Baryon Spectroscopy and the Origin of Mass

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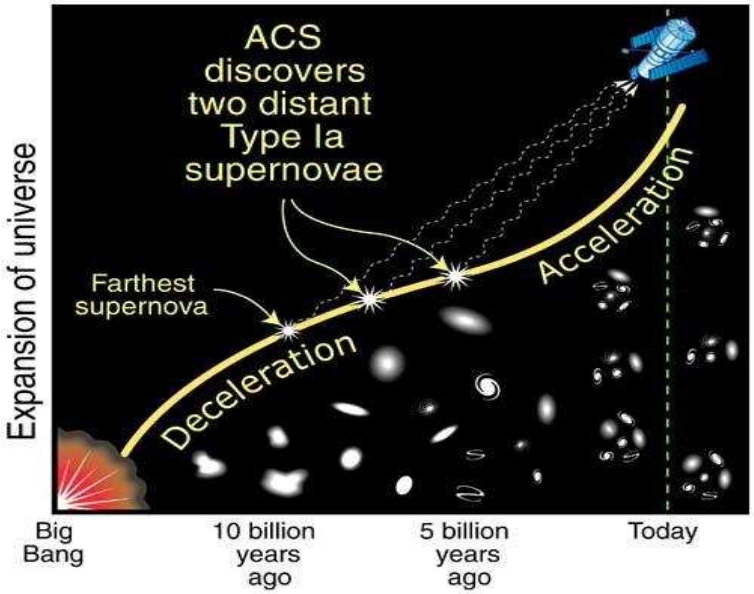
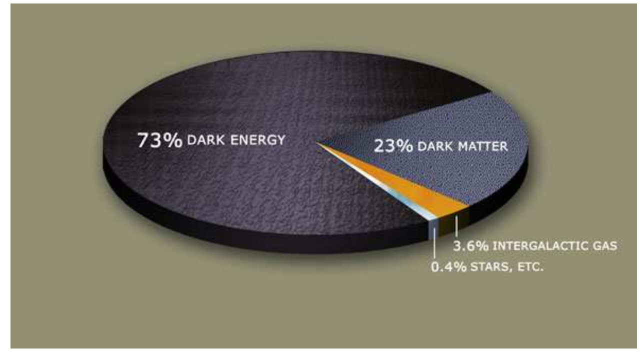
Topics

1. **Why Baryon Spectroscopy?**
2. **Baryon Resonance Spectrum: Status**
   - **How many N and Δ resonances do we know?**
   - **$\Delta_{3/2^+}(1600)$ from $\pi^+ p \to \Sigma^+ K^+$**
   - **$N_{3/2^+}(1900)$ from $\gamma p \to \Lambda K^+$, $\gamma p \to \Sigma^0 K^+$, and $\gamma p \to \Sigma^+ K^0$**
   - **$\Delta_{3/2^+}(1920)$ and $\Delta_{3/2^-}(1940)$ from $\gamma p \to p\pi^0\eta$**
3. **Baryon Resonance Spectrum: Interpretation**
   - **Quark models**
   - **AdS/QCD**
   - **Dynamical generation of resonances**
   - **Chiral symmetry restoration**
4. **Baryon Resonance Spectrum: Perspectives**
5. **Summary**

Why Baryon Spectroscopy?



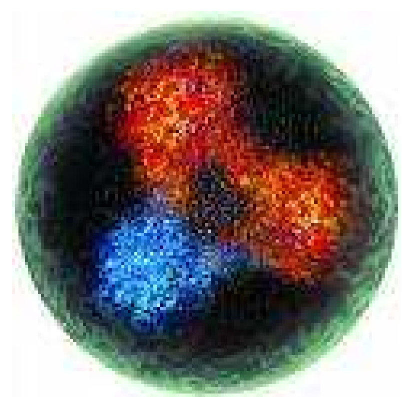


- **Mass of the Universe:**

Dark energy	**73%**	
Dark matter	**23%**	
Intergalactic gas	**3.6%**	} **atoms**
Stars	**0.4%**	

Mass of atoms

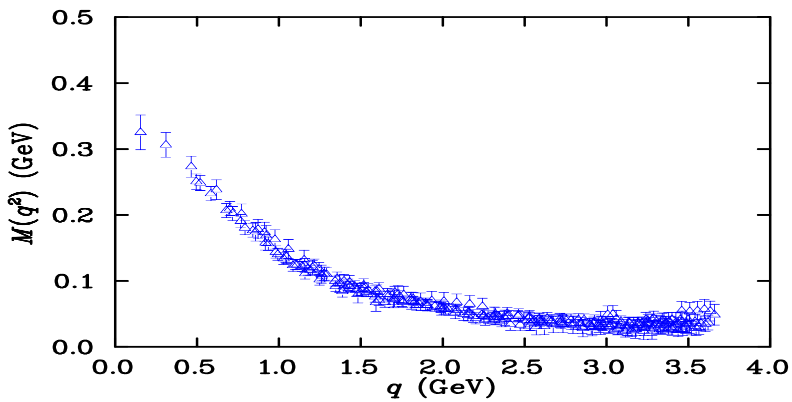
Mass of quarks	**1%**
Mass of electrons	**0.1%**
Field energy	**99%**

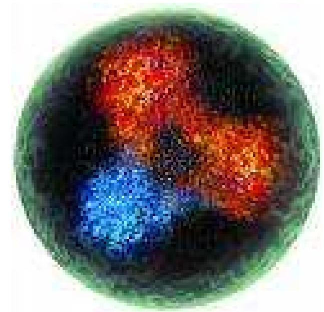


What are ⇑ these objects?

- **What are constituent quarks?**

(-) From lattice QCD:





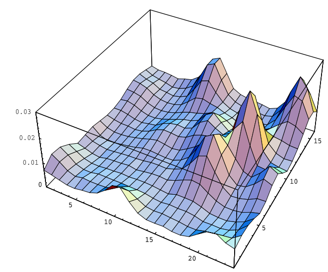
P. O. Bowman et al.,
Phys. Rev. D 71, 054507 (2005).

