Baryon Spectroscopy: what do we learn, what do we need?

E. Klempt

Helmholtz-Institut für Strahlen– und Kernphysik
Universität Bonn
Nußallee 14-16, D-53115 Bonn, GERMANY
e-mail: `klempt@hiskp.uni-bonn.de`

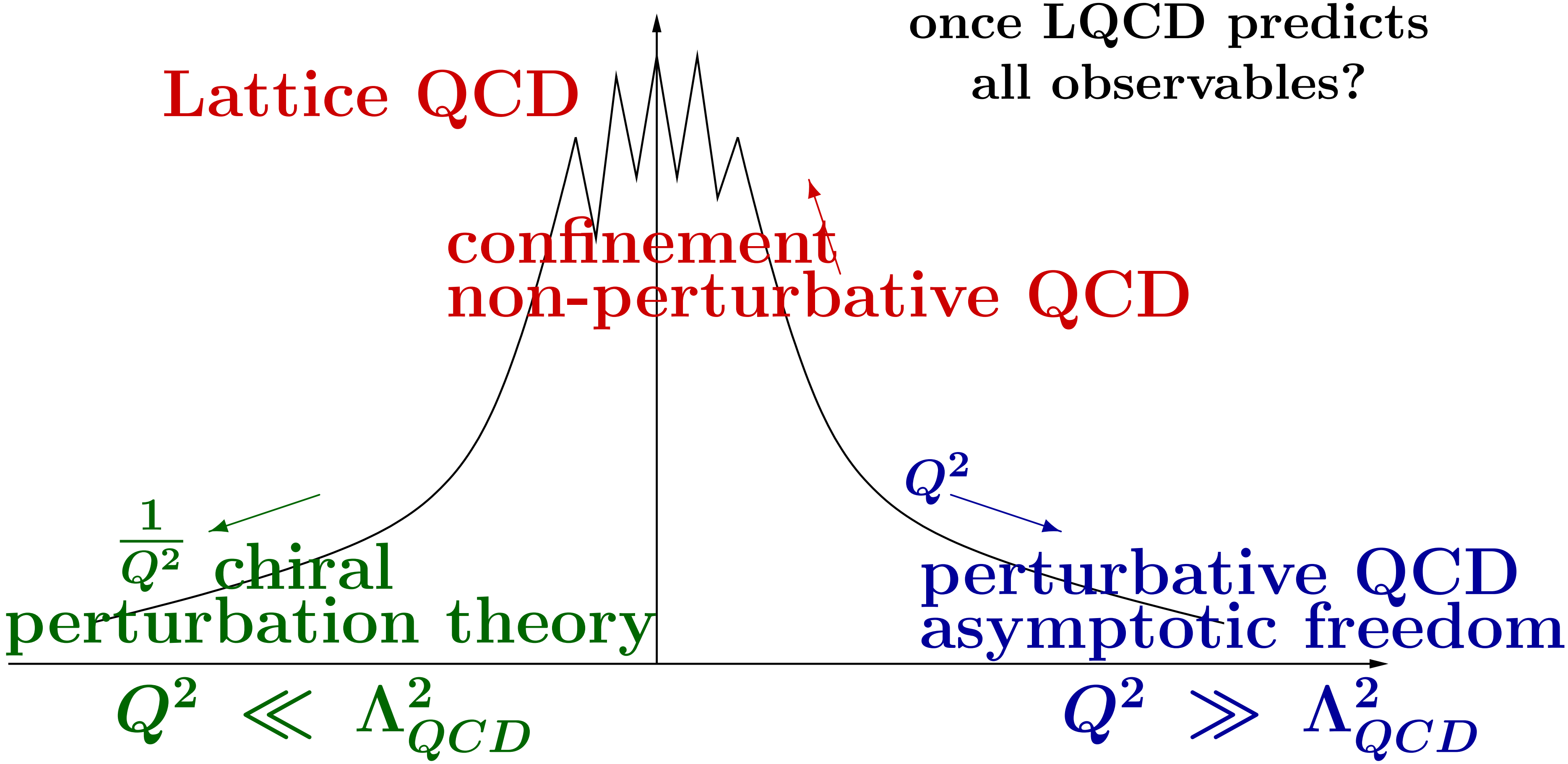
Sixth International Workshop on Pion-Nucleon Partial-Wave Analysis
and the Interpretation of Baryon Resonances
23-27 May, 2011, Washington, DC, U.S.A.

