Spectroscopy

Hadron physics

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Outline

- Lecture 1: Baryon spectroscopy
- Lecture 2: Meson spectroscopy
- Lecture 3: How to discover a particle

The Bible

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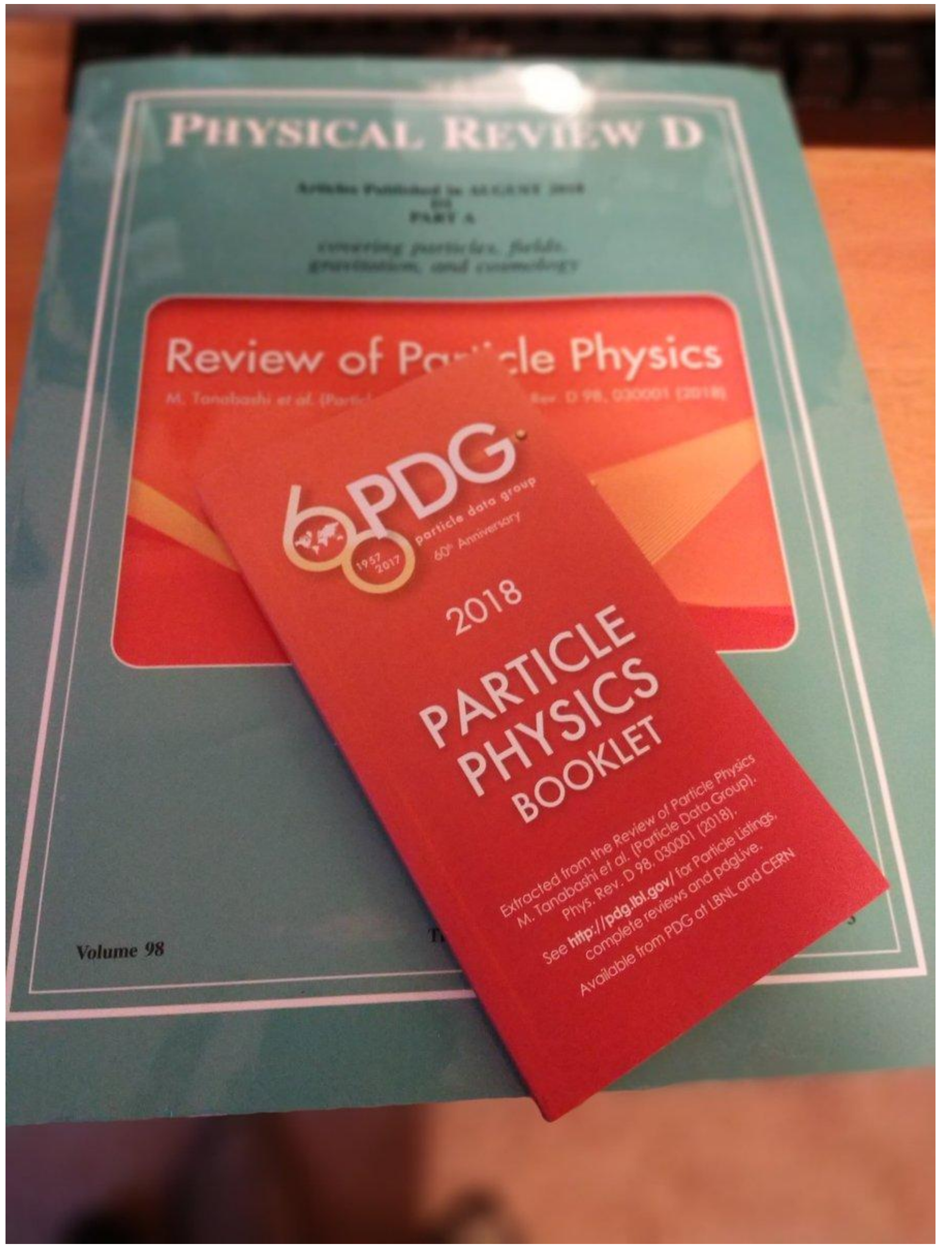
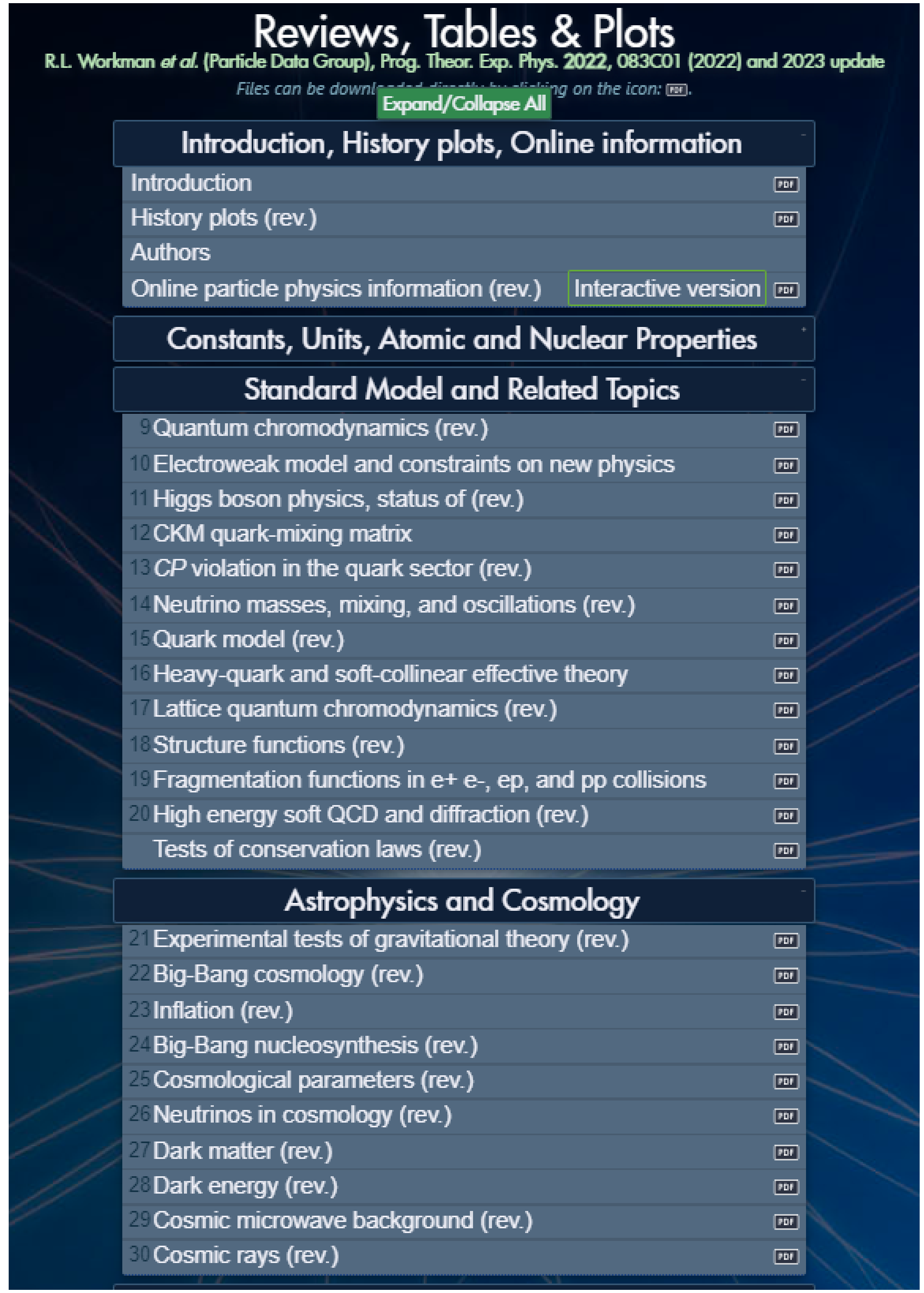


http://pdg.lbl.gov/



Reviews, Tables & Plots

R.L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update

Files can be downl… ing on the icon: PDF.

Expand/Collapse All

Introduction, History plots, Online information

- Introduction
- History plots (rev.)
- Authors
- Online particle physics information (rev.) — Interactive version

Constants, Units, Atomic and Nuclear Properties

Standard Model and Related Topics

- 9 Quantum chromodynamics (rev.)
- 10 Electroweak model and constraints on new physics
- 11 Higgs boson physics, status of (rev.)
- 12 CKM quark-mixing matrix
- 13 *CP* violation in the quark sector (rev.)
- 14 Neutrino masses, mixing, and oscillations (rev.)
- 15 Quark model (rev.)
- 16 Heavy-quark and soft-collinear effective theory
- 17 Lattice quantum chromodynamics (rev.)
- 18 Structure functions (rev.)
- 19 Fragmentation functions in e+ e-, ep, and pp collisions
- 20 High energy soft QCD and diffraction (rev.)
- Tests of conservation laws (rev.)

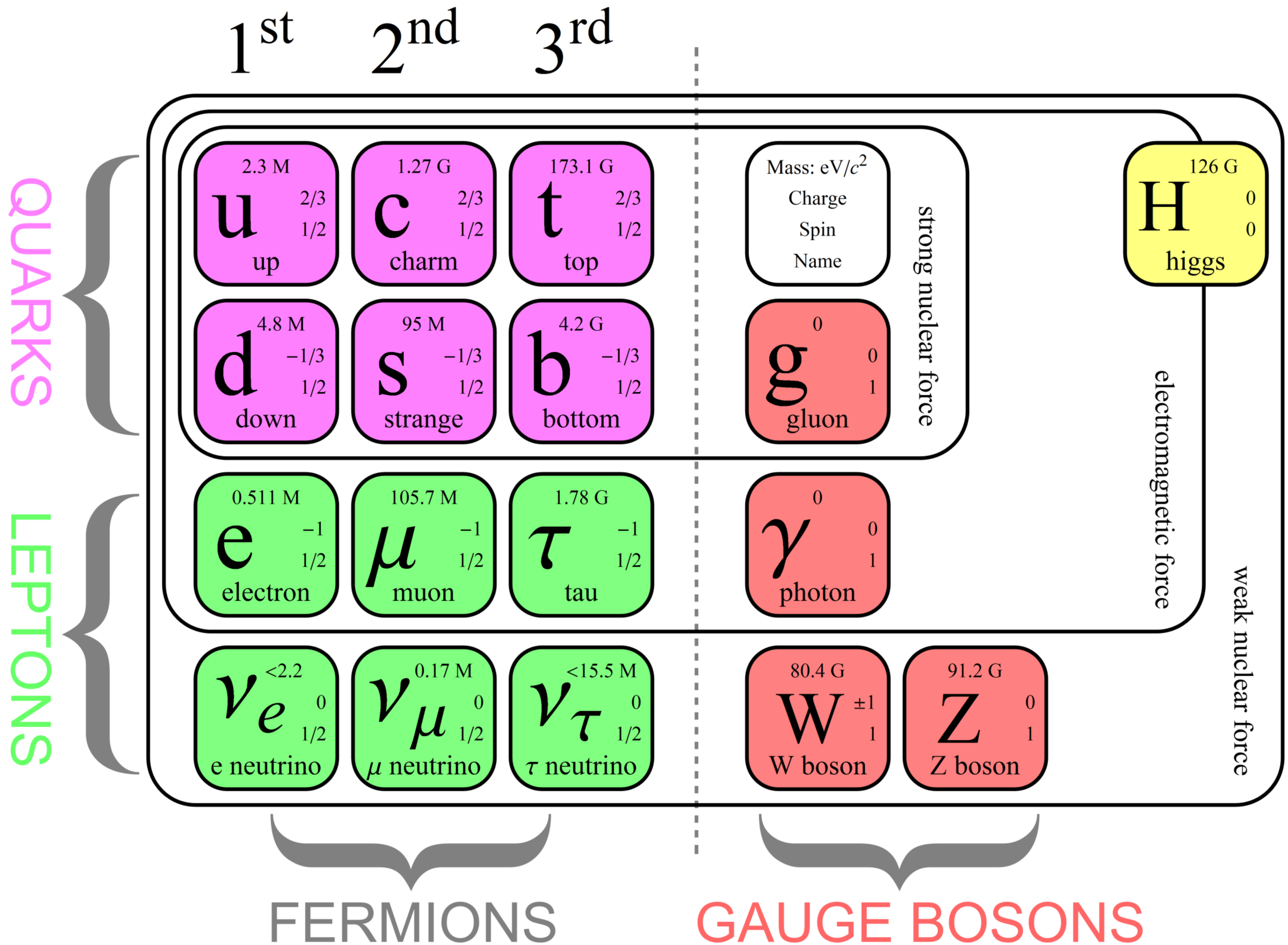
Astrophysics and Cosmology

- 21 Experimental tests of gravitational theory (rev.)
- 22 Big-Bang cosmology (rev.)
- 23 Inflation (rev.)
- 24 Big-Bang nucleosynthesis (rev.)
- 25 Cosmological parameters (rev.)
- 26 Neutrinos in cosmology (rev.)
- 27 Dark matter (rev.)
- 28 Dark energy (rev.)
- 29 Cosmic microwave background (rev.)
- 30 Cosmic rays (rev.)

Latest information about particles (masses, widths, decays)

Common information

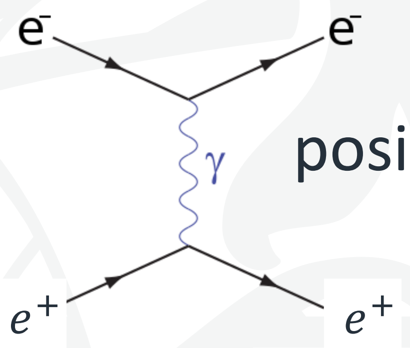
Standard Model



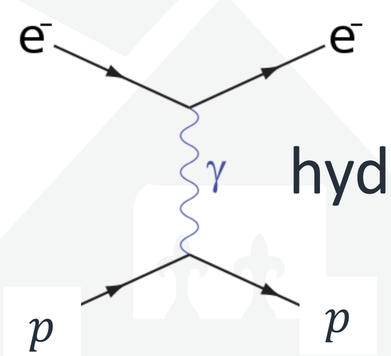
States in Standard model

Electromagnetic force

Atom



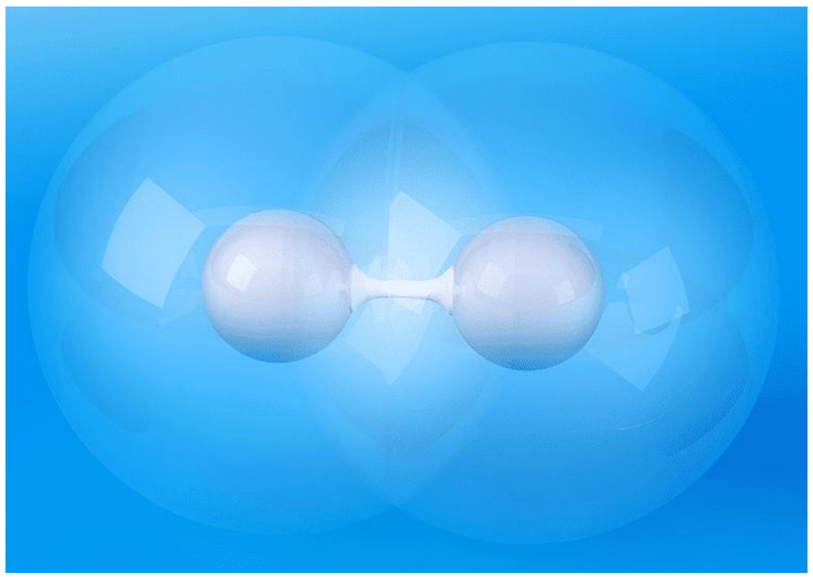
positronium



hydrogen

Photon couples to charge

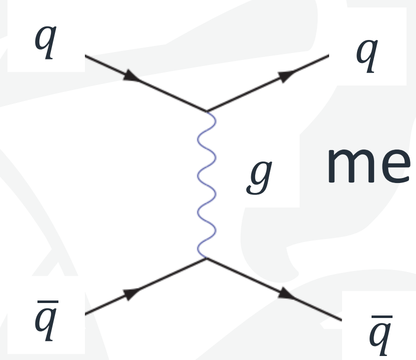
Molecule



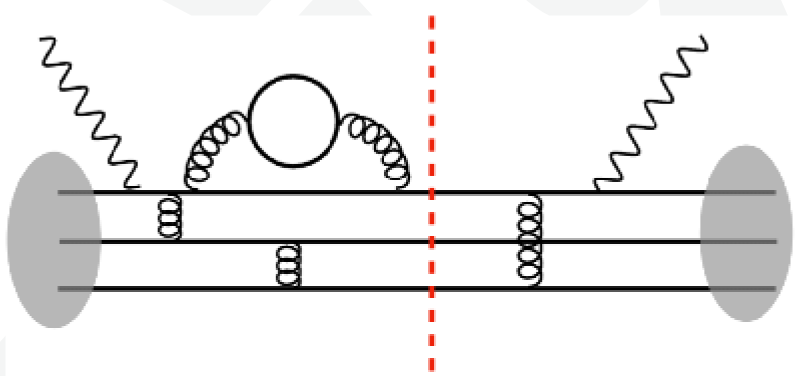
Two charge neutral objects
Residual force

Strong force

"Atom" analogue



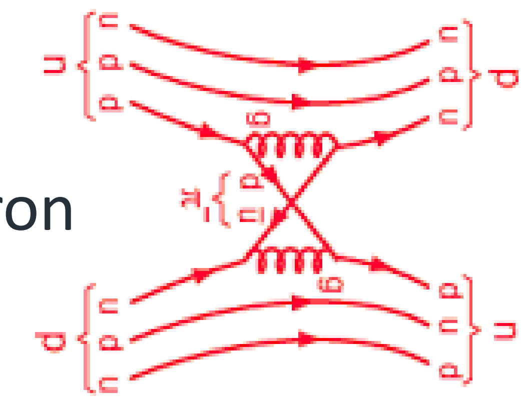
meson

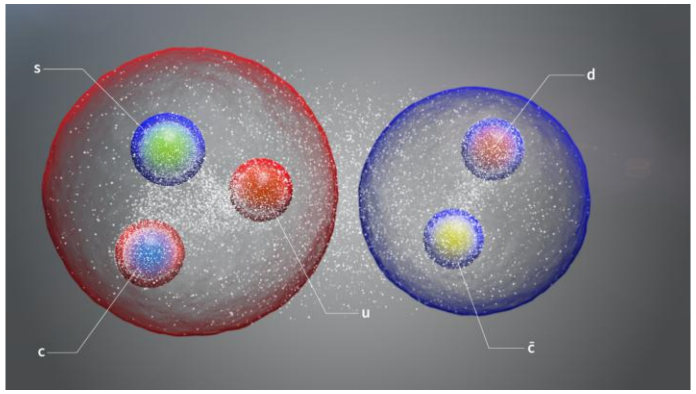


Gluon couples to charge
Mesons, baryons….
Colour components bound by colour force

Molecule analogue

deuteron





Two colour-neutral objects
Residual force
(meson-meson, meson baryon, baryon-baryon molecules)
All nuclei are molecules

Forces

Force	Strength	Theory	Mediator
Strong	10	Chromodynamics	Gluon
Electromagnetic	10^{-2}	Electrodynamics	Photon
Weak	10^{-13}	Flavordynamics	W and Z
Gravitational	10^{-42}	Geometrodynamics	Graviton

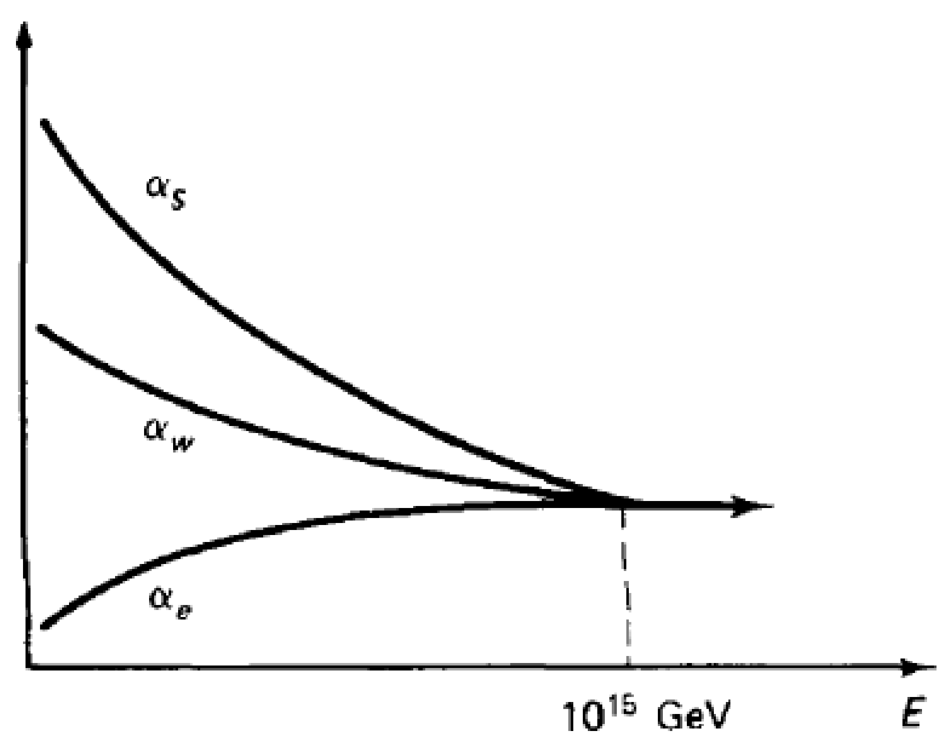
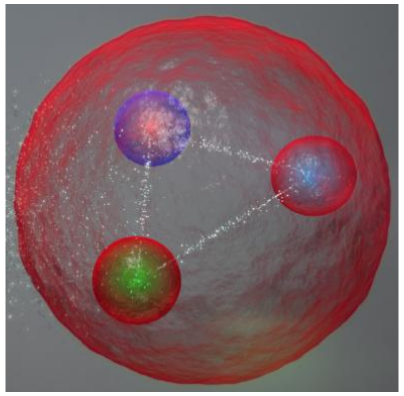


Figure 2.5 Evolution of the three fundamental coupling constants.

