Light Baryon Spectroscopy

Annika Thiel

19th International Conference on Hadron Spectroscopy and Structure

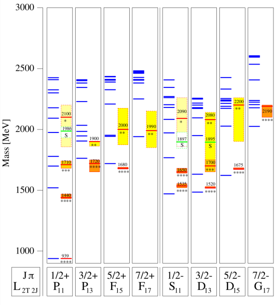
27/07/2021

Helmholtz-Institut für Strahlen- und Kernphysik, University of Bonn, Germany
and
School of Physics and Astronomy, University of Glasgow, Scotland

Motivation

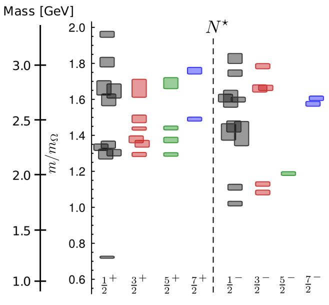
Theoretical Predictions

Quark Model



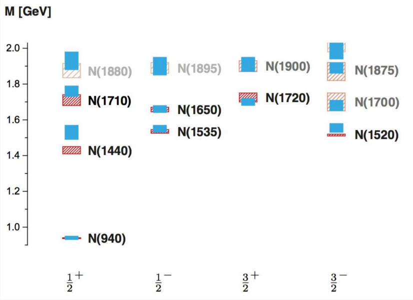
[U. Loering, et al., Eur.Phys.J.A10:395 (2001)]

Lattice QCD Calculations



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

Dyson–Schwinger/Bethe–Salpeter approach



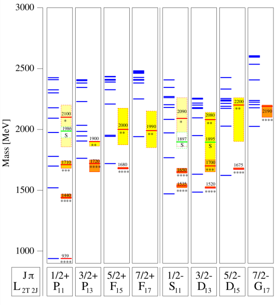
[Eichmann, Fischer, Few Body Syst. 60 (2019) 1,2]

Discrepancies between measurement and calculations:

"missing resonances" and level ordering

Theoretical Predictions

Quark Model



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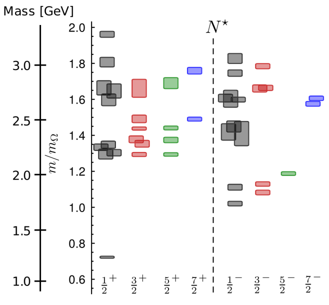

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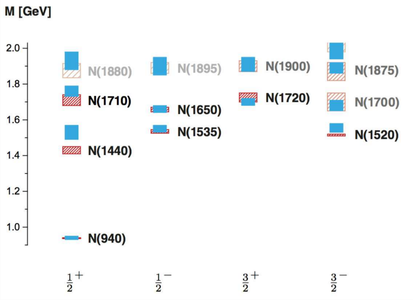

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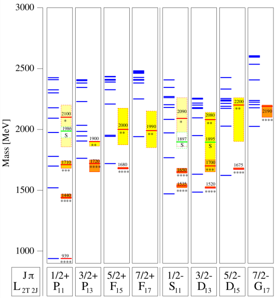
→ What are the relevant degrees of freedom?

Theoretical Predictions

Quark Model



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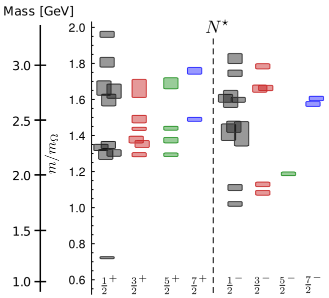

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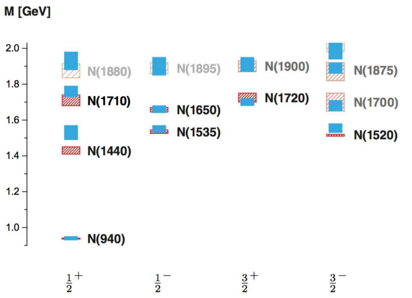

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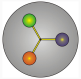
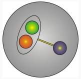
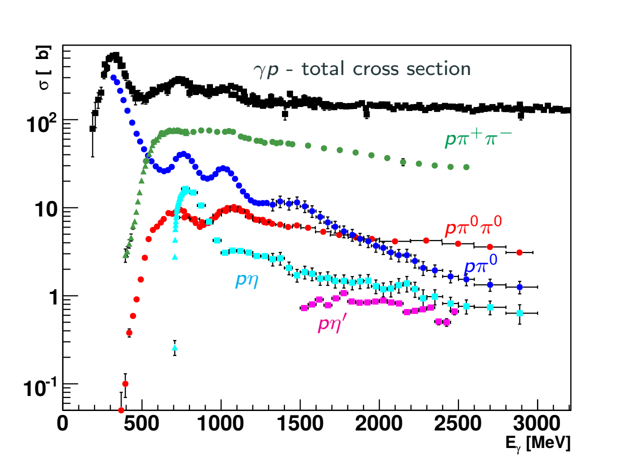




Most resonances observed in πN scattering:

→ Experimental bias?

