Completing the Nucleon Spectrum

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Strong QCD from Hadron Structure Experiments Workshop, JLab

11/09/2019

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and
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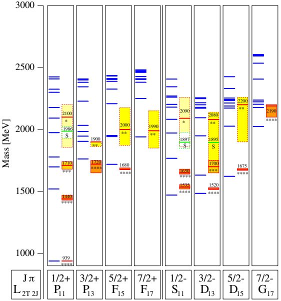
Motivation

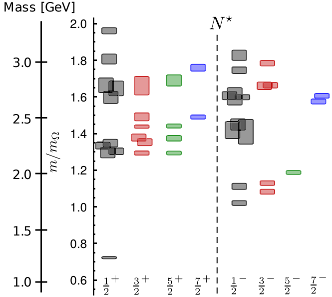
Theoretical Predictions

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

Discrepancies between measurement and calculations: "missing resonances"

Theoretical Predictions

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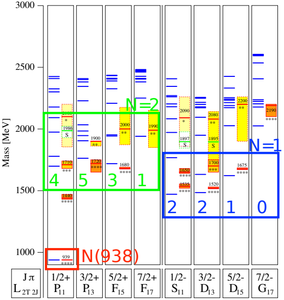

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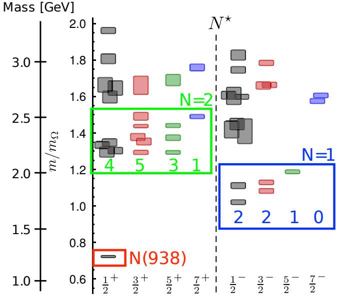

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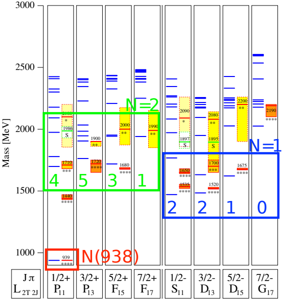

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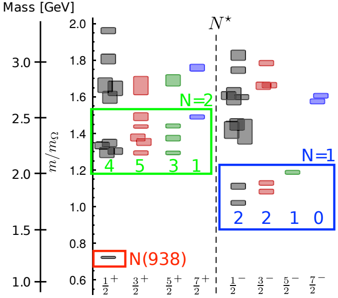
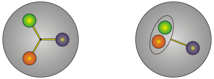


R. Edwards et al., Phys.Rev.D 84 (2011) 07450

Discrepancies between measurement and calculations: "missing resonances"

→ What are the relevant degrees of freedom?



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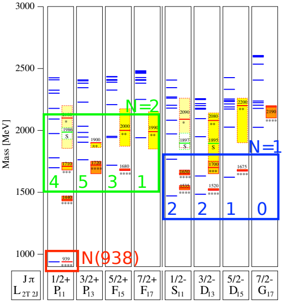

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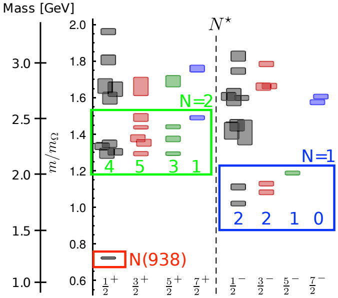
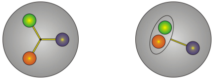


R. Edwards et al., Phys.Rev.D 84 (2011) 07450

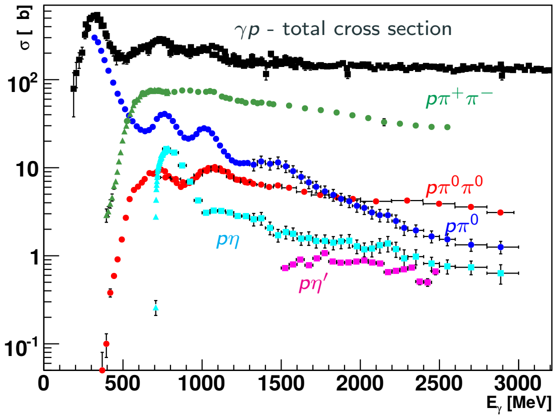
Discrepancies between measurement and calculations: "missing resonances"

→ What are the relevant degrees of freedom?

Most resonances observed in πN scattering:
→ experimental bias?

