Polarization observables as a tool to extract resonance parameters

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International Workshop XLVI on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria

01/18/2018

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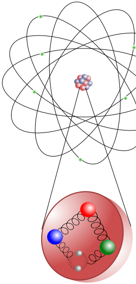
Outline

Motivation

Structure of Matter: Spectroscopy

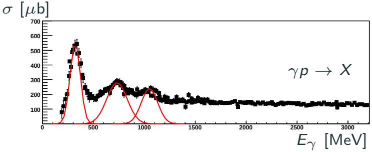
excitation spectrum

Spectroscopy of atoms



→ information about QED

Spectroscopy of hadrons



→ information about QCD

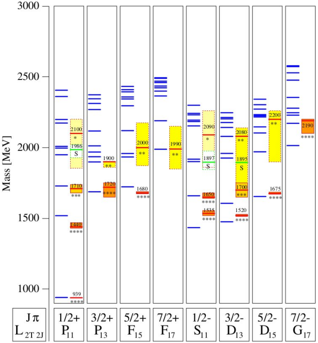
Spectroscopy of Hadrons

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

→ Baryon excitation spectrum needs to be understood

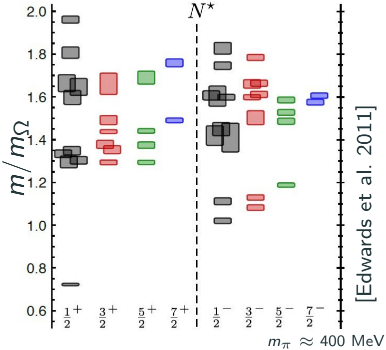
Theoretical Predictions

Quark models



[Löring et al. 2001]

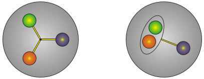
Lattice QCD calculations



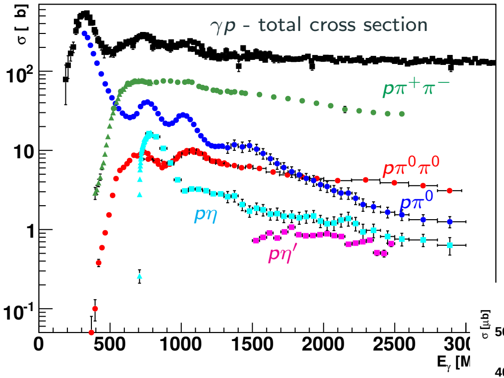
[Edwards et al. 2011]

Calculations predict more resonances than have been measured ("missing resonances")

→ What are the relevant degrees of freedom?



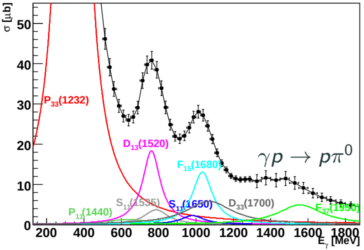
Resonances



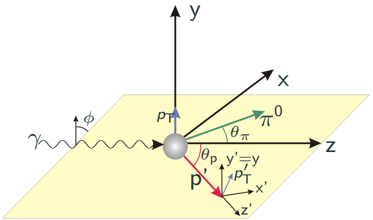
Resonances overlap strongly with different strengths and widths

→ Weak resonance contributions difficult to measure

Partial wave analysis needed to disentangle the resonances.



Polarization Observables



16 Polarization Observables in photoproduction of pseudoscalar mesons:

		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	$-C_{x'}$	–	$-C_{z'}$	–	–	–	–

For a complete model-independent partial wave analysis ('complete experiment'):

At least 8 well-chosen observables needed

[Chiang, Tabakin Phys. Rev. C55 (1997)]

Complete Experiment

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

We do experiments with polarized photon beams and a polarized target.

Are we now close to a complete experiment?

Complete Experiment

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

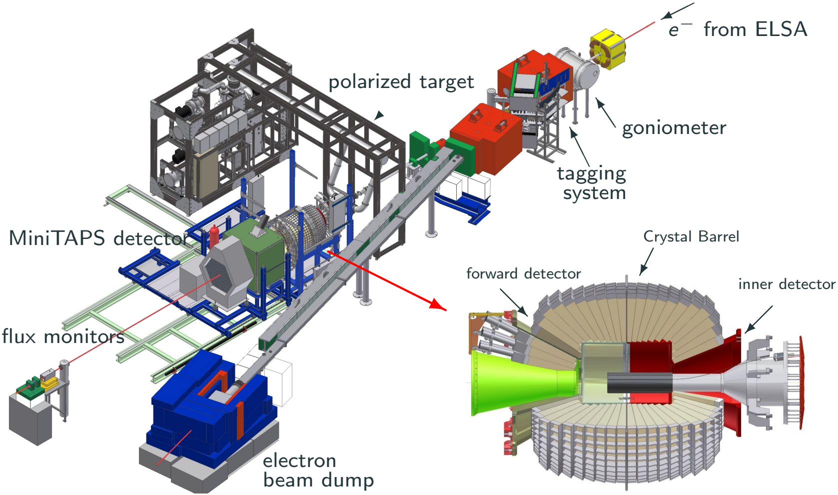
We do experiments with polarized photon beams and a polarized target.

Are we now close to a complete experiment?

- 8 "well-chosen" observables needed
  $\rightarrow$ this includes observables with recoil polarization
- Theoretical calculation by Chiang and Tabakin
  $\rightarrow$ assumption of full angular coverage and no error in the measurements

$\rightsquigarrow$ As many observables need to be measured as possible

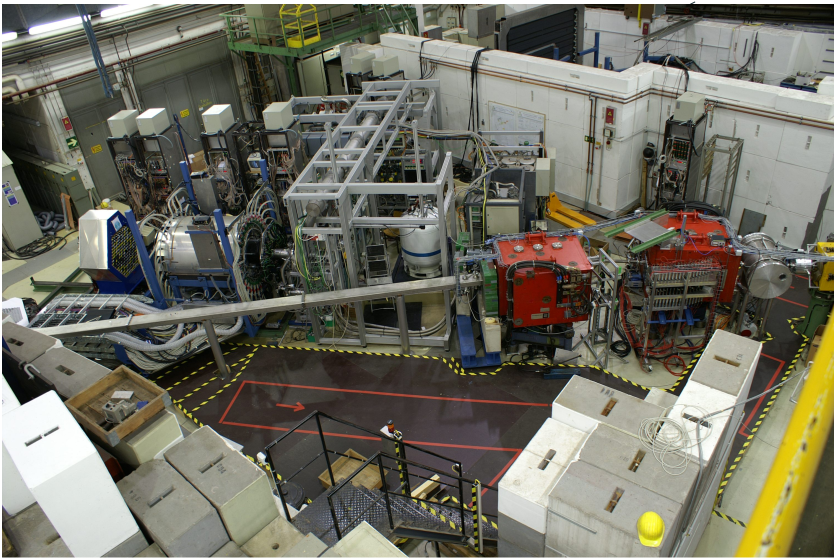
The Setup of the CBELSA/TAPS Experiment



$\rightarrow$ nearly full 4π angular coverage

Detector system ideally suited for the detection of neutral final states!

