# Introduction to particle physics at LHC

Limassol — July 19, 2025

## Relativistic kinematics

1. Find the inverse lorentz transformation for time and space.
2. Show, that in the non-relativistic limit ($v \ll c$) total energy equals the sum of a mass and a classic kinematic energy of a particle.
3. Show that massless particle cannot decay into two massive particles.
4. Can a massive particle decay into two massless particles?
5. Can two massive particles be produced in collision of two massless particles?
6. Can a $K^+$ meson decay into $\pi^+\pi^+\pi^-$ ?
7. Heavy particle with mass $M$ decays into two lighter particles, $m_1$ and $m_2$. Find the momenta of the decay products of initial particle and draw their momentum distributions. How is this momentum distribution related to the beta decay problem, discussed in the lecture?
8. Hypothetical particle decays into 4 very light particles , their measured momentum components in the detector are $p_{x,1}, p_{x,2}, ...p_{z,3}, p_{z,4}$. What is the measured invariant mass of the initial particle? Consider general case, when there are $N$ particles with measured momenta.

## General particle physics problems

1. Estimate the ratio of number of Z bosons and Higgs boson produced in 2012 at LHC.
2. Estimate the ratio of number of Z and Higgs bosons, decaying to muons.

Table 1: Masses of Elementary Particles (in GeV)

| **Particle** | **Mass (GeV)** |
|---|---|
| **Quarks** | |
| Up (u) | $\sim$0.0022 |
| Down (d) | $\sim$0.0047 |
| Charm (c) | 1.27 |
| Strange (s) | $\sim$0.096 |
| Top (t) | 172.76 |
| Bottom (b) | 4.18 |
| **Leptons** | |
| Electron ($e^-$) | 0.000511 |
| Muon ($\mu^-$) | 0.10566 |
| Tau ($\tau^-$) | 1.77686 |
| Electron Neutrino ($\nu_e$) | $< 2.2 \times 10^{-9}$ |
| Muon Neutrino ($\nu_\mu$) | $< 0.17 \times 10^{-6}$ |
| Tau Neutrino ($\nu_\tau$) | $< 18.2 \times 10^{-6}$ |
| **Bosons** | |
| Photon ($\gamma$) | 0 |
| Gluon (g) | 0 |
| $W^\pm$ boson | 80.379 |
| Z boson | 91.1876 |
| Higgs boson (H) | 125.25 |

Table 2: Masses of Selected Mesons and Baryons (in GeV/$c^2$)

| **Particle** | **Type** | **Mass (GeV/$c^2$)** |
|---|---|---|
| **Mesons** | | |
| $\pi^+$ (Charged pion) | Light meson | 0.13957 |
| $\pi^0$ (Neutral pion) | Light meson | 0.13498 |
| $K^+$ (Charged kaon) | Strange meson | 0.49368 |
| $K^0$ (Neutral kaon) | Strange meson | 0.49761 |
| $\eta$ | Light meson | 0.54786 |
| $D^0$ | Charmed meson | 1.86483 |
| $D^+$ | Charmed meson | 1.86965 |
| $B^0$ | Bottom meson | 5.27963 |
| $B^+$ | Bottom meson | 5.27934 |
| $J/\psi$ ($c\bar{c}$) | Charmonium | 3.09690 |
| $\Upsilon(1S)$ ($b\bar{b}$) | Bottomonium | 9.46030 |
| **Baryons** | | |
| Proton ($p$) | Nucleon | 0.93827 |
| Neutron ($n$) | Nucleon | 0.93957 |
| $\Lambda$ | Strange baryon | 1.11568 |
| $\Sigma^+$ | Strange baryon | 1.18937 |
| $\Sigma^0$ | Strange baryon | 1.19264 |
| $\Xi^0$ | Doubly strange | 1.31486 |
| $\Omega^-$ | Triply strange | 1.67245 |
| $\Lambda_c^+$ | Charmed baryon | 2.28646 |
| $\Xi_c^0$ | Charmed baryon | 2.47087 |
| $\Lambda_b^0$ | Bottom baryon | 5.61960 |

Table 3: Production Cross Sections at $\sqrt{s} = 13$ TeV (LHC)

| **Process** | **Production Mode** | **Cross Section (pb)** |
|---|---|---|
| **Higgs Boson** | | |
| Higgs ($H$) | Gluon Fusion (ggF) | $\sim$48.6 |
| | Vector Boson Fusion (VBF) | $\sim$3.8 |
| | WH associated | $\sim$1.4 |
| | ZH associated | $\sim$0.9 |
| | $t\bar{t}H$ associated | $\sim$0.5 |
| **Electroweak Bosons** | | |
| Z boson ($Z$) | Inclusive (Drell–Yan) | $\sim$57,000 |
| $W^{\pm}$ boson | Inclusive (Drell–Yan) | $\sim$95,000 |
| **Top Quark** | | |
| $t\bar{t}$ pair | QCD production | $\sim$832 |
| Single top | $t$-channel | $\sim$136 |
| | $s$-channel | $\sim$7.1 |
| | $tW$ associated | $\sim$71.7 |

Table 4: Branching Fractions of the W, Z, and Higgs Bosons (approximate)

| **Boson** | **Decay Mode** | **Branching Fraction (%)** |
|---|---|---|
| W | $W \to e\nu_e$ | 10.8 |
| W | $W \to \mu\nu_\mu$ | 10.6 |
| W | $W \to \tau\nu_\tau$ | 11.3 |
| W | $W \to$ hadrons | 67.6 |
| Z | $Z \to e^+e^-$ | 3.37 |
| Z | $Z \to \mu^+\mu^-$ | 3.37 |
| Z | $Z \to \tau^+\tau^-$ | 3.37 |
| Z | $Z \to \nu\bar{\nu}$ (all flavors) | 20.0 |
| Z | $Z \to$ hadrons | 69.9 |
| H | $H \to b\bar{b}$ | 58.0 |
| H | $H \to WW^*$ | 21.5 |
| H | $H \to gg$ | 8.5 |
| H | $H \to \tau^+\tau^-$ | 6.3 |
| H | $H \to c\bar{c}$ | 2.9 |
| H | $H \to ZZ^*$ | 2.6 |
| H | $H \to \gamma\gamma$ | 0.23 |
| H | $H \to Z\gamma$ | 0.15 |
| H | $H \to \mu^+\mu^-$ | 0.02 |