Spin

- Particles have spin – consequences for how they can assemble

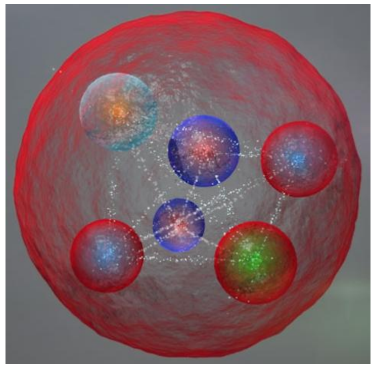


Half-integer spin (Fermion)

e.g. Proton, neutron, electron,..

<u>Pauli exclusion principle</u>:

Identical Fermions **cannot** occupy the same quantum state



Integer spin (Boson)

e.g. Photon, pi-meson, d*

<u>Bose-Einstein Condensate</u>:

Identical Bosons **want to** occupy same quantum state !!

Spin

Fermions
(Half-integer spin)

Bosons
Integer spin

Particles and antiparticles

Quark $J^P = \frac{1}{2}^+$ Antiquark $J^P = ?$

$Spin^{Parity}$

Particles and antiparticles

Quark $J^P = \frac{1}{2}^+$ Antiquark $J^P = \frac{1}{2}^-$ $Spin^{Parity}$

Lepton $J^P = \frac{1}{2}^+$ Antilepton $J^P = \frac{1}{2}^-$

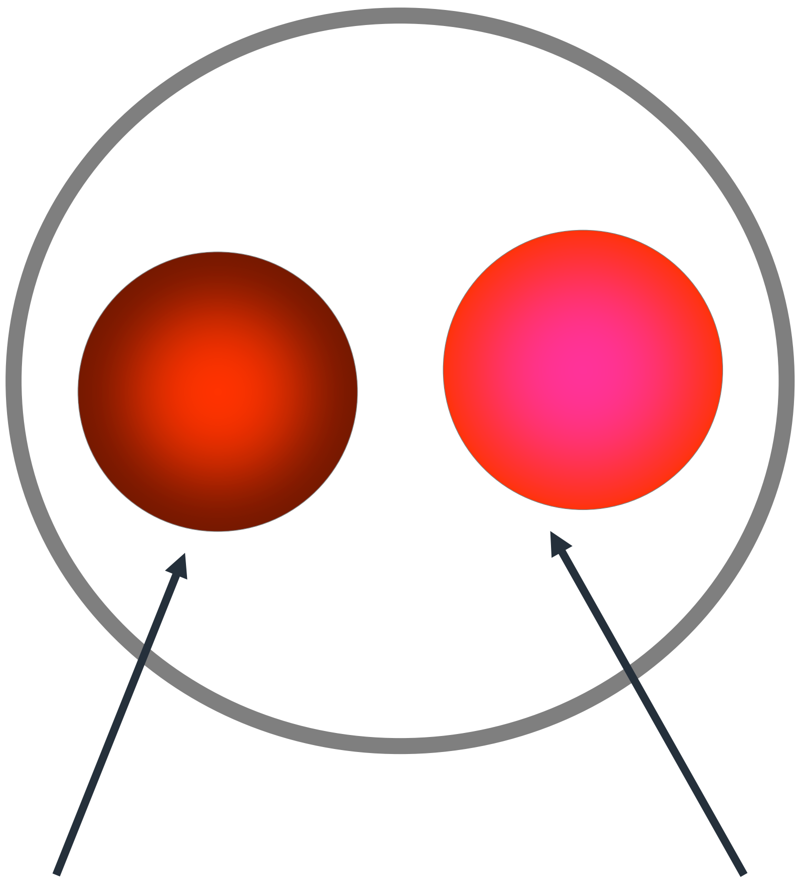
Electron (e^-) $J^P = \frac{1}{2}^+$ Positron (e^+) $J^P = \frac{1}{2}^-$

Mass(particle)=Mass(antiparticle)

Baryon spectroscopy

Types of particles/resonances

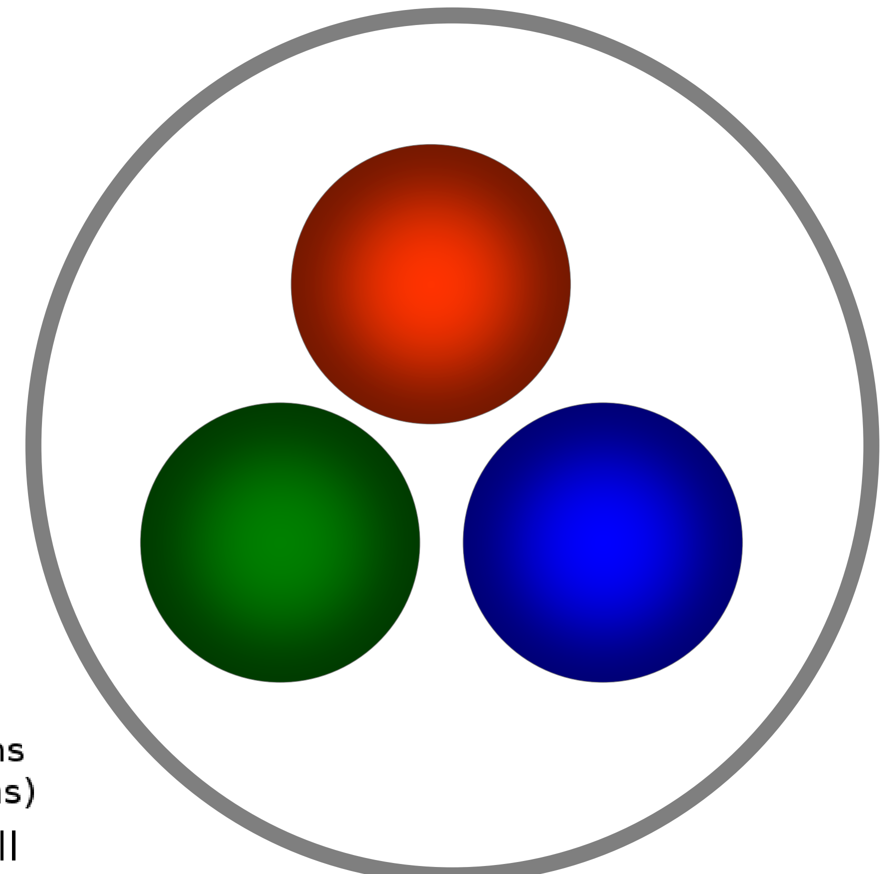
Meson

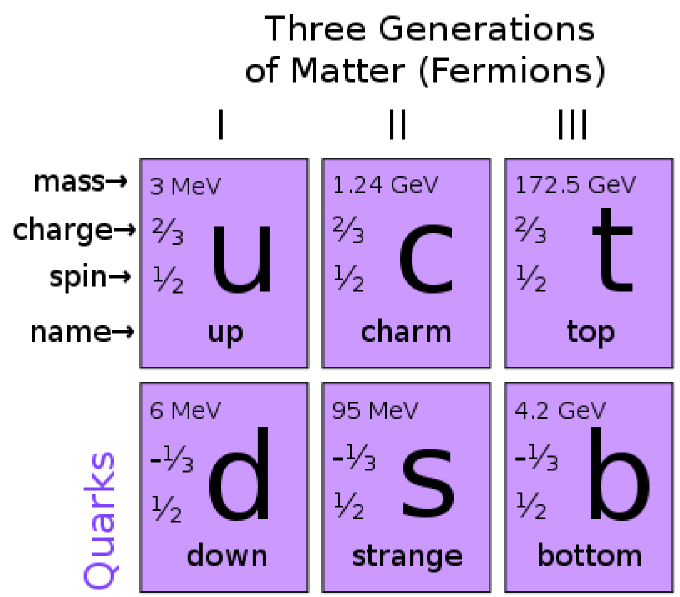


color

anticolor

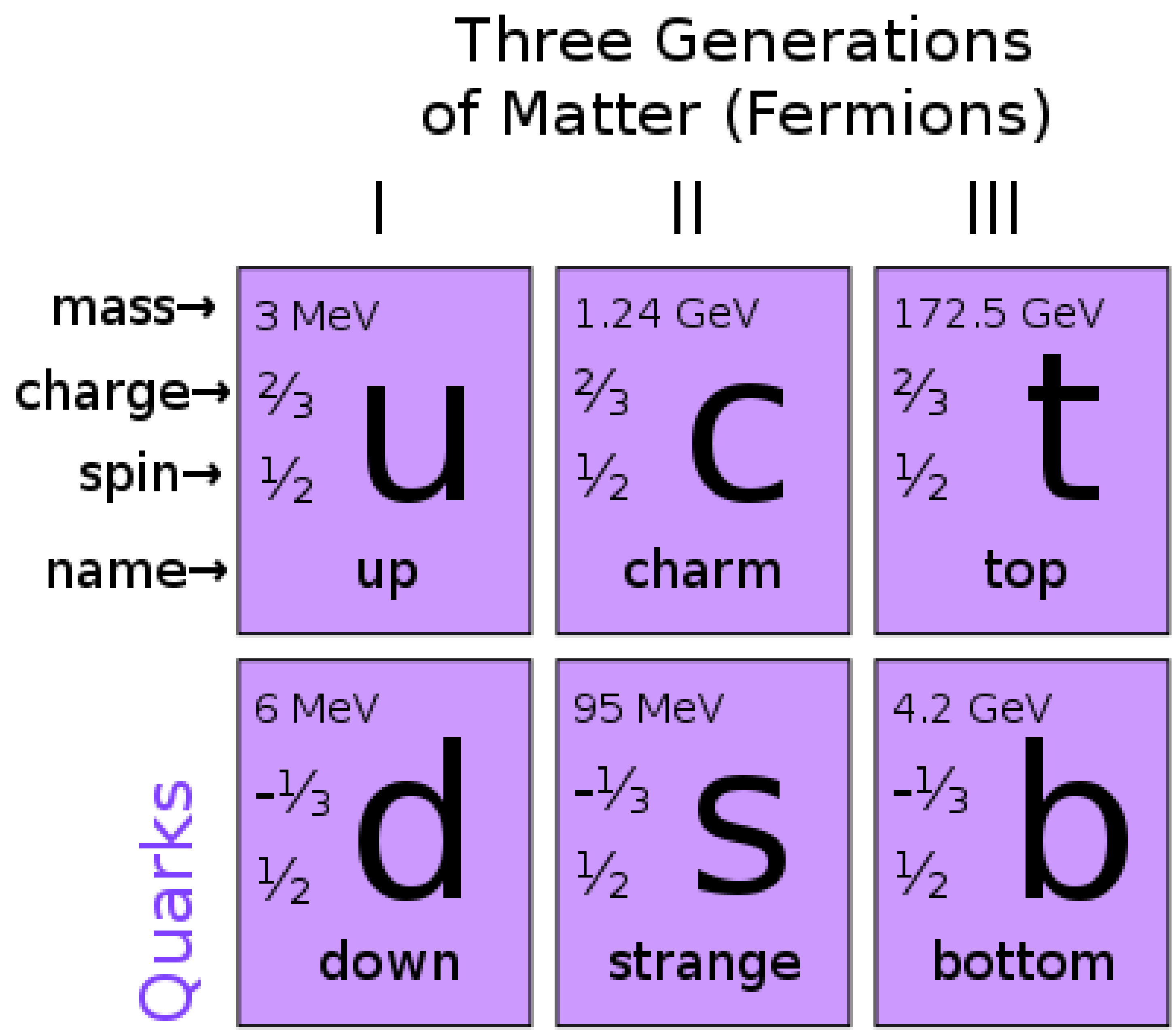
Baryon





Quarks

- fermions
- 3 colors
- Parity +1
- Constituent quarks:
  - $M_{u/d} \sim 300\ MeV$
  - $M_s \sim 500\ MeV$



Constituent quarks

Flavour	B	J	I	I_3	s	Q/e
u	1/3	1/2	1/2	$+\frac{1}{2}$	0	$+\frac{2}{3}$
d	1/3	1/2	1/2	$-\frac{1}{2}$	0	$-\frac{1}{3}$
s	1/3	1/2	0	0	-1	$-\frac{1}{3}$

B – baryon number

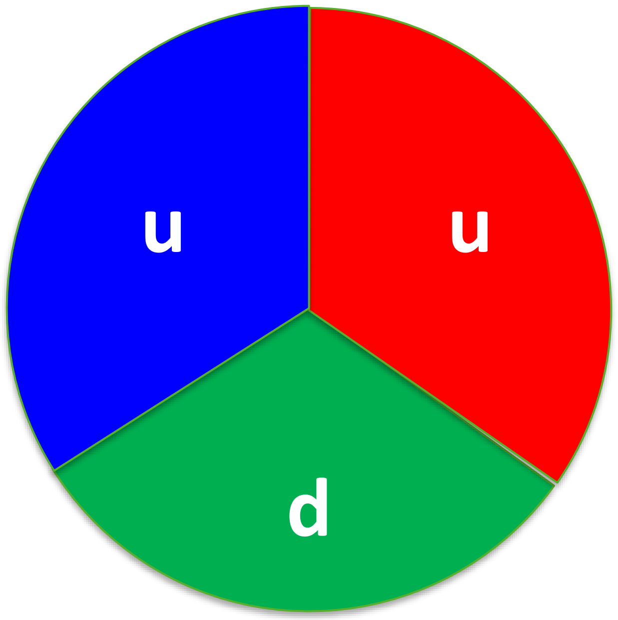
J – spin

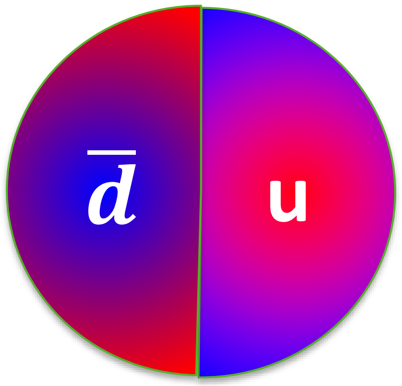
I – isospin

I_3- z-projection of isospin

s- strangeness

Q - charge





Quark states in SU(3) symmetry

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

Baryons: $3 \otimes 3 \otimes 3 = 3 \otimes (6 \oplus \bar{3}) =$

$= 10_S \oplus 8_{M,S} \oplus 8_{M,A} \oplus 1_A$

$3 \otimes 3 = (6 \oplus \bar{3})$:

6	$\bar{\mathbf{3}}$
uu	
$\frac{1}{\sqrt{2}}(ud + du)$	$\frac{1}{\sqrt{2}}(ud - du)$
dd	
$\frac{1}{\sqrt{2}}(us + su)$	$\frac{1}{\sqrt{2}}(us - su)$
ss	
$\frac{1}{\sqrt{2}}(ds + sd)$	$\frac{1}{\sqrt{2}}(ds - sd)$
symmetric	antisymmetric

Quark states in SU(3) symmetry

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

Baryons: $3 \otimes 3 \otimes 3 = 3 \otimes (6 \oplus \bar{3}) =$

$= 10_S \oplus 8_{M,S} \oplus \cancel{8_{M,A}} \oplus 1_A$

$3 \otimes 3 = (6 \oplus \cancel{\bar{3}})$:

6	$\bar{3}$
uu	
$\frac{1}{\sqrt{2}}(ud + du)$	$\cancel{\frac{1}{\sqrt{2}}(ud - du)}$
dd	
$\frac{1}{\sqrt{2}}(us + su)$	$\cancel{\frac{1}{\sqrt{2}}(us - su)}$
ss	
$\frac{1}{\sqrt{2}}(ds + sd)$	$\cancel{\frac{1}{\sqrt{2}}(ds - sd)}$
symmetric	antisymmetric

Quark states in SU(3) symmetry

$\begin{pmatrix} u \\ d \\ s \end{pmatrix}$ Baryons: $3 \otimes 3 \otimes 3 = 3 \otimes \left(6 \oplus \bar{3}\right) = 10_S \oplus 8_{M,S} \oplus 8_{M,A} \oplus 1_A$

$6 \otimes 3 = (10 \oplus 8)$:

symmetric

10
uuu
$\frac{1}{\sqrt{3}}(uud + udu + duu)$
$\frac{1}{\sqrt{3}}(udd + dud + ddu)$
ddd
$\frac{1}{\sqrt{3}}(uus + usu + suu)$
$\frac{1}{\sqrt{3}}(uss + sus + ssu)$
sss
$\frac{1}{\sqrt{3}}(dds + dsd + sdd)$
$\frac{1}{\sqrt{3}}(dss + sds + ssd)$
$\frac{1}{\sqrt{6}}(uds + usd + dus + sud + sdu + dsu)$

mixed

8
$\frac{1}{\sqrt{6}}\left((ud + du)u - 2uud\right)$
$\frac{1}{\sqrt{6}}\left((ud + du)d - 2ddu\right)$
$\frac{1}{\sqrt{6}}\left((us + su)u - 2uus\right)$
$\frac{1}{\sqrt{6}}\left((ds + sd)d - 2dds\right)$
$\frac{1}{\sqrt{6}}\left((us + su)s - 2ssu\right)$
$\frac{1}{\sqrt{6}}\left((ds + sd)s - 2ssd\right)$
$\frac{1}{2}\left((ds - sd)u + (us - su)d\right)$
$\frac{1}{\sqrt{12}}(2(ud - du)s + (us - su)d + (sd - ds)u)$

Quark states in SU(3) symmetry

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

Baryons: $3 \otimes 3 \otimes 3 = 3 \otimes (6 \oplus \bar{3}) =$

$= 10_S \oplus 8_{M,S} \oplus 8_{M,A} \oplus 1_A$

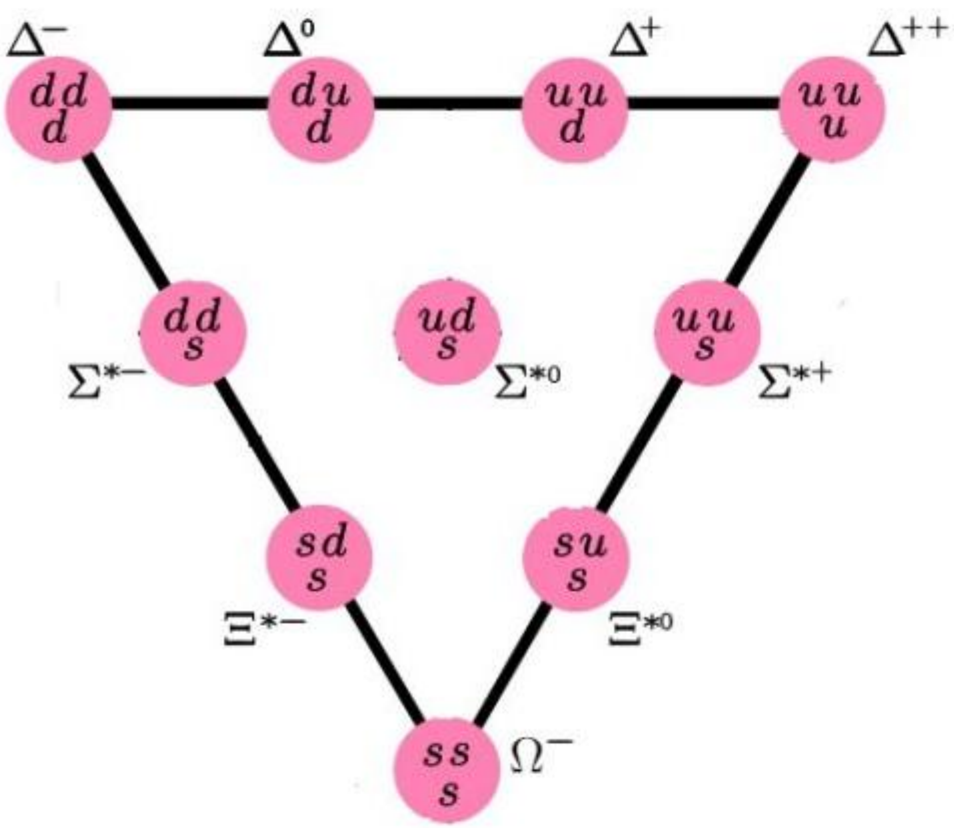
Decuplet

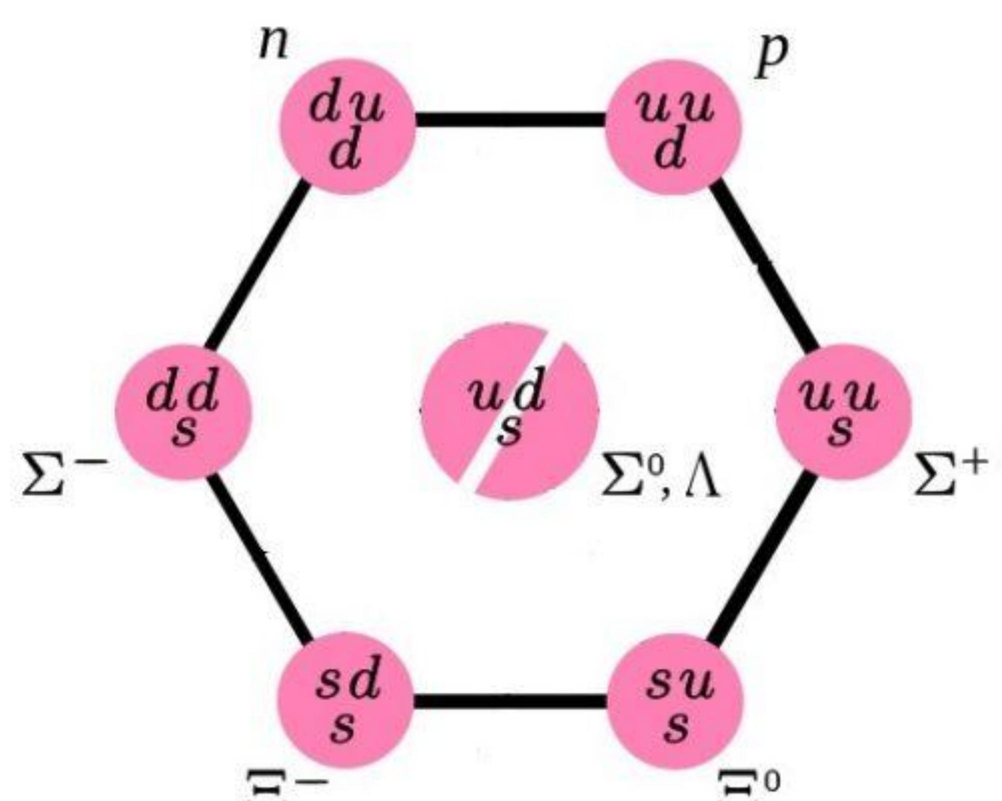
$\uparrow\uparrow\uparrow$

Octet

$\uparrow\uparrow\downarrow + \uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow$