Resonances

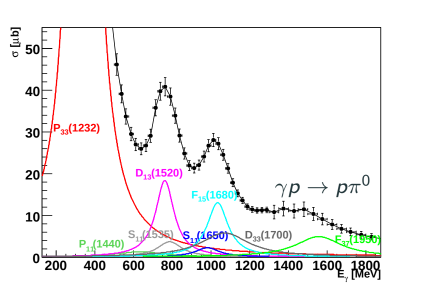


Total cross section sensitive to dominant resonance contributions:

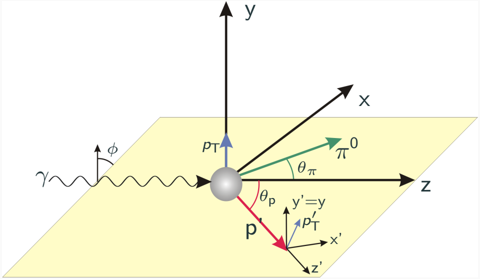
$\sigma \sim |E_{0+}|^2 + |E_{1+}|^2 + |M_{1+}|^2 + |M_{1-}|^2 + \dots$

Huge experimental effort from different experiments:

Measurement of a wide range of final states



Polarization Observables in photoproduction of pseudoscalar meson



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	-$C_{x'}$	–	-$C_{z'}$	–	–	–	–

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]

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Extraction of the amplitudes without model dependence

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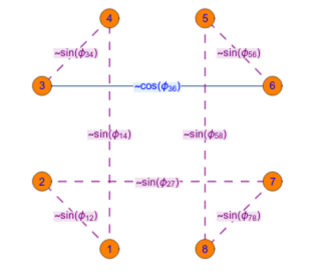
Extraction of complete sets using graph theory:



Electroproduction: 13 Observables

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

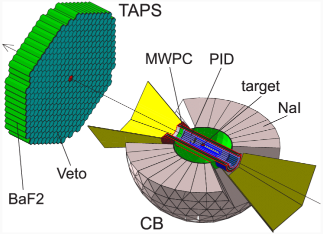
Two meson photoproduction: 16 Observables

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

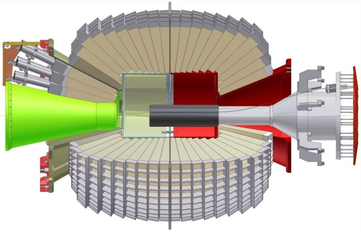
See presentations by Y. Wunderlich and P. Kroenert on Wednesday at 9:00h and 9:25!

Examples of Important Experiments in the Last Years

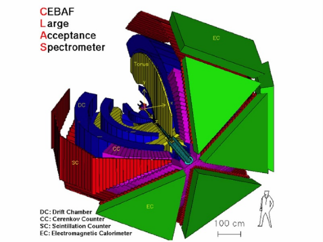
A2 experiment at MAMI
Mainz, Germany



CBELSA/TAPS experiment
Bonn, Germany



CLAS experiment at JLAB
Newport News, US



Common features:

- Good angular coverage of detector systems
- Polarized photons and polarized targets

Important differences:

- Different sensitivities (for charged or neutral particles)
- Different photon energies

$\rightarrow$ Different physical foci

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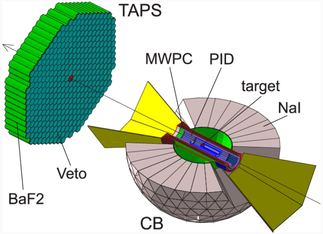

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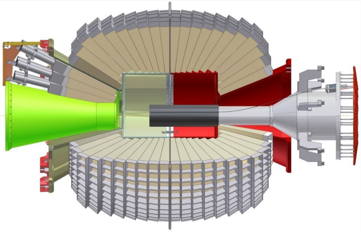