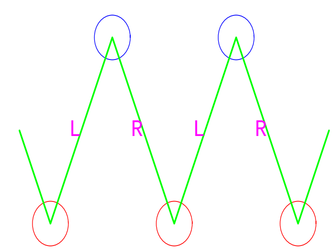
(-) By expelling the chiral condensate:

$$< \overline{\psi}\psi >= -(0.23)^3 \text{ GeV}^3$$

A. Chodos, R. L. Jaffe,
K. Johnson and C. B. Thorn,
Phys. Rev. D 10, 2599 (1974).

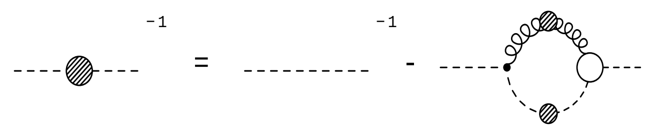
(-) From instantons:





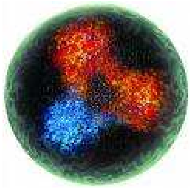
D. Diakonov and V. Y. Petrov,
Sov. Phys. JETP 62, 204 (1985)
[Zh. Eksp. Teor. Fiz. 89, 361 (1985)].

(-) Gluon propagator from Dyson-Schwinger equation:

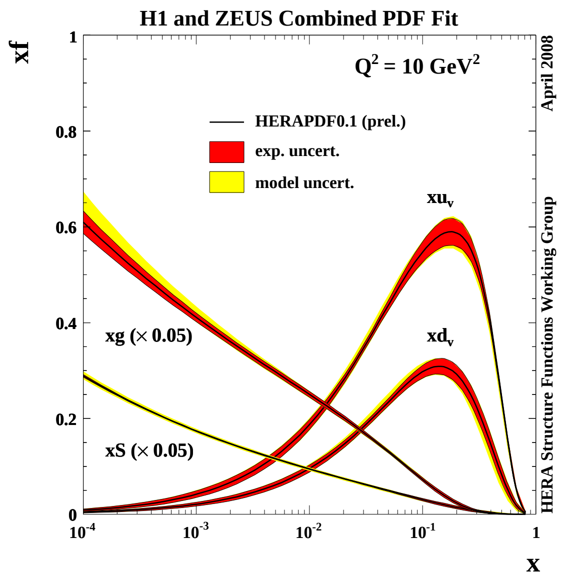


M. S. Bhagwat, M. A. Pichowsky, C. D. Roberts and P. C. Tandy,
Phys. Rev. C 68, 015203 (2003).

How to explore constituent quarks?



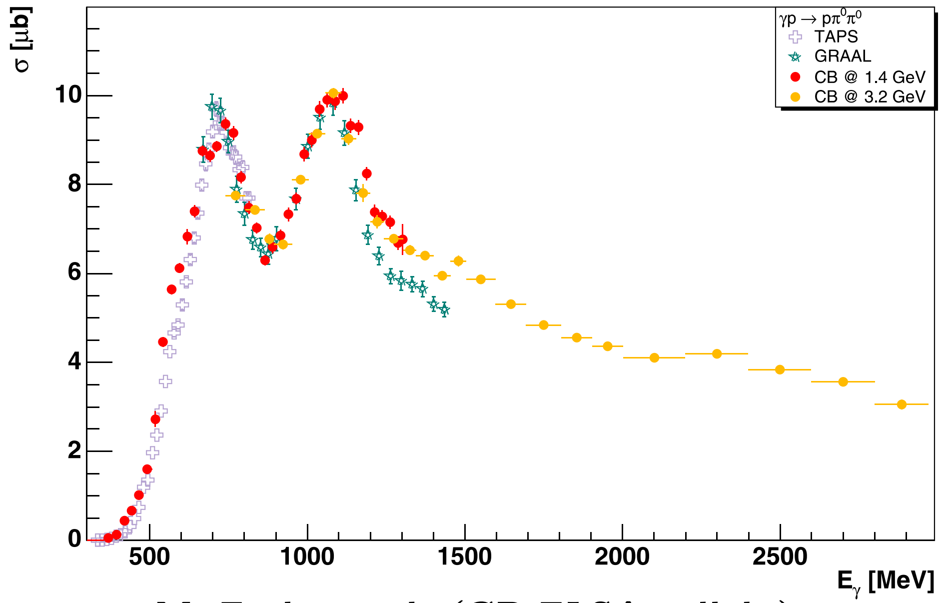
Nucleon tomography:



Goal: Distribution of linear
and angular momenta
of gluons and quarks in space

Collectivity is lost!

Nucleon spectroscopy:



M. Fuchs et al. (CB-ELSA collab.)
in preparation

Wave length matches
the size of constituents

Explores collective response!

Baryon Resonance Spectrum: Status

(PDG, mostly from Höhler and Cutkovsky)

