25. QUARKS AND THE STANDARD MODEL

The physics of electrons and quantum mechanics enables us to understand the periodic table and chemistry. By the 1960s, a combination of cosmic ray and accelerator physics had already revealed a profusion of "Hadrons" — today more than a hundred are known — this suggests that these particles are not fundamental.

The solution to this problem was first proposed by Ne'eman + Gell-Mann, who proposed that the Hadrons are bound states of particles of fractional charge that Gell Mann named "quarks", according to which

BARYON = qqq

ANTIBARYON = $\bar{q}\bar{q}\bar{q}$

MESON = $q\bar{q}$

This scheme requires particles of fractional charge. Initially, the "up" and "down" quarks – with charges $2/3$ & $-1/3$ respectively. To account for the "strange" particles requires a third "strange quark" s with charge $-\frac{1}{3}$.

THREE ORIGINAL QUARKS

SYMBOL	Q/e	Spin	Baryon #	Strangeness S	I_3	Y
u	2/3	1/2	1/3	0	$\frac{1}{2}$	1/3
d	-1/3	1/2	1/3	0	$-\frac{1}{2}$	1/3
s	-1/3	1/2	1/3	-1	0	-2/3

ANTIQUARKS

	Q/e	Spin	B.	S	I_3	Y
$\bar{u}$	$-2/3$	$\frac{1}{2}$	$-1/3$	0	$-\frac{1}{2}$	$-1/3$
$\bar{d}$	$1/3$	$\frac{1}{2}$	$-\frac{1}{3}$	0	$+1/2$	$-1/3$
$\bar{s}$	$1/3$	$\frac{1}{2}$	$-\frac{1}{3}$	+1	0	$2/3$

In describing the various particle multiplets that arise from combining quarks, there are two useful quantities,

"HYPERCHARGE" $\quad Y = B + S$

"ISOSPIN" $\quad I_3 \quad \begin{cases} I_3(u) = +\frac{1}{2} \\ I_3(d) = -\frac{1}{2} \end{cases}$

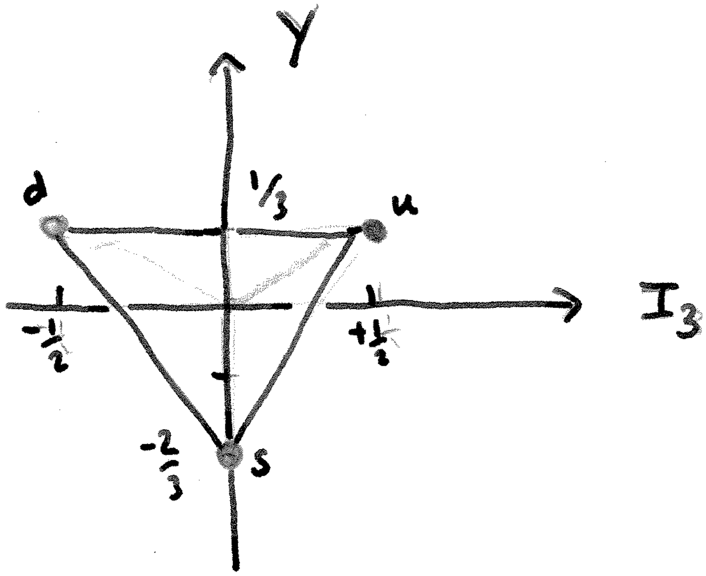
which delineates between "u" & "d" quarks. — determines charge in multiplet

The charge is related to the isospin & hypercharge according to

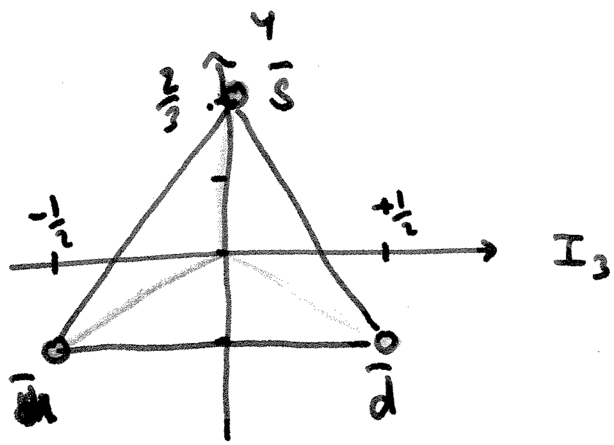
$$Q = I_3 + Y/2$$

e.g p, n $\quad I_3 = \pm\frac{1}{2} \quad Y =$ [redacted] $\quad Q = I_3 + \frac{1}{2}$.