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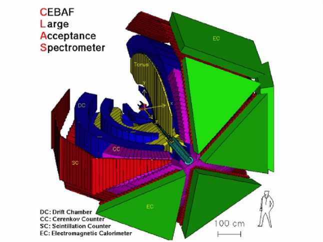
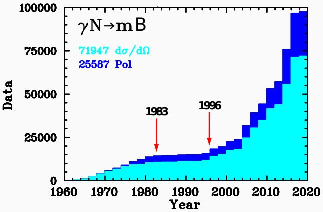




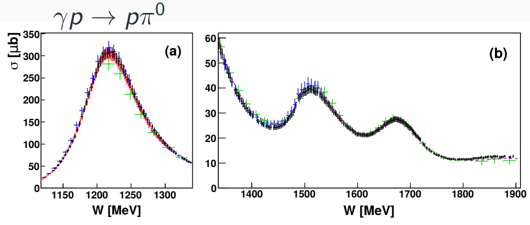
Large data set collected in the last years

Increasing effort also for polarized data

[D. Ireland et al., Prog.Part.Nucl.Phys. 111 (2020) 103752]

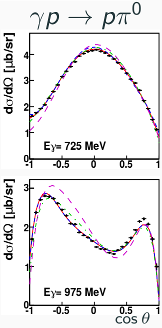
Measurement of Observables

Cross Section Measurements at A2



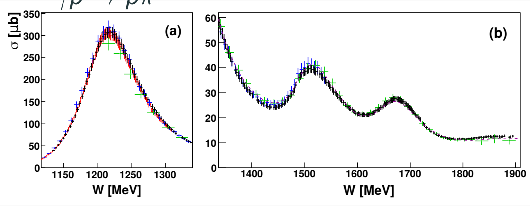
High statistics measurements of the total and differential cross section

[P. Adlarson et al. Phys. Rev. C **92**, no. 2, 024617 (2015)]



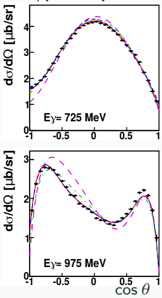
Cross Section Measurements at A2

$\gamma p \to p\pi^0$

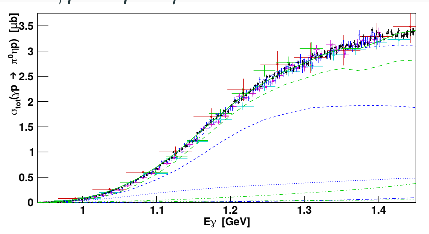


For single and multi-meson final states!

$\gamma p \to p\pi^0$



$\gamma p \to p\pi^0\eta$



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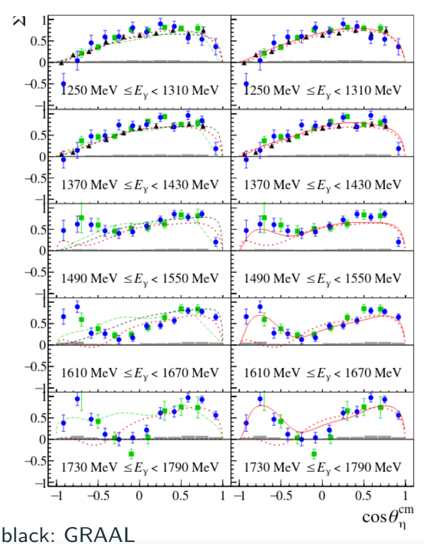
[V. Sokhoyan et al., Phys. Rev. C **97**, no. 5, 055212 (2018)]

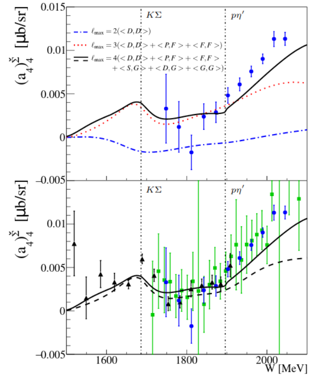
Cusp Effect visible in η Photoproduction by CBELSA/TAPS



black: GRAAL
green: CLAS   blue: CBELSA/TAPS

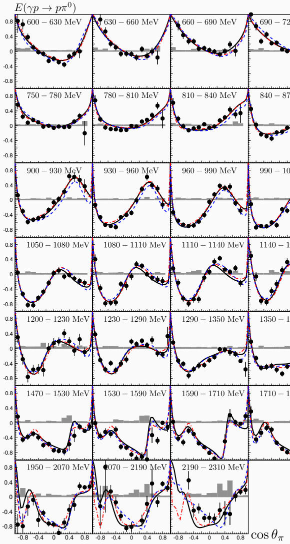
High precision measurement of the Beam Asymmetry with high angular coverage

