The Standard Model

Interactions

- 4 types of interaction ("force") known in Nature

	Relative Strength
Gravitational	10^{-39}
Weak	10^{-7}
Electromagnetic	10^{-2}
Strong	1

- All interactions are the result of the exchange of virtual field quanta ("Gauge Bosons" – they have to be bosons to conserve angular momentum)

Field Quanta

	Field Quantum
Gravitational	graviton
Weak	$W^{\pm}$, Z^0
Electromagnetic	photon
Strong	gluon

All are spin-1 except the graviton which is spin-2

There are 8 gluons e.g. red – anti-blue

Matter

- The fundamental particles comprising "ordinary matter" i.e. atoms, are

$$e^-$$
$$u-quark$$
$$d-quark$$

$$\begin{pmatrix} p = uud \\ n = udd \end{pmatrix}$$

- The FIRST GENERATION comprises

$$\left\{ e^-, \nu_e\ ,\ u,\ d \right\}$$

- The SECOND GENERATION comprises

$$\left\{ \mu^-, \nu_\mu\ ,\ s,\ c \right\}$$

- The THIRD generation comprises

$$\left\{ \tau^-, \nu_\tau\ ,\ b,\ t, \right\}$$

Generations

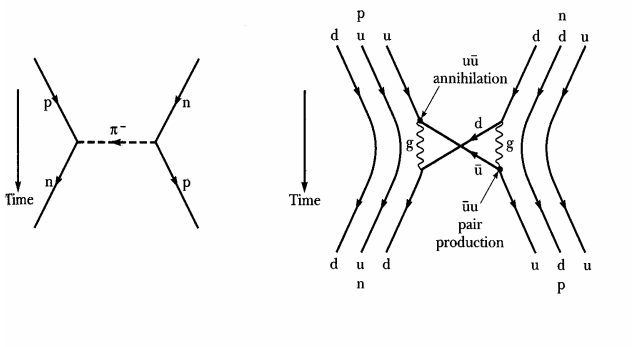
- The generations are 'identical' except for the masses of the particles (tabulated in MeV/c^2)

up	down	strange	charm	bottom	top
336	338	540	1,500	5,000	174,000

electron	muon	tau
0.511	105.7	1,777

(Colour) Force between nucleons (Yukawa)

- Yukawa explained the force between nucleons in terms of the exchange of virtual pions
- The same process can be explained in QCD

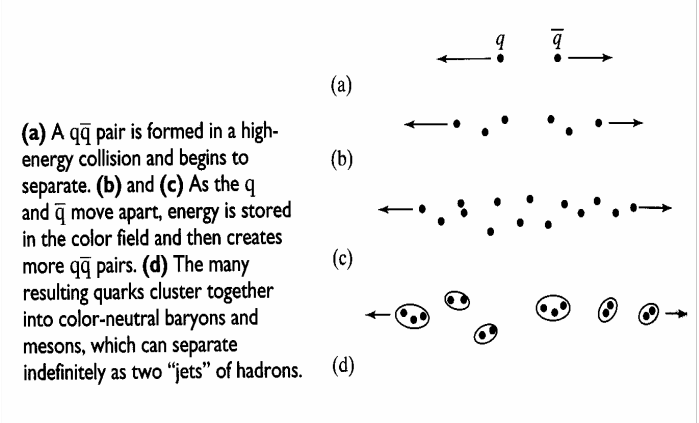


- Each quark in the proton and neutron constantly emits and absorbs virtual gluons and thereby creates and annihilates virtual $q\bar{q}$ pairs (i.e.. Mesons)

Serway 15.13

QCD

- According to QCD, quarks and gluons carry 'colour' and experience a 'colour force'
- No isolated quarks or gluons have ever been observed (i.e. you cannot directly observe colour)

