Light quark baryons

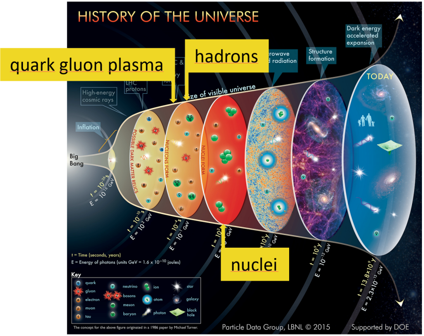
U. Thoma, Bonn

Contents:

- Introduction
- Experimental data
- Results on the spectrum
- Open questions
- Summary

Why baryons?

⇔ **They played am important role in the development of our universe**



⇔ **Transition from a soup of quarks and gluons → hadrons:**
∼ 1/100 ms after the big bang

⇕

depends on the existing baryon resonances

⇔ baryons = dominant part of visible matter in the universe

$\Delta^{++} \rightarrow$ color ↔ non-abelian character of QCD

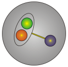
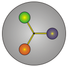
⇔ **Can we claim that we have understood Quantum Chromodynamics without understanding its bound states? ⇔ NO!**

⇔ **One of the worst understood areas of the standard model = a challenge!**

⇔ **How does QCD produce its massive bound states from almost massless quarks?**

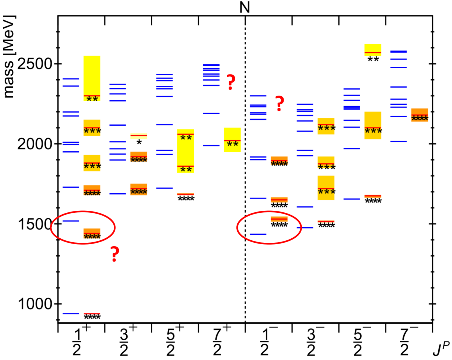
Aim: Good understanding of the spectrum and the properties of baryon resonances $\leftrightarrow$ bound states of strong QCD

- What are the relevant degrees of freedom ?

- Effective forces between them ? **e.g.:**  **or**  **?**

Symmetric quark models:

$\rightarrow$ more resonances expected than observed yet

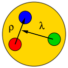


non-strange N*-resonances **(PDG)**

U. Loering, B. Metsch, H. Petry et al. (2001)

relativistic quark model

Constituent quarks, confinement potential + residual interaction



$$|\vec{J}| = |\vec{L} + \vec{S}_{qqq}|$$

$\leftrightarrow$ **specific configurations seem to be missing** (symmetries)

Baryon Spectroscopy

Or does the quark model just use the wrong degrees of freedom?

$\leftrightarrow$ Mesons-Baryon degrees of freedom?

... seems to work nicely for certain resonances ...

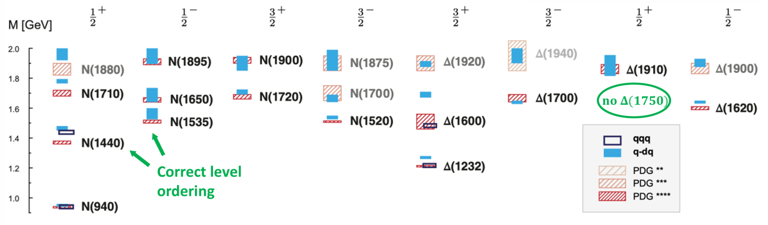
e.g. Coupled-channel unitarized chiral perturbation theory:

N(1535)1/2$^-$, N(1650)1/2$^-$ dynamically generated but not Δ(1620)1/2$^-$

(Bruns, Mai, Meißner, PLB 697 (2011) 254,   Mai, Bruns, Meißner, PRD 86 (2012) 094033)

$\leftrightarrow$ Functional methods (Dyson-Schwinger/Bethe-Salpeter equations)

Nice results! ... spectrum so far only J=1/2, 3/2 (up to $\sim$ 1950 MeV)



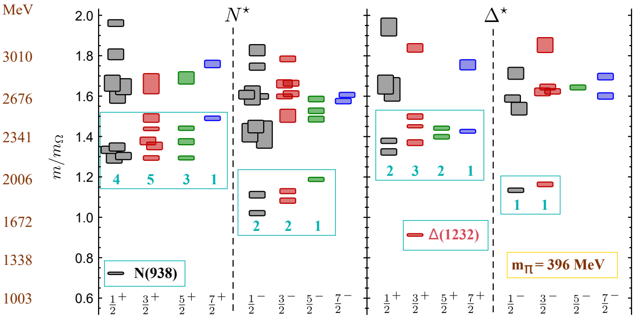
Eichmann, Fischer, Sanchis-Alepuz, PRD 94 (2016) 094033
Eichmann, Fischer, Few Body Syst. 60 (2019) no 1,2
Eichmann, Few Body Syst. 63 (2022) no 3

Baryon Spectroscopy

Aim: Good understanding of the spectrum and the properties of baryon resonances = the bound states of strong QCD

- Effective degrees of freedom ? / Effective forces between them ?