Resonance	Mass	Resonance	Mass	Resonance	Mass
N(940)	940	$\Delta(1232)$	1232 ± 1	$N_{1/2+}(1440)$	1450 ± 32
$N_{1/2-}(1535)$	1538 ± 10	$N_{3/2-}(1520)$	1522 ± 4	$N_{1/2-}(1650)$	1660 ± 18
$N_{3/2-}(1700)$	1725 ± 50	$N_{5/2-}(1675)$	1675 ± 5	$\Delta_{1/2-}(1620)$	1626 ± 23
$\Delta_{3/2-}(1700)$	1720 ± 50	$\Delta_{3/2+}(1600)$	1615 ± 80	$N_{3/2+}(1720)$	1730 ± 30
$N_{5/2+}(1680)$	1683 ± 3	$N_{1/2+}(1710)$	1713 ± 12	$\Delta_{1/2+}(1750)$	
$N_{1/2-}(1905)$	1905 ± 50	$N_{3/2-}(1860)$	1850 ± 40	$N_{1/2+}(1880)^{a}$	
$N_{3/2+}(1900)^{a}$		$N_{5/2+}(1910)$	1880 ± 40	$N_{7/2+}(1990)$	2020 ± 60
$\Delta_{1/2-}(1900)$	1910 ± 50	$\Delta_{3/2-}(1940)$	1995 ± 60	$\Delta_{5/2-}(1930)$	1930 ± 30
$\Delta_{1/2+}(1910)$	1935 ± 90	$\Delta_{3/2+}(1920)$	1950 ± 70	$\Delta_{5/2+}(1905)$	1885 ± 25
$\Delta_{7/2+}(1950)$	1930 ± 16	$N_{1/2+}(2100)$	2090 ± 100	$N_{1/2-}(2090)$	
$N_{3/2-}(2080)$	2100 ± 55	$N_{5/2-}(2060)^{a}$	2065 ± 25	$N_{7/2-}(2190)$	2150 ± 30
$N_{5/2-}(2200)$	2160 ± 85	$N_{9/2-}(2250)$	2255 ± 55	$\Delta_{1/2-}(2150)$	
$\Delta_{5/2-}(2223)^{b}$		$\Delta_{7/2-}(2200)$	2230 ± 50	$N_{9/2+}(2220)$	2360 ± 125
$\Delta_{7/2+}(2390)$	2390 ± 100	$\Delta_{9/2+}(2300)$	2360 ± 125	$\Delta_{11/2+}(2420)$	2462 ± 120
$\Delta_{9/2-}(2400)$	2400 ± 190	$\Delta_{3/2-}(2350)$	2310 ± 85	$N_{11/2-}(2600)$	2630 ± 120
$N_{13/2+}(2800)$	2800 ± 160	$\Delta_{13/2-}(2750)$	2720 ± 100	$\Delta_{15/2+}(2950)$	2920 ± 100

$N_{1/2-}(1535)$ used instead of $N(1535)S_{11}$ $\qquad$ ^{a}: BnGa; ^{b}: GWU

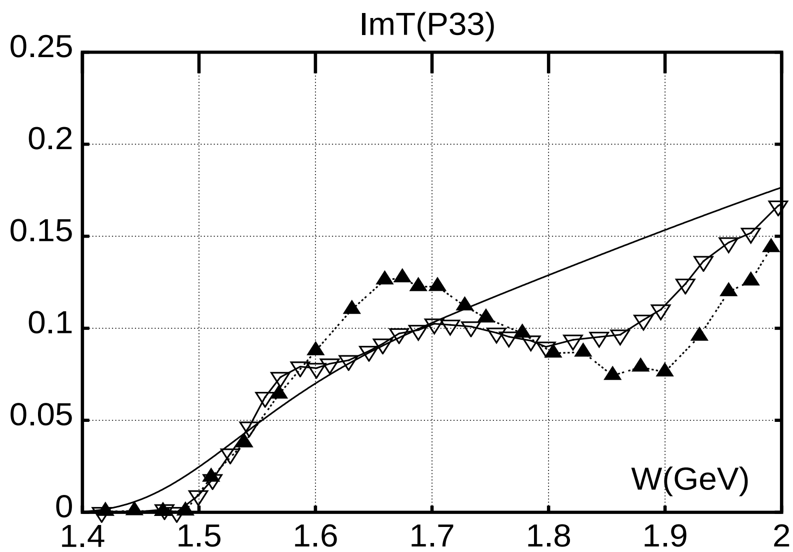
SAID spectrum based on increased data base

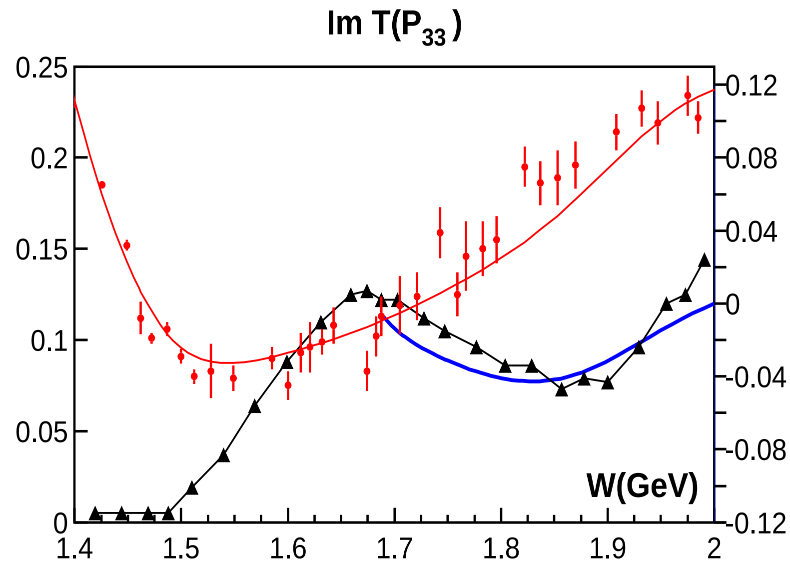
Resonance	Mass	Resonance	Mass	Resonance	Mass
$N(940)$	940	$\Delta(1232)$	1232 ± 1	$N_{1/2^+}(1440)$	1450 ± 32
$N_{1/2^-}(1535)$	1538 ± 10	$N_{3/2^-}(1520)$	1522 ± 4	$N_{1/2^-}(1650)$	1660 ± 18
$N_{3/2^-}(1700)$	1725 ± 50	$N_{5/2^-}(1675)$	1675 ± 5	$\Delta_{1/2^-}(1620)$	1626 ± 23
$\Delta_{3/2^-}(1700)$	1720 ± 50			$N_{3/2^+}(1720)$	1730 ± 30
$N_{5/2^+}(1680)$	1683 ± 3				
				$\Delta_{5/2^-}(1930)$	1930 ± 30
$\Delta_{1/2^+}(1910)$	1935 ± 90			$\Delta_{5/2^+}(1905)$	1885 ± 25
$\Delta_{7/2^+}(1950)$	1930 ± 16				
$\Delta_{5/2^-}(2223)^{b}$		$\Delta_{7/2^-}(2200)$	2230 ± 50	$N_{9/2^+}(2220)$	2360 ± 125
				$\Delta_{11/2^+}(2420)$	2462 ± 120
$\Delta_{9/2^-}(2400)$	2400 ± 190			$N_{11/2^-}(2600)$	2630 ± 120

50% of all resonances have disappeared !

