UNIVERSITÄT BONN

Light baryon spectroscopy (@ELSA)

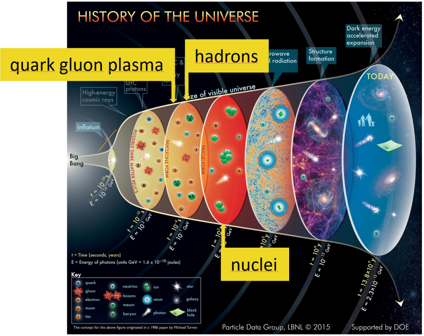
U. Thoma, Bonn

Contents:

- Introduction
- Experimental data
- Results on the spectrum
- Interpretations / open questions
- Future plans @ELSA
- 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!**

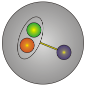
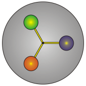
⇔ **One of the worst understood areas of the standard model = a challenge!**

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

Baryon Spectroscopy

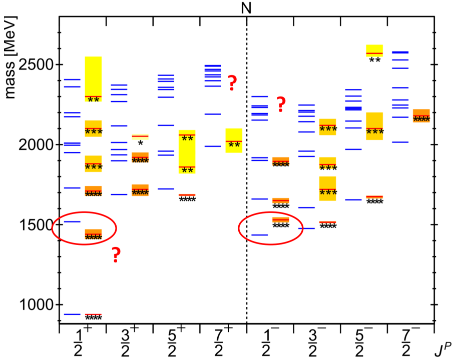
Aim: Good understanding of the spectrum and the properties of baryon resonances $\leftrightarrow$ bound states of strong QCD

- What are the relevant degrees of freedom ?
- Effective forces between them ?

e.g.:  or  ?

Symmetric quark models:

$\rightarrow$ **many more resonances expected than observed yet**



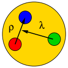
non-strange N*-resonances

(PDG'2018)

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

relativistic quark model

Constituent quarks, confinement potential + residual interaction



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

Baryon Spectroscopy

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

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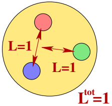
  $\rightarrow$ **many more resonances expected than observed yet (certain configurations completely missing)**

  $\Leftrightarrow$ **Certain configurations not realised by QCD ? Why ?**

  $\Leftrightarrow$ **Experimental bias?**

e.g.:



... not yet identified
(non-relativistic picture)

Baryon Spectroscopy

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

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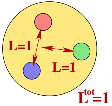


... not yet identified
(non-relativistic picture)

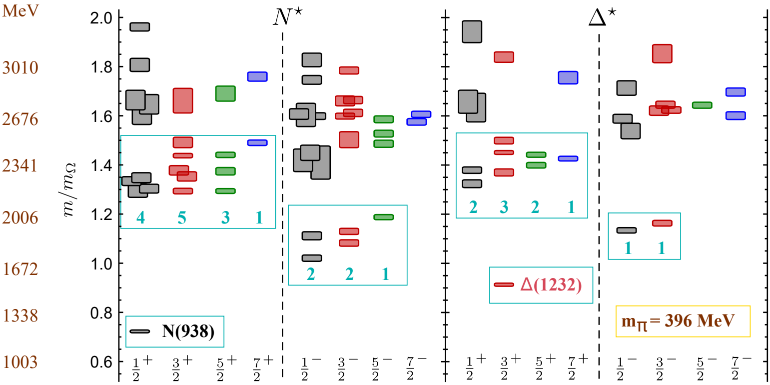
Or does the quark model just use the wrong degrees of freedom?

$\leftrightarrow$ **Mesons-Baryon degrees of freedom?**
... seems to work nicely for certain resonances ...