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



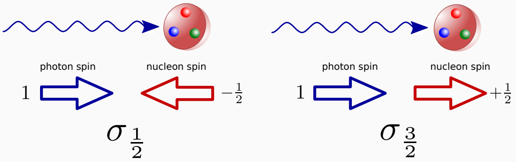
[F. Afzal et al, Phys.Rev.Lett. 125 (2020) 15, 152002]

Double Polarization Observable E ($\gamma p \to p\pi^0$): CBELSA/TAPS



E is a helicity asymmetry:

Two spin configurations possible



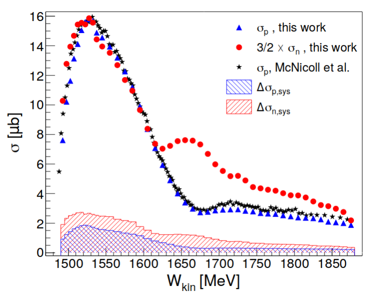
$$E(\theta, E_\gamma) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

Fits to the data:

- BnGa14-02
- SAID 2015
- JüBo16-1

[M. Gottschall et al.,
Phys. Rev. Lett. 112, 012003 (2014)
Eur. Phys. J. A 57.1 (2021), p. 40]

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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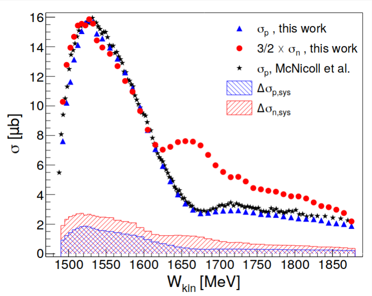

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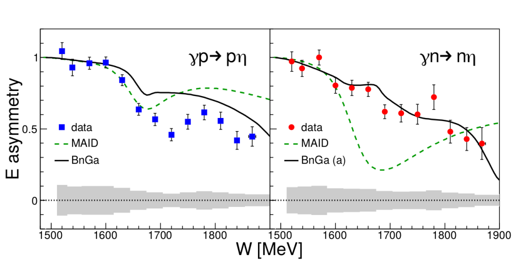

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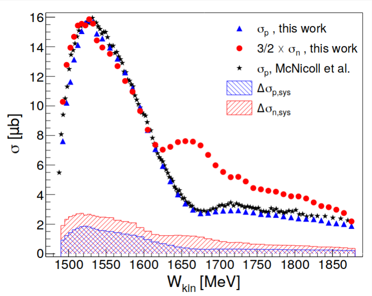

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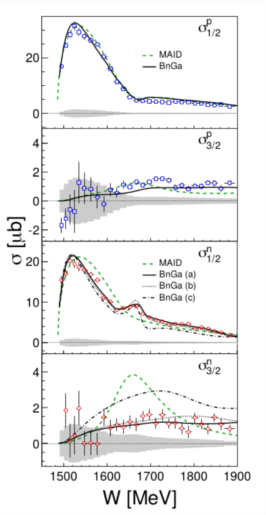

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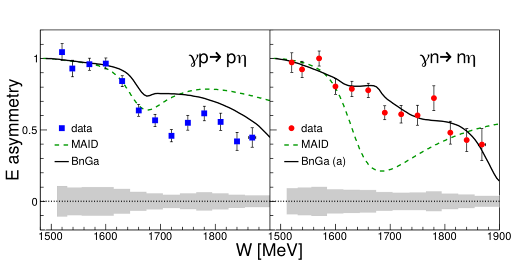
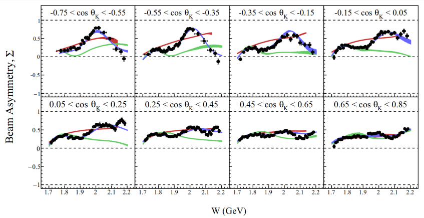
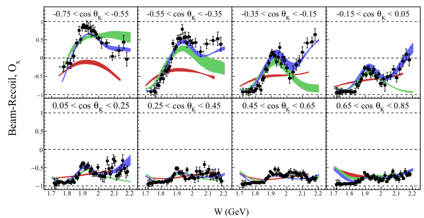