$J^P = \frac{3}{2}^+$





$J^P = \frac{1}{2}^+$

Hyperfine splitting, ↑↓ vs ↑↑

- E-M force, magnetic moment interaction: $\Delta E = \mu \cdot B = \frac{2}{3}\mu_i\mu_j|\Psi(0)|^2 = \frac{2\pi}{3} \cdot \frac{\alpha}{m_i m_j}|\Psi(0)|^2\sigma_i\sigma_j$

Pauli matrixes, spin

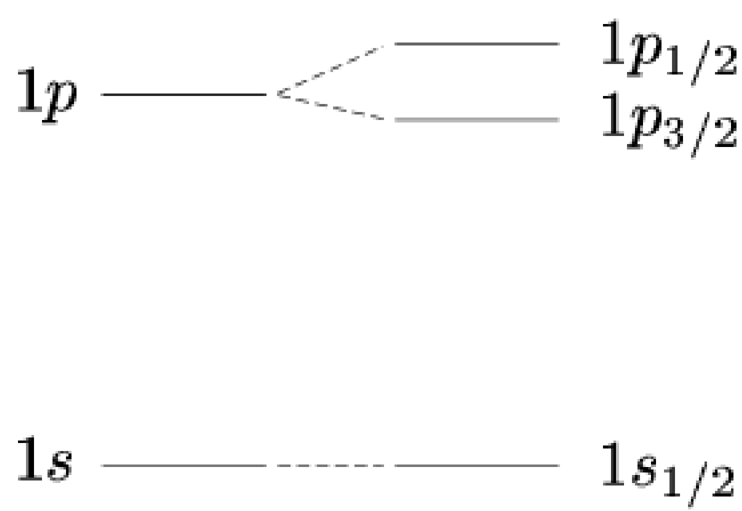
Hyperfine splitting, ↑↓ vs ↑↑

- E-M force, magnetic moment interaction: $\Delta E = \mu \cdot B$

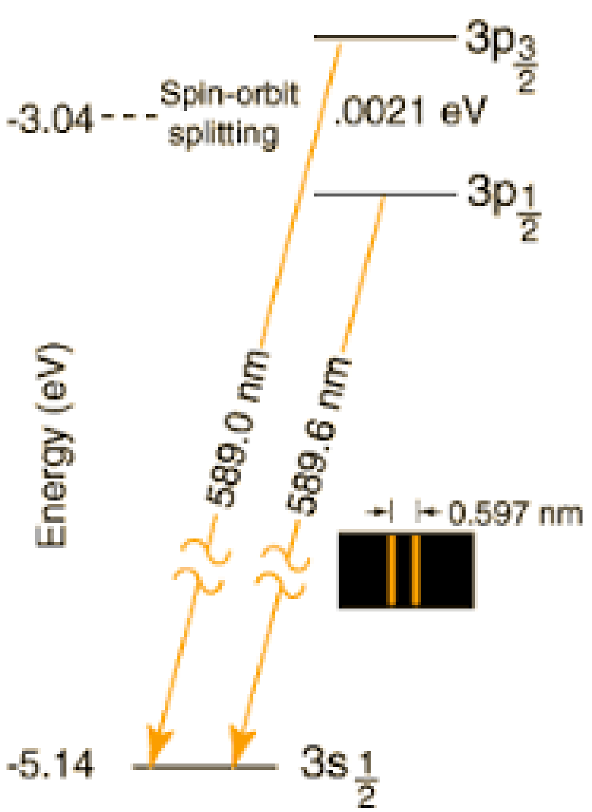
$$= \frac{2}{3}\mu_i \mu_j |\Psi(0)|^2 = \frac{2\pi}{3} \cdot \frac{\alpha}{m_i m_j} |\Psi(0)|^2 \sigma_i \sigma_j$$

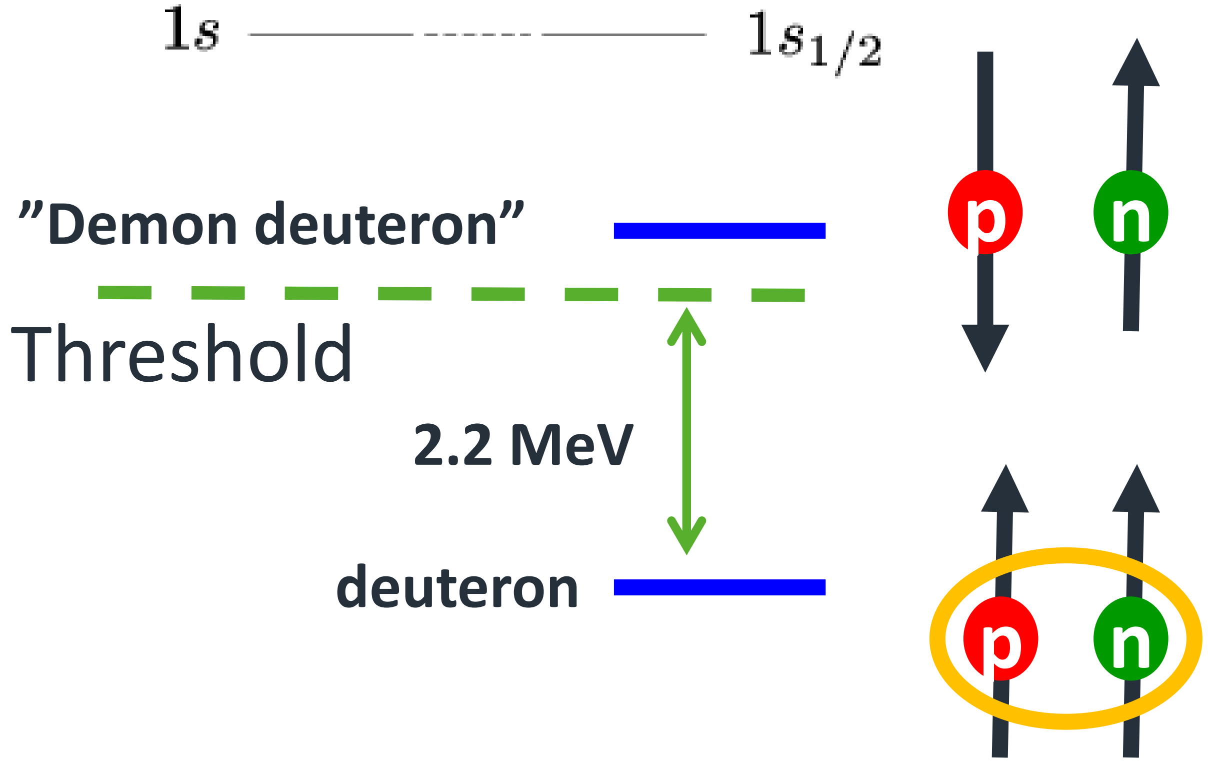
Pauli matrixes, spin

Nuclear

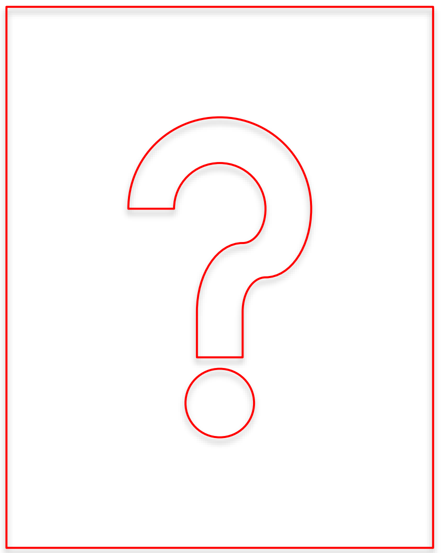


Atoms (Na doublet)





Quarks

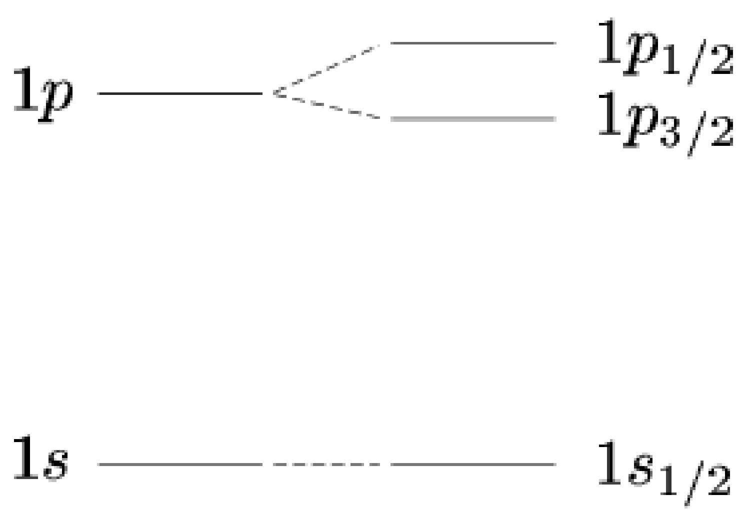


Hyperfine splitting, ↑↓ vs ↑↑

Nuclear

Photon/Gluon

Pion exchange $J^P = 0^-$



$p_{3/2}$

$p_{1/2}$

$s_{1/2}$

$p_{1/2}$

$p_{3/2}$

$d_{5/2}$

$s_{1/2}$

Same for $J^P = 0^-, J^P = 1^+$

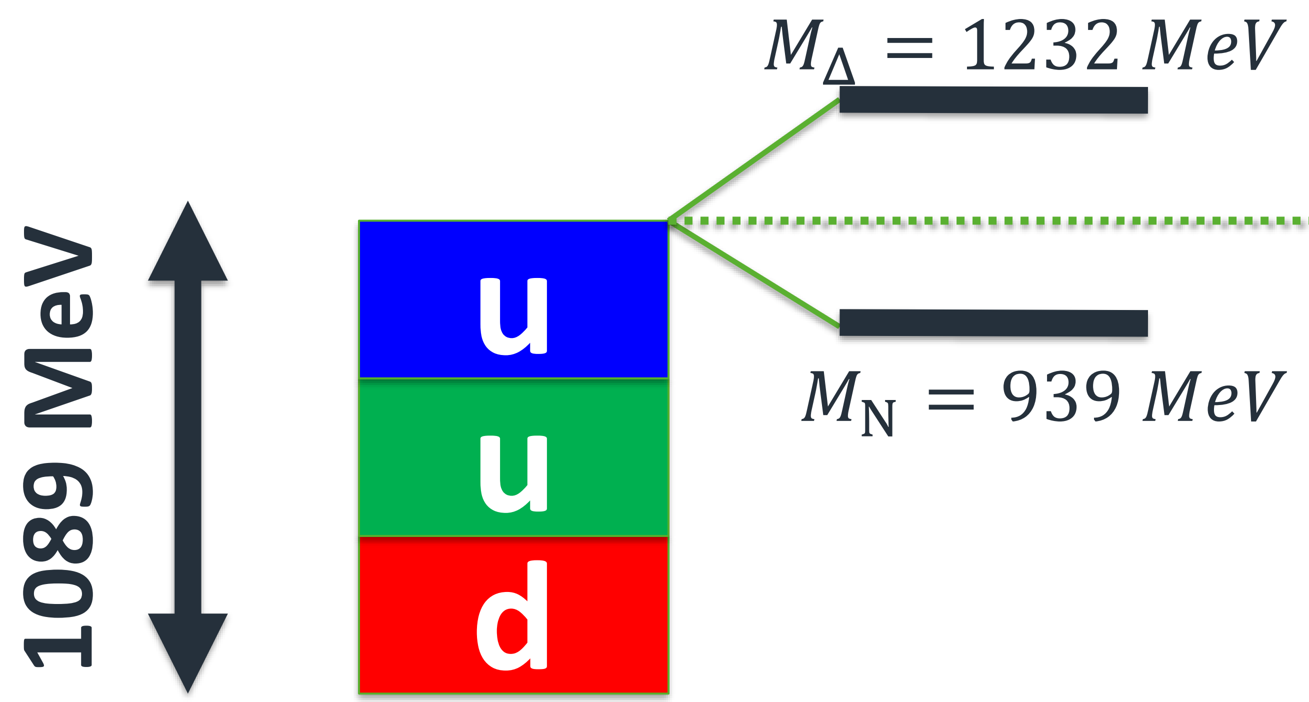
$J^P = 0^+, J^P = 1^-$

$J^P = 2^+$

Hyperfine splitting, ↑↓ vs ↑↑

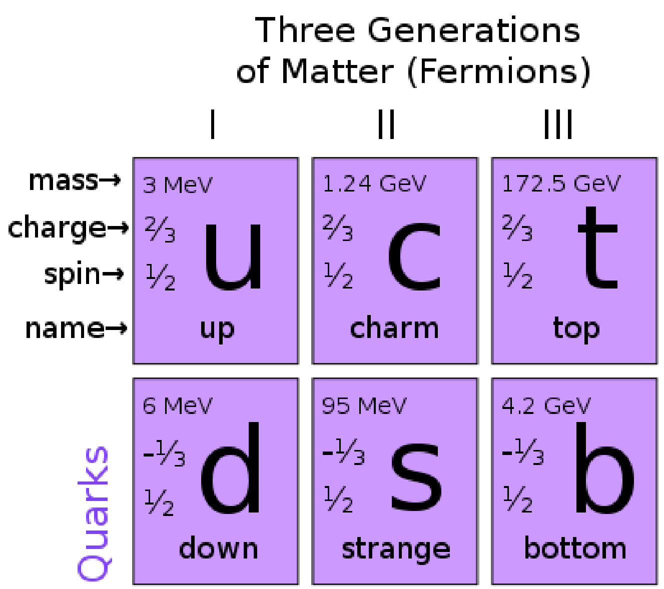
- $m_u \approx m_d = m_n = 363\ MeV$
- $m_s = 538\ MeV$
- $\frac{K}{m_n^2} = 50\ MeV$
- $\Delta E_\Delta = +3\frac{K}{m_n^2}$

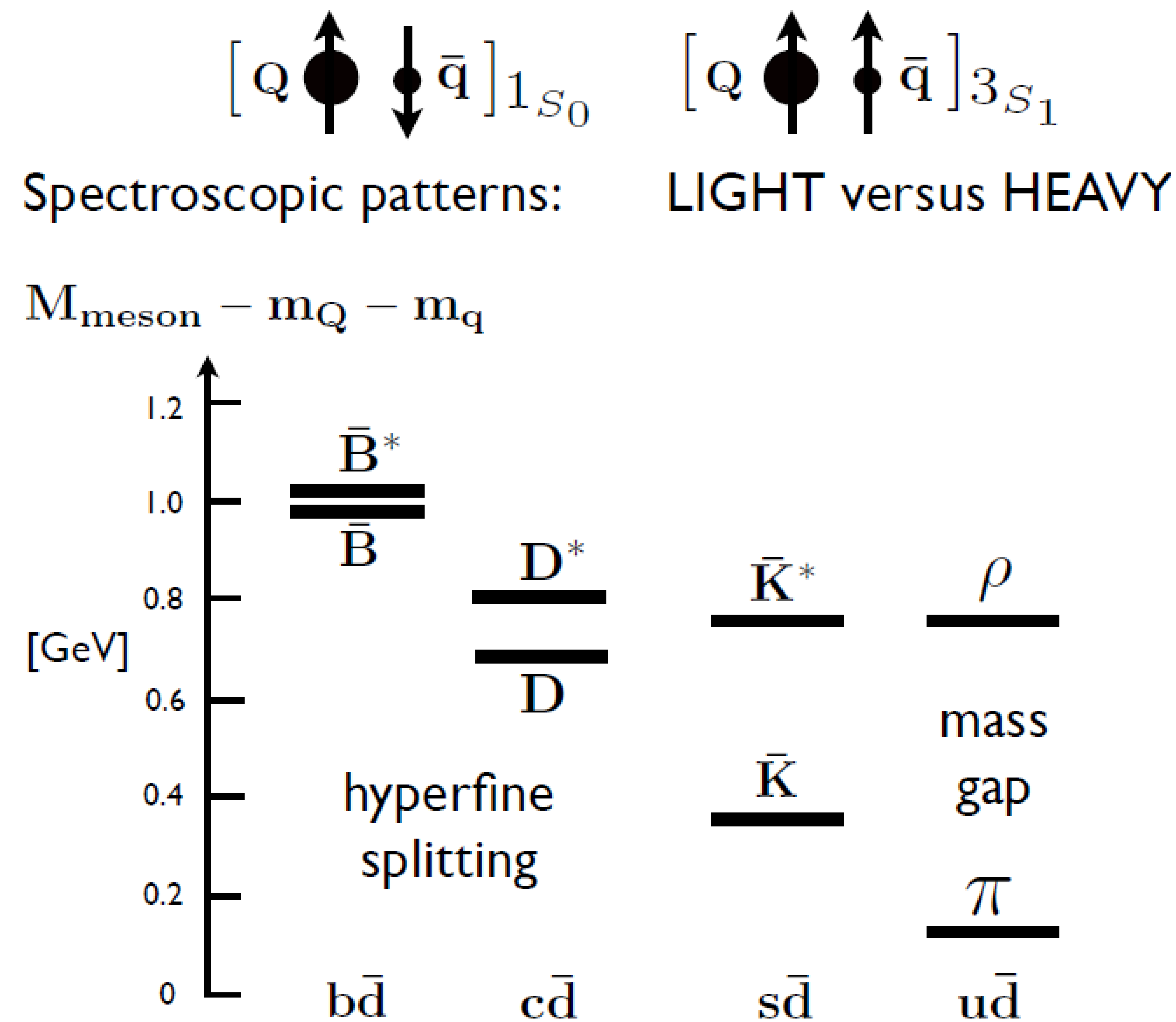
  $\Delta E_\mathrm{N} = -3\frac{K}{m_n^2}$



- $\Delta^+(u\uparrow u\uparrow d\uparrow), M = 1232\ MeV$
- $p(u\uparrow u\downarrow d\uparrow), M = \quad 939\ MeV$

Scales and interactions





$$M_B = 5279\ MeV$$
$$M_D = 1870\ MeV$$
$$M_K = 494\ MeV$$
$$M_\pi = 140\ MeV$$

W. Weise „**The QCD vacuum and its hadronic excitations** “

Baryon summary table, PDG

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p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1685)$		*
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	***
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	**
$N(1895)$	$1/2^-$	**
$N(1900)$	$3/2^+$	***
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	*
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	***
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1710)$	$1/2^+$	*
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$		*
$\Lambda(2020)$	$7/2^+$	*
$\Lambda(2050)$	$3/2^-$	*
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	*
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1690)$		**
$\Sigma(1730)$	$3/2^+$	*
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1770)$	$1/2^+$	*
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1840)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1900)$	$1/2^-$	*
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^+$	*
$\Sigma(1940)$	$3/2^-$	***
$\Sigma(2000)$	$1/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	**
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

