Exotic baryons: discoveries and new perspectives

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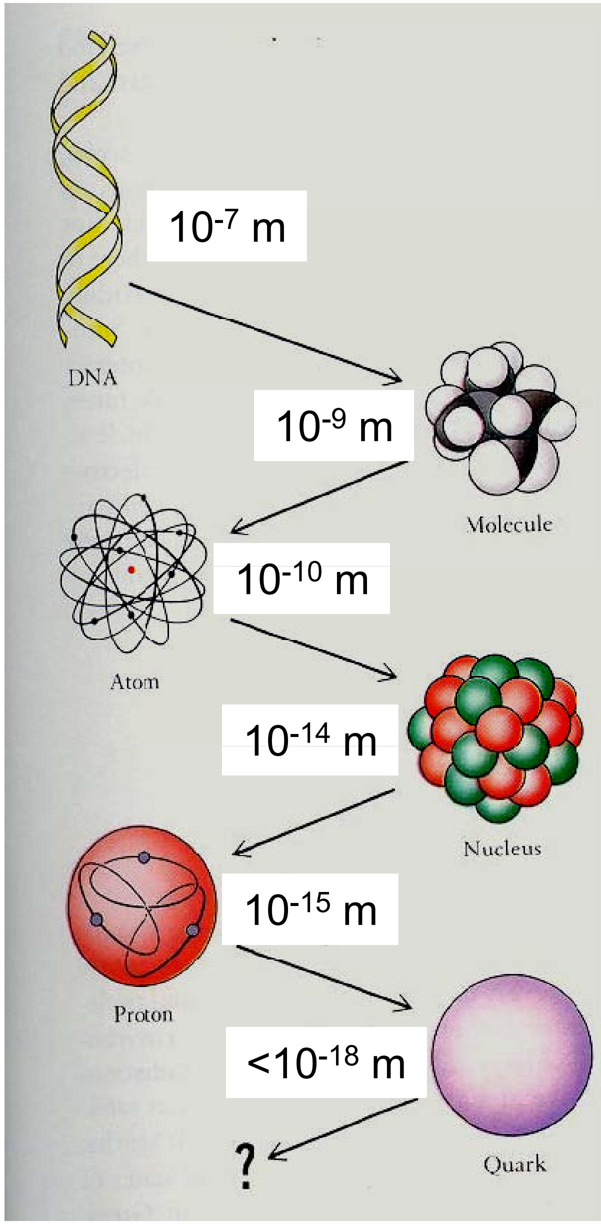
Outline:

- hadron families and quarks
- prediction of pentaquarks
- discovery (2003)
- QCD and chiral solitons
- postdictions
- implications

Bochum, Jan 22, 2004

Families within families of matter



DNA

Molecule

Atom

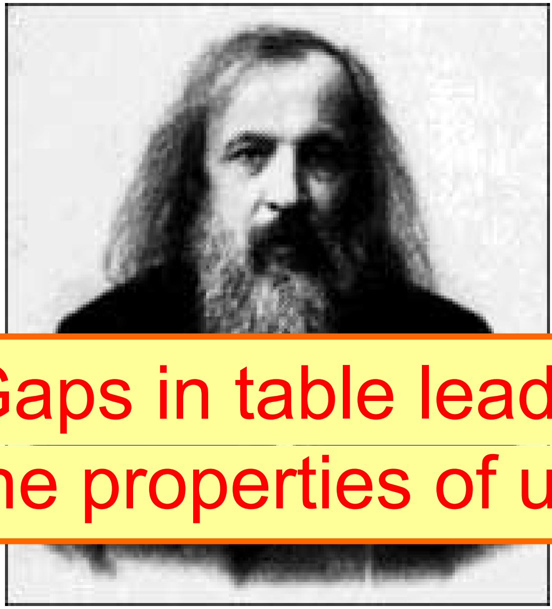
Nucleus

Proton

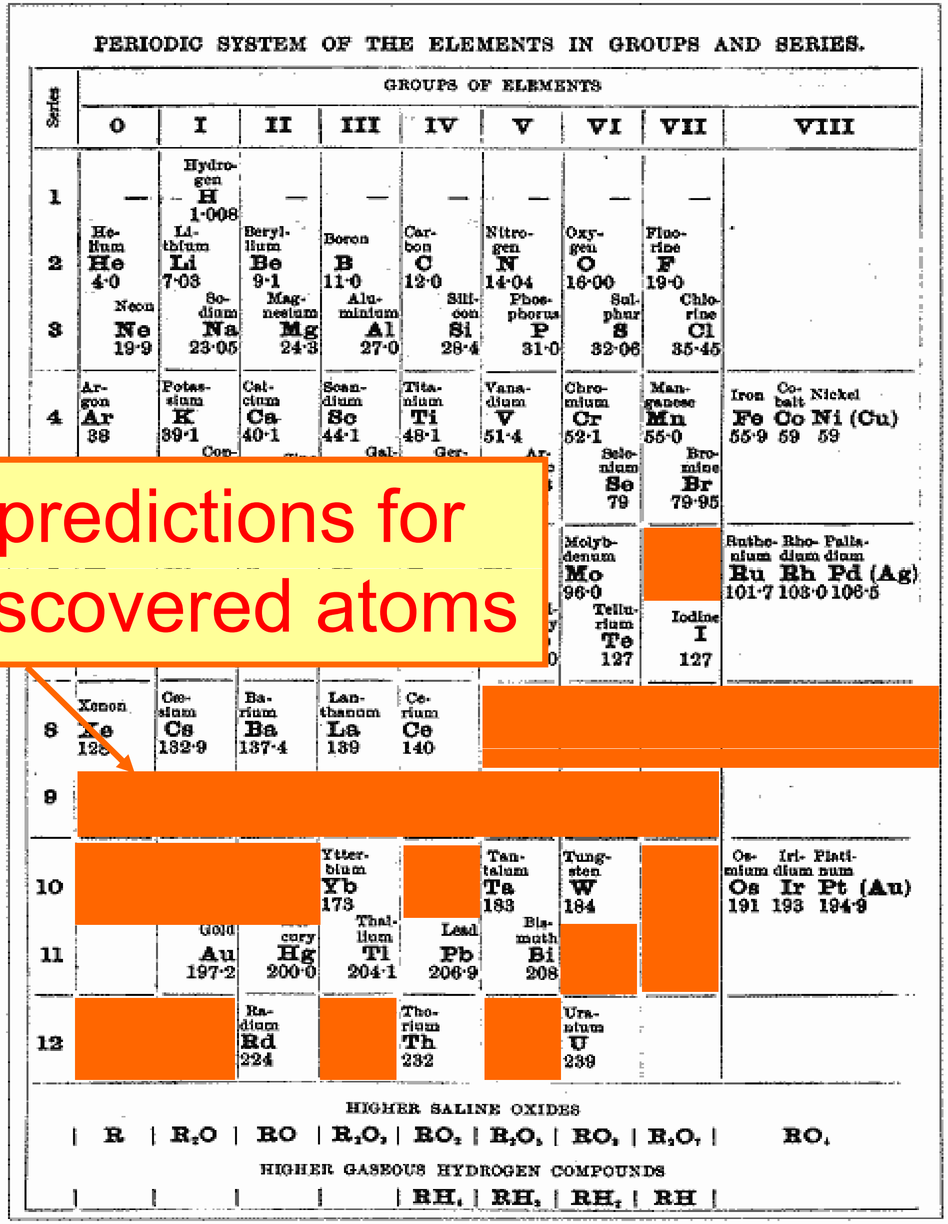
Quark

Families of atoms

Gaps in table lead to predictions for the properties of undiscovered atoms



Mendeleev (1869)



PERIODIC SYSTEM OF THE ELEMENTS IN GROUPS AND SERIES.

Series	0	I	II	III	IV	V	VI	VII	VIII
1	—	Hydrogen H 1·008	—	—	—	—	—	—	
2	Helium He 4·0	Lithium Li 7·03	Beryllium Be 9·1	Boron B 11·0	Carbon C 12·0	Nitrogen N 14·04	Oxygen O 16·00	Fluorine F 19·0	
3	Neon Ne 19·9	Sodium Na 23·05	Magnesium Mg 24·3	Aluminium Al 27·0	Silicon Si 28·4	Phosphorus P 31·0	Sulphur S 32·06	Chlorine Cl 35·45	
4	Argon Ar 38	Potassium K 39·1	Calcium Ca 40·1	Scandium Sc 44·1	Titanium Ti 48·1	Vanadium V 51·4	Chromium Cr 52·1	Manganese Mn 55·0	Iron Cobalt Nickel Fe Co Ni (Cu) 55·9 59 59
5							Selenium Se 79	Bromine Br 79·95	
6							Molybdenum Mo 96·0		Ruthenium Rhodium Palladium Ru Rh Pd (Ag) 101·7 103·0 106·5
7							Tellurium Te 127	Iodine I 127	
8	Xenon Xe 128	Caesium Cs 132·9	Barium Ba 137·4	Lanthanum La 139	Cerium Ce 140				
9									
10				Ytterbium Yb 173		Tantalum Ta 183	Tungsten W 184		Osmium Iridium Platinum Os Ir Pt (Au) 191 193 194·9
11		Gold Au 197·2	Mercury Hg 200·0	Thallium Tl 204·1	Lead Pb 206·9	Bismuth Bi 208			
12			Radium Rd 224		Thorium Th 232		Uranium U 239		