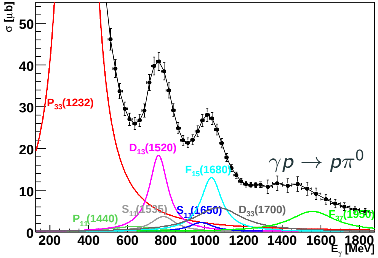


Resonances



Huge experimental effort from different experiments:

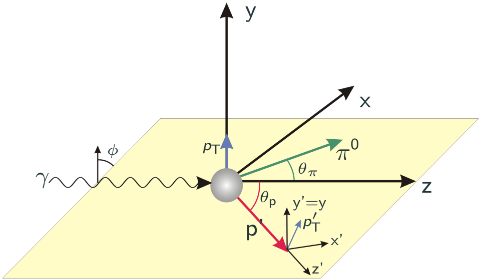
Measurement of a wide range of final states



Total cross section sensitive to dominant resonance contributions:

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

Polarization Observables in photoproduction of pseudoscalar meson



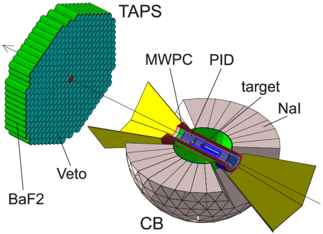
Polarization Observables are a tool to access weak resonance contributions, sensitive to interference terms:

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

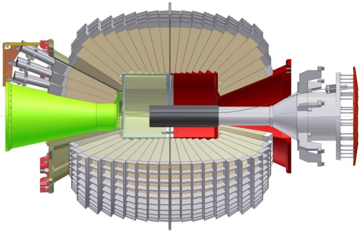
		Target			Recoil			Target+Recoil			
		–	–	–	x'	y'	z'	x'	x'	z'	z'
Photon		x	y	z	–	–	–	x	z	x	z
unpolarized	σ	–	T	–	–	P	–	$T_{x'}$	-$L_{x'}$	$T_{z'}$	$L_{z'}$
linearly pol.	Σ	H	(-P)	-G	$O_{x'}$	(-T)	$O_{z'}$	–	–	–	–
circularly pol.	–	F	–	-E	-$C_{x'}$	–	-$C_{z'}$	–	–	–	–

Examples of Important Experiments in the Last Years

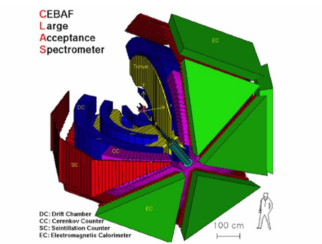
A2 experiment at MAMI
Mainz, Germany



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

→ Different physical focus

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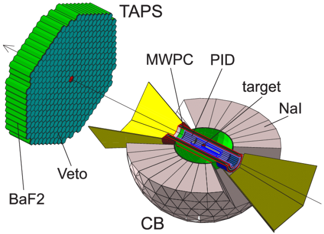

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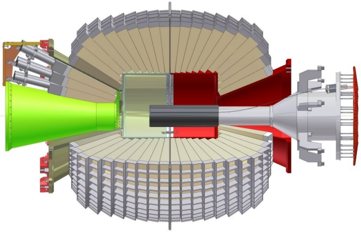

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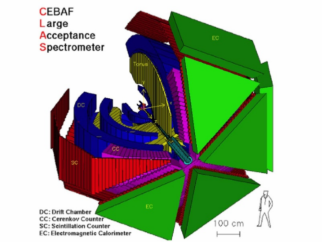
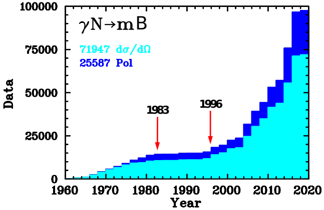




Large data set collected in the last years

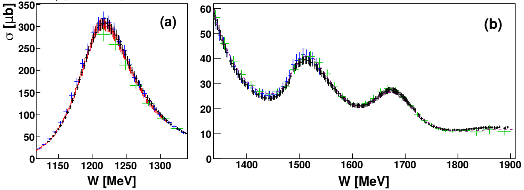
Increasing effort also for polarized data

D. Ireland et al., arXiv:1906.04228

Measurement of Observables

Cross Section Measurements at A2

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



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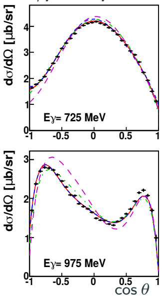

High statistics measurements of the total and differential cross section

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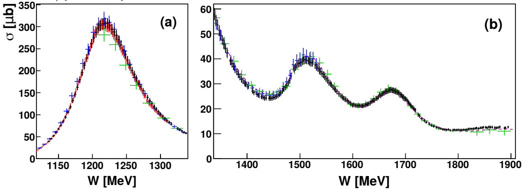
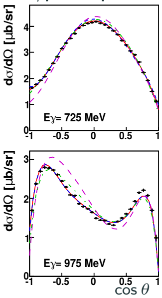
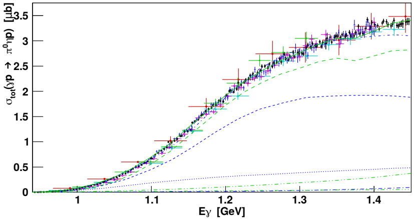


For single and multi-meson final states!