Excited baryons from Lattice QCD:



R.Edwards et al.,
Phys. Rev. D84 (2011) 074508

↔ further results on the low lying resonances during this conference

Exhibits the broad features expected from SU(6)⊗O(3)-symmetry

→ Counting of levels consistent with non-rel. quark model ⇔ "missing resonances"

→ no parity doubling

Of course there are also approximations made by lattice QCD (e.g. m_π=396 MeV)

Baryon Spectroscopy

$\Rightarrow$ **Good understanding of the spectrum and properties of baryon resonances**

Experimentally:
Broad and strongly overlapping resonances

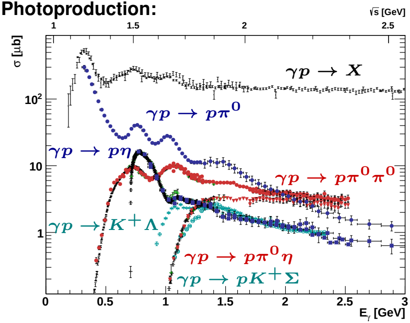
Important:

$\rightarrow$ **Investigation of different final states**

$\rightarrow$ **Investigation of different production processes: πN, γN, $\gamma^* N$, Ψ, Ψ'-decays, ...**

$\rightarrow$ **Measurement of polarization observables (unambiguous PWA)**

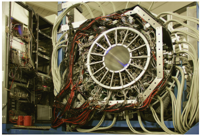
Photoproduction:



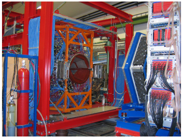
Recently: a lot of progress from photoproduction experiments:

CLAS (JLab),

CBELSA/TAPS (ELSA),



CBALL (MAMI),



LEPS (Spring-8), BGOOD (ELSA), GlueX (JLab), ...

$\Leftrightarrow$ **polarized beam, polarized target**

Baryon Spectroscopy

⇒ **Good understanding of the spectrum and properties of baryon resonances**

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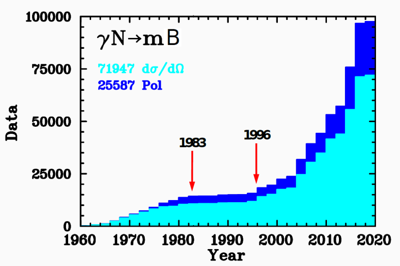

D. Ireland et al., Prog. Part. Nucl. Phys. 111 (2020) 103752

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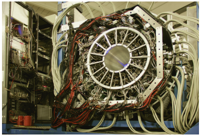

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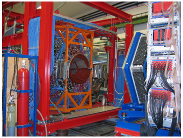


LEPS (Spring-8), BGOOD (ELSA), GlueX (JLab), ...

⇔ **polarized beam, polarized target**

Double Polarization Experiments - Selected Results -

Circularly polarized photons, longitudinally polarized target

CBELSA/TAPS

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

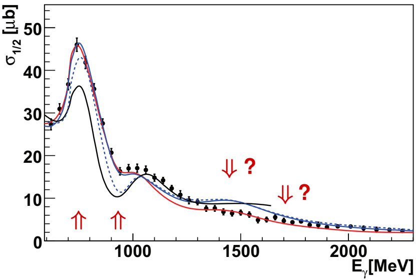
PWAs:

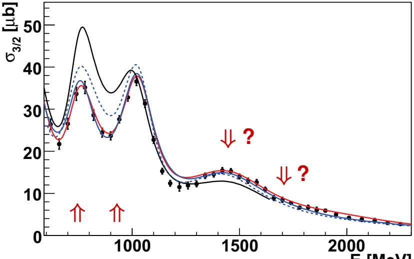
SAID (SN11, CM12), **MAID**
BnGa (2011_2)