- **First example: The $\Delta_{3/2^+}(1600)$ from $\pi^+ p \to \Sigma^+ K^+$** **BnGa**

Amplitude from elastic scattering **Amplitude from inelastic scattering**





▽	**Carnegie Mellon**
▲	**Karlsruhe Helsinki**
Straight line:	**GWU (SAID)**

$\Delta_{3/2^+}(1600)$ confirmed!

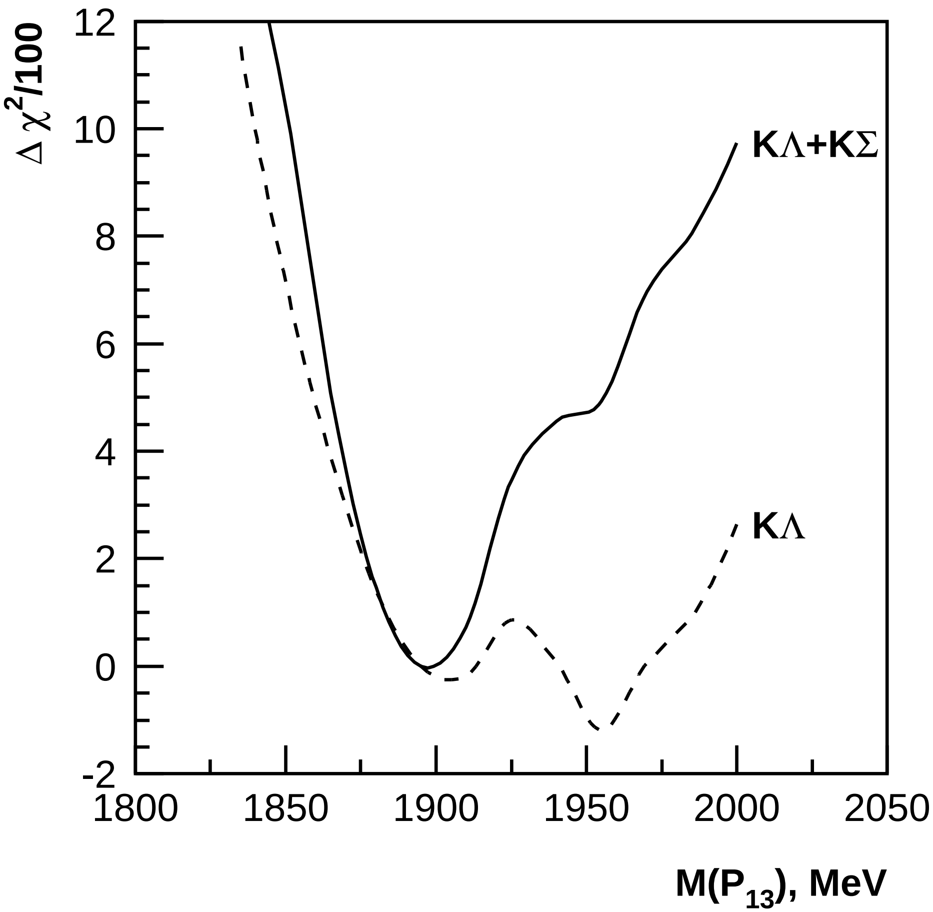
Pick up of noise by CM and KH? **Resonances lost due to smoothing (GWU)?**

$(M = 1640 \pm 50,\ \Gamma = 480 \pm 100\,\text{MeV})$

BnGa: See talks by A. Anisovich (8A), A. Sarantsev (9)

- **Second example: The $N_{3/2^+}(1900)$ from $\gamma p \to \Lambda K^+$ and $\gamma p \to \Sigma K^+$**

BnGa



Excellent data base with

- **+ high-statistics angular distributions,**
- **+ several single (Σ, T and P) and**
- **+ double polarization observables (C_x, C_z, O_x, O_z).**
- **+ Large data base included in the fits.**

- **- No full reconstruction of partial wave amplitude.**
- **- χ^2 minimization.**

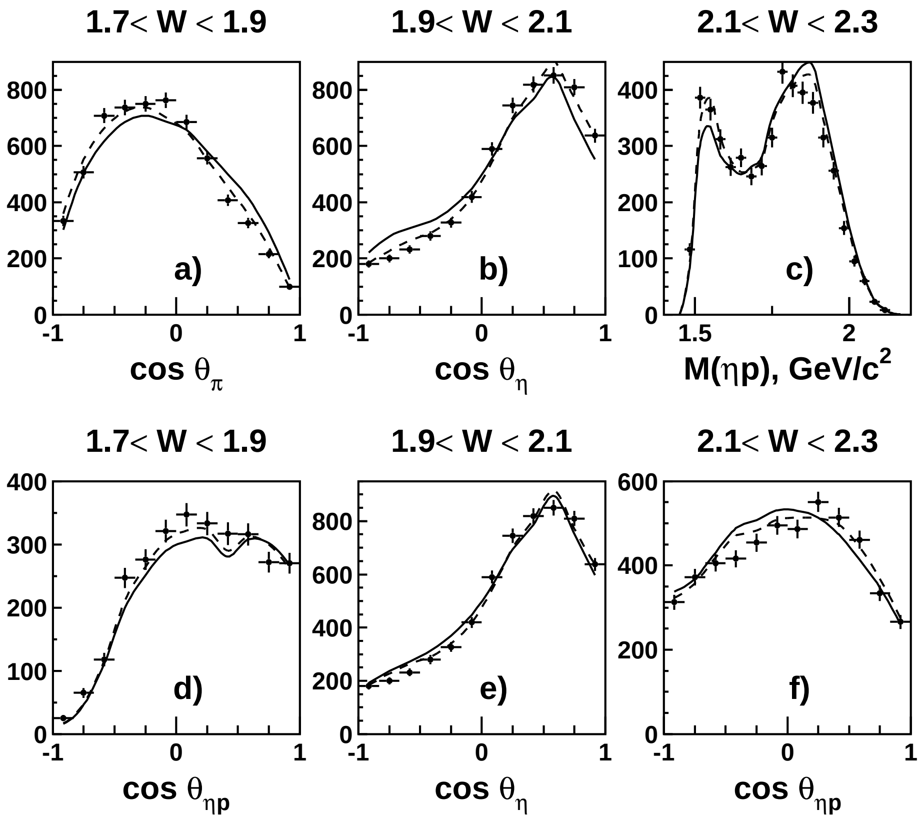
$N_{3/2^+}(1900)$ confirmed!