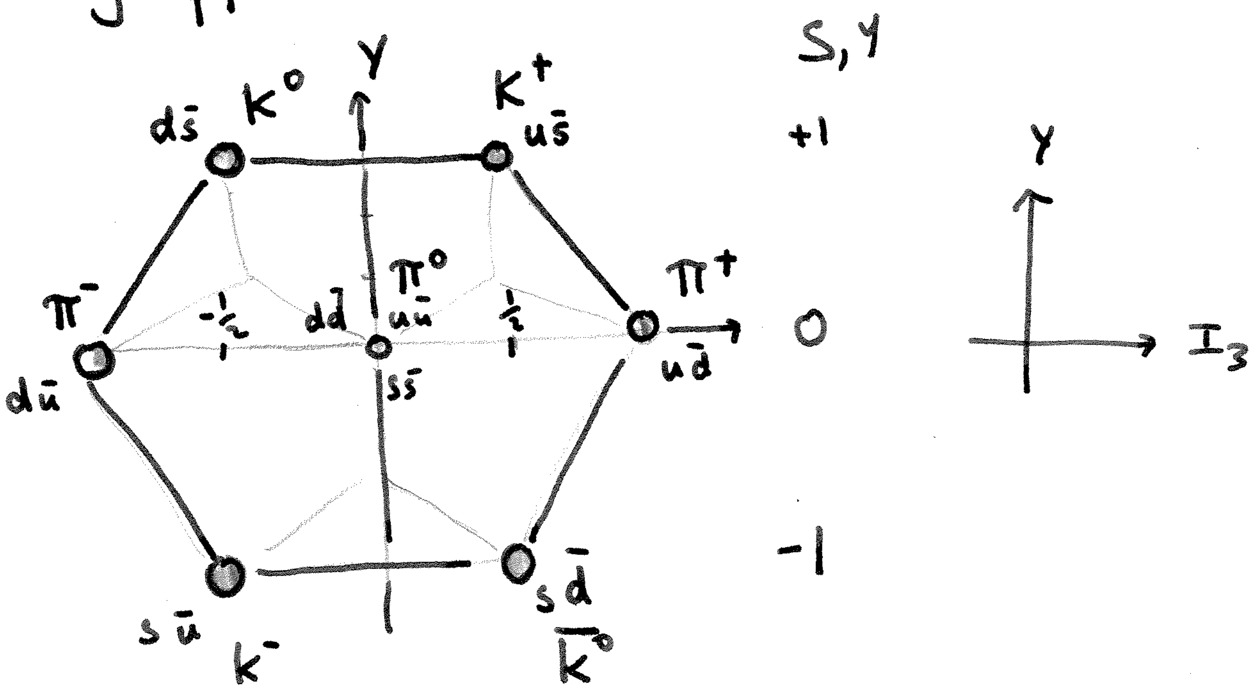
Quarks



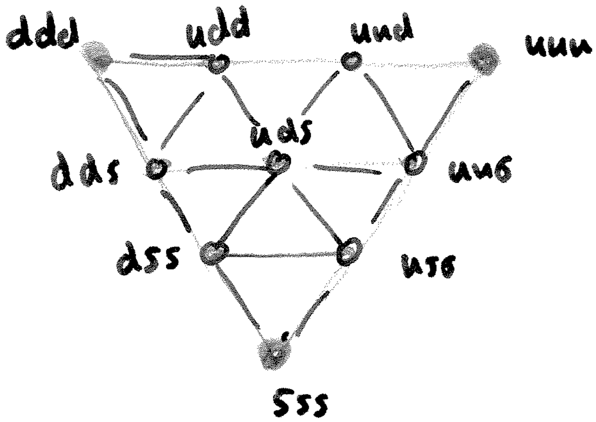
Antiquarks $\bar{q}$



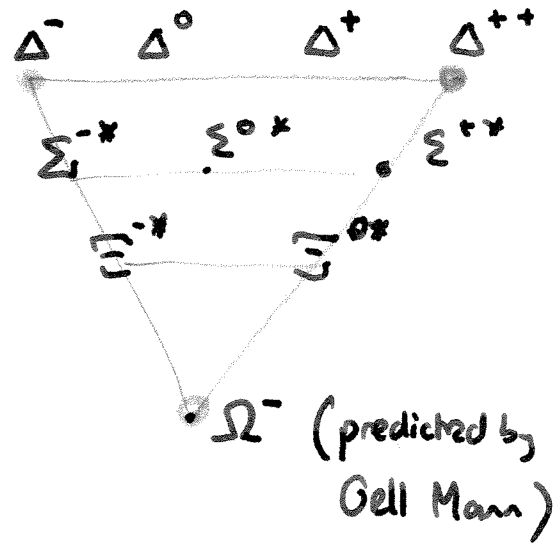
By combining $q\bar{q}$ we make the mesons



