Summary - Elementary particle dynamics

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This summary is based on: Chapters 1.11, 2.1 - 2.4.4 from Griffiths, David J. Introduction to Elementary Particles

1 Elementary particles and Forces

Antiparticles: An antiparticle is a particle that has the same mass and spin as the regular particle, but it has opposite charge and all other quantum numbers are opposite. All charged particles have anti particles, whether the particle is an elementary particle or a hadron. The neutron and the neutrinos have anti particles, however neither the photon (γ) nor the neutral pion (π^0) has a distinct antiparticle. It is a convention to call the electron the particle and the positron its antiparticle.

For example: The e^- has a negative charge, 1/2 spin, an electron number of 1 and a lepton number of 1. The e^+ has a positive charge, 1/2 spin, an electron number of -1 and a lepton number of -1.

Elementary Particles:

- **Fermions:** particles with half-integer spin.
  - **Leptons**: do not interact trough the strong force. Have spin $\frac{1}{2}$. Examples: e^-, μ^-, τ^-, ν_e, ν_μ, ν_τ
  - **Quarks**: interact trough the strong force. Have spin $\frac{1}{2}$. Examples: u, d, c, s, t, b
- **Bosons:** particles with integer spin. Examples: γ, gluons, W^+, W^-, Z, Higgs boson

Composite Particles:

- **Hadrons:** bound state of quarks or antiquarks
  - **Baryons:** bound state of 3 quarks or antiquarks. Example: proton, neutron, antiproton
  - **Mesons:** bound state of an equal number of quarks and antiquarks. The most typical ones have one quark and an antiquark. Examples: π^0, π^+, π^-

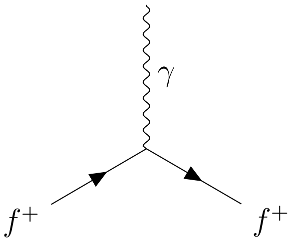
Basic Forces:

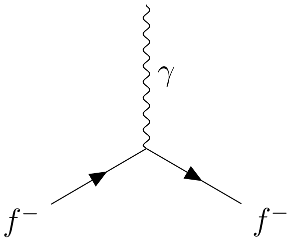
- **electromagnetic:** acts between charged particles, the force carrier particle is the photon.
- **strong:** acts between quarks, the force carrier particles are the gluons.
- **weak:** acts between all fermions. The force carrier particles are: W^+, W^-, Z bosons
- **gravity** (negligible for nuclear and particle physics): acts between all particles with mass

2 Quantum electrodynamics - QED

participating particles: charged fermions
force carrier: γ

Fundamental vertex:

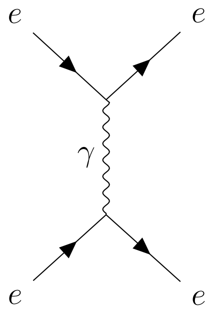




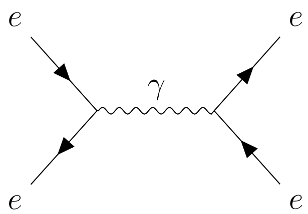
- In this document for all Feynman diagrams **time goes from left to right**.
- A fundamental vertex is not a real physical phenomena
- Real phenomena contain at least 2 vertices.
- One vertex consists of three connected lines.
- **Feynman diagrams** are a visual **representation of particle interactions** $\rightarrow$ they are symbolic and are designed to understand phenomena and to aid calculations.
- Energy and momentum get conserved in the Feynman diagrams

2.1 examples

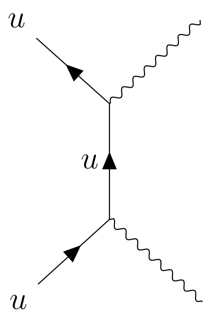
Coulomb repulsion - Møller scattering ($e^- + e^- \rightarrow e^- + e^-$):



Coulomb attraction - Bhabha scattering ($e^- + e^+ \rightarrow e^- + e^+$):



Pair annihilation ($u + \bar{u} \rightarrow \gamma + \gamma$):



- **Crossing symmetry:** rotating or twisting the diagrams $\rightarrow$ particles are indistinguishable from antiparticles travelling back in time

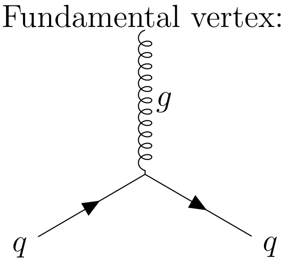
- **external lines:** real particles, describe what physical process is occurring.
- **internal lines:** virtual particles, describe the mechanism for the interaction

To analyse a particular physical process using Feynman diagrams:
- draw all possible diagrams (in practice usually only up to 4 vertices)
- weight diagrams based on how many vertices they have
- each QED vertex introduces a factor of $\alpha = \frac{e^2}{\hbar c} = \frac{1}{137}$ (fine structure constant). The weights are different for the other forces.
- The total sum of the Feynman diagrams represents the full process.

