Subatomic Physics 2024-2025
Resit Exam

Thursday, 10 April 2025, 08:30 - 10:30 CET

Student name: ______________________________

Student number: ______________________________

Question	1	2	3	$\sum$	Grade
Points	30	30	30	90	
Score		X			

Remarks

- Please write the following on every sheet:
  - your name
  - your student number
  - consecutive page numbers
- The exam consists of 3 parts with subquestions. You receive a total of 4 A4 pages. The questions start on page 3.
- Please provide your answers with clear context and explanations.
- You can achieve up to 90 points in the exam. The amount of points per (sub-)question is listed.
- The grade of the exam is $1 + 1/10 \times$ (number of points achieved).
- You are allowed to use a simple scientific (not graphical) calculator and a handwritten formula sheet of size A4 (both sides).
- At the end of the exam, please only hand in your solutions. No need to hand in the problem sheet, scratch paper or formula sheet.

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1 General Questions (30 points)

Please give a brief answer to these questions. Only around one to three sentences and/or a quick calculation are necessary.

a) (6) Assume we want to produce antiprotons in proton-proton collisions:

$$pp \to ppp\overline{p}\,.$$

What would be the minimum kinetic energy necessary for this reaction if the two proton beams have equal kinetic energy and collide head-on in the laboratory frame? Give your answer in MeV.

b) (6) At the Large Electron-Positron Collider (LEP) at CERN, beams of electrons and positrons were collided at centre-of-mass energies of 209 GeV with an instantaneous luminosity of $\mathcal{L} = 1 \times 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.
How many Z bosons were produced per second via the reaction $e^+e^- \to ZZ$ which has a cross section of $\sigma = 1.1\,\mathrm{pb} = 1.1 \times 10^{-12}\,\mathrm{b}$?

c) (6) Can you detect a charged pion at 75 % of the speed of light in vaccuum in a Cherenkov detector with refractive index $n = 1.25$?

d) (12) Are the following processes allowed in the Standard Model of Particle Physics or not?
For allowed reactions, please draw one possible Feynman diagram.
For not allowed processes, please explain why this is the case.

i) (3) $e^+e^- \to \nu_\mu\overline{\nu}_\mu$

ii) (3) $\nu_\tau p \to \mu^- n$

iii) (3) $\pi^+\pi^- \to n\pi^0$

iv) (3) $\Delta^+ \to n\pi^+$ (*Note*: the Δ^+ has the same quark composition as the proton.)

2 Potassium Going Bananas on Mars (30 points)

This question is not relevant for the upcoming Particle Physics 2025 exam.

3 Charged Kaons (30 points)

Kaons are the lightest spin-zero mesons with strangeness. Charged kaons have several weak interaction decay modes, the largest of which are

$$K^+ \to \mu^+ \nu_\mu \quad (1)$$
$$K^+ \to \pi^+ \pi^0 \quad (2)$$
$$K^+ \to \pi^+ \pi^+ \pi^- \,. \quad (3)$$

a) (3) What is the helicity of the μ^+ in $K^+ \to \mu^+ \nu_\mu$ decays at rest assuming that neutrinos are massless?

b) (5) Calculate the branching ratio for the decay $K^+ \to \pi^+ \pi^0$, given the partial decay width $\Gamma(K^+ \to \pi^+ \pi^0) = 1.1 \times 10^{-8}\,\text{eV}$ and the mean kaon lifetime $\tau(K^+) = 1.2 \times 10^{-8}\,\text{s}$ (in natural units).

c) (4) Consider the two Feynman diagrams shown in Fig. 1. Do both diagrams contribute equally or not to the decay amplitude of $K^+ \to \pi^+ \pi^0$? Explain your reasoning.

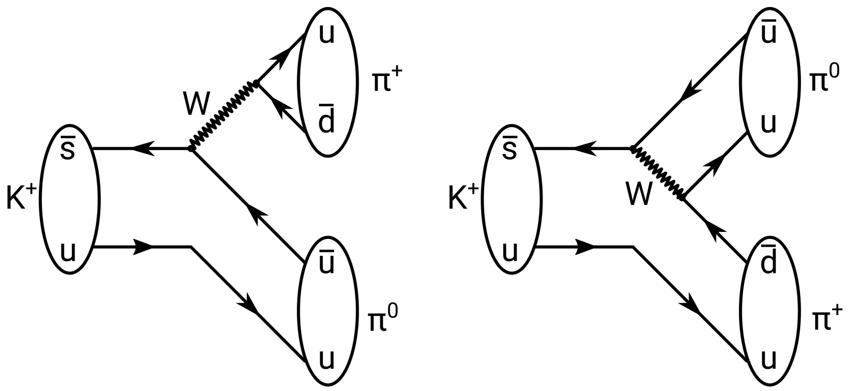

Figure 1: Feynman diagrams of the decays $K^+ \to \pi^+ \pi^0$.

d) (6) Consider the decay $K^+ \to \pi^+ \pi^+ \pi^-$. Draw a possible Feynman diagram of this decay. What CKM matrix elements are involved? Order them by size.

e) (5) In the absence of orbital angular momentum between the pions, determine the parity of the K^+ based on the decay $K^+ \to \pi^+ \pi^0$.
Show that the existence of the decays $K^+ \to \pi^+ \pi^0$ and $K^+ \to \pi^+ \pi^+ \pi^-$ implies that parity is violated in weak decays of kaons.
Hint: Recall that pions are pseudoscalar mesons.

f) (3) Is it also possible to determine the eigenvalue of charge conjugation for K^+?

g) (4) In contrast to the above mentioned decay modes, $K^+ \to \pi^+ \nu_\mu \bar{\nu}_\mu$ is a very rare process with branching ratios in the order of 10^{-10}.
In the Standard Model, is it possible to mediate this decay via the exchange of a single gauge boson? Explain your reasoning.