Polarization

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

η-photoproduction:

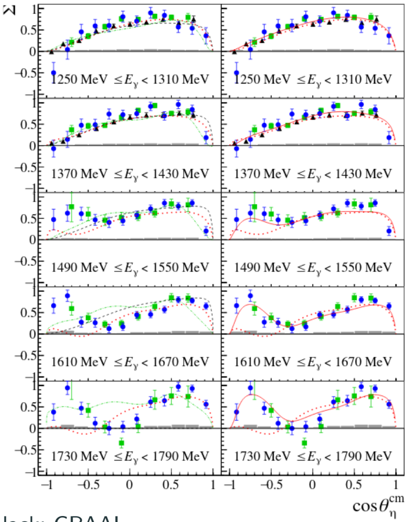
Σ:

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

T, P, H, G, E:

J. Müller et al. Phys.Lett.B 803 (2020) 135323

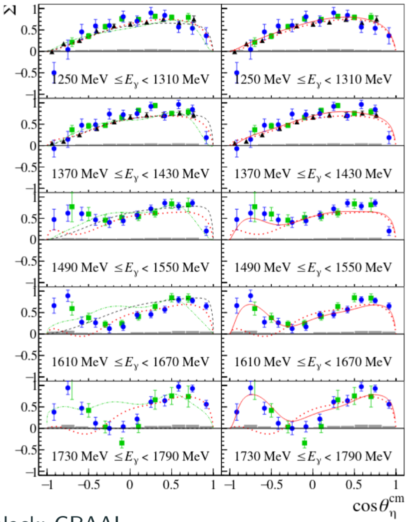
Cusp Effect visible in η Photoproduction



black: GRAAL
green: CLAS blue: CBELSA/TAPS

High precision measurement of the Beam Asymmetry with high angular coverage

Cusp Effect visible in η Photoproduction



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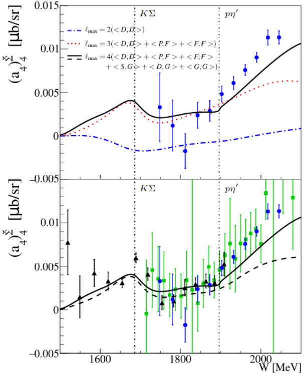
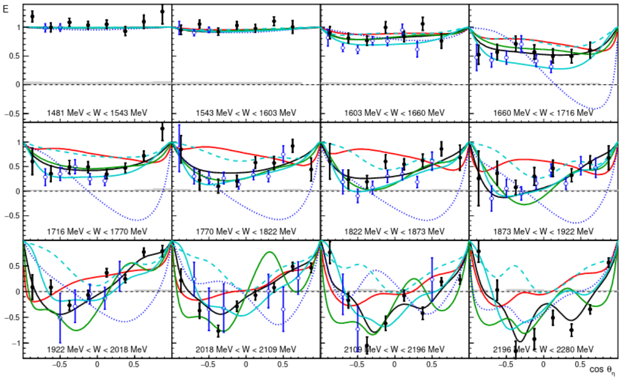
High precision measurement of the Beam Asymmetry with high angular coverage

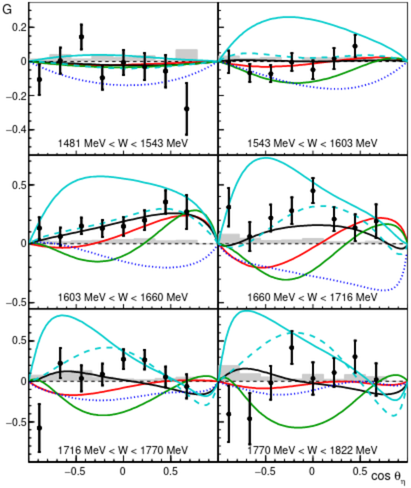
Cusp effect of the η' threshold visible in the Legendre coefficients



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

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





— BnGa 2011-02

— BnGa Refit

— MAID2018

... SAID (GE09)

