NATURAL SCIENCES TRIPOS Part III

Tuesday 16 January 2001 2.00 to 3.30

EXPERIMENTAL AND THEORETICAL PHYSICS (4)
Particle Physics

Answer **two** *questions only. The approximate number of marks allotted to each part of a question is indicated in the right margin where appropriate. The paper contains FOUR sides and is accompanied by a book giving values of constants and containing mathematical formulae which you may quote without proof.*

1 Write brief accounts of **three** of the following:

(a) colour forces and the inter-quark potential; [10]

(b) CP violation in the neutral Kaon system; [10]

(c) b-tagging and its uses; [10]

(d) successes and outstanding problems of the Standard Model; [10]

(e) the solar neutrino problem. [10]

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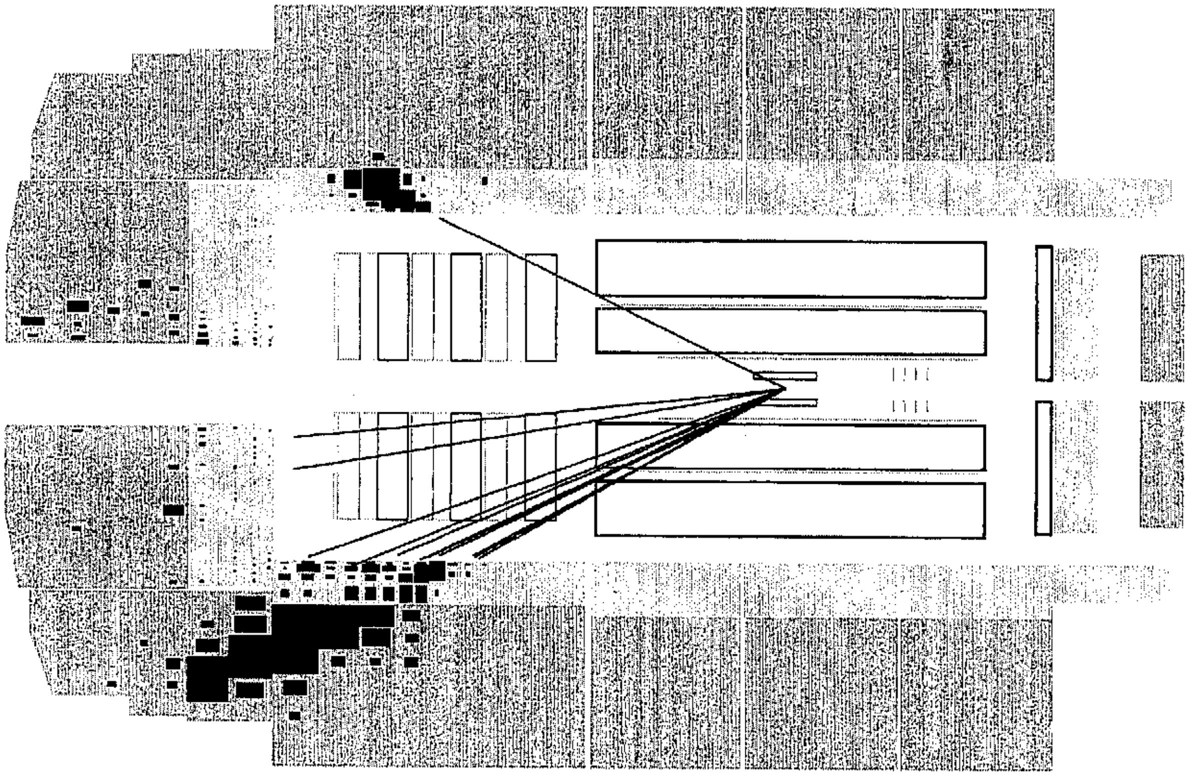

2 The figure above shows a deep-inelastic scattering event $e^+p \to e^+X$ recorded by the H1 experiment at the HERA ep collider. Explain the principal features seen in the diagram and outline the physics processes and operating principles underlying the primary detector components. [10]

The positron and proton beam energies at HERA are 27.5 GeV and 820 GeV, respectively. The measured energy of the outgoing positron in the event shown is 240 GeV. Estimate the values of q^2 and x for this event, and give a physical interpretation of these quantities in the quark-parton model of deep-inelastic scattering. [6]

[If p_1 and p_3 are the 4-momenta of the initial and final state e^+ and p_2 is the 4-momentum of the incoming proton, then x is given by $x = -q^2/2M\nu$ where $q = p_1 - p_3$, $\nu = p_2.q/M$ and $M = 0.938$ GeV is the proton mass.]