$\leftrightarrow$ **Functional methods (Dyson-Schwinger/Bethe-Salpeter equations)**
Nice results! ... spectrum so far only J=1/2, 3/2 (up to $\sim$ 1900 MeV) ($\rightarrow$ talk G. Eichmann)

Baryon Spectroscopy

Excited baryons from Lattice QCD:



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

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

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

Experimentally:
Broad and strongly overlapping resonances

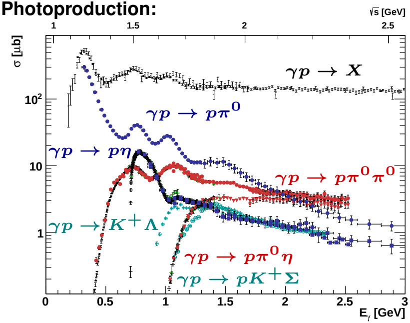
Important:

→ **Investigation of different final states**

→ **Investigation of different production processes: $\pi N, \gamma N, \gamma^* N$, Ψ, Ψ'-decays, ...** ($\gamma^* N \rightarrow$ talk V.Burkert)

→ **Measurement of polarization observables (unambiguous PWA)**

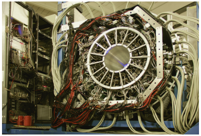
Photoproduction:



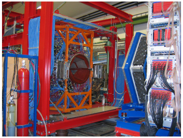
Recently: a lot of progress from photoproduction experiments:

CLAS (JLab),

CBELSA/TAPS (ELSA),



CBALL (MAMI),



LEPS (Spring-8), BGOOD (ELSA), GRAAL (ESRF), ...

⇔ **polarized beam, polarized target**

Double Polarization Experiments - Selected Results -

Circularly polarized photons, longitudinally polarized target

CBELSA/TAPS

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

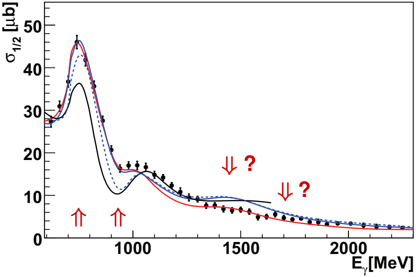
PWAs:

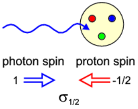
SAID (SN11, CM12), MAID
BnGa (2011_2)

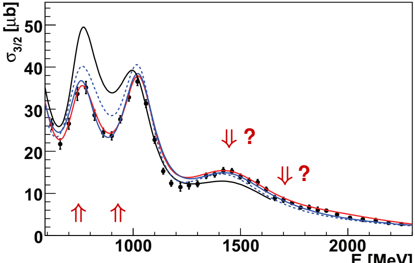
$\leftrightarrow$ describe the so far existing photoproduction data, but ...

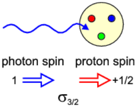
large deviations observed $\rightarrow$

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









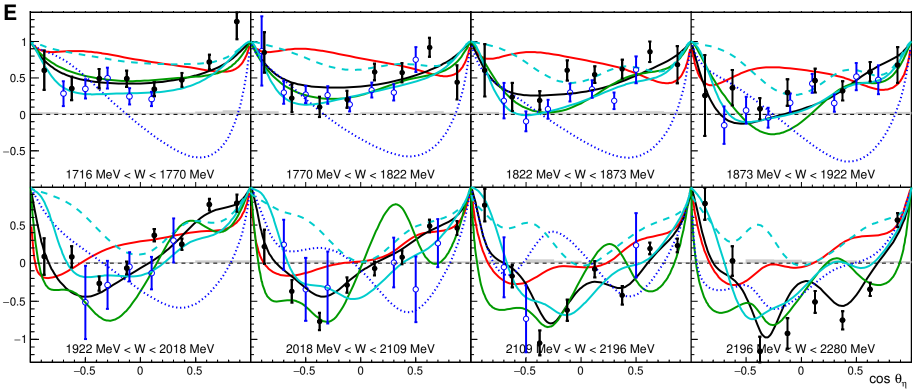
$\Rightarrow$

Sensitivity on high mass resonances !