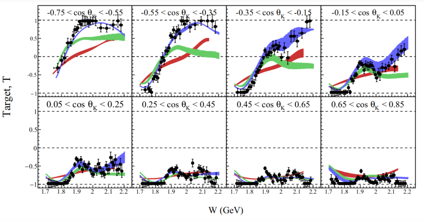
Strangeness Production with CLAS: $\gamma p \to K\Lambda$

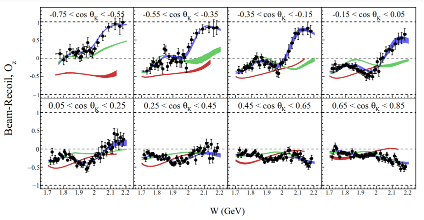
Strangeness production self analyzing,
allows the extraction of observables with recoil polarization

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \{1 - P^\gamma \Sigma \cos 2\phi + \alpha \cos\theta_x P^\gamma O_x \sin 2\phi$$
$$+ \alpha \cos\theta_y P - \alpha \cos\theta_y P^\gamma T \cos 2\phi$$
$$+ \alpha \cos\theta_z P^\gamma O_z \sin 2\phi\}.$$







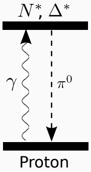


red: ANL-Osaka
green: BnGa14
blue: BnGa refit

[C. A. Paterson et al., Phys. Rev. C 93, 065201 (2016)]

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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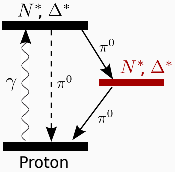

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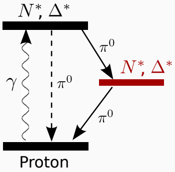
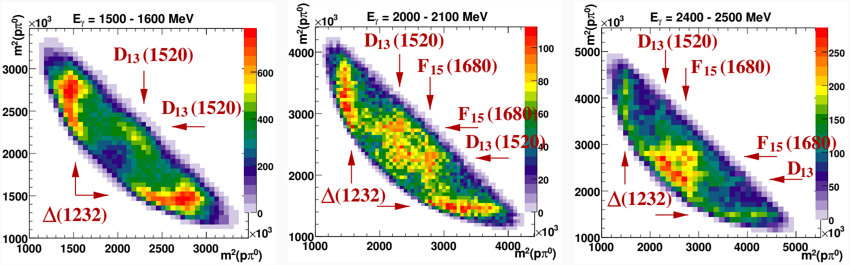


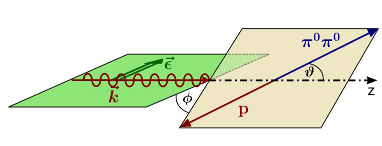


[V. Sokhoyan et al., Eur.Phys.J. A51 (2015) no.8, 95]
[A. Thiel et al., Phys.Rev.Lett. 114 (2015) no.9, 091803]

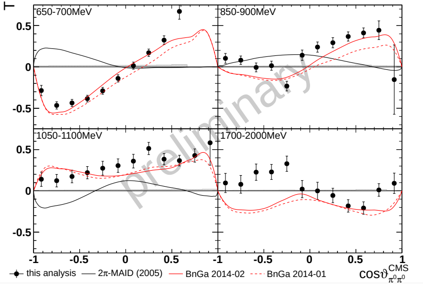
Polarization Observables T, P, H ($\gamma p \to p\pi^0\pi^0$): CBELSA/TAPS

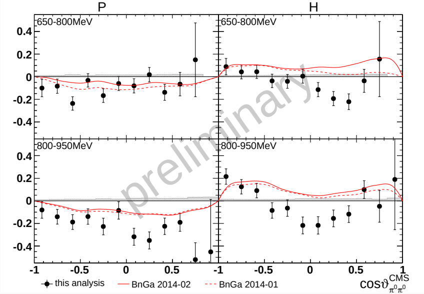
Here:

only results shown in quasi two-body kinematics



T. Seifen



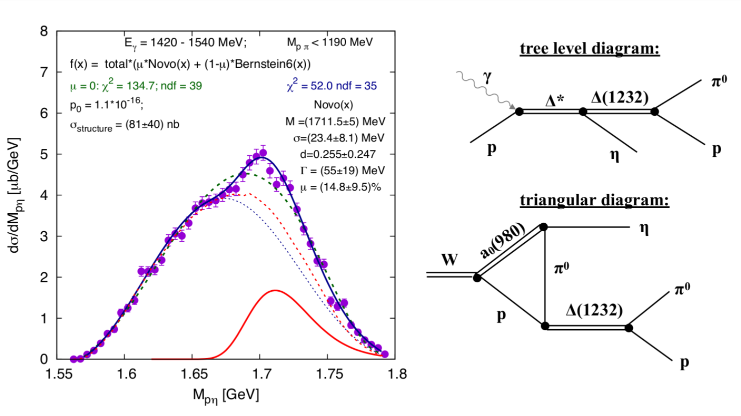


Observables also extracted for different kinematic variables

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

Talk by T. Seifen on Wednesday at 07:45h!