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



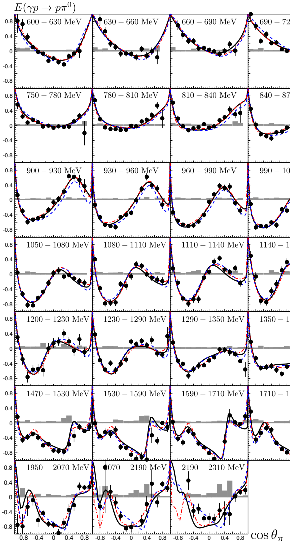
$\gamma p \to p\pi^0\eta$



High statistics measurements of the total and differential cross section

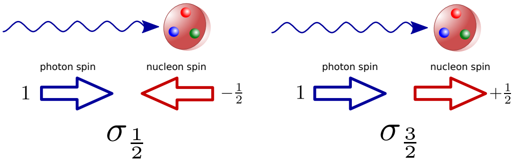
P. Adlarson et al. Phys. Rev. C **92**, no. 2, 024617 (2015)
V. Sokhoyan et al., Phys. Rev. C **97**, no. 5, 055212 (2018)

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



E is a helicity asymmetry:

Two spin configurations possible



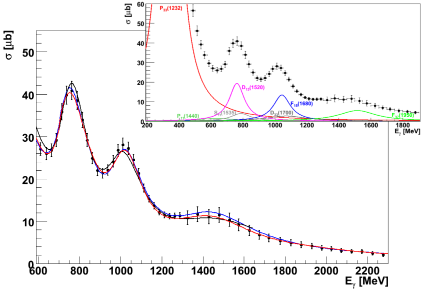
$$E(\theta, E_\gamma) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

Fits to the data:

- BnGa14-02
- SAID 2015
- JüBo16-1

M. Gottschall et al.,
Phys. Rev. Lett. 112, 012003 (2014)
arXiv:1904.12560 [nucl-ex],
submitted to EPJA

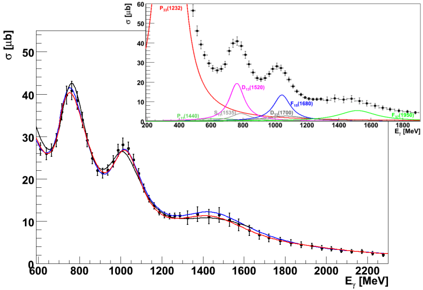
Spin Dependent Cross Section ($\gamma p \to p\pi^0$): CBELSA/TAPS



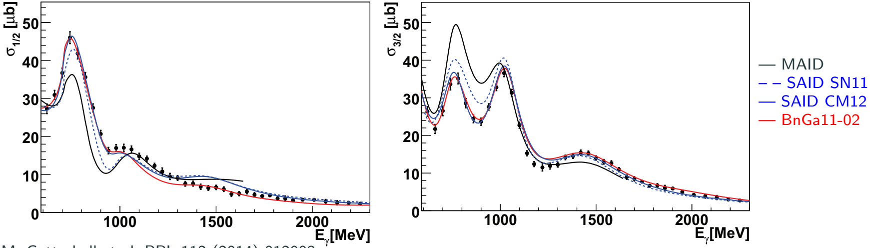
- Different models show good description of the cross section
- Spin dependent cross section can be extracted: $\sigma^{1/2(3/2)} = \sigma_0 \cdot (1 \pm E)$

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

Spin Dependent Cross Section ($\gamma p \rightarrow p\pi^0$): CBELSA/TAPS

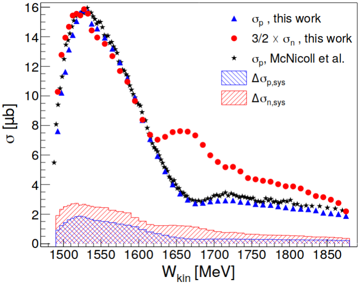


- Different models show good description of the cross section
- Spin dependent cross section can be extracted: $\sigma^{1/2(3/2)} = \sigma_0 \cdot (1 \pm E)$
- Large differences occur in $\sigma^{1/2}$ and $\sigma^{3/2}$ cross sections