M. Gottschall et al. (CBELSA/TAPS) Phys. Rev. Lett. 112, 012003 (2014), Eur. Phys. J. A57, 40 (2021)

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!**

—- BnGa refit —- BnGa 2011-02 —- MAID 2018
—- SAID (GE09) —- JüBo 2015/2015-3

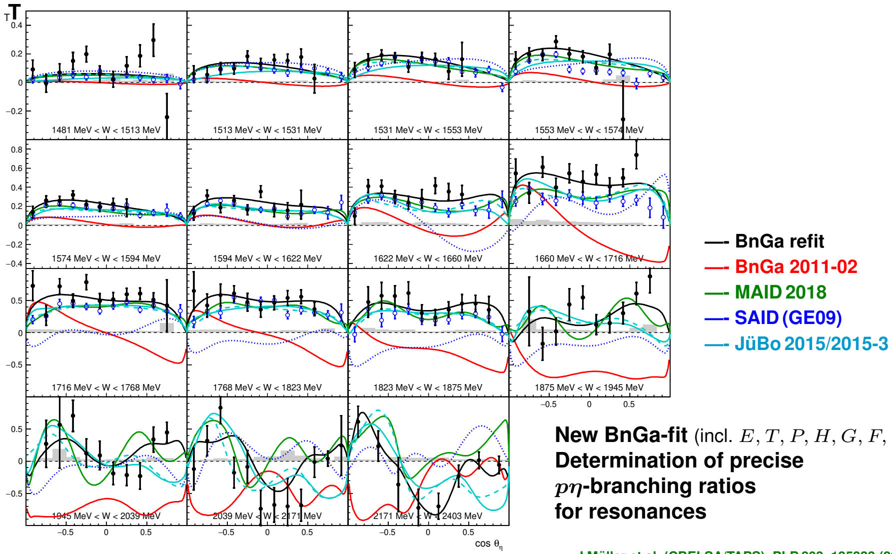
⇒ data approaches the high mass region

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

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

Polarization observables – selected results: $\vec{\gamma}\vec{p} \rightarrow p\eta$

lin. pol. photons, transv. pol. target, CBELSA/TAPS high energy bins, **blue: MAMI**



New BnGa-fit (incl. $E, T, P, H, G, F, \Sigma, \sigma$)**:**
Determination of precise
$p\eta$**-branching ratios**
for resonances

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

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)

	$N(1535)1/2^-$	$N(1650)1/2^-$	$N(1710)1/2^+$	$N(1895)1/2^-$
BnGa	**0.41±0.04**	**0.33±0.04**	**0.18±0.10**	**0.10±0.05**
PDG'2012	**0.42±0.10**	**0.05 - 0.15**	**0.10 - 0.30**	no PDG estimate

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

⇓

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 (double) polarization data was also included in JüBo:

D. Rönchen et al., Eur. Phys. J. A58 (2022) 229

⇓

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

Next step: Comparison of PWA-results of different groups including the new data
⇔ convergence towards consistent results?
JüBo, BnGa, MAID, SAID ...

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$^-$	*	***	***

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

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

(before: almost entirely πN-scattering and some π-photoproduction)

Photoproduction provides access to the "inelastic channels"

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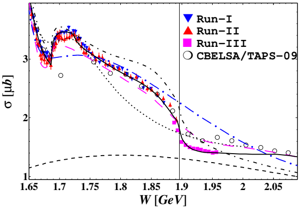
N(1900)3/2$^+$	**	****	****
N(2060)5/2$^-$		***	***
N(2100)1/2$^+$	*	***	***
N(2120)3/2$^-$		***	***
Δ(1600)3/2$^+$	***	***	****
Δ(1900)1/2$^-$	*	***	***
Δ(1940)3/2$^-$	*	**	**
Δ(2200)7/2$^-$	*	***	***

$\Leftrightarrow$

Interesting recent MAMI-data:

$\gamma p \rightarrow \eta p$



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

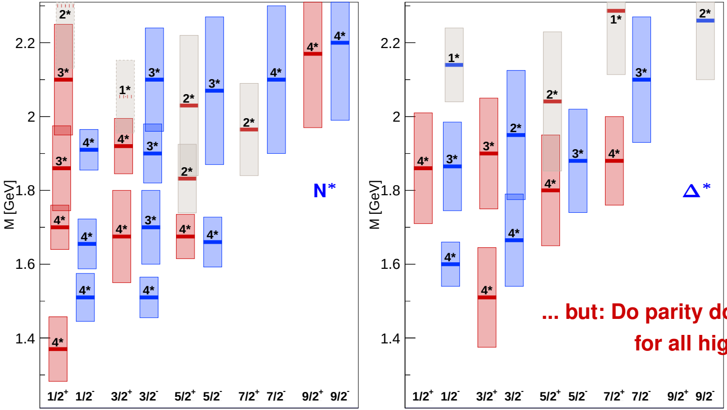
$\Rightarrow$ **cusp effect $\eta' p$-threshold observed**

