UNIVERSITÄT BONN

The N*-spectrum and strong QCD

U. Thoma, Bonn

Contents:

- Introduction
- Experimental data
- Results on the spectrum
- Interpretations / open questions
- Summary

... before I start:

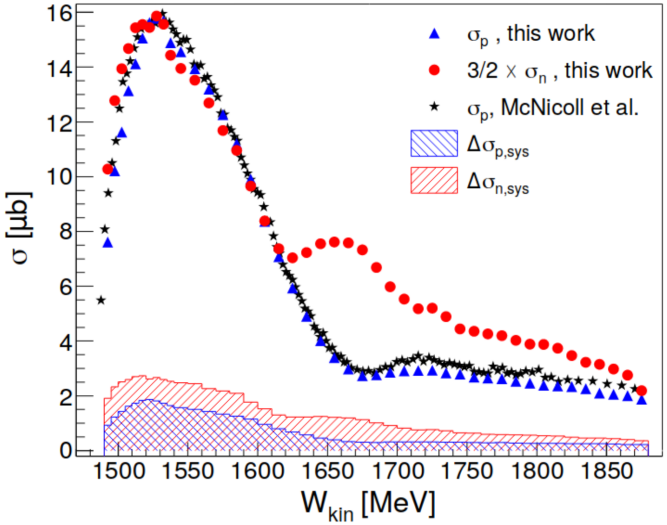
I would like to remember Bernd Krusche ...

.... who passed away much too early

„In memoriam Bernd Krusche“
V. Metag, Thursday, Oct. 20th

Many, many contributions to the field, e.g.:

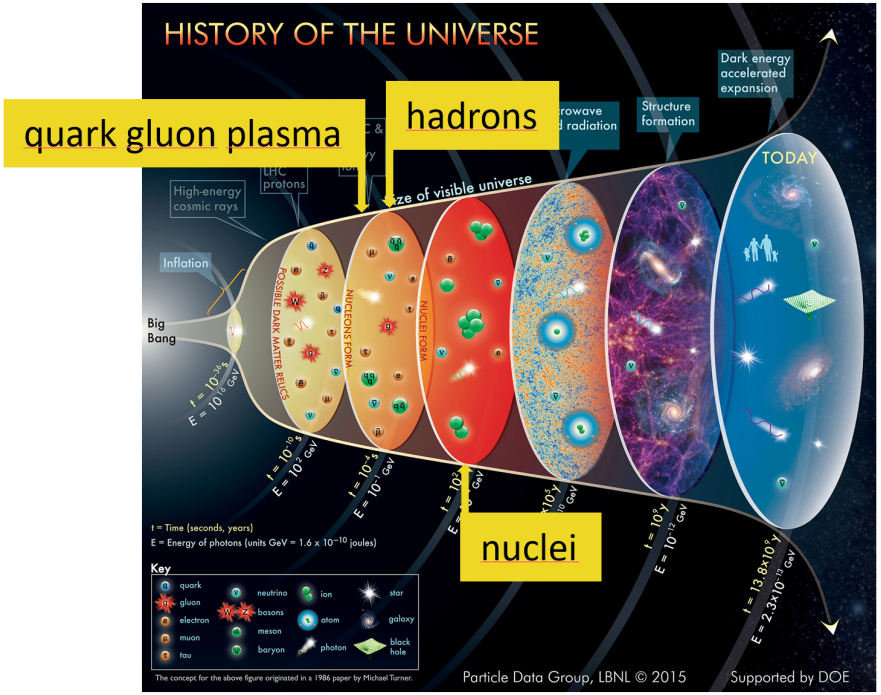
⇔ η-photoproduction off the neutron and proton



L. Witthauer / D. Werthmüller - Basel

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 $\leftrightarrow$ non-abelian character of QCD

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

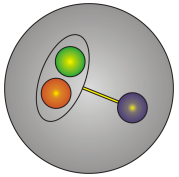
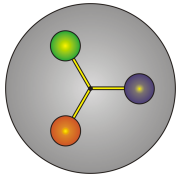
⇔ **One of the worst understood areas of the standard model = a challenge!**

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

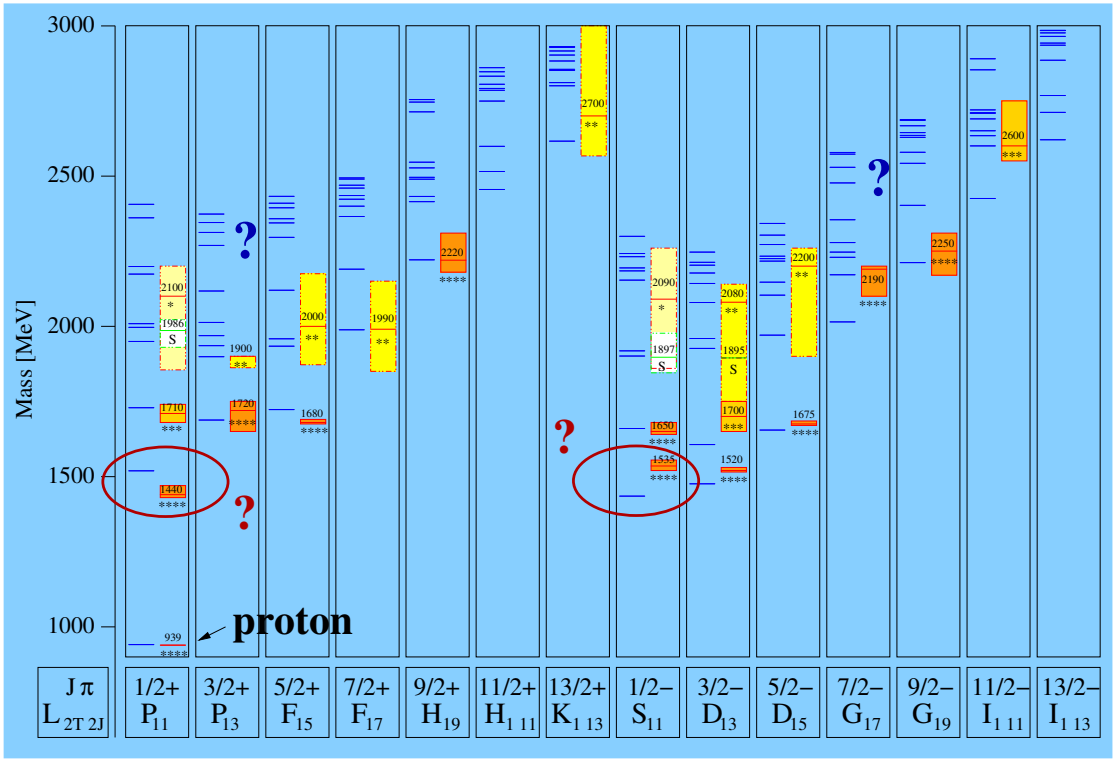
Baryon Spectroscopy

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

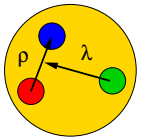


non-strange N*-resonances

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

relativistic quark model

Constituent quarks, confinement potential + residual interaction



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

$\leftrightarrow \mathbf{J^P}$

Baryon Spectroscopy

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

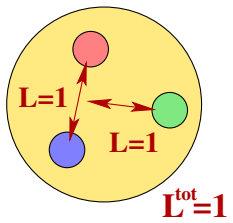
- What are the relevant degrees of freedom ?
- Effective forces between them ?

- **Symmetric quark models:**
  $\rightarrow$ **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

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 ?
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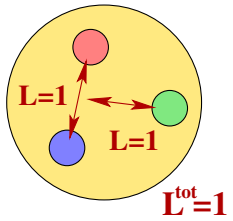


... not yet identified

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 ...

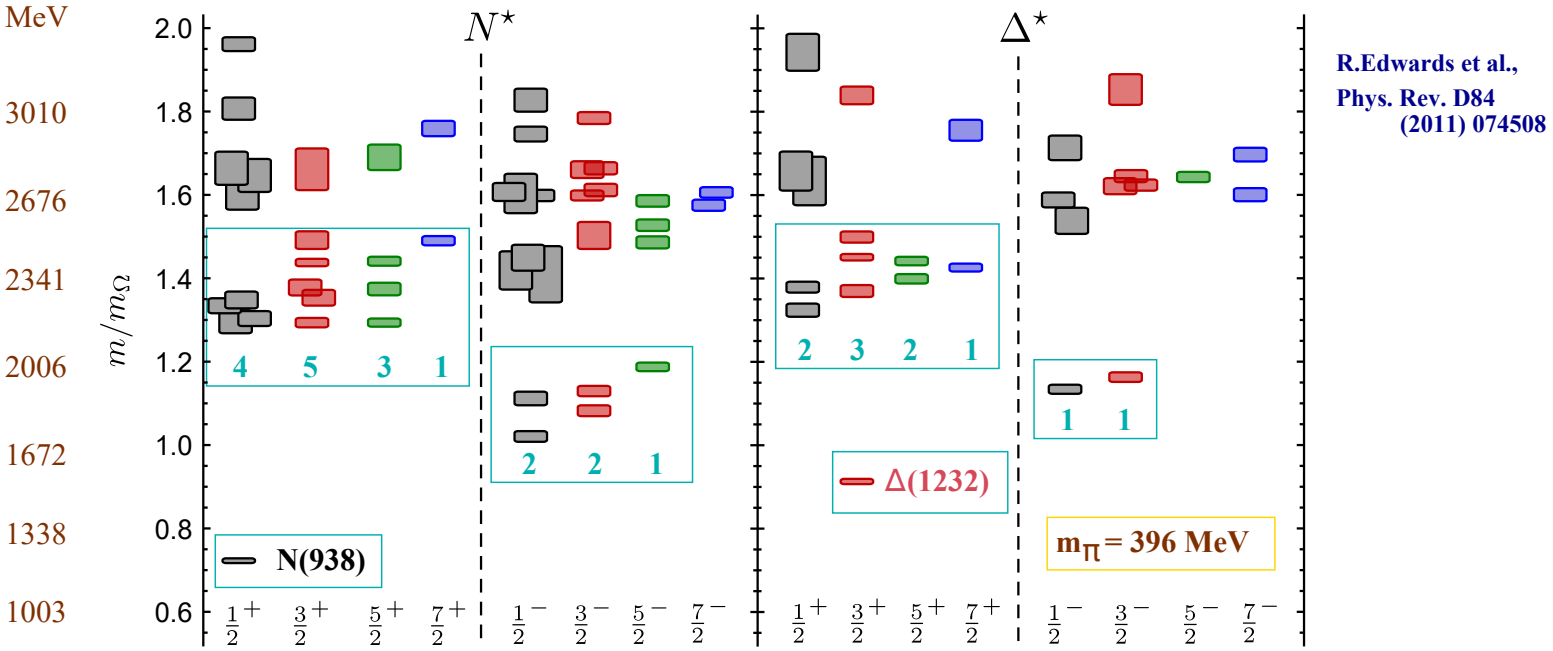
$\leftrightarrow$ **Functional methods (Dyson-Schwinger/Bethe-Salpeter equations)**
Nice results! ... spectrum so far only J=1/2, 3/2 (up to $\sim$ 1900 MeV)

