Exercises for Neutrino Physics: Theory and Experiment

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Sheet 5: Experiment

1. **Neutrino beam production [6 Points]**

   Let us consider that after an energetic proton beam hits onto a carbon target, a 10 GeV beam consisting of positive pions and kaons is created. This beam is then brought into a 500 m long decay pipe.

   (a) What is the fraction of pions and kaons (respectively) decaying in the tube? *Note: Look up the meson masses and lifetimes.*

   (b) Determine the maximum energy of the generated neutrino beam from pion and kaon decay.

   (c) Demonstrate that the minimum neutrino energy is vanishing in good approximation.

2. **Energy profile of neutrino beams [6 Points]**

   A neutrino beam of energy $E_\nu = 20$ GeV is produced from the decay of charged pions.

   (a) Write down all decay channels leading to neutrinos.

   (b) Estimate the energy of the pion beam that has generated the neutrino beam (assuming monochromaticity)

   (c) Estimate the divergence of the neutrino beam at the far detector located at a distance of 100 km downstream of the beam pipe

   (d) Estimate the order of magnitude of the neutrino-nucleus cross section. Take into account the different contributions showcased in Figure 1

   (e) Estimate the mean free path of those neutrinos in water.

3. **Measuring $\delta_{\rm CP}$ [3 Points]**

   Neutrino beams offer a very good tool to determine the value of $\delta_{\rm CP}$. Which parameter should be derived in order to determine this value? Briefly describe the strategy used by the two upcoming experiments T2HK and DUNE.

4. **CP-Asymmetry [5 Points]**

   (a) Consider two transition amplitudes

$$A_i = A \exp\{i\rho_i\} \exp\{i\alpha_i\} \quad , i \in \{1, 2\} \,. \tag{1}$$

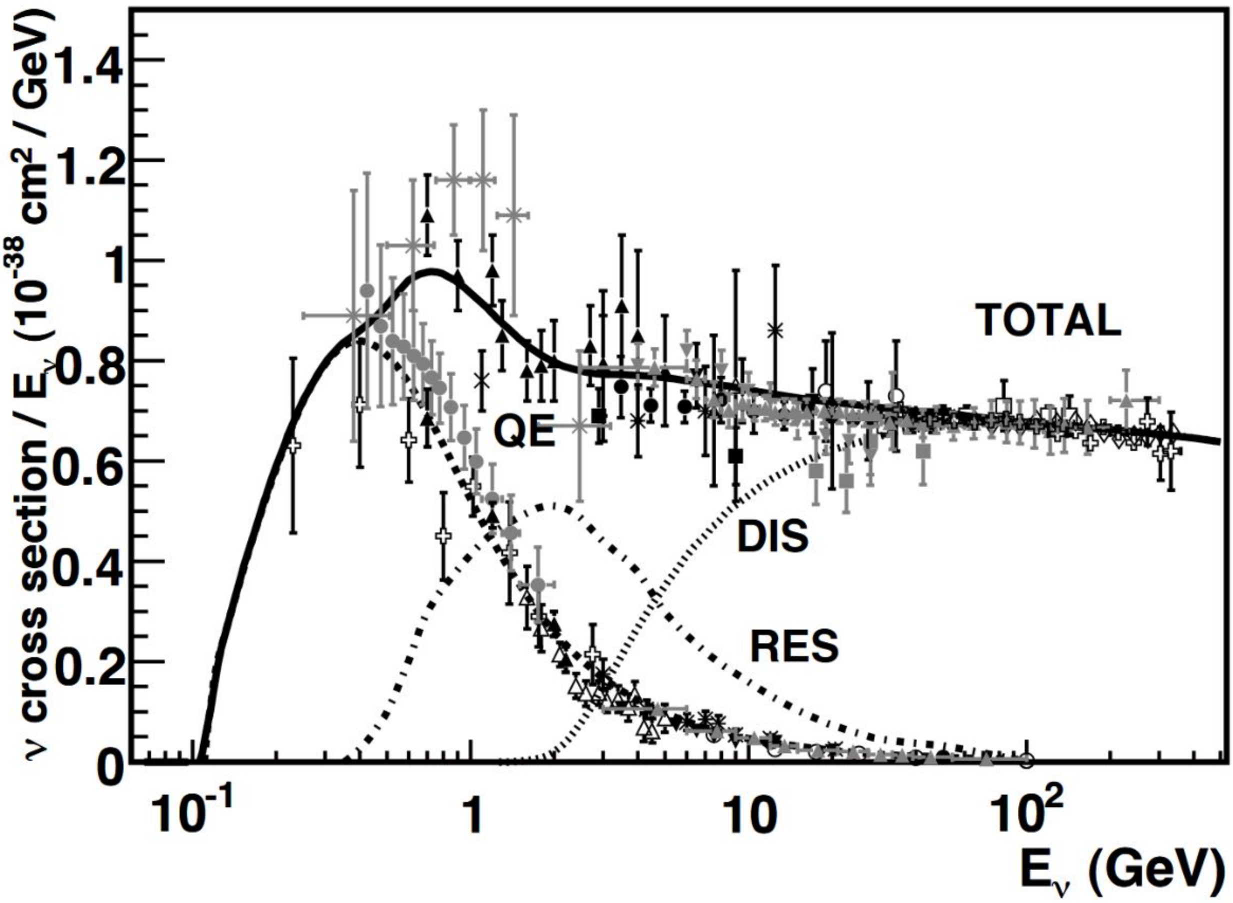

Figure 1: Total neutrino and antineutrino per nucleon CC cross sections (for an isoscalar target) divided by neutrino energy and plotted as a function of energy. Also shown are the variou scontributions from quasi-elastic (QE), resonance production (RES), and deep-inelastic scattering(DIS). *Taken from: From: Formaggio, Zeller Rev. Mod. Phys. 84, 1307 (2012), arXiv:1305.7513*

with a "strong" phase ρ_i and a "weak" phase α_i such that

$$\rho_i \xrightarrow{CP} \rho_i \tag{2}$$

$$\alpha_i \xrightarrow{CP} -\alpha_i. \tag{3}$$

Calculate the CP-asymmetry $\Delta_{\rm CP} \equiv |A_1 + A_2|^2 - |A_1 + A_2|^2_{\rm CP}$

(b) What are the conditions for $\Delta_{\rm CP} \neq 0$?

(c) Consider now, again, the case of two flavor neutrino oscillations as discussed on the first exercise sheet. What are $\Delta\rho$ and $\Delta\alpha$ now?