Topics:

1. Introduction
2. Are three-quark baryons, pentaquarks $(qqqq\bar{q})$, hybrids, and dynamically generated resonances realized independently in Nature (even though mixing) ?
3. Can quark spin and orbital angular momenta be defined for baryon resonances ?
4. Can missing resonances be uncovered in inelastic reactions ?
5. Can missing resonances be explained by a quark-diquark structure ?
6. Are missing resonances clustered in few SU(6) multiplets ?
7. Is chiral symmetry restored in highly excited baryons ?
8. Summary

1. Introduction: Strong QCD, the physics of strongly interacting hadrons.

Do we understand QCD once LQCD predicts all observables?



Lattice QCD

confinement
non-perturbative QCD

$\frac{1}{Q^2}$ **chiral perturbation theory**

Q^2 **perturbative QCD asymptotic freedom**

$Q^2 \ll \Lambda^2_{QCD}$

$Q^2 \gg \Lambda^2_{QCD}$

QCD observables as a function of Q^2.

Aim: to understand the dynamics of strongly interacting hadrons at the level of quarks and gluons and their interactions.

Naming scheme:

- $\Delta^{++}(2420)$ requires knowledge of quantum numbers "by heart"
- $\Delta^{++}(2420)H_{3,11}$ requires knowledge that H is even and corresponds to $L = 4$. Refers to π^+p scattering. Not straightforward to calculate $N\omega$ partial wave (which is $L = 6$).
- $\Delta^{++}(2420)(11/2)^+$ is self explanatory.
- $\Delta^{++}_{11/2^+}(2420)$ is compact, self explanatory; close to mesons: $a_2(1320)$

$\Delta_{11/2^+}(2420)$ used here!

2. Are three-quark baryons, pentaquarks, hybrids, and dynamically generated resonances realized independently in Nature ?

Fock expansion

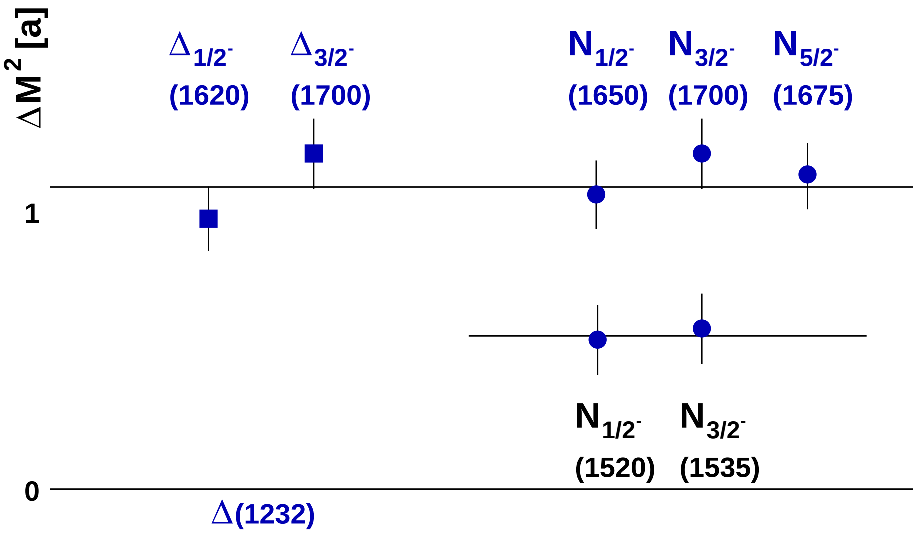
$$|\psi(Q) > = \alpha_1 |qqq(Q) > + \alpha_2 |qqqq\bar{q}(Q) > \\ + \alpha_3 |qqqg(Q) > + \alpha_4 |b_1 m_2(Q) >$$

