HL Paper 3

A positive pion decays into a positive muon and a neutrino.

$$\pi^+ \rightarrow \mu^+ + v_\mu$$

The momentum of the muon is measured to be 29.8 MeV c^{-1} in a laboratory reference frame in which the pion is at rest. The rest mass of the muon is 105.7 MeV c^{-2} and the mass of the neutrino can be assumed to be zero.

For the laboratory reference frame

a.i. write down the momentum of the neutrino. [1]

a.ii. show that the energy of the pion is about 140 MeV. [2]

b. State the rest mass of the pion with an appropriate unit. [1]

This question is about interactions and quarks.

For the lambda baryon Λ^0, a student proposes a possible decay of Λ^0 as shown.

$$\Lambda^0 \rightarrow p + K^-$$

The quark content of the K^- meson is $\bar{\text{u}}\text{s}$.

a. A lambda baryon Λ^0 is composed of the three quarks uds. Show that the charge is 0 and the strangeness is -1. [2]

b.i. Discuss, with reference to strangeness and baryon number, why this proposal is feasible. [4]

Strangeness:

Baryon number:

b.ii. Another interaction is [1]

$$\Lambda^0 \rightarrow p + \pi^-.$$

In this interaction strangeness is found **not** to be conserved. Deduce the nature of this interaction.

This question is about particle interactions.

An electron and a positron interact to produce a muon and antimuon through a weak interaction. The weak interaction involves one of the virtual particles W^{-}, W^{+} or Z^{0} boson.

a.i. Describe what is meant by a virtual particle. [1]

a.ii. Draw a Feynman diagram which represents this interaction. [2]

a.iii Explain whether this interaction involves the W^{-}, W^{+} or Z^{0} boson. [1]

This question is about particles and interactions.

When a free neutron decays to a proton, an electron is one of the decay products.

(i) State the name of the exchange particle and the interaction involved in this decay.

(ii) The interaction and the exchange particle in (a)(i) may arise when a quark decays. Describe the change in the quark structure of the neutron.

This question is about a K meson decay.

The positive kaon K^+ has a strangeness of +1. It can decay through the interaction

$$K^+ \rightarrow \mu^+ + v_\mu.$$

Charge, energy and momentum are conserved in this decay.

a. State the quark structure of the K^+. [1]

b. Deduce one further quantity in this decay that is [2]

(i) conserved.

(ii) not conserved.

This question is about the standard model.

a. State what is meant by the standard model. [3]

b. Use the conservation of lepton number and charge to deduce the nature of the particle *x* in the following reaction. [1]

$$v_{\mathrm{e}} + \mu^{-} \rightarrow e^{-} + x$$

c. State what is meant by deep inelastic scattering. [1]

This question is about particle production.

In a particular experiment, moving kaon mesons collide with stationary protons. The following reaction takes place

$$p + K^- \rightarrow K^0 + K^+ + X$$

where X is an unknown particle. This process involves the strong interaction. The quark structure of the kaons is $K^- = \bar{u}s$, $K^0 = d\bar{s}$, and $K^+ = \bar{u}s$.

(i) State the strangeness of the unknown particle X.

(ii) Particle X is a hadron. State and explain whether X is a meson **or** a baryon.

This question is about elementary particles.

The quark is said to be an elementary particle.

(i) State what is meant by the term elementary particle.

(ii) Identify another elementary particle other than the quark.

This question is about linear accelerators.

b. A moving proton is incident on a stationary pion, producing a kaon (*K* meson) and an unknown hadron X according to the reaction given below. [2]

$$p + \pi^- \rightarrow X + K^-$$

(i) State, with a reason, the electric charge of X.

(ii) State, with a reason, if X is a baryon **or** a meson.

c. In a deep inelastic scattering experiment, protons of momentum 2.70×10^{-18} N s are scattered by gold nuclei. [3]

Given that the diameter of nucleons is of the order 10^{-15} m and the diameter of quarks is less than 10^{-18} m, determine if these protons will be able to resolve

(i) nucleons within the gold nuclei.