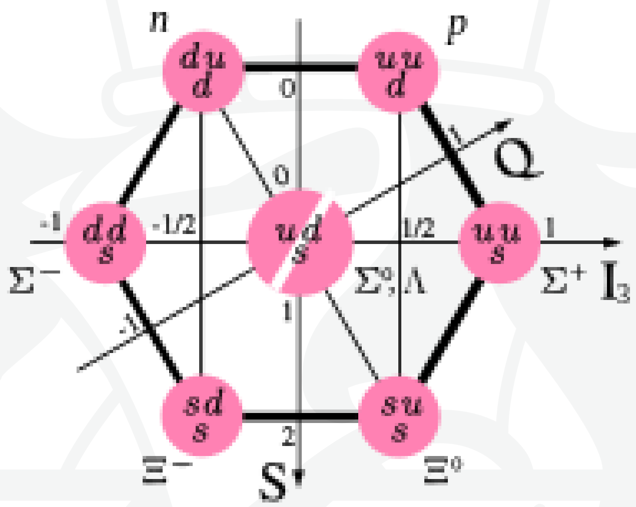
Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$		***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	***
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		**
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
Ξ_{cc}^+		*
Λ_b^0	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
Ω_b^-	$1/2^+$	***

Number of 3- and 4-star Resonances

Baryon	2004	2020
N^*	15	21
Δ	10	12
Λ	14	14
Σ	10	9*
Ξ	6	6
Ω	2	2

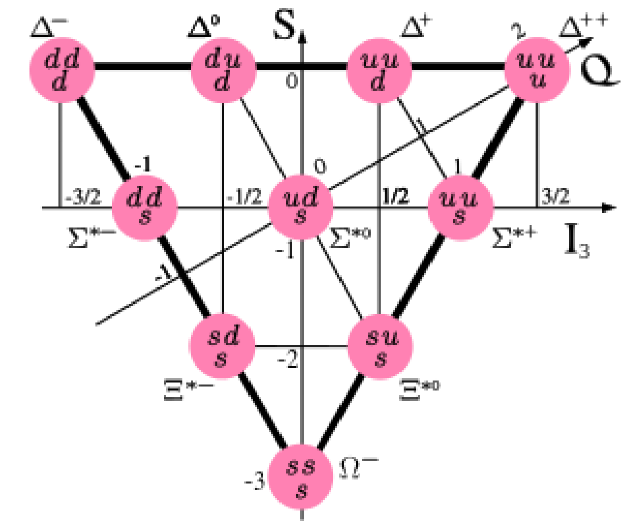
*$\Sigma(2250)$ was downgraded

Baryons



Octet: N^*, $\boldsymbol{\Lambda}^*$, $\boldsymbol{\Sigma}^*$, $\boldsymbol{\Xi}^*$

Decuplet: Δ^*, $\boldsymbol{\Sigma}^*$, $\boldsymbol{\Xi}^*$, $\boldsymbol{\Omega}^*$



	LQCD* ($M < 2M_\Omega$)	"Observed", PDG	Counting based on N*'s
N^*	62	21	21
Δ^*	38	12	21
$\boldsymbol{\Lambda}^*$	**71**	**14**	**21**
$\boldsymbol{\Sigma}^*$	**66**	**9**	**42**
$\boldsymbol{\Xi}^*$	**73**	**6**	**42**
$\boldsymbol{\Omega}^*$	**36**	**2**	**21**

*R.G. Edwards et al, *Phys.Rev.D* 87 (2013) 5, 054506

Baryon Spectroscopy

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

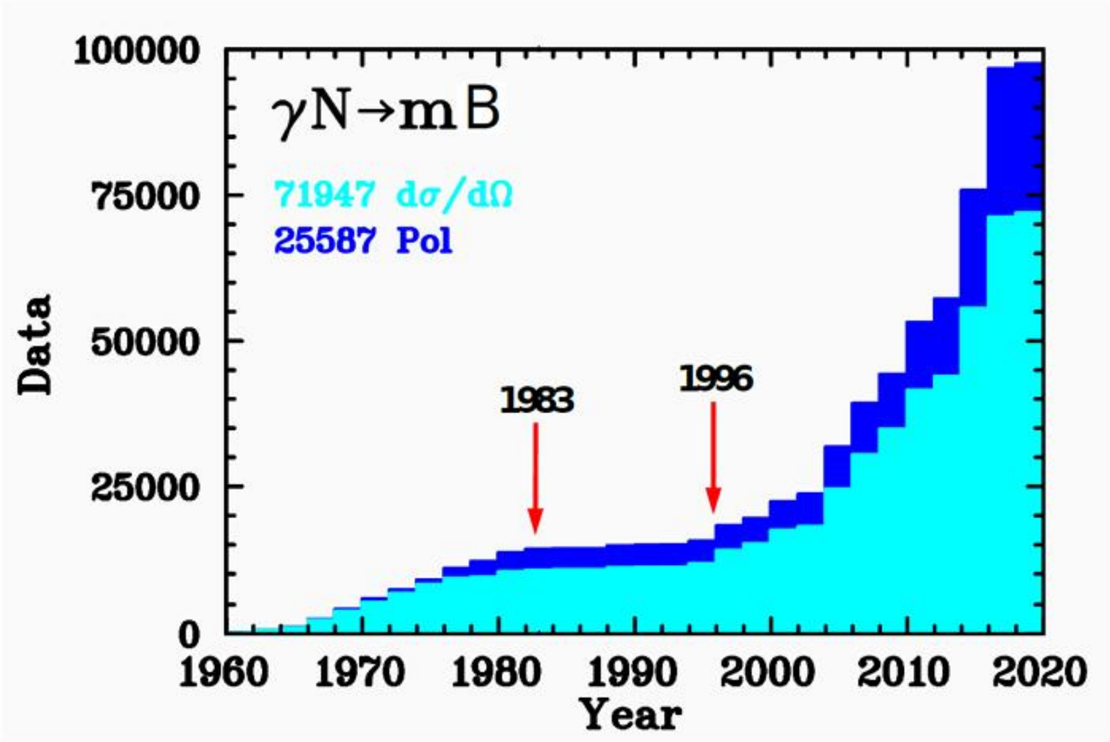
Experimentally:
Broad and strongly overlapping resonances

Important:

→ **Investigation of different final states**

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

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

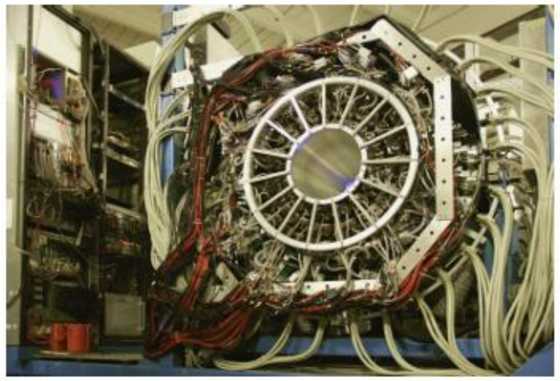


D. Ireland et al., Prog. Part. Nucl. Phys. 111 (2020) 103752

Recently: a lot of progress from photoproduction experiments:

CLAS (JLab),

CBELSA/TAPS (ELSA),



CBALL (MAMI),

LEPS (Spring-8), BGOOD (ELSA), GlueX (JLab), ...

⇔ **polarized beam, polarized target**

Double Polarization Experiments - Selected Results -

Circularly polarized photons, longitudinally polarized target

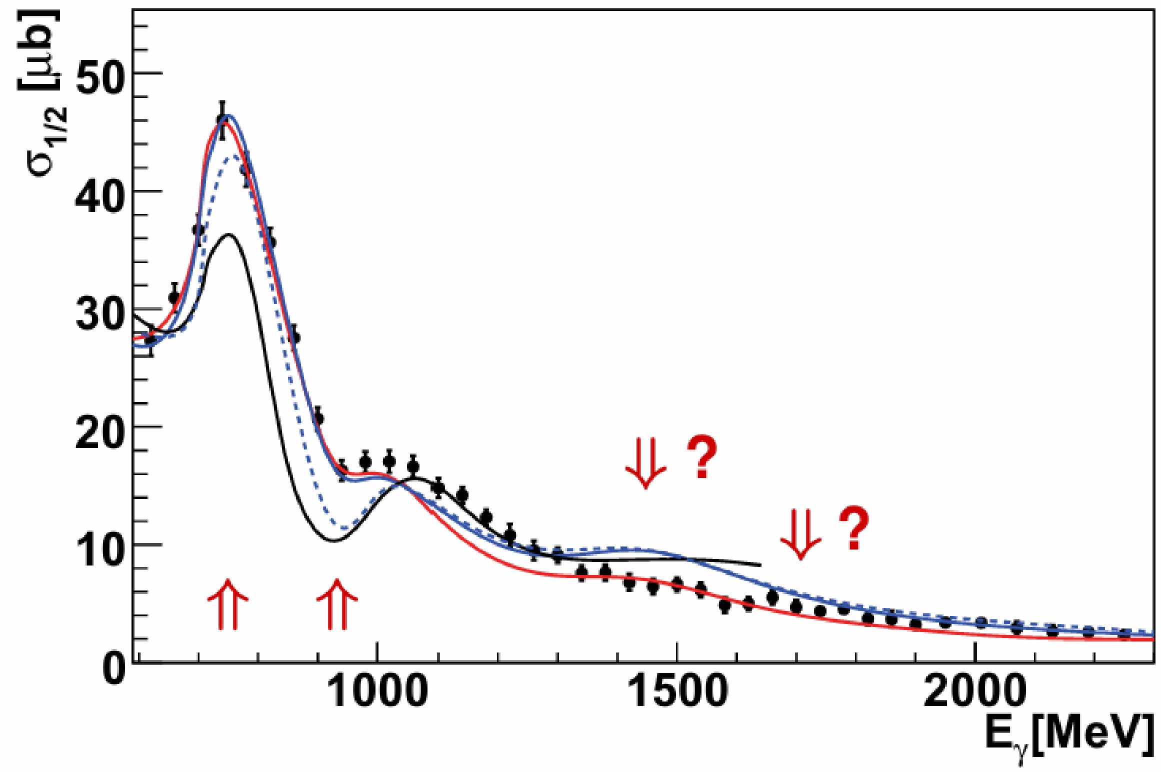
CBELSA/TAPS

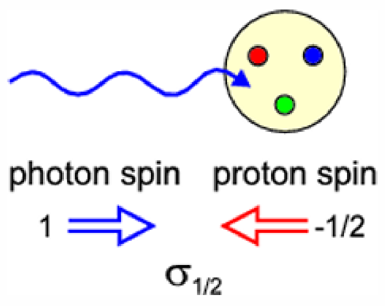
$\gamma p \to p\pi^0$:

PWAs:

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

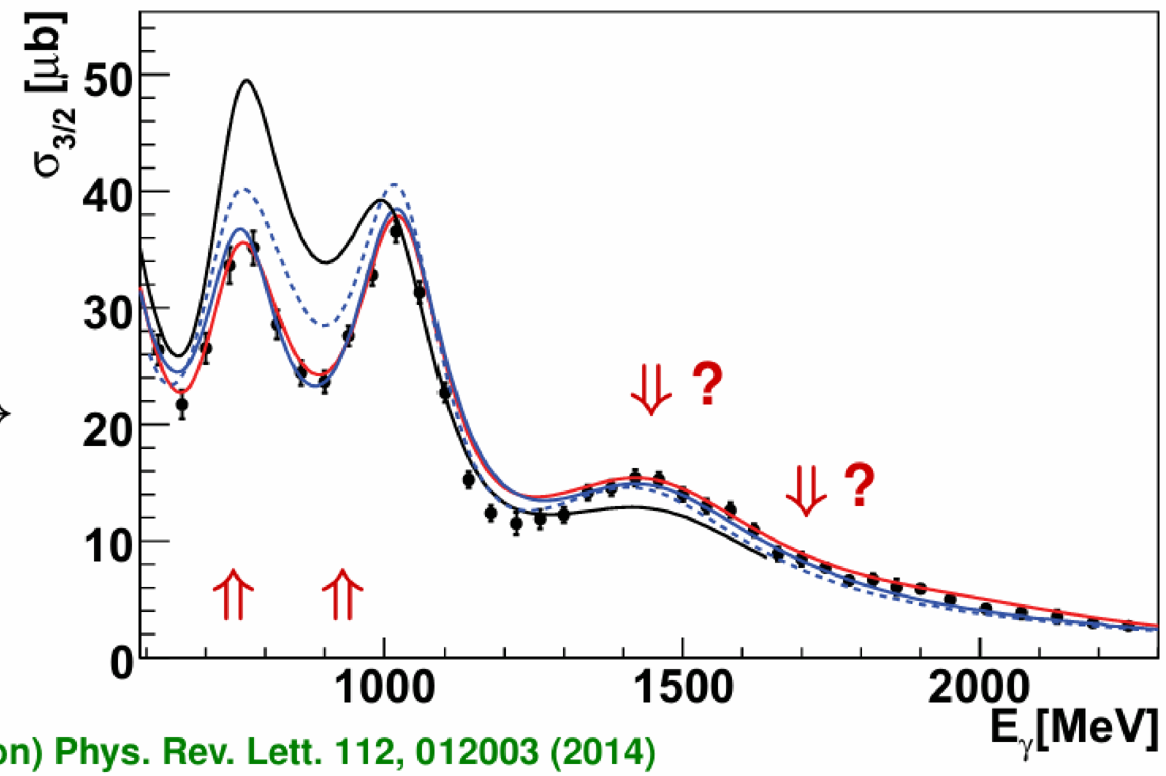
$\leftrightarrow$ **describe the so far existing photoproduction data, but ...**

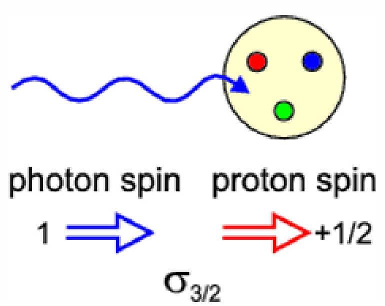




large deviations observed $\to$

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





$\Rightarrow$ **Sensitivity on high mass resonances !**

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

Results: The Spectrum of Baryon Resonances

Multi-channel Bonn-Gatchina PWA:

$\Rightarrow$ **Confirmation known resonances, better determination of their properties**

$\Rightarrow$ **New resonances observed**

	RPP 2010	our analyses	RPP'22 (2018-22)
$N(1710)1/2^+$	***	****	****
$N(1860)5/2^+$		*	**
$N(1875)3/2^-$		***	***
$N(1880)1/2^+$		***	***
$N(1895)1/2^-$		****	****
$N(1900)3/2^+$	**	****	****
$N(2060)5/2^-$		***	***
$N(2100)1/2^+$	*	***	***
$N(2120)3/2^-$		***	***
$\Delta(1600)3/2^+$	***	***	****
$\Delta(1900)1/2^-$	*	***	***
$\Delta(1940)3/2^-$	*	**	**
$\Delta(2200)7/2^-$	*	***	***

only examples shown

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

$\leftrightarrow$ **Results from photoproduction do enter the PDG and determine the properties of baryon resonances!**

before: almost entirely πN-elastic scattering and some π-photoproduction

At higher $\sqrt{s}$:

$\Leftrightarrow$ elastic cross section decreases

$\Leftrightarrow$ more an more inelastic channels open

Photoproduction provides access to the "inelastic channels"

$\Rightarrow$ **resonance properties**

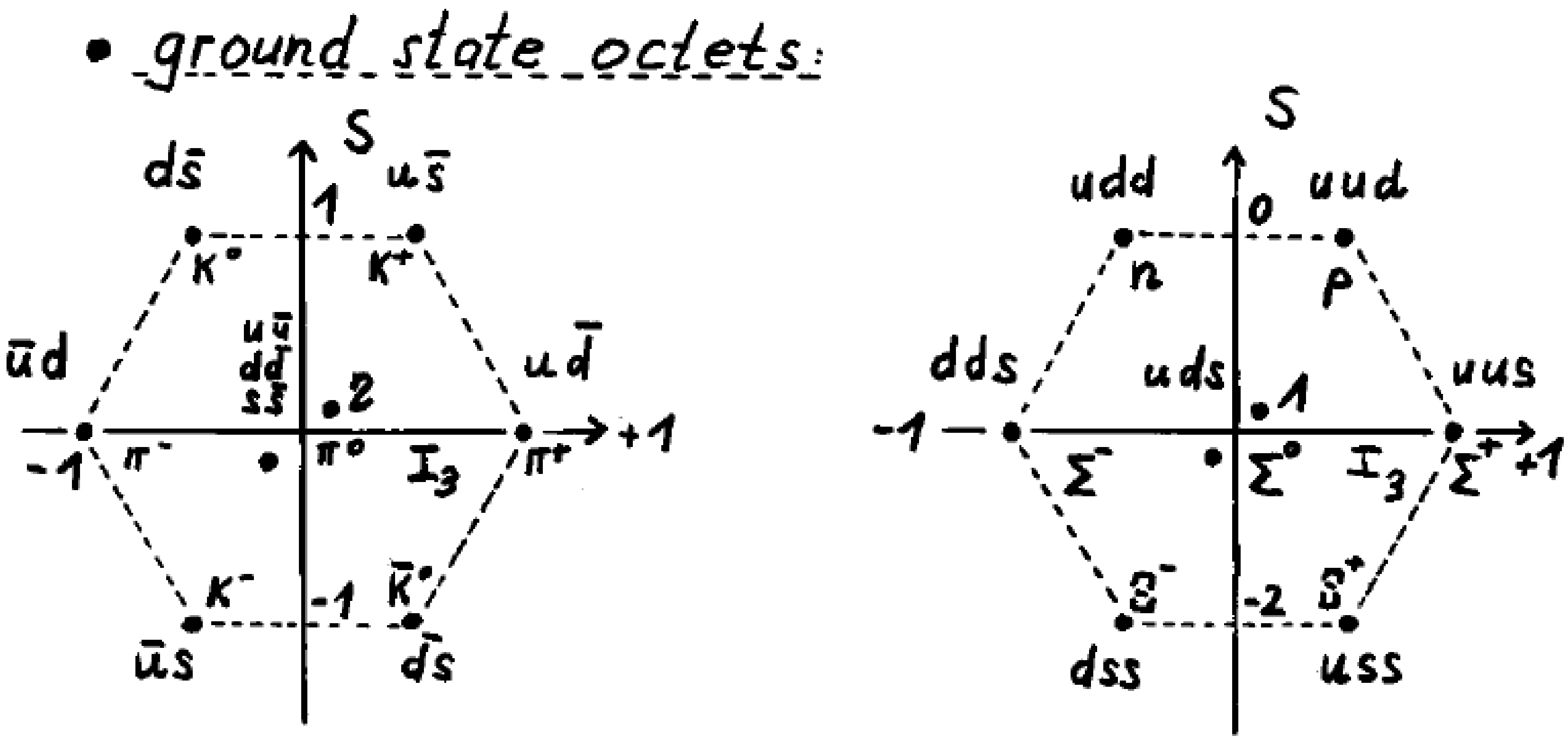
BnGa-PWA: A. V. Anisovich et al., EPJA 48 (2012) 15, PRL 119 (2017) 062004, PLB 772 (2017) 247, J. Müller et al.,PLB 803 (2020) 135323 ...