HIGHER SALINE OXIDES

R	R_2O	RO	R_2O_3	RO_2	R_2O_5	RO_3	R_2O_7	RO_4

HIGHER GASEOUS HYDROGEN COMPOUNDS

				RH_4	RH_3	RH_2	RH

Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the main Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the short table are not established as baryons. The names with masses are of baryons that decay strongly. For N, Δ, and Ξ resonances, the partial wave is indicated by the symbol $L_{2I,2J}$, where L is the orbital angular momuntum (S, P, D, ...), I is the isospin, and J is the total angular momentum. For Λ and Σ resonances, the symbol is $L_{I,2J}$.

p	P_{11}	****
n	P_{11}	****
$N(1440)$	P_{11}	****
$N(1520)$	D_{13}	****
$N(1535)$	S_{11}	****
$N(1650)$	S_{11}	****
$N(1675)$	D_{15}	****
$N(1680)$	F_{15}	****
$N(1700)$	D_{13}	***
$N(1710)$	P_{11}	***
$N(1720)$	P_{13}	****
$N(1900)$	P_{13}	**
$N(1990)$	F_{17}	**
$N(2000)$	F_{15}	**
$N(2080)$	D_{13}	**
$N(2090)$	S_{11}	*
$N(2100)$	P_{11}	*
$N(2190)$	G_{17}	****
$N(2200)$	D_{15}	**
$N(2220)$	H_{19}	****
$N(2250)$	G_{19}	****
$N(2600)$	$I_{1,11}$	***
$N(2700)$	$K_{1,13}$	**

$\Delta(1232)$	P_{33}	****
$\Delta(1600)$	P_{33}	***
$\Delta(1620)$	S_{31}	****
$\Delta(1700)$	D_{33}	****
$\Delta(1750)$	P_{31}	*
$\Delta(1900)$	S_{31}	**
$\Delta(1905)$	F_{35}	****
$\Delta(1910)$	P_{31}	****
$\Delta(1920)$	P_{33}	***
$\Delta(1930)$	D_{35}	***
$\Delta(1940)$	D_{33}	*
$\Delta(1950)$	F_{37}	****
$\Delta(2000)$	F_{35}	**
$\Delta(2150)$	S_{31}	*
$\Delta(2200)$	G_{37}	*
$\Delta(2300)$	H_{39}	**
$\Delta(2350)$	D_{35}	*
$\Delta(2390)$	F_{37}	*
$\Delta(2400)$	G_{39}	**
$\Delta(2420)$	$H_{3,11}$	****
$\Delta(2750)$	$I_{3,13}$	**
$\Delta(2950)$	$K_{3,15}$	**

Λ	P_{01}	****
$\Lambda(1405)$	S_{01}	****
$\Lambda(1520)$	D_{03}	****
$\Lambda(1600)$	P_{01}	***
$\Lambda(1670)$	S_{01}	****
$\Lambda(1690)$	D_{03}	****
$\Lambda(1800)$	S_{01}	***
$\Lambda(1810)$	P_{01}	***
$\Lambda(1820)$	F_{05}	****
$\Lambda(1830)$	D_{05}	****
$\Lambda(1890)$	P_{03}	****
$\Lambda(2000)$		*
$\Lambda(2020)$	F_{07}	*
$\Lambda(2100)$	G_{07}	****
$\Lambda(2110)$	F_{05}	***
$\Lambda(2325)$	D_{03}	*
$\Lambda(2350)$	H_{09}	***
$\Lambda(2585)$		**

Σ^+	P_{11}	****
Σ^0	P_{11}	****
Σ^-	P_{11}	****
$\Sigma(1385)$	P_{13}	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	D_{13}	**
$\Sigma(1620)$	S_{11}	**
$\Sigma(1660)$	P_{11}	***
$\Sigma(1670)$	D_{13}	****
$\Sigma(1690)$		**
$\Sigma(1750)$	S_{11}	***
$\Sigma(1770)$	P_{11}	*
$\Sigma(1775)$	D_{15}	****
$\Sigma(1840)$	P_{13}	*
$\Sigma(1880)$	P_{11}	**
$\Sigma(1915)$	F_{15}	****
$\Sigma(1940)$	D_{13}	***
$\Sigma(2000)$	S_{11}	*
$\Sigma(2030)$	F_{17}	****
$\Sigma(2070)$	F_{15}	*
$\Sigma(2080)$	P_{13}	**
$\Sigma(2100)$	G_{17}	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0, Ξ^-	P_{11}	****
$\Xi(1530)$	P_{13}	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	D_{13}	***
$\Xi(1950)$		***
$\Xi(2030)$		***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-		****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**
Λ_c^+		****
$\Lambda_c(2593)^+$		***
$\Lambda_c(2625)^+$		***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$		**
$\Sigma_c(2455)$		****
$\Sigma_c(2520)$		***
Ξ_c^+, Ξ_c^0		***
$\Xi_c^{\prime +}$, $\Xi_c^{\prime 0}$		***
$\Xi_c(2645)$		***
$\Xi_c(2790)$		***
$\Xi_c(2815)$		***
Ω_c^0		***
Λ_b^0		***
Ξ_b^0, Ξ_b^-		*

**** Existence is certain, and properties are at least fairly well explored.

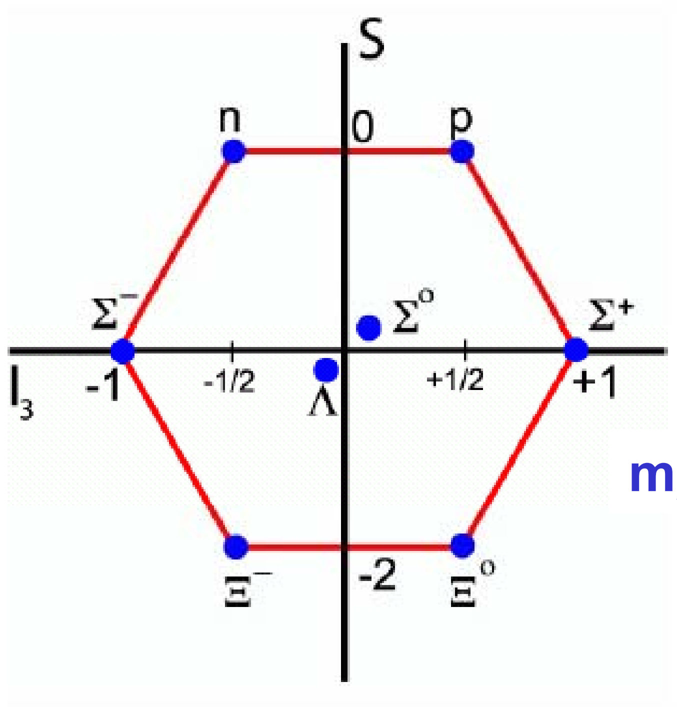
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

** Evidence of existence is only fair.

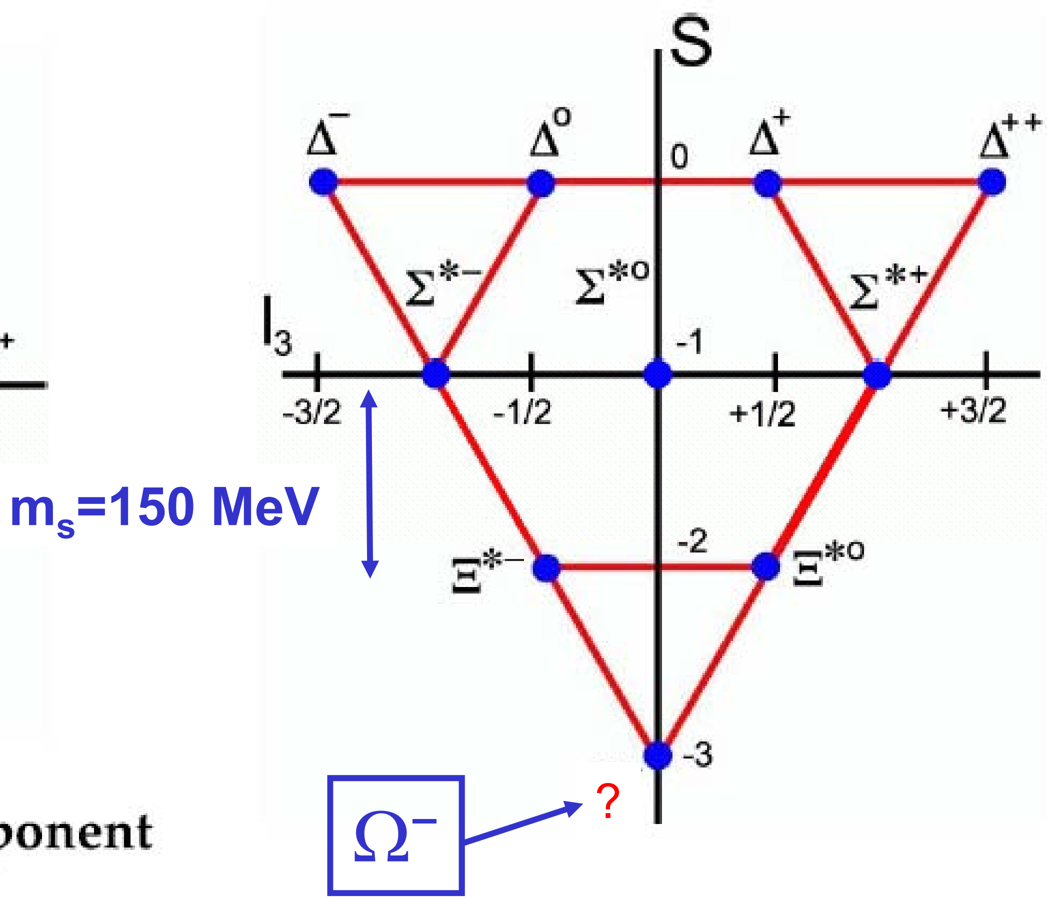
* Evidence of existence is poor.