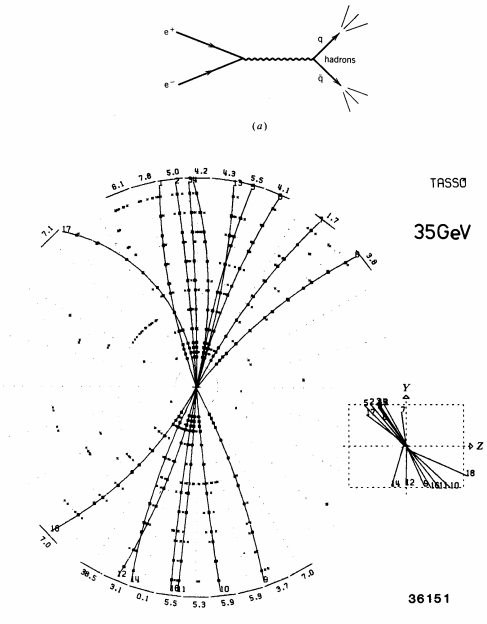


(a) A $q\bar{q}$ pair is formed in a high-energy collision and begins to separate. **(b)** and **(c)** As the q and $\bar{q}$ move apart, energy is stored in the color field and then creates more $q\bar{q}$ pairs. **(d)** The many resulting quarks cluster together into color-neutral baryons and mesons, which can separate indefinitely as two "jets" of hadrons.

Taylor 18.15

Hadron jets

- Electron-positron annihilation experiments show the hadron jets which result from the quark-anti-quark pairs (DESY – Germany)



Krane 18.17

Asymptotic Freedom Confinement

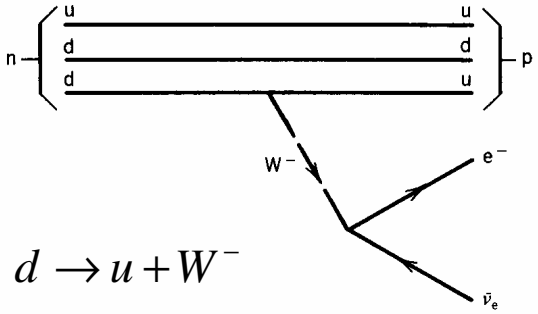
- The force ('coupling') between quarks gets stronger with separation
- Inside a hadron, the quarks behave as more or less free particles
- Gross, Wilczek and Politzer – Nobel 2004

The Weak Interaction

- The Weak interaction is mediated by three bosons W^+, W^-, Z^0
- Rubbia and van der Meer – Nobel 1984
- Short-range, the bosons are massive
- The Weak interaction governs the stability of particles
- It is responsible for the decay of the *c, s, b* and *t* quarks into the more stable *u* and *d* quarks
- It is also responsible for the decay of the heavier leptons (μ and τ) into the stable electrons
- Glashow, Salam & Weinberg – unified the Weak and EM interactions (Nobel 1979)

The Weak Interaction

- e.g. $n \rightarrow p + e^- + \bar{\nu}_e$



$d \rightarrow u + W^-$

$-\frac{1}{3} \rightarrow +\frac{2}{3} - 1$ ← Charge

NB: the leptons are NOT connected DIRECTLY to the quarks

Krane 18.26

The Standard Model Problems

- Gravity ? Doesn't have the same 'structure' as the other 3 forces
- The values of the Quark and Lepton masses cannot be explained
- Why are there 3 generations of particles ? (everyday matter comprises particles only from generation-1).
- A fraction (1/4) of the matter in the Universe is cold, dark matter which are not SM particles.
- Particles acquire mass through interactions with the Higgs field (Higgs boson). What type of interaction is this ?

The Standard Model Problems

- Dark Energy ? The expansion of the Universe is accelerating due to Dark Energy. What is it ?
- 'Inflation' – the Universe underwent a rapid expansion in the first fraction of a second after the Big Bang. Cannot be SM physics !
- If the Big Bang were simple a burst of energy the Universe should have evolved with equal parts of matter and antimatter – annihilation – Universe should be energy alone
- {Supersymmetry ? Strings ? Branes ? }

- [Gordon Kane's article in Scientific American Vol 15 (3), 2005
- Also, Chris Quigg's article, April 1985]