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

Measurements off (polarized) Neutrons with A2



Narrow peak observed in η photoproduction

Polarization observables used to shed further light on this structure

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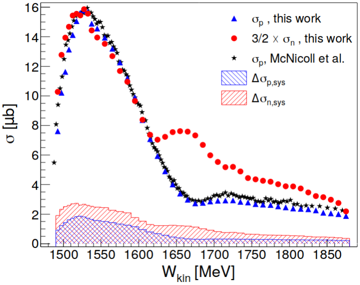

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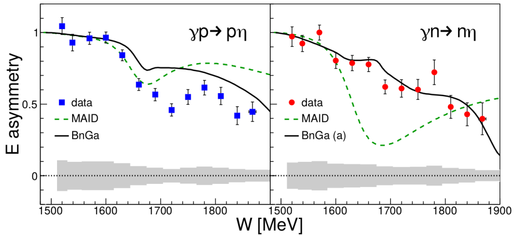
D. Werthmüller et al., Phys.Rev. C90 (2014) no.1, 015205

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



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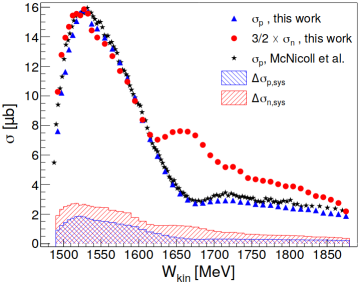

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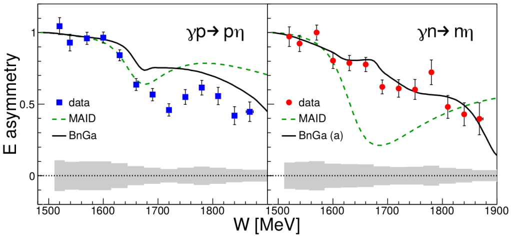
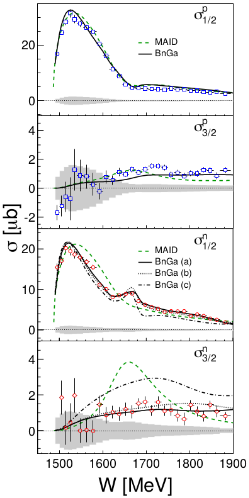
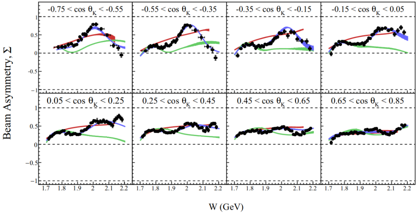


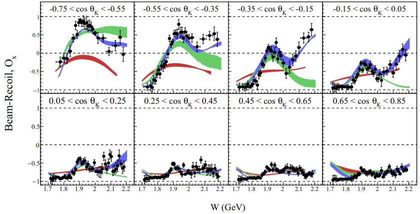


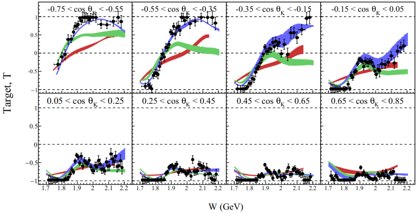
Strangeness Production with CLAS: $\gamma p \rightarrow K\Lambda$

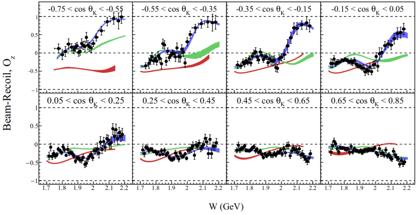
Strangeness production self analyzing,
allows the extraction of observables with recoil polarization

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







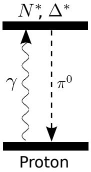


red: ANL-Osaka
green: BnGa14
blue: BnGa refit

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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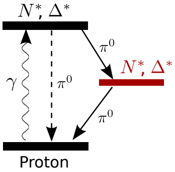