Excitations

The early days

Murray Gell Mann 1964

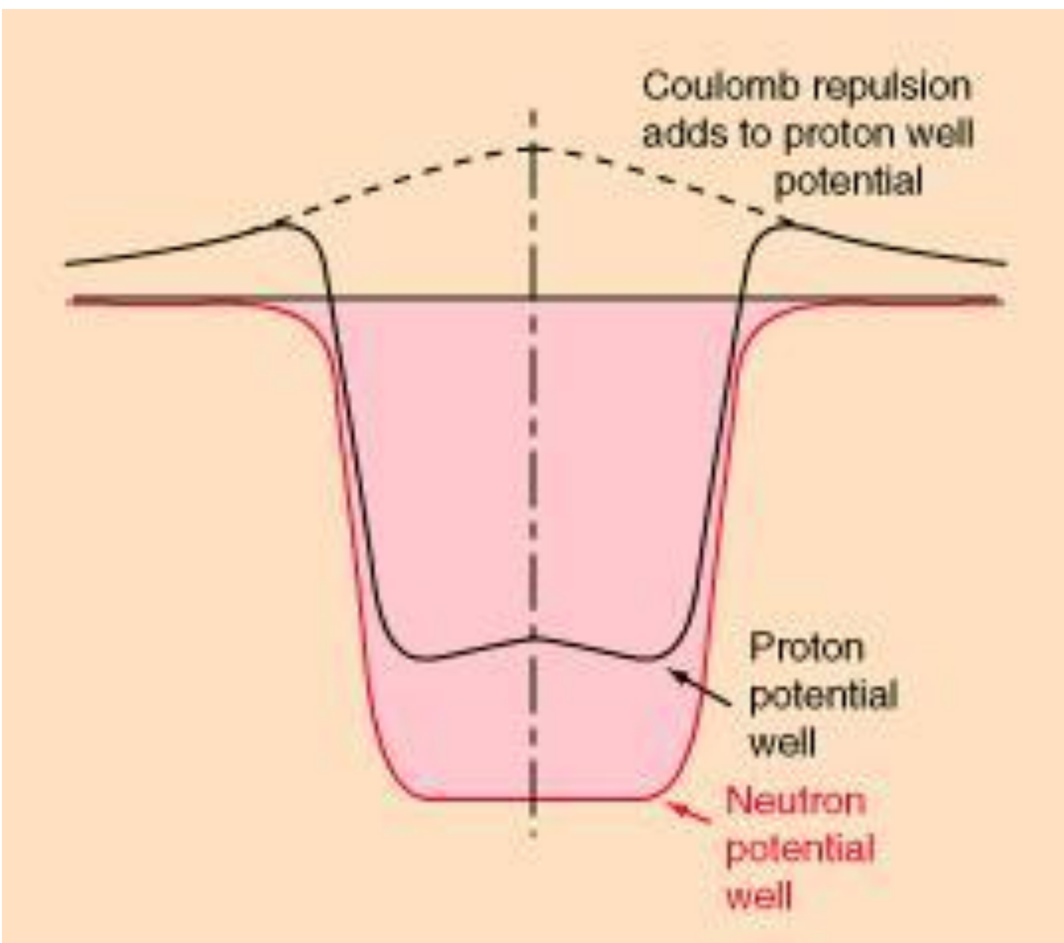
"A schematic model of baryons and mesons"

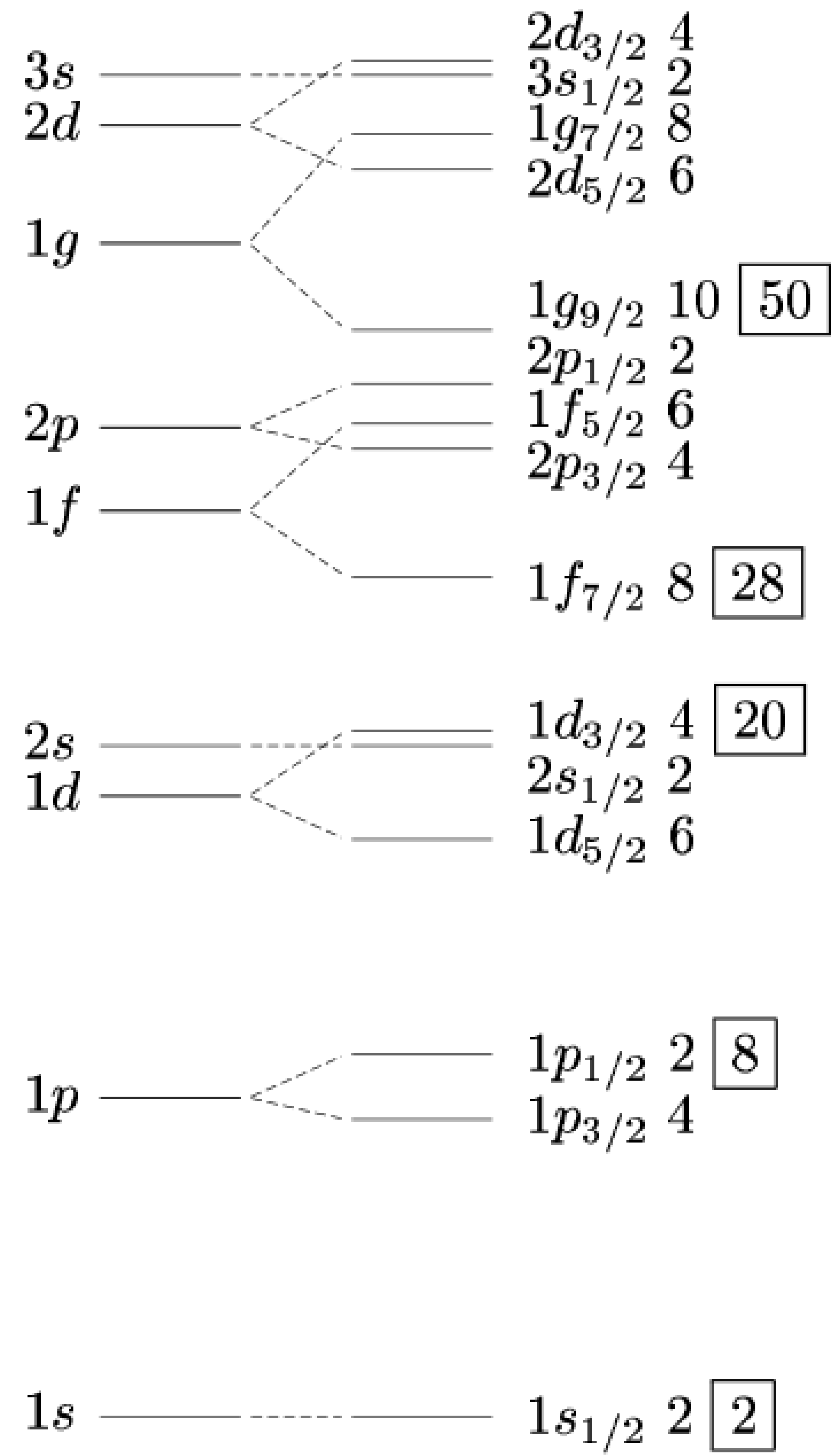


- Baryons are 3 quark systems
- Mesons are quark-antiquark systems

Excited states?

Shell model



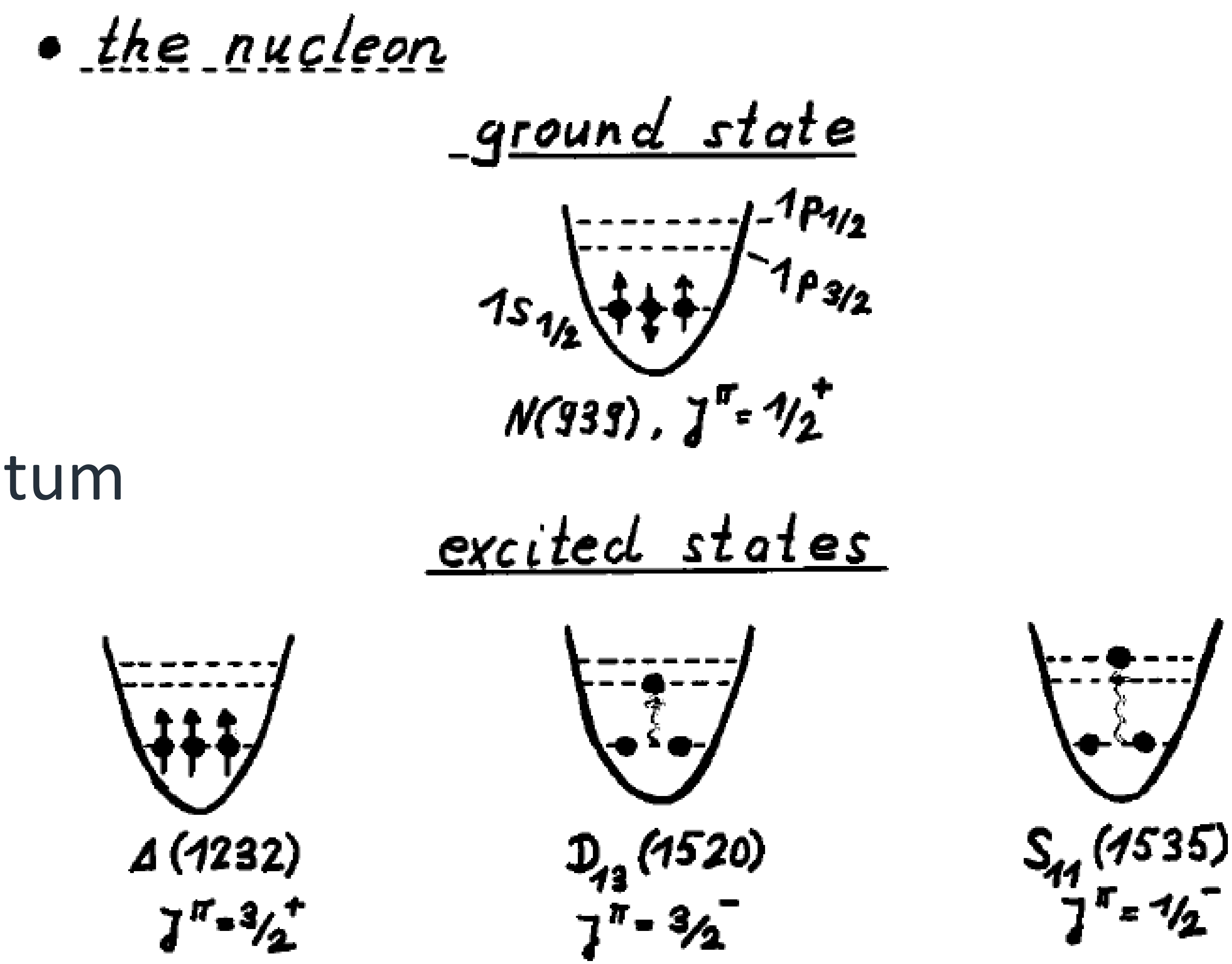


Nucleon excited states?