3 Quantum chromodynamics - QCD

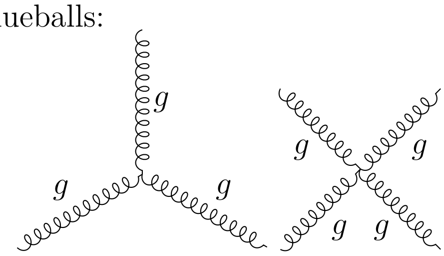
participating particles: quarks
force carrier: gluons

Fundamental vertex:



- colour plays the role of the charge, also called colour charge
- there are 3 colours: r, g, b for the quarks
- there are 3 anticolours: $\bar{r}, \bar{g}, \bar{b}$ for the antiquarks
- each quark has 1 colour
- the gluons carry colour: each gluon has 1 colour and 1 anticolour (there are 8 different gluons based on the colour combinations)
- colour is always conserved (like electric charge)
- all naturally occurring composite particles are colourless (baryons have one of each colour, mesons have 1 colour and the same anticolour)
- There are no free quarks or gluons naturally in our Universe at the present time. There are unbound quarks and gluons in quark-gluon plasma (in the very early Universe).
- gluons can couple to other gluons: glueballs (bound state of gluons with no quarks)

Glueballs:



The coupling constant (the weighting of the Feynman diagrams) in QCD is different from the one in QED (α). In QCD we have a **'running' coupling constant**:
- for the "large" distances of nuclear physics the constant is large
- for the "short" distances of particle physics the constant is small
- This is also called **asymptotic freedom** - similar to **vacuum polarisation**, the virtual quarks and gluons shield the colour of actual particles and the coupling is different depending on the distance between particles.

- in QCD we have **quark polarisation** and **gluon polarisation**

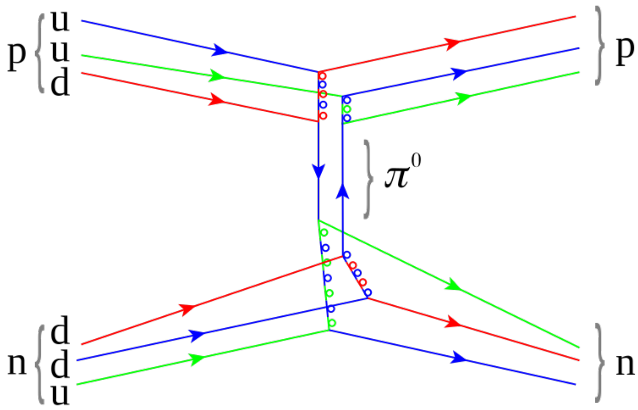


Figura 1: p$^+$ - n$^-$ interaction. The middle section of the diagram shows a u and $\bar{u}$ or d and $\bar{d}$ quark which combine to a π^0. This is representing the meson exchange model of the strong nuclear force. Note that the coupling constant between the individual quarks inside the p^+ and n^0 is different from the coupling between the quarks in the two different hadrons.

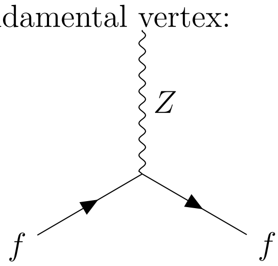
4 Weak interaction

participating particles: fermions
force carrier: W^+, W^-, Z
notes:

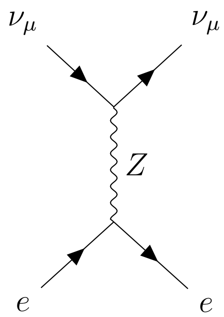
- neutrinos (ν) only participate in weak interactions
- the only interaction that can change flavour $\rightarrow$ true decays only happen trough weak interactions
- There are two kinds of weak interaction:
  - charged - mediated by the W^+, W^-
  - neutral - mediated by the Z
- Based on the participating particles we can have the following types of process:
  - leptonic process (only leptons)
  - semi-leptonic process (leptons + quarks)
  - hadronic process (only quarks)

4.1 Neutral weak interaction

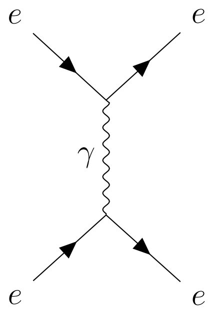
Fundamental vertex:

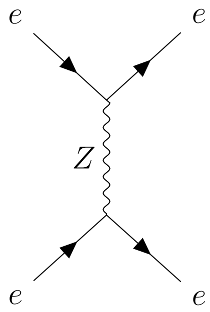


Example: neutrino - electron scattering $e^- + \nu_\mu \rightarrow e^- + \nu_\mu$



Any process mediated by the γ can also be mediated by the Z. This can add a tiny contribution to the Coulomb force. Example: $e^- + e^- \to e^- + e^-$

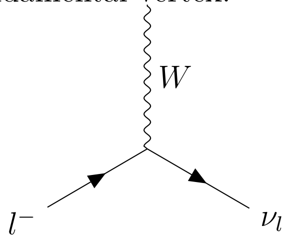




4.2 Charged weak interactions

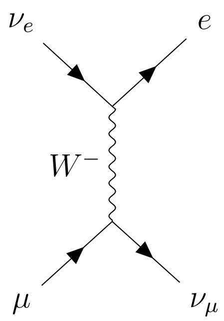
4.2.1 Leptonic processes

Fundamental vertex:



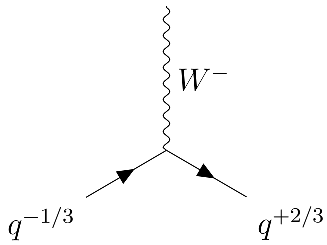
- Leptionic vertices connect only leptions of the same generations. e.g. e^- only to ν_e, μ^- only to ν_μ.
- Conservation of electron number, muon number and tau number

Example: neutrino - muon scattering $\mu + \nu_e \to e + \nu_\mu$



4.2.2 Quarks

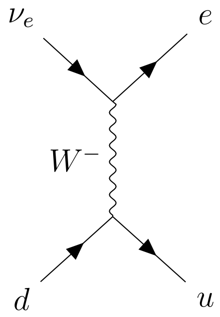
Fundamental vertex:



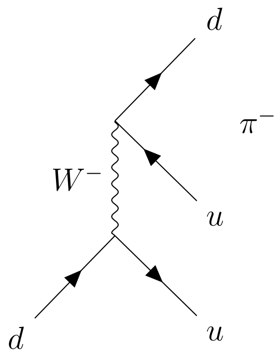
There are two types of processes that involve quarks:

- 'semileptonic' processes: quarks interact with leptons
- hadronic processes: only quarks interact

Example for a semileptionic process: $d + \nu_e \rightarrow u + e$



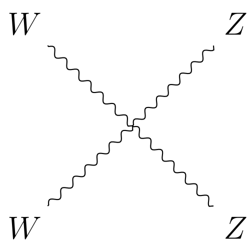
Example for a hadronic process: $d \rightarrow u + d + \bar{u}$

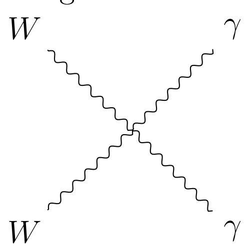


All quark generations are 'skewed' for the purposes of the weak interactions. "Strangeness" is not conserved. The reason is the coupling of quarks trough the Kobayashi-Maskawa matrix.

4.2.3 Weak and electromagnetic Couplings of W and Z

- the Ws can couple to the Zs, similar to glueballs.
- because the W is charged it can also couple to the γ $\rightarrow$ electroweak interaction





5 Decays

Generally every particle tends to decay into lighter particles unless a conservation law prevents it from doing so.

Stable particles:

- γ
- e^-
- p^+
- ν
- (n^0 is semi stable: stable inside a nucleus)

Unstable particles have a characteristic mean lifetime τ. $t_{1/2} = (ln2)\tau$.

Decays are governed by one of 3 forces. Depending on the force, the mean lifetimes are very different. The stronger the force, the shorter the mean lifetime. In addition, the decay is generally faster if there is a large mass difference between the decaying particle and the resultant particles. This is also related to a larger energy release.

We consider true decays happen only trough the weak force, since the weak force is the only one that can change the flavour of a particle. However, there are other processes that can be considered decays, such as the decay of the π^0. The π^0 decays trough the electromagnetic force trough the annihilation of the quarks inside it.

6 Conservation laws

Kinematic conservation laws derived from special relativity:

- energy conservation
- momentum conservation
- angular momentum conservation

Dynamical conservation laws based on fundamental vertices:

- charge conservation
- colour conservation
- baryon number conservation
  - baryon: 1
  - antibaryon: -1
  - meson: 0
- lepton number conservation
- flavour conservation (violated by the weak interaction - "approximately" conserved)

The **OZI rule**:

- related to the asymptotic freedom
- the coupling trough high energy gluons is suppressed
- Feynman diagram rule: if the gluon can be cut with a straight line without crossing external lines $\rightarrow$ the process is OZI suppressed $\rightarrow$ no decay