The Setup of the CBELSA/TAPS Experiment



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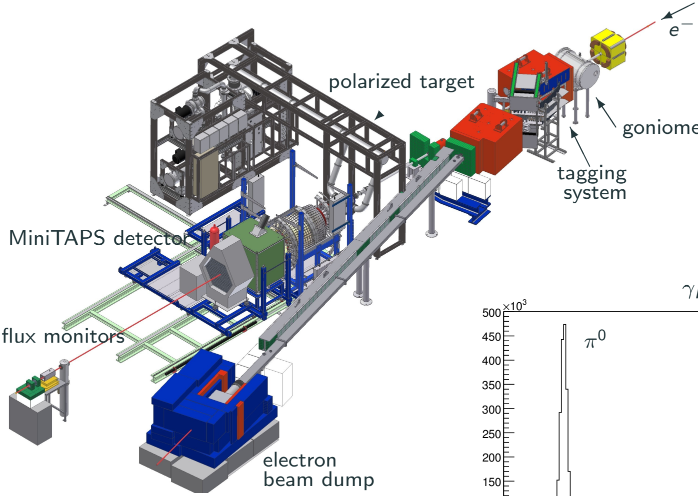

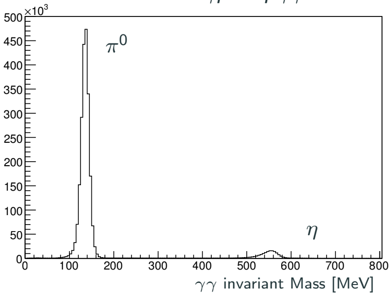

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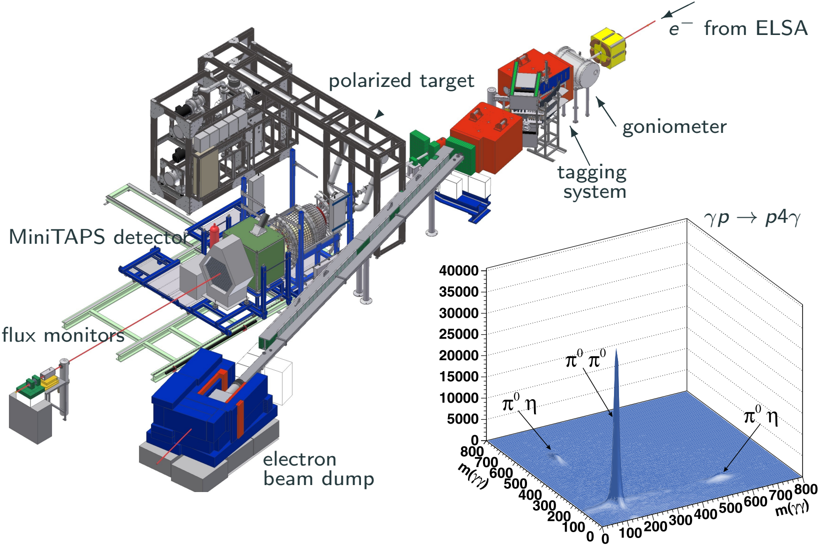
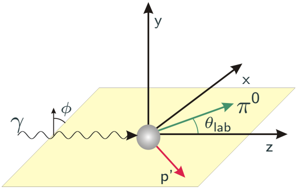


Extraction of the observables

Cross Section with Beam und Target Polarization



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

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

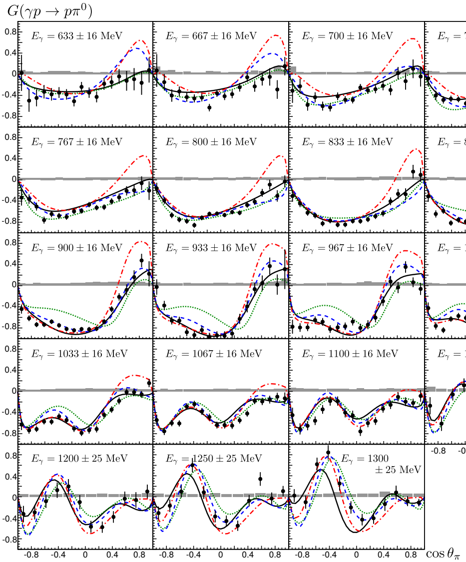
π^0-photoproduction:

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

η-photoproduction:

publication in preparation

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



Predictions to the data:

BnGa11-02

SAID (CM12)

MAID07

JüBo13-1

A.Thiel et al.,
PRL 109 (2012) 102001
Eur.Phys.J. A53 (2017) 1, 8

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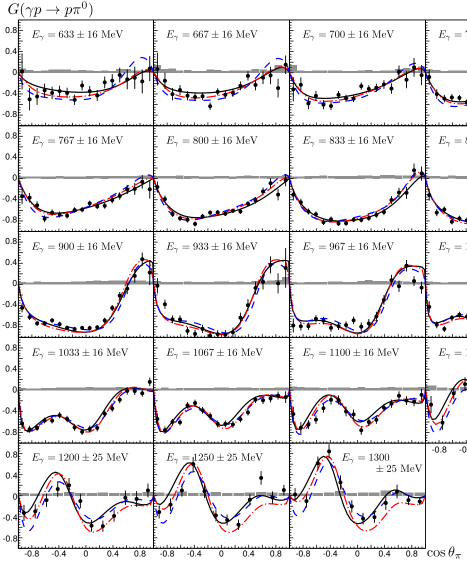


