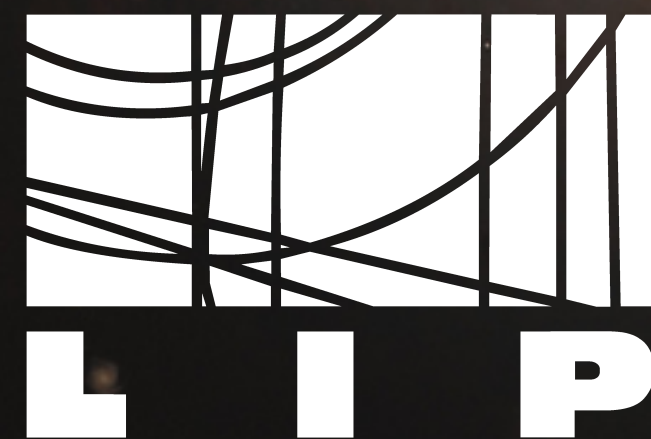


Astroparticle Physics

Exercises

Ruben Conceição



TÉCNICO
LISBOA

Production of Cosmic Rays

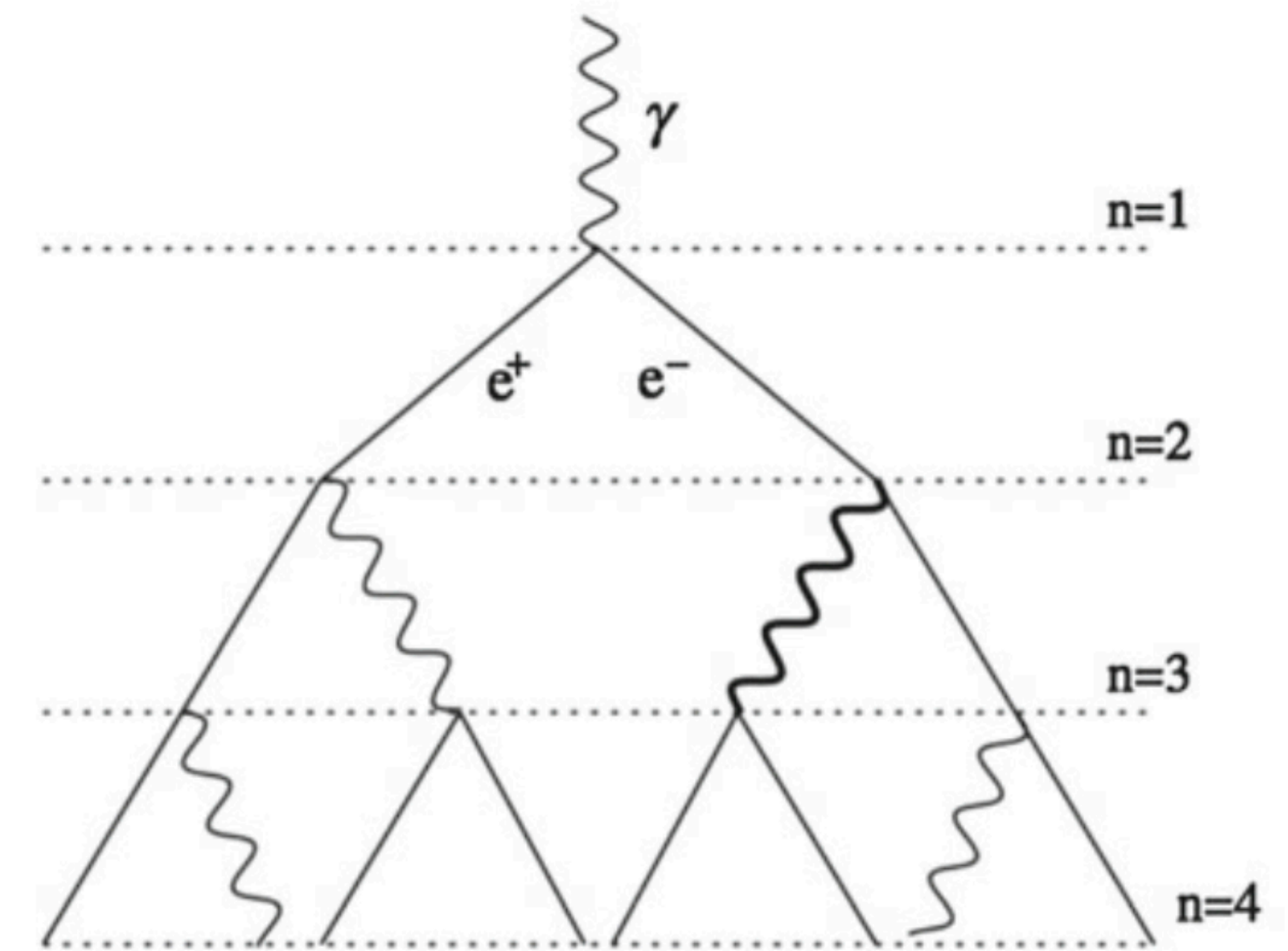
- 1.** In the Fermi acceleration mechanism, charged particles increase considerably their energies crossing back and forth many times the border of a magnetic cloud (second-order Fermi mechanism) or of a shock wave (first-order Fermi mechanism). Compute the number of crossings that a particle must do in each of the mechanisms to gain a factor 10 on its initial energy assuming:
- a.** $\beta = 10^{-4}$ for the magnetic cloud and $\beta = 10^{-2}$ for the shock wave;
 - b.** $\beta = 10^{-4}$ for both acceleration mechanisms.
- where β is the velocity of the astrophysical object (shock wave or cloud).

