Chapter 18

As particle accelerators increased their energy range, more elementary particles were discovered $\Rightarrow$ proposal emerged that many of these are composite particles. (parton model).

Evidence of parton model emerged from neutrino-nuclear and electron-nuclear scatterings.

Consider ν + nuclear : $\sigma \propto E$

$\uparrow$ charact. for pointlike interaction. Why?

$\bullet \longrightarrow \nu$ $\quad$ $\cdot$ parton

$\uparrow$ pointlike $\quad$ $\uparrow$ pointlike

$\hookrightarrow$ no internal degrees of freedom. $\Rightarrow$ elastic scattering

$\downarrow$

phase space depends only on momentum $\Rightarrow$ equals momentum space.

\# of states between p and $p+dp$ =

$$= (4\pi p^2)\,dp$$

$\Rightarrow \quad \sigma \propto p^2 = \dfrac{mE}{2} \quad \Rightarrow$ observations are consistent with ν scatterings of

a point-like parton and
not of the entire nucleus.

Similar conclusions were obtained from electron-proton scatterings. Various features are observed in these interactions:

1). forward angles: elastic + excitation of nuclear levels.
↳ small Δp

2). larger angles: increase in contribution of e^--nucleon scatterings. Due to the spread in p, Δp, the interactions happen at different energies ⇒ not a sharp peak but a broad bump.

3). backward angles: large Δp. Two main features: ⊛ production of nucleon-like states.
⊛ elastic scattering of charged partons.

These experiments provide compelling evidence of the existence of partons. Information about partons was obtained by looking at "grouping" of the particles (<u>note</u>: remember the periodic table).

Basic group: SU(2) based on conservation of j and isospin.

↳ no change in strong interactions for A with Z ps and A with Z' ps.

Examples: 2 group $p+n$
$T=1/2$

$\bar{2}$ group $\bar{p}+\bar{n}$
$T=1/2$

$2 \otimes \bar{2}$ can make a singlet or triplet $\Rightarrow$ $2 \otimes \bar{2} = 1 \oplus 3$

$T=0$ η^0 $T=1$ π^+, π^0, π^-

$\Rightarrow$ 2 partons can combine to make 4 particles.

SU(3) was introduced to account for strangeness.

$\hookrightarrow$ 3 basic quantum numbers.
instead of S, introduce hyper charge
$Y = S + B$

3 and $\bar{3}$ are the simplest groups

mesons: $3 \otimes \bar{3} = 1 \oplus 8$ You can group mesons according to parity and spin

Singlet
Triplet

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

In principle, since all members of a multiplet have the same spin and parity they should have the same mass.

but: masses are different $\Rightarrow$ broken symmetry.

The initial impact of SU(3) was to bring order in the chaos. But the 3 group may be more than a "math" trick.

SU(3): 3 fundamental particles, baryon number = 1/3

Information about these fundamental particles:

1). Ω^- is part of decuplet and has $S=-3$
$\hookrightarrow$ also $T = T_z = 0$

$\Rightarrow$ Ω^- must contain 3 s-quarks
$\downarrow$
$S = -1$
$T_z = 0$

2). Δ^{++} has $S=0$, $T_z = 3/2$
$\hookrightarrow$ must contain non-strange quarks. These are the up quarks with $T_z = 1/2$

3). Δ^{-} has $S=0$, $T_z = -3/2$
$\hookrightarrow$ non-strange quarks. These are down quarks with $T_z = -1/2$