Combining qqq we can make a decuplet and an octet

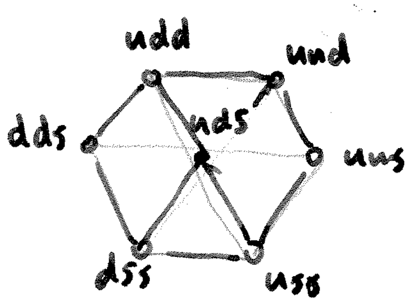


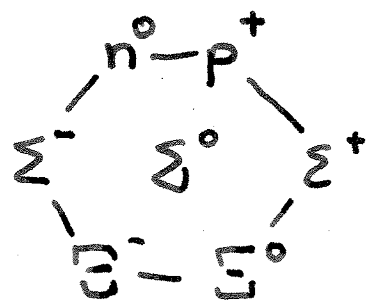
S	Y
0	1
-1	0
-2	-1
-3	-2



These are the $S = 3/2$ Baryons

One can also form $S = 1/2$ Baryons





S	Y
0	1
-1	0
-2	-1

e.g $\pi^0 + n \longrightarrow K^+ + \Sigma^-$

	π^0	n	K^+	Σ^-
	$u\bar{u}$	udd	$u\bar{s}$	
S	0	0	1	-1

Q. What is the quark composition of Σ^- ?

A. When the π^0 & n combine, the effective quark composition of the intermediate state is

$u\bar{u}\,udd \equiv udd$ because the quantum numbers of $u\bar{u}$ cancel.

$udd \longrightarrow u\bar{s} + sdd$ because the $\bar{s}$ formed in the K^+ must be cancelled by the s in the Σ^-

$\Sigma^- \equiv sdd$

check $Q = -\frac{1}{3} -\frac{1}{3} -\frac{1}{3}$ ✓

$B = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1$ ✓

e.g. Σ^+ & Λ^0 are baryons with strangeness $S=-1$. Given that they only contain u d s or $\bar{u}, \bar{d}, \bar{s}$, find their quark content.

A. Since $S=-1 \Rightarrow$ one s quark. $Q_s = -\frac{1}{3}$.

Λ^0 must contain an up & a down $Q_u + Q_d = +1/3$

$Q_u + Q_d + Q_s = \frac{1}{3} - \frac{1}{3} = 0$ $\quad \Lambda^0 \equiv uds$

Σ^+ must contain two ups $2Q_u = 4/3$

$2Q_u + Q_s = +1$. $\quad \Sigma^+ \equiv uus$.

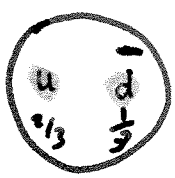
Quarks carry "color" charge. (RED, GREEN, BLUE).

Hadrons are "color neutral".

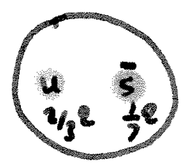
n

p

BARYON



π^+



K^+

MESON.

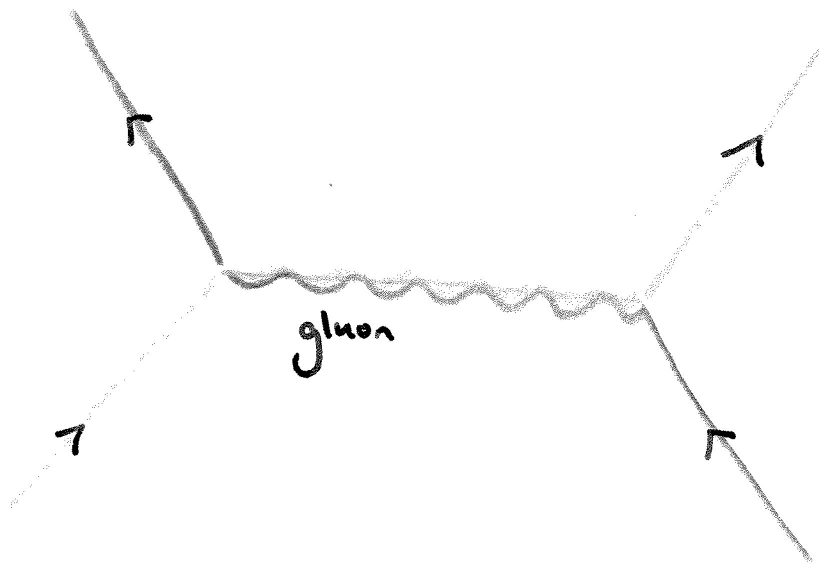
blue - $\overline{\text{blue}}$

The color force is mediated by <u>gluons</u>.