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:



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

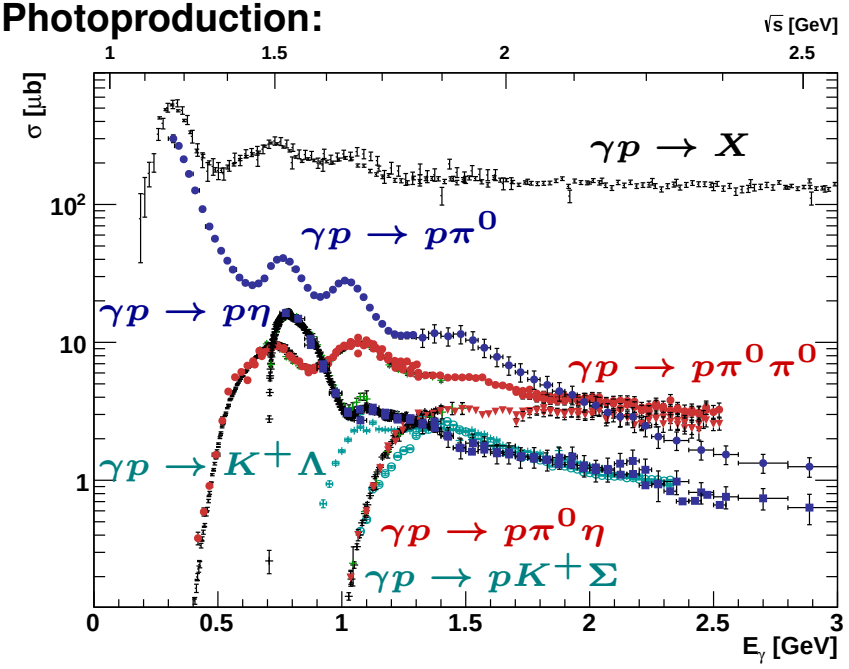
Important:

→ **Investigation of different final states**

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

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

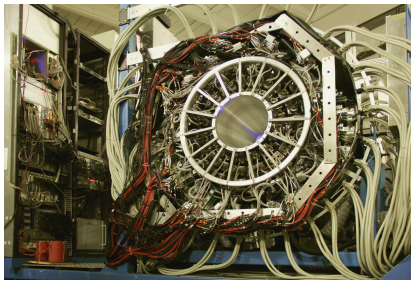
Photoproduction:



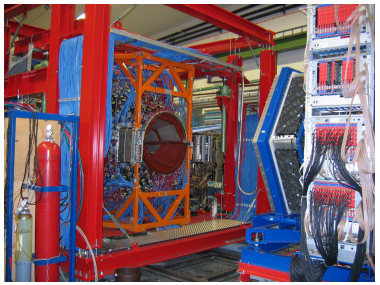
Recently: a lot of progress from photoproduction experiments:

CLAS (JLab),

CBELSA/TAPS (ELSA),



CBALL (MAMI),



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

⇔ **polarized beam, polarized target**

Baryon Spectroscopy

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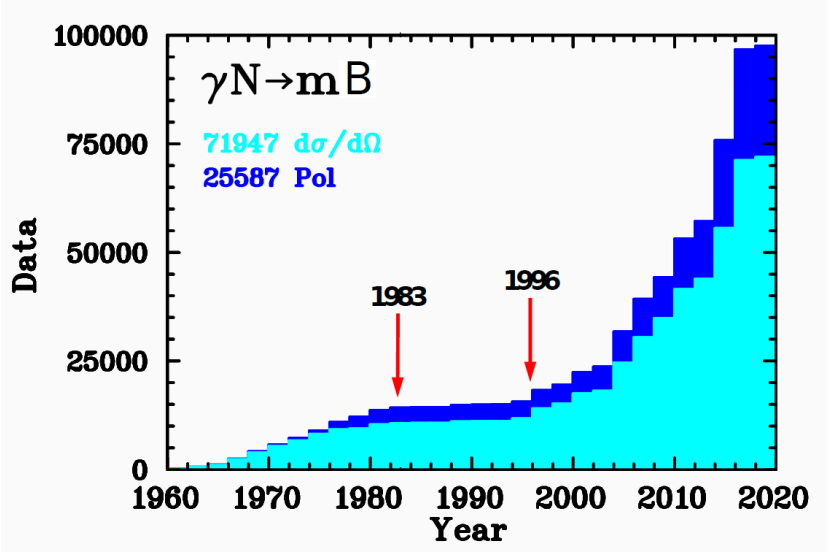

D. Ireland et al., Prog. Part. Nucl. Phys. 111 (2020) 103752

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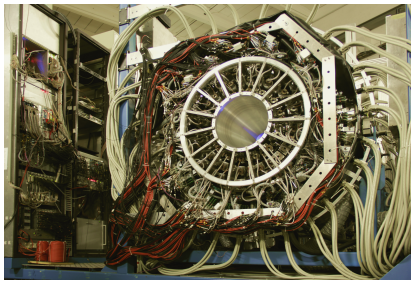

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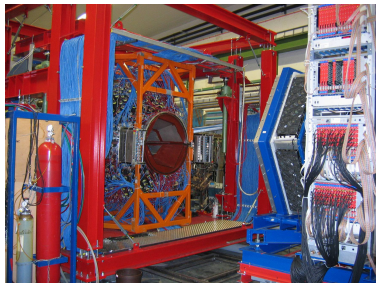


LEPS (Spring-8), BGOOD (ELSA), GRAAL (ESRF), ...

⇔ **polarized beam, polarized target**

Double Polarization Experiments - Selected Results -

Circularly polarized photons, longitudinally polarized target

CBELSA/TAPS

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

PWAs:

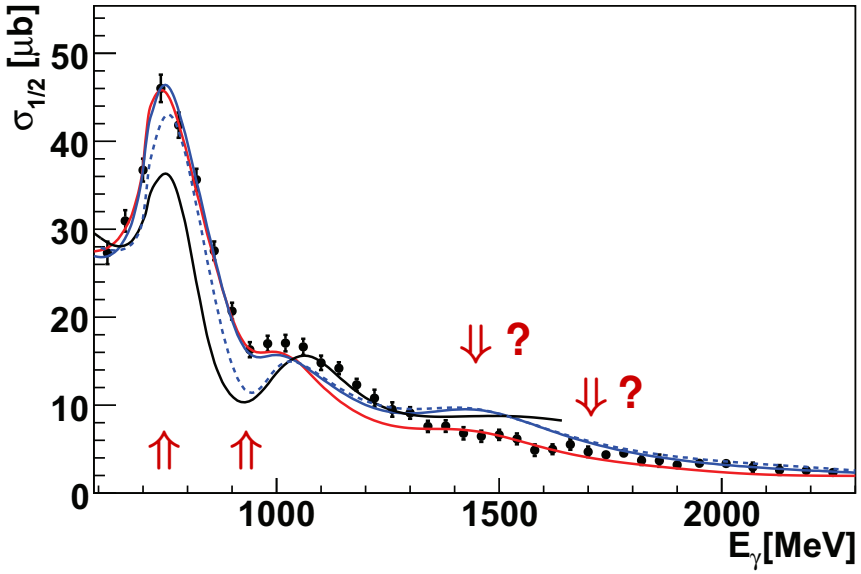
SAID (SN11, CM12), **MAID**

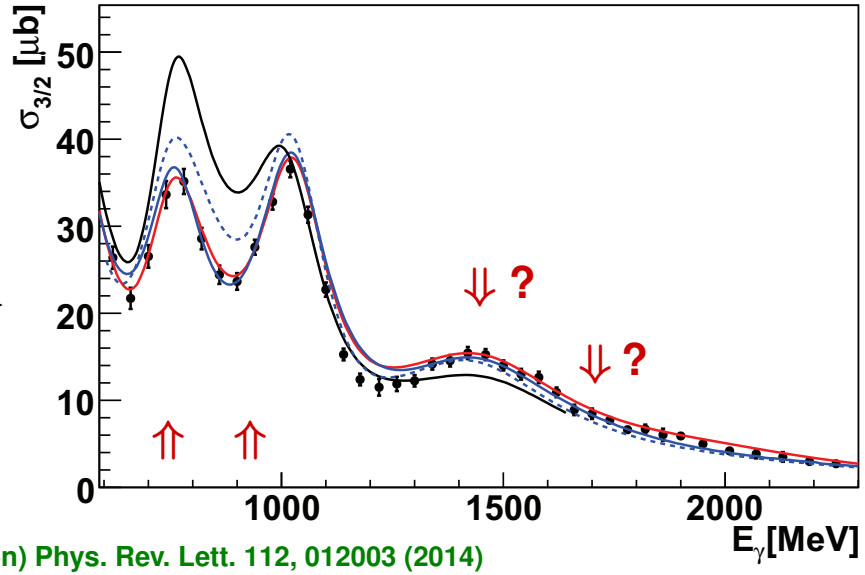
BnGa (2011_2)

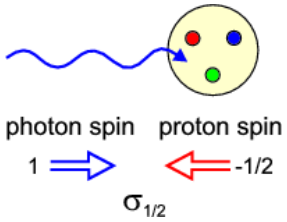
$\leftrightarrow$ **describe the so far existing photoproduction data, but ...**