— JüBo2015

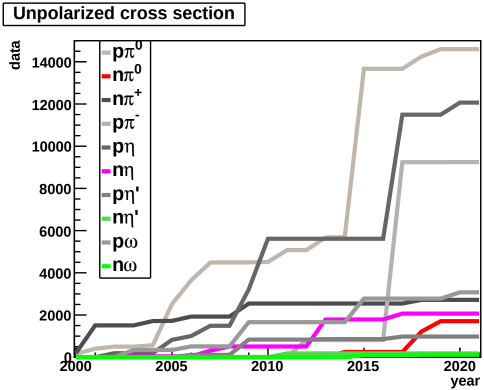
– – JüBo2015-3

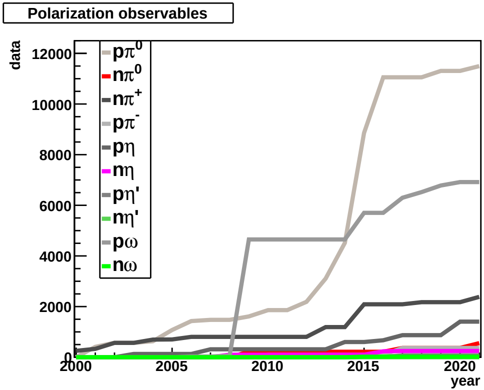
Black dots: CBELSA/TAPS

Blue open circles: CLAS

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

Measurements off Neutrons





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

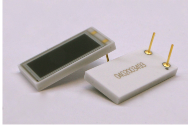
$\rightarrow$ Readout of the CBELSA/TAPS experiment upgraded

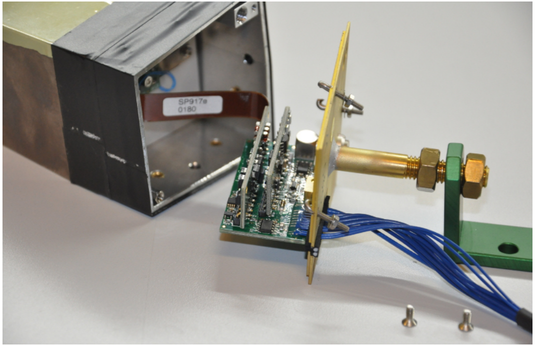
Recent Developments

- 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

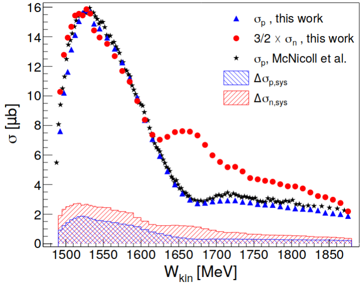




[C. Honisch, ..., AT et al., arXiv:2212.12364]

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

Measurements off (polarized) Neutrons with A2



Narrow peak observed in η photoproduction

Polarization observables used to shed further light on this structure

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

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

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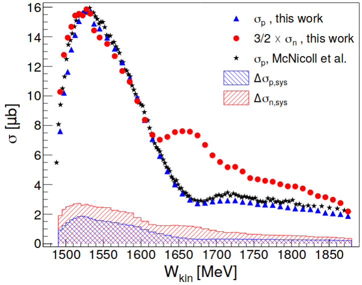

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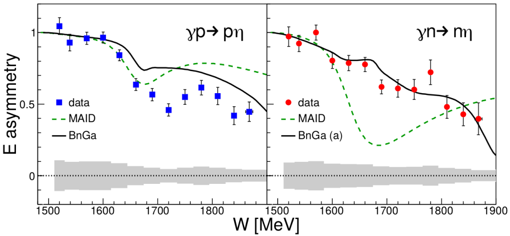

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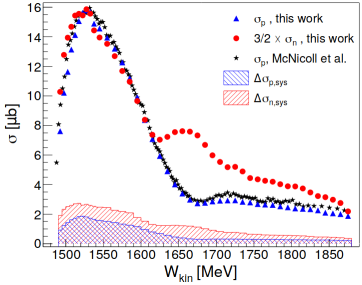

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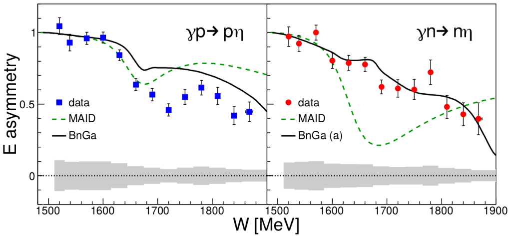