Fits to the data:

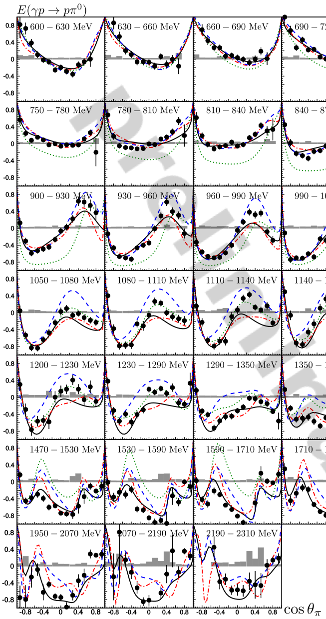
BnGa14-02

SAID

JüBo16-1

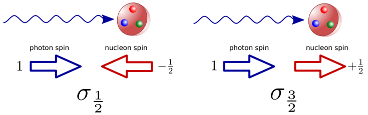
A.Thiel et al.,
PRL 109 (2012) 102001
Eur.Phys.J. A53 (2017) 1, 8

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



E is a helicity asymmetry:

Two spin configurations possible



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

Predictions to the data:

BnGa11-02

MAID07

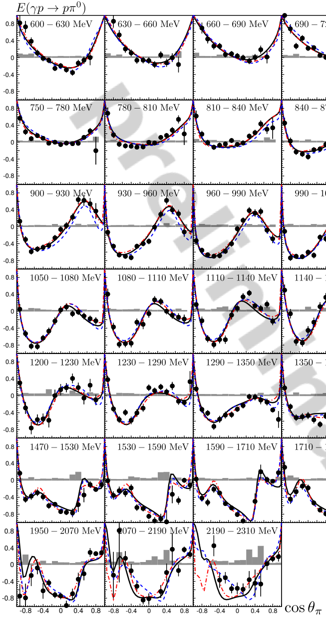
SAID CM12

JüBo15-B

M. Gottschall et al.,
Phys. Rev. Lett. 112, 012003 (2014)

to be submitted to EPJA

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



Fits to the data:

BnGa14-02
SAID 2015
JüBo16-1

M. Gottschall et al.,
Phys. Rev. Lett. 112, 012003 (2014)

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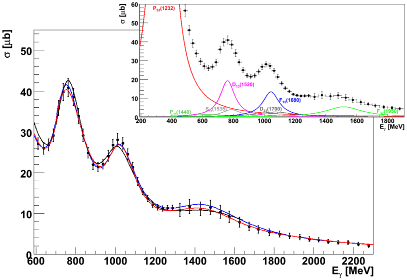
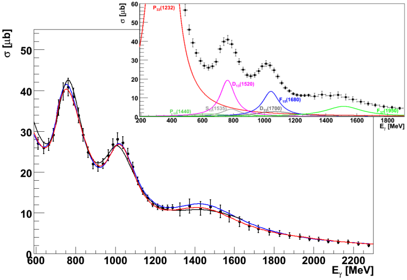


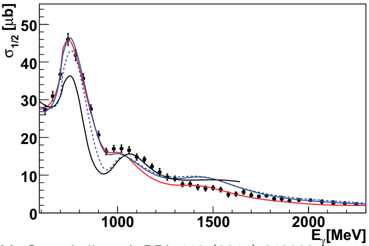
- Different models show good description of the cross section
- Spin dependent cross section can be extracted: $\sigma^{1/2(3/2)} = \sigma_0 \cdot (1 \pm E)$

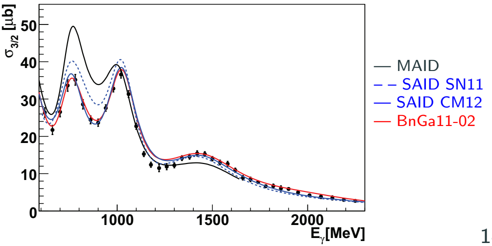
M. Gottschall et al. PRL 112 (2014) 012003

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



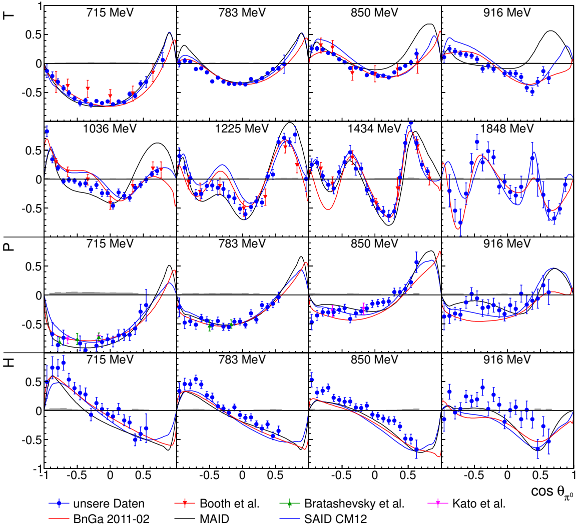
- Different models show good description of the cross section
- Spin dependent cross section can be extracted: $\sigma^{1/2(3/2)} = \sigma_0 \cdot (1 \pm E)$
- Large differences occur in $\sigma^{1/2}$ and $\sigma^{3/2}$ cross sections





M. Gottschall et al. PRL 112 (2014) 012003

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



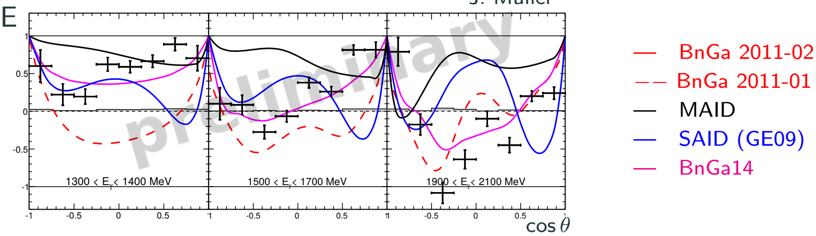
High quality data set with large angular coverage and wide energy range

Only selected bins shown here

J. Hartmann et al.,
PRL 113 (2014) 062001
Phys.Lett. B748 (2015) 212-220

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

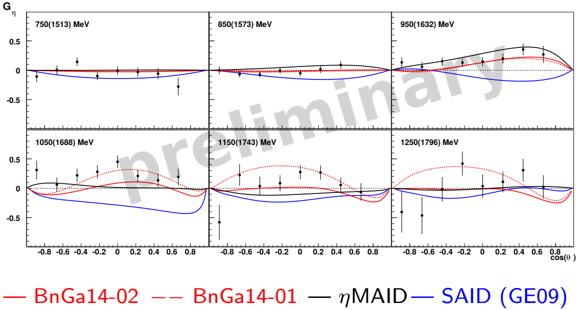
J. Müller



M. Grüner

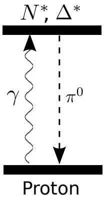
Same observables measured as for $\gamma p \to p\pi^0$!

