Particle Physics and The Standard Model

Q1.

A cosmic ray, consisting of a fast-moving proton, collides with a proton within the nucleus of an atom in the upper atmosphere. Three particles, a proton, a neutron and a pion result from the collision.

Write a particle equation for this collision.

(2)

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(Total for question = 2 marks)

Q2.

Which of the following particles is an example of a fundamental particle?

☐ **A** nucleus

☐ **B** neutrino

☐ **C** pion

☐ **D** proton

(Total for question = 1 mark)

Q3.

A particle has a mass of 1 u and a charge of -1.6×10^{-19} C.

Which of the following could be the particle?

☐ **A** antiproton

☐ **B** electron

☐ **C** neutron

☐ **D** positron

(Total for question = 1 mark)

Q4.

The neutral lambda Λ^0 particle is a baryon of mass 1116 MeV/c^2 and contains one strange quark.

The table shows quarks and their relative charge.

Quark	Charge / *e*
u	+2/3
d	−1/3
s	−1/3

Calculate the mass of the Λ^0 particle in kg.

(3)

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Mass of Λ^0 particle = ... kg

(Total for question = 3 marks)

Q5.

A proton has a mass of 1.67×10^{-27} kg.

Which of the following shows the conversion of this mass to GeV/c^2 ?

☐ **A** $\dfrac{1.67 \times 10^{-27} \times 1.60 \times 10^{-10}}{(3.00 \times 10^8)^2}$

☐ **B** $\dfrac{1.67 \times 10^{-27} \times 1.60 \times 10^{-19}}{(3.00 \times 10^8)^2}$

☐ **C** $\dfrac{1.67 \times 10^{-27} \times (3.00 \times 10^8)^2}{1.60 \times 10^{-10}}$

☐ **D** $\dfrac{1.67 \times 10^{-27}}{1.60 \times 10^{-10} \times (3.00 \times 10^8)^2}$

(Total for question = 1 mark)

Q6.

Which of the following particle equations is correct for the decay of a proton within a nucleus?

☐ **A** $p \rightarrow n + \beta^+$

☐ **B** $p \rightarrow p + \beta^+$

☐ **C** $p \rightarrow n + \beta^+ + \nu$

☐ **D** $p \rightarrow p + \beta^+ + \nu$

(Total for question = 1 mark)

Q7.

A high energy proton collides with a stationary proton and a π^0 particle is produced.
The equation for the reaction is

$$p + p \rightarrow p + p + \pi^0$$

(i) Explain why the proton must have a high energy in order for this reaction to occur.

(2)

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(ii) The rest mass of the π^0 is $\frac{1}{7}$ of the rest mass of a proton.
In this reaction the total kinetic energy of the particles decreases.
Calculate the minimum decrease in kinetic energy if the reaction is to occur.
rest mass of proton = 938 GeV/c^2

(2)

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Minimum decrease in kinetic energy = ...

(Total for question = mark)

Q8.

A high-energy proton can interact with a photon to produce two particles.

Which of the following could be the two particles produced?

☐ **A** $n + \pi^0$

☐ **B** $n + \pi^+$

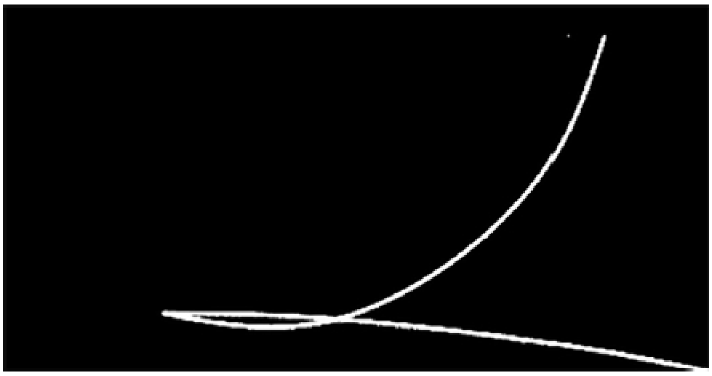
☐ **C** $\pi^0 + \pi^+$

☐ **D** $\pi^- + \pi^+$

(Total for question = 1 mark)

Q9.

The bubble chamber photograph shows tracks made by a proton and a pion. The proton and pion were both created by the decay of a lambda particle. No other particles were produced.