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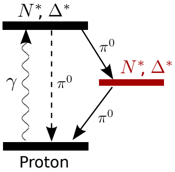
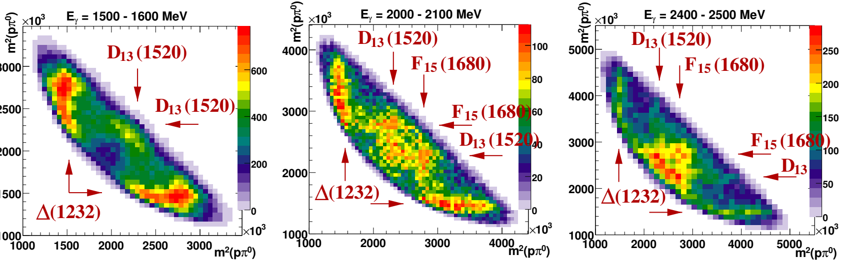


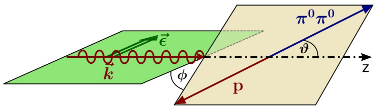


V. Sokhoyan et al., Eur.Phys.J. A51 (2015) no.8, 95
A. Thiel et al., Phys.Rev.Lett. 114 (2015) no.9, 091803

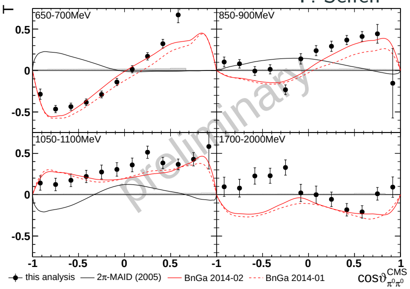
Polarization Observables T, P, H ($\gamma p \to p\pi^0\pi^0$): CBELSA/TAPS

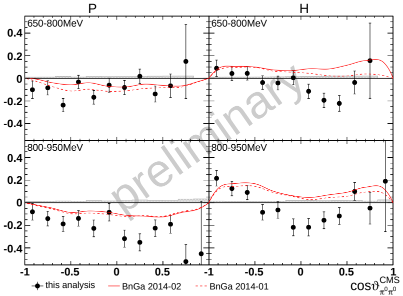
Here:

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.

Interpretation

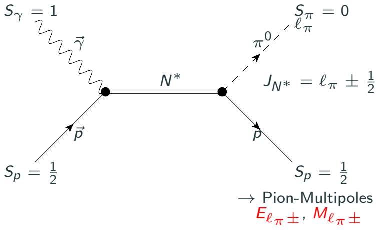
Multipoles and CGLN Amplitudes

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

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

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

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



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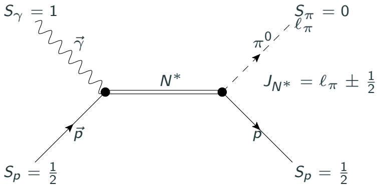

All observables can be expressed in CGLN amplitudes, for example:

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

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

Multipoles and CGLN Amplitudes

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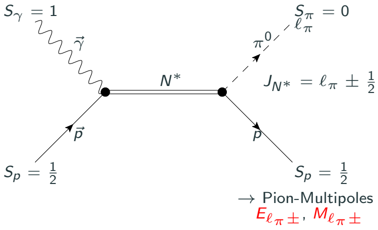
$$F_1(W,z) = \sum_{\ell=0}^{\ell_{max}} [\ell M_{\ell+} + E_{\ell+}] \cdot P'_{\ell+1}(z) + [(\ell+1)M_{\ell-} + E_{\ell-}] \cdot P'_{\ell-1}(z)$$

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

Truncation at a certain level

$\rightarrow$ Truncated PWA



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

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 $\rho_0 = k/q$.

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 ($L_{max} = 1$):

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

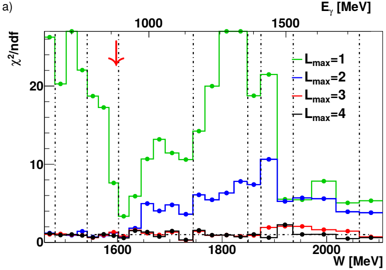
- using S-, P- and D-waves ($L_{max} = 2$):

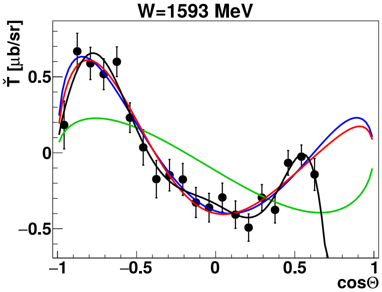
$$\check{T} = \frac{q}{k} \sin\theta [A_0 + A_1 \cdot \cos\theta + A_2 \cdot \cos^2\theta + A_3 \cdot \cos^3\theta]$$

