**Interactions**
There are four types of interaction:
- Strong – binds quarks together in the Hadrons. Sub-nuclear.
  It is also responsible for binding nucleons in the nucleus.
- ElectroMagnetic – interaction between all particles with electric charge. On the grand scale of things, this is what holds everything together.
- Weak – responsible for $\beta$ decay $\left(n \to p\right)$.
  All particles affected, but at relative levels.
- Gravity – Interaction between all particles with mass. So weak cf. the other forces that it won't be mentioned much more.

GUTs – Grand Unified Theories
TOEs – Theories of Everything

Protons have quarks → strong interaction. They have charge → EM interaction. All particles have weak interactions. It also has mass → gravity.
When a particle can have all the interactions, then the strongest that can happen will dominate.
Interaction does not necessarily determine the decay process and lifetime (i.e. strongest is not always responsible for the decay). This is due to conservation laws (later on).

**EM Interaction**:

Classically, particles (e.g. $e^-$) created an E field where $E\left(r\right) \propto \frac{e}{r^2}$. If another particle was near, then the force between them was $F \propto \frac{e_1 e_2}{r^2}$. There was no explanation of where this E field comes from.

The Quantum Mechanical approach is that the electron exchanges a virtual photon of momentum p with another electron. This transfer of momentum is the force.

If the electron was stationary, then the energy must come from the mass – but how can this be, when the mass must remain the same? We have to invoke the uncertainty principle. The virtual photon can only take away energy $\Delta E$ for a time $\Delta t$ such that $\Delta E \Delta t \sim \hbar$.

If there is no electron nearby for the photon to interact with, then it will turn round and come back. How does it know which direction to go? It doesn't – there's lots of them in a cloud of photons. This cloud isn't uniformly dense – they can travel for a long energy. But the energy is related to the distance that the photon travels from the electron. If the energy is very small, then the amount of time it can be separated from the electron is near infinity.
As $\Delta E \to 0$, $\Delta t \to \infty$.
Hence infinite range of the EM field.

The other formulation of the uncertainty principle is $\Delta p \Delta x \sim \hbar$. Therefore;
$pr \sim \hbar$

where r is the range. The force per photon is the rate of change of momentum which goes as $\frac{p}{t} = \frac{pc}{r} = \frac{\hbar c}{r^2} \propto \frac{1}{r^2}$.
The number of photons emitted is proportional to the charge $e$. So the force between two electrons $\propto \frac{e^2}{r^2}$.

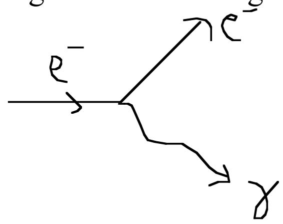
In order to balance the energy, then for each photon that travels from one electron to the other must have a corresponding photon going in the other direction.

General interaction carried (mediated) by virtual boson associated with that particlular interaction. For EM, this boson is the photon.
The source of the EM interaction is the electric charge ($e$ for the electronic charge).
The propagator of the EM interaction is the photon. This determines the range of the interaction. In this case, as the photon has no mass, it has an infinite range.
The strength of the interaction is characterized by a coupling constant which for the EM is called $\alpha$. It should really be $\alpha_{em}$, but as it was the first one that was discovered it doesn't have the sub notation. $\alpha$ in all EM cross-sections. For QM, $\sqrt{\alpha}$ is involved in all EM amplitudes.
$\alpha$ must be proportional to $e^2$.

$$\rightarrow \alpha = \frac{e^2}{(4\pi\varepsilon_0)\hbar c} = \frac{1}{137}$$

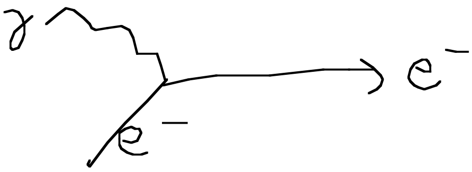
This is the "fine structure constant". The $4\pi\varepsilon_0$ is there to make the equation dimensionless.
This number is not constant – it depends on the energy. It is only this at normal lab temperature. At high T, this goes to $1/128$ This is called a running coupling constant.
How does this vary when all the constituents of it are all standard constants…?

Visualize with Feynman diagrams. Note that the photons used here are not real – they are virtual.
e.g. Bremsstrahlung.



