

Outline

- Relativistic Kinematics
 - ▶ (4-momentum)² invariance, invariant mass
 - ▶ Hypothesis testing, production thresholds
 - ▶ Cross-sections, flux and luminosity, accelerators
 - ▶ Particle lifetime, decay length, width
- Classification of particles
 - ▶ Fermions and bosons
 - ▶ Leptons, hadrons, quarks
 - ▶ Mesons, baryons
- Quark Model
 - ▶ Meson and baryon multiplets
 - ▶ Isospin, strangeness, c, b, t quarks
- Particle Interactions
 - ▶ Virtual particles and range of forces
 - ▶ Strong and weak decays, conservation rules
 - ▶ Parity, charge conjugation, CP
 - ▶ Weak decays of quarks
 - ▶ Colour charge, QCD, gluons
 - ▶ Charmonium and upsilon systems
- Electroweak Interactions
 - ▶ Charged and neutral currents
 - ▶ W, Z, LEP experiments
 - ▶ Higgs and the future
- LHC Experiments
- Future - introduction to accelerator physics

Please see web page for specific references to textbooks and brief reviews from PDG.

u, d meson groupings

$q\bar{q}$	S=0	S=1
$u\bar{d}$	$\pi^+(140)$	$\rho^+(770)$
$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$	$\pi^0(135)$	$\rho^0(770)$
$\bar{u}d$	$\pi^-(140)$	$\rho^-(770)$

■ Meson triplet and singlet with u, d flavours

■ (xxx) are masses in MeV - conventional

$\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$	$\eta(548)$	$\omega(782)$
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Strangeness: light meson nonets

$q\bar{q}$	$^1S_0, J=0$	$^3S_0, J=1$
$u\bar{d}$	$\pi^+(140)$	$\rho^+(770)$
$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$	$\pi^0(135)$	$\rho^0(770)$
$\bar{u}d$	$\pi^-(140)$	$\rho^-(770)$
$u\bar{s}$	$K^+(494)$	$K^{*+}(892)$
$d\bar{s}$	$K^0(498)$	$K^{*0}(896)$
$\bar{u}s$	$K^-(494)$	$K^{*-}(892)$
$\bar{d}s$	$\bar{K}^0(498)$	$\bar{K}^{*0}(896)$
$\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$	$\eta(548)$	$\omega(782)$
$s\bar{s}$	$\eta'(958)$	$\phi(1020)$

- Extend meson combinations by introduction of s quark, gives "nonets"
- Note η, η' are actually mixed states from $u\bar{u}, d\bar{d}, s\bar{s}$
- ω and ϕ also slight admixtures
- (xxx) are masses in MeV - conventional