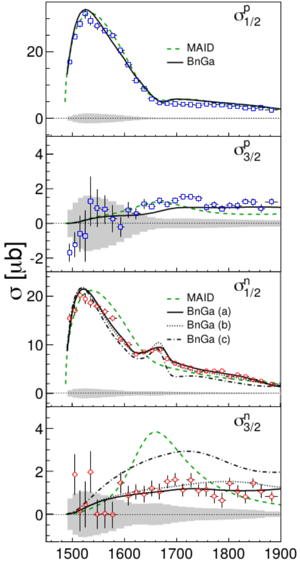

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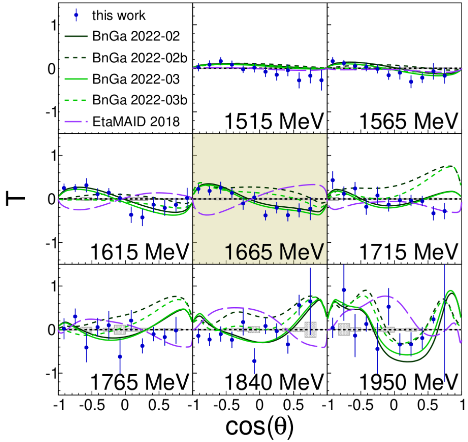
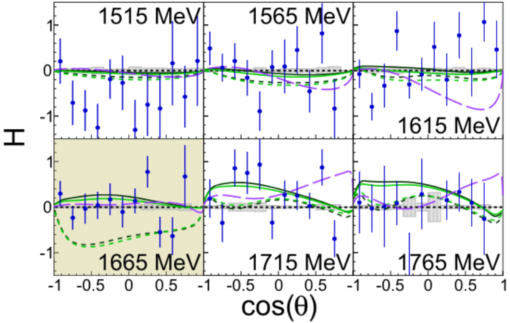


[N. Jermann, Eur.Phys.J.A 59 (2023) 10, 232]



- First extraction of the observables T, P and H off neutrons
- S_{11} interference preferred compared to a new resonant structure

Interpretation

Multipoles and CGLN Amplitudes

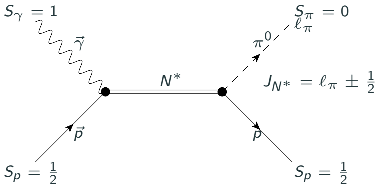
Multipoles give information about the intermediate states, can be combined into four CGLN amplitudes:

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

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

...

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



$\rightarrow$ Pion-Multipoles
$E_{\ell_\pi \pm}$, $M_{\ell_\pi \pm}$

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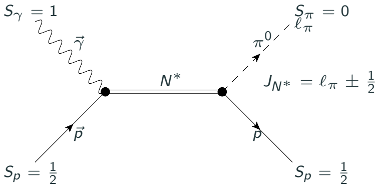

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All observables can be expressed in CGLN amplitudes, for example:

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

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:

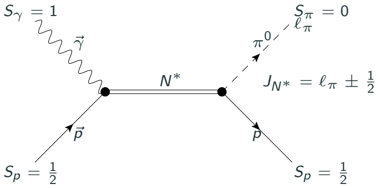
$$F_1(W,z) = \sum_{\ell=0}^{\ell_{max}} [\ell M_{\ell+} + E_{\ell+}] \cdot P'_{\ell+1}(z) + [(\ell+1)M_{\ell-} + E_{\ell-}] \cdot P'_{\ell-1}(z)$$

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

...

