2. Introduction on Particle Physics

Particles & interactions

Elementary particles
- Leptons
- Quarks

Interactions
- Strong interaction
- Weak interaction
- Electromagnetic interaction
- Gravity

Particle ‘classes’
- Fermions (particles with half-integer spin, e.g., spin = 1/2 \( \hbar \))
- Bosons (particles with integer spin, e.g., spin = 1 \( \hbar \))
  carriers of all the interactions
  gluons (\( g \)), \( W^\pm \) and \( Z^0 \) bosons, photons (\( \gamma \)), graviton (\( G \))
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Terminology

- **Leptons** – elementary particles not feeling strong interaction ($e$, $\mu$, ...)
- **Hadrons** – strongly interacting particles ($p$, $n$, $\pi$, ...), consists of two or three quarks
  - Baryons – particles with half-integer spin ($p$, $n$)
  - Mesons – particles with integer spin ($\pi$)
- **Fermions** – particles with half-integer spin
  - both leptons and hadrons
- **Bosons** – particles with integer spin
  - mesons
  - gauge bosons (photon, gluon, ... )
  - Higgs boson (not yet confirmed)
- **Nucleon**
  - proton or neutron
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Leptons

- Leptons are elementary particles
- They belong to fermions
- They interact via weak and electromagnetic interaction, but neutrinos interact only via weak interaction

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<tbody>
<tr>
<td>electron</td>
<td>e^-</td>
<td>0.511</td>
<td>stable</td>
<td>-1</td>
<td>1/2</td>
<td>e^+</td>
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<tr>
<td>muon</td>
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<td>105.7</td>
<td>2.2 µs</td>
<td>-1</td>
<td>1/2</td>
<td>µ^+</td>
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<td>tau</td>
<td>τ^-</td>
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<td>290 fs</td>
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<td>τ^+</td>
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<td>0</td>
<td>1/2</td>
<td>ν̅_τ</td>
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</table>
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Quarks

- Quarks are elementary particles
- They are fermions and are forming hadrons
  \[ p = uud, \quad n = udd, \quad \pi^- = \bar{u}d, \quad \pi^+ = u\bar{d} \]
- They feel all four interactions,
  strong interaction keeps them together

<table>
<thead>
<tr>
<th>Flavour Symbol &amp; Name</th>
<th>Mass [GeV/c^2]</th>
<th>Q</th>
<th>J</th>
<th>anti-particle</th>
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<tbody>
<tr>
<td>( u, ) up (ylös)</td>
<td>( \sim 3 \times 10^{-3} )</td>
<td>+2/3</td>
<td>1/2</td>
<td>( \bar{u} )</td>
</tr>
<tr>
<td>( d, ) down (alus)</td>
<td>( \sim 3 \times 10^{-3} )</td>
<td>−1/3</td>
<td>1/2</td>
<td>( \bar{d} )</td>
</tr>
<tr>
<td>( s, ) strange (outo)</td>
<td>( \sim 0.1 )</td>
<td>−1/3</td>
<td>1/2</td>
<td>( \bar{s} )</td>
</tr>
<tr>
<td>( c, ) charm (lumo)</td>
<td>( \sim 1.2 )</td>
<td>+2/3</td>
<td>1/2</td>
<td>( \bar{c} )</td>
</tr>
<tr>
<td>( b, ) bottom (pohja)</td>
<td>( \sim 4.2 )</td>
<td>−1/3</td>
<td>1/2</td>
<td>( \bar{b} )</td>
</tr>
<tr>
<td>( t, ) top (huippu)</td>
<td>( \sim 174 )</td>
<td>+2/3</td>
<td>1/2</td>
<td>( \bar{t} )</td>
</tr>
</tbody>
</table>

bottom and top quarks may also be called beauty (kauneus) and truth (totoo)
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Interactions and their carriers

The different interactions are described – in quantum language – by the exchange of characteristic bosons (between the fermion constituents)

The boson force mediators are

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<tr>
<td>strong</td>
<td>gluon, $g$</td>
<td>$1^-$</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>electromagnetic</td>
<td>photon, $\gamma$</td>
<td>$1^-$</td>
<td>0</td>
<td>0</td>
<td>10$^{-2}$</td>
</tr>
<tr>
<td>weak</td>
<td>$W^\pm, Z^0$</td>
<td>$1^-, 1^+$</td>
<td>80.4, 91.2</td>
<td>-1,+1, 0</td>
<td>10$^{-7}$</td>
</tr>
<tr>
<td>gravity</td>
<td>graviton, $G$</td>
<td>$2^+$</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</table>

Electromagnetism + weak interaction $\implies$ electroweak theory

Electroweak theory + strong interaction $\implies$ GUT, Grand Unified Theory
Strong interaction is responsible for binding quarks together, for example in proton and neutron. It – more accurately, the residual force – also binds protons and neutrons within the nuclei. The force between the quarks is mediated by the massless particle, the gluon.

Weak interaction processes are responsible for nuclear $\beta$-decay. The mediators of the weak interactions are massive $W^\pm$ and $Z^0$ bosons.

Electromagnetic interactions are responsible for nearly all the phenomena in extra-nuclear physics, i.e. with atoms and molecules. These interactions are mediated by photon exchange.

Gravitational interactions are supposedly mediated by graviton, a spin-2 boson. It has not yet experimentally observed.
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The standard model of particle physics – 1

- Only six particles are needed to make ordinary (normal) matter
  - electron
  - up and down quarks
  - gluon (gluon and photon are mediators)
  - photon (of interactions)
  - Higgs boson (creates the mass)

  ▸ others except Higgs boson found

- Proton = 2 \times up \text{ quark} + down \text{ quark} + gluons
- Neutron = up \text{ quark} + 2 \times down \text{ quark} + gluons

- In addition there are 11 other particles
  - muon and tau
  - four quarks
  - two bosons
  - three neutrinos
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The standard model of particle physics – 2

The standard model is the most comprehensive theory to explain particles and basic interactions of the Nature.

With these 17 particles and three different interactions the standard model is able to describe the *normal world* and nearly all the information collected in particle physics experiments.

- It has predicted new particles
  - W- ja Z-bosons
  - Higgs boson

- It does not explain all observations
  - neutrino masses
  - dark matter (probably unknown weakly interacting massive particles)
  - CP-violation (why matter dominates over anti-matter)

- Standard model can be extended
  - supersymmetry (able to explain dark matter)
  - string theory (the best theory(?) for gravity)
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Particle production

- Electron: \(<10^{-16}\) cm
- Quark: \(<10^{-16}\) cm
- Proton (neutron): \(~10^{-13}\) cm
- Atom: \(~10^{-8}\) cm
- Nucleus: \(~10^{-12}\) cm
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Particle production – Fusion reaction, $\sim 5$ MeV/nucleon
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Particle production – Spallation reaction, 1 GeV proton + Pb, U
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Particle production

CMS event at LHC
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Particle production

Simulated air shower
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Cross sections

Typical nuclear and particle physics reaction could look as

\[ p + ^{208}\text{Pb} \rightarrow X \rightarrow x + y + z + \ldots \]

The production "probabilities" of \( X \) and reaction products \( x \), \( y \) and \( z \) can be described by cross section (\( \sigma \))

- total cross section (\( \sigma_{\text{tot}} \))
- cross section for specific reaction channel (\( \sigma_x \))
- differential cross sections (\( d\sigma/dE \), \( d\sigma/d\theta \))

the unit of cross section is defined as the barn:

\( 1 \text{ b} = 10^{-28} \text{ m} = 10^{-24} \text{ cm} \) (range generally from pb to mb)

In the most simple case, the cross section can be considered as an effective (overlapping) area of two particles

\[ \sigma = \pi(r_p + r_t)^2 \]

where the particle cross area is \( A = \pi r^2 \).
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Cross section – Total cross section of $p + \text{Air}$
In astroparticle physics the energies involved are generally such that relativistic kinematics should be used.

The total energy \( E \) and mass \( m \) of the particle are related by

\[
E = mc^2
\]

where \( c \) is the velocity of light \( (c \approx 3 \times 10^8 \text{ m/s} = 30 \text{ cm/ns}) \).

The mass \( m \) of the particle is given as

\[
m = \frac{m_0}{\sqrt{1 - \beta^2}} = \gamma m_0, \quad \gamma = \frac{1}{\sqrt{1 - \beta^2}}
\]

where \( m_0 \) is the rest mass and \( \beta = v/c \) is the velocity of the particle. The quantity \( \gamma \) is called the Lorentz factor.
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High-energy kinematics – 2

The total energy \( E \) can thus also be written as

\[
E = \gamma m_0 c^2
\]

and \( m_0 c^2 \) is the rest energy.

