Answer TWO questions.

The numbers in square brackets in the right-hand margin indicate the provisional allocation of maximum marks per sub-section of a question.

You may assume the following data:

Particle name	Approx.Mass
Z	91 GeV
W	80 GeV
γ	0 GeV
gluon	0 GeV
proton	1 GeV
π	0.14 GeV

Mandelstam variables:

For a two-body scattering $A + B \to C + D$, the Mandelstam variables are given by:

$$\begin{aligned} s &= (p_A + p_B)^2 \\ t &= (p_A - p_C)^2 \\ u &= (p_A - p_D)^2 \end{aligned}$$

where p_A is the four-momentum of particle A, and so on.

[Part marks]

1. At the LEP accelerator e^+ and e^- collided head-on with energies around 45 GeV each. In a particular class of event, two high energy muons are observed in the OPAL detector. The muons have four-momenta p_C, p_D, and are the only particles produced in the collision.

   Sketch the behaviour of the cross section for this process as the LEP centre-of-mass energy is varied between 85 GeV $< \sqrt{s} <$ 95 GeV. What value of $\sqrt{s}$ would give the highest cross section for this process, and why? [3]

   Draw the leading order Feynman diagram(s) contributing to this process. Indicate the time direction and all particle names, including the propagator, and give an expression for the propagator in each case in terms of particle masses and four-momenta. Say which diagram is the most important in the given energy range. [4]

   Say how the muons could be:

   - Distinguished from electrons.
   - Distinguished from taus.
   - Disinguished from cosmic ray muons
   - Disinguished from muon neutrinos

   [6]

   How could the muon momentum be measured? [2]

   Give an expression for the e^-e^+ centre-of-mass energy, $\sqrt{s}$, in terms of the muon four-momenta. A LEP detector can only see muons which have an angle $30^\circ < \theta < 150^\circ$ to the beam direction. What is the lowest muon transverse momentum which could be observed when the beam have equal and opposite momenta of exactly 45 GeV each? [5]

2. Draw a diagram indicating the basic features of a lead scintillator calorimeter and explain how it can be used to measure the energies of incident particles. [5]

   At the HERA accelerator, 30 GeV electrons collide with 820 GeV protons. In a particular class of event, electrons scatter from a proton at an angle θ and hit a such a calorimeter. In the calorimeter, how may an e^- be distinguished from a hadron of the same energy? [3]

   Draw the most important Feynman diagram(s) for the process e quark $\rightarrow e$ quark. The propagator in this process is given by $-i\frac{g^{\mu\nu}}{q^2}$. Show that

$$q^2 = -2E_A E_B(1 - \cos\theta)$$

   where E_A, E_B are the incoming and outgoing electron energies respectively (Neglect the electron and quark masses). [5]

   At low values of $|q^2|$, the process e quark $\rightarrow e$ quark can no longer be used to help calculate the electron-proton cross section. At roughly what value of $|q^2|$ does this happen. Why? [3]

   At high values of $|q^2|$, another Feynman diagram starts to make an important contribution to the process $eq \rightarrow eq$. At roughly what value of $|q^2|$ does this happen. Why? Draw the diagram. [4]

3. Proton anti-proton collisions take place at the Tevatron at a centre of mass energy of 1800 GeV. Two processes which can take place are $u\bar{u}$ annihilation and $d\bar{d}$ annihilation. Say which has the largest cross section and why. [2]

The process $u\bar{d} \to \mu^+\nu_\mu$ can also take place.

(a) Draw the leading order Feynman diagram(s) for this process. [2]

(b) Draw a schematic diagram of a $p\bar{p} \to \mu^+\nu_\mu + X$ event indicating what happens to the other quarks and antiquarks. [2]

A pair of back-to-back high transverse energy jets are observed in the centre of the detector, at 90^0 to the beam. One jet has an energy of 110 GeV and contains a b quark. The other jet has an energy of 116 GeV and contains a $\bar{b}$ quark.

How might the b and $\bar{b}$ quarks be identified in a detector?. [4]

Assume the detector gives a perfect measurement of the energies of all the particles it detects. Suggest two reasons which might explain why the jets do not balance exactly in transverse energy. [4]

If the event came from the collision of a parton carrying a fraction x_1 of the proton's momentum and a parton carrying fraction x_2 of the antiproton's momentum, give an estimate of x_1 and x_2. [5]

Draw a possible Feynman diagram for the event. [1]

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