Advanced Theoretical Astro–Particle Physics (WS 22/23)
Homework no. 6 November 16, 2022)

To be completed by: Thursday, November 23.

1 IceCube and Very Energetic Neutrinos

The total νp scattering cross section at energies above 0.1 TeV can very roughly be parameterized as

$$\sigma_{\nu p} = \begin{cases} 10^{-35}\ \mathrm{cm}^2 \cdot (E_\nu/1\ \mathrm{TeV})\,, & \text{for } E_\nu \leq 10\ \mathrm{TeV} \\ 10^{-33}\ \mathrm{cm}^2 \cdot \sqrt{(E_\nu/1\ \mathrm{PeV})}\,, & \text{for } E_\nu \geq 10\ \mathrm{TeV} = 0.01\ \mathrm{PeV}\,. \end{cases} \tag{1}$$

This extends eq.(I.103) to higher energies; eq.(1) breaks down above $\sim 10^{18}$ eV.

1. Show that neutrinos with energies well above a TeV traveling through the Earth (distance $\sim 10^4$ km, average density ~ 5 g/cm^3) begin to have a sizable probability to interact at least once, and that the Earth is basically opaque to neutrinos with energies above a PeV. How could one interpret the observation of events coming from below with energy well above 1 PeV?

2. Discuss qualitatively what happens when ν_e, ν_μ and ν_τ undergo neutral current or charged current interactions while traversing the Earth. Note that the NC scattering contributes about one third to the total cross section (1), and assume that the outgoing lepton on average carries about half the energy of the incoming one. In case of ν_μ CC interactions, compare the stopping length of a muon, given by

$$L_{\mu,\mathrm{stop}} \simeq 2.5 \cdot 10^5 \frac{\mathrm{g}}{\mathrm{cm}^2} \frac{1}{\rho} \ln\left(1 + \frac{E_\mu}{0.5\ \mathrm{TeV}}\right)\,, \tag{2}$$

   see eqs.(I.109), (I.110), with its decay length. The lifetime of τ leptons is about $3 \cdot 10^{-13}$ s.

3. Assuming an isotropic flux of primary cosmic rays, show that IceCube will see an equal number of neutrinos produced in air showers from all directions, if absorption in the Earth can be neglected, although it is located very far from the center of the Earth. How can this be used to measure the total νp cross section at high energies? (This measurement has actually been performed, see arXiv:1711.08119.)

4. The mass of a τ lepton is about 1.8 GeV. What is the minimal τ energy where IceCube can see a “double bang” (a.k.a. cascade) signature, with production and decay vertex at least 20 m apart? (The separation between optical modules in IceCube is about 15 m vertically, i.e. along a string; the horizontal distance between strings is 125 m.) *Note:* Due to their unique signature, this kind of events can even be

observed for downgoing neutrinos, where most other signatures are overwhelmed by the background of muons produced in air showers. In fact, it probably has been observed, see arXiv:1908.05506.