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 ∼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)**$5/2^-$ **???** $7/2^-$

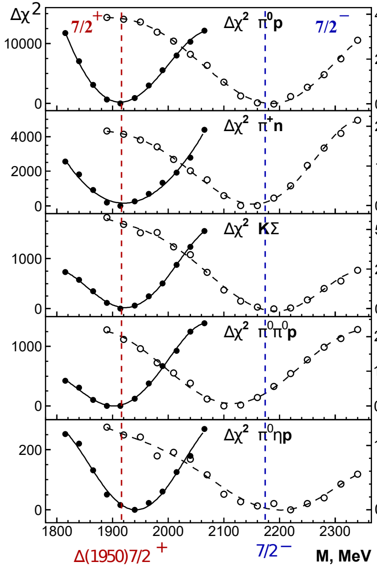
Search for the parity partner of the well known Δ(1950)$7/2^+$ (4*) ⟹

⇒ **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

The baryon spectrum

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

⇔ **Does the SU(6)xO(3) 20'plet exist? / or in generell the still *missing* states?**

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

- **Existing but experimentally not found yet?**
  - ⇔ **photoproduction of the neutron** ⟵ next
  - ⇔ **multi-meson photoproduction** ⟵ interesting results - not discussed today

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

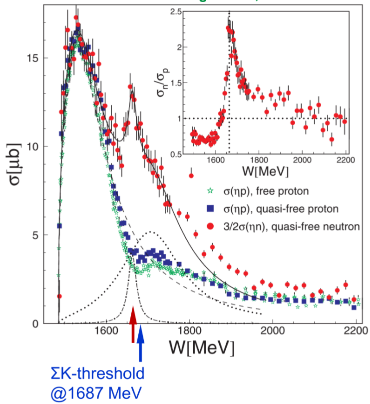
(SU(6): u ↑↓ d ↑↓ **s** ↑↓)

⇔ **photoproduction of strange baryons**

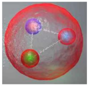
= the obvious next step into the future ⟵ plans at ELSA

η - photoproduction off the neutron

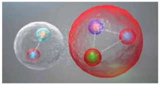
I.Jaegle et al., CBELSA/TAPS



Nature of complex bound states in QCD = ?



qqq



meson-baryon

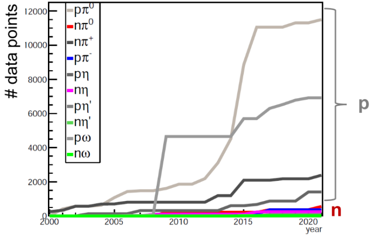
Photoproduction off the neutron

≠ Photoproduction of the proton (Isospin dependence)

⇔ **Interesting structures**

⇔ **New states?**

Existing polarization data



A. Thiel, F. Afzal, Y. Wunderlich, PPNP 125 (2022) 103949

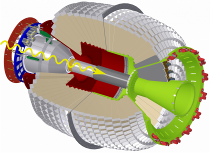
Measurement of polarization observables important

but: Very scarce !

N*-resonances may decouple from the proton and couple to the neutron

Photoproduction off the neutron at ELSA

Recent Crystal Barrel calorimeter upgrade:



APDs and Sampling
ADC-readout ⇔ **Trigger/time**

⇒ **Flat trigger acceptance for all neutral final states**

→ **Photoproduction off the neutron**

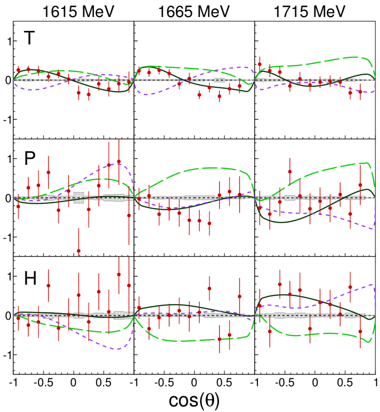
⇒ **Higher data taking rates** (factor ∼7)