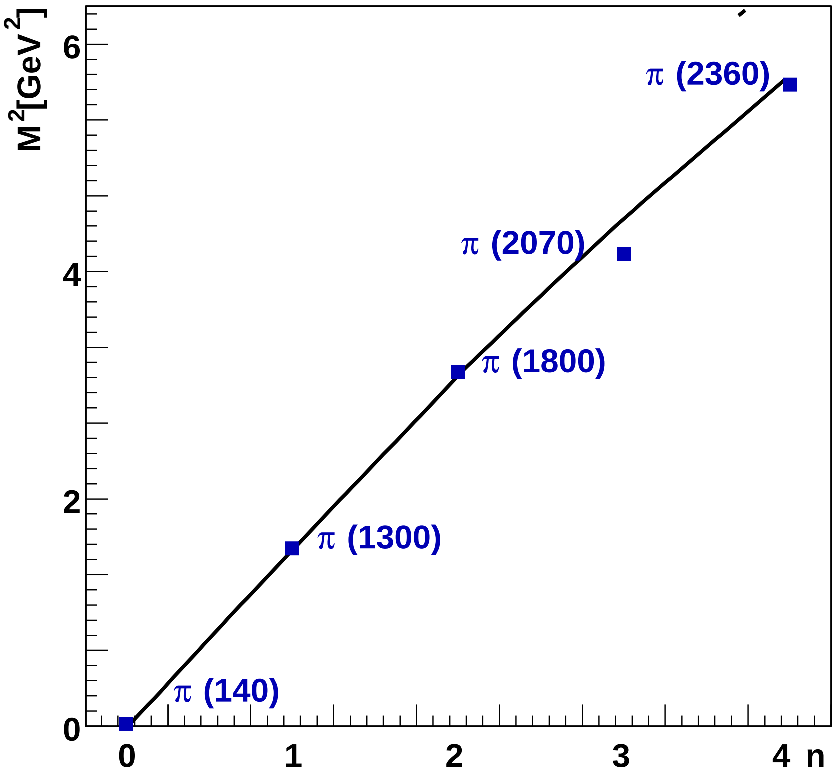
baryons pentaquarks hybrids dyn. gen. res.

Two examples:

There is no super-numerocity

- neither for baryons
- nor for mesons





There are no mesons or baryons beyond the quark model.[1]

---

[1] There are fiercely defended candidates for glueballs ($f_0(1500)$), hybrids ($\pi_1(1600)$), and dynamically generated resonances ($a_0(980)$, $f_0(980)$).
Quantum number exotics and heavy-light tetraquarks may exist

3. Can quark spin S and orbital angular momenta L be defined quantities for baryon resonances ?

A simple mass formula with two parameters using L and S

$$M^2 = \; a \cdot (L + \mathtt{N} + 3/2) \; - b \cdot \alpha_D$$

a: Regge slope, b: fraction of "good" diquarks

(i.e. ↑↓ − ↓↑ in spin and isospin)

reproduces the baryon masses with surprising accuracy:

$(\delta M/M)_{\mathrm{FK}} = 2.5\%$ (2p); $(\delta M/M)_{\mathrm{CI}} = 5.6\%$ (9p)

$(\delta M/M)_{\mathrm{BnA}} = 5.1\%$ (7p); $(\delta M/M)_{\mathrm{BnB}} = 5.4\%$ (7p)

$(\delta M/M)_{\mathrm{KM}} = 9.1\%$ (2p).