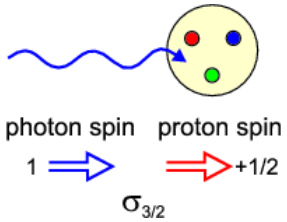
large deviations observed $\rightarrow$

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









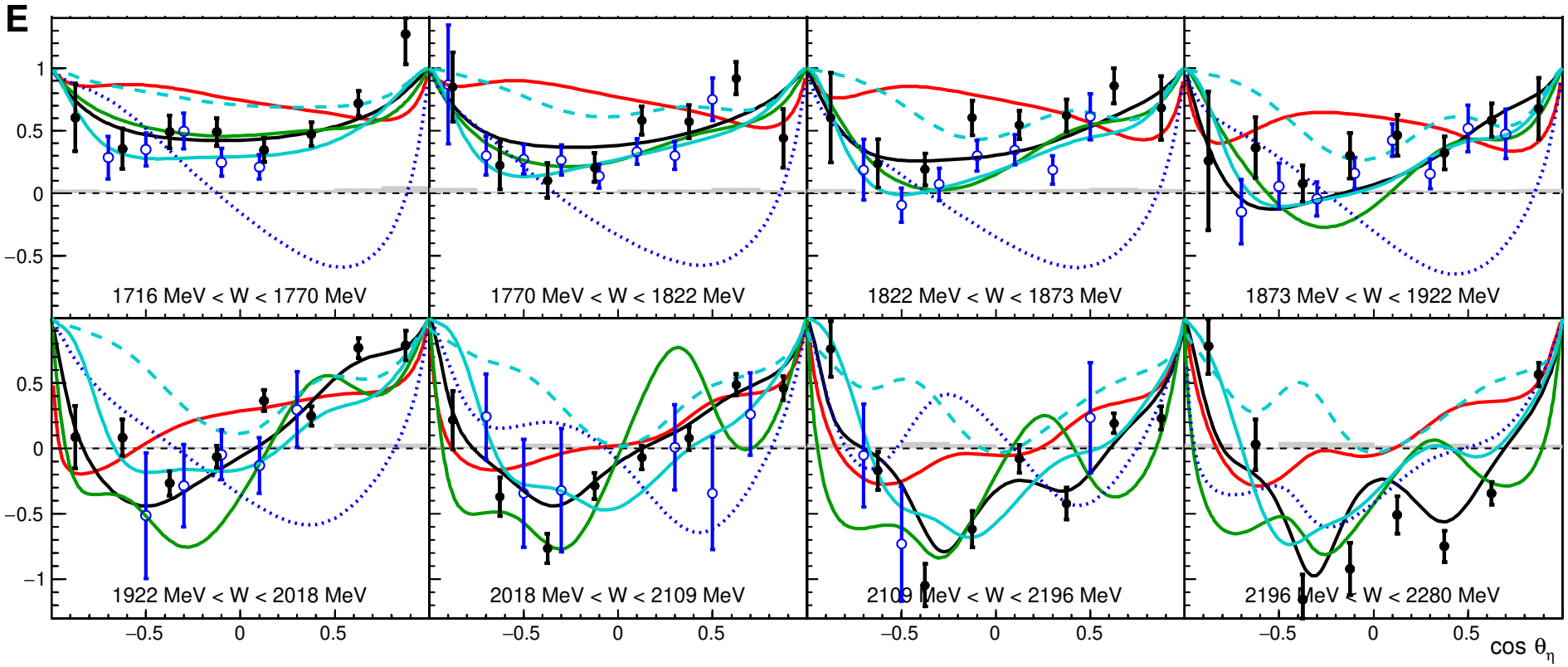
$\Rightarrow$

Sensitivity on high mass resonances !

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

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

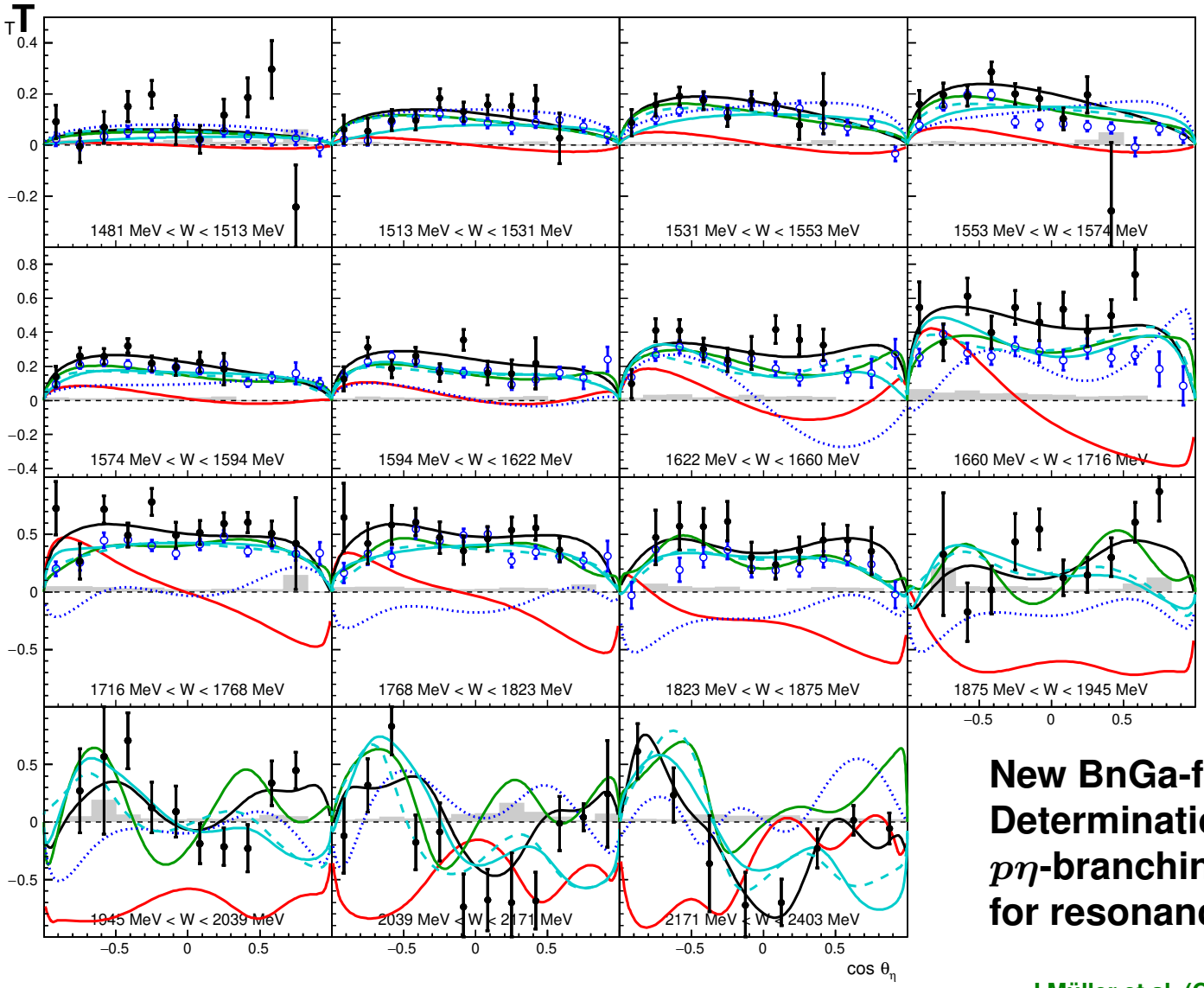
⇒ data approaches the high mass region

— 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: $\vec{\gamma}\vec{p} \to p\eta$

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



—- BnGa refit
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—- JüBo 2015/2015-3

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)

$\vec{\gamma}\vec{p} \to p\eta$ - 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)

	$N(1535)1/2^-$	$N(1650)1/2^-$	$N(1710)1/2^+$	$N(1895)1/2^-$
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

$\Leftrightarrow$ **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 (double) polarization data was also included in JüBo:

D. Rönchen et al., e-Print: 2208.00089 [nucl-th]

$\Downarrow$

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
$\Leftrightarrow$ 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 ...

Results: The Spectrum of Baryon Resonances

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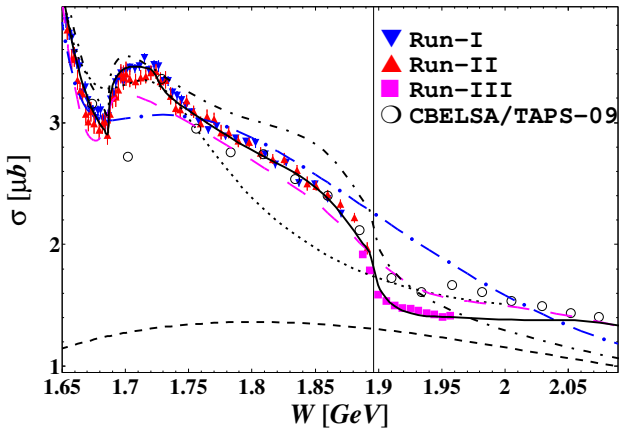
N(1895)1/2$^-$		****	****
N(1900)3/2$^+$	**	****	****
N(2060)5/2$^-$		***	***
N(2100)1/2$^+$	*	***	***
N(2120)3/2$^-$		***	***
Δ(1600)3/2$^+$	***	***	****
Δ(1900)1/2$^-$	*	***	***
Δ(1940)3/2$^-$	*	**	**
Δ(2200)7/2$^-$	*	***	***

⇔

Interesting recent MAMI-data:

$\gamma p \to \eta p$



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

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

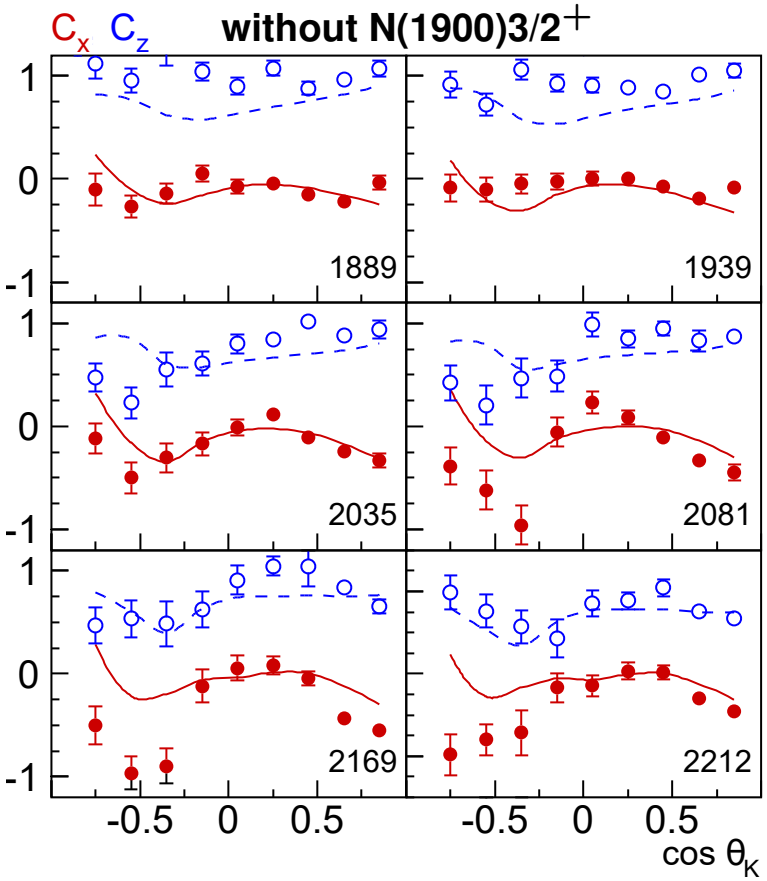
MAID-analysis of $\gamma p \to \eta p$, $\gamma p \to \eta' p$ confirms N(1895)1/2$^-$ coupling to $p\eta$, $p\eta'$

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 ...

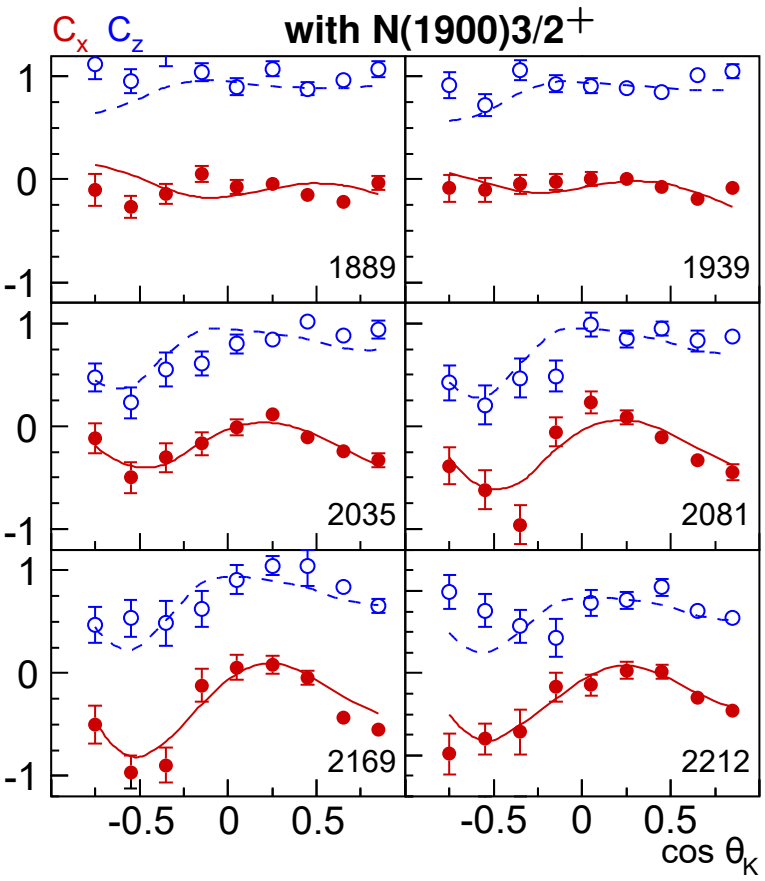
Strangeness Photoproduction: $\gamma p \to K^+\Lambda \to K^+ p\pi^-$

CLAS

Beam-Recoil polarization:



R. K. Bradford et al. (CLAS), PRC75, 035205 (2007)



V. Nikonov et al. (BnGa-PWA), PLB662, 245 (2008)

data for all possible 16 observables has been taken

(only 8 needed for the complete experiment)

Fit within the Bonn-Gatchina multi-channel PWA: Favours the existence of the N(1900)3/2$^+$

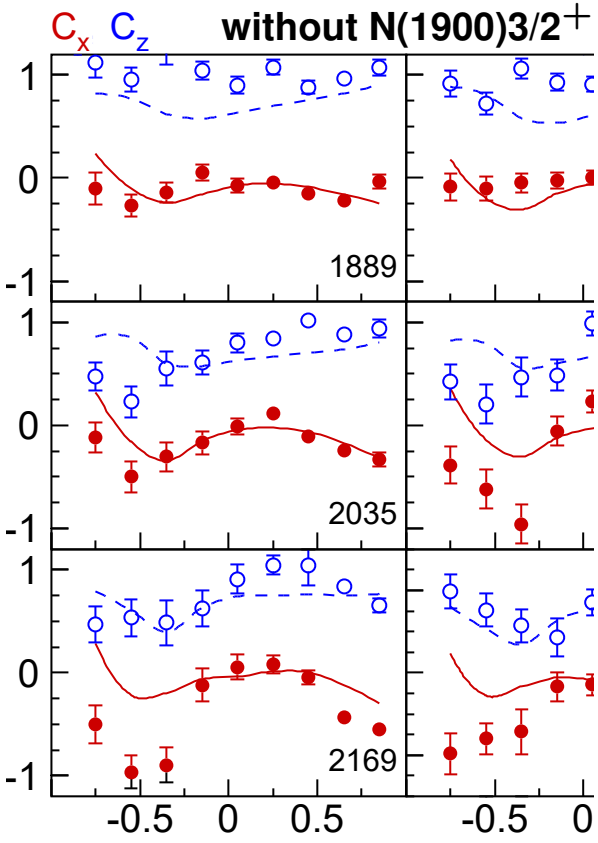
(confirmed by O. V. Maxwell, PRC85, 034611 (2012), T. Mart, M. Kholili, PRC86, 022201 (2012))

$\Leftrightarrow$ **Evidence against the quark-diquark model**

Strangeness Photoproduction: $\gamma p \to K^+\Lambda \to K^+ p \pi^-$

CLAS

Beam-Recoil polarization:

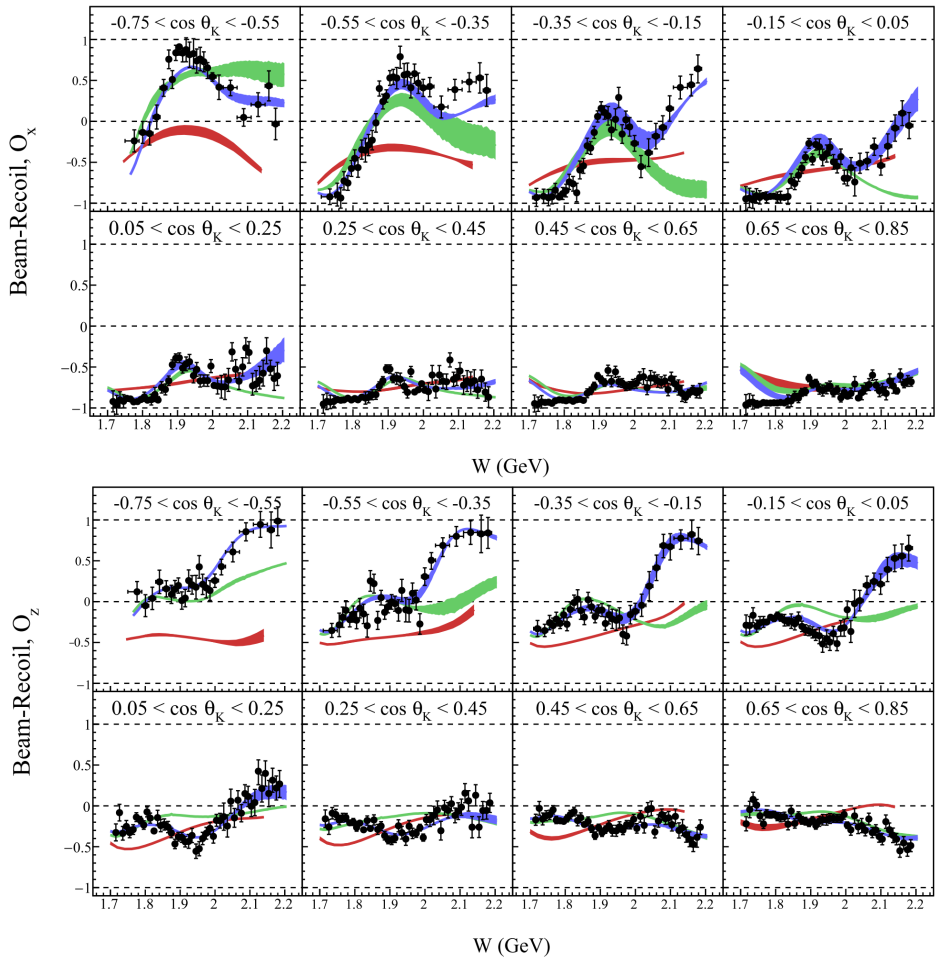


R. K. Bradford et al. (CLAS), PRC75, 03520

Fit within the Bonn-Gatchina

(confirmed by O. V. Maxwell, PRC85, 034611 (2

Linearly polarized photons + recoil polarization



ANL-Osaka
BnGa 2014
BnGa refit

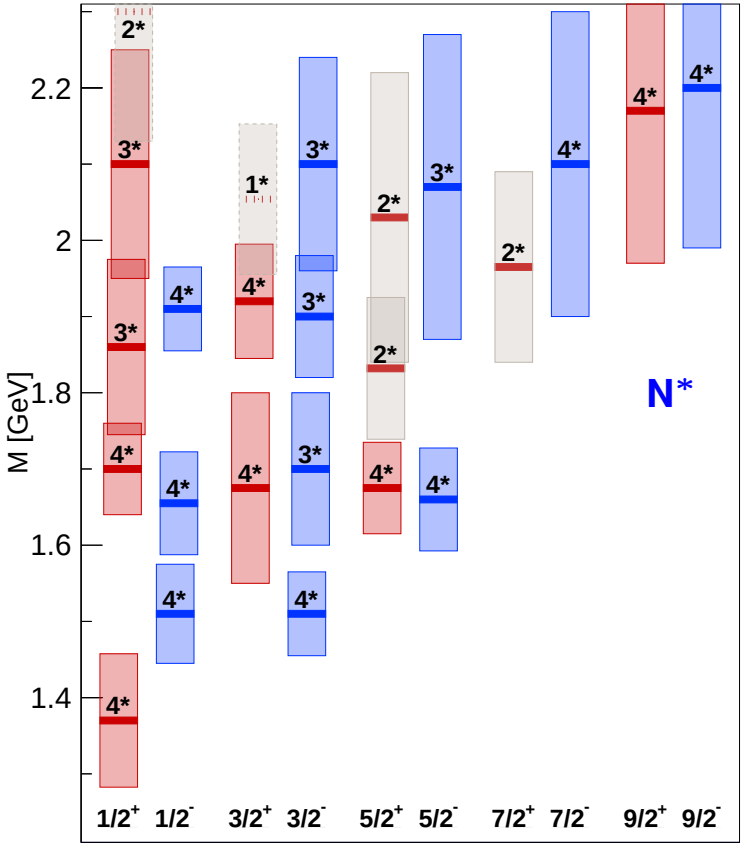
= additional constraints for PWAs

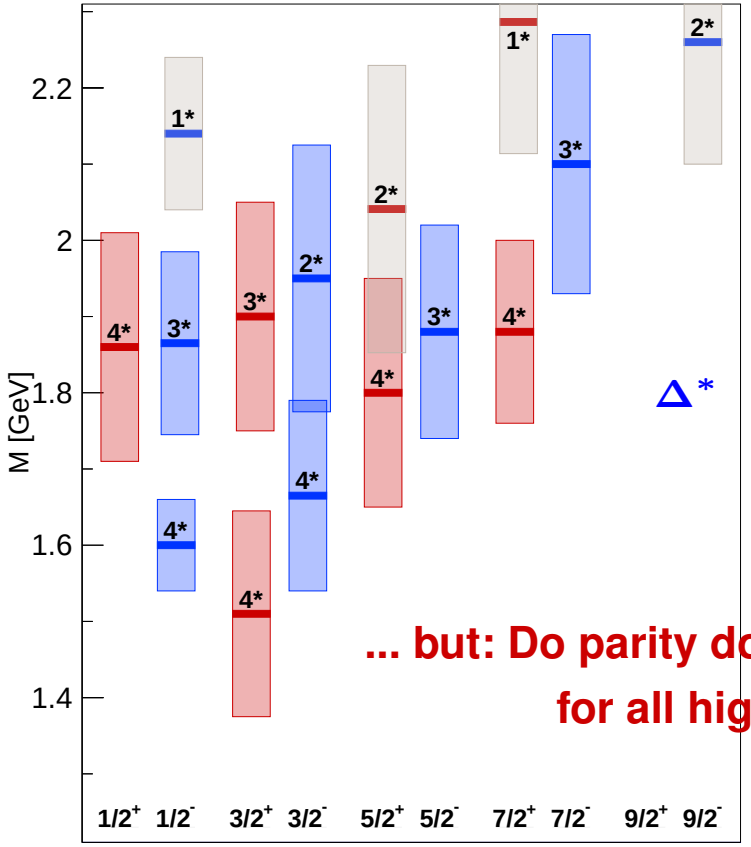
... e.g. JüBo (next talk)

C. A. Paterson, PRC93, 065201 (2016)

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 !

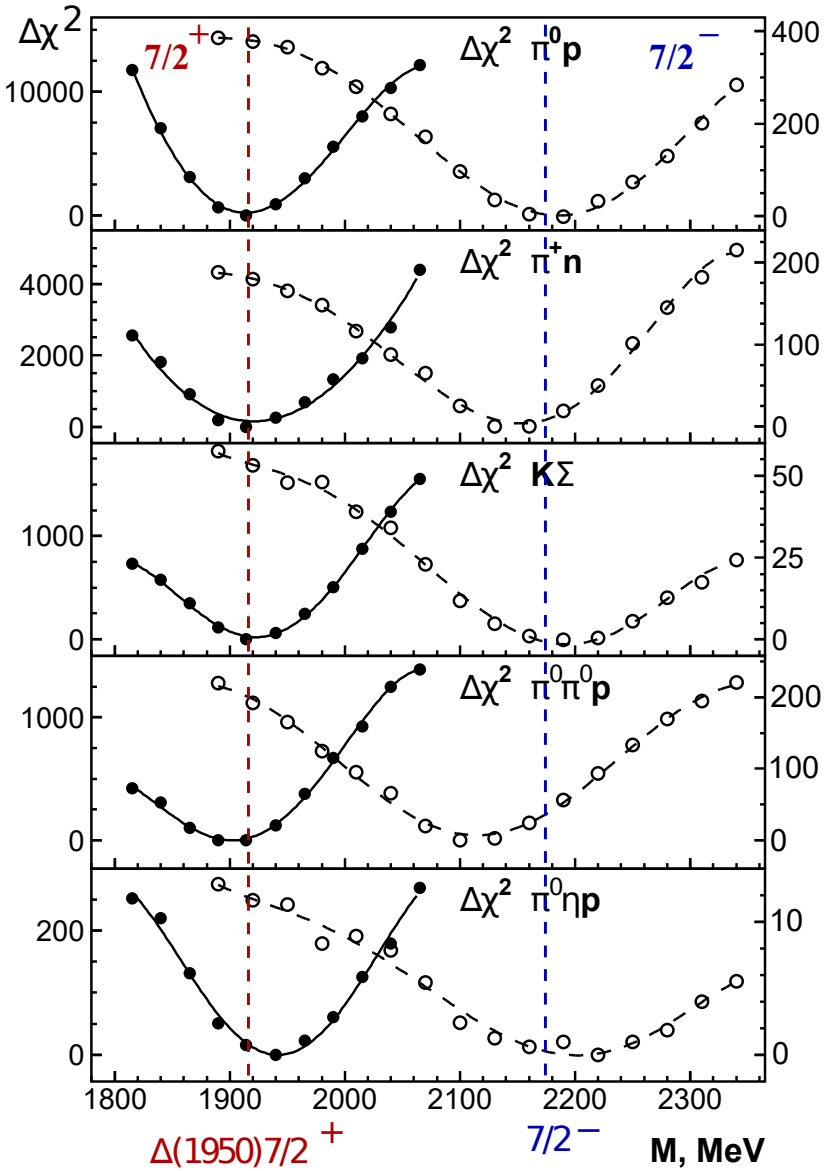
Search for parity doublets - Δ-states at $\sim$1900 MeV

$\Rightarrow$ **Do ALL high mass states have parity partners?**

$\Downarrow$

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*) $\Longrightarrow$



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

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

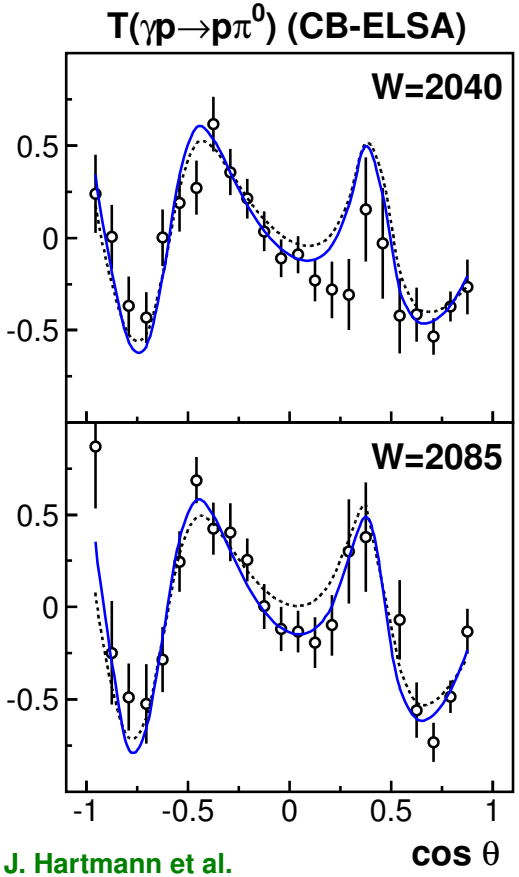
$\Leftrightarrow$ **No parity-partner found**

$\Rightarrow$ **Certain states have parity partners, others not**
$\Rightarrow$ **Not yet understood!**

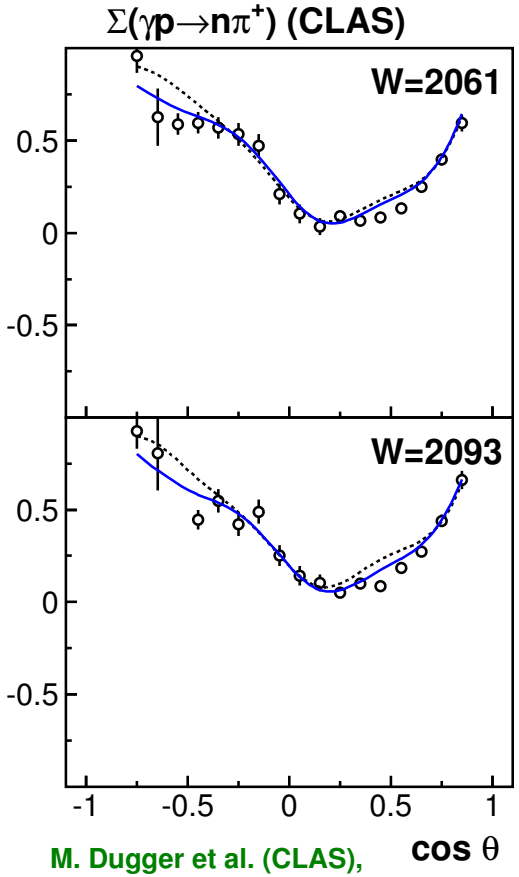
V. Anisovich et al. (BnGa-PWA), Phys.Lett. B766 (2017) 357