For $e^{\pm}p$ scattering, the quark-parton model predicts that

$$2xF_1^{ep} = F_2^{ep} = \sum_i z_i^2 x q_i(x, q^2)$$

where z_i is the charge of the parton of type i, in units of $|e|$. Without detailed mathematics, explain the origin of the relationship between F_1 and F_2. Interpret the functions $q_i(x, q^2)$ and describe qualitatively how they depend on x and q^2 for different types of parton. Indicate to what extent the dependence on x and q^2 can be understood in the parton model and QCD. [6]

Neglecting the contributions from strange quarks and antiquarks and heavier partons, show that the parton model predicts that

$$\int_0^1 \frac{1}{x}\left(F_2^{ep} - F_2^{en}\right) dx = \frac{1}{3} ,$$

making clear any assumptions you make. How would you expect the ratio F_2^{en}/F_2^{ep} to behave as $x \to 0$ and $x \to 1$? [8]

3 Explain what is meant by the *helicity* of a particle, and show that, for a free spin half particle of rest mass m moving with total energy $E \gg m$, the left-handed and right-handed components of the particle spinor become eigenstates of the helicity operator. [7]

The vertex factors governing the interaction of a fermion with a $W^{\pm}$ or Z^0 boson are $-i(g_W/\sqrt{2}).\gamma^\mu \frac{1}{2}(1-\gamma^5)$ and $-i(g_Z/2).\gamma^\mu(c_V - c_A\gamma^5)$, respectively, where $c_V = c_L + c_R$, $c_A = c_L - c_R$ and

$$c_L = I_W^{(3)} - Q\sin^2\theta_W \qquad\qquad c_R = -Q\sin^2\theta_W .$$

Explain the meaning of the various constants in these expressions. Compare the roles of left-handed and right-handed fermion components in interactions with the Z^0 boson, the $W^{\pm}$ boson and the photon. Comment on the implications for neutrinos. [5]

The differential cross section for $\nu_\mu e^- \to \mu^- \nu_e$ scattering in the centre of mass frame, in the limit in which the electron and muon masses can be neglected, is given by

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left(\frac{g_W^2}{8\pi m_W^2}\right)^2 s$$

where $s = (p_1 + p_2)^2$ and p_1 and p_2 are the 4-momenta of the ν_μ and e^-, respectively. Draw the leading order Feynman diagram for this process. Also, draw a diagram to illustrate the spin eigenstates of the particles involved in the scattering, giving reasons for your choices. Explain why the cross section is independent of angle. [5]

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Draw the leading order Feynman diagram for the scattering process $\nu_\mu e^- \to \nu_\mu e^-$. Draw diagrams to illustrate the allowed configurations of spins for the particles involved in the scattering, and, without detailed mathematics, obtain an expression for the differential cross section. [8]

Show that the total cross sections for $\nu_\mu e^- \to \nu_\mu e^-$ and $\nu_\mu e^- \to \mu^- \nu_e$ scattering are expected to be in the ratio

$$\frac{\sigma(\nu_\mu e^- \to \nu_\mu e^-)}{\sigma(\nu_\mu e^- \to \mu^- \nu_e)} = (c_L^e)^2 + \frac{1}{3}\,(c_R^e)^2 \ .$$

Calculate the value of $\sin^2\theta_W$ corresponding to a measured value of the cross section ratio of 0.09. [5]

[The free particle Dirac spinors are

$$u_1 = N \begin{pmatrix} 1 \\ 0 \\ p_z/(E+m) \\ (p_x + ip_y)/(E+m) \end{pmatrix}, \quad u_2 = N \begin{pmatrix} 0 \\ 1 \\ (p_x - ip_y)/(E+m) \\ -p_z/(E+m) \end{pmatrix}$$

where $N = \sqrt{E+m}$. The Dirac matrix γ^5 is:

$$\gamma^5 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} .$$

The constants g_W and g_Z are related via $g_W = g_Z \cos\theta_W$, and the $W^\pm$ and Z^0 masses via $m_W = m_Z \cos\theta_W$.]