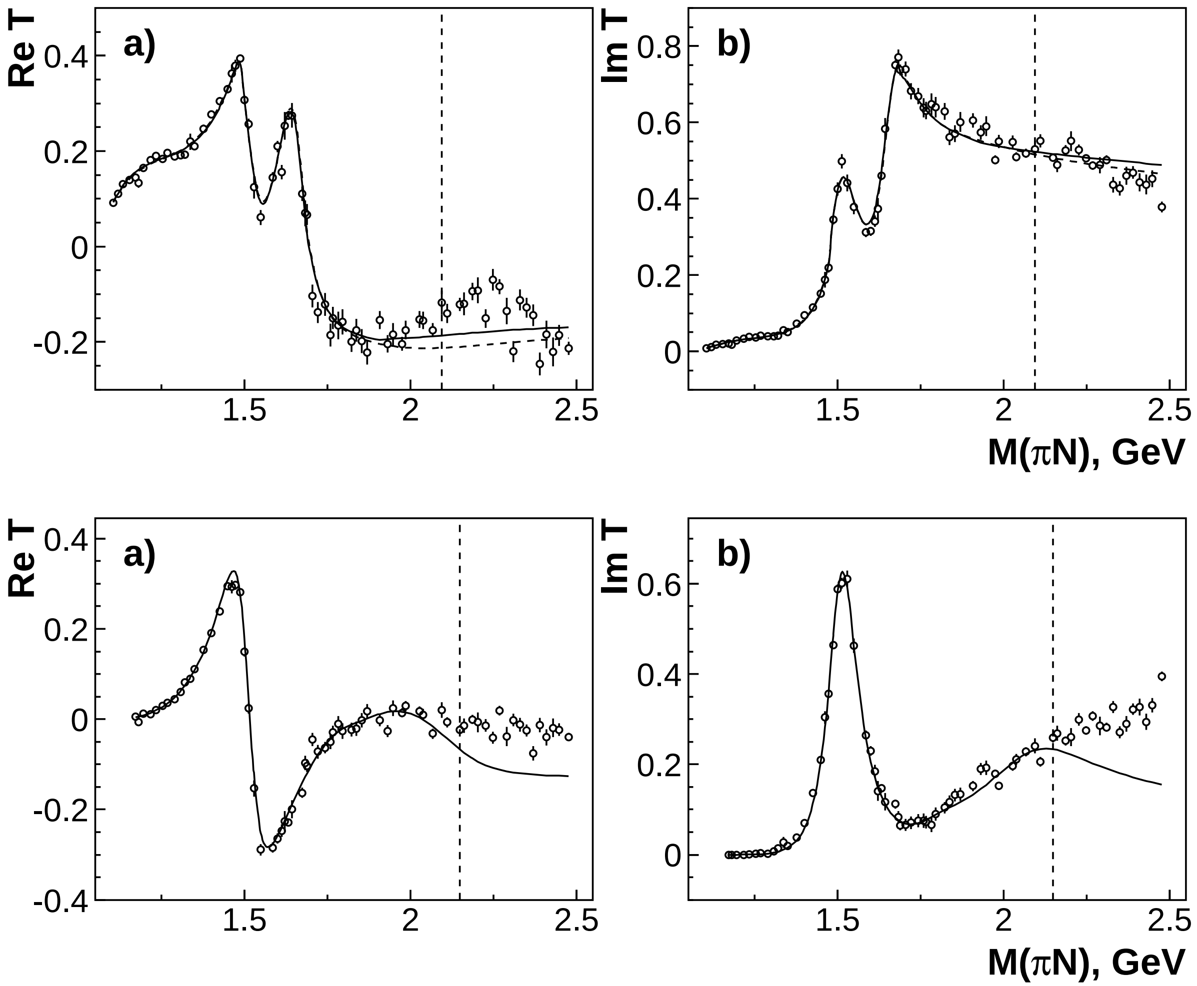
FK: AdS/QCD (Forkel, Klempt) **CI: Quark model (Capstick, Isgur)**

Bn: Quark model (Löring et al.) **KM: Skyrme model (Karliner, Mattis)**

Is the baryon a non-relativistic system?

What is the mass of quark plus string?

4. Can missing resonances be found in inelastic reactions ?



The elastic πN amplitude for the $I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ and $\frac{1}{2}(\frac{3}{2}^-)$ waves have little sensitivity for resonances above the first excitation shell!

Need inelastic reactions!