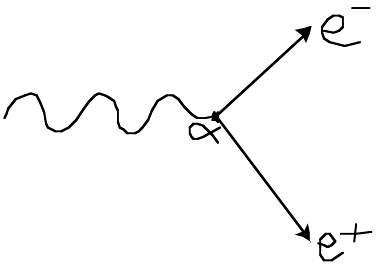

As normal, time across, space up.
The electron given off has to have lower energy
This is not real – need the presence of a nucleus to conserve momentum.
At the confluence, there must be the $\alpha$ factor.

Photoelectric Effect

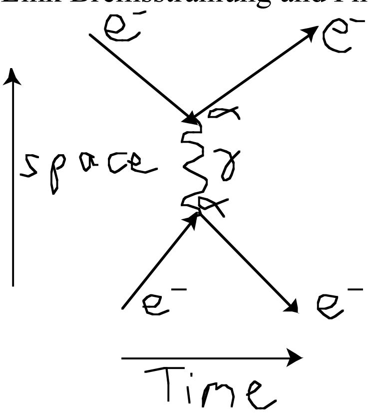



Again, not real – we need an atom. The cross-section at the vertex has a factor of $\alpha$ in it.

Pair Production:




Link Bremsstrahlung and Photoelectric effect:

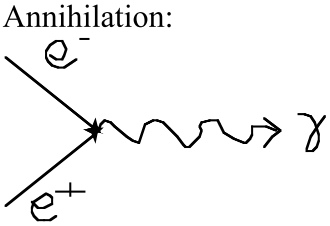



Coulomb scattering.

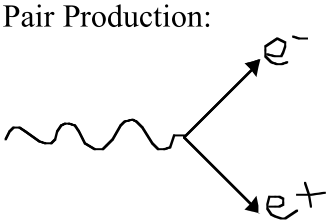
Cross-section $\sigma \propto \alpha^2$ i.e. $\propto e^4$ (as in Rutherford scattering).

Note that the photon is time-instantaneous.

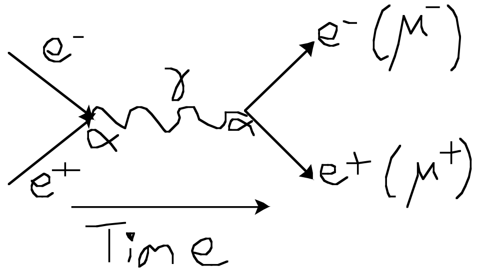
Annihilation:




Pair Production:



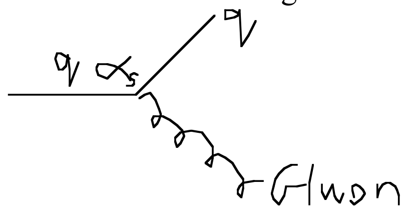

Merged:



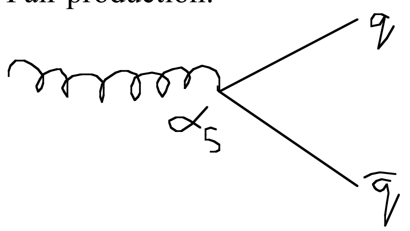
Here, the photon exists for a finite time.
Produced particles can be different from the start. (starting particles are gone, new particles created at the end).
This is the b asis of QEM (Quantum Electro Mechanics).
Works over distances of $10^9 m$ (measurements of the magnetic fields of Jupiter) to $< 10^{-19} m$ (electron / quark).
If QED is correct then leptons are all pointlike.

**Strong Interaction**
EM: $\gamma$ was propagated between electric charges.
By analogy, in the strong interaction the Gluon propagates between colour charges. This colour is a property only of quarks. The coupling constant for strong interaction is $\alpha_s$. $\alpha_s \sim 1$. It is not constant, even less than $\alpha$.

Gluon Bremsstrahlung



The quark given off is of lower energy than the original one.
Pair production:



As $\alpha_s >> \alpha$, if a particle can decay through the strong interaction then it will do so in preference to doing so through EM. Decays which go through the strong interaction have a high cross-section, so have very short lifetimes ($\sim 10^{-23} s$).
Because the strong force is coupled to the colour charges, it is only interactions involving quarks. Therefore it is not involved with leptons.
There is one other type of particle that has colour. Unlike the photon that has no electric charge, the Gluon does have colour. Therefore gluon emission by a quark changes the quark colour. It does not change the quark flavour.
A lot of the stuff about virtuality aid about EM is also applicable to Strong. We will go on to say that these are actual physical particles later.

There is interaction between two hadrons in the form of second order effects, i.e. that created by instantaneous dipoles set up by the quark colours (the same as van der vaal interaction between atoms, where the electric charges have dipoles that attract particles.) This is what holds protons together in the nucleus, for example

**Weak Interaction**

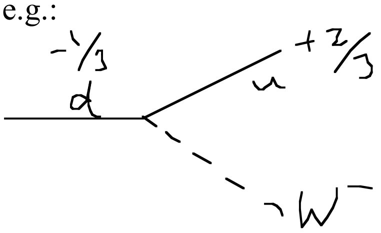
Propagators are $W^{\pm}$ and $Z^0$.
Weak interaction acts on all particles, therefore must couple to both quarks and leptons.
The mass of the $W$ and $Z$ is very large, around $100\,{GeV}/{c^2}$. The W is $80GeV$, while the Z is $91GeV$. This has the consequence on the apparent strength of the weak interaction.

Look at the range of the weak interaction. This is goverened by the uncertainty principle. $\Delta E \Delta t \sim \hbar$. As the energies are so large, the maximum time that energy associated with emitted W or Z can be "lost" as $\Delta t \sim {\hbar}/{\Delta E}$. The maximum distance that W or Z can travel is $= \Delta t c \sim {\hbar c}/{\Delta E}$. Equate this to the range. The maximum range of the W or Z (i.e. the weak interaction) is

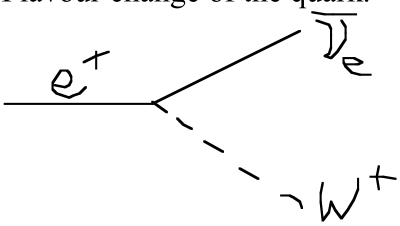
$$\frac{6.6 \times 10^{-22}\left(MeV\, s\right) \times 3 \times 10^{8}\left(s\right)}{100 \times 10^{3}\left(MeV\, c^{-2}\right)} \approx 10^{-18} m .$$

This is a very small distance – 3 orders of magnitude smaller than the size of the proton $\left(\sim 10^{-15} m\right)$. This is the reason for the small effective coupling of the weak interaction. → this leads to small cross-sections and thus leads to long lifetimes.

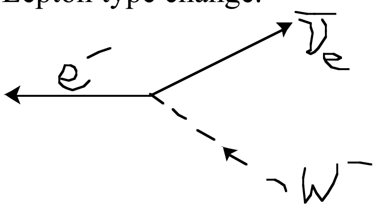
$W^{\pm}$ is electrically charged, thus it must carry away electric charge from the emitting particles. Therefore they must change the type / flavour of the lepton / quark.
e.g.:



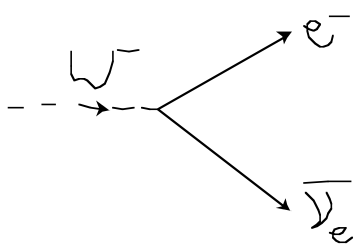

Flavour change of the quark.

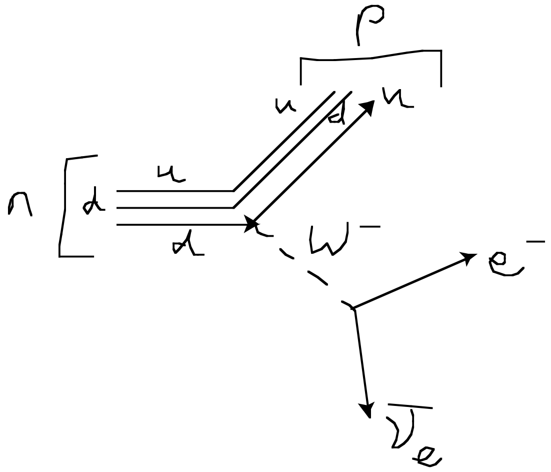



Lepton type change.




This is an intermediate state, and is not realistic. The following, however, is:



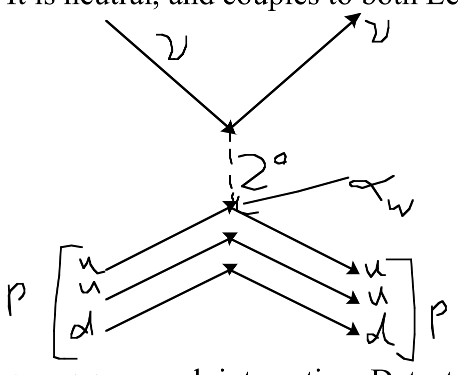

The two quarks at the top are called spectator particles. This decay shows the neutron decaying into a proton, an electron and an anti-electron neutrino. This is $\beta$-decay.

The $W^-$ boson here has, in principle, a mass of $80GeV$. The neutron at the start has an energy of around $1GeV$. The proton has an energy only a bit smaller. Energy conservation is not applying here – the energy available is much less than the energy needed to create a real $W^-$. So it can't be a real $W^-$ - it's a virtual particle. i.e. it has all the right properties, but it doesn't have the right energy / mass. The fact that it is very far away from its' normal mass means that it is very virtual. This is the cause of this decay process being very slow – 900 seconds. This particle cannot be detected, as if it were the energies would have to balance.

$Z^0$

This was first put forward in the 1960's as a completely separate particle – this was disproved by Fred, and was then reincarnated in a different form.

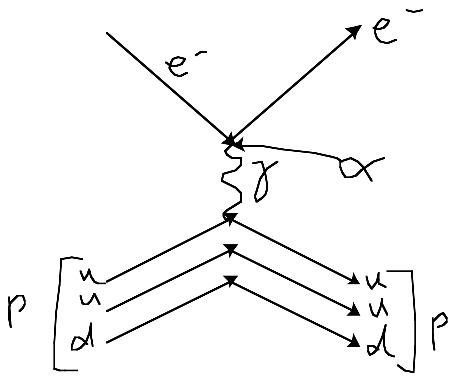
It is neutral, and couples to both Leptons and Quarks.




$\nu p \rightarrow \nu p$ weak interaction. Detected in a bubble chamber in the late 1970's.

Very short range - $\sim 10^{-18} m$.

Does not change Lepton type, or quark flavour. It is very similar to the photon (e.g. electron interacting with a proton through the exchange of a photon).




Very long range – pretty much infinite.

Higher energy particles probe shorter distances $\Delta p \Delta x \sim \hbar$ or $\lambda = \frac{h}{p}$. Therefore get into the range of the weak interaction. As this happens, the effects of the weak interactions increases as the energy increases. This happens as the energy approaches $100GeV$, which is not coincidentally the mass of the W and Z. Here, the EM interaction is roughly equal to the weak interaction in terms of both features and strength. This is called ElectroWeak unification.

These are all called intermediate vector bosons. The only one we have left out is Gravity.

**Gravity**

The propagator here is the Graviton (never yet discovered). It has mass 0 → infinite range. It supposedly has spin 2, so it is still a Boson.

If you look at 2 protons, then the force due to gravity is about $10^{-36}$ times that of electrostatic, hence it is generally ignored.

**Force Bosons: Real or Imaginary?**

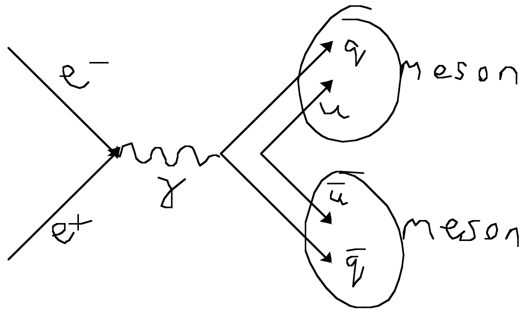
So far we have created a mathematical picture. Now we need to show that they have a concrete base in reality.

Strong: Gluon
ElectroMagnetic: Photon
Weak: $Z^0$, $W^{\pm}$.

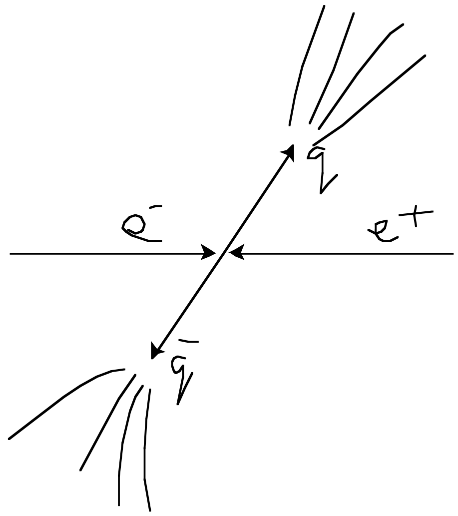
Don't need to look at the Photon – that's generally accepted to exist. Look at the others.