(ii) quarks within the gold nuclei.

d. Outline how deep inelastic scattering experiments led to the conclusion that gluons exist. [2]

This question is about deep inelastic scattering.

a. A student states that “the strong nuclear force is the strongest of the four fundamental interactions”. Explain why this statement is not correct. [2]

b. Describe how deep inelastic scattering experiments support your answer to (a). [2]

c. State **two** other conclusions that may be reached from deep inelastic scattering experiments. [2]

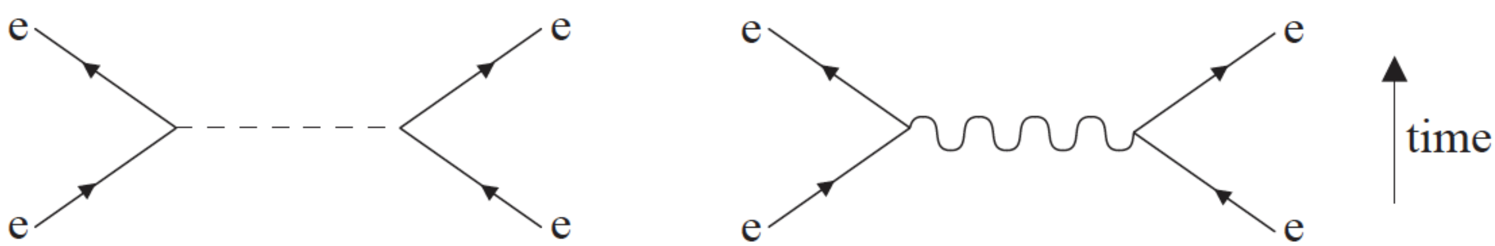
This question is about conservation laws and the standard model.

A muon decays into an electron and two other particles according to the reaction equation $\mu^{-} \rightarrow e^{-} + ? + ?$.

State the names of the **two** other particles that are produced in this decay explaining your answer.

This question is about the standard model.

The Feynman diagrams show two electroweak interactions between electrons. The particle represented by the wavy line is a photon.



a. State [2]

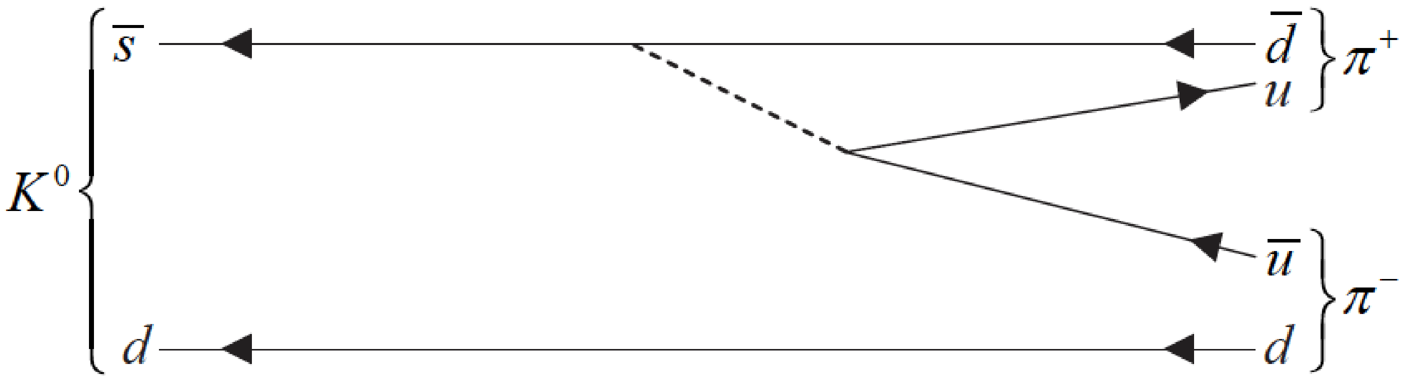
(i) the name of the exchange particle represented by the dotted line.
(ii) one difference between the two exchange particles.