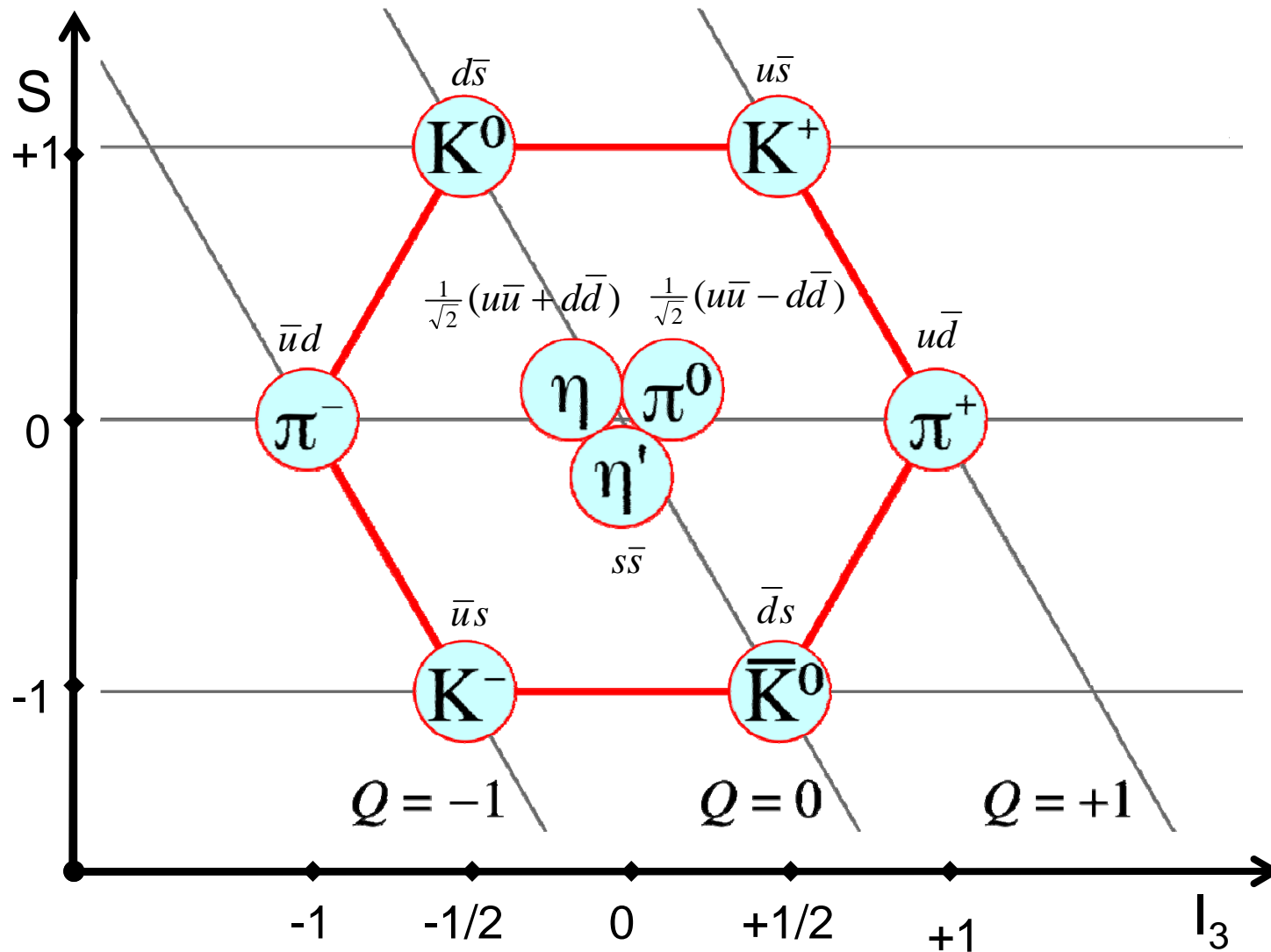
Quantum Numbers of Quarks

TABLE 1.1: Additive quantum numbers of the quarks.

Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
I_z – isospin z -component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	-1	0	0	0
C – charm	0	0	0	+1	0	0
B – bottomness	0	0	0	0	-1	0
T – topness	0	0	0	0	0	+1

