Recent Results from the CBELSA/TAPS Experiment

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MITP - Hadron Spectroscopy: The Next Big Steps

23/03/2022

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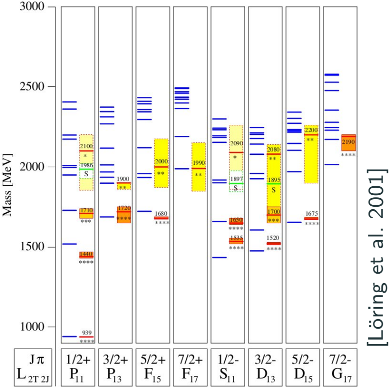
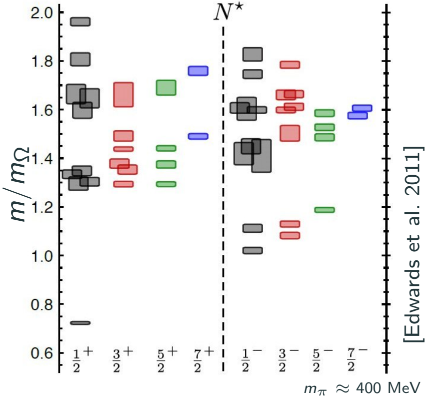
Motivation

Theoretical Predictions

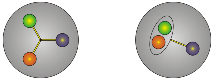
Quark models



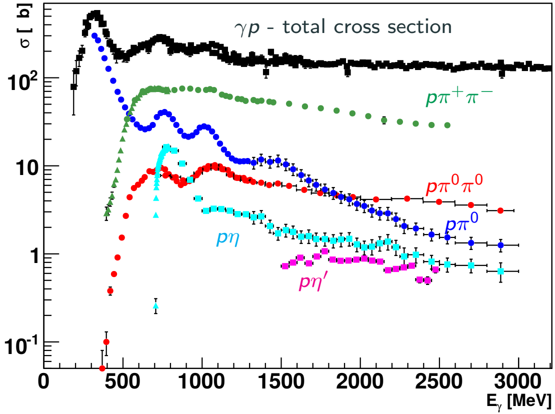
Lattice QCD calculations



Calculations predict more resonances than have been measured
("missing resonances")
→ What are the relevant degrees of freedom?



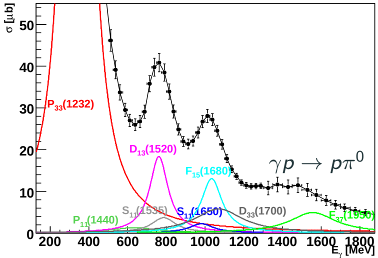
Resonances



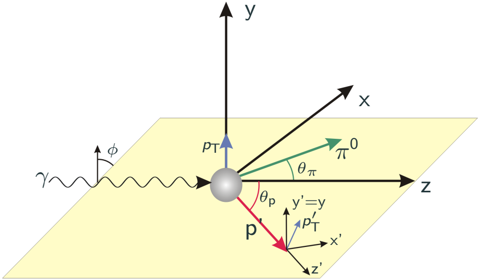
Resonances overlap strongly with different strengths and widths

→ Weak resonance contributions difficult to measure

Partial wave analysis needed to disentangle the resonances.