→ **e.g. multi-particle final states (higher stat.)**

Linearly polarized photon beam on transversaly polarized target ⇔ T, P, H

Narrow resonance structure (pentaquark?) **or interference effect?**

showing 3 bins only:



N. Jermann (CBELSA/TAPS) submitted for publ.

Predictions:

BnGa: interference in the 1/2$^-$-wave

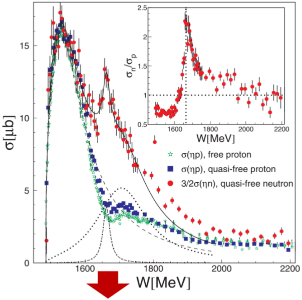
BnGa: structure explained by narrow N(1685)1/2$^+$

MAID: N(1535)1/2$^-$ N(1710)1/2$^+$

Present BnGa-fits including the new data:
Best fit to all $\gamma n \rightarrow n\eta$ data: No narrow 1/2$^+$-state needed!

Photoproduction off the neutron at ELSA

I. Jaegle et al, EPJA 47 (2012) 89 (CBELSA/TAPS)



$\mathbf{W = 1665 \pm 25\ MeV}$

⇔

Linearly polarized photon beam on transversaly polarized target ⇔ T, P, H

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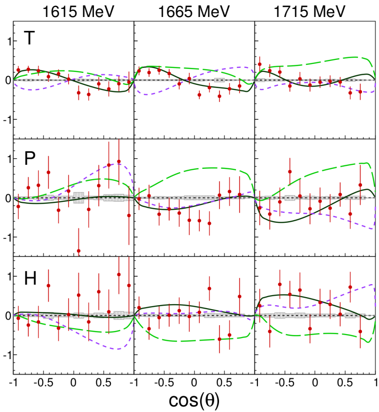
showing 3 bins only:



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Strange baryons: **"... the field is starved for data " (PDG'2022)**

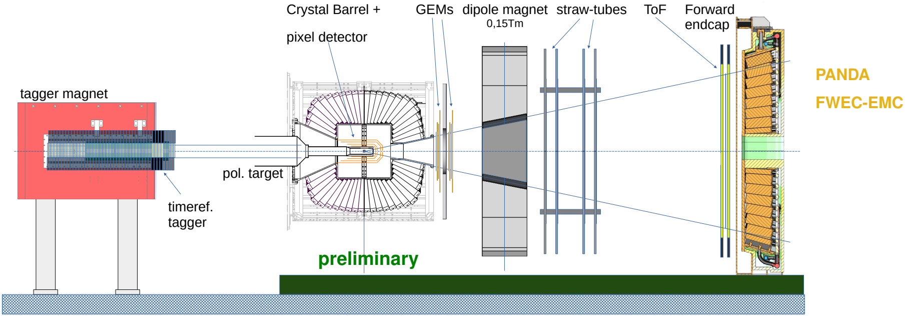
Established resonances remained the same for the last $\sim$40 years!

Interesting exception: Two pole structure of the $\Lambda(1405)$

$\Leftrightarrow$ **Not even all states of the first excitation band known**

- **spectrum and properties of Λ^*, Σ^*** $\leftrightarrow$ SU(6)xO(3)?
- **multi-quark states? molecules? 2-pole structures?**

$\Leftrightarrow$ **New data urgently needed!**



$\Leftrightarrow$ **new final states including strange baryons!**

@ELSA, e.g.:

$$\gamma p \rightarrow K^+ \Lambda^* \rightarrow K^+ \Sigma^0 \pi^0$$ isospin selective
$$\rightarrow K^+ \Lambda \gamma \pi^0$$
$$\rightarrow K^+ (p\pi^-) \gamma \pi^0$$

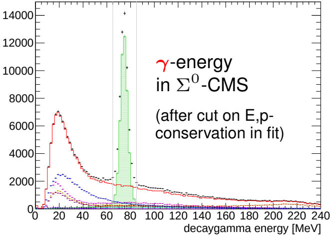
$$\gamma p \rightarrow K^+ \Sigma^{*0} \rightarrow K^+ \Lambda \pi^0$$ isospin selective
$$\rightarrow K^+ (p\pi^-) \pi^0$$

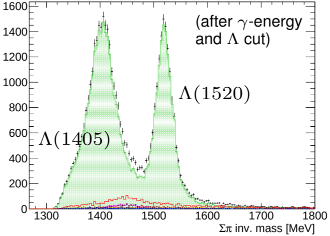
How well can we measure strange baryons?

