2^{nd} exam January 28th 2016: 8h00 Duration of the test: 1h30 Duration of the exam: 3h00

Mestrado em Eng. Física Tecnológica (MEFT)
Particle Physics
1^{st} semester of 2015-16

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

- The allowed elements for consult during the test are:
  - the PDG (Particle Data Book)
  - one single A4 page with formulas.
- Clearly identify all pages of the test.
- The exam has 5 questions (2 pages).

1^{st} test

1. **[5 val]** During 2012 LHC delivered to the experiments an integrated luminosity of about $20\,\text{fb}^{-1}$. This data was used to establish that existence of a scalar boson, consistent with the Higgs boson predicted in the Standard Model.

a) Knowing that the Higgs boson production cross-section at $\sqrt{s} = 7\,\text{TeV}$ is $\sigma_H \sim 21\,\text{pb}$ and its branching ratio for $H \to \gamma\gamma$ is $BR = 2.28 \times 10^{-3}$, evaluate the maximum number of Higgs into $\gamma\gamma$ that could be observed by the LHC experiments.

b) The decay of the Higgs into $\gamma\gamma$ can be detected in the electromagnetic calorimeter. Describe qualitatively how a photon is detected in a calorimeter and state the main sources of uncertainty to the reconstruction of the photon energy.

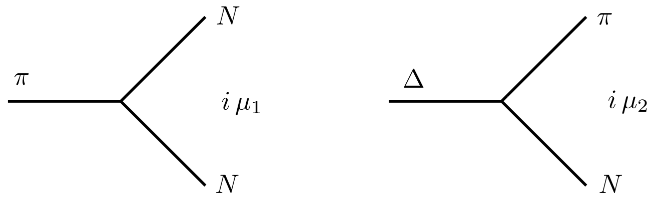
c) Consider the decay of a Higgs boson candidate into two photons. The photons were measured with $E_1 = 123.3\,\text{GeV}$, $E_2 = 36.7\,\text{GeV}$ and making an angle between them of $\theta = 136.3°$. Determine the momentum of this Higgs boson candidate in the laboratory, and calculate its invariant mass.

d) Consider now that it was observed Higgs bosons with momenta between 0 and 100 GeV.

(i) Compute the minimum and maximum angle between the emitted photons in the LAB reference frame, for the two limiting energies.

(ii) Draw the energy spectrum of the photons in the LAB indicating the minimum and maximum energy, for $P_{Higgs} = 0\,\text{GeV}$ and $P_{Higgs} = 100\,\text{GeV}$.

2. **[5 val]** A very simple model for NN and πN scattering (N=nucleon=neutron or proton), can be used when we neglect spin. The model is described by the interactions



where the constants μ_1 e μ_2 have dimension of a mass in our natural system of units ($\hbar = c = 1$). The charges of the particles are such that the charge is conserved at each vertex.

a) Consider the elastic scattering $\pi^+ + n \to \pi^+ + n$. Draw the Feynman Diagram(s) for the process.

b) Consider now the process $\Delta^+(1232)(p_1) \to \pi^+(p_2) + n(p_3)$. What is the energy of the π^+ in the rest frame of the decaying $\Delta^+(1232)$?

c) Evaluate the width of the process in b).

d) Consider now the process $N^+(1440)(p_1) \to p(p_2) + \pi^0$. Evaluate the width for this process.

e) Taking the widths from the PDG (consider the average values) and considering that the branching ratio for $N^+(1440)(p_1) \to p(p_2) + \pi^0$ is 65% (average value from the PDG) determine the constants μ_1 and μ_2.

2^{nd} *test*

3. **[2 val]** The Higgs boson properties have been investigated in the LHC by looking to its different decay channels.

a) Indicate the possible decays of a Higgs boson with a mass of 125 GeV and its respective diagram. Which is the dominant decay and why?

b) Discuss the following statement *If LEP (an e^+e^- collider), would had enough energy to produce the Higgs boson, its properties would be more easily accessed than currently in LHC.*

4. **[3 val]** At LHC b mesons are an important background that need to be under control so that the properties of the Higgs boson can be investigated.

a) Enumerate the names of the ground state mesons that contain at least one quark b, or an antiquark $\bar{b}$, making explicit its quark content.

b) Consider the following decays of the B^0 and verify which ones are possible, indicating the reason if not.