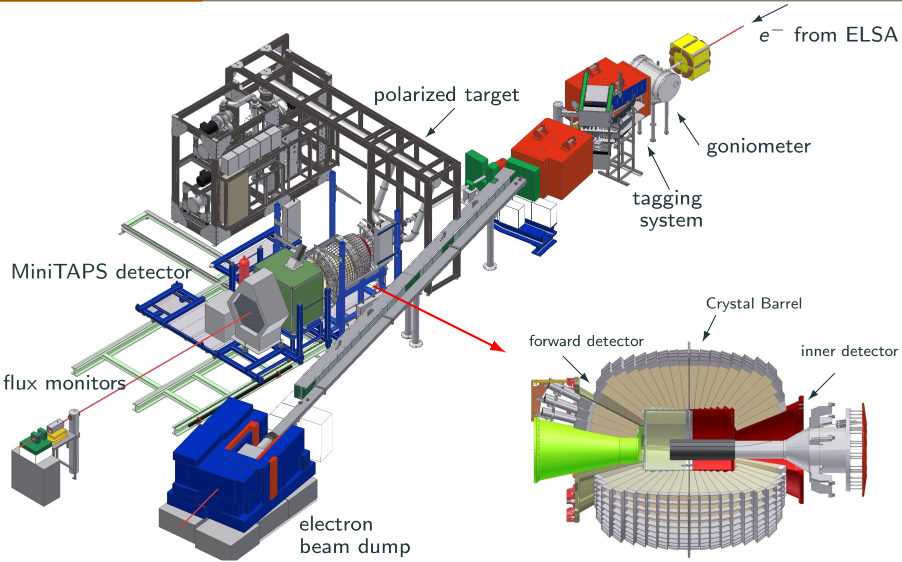
Polarization Observables



16 Polarization Observables in photoproduction of pseudoscalar mesons:

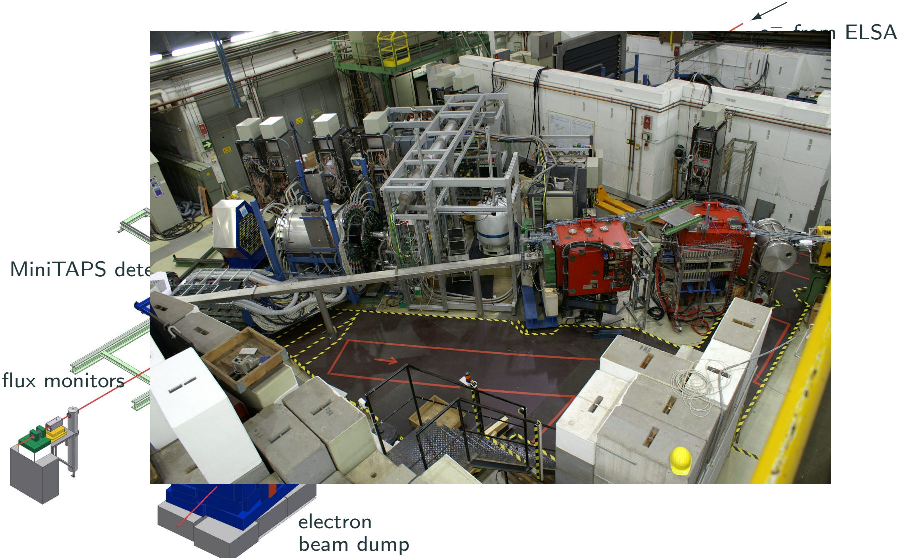
Photon		Target			Recoil			Target+Recoil			
		–	–	–	x'	y'	z'	x'	x'	z'	z'
		x	y	z	–	–	–	x	z	x	z
unpolarized	σ	–	T	–	–	P	–	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
linearly pol.	Σ	H	(-P)	-G	$O_{x'}$	(-T)	$O_{z'}$	–	–	–	–
circularly pol.	–	F	–	-E	$-C_{x'}$	–	$-C_{z'}$	–	–	–	–

The Setup of the CBELSA/TAPS Experiment



$\rightarrow$ nearly full 4π angular coverage

The Setup of the CBELSA/TAPS Experiment



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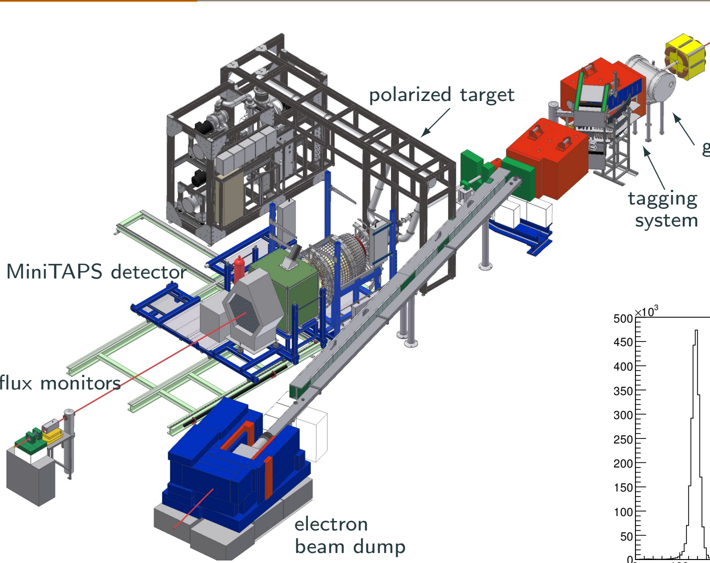