Baryon Families

Octet (S=1/2)



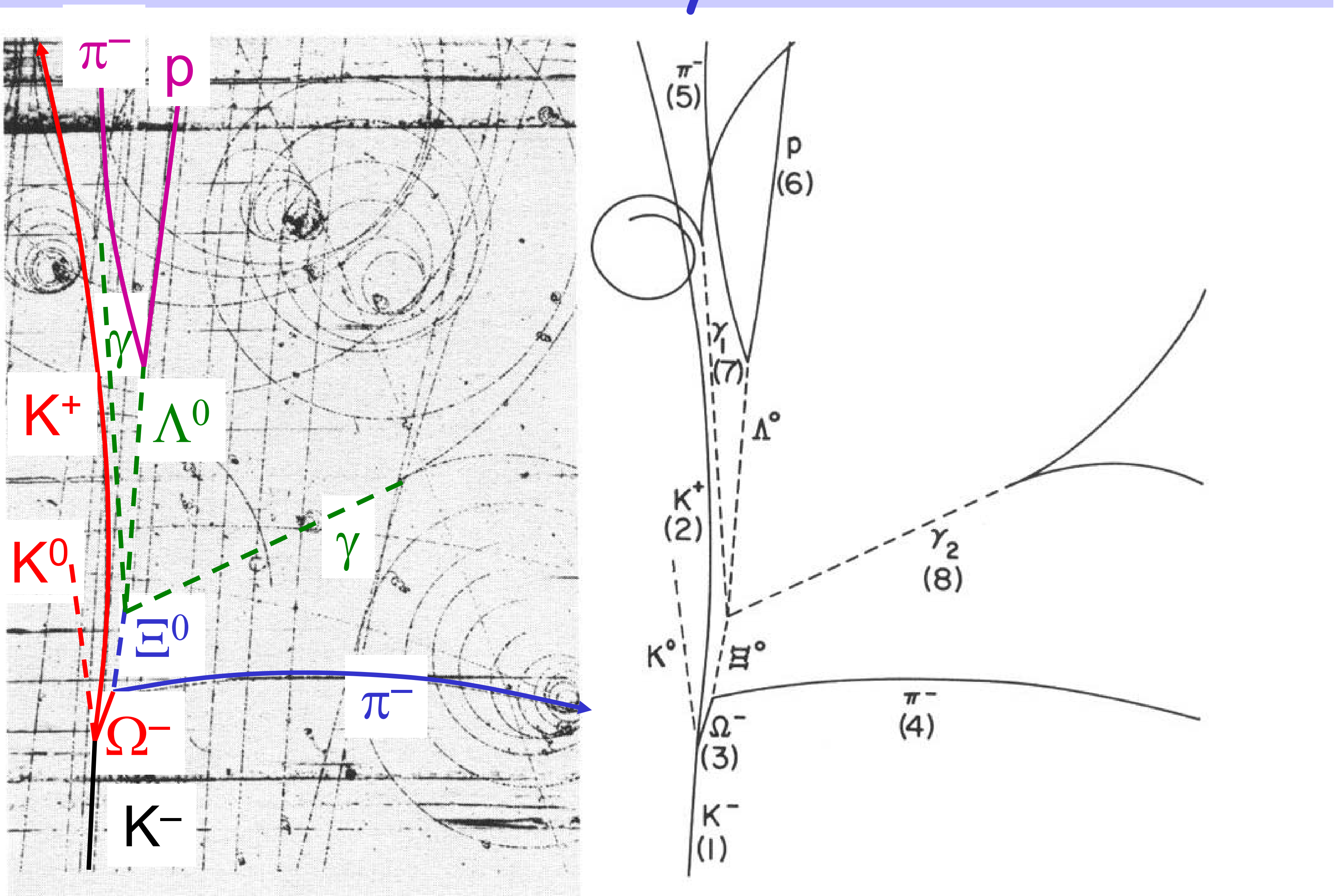
Decuplet (S=3/2)



Strangeness vs. Isospin Component

Gell-Mann, Neeman SU(3) symmetry

Production and decay of $\Omega^- \rightarrow \Xi^o \pi^-$



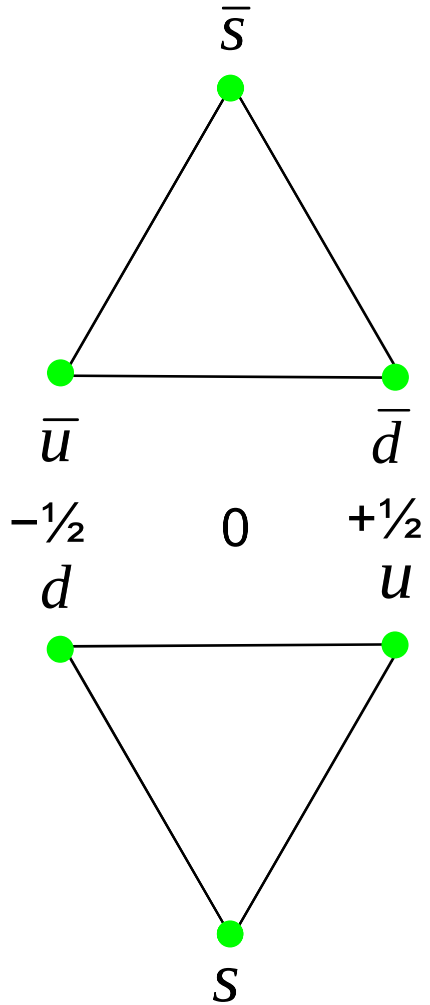
V.E. Barnes et. al., Phys. Rev. Lett. 8, 204 (1964)

FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

(sub)Family of quarks

Gell-Mann, Zweig `63

$$I_3 = Q - \tfrac{1}{2}(B+S)$$



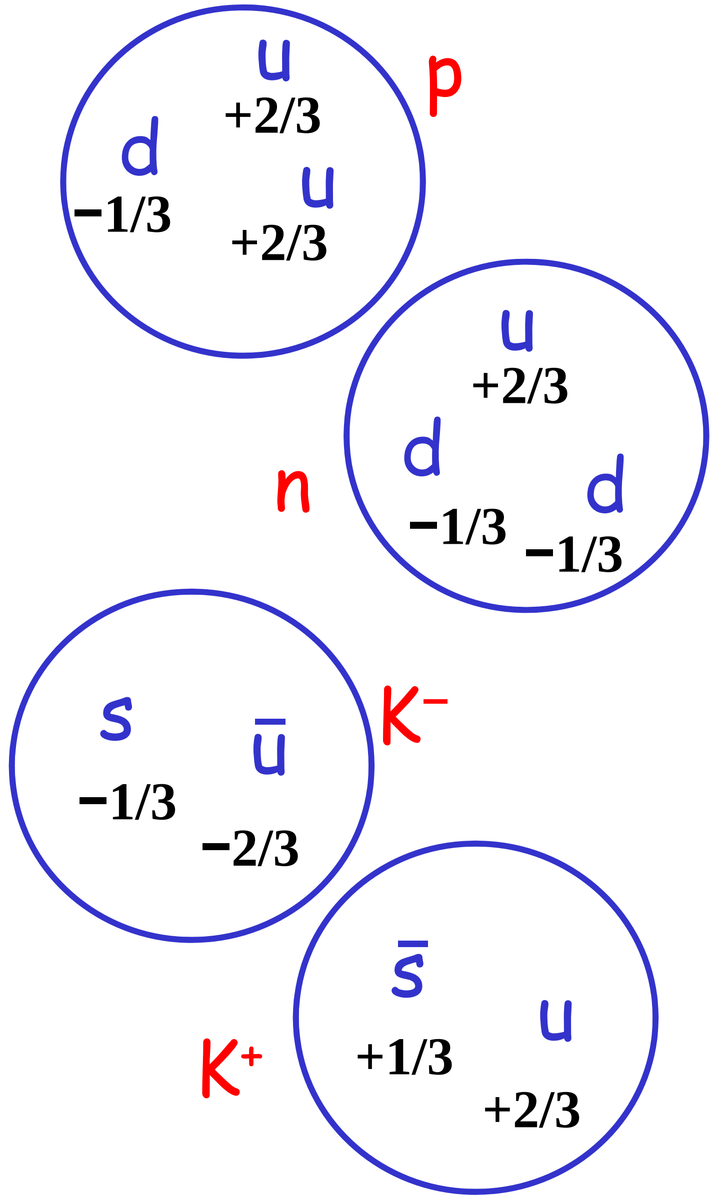
S=+1

S= 0

S=−1

Properties of quarks

Quark Flavor	Charge (Q)	Baryon number	Strangeness (S)
u	+2/3	+1/3	0
d	−1/3	+1/3	0
s	−1/3	+1/3	−1
$\bar{u}$	− 2/3	−1/3	0
$\bar{d}$	+1/3	−1/3	0
$\bar{s}$	+1/3	−1/3	+1

