1^{st} Exam
January 18^{th} 2016: 11h30
Duration of the test: 1h30
Duration of the exam: 3h00

Mestrado em Eng. Física Tecnológica (MEFT)
Particle Physics
1^{st} semester of 2016-17

Prof. Jorge Romão
Prof. Mário Pimenta
Prof. Ruben Conceição

- The allowed elements for consult during the test are:
  - the PDG (Particle Data Book)
  - one single A4 page with formulas.
- Carefully justify all your answers.
- Each test has 1 question with 9 items.

1^{st} test

The direct observation of the tau neutrino , ν_τ, occurred in the year of 2000 by the DONuT experiment. Such experiment detected the ν_τ through charged current interactions using nuclear emulsion targets.

1. **[10 val]**

a) The beam of tau neutrinos were produced colliding protons of 800 GeV against a target of 1 m of Tungsten. Knowing that the beam contains 10^{12} protons per second, there was a total of 10^{17} proton interaction during the operation of the experiment and the $\sigma_{pp} \sim 40\,\text{mb}$, compute the effective time of beam. Assume that the proton-nucleus cross-section scales linearly with the number of nucleons.

b) In these interactions there is, among others, the production of pions. Determine what is mean energy of pions, for which its decay length is smaller than its interaction length. Assume that $\sigma_{\pi p} \sim \frac{2}{3}\sigma_{pp}$.

c) Muons can arise from the decay of charged pions. Consider a pion decay into a muon and a muon neutrino. Assuming that the pion as an energy in the Laboratory reference frame of 10 GeV, indicate what is the expected muon energy spectrum in the LAB, evaluating its minimum and maximum possible energy.

d) Assuming that the muon has an energy of 5 GeV evaluate the mean energy that the muon loses while crossing the full Tungsten target. Assume that the properties of Tungsten are similar to the ones from Lead.

e) The tau neutrinos measured at DONuT came essentially from the decays of charged mesons, in particular from the D_s^+ state. Knowing that the production cross-section of D_s^+, $\sigma_{D_s^+} \sim 300\,\text{nb}$, compute the number of D_s^+ produced in the experiment.

f) Enumerate the ground state mesons that contain at least one quark c indicating its quark content.

g) Explicitly show, using the quantum numbers conservation, which of the following decays of the D_s^+ are possible.

(i) $D_s^+ \to \mu^+ \, \overline{\nu}_\mu$ (ii) $D_s^+ \to \pi^+ \, \pi^+ \, \pi^-$ (iii) $D_s^+ \to p \, K^+ \, K^-$ (iv) $D_s^+ \to K^+ \, K^- \, \pi^+$

h) Compute the number of tau neutrinos produced in the experiment, considering that they come all from the D_s^+ decay.

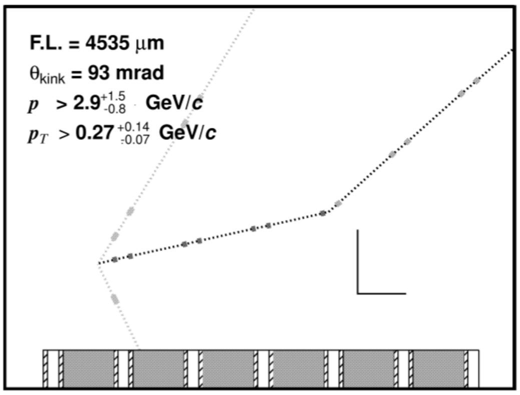


Figure 1: DONuT event.

i) The neutrino beam that hits the sensitive region of the DONuT experiment is composed by ν_e, ν_μ and ν_τ. The experimental signature that allowed the detection of the tau neutrino is: *charged trace followed by other charged trace with a small angle with respect to the first one*, the so-called *kink* (see figure 1). Justify the choice of this signature.

2^{nd} *test*

2. **[10 val]** The neutrino beam used in the DONuT experiment contains neutrino of all families, ν_e, ν_μ and ν_τ.

a) Draw the Feynman diagrams for the processes

$$\nu_e + e^- \to e^- + \nu_e; \quad \nu_\tau + e^- \to \tau^- + \nu_e$$

b) State what can be the valence quarks, q, q', in the process

$$\nu_\tau + q \to \tau^- + q',$$

and draw the corresponding Feynman diagram.

c) Consider now the process $\nu_\tau + e^- \to \tau^- + \nu_e$. Write the amplitude $\mathcal{M}$ without approximations.

d) Neglecting the lepton masses and assuming that the CM energy $\sqrt{s} \ll M_W, M_Z$ write a simplified expression for the amplitude $\mathcal{M}$. Justify the various steps.

e) What are the non-vanishing helicity amplitudes? Evaluate the spin averaged squared amplitude $\langle |\mathcal{M}|^2 \rangle$.

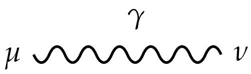
f) For this process evaluate the differential cross section $d\sigma/d\Omega$ in the CM frame as a function of the square of the energy in the CM frame, $s = (p_1 + p_2)^2$.

g) Evaluate the total cross section $\sigma(\nu_\tau + e^- \to \tau^- + \nu_e)$. For $\sqrt{s} = 1$ GeV, express the result in fb.

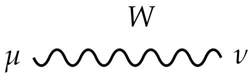
h) Is it more likely for the τ^- to be emitted in the front direction (that is with the angle $\theta \in [0, \pi/2]$ where θ is the angle in the center-of-mass reference frame that the emitted τ^- makes with the direction of the ν_τ beam) or on the backwards direction ($\theta \in [\pi/2, \pi]$)?

i) Figure 1 shows a typical event of the interaction of ν_τ with ordinary matter (protons, neutrons and electrons). Indicate, justifying, the probable Feynman diagram for this event.

