Introduction

Section is a recap of PEP4.

Elementary particle and their interactions are described by the Standard Model (SM): SM is a gauge theory describing the weak, electromagnetic and the strong interactions by the exchange of gauge bosons.

The Standard Model provides a successful description of current experimental data. The prediction and the experimental discovery of the Higgs boson was triumph of the model and of physics in general.

However there are observations which are not described by the model
- Massive neutrinos (however, they can be added)
- Dark matter
- Baryon asymmetry of the universe

There are also conceptual problems/questions of the theory:
- Hierarchy problem
- The flavor structure of the fermions (matter particles)
- How to include gravity

This is why people believe that the SM is a low energy “effective” theory of a more complex theory with new phenomena at higher energies

Fundamental matter particles

Fundamental constituents of matter are the spin ½ fermions.

We distinguish between **leptons** (like the electron) and **quarks.**
Both appear in 3 (!) generations.

Leptons:

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}\quad\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}\quad\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}\quad\begin{array}{c} Q_e[e]\\ 0\\ -1\end{array}$$

Lepton number $L_e = +1 \quad L_\mu = +1 \quad L_\tau = +1$

Anti-particles

$$\begin{array}{c} Q_e[e]\\ 0\\ 1\end{array}\quad\begin{pmatrix}\bar{\nu}_e\\ e^+\end{pmatrix}\quad\begin{pmatrix}\bar{\nu}_\mu\\ \mu^+\end{pmatrix}\quad\begin{pmatrix}\bar{\nu}_\tau\\ \tau^+\end{pmatrix}$$

$L_e = -1 \quad L_\mu = -1 \quad L_\tau = -1$

Lepton numbers L_i are separately conserved in all interactions:

$$\begin{array}{lll} & \mu^- & \rightarrow \nu_\mu\, e^-\, \bar{\nu}_e \\ L_\mu & = +1 & = +1 \\ L_e & = 0 & = 1-1 \end{array}$$

Beside their different masses and their different lepton numbers the leptons of the different generations behave the same and participate in the same interactions.

Lepton masses:

$$m_e \approx 511\,\mathrm{KeV}/c^2$$

$$m_\mu \approx 106\,\mathrm{MeV/c^2}$$

$$m_\mu \approx 1777\,\mathrm{MeV/c^2}$$

$m_\nu < 0.8\,\mathrm{eV}/c^2$ (direct meas.)

<150 meV/c^2 (cosmology)

Remark: Neutrinos

Compared to the other fermions, neutrinos are very light.
It was found that the observed lepton flavor states ν_e, ν_μ, ν_τ are mixtures of the mass eigenstates ν_1 , ν_3 , $\nu_{3.}$

Because neutrinos are neutral they could be (we don't know) their own anti-particles = Majorana particles: open question of current research?

Quarks:

$$\begin{array}{l} Q_e[e] \\ +2/3 \\ -1/3 \end{array} \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

… and the corresponding anti-quarks

Quark flavor is conserved in strong and electromagnetic interactions. Weak interaction does not conserve quark flavor:

e.g.: $s \rightarrow u + \ell^- \overline{\nu}_\ell$

Masses:

$$\boxed{\begin{array}{l} m_u \approx 2.2\, MeV / c^2 \\ m_d \approx 4.7\, MeV / c^2 \\ m_s \approx 93\, MeV / c^2 \\ m_c \approx 1.27\, GeV / c^2 \\ m_b \approx 4.2\, GeV / c^2 \\ m_t \approx 173\, GeV / c^2 \end{array}}$$

Quarks do not exist as free particles – mass definition is a bit involved.

Interactions (w/o gravity)

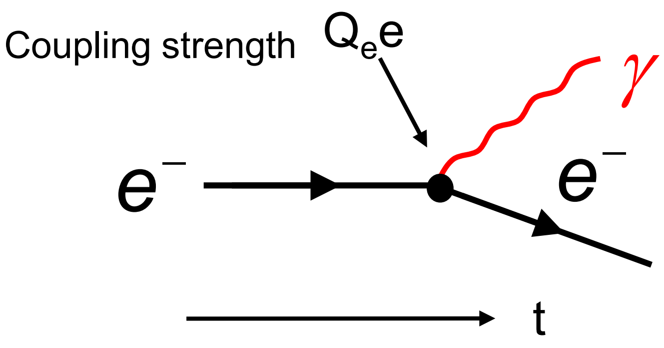
		weak	electro-magn.	strong
Leptons	ν	X	--	--
	ℓ	X	X	--
Quarks	u	X	X	X
	d	X	X	X