Precise measurements of polarisation observables

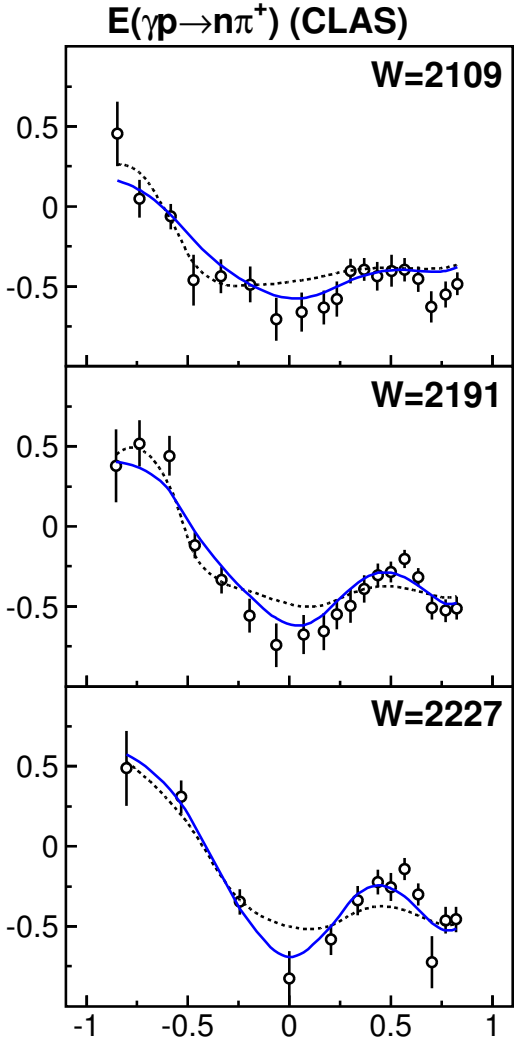
CBELSA/TAPS, CLAS-data (only a few of the measured bins shown:)



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



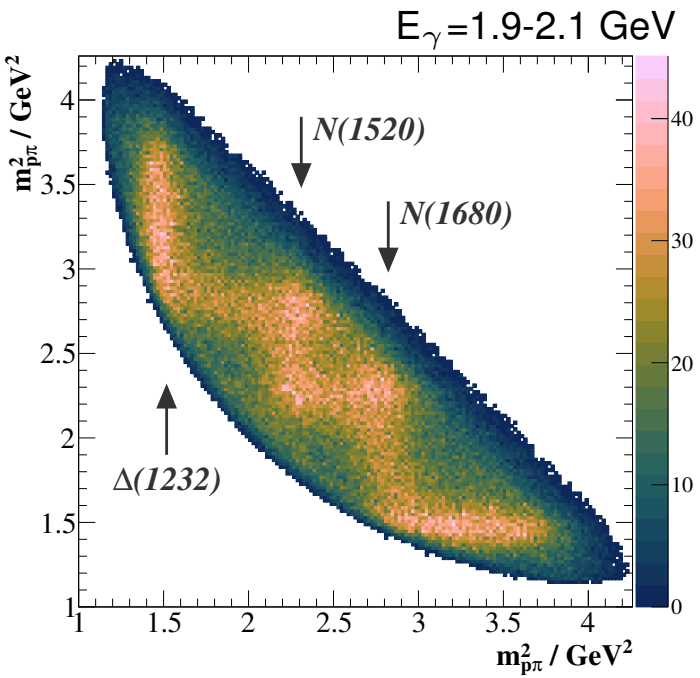
M. Dugger et al. (CLAS), PRC 88, 065203 (2013)



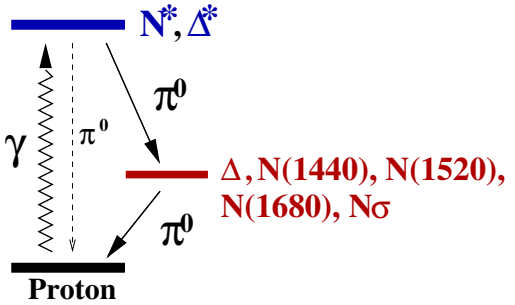
S. Strauch et al. (CLAS), PLB 750, 53 (2015)

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

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 ?

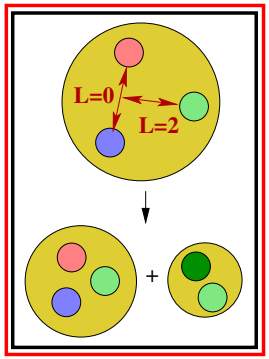
V. Sokhoyan et al. (CBELSA/TAPS-collaboration), EPJA 51 (2015) 95
A. Thiel et al. (CBELSA/TAPS-collaboration), PRL 114 (2015) 091803, T.Seifen et al., arXiv:2207.01981 [nucl-ex]

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

An interpretation using quarkmodel-wave-functions:

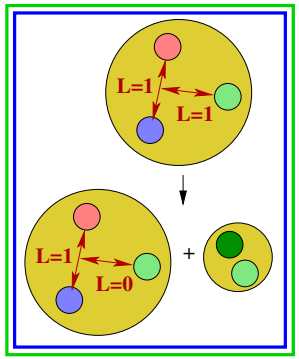
Δ^*'s @1900 MeV:

symmetric wave function (56'plet)

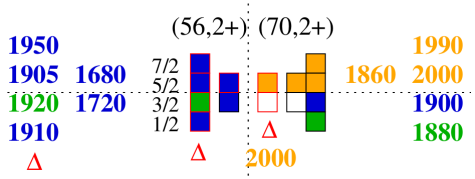


N*'s @1900 MeV:

wave function: M_S / M_A (70'plet)

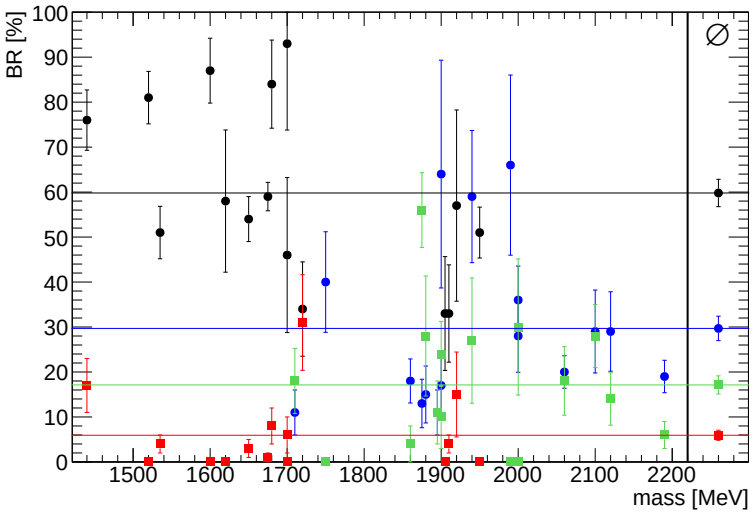


SU(6)⊗O(3) for L=2, N=0



⇒ **would explain the observation!**

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



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

(↔ talk N. Stausberg, today)

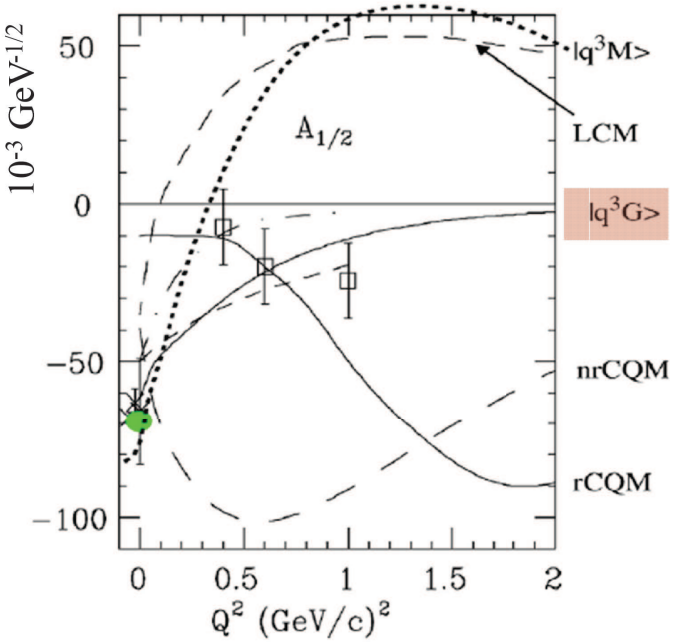
⇔ **supports a two-oscillator picture of resonances (3q)**

... confirmation in further (polarisation) measurements

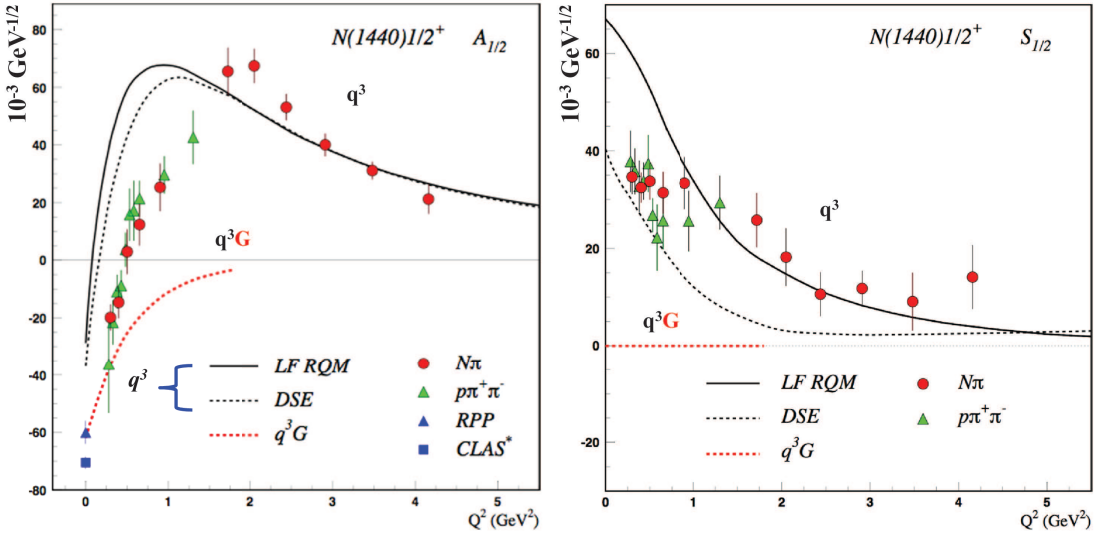
The nature of states: Roper resonance - N(1440)1/2$^+$