Publication in preparation



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



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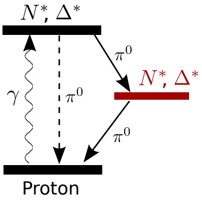

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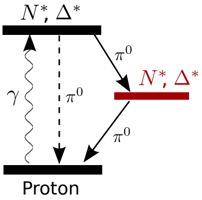
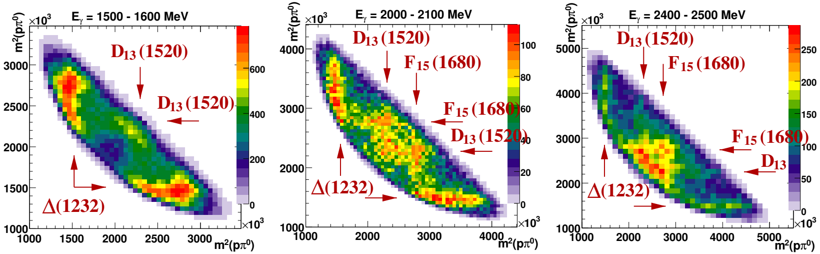


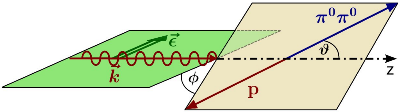


V. Sokhoyan et al., Eur.Phys.J. A51 (2015) no.8, 95

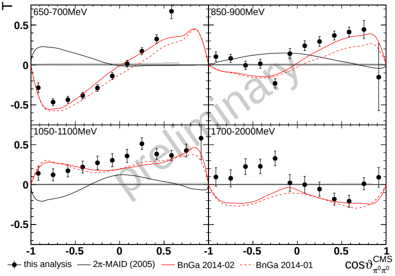
$\gamma p \rightarrow p\pi^0\pi^0$: Polarization Observables T, P, H

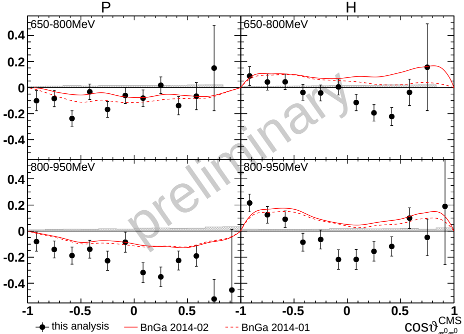
Here:

only results shown in quasi two-body kinematics



T. Seifen



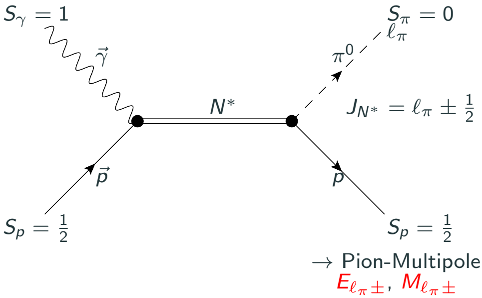


Observables also extracted for different kinematic variables

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

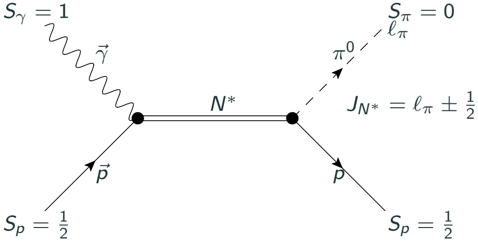
Interpretation

Multipole



Multipoles give informations about the intermediate states.

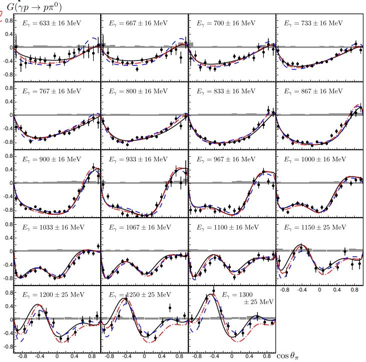
Multipole



Multipoles give informations about the intermediate states.

$\rightarrow$ Pion-Multipole

$E_{\ell_\pi \pm}$, M_ℓ



But how to extract information about the Multipoles from the polarization observables?

CGLN Amplitudes

Multipoles can be combined into CGLN amplitudes:

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

$$F_2(W,z) = \sum_{\ell=1}^{\infty}[(\ell+1)M_{\ell+} + \ell M_{\ell-}] \cdot P'_{\ell}(z)$$

$$F_3(W,z) = \sum_{\ell=1}^{\infty}[E_{\ell+} - M_{\ell+}] \cdot P''_{\ell+1}(z) + [E_{\ell-} + M_{\ell-}] \cdot P''_{\ell-1}(z)$$

$$F_4(W,z) = \sum_{\ell=1}^{\infty}[M_{\ell+} - E_{\ell+} - M_{\ell-} - E_{\ell-}] \cdot P''_{\ell}(z)$$

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

$\rightarrow$ Angular dependence separated into Legendre polynomials, multipoles just energy dependent

Polarization Observables

All observables can be expressed in CGLN amplitudes

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

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

Truncate Partial Wave Analysis

- CGLN amplitudes are sums over the angular momenta to infinity
- For example:

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

What is the role of M_{75+} or E_{143-}?

Truncate Partial Wave Analysis

- CGLN amplitudes are sums over the angular momenta to infinity
- For example:

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

What is the role of M_{75+} or E_{143-}?