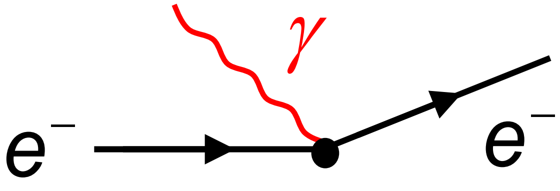
The interaction between particles are described by the exchange of gauge bosons with spin 1:

e.m.:	Photon γ, $Q_e = 0$, $m_\gamma = 0$
weak:	$W^\pm$, Z carry weak and electrical charge (W) Massive: $m_W \approx 80$ GeV/c^2 $m_z \approx 91$ GeV/c^2
strong:	8 gluons, carry color charge, $m_g = 0$

Electro-magnetic interaction

Fundamental process is the emission or absorption of a photon by a fermion:





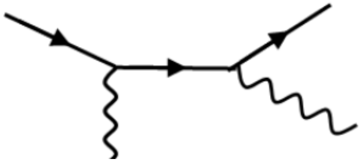
Reminder:

$$e \sim \sqrt{\alpha} = \sqrt{\frac{e^2}{4\pi\varepsilon_0 \hbar c}}$$

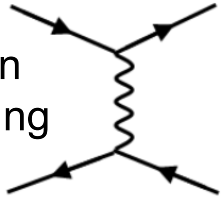
At each vertex 4-momentum (energy & momentum, charge, flavor number, etc. is conserved.

Since the photon is massless, 4-momentum conservation requires at least 2 QED vertices – examples. of possible processes:

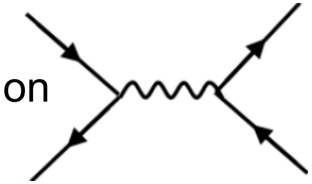
Compton-scattering



Fermion scattering



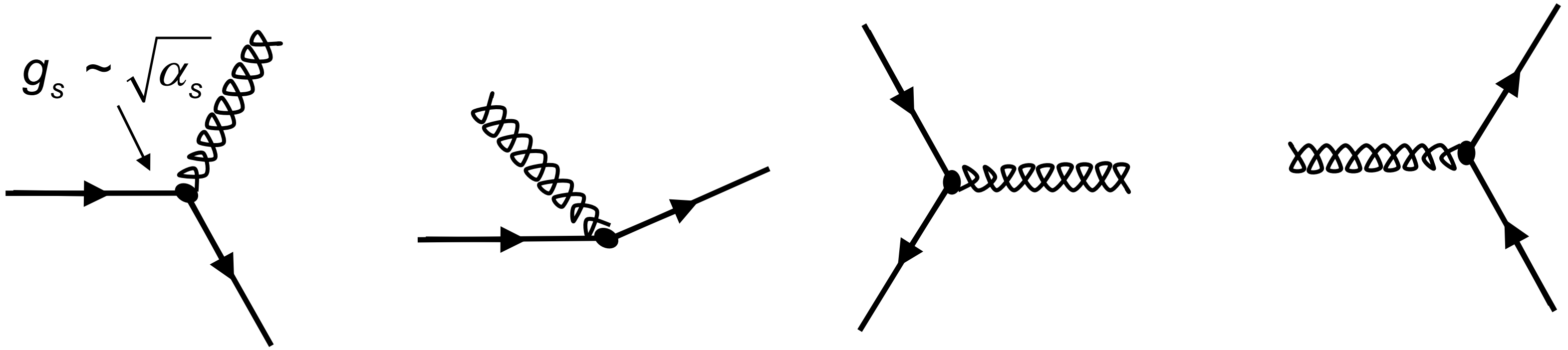
annihilation



Strong interaction

Quantum chromo-dynamics (QCD) is the gauge theory of the strong interaction. Similar to QED, the fundamental process is the absorption and the emission of gluons.

While photons couple to the electrical charge, gluons couple to color charged objects such as quarks:



Difference w/r to QED: gluons themselves carry color charge: emission and absorption of gluon by quarks change the color charge of the quarks.

There are three color (anti-color) states of (anti)quarks: $r, g, b \;\; (\bar{r}, \bar{g}, \bar{b})$

To change the color state, gluons must carry color/anti-color
The group structure of the underlying symmetry group explains why there are 8 gluons.