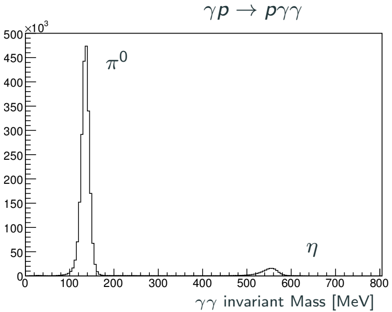

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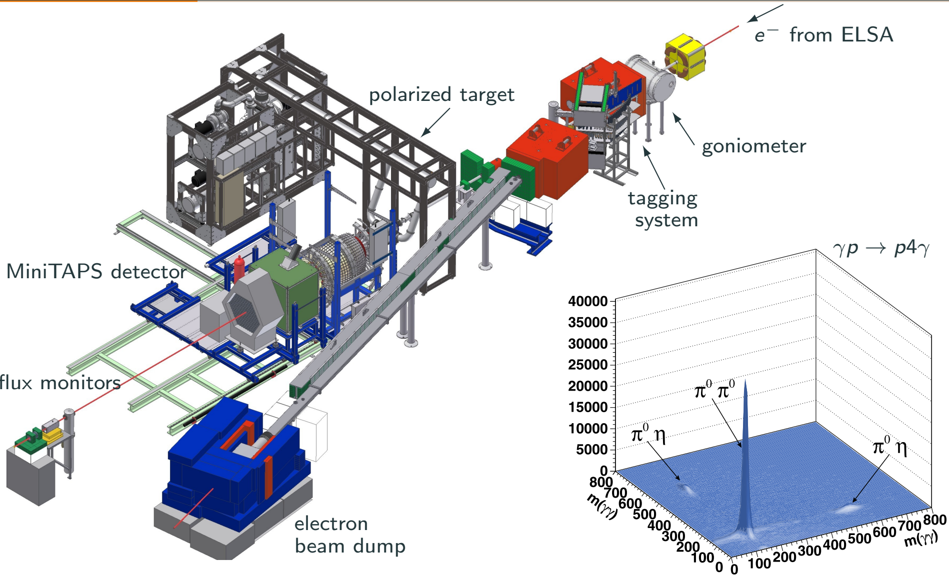
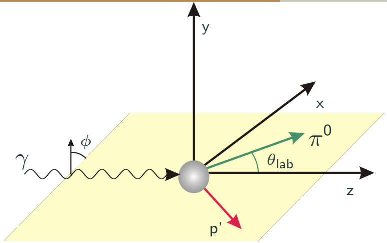


Extraction of the observables

Cross Section with Beam und Target Polarization



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

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

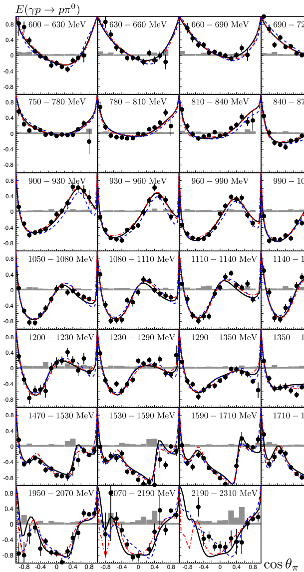
π^0-photoproduction:

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

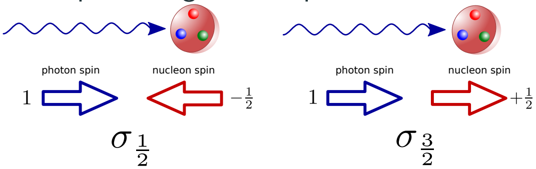
T, **P**, **H**: J. Hartmann et al., PRL 113 (2014) 062001
Phys.Lett. B748 (2015) 212

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



E is a helicity asymmetry:

Two spin configurations possible

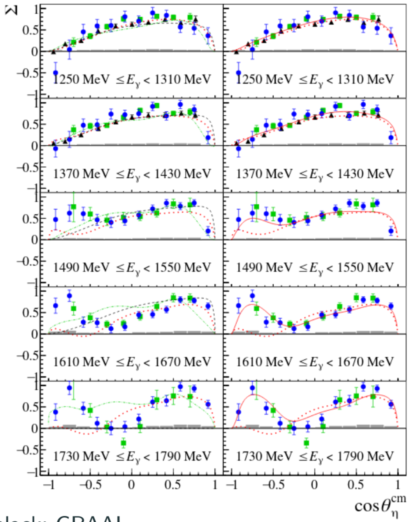


$$E(\theta, E_\gamma) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

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)

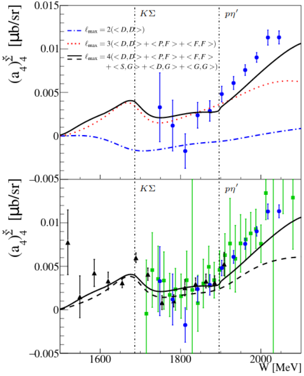
Cusp Effect visible in η Photoproduction



black: GRAAL
green: CLAS blue: CBELSA/TAPS

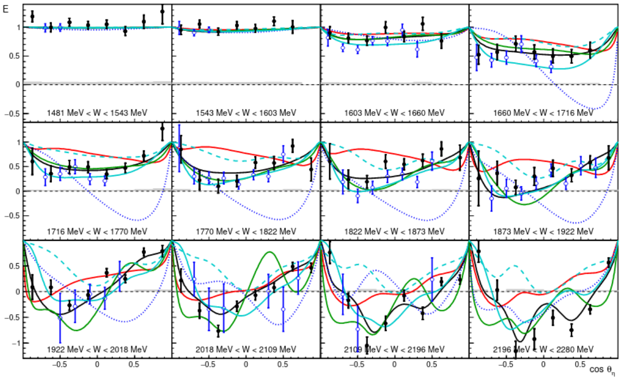
High precision measurement of the Beam Asymmetry with high angular coverage

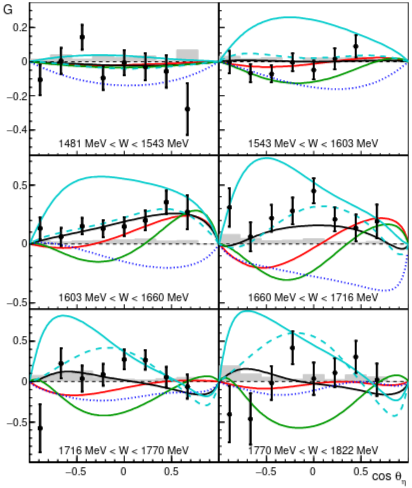
Cusp effect of the η' threshold visible in the Legendre coefficients



[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)

— JüBo2015-3

– – JüBo2015-3

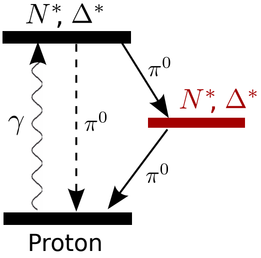
Black dots: CBELSA/TAPS

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



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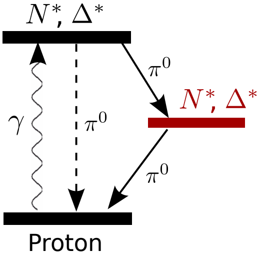
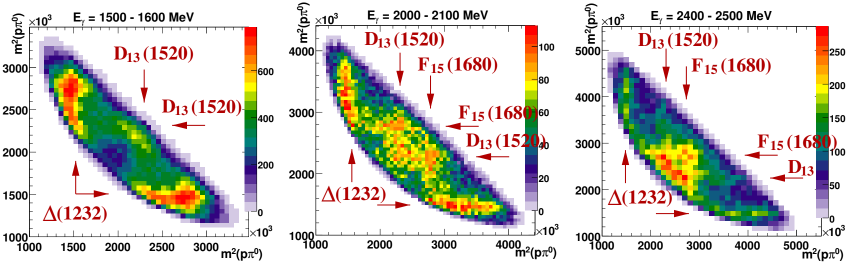