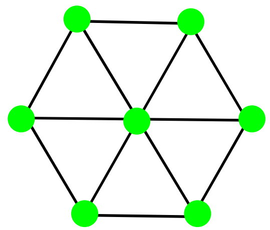


Protons are made of (*uud*)
Neutrons are made of (*ddu*)

Hadron multiplets

Mesons $q\bar{q}$

$$3 \otimes \bar{3} = 8 \oplus 1$$



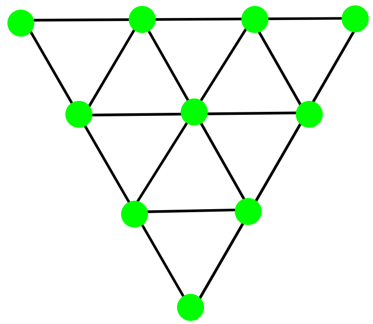
K

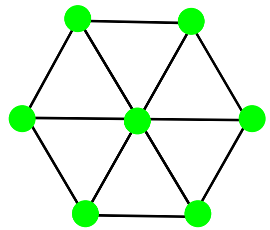
π

$\bar{\mathbf{K}}$

Baryons qqq

$$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$$





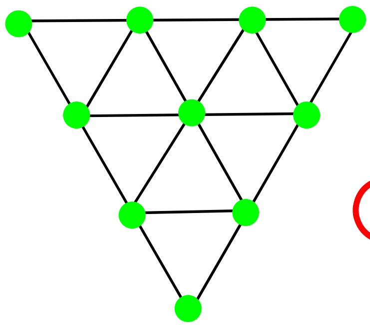
N

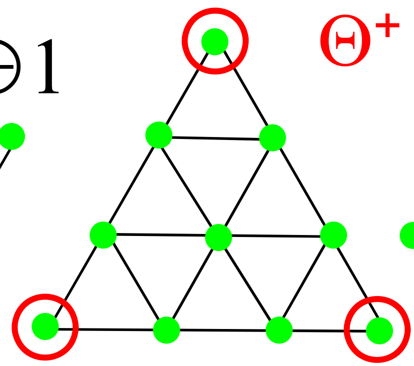
Σ

Ξ

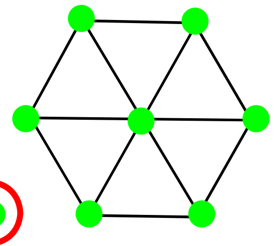
Baryons built from meson-baryon, or $qqqq\bar{q}$

$$8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1$$





Θ^+



What are pentaquarks?

- Minimum content: 4 quarks and 1 antiquark $\left(qqqq\overline{Q}\right)$
- "Exotic" pentaquarks are those where the antiquark has a different flavour than the other 4 quarks
- Quantum numbers cannot be defined by 3 quarks alone.

Example: $uuds\bar{s}$, non-exotic

Baryon number = 1/3 + 1/3 + 1/3 + 1/3 – 1/3 = 1

Strangeness = 0 + 0 + 0 – 1 + 1 = 0

The same quantum numbers one obtains from uud

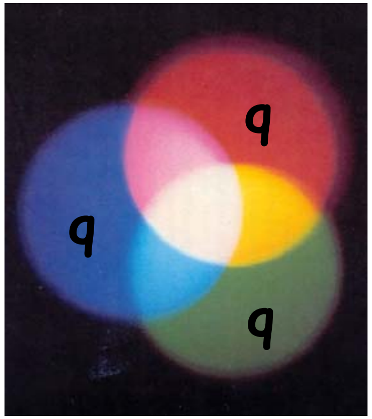
Example: $uudd\bar{s}$, exotic

Baryon number = 1/3 + 1/3 + 1/3 + 1/3 – 1/3 = 1

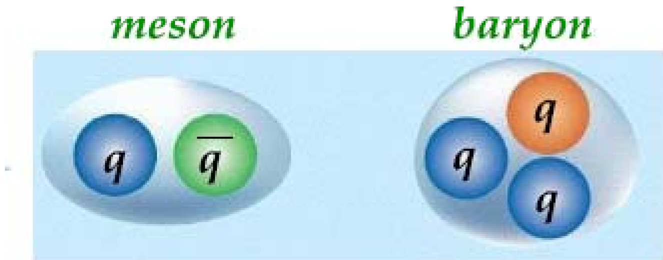
Strangeness = 0 + 0 + 0 + 0 + 1 = +1

Impossible in trio qqq

Quarks are confined inside colourless hadrons



Mystery remains:
Of the many possibilities for combining quarks with colour into colourless hadrons, only two configurations were found, till now…



Particle Data Group 1986 reviewing evidence for *exotic baryons states*

"…The general prejudice against baryons not made of three quarks and the lack of any experimental activity in this area make it likely that it will be another 15 years before the issue is decided.

PDG dropped the discussion on pentaquark searches after 1988.

Baryon states

All baryonic states listed in PDG can be made of 3 quarks only

* classified as octets, decuplets and singlets of flavour SU(3)
* Strangeness range from S=0 to S=-3

A baryonic state with S=+1 is explicitely EXOTIC

- Cannot be made of 3 quarks
- Minimal quark content should be $qqqq\bar{s}$, hence pentaquark
- Must belong to higher SU(3) multiplets, e.g anti-decuplet

observation of a S=+1 baryon implies a new large multiplet of baryons (pentaquark is always ocompanied by its large family!) ⬅ important

Searches for such states started in 1966, with negative results till autumn 2002 [16 years after 1986 report of PDG !]

…it will be another <u>15 years</u> before the issue is decided.

Theoretical predictions for pentaquarks

1. Bag models [R.L. Jaffe '77, J. De Swart '80]
$J^p = 1/2^-$ lightest pentaquark
Masses higher than 1700 MeV, width ~ hundreds MeV

Mass of the pentaquark is roughly 5 M +(strangeness) ~ 1800 MeV
An additional q –anti-q pair is added as constituent

2. Skyrme models [Diakonov, Petrov '84, Chemtob'85, Praszalowicz '87, Walliser '92, Weigel `94]
Exotic anti-decuplet of baryons with lightest S=+1
$J^p = 1/2^+$ pentaquark with mass in the range 1500-1800 MeV.

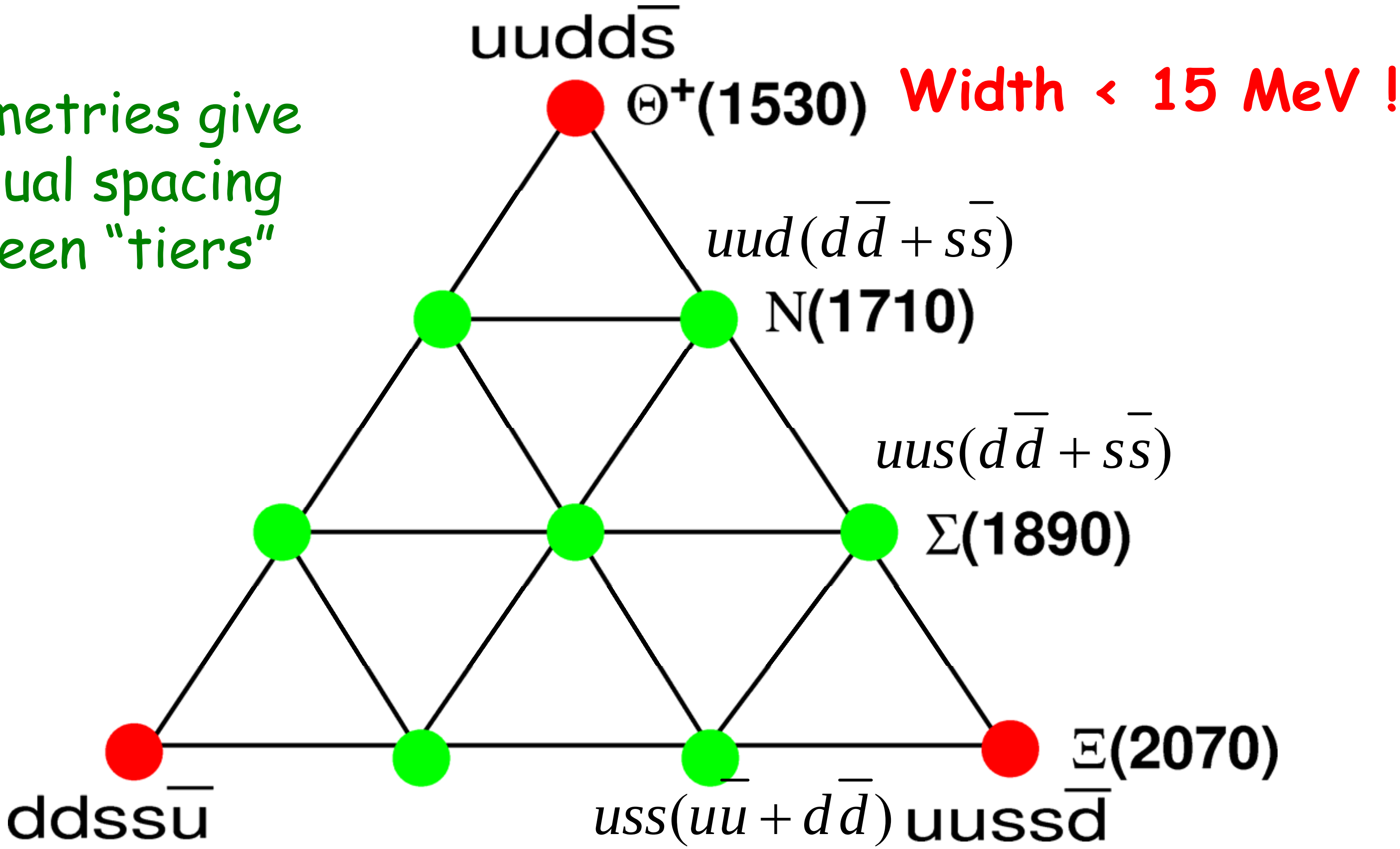
Mass of the pentaquark is rougly 3 M +(1/baryon size)+(strangeness) ~ 1500MeV
An additional q –anti-q pair is added in the form of excitation of nearly massless chiral field