($M = 1915 \pm 60$, $\Gamma = 180 \pm 40$ MeV)

- **Third example: $\Delta_{3/2^+}(1920)$ and $\Delta_{3/2^-}(1940)$ from $\gamma p \to p\pi^0\eta$**

BnGa

Fits with/without $\Delta_{3/2^+}(1920)$ or $\Delta_{3/2^-}(1940)$



$\Delta_{3/2^+}(1920)$ and $\Delta_{3/2^-}(1940)$ confirmed!

$(M = 1950 \pm 50,\ \Gamma = 330 \pm 50\,\text{MeV})$

$(M = 1995 \pm 40,\ \Gamma = 360 \pm 50\,\text{MeV})$

Conclusions:

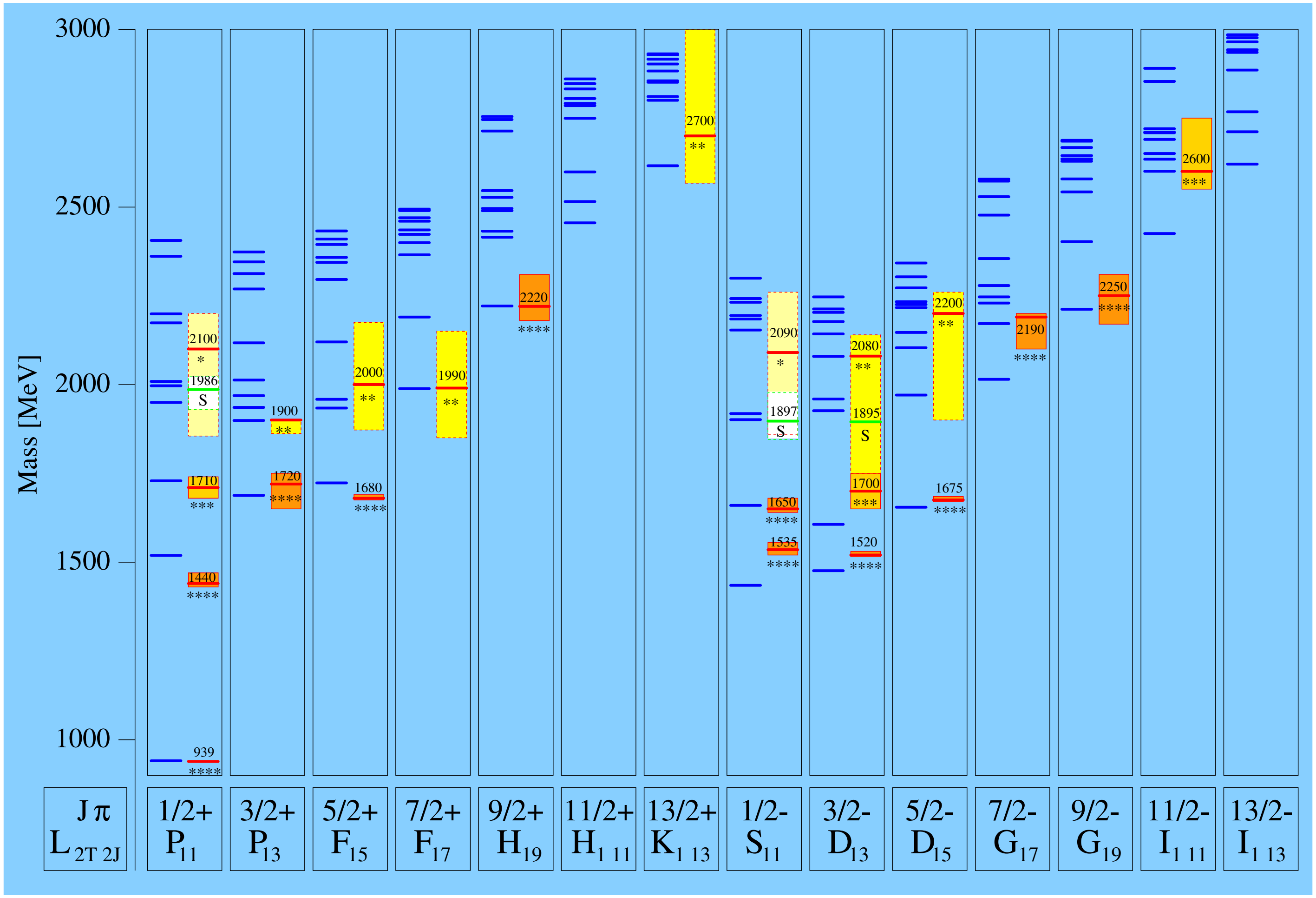
At the moment, we should not abandon all the resonances seen by Höhler and Cutkovsky.

Photoproduction begins to make a significant impact on baryon spectroscopy.

The Baryon Resonance Spectrum: Interpretation

- **Quark models:**

Ingredients are:
(-) constituent quarks with defined rest masses,
(-) confinement potential,
(-) some residual interaction
(effective one-gluon exchange, instantons).