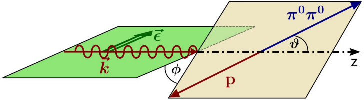


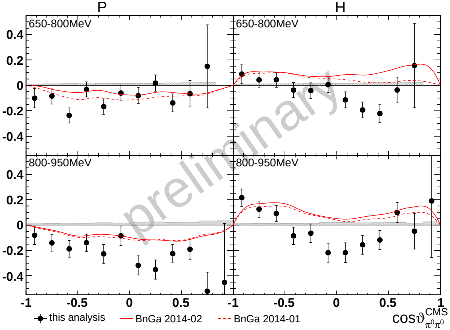
[V. Sokhoyan et al., Eur.Phys.J. A51 (2015) no.8, 95]

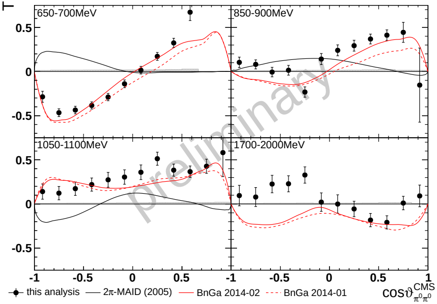
$\gamma p \to p\pi^0\pi^0$: Polarization Observables T, P, H

T. Seifen

Only results shown in quasi two-body kinematics



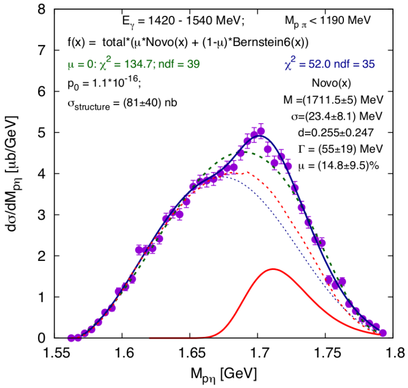


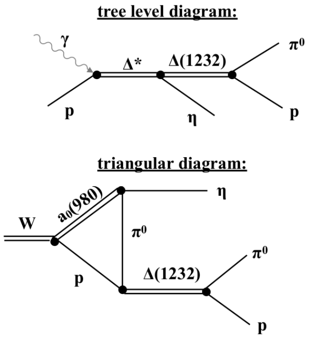


Observables also extracted for different kinematic variables

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

First Indication of Triangle Singularities in $\gamma p \to p\pi^0\eta$





[V. Metag et al. Eur.Phys.J.A 57 (2021) 12, 325]

Structure observed in the $p\eta$ invariant mass

Triangle singularity can describe this structure

Observation of a triangle singularity in baryon spectroscopy?

Interpretation

Multipoles and CGLN Amplitudes

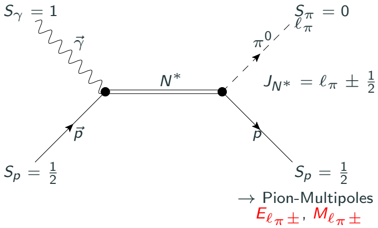
Multipoles give informations about the intermediate states, can be combined into four CGLN amplitudes:

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

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

...

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



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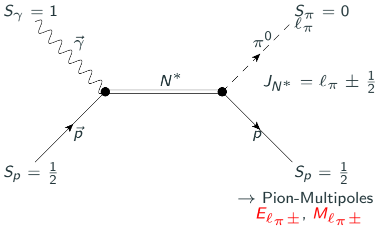

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$$\dots$$

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

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

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

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

Multipoles and CGLN Amplitudes

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

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

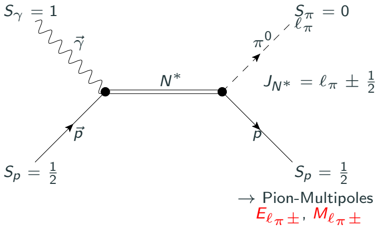
$$F_2(W,z) = \sum_{\ell=0}^{\ell_{max}} \dots$$

...