*Gluon*

Discovered in 1979 at PETRA in Hamburg
$e^+e^- \rightarrow hadrons$

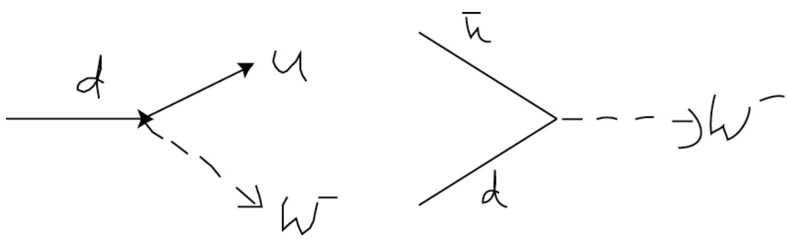


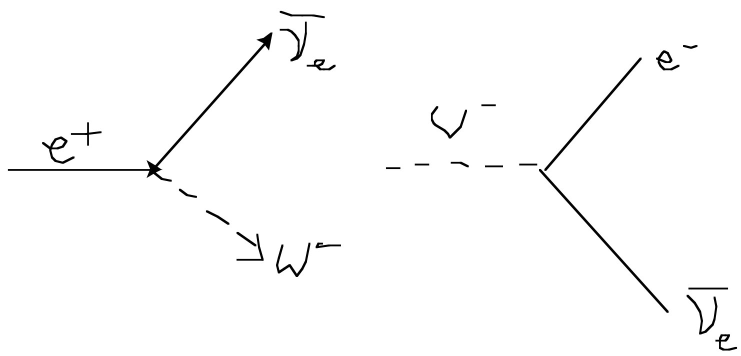

In reality, a jet of hadrons is created from the right side of this transfer.
Lab:



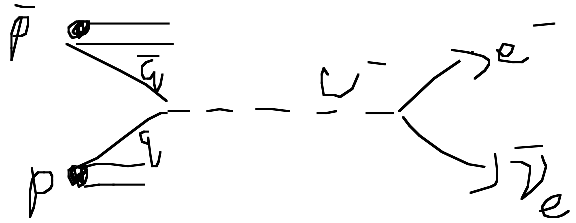

Two opposite jets of hadrons are created, with equal and opposite momentum (to conserve it)
It was not expected that either of the quarks given off could emit a gluon. Here, there is not need for it to be virtual – it could be real, so we could observe it. The Gluon then produces a pair of quarks, which then produce jets of Hadrons. These jets are generally merged together, as they are going in the same direction. This is the proof that gluons exist.
This emission has an $\alpha_s$ at the Gluon splitting from the Quark, so the probability of this interaction can be generated.

<u>$W^{\pm}$</u>
Couples to quarks and leptons.



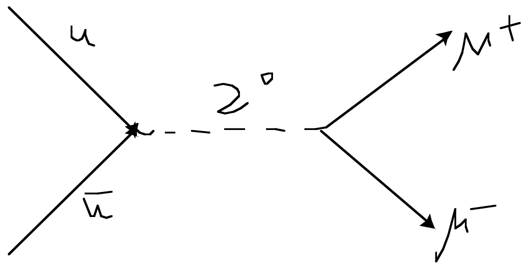


So we can produce a W, as well as detect one.

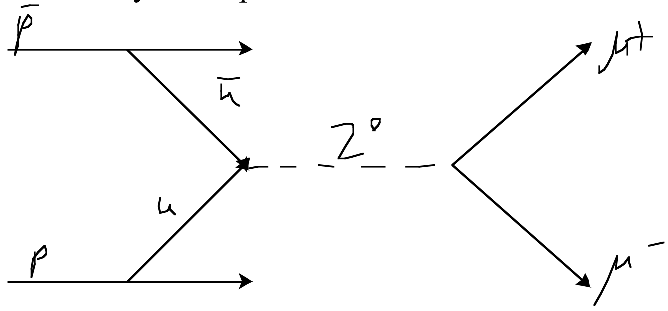


Measure the electron energy. Deduce the neutrino missing energy. Add these together in the centre of mass, and you get the mass of the particle that produced them in the first place. (You don't know the input energy transferred by the quarks, but you do know the outgoing.) Hence you can get the mass of the producing particle, which turned out to be $80GeV$. If this was not a unique value, then the particle wouldn't exist. However as it was, the particle does exist. (This was done at CERN.)

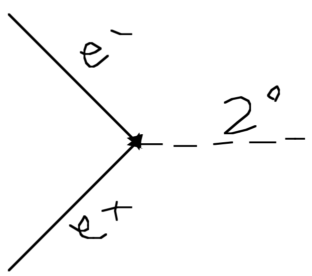
$Z^0$



Same story as the previous boson.



Detect and measure the energy. The mass of the producing particle $M_{Z^0} = 91GeV$.



Here the $Z^0$ boson can be real if $E_{cm} = 91GeV$.

Glashow, Weinberg, Salam were the people that first invented the weak interaction, and were theorists (1960's).
Rubbia (boss of the experiment - experimentalist), Van de Meer (Machine physicist – the guy that invented the technology used).