$N(1440)P_{11}$	47 ± 3	-(83 ± 10)°	BG2010
	38	-98°	Arndt:2006
	40		Hohler:1993
	52 ± 5	-(100 ± 35)°	Cutkosky:1980rh
$N(1710)P_{11}$	5 ± 4	-(80 ± 40)°	BG2010-01
	7 ± 3	-(190 ± 25)°	BG2010-02
	15		Hohler:1993xq
	8	-167°	Cutkosky:1980rh
$N(1720)P_{13}$	22 ± 5	-(85 ± 20)°	BG2010-01
	28 ± 6	-(85 ± 20)°	BG2010-02
	25	-94°	Arndt:2006
	15		Hohler:1993
	8 ± 2	-(160 ± 30)°	Cutkosky:1980
$\Delta(1232)P_{33}$	51.4 ± 0.5	-(47 ± 1)°	BG2010
	52	-47°	Arndt:2006
	50	-48°	Hohler:1993
	52 ± 5	-47°	Cutkosky:1980
$\Delta(1600)P_{33}$	14 ± 3	-(170 ± 15)°	BG2010
	44	-147°	Arndt:2006
	17 ± 4	-(150 ± 30)°	Cutkosky:1980
$\Delta(1910)P_{31}$	38 ± 8	-(120 ± 15)°	BG2010
	38		Hohler:1993
	20 ± 4	-(90 ± 30)°	Cutkosky:1980
$\Delta(1920)P_{33}$	10 ± 6	(20 ± 60)°	BG2010
	24 ± 4	-(150 ± 30)°	Cutkosky:1980

5. Can missing resonances be explained by a quark-diquark structure ?

There are ambiguous solutions which lead to different interpretations.

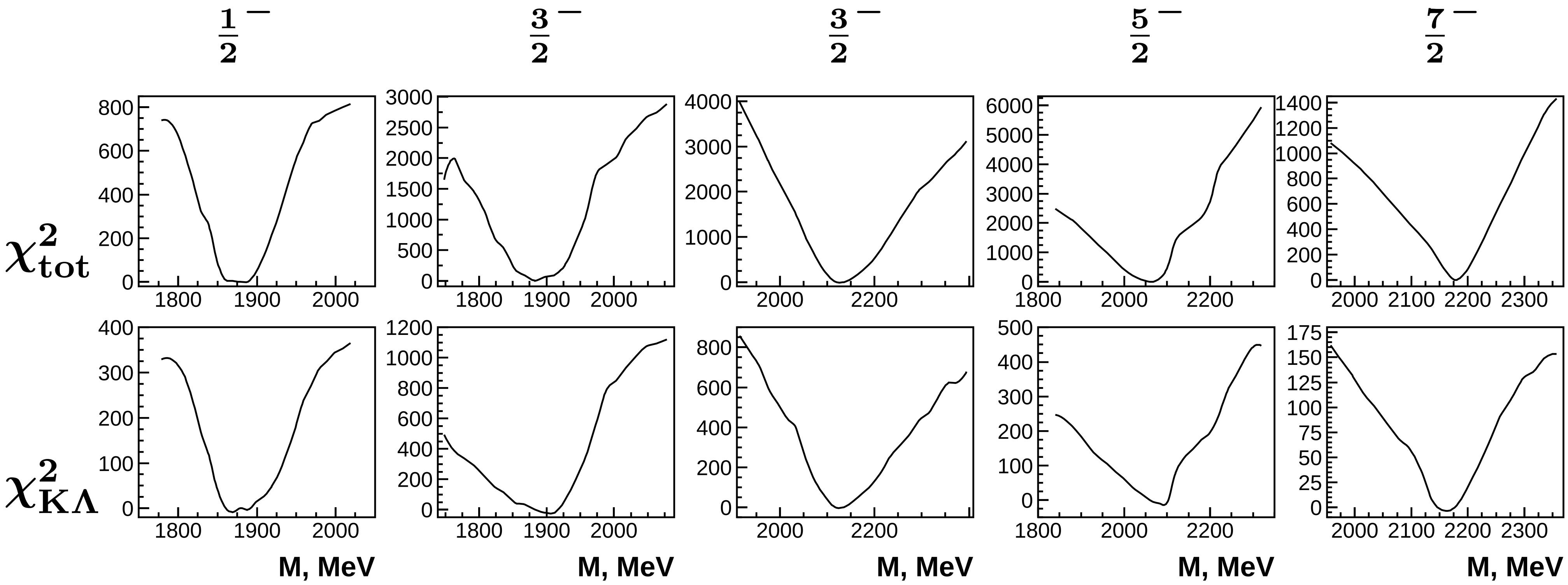
$\frac{1}{2}^+$**-wave:**	$N_{1/2^+}(1870)$	**and (?)** $N_{1/2^+}(2100)$
$\frac{3}{2}^+$**-wave:**	$N_{3/2^+}(1900)$	**and (?)** $N_{3/2^+}(1975)$
$\frac{5}{2}^+$**-wave:**	$N_{5/2^+}(1975)$	**or** $N_{5/2^+}(2090)$
$\frac{7}{2}^+$**-wave:**	$N_{7/2^+}(1980)$	**or** $N_{7/2^+}(2070)$