One example (simulations)**:**

$$\gamma p \rightarrow K^+ \Lambda^* \rightarrow K^+ \Sigma^0 \pi^0 \rightarrow K^+ \Lambda \gamma \pi^0 \rightarrow K^+ (p\pi^-) \gamma \pi^0$$

$\Leftrightarrow$ $K^+ \Lambda(1405)$ $(0.5\mu b)$ **and** $K^+ \Lambda(1520)$ $(0.7\mu b)$





background channels:

- $K^+\Sigma(1385)$: $0.8\mu b$
- $K^0\Sigma^+$: $0.6\mu b$
- $K^+\Sigma^0$: $1.8\mu b$
- $p\pi^0\eta$: $3.5\mu b$
- $p\pi^+\pi^-\pi^0$: $9\mu b$
- $K^+\Sigma(1385)\pi^0$: $0.4\mu b$
- $K^+\Sigma^+\pi^-$: $1\mu b$
- $K^+\Lambda\pi^0$: $1\mu b$
- sum

$\leftrightarrow$ Very convincing signal

Summary: N^* and Δ^* resonances

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

$\leftrightarrow$ single and double polarisation experiments (many final states)

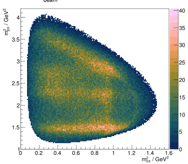
$\Rightarrow$ **Observation of new resonances**

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

e.g.: - puzzeling difference between $p\eta$-BR of N(1535)1/2$^-$ and N(1650)1/2$^-$ now very much reduced
- multi-meson-decays of baryon resonances

$\Rightarrow$ **much more interesting results to come and data to be analysed**

$\gamma p \rightarrow p\pi^0\pi^0$



+ polarisation obs.

$\Rightarrow$ **Many interesting results on the spectrum and the properties of baryon resonances**

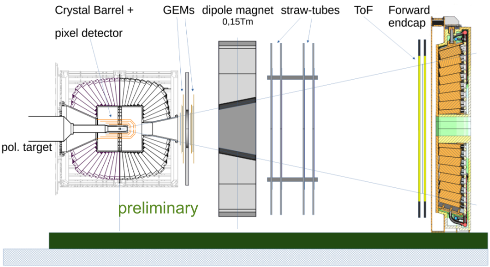
$\Leftrightarrow$ **Quark models/first lattice calculations do not yet provide the expected systematics in the spectrum**

Experiment: - no alternating pattern of positive and negative parity states
- parity doublets observed (not for all states (?))

$\Downarrow$

Bound states of QCD are not yet understood! $\Leftrightarrow$ new insights: strange baryons

.... future plans @ ELSA



4π measurement of photons and detection of charged particles

$\sqrt{s_{\max}} = 2.6\ \mathrm{GeV}$

+ polarisation measurements

Non-strange baryon spectroscopy:

Gain a complete picture of the light-quark N^*, Δ^*- baryon spectrum:

- **Polarized photoproduction off the polarized proton <u>and</u> neutron!**

⇔ unambiguous PWA not possible without the measurement of polarization observables

- **Multi-meson photoproduction**

Strange baryon spectroscopy (Λ^*, Σ^*):

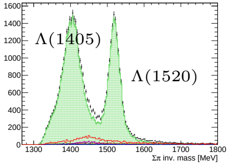
More states expected than in the u, d-sector but much less states found so far!

⇔ **Do they exist ?**

⇔ **Are they consistent with SU(6)xO(3)- symmetry?**

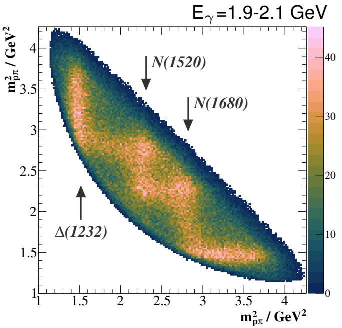
⇔ **Nature of the observed states=?**

e.g. Λ(1405), 2-pole structures / multiquark-states?