The question what is the width of the exotic pentaquark
In Skyrme model has not been address untill 1997

It came out that it should be „anomalously" narrow!
Light and narrow pentaquark is expected –>
drive for experiments
[D. Diakonov, V. Petrov, M. P. '97]

The Anti-decuplet

Symmetries give an equal spacing between "tiers"



Diakonov, Petrov, MVP 1997

2003 - Dawn of the Pentaquark

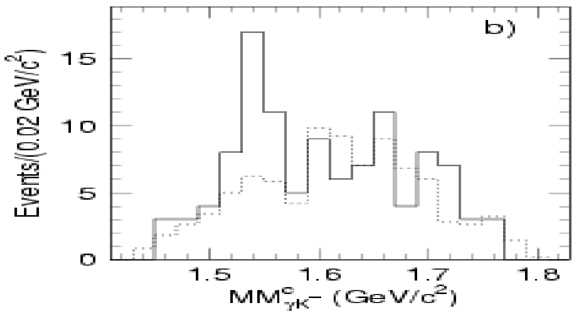
Θ^+ first particle which is made of more than 3 quarks !

Particle physics laboratories took the lead

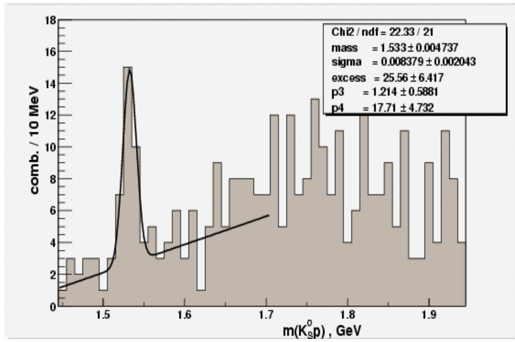
Spring-8: LEPS (Carbon)
JLab: CLAS (deuterium & proton)
ITEP: DIANA (Xenon bubble chamber)
ELSA: SAPHIR (Proton)
CERN/ITEP: Neutrino scattering
CERN SPS: NA49 (pp scattering)
DESY: HERMES (deuterium)
ZEUS (proton)
COSY: TOF (pp-> $\Theta^+ \Sigma^+$)
SVD (IHEP) (p A collisions)
HERA-B (pA) Negative Result

$\Theta^+ \; \Theta^+ \; \Theta^+ \; \Theta^+ \ldots$

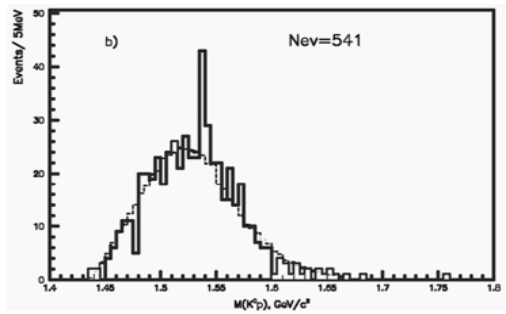
LEPS@SPring8



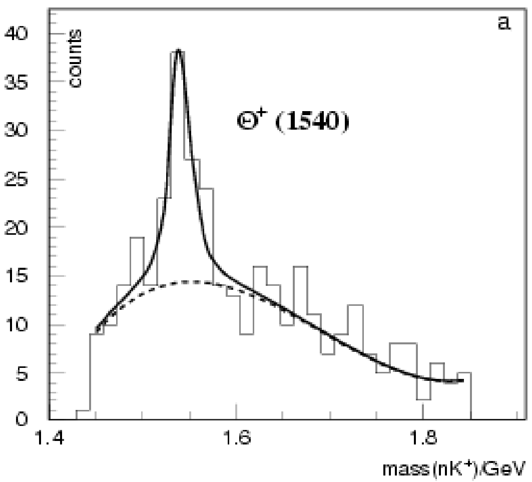
ITEP



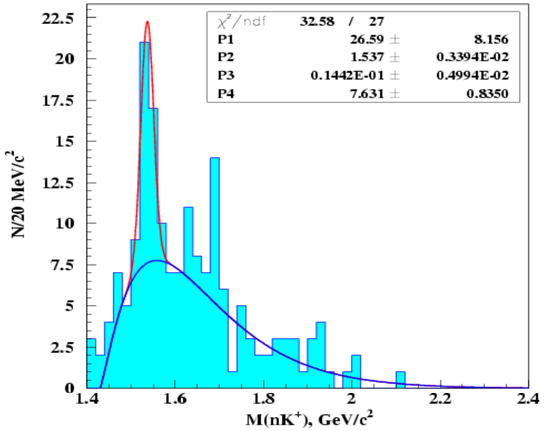
DIANA@ITEP



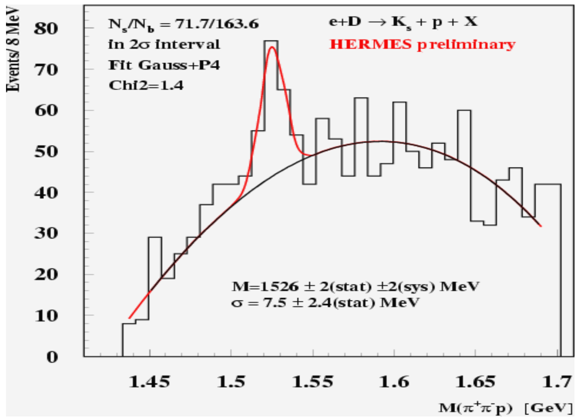
SAPHIR @ ELSA



CLAS@JLAB



HERMES@DESY



Where do we stand with the Θ^+?

Experiments	Results: Mass (MeV)	Width (Mev)	Significance (σ)
LEPS	$1540 \pm 10 \pm 5$	$\Gamma < 25$	4.6 ± 1
DIANA	$1539 \pm 2 \pm$ "few"	$\Gamma < 8$	4.4
CLAS	$1542 \pm 2 \pm 5$	FWhM < 21	5.3 ± 0.5
SAPHIR	$1540 \pm 4 \pm 2$	$\Gamma < 25$	4.8
ITEP (ν's)	1533 ± 5	$\Gamma < 29$	6.7
HERMES	$1526 \pm 2 \pm 2.5$	$\Gamma < 20$	5.6
World Average	**1535 ± 2.5**	Very Narrow	
Prediction	1530	$\Gamma < 15$	I=0 S=+1 $J^P = \frac{1}{2}^+$

All above are results of reanalyzing the existing data.

What's next ?

- Θ^+(1540)
  - ✓Spin, **parity**, isospin
  - ✓Total decay width
  - ✓ Cross section in various reactions
  - ✓ Production mechanism
  - ✓ Production at B-factories -> low background

- Search for other exotic Pentaquark States Ξ^{--}, Ξ^+ in electromagnetic interactions

- Search for non-exotic Pentaquark states (P_{11}(1440), P_{11}(1710), Σ's …), what are their signatures to distinguish them from the q^3 states?

- Excited states of Θ^+(1540) ? Are they also narrow ?

- Pentaquarks with anti-charm quark->B-factories, GSI

Quantum Chromodynamics

$$L_{QCD} = -\frac{1}{4g^2} F^a{}_{\mu\nu} F^{a\mu\nu} + \sum_{f=1}^{6} \bar{\psi}_f (i\gamma_\mu \nabla^\mu - m_f)\psi_f$$

$$F_{\mu\nu}{}^a = \partial_\mu A_\nu{}^a - \partial_\nu A_\mu{}^a + f^{abc} A_\mu{}^b A_\nu{}^c$$

Contains everything about from pions to uranium nuclei !

