Particle Physics 2024-2025
Exam

Tuesday, 28 October 2025, 18:15 - 20:15 CET

Student name: ______________________________

Student number: ______________________________

Question	1	2	3	Σ	Grade
Points	35	25	30	90	
Score					

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.

d) (5) The neutral kaon can transition to a neutral anti-kaon.
Draw one possible Feynman diagram of the transition $K^0 \rightarrow \overline{K}^0$. State all CKM matrix elements that are involved in your chosen diagram.

e) (4) Charged kaons can decay to a charged lepton and a neutrino. We observe branching fractions of $\mathcal{B}(K^- \rightarrow e^- \overline{\nu}_e) = 1.58 \times 10^{-5}$ and $\mathcal{B}(K^- \rightarrow \mu^- \overline{\nu}_\mu) = 63.6\,\%$ for decays to electrons and muons, respectively.
Which of the following three concepts causes this behaviour?

i) Suppression due to Cabibbo angle
ii) Suppression due to helicity
iii) Lepton universality

Explain briefly your chosen concept and how it applies in $K^- \rightarrow \ell^- \overline{\nu}_\ell$ decays. You can assume that the antineutrino is massless.

f) (3) Can a *single* particle with strangeness $S = \pm 1$ be produced by reactions that otherwise involve only particles with $S = 0$ in the initial and/or final state? Give reasons.

3 Search for W and Z Bosons (30 points)

In the 1980s, the W and Z bosons were discovered in $p\overline{p}$ collisions. The proton beam and antiproton beam had each an energy of $E = 270\,\text{GeV}$ and they collided heads-on.
The mean Bjorken-x of valence quarks in a proton is $\langle x^p_{\text{valence}} \rangle \approx 0.15$, and the mean Bjorken-$x$ of sea quarks is $\langle x^p_{\text{sea}} \rangle \approx 0.04$, respectively.

a) (6) Give one possible production and one possible decay mode for W bosons in $p\overline{p}$ collisions at the level of fundamental particles. Do the same for the Z boson. Draw the respective Feynman diagrams.

b) (3) What is the center-of-mass energy of the $p\overline{p}$ collisions?

c) (6) What is the minimum value of the Bjorken-x required to produce a Z boson at rest? Is it realistic to produce Z bosons in the above-mentioned experiment? Give reasons.
Hint: For simplicity, you can assume that each participating particle has the same x and that all particle masses except for the Z can be neglected.

d) (4) The cross-section for Z production in $p\overline{p}$ collisions is

$$\sigma(p\overline{p} \rightarrow Z + X) \approx 1.0\,\text{nb}\,.$$

The X denotes any other particles that are produced alongside the Z.
How large does the instantaneous luminosity $\mathcal{L}$ need to be to be able to produce on average one Z boson per week? Give your result in units of $\text{cm}^{-2}\,\text{s}^{-1}$.

e) (4) Would the Z production rate be lower, higher or the same if two proton beams were collided instead of $p\overline{p}$? Explain qualitatively.

f) (7) The decay width for Z decays to fermion-antifermion pairs is proportional to $(c_V^2 + c_A^2)$ with c_V and c_A denoting the coefficients of the vector and axial-vector couplings, respectively.
Without considering phase space, how large is the branching fraction of $Z \rightarrow e^+e^-$?
Hint: Remember that $c_V = I_W^{(3)} - 2Q \sin^2\theta_W$ and $c_A = I_W^{(3)}$ with the third component of the weak isospin $I_W^{(3)}$ and the electric charge Q of the particle in the reaction, and the weak mixing angle θ_W ($\sin^2\theta_W = 0.2315$).

~~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.

(6) Consider the following reaction (photo-production of pions).

$$\gamma p \to p\pi^0$$

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.

(6) The Large Electron-Positron Collider (LEP) was an e^+e^- collider at CERN with a radius of $R = 8.49\,\text{km}$. The colliding beams were accelerated to $E_e = 104\,\text{GeV}$, respectively.
To which beam energy could the electrons and positrons be accelerated if the radius were doubled while all other conditions such as the maximum strength of the bending magnets were kept the same? You can ignore synchrotron radiation effects in your answer.

(5) Does the gluon have a strangeness quantum number S of 0, 1 or -1?

(9) 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) $\tau^- \to \pi^- \nu_\tau$
ii) (3) $\Lambda^0 \to \pi^+ e^- \overline{\nu}_e$
iii) (3) $\Delta^+ \to p\pi^0$

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

i) (3) $(Q, A, S, C, B) = (-1, 0, 0, 0, 0)$,
ii) (3) $(Q, A, S, C, B) = (0, -1, 0, 0, 1)$,
iii) (3) $(Q, A, S, C, B) = (0, 0, -2, 1, 0)$.

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 the quark composition. If the state is not allowed, explain why.

~~2 Physics with Kaons (25 points)~~

Hitting a target with a proton beam, we get the following strong reaction: $p\,n \to p\,\Lambda^0$+kaon.

(3) Which kind of kaon is produced? Give the quark composition.

(4) What is the parity eigenvalue P of the neutral kaon K^0? Give reasons.
Can you also give the charge conjugation eigenvalue C of the neutral kaon? If yes, state C. If no, explain why.

(6) The neutral kaon is observed to decay to final states with two pions ($\pi^+\pi^-$ and $\pi^0\pi^0$) and to final states with three pions ($\pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$).
Based on these decay modes, is parity conserved in the decay of neutral kaons? Without drawing a Feynman diagram, say if these decays proceed via the electromagnetic, strong or weak interaction?
Hint: You can assume that there is no relative angular momentum between the pions in the final state.