Truncation at a certain level

$\rightarrow$ Truncated PWA



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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 ($L_{max} = 1$):

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

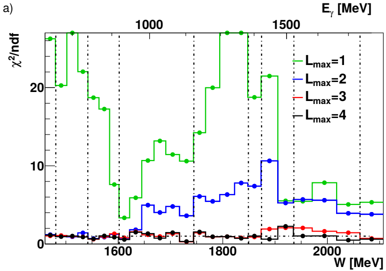
- using S-, P- and D-waves ($L_{max} = 2$):

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

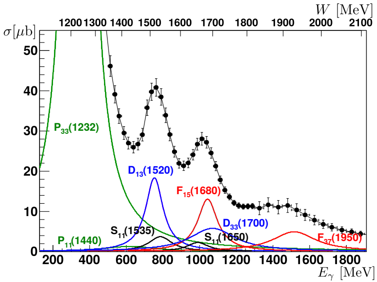
- using S-, P-, D- and F-waves ($L_{max} = 3$):

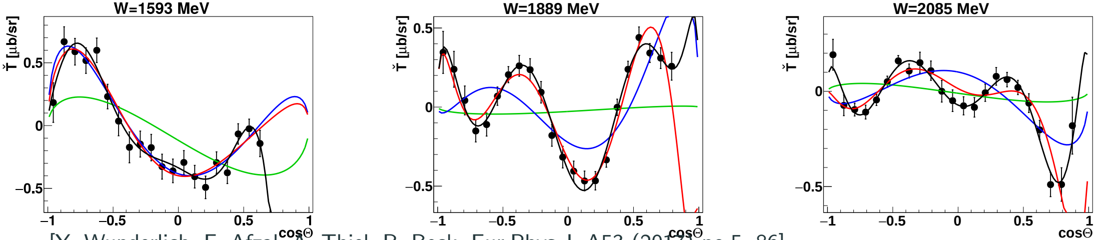
$$\check{T} = \frac{q}{k} \sin\theta [A_0 + A_1 \cdot \cos\theta + A_2 \cdot \cos^2\theta + A_3 \cdot \cos^3\theta + A_4 \cdot \cos^4\theta + A_5 \cdot \cos^5\theta]$$

First Interpretation with a Truncated Partial Wave Analysis



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





[Y. Wunderlich, F. Afzal, A. Thiel, R. Beck, Eur.Phys.J. A53 (2017) no.5, 86]

TPWA for η photoproduction

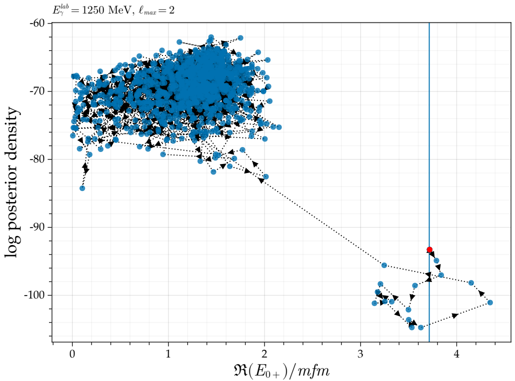
Further improvement: Using Bayesian statistics

$$\underbrace{p(\boldsymbol{\theta}|\boldsymbol{y})}_{\text{'posterior'}} = \frac{\overbrace{p(\boldsymbol{y}|\boldsymbol{\theta})}^{\text{'likelihood'}}\ \overbrace{p(\boldsymbol{\theta})}^{\text{'prior'}}}{\underbrace{\int d^D\theta\, p(\boldsymbol{y}|\boldsymbol{\theta})\, p(\boldsymbol{\theta})}_{\text{'Bayesian evidence'}}}$$

θ: parameters, in our case $E_{\ell\pm}$,$M_{\ell\pm}$

y: data, in our case measured polarization observables

Marginalized distributions of the posteriors determined using Markov Chain Monte Carlos:

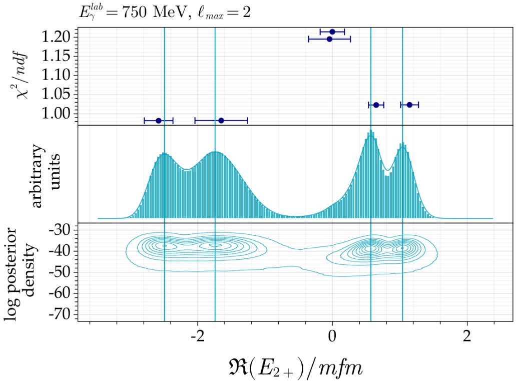


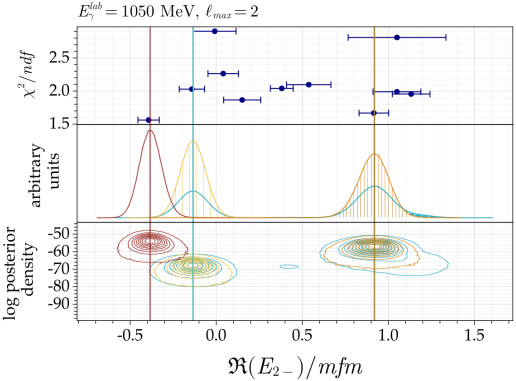
TPWA for η photoproduction: Used data sets

