# Chapter 1

# Introduction and Overview

Particle physics is the most fundamental science there is. It is the study of the ultimate constituents of matter (the elementray particles) and of how these particles interact with one another (the fundamental forces). The primary aim of this module is to introduce you to what people mean when they refer to the Standard Model of Particle Physics

To do this we need to describe the very *small* (via quantum mechanics) and the very *fast* since when elementary particles move, they travel at or close to the speed of light (via special relativity). These requirements demand we work in the language of Quantum Field Theory(QFT). QFT as a subject is a huge (and rather advanced) subject in its own right but thankfully we will be able to use a prescriptive (and rather simple) approach to the QFT which is embodied in the Feynman Rules - for those who want to go further into the theoretical structure of the Standard Model see module PX430 - Gauge Theories of Particle Physics.

It is a remarkable fact that, theoretically, the fundamental interactions derive from an invariance of the QFT with respect to certain internal symmetry transformations known as *local gauge transformations*. The resulting dynamical theories of electromagnetism, the weak interaction and the strong interaction and known respectively as Quantum Electrodynamics(QED), the electroweak (or Glashow-Weinberg-Salam) theory and Quantum Chromodynamics(QCD). It is this collection of local gauge theories which have become known as the Standard Model(SM). N.B. Gravity plays a negligible role in Particle Physics and a workable quantum theory of gravity does not exist. We will study the theoretical structure of the SM and see how it accomodates every elementary particle and interaction currently known.

Experimentally, information comes from one of three sources: (1) collision experiments where one particle is fired at another to record either the details of the resulting scatter or the emission of new particles which may result;(2) the spontaneous decay or disintigration of one state into another state(s); (3) bound states in which one or more particles stick together and the properties of the composite body are recorded. We will see how the SM has passed essentially every experimental check to date either directly or by accomodating effects within the existing framework. In the process of this we will learn the main features of the weak and strong interaction and will briefly review how modern particle physics experiments work.

Despite its successes, the SM is not yet the complete and fully predictive theory of the fundamental interactions we need it to be. Apart from not including gravity, the electroweak theory and QCD are not unified and there are many parameters that have to be inserted by-hand from experimental measurements in order to make the theory predictive.We will take a brief look at what may lie beyond the SM and at the intrinsic connection with understanding the early universe/cosmology.

## 1.1 The Structure of Matter

The building blocks of all the stable matter in the universe are:

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \tag{1.1}$$

But we now know that there are (at least) two exact copies of this set of particles that differ only by their mass:

$$\begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}; \begin{pmatrix} t \\ b \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \tag{1.2}$$

These are the so-called *3-Generations* of fundamental particles. As we go from Generation I to III, so the mass of the particles increases. Why this generation structure exists is one of the biggest open questions in particle physics today. All particles in Generation II and III are very short-lived and have to be made in particle accelerators or occasionally appear from the collision of cosmic rays with nucleii in the Earth's atmosphere.

Our universe held together by 4 forces:

- Gravity - acts between masses, responsible for large scale structure of universe
- Electromagnetic - acts between particles carrying electric charge, responsible for chemistry, electromagnetic waves etc
- Weak - acts between particles with 'weak charge', responsible for radioactive decays
- Strong - acts between particles carrying 'colour charge', holds the atomic nucleus together

### 1.1.1 Fermions

The building blocks of matter are generically known as **fermions**. There are two very different types of fermion:

(1) Leptons: These are particles that do not feel the strong interaction i.e. they have zero colour charge. There are six distinct flavours of lepton, 3 charged $(e^-, \mu^-, \tau^-)$ which feel the electromagnetic and weak force and 3 neutral neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ which only feel the weak interaction – this makes neutrinos very hard to detect and in fact it is estimated that passing through an average person every second there are, $10^{14}$ solar neutrinos, $10^3$ neutrinos made in the Earth's atmosphere by cosmic rays plus others from e.g. natural radioactivity, flux from early universe etc. There are thought to be $\sim 10^9 \nu$'s per proton in the universe.

| Generation | Flavour | | Q | Mass |
|---|---|---|---|---|
| 1st | electron | $e^-$ | $-1$ | $0.511\text{MeV}/c^2$ |
| 1st | electron neutrino | $\nu_e$ | 0 | $< 2.2\text{eV}/c^2$ |
| 2nd | muon | $\mu^-$ | $-1$ | $105.7\text{MeV}/c^2$ |
| 2nd | muon neutrino | $\nu_\mu$ | 0 | $< 0.17\text{MeV}/c^2$ |
| 3rd | tau | $\tau^-$ | $-1$ | $1777.0\text{MeV}/c^2$ |
| 3rd | tau neutrino | $\nu_\tau$ | 0 | $< 15\text{MeV}/c^2$ |

(2) Quarks: Come in six distinct flavours and carry fractional electric charge.

| Generation | Flavour | | Q | 'Composite Mass' |
|---|---|---|---|---|
| 1st | down | $d$ | $-1/3$ | $\sim 300\text{MeV}/c^2$ |
| 1st | up | $u$ | $+2/3$ | $\sim 300\text{MeV}/c^2$ |
| 2nd | strange | $s$ | $-1/3$ | $\sim 500\text{MeV}/c^2$ |
| 2nd | charm | $c$ | $+2/3$ | $\sim 1.5\text{GeV}/c^2$ |
| 3rd | bottom | $b$ | $-1/3$ | $\sim 5\text{GeV}/c^2$ |
| 3rd | top | $t$ | $+2/3$ | $\sim 175\text{GeV}/c^2$ |

N.B. 1) Individual quark masses are not well defined and we quote composite masses e.g. $m_u, m_d \sim 300$ MeV/$c^2$ which is one- third of the proton/neutron mass.
N.B. 2) Quarks experience all of the forces: electromagnetic, strong and weak.
N.B. 3) Quarks come in 3 'colours': red, green, blue. This is purely a label for the the strong interaction charge-type and is in contrast to the single type of charge that the electromagnetic interaction couples to i.e. the electronic charge $-e$.

### 1.1.2 Bosons

There is another class of fundamental particle, called **bosons** which are responsible for mediating the forces with which fermions interact with one another – see Fig. 1.1. The bosons of the four interactions are: $X = \gamma, W^\pm, Z^0$, gluon and 'graviton'.

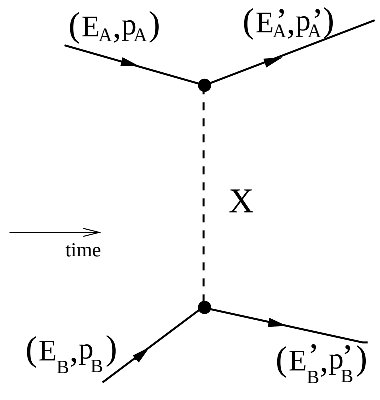


Figure 1.1: Scattering of particle A off particle B mediated by the exchange of boson X.

There are fundamental differences between fermions and bosons:

(1) Fermions have half-integral spin angular momentum ($\frac{n\hbar}{2}; n = 1, 3, 5,$) whereas bosons have integer spin ($n\hbar; n = 0, 1, 2,$) N.B. the fundamental fermions all have

spin $S = \hbar/2$ while the fundamental bosons, $\gamma, W^{\pm}, Z^0$ have $S = \hbar$ (the graviton is expected to have $S = 2\hbar$).

(2) The wavefunction describing identical bosons(fermions), $\psi_{1,2}$, is symmetric(anti-symmetric) under interchange $1 \leftrightarrow 2$ of the two particles. i.e.
for bosons: $\psi_{1,2} \stackrel{1\leftrightarrow 2}{\rightarrow} \psi_{2,1} = +\psi_{1,2}$
for fermions: $\psi_{1,2} \stackrel{1\leftrightarrow 2}{\rightarrow} \psi_{2,1} = -\psi_{1,2}$

The Pauli Exclusion Principle is a consequence of the interchange symmetry of fermion wavefunctions since,

- two identical particles in the *same* quantum state are described by a wavefunction $\psi$ that is necessarily symmetric.
- This violates the rule that identical fermions must have $\psi$ anti-symmetric and therefore identical fermions cannot exist in the same state – the Pauli principle.

This is the basis of atomic energy levels, the periodic table etc. There is no such restriction on bosons (in fact bosons have a propensity to reside in the same state!).

### 1.1.3 Hadrons

Free quarks are never seen in nature, instead combinations of quarks bind themselves together to form *hadrons* of which there are two types: *mesons* consisting of a quark-antiquark pair e.g.

| Meson | Quark content | Mass ($MeV/c^2$)) |
|---|---|---|
| Pion: $\pi^+, \pi^-, \pi^0$ | $u\bar{d}, d\bar{u}, (d\bar{d} - u\bar{u})/\sqrt{2})$ | $\sim 140$ |
| Kaon: $K^+, K^-, K^0$ | $u\bar{s}, \bar{u}s, d\bar{s}$ | $\sim 500$ |
| $D^+, D^-, D^0$ | $c\bar{d}, \bar{c}d, c\bar{u}$ | $\sim 1800$ |
| $B^+, B^-, B^0$ | $\bar{b}u, b\bar{u}, \bar{b}d$ | $\sim 5200$ |

Table 1.1: Some mesons commonly produced in particle physics experiments.

and *baryons* which are conbinations of 3 quarks e.g.

| Baryon | Quark content | Mass ($MeV/c^2$) |
|---|---|---|
| Neutron: $n$ | $ddu$ | 939 |
| Proton: $p$ | $uud$ | 938 |
| Lambda: $\Lambda^0$ | $uds$ | $\sim 1100$ |
| Sigma: $\Sigma^+, \Sigma^-, \Sigma^0$ | $uus, dds, uds$ | $\sim 1200$ |

Table 1.2: Some baryons commonly produced in particle physics experiments.

- A meson $q\bar{q}$ combination has zero resultant colour charge i.e. the anti-quark carries an 'anti-colour' charge that exactly cancels the charge on the quark e.g. $(red + \overline{red}) = white$

- The three quarks in baryons all have different colour charge which sum to zero i.e. $(red + blue + green) = white$

Only colourless objects with integer electric charge values are ever observed as free particles in nature.

### 1.1.4 Relative Strength

Can immediately conclude that the electromagnetic force must be much weaker than the strong force simply because to hold a nucleus together the electromagnetic repulsion of the protons must be overcome and further, the nucleus is compacted all into a scale of $10^{-14}$m!

What is the relative strength of the electromagnetic and gravitational force?
The Coulomb force between two protons: $F_{EM} = e^2/4\pi\epsilon_0 r^2$.
The 'strength' of the force is characterised by the (dimensionless) *fine-structure constant*:

$$\alpha = \frac{e^2}{4\pi\epsilon_0}\left(\frac{1}{\hbar c}\right) \sim 1/137,\ \hbar c \sim 200 \text{ MeVfm} \tag{1.3}$$

This is the electromagnetic interaction 'coupling constant'.

**Exercise 1.1** *Now compute the same quantity for the gravitational force between two protons:* $F_G = G_N m_p^2/r^2$ *where the dimensionless gravitational coupling constant is given* $\alpha_G = G_N m_p^2/\hbar c$. *Assume that* $G_N = 6.7\times 10^{-39}\hbar c\,[\text{GeV}/c^2]^{-2}$ *and* $m_p \sim 1 GeV/c^2$.

$G_N m_p^2/\hbar c = 6.7\times 10^{-39}$ *i.e. gravity is* $6.7\times 10^{-39}/7.3\times 10^{-3} \sim 1\times 10^{-36}$ *times weaker !! (for comparison* $\alpha_{weak} \sim 10^{-5}$ *and* $\alpha_s \sim 1$*)*

N.B. We will see that the coupling constants are in fact not true constants but vary as a function of the energy scale i.e. the strengths of the fundamental interactions vary with energy.

**Exercise 1.2** *At what mass scale does gravity become strong i.e.* $\alpha_G \sim 1$*?*

$$\begin{aligned} G_N m^2/\hbar c &= 1 \\ m &= \sqrt{\frac{\hbar c}{G_N}} = 1.2\times 10^{19}\text{GeV}/c^2 \end{aligned}$$

N.B. This is known as the Planck mass and represents roughly speaking the size of particle masses needed before the grav. interaction would rival the strength of the strong interaction.

### 1.1.5 Introducing Feynman Diagrams

Consider the *scattering* of an electron off a positron Fig. 1.2 via the exchange of a photon between them (this is known as Bhabha scattering). These are examples of *Feynman diagrams*. Time runs along the $x$-axis. The first diagram shows a the electron emitting a photon at the upper vertex which is absorbed at a later time by the positron at the lower vertex. The second diagram shows the reverse process of the positron emitting a photon which is absorbed at a later time by the electron. Both processes are needed to describe

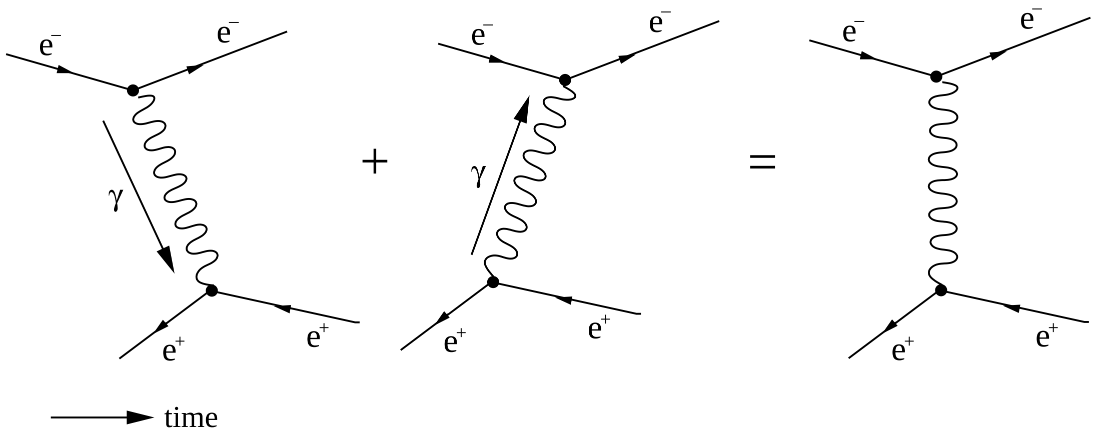


Figure 1.2:

BhaBha scattering and their sum is illustrated by the photon line being placed vertically. **WARNING!** Don't interpret the diagrams too literally. The lines do not represent particle trajectories as you might reconstruct them in a detector. The horizontal axis is time but the vertical dimension does not represent physical separation distance.

Note that:

- Arrows on particle lines distinquish between particle/anti-particle. The rule is that a particle labelled travelling 'backwards in time' is to be interpretted as the anti-particle travelling forwards. This means that arrows on anti-particles point away from intial-state vertices and into vertices involving final state particles - see Fig.1.3. Particles which are their own anti-particles, e.g. photons, should carry no arrow labels.

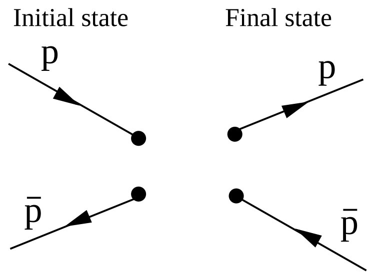


Figure 1.3:

- Internal lines i.e. those that begin and end within the diagram are particles that are not observed and in fact cannot be observed without completely changing the process in question.

- Feynman diagrams are sometimes presented with time running vertically.

The BhaBha process of $e^+e^-$ in the initial state and (different) $e^+e^-$ in the final state, can also occur by a completely different mechanism whose diagram is obtained by rotating the scattering diagram by 90° Fig.1.4. In this case an electron and positron *annihilate* to give a photon which at a later time converts back into a $e^+e^-$ pair. This illustrates the two general classes of particle interaction: (a)scattering and (b)annihilation.

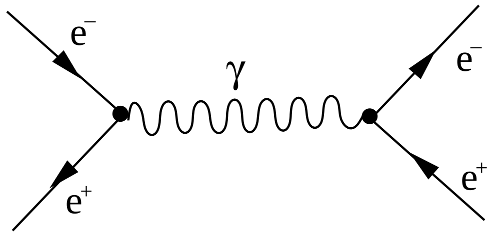


Figure 1.4:

Each Feynman diagram represents a number which is the QM amplitude (or 'matrix element') for that process. This is calculated by applying the 'Feynman rules'. The |amplitude|$^2$ is proportional to the *probability* for the process to occur. In order to calculate any specific process, you need to sum all possible diagrams that contribute. We have so far only considered 2-vertex diagrams of the Bhabha process but many more complex diagrams will also contribute. for example, some 4-vertex diagrams are shown in Fig. 1.5. In fact, for any process, there are infinitely many diagrams! For electromagnetic processes

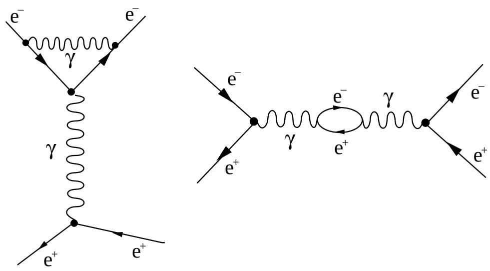

Figure 1.5:

this turns out not to be a problem since associated with each vertex is a *coupling* factor, $\sqrt{\alpha}$, where $\alpha$ is the fine structure constant ($\alpha = e^2/\hbar c = 1/137$). Since this is a small number, diagrams with more and more vertices contribute less and less to the final result and the sum can be cut-off at the level of precision required. This procedure is formally a perturbation series expansion and it depends crucially on the coupling being small i.e. $< 1$. We will see later that this is a massive problem for the treatment of the strong interaction where the couplings can be large.

### 1.1.6 Virtual Particles

Classically these forces would be 'explained' by a potential or field due to one particle acting on another, producing an 'interation at a distance'. The quantum field theory explanation links the force to the change in momentum of the particle as it emits(or absorbs) a boson i.e.the momentum *transferred* by the boson. An often used analogy is that of two people on ice throwing a ball between them to illustrate how boson exchange can mediate a repulsive force. The analogy breaks down for attractive forces which involve negative momentum transfer (the pair trying to wrestle the ball from each other?

This picture imediately introduces a problem however - consider again the basic interaction vertices of Bhabha scattering Fig.1.6 $e^- \rightarrow e^- + \gamma$ violates conservation of energy: in the COM frame the $e^-$ is initially at rest and so has energy $m_e c^2$ which means it

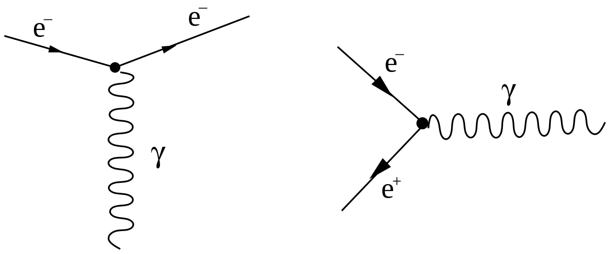


Figure 1.6:

cannot decay into a photon plus a recoiling electron which alone would have rest energy of $m_e c^2$. Similarly for $e^+ + e^- \rightarrow \gamma$: in the COM the colliding electron/positron pair have zero momentum but this cannot be true for the photon produced travelling at light speed. We conclude that this type of 3-particle vertex interaction cannot conserve energy/momentum and the calculated matrix element would be exactly zero since the Feynman rules demand energy/momentum is conserved at every vertex. The way out of this dilema is to recognise that these 3-particle vertices only appear as part of larger diagrams, not in isolation, and the internal lines that result, since they are never seen as free particles, are not constrained to have the 'correct mass' for their particle type. Such particles are known as *virtual* particles for which $E^2 - \underline{p}^2$ can take on *any* value and hence ensure that energy and momentum are conserved at each vertex node of Feynman diagrams. Because of this, virtual particles are said to be 'off mass shell'.

Note that even though the $e^+e^-$ annihilation vertex of Fig.1.6 cannot exist via one photon by momentum conservation, it can via two photons whose resultant COM momentum can sum to zero - see Fig.1.7(a).This is the diagram for $e^+e^-$ annihilation and by swapping the electron and photon states we obtain the diagram for photon 'pair-production'- Fig.1.7(b).

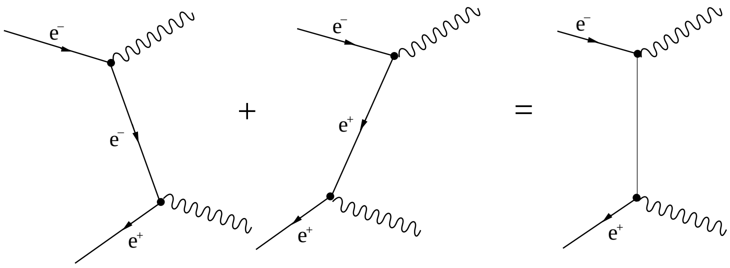


Figure 1.7:

**Exercise 1.3: Draw a Feynman diagram for the Compton scattering process** $\gamma + e^- \rightarrow \gamma + e^-$

Note that virtual particles will in general carry other properties of physical particles e.g. spin, electric charge, etc and these must obey all the normal conservation rules that their free particle states obey.

## 1.2 The Fundamental Interactions/Forces

Quantum Field Theory has been a tremendously successful approach in describing the fundamental interactions. The field theories of electromagnetism, and the strong inter-

| Force | Boson | Spin | Mass (GeV/$c^2$) | Range (m) |
|---|---|---|---|---|
| Electromagnetic | photon | $1\hbar$ | massless | $\infty$ |
| Weak | $W^{\pm}, Z^0$ | $1\hbar$ | 80/90 | $10^{-18}$m |
| Strong | gluon | $1\hbar$ | massless | $\infty/10^{-15}$m |
| Gravity | graviton | $2\hbar$ | massless | $\infty$ |

Table 1.3: *Summary of the properties of the fundamental interaction bosons. (NB The graviton remains hypothetical)*

action are known as Quantum Electrodynamics (QED) and Quantum Chromodynamics (QCD). The correct quantum description of the weak interaction was only possible in a joint treatment with electromagnetism (the so-called Electroweak theory) in a way analogous to the unification of electricity and magnetism achieved by Maxwell's equations.

In QCD *colour charge* plays the role of electric charge in QED, gluons take the place of photons and the basic interaction vertex analogous to $e^- \rightarrow e^- + \gamma$ is $q \rightarrow q + g$. A major difference between QCD and QED is that there are 3 types of colour charge (red, green, blue) and quark charge can change in QCD processes. Leptons do not carry colour charge and so take no part in QCD. Since colour charge must be conserved at interaction vertices (as for electric charge in QED), the gluons must themselves carry colour charge as in Fig.1.8 where a red quark converts into a blue quark and gluon requiring the gluon to carry 'red-antiblue' colour charge to conserve colour charge at the vertex. Note that

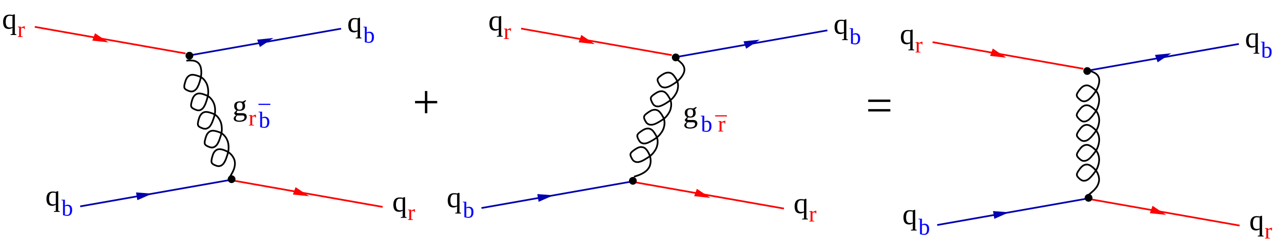


Figure 1.8: *Gluon exchange between quarks resulting in a 'red' quark transforming into a 'blue' quark and a 'blue' quark transforming into a 'red' quark. The process can occur by either of the quarks emmitting/absorbing the gluon, represented by the summed diagram which shows no time-odering.*

the fundamental interaction is the inter-quark process above. The inter-nucleon strong interaction, that Yukawa hypothesised was due to pion exchange in the 1930's, is then the result of a complicated multiple quark-gluon interaction (Fig.1.9) analogous to the Van der Vaals interaction between neutral molecules. Protons and neutrons were found to also interact via the exchange of the heavier mesons that were discovered during the 1960's (rho's,eta's, kaons, phi's etc) and behind it all was QCD and the property of colour confinement.

All quarks and all leptons carry 'weak charge' and hence take part in weak interactions. Neutrinos do not carry electric or colour charge and so only take part in the weak interaction. There are two types of weak interaction: 'charged current' interactions mediated by the exchange of $W^{\pm}$ bosons and 'neutral current' interactions mediated by $Z^0$ bosons. These are illustrated in Fig. 1.10 by beta decay and neutrino-electron scattering respectively. Note that the charge-current interaction changes the type or 'flavour'

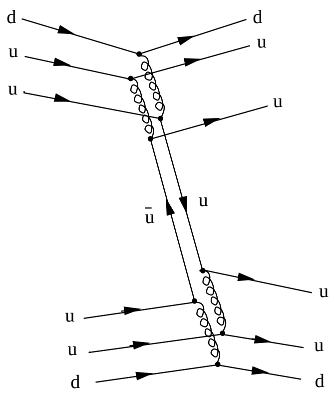


Figure 1.9: *One of the possible diagrams describing the proton-proton interaction by* $\pi^0$ *exchange(colours have been ignored for clarity, but assume they are conserved at each vertex interaction).*

of the participating particles e.g. down quark transforms into an up quark in beta decay. Changing flavour is a unique feature of the weak interaction.

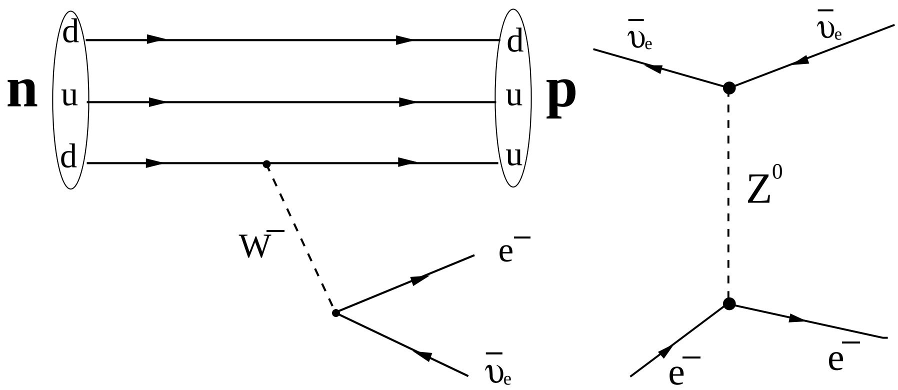


Figure 1.10: *Example of a W-mediated weak process: neutron beta decay. Example of a Z-mediated weak process:* $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$*, the elastic scattering of a neutrino off an electron in a 'neutral-current' event (this type of event was first seen in* $\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$ *at the CERN Gargamelle bubble chamber in 1973).*

## 1.3 Conservation Laws

A general property of elementary particles is that they will decay into states with a smaller rest mass than themselves unless prevented from doing so by some conservation law. Photons and neutrinos are stable because, being massless, there is nothing lighter to decay into; electrons, being the lightest electrically charged particles, are stable since any decay would break charge conservation; protons are the lightest baryons and would violate baryon number conservation if ever found to decay [1]

Each unstable particle has a characteristic mean lifetime which is governed by which fundamental interaction is responsible for the decay:$10^{-23}$s for a strong decay, $10^{-16}$s for

[1]the decay channel $p \rightarrow \pi^0 e^+$ has been investigated by a number of experiments but not (yet) seen, implying proton lifetime $> 10^{33}$ years.

an electromagnetic decay and longer times for weak decays i.e. $10^{-13}$s for $\tau$ decay up to 15min for $n \to p^+ + e^- + \bar{\nu}_e$.

The link between lifetime and interaction type is well illustrated by the decays of sigma baryons ($\Sigma^0(uds), \Sigma^+(uus)$):

$$\begin{array}{lll}\Sigma^0(1192) \to \Lambda + \gamma & Q = 74\text{MeV} & \tau = 10^{-19}\text{s} \\ \Sigma^+(1189) \to p + \pi^0 & Q = 189\text{MeV} & \tau = 10^{-10}\text{s} \\ \Sigma^0(1385) \to \Lambda + \pi^0 & Q = 208\text{MeV} & \tau = 10^{-23}\text{s}\end{array}$$

All have similar $Q$-values (liberated kinetic energy) and quark content so why do they have such drastically different lifetimes ?? The answer is that each decays by a different interaction:

- [1] $\Sigma^0(1385) \to \Lambda + \pi^0$, see Fig. 1.11

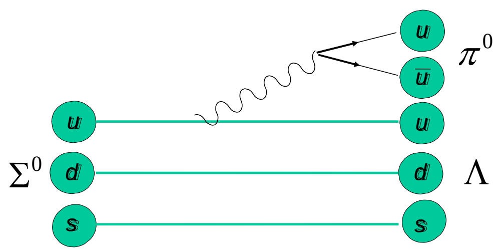


Figure 1.11:

  - Classic strong decay with characteristic decay time $\tau \sim 10^{-23}$s
  - Up quark emits a gluon which 'fragments' into a $u\bar{u}$ pair
  - Every state is colour neutral and no quark flavour change occurs

- [2] $\Sigma^+(1189) \to p + \pi^0$, see Fig. 1.12

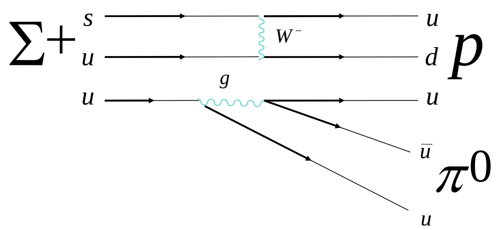


Figure 1.12:

  - Hybrid decay involving the weak interaction ⇒ relatively long decay time $\tau \sim 10^{-10}$s
  - Internal $W^-$ exchange resulting in double quark flavour change

- [3] $\Sigma^0(1192) \to \Lambda + \gamma$, see Fig. 1.13

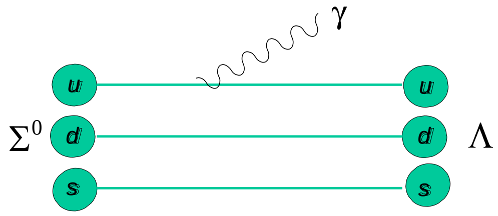


Figure 1.13:

– $\Sigma(1192) \rightarrow \pi^0 + \Lambda$ is impossible since: $1192\text{MeV} < (140\text{MeV} + 1116\text{MeV}) = 1256\text{MeV}$

– But a lighter state with the same quark content exists, $\Lambda(uds)$, and so electromagnetic decay is possible (NB the spectator quarks must exchange gluons so that momentum is conserved overall). Characteristic decay time $\tau \sim 10^{-19}$ s

– Note that if strong decay is not possible, electromagnetic decay will always happen before weak decay

So what are the conservation laws that govern whether a process will happen or not? There are some quantities that are found to be conserved (either absolutely or nearly so) at *every* interaction vertex of Feynman diagrams:

- **Kinematics:** Energy and momentum (linear and angular) are always conserved by all of the interactions.

- **Electric charge**: Absolutely conserved by all interactions.

- **Colour charge**: Electromagnetic and weak interaction don't couple to colour charge but it is conserved at all strong interaction vertices.

- **Baryon number(B)**: For all interaction vertices, the number of quarks is always constant i.e. if a quark goes into a vertex a quark always comes out (irrespective of the quark *flavour*). This can be quantified by assigning a number +1 to quarks and −1 to anti-quark but since we never see free quarks only baryons(quark number 3), anti-baryons(quark number −3) and mesons(quark number 0) it is more convenient to talk of conservation of baryon number (B = 1 for baryons,B = −1 for anti-baryons and B = 0 for everything else).

  **Examples**

  (1)

$$\begin{aligned} \bar{p} + p &\rightarrow n + \bar{n} \\ \mathrm{B}: (-1) + 1 &\rightarrow 1 + (-1) \end{aligned}$$

Allowed

(2)

$$\begin{aligned} \bar{p} + p &\rightarrow \pi^+ + \pi^- \\ \mathrm{B} : (-1) + 1 &\rightarrow 0 + 0 \end{aligned}$$

Allowed

(3)

$$\begin{aligned} \bar{p} + p &\rightarrow n + n \\ \mathrm{B} : (-1) + 1 &\rightarrow 1 + 1 \end{aligned}$$

Not allowed

(4)

$$\begin{aligned} \bar{p} + p &\rightarrow p + \pi^- \\ \mathrm{B} : (-1) + 1 &\rightarrow 1 + 0 \end{aligned}$$

Not allowed

- **Lepton number(L)**: The strong force does not act on leptons at all and in electromagnetic vertices do not change the lepton type e.g. $e^- \rightarrow e^- + \gamma$. Weak interactions do change the lepton type but only within the *same generation* e.g. $e^- \rightarrow \nu_e + W^-$ and so *electron number, muon number, tau number* are all individually conserved by all interactions.

  **Examples**

  (1) Familiar example of beta decay $n \rightarrow p + e^- + \bar{\nu}_e$. Underlying interaction is:

$$\begin{aligned} d &\rightarrow u + e^- + \bar{\nu}_e \\ \mathrm{L_e} : 0 &\rightarrow 0 + 1 + (-1) \end{aligned}$$

  (2)

$$\begin{aligned} \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\ \mathrm{L}_\mu : 0 &\rightarrow 1 + (-1) \end{aligned}$$

  (3)

$$\begin{aligned} \mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\ \mathrm{L_e} : 0 &\rightarrow (-1) + 1 + 0 \\ \mathrm{L}_\mu : -1 &\rightarrow 0 + 0 + (-1) \end{aligned}$$

**Exercise 1.4: Write down the decay products if the anti-particle of the state was decaying in each case.**

N.B. There is no corresponding conservation of quark generation number because of a curious mixing between the 3 generations of quarks (known as CKM mixing). There is growing evidence that a similar mixing also exists between the leptons so that (at a very low level) lepton number may not be absolutely conserved.

**Quark Flavour** e.g. up-ness, down-ness etc is a quantity that is absolutely conserved by the electromagnetic and strong interactions but not by the weak. The weak interaction can mediate processes like $d \to u + W^-$(beta decay) and is the *only* interaction that can change quark flavour. This 'explains' the relatively long lifetimes of particle decays such as,

$$\Lambda \to p + \pi^-, \ \ \tau = 2.6 \times 10^{-10} s \tag{1.4}$$

$$K^0 \to \pi^+ + \pi^-, \ \ \tau = 0.9 \times 10^{-10} s \tag{1.5}$$

These states are the lightest baryon and meson that contain a strange quark $\Lambda = (uds)$, $K^0 = \bar{s}d$ and so the only way in which they can decay to a lighter state is via a weak decay which can change $s \to u$ and has a characteristically long lifetime. Quark flavour conservation can be quantified by assigning $+1(-1)$ to individual quark(anti-quark) flavours e.g.

**Examples**

(1)

$$\begin{aligned} \pi^- + p &\to \Lambda + K^0 \\ \mathrm{S} : 0 + 0 &\to -1 + 1 \end{aligned}$$

Strong interaction and $\Delta s = 0$ and so process is allowed

(2)

$$\begin{aligned} \pi^- + p &\to K^0 + n \\ \mathrm{S} : 0 + 0 &\to 1 + 0 \end{aligned}$$

Strong interaction and $\Delta s \neq 0$ and so process is not allowed

(3)

$$\Lambda \to \pi^- + p$$

Weak decay which does not conserve S.

mention Naeothrs theorem, fact that lepton number and baryon number not on same footing as cons. of electric/colour charge (p77 griffiths) leave predicting outcomes of reactions to exercises but mention if you see a photon then e-mag, neutrino , weak etc.

The symmetry or invariance of the equations of quantum field theory under various symmetry operations is the most important concept in particle physics. One reason for this is Noether's Theorem (1917) which states that every symmetry of nature yields a conservation law (and conversely every conservation law is associated with a symmetry of some kind). We are already familar with this idea for the space-time symmetries of nature:

- the invariance of physics to spatial translations leads to conservation of linear momentum;
- the invariance of physics to spatial rotations leads to conservation of angluar momentum;
- the invariance of physics to the direction of time implies conservation of energy.

Similarly the invariance of the QFT description of the fundamental interactions with respect to local gauge transformations (internal symmetries) 'explains' some of the observed conservation laws e.g. the invariance of QED w.r.t. $U(1)$ transformations leads to the conservation of electric charge and the invariance of QCD w.r.t. $SU(3)_c$ transformations corresponds to the conservation of colour charge.
N.B. No internal symmetry is known that corresponds to the conservation of lepton and baryon number (unlike electric and colour charge). Because of this it is thought likely that lepton and baryon number are not absolutely conserved quantities and we have already mentioned that evidence for lepton number violation may already exist. It is thought that new interactions that violate baryon number were possible in the conditions of the early universe.

Summary of conserved quantities:

| Conserved quantity ? | Strong | Electromagnetic | Weak |
|---|---|---|---|
| Electric charge | Yes | Yes | Yes |
| Lepton number | Yes | Yes | Yes |
| Baryon number | Yes | Yes | Yes |
| Quark flavour (U,D,S,C,T,B) | Yes | Yes | No |

Table 1.4: *A summary of some conserved quantities.*

### 1.3.1 Predicting Interaction Outcomes

One can go a long way in predicting particle reactions, armed with just a knowledge of the conservation rules outlined above. When presented with an unfamiliar decay chain or interaction process, go through the following check-list:

1) Is electric charge conserved?

2) Is it a *decay* or *interaction*?

3) What type of process is at work?
If there are photons involved, it is electromagnetic (e.g. $\pi^0 \rightarrow \gamma\gamma$). If there are neutrinos involved, it is a weak process (neutrinos only feel the weak force). If there is a process only involving hadrons, chances are you are dealing with a strong process. Hadrons will normally preferentially interact by the strong interaction primarily because $\alpha_s$ is much larger than the electromagnetic or weak coupling strengths. Exceptions are where the interaction involves leptons (which do not feel the strong interaction) or if there has been a violation of one of the strong interaction conservation rules e.g. quark flavour conservation. Examples of interactions involving the weak and electromagnetic interaction are shown in Fig. 1.14: (left) weak interaction–

a neutrino scattering off an electron or quark ; (right) electromagnetic interaction– so-called 'Drell-Yan' lepton pair production from pion-nucleon (N=p or n) scattering experiments.

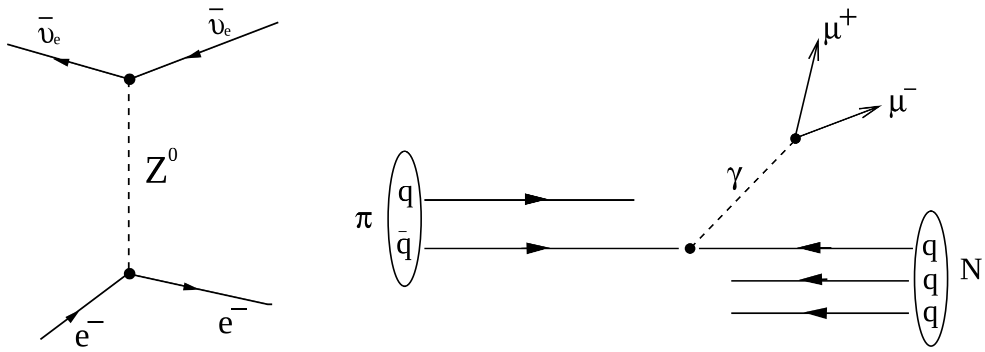


Figure 1.14:

N.B. The weak interaction is so weak that states will only decay weakly if all other possibilities to decay are ruled out i.e. the only way to transform into a lighter state is to undergo a quark flavour change.

4) Is lepton number conserved?

5) Is baryon number conserved?

6) If a strong or electromagnetic process, is quark flavour conserved?

7) In the case of a decay, is mass-energy conserved?
A decay, unlike an interaction, is a 'centre-of-mass' phenomenon i.e. it is irrelevant how much energy the decaying state has in the lab. frame, if the mass-energy on the left-hand side is less than the right-hand side the decay cannot happen e.g. the decay of a free proton, $p \to n + e^+ + \nu_e$ is not kinematically allowed since the mass of a proton is $m(p) = 938\text{MeV}/c^2$ whereas the mass of the right-hand-side is at least $m(n) + m(e) = 939 + 0.5 = 939.5\text{Mev}/c^2$.

**More examples:** Can the following processes occur and if not, why not?

- $D^0 \to K^- + \pi^+$ (allowed weak decay)
- $\pi^- + p \to K^- + p$ (not allowed, strong interaction that violates strangeness conservation)
- $\pi^+ + n \to K^+ + \Lambda$ (strong interaction, allowed)
- $K^-(\bar{u}s) + p \to K^+(u\bar{s}) + \Sigma^-(dds)$ (not allowed, strong interation that violates strangeness conservation)
- $\pi^- + p \to \pi^0 + n$ (strong interaction, allowed)

## 1.4 Summary- what you should know

- The fundamental structure of matter, 3 generations of elementary particles
- The role and properties of fermions/bosons
- The most common baryon and meson states
- Feynman diagrams: coupling constants, virtual boson exchange
- The main characteristics of the weak, strong and electromagnetic interactions
- The link between interaction type and lifetime
- Conservation laws: link to symmetry/invariances and using these laws to predict/explain particle interactions

## 1.5 Reading

Introduction, Chapter 1 and aspects of Chapter 2 of Griffiths