Lecture 4

	e	ν_e	μ	ν_μ	τ	ν_τ
$e\#$	1	1	0	0	0	0
$\mu\#$	0	0	1	1	0	0
$\tau\#$	0	0	0	0	1	1

with negative values for the antiparticles.

Recent discoveries of neutrino oscillations show that this is not exactly conserved, but they are a good approximation in most circumstances. Unless the neutrinos are propagating a long distance, oscillations are unlikely to happen. However, the total lepton number:

$$L = N_e + N_\mu + N_\tau$$

is exactly conserved in all processes. For all leptons $L = +1$ and for all antileptons $L = -1$. Quarks have zero lepton number.

Fundamental Forces

Spin-Fermions and Bosons

Many elementary particles carry another quantity called spin. The laws of quantum mechanics require that spin is quantised in $\frac{1}{2}\hbar$ where $\hbar = \frac{h}{2\pi}$. Spin has the dimensions of angular momentum, and can be thought of as intrinsic angular momentum. Think of the particle as spinning on its axis like a small rotating ball. It cannot be stopped; if it has spin it will always have it. This is even though they are point-like particles.

The behaviour of elementary particles depends on whether their spin is integer (0, 1, etc., in units of $\hbar$) or half-integer ($\frac{1}{2}$, $\frac{3}{2}$, ... etc.). Hence we discriminate between these two types of particles by the terms:

fermions: $\frac{1}{2}$-integer spin
bosons: integer spin

Quarks and leptons all have spin $= \frac{1}{2}\hbar$. Gluons and photons have spin $= 1\hbar$. The Higg's Boson has spin $= 0\hbar$. The graviton has spin $= 2\hbar$ (a particle of the gravitational field).

Non-elementary particles can also have spin. Protons and neutrons have spin $= \frac{1}{2}$ as do many other baryons. Some baryons have spin $\frac{3}{2}$.

Angular momentum is a vector quantity. Spin is quantised in a particular direction (e.g. in the z-direction) and can only add along this direction. For a $q\bar{q}$ pair (a meson) - can have either:

$$\uparrow\left(\frac{1}{2}\right) + \downarrow\left(-\frac{1}{2}\right) = 0 \text{ (spin 0 meson)}$$
$$\uparrow\left(\frac{1}{2}\right) + \uparrow\left(\frac{1}{2}\right) = 1 \text{ (spin 1 meson)}$$

For baryons, we can have:

$$\uparrow\left(\frac{1}{2}\right) + \uparrow\left(\frac{1}{2}\right) + \downarrow\left(-\frac{1}{2}\right) = +\frac{1}{2} \text{ (spin } \frac{1}{2} \text{ baryon)}$$
$$\uparrow\left(\frac{1}{2}\right) + \uparrow\left(\frac{1}{2}\right) + \uparrow\left(\frac{1}{2}\right) = +\frac{3}{2} \text{ (spin } \frac{3}{2} \text{ baryon)}$$

Going back to elementary particles, for which spin-$\frac{1}{2}$ are matter constituents. Force-carrying particles are always bosons.

Particles and Force Mediators

Classically, a force is proportional to a rate of change of momentum.

$$\mathbf{F} = m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} \\ = \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t}$$

So that a force acting for a time produces a change of momentum, Δp.

In the quantum world, continuous processes do not occur and forces between particles act as single, discrete 'events', in which a third particle is exchanged between them, carrying momentum from one to the other.

Represented by a so-called Feynmann Diagram; a picture of what happens. e.g. the repulsion between two electrons:

[Image here]

In this picture, the electrons repel each other by exchanging a photon γ. Think of γ as being emitted by e_1^-, and absorbed by e_2^-. The photon momentum is:

$$\mathbf{p}_\gamma = \mathbf{p}_2' - \mathbf{p}_2 = \mathbf{p}_1 - \mathbf{p}_1'$$

N. B. Momentum is conserved at both vertices (the emission and absorption point). Final overall momentum is equal to the initial overall momentum.

$$\mathbf{p}_1' + \mathbf{p}_2' = \mathbf{p}_1 + \mathbf{p}_2$$

As well as momentum, energy is also conserved:

$$E_\gamma = E_2' - E_2 = E_1 - E_1'$$

Often such intermediate force-carrying particles are named 'virtual' particles. Force-carrying particles always have integer spin and are therefore bosons.