The GZK effect

- 2.** The Cosmic Microwave Background fills the Universe with photons with a peak energy of 0.37 meV and a number density of $n \sim 400/\text{cm}^3$.
- a.** Determine the minimal energy (known as the GZK threshold) that a proton should have in order that the reaction $p\gamma \rightarrow \Delta$ may occur.
 - b.** The GZK threshold is 6×10^{19} eV. Discuss the probable origin of the discrepancy found in the previous question.

The Heitler model for EAS

3. The main characteristic of an electromagnetic shower (say, initiated by a photon) can be obtained using a simple Heitler model. Let E_0 be the energy of the primary particle and consider that the electrons, positrons and photons in the cascade always interact after traveling a certain atmospheric depth $d = X_0$, and that the energy is always equally shared between the two particles. With this assumptions, we can schematically represent the cascade as in the shown in the figure.



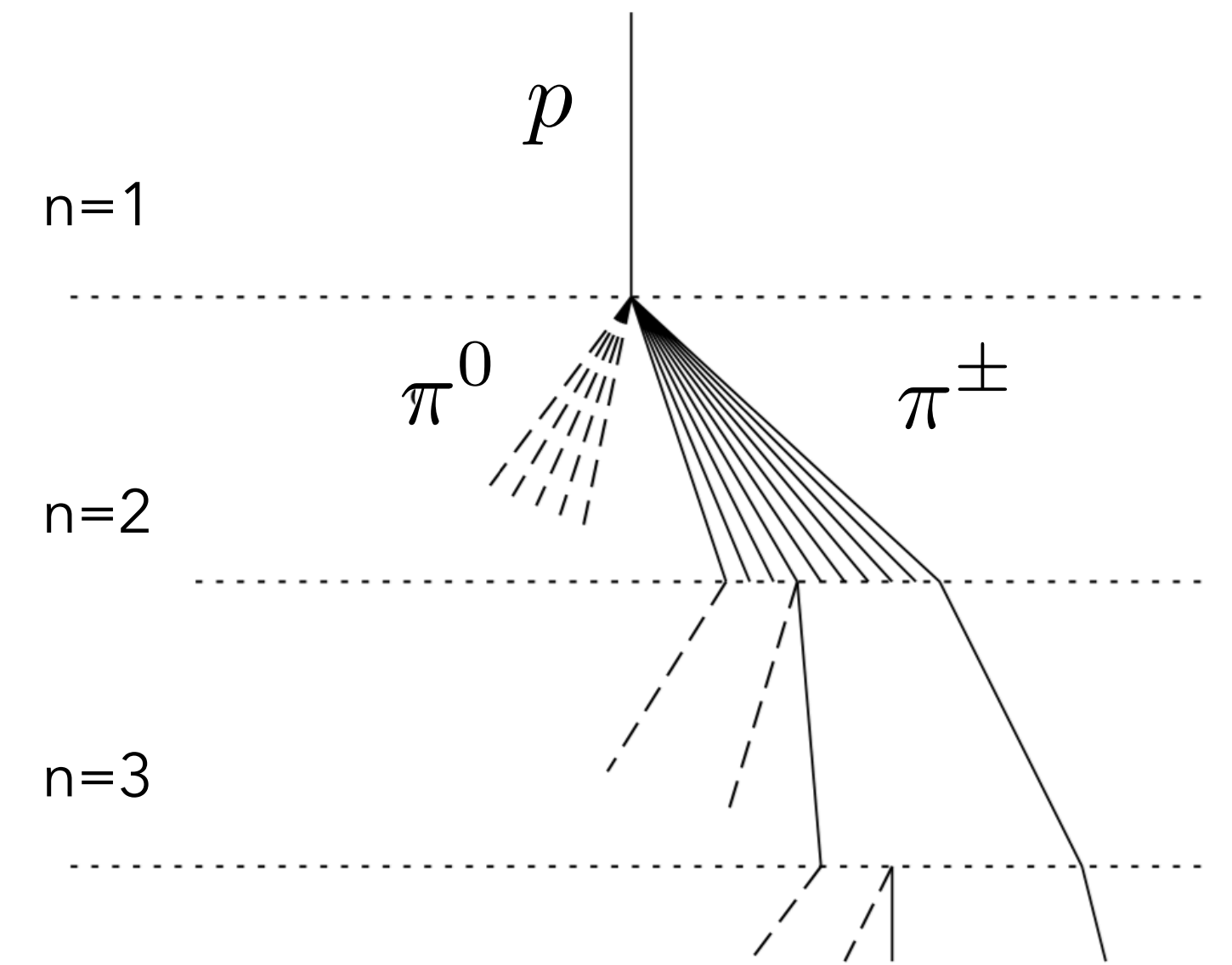
a. Write the analytical expressions for the number of particles and for the energy of each particle at depth X as a function of d , n and E_0 .

b. The multiplication of the cascade stop when the particles reach a critical energy, E_c (when the decay probability surpasses the interaction probability). Using the expressions obtained in the previous question, write as a function of E_0 , E_c and $\lambda = d / \ln 2$, the expressions, at the shower maximum, for:

- i.** The average energy of the particles;
- ii.** The number of particles, N_{\max} ;
- iii.** The atmospheric depth, X_{\max} .

Heitler-Matthews model for EAS

4. Consider a shower initiated by a proton of energy E_0 . We will describe it with a simple Heitler-like model: after each depth d an equal number of pions, n_π , and each of the 3 types is produced: π^0 , π^+ , π^- . Neutral pions decay through $\pi^0 \rightarrow \gamma\gamma$ and their energy is transferred to the electromagnetic cascade. Only the charged pions will feed the hadronic cascade. We consider that the cascade ends when these particles decay as they reach a given decay energy E_{dec} , after n interactions, originating a muon (plus an undetected neutrino).



Assuming the validity of the superposition principle, according to which a nucleus of mass number A and energy E_0 behaves like A nucleons of energy E_0/A , derive expressions for:

- a.** the depth where this maximum is reached, X_{max} ;
- b.** the number of muons produced in the shower, N_μ .

Acknowledgements