$$P = (-1)^L$$

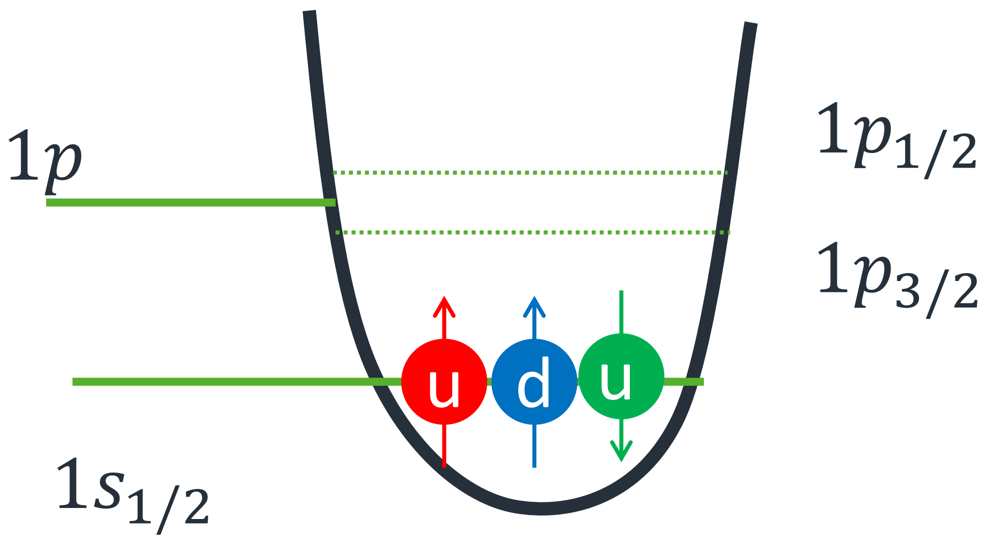
P – parity

L – angular momentum



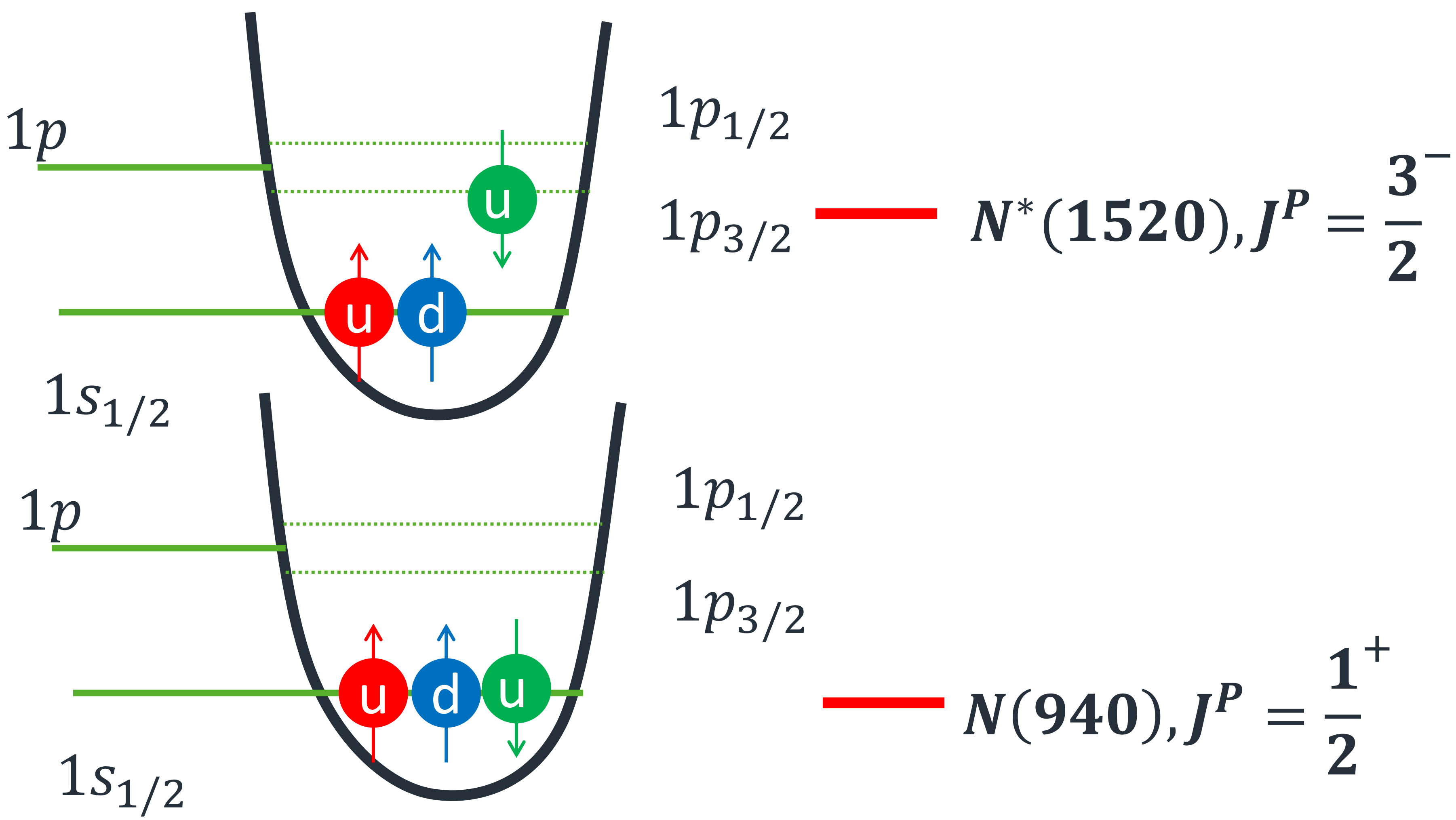
"N" baryons I=1/2 , "Δ" baryons I=3/2

Excited states - expectation

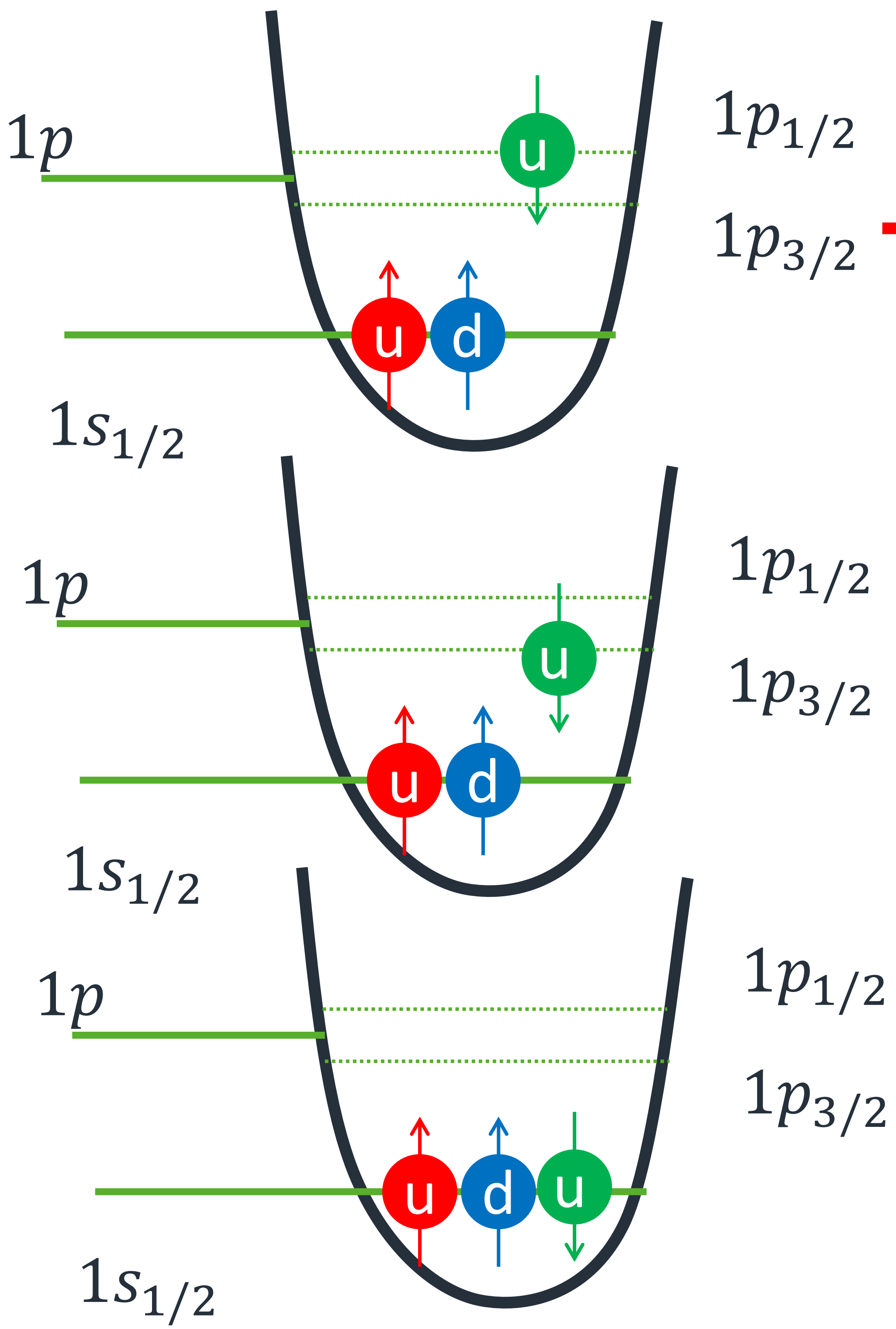


$N(940), J^P = \frac{1}{2}^+$

Excited states - expectation



Excited states - expectation

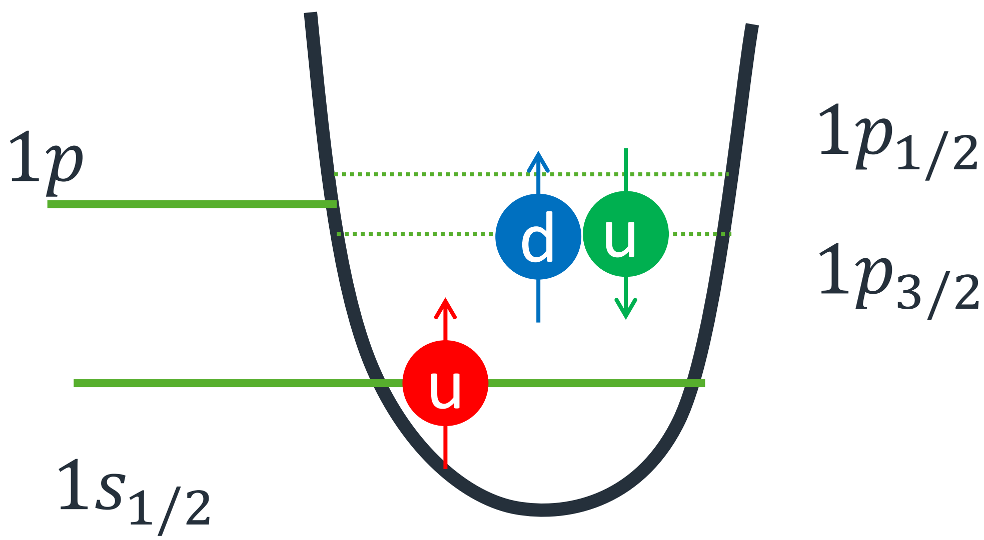


$N^*(1535), J^P = \frac{1}{2}^-$

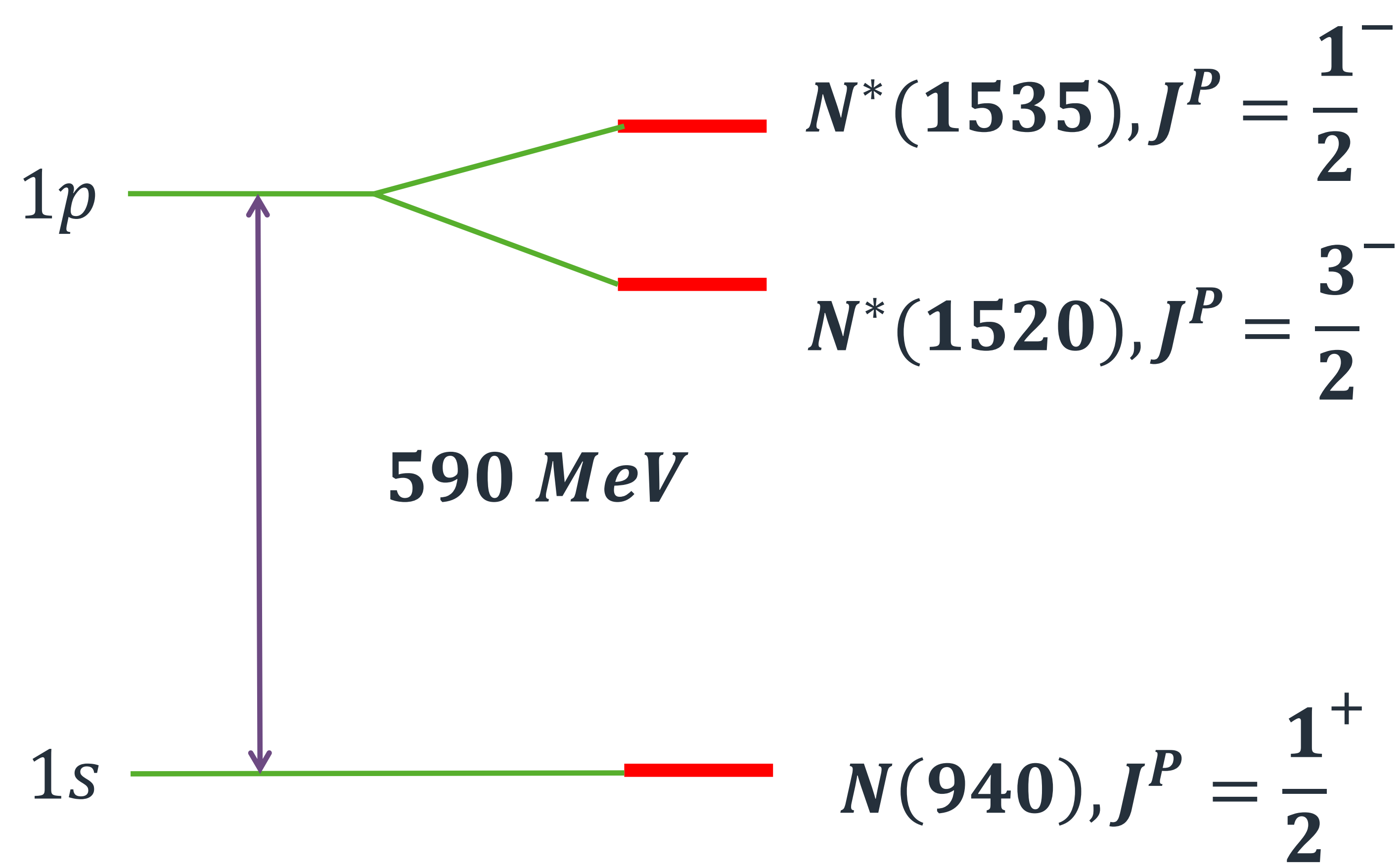
$N^*(1520), J^P = \frac{3}{2}^-$

$N(940), J^P = \frac{1}{2}^+$

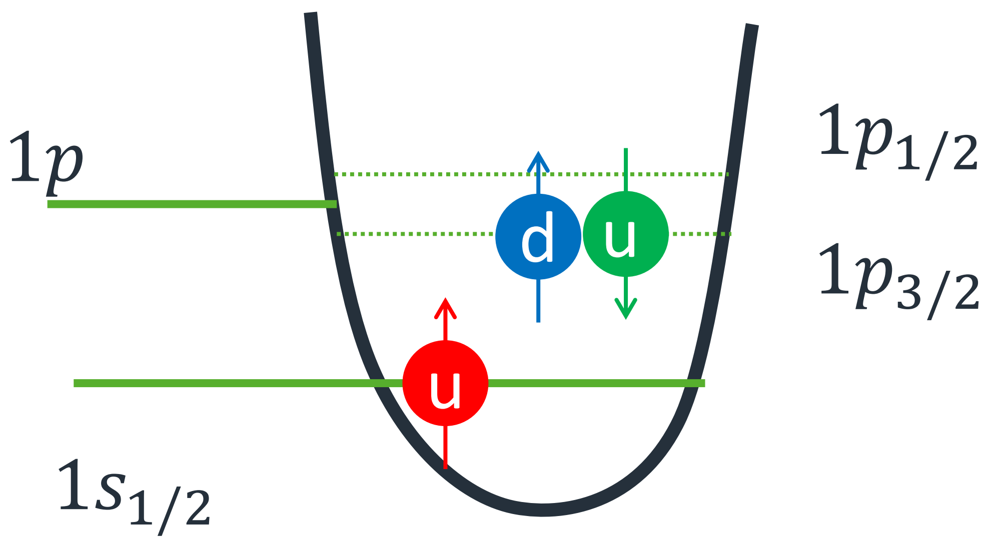
Excited states - expectation

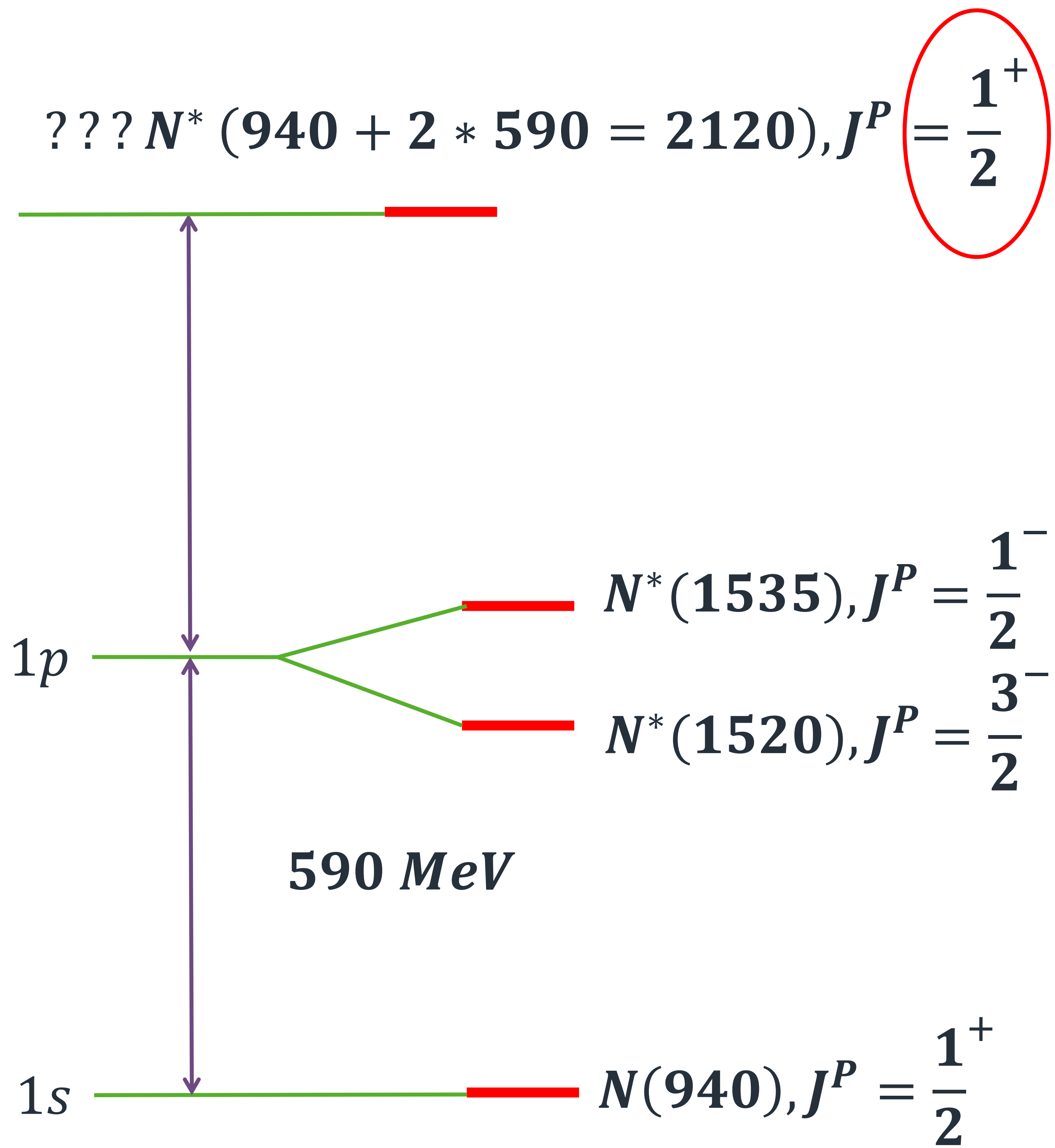


$$N^*(???), J^P = \frac{1}{2}^+$$

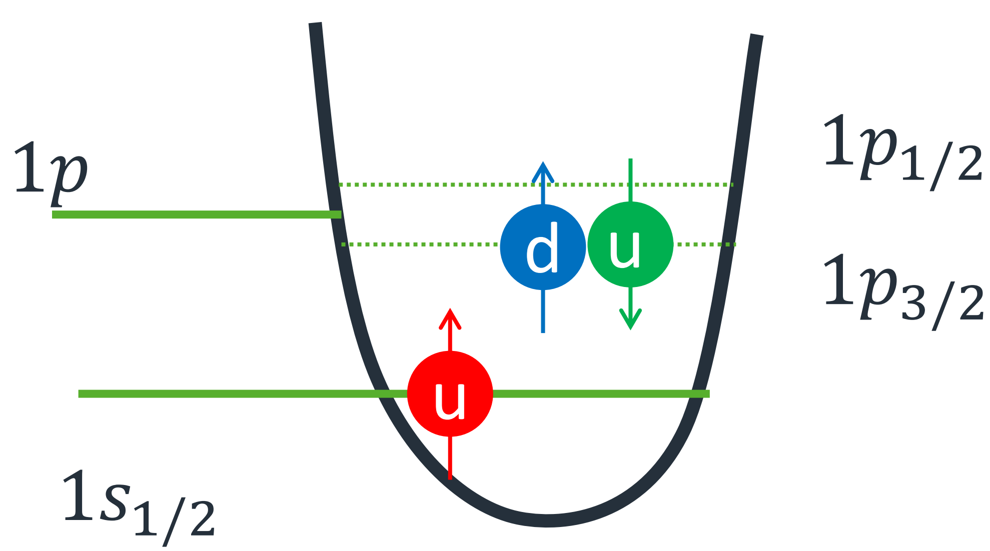


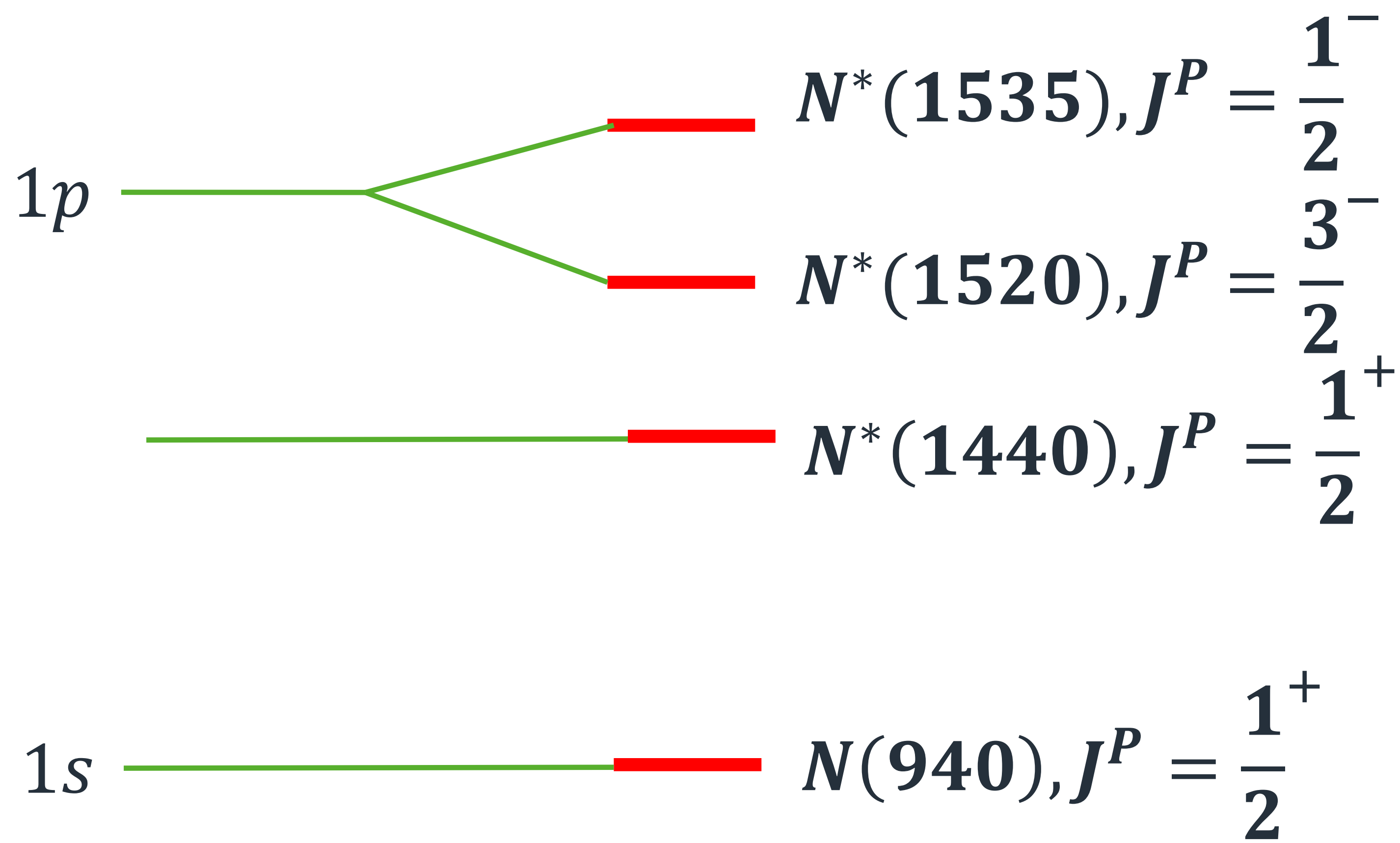
Excited states - expectation



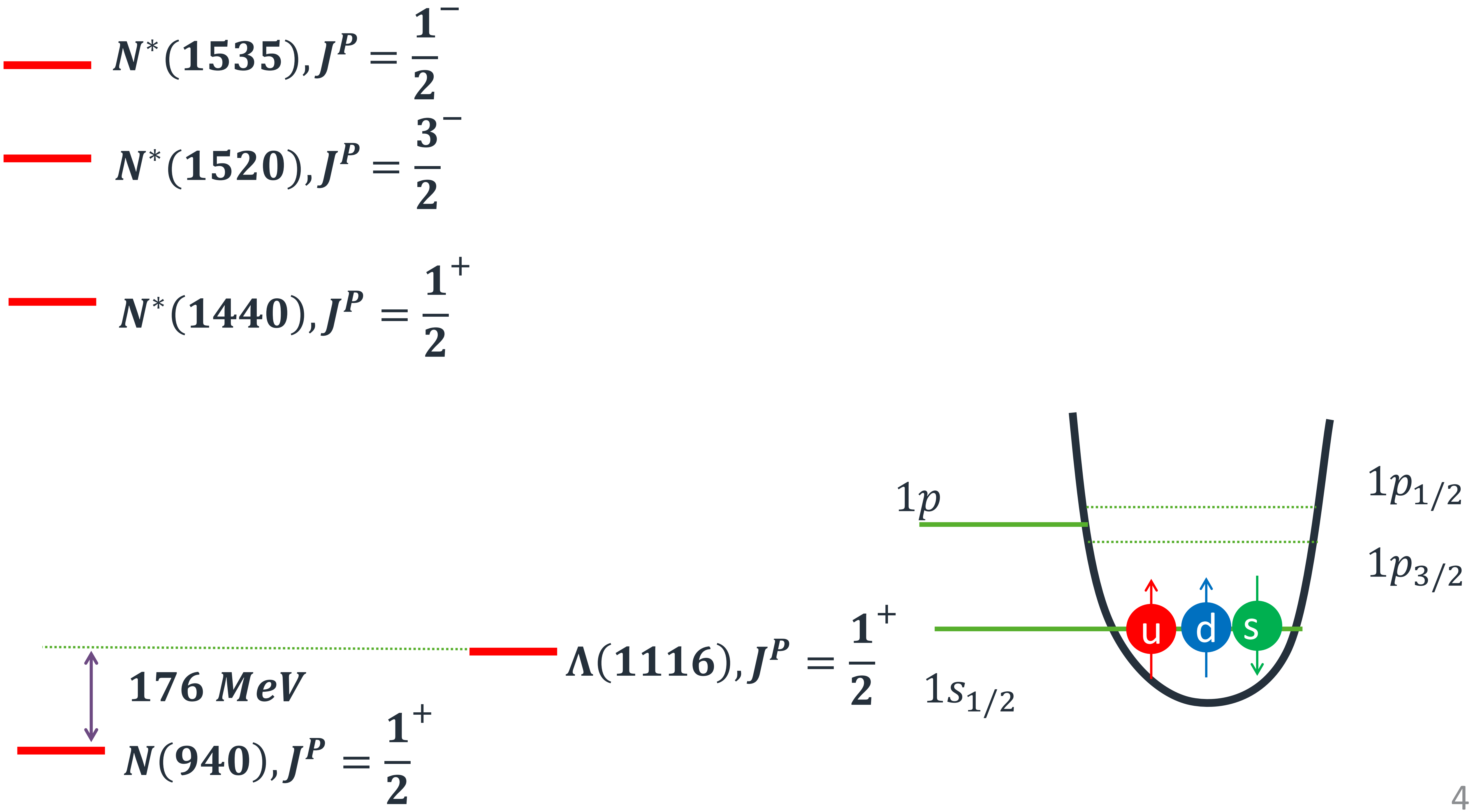


Excited states - reality



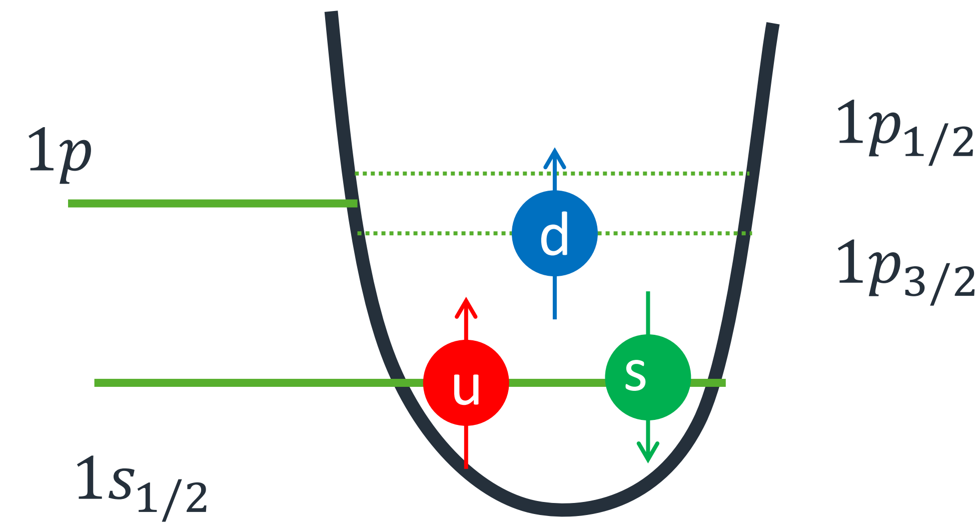


Hyperons



$N^*(1535), J^P = \frac{1}{2}^-$
$N^*(1520), J^P = \frac{3}{2}^-$
$N^*(1440), J^P = \frac{1}{2}^+$
$\Lambda(1116), J^P = \frac{1}{2}^+$
$176\ MeV$
$N(940), J^P = \frac{1}{2}^+$
$1p$
$1p_{1/2}$
$1p_{3/2}$
$1s_{1/2}$
u
d
s

Excited hyperons?