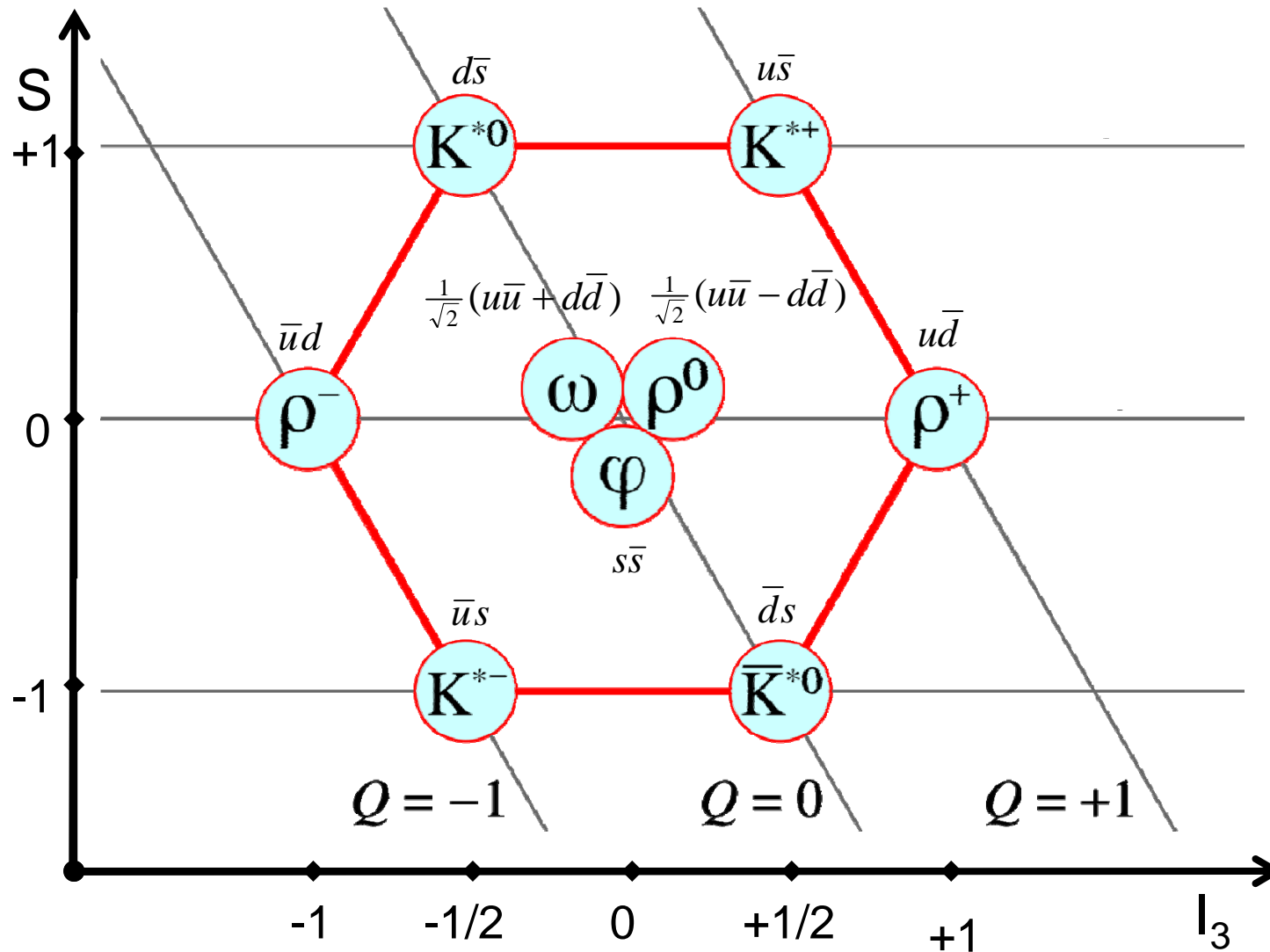
- These quantum numbers are additive
- Flavour is conserved by strong and e.m. interactions.
- E.m. charge is given by Gell-Mann-Nishijima formula $Q = I_3 + \frac{1}{2}(S+C+T+B)$
- Use B to denote baryon number ($1/3$ for quarks, $-1/3$ for anti-quarks)
- Flavour is not conserved by weak interactions mediated by W^+ , W^- (“charged current”).

