3. Explain briefly what neutrino oscillations are, and give an example of experimental evidence for their existence. What does the observation of the oscillations imply for the masses of the neutrinos? **[5]**

4. The K^0 meson has a mass of $497.6\,\mathrm{MeV}/c^2$ and it decays into two charged pions of mass $139.6\,\mathrm{MeV}/c^2$. What is the energy of a pion as observed in the rest frame of the K^0?

The K^0 lifetime is $0.89 \times 10^{-10}\,\mathrm{s}$. State what interaction is responsible for the decay, and justify briefly your answer. **[5]**

7. What are antiparticles? Describe the interpretation of these given by Feynman. Considering the case of muons and antimuons, comment on the relations between the charge and the lepton family number, L_μ, of particles and antiparticles. **[6]**

Draw the lowest order Feynman diagram for the electromagnetic process $e^+e^- \rightarrow \mu^+\mu^-$. Neglecting the spins of the initial and final state particles, state the main features of the matrix element, $\mathcal{M}$, for this process. Show that the cross section, σ, for this process must have the form $\sigma \propto \alpha^2$ where $\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c}$ is the fine structure constant. **[6]**

At the PETRA accelerator, electrons and positrons were colliding head-on. Using four-momentum conservation, show that the centre-of-mass energy, $\sqrt{s}$, for total energies of $E = 17.5$ GeV for both electron and positron beams is equal to $\sqrt{s} = 2E = 35\,\text{GeV}$. **[4]**

The exact cross section for $e^+e^- \rightarrow \mu^+\mu^-$ is $\sigma = \frac{87\,\text{nb}}{s\,[\text{GeV}^2]}$. Using the above relation, and the collider luminosity $\mathcal{L} = 1 \times 10^{31}\ \text{cm}^{-2}\text{s}^{-1}$, calculate the number of $e^+e^- \rightarrow \mu^+\mu^-$ events observed in 30 days assuming that the accelerator was working during half of this time. Note that 1 barn (b) $= 10^{-24}\ \text{cm}^2$. **[4]**

3. What interactions are responsible for the following processes? Justify very briefly your answers.

$$\pi^0 \rightarrow \gamma\gamma$$
$$\pi^+ \rightarrow \mu^+\nu_\mu$$
$$\pi^- p \rightarrow \Delta(1232) \rightarrow \pi^0 n$$

[5]

4. What are the quark contents of the charmed D^0 and D^{*+} mesons?

A D^{*+} meson has a mass of 2010 MeV/c^2 and it decays into a D^0 and a π^+ meson with masses of $m_{D^0} = 1864.5$ MeV/c^2 and $m_\pi = 139.6$ MeV/c^2, respectively. Calculate the energy of the π^+ in the rest frame of the D^{*+}. [5]

7. Draw the lowest order Feynman diagram for the decay of a muon $\mu^- \to e^- \bar{\nu}_e \nu_\mu$. Describe the meaning of the symbols and their significance in the following equation:

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8M_W^2}$$

Discuss the W boson propagator, and why it produces a muon decay rate $\Gamma_\mu = \Gamma(\mu^- \to e^- \bar{\nu}_e \nu_\mu)$ which is proportional to G_F^2. [7]

Explain why the decay $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ is allowed and why $\mu^+ \to e^+ \gamma$ and $\mu^+ \to e^+ e^- e^+$ are forbidden. [4]

Cosmic ray muons are produced high in the atmosphere, say at 10 km, and have an energy of about 2 GeV. What is the speed $\beta = v/c$ of such a muon? How far will the muon travel on average before it decays? [4]

(The muon mass is $m_\mu = 105.7$ MeV/c^2, and the muon lifetime is $\tau_\mu = 2.197$ μs, respectively.)

Describe lepton universality in weak decays and apply it to find a relation between the decay rates of the tau decays $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ and $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$. [5]

I.2 In a synchrotron accelerator, a charged particle has an energy loss per cycle of:

$$\Delta E \propto \gamma^4$$

where:

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} \quad .$$

What is the origin of this energy loss? Calculate the ratio of the energy losses for an electron and proton of a given energy, E. Comment on the significance of your answer. **[5]**

I.3 Describe what is meant by *colour confinement*. Briefly discuss the properties of gluons which explain confinement. **[5]**

II.3 The lifetime of the muon (μ^-) is 2.20×10^{-6} s. The lifetime of the tau-lepton (τ^-) is 2.91×10^{-13} s.

(a) What force is responsible for the decays of these leptons? **[2]**

(b) Write down the main decay mode of μ^-. Why don't muons decay into hadrons? **[3]**

(c) What are the allowed decays of τ^- into quarks and leptons? Draw two Feynman diagrams, one representing the decay of a μ^- and one representing the decay of a τ^-. **[5]**

(d) The Fermi coupling constant, G_F, can be written as:

$$G_F = \frac{\sqrt{2}\, g_w^2}{8\, m_W^2}$$

where m_W is the mass of the W-boson and g_w is the weak coupling constant.

Find a relationship between the width of the muon (Γ_μ), G_F and the mass of the muon (m_μ) in the form: $\Gamma_\mu = K\, G_F^a\, m_\mu^b$, where K is a dimensionless constant. Hence explain the relationship between the muon and tau-lepton lifetimes. **[10]**

3. The LHC collider at CERN is designed to collide bunches of protons head-on.

When it is fully operational, the LHC will circulate 2808 bunches of protons in each direction. Each bunch will contain 1.1×10^{11} protons, and each proton will have an energy of $E_p = 7$ TeV.

(a) Write down the definition of the Lorentz invariant quantity s for a collider and hence show that the centre of mass energy for the LHC is 14 TeV.

(b) What is the total energy stored in the combined LHC beams in Joules?

[6]

In one particular collision at the LHC, a Higgs boson is produced via gluon-gluon scattering, $gg \to H$. The interacting partons have $x_1 = 0.015$ and $x_2 = 0.01$, where $x_{1,2}$ is the fraction of the proton's momentum carried by the parton.

(c) What is meant by the term *parton*? Describe the parton content of the proton at LHC energies. In your description discuss the three types of parton and typical values of x for each of these parton types. You may find it useful to draw a sketch of the partons in the proton. [6]

(d) Derive an expression for the effective centre of mass energy, $\sqrt{\hat{s}}$, in terms of x_1 and x_2, and hence calculate the maximum value for the Higgs boson mass that could be produced in this collision. [4]

The Higgs boson subsequently decays into two W-bosons. The two W-bosons decay as: $W^- \to e^- \bar{\nu}_e$ and $W^+ \to \mu^+ \nu_\mu$.

(e) Describe the signature of each of the final state particles in a detector, such as the ATLAS detector. [4]

(f) Comment on the reconstruction of the final state particles' momenta and on the reconstruction of the Higgs boson mass. [5]