ONE HOUR THIRTY MINUTES

A list of constants is enclosed.

UNIVERSITY OF MANCHESTER

Particle Physics

15 May 2019, 09:45 - 11:15

Answer **ALL** parts of question 1 and **TWO** other questions

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Electronic calculators may be used, provided that they cannot store text.

The numbers are given as a guide to the relative weights of the different parts of each question.

1. a) Write down the formulae for instantaneous and integrated luminosity and define all terms.

[5 marks]

b) Sketch the parton distribution functions for valence quarks, sea quarks and gluons inside a proton. Label the axes and briefly describe the structures of the PDFs.

[5 marks]

c) Draw a fully-labeled Feynman diagram showing how gluon-gluon fusion can produce a Higgs boson that decays to a final state of two electrons and two positrons.

[5 marks]

d) A K^+ meson, of mass 493.7 MeV/c^2, is at rest. It decays through the process $K^+ \rightarrow \mu^+ + \nu_\mu$. Calculate the lifetime of the μ^+ in the lab frame. The μ^+ has a mass of 105.7 MeV/c^2 and a lifetime of 2.20×10^{-6} s in the rest frame.

[5 marks]

e) State the Sakharov conditions required for the development of a matter-dominated universe.

[5 marks]

2. a) Sketch and label the cross section for $p+p \rightarrow \mu^+ + \mu^-$ as a function of centre-of-mass energy, E_{CM}, in the region around $E_{CM} = M_Z c^2 = 91.2$ GeV. Briefly explain the features of the graph and how they relate to properties of the Z boson.

[5 marks]

b) Draw fully labeled Feynman diagrams for all processes contributing to $p + p \rightarrow \mu^+ + \mu^-$ at leading order.

[4 marks]

c) i) Draw a cross section of a general-purpose detector and label the components from the inside to the outside.

[5 marks]

ii) State in which of those components a muon would interact. For each component state briefly the main interaction mechanism.

[3 marks]

iii) Briefly describe the importance of transverse momentum in identifying events of interest in a general-purpose detector.

[3 marks]

d) In one collision, the muon and antimuon are measured to have the following momenta, in cartesian coordinates:

$$\begin{aligned} \mathbf{p}_{\mu^+} &= (37, 22, 9)\ \mathrm{GeV/c^2}, \\ \mathbf{p}_{\mu^-} &= (-22, -31, -8)\ \mathrm{GeV/c^2}. \end{aligned}$$

Calculate the invariant mass of the particle that decayed to produce the muon and antimuon. You may neglect the muon mass.

[5 marks]

3. Consider the process $e^+ + e^- \to q + \bar{q} + g$ at a high energy collider with equal beam energies of $E_b = 175$ GeV.

a) Draw a fully labeled Feynman diagram for this process, including the coupling strengths at each vertex.

[4 marks]

b) State what objects can be seen in the detector. Briefly describe the relevant mechanism.

[4 marks]

c) Sketch the potential for the strong force and write down the formulae for how the strength of the potential depends on the separation of the quarks for very small and very large distances.

[5 marks]

d) For the same collider, consider the process $e^+ + e^- \to t + \bar{t}$.

i) Sketch the development of the cross section (in arbitrary units) with respect to the collision energy between beam energies of $E_b = 170$ GeV and $E_b = 180$ GeV. Briefly describe the behaviour.

[3 marks]

ii) List the possible final state objects this process would have. Which parts of the detector would see the different objects?

[5 marks]

iii) Assume a luminosity L of 300 pb^{-1}, and a production cross section $\sigma_{t\bar{t}}$ of 0.6 pb. The efficiency to detect a jet is 50%. The efficiency to detect a lepton is 70%. Calculate the number of $t\bar{t}$ pairs that are measured, assuming one top quark decays leptonically and the other hadronically.

[4 marks]

4. You may find the following meson quark contents and particle masses useful. $\pi^-(d\overline{u})$, $m_\pi = 139.6$ MeV/c^2. $K^-(s\overline{u})$, $m_K = 493.7$ MeV/c^2. $D^0(c\overline{u})$, $m_D = 1,865$ MeV/c^2. $B^-(b\overline{u})$, $m_B = 5,279$ MeV/c^2. $m_\mu = 105.7$ MeV/c^2, $m_p = 938.3$ MeV/c^2, $m_n = 939.6$ MeV/c^2.

a) Draw fully-labeled Feynman diagrams for the following processes:

i) $\nu_\mu + n \to \mu^- + D^0 + p$,

ii) $D^0 \to K^- + \mu^+ + \nu_\mu$.

[6 marks]

b) Explain which ratios of CKM matrix elements can be measured using the following quantities:

i)

$$\frac{\Gamma(D^0 \to K^- + \mu^+ + \nu_\mu)}{\Gamma(D^0 \to \pi^- + \mu^+ + \nu_\mu)},$$

ii)

$$\frac{\Gamma(D^0 \to \pi^- + \mu^+ + \nu_\mu)}{\Gamma(B^- \to D^0 + \mu^- + \nu_\mu)}.$$

[4 marks]

c) Write down the CP-even and CP-odd states that can be formed from the $\left|D^0\right\rangle$ and $\left|\overline{D}^0\right\rangle$ particle states.

[4 marks]

d) Neutral D-meson mixing means that it is possible for a μ^- to be produced from the decay of a particle that is initially a D^0. Using Feynman diagrams, explain how this can happen.

[5 marks]

e) Considering the process $\nu_\mu + n \to \mu^- + D^0 + p$, calculate the minimum energy a neutrino must have when hitting a neutron at rest for this process to be possible.

[6 marks]

END OF EXAMINATION PAPER