(i) $B^0 \to e^+\,\gamma$ (ii) $B^0 \to \pi^-\,e^+\,\nu_e$ (iii) $B^0 \to p\,\overline{p}\,n$ (iv) $B^0 \to e^+\,e^-\,\overline{\nu}_e$

5. **[5 val]** Consider, in the standard model framework, the following elastic scattering,

$$\overline{\nu}_e(p_1) + e^-(p_2) \to \mu^-(p_3) + \overline{\nu}(p_4)$$

a) Write the amplitude(s) at the lowest order without approximations.

b) Consider now that the CM energy, $\sqrt{s}$, is such that

$$m_e, m_\nu \ll \sqrt{s} \ll M_W, M_Z$$

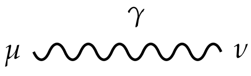
Write down a simplified expression for the amplitude $\mathcal{M}$. Justify the steps.

c) In the same limit as in the previous question, identify the non-zero helicity amplitudes and use this method to find $\langle|\mathcal{M}|^2\rangle$.

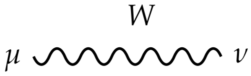
d) Evaluate $d\sigma/d\Omega$ in the CM reference frame.

e) In the same conditions find the total cross section. If $\sqrt{s} \geq M_W$, M_Z what would be the result? Comment on this result.

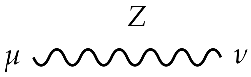
Propagators



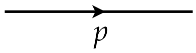
$$-i\frac{g_{\mu\nu}}{k^2} \tag{1}$$



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



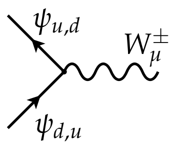
$$-i\frac{g_{\mu\nu}-\frac{k_\mu k_\nu}{M_Z^2}}{k^2-M_Z^2+i\,M_Z\Gamma_Z} \tag{3}$$



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

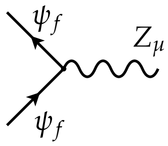
Vertices

Charged Current

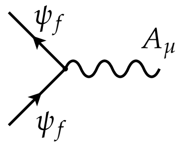


$$-i\frac{g}{\sqrt{2}}\gamma_\mu\frac{1-\gamma_5}{2} \tag{5}$$

Neutral Current



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



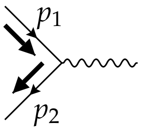
$$-ieQ_f\gamma_\mu \tag{6}$$

where

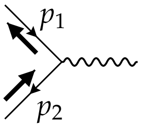
$$g_V^f=\frac{1}{2}T_f^3-Q_f\sin^2\theta_W,\quad g_A^f=\frac{1}{2}T_f^3\,. \tag{7}$$

Results for the Helicity Currents

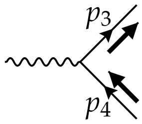
s-channel



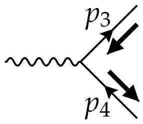
$$J_{u_1 v_2}(\uparrow,\downarrow) = \sqrt{s}\,(0,-1,-i,0) \tag{8}$$



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

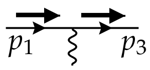


$$J_{u_3 v_4}(\uparrow,\downarrow) = \sqrt{s}\,(0,-\cos\theta,i,\sin\theta) \tag{10}$$

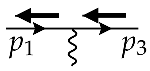


$$J_{u_3 v_4}(\downarrow,\uparrow) = \sqrt{s}\,(0,-\cos\theta,-i,\sin\theta) \tag{11}$$

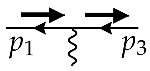
t-channel



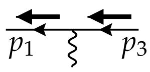
$$J_{u_1 u_3}(\uparrow,\uparrow) = \sqrt{s}\,\left(\cos\frac{\theta}{2},\sin\frac{\theta}{2},i\sin\frac{\theta}{2},\cos\frac{\theta}{2}\right) \tag{12}$$



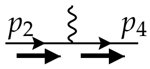
$$J_{u_1 u_3}(\downarrow,\downarrow) = \sqrt{s}\,\left(\cos\frac{\theta}{2},\sin\frac{\theta}{2},-i\sin\frac{\theta}{2},\cos\frac{\theta}{2}\right) \tag{13}$$



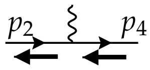
$$J_{v_1 v_3}(\uparrow,\uparrow) = \sqrt{s}\,\left(\cos\frac{\theta}{2},\sin\frac{\theta}{2},i\sin\frac{\theta}{2},\cos\frac{\theta}{2}\right) \tag{14}$$



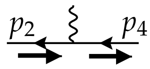
$$J_{v_1 v_3}(\downarrow,\downarrow) = \sqrt{s}\,\left(\cos\frac{\theta}{2},\sin\frac{\theta}{2},-i\sin\frac{\theta}{2},\cos\frac{\theta}{2}\right) \tag{15}$$



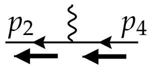
$$J_{u_2 u_4}(\uparrow,\uparrow) = \sqrt{s}\,\left(\cos\frac{\theta}{2},-\sin\frac{\theta}{2},i\sin\frac{\theta}{2},-\cos\frac{\theta}{2}\right) \tag{16}$$



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



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



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