Chapter 15

Classification of Particles

Particle type		**Strong interaction**	**Weak interaction**	**Electromagnetic interaction**	**Spin**
Leptons		No	Yes	Some	$\frac{1}{2}$
	Mesons	Yes	Yes	Yes	integer
Hadrons	Baryons	Yes	Yes	Yes	half-integer

Interaction carriers

Interaction	**Gauge-boson**
strong	gluon
weak	$W^{\pm},\ Z$
electromagnetic	photon (γ)

15.1 Leptons

The electron and the neutrino are leptons. They partake in the weak interactions and the electron, being electrically charged, also has electromagnetic interactions. They do *not* interact strongly and are not found inside the nucleus.

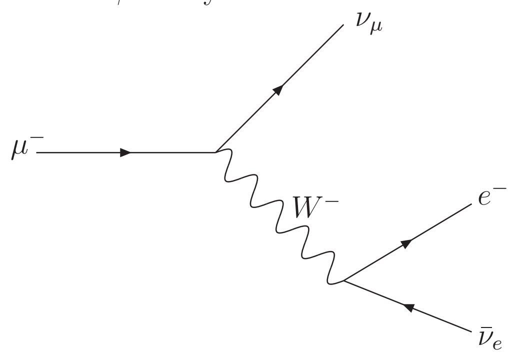
In terms of coupling to gauge bosons, this means that they both couple to $W^{\pm}$- and Z-bosons and the electron couples to the photon. There is no coupling between leptons and gluons.

Nature gives us three copies of each "family" or "generation" of particles. There are, therefore, two particles with similar properties to the electron (electric charge $-e$, spin-$\frac{1}{2}$, weakly interacting but not strongly interacting). These are called the muon (μ) and the tau (τ). Each of these has its own neutrino, ν_μ and ν_τ respectively.

Thus the six leptons are

Leptons			Electric Charge
ν_e	ν_μ	ν_τ	0
e	μ	τ	-1

The electron has a mass of 0.511 Mev/c^2, the muon a mass of 106 Mev/c^2 and the tau a mass of 1.8 Gev/c^2. The heavier charged leptons can decay via the weak interactions into an electron a neutrino and an anti-neutrino. The charged lepton emits a W^- and converts into its own neutrino. The W^- then decays into an electron and an electron-type anti-neutrino - just as in the β-decay of a neutron.



The muon has a lifetime of about 2×10^{-6} s. and the tau about 3×10^{-11} s. (these are regarded as "long-lived" particles!)

In the same way that the electron has an antiparticle (positron) with positive electric charge and the same mass and spin, the μ^-, and τ- also have antiparticles, μ^+ and τ^+, respectively. Likewise ν_μ and ν_τ have antiparticles $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$, respectively.

15.2 Hadrons

These are particles that partake in the strong interactions.

Hadrons with integer spins (bosons) are called "mesons", whereas hadrons with half (odd-)integer spins (fermions) are called "baryons".

Well over one hundred of each type have been identified so far. For this reason, hadrons are no longer considered to be elementary particles (leptons probably are) but to be constructed out of elementary spin-$\frac{1}{2}$ particles known as "quarks".

Mesons are bound states of a quark and an anti-quark and can therefore have integer spin. Baryons are bound states of three quarks and can have spin-$\frac{1}{2}$ or spin-$\frac{3}{2}$.

The proton is the only hadron which is absolutely stable (the lifetime is known to be greater than 10^{32} years!). All other hadrons decay eventually into protons, leptons and photons.

Hadrons participate in all interactions since quarks from which they consist participate in all interactions. As for leptons, there are also 3 generations for quarks

Quarks			Electric Charge
u	c	t	+2/3
d	s	b	-1/2

Some hadrons cannot decay via the strong interactions and can only decay weakly (the neutron is such an example). This is because the quarks come in different types called "flavours" and the strong interactions conserve this flavour. For example the meson K^- is a bound state of a s-quark and an $\bar{u}$ anti-quark. The s-quark has a flavour called "strangeness" (for unfortunate historical reasons the s-quark is assigned strangeness -1 - and its antiparticle has strangeness +1). The strong interactions conserve flavor and strangeness in particular, and since the K^- is the lightest meson which contains an s-quark, it cannot decay via the strong interactions.