All other particles are combinations of these quarks

Charge : $Q = T_z + \frac{1}{2}(B + S)$

$\downarrow$

$1/3$ for quarks

$\Rightarrow$ up: $Q = +2/3$

down: $Q = -1/3$

strange: $Q = -1/3$

$\Omega^- = sss$: $Q = -1/3 - 1/3 - 1/3 = -1$

$\Delta^{++} = uuu$: $Q = 2/3 + 2/3 + 2/3 = +2$

$\Delta^- = ddd$: $Q = -1/3 - 1/3 - 1/3 = -1$

$p = uud$: $Q = +2/3 + 2/3 - 1/3 = 1$

$n = udd$: $Q = +2/3 - 1/3 - 1/3 = 0$

since $m_p \simeq m_n \Rightarrow m_u \simeq m_d = 0.3$ GeV

Σ : contains 1 strange quark + 2 u/d

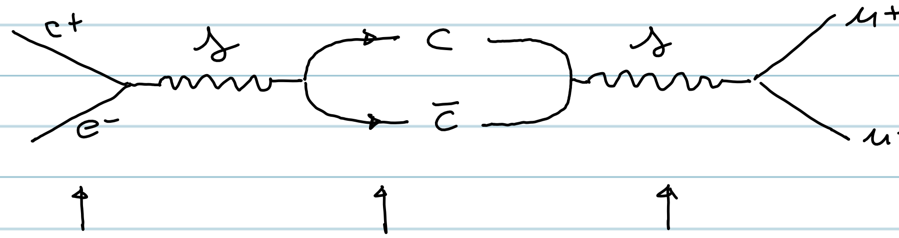
Δ : contains 3 u/d quarks

mass difference = 150 MeV = $m_s - m_{u/d} \Rightarrow$

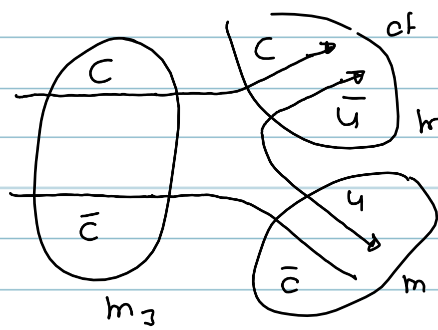
$m_s \simeq 0.45$ GeV.

More experiments required more quarks:

1). meson production (quark - anti-quark systems) in collider experiments.

2). 

no charm — no charm — em decay ⇒ longer time scale than strong decay ⇒ narrow energy peak in mass spectrum of $\mu^+ - \mu^-$.

3). 

Require that "charm" is conserved in strong interaction.

at threshold : $m_3 < m_1 + m_2 \Rightarrow$ strong decay not possible.

4). $c\bar{c}$ discovered at BNL : J meson, SLAC : ψ meson $\Big\} \Rightarrow$ now known as J/ψ meson.

5). excited states of J/ψ are known. $(J/\psi)''$ is massive enough to decay into $D + \bar{D}$ where $D^0 \cdot c\bar{u}$

6). additional quarks + quantum numbers:

c : charm
b : bottom
t : top

New charge rule:

$$Q = T_z + \frac{1}{2}(B + S + C + \mathcal{B} + T)$$

- t quark: $T = 1$, $q = 2/3$
- b quark: $\mathcal{B} = -1$, $q = -1/3$
- c quark: $C = +1$, $q = 2/3$
- s quark: $S = -1$, $q = -1/3$
- u, d quarks: $q = +2/3$ and $-1/3$

all have $B = 1/3$.

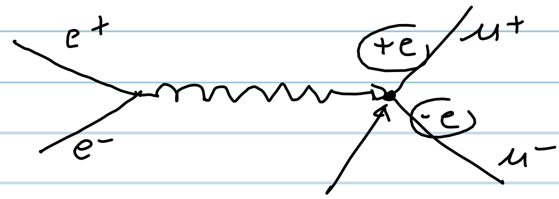
But that is not all: there must be at least one more quantum number. Why?