This is the physics of Quantum Chromodynamics (QCD).

Color is needed to satisfy the Pauli Exclusion principle.

uuu = red, blue & green ups



QCD

There are three other types of quark — "charm" (c), "top" and "bottom" (b).

	Q/e	Strangeness	C	B = bottomness	T = topness
u	2/3	0			
d	-1/3	0			
s	-1/3	-1	0	0	0
c	2/3	0	1	0	0
b	-1/3	0	0	1	0
t	2/3	0	0	0	1

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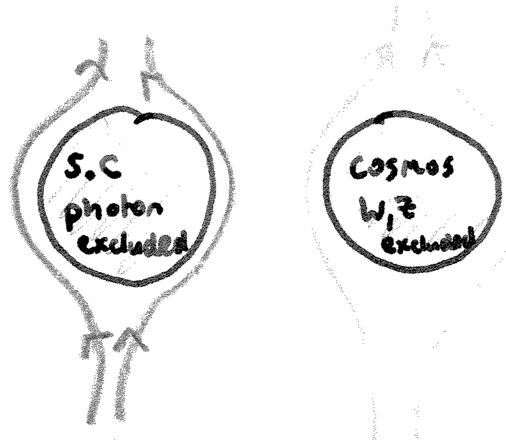
44.5 ELECTROWEAK

1960s : Glashow, Salam + Weinberg

γ
Z
$W^{\pm}$

Family of four S=1 bosons.



Analogy with superconductor

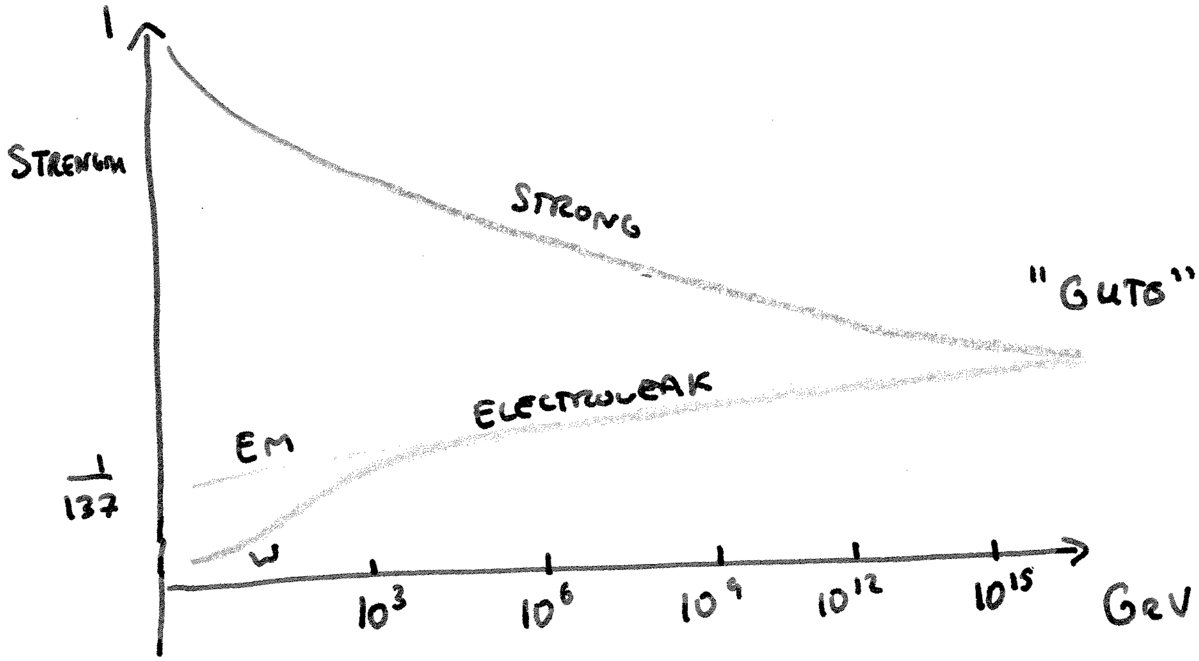
SUPERCONDUCTOR	COSMOS
"Condensate" of electron pairs	Condensate of "Higgs" bosons (Like a B.E.C.)
Magnetic force expelled	Weak force field "expelled"
Photon becomes Massive	Z & W particles become massive

$E > 100\,GeV$ $\gamma, Z, W^{\pm}$ become indistinguishable

$d \lesssim 10^{-17} m$

Grand Unified Theories

Believed that at very high energies the strong & the electroweak forces unify into a single force.



- Predict proton will decay — never seen.
- Can not account for "generations" of leptons & quarks.
- Recent discovery of neutrino oscillations shows that leptons from different generations can interconvert.