$\Lambda^*(1700?), J^P = \frac{3}{2}^-$

$1700 = 1520 + 176$

$N^*(1535), J^P = \frac{1}{2}^-$

$N^*(1520), J^P = \frac{3}{2}^-$

$N^*(1440), J^P = \frac{1}{2}^+$

$\Lambda(1116), J^P = \frac{1}{2}^+$

$176\ MeV$

$N(940), J^P = \frac{1}{2}^+$

Excited hyperons - reality

$N^*(1535), J^P = \frac{1}{2}^-$

$N^*(1520), J^P = \frac{3}{2}^-$

$\Lambda(1520), J^P = \frac{3}{2}^-$

$N^*(1440), J^P = \frac{1}{2}^+$

$\Lambda(1405), J^P = \frac{1}{2}^-$

$\Lambda(1116), J^P = \frac{1}{2}^+$

$176\ MeV$

$N(940), J^P = \frac{1}{2}^+$

Excited hyperons - reality

$N^*(1535), J^P = \frac{1}{2}^-$

$N^*(1520), J^P = \frac{3}{2}^-$

$\Lambda(1520), J^P = \frac{3}{2}^-$

$N^*(1440), J^P = \frac{1}{2}^+$

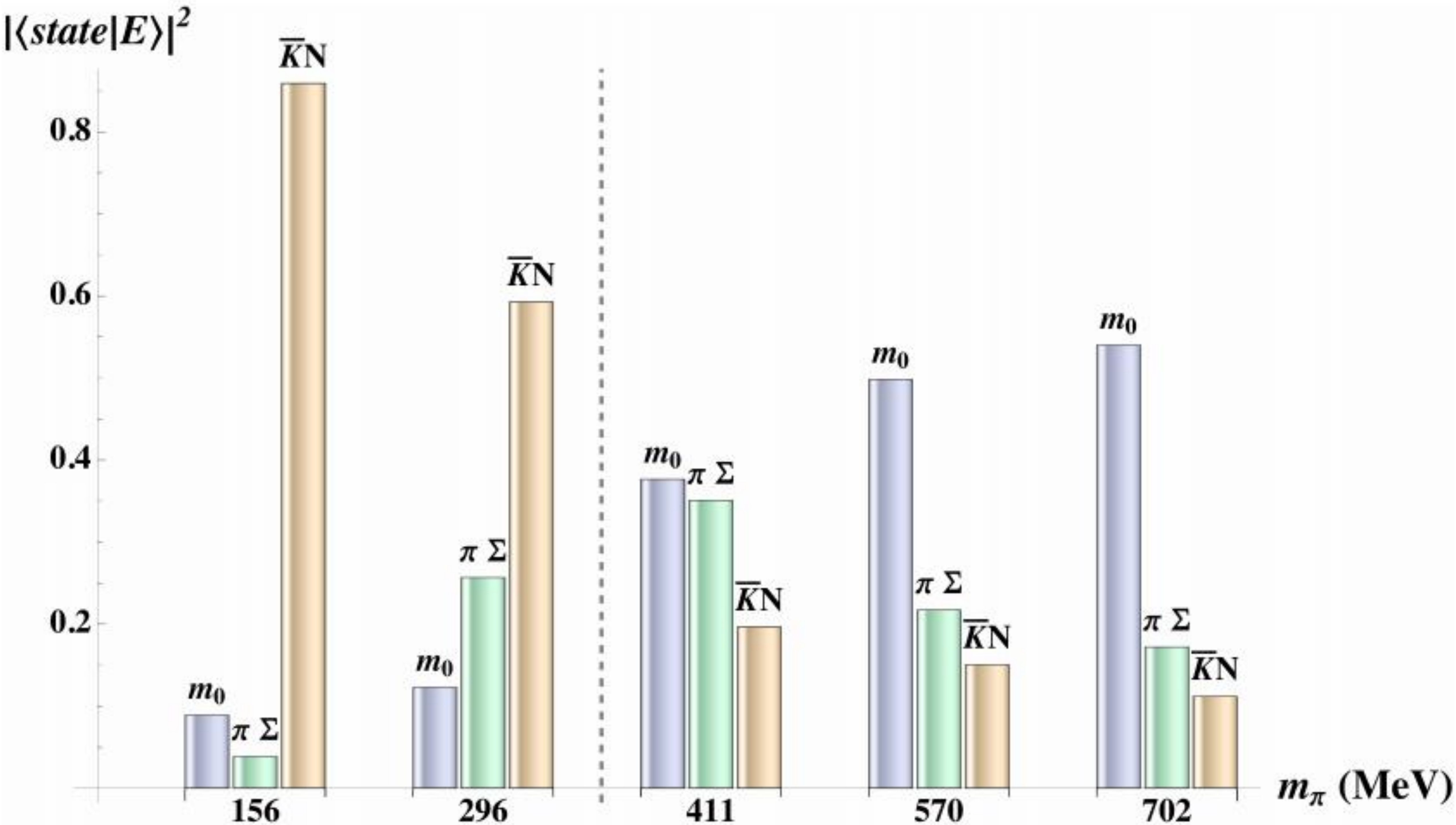
$\Lambda(1405), J^P = \frac{1}{2}^-$

$\Lambda(1116), J^P = \frac{1}{2}^+$

$176\ MeV$

$N(940), J^P = \frac{1}{2}^+$

Λ(1405) from Lattice QCD



Molecular states

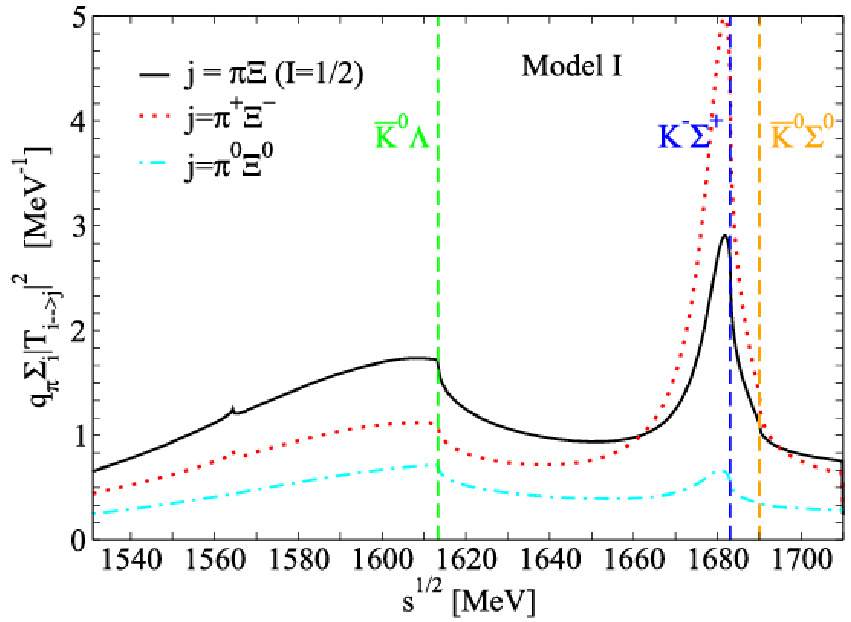
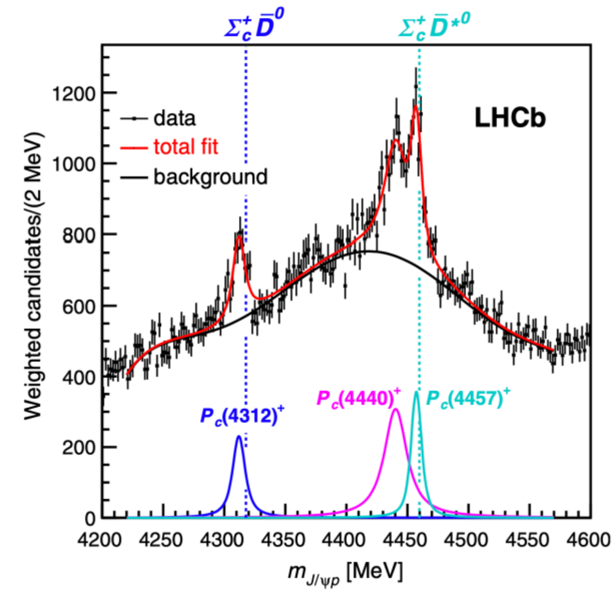


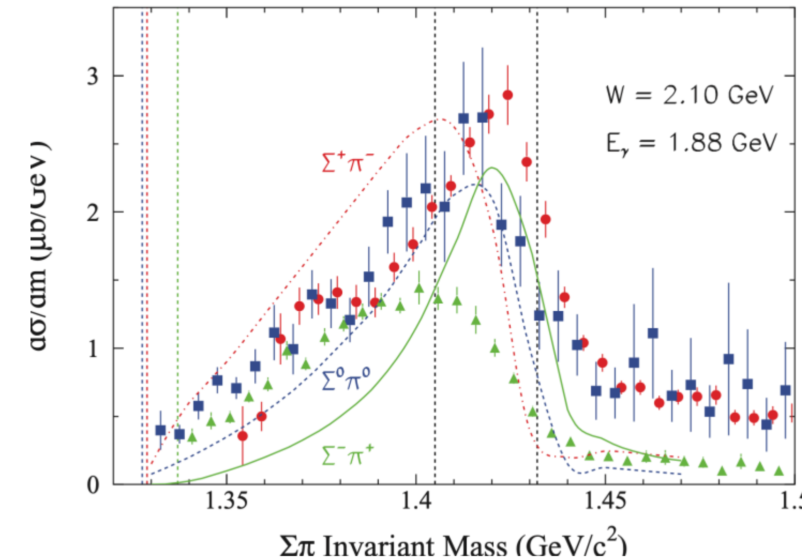
Fig. 2. Sum of amplitudes squared times a phase space factor. The vertical dashed lines represent the channel threshold locations.

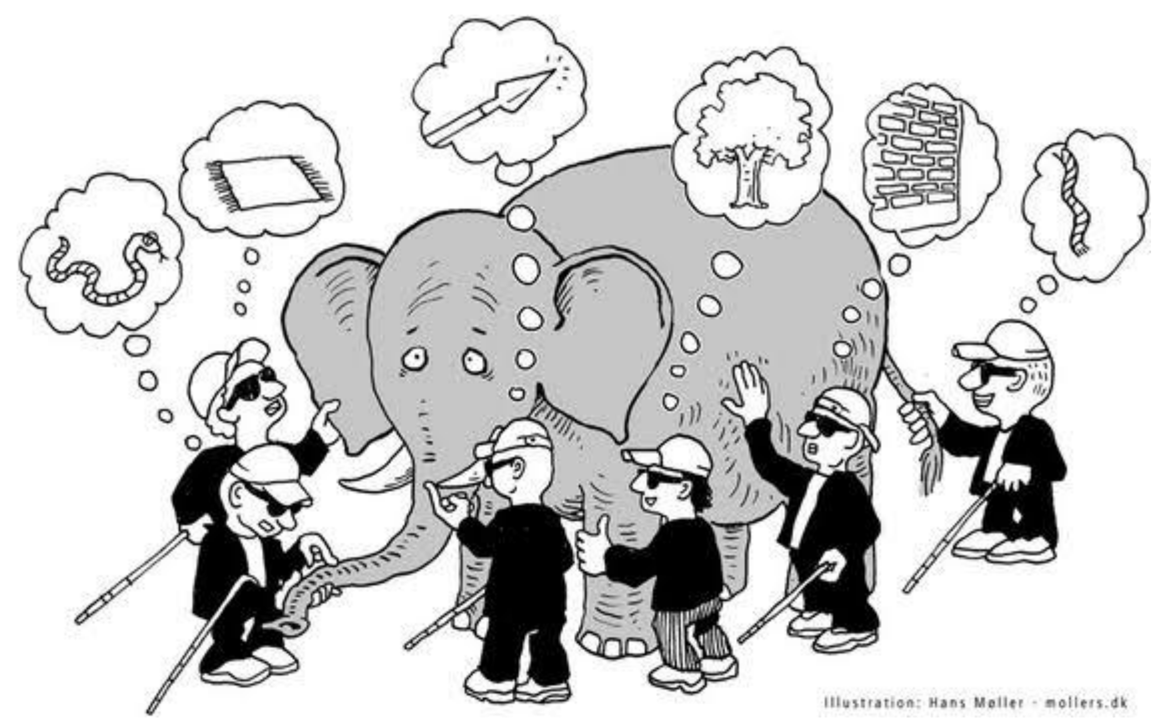
Pentaquarks at LHCb

PRL 155, 072001 (2015), PRL 112, 222001 (2019)



Moriya et al., (CLAS) PRC 87, 035206 (2013)





Molecular states. Mesons

$\sigma(500)$: $\pi - \pi$ molecule

$f_0/a_0(980)$: $K - K$ molecule

$\kappa(700)$: $K - \pi$ molecule

Molecular states. Baryons

$N^*(1440)$: $N - \sigma$ molecule: $|uud + \bar{u}d + u\bar{d}\rangle$

$\Lambda(1405)$: $N - \bar{K}$ molecule: $|udd + s\bar{d}\rangle$

$\mathrm{N}^*(1535)$: $\Sigma - K$ molecule: $|uds + d\bar{s}\rangle$

Excited hyperons - reality

$\mathrm{N}^*(1535)$: $\Sigma - K$ molecule: $|uds + d\bar{s}\rangle$

$\boldsymbol{N^*(1535), J^P = \frac{1}{2}^-}$

$\Lambda(1405)$: $\mathrm{N} - K$ molecule: $|uud + s\bar{d}\rangle$

$\boldsymbol{\Lambda(1405), J^P = \frac{1}{2}^-}$

$\boldsymbol{\Lambda(1116), J^P = \frac{1}{2}^+}$

$\boldsymbol{176\ MeV}$

$\boldsymbol{N(940), J^P = \frac{1}{2}^+}$

Excited hyperons - reality

$M_{\mathrm{N}^*(1535)} - M_{\Lambda(1405)} = 130\ MeV$

$\mathrm{N}^*(1535)$: $\Sigma - K$ molecule: $|uds + d\bar{s}\rangle$

2 s-quarks

$\boldsymbol{N^*(1535), J^P = \frac{1}{2}^-}$

1 s-quark

$\Lambda(1405)$: $\mathrm{N} - K$ molecule: $|uud + s\bar{d}\rangle$

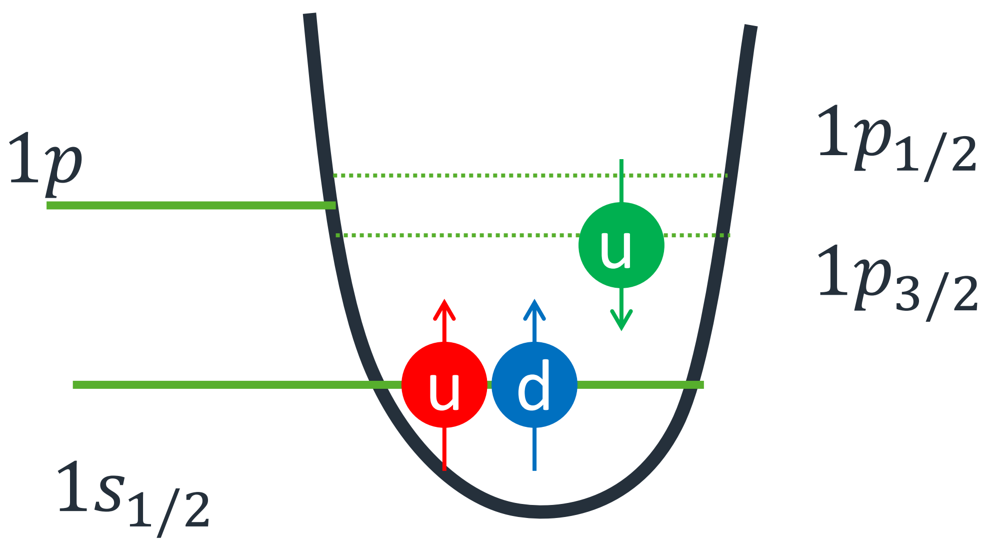
$\boldsymbol{\Lambda(1405), J^P = \frac{1}{2}^-}$

$\boldsymbol{\Lambda(1116), J^P = \frac{1}{2}^+}$

$\boldsymbol{176\ MeV}$

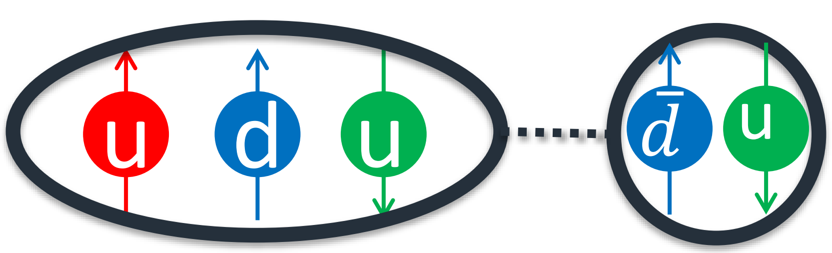
$\boldsymbol{N(940), J^P = \frac{1}{2}^+}$

Excited states



Single quark excitations are expensive (in terms of Energy ~ 700 MeV)

Low energy spectrum is dominated by molecular states!



Adding extra particle is cheap (140 MeV)

Baryon summary table, PDG

p	$1/2^+$	****	$\Delta(1232)$	$3/2^+$	****	Σ^+	$1/2^+$	****	Ξ^0	$1/2^+$	****	Λ_c^+	$1/2^+$	****
n	$1/2^+$	****	$\Delta(1600)$	$3/2^+$	***	Σ^0	$1/2^+$	****	Ξ^-	$1/2^+$	****	$\Lambda_c(2595)^+$	$1/2^-$	***
$N(1440)$	$1/2^+$	****	$\Delta(1620)$	$1/2^-$	****	Σ^-	$1/2^+$	****	$\Xi(1530)$	$3/2^+$	****	$\Lambda_c(2625)^+$	$3/2^-$	***
$N(1520)$	$3/2^-$	****	$\Delta(1700)$	$3/2^-$	****	$\Sigma(1385)$	$3/2^+$	****	$\Xi(1620)$		*	$\Lambda_c(2765)^+$		*
$N(1535)$	$1/2^-$	****	$\Delta(1750)$	$1/2^+$	*	$\Sigma(1480)$		*	$\Xi(1690)$		***	$\Lambda_c(2880)^+$	$5/2^+$	***
$N(1650)$	$1/2^-$	****	$\Delta(1900)$	$1/2^-$	**	$\Sigma(1560)$		**	$\Xi(1820)$	$3/2^-$	***	$\Lambda_c(2940)^+$		***
$N(1675)$	$5/2^-$	****	$\Delta(1905)$	$5/2^+$	****	$\Sigma(1580)$	$3/2^-$	*	$\Xi(1950)$		***	$\Sigma_c(2455)$	$1/2^+$	****
$N(1680)$	$5/2^+$	****	$\Delta(1910)$	$1/2^+$	****	$\Sigma(1620)$	$1/2^-$	*	$\Xi(2030)$	$\geq \frac{5}{2}?$	***	$\Sigma_c(2520)$	$3/2^+$	***
$N(1685)$		*	$\Delta(1920)$	$3/2^+$	***	$\Sigma(1660)$	$1/2^+$	***	$\Xi(2120)$		*	$\Sigma_c(2800)$		***
$N(1700)$	$3/2^-$	***	$\Delta(1930)$	$5/2^-$	***	$\Sigma(1670)$	$3/2^-$	****	$\Xi(2250)$		**	Ξ_c^+	$1/2^+$	***
$N(1710)$	$1/2^+$	***	$\Delta(1940)$	$3/2^-$	**	$\Sigma(1690)$		**	$\Xi(2370)$		**	Ξ_c^0	$1/2^+$	***
$N(1720)$	$3/2^+$	****	$\Delta(1950)$	$7/2^+$	****	$\Sigma(1730)$	$3/2^+$	*	$\Xi(2500)$		*	$\Xi_c'^+$	$1/2^+$	***
$N(1860)$	$5/2^+$	**	$\Delta(2000)$	$5/2^+$	**	$\Sigma(1750)$	$1/2^-$	***				$\Xi_c'^0$	$1/2^+$	***
$N(1875)$	$3/2^-$	***	$\Delta(2150)$	$1/2^-$	*	$\Sigma(1770)$	$1/2^+$	*	Ω^-	$3/2^+$	****	$\Xi_c(2645)$	$3/2^+$	***
$N(1880)$	$1/2^+$	**	$\Delta(2200)$	$7/2^-$	*	$\Sigma(1775)$	$5/2^-$	****	$\Omega(2250)^-$		***	$\Xi_c(2790)$	$1/2^-$	***
$N(1895)$	$1/2^-$	**	$\Delta(2300)$	$9/2^+$	**	$\Sigma(1840)$	$3/2^+$	*	$\Omega(2380)^-$		**	$\Xi_c(2815)$	$3/2^-$	***
$N(1900)$	$3/2^+$	***	$\Delta(2350)$	$5/2^-$	*	$\Sigma(1880)$	$1/2^+$	**	$\Omega(2470)^-$		**	$\Xi_c(2930)$		*
$N(1990)$	$7/2^+$	**	$\Delta(2390)$	$7/2^+$	*	$\Sigma(1900)$	$1/2^-$	*				$\Xi_c(2980)$		***
$N(2000)$	$5/2^+$	**	$\Delta(2400)$	$9/2^-$	**	$\Sigma(1915)$	$5/2^+$	****				$\Xi_c(3055)$		**
$N(2040)$	$3/2^+$	*	$\Delta(2420)$	$11/2^+$	****	$\Sigma(1940)$	$3/2^+$	*				$\Xi_c(3080)$		***
$N(2060)$	$5/2^-$	**	$\Delta(2750)$	$13/2^-$	**	$\Sigma(1940)$	$3/2^-$	***				$\Xi_c(3123)$		*
$N(2100)$	$1/2^+$	*	$\Delta(2950)$	$15/2^+$	**	$\Sigma(2000)$	$1/2^-$	*				Ω_c^0	$1/2^+$	***
$N(2120)$	$3/2^-$	**				$\Sigma(2030)$	$7/2^+$	****				$\Omega_c(2770)^0$	$3/2^+$	***
$N(2190)$	$7/2^-$	****	Λ	$1/2^+$	****	$\Sigma(2070)$	$5/2^+$	*						
$N(2220)$	$9/2^+$	****	$\Lambda(1405)$	$1/2^-$	****	$\Sigma(2080)$	$3/2^+$	**				Ξ_{cc}^+		*
$N(2250)$	$9/2^-$	****	$\Lambda(1520)$	$3/2^-$	****	$\Sigma(2100)$	$7/2^-$	*						
$N(2300)$	$1/2^+$	**	$\Lambda(1600)$	$1/2^+$	***	$\Sigma(2250)$		***				Λ_b^0	$1/2^+$	***
$N(2570)$	$5/2^-$	**	$\Lambda(1670)$	$1/2^-$	****	$\Sigma(2455)$		**				$\Lambda_b(5912)^0$	$1/2^-$	***
$N(2600)$	$11/2^-$	***	$\Lambda(1690)$	$3/2^-$	****	$\Sigma(2620)$		**				$\Lambda_b(5920)^0$	$3/2^-$	***
$N(2700)$	$13/2^+$	**	$\Lambda(1710)$	$1/2^+$	*	$\Sigma(3000)$		*				Σ_b	$1/2^+$	***
			$\Lambda(1800)$	$1/2^-$	***	$\Sigma(3170)$		*				Σ_b^*	$3/2^+$	***
			$\Lambda(1810)$	$1/2^+$	***							Ξ_b^0, Ξ_b^-	$1/2^+$	***
			$\Lambda(1820)$	$5/2^+$	****							$\Xi_b(5945)^0$	$3/2^+$	***
			$\Lambda(1830)$	$5/2^-$	****							Ω_b^-	$1/2^+$	***
			$\Lambda(1890)$	$3/2^+$	****									
			$\Lambda(2000)$		*									
			$\Lambda(2020)$	$7/2^+$	*									
			$\Lambda(2050)$	$3/2^-$	*									
			$\Lambda(2100)$	$7/2^-$	****									
			$\Lambda(2110)$	$5/2^+$	***									
			$\Lambda(2325)$	$3/2^-$	*									
			$\Lambda(2350)$	$9/2^+$	***									
			$\Lambda(2585)$		**									