* Explain how observations and measurements from the photograph can be used to establish information about the lambda particle.

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(Total for question = 6 marks)

Q10.

The bubble chamber photograph shows tracks made by a proton and a pion. The proton and pion were both created by the decay of a lambda particle. No other particles were produced.

[Same Image as in Q9]

The rest mass of the lambda particle is 1115 MeV / c^2.

(i) Calculate this mass in kg.

(3)

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Mass = ... kg

(ii) The rest mass of a proton is 940 MeV / c^2. The rest mass of a pion is 140 MeV / c^2.

The kinetic energy of the lambda particle just before decay is 4.95 GeV.
Calculate the total kinetic energy of the proton and pion in MeV.

(3)

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Total kinetic energy = ... MeV

(Total for question = 6 marks)

Q11.

The bubble chamber photograph shows tracks made by a proton and a pion. The proton and pion were both created by the decay of a lambda particle. No other particles were produced.

[Same Image as in Q9]

The lambda particle consists of up, down and strange quarks.

Explain how the conservation of charge, baryon number and lepton number apply to the decay of the lambda particle.

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(Total for question = 3 marks)

Q12.

The bubble chamber photograph shows tracks made by a proton and a pion. The proton and pion were both created by the decay of a lambda particle. No other particles were produced.

[Same Image as in Q9]

Write an equation to represent the decay of the lambda (Λ) particle.

(1)

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(Total for question = 1 mark)

Q13.

Which row of the table summarises the mass and charge of an antineutron?

	Mass / u	Charge / e
☐ **A**	0	0
☐ **B**	0	−1
☐ **C**	1	0
☐ **D**	1	+1

(Total for question = 1 mark)

Q14.

The π^- particle has a mass of 140 MeV / c^2.

Which row of the table is correct for the antiparticle of a π^- ?

	Particle classification	Mass / MeV/c^2
☐ **A**	Baryon	+140
☐ **B**	Baryon	−140
☐ **C**	Meson	+140
☐ **D**	Meson	−140

(Total for question = 1 mark)

Q15.

A muon (μ) is a lepton with a mass of 106 MeV/c^2.

Calculate the mass of a muon in kg.

(3)

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Mass of muon = ... kg

(Total for question = 3 marks)

Q16.

The neutral lambda Λ^0 particle is a baryon of mass 1116 MeV/c^2 and contains one strange quark.

The table shows quarks and their relative charge.

Quark	Charge / *e*
u	+2/3
d	–1/3
s	–1/3

The Λ^0 particle cannot be directly observed in particle experiments, however some of the decay products can.

Explain why the Λ^0 particle cannot be directly observed but information about it can be obtained by studying its decay particles.

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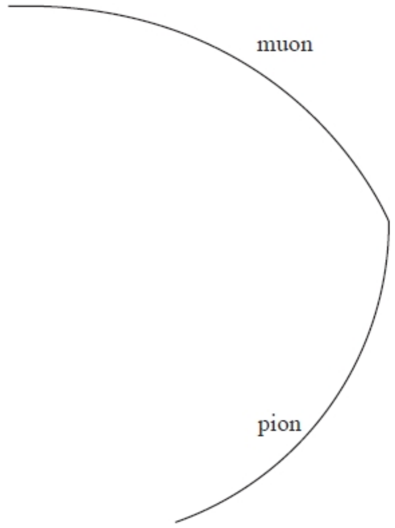
(Total for question = 3 marks)

Q17.

A negatively charged pion decays into a muon and an antineutrino. The diagram shows tracks in a particle detector formed in such an event.



Write a particle equation to represent this decay.

(1)

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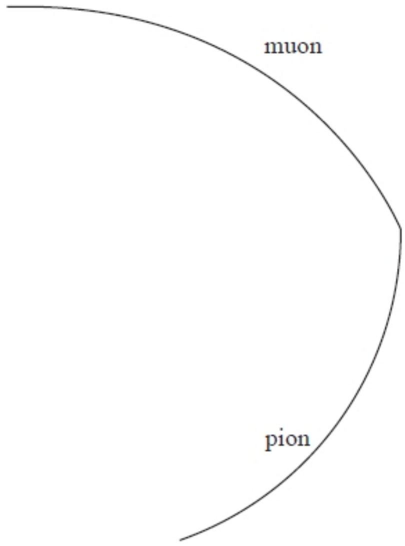
(Total for question = 1 mark)

Q18.

A negatively charged pion decays into a muon and an antineutrino. The diagram shows tracks in a particle detector formed in such an event.



According to the standard model, the pion and muon are classified within two different groups of particles.

State which group each particle belongs to and describe the two groups.

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(Total for question = 4 marks)

Q19.

Pions (π^+, π^-, π^0) are created in the upper atmosphere when cosmic rays collide with protons. Pions are unstable and decay rapidly.

(a) Pions are the lightest of the hadrons. Charged pions (π^+ and π^-) decay to produce muons which then decay to positrons or electrons.

(i) A positive pion π^+ has a quark composition $u\bar{d}$.
State with a justification the possible quark compositions of a neutral pion π^0.

(2)

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(ii) Muons are examples of leptons whereas pions are examples of mesons.
State a structural difference between leptons and mesons.

(1)

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(b) Muons with a speed of $0.99c$ travel a distance of 15 km to reach the surface of the Earth from the upper atmosphere.

(i) Show that the time it takes a muon to travel this distance is about 51 μs.

(2)

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(ii) The muons are unstable particles.
Calculate the fraction of muons which would remain after a time of 51 μs.
half-life of muon = 2.2 μs

(4)

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Fraction = ...

(iii) In fact the fraction of muons reaching the surface of the Earth is about 0.1 Explain the discrepancy.

(4)

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(Total for question = 11 marks)

Q20.

A muon (μ) is a lepton with a mass of 106 MeV/c^2.

Muons are produced from the decay of pions in the upper atmosphere.

An example of this decay is given by the equation

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

(i) Explain how this decay obeys the laws of conservation of charge, baryon number and lepton number.

(3)

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(ii) The masses of these three particles, in MeV/c^2, are given below.

π^-	μ^-	$\bar{\nu}_\mu$
140	106	≈0

Explain why the total kinetic energy of the products of this decay is approximately 34 MeV. Assume the π^- is stationary.

(2)

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(iii) State which two conservation laws could be used to calculate the kinetic energy of the μ– and the $\bar{\nu}_\mu$ just after the decay of the π^-.

(2)

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* (iv) The muons are produced at a height of 10 km in the atmosphere. The velocity of the muons is 0.99 *c*. The average lifetime for muons is normally 2.2 μs and yet muons produced in the upper atmosphere are found in significant numbers at sea level.

Discuss this apparent anomaly.

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(Total for question = 13 marks)

Q21.

Protons interact with particles in the upper atmosphere and create new particles. Pions can be produced from high energy proton collisions.

(i) State why the following reaction is not possible.

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

(1)

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(ii) State one similarity and one difference between the electric field of a proton and the electric field of a π^-.

(2)

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(Total for question = 3 marks)

Q22.

The neutral lambda Λ^0 particle is a baryon of mass 1116 MeV/c^2 and contains one strange quark.

The table shows quarks and their relative charge.

Quark	Charge / *e*
u	+2/3
d	–1/3
s	–1/3

A student suggests five ways a Λ^0 particle might decay. These are

$$\Lambda^0 \rightarrow p + \pi^-$$
$$\Lambda^0 \rightarrow e^+ + e^-$$
$$\Lambda^0 \rightarrow n + \pi^0$$
$$\Lambda^0 \rightarrow n$$
$$\Lambda^0 \rightarrow p + \pi^0$$

Deduce which of these decay processes are **not** possible.

(6)

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(Total for question = 6 marks)

Q23.

Which of these is **not** made from quarks?

☐ **A** proton

☐ **B** neutron

☐ **C** lepton

☐ **D** meson

(Total for question = 1 mark)

Q24.

The discovery of the Higgs particle was an important contribution to our understanding of particle physics.

(a) Describe the standard model for subatomic particles. You should identify the fundamental particles and the composition of the particles we can observe.

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(b) The mass of the Higgs particle is 2.2×10^{-25} kg.

Calculate this mass in GeV/c^2.

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Mass = ... GeV/c^2

(c) The Higgs particle was discovered using the Large Hadron Collider (LHC) in 2012. Two beams of very high energy protons, moving in opposite directions, were made to collide.

(i) Explain the need for such high energy collisions.

(3)

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(ii) The beams of protons are contained within a ring of superconducting magnets.

Calculate the momentum of a proton in a beam.

(3)

magnetic field strength = 8.3 T
circumference of the ring = 27 km

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Momentum = ...

(iii) State the total momentum of the products of the collision between the two beams of protons.

(1)

Total momentum = ...

(d) A student used the equation $E_k = \frac{p^2}{2m}$ to predict the energy of a proton in the beam, using the momentum calculated in (c)(ii), but found the energy was far higher than 7 TeV.

Explain why.

(2)

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(Total for question = 17 marks)

Q25.

The neutral lambda Λ^0 particle is a baryon of mass 1116 MeV/c^2 and contains one strange quark.

The table shows quarks and their relative charge.

Quark	Charge / *e*
u	+2/3
d	−1/3
s	−1/3

State, with justification, the quark content of a Λ^0 particle.

(2)

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(Total for question = 2 marks)

Q26.

A cosmic ray, consisting of a fast-moving proton, collides with a proton within the nucleus of an atom in the upper atmosphere. Three particles, a proton, a neutron and a pion result from the collision.

The mass of a neutron is about the same as the mass of a proton. A student suggests that the minimum kinetic energy the cosmic ray proton would need to create the pion in this collision is 140 MeV.

Discuss whether this suggestion is correct. Your answer should include reference to the laws of conservation of momentum and conservation of energy.

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(Total for question = 4 marks)

Q27.

A cosmic ray, consisting of a fast-moving proton, collides with a proton within the nucleus of an atom in the upper atmosphere. Three particles, a proton, a neutron and a pion result from the collision.

The mass of a pion is 140 MeV / c^2 .

Calculate the mass of the pion in kg.

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Mass = ... kg

(Total for question = 3 marks)

Q28.

A cosmic ray, consisting of a fast-moving proton, collides with a proton within the nucleus of an atom in the upper atmosphere. Three particles, a proton, a neutron and a pion result from the collision.

The table shows the properties of two quarks.

Quark	Charge / *e*
u	+2 / 3
d	−1 / 3

Give the quark structure for each of the particles produced by this collision.

(3)

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(Total for question = 3 marks)

Mark Scheme – Particle Physics The Standard Model

Q1.

Question Number	Acceptable answers	Additional guidance	Mark
	• Correct equation ignoring charges (1) Charge on pion + (1) (1)	$p + p \rightarrow p + n + \pi^+$	2

Q2.

Question Number	Acceptable answers	Additional guidance	Mark
	B		1

Q3.

Question Number	Acceptable answers	Additional guidance	Mark
	The only correct answer is A *B is not correct because an electron has a much smaller mass* *C is not correct because a neutron has no charge* *D is not correct because a positron has a much smaller mass and is positive*		1

Q4.

Question Number	Acceptable answers	Additional guidance	Mark
	• converts eV using 1.6×10^{-19} (1) • divides by c^2 i.e. $(3 \times 10^8)^2$ (1) • mass = 2.0×10^{-27} kg (1)	Example of calculation $m = \frac{1116\text{V} \times 10^6 \times 1.6 \times 10^{-19}\text{C}}{(3 \times 10^8\,\text{m s}^{-1})^2}$ $m = 2.0 \times 10^{-27}\,\text{kg}$	3

Q5.

Question Number	Acceptable answers	Additional guidance	Mark
	The only correct answer is C $\frac{1.67 \times 10^{-27} \times (3.00 \times 10^8)^2}{1.60 \times 10^{-10}}$	A,B and D all contain numerical errors	1

Q6.

Question Number	Acceptable answers	Additional guidance	Mark
	The only correct answer is C A *is not correct because lepton number is not conserved* B *is not correct because charge conservation is not obeyed* D *is not correct because charge conservation is not obeyed*	$p \rightarrow n + \beta^{+} + \nu$	1

Q7.