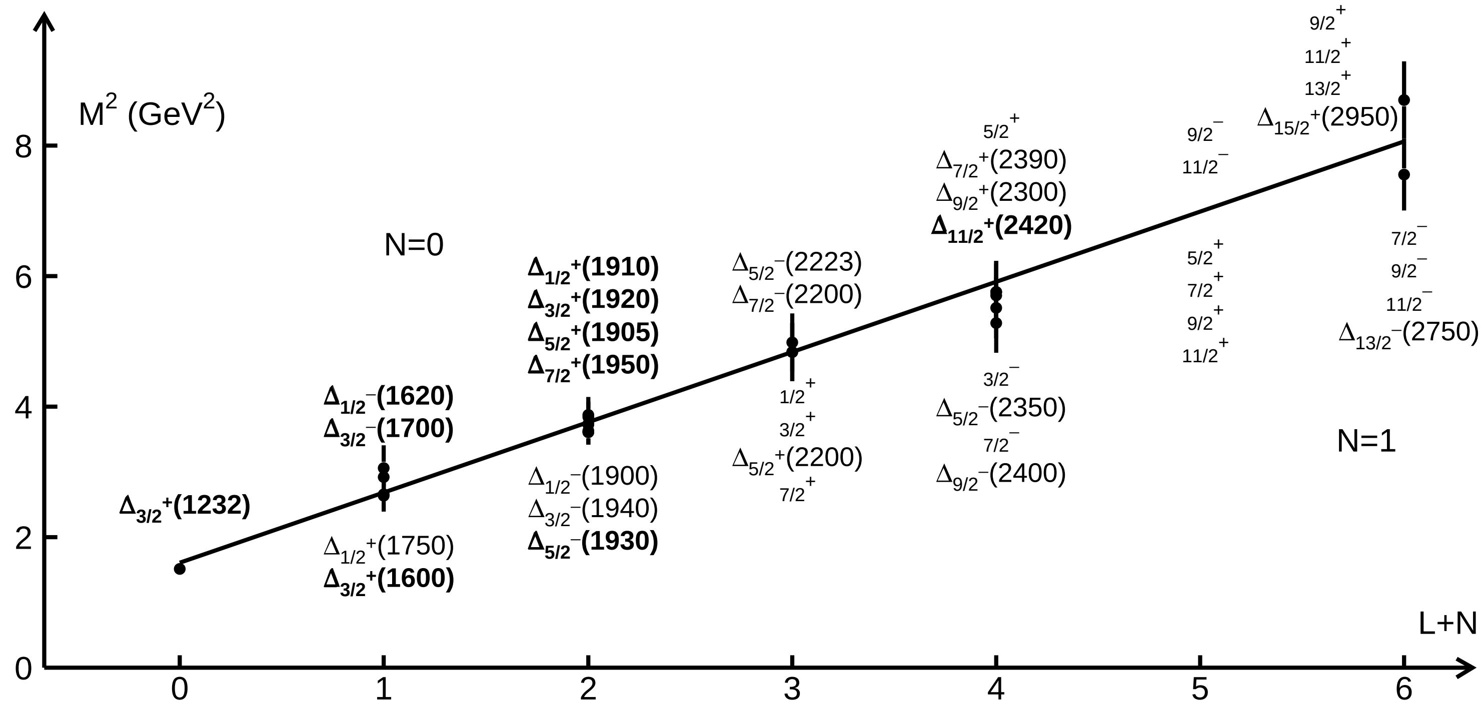


- **AdS/QCD:**

Analytically solvable model of QCD with constant α_s. which ontains only one parameter, “size”.

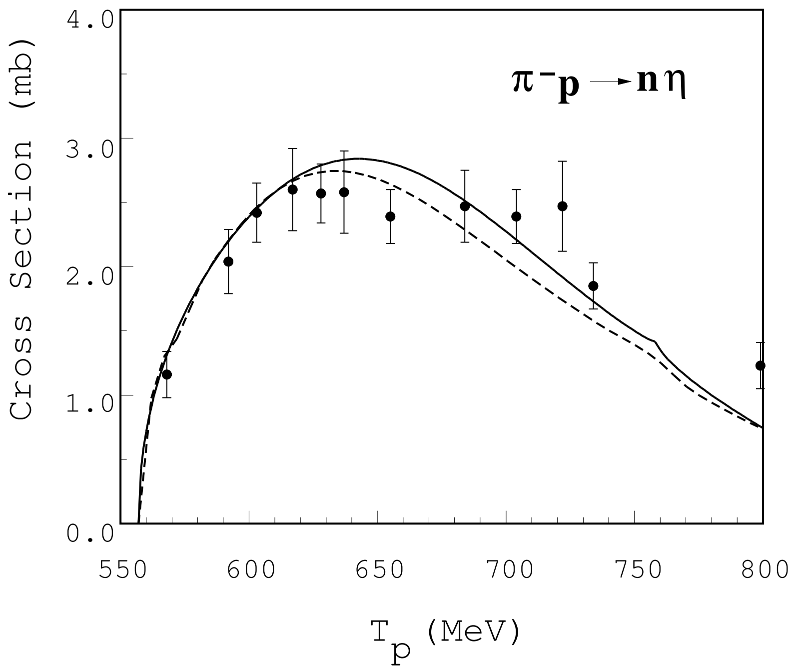
$$\mathbf{M^2 = a \cdot (L + N + 3/2) - b \cdot \alpha_D \; [GeV^2]}$$

$\mathbf{a = 1.04\,GeV^2}$ **and** $\mathbf{b = 1.46\,GeV^2}$**.**



- **Dynamical generation of baryon resonances:**

At low energies the building blocks of hadron resonances could be the ground state mesons and baryons. Resonance properties are derived from chiral Lagrangians. $N_{1/2^-}(1535)$, e.g., is a quasi-bound ΛK–ΣK state.



N. Kaiser, P. B. Siegel and W. Weise, Phys. Lett. B 362, 23 (1995).

Are dynamically generated states additional states, atop of quark model states?

Or are quark model and dynamically generated resonance dual descriptions?

Examples:

$\mathbf{N_{1/2^-}(1535), \Lambda_{1/2^-}(1405)}$
$\mathbf{a_0(980), f_0(980), D_s(2317), X(3872),}$
$\sigma\mathbf{(470)}, \kappa\mathbf{(700)}$

Are these states additional to the quark model?