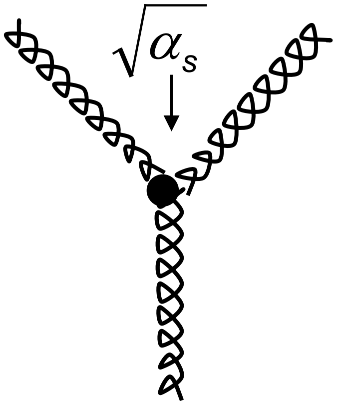
Like in QED, 4-momentum, flavor-number, charge and color-charge is conserved at any vertex.

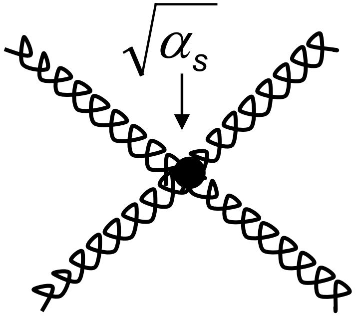
The strength of the gluon coupling to the quarks is equal for all (anti) quarks:

$$g_s \sim \sqrt{\alpha_s}$$

Gluon self-coupling:

As gluons carry color charge they can couple to each other: 3- and 4-gluon coupling:





Property of the strong interaction as result of the gluon self-coupling: The effective coupling constant α_s depends rather strongly on the distance / momentum scale. At very short distances (in scattering processes this corresponds to a large Q^2 of the 4-momentum exchange) α_s becomes very small; At large distance (small Q^2) α_s becomes very large. →

Confinement:

If one separates two (anti)quarks the potential energy increase w/ distance. It is therefore not possible to separate the two quarks – they are confined within each others color potential and do not exist free.

Hadrons:

Quarks are bound in hadrons.

$q\bar{q}$	Mesons such as $\pi^{\pm}$ ($u\bar{d}$), π^0, $K^{\pm}$, K^0
qqq	Baryons (or ante-baryons) such as p (uud), n, Λ

Recently observed: $q\bar{q}q\bar{q}$, $qqqq\bar{q}$ = bound tetra and pentaquark states

Mesons: We often deal with meson, so better know the convention

	$\bar{d}$	$\bar{u}$	$\bar{s}$	$\bar{c}$	$\bar{b}$	$\bar{t}$
d	π^0	π^-	K^0	D^-	$\bar{B}^0$	–
u	π^+	π^0	K^+	$\bar{D}^0$	B^+	–
s	$\bar{K}^0$	$\bar{K}^-$	η	D_s^-	B_s^0	–
c	D^+	D^0	D_s^+	η_c	B_c^+	–
b	$\bar{B}^0$	B^-	$\bar{B}_s^0$	B_c^-	η_b	–
t	–	–	–	–	–	–

all spin 0

Top quarks do not form bound states, because their lifetime (0.5×10^{-24} s) is smaller than the typical "hadronization time" (0.2×10^{-23} s ≈ time to separate ~1 fm). Top decay: $t \rightarrow b + W^+$

Baryons:

n, p, N: u,d quarks. I=1/2
Δ: u, d quarks, I=3/2

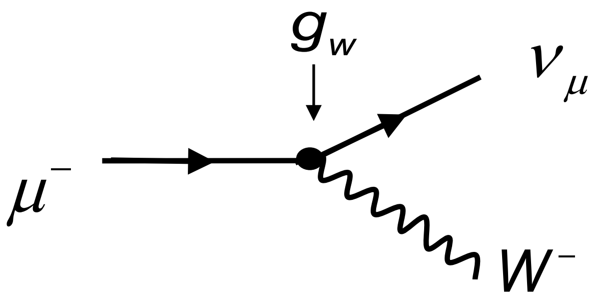
I = isospin, S=strangeness

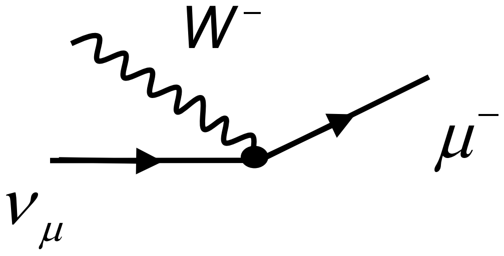
Λ: uds I=0, S=-1
Σ: u,d und ein s-quark I=1, S=-1
Ξ: uss, dss, I=1/2, S=-2