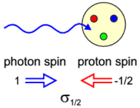
$\leftrightarrow$ **describe the so far existing photoproduction data, but ...**

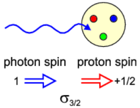
large deviations observed $\rightarrow$

Differences even at low energies where everything was thought to be well understood ... $\rightarrow$









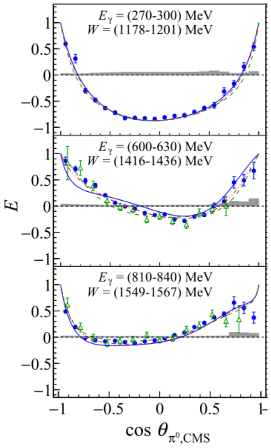
$\Rightarrow$

Sensitivity on high mass resonances !

M. Gottschall et al. (CBELSA/TAPS-collaboration) Phys. Rev. Lett. 112, 012003 (2014)

$\vec{\gamma}\vec{p} \to p\pi^0$: Recent results on E $= \frac{\sigma_{1/2}-\sigma_{3/2}}{\sigma_{1/2}+\sigma_{3/2}}$

A2-MAMI / CBELSA/TAPS



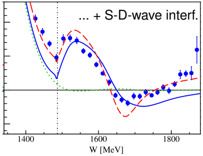
New data: extending the CBELSA/TAPS (2014) data especially to lower energies

Improving statistical precision

$\leftrightarrow$ **good consistency** (mostly)

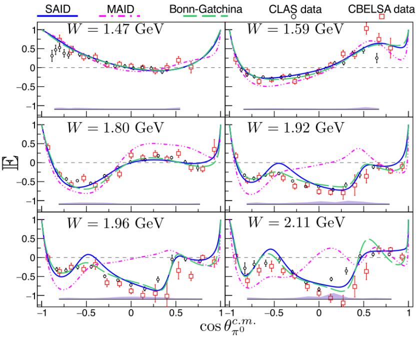
Legendre Coeff.

$(a_3)_2^{\check{E}}$ $[\mu b/sr]$



***η*-cusp**

CLAS / CBELSA/TAPS

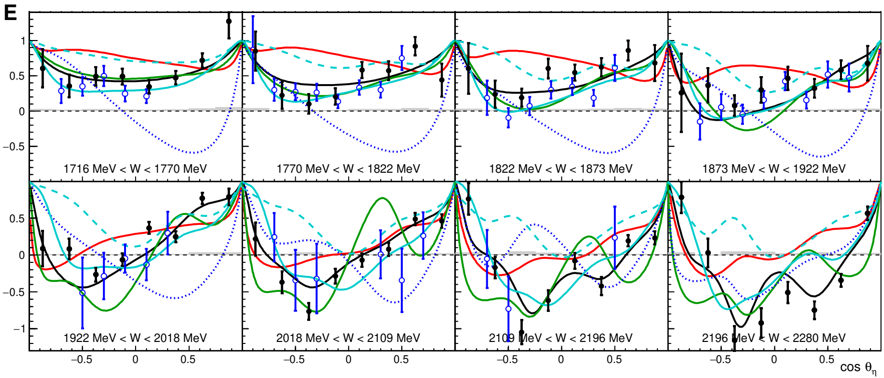


$\Leftrightarrow$ **Coupled channel PWA important!**

M. Gottschall et al. (CBELSA/TAPS-collaboration) Phys. Rev. Lett. 112, 012003 (2014), Eur. Phys. J. A 57, 40 (2021)
C. W. Kim, N. Zachariou et al. [CLAS-collaboration], Eur. Phys. J. A 59 217 (2023)
F. Afzal et al. [A2-collaboration], Phys. Rev. Lett. 132 12190 (2024)

Polarization observables − selected results: $\vec{\gamma}\vec{p} \to p\eta$

circ. pol. photons, long. pol. target, CBELSA/TAPS high energy bins, **blue: CLAS**



⇓

⇔ **Large sensitivity!**

⇒ **data approaches the high mass region**

— **new BnGa-fit : Determination of precise $p\eta$-branching ratios for resonances**

J.Müller et al. (CBELSA/TAPS), PLB 803, 135323 (2020)

$\vec{\gamma}\vec{p} \to p\eta$ - Results including new data on E, G, T, P, H, Σ, σ

Data allowed a new determination of $p\eta$-branching ratios for many resonances, e.g.:

J.Müller et al. (CBELSA/TAPS), PLB 803, 135323 (2020)