1S_0 Meson Nonet



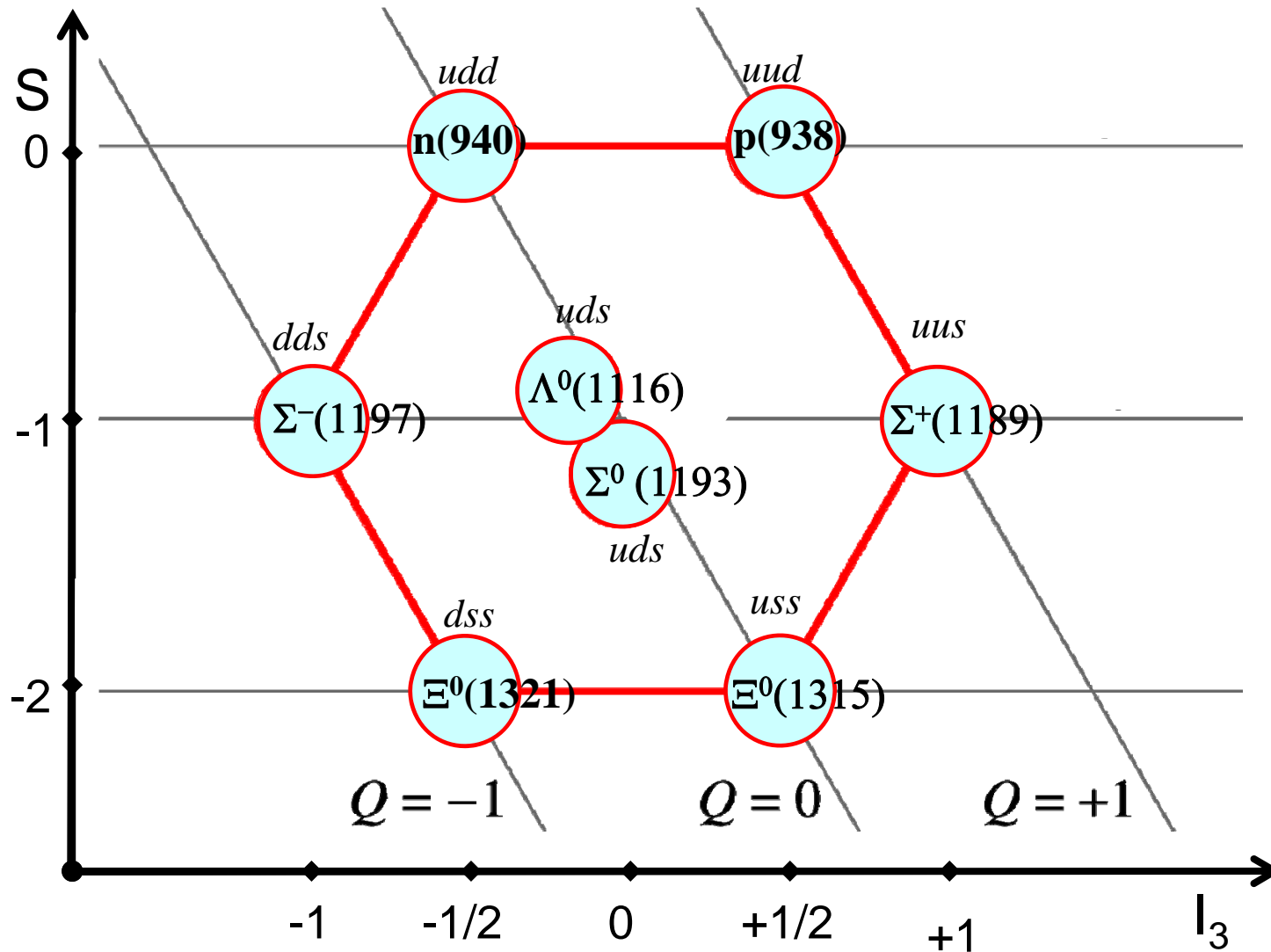
[adapted from http://en.wikipedia.org/wiki/File:Meson_nonet_-_spin_0.svg]

3S_1 Meson Nonet



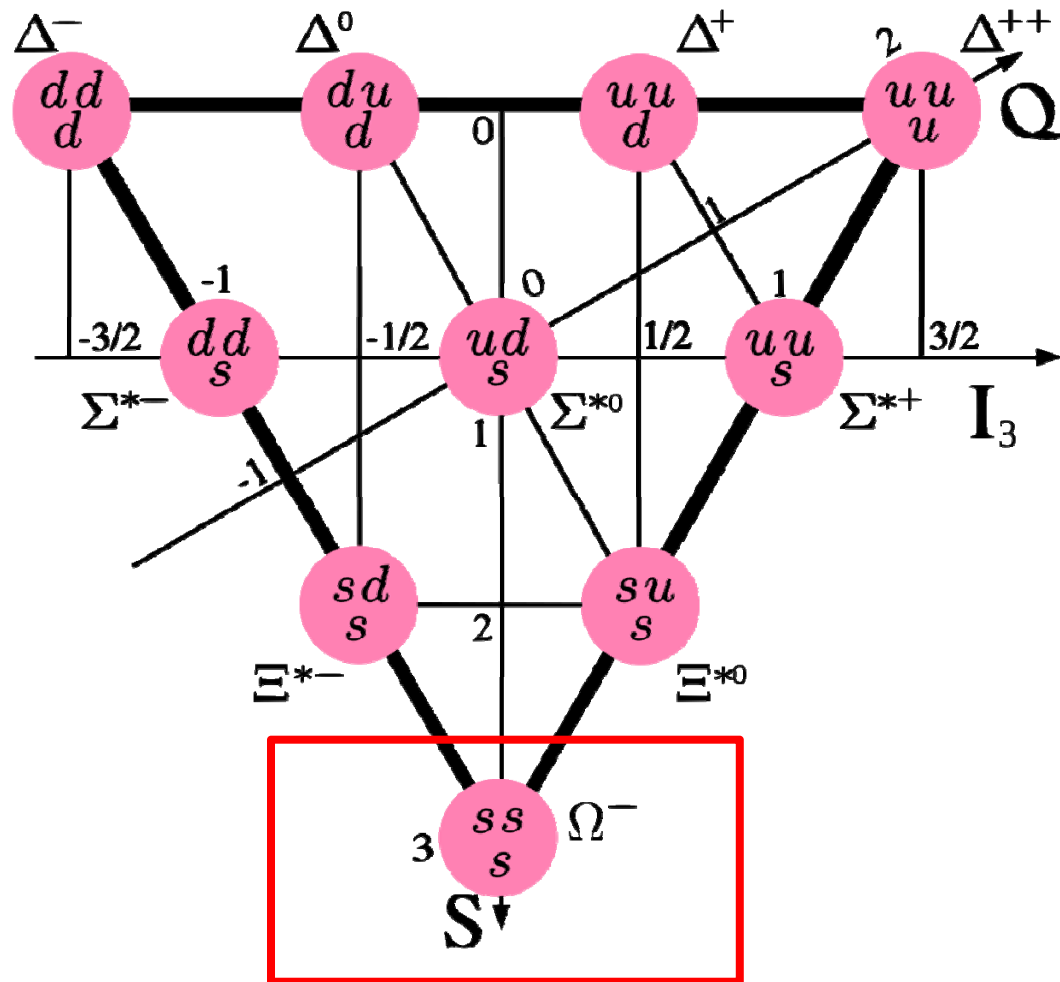
[adapted from http://en.wikipedia.org/wiki/File:Meson_nonet_-_spin_1.svg]