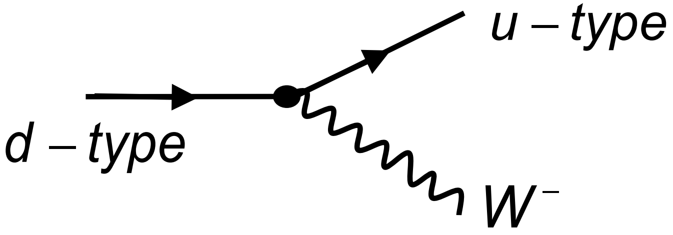
Weak interaction

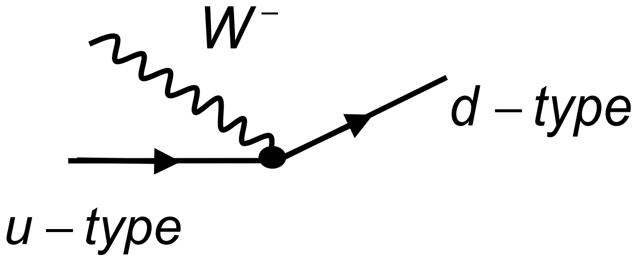
Weak processes are described by the emission or the absorption of massive $W^{\pm}$ bosons ($m_W \approx 80$ GeV/c^2) or Z bosons ($m_W \approx 91$ GeV/c^2). Both bosons carry weak charge. They couple to leptons and quarks with the strength g_w and g_Z.

"charged weak interaction": $W^{\pm}$ exchange

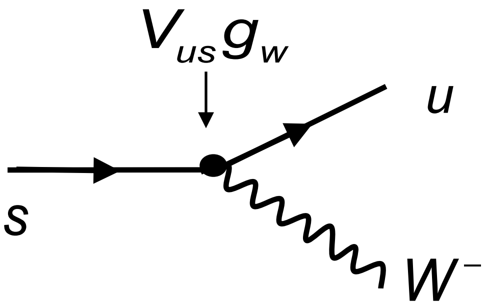


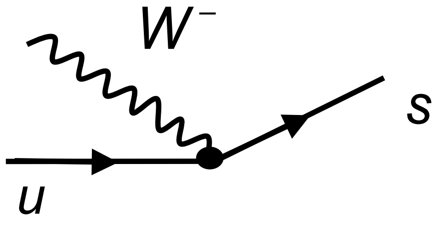






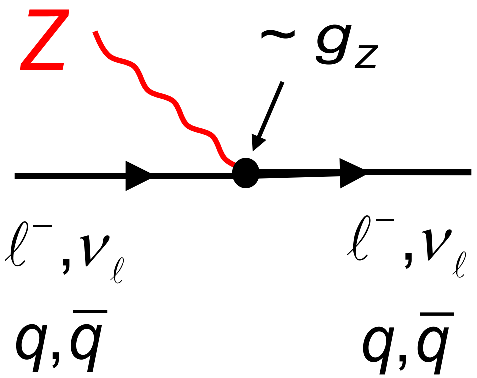
For leptons the transitions stay within the same generations $\mu \leftrightarrow \nu_\mu$, for quarks transitions across generations are possible: $s \rightarrow u$

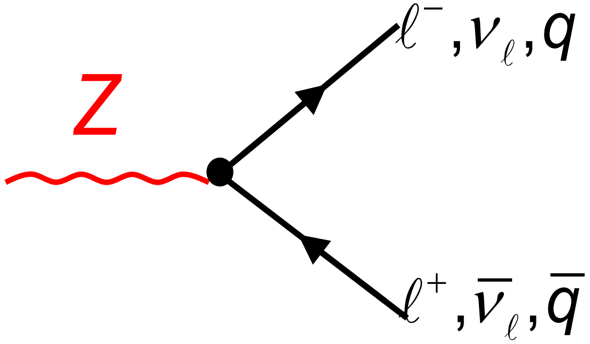




Mixing of generation is described by the CKM-matrix – coupling strength is modified w/r to lepton coupling.

