1. A 10 GeV muon can be considered as a MIP with a mean $\mathrm{d}E/\mathrm{d}x \approx 1.5\,\mathrm{MeV\,g^{-1}\,cm^2}$ in most materials.

   (a) What is the rate of energy loss in MeV/ m of a 10 GeV muon travelling through pure nitrogen at atmospheric pressure (density = 1 g/litre)?

   (b) Estimate the range (i.e. the distance travelled before coming to rest) of a 10 GeV muon travelling through steel (density = $7.9\,\mathrm{g\,cm^{-3}}$).

2. Consider a wire or strip detector in the xy plane, with thin detector elements in the x direction separated by a distance (called the *pitch*) Δy. A particle travelling in the z direction passes between two wires. Show that the intrinsic resolution (defined as the RMS distance between the measured and true particle positions) is given by $\Delta y/\sqrt{12}$.

3. A 4 m long TPC was used as the main tracking detector for the ALEPH experiment at LEP. Explain why a similar device was not considered for the ATLAS or CMS detectors at the LHC (Typical drift speed in a TPC is $5\,\mathrm{cm}/\,\mu\mathrm{s}$).

4. Consider a strip detector made from $300\,\mu$m thick silicon with resistivity $5\,k\Omega\,$cm.

   (a) What applied voltage is required to fully deplete the silicon?

   (b) What is the mean energy deposited by a MIP traversing normally to the wafer (assume $\mathrm{d}E/\mathrm{d}x = 1.5\,\mathrm{MeV\,g^{-1}\,cm^2}$, silicon density = $2.3\,\mathrm{g\,cm^{-3}}$) ?

   (c) Calculate the energy required on average to create an electron-hole pair (assume a MIP particle creates $7.5 \times 10^7\,\mathrm{m^{-1}}$ electron-hole pairs in the depletion region). Why is this greater than the 1.1 eV band gap in silicon?

5. An electromagnetic calorimeter is made from layers of 1 mm thick tungsten interspersed with 1 mm layers of scintillator. Tungsten has $Z = 74$, $A = 184$ and a density of $19.3\,\mathrm{g\,cm^{-3}}$.

   (a) What is the radiation length X_0 (in cm) of Tungsten?

   (b) A simplified description of an EM shower is that every X_0 the number of particles doubles, with the energy of each particle halving. The shower will stop when the energy falls below the critical energy. Estimate the thickness of the calorimeter required to completely contain the shower caused by a 100 GeV electron. (The critical energy in Tungsten is 8.3 MeV, and you can ignore interactions in the scintillator).

   (c) If the scintillator density is $1.1\,\mathrm{g\,cm^{-3}}$, what is the total ionisation energy deposited in the scintillator by the particles in the shower? (treat all particles as MIPs).

   (d) If the efficiency of detecting a scintillation photon is 5%, how many photons will be collected in total (assume 1 photon is created per 100 eV)?

   (e) How many nuclear interaction lengths (λ_{int}) thick is this calorimeter?

6. (a) Write down the expression for the RMS scattering angle for a particle passing through a 1 mm layer of aluminium as a function of the particle momentum ($X_0 = 8.9\,$cm).

   (b) A 500 MeV pion travel 6 cm at which point it hits a 1 mm thick sheet of Aluminium. After a further 6 cm it travels through a tracking detector that precisely measures its trajectory of in order to measure its exact point of production. What is the error (in cm) in the measurement of the point of origin caused by the multiple scattering in the aluminium?