Queen Mary & Westfield College
Royal Holloway UoL
University College
Brunel University

Intercollegiate Postgraduate Course in Elementary Particle Physics

Paper 2: Friday, 21 January 2000

Time allowed for the Examination: 3 hours

Attempt THREE *questions - One from section A and Two from Section B*

Section A: Electroweak Interactions part 2
Section B: Experimental Techniques

Section A : Electroweak Interactions

Question 1

(a) Starting from the charged weak current expressed in the form

$$J^{+\mu} = \frac{g_w}{\sqrt{2}} \overline{u_\nu} \gamma^\mu \frac{1}{2}(1-\gamma^5) u_e$$

show that the weak charged current may be written as

$$J^{+\mu} = \frac{g_w}{\sqrt{2}} \overline{\lambda_l} \gamma^\mu \tau^+ \lambda_l$$

where λ_l are lepton weak isospin doublets, and τ^+ is the weak isospin raising operator.

Show that g_w is related to the Fermi constant G_F by

$$\frac{G_F}{\sqrt{2}} = \frac{g_w^2}{8M_w^2}$$

(b) Explain what is meant by weak hypercharge Y where $Y = 2Q - 2T^3$.

(c) Starting from the interaction term

$$g_w J^{\mu 3} W^3_\mu + \frac{g^{'}}{2} J^\mu_Y B_\mu$$

and making the massless W^3 and B fields superpositions of the photon and Z^0 fields show that the neutral current coupling is given by

$$\frac{g_w}{cos\theta_w} \overline{u_f} \gamma^\mu \frac{1}{2}(c^f_V - c^f_A \gamma^5) u_f$$

where $c^f_V = T^3_f - 2sin^2\theta_w$ and $c^f_A = T^3_f$. In the above θ_w is the Weinberg angle, T^3 is the third component of the weak isopin and the suffix f signifies a fermion.

(d) Write down the propagator for a massive spin one particle and show how this may be modified for an unstable spin one particle whose full width Γ is much less than the mass M.

(e) Write down the matrix element for e^+e^- annihilation through the Z^0 to $f\overline{f}$ fermion pairs. Evaluate the "matrix element squared" ,summed over the spin states and averaged over the initial spins, as far as the trace evaluation.

(f) Explain how and why the resonant shape determined experimentally at LEP is altered from the theoretical shape predicted above.

Question 2

(a) Define, in terms of the usual four vectors, the scaling variables x and y for deep inelastic lepton - nucleon scattering (DIS). Give simple interpretations of the variables x and y in terms of the parton model and the lepton parton CM frame.

(b) Explain what is meant by scaling in deep inelastic processes.

(c) For Q^2 much smaller than M_W^2 the neutrino deep inelastic cross section is given by

$$\frac{d^2\sigma^{\nu\overline{\nu}}}{dxdy} = \frac{G_F^2}{2\pi}s\left[F_2\frac{(1+(1-y)^2)}{2} \pm xF_3\frac{(1-(1-y)^2)}{2}\right]$$

where s is the square of the CMS energy, F_2 and F_3 are the structure functions, and G_F is the Fermi constant. (In this question the Cabibbo angle is ignored).

If the ν quark and ν antiquark cross sections are given by

$$\frac{d\sigma^\nu}{d\Omega} = \frac{G_F^2}{4\pi^2}\hat{s} \text{ and } \frac{d\sigma^\nu}{d\Omega} = \frac{G_F^2}{4\pi^2}\hat{s}\left[\frac{1+cos\theta}{2}\right]^2$$

where $\hat{s}$ and θ are respectively the square of the CM energy and the scattering angle in the lepton quark CM frame, show that

$$F_2^\nu = 2x(Q(x) + \overline{Q(x)}) \text{ and } xF_3^\nu = 2x(Q(x) - \overline{Q(x)})$$

here $Q(x)$ and $\overline{Q(x)}$ are the appropriate quark probability distributions within the nucleon.

(d) At HERA 27.6 GeV electrons are in head on collision with 920 GeV protons. Describe the appearance of events in the detector for $x \ll 0.03$, $x = 0.03$ and $x \gg 0.03$.

(e) Draw and label the Feynman diagrams of two processes that lead to scaling violations.

(f) Write down the matrix element for Compton scattering and then write down the corresponding matrix element for QCD Compton scattering.

Section B : Experimental Techniques

Question 3

(a) Draw the leading order Feynman diagrams for the following processes and briefly outline how such events might be identified in a LEP detector. (e^+e^- collisions took place at LEP at $\sqrt{s} \approx 90$ GeV.) Say clearly which detector components would be required and how the data they provide would be used.

$$\begin{aligned} e^+e^- &\rightarrow e^+e^- \\ e^+e^- &\rightarrow \mu^+\mu^- \\ e^+e^- &\rightarrow \gamma\gamma \\ e^+e^- &\rightarrow b\bar{b} \end{aligned}$$

9 marks

(b) At HERA, 920 GeV protons are in head-on collisions with 27.6 GeV electrons. Both charged- and neutral-current deep inelastic scattering (DIS) processes are observed, as well as large background from $p + A$ processes where A is the nucleus of an atom of residual gas in the beampipe. An experiment has a fast first level trigger which has access only to the energy measurements from the calorimeter cells. The calorimeter is hermetic except for small holes for the beampipe. The energy from these cells may be combined in any way desired.

Suggest two sets of selection cuts using this information, one of which would accept neutral-current DIS events the other which would accept charged-current events. In each case state clearly why $p + A$ events would fail the trigger. **9 marks**

(c) For which of the two classes of deep inelastic scattering event would you expect the final (offline) x and Q^2 resolution to be better? Why? **2 marks**

Question 4

(a) Triggering is a necessary evil - discuss. **4 marks**

(b) Discuss why multi-level triggers are used and describe briefly the different functