Classification of Particles

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

Leptons

Leptons partake in weak interactions, and the electron will also partake in EM interactions. They do <u>not</u> interact strongly and are not found inside the nucleus.

Leptons couple to both $W^{\pm}$ Bosons and Z-Bosons (due to weak interaction) and the electron also couples to the photon.

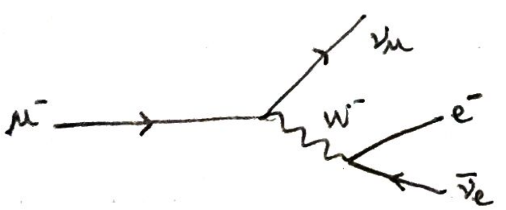
There are always 3 copies of each "family" or "generation" of particles. So there are 2 particles with similar properties to the electron, i.e they have charge $-e$, and spin $\frac{1}{2}$. These are the muon and tauon. Each has a corresponding neutrino. So the leptons are:

leptons			charge
ν_e	ν_μ	ν_τ	0
e	μ	τ	-1

The masses are:

e - $0.511\ MeV/c^2$
μ - $106\ MeV/c^2$
τ - $1.8\ GeV/c^2$

The heavier leptons decay into an electron, a neutrino and an antineutrino via weak interactions.



The muon emits a W^- and converts into its own neutrino. The W^- decays into e and $\bar{\nu}_e$ as in β decay.

The muon has lifetime $\sim 2 \times 10^{-6}$ seconds and the tauon has lifetime $\sim 3 \times 10^{-11}$ seconds, but these are regarded as long-lived!

Each of the leptons has a corresponding antiparticle.

Hadrons

Hadrons with integer spins (bosons) are called mesons.
Hadrons with half integer spins (fermions) are called baryons.
Over a hundred of each type have been identified so far (2020) so hadrons are no longer considered to be elementary particles, but instead are considered to be constructed out of spin-$\frac{1}{2}$ elementary particles known as quarks.

Mesons are made up of a quark anti-quark pair, so can have only integer spin.
Baryons are made up of three quarks and can have spin $\frac{1}{2}$ or $\frac{3}{2}$.

The proton is the only hadron which is absolutely stable, the others eventually decay into protons, leptons and photons.

There are 3 generations of each of the two charges of quarks:

Quarks			Charge
up	charm	top	$+2/3$
down	strange	bottom	$-1/2$

Some hadrons (such as neutrons) can only decay weakly and not via strong interactions. This is because the strong interactions conserve the "flavour" of some quarks. eg. The K^- meson is a s-quark and $\bar{u}$ antiquark pair. The s quark has a flavour called strangeness. The strong interactions conserve strangeness and since the K^- meson is the lightest meson with an s quark, it cannot decay via strong interactions.

The weak interactions don't necessarily conserve flavour so that via weak interactions, the s-quark can decay into a u quark, emitting a W^- which decays into an electron and anti-neutrino. The final state meson is the bound state of u-quark and $\bar{u}$ anti-quark, which is a neutral pion π^0:

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

On the other hand K^{*-} is a meson made of s and $\bar{u}$ but in an excited state and with mass greater than K^- and π^0 combined. Thus

$$K^{*-} \to K^- + \pi^0$$ can proceed via strong interaction.

Detection of Long Lived Particles

A particle with a lifetime 10^{-11} s and travelling at near the speed of light suffers considerable time dilation so ~~its~~ lifetime in the lab frame is larger than its lifetime in the particle frame, so it is possible to detect.

The first particle detectors were bubble chambers which were filled with saturated vapour. When a particle travelled through the vapor, small bubbles would condense on it, leaving a visible track. If the chamber was placed in a B field, the particle would move in a curved path that depends on its mass and momentum, enabling the particle to be identified, and momentum to be measured. Neutral particles leave no tracks and decay into 2 or more particles, allowing us to see a visible "vertex".

Modern detectors consist of arrays of electrical wires, which record an electric discharge that happens when a charged particle approaches. By tracking which of the wires have discharges, we know the particle path.