	$N(1535)1/2^-$	$N(1650)1/2^-$	$N(1895)1/2^-$
BnGa	**0.41±0.04**	**0.33±0.04**	**0.10±0.05**
PDG'2012	**0.42±0.10**	**0.05 - 0.15**	no PDG estimate

$\Leftrightarrow$ **Additional constraints from new (polarization) data fix PWA-solutions much better than before**

$\Downarrow$

Large and heavily discussed difference in the $p\eta$-branching ratio of N(1535)1/2$^-$ and N(1650)1/2$^-$ now significantly reduced

New data also included in JüBo:

D. Rönchen et al, EPJA 58:229 (2022)

$\Downarrow$

ηN residue of N(1650)1/2$^-$ increased by almost a factor of 2!

= Power of polarisation data!

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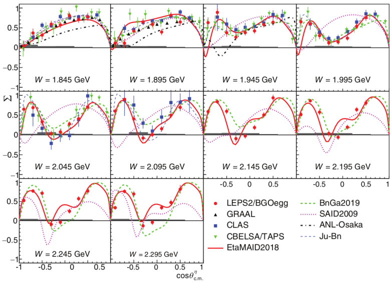
New Σ-data at high E - LEPS2

Laser Compton backscattering



$\Leftrightarrow$ **constraints for the high mass regime**

T. Hashimoto *et al.* [LEPS2/BGOegg], PRC 106 035201 (2022)

Results: The Spectrum of Baryon Resonances

Multi-channel Bonn-Gatchina PWA:

⇒ **Confirmation known resonances, better determination of their properties**

⇒ **New resonances observed**

	RPP 2010	our analyses	RPP'22 (2018-22)
N(1710)1/2$^+$	***	****	****
N(1860)5/2$^+$		*	**
N(1875)3/2$^-$		***	***
N(1880)1/2$^+$		***	***
N(1895)1/2$^-$		****	****
N(1900)3/2$^+$	**	****	****
N(2060)5/2$^-$		***	***
N(2100)1/2$^+$	*	***	***
N(2120)3/2$^-$		***	***
Δ(1600)3/2$^+$	***	***	****
Δ(1900)1/2$^-$	*	***	***
Δ(1940)3/2$^-$	*	**	**
Δ(2200)7/2$^-$	*	***	***

only examples shown

from 2000-2010 not one new baryon resonance was considered by the PDG

↔ **Results from photoproduction do enter the PDG and determine the properties of baryon resonances!**

before: almost entirely πN-elastic scattering and some π-photoproduction

At higher $\sqrt{s}$:

⇔ elastic cross section decreases

⇔ more an more inelastic channels open

Photoproduction provides access to the "inelastic channels"

⇒ **resonance properties**

BnGa-PWA: A. V. Anisovich et al., EPJA 48 (2012) 15, PRL 119 (2017) 062004, PLB 772 (2017) 247, J. Müller et al., PLB 803 (2020) 135323 ...

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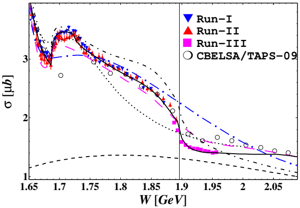
N(1895)1/2$^-$		****	****
N(1900)3/2$^+$	**	****	****
N(2060)5/2$^-$		***	***
N(2100)1/2$^+$	*	***	***
N(2120)3/2$^-$		***	***
Δ(1600)3/2$^+$	***	***	****
Δ(1900)1/2$^-$	*	***	***
Δ(1940)3/2$^-$	*	**	**
Δ(2200)7/2$^-$	*	***	***

$\Leftrightarrow$

Interesting recent MAMI-data:

$\gamma p \rightarrow \eta p$



(V.L.Kashevarov et al., PRL 118 (2017) 212001

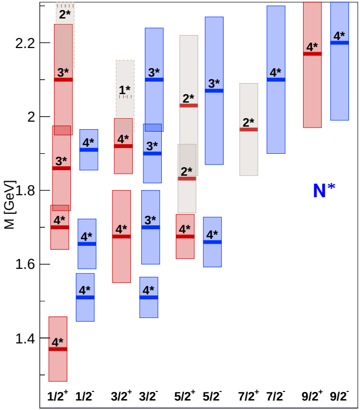
$\Rightarrow$ **cusp effect $\eta' p$-threshold observed**