b. Outline how the observation of the interaction represented by the diagram with the dotted line provides evidence for the standard model. [2]

This question is about quarks.

a. State the name of a particle that is its own antiparticle. [1]

b. The meson K^0 consists of a d quark and an anti s quark. The K^0 decays into two pions as shown in the Feynman diagram. [6]



(i) State a reason why the kaon K^0 cannot be its own antiparticle.

(ii) Explain how it may be deduced that this decay is a weak interaction process.

(iii) State the name of the particle denoted by the dotted line in the diagram.

(iv) The mass of the particle in (b)(iii) is approximately 1.6×10^{-25}kg. Determine the range of the weak interaction.

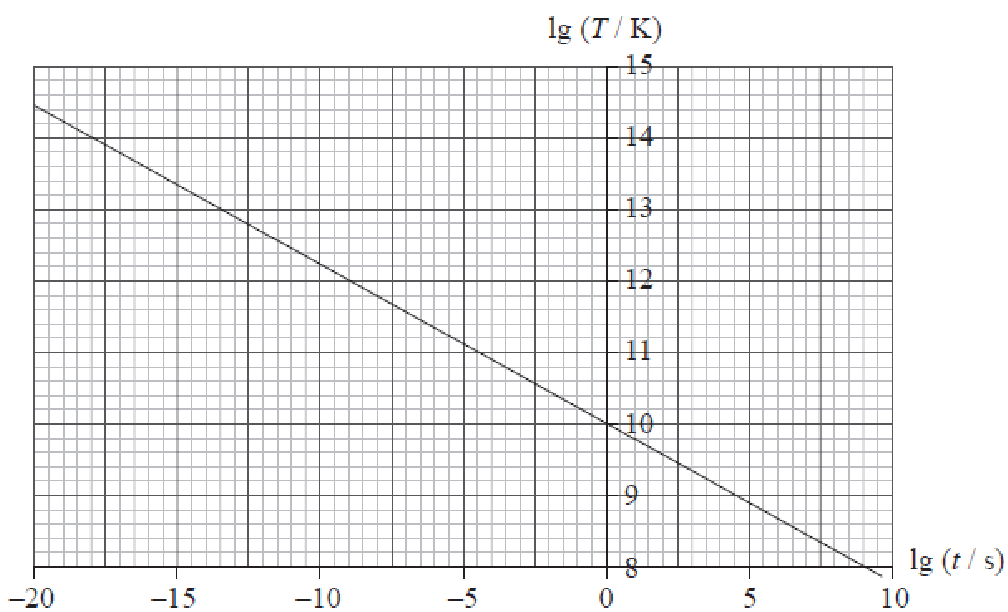
This question is about hadrons.

The interaction in (a) can also occur via the weak interaction with neutral current mediation producing an up and anti-up quark pair.

Draw a labelled Feynman diagram for this interaction. Time on your diagram should go from left to right.

This question is about the early universe and the Higgs boson.

The graph shows the variation of the logarithm of the temperature *T* of the universe with the logarithm of the time *t* after the Big Bang.