Detection of Short-Lived Particles - Resonances

Particles with a lifetime less than 10^{-11} s do not live long enough to leave a track in the detector. So instead we have to observe them with "resonances"; these are:

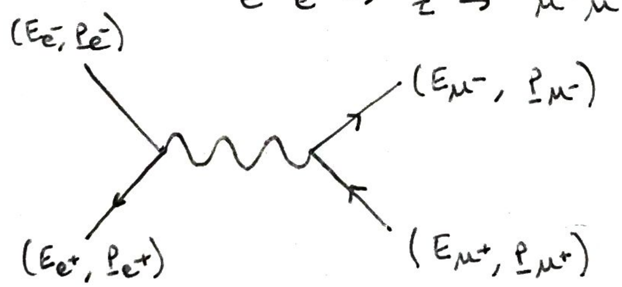
i) peaks in production cross-sections
or
ii) peaks in decay channels when the C of M energy of incident particles in a scattering experiment is equal to the mass of resonance particle ($\times c^2$), or if the C of M energy of some subset of the final state particles is equal to the mass of the resonance particle ($\times c^2$)

We define Γ to be the width of the peak, which corresponds to the uncertainty in their Energy since they have such a short lifetime τ. From the uncertainty principle:

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

Let's consider the Z-boson as an example. This neutral particle couples to all particles that partake in the weak interaction. We can study it in more detail in electron positron scattering, in which the C of M energy is tuned to match the rest energy of the Z-boson:

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



The amplitude for the exchange of Z is:

$$\frac{1}{s - M_Z^2 c^4}$$

where $s = (E_{e^-} + E_{e^+})^2 - (p_{e^-} + p_{e^+})^2 c^2$ is the square of $E_{C of M}$ of incident $e^- e^+$ pair if we tune $\sqrt{s}$ such that it is exactly equal to $M_Z c^2$, the amplitude diverges. The reason for this is that we neglected the fact that the particle is unstable and has a width Γ. Neglecting is a reasonable approximation far from the resonant energy, but in the resonant region, the amplitude is modified to:

$$\frac{1}{s - M_Z^2 c^4 + i\Gamma M_Z c^2}$$

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

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

which has a maximum when $\sqrt{s} = M_Z c^2$, i.e when E_{CofM} is equal to rest mass energy of Z.

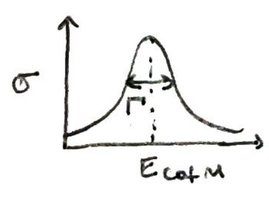
σ falls to $\frac{1}{2}$ its maximum when $\sqrt{s} = M_Z c^2 \pm \frac{1}{2}\Gamma$

Strongly interacting particle resonance will occur wherever the rest energy of a particle with the same flavour as the sum of flavours of incident particles is close to E_{CofM} of the incident particles.

So, the resonant particle can be made up from the same quarks and antiquarks as the two incident particles. eg. the Δ^0 baryon which has 0 charge, 0 strangeness, spin $\frac{3}{2}$:

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

If we plot the cross-section for this scattering, we see a resonance:



We can't always prepare an initial state with the exact flavour for the production of a particular particle.

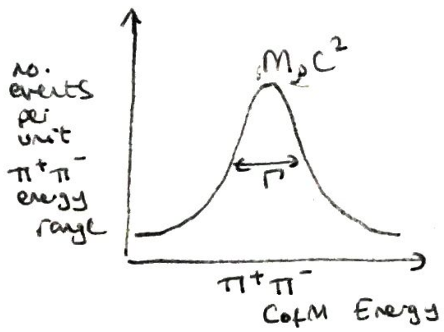
In these cases, we have to look for resonances in the decay of the resonant particle when the E_{CofM} of the decay products is equal to rest energy of resonant particle.

eg. in $p + \pi^- \rightarrow \pi^+ + \pi^- + n$

Pions leave tracks in detectors so we can measure their momenta. Thus, we can work out the Lorentz invariant quantity that is the E_{CofM} of the two pion system:

$$E_{\pi\pi} = \sqrt{(E_{\pi^+} + E_{\pi^-})^2 - (p_{\pi} + p_-)^2 c^2}$$

There is a particle called ρ^0 which has same flavour as $\pi^+\pi^-$ pair. If we plot no. events for a given $\pi^+\pi^-$ energy range against the CofM energy, we again observe resonance.



Partial Widths

An unstable particle can decay in several ways, called "channels". The fraction of decays that happen in one particular channel is called branching ratio.

eg. the branching ratio for $Z \to \mu^+\mu^-$ is denoted $B_{Z\to\mu^+\mu^-}$ and is equal to 3.4%.

The width of resonance in the process $e^+e^- \to Z \to \mu^+\mu^-$ is called the partial width since there are other channels through which Z could have decayed.

The total width Γ_{tot} is the sum of all partial widths and is related to branching ratio by:

$$B_x = \frac{\Gamma_x}{\Gamma_{tot}}$$

so we can calculate Γ_{tot} in our example case:

if $\Gamma_{Z\to\mu^+\mu^-} = 0.084$ GeV, then

$$\Gamma_{tot} = \frac{0.084}{0.034} = \underline{2.47 \text{ GeV}}$$