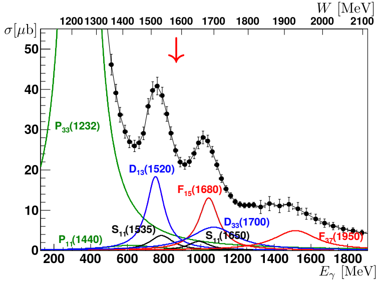
- using S-, P-, D- and F-waves ($L_{max} = 3$):

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

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, 8

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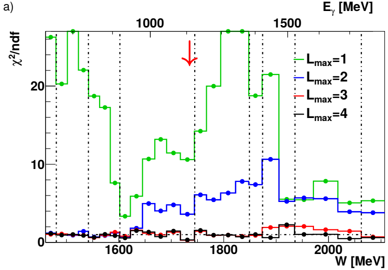

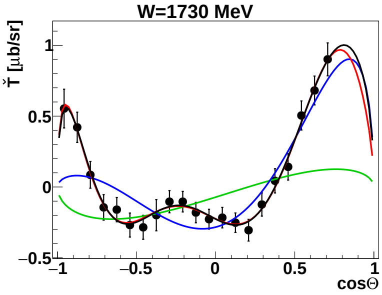

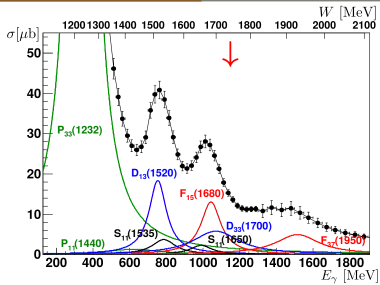

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Y. Wunderlich, F. Afzal, A. Thiel, R. Beck, Eur.Phys.J. A53 (2017) no.5, 86

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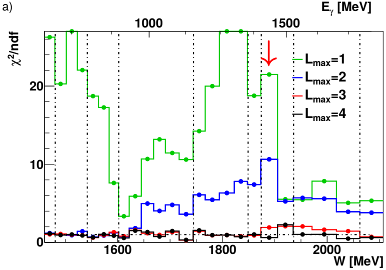

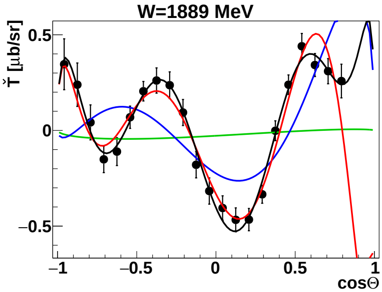

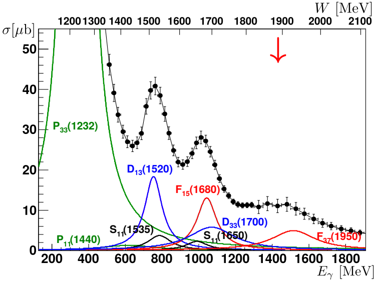

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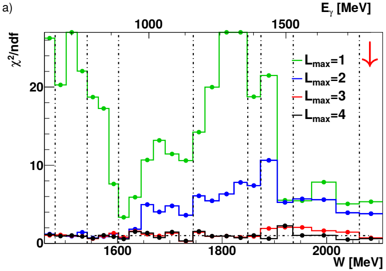

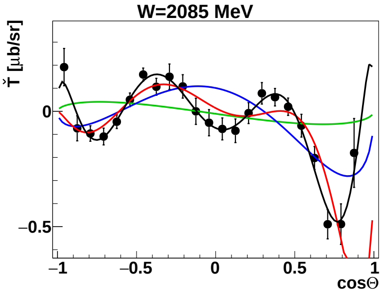

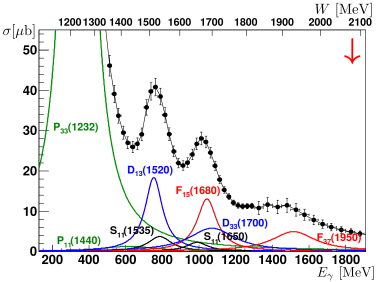

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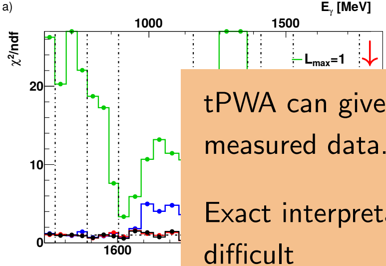
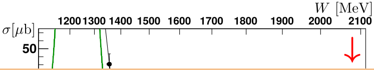
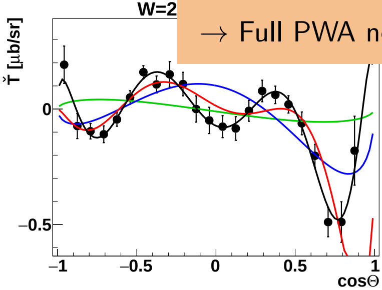




tPWA can give first insight into the sensitivity of the measured data.