Question Number	Acceptable Answer	Additional guidance	Mark
(i)	An explanation that makes reference to the following points: • energy conserved (1) • so energy needed over and above rest energy of proton in order to provide the mass of the π^0 particle (1)		**(2)**

Question Number	Acceptable Answer	Additional guidance	Mark
(ii)	• calculates rest energy of π^0 (1) • 134 GeV (1)	<u>Example of calculation:</u> $E_k = \frac{938\text{ GeV}}{7} = 134\text{ GeV}$	**(2)**

Q8.

Question Number	Acceptable answers	Additional guidance	Mark
	The only correct answer is B $n + \pi^{+}$	A, C and D do not follow conservation laws	1

Q9.

Question Number	Acceptable Answers
*	This question assesses a student's ability to show a coherent and logically structured answer with linkages and fully-sustained reasoning. Marks are awarded for indicative content and for how the answer is structured and shows lines of reasoning. The following table shows how the marks should be awarded for indicative content. Indicative content: • the lambda particle is neutral • because it does not leave a track Or two tracks are opposite charged • momentum of proton/ pion can be determined by measuring radius of curve • using $p = Bqr$ • law of conservation of momentum can then be applied • so momentum/energy of the lambda particle can be determined

Additional Guidance	Mark
	6

IC points	IC mark	Max linkage mark available	Max final mark
6	4	2	**6**
5	3	2	**5**
4	3	1	**4**
3	2	1	**3**
2	2	0	**2**
1	1	0	**1**
0	0	0	**0**

IC4 – p and r recognisable from the context of the answer

IC5 and 6 can be awarded for a labelled momentum vector triangle

Q10.

Question Number	Acceptable answers	Additional guidance	Mark
(i)	• Converts eV to J (1) • use of $\Delta m = \Delta E / c^2$ (1) • mass = 1.98×10^{-27} (kg) (1)	Example of calculation $m = \frac{1115 \text{ V} \times 1.6 \times 10^{-19}\text{C} \times 10^6}{(3 \times 10^8)^2(\text{ms}^{-1})^2}$ $m = 1.98 \times 10^{-27}$ kg	3
(ii)	• Converts prefix G to M Or M to G (1) • Determines total energy / mass of lambda before decay (1) • kinetic energy = 4985 MeV (1)	Example of calculation 4.95 GeV = 4950 MeV Total Energy and mass before decay = 4950 + 1115 = 6065 MeV Total after = 140 + 940 + E_k E_k = 6065 – 1080 = 4985 MeV	3

Q11.

Question Number	Acceptable answers	Additional guidance	Mark
	An explanation that makes reference to the following points: • charge: 0 = +1 identified as proton −1 identified as pion (1) • Baryon number: 1 = 1 identified as proton + 0 identified as pion (1) • Lepton number: 0 = 0 + 0 Or there are no leptons involved (1)		3

Q12.

Question Number	Acceptable answers	Additional guidance	Mark
	• $(\Lambda^0) \rightarrow p^{(1)} + \pi^{-1}$ (1)		1

Q13.

Question Number	Acceptable answers	Additional guidance	Mark
	The only correct answer is C 1 | 0	A and B are incorrect as a neutron has mass D is incorrect as a neutron is neutral	1

Q14.

Question Number	Acceptable answers	Additional guidance	Mark
	The only correct answer is C A is not correct as the particle is a meson B is not correct as the particle is a meson D is not correct as the mass cannot be negative		**1**

Q15.

Question Number	Acceptable answers	Additional guidance	Mark
	• converts eV to J (1) • use of $\Delta m = \Delta E / c^2$ (1) • mass = 1.9×10^{-28} (kg) (1)	Example of calculation: $m = \dfrac{106\,\text{V} \times 1.6 \times 10^{-19}\,\text{C} \times 10^6}{(3 \times 10^8)^2 (\text{ms}^{-1})^2}$ $m = 1.88 \times 10^{-28}\,\text{kg}$	(3)

Q16.

Question Number	Acceptable answers	Additional guidance	Mark
	• Neutral particles do not leave a track/ionise (1) • Reference to conservation laws to deduce the properties of particles (1) • Tracks of decay particles can determine momentum of lambda particle (1)		3

Q17.

Question Number	Acceptable answers	Additional guidance	Mark
	• $\pi^- \rightarrow \mu(^-) + \overline{\nu_{(\mu)}}$ (1)	Any symbol allowed for the muon	1

Q18.