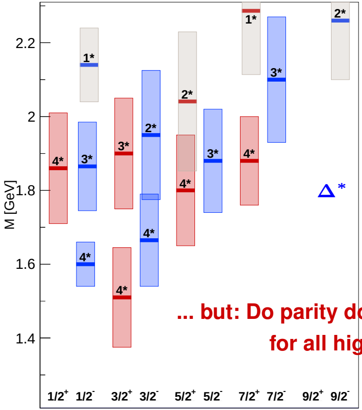
MAID-analysis of $\gamma p \rightarrow \eta p$, $\gamma p \rightarrow \eta' p$ confirms N(1895)1/2$^-$ coupling to $p\eta$, $p\eta'$

BnGa-PWA: A. V. Anisovich et al., EPJA 48 (2012) 15, PRL 119 (2017) 062004, PLB 772 (2017) 247, J. Müller et al.,PLB 803 (2020) 135323 ...

Baryon Resonances - Parity doublets -

N*-, Δ*- pole positions:





(PDG'2022)

... but: Do parity doublets exist for all high mass states ?

⇔ **Parity doublets occur!**

- not expected by present lattice QCD calculations or constituent quark-models

⇔ **Strong QCD not yet understood !**

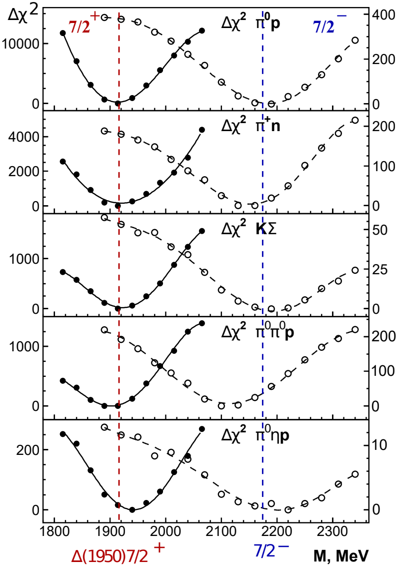
Search for parity doublets - Δ-states at $\sim$1900 MeV

⇒ **Do ALL high mass states have parity partners?**

⇓

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

Search for the parity partner of the well known Δ(1950)$7/2^+$ (4*) ⟹



⇒ **J^P = 7/2$^-$-state found at a significantly higher mass: m = 2200 MeV**

(7/2$^-$ (2200) - (1*)-resonance (PDG) confirmed)

⇔ **No parity-partner found**

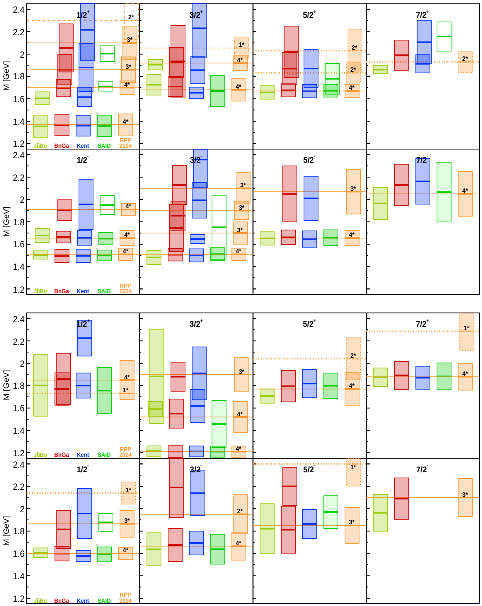
⇒ **Certain states have parity partners, others not**
⇒ **Not yet understood!**

V. Anisovich et al. (BnGa-PWA), Phys.Lett. B766 (2017) 357

PWA-results of different groups

N^*-
pole positions

Δ^*-
pole positions



BnGa'2024 - preliminary

Kent: B. Hunt, M. Manley PRC 99, 055205 (2019)

JüBo: D. Rönchen et al., EPJA 58:229 (2022)

SAID: W. Briscoe et al.,PRC 108, 065205 (2023) / A. Svarc et al.,PRC 91, 015207 (2015)

RPP'2024

of course:
results not model independent

analyses not all based on the same data

Pole positions:

⇔ **Good consistency for many resonances** (results converge)

⇔ **Some areas are more difficult than others: e.g.** $N^*\ 3/2^-$

⇔ **Still not all quark model resonances observed**

The baryon spectrum

⇔ **Do all the expected qqq-SU(6)xO(3)-states exist? / the still *missing* states?**

- **Existing but experimentally not found yet?**
  - ⇔ **photoproduction of the neutron   + other production processes**
  - ⇔ **multi-meson photoproduction, further final states**

⇔ **Certain resonances have parity partners others don't** ⇔ **Why?**

- **Needs to be explained by theory**
  - ⇔ **effective degrees of freedom / effective forces**
  - ⇔ **meson-baryon or 3q or .....**

... also relates to the first point ...