<u>“neutral weak interaction”:</u> Z exchange



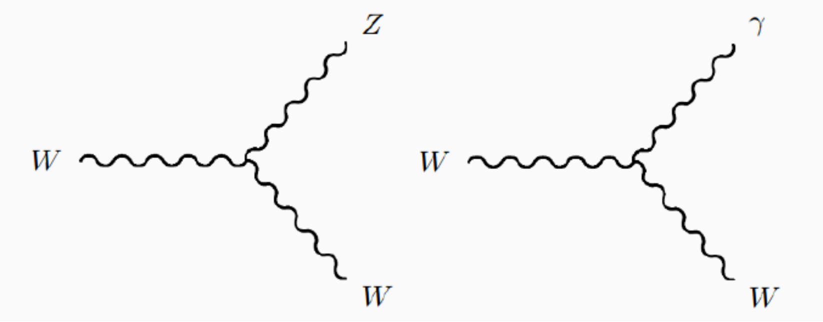


Coupling strength is proportional to g_Z but depend also on fermion type. (weak isospin)

Boson-boson coupling:

Since both bosons carry “weak charge” they also couple to each other:

There are therefore triple boson and also quartic boson couplings.



Triple boson couplings:

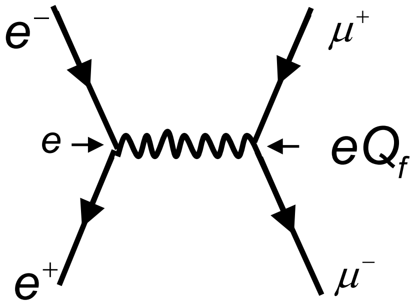
Remark: Weak interaction cannot be treated alone. Only together with the electromagnetic interaction, the electroweak theory forms a renormalizable gauge theory (electroweak Standard Model).

Observables

Feynman diagrams allow to calculate the transition amplitudes (matrix element) $\mathcal{A}_{fi}$ (or in the Lorentz invariant form $\mathcal{M}_{fi}$, see bleow) for a process.

Observables, such as cross sections σ or decay width (or decay rates) Γ are proportional to | $\mathcal{A}_{fi}$ $|^2$:

e.g. $e^+e^- \rightarrow \mu^+\mu^-$



$$\mathcal{A}_{fi} \sim e^2$$

$$\sigma \sim |\mathcal{A}_{fi}|^2 \sim e^4 \sim \alpha^2$$

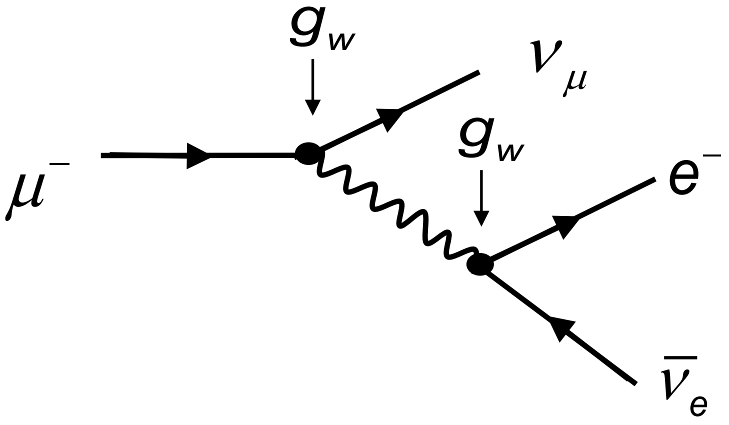
$$\boxed{\sigma = \frac{4\alpha^2 Q_f^2}{3} \frac{1}{E_{\text{CMS}}^2} (\hbar c)^2}$$