1). Consider $\Delta^{++} = uuu$
2). spin $3/2$ $\Rightarrow$ spins of u's must be parallel.
3). even parity $\Rightarrow$ in g.s. all quarks must have 0 angular momentum (orbital).
4). all in same state? Impossible $\Rightarrow$ new quantum number must "distinguish" them $\Rightarrow$ introduce color:

$$\left.\begin{array}{l}\text{red}\\ \text{green}\\ \text{blue}\end{array}\right\} \Rightarrow \Delta^{++} = u_r u_g u_b.$$

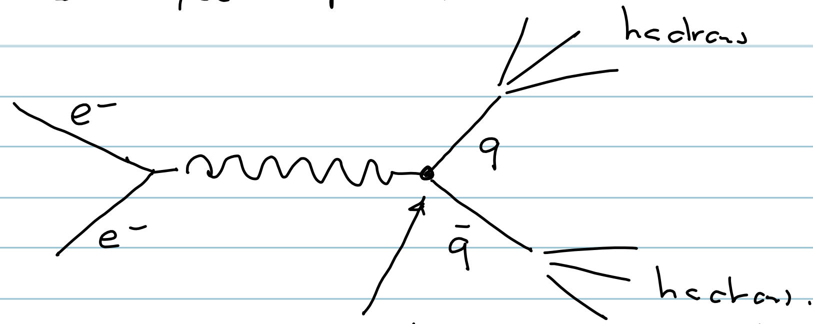
white – colorless

5). mesons are also colorless $\Rightarrow$ green + anti-green etc.
6). How do we verify this? Use $e^+ + e^-$ reactions to look at $e^+ + e^- \to$ hadrons and $e^+ + e^- \to \mu^+ + \mu^-$



em interaction : $\sigma \propto \dfrac{e^2}{4\pi\varepsilon_0 \hbar c}$

Hadron production requires the creation of quark - anti-quark pair :



em interaction: $\sigma \propto \dfrac{q^2}{4\pi\varepsilon_0 \hbar c}$

Contributions:

	Q^2	+ color	Σ
u_b, u_g, u_r:	$(2/3)^2 = (4/9)$	$4/3$	$4/3$
d	$(1/3)^2 = 1/9$	$1/3$	$5/3$
s	$(1/3)^2 = 1/9$	$1/3$	$6/3$
c	$(2/3)^2 = 4/9$	$4/3$	$10/3$
b	$(-1/3)^2 = 1/9$	$1/3$	$11/3$

$\Rightarrow$ if $E_{cm} < 2m_t$ but $E_{cm} > 2m_b$

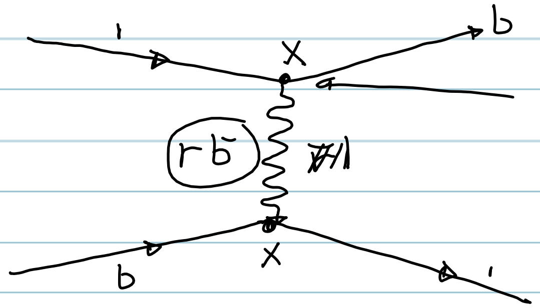
$$\Rightarrow \quad \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \frac{(11/3)\, e^2/(4\pi\varepsilon_0\hbar c)}{e^2/(4\pi\varepsilon_0\hbar c)} = \frac{11}{3}$$

without color : ratio $= \dfrac{11}{9}$

experiments show ratio $= 11/3 \Rightarrow$ <u>color</u>.

The colored quarks interact via the exchange of gluons : this is the "true" strong interactions.

But gluons have color :



color charge.

probability depends on X^2 + color of gluon.

<u>Note</u>: very different from em interaction where γ's do not carry charge.

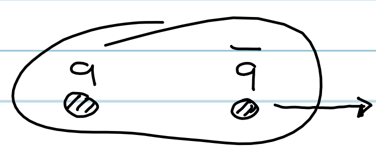
Fits of energy levels in quark-anti-quark systems show that

$$V_c = \underbrace{-\frac{k_1}{r}}_{} + k_2 r$$

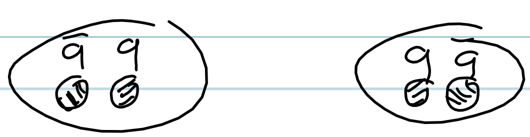
↑ charm

$\hookrightarrow$ term responsible for quark confinement.

Coulomb-like term due to exchange of massless gluons



pull $\Rightarrow$ V ↑ $\Rightarrow$ at one point you can create $q\bar{q}$ pair



$\boxed{\text{no free quarks}}$