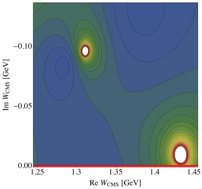
⇒ **Clarify the systematics in the system!**

(SU(6): u↑ ↓ d↑ ↓ s↑ ↓)

⇔ **also strange baryons of large interest**

... two low mass Λ-states would break the systematics of the quarkmodel ...

- **$\Lambda(1405)$: 2 pole structure**
  chiral unitary approach
  ↔ meson-baryon interaction



M. Mai EPJST (2021) 230:1593

$(m,\Gamma)=(1325\pm16, 180^{+24}_{-36})$MeV

$(m,\Gamma)=(1429^{+8}_{-7}, 24^{+4}_{-6})$MeV

Summary

- Based on the new data, our knowledge of the spectrum and the properties of baryons is steadily increasing !

$\leftrightarrow$ **Important contributions from photoproduction experiments**
(single and double polarisation experiments (many final states))

$\Rightarrow$ **Observation of new resonances**

$\Rightarrow$ **Confirmation of known states, determination of their properties**

But: Complex bound states of QCD are not yet understood!

$\Leftrightarrow$ **Systematics in the spectrum** $\leftrightarrow$ theoretical explanation?

$\Leftrightarrow$ **Inner structure of the states?** - qqq / meson-baryon / both / .... ?

Experiment:

more interesting results: $\rightarrow$ **to be shown during this conference**

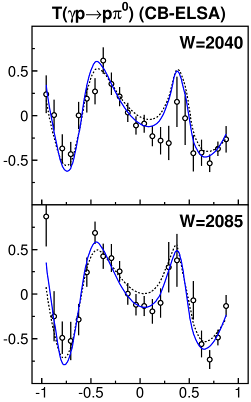
$\rightarrow$ **to come!**

e.g.: - KY-photoproduction data - polarisation observables
- photoproduction off the neutron - polarisation observables
- additional final states, production processes
- Q^2-dependence $\leftrightarrow$ transition FF / other probes
- strange baryons
- ....

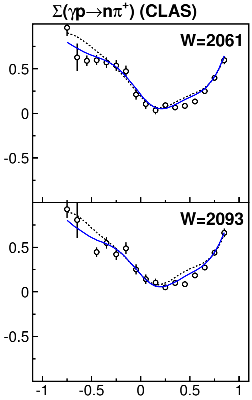
Theory $\rightarrow$ **results from the lattice, 2 pole structures, functional methods, ...**

Precise measurements of polarisation observables

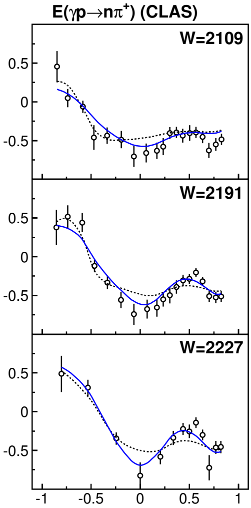
CBELSA/TAPS, CLAS-data (only a few of the measured bins shown:)



J. Hartmann et al.
(CBELSA/TAPS), PLB 748, 212 (2015)



M. Dugger et al. (CLAS),
PRC 88, 065203 (2013)



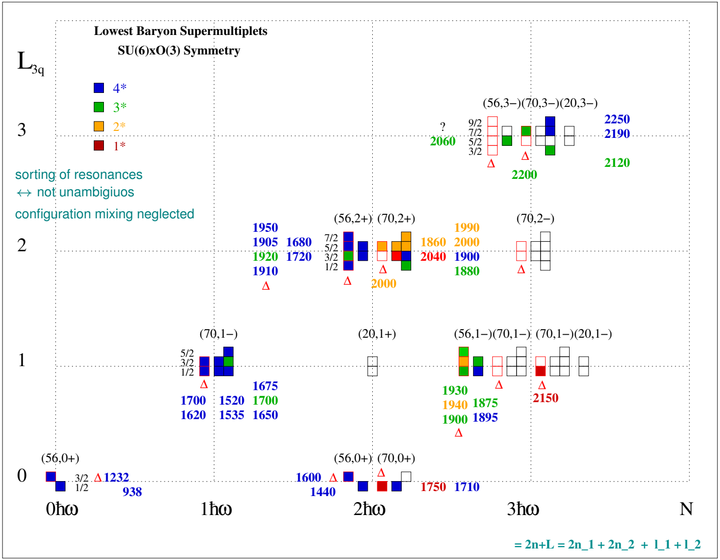
S. Strauch et al. (CLAS),
PLB 750, 53 (2015)

data included in the multi-channel BnGa-PWA:
fit with (——) / without (- - - -) $\Delta(2200)7/2^-$