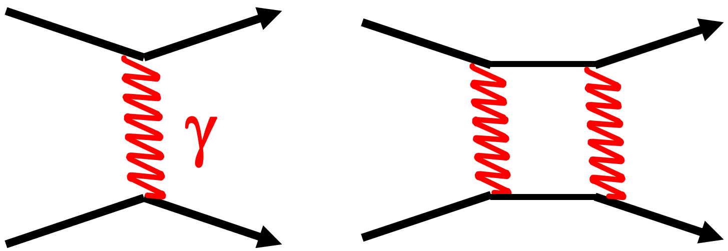
$$m_u \approx 4MeV, m_d \approx 7MeV$$

Proton =uud, its mass is 940 MeV

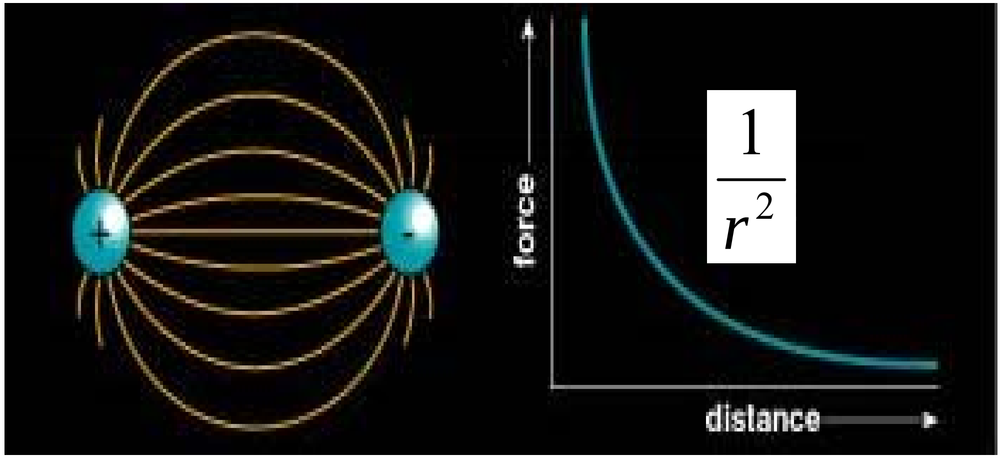
How come the nucleon is almost 100 times heavier its constituents ?

Electromagnetic and colour forces

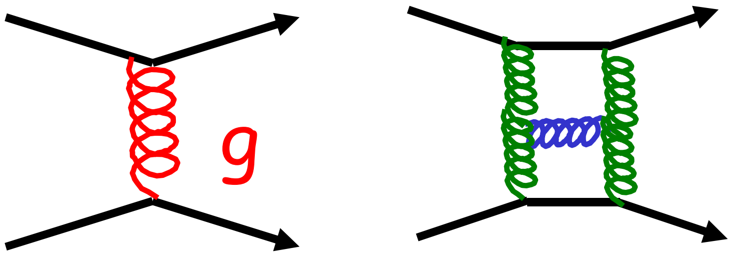
$O(\alpha) \sim 0.01$



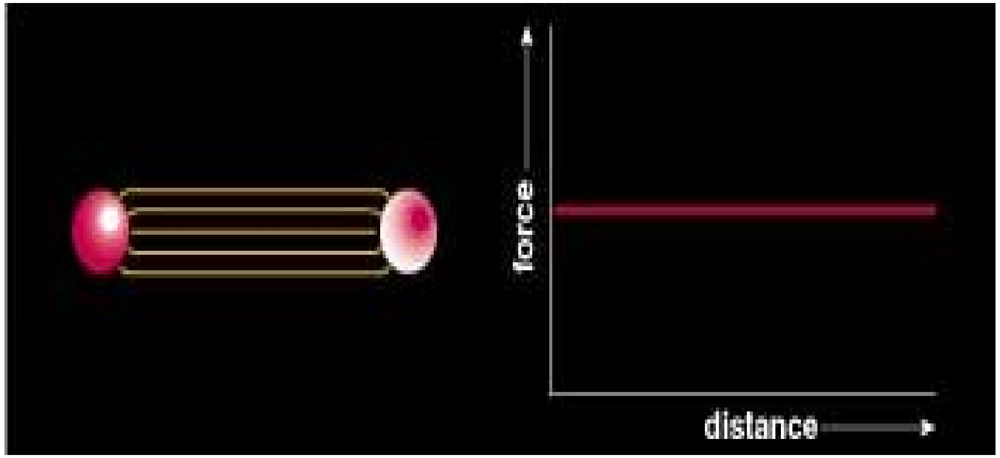
±1 charge



$O(\alpha_s) \sim 1$



3 "colour" charges



Chiral Symmetry of QCD

QCD in the chiral limit, i.e. Quark masses ~ 0

$$L_{\mathrm{QCD}} = -\frac{1}{4g^2} F^a_{\mu\nu} F^{a\mu\nu} + \bar{\psi}(i\gamma^\mu \partial_\mu + \gamma^\mu A_\mu)\psi$$

Global QCD-Symmetry → Lagrangean invariant under:

$$SU(2)_V : \quad \psi = \begin{pmatrix} \psi_u \\ \psi_d \end{pmatrix} \rightarrow \psi' = \exp\left\{-i\alpha^A \tau^A\right\} \begin{pmatrix} \psi_u \\ \psi_d \end{pmatrix}$$

hadron multiplets

$$SU(2)_A : \quad \psi = \begin{pmatrix} \psi_u \\ \psi_d \end{pmatrix} \rightarrow \psi' = \exp\left\{-i\alpha^A \tau^A \gamma_5\right\} \begin{pmatrix} \psi_u \\ \psi_d \end{pmatrix}$$

No Multiplets Symmetry is sponteneousl broken

Symmetry of Lagrangean is not the same as the symmetry of eigenstates

Unbroken chiral symmetry of QCD would mean
That all states with opposite parity have equal masses

But in reality: $$N^*(\frac{1}{2}^-) - N(\frac{1}{2}^+) = 600 MeV$$

The difference is too large to be explained by
Non-zero quark masses

➡ chiral symmetry is spontaneously broken

➡ pions are light [=pseudo-Goldstone bosons]

➡ nucleons are heavy

➡ nuclei exist

➡ ... we exist

Three main features of the SCSB

- Order parameter: chiral condensate $< \bar{q}q > \simeq -250 MeV^3 \neq 0$
  [vacuum is not „empty“ !]

- Quarks get dynamical masses: from the „current“
  masses of about m=5MeV to about M=350 MeV

- The octet of pseudoscalar meson are anomalously
  light (pseudo) Goldstone bosons.

Spontaneous breakdown of chiral symmetry

Simplest effective Lagrangean for quarks:

$$L_{eff} = \overline{\psi}(i\gamma^{\mu}\partial_{\mu} - M)\psi$$

Invariant: flavour vector transformation

Not invariant: flavour axial transformation

$$L_{eff} = \overline{\psi}(i\gamma^{\mu}\partial_{\mu} - MU)\psi$$

Invariant: both vector and axial transf. → U(x) must transform properly → should be made out of Goldstone bosons

Chiral Quark Soliton Model (ChQSM):

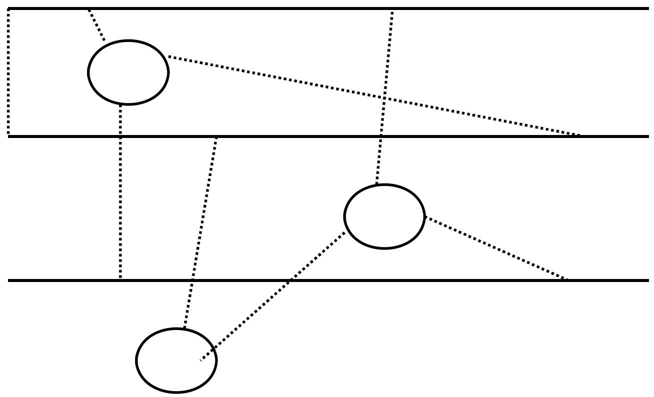
$$L_{eff} = \psi(i\gamma^{\mu}\partial_{\mu} - MU)\psi \qquad U(x) = \exp(\frac{i}{f_{\pi}}\tau^{A}\pi^{A}(x)\gamma_{5})$$

Pseudo-scalar pion field

Quarks that gained a dynamical mass interact with Goldstone bosons very strongly

$$g_{\pi qq} \approx 4$$

Multiple pion exchanges inside nucleon are important



Fully relativistic quantum field theory

A lot of quark-antiquark pairs in WF

Can be solved using mean-filed method if one assumes that 3>> 1

Fock-State: Valence and Polarized Dirac Sea

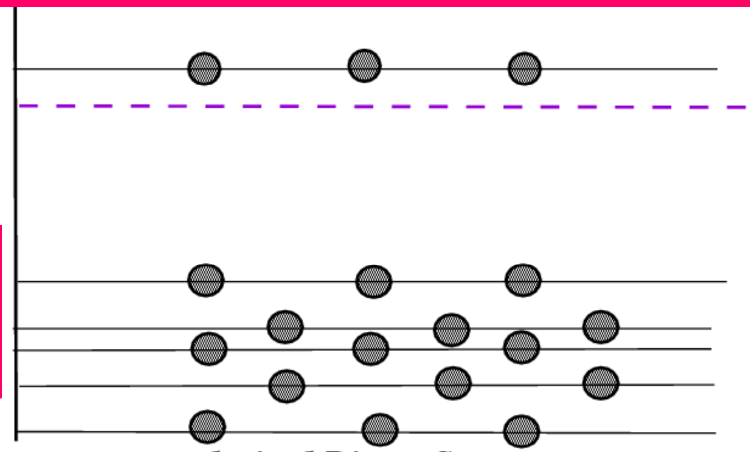
Dirac-Equation: $\left(-i\alpha\nabla + \beta MU\right)\phi_i = \varepsilon_i \phi_i$

$$\phi_i(x) = < x \mid a_i{}^\dagger \mid 0 >$$

S

Natural way for light baryon exotics. Also usual „3-quark“ baryons should contain a lot of antiquarks

$$|\psi(N_c)\rangle = \left(\prod_{val=1,N_c}^{N_c} a^\dagger_{val}\right)\left(\prod_{j\in sea} a^\dagger_{sea}\right)|0\rangle$$



polarized Dirac−Sea

Quark-anti-quark pairs „stored“ in chiral mean-field

Quantum numbers originate from 3 valence quarks AND Dirac sea !