There are four positive-parity resonances within 100 MeV, forming a spin quartet of resonances with $L = 2, S = 3/2$.

spin	flavor	spatial
$S = 3/2$	$I = 1/2$	$L = 2$
symm.	mixed	mixed

If (qq) diquark in
S-wave, then $L = 2$
wave function symmetric.
Diquark models ruled out !

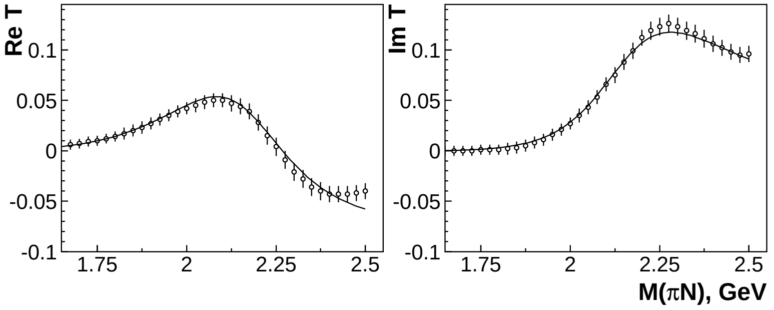
6. Are missing resonances clustered in few SU(6) multipl. ?



$N_{1/2^-}(1880)$ **$N_{3/2^-}(1890)$** **$N_{3/2^-}(2130)$** **$N_{5/2^-}(2075)$** **$N_{7/2^-}(2185)$**

No $\frac{9}{2}^-$ in γp:

$N_{9/2^-}(2250)$ from πN



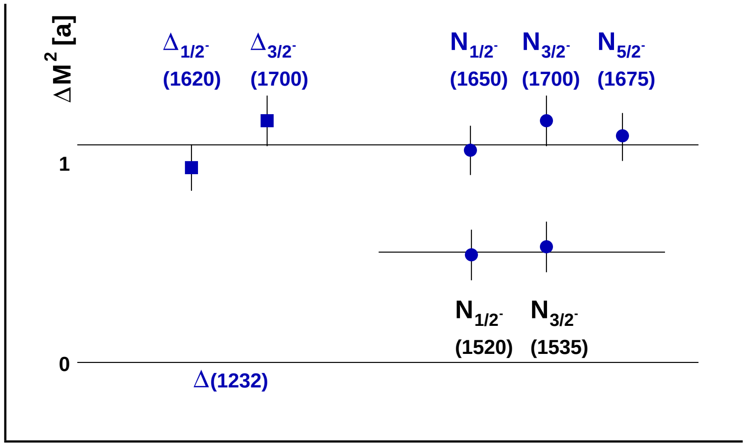
$\mathrm{N}_{1/2^-}(1880)$ $\mathrm{N}_{3/2^-}(1890)$ $L=1, S=1/2$ doublet

$\mathrm{N}_{3/2^-}(2130)$ $\mathrm{N}_{5/2^-}(2075)$ $\mathrm{N}_{7/2^-}(2185)$ $\mathrm{N}_{9/2^-}(2250)$

$L=3, S=3/2$ quartet

$\mathrm{N}_{1/2^-}(1880)$, $\mathrm{N}_{3/2^-}(1890)$ have no close-by $\mathrm{N}_{5/2}$ (xxx) companion. This is not a triplet plus doublet, it is an isolated doublet.

Remainder:



$\mathrm{N}_{3/2^-}(2130)$, $\mathrm{N}_{5/2^-}(2075)$, $\mathrm{N}_{7/2^-}(2185)$, $\mathrm{N}_{9/2^-}(2250)$ is a quartet, a doublet may be unresolved or unresolvable.