First Indication of Triangle Singularities in $\gamma p \to p\pi^0\eta$ by CBELSA/TAPS



Structure observed in the $p\eta$ invariant mass

Triangle singularity can describe this structure

First observation of a triangle singularity in baryon spectroscopy?

See presentation by M. Nanova on Wednesday at 09:50!

Interpretation

Multipoles and CGLN Amplitudes

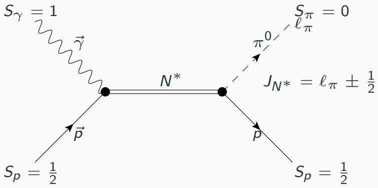
Multipoles give informations about the intermediate states, can be combined into four CGLN amplitudes:

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

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

$$\dots$$

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



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

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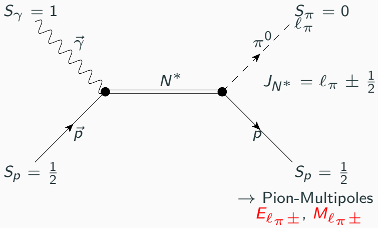

$$F_1(W,z) = \sum_{\ell=0}^{\infty} [\ell M_{\ell+} + E_{\ell+}] \cdot P'_{\ell+1}(z) + [(\ell+1)M_{\ell-} + E_{\ell-}] \cdot P'_{\ell-1}(z)$$

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

$$\dots$$

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

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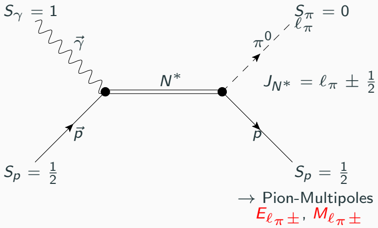

$$F_1(W,z) = \sum_{\ell=0}^{\ell_{max}} [\ell M_{\ell+} + E_{\ell+}] \cdot P'_{\ell+1}(z) + [(\ell+1)M_{\ell-} + E_{\ell-}] \cdot P'_{\ell-1}(z)$$

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

...

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 ($L_{max} = 1$):

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

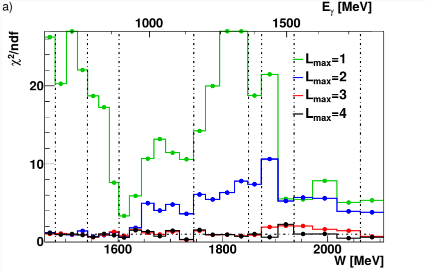
- using S-, P- and D-waves ($L_{max} = 2$):

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

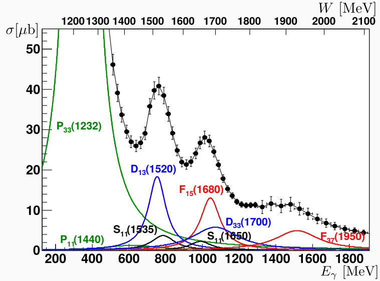
- using S-, P-, D- and F-waves ($L_{max} = 3$):

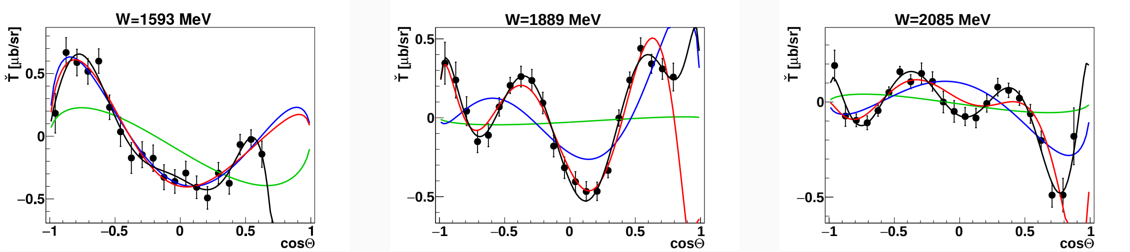
$$\check{T} = \frac{q}{k} \sin\theta [A_0 + A_1 \cdot \cos\theta + A_2 \cdot \cos^2\theta + A_3 \cdot \cos^3\theta$$
$$+ A_4 \cdot \cos^4\theta + A_5 \cdot \cos^5\theta]$$