The Spectrum of Baryon Resonances - SU(6)xO(3)-Multiplets

$56 = {}^4 10 + {}^2 8$ **(S)** $\quad 20 = {}^2 8 + {}^4 1_\Lambda$ **(A)**

$70 = {}^2 10 + {}^4 8 + {}^2 8 + {}^2 1_\Lambda$ **(M)**



- **first excitation band: filled**
- **second excitation band: most resonances found**

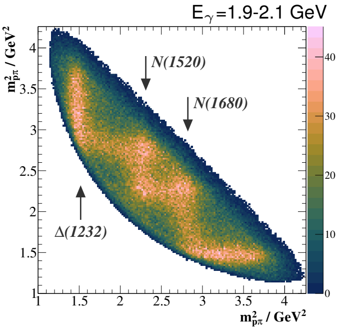
but:

⇔ 20'plet = ??

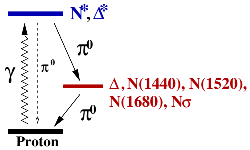
⇔ Three/four $3/2^+$-states missing ...

⇔ Several states need confir-mation (1* / 2*)

Multi-Meson-Photoproduction: $\gamma p \rightarrow p\pi^0\pi^0, \gamma p \rightarrow p\pi^0\eta$



⇔ **Observation of cascade decays:**



- Event based maximum likelihood fit of unpolarised data
- including single and double polarisation observables in the fit

- $\Delta(1910)1/2^+, \Delta(1920)3/2^+, \Delta(1905)5/2^+, \Delta(1950)7/2^+$
  in average: negligible decay fraction $(5 \pm 2\%)$ **into:**
  $N(1520)3/2^-\pi, N(1535)1/2^-\pi,$ ($L \neq 0$-resonances)

- $N(1880)1/2^+, N(1900)3/2^+, N(2000)5/2^+, N(1990)7/2^+$
  in average: 21% decays into:
  $N(1520)3/2^-\pi, N(1535)1/2^-\pi, N\sigma$ ($L \neq 0$-resonances)

... Why ?

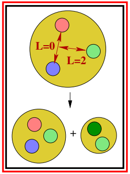
V. Sokhoyan et al. (CBELSA/TAPS-collaboration), EPJA 51 (2015) 95
A. Thiel et al. (CBELSA/TAPS-collaboration), PRL 114 (2015) 091803, T.Seifen et al., arXiv:2207.01981 [nucl-ex]

Multi-Meson-Photoproduction: $\gamma p \rightarrow p\pi^0\pi^0, \gamma p \rightarrow p\pi^0\eta$

An interpretation using quarkmodel-wave-functions:

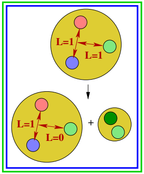
Δ^*'s
@1900 MeV:

symmetric
wave function
(56'plet)

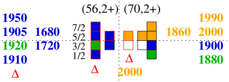


N*'s
@1900 MeV:

wave function:
M_S / M_A
(70'plet)

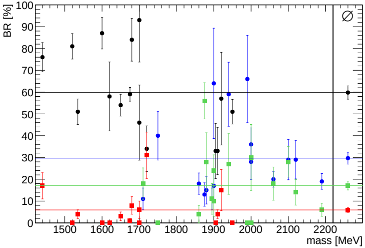


SU(6)⊗O(3) for L=2, N=0



⇒ would explain the observation!

... and it seems to hold more general ...