Question Number	Acceptable answers	Additional guidance	Mark
	• Muon is a lepton (1) • Muons / leptons are fundamental particles (1) • Pion is a meson (1) • Pions / mesons consist of a quark and antiquark (1)		4

Q19.

Question Number	Acceptable Answer	Additional Guidance	Mark
(a)(i)	• a π^0 may be $u\bar{u}$ **Or** $d\bar{d}$ (1) • it must be a quark combined with its own antiquark so that overall charge is 0 (1) OR it can only contain up or down quarks (as it is not a strange particle)	Allow $s\bar{s}$	**(2)**
(a)(ii)	mesons are made up of quarks, whereas leptons are fundamental particles (1)		**(1)**

Question Number	Acceptable Answer	Additional Guidance	Mark
(b)(i)	• use of v = s/t (1) • t = 5.05 × 10^{-5} s (1)	Example of calculation: $t = \frac{s}{v} = \frac{15\times10^3\text{ m}}{0.99\times3\times10^8\text{ ms}^{-1}} = 5.05\times10^{-5}\text{ s}$	(2)
(b)(ii)	• use of $\lambda t_{1/2} = 0.693$ (1) • λ = 3.15 × 10^5 s^{-1} (1) • use of $N = N_0 e^{-\lambda t}$ (1) • $\frac{N}{N_0} = 1.23\times10^{-7}$ (1)	Example of calculation: $\lambda = \frac{\ln 2}{t_{1/2}} = \frac{0.693}{2.2\times10^{-6}\text{ s}} = 3.15\times10^5\text{ s}^{-1}$ $\frac{N}{N_0} = e^{-\lambda t} = e^{-3.15\times10^5\text{ s}^{-1}\times5.05\times10^{-5}\text{ s}} = 1.23\times10^{-7}$ $\frac{N}{N_0} = 1.1\times10^{-7}$ if "show that" value used	(4)
(b)(iii)	• This is much smaller than 10% indicating the muon lifetime is much greater than the expected value (1) • The high speed of the muon has led to relativistic effects (1)		(2)

Q20.

Question Number	Acceptable answers	Additional guidance	Mark
(i)	• Charge: -1 = -1 + 0 (1) • Baryon number: needs to be stated as 0 (1) • Lepton number: 0 = +1 + (-1) (1)		(3)
(ii)	• Mass difference = 34 (MeV/c^2) (1) • $E = \Delta mc^2$ so E = 34 MeV (1)	alt to $E = \Delta mc^2$ to show unit $\frac{MeV}{c^2} \times c^2$	(2)
(iii)	• Mass - energy (1) • Momentum (1)		(2)

<table>
<tr><th>Question Number</th><th>Acceptable answers</th><th>Additional guidance</th><th>Mark</th></tr>
<tr><td>*(iv)</td><td>This question assesses a student's ability to show a coherent and logically structured answer with linkages and fully-sustained reasoning.

Marks are awarded for indicative content and for how the answer is structured and shows lines of reasoning.

The following table shows how the marks should be awarded for indicative content.

Indicative content:
• Uses velocity = distance/time
• Calculates a time = 3×10^{-5}s
• Compares with 2.2×10^{-6}s which is (15 times) smaller
• Identifies relativistic speed/effects (as velocity close to c)
• Time (between events is much) slower/longer
Or mentions time dilation
• So increase in muon lifetime</td><td>

IC points	IC mark	Max linkage mark	Max final mark
6	4	2	6
5	3	2	5
4	3	1	4
3	2	1	3
2	2	0	2
1	1	0	1
0	0	0	0

Alternative for ic 2 and 3
Calculates height of atmosphere = 653 m

Compares with 10 km which is larger

Example of calculation:
Time = $10000(\text{m})/0.99 \times 3 \times 10^8(\text{ms}^{-1})$</td><td>(6)</td></tr>
</table>

Q21.

Question Number	Acceptable Answer	Additional guidance	Mark
(i)	charge not conserved		(1)

Question Number	Acceptable Answer	Additional guidance	Mark
(ii)	• both radial fields OR (1) the magnitude of the fields is the same (at a given distance) • different directions (1)		(2)

Q22.