Exact interpretation of the contributing resonances difficult

$\rightarrow$ Full PWA needed



…nta directy

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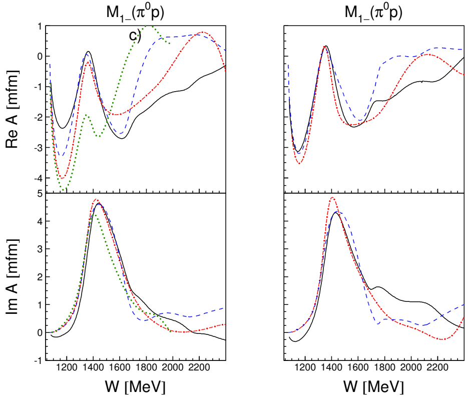
New Fits from different Analyses

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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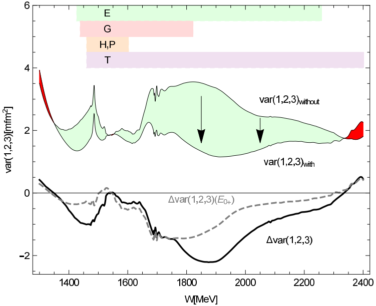
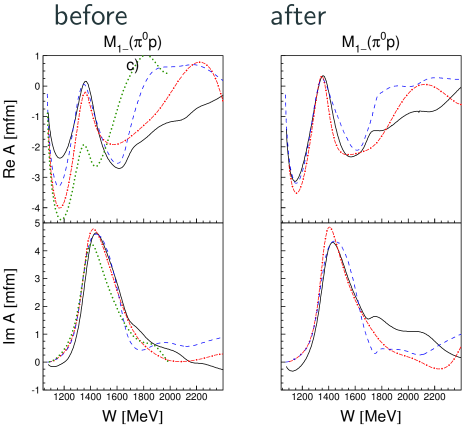
Variance between the different analyses decreases!





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

Comparison between PDG values and BnGa results

- 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

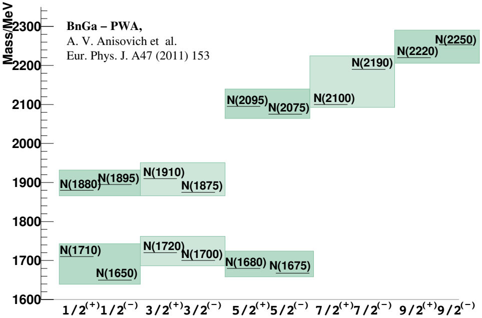
The impact of photoproduction on baryon resonances		Decay modes of nucleon resonances		
	black:	PDG 2004	****	Existence is certain.
	red:	PDG 2018	***	Existence is very likely.
	blue:	BESIII resonances	**	Evidence of existence is fair.
			*	Evidence of existence is poor.

		overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$	$N_{1440}\pi$	$N_{1520}\pi$	$N_{1535}\pi$	$N_{1680}\pi$
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...

- Parity doublets occuring at high energies. Do they exist for all high mass states? They are not predicted by the current lattice QCD calculations nor by constituent quark models.



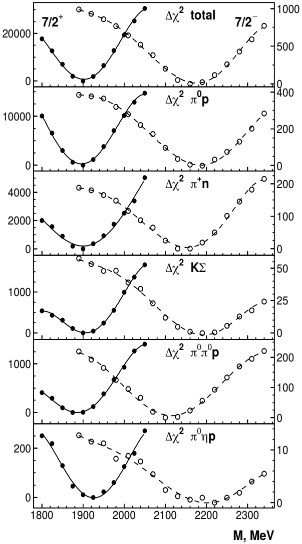
Parity Doublets at high masses:

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

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

Search for Parity Doublets

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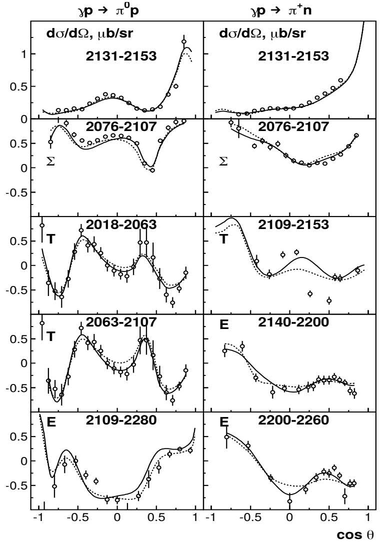
Fit with and without $\Delta(2200)7/2^-$ reveals high sensitivity of the data sets

Further identification of weak resonance contributions possible!