Number of 3- and 4-star Resonances

Baryon	2004	2020
N^*	15	21
Δ	10	12
Λ	14	14
Σ	10	9*
Ξ	6	6
Ω	2	2

*$\Sigma(2250)$ was downgraded


SO FAR, SO GOOD
NIGHT SKY JIGSAW
10,000 PIECE
10,000 PIECES
CHRIS MADDEN.
www.chrismadden.co.uk

Conclusion

- 3q states – a lot of progress
  - Large splitting
  - Dominated by molecules
  - mixing
- Molecules
  - Some thresholds have states
  - Some thresholds do not.
  - Shapes (production/decay channels)
- Hybrid baryons?
- Pentaquarks vs meson-baryon molecules?
- Precise, high stats experiments are the key

Questions

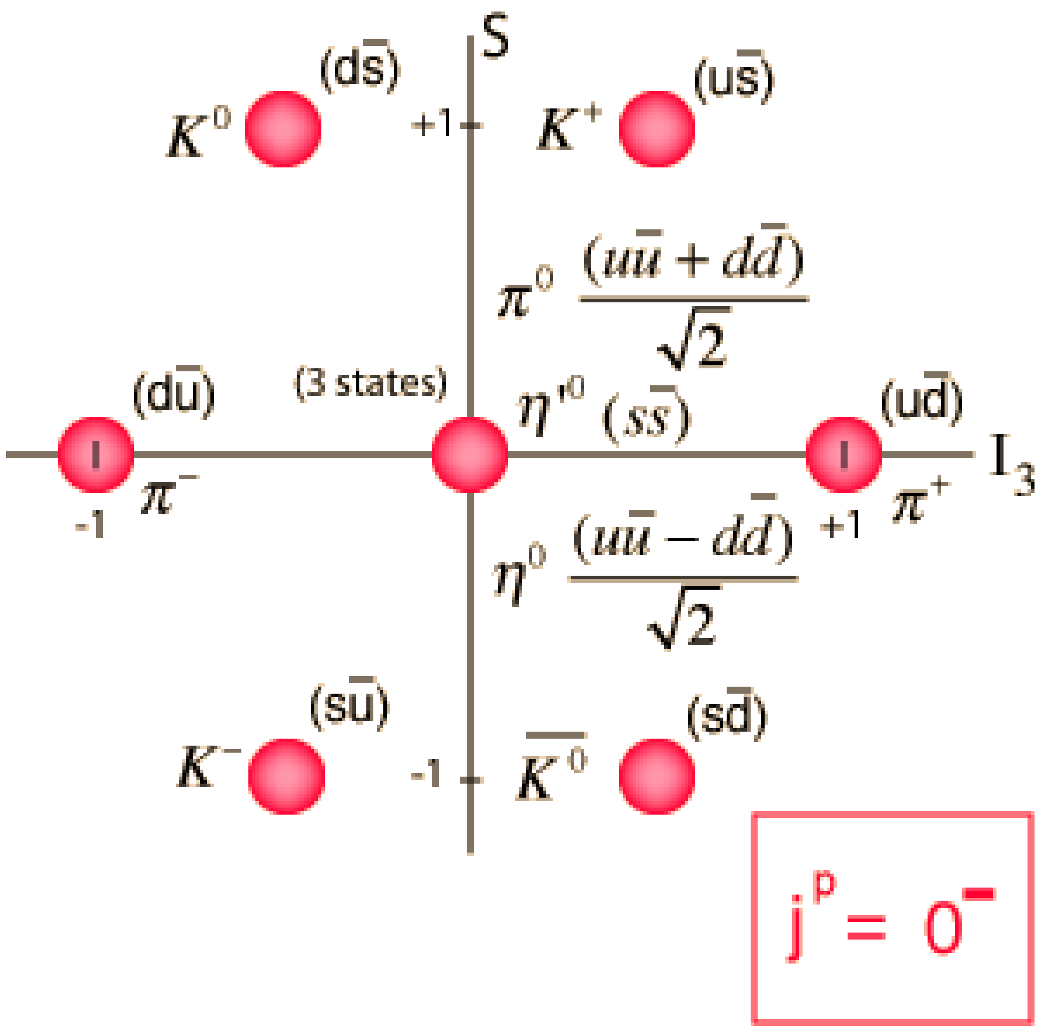
- Problem tasks:

1. The Roper resonance, $N^*(1440)$, has a quantum numbers $J^P = \frac{1}{2}^+$ and a pole position $M = 1395\ MeV$. Deduce what could be its SU(3) multiplet companions in single and double-strange sector and what could be their masses (might not be discovered yet)? . Hint: you can consider that Roper resonance is an interplay between $N\sigma$ and $\Delta\pi$ components
2. Perform similar research for the $N^*(1535)$
3. For the light N^* spectrum calculate possible meson-baryon thresholds which might be relevant and confront them with known states
4. For the meson baryon molecular states, calculate the quantum numbers of possible generated resonances (use two lowest lying baryon multiplets – octet and decuplet and two lowest meson nonets)

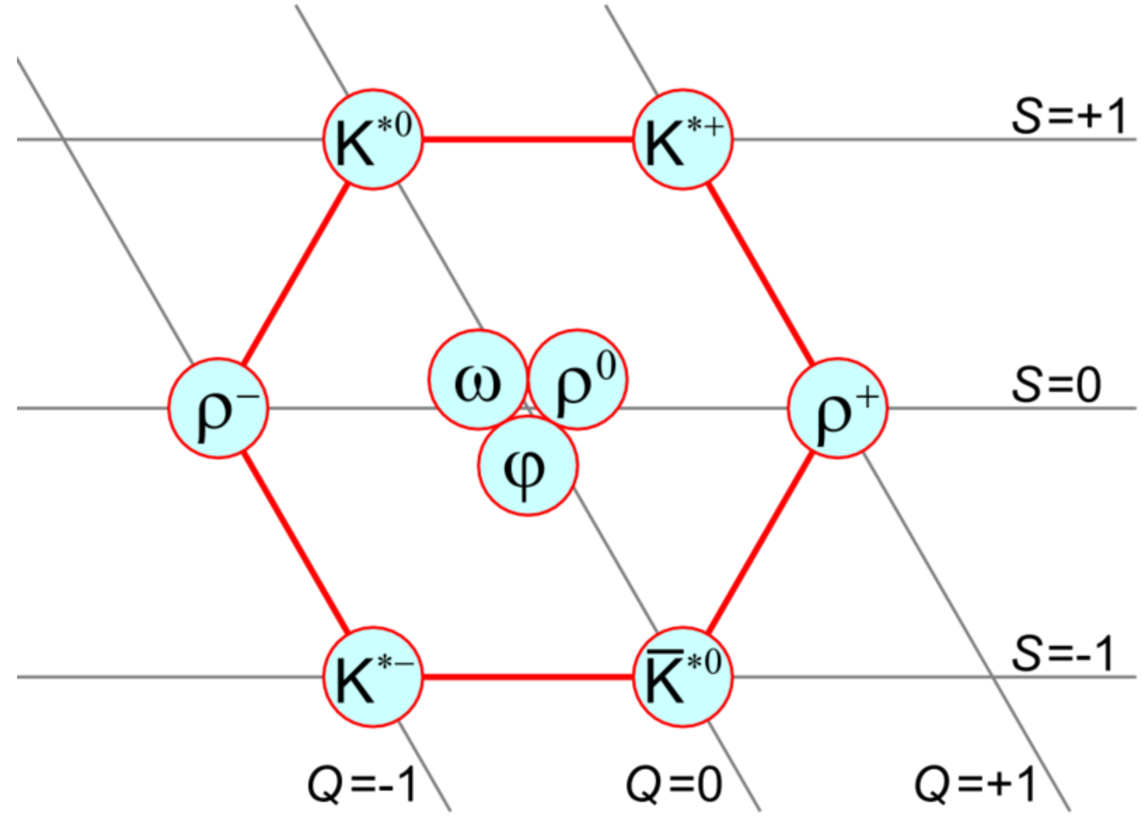
Mesons

Two lightest multiplets

Pseudoscalar: ↓↑ $J^P = 0^-$



Vector: ↑↑ $J^P = 1^-$



$$\rho = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$$

$$\omega = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$$

$$\phi = s\bar{s}$$

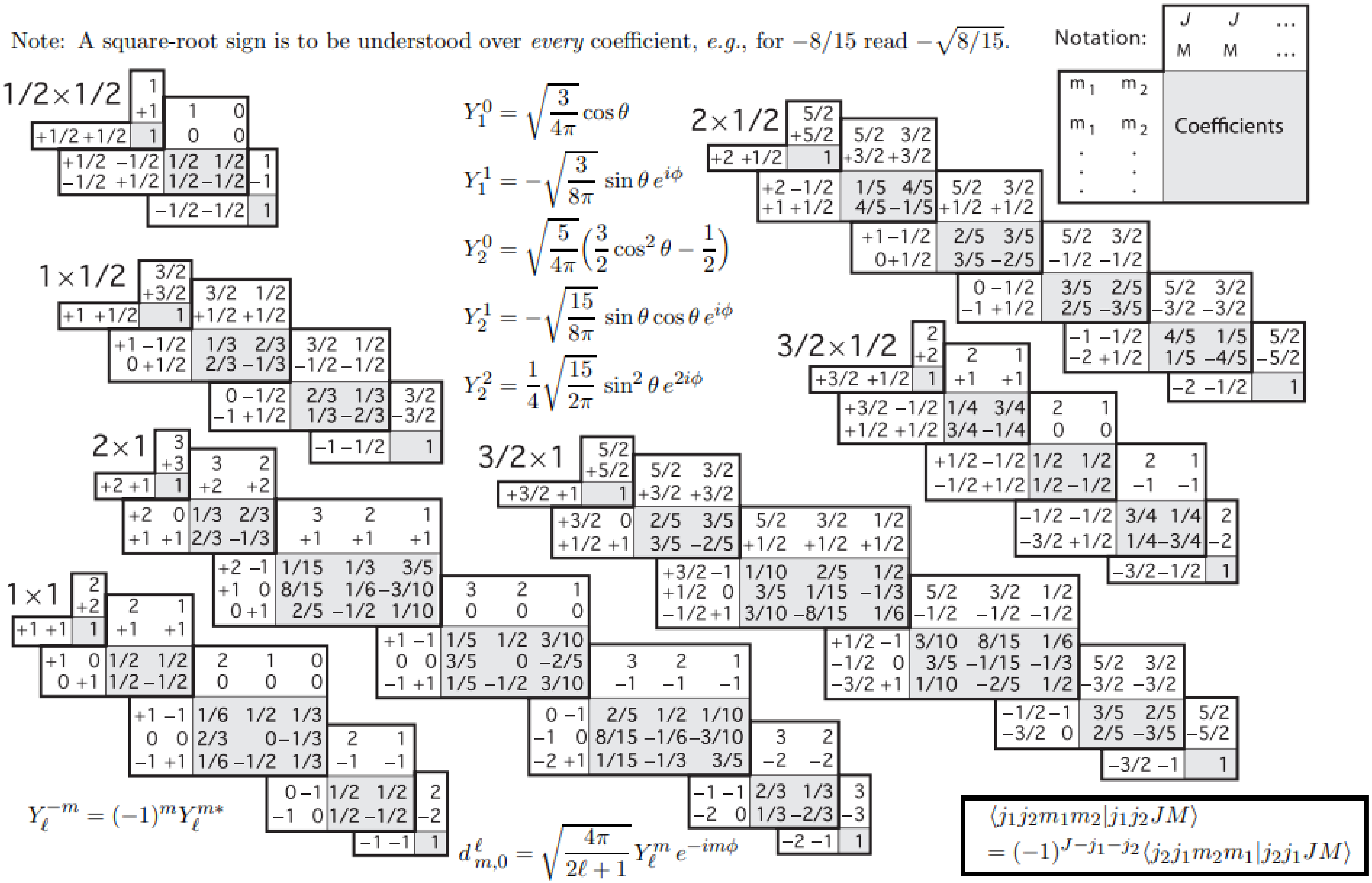
Pion multiplet

Particle	Quarks	S	Isospin I, I_3	J^{PC}	Mass [MeV]
K^+	$u\bar{s}$	+1	1/2, +1/2	0^{-+}	494
K^0	$d\bar{s}$	+1	1/2, -1/2	0^{-+}	498
π^+	$u\bar{d}$	0	1,+1	0^{-+}	140
π^0	$\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$	0	1,0	0^{-+}	135
π^-	$d\bar{u}$	0	1,-1	0^{-+}	140
η	$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$	0	0,0	0^{-+}	548
η'	$s\bar{s}$	0	0,0	0^{-+}	958
$\overline{K^0}$	$s\bar{d}$	-1	1/2, +1/2	0^{-+}	498
K^-	$s\bar{u}$	-1	1/2, -1/2	0^{-+}	494

Rho multiplet

Particle	Quarks	S	Isospin I, I_3	J^{PC}	Mass [MeV]
K^{*+}	$u\bar{s}$	+1	1/2, +1/2	1^{--}	892
K^{*0}	$d\bar{s}$	+1	1/2, -1/2	1^{--}	892
ρ^{+}	$u\bar{d}$	0	1,+1	1^{--}	770
ρ^{0}	$\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$	0	1,0	1^{--}	770
ρ^{-}	$d\bar{u}$	0	1,-1	1^{--}	770
ω	$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$	0	0,0	1^{--}	782
ϕ	$s\bar{s}$	0	0,0	1^{--}	1020
$\overline{K^{*0}}$	$s\bar{d}$	-1	1/2, +1/2	1^{--}	892
K^{*-}	$s\bar{u}$	-1	1/2, -1/2	1^{--}	892

Clebsch-Gordan coefficients



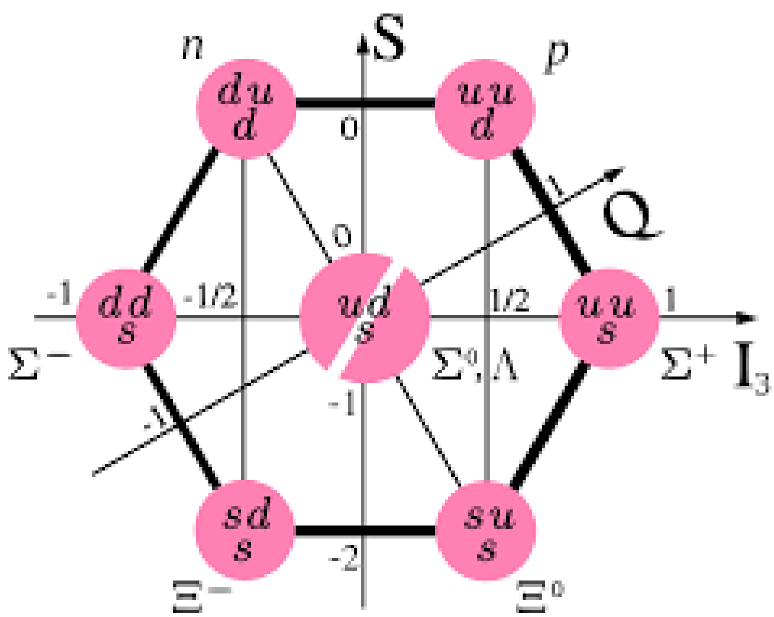
From PDG (particle data group)

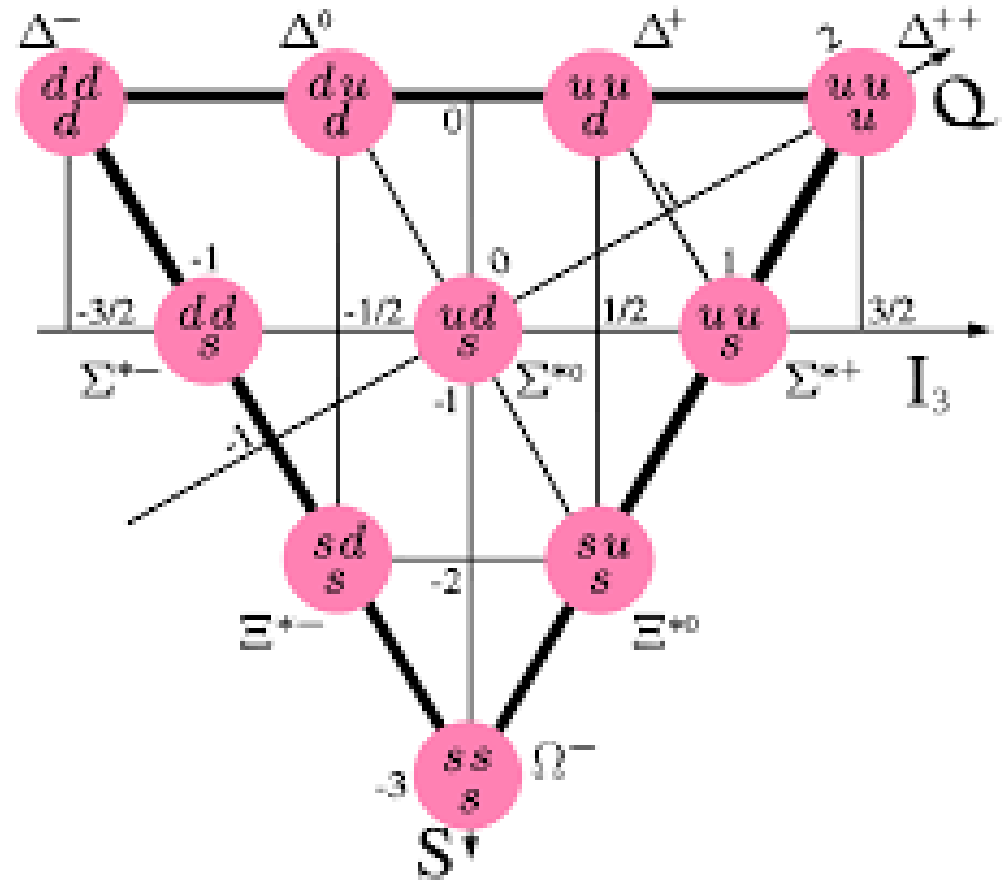
Baryons

Two lightest multiplets

Octet:↑↓↑ $J^P = \frac{1}{2}^+$

Decuplet: ↑↑↑ $J^P = \frac{3}{2}^+$





Nucleon octet

Particle	Quarks	S	Isospin I, I_3	J^{PC}	Mass [MeV]
p	uud	0	1/2, +1/2	$1/2^+$	938
n	udd	0	1/2, -1/2	$1/2^+$	939
Σ^+	uus	-1	1,+1	$1/2^+$	1189
Σ^0	uds	-1	1,0	$1/2^+$	1193
Σ^-	dds	-1	1,-1	$1/2^+$	1197
Λ	uds	-1	0,0	$1/2^+$	1116
Ξ^0	uss	-2	1/2, +1/2	$1/2^+$	1315
Ξ^-	dss	-2	1/2, -1/2	$1/2^+$	1322

Delta decuplet

Particle	Quarks	S	Isospin I, I_3	J^{PC}	Mass [MeV]
Δ^{++}	uuu	0	3/2, +3/2	$3/2^+$	1232
Δ^{+}	uud	0	3/2, +1/2	$3/2^+$	1232
Δ^{0}	udd	0	3/2, -1/2	$3/2^+$	1232
Δ^{-}	ddd	0	3/2, -3/2	$3/2^+$	1232
Σ^{+}	uus	-1	1,+1	$3/2^+$	1385
Σ^{0}	uds	-1	1,0	$3/2^+$	1385
Σ^{-}	dds	-1	1,-1	$3/2^+$	1385
Ξ^{0}	uss	-2	0,0	$3/2^+$	1530
Ξ^{-}	dss	-2	0,0	$3/2^+$	1530
Ω	sss	-3	1/2, +1/2	$3/2^+$	1672