Data Provided:
A formula sheet and table of physical constants is attached to this paper.

DEPARTMENT OF PHYSICS & ASTRONOMY

Autumn Semester 2016-2017

PARTICLE PHYSICS **2 HOURS**

Answer question ONE (Compulsory) and TWO other questions.

Please clearly indicate the question numbers on which you would like to be examined on the front cover of your answer book. Cross through any work that you do not wish to be examined.

The compulsory question is marked out of 20. All other questions are marked out of 15. The breakdown on the right-hand side of the paper is meant as a guide to the marks that can be obtained from each part.

THIS QUESTION IS COMPULSORY.

1 (a) Give two common properties shared by quarks and leptons. **[2]**

(b) Give two differences between quarks and leptons. **[2]**

(c) Draw a labelled Feynman diagram at the quark level for the reaction $K^+ \rightarrow \pi^0 e^+ \nu_e$. **[2]**

(d) What are the values of the spin, isospin, charge and strangeness quantum numbers of the s quark? **[2]**

(e) What is the relationship between the hypercharge, the strangeness and the baryon number of a particle? What is the value of the hypercharge for a strange quark? **[2]**

(f) Which interaction is responsible for the decay $K^0 \rightarrow \pi^+ \pi^-$, and why? **[2]**

(g) What are the quark contents of the Ξ^- and π^-? **[2]**

(h) A positive kaon at rest decays into a muon, μ^+, and neutrino, ν_μ, according to $K^+ \rightarrow \mu^+ \nu_\mu$. What is the energy of the muon? Masses of kaon and muon are 494 and 106 MeV/c^2 respectively; the neutrino is effectively massless. **[3]**

(i) What is the effect of the charge conjugation operator? **[1]**

(j) Explain how symmetry constraints allow only one of the two reactions $\rho^0 \rightarrow \pi^+ \pi^-$ and $\rho^0 \rightarrow \pi^0 \pi^0$. (The ρ is a spin-1 meson while the π has spin 0.) **[2]**

2 (a) The combinations of quarks which can form a baryon are dictated by symmetry constraints. Explain these constraints in terms of the spin, flavour (or isospin) and colour wavefunctions of the quarks. **[4]**

(b) Baryons composed of two light (u or d) quarks and one s quark form spin-$\frac{1}{2}$ baryons (Σ^+, Σ^0, Σ^- and Λ) and spin-$\frac{3}{2}$ baryons (the $\Sigma(1385)$ triplet). State, with justification, what the flavour and spin wavefunctions are for the light quarks in the spin-$\frac{1}{2}$ baryons. Explain clearly why there is no spin-$\frac{3}{2}$ singlet (equivalent to the Λ). (You may use u and d to represent $I_3 = \frac{1}{2}$ and $I_3 = -\frac{1}{2}$ states respectively, $\uparrow$ and $\downarrow$ for spin up and spin down respectively.) **[6]**

(c) Indicate, *with an explanation*, whether the following interactions proceed through the strong, electromagnetic or weak interactions, or whether they do not occur:

(i) $\pi^0 \to \gamma + \gamma$

(ii) $\tau^+ \to \mu^+ + \nu_\mu$

(iii) $\Xi^- \to \Lambda + \pi^-$

(iv) $\Delta^{++} \to p + \pi^+$

(v) $\Omega^- \to n + K^-$

(vi) $K^+ + n \to \Lambda + \pi^+$

(vii) $K^- + n \to \Lambda + \pi^-$

(viii) $\mu^+ + \mu^- \to \nu_\tau + \bar{\nu}_\tau$. **[5]**

3 (a) Quark flavour is conserved in the strong interaction, while the weak interaction allows the decay of heavy quarks into lighter ones. Explain how such decays are permitted according to Cabibbo theory. What is the significance of the magnitude of the different elements of the CKM matrix for these decays? **[5]**

(b) Can the charm (c) quark decay into a b, s, u or d quark? For each case, state with an explanation whether the decay is forbidden, allowed but unlikely or likely to occur. Draw a fully-labelled Feynman diagram of the most probable decay mode. **[6]**

(c) One of the weak decays of the τ lepton is to a charged pion and a neutrino. A τ with an energy of 2.50 GeV is observed to decay in this mode. State what condition must be fulfilled for the produced pion to have the maximum energy, and calculate the energy in this case. **[4]**
[Mass of τ is 1777.0 MeV/c^2; mass of π is 139.6 MeV/c^2; ν is effectively massless.]

4 (a) Explain what is meant by the term "colour" when used in particle physics. Include in your account the properties of the boson responsible for strong interactions and a discussion of why hadrons are formed of three quarks (baryons) or a quark and antiquark (mesons). How does the strength of the interaction vary with distance, and is the strong interaction considered a short-range or long-range force? **[6]**

(b) Describe the phenomenon of confinement. What happens if an attempt is made to eject a quark from a proton, by striking it with a high energy muon? **[4]**

(c) Amongst the debris from a struck proton, two particles are identified as a proton and a π^-. If they have momenta of 5.60 GeV/c and 0.800 GeV/c respectively and the angle between them is 7.9°, could they have originated from the decay of a Λ^0 particle, of mass 1116 MeV/c^2? Justify your answer. **[5]**

[Mass of proton is 938 MeV/c^2, mass of π^- is 140 MeV/c^2.]

5 (a) Explain the significance of the form factor, $F(q)$, used to describe scattering, for example, of muons off protons. (Here q is the momentum transfer in the scattering.) **[2]**

(b) The form factor is the Fourier transform of the normalised charge density distribution

$$F(q) = \int e^{i\underline{q}\cdot\underline{r}/\hbar}\rho(\underline{r})\,\mathrm{d}^3\underline{r}\ .$$

Show that for a simple model of the proton, considered as a uniform sphere of radius R of *constant* charge density, $F(q)$ is given by

$$F(q) = \frac{3\hbar^2}{R^3 q^2}\left(\frac{\hbar}{q}\sin\frac{qR}{\hbar} - R\cos\frac{qR}{\hbar}\right).$$

[5]

(c) Use this expression for $F(q)$ to find the limiting value of F as q tends to zero. What is the significance of this result? **[3]**

(d) Explain what is meant by the term *four-momentum transfer*, q? **[2]**

(e) Show that for a high energy muon scattering through an angle θ, the value of q^2 is given approximately by

$$\mathsf{q}^2 \simeq 2E_\mathrm{i}E_\mathrm{f}\left(1-\cos\theta\right),$$

where E_i and E_f are the initial and final values of the muon's energy. State when this approximation is justified. **[3]**

END OF QUESTION PAPER