The weak interactions do not necessarily conserve flavour, so that via the weak interactions the $s-$quark can decay into a $u-$quark, emitting a W^- which decays into and electron and anti-neutrino. The final state meson is a bound state of an u-quark and its anti-quark, which can bind together to form a neutral pion, π^0. Thus the decay

$$K^- \ \rightarrow \pi^0 + e^- + \bar{\nu}_e$$

can proceed through the weak interactions. The lifetime of the K^- is 1.2×10^{-8} s. (another long-lived particle)

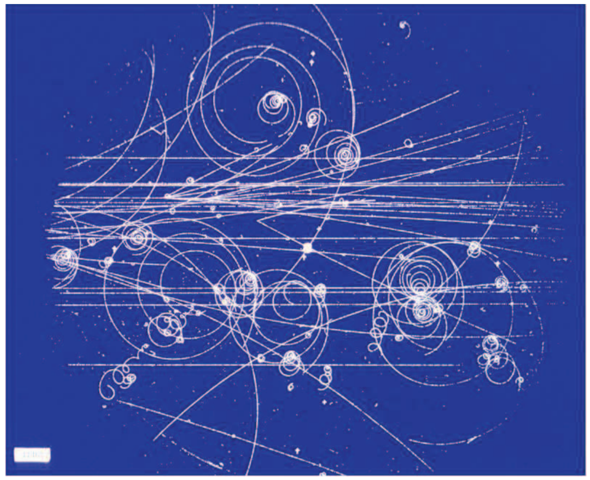
On the other hand there exists a meson K^{*-}, which is also a bound state of an $s-$quark and a $\bar{u}$ anti-quark, but in an excited state and with a mass which is greater than that of a K^- and a π^0 combined. The decay

$$K^{*-} \ \rightarrow \ K^- + \pi^0,$$

can indeed proceed via the strong interactions, since flavour is conserved (note that an anti-quark always has the opposite flavour of the corresponding quark - which means that a π^0 is flavour neutral). Typical lifetimes of particles that can decay through strong interactions are 10^{-23} s.

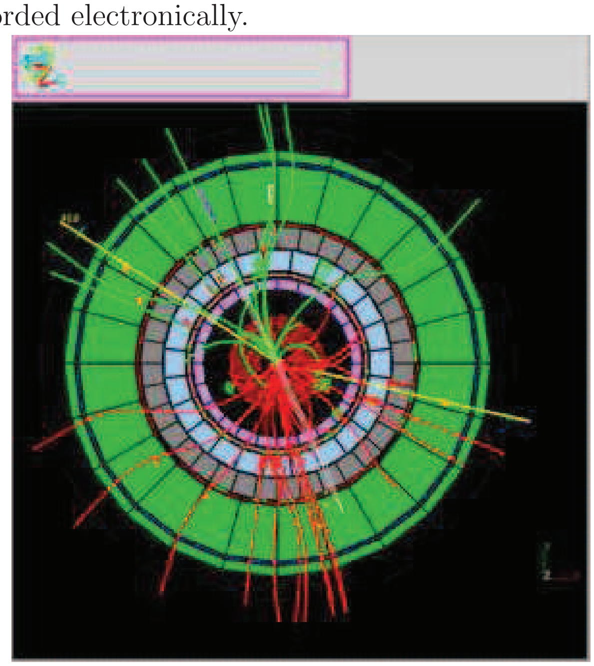
15.3 Detection of "Long-lived" particles

A particle whose lifetime exceeds about 10^{-11} s. and is travelling almost with the speed of light can leave a discernible track in a detector (recall that particles travelling with velocities very close to the velocity of light suffer a considerable time dilation so that the lifetime in the laboratory is larger than the lifetime in the frame of the particle - so that the track left is longer.)



The first particle detectors were bubble chambers. These were filled with saturated vapour. When a charged particle travelled through the vapour small bubbles would condense on it leaving a visible track. The bubble chamber was placed in a magnetic field which caused the path of the charged particle to curve by an amount which depends on its momentum and mass - this enables the particle to be identified (for example electron tracks have a very small radius of curvature) and the momentum of the particle to be measured. 'Vertices' can also be seen - these are caused by a neutral particle, which leaves no track, decaying into two (or more) charged particles.

Modern detectors do not give rise to visible tracks. Some types consist of arrays of electric wires, fibers or silicon layers. When a charged particle approaches a wire it causes an electric discharge which is recorded electronically.



By tracking which of the wires discharge it is possible to reconstruct the paths of the charged particles.

15.4 Detection of Short-lived particles - Resonances

Particles with a lifetime of less than about 10^{-11} s. do not live long enough to leave a track in a detector. They are observed as "resonances" - peaks in production cross-sections or in decay channels when the centre-of-mass energy of the incident particles in a scattering experiment is equal to the mass of the resonance particle (times c^2), or if the centre-of-mass energy of some subset of the final state particles is to the mass of the resonance particle (times c^2).