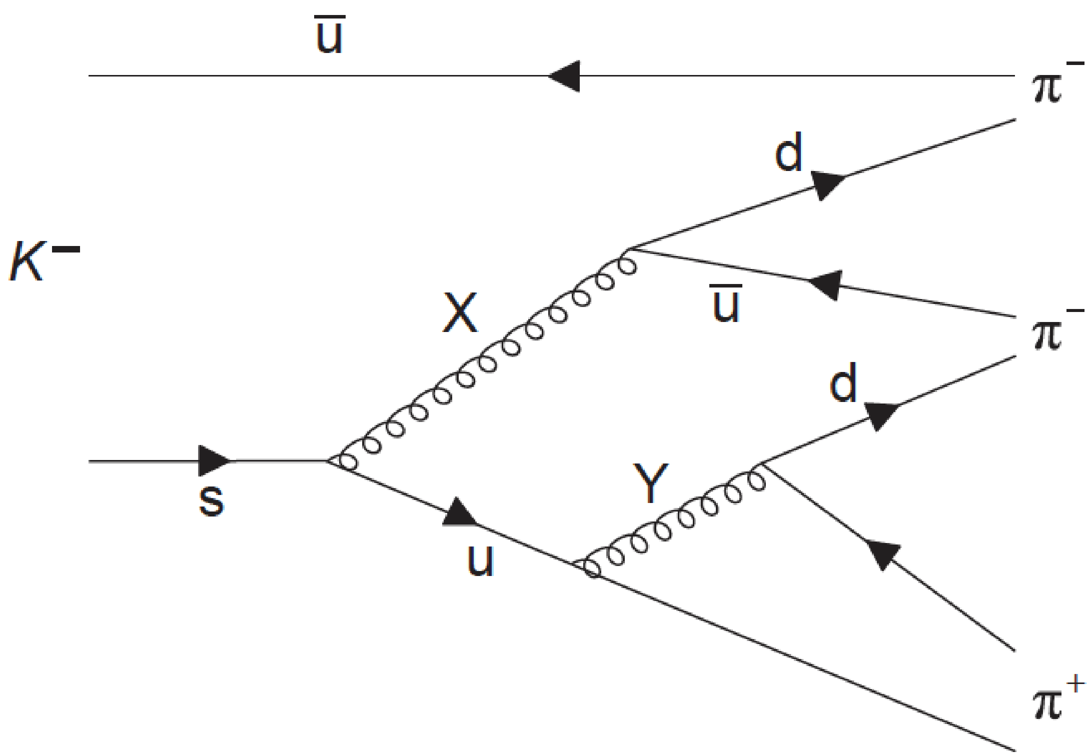
Evidence for the Higgs boson might be discovered at the Large Hadron Collider (LHC) at CERN. Outline why such a discovery would be of crucial significance to the standard model.

This question is about particles and interactions.

a. (i) State what is meant by an antiparticle. [3]

(ii) Some particles are identical to their antiparticles. Discuss whether the neutron and the antineutron are identical.

b. The Feynman diagram represents the decay $K^- \to \pi^+ + \pi^- + \pi^-$. [5]



Particles X and Y are exchange particles.

(i) Explain what is meant by an exchange particle.

(ii) Identify X.

(iii) Determine the electric charge of Y.

(iv) Calculate the change in strangeness in the decay of the K^-.

