Summary - Elementary particle dynamics

by Dr. Helga Dénes (hdenes@yachaytech.edu.ec)

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: 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.

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^-

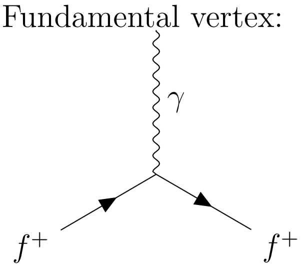
Basic Forces:

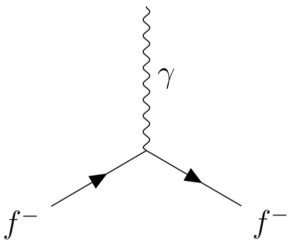
- **electromagnetic:** acts between charged particles, the force carrier particle is the photon.
- **strong:** acts between quarks, the force carrier particles are the gluons.
- **weak:** acts between all fermions. The force carrier particles are: W^+, W^-, Z bosons
- **gravity** (negligible for nuclear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

2 Quantum electrodynamics - QED

participating particles: charged fermions
force carrier: γ

Fundamental vertex:

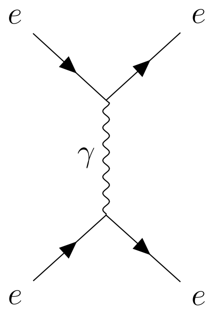




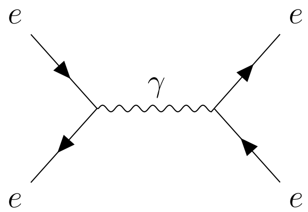
- In this document for all Feynman diagrams **time goes from left to right**.
- A fundamental vertex is not a real physical phenomena
- Real phenomena contain at least 2 vertices.
- One vertex consists of three connected lines.
- **Feynman diagrams** are a visual **representation of particle interactions** $\rightarrow$ 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

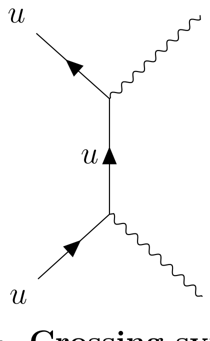
Coulomb repulsion - Møller scattering ($e^- + e^- \rightarrow e^- + e^-$):



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

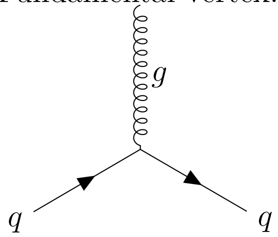
To analyse a particular physical process using Feynman diagrams:
- draw all possible diagrams (in practice usually only up to 4 vertices)
- weight diagrams based on how many vertices they have

- 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

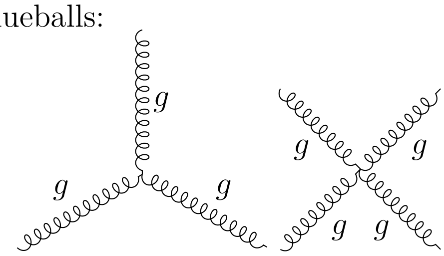
participating particles: quarks
force carrier: gluons

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**

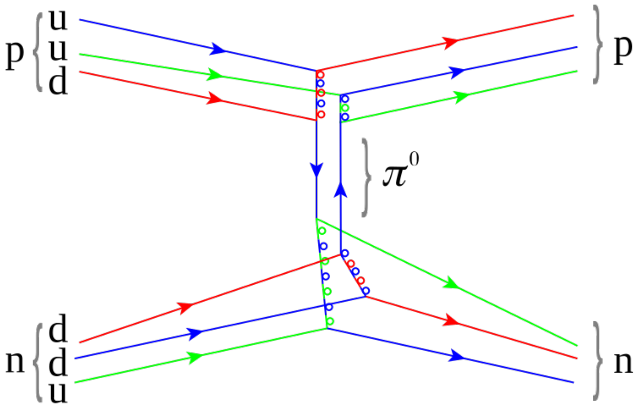


Figura 1: p^+ - n^- interaction. The middle section of the diagram shows a u and $\bar{u}$ or d and $\bar{d}$ quark which combine to a π^0. This is representing the meson exchange model of the strong nuclear force. Note that the coupling constant between the individual quarks inside the p^+ and n^0 is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

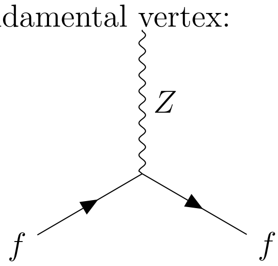
4 Weak interaction

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

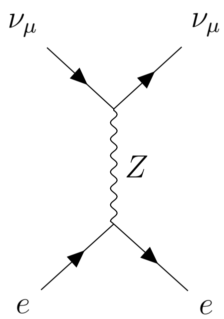
- neutrinos (ν) only participate in weak interactions
- the only interaction that can change flavour $\rightarrow$ true decays only happen trough weak interactions
- There are two kinds of weak interaction:
  - charged - mediated by the W^+, W^-
  - neutral - mediated by the Z

4.1 Neutral weak interaction

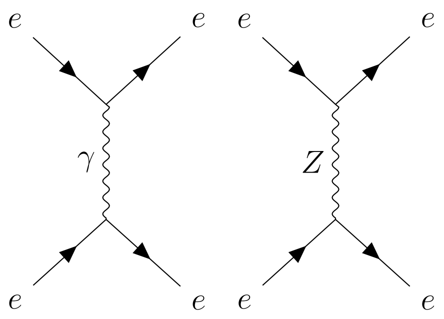
Fundamental vertex:



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



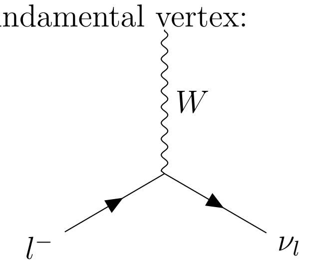
Any process mediated by the γ can also be mediated by the Z. This can add a tiny contribution to the Coulomb force. Example: $e^- + e^- \rightarrow e^- + e^-$



4.2 Charged weak interactions

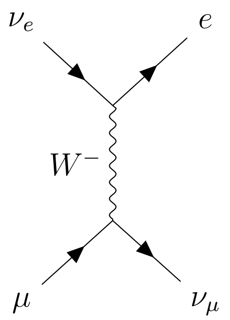
4.2.1 Leptonic processes

Fundamental vertex:



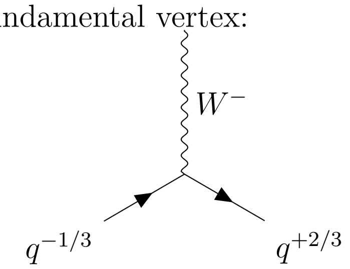
- Leptionic vertices connect only leptions of the same generations. e.g. e^- only to ν_e, μ^- only to ν_μ.
- Conservation of electron number, muon number and tau number

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



4.2.2 Quarks

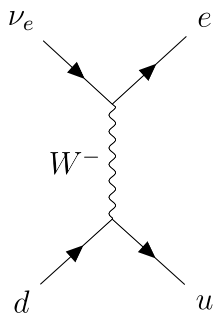
Fundamental vertex:



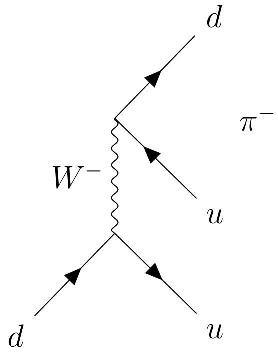
There are two types of processes that involve quarks:

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

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



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



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 $\to$ electroweak interaction