Electroproduction data from CLAS: Q^2-dependence of helicity amplitudes

in 2002 Roper was still consistent with a hybrid state



$\Rightarrow$ the new data:



LF RQM descibes helicity amplitudes at $Q^2 > 1.5\text{-}2.5\,\mathrm{GeV}^2$

Interpretation: Meson-baryon contributions dominate low Q^2-behaviour

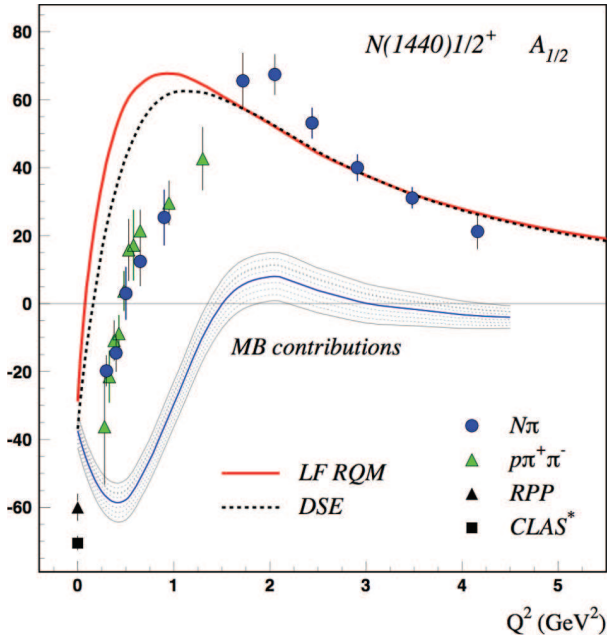
CLAS results: Identify Roper resonance as first radial excitation of the proton

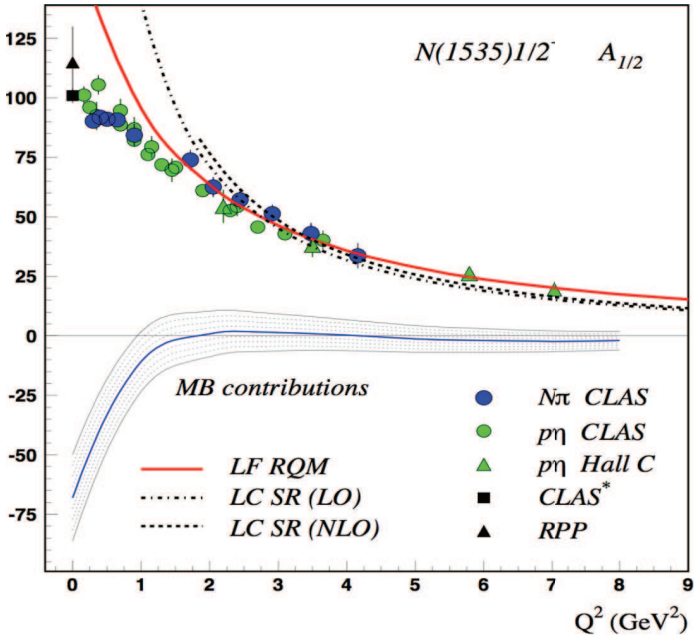
The 1st radial excitation of the 3q-core emerges as the probe penetrates the MB cloud

The nature of states: N(1440)1/2$^+$, N(1535)1/2$^-$

Electroproduction data from CLAS: Q^2-dependence of helicity amplitudes

N(1440)1/2$^+$ **N(1535)1/2$^-$**





LC SR: I. Anikin, V. Braun, N. Offen, PRD92 (2015) 014018

LF RQM: I. Aznauryan, V. Burkert, arXiv:1603.06692

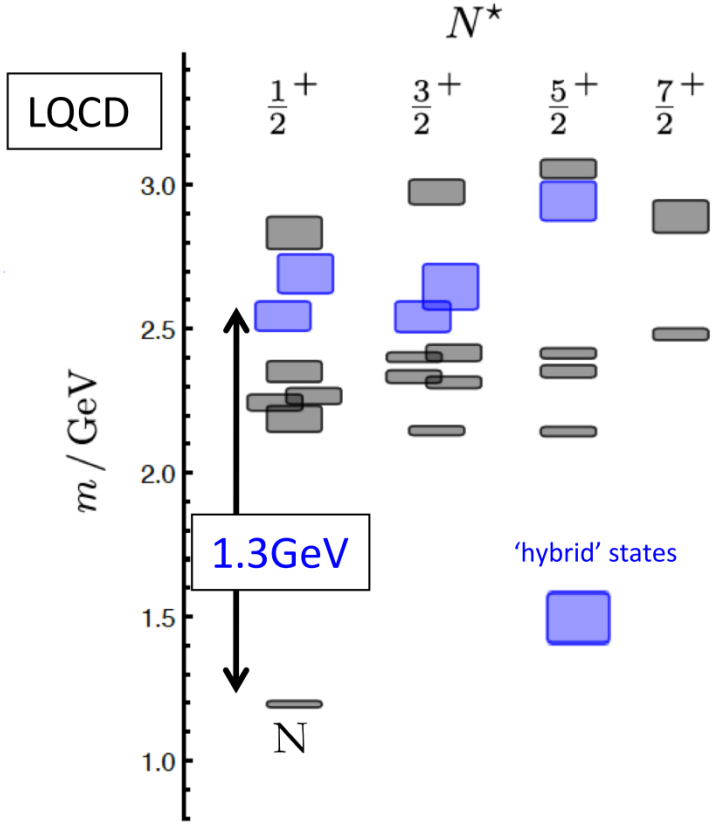
LF RQM descibes helicity amplitudes at Q^2 $>$1.5-2.5 GeV^2

Interpretation: Meson-baryon contributions dominate low Q^2-behaviour

Understanding the nature of the states further: qqq, meson-baryon, hybrid via measurement of the Q^2-dependence of the helicity amplitudes

$\Rightarrow$ **Further data to come from CLAS12** $\Leftrightarrow$ Extending the Q^2-range!

Hybrid states



J.J. Dudek and R.G. Edwards, PRD 85 (2012) 054016

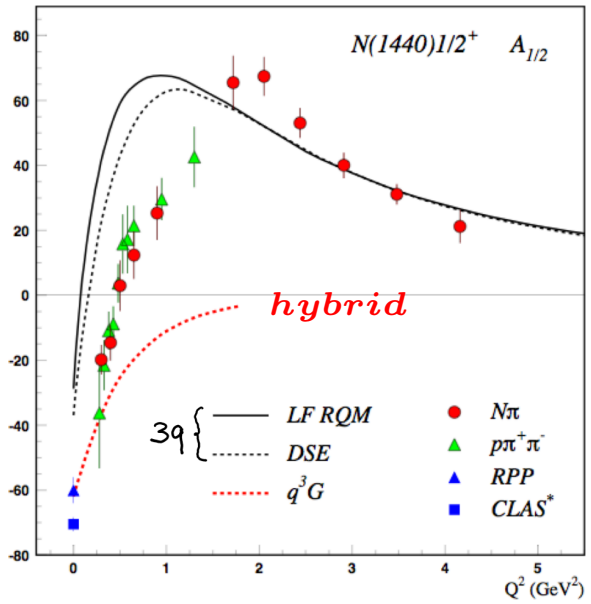
⇔ **Hybrid states expected around ∼2.2 GeV**

⇔ **additional supernumerous states in a probably "crowded" area (many states)**

⇓

Advantage of electroproduction: Different Q^2-dependence of resonances

⇒ **helps to extract the resonances from the data**



· · · while $S_{1/2}(Q^2) \approx 0$

CLAS'12 -proposal "A Search for Hybrid Baryons in Hall B with CLAS12" (Annalisa D'Angelo)

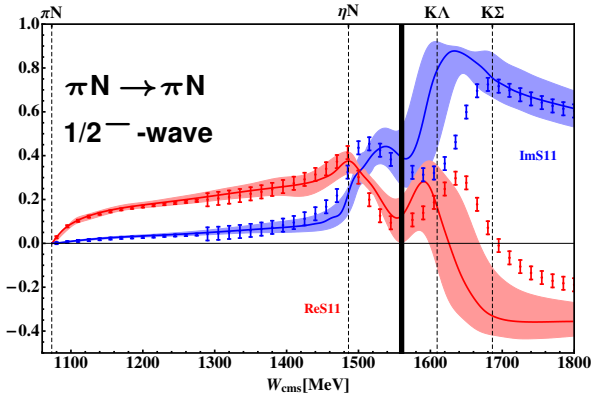
Interpretations of the $1/2^-$ states: N(1535)$1/2^-$, N(1650)$1/2^-$

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

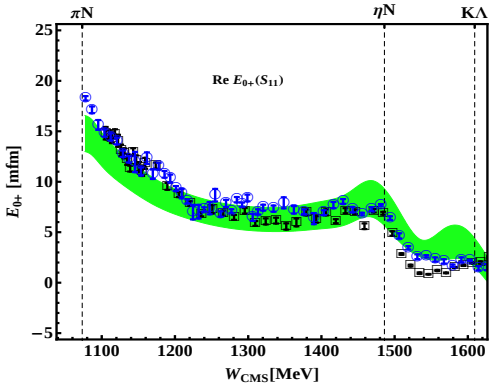
- **Coupled-channel unitarized chiral pert. theo.:**

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

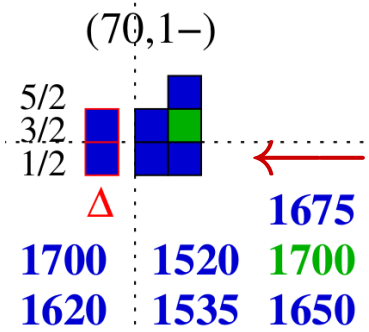


Bruns, Mai, Meißner, PLB 697 (2011) 254

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 ...