J=1/2 Baryon Octet



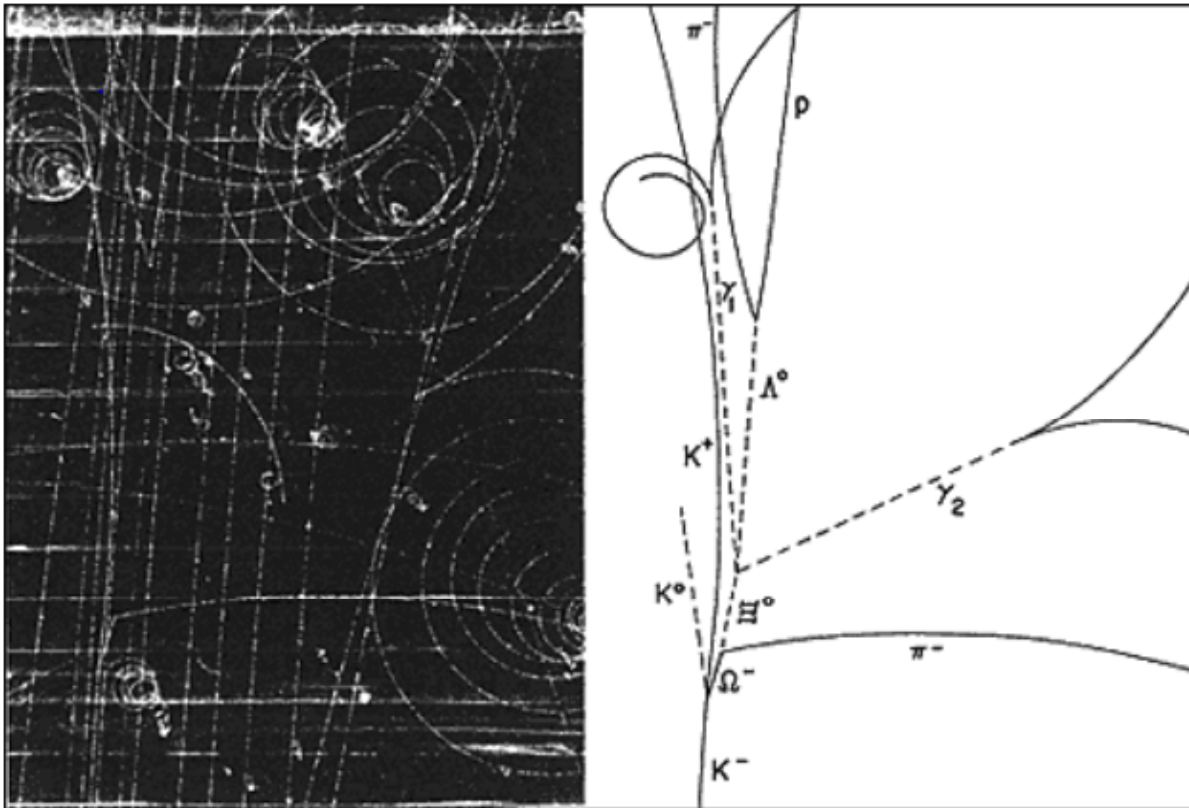
[adapted from http://en.wikipedia.org/wiki/File:Meson_nonet_-_spin_1.svg]