T.Seifen et al. (CBELSA/TAPS), arXiv:2207.01981 [nucl-ex]

⇔ supports a two-oscillator picture of resonances (3q)

... confirmation in further (polarisation) measurements

Hyperons

SU(6)xO(3):

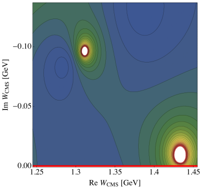
(D, L_N^P)	S	J^P	Singlet	Octet			Decuplet	
$(56, 0_0^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$		$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$		
	$\frac{3}{2}$	$\frac{3}{2}^+$					$\Delta(1232)$	$\Sigma(1385)$
$(70, 1_1^-)$	$\frac{1}{2}$	$\frac{1}{2}^-$	$\Lambda(1405)$	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Delta(1620)$	$\Sigma(1900)^a$
		$\frac{3}{2}^-$	$\Lambda(1520)$	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Delta(1700)$	$\Sigma(1910)^a$
	$\frac{3}{2}$	$\frac{1}{2}^-$		$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$		
		$\frac{3}{2}^-$		$N(1700)$	-	-		
		$\frac{5}{2}^-$		$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$		
$(56, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$		$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$		
	$\frac{3}{2}$	$\frac{3}{2}^+$					$\Delta(1600)$	$\Sigma(1780)$
$(70, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$\Lambda(1710)$	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Delta(1750)$	-
	$\frac{3}{2}$	$\frac{3}{2}^+$		-	-	-		
$(56, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$		$N(1720)$	$\Lambda(1890)$	$\Sigma(1940)$		
	$\frac{1}{2}$	$\frac{5}{2}^+$		$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$		
	$\frac{3}{2}$	$\frac{1}{2}^+$					$\Delta(1910)$	-
	$\frac{3}{2}$	$\frac{3}{2}^+$					$\Delta(1920)$	$\Sigma(2080)$
	$\frac{3}{2}$	$\frac{5}{2}^+$					$\Delta(1905)$	$\Sigma(2070)$
	$\frac{3}{2}$	$\frac{7}{2}^+$					$\Delta(1950)$	$\Sigma(2030)$
$(70, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$	$\Lambda(2070)$	-	-	-	-	-
		$\frac{5}{2}^+$	$\Lambda(2110)$	$N(1860)$	-	-	$\Delta(2000)$	-
	$\frac{3}{2}$	$\frac{1}{2}^+$		$N(1880)$	-	-		
		$\frac{3}{2}^+$		$N(1900)$	-	-		
		$\frac{5}{2}^+$		$N(2000)$	-	-		
		$\frac{7}{2}^+$		$N(1990)$	$\Lambda(2085)$	-		
$(20, 1_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	-	-	-	-		
		$\frac{3}{2}^+$	-	-	-	-		
		$\frac{5}{2}^+$	-					
$(56, 1_3^-)$	$\frac{1}{2}$	$\frac{1}{2}^-$		$N(1895)$	$\Lambda(2000)$	$\Sigma(1900)^a$		
		$\frac{3}{2}^-$		$N(1875)$	$\Lambda(2050)$	$\Sigma(1910)^a$		
	$\frac{3}{2}$	$\frac{1}{2}^-$					$\Delta(1900)$	$\Sigma(2110)^a$
		$\frac{3}{2}^-$					$\Delta(1940)$	$\Sigma(2010)^a$
		$\frac{5}{2}^-$					$\Delta(1930)$	-
$(70, 3_3^-)$	$\frac{1}{2}$	$\frac{5}{2}^-$	$\Lambda(2080)$	$N(2060)^b$	-	-	-	-
		$\frac{7}{2}^-$	$\Lambda(2100)$	$N(2190)^b$	-	$\Sigma(2100)$	$\Delta(2200)$	-
$(70, 3_3^-)$	$\frac{3}{2}$	$\frac{3}{2}^-$		$N(2120)$	-	-	-	-
		$\frac{5}{2}^-$		$N(2060)^b$	-	-	-	-
		$\frac{7}{2}^-$		$N(2190)^b$	-	-	-	-
		$\frac{9}{2}^-$		$N(2290)$	-	-	-	-

No state / state assigned twice

No 3*/4*-resonances

Effective degrees of freedom?
Meson – Baryon
or
qqq-states ⇔ SU(6)xO(3)

- e.g. more than 50% of the expected Σ^*-states not/badly known
- $\Lambda(1405)$: 2 pole structure chiral unitary approach $\leftrightarrow$ meson-baryon interaction



M. Mai EPJST (2021) 230:1593

$\Lambda(1325)$: m=1325±16 , Γ=180^{+24}_{-36} '1' (dom.)

$\Lambda(1405)$: m=1429^{+8}_{-7} , Γ=24^{+4}_{-6} '8' (dom.)