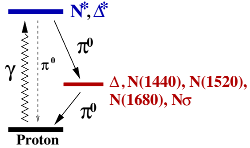


PDG'2022: ".., the field is starved for data"

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



⇔ **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 ?

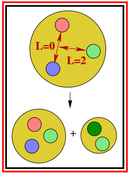
V. Sokhoyan et al. (CBELSA/TAPS-collaboration), EPJA 51 (2015) 95
A. Thiel et al. (CBELSA/TAPS-collaboration), PRL 114 (2015) 091803, T.Seifen et al., arXiv:2207.01981 [nucl-ex]

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

An interpretation using quarkmodel-wave-functions:

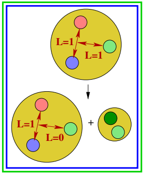
Δ^*'s @1900 MeV:

symmetric wave function (56'plet)

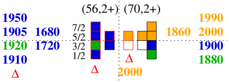


N*'s @1900 MeV:

wave function: M_S / M_A (70'plet)

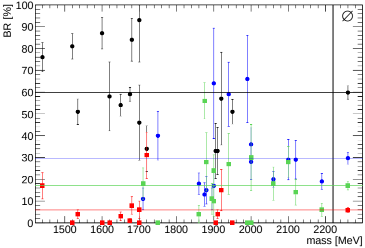


SU(6)⊗O(3) for L=2, N=0



⇒ **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

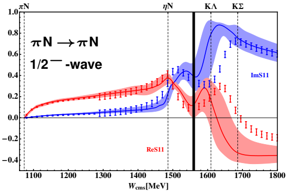
Interpretations of the 1/2$^-$ states: N(1535)1/2$^-$, N(1650)1/2$^-$

Effective degrees of freedom: 3q vs. meson-baryon

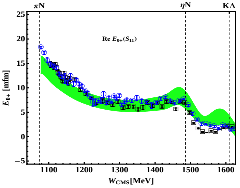
- **Coupled-channel unitarized chiral pert. theo.:**

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

parameters fixed in the strong sector:



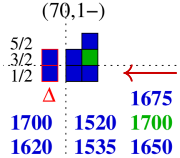
parameter-free prediction $\gamma p \to p\pi^0$:



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

- **SU(6)xO(3):**

N(1535)1/2$^-$, N(1650)1/2$^-$, Δ(1620)1/2$^-$ are part of the 70'plet



seems unnatural to steal two of those ...

⇓

- are dynamically generated poles and "3q"-poles different descriptions of the same object?

$\leftrightarrow$ 3q and molecular component?

- or orthogonal states?

$\Leftrightarrow$ No spectrum of molecular states (N^*/Δ^*) predicted, yet

Interpretations of the $1/2^-$ states:

Effective degrees of freedom in the baryon spectrum: 3q vs. meson-baryon

Non-strange baryon sector:

- **Coupled-channel unitarized chiral pert. theo.:**

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

e.g. Mai, Bruns, Meißner, PRD 86 (2012) 094033

- **SU(6)xO(3):**

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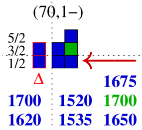


seems unnatural to steal two of those ...

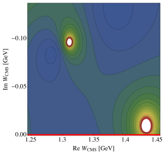
$\leftrightarrow$ 3q and molecular component ?

Strange baryon sector:

- **Coupled-channel unitarized chiral pert. theo.**

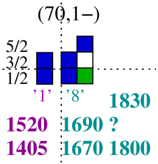
$\Leftrightarrow$ 2-pole structure of $\Lambda(1405)$

$\Lambda(1325) \leftrightarrow$ '1' (dom.)
$\Lambda(1405) \leftrightarrow$ '8' (dom.)

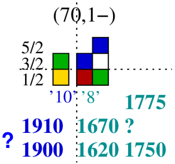


- **SU(6)xO(3):**

Λ^*:



Σ^*:



$\leftrightarrow \Lambda(1325)$ cannot be accomodated ...

Here we are in contradiction with an simple qqq-model picture