1. **Laboratory and center-of-mass coordinate systems**
Consider the collision of two particle of equal mass M travelling in opposite directions with the same speed. The center-of-mass energy is now $E_{cm} = Wc^2 = \sqrt{s}$. Show that the energy of the moving particle E_1 in the laboratory system is
$$E_1 = \frac{E_{cm}^2}{2Mc^2} - Mc^2.$$
The target particle 2 is at rest: $E_2 = Mc^2$.
Hint: s is a Lorentz-invariant variable.

2. **Relativistic kinematics, time dilation, particle decay**
Cosmic-ray muons are produced in the upper parts of the atmosphere from where they may propagate down to the Earth's surface.
Calculate the average minimum kinetic energy needed for a cosmic-ray muon to propagate down to the sea level before decaying. The production altitude of muons is taken to be 20 km. Assume no interaction in the atmosphere. Average lifetime of the muon is $\tau_\mu = 2.197\ \mu\text{s}$ and its rest mass is $m_\mu = 105.66\ \text{MeV}/c^2$.

3. **Cross section**
The mean free path λ is related to the nuclear cross section σ_N by
$$\lambda = \frac{1}{N_A \sigma_N}$$
where N_A is the Avogadro number, i.e., the number of nucleons per gram and σ_N is the cross section per nucleon.
The number of particles, N, penetrating a target of thickness x unaffected by the interactions is
$$N = N_0 e^{-x/\lambda},$$
where N_0 is the initial number of particles.
Assume target thickness of 100 mg/cm^2, 10^8 beam particles and cross section of 1b. (1 b $= 10^{-28}$ m^2)
How many collisions happen? Use thin-target approximation ($x \ll \lambda$) and series expansion to create simple expression.

4. **Cross section**
Pion-particle flow is guided through a target of liquid hydrogen. The reaction
$$\pi^- + p \to K^0 + \Lambda,$$
where K^0-mesons and Λ-baryons are produced, is observed.
Calculate the production rate of Λ-baryons, when the pion flux is $10^7\text{m}^{-2}\text{s}^{-1}$, the target volume is 10^{-4}m^3 and the density of target matter is 71 kg m^{-3}. The cross-section of the particular process is 0.4 mb.