Particle Physics 2025
Resit Exam

Monday, 1 December 2025, 09:00 - 11:00 CET

Student name: [redacted]

Student number: [redacted]

Question	1	2	3	4	Σ	Grade
Points	35	10	20	25	90	
Score						

Remarks

- Please write the following on every sheet:
  - your name
  - your student number
  - consecutive page numbers
- The exam consists of 4 parts with subquestions. You receive a total of 5 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 (35 points)

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

a) (6) Consider the following reaction.

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

If we irradiate a fixed proton target with photons, what is the minimum photon energy E_γ in the laboratory frame that is necessary for this reaction to happen? Give your result in units of MeV.

b) (6) What limits the maximum energy to which an electron can be accelerated in a synchrotron? List four possible factors.

c) (5) List all constituents of a proton in the parton model.

d) (9) State if the following processes are 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) $\tau^- \rightarrow \pi^-\bar{\nu}_\tau$

ii) (3) $B^+ \rightarrow \pi^0 e^+ \nu_e$ *Note:* B^+ has a quark composition of $u\bar{b}$

iii) (3) $n \rightarrow p e^- \bar{\nu}_e \gamma$

e) (9) Someone reports the observation of hadrons with the following quantum numbers:

i) (3) $(Q, A, S, C, B) = (0, 0, 0, 0, 0)$,

ii) (3) $(Q, A, S, C, B) = (-1, 0, 0, 1, 0)$,

iii) (3) $(Q, A, S, C, B) = (-1, 1, -3, 0, 0)$.

Herein, Q denotes the electric charge, A the baryon number and S, C, B the strange, charm and bottom flavour quantum number, respectively.
Check if these states are compatible with allowed hadron states. If the state is allowed, state a possible quark composition. If the state is not allowed, explain why.

2 The η' Meson (10 points)

The η' is a spin-0 meson with a mass of 957.78 MeV and decay width $\Gamma = 0.188\,\text{MeV}$. Its quark composition is a linear combination of $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$.

a) (3) What is the lifetime of η'?

b) (4) In the absence of orbital angular momentum between the pions, determine the parity (P) and charge conjugation (C) eigenvalue of η' based on the decay $\eta' \to \pi^0\pi^0\pi^0$. Give reasons. *Hint*: Recall that pions are pseudoscalar mesons with $C(\pi^0) = +1$.

c) (3) One decay mode of η' is $\eta' \to \omega^0\gamma$. The ω^0 is a vector meson with mass 782.66 MeV. Suppose the ω^0 has the same quark composition as the η', explain why there needs to be at least a second particle in the final state in decays of η' to ω^0 (like the γ in $\eta' \to \omega^0\gamma$).

3 Annihilation of e^+e^- (20 points)

At an e^+e^- collider, processes of the type $e^+e^- \to f\bar{f}$ can be generated (f: fundamental fermion). Let's compare the production of muons and charm quarks at $\sqrt{s} = 10\,\text{GeV}$: $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to c\bar{c}$.

a) (4) Which interactions can mediate the processes $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to c\bar{c}$? Which interaction is dominant?

For the following questions, only consider the dominant interaction at lowest order.

b) (4) Draw the Feynman diagrams of $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to c\bar{c}$.

c) (6) What are the vertex factors involved in $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to c\bar{c}$?

d) (6) Calculate the relative ratio R of the decay rates Γ of the two processes:

$$R = \frac{\Gamma(e^+e^- \to c\bar{c})}{\Gamma(e^+e^- \to \mu^+\mu^-)} \quad .$$

You can assume that $\sqrt{s}$ is high enough such that the masses of e, μ and c can be neglected.

4 The NA62 Experiment (25 points)

The NA62 experiment in the CERN North Area (NA) produces kaons by colliding 400 GeV protons on a Beryllium target.
The charged kaon K^+ has a lifetime of 1.24×10^{-8} s. The dominant decay mode of the charged kaon to hadrons is $K^+ \to \pi^+\pi^0$ with a branching fraction of 20.67 %.

The NA62 experiment investigates the very rare decay $K^+ \to \pi^+\nu\bar{\nu}$. This decay proceeds via loop diagrams such as the one shown in Figure 1. The branching ratio of this decay is measured to be $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = 13.0 \times 10^{-11}$.

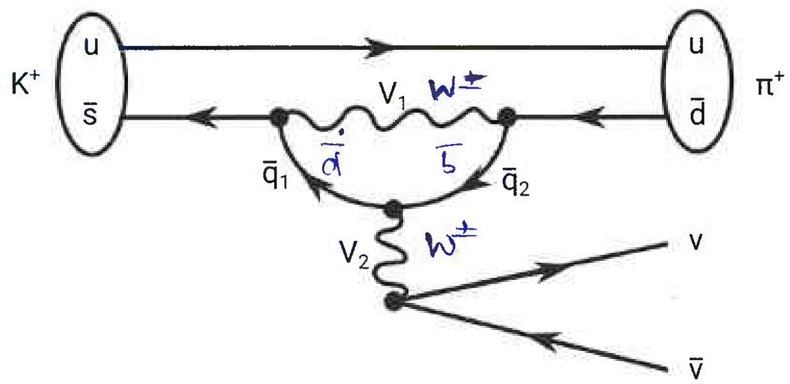

Figure 1: Feynman diagram of the decay $K^+ \to \pi^+\nu\bar{\nu}$.
V_1 and V_2 are placeholders for gauge bosons, and $\bar{q}_1$ and $\bar{q}_2$ placeholders for antiquarks.

a) (5) Take a closer look at the Feynman diagram of $K^+ \to \pi^+\nu\bar{\nu}$ shown in Figure 1. V_1 and V_2 are placeholders for gauge bosons, and $\bar{q}_1$ and $\bar{q}_2$ are placeholders for antiquarks.
Which gauge bosons are V_1 and V_2? What combinations of two antiquarks are allowed for $\bar{q}_1$ and $\bar{q}_2$?

b) (6) In order to measure the small branching fraction of $K^+ \to \pi^+\nu\bar{\nu}$ decays, a large number of charged kaons need to be produced.
The Beryllium target has a mass density ρ of 1.85 g cm^{-3}, a thickness d of 0.4 m and an atomic mass m(Be) of 9.012 u. The cross-section σ for charged pion production at NA62 is 1 mb.
How many protons per second are required to hit the target in order to achieve a production rate of 45×10^6 charged kaons per second?
Hint: $1\,\text{u} = 1.660 \times 10^{-27}$ kg

c) (5) A possible background to the search for $K^+ \to \pi^+\nu\bar{\nu}$ are K^+ that do not decay in the detector and are mistaken for a π^+.
Give and shortly explain a detection principle that could be used to distinguish between K^+ and π^+. You can assume that the momentum of the particle is precisely known.

d) (5) Draw a Feynman diagram of the decay $K^+ \to \pi^+\pi^0$. Which CKM elements are involved? Order them from small to large.

e) (4) The π^0 in $K^+ \to \pi^+\pi^0$ decays promptly to two photons.
Give and shortly explain a detection principle that could be used to distinguish the background decay $K^+ \to \pi^+\pi^0 (\to \gamma\gamma)$ from the rare signal decay $K^+ \to \pi^+\nu\bar{\nu}$.