M.Sc. (Physics) 4th Semester Examination 2021
PHY 522 (Particle Physics)

Answer in your own words as far as practicable. The marks on the right-hand margin indicate the full marks for the question.

Full marks: 50 Time: 2.5 hrs

(2 hours for answering and 30 minutes for downloading, scanning, and uploading)

Answer any *five* questions.

Instructions:

(i) Please write your Examination Roll Number and Registration Number (from an earlier admit card) at the top of your answer script. Do not write your name or class roll number anywhere.

(ii) Scan the complete answer script into a single pdf file and mail it to the e-mail from where you got the paper. The return mail should preferably be sent from the e-mail. in reply mode. to which the question paper was delivered.

(iii) The answer script file for the paper PHY522 must be named as instructed:

Note that your Examination Roll Number is of the form ZZZ/PHY/XXXXXX. where ZZZ is the college identifier (like C91, 031, etc.), and XXXXXX is a 6-digit number like 191099.

— For CU students. the filename must be CUXXXXXXPHY522.pdf. For example. the script of PHY522 coming from C91/PHS/191099 must be named **CU191099PHY522.pdf**.

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1. a) Show that $(\bar{\psi}_1 O \psi_2)^\dagger = \bar{\psi}_2 \tilde{O} \psi_1$ where $\tilde{O} = \gamma^0 O^\dagger \gamma^0$. If $O = \gamma^\mu(1-\gamma_5)$, show that $\tilde{O} = \gamma^\mu(1-\gamma_5)$.

(2+1 marks)

b) In the Standard Model, π^0 cannot decay into $\nu\overline{\nu}$, but the Z boson can: explain why. **(4 marks)**

c) The equation for the massive spin-one boson is $\partial_\mu F^{\mu\nu} + M^2 A^\nu = j^\nu$. Find the propagator. **(3 marks)**

2. a) Use dimensional analysis to show that the decay rate of the muon goes like m_μ^5 in the Fermi theory if the masses of the decay products are neglected. **(2 marks)**

b) ψ is a fermion of charge Q, ψ_L has eigenvalue T_3 under $SU(2)_L$, and ψ_R is an $SU(2)_L$ singlet. Show that the interaction of ψ with the Z boson is given by

$$\mathcal{L}_{int} = -\frac{g}{\cos\theta_W}\overline{\psi}\gamma^\mu(T_3 L - Q\sin^2\theta_W)\psi Z_\mu .$$

(4 marks)

c) Let Φ denote the complex scalar doublet in the Standard Model. Find out whether a term $\Phi^\dagger\tilde{\Phi} + \tilde{\Phi}^\dagger\Phi$ is allowed by looking at its $SU(2)_L$ and $U(1)_Y$ transformations. **(2 marks)**

d) In the $SU(2)_L \times U(1)_Y$ theory, consider an $SU(2)$ triplet of scalar fields having charges 0, 1 and 2, denoted by H^0, H^+ and H^{++}. Which field is the uppermost member of the triplet? What is the hypercharge of this triplet? **(1+1 marks)**

3. a) Write down, with justification, the baryon number of the Higgs boson in the Standard Model. **(2 marks)**

b) Draw the gluon fusion diagram for Higgs boson production at the LHC. Which fermion in the loop gives the maximum contribution and why? Why cannot be there a charged lepton in the loop? **(1+1+1+1 marks)**

c) Draw all the tree-level Feynman diagrams for the following processes in the Standard Model: (i) $W^+W^- \to ZZ$, (ii) $q\overline{q} \to GG$ (with G denoting the gluon). **(2+2 marks)**

4. The formula for the differential scattering cross-section is:

$$d\sigma = \frac{1}{4\sqrt{(p_1\cdot p_2)^2 - m_1^2 m_2^2}}\left(\prod_a \frac{d^3p'_a}{(2\pi)^3 2E'_a}\right) \times (2\pi)^4\delta^4(p_1 + p_2 - \sum_a p'_a)|\mathcal{M}|^2 .$$

a) What do the symbols p_1 and p_2 stand for in this formula? **(1 mark)**

b) If the final state contains N particles, what is the mass dimension of $\mathcal{M}$? **(3 marks)**

c) At energies much larger than the masses of all participating particles, how will the total cross-section depend on the total energy in the initial state? **(2 marks)**

d) For 2 particles in the final state of scattering, three Mandelstam variables can be defined. Write them down, explaining your notation. The total cross-section can depend only on one of them. Identify which one, and argue why the other ones cannot appear in this expression. **(2+2 marks)**

5. a) Usually only the photon exchange diagram is considered while analyzing electron-proton scattering at the tree level. Which other particles of the Standard Model can mediate the same process at the tree level? Why are these other ones disregarded in the discussion? **(2+1 marks)**

b) Suppose you have an inelastic electron-proton scattering, but the final state still has two particles. Can you think of a process like this? Which particles of the Standard Model can mediate such a process? **(2+2 marks)**

c) In the rest frame of the proton, what would be the minimum kinetic energy of the electron necessary for this process to happen? (No numerical value is needed. Only give an algebraic expression.) **(3 marks)**

6. a) Explain the origin of the unitarity triangles. How do you interpret the area of a unitarity triangle? **(2+2 marks)**

b) Assuming that (CP) is conserved, construct the Hamiltonian of the $|K^0\rangle$-$|\overline{K}^0\rangle$ system. Identify the eigenstates of this Hamiltonian and determne their (CP) properties. **(2+1 marks)**

c) A beam of neutral kaons of energy 10 GeV travel a distance of 10m. Estimate the ratio (No. of $|K_S\rangle$)/(No. of$|K_L\rangle$) given that the approximate restframe lifetimes of $|K_S\rangle$ and $|K_L\rangle$ are 5×10^{-8}s and 10^{-10}s respectively. What is meant by the phenomenon of regeneration for the neutral Kaon system? **(1+2 marks)**

7. a) Which gauge bosons of the Standard Model couple to the neutrinos? Draw example diagrams indicating how they mediate interactions of electrons with muon neutrinos at the tree level. **(1+1 marks)**

b) Explain the origin of atmospheric neutrinos and estimate therefrom the expected ratio of the number of $(\nu_e + \overline{\nu}_e)$ to $(\nu_\mu + \overline{\nu}_\mu)$. How can the observed zenith angle dependence of atmospheric neutrinos be explained in terms of neutrino oscillations? From this, make a rough estimate of the relevant mass-square-splitting. **(2+1+2 marks)**

c) The SNO Neutral Current experiment had a critical role in establishing the oscillation of solar neutrinos. Explain. **(3 marks)**