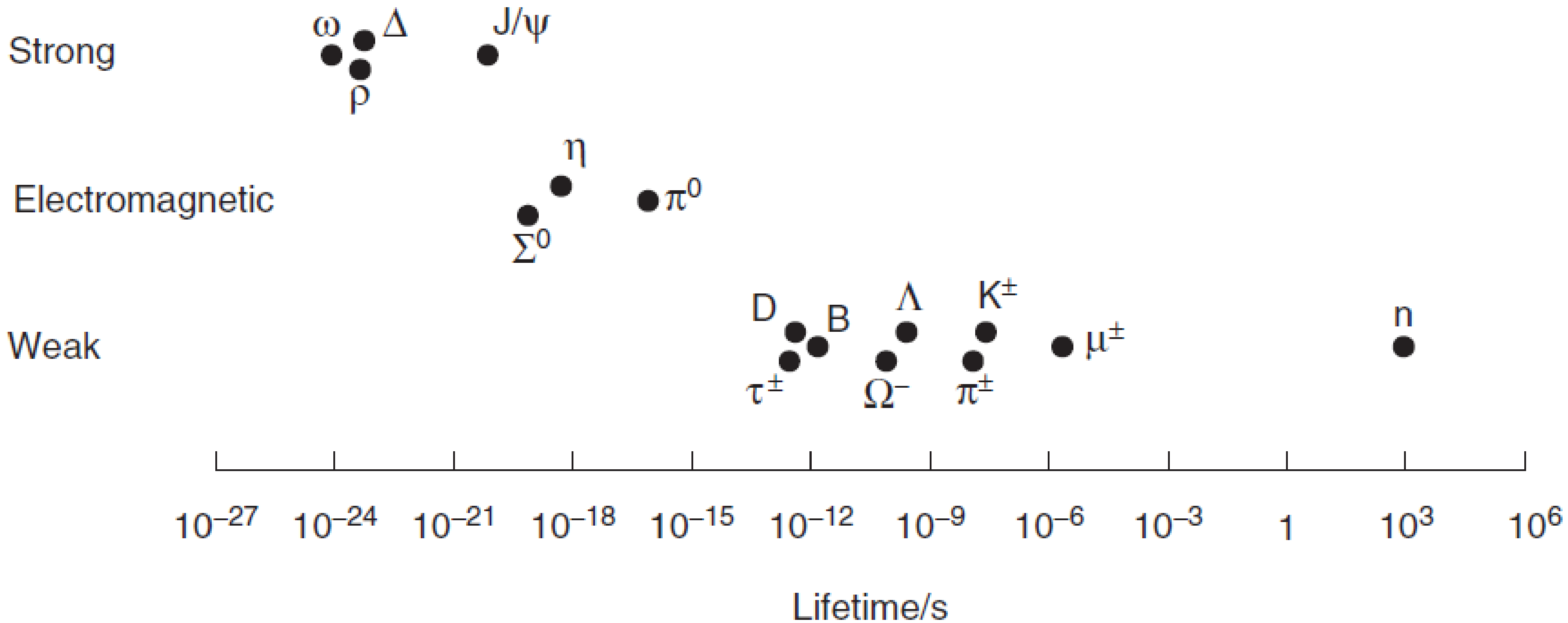
In addition to the square of the transition amplitude, the phase space of the final state particles which is related to the density of possible states at the final state energy E_f plays an important role (see below).

Example: Particle decay

$$\mu^- \to \nu_\mu e^- \overline{\nu}_e$$

$$\frac{1}{\tau} = \frac{\Gamma}{\hbar} \sim \left|\mathcal{A}_{fi}\right|^2 \sim g_w{}^4$$





from M. Thomson

A few underlying concepts

Units in particle physics

When quoting single particles mass, momentum and energy, SI units are not very practical. Instead we use GeV (MeV) as the base unit:

Mass	GeV/c^2		
Momentum	GeV/c		
Energy	GeV		
Length	$(\mathrm{GeV}/\hbar c)^{-1}$	→	$0.197\,\mathrm{fm}$
Time	$(\mathrm{GeV}/\hbar)^{-1}$	→	$0.658 \cdot 10^{-24}\,s$
Cross section	$(\mathrm{GeV}/\hbar c)^{-2}$	→	$0.389 \cdot \mathrm{mb}$ $0.389 \cdot 10^{-27}\,\mathrm{cm}^2$

$$\hbar c = 0.197\,\mathrm{GeV} \cdot \mathrm{fm}$$

$$\hbar = 0.658\,\mathrm{GeV} \cdot 10^{-24}\,s$$

$$(\hbar c)^2 = 0.389\,\mathrm{GeV}^2 \cdot \mathrm{mbarn} \qquad 1\,\mathrm{barn} = 1\,\mathrm{b} = 10^{-28}\,\mathrm{m}^2$$

Natural units $\hbar = c = 1$ in addition: $\varepsilon_0 = \mu_0 = 1$

Simplification of formulae: $E^2 = p^2 + m^2$

All components of a 4-vetor have the same dimension / unit.

All units can be now expressed in GeV. To calculate a result in SI units, need to multiply result with powers of $\hbar c$, $\hbar$, or c

Definition of α: $\alpha = \frac{e^2}{4\pi} = \frac{1}{137}$ (In SI units: $\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c} = \frac{1}{137}$)

E.g.: Lifetime of a particle τ.

To determine the lifetime of a particle the total decay widths Γ (=sum of partial decay widths Γ_i) is calculated. The dimension of the decay widths is energy. With $\hbar = 1$ the relation between lifetime and Γ simplifies to:

$$\tau = \frac{1}{\Gamma}$$

Lifetime in units 1/GeV can be easily converted into seconds by multiplying with $\hbar = 0.658\,\mathrm{GeV} \cdot 10^{-24}\,s$