J=3/2 Baryon Decuplet



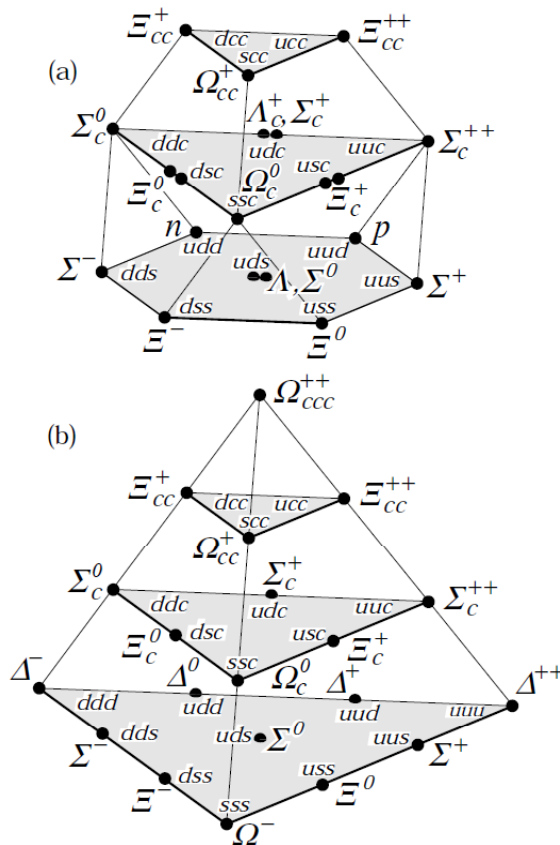
- Ω^- not observed initially but predicted from pattern in quark model.
- Existence of the $S=-3$ (sss) baryon at mass $\sim 1680 \text{ MeV}/c^2$
- Identified based on a single event in bubble chamber (1964)
 - ▶ 3 very characteristic weak decays
 - ▶ 1st successful prediction of quark model!

Discovery of Ω^- at BNL (1964)



- V. E. Barnes *et al.* (1964), "Observation of a Hyperon with Strangeness Number Three", Phys. Rev. Lett. 12, 204-206 (1964)

4 flavour baryon multiplets



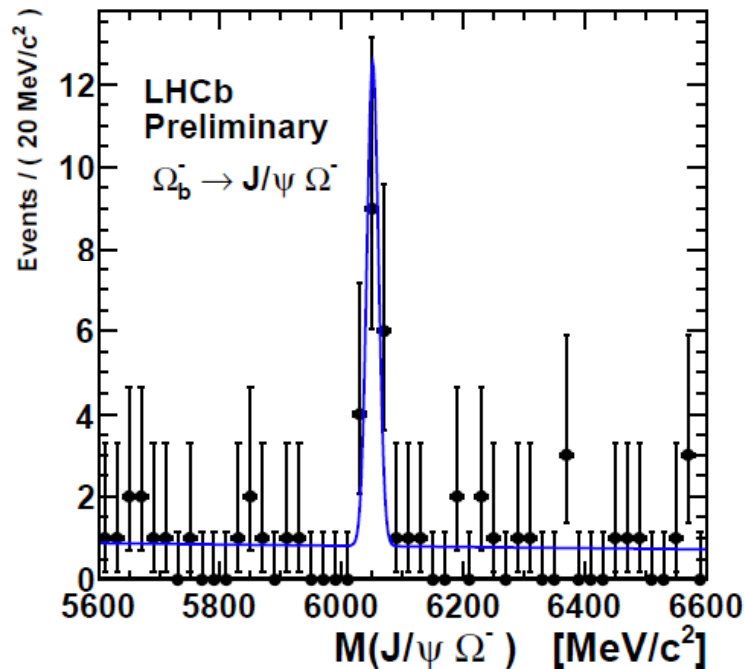
- Addition of c quark...
 - ▶ Extra dimension required to visualise
- Some c baryons discovered, so far none with $C=+2$
- Inclusion of b quark, very hard to visualise in this manner

Example of SU(4) baryon multiplets with four flavours

[<http://hepdata.cedar.ac.uk/lbl/2011/reviews/rpp2011-rev-quark-model.pdf>]

K. Nakamura *et al.*, JPG 37, 075021 (2010)

Recent progress on baryons...