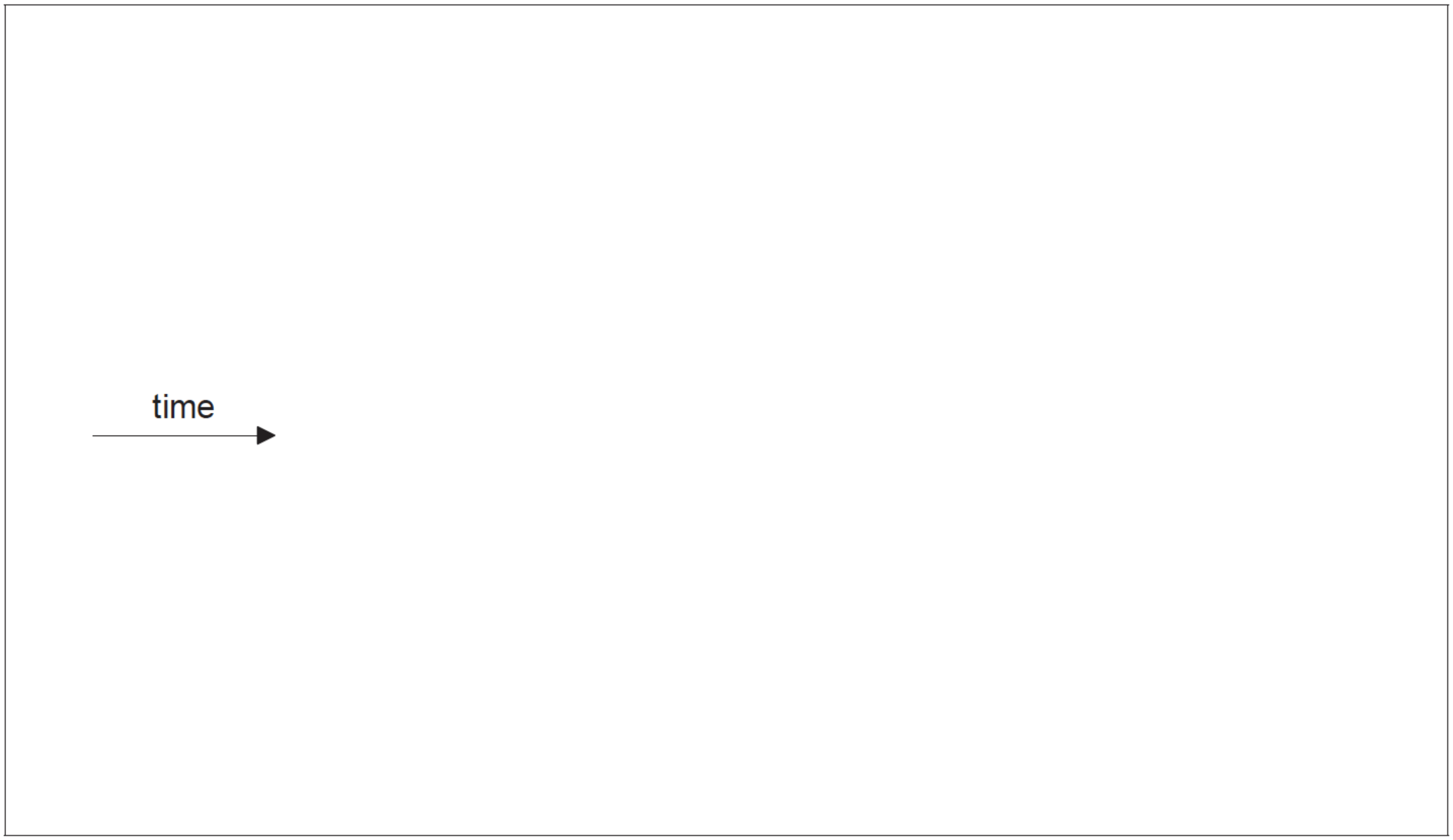
This question is about the standard model and the Pauli exclusion principle.

a. State **one** conservation law that would be violated, if the following reactions were to occur. [2]

(i) $\pi^0 \to e^+ + \mu^-$

(ii) $p^+ + \bar{n} \to e^+ + e^- + \bar{v}_e + v_e$

b. The reaction $\overline{v}_\mu + e^- \rightarrow \overline{v}_\mu + e^-$ is an example of a neutral current reaction. Draw a Feynman diagram for this reaction labelling all the particles involved. The arrow provided indicates the direction of time. [3]



This question is about the standard model.

Muons can decay via the weak interaction into electrons and neutrinos. One such decay is

$$\mu^+ \rightarrow e^+ + v_e + \overline{v}_\mu$$

(i) Using the table provided, show that in this decay, lepton number L, electron lepton number L_e and muon lepton number L_μ are all conserved.

	μ^+	e^+	ν_e	$\overline{\nu}_\mu$
L				
L_e				
L_μ				

(ii) Label the Feynman diagram below for the decay of a positive muon (μ^+).