The momentum \( p \) is

\[
p = mv = \gamma m_0 \beta c \quad (= \beta E/c)
\]

The total energy \( E \) can also be expressed as

\[
E^2 = c^2 (p^2 + m_0^2 c^2)
\]

This holds for all particles and is a Lorentz-invariant quantity. For massless particles (particles with rest mass zero) it yields

\[
E^2 = c^2 p^2
\]
For the general case of a collision of two particles with total energy $E_1$ and $E_2$ and momentum $p_1$ and $p_2$, the Lorentz-invariant center-of-mass energy $W$ can be expressed as

\[ W = \sqrt{s} = \ldots = \left[ m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2 \cos \theta) \right]^{1/2} \]

where the angle $\theta$ is the angle between $p_1$ and $p_2$.

At high energies, $\beta$’s $\rightarrow 1$ and $m_1, m_2 \ll E_1, E_2$

Threshold energy for production of particle of mass $m$:

\[ mc^2 \leq W = \sqrt{s} \]

In general, reaction kinematics is easy (easier) to calculate in the center-of-mass than in the laboratory system.
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High-energy kinematics – collisions – 2

(1) **Fixed-target accelerators**

Target (particle 2) at rest: \( E_2 = m_2 c^2 \), \( \beta_2 = 0 \)

The center-of-mass energy is now

\[
W = \sqrt{s} = \left[ m_1^2 + m_2^2 + 2E_1 m_2 c^2 \right]^{1/2} \approx \sqrt{2E_1 m_2 c^2}
\]

(2) **Colliding-beam accelerators**

Particles moving in opposite directions \( \implies \cos \theta = -1 \) (head-on collision)

The center-of-mass energy is now

\[
W = \sqrt{s} = \left[ m_1^2 + m_2^2 + 4E_1 E_2 \beta_1 \beta_2 \right]^{1/2} \approx 2 \sqrt{E_1 E_2}
\]
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High-energy kinematics – collider energies

**Example**

At the Tevatron collider at Fermilab protons and antiprotons can be accelerated up to the energy of 1 TeV. The center-of-mass energy $W$ is then

$$W = 2 \sqrt{E_1 E_2} = 2E = 2 \text{ TeV}$$

In order to obtain the same center-of-mass energy with a fixed-target accelerator, the energy of the proton beam, in collision with proton target, would have to be

$$E_1 = \frac{s}{2m^2c^2} = 2000 \text{ TeV} = 2 \text{ PeV}$$

For comparison: at LHC, $W = 7 \text{ TeV} + 7 \text{ TeV} = 14 \text{ TeV}$
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Comparison of cosmic-ray and accelerator energies
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Neutrinos – 1

- Neutrinos exist in three flavors: $\nu_e, \nu_\mu, \nu_\tau$ (and their anti-$\nu$’s)
- If neutrinos have mass (mass eigenstates $\nu_1, \nu_2, \nu_3$) flavors can mix, and the flavor states can be described as a superposition of mass eigenstates

$$\nu_\ell = \sum_{i=1}^{3} U_{\ell i} |\nu_i\rangle,$$

where $\ell = e, \mu, \tau$ and $U_{\ell i}$ is an element of the mixing matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix}$$

- The mixing matrix is called Maki-Nakagawa-Sakata-Pontecorvo (MNSP) matrix
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Neutrinos – 2

- The MNSP matrix can be factorized as

\[ U = U_{12} \times U_{23} \times U_{13} \]

with

\[ U_{12} = \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad U_{23} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}, \]

\[ U_{13} = \begin{bmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \]

and

\[ c_{ij} = \cos \Theta_{ij}, \quad s_{ij} = \sin \Theta_{ij} \]

where \( \Theta_{ij} \)'s are called the mixing angles (\( \Theta = 45^\circ \) is full mixing), and the phase factor \( \delta \) contains the possible CP-violation.
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Neutrinos – 3

- The probability of electron neutrino of energy $E$ [MeV] to survive in electron state after the distance $L$ [m] is

$$P_e = 1 - \sin^2 \Theta_{12} \cdot \sin^2 \left(1.27 \frac{\Delta m_{12}^2 \cdot L}{E}\right)$$

where $\Delta m_{12}^2 = m_2^2 - m_1^2$ is the difference of mass squares

- If the oscillation takes place ($P_e < 1$)

$$\implies \Delta m_{12}^2 \neq 0 \implies m_1 \neq 0 \text{ and/or } m_2 \neq 0$$

- Matter effects

- How to study (sources)
  - $U_{12}$ – Sun and reactor neutrinos
  - $U_{23}$ – atmospheric neutrinos
  - $U_{13}$ – neutrino beams (accelerators)