Recap: SU(6) decomposition:

$$\begin{aligned} 6 \otimes 6 \otimes 6 &= 56_S \oplus 70_M \oplus 70_M + 20_A \\ 56 &= {}^4 10 + {}^2 8 \\ 70 &= {}^2 10 + {}^4 8 + {}^2 8 + {}^2 1 \end{aligned}$$

- **The spin-doublet $N_{1/2}$ (1880), $N_{3/2}$ (1890) must be accompanied with a spin triplet of Δ states. Indeed, there are $\Delta_{1/2^-}(1900)$, $\Delta_{3/2^-}(1940)$, $\Delta_{5/2^-}(1930)$.**
  These resonance are radial excitations belonging to the third shell.

- **The spin quartet $N_{3/2^-}(2130)$, $N_{5/2^-}(2075)$, $N_{7/2^-}(2185)$, $N_{9/2^-}(2250)$ likely hides or absorbs the spin doublet. The Δ spectrum adds a doublet: $\Delta_{7/2^-}(2200)$ and a $\Delta_{5/2^-}(2223)$ from GWU.**

The resonances above all belong to the third excitation shell.

3^{rd}	$J^P =$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{5}{2}^-$	$\frac{7}{2}^-$	$\frac{9}{2}^-$
$(56, 1_3^-)$	$S = 3/2; L = 1;$ N=1	$\Delta_{1/2^-}(1900)$	$\Delta_{3/2^-}(1940)$	$\Delta_{5/2^-}(1930)$		
	$S = 1/2; L = 1;$ N=1	$N_{1/2^-}(1880)$	$N_{3/2^-}(1870)$			
$(70, 3_3^-)$	$S = 1/2; L = 3;$ N=0			$\Delta_{5/2^-}(2223)$	$\Delta_{7/2^-}(2200)$	
	$S = 3/2; L = 3;$ N=0		$N_{3/2^-}(2170)$	$N_{5/2^-}(2070)$	$N_{7/2^-}(2190)$	$N_{9/2^-}(2250)$
	$S = 1/2; L = 3;$ N=0					
		$(56, 3_3^-)$, $(20, 3_3^-)$, $(70, 2_3^-)$, $(70, 1_3^-)$, $(70, 1_3^-)$, $(20, 1_3^-)$: Many states predicted, no candidates known				

All observed resonances in the third shell fit into two multiplets. Theses are (nearly) full. Six multiplets are empty.

- **accidental ?**
- **max and min moments of inertia ?**
- **else ?**

7. Is chiral symmetry restored in highly excited baryons ? (Glozman and others)

Choosing the alternative solution:

$\frac{1}{2}^{+}$-wave: $N_{1/2+}(1870)$ and (?) $N_{1/2+}(2100)$
$\frac{3}{2}^{+}$-wave: $N_{3/2+}(1900)$ and (?) $N_{3/2+}(1975)$
$\frac{5}{2}^{+}$-wave: $N_{5/2+}(1975)$ or $\underline{N_{5/2+}(2090)}$
$\frac{7}{2}^{+}$-wave: $N_{7/2+}(1980)$ or $\underline{N_{7/2+}(2070)}$

$N_{1/2+}(1710)$	$N_{1/2-}(1650)$	$N_{3/2+}(1720)$	$N_{3/2-}(1700)$
$N_{5/2+}(1680)$	$N_{5/2-}(1675)$	$N_{1/2+}(1880)$	$N_{1/2-}(1895)$
$N_{3/2+}(1900)$	$N_{3/2-}(1875)$	$N_{5/2+}(2090)$	$N_{5/2-}(2075)$
$N_{7/2+}(2070)$	$N_{7/2-}(2190)$	$N_{9/2+}(2220)$	$N_{9/2-}(2250)$

The new resonances yield new parity doublets!

8. Summary

Baryon spectroscopy may reveal fundamental aspects of strong QCD.

Highly sensitive data have been taken and are being taken boosting the data base for excited baryon analyses.

Methods have been developed suited to raise the treasure hidden in the data.

We may expect a breakthrough in baryon spectroscopy in the forthcoming years.