Quantization of the mean field

Idea is to use symmetries

if we find a mean field π^a minimizing the energy

than the flavour rotated $R^{ab}\pi^b$ mean field

also minimizes the energy

- Slow flavour rotations change energy very little
- One can write effective dynamics for slow rotations [the form of Lagrangean is fixed by symmeries and axial anomaly ! See next slide]
- One can quantize corresponding dynamics and get spectrum of excitations [like: rotational bands for moleculae]

Presently there is very interesting discussion whether large Nc limit justifies slow rotations [Cohen, Pobylitsa, Witten....].
Tremendous boost for our understanding of soliton dynamics!
-> new predictions

SU(3): Collective Quantization

$$L_{coll} = M_0 + \frac{I_1}{2}\sum_{a=1}^{3}\Omega^a\Omega^a + \frac{I_2}{2}\sum_{a=4}^{7}\Omega^a\Omega^a + \frac{\sqrt{3}}{2}\Omega^8$$

$$J^a = \frac{\partial L}{\partial \Omega^a} \qquad \hat{H}_{coll} = \frac{1}{2I_1}\sum_{a=1}^{3}\hat{J}^a\hat{J}^a + \frac{1}{2I_2}\sum_{a=4}^{7}\hat{J}^a\hat{J}^a + \text{constraint}$$

$$J^8 = -\frac{N_c B}{2\sqrt{3}} \qquad Y' \equiv -\frac{2\hat{J}^8}{\sqrt{3}} = 1$$

From Wess-Zumino -term

$$\left[\hat{J}^a, \hat{J}^b\right] = i f^{abc}\hat{J}^c$$

Calculate eigenstates of H_{coll} and select those, which fulfill the constraint

SU(3): Collective Quantization

$$L_{coll} = M_0 + \frac{I_1}{2}\sum_{a=1}^{3}\Omega^a\Omega^a + \frac{I_2}{2}\sum_{a=4}^{7}\Omega^a\Omega^a + \frac{\sqrt{3}}{2}\Omega^8$$

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$$J^8 = -\frac{N_c B}{2\sqrt{3}} \qquad \mathrm{Y}' \equiv -\frac{2\hat{\mathrm{J}}^8}{\sqrt{3}} = 1$$

$$\left[\hat{J}^a, \hat{J}^b\right] = if^{abc}\hat{J}^c$$

Known from delta-nucleon splitting

$$\cancel{1}, \cancel{\overline{3}}, \cancel{6}, 8, 10, \overline{10}, 27, \ldots$$

$$\mathrm{J{=}T} \rightarrow \quad \frac{1^+}{2} \quad \frac{3^+}{2} \quad \frac{1^+}{2} \quad \ldots.$$

$$\Delta_{10\text{-}8} = \frac{3}{2\mathrm{I}_1} \qquad \Delta_{\overline{10}\text{-}8} = \frac{3}{2\mathrm{I}_2}$$

$$\Delta_{\overline{10}\text{-}10} = \frac{3}{2\mathrm{I}_2} - \frac{3}{2\mathrm{I}_1}$$

Spin and parity are predicted !!!

General idea: 8, 10, anti-10, etc are various excitations of the same mean field → properties are interrelated

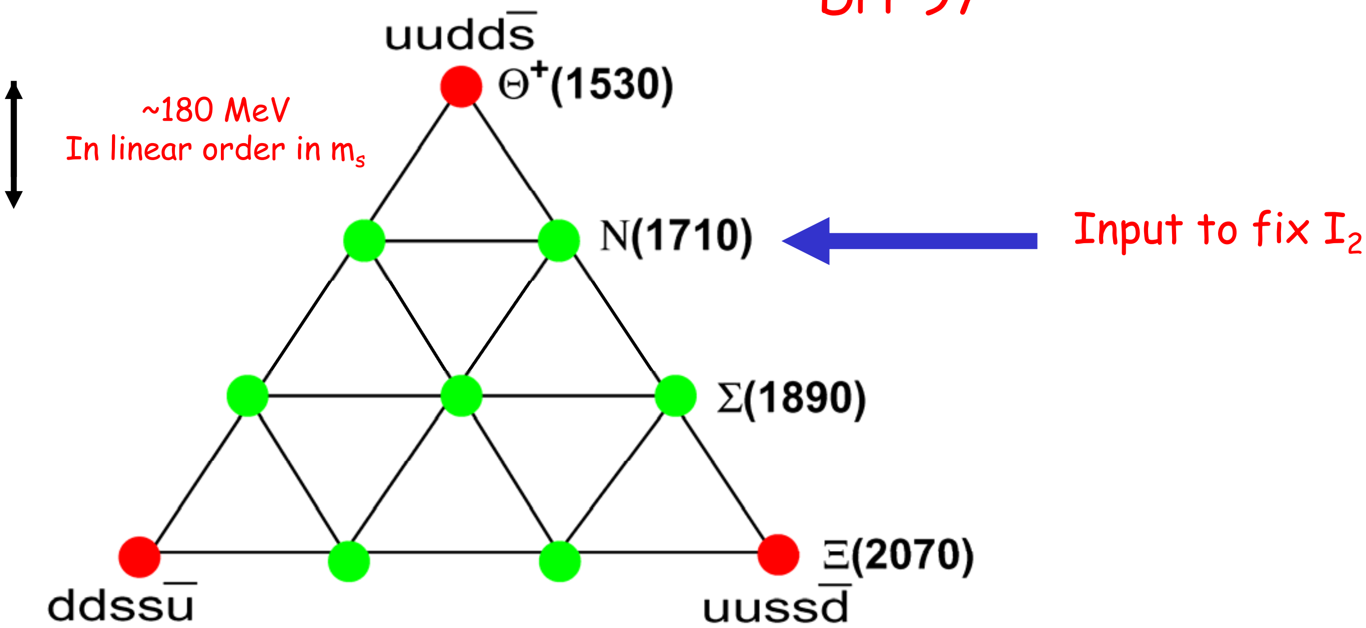
Example [Gudagnini '84]

$$8(m_{\Xi^*} + m_N) + 3m_\Sigma = 11m_\Lambda + 8m_{\Sigma^*}$$

Relates masses in 8 and 10, accuracy 1%

To fix masses of anti-10 one needs to know the value of I_2 which is not fixed by masses of 8 and 10

DPP'97



$J^p = 1/2^+$

Mass is in expected range (model calculations of I_2)
P_{11}(1440) too low, P_{11}(2100) too high

Decay branchings fit soliton picture better

Decays of the anti-decuplet

All decay constants for 8,10 and anti-10 can be expressed in terms of 3 universal couplings: G_0, G_1 and G_2

$$\Gamma_{\text{decuplet}} \sim [G_0 + \frac{1}{2} G_1]^2 \qquad \Gamma_{\text{anti-decuplet}} \sim [G_0 - G_1 - \frac{1}{2} G_2]^2$$

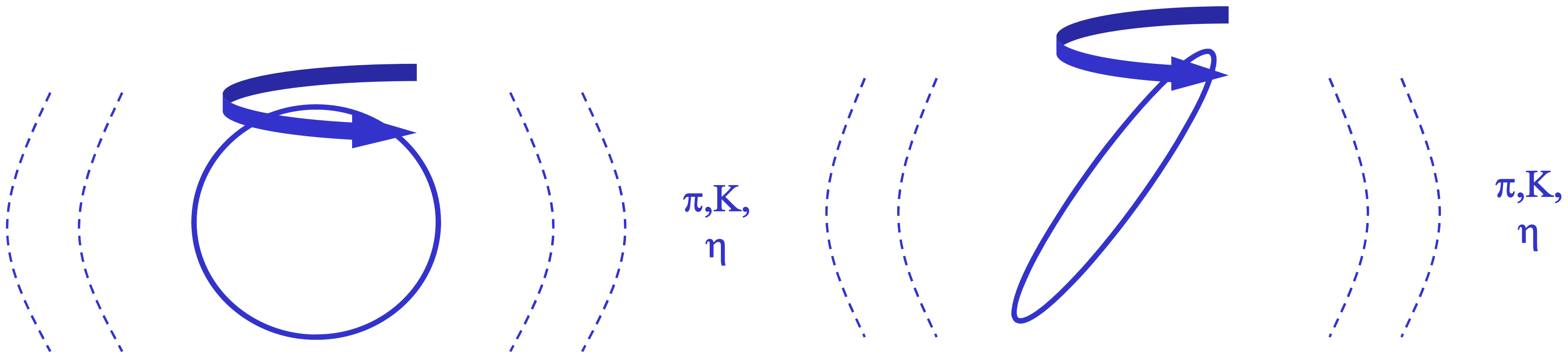
$$G_0 - G_1 - \frac{1}{2} G_2 \to 0$$ In NR limit ! DPP'97