Question Number	Acceptable answers		Additional guidance	Mark
	$\Lambda^0 \rightarrow e^+ + e^-$ (no 2) baryon number not conserved	(1) (1)	More than 3 decays identified as not possible max 2 marks for the decays.	
	$\Lambda^0 \rightarrow$ n only (no 4) momentum or energy cannot be conserved	(1) (1)		
	$\Lambda^0 \rightarrow$ p and π^0 (no 5) charge not conserved	(1) (1)		6

Q23.

Question number	Acceptable answers	Additional guidance	Mark
	C		1

Q24.

Question Number	Acceptable Answers		Additional guidance	Mark
a	• fundamental – quarks and leptons	(1)		
	• Baryons made of 3 q	(1)	MP2 and 3 could be given for a named particle and its quark composition	
	• Mesons made of quark and antiquark	(1)	Can be inferred if either set named	5
	• 6 quark Or 6 leptons	(1)		
	• Each particle has an antiparticle	(1)		

Question Number	Acceptable Answers		Additional guidance	Mark
b	• Use of $\Delta E = \Delta mc^2$	(1)	Example of calculation: $E = 2.2 \times 10^{-25}\text{kg} \times (3.0 \times 10^8)^2 (\text{ms}^{-1})^2$	3
	• Conversion of J to eV	(1)	$E = 1.98 \times 10^{-8}\text{ J}$ $E = 1.98 \times 10^{-8}\text{ J} \div 1.6 \times 10^{-19}\text{ JeV}^{-1}$	
	• mass = 120 GeV/c^2	(1)	$E = 124 \times 10^9\text{ eV}$	

Question Number	Acceptable Answers		Additional guidance	Mark
c(i)	• Energy (of protons) converted to mass (of Higgs) **Or** Energy is required to overcome electrostatic repulsion between protons • Reference to $E = mc^2$ (can be written in any form) • Because c^2 is very large (E must be large) **Or** Higgs particle is massive so needs a lot of energy to create it	(1) (1) (1)	Alternative based on numerical values: Observation that Higgs mass is 120 GeV/c^2 This requires an energy of at least 120 GeV Each beam of protons would need an energy of at least 60 GeV	3
c(ii)	• Use of circumference = $2\pi r$ • Use of $p = Bqr$ • $p = 5.7 \times 10^{-15}$ Ns	(1) (1) (1)	Example of calculation: $r = 27000 \div 2\pi$ $r = 4300$ m $p = 8.3\text{T} \times 1.6 \times 10^{-19}\text{C} \times 4300\text{m}$ $p = 5.7 \times 10^{-15}$Ns	3
ciii	0	(1)	zero	1

Question Number	Acceptable Answers		Additional guidance	Mark
d	• High speeds **Or** relativistic • Mass (of proton) increases • **Or** this equation is only valid at non-relativistic speeds	(1) (1)	Alt: speeds close to speed of light	2

Q25.

Question Number	Acceptable answers		Additional guidance	Mark
	• See u d s • Comment that charge is zero	(1) (1)	If a meson or an incorrect baryon is given which has zero charge, MP2 can be awarded for comment of zero charge.	2

Q26.

Question Number	Acceptable answers		Additional guidance	Mark
	• extra mass after collision is the mass of pion **Or** energy must be conserved so E_k is required for pion • According to $\Delta E = c^2 \Delta m$ (if extra mass is pion) then ΔE required is 140 MeV **Or** extra mass is 140 MeV/c² so E required is 140 MeV • Momentum conservation means that the (three) resulting particles after the collision must have some momentum/E_k • The incoming proton needs 140 MeV plus the E_k of the product particles so statement is inaccurate	(1) (1) (1) (1)		4

Q27.

Question Number	Acceptable answers		Additional guidance	Mark
	• Convert eV to J • Convert J to kg • mass = 2.5 ×10⁻²⁸ (kg)	(1) (1) (1)	Example of calculation: $m = \frac{140\ (\text{MeV}/c^2) \times 1.6 \times 10^{-13}\ \text{J MeV}^{-1}}{(3 \times 10^8)^2\ (\text{m s}^{-1})^2}$ $m = 2.49 \times 10^{-28}$ (kg)	3

Q28.

Question Number	Acceptable answers		Additional guidance	Mark
	• **p** : u u d • **n** : u d d • π : u $\bar{d}$	(1) (1) (1)	Accept labelled π− : ū d	3