First Interpretation with a Truncated Partial Wave Analysis



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]

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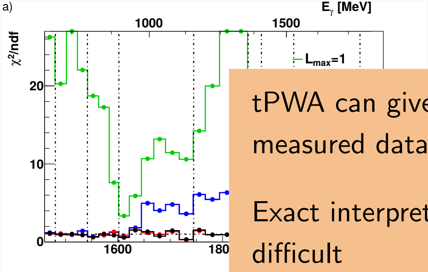
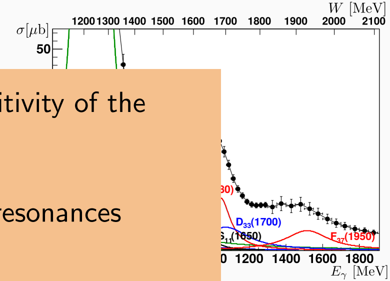
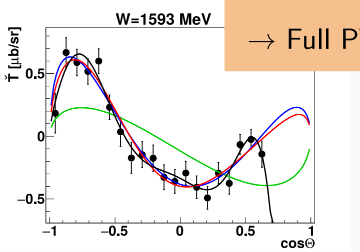
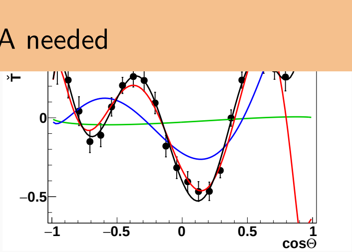
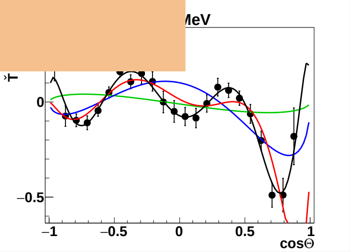


Fits with different









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

Exact interpretation of the contributing resonances difficult

$\rightarrow$ Full PWA needed

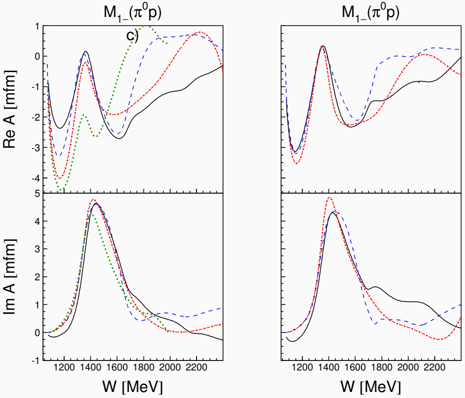
[Y. Wunderlich, F. Afzal, A. Thiel, R. Beck, Eur.Phys.J. A53 (2017) no.5, 86]

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)

before after



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

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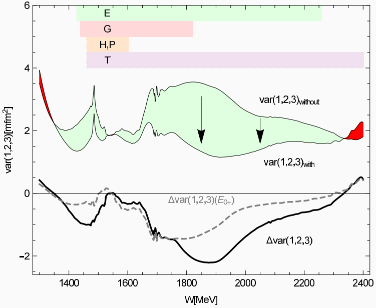
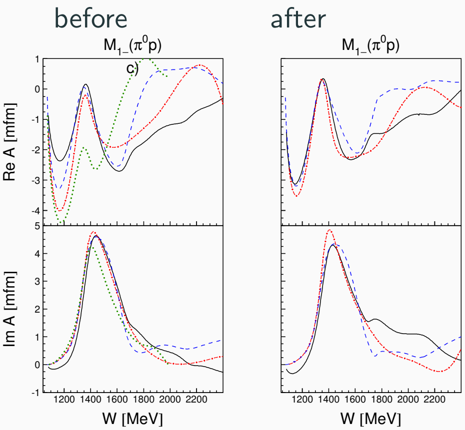
Variance between the different analyses decreases!





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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

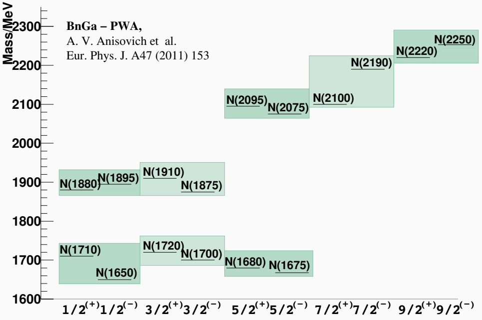
Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***	-			-		
$N(1520)$	$3/2^-$	****	****	****	****	**	****			- - - -		
$N(1535)$	$1/2^-$	****	****	****	***	*	****			- -		
$N(1650)$	$1/2^-$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

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

Still Many Open Questions...