- Higher order angular momenta play a suppressed role depending on the energy

→ Truncation of the sum over angular momenta at a certain level ℓ_{max}

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 ($L_{max} = 1$):

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

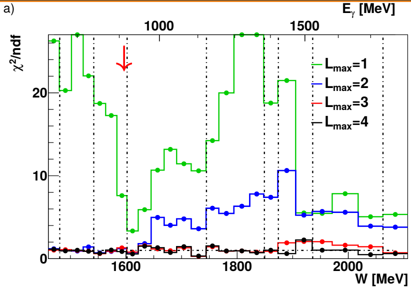
- using S-, P- and D-waves ($L_{max} = 2$):

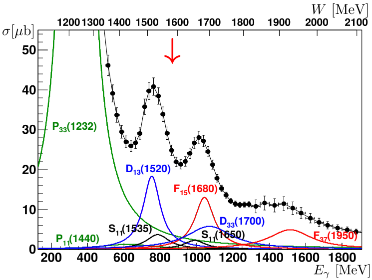
  $$\check{T} = \frac{q}{k} \sin\theta [A_0 + A_1 \cdot \cos\theta + A_2 \cdot \cos^2\theta + A_3 \cdot \cos^3\theta]$$

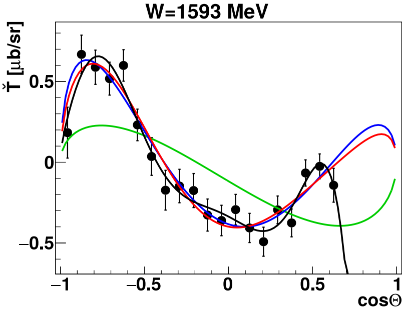
- using S-, P-, D- and F-waves ($L_{max} = 3$):

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

First Interpretation with a Truncated Partial Wave Analysis



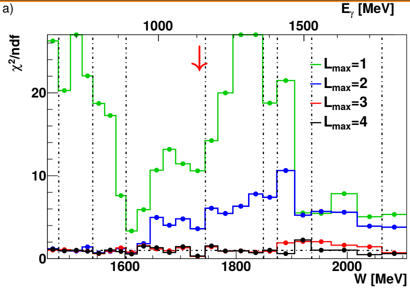


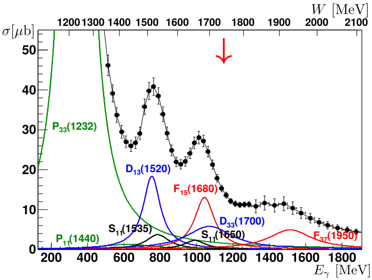


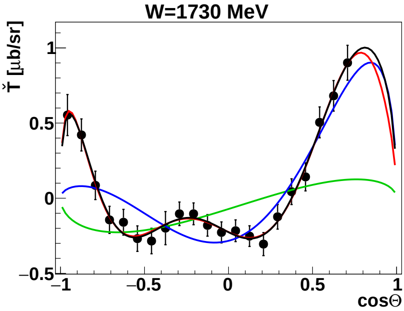
- Sensitivity to different angular momenta directy visible in the observables!
- Energies below $W \lesssim 1650$ MeV: $L = 2$ sufficient (up to D waves)
- $L = 3$ (F waves) strength visible for $W \gtrsim 1650$ MeV
- Above $W \gtrsim 1850$ MeV indication for $L = 4$ signal (G waves)

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

First Interpretation with a Truncated Partial Wave Analysis







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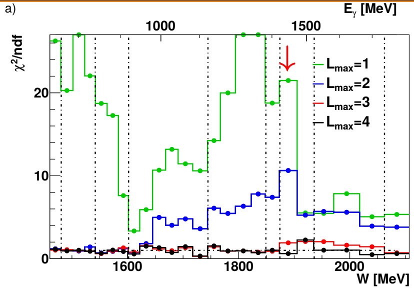

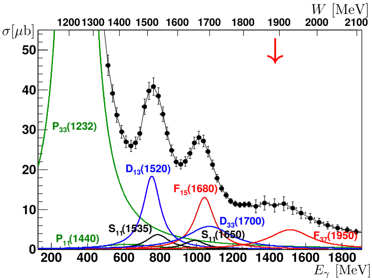

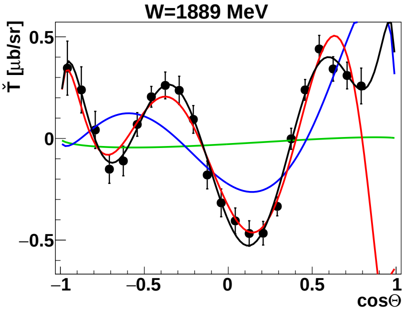

- Sensitivity to different angular momenta directy visible in the observables!
- Energies below $W \lesssim 1650$ MeV: $L = 2$ sufficient (up to D waves)
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Y. Wunderlich, F. Afzal, A. Thiel, R. Beck, Eur.Phys.J. A53 (2017) no.5, 86

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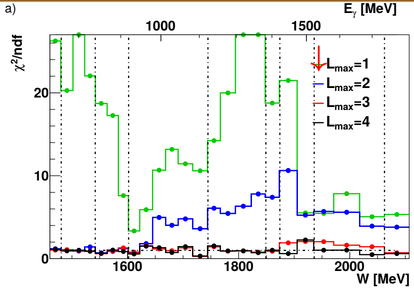

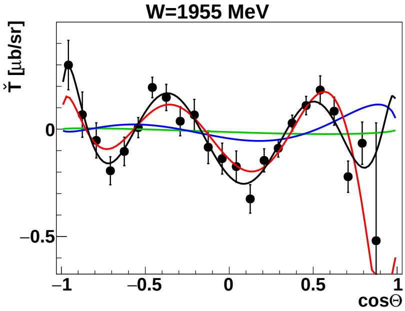

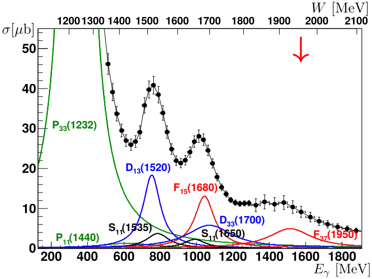

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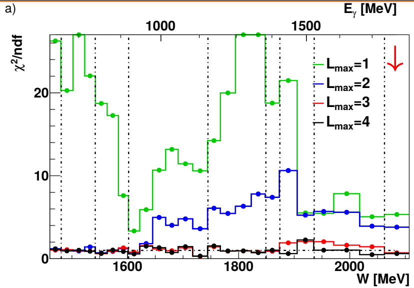