LHCb-CONF-2011-060 ; CERN-LHCb-CONF-2011-060, "Measurement of the masses of the Ξ_b^- and Ω_b^- "

<https://cdsweb.cern.ch/record/1395530?ln=en>

Preliminary result, appears to help clarify discrepancies between CDF and D0.

Table 3: LHCb mass measurements, compared to the PDG averages [4] and the results of the CDF [2] and DØ [1] experiments. The quoted errors include statistical and systematic uncertainties. All values are in MeV/c^2 .

	$M(\Xi_b^-)$	$M(\Omega_b^-)$
DØ	5774 ± 19	6165 ± 16
CDF	5790.9 ± 2.7	6054.4 ± 6.9
PDG	5790.5 ± 2.7	6071 ± 40
LHCb	5796.5 ± 1.7	6050.3 ± 5.0

Mesons Stable Against Strong Decay

Particle (Anti-particle)	J	I ₃	S	C	B	Mass (MeV/c ²)	Mean Life (s)
π^+ (π^-)	0	+1(-1)	0	0	0	139.6	2.60×10^{-8}
π^0	0	0	0	0	0	135.0	8.4×10^{-17}
K^+ (K^-)	0	+(-)	+1(-1)	0	0	493.7	1.24×10^{-8}
K^0 (\bar{K}^0)	0	-(+)	+1(-1)	0	0	497.6	{ 9.0×10^{-11} 5.1×10^{-8} }
η^0	0	0	0	0	0	547.9	5.1×10^{-19}
D^+ (D^-)	0	+(-)	0	+1(-1)	0	1870	1.0×10^{-12}
D^0 (\bar{D}^0)	0	-(+)	0	+1(-1)	0	1865	4.1×10^{-13}
D_s^+ (D_s^-)	0	0	+1(-1)	+1(-1)	0	1968	5.0×10^{-13}
B^+ (B^-)	0	+(-)	0	0	+1(-1)	5279	1.6×10^{-12}
B^0 (\bar{B}^0)	0	-(+)	0	0	+1(-1)	5280	1.5×10^{-12}
B_s^0 (\bar{B}_s^0)	0	0	(+1)	0	+1(-1)	5366	1.5×10^{-12}
B_c^+ (B_c^-)	0	0	0	+1(-1)	+1(-1)	6276	4.6×10^{-13}

Baryons Stable Against Strong Decay

Particle	J	I ₃	S	C	B	Mass (MeV/c ²)	Mean Life (s)
p	1/2	1/2	0	0	0	938.3	> 2.1 x 10 ²⁹ years
n	1/2	-1/2	0	0	0	939.6	886
Λ	1/2	0	-1	0	0	1116	2.6 x 10 ⁻¹⁰
Σ ⁺	1/2	+1	-1	0	0	1189	8.0 x 10 ⁻¹¹
Σ ⁰	1/2	0	-1	0	0	1193	7.4 x 10 ⁻²⁰
Σ ⁻	1/2	-1	-1	0	0	1197	1.5 x 10 ⁻¹⁰
Ξ ⁰	1/2	+1/2	-2	0	0	1315	2.9 x 10 ⁻¹⁰
Ξ ⁻	1/2	+1/2	-2	0	0	1322	1.6 x 10 ⁻¹⁰
Ω ⁻	1/2	0	-3	0	0	1672	8.2 x 10 ⁻¹¹
Λ _c ⁺	1/2	0	0	1	0	2286	2.0 x 10 ⁻¹³
Ξ _c ⁺	1/2	+1/2	-1	1	0	2468	4.4 x 10 ⁻¹³
Ξ _c ⁰	1/2	-1/2	-1	1	0	2471	1.1 x 10 ⁻¹³
Ω _c ⁰	1/2	0	-2	1	0	2698	6.9 x 10 ⁻¹⁴
Λ _b ⁰	1/2	0	0	0	-1	5620	1.4 x 10 ⁻¹²