Truncation at a certain level

$\rightarrow$ Truncated PWA

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



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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 ($L_{max} = 1$):

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

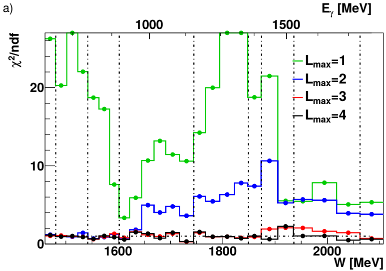
- using S-, P- and D-waves ($L_{max} = 2$):

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

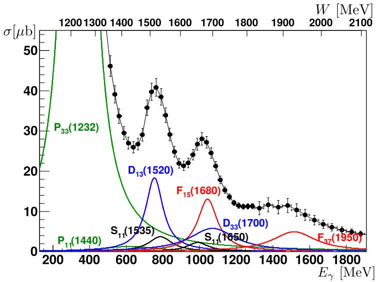
- using S-, P-, D- and F-waves ($L_{max} = 3$):

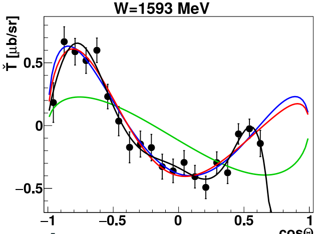
$$\check{T} = \frac{q}{k} \sin\theta [A_0 + A_1 \cdot \cos\theta + A_2 \cdot \cos^2\theta + A_3 \cdot \cos^3\theta \\ + A_4 \cdot \cos^4\theta + A_5 \cdot \cos^5\theta]$$

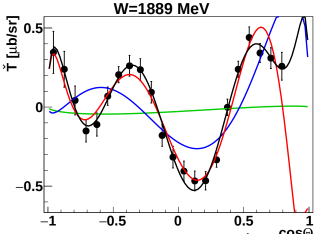
First Interpretation with a Truncated Partial Wave Analysis

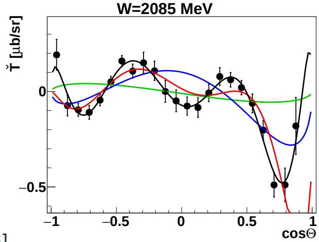


Fits with different L_{max} reveal sensitivity of the data!



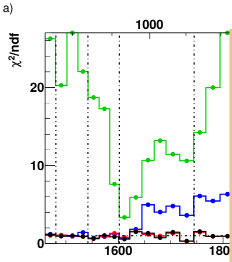


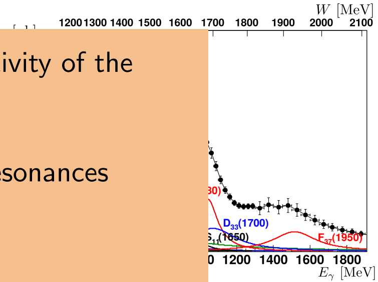




[Y. Wunderlich, F. Afzal, A. Thiel, R. Beck, Eur.Phys.J. A53 (2017) no.5, 86]

First Interpretation with a Truncated Partial Wave Analysis

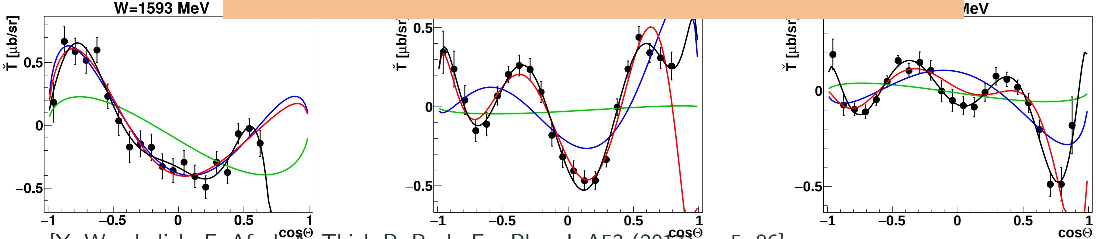




tPWA can give first insight into the sensitivity of the measured data.

Exact interpretation of the contributing resonances difficult

$\rightarrow$ Full PWA needed

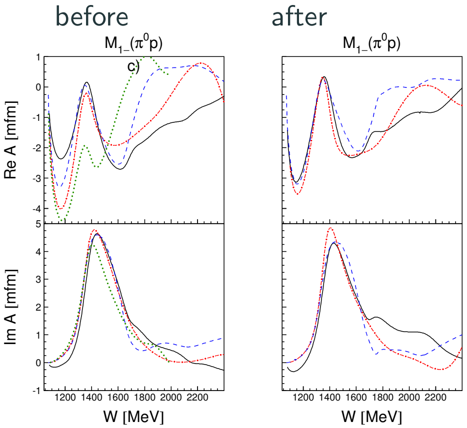


[Y. Wunderlich, F. Afzal, A. Thiel, R. Beck, Eur.Phys.J. A53 (2017) no.5, 86]