These peaks have a width Γ, corresponding to the uncertainty in their energy due to the fact that they have a short lifetime, τ. According to Heisenberg's uncertainty relation

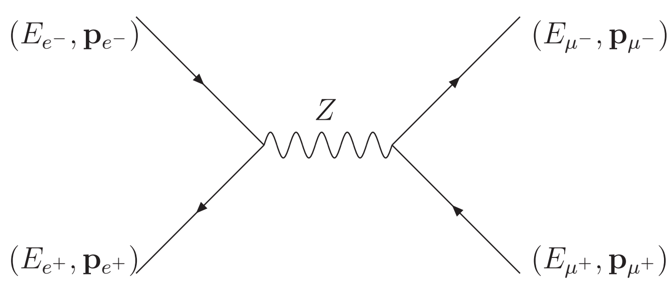
$$\Gamma = \frac{\hbar}{\tau}$$

For example, consider the Z-boson. This is a neutral particle that couples to all particles that partake in the weak interaction. Thus it can decay into a pair of charged leptons (i.e. a charged lepton and its antiparticle), a pair of neutrinos, or into quarks - ending up as showers of hadrons. It can also be produced by the annihilation of any of the above-mentioned pairs of particles. It was discovered in 1983 in an proton-antiproton scattering, but studied in more detail in electron-positron scattering in which the centre-of-mass energy was tuned to match the rest energy of the Z-boson.

The Feynman graph for a typical production and decay process

$$e^+ e^- \rightarrow Z \rightarrow \mu^+ \mu^-$$

is



The amplitude for the exchange of the Z is (up to an overall constant)

$$\frac{1}{(s - M_z^2 c^4)}$$

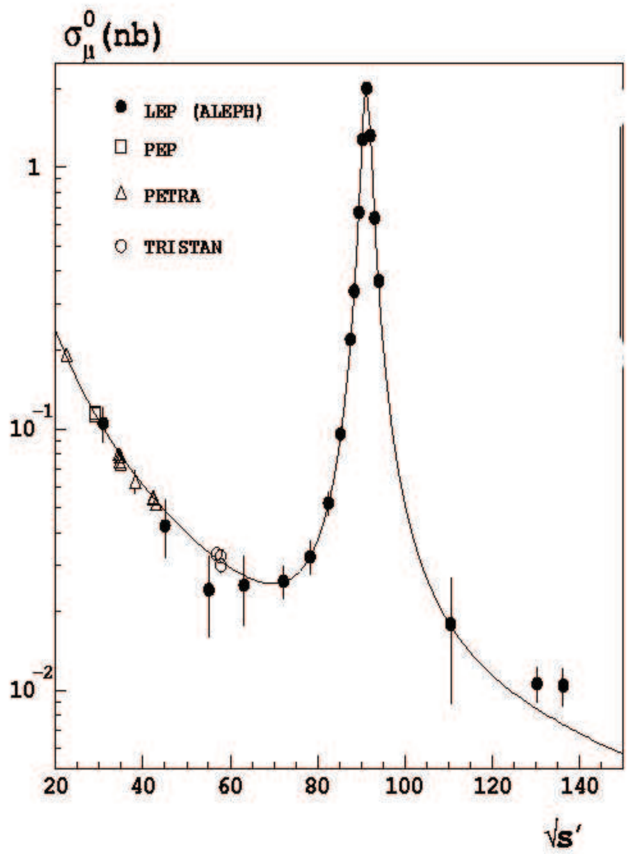
where $s = (E_{e^-} + E_{e^+})^2 - (\mathbf{p}_{e^-} + \mathbf{p}_{e^+})^2 c^2$, is the square of the centre-of-mass energy of the incident electron-positron pair.

We see that if we tune $\sqrt{s}$ to be exactly equal to $M_Z c^2$ this diverges. The above formula neglects the fact that the particle is unstable and has a width, Γ. Far away from the resonant energy this approximation is reasonable, but in the resonant region the above amplitude is modified to the (complex) expression

$$\frac{1}{(s - M_z^2c^4 + i\Gamma M_z c^2)}$$

The transition probability is the square modulus of the amplitude, so that the scattering cross-section is proportional to