$\Downarrow$

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

- or are they orthogonal states?

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

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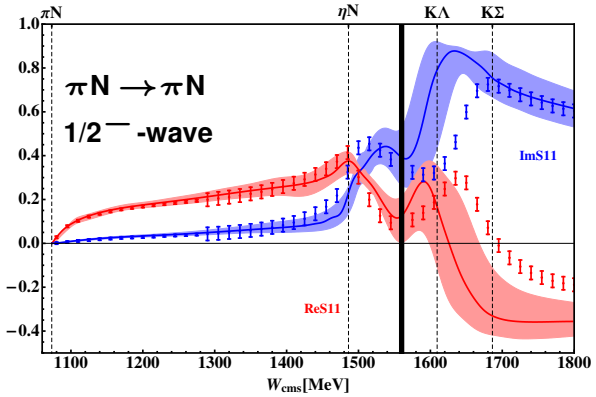
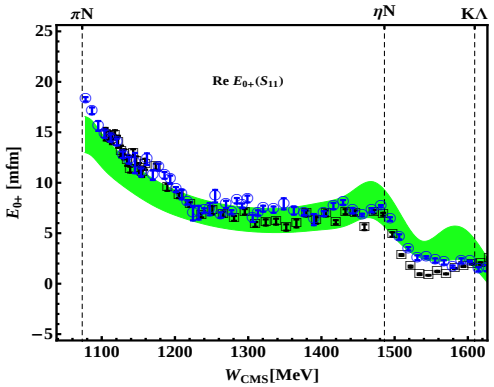


parameter-free prediction $\gamma p \to p\pi^0$:

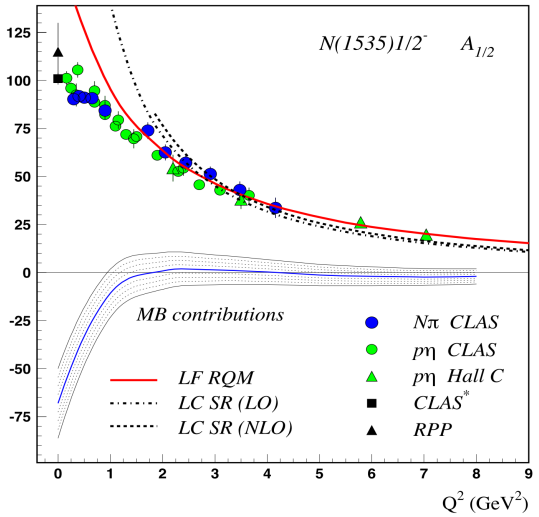


Bruns, Mai, Meißner, PLB 697 (2011) 254

Mai, Bruns, Meißner, PRD 86 (2012) 094033

- **Electroproduction:**

N(1535)$1/2^-$ is a 3-quark state



← **3q-state**

⇓

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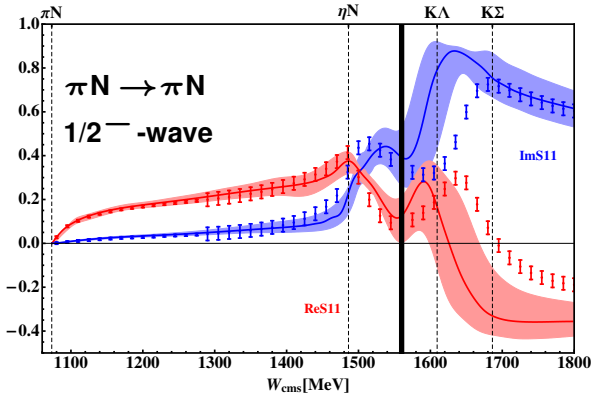

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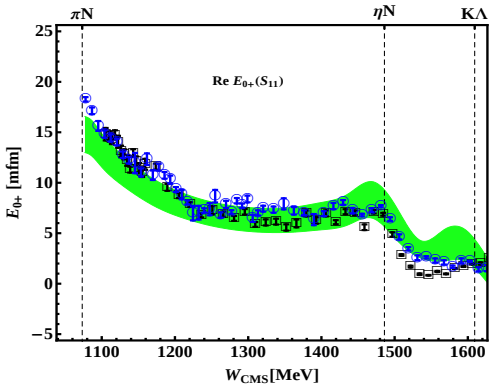

Bruns, Mai, Meißner, PLB 697 (2011) 254

Mai, Bruns, Meißner, PRD 86 (2012) 094033

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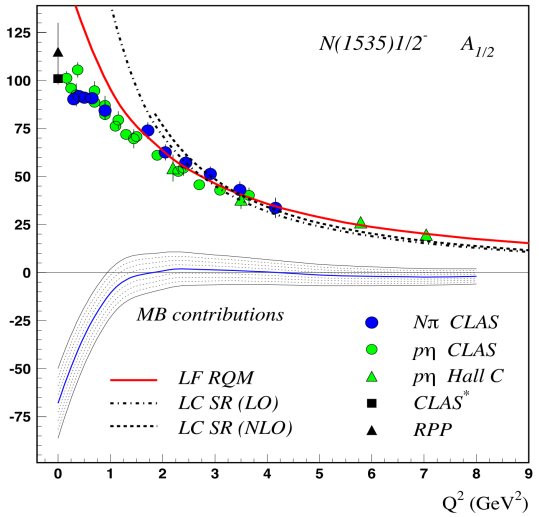


← **3q-state**

⇓

⇒ **Can electroproduction help here in general?**

At large Q^2: only states with a hard "3q"-core remain?

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**

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**

e.g.:
- γn-data *following talks*
- additional final states *following talks*
- electroproduction.:
CLAS 12: extends CLAS studies $Q^2 \rightarrow 12\,GeV^2$
e.g. talk D. Carman - KY-data

$\Rightarrow$ **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 (?))
- Baryons fall on Regge-trajectories, Why ?

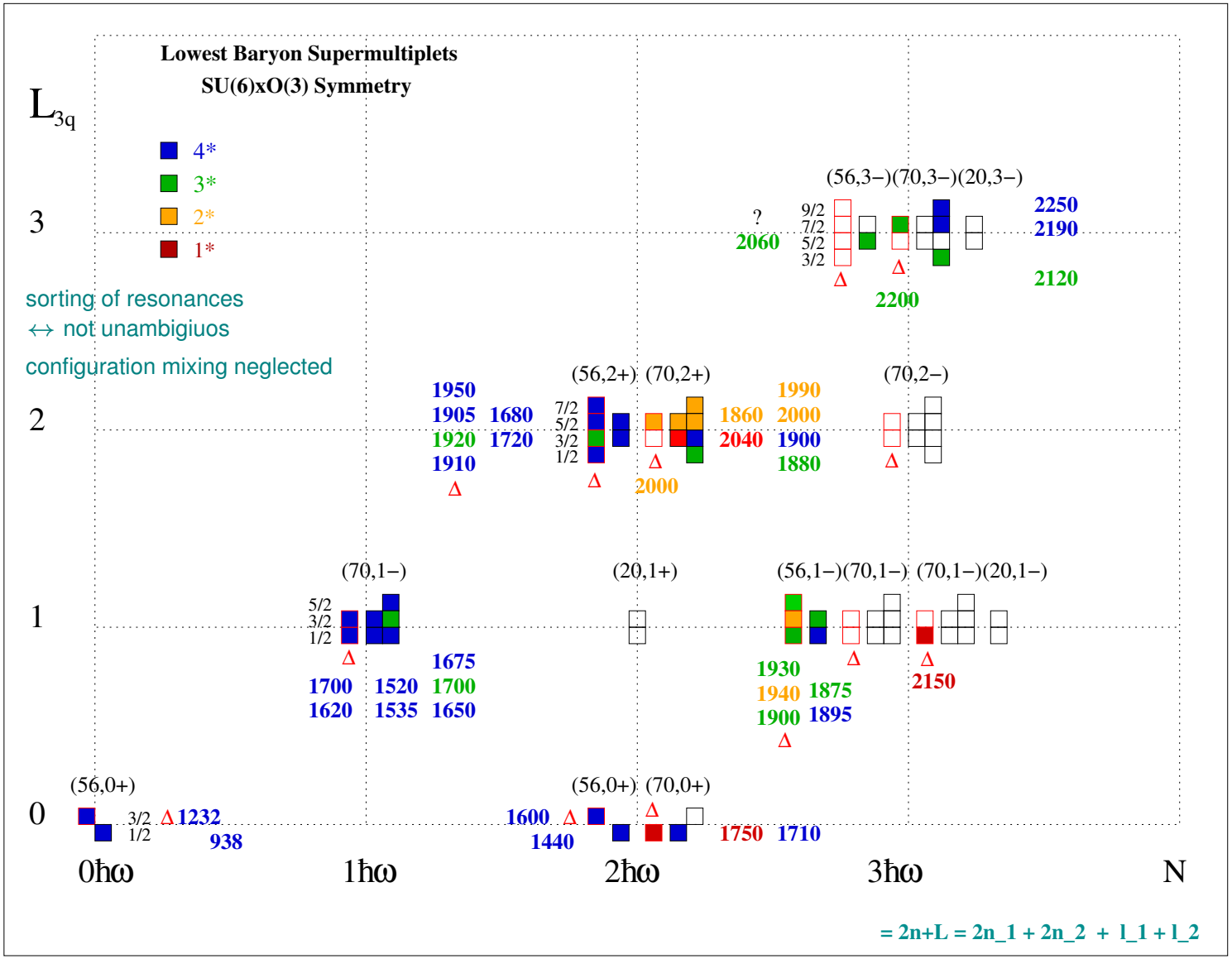
$\Downarrow$

Bound states of QCD are not yet understood!

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

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