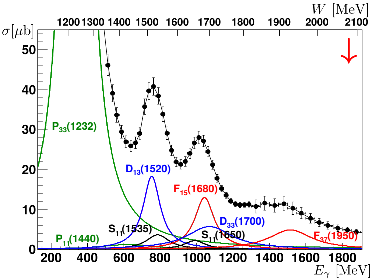

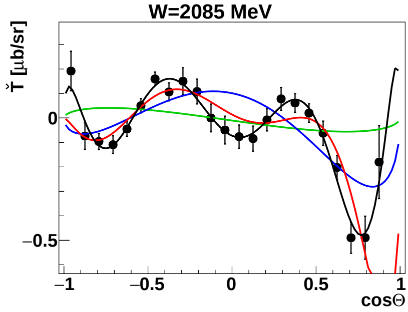

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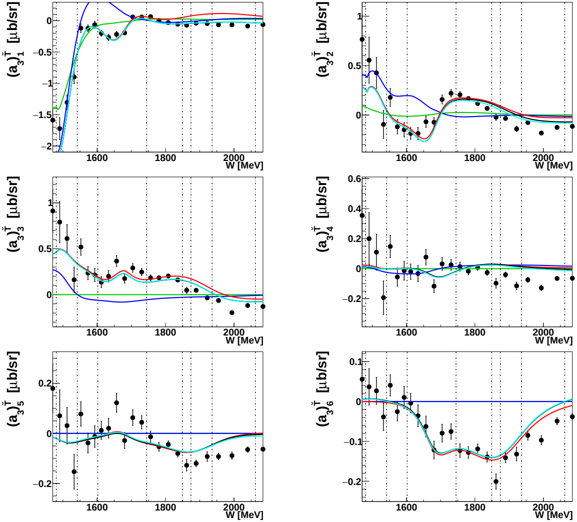
Interpretation of the Fit Parameters



- Fit parameters for $L_{max} = 3$

Predictions from BnGa PWA:

— L=1 — L=3
— L=2 — L=4

Fit parameters are linear combinations of different multipoles, can be compared to predictions by the BnGa PWA

Higher orders ($L > 2$) are needed to describe the fit parameters

Description not sufficient for the highest energies

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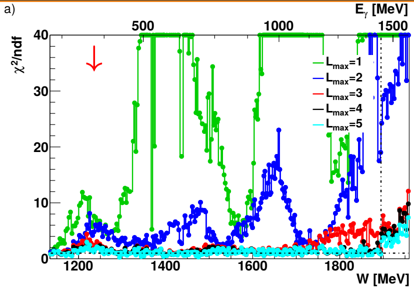
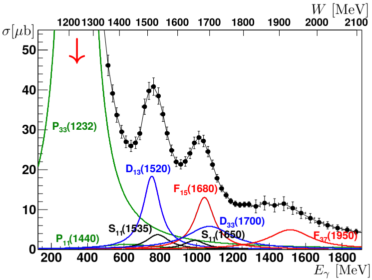
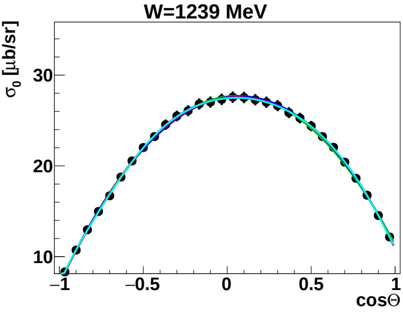
Truncated Partial Wave Analysis for High Statistics Data Set







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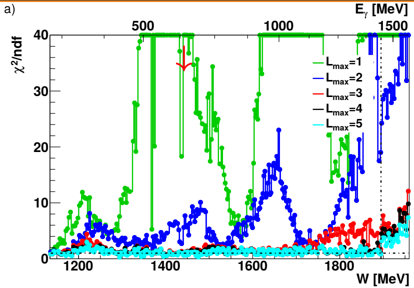

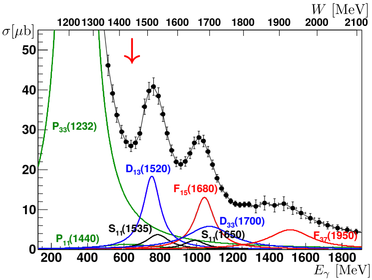

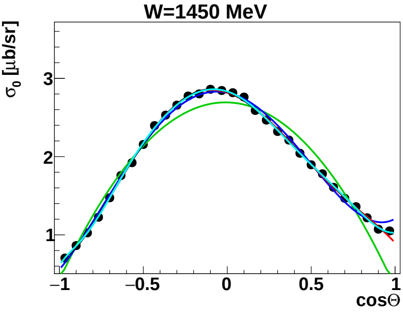

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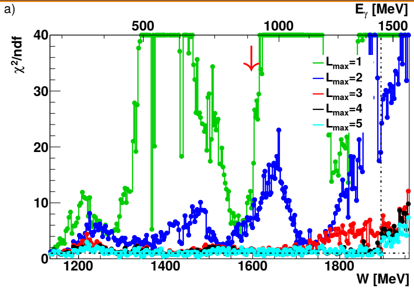