$$\sigma \propto \frac{1}{(s - M_z^2c^4)^2 + \Gamma^2 M_Z^2 c^4}.$$

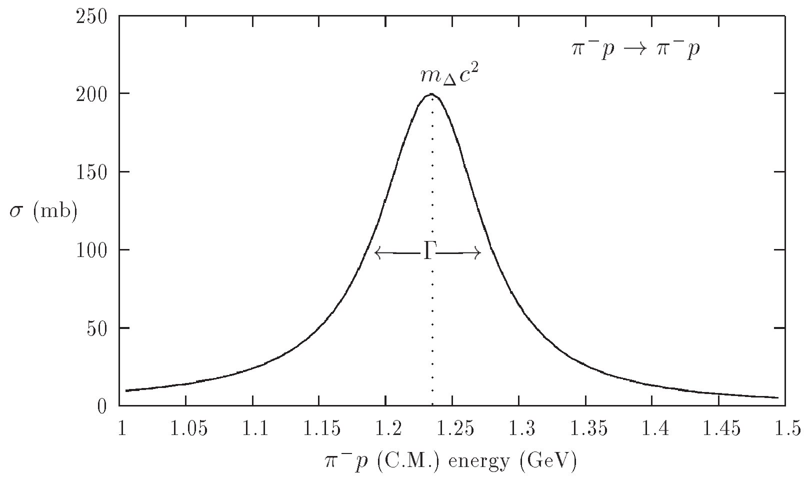


We note that this has a maximum when $\sqrt{s} = M_z c^2$ i.e. when the centre-of-mass energy is exactly equal to the rest-energy of the Z and the cross-section falls to one-half its maximum value when $\sqrt{s} = M_z c^2 \pm \frac{1}{2}\Gamma$

A strongly interacting particle resonance will occur whenever the centre-of-mass of the incident scattering particles is close to the rest energy of a particle that has the same flavour as the sum of the flavours of the incoming particles - this means that the resonant particle can be made up from the same quarks (and anti-quarks) as the two incident particles. For example, there exists a baryon called the Δ^0 which has the same flavour as a neutron (zero electric charge, zero strangeness etc. - although it does have spin-$\frac{3}{2}$). This can be produced in the scattering of a proton against a negative pion.

$$p + \pi^- \rightarrow \Delta^0 \rightarrow p + \pi^-$$

If we plot the cross-section for this scattering in the region of centre-of-mass energy 1 - 1.5 GeV, we get a resonance



We see that the Δ^0 has a mass of 1.23 GeV/c^2 and a width of about 0.1 GeV.

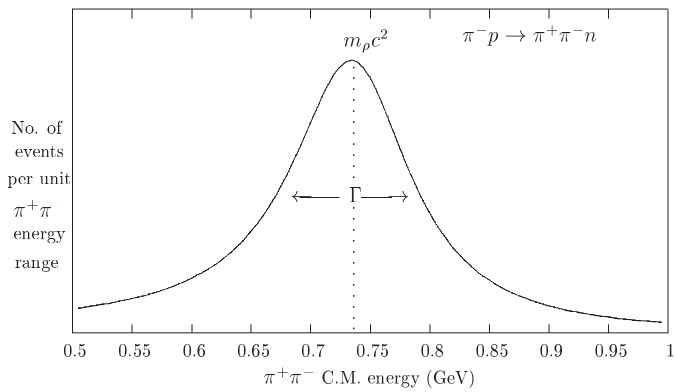
It is not always possible to prepare an initial state state with the correct flavour for the production of a given particle. In such cases one can look for resonances in the decay of the resonant particle when the centre-of-mass energy of the decay products is equal to the rest energy of the resonant particle. For example, consider the process

$$p + \pi^- \rightarrow \pi^+ + \pi^- + n$$

The pions leave tracks in detectors and their momenta can be measured by observing the radius of curvature of the tracks in a magnetic field. Thus we can contract the Lorentz invariant quantity which is the centre-of-mass energy of the two-pion system

$$E_{\pi\pi} = \sqrt{(E_{\pi^+} + E_{\pi^-})^2 - (\mathbf{p}_{\pi^+} + \mathbf{p}_{\pi^-})^2 c^2}$$

There is a particle called a ρ^0 which has the same flavour as the $\pi^+ \pi^-$ pair and a mass of 740 MeV/c^2 and a width of about 0.1 GeV. If we plot the number of events for a given $E_{\pi\pi}$ against $E_{\pi\pi}$, we observe a resonance.



15.5 Partial Widths

An unstable particle can usually decay into several different possible "channels". The fraction of the decays into a particular channel is called the "branching ratio". For example the branching ratio for a Z to decay into a $\mu^+ \mu^-$ pair, $B_{Z\rightarrow\mu\mu}$ is 3.4 %. The width of the resonance in the process

$$e^+ e^- \ \rightarrow Z \ \rightarrow \mu^+ \mu^-$$

is the "partial width", $\Gamma_{Z\rightarrow\mu\mu}$ and in this case it is 0.084 GeV. The total width Γ_{tot} is the sum of all the partial widths. The branching ratio is the ratio of the partial width for a particular channel and the total width

$$B_X \ = \ \frac{\Gamma_X}{\Gamma_{tot}}.$$

Thus in the case of the Z a measurement of the partial width for the decay channel into a muon pair and a determination of the branching ratio yields the total width

$$\Gamma_{tot} \ = \ \frac{\Gamma_{Z\rightarrow\mu\mu}}{B_{Z\rightarrow\mu\mu}} \ = \ 2.5 \text{ GeV}.$$