- Do parity doublets exist? Is chiral symmetry restored at high energies? Do they exist for all high mass states?

  Not predicted by the current lattice QCD calculations nor by constituent quark models.



Search for Parity Doublets

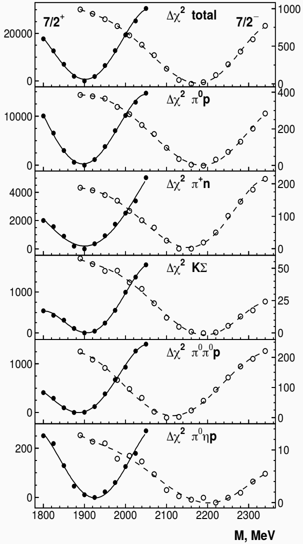
Parity Doublets at high masses:

$\Delta(1910)1/2^+$	$\Delta(1920)3/2^+$	$\Delta(1905)5/2^+$	$\Delta(1950)7/2^+$
$\Delta(1900)1/2^-$	$\Delta(1940)3/2^-$	$\Delta(1930)5/2^-$	?

Partner of the $\Delta(1950)7/2^+$ seems to be missing

Search in different final states revealed state with $7/2^-$ at much higher masses (2200 MeV)

$\rightarrow$ No parity partner found



[A. Anisovich et al., Phys.Lett. B766 (2017) 357-361]

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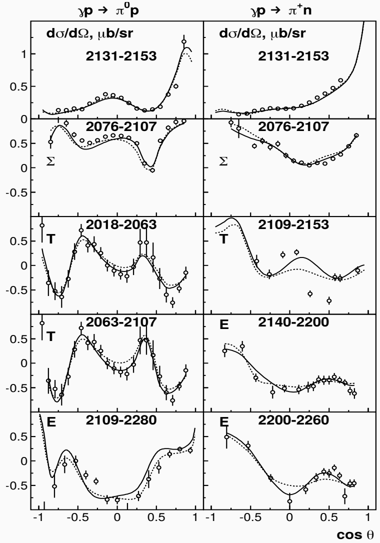
Fit with and without $\Delta(2200)7/2^-$ reveals high sensitivity of the data sets

Further identification of weak resonance contributions possible!



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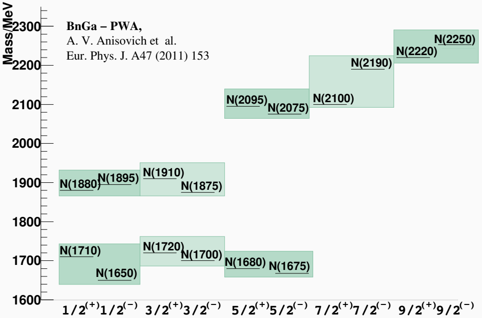

- Is it possible to do a complete experiment? How many observables and which precision is needed?

Measurement of Multiple Observables

Recently: Correction of the decay parameter α by BESIII [M. Ablikim et al., Nature Phys.15, 631 (2019)]

Parameter has a substantial influence on the polarization observable for Λ production

Fierz identities of the measured (double) polarization observables

$$O_x^2 + O_z^2 + C_x^2 + C_z^2 + \Sigma^2 - T^2 + P^2 = 1$$
$$\Sigma P - C_x O_z + C_z O_x - T = 0$$

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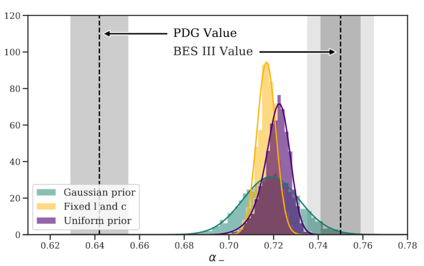

Measured (double) polarization observables for $\gamma p \to K\Lambda$ can be used to give an additional view on the value the decay parameter

[D. Ireland et al., Phys.Rev.Lett. 123 (2019) no.18, 182301]

Summary

Conclusion and Outlook

- New era of experiments allows precise measurements of (polarization) observables for various reactions

- 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

$\rightarrow$ **Baryon Spectroscopy has reached the high precision area!**

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Thank you for your attention.