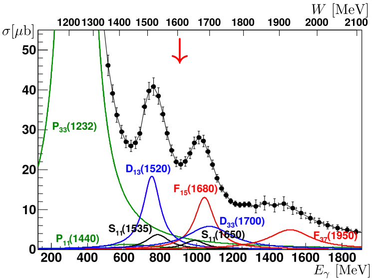

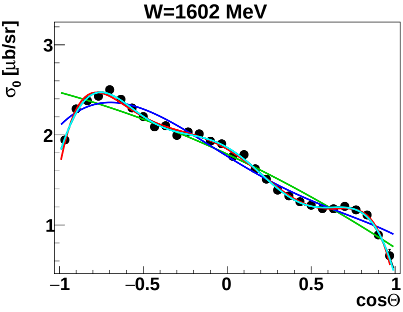

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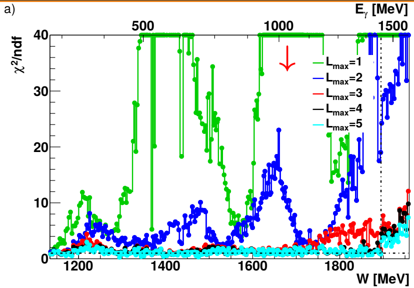

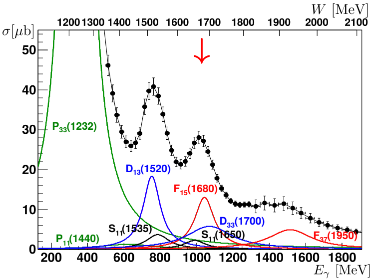

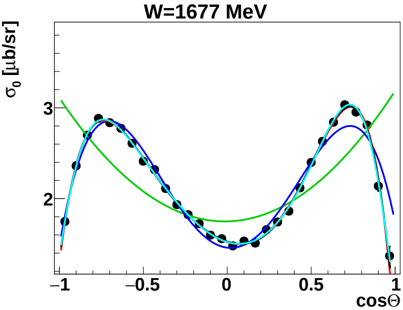

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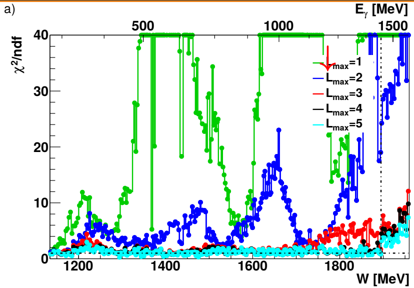

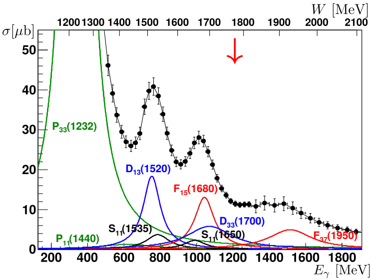

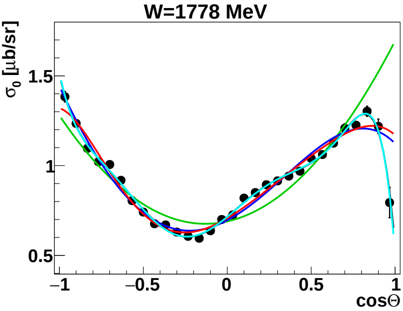

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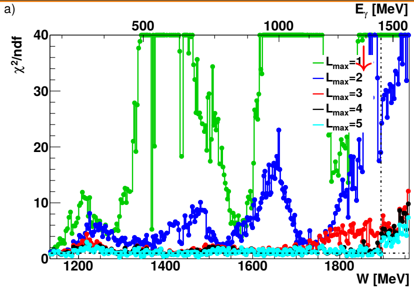

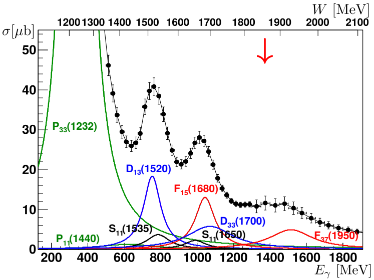

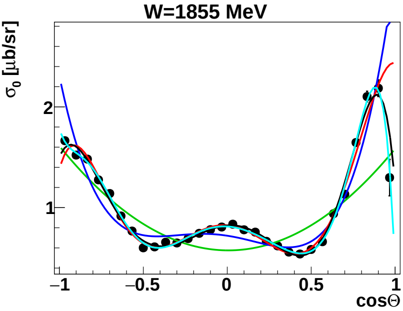

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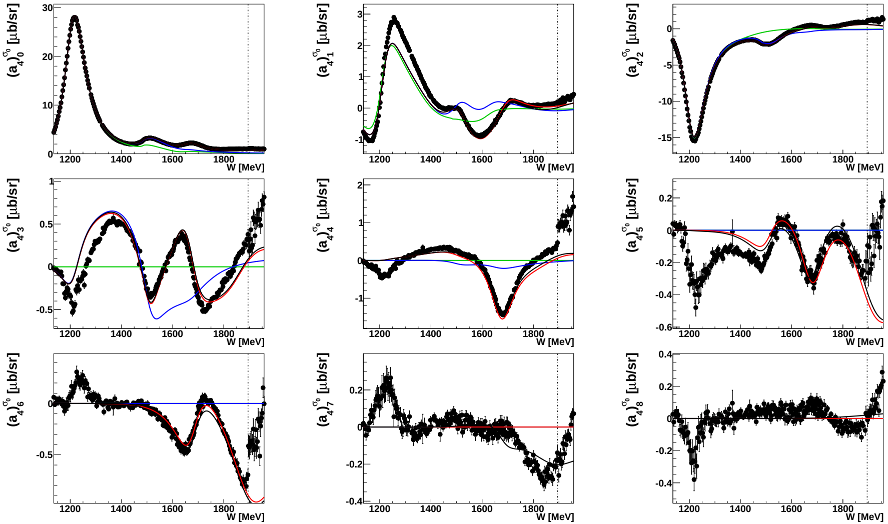

- Fit parameters for $L_{max} = 4$

Predictions from BnGa PWA:

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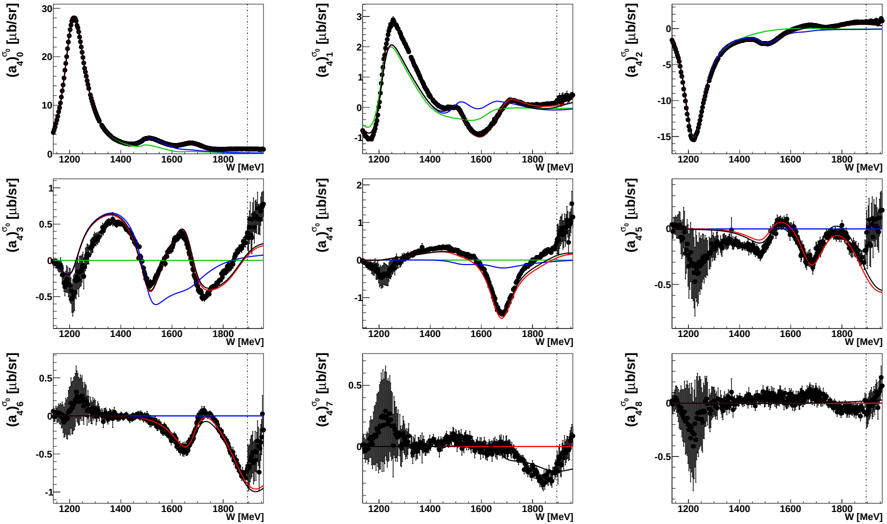
Interpretation of the Fit Parameters with Systematic Errors



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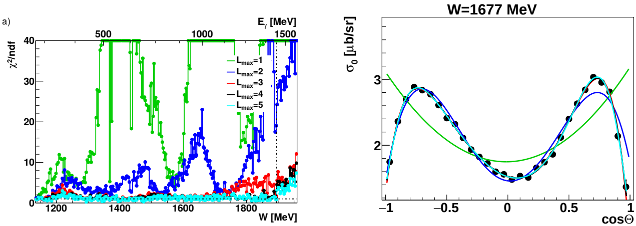
Summary of the Truncated Partial Wave Analysis

- What is the correct order of the fit? How to determine this?

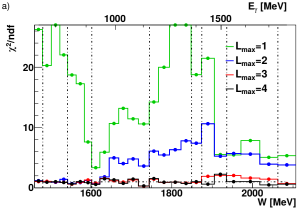
  See fits to the cross section:

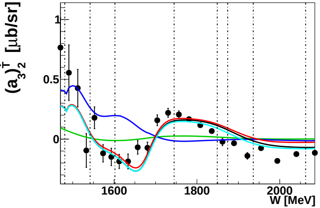


Summary of the Truncated Partial Wave Analysis

- What is the correct order of the fit? How to determine this?
- Influence of variing angular coverage and statistical errors non-trivial

See fits to T: variation of the angular coverage marked by vertical lines





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But:

- tPWA can give first insight into problems of the measured data
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- Exact interpretation of the contributing resonances difficult, but the sensitivity of the measured observables can be seen!

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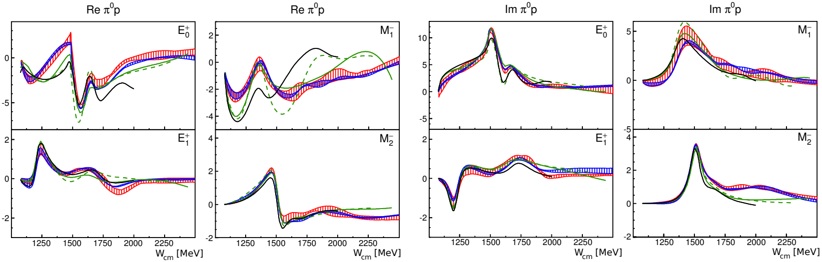
For a full interpretation:
include the data in a partial wave analysis!

Fit from BnGa to the π^0 Polarization Observables



J. Hartmann et al., Phys.Lett. B748 (2015) 212

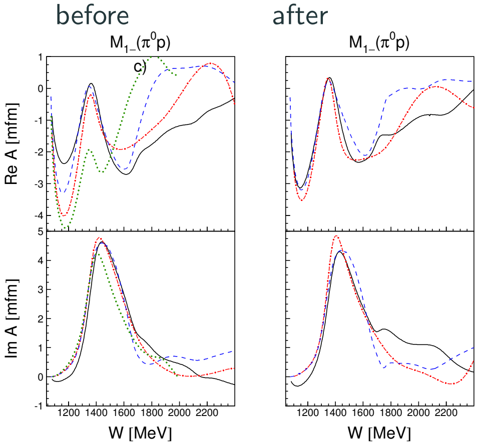
MAID, SAID CM12 (solid) SN11 (dashed), BnGa, BnGa with double pol. obs.

- Still large differences in the different PW analyses visible
- By using additional observables, the fit error bands get smaller

New Fits from different Analyses

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

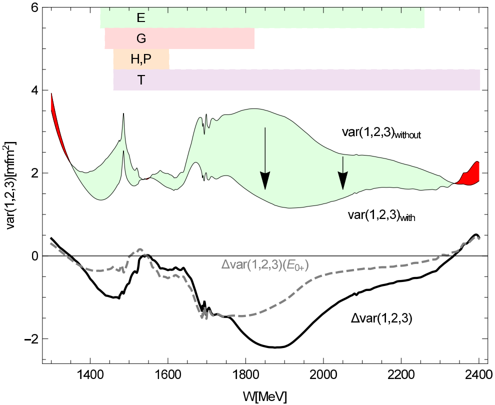
- BnGa (black)
- JüBo (red)
- SAID (blue)



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

New Fits from different Analyses

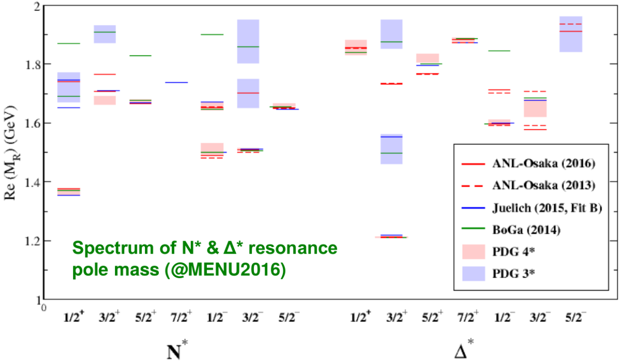
Variance between the different analyses decreases!



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

→ Including more polarization observables will converge all analyses to the same solution

Partial Wave Analyses



H. Kamano at the NSTAR 2017 conference

By having similar multipoles:

The resulting resonances should agree and hopefully new resonances can be found!

More and precise measurements can pave the way to futher discoveries.

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 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
- 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

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Thank you
for your attention.

Supported by the
DFG