Observable	No. of datapoints	Exp. facility	References
σ_0	5736	MAMI	[Kashevarov et al., PRL **118**, 212001 (2017)]
T, F	144	MAMI	[Akondi et al., PRL **113**, 102001 (2014)]
Σ	140	GRAAL	[Bartalini et al., EPJ A **33**, 169 (2007)]
E	84	MAMI	[F. Afzal, PhD thesis, ULB Bonn (2019)]
G	47	CBELSA/TAPS	[Müller et al., Phys. Lett. B **803**, 135323 (2020)]

- Data fitted with $\ell_{max} = 1$ and 2
- Flat prior in the physically allowed region
- Results compared to 'conventional' maximum likelihood fits

TPWA for η photoproduction: Examples



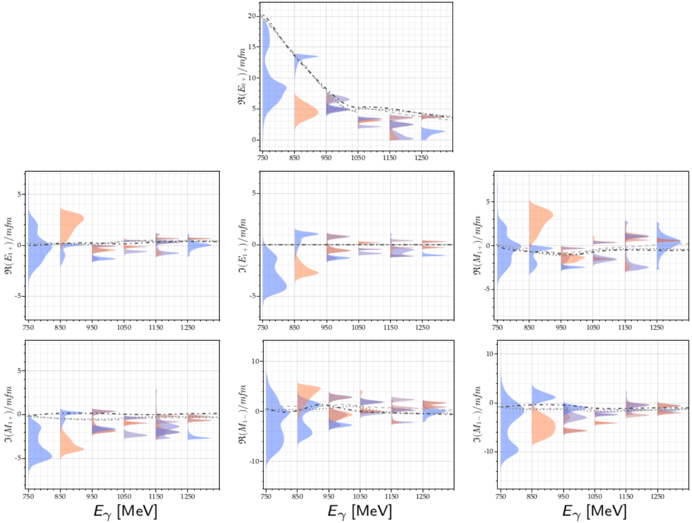


- Log posterior density gives estimate about the likelihood
- At low energies: a single chain mapping the probability space
- At higher energies: Different chains map different regions

$\rightarrow$ Significant increase in information content by providing error distributions!

P. Kroenert et al., Phys.Rev.C 109 (2024) 4, 045206

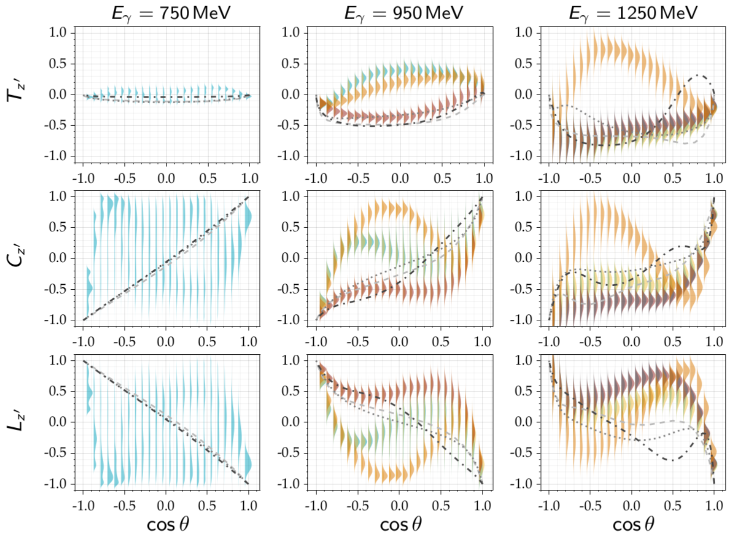
TPWA for η photoproduction



- Extraction of multipoles possible
- Results agree with the different PWA solutions