- **Excursion to heavy baryon resonances:**

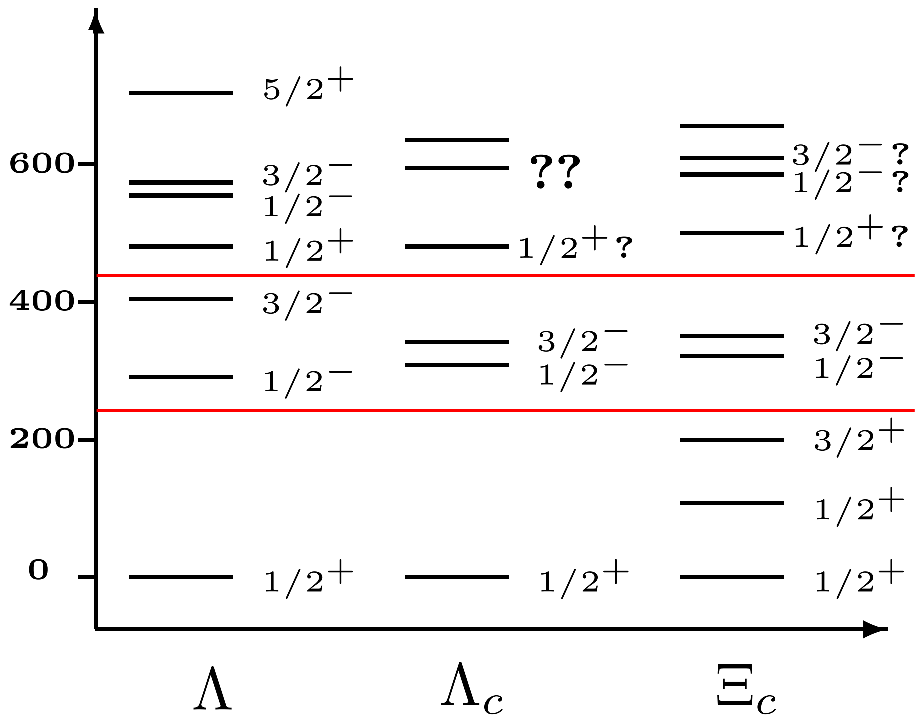
Masses (in MeV) of heavy baryons.

The isospin of $\Lambda_c^+/\Sigma_c^+(2765)$ (faint) is unknown.

Λ_c^+	2286.5±0.2	2595.4±0.6	2628.1±0.6	2766.6±2.4	2881.5±0.4
Σ_c^{++}	2454.0±0.2	2518.4±0.6	2801^{+4}_{-6}	| Λ_c^+:	2939.3±1.4
Σ_c^+	2452.9±0.4	2517.5±2.3	2792^{+14}_{-5}	2766.6±2.4	
Σ_c^+	2453.8±0.2	2518.0±0.5	2802^{+4}_{-7}		
Ξ_c^+	2467.9±0.4	2575.7±3.1	2646.6±1.4	2789.2±3.2	2816.5±1.2
		2969.3±2.8	3054.2±1.3	3077.0±0.5	3122.9±1.3
Ξ_c^0	2471.0±0.4	2578.0±2.9	2646.1±1.2	2791.9±3.3	2818.2±2.1
		2972.9±4.7		3079.3±1.1	
Ω_c^0	2697.5±2.6	2768.3±3.0		| Ξ_{cc}^+:	3518.9±0.9
Λ_b^0	5620.2±1.6				
Σ_b^+	5807.8±2.7	5829.0±3.4	| Σ_b^-:	5815.2±2.0	5836.4±2.8
Ξ_b^-	5793.8±3.8		| Ω_b^-:	6165±17 or 6054.4±6.8	

$\Xi_b^- = (bsd) \Rightarrow$ **three generations!**

Only very few measured spin-parities!



The lowest-mass Λ, Λ_c, and Ξ_c negative-parity states have fully antisymmetric spin-flavor wave functions. In the Λ spectrum, the Roper-like state is above the two singlet states, then the two negative-parity octet (mixed symmetry) states follow. The Λ_c and Ξ_c exhibit the same pattern but spin-parities are not known.

Wohl in PDG: *The clean Λ_c spectrum has in fact been taken to settle the decades-long discussion about the nature of the $\Lambda(1405)$ - true 3-quark state or $\overline{K}p$ threshold effect? - unambiguously in favor of the first interpretation.*

Heavy-quark and light-quark spectroscopy benefit from each other!

Restoration of chiral symmetry:

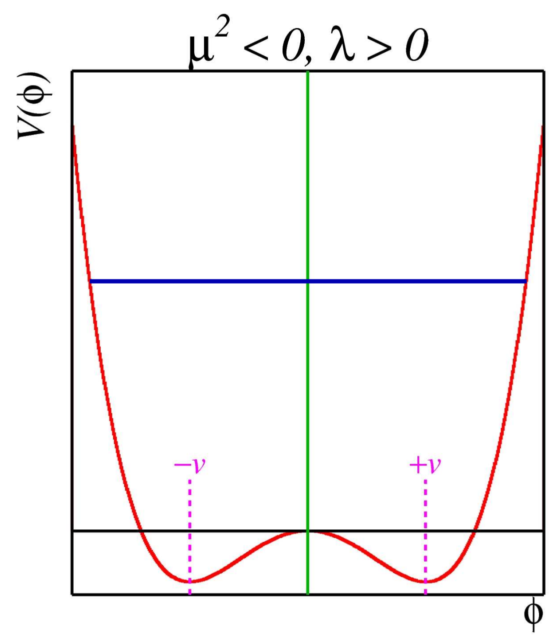
Chiral multiplets for $J = 1/2$, $3/2$, $5/2$ (first three lines) and for $J = 1/2, \cdots, 7/2$ (last four lines) for nucleon and Δ resonances.