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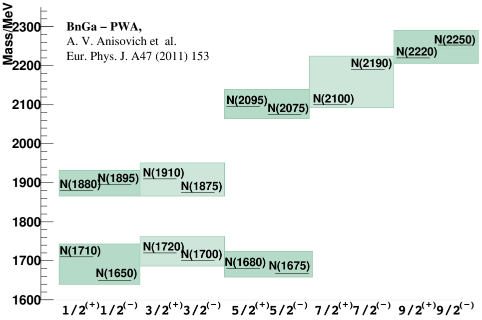
Still Many Open Questions...

- Parity doublets occuring at high energies. Do they exist for all high mass states? They are not predicted by the current lattice QCD calculations nor by constituent quark models.

- Still many missing resonances. Why haven't we found them yet?



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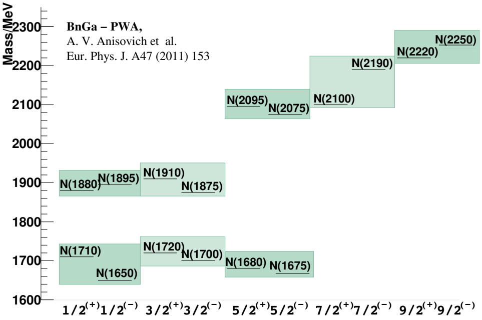

- Is it possible to do a complete experiment? How many observables and which precision is needed?

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

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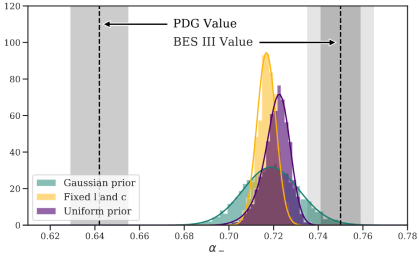


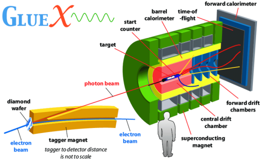
Measured (double) polarization observables for $\gamma p \to K\Lambda$ can be used to give an additional view on the value the decay parameter

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

Future Developments

GlueX at JLAB

Photoproduction with linearly polarized photons at high energy (up to 12 GeV)



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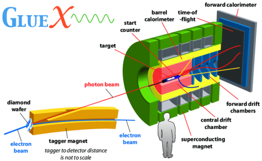
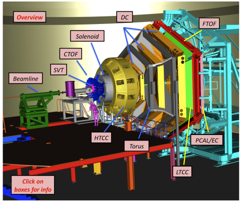


CLAS12 at JLAB

Electroproduction experiment



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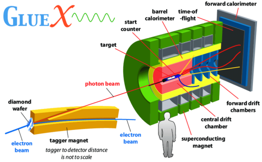

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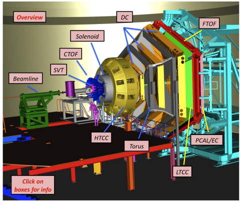
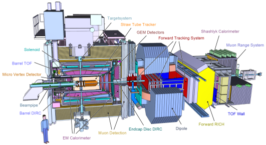


Panda at FAIR

Proton Antiproton annihilation



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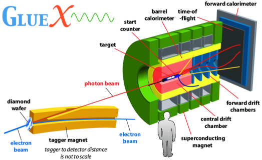

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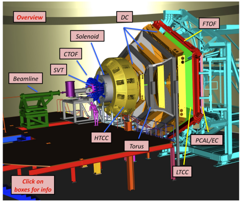

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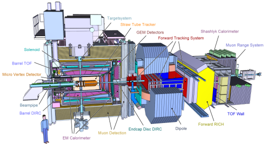

EIC

Electron ion collisions

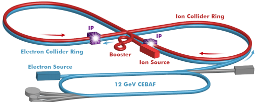

Figure 1. Schematics of the JLEIC facility.

Summary

Conclusion and Outlook

- New era of experiments allows precise measurements of (polarization) observables for various reactions
- 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
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Thank you
for your attention.