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)
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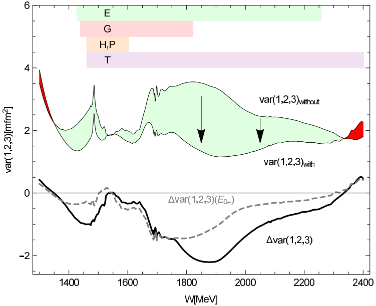
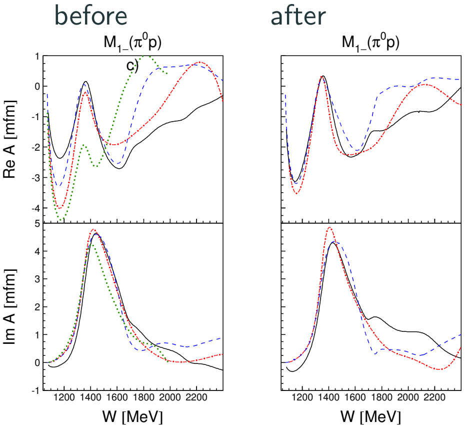
Variance between the different analyses decreases!





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

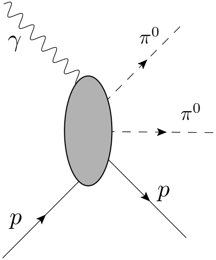
Comparison between PDG values

- 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

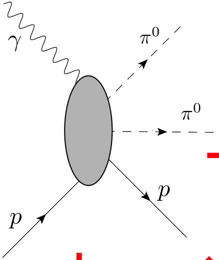
Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***	-			-		
$N(1520)$	$3/2^-$	****	****	****	****	**	****			- - - -		
$N(1535)$	$1/2^-$	****	****	****	***	*	****			- -		
$N(1650)$	$1/2^-$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

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

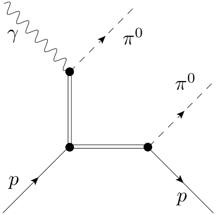
Baryon and Meson Production in the t-channel



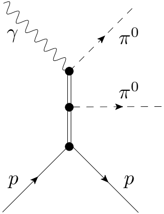
Baryon and Meson Production in the t-channel



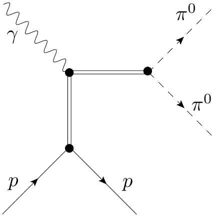
Baryon production:



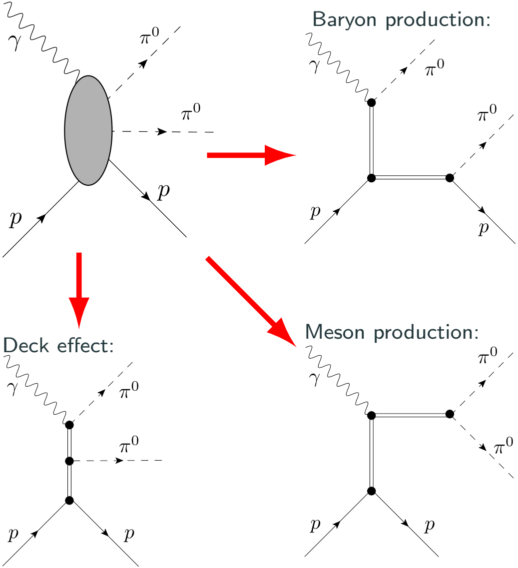
Deck effect:



Meson production:



Baryon and Meson Production in the t-channel



Baryon Spectroscopy as a Basis for Meson PWA

Possible options:

- Remove background of baryon resonances from meson spectroscopy data sets
- Describe the background of baryon resonances
- ...

Well-know baryon spectrum is needed for high precision meson spectroscopy!

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
- Different single and double polarization observables have been successfully extracted over a wide energy range
- 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

Outlook

- Data has been included in a truncated partial wave analysis, which gives a first indication about the sensitivity of the observables
- 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

Outlook

New Review Paper:

A. T., F. Afzal and Y. Wunderlich, **Light Baryon Spectroscopy**

Accepted for publication in **Progress in Particle and Nuclear Physics**

e-Print: 2202.05055 [nucl-ex]

Thank you for your attention!