$\mathbf{N}_{1/2^+}(1710)$ **	$\mathbf{N}_{1/2^-}(1650)$ ****	$\Delta_{1/2^+}(1750)$	$\Delta_{1/2^-}(1620)$ ****
$\mathbf{N}_{3/2^+}(1720)$ ****	$\mathbf{N}_{3/2^-}(1700)$ ***	$\Delta_{3/2^+}(1600)$ ***	$\Delta_{3/2^-}(1700)$ ****
$\mathbf{N}_{5/2^+}(1680)$ ****	$\mathbf{N}_{5/2^-}(1675)$ ****	**no chiral partners**	
$\mathbf{N}_{1/2^+}(1880)$ **	$\mathbf{N}_{1/2^-}(1905)$ *	$\Delta_{1/2^+}(1910)$ ****	$\Delta_{1/2^-}(1900)$ **
$\mathbf{N}_{3/2^+}(1900)$ **	$\mathbf{N}_{3/2^-}(1860)$ **	$\Delta_{3/2^+}(1920)$ ***	$\Delta_{3/2^-}(1940)$ **
no chiral partners		$\Delta_{5/2^+}(1905)$ ****	$\Delta_{5/2^-}(1930)$ ***
$\mathbf{N}_{7/2^+}(1990)^a$ **	$\mathbf{N}_{7/2^-}(2190)$ ****	$\Delta_{7/2^+}(1950)$ ****	$\Delta_{7/2^-}(2200)$ *
$\mathbf{N}_{9/2^+}(2220)$ ****	$\mathbf{N}_{9/2^-}(2250)$ ****	$\Delta_{9/2^+}(2300)$ **	$\Delta_{9/2^-}(2400)$ **

Limited predictive power.

Mass of ground-state baryons due to spontaneous breaking of chiral symmetry. Thus, $N_{1/2^-}(1535)$ is much heavier than its chiral partner, $N_{1/2^+}(940)$.

At high excitation energies, details of the chiral potential could be irrelevant. Chiral symmetry could be restored. Then: chiral multiplets should occur.



Comparison model versus data:

- **Quark model with eff. one-gluon exchange:** $(\delta M/M) = \mathbf{5.6\%}$ **(7p)**

  S. Capstick and N. Isgur, "Baryons In A Relativized Quark Model With Chromodynamics," Phys. Rev. D 34, 2809 (1986).

- **Quark model with instanton induced forces:** $(\delta M/M) = \mathbf{5.1\%}$ **(5p)**

  U. Loring, B.C. Metsch and H.R. Petry, "The light baryon spectrum in a relativ. quark model with instanton-induced quark forces," Eur. Phys. J. A 10, 395, 447 (2001).

- **AdS/QCD model with "good diquarks":** $(\delta M/M) = \mathbf{2.5\%}$ **(2p)**

  H. Forkel and E. Klempt, "Diquark correlations in baryon spectroscopy and holographic QCD," Phys. Lett. B 679, 77 (2009)."

- **Skyrme model:** $(\delta M/M) = \mathbf{9.1\%}$ **(2p)**

  M. P. Mattis and M. Karliner, "The Baryon Spectrum Of The Skyrme Model," Phys. Rev. D 31, 2833 (1985).

The 2-parameter AdS/QCD mass formula gives the best description of the data:

- **Masses are well reproduced**
- **Parity doublets are predicted where they are observed (and only there)**
- **Abundance of states seems realistic**

Both parameters are related to the size of baryons:

- **a gives the increase of the size of baryons with L and N**
- **b suggests a shrinkage of the size of "good diquarks".**

These observations suggest that the origin of the masses of excited baryons is - as in the ground states - spontaneous breaking of chiral symmetry. In bag model language: in resonances, the chiral condensates are expelled out of a larger region in space, and this is the reason for the increase in mass.

It ain't necessarily be so!

The Baryon Resonance Spectrum: Perspectives

1. **Baryons provide an excellent tool to study strong QCD. Fundamental questions are at stake: is chiral symmetry breaking - responsible for the mass of ground state baryons - responsible as well for the mass of excited states? Why is AdS/QCD so successful in reproducing the mass spectrum?**
2. **There is an ongoing ambitious program: photoproduction of baryon resonances.**

   High-statistics photoproduction experiments with polarized photons and targets (CLAS, ELSA, MAMI-C, SPring-8)

   Multi-channel partial wave analyses (BnGa, Ebac, Jϊich, MAID, SAID, among others).

   The existence and the properties of a few states are decisive for different scenarios like quark models, the role of dynamically generated resonances, gravitational theories, and the conjecture that chiral symmetry may be restored in high-mass excitations.
3. **A couple of key questions should be answered:**

- **Is the quark model a valid approximation up to the second shell?**

The quark model predicts a doublet of positive-parity states - $N_{1/2^+}$ and $N_{3/2^+}$ - with $L = 1, S = 1/2$. These states have both oscillators excited; one should expect them to decay in a cascade. Based on the mass formula, I expect these states at $\approx 1780\,\mathrm{MeV}$ and to be found in the reaction chain $\gamma p \to N_{1/2^-}(1535)\pi \to N\pi\eta$ and $\gamma p \to N_{3/2^-}(1520)\pi \to N\pi\pi$, respectively.

- **Are dynamically generated resonances additional resonances atop of quark model states or are these dual views onto the same objects?**

Decide if $\Lambda_{1/2^-}(1405)$ split is really into two states, one mainly singlet, one mainly octet. Best experimental chance in $J/\psi \to \Lambda_{1/2^-}(1405)\overline{\Lambda}_{1/2^-}(1405)$. Explore link to heavy baryon spectroscopy.

- **Is chiral symmetry is restored in high-excitation states?**

What is the mass of $\Delta_{7/2^-}$?

[a] About $1950\,\mathrm{MeV}$;

then $\Delta_{7/2^-}$ forms a chiral doublet with $\Delta_{7/2^+}(1950)$ and supports chiral symmetry restoration.

[b] About $2200\,\mathrm{MeV}$;

then it supports quark models and AdS/QCD.

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.