Γ_Θ < 15 MeV „Natural" width ~100 MeV

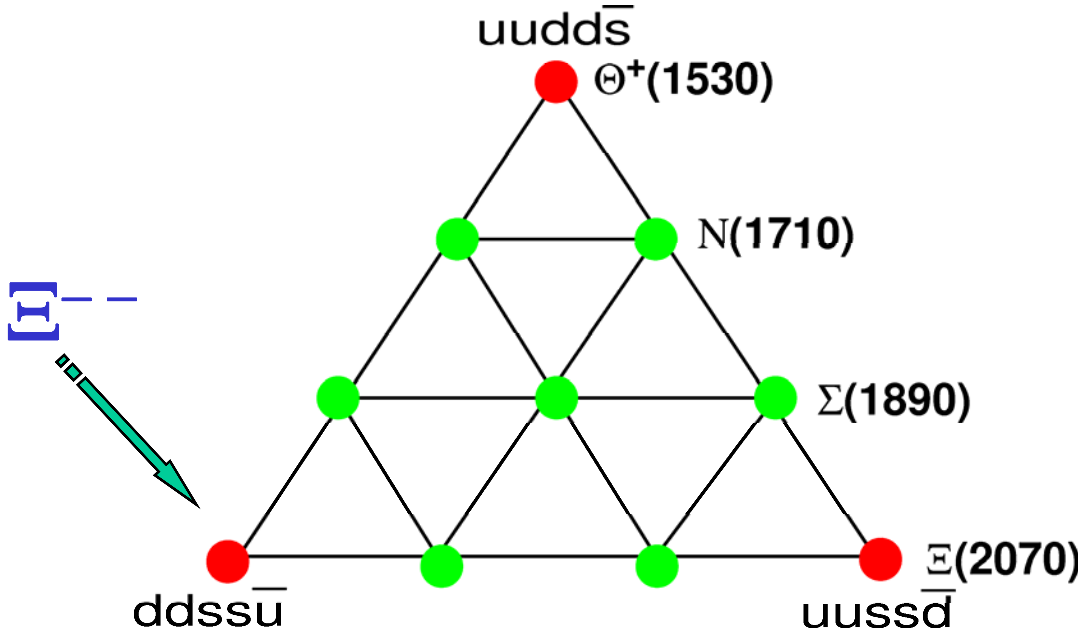
Where to stop ?

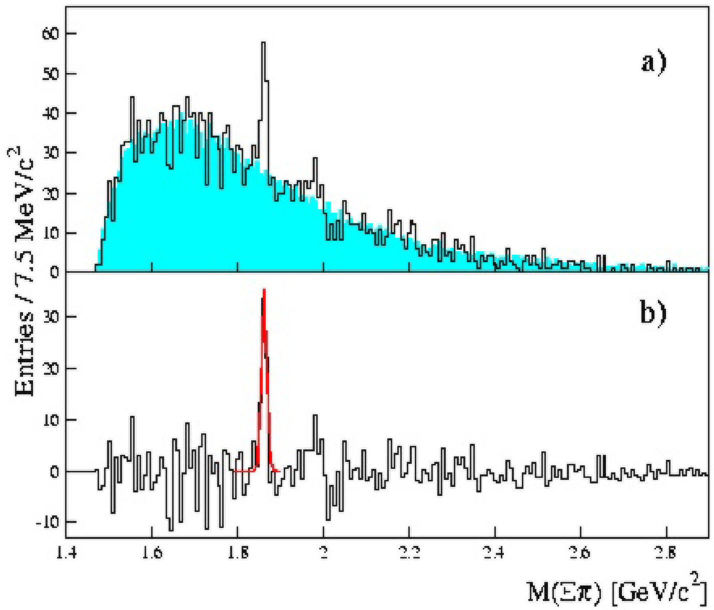
The next rotational excitations of baryons are (27,1/2) and (27,3/2). Taken literary, they predict plenty of exotic states. However their widths are estimated to be > 150 MeV. Angular velocities increase, centrifugal forces deform the spherically-symmetric soliton.

In order to survive, the chiral soliton has to stretch into sigar like object, such states lie on linear Regge trajectories [Diakonov, Petrov `88]



Very interesting issue! New theoretical tools should be developed! New view on spectroscopy?





CERN NA49 reported evidence for Ξ^{--} with mass around 1862 MeV and width <18 MeV

For Ξ symmetry breaking effects expected to be large [Walliser, Kopeliovich]

Update of $\pi N \Sigma$ term gives 180 Mev -> 110 MeV [Diakonov, Petrov]

Small width of Ξ is trivial consequence of SU(3) symmetry

Are we sure that Ξ is observed ? -> DESY, GSI can check this! And go for charm

Theory Response to the Pentaquark

More than 120 papers since July 1, 2003.

Rapidly developing theory: > 3 resubmissions per paper in hep

- Kaon+Skyrmion
- Θ^+ as isotensor pentaquark
- di-quarks + antiquark
- colour molecula
- Kaon-nucleon bound state
- Super radiance resonance
- QCD sum rules
- Lattice QCD P=-
- Higher exotic baryons multiplets
- Pentaquarks in string dynamics
- $P_{11}(1440)$ as pentaquark
- $P_{11}(1710)$ as pentaquark
- Topological soliton
- $\Theta^+(1540)$ as a heptaquark
- Exotic baryons in the large N_c limit
- Anti-charmed Θ^+_c , and anti-beauty Θ^+_b
- Θ^+ produced in the quark-gluon plasma
- …….

Constituent quark model

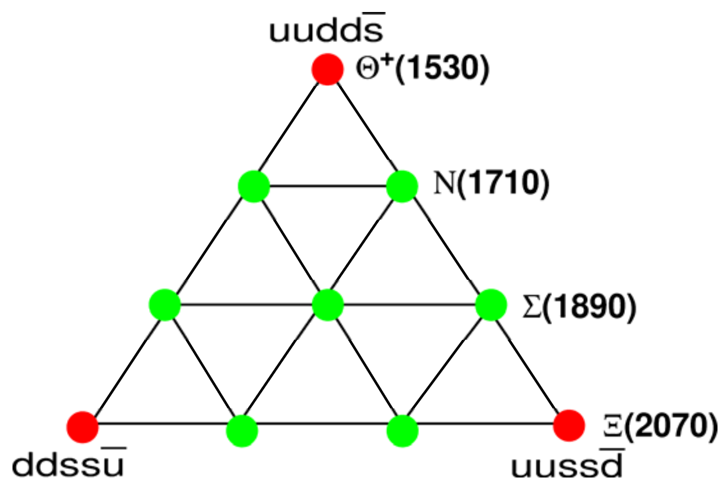
If one employs flavour independent forces between quarks (OGE) natural parity is negative, although P=+1 possible to arrange

With chiral forces between quarks natural parity is P=+1
[Stancu, Riska; Glozman]

- No prediction for width
- Implies large number of excited pentaquarks

Missing Pentaquarks ?
(And their families)

Mass difference $\Xi - \Theta \sim 150$ MeV

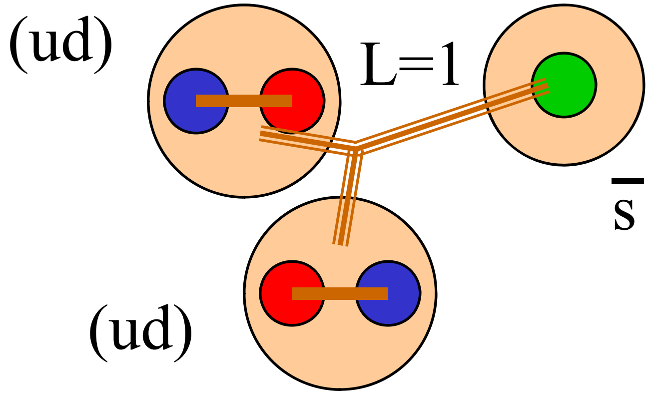


Diquark model [Jaffe, Wilczek]

No dynamic explanation of
Strong clustering of quarks

Dynamical calculations suggest large mass
[Narodetsky et al.; Shuryak, Zahed]

$J^P=1/2^+$ is assumed, not computed



$J^P=3/2^+$ pentaquark should be close in mass [Dudek, Close]

Anti-decuplet is accompanied by an octet of pentaquarks.
P11(1440) is a candidate

No prediction for width

Mass difference $\Xi - \Theta \sim 150$ MeV -> Light Ξ pentaquark

Implications of the Pentaquark

- Views on what hadrons "made of" and how do they "work" may have fundamentally changed
  - renaissance of hadron physics
  - need to take a fresh look at what we thought we knew well.

- Quark model & flux tube model are incomplete and should be revisited

- Does Θ start a new Regge trajectory? -> implications for high energy scattering of hadrons !

- Can Θ become stable in nuclear matter? -> physics of compact stars! New type of hypernuclei !

- Issue of heavy-light systems should be revisited ("BaBar" resonance, uuddc-bar pentaquarks). Role of chiral symmetry can be very important !!!

- Assuming that chiral forces are essential in binding of quarks one gets the lowest baryon multiplets
  $(8, 1/2^+)$, $(10, 3/2^+)$, $(\text{anti-}10, 1/2^+)$
  whose properties are related by symmetry

- Predicted Θ pentaquark is light NOT because it is a sum of 5 constituent quark masses but rather a collective excitation of the mean chiral field. It is narrow for the same reason

- Where are family members accompaning the pentaquark
  Are these "well established 3-quark states"? Or we should look for new "missing resonances"? Or we should reconsider fundamentally our view on spectroscopy?

Surely new discoveries are waiting us around the corner !