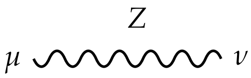
Propagators



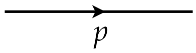
$$-i\frac{g_{\mu\nu}}{k^2} \tag{1}$$



$$-i\frac{g_{\mu\nu}-\frac{k_\mu k_\nu}{M_W^2}}{k^2-M_W^2+i\,M_W\Gamma_W} \tag{2}$$



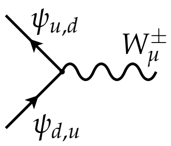
$$-i\frac{g_{\mu\nu}-\frac{k_\mu k_\nu}{M_Z^2}}{k^2-M_Z^2+i\,M_Z\Gamma_Z} \tag{3}$$



$$\frac{i(\not{p}+m_f)}{p^2-m_f^2} \tag{4}$$

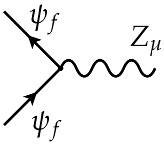
Vertices

Charged Current

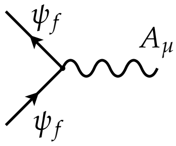


$$-i\frac{g}{\sqrt{2}}\gamma_\mu\frac{1-\gamma_5}{2} \tag{5}$$

Neutral Current



$$-i\frac{g}{\cos\theta_W}\gamma_\mu\left(g_V^f-g_A^f\gamma_5\right)$$



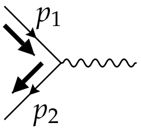
$$-ieQ_f\gamma_\mu \tag{6}$$

where

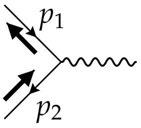
$$g_V^f=\frac{1}{2}T_f^3-Q_f\sin^2\theta_W,\quad g_A^f=\frac{1}{2}T_f^3\,. \tag{7}$$

Results for the Helicity Currents

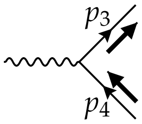
s-channel



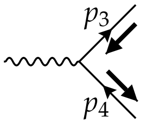
$$J_{u_1 v_2}(\uparrow,\downarrow) = \sqrt{s}\,(0,-1,-i,0) \tag{8}$$



$$J_{u_1 v_2}(\downarrow,\uparrow) = \sqrt{s}\,(0,-1,i,0) \tag{9}$$

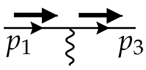


$$J_{u_3 v_4}(\uparrow,\downarrow) = \sqrt{s}\,(0,-\cos\theta,i,\sin\theta) \tag{10}$$

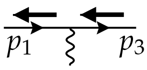


$$J_{u_3 v_4}(\downarrow,\uparrow) = \sqrt{s}\,(0,-\cos\theta,-i,\sin\theta) \tag{11}$$

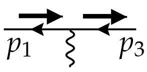
t-channel



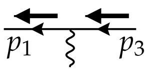
$$J_{u_1 u_3}(\uparrow,\uparrow) = \sqrt{s}\,\left(\cos\frac{\theta}{2},\sin\frac{\theta}{2},i\sin\frac{\theta}{2},\cos\frac{\theta}{2}\right) \tag{12}$$



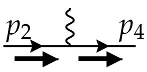
$$J_{u_1 u_3}(\downarrow,\downarrow) = \sqrt{s}\,\left(\cos\frac{\theta}{2},\sin\frac{\theta}{2},-i\sin\frac{\theta}{2},\cos\frac{\theta}{2}\right) \tag{13}$$



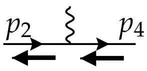
$$J_{v_1 v_3}(\uparrow,\uparrow) = \sqrt{s}\,\left(\cos\frac{\theta}{2},\sin\frac{\theta}{2},i\sin\frac{\theta}{2},\cos\frac{\theta}{2}\right) \tag{14}$$



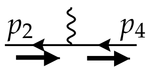
$$J_{v_1 v_3}(\downarrow,\downarrow) = \sqrt{s}\,\left(\cos\frac{\theta}{2},\sin\frac{\theta}{2},-i\sin\frac{\theta}{2},\cos\frac{\theta}{2}\right) \tag{15}$$



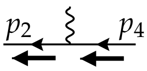
$$J_{u_2 u_4}(\uparrow,\uparrow) = \sqrt{s}\,\left(\cos\frac{\theta}{2},-\sin\frac{\theta}{2},i\sin\frac{\theta}{2},-\cos\frac{\theta}{2}\right) \tag{16}$$



$$J_{u_2 u_4}(\downarrow,\downarrow) = \sqrt{s}\,\left(\cos\frac{\theta}{2},-\sin\frac{\theta}{2},-i\sin\frac{\theta}{2},-\cos\frac{\theta}{2}\right) \tag{17}$$



$$J_{v_2 v_4}(\uparrow,\uparrow) = \sqrt{s}\,\left(\cos\frac{\theta}{2},-\sin\frac{\theta}{2},i\sin\frac{\theta}{2},-\cos\frac{\theta}{2}\right) \tag{18}$$



$$J_{v_2 v_4}(\downarrow,\downarrow) = \sqrt{s}\,\left(\cos\frac{\theta}{2},-\sin\frac{\theta}{2},-i\sin\frac{\theta}{2},-\cos\frac{\theta}{2}\right) \tag{19}$$