P. Kroenert et al., Phys.Rev.C 109 (2024) 4, 045206

TPWA for η photoproduction



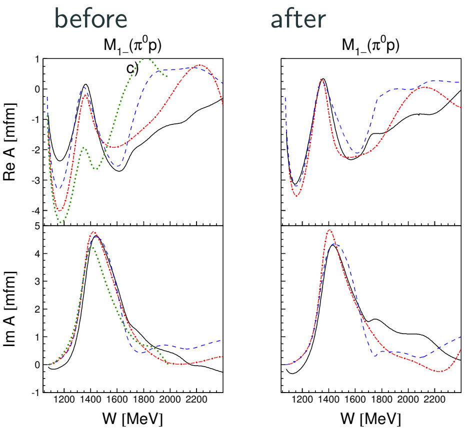
- Predictions for up to now unmeasured observables
- Provide information about the most useful measurements to resolve ambiguities

P. Kroenert et al., Phys.Rev.C 109 (2024) 4, 045206

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]

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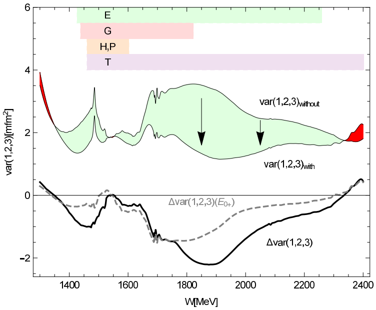
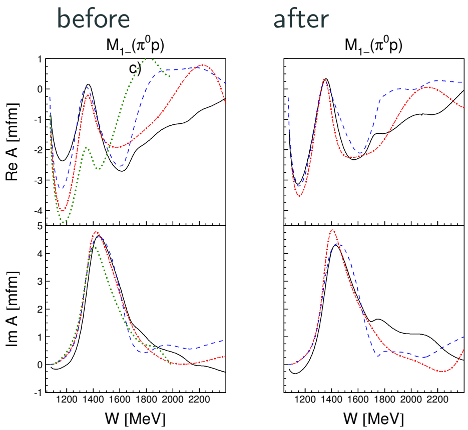
- JüBo (red)
- SAID (blue)

Variance between the different analyses decreases!





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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	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***	-			-		
$N(1520)$	$3/2^-$	****	****	****	****	**	****			- - - -		
$N(1535)$	$1/2^-$	****	****	****	***	*	****			- -		
$N(1650)$	$1/2^-$	****	****	****	***	*	****	*- -	- -	- -		
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*	-		
$N(1680)$	$5/2^+$	****	****	****	****	***	*	*	*	- - - -		
$N(1700)$	$3/2^-$	***	**	***	***	*	*	- -	-	-		
$N(1710)$	$1/2^+$	****	****	****	*-		***	**	*	*	*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	*-	*	
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**	-	*	**
$N(1990)$	$7/2^+$	**	**	**			*	*	*			
$N(2000)$	$5/2^+$	**	**	*-	**	*	*	-	-	- -	*	
$N(2040)$	$3/2^+$	*		*								
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*	
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**
$N(2120)$	$3/2^-$	***	***	**	**	**		**	*		*	*
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*	
$N(2220)$	$9/2^+$	****	**	****			*	*	*			
$N(2250)$	$9/2^-$	****	**	****			*	*	*			
$N(2300)$	$1/2^+$	**		**								
$N(2570)$	$5/2^-$	**		**								
$N(2600)$	$11/2^-$	***		***								
$N(2700)$	$13/2^+$	**		**								

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

Summary

Conclusion

- Reactions like $\gamma p \to p\pi^0$, $p\eta$, $p\eta'$, $p\pi^0\pi^0$, ... 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
- Crystal Barrel detector was upgraded for a higher detection efficiency for photoproduction off the neutron
- Data is included in the different partial wave analyses and the multipoles are converging
- 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

Summary

Review Paper:

A. T., F. Afzal and Y. Wunderlich,

Light Baryon Spectroscopy

Progress in Particle and Nuclear Physics 125 (2022) 103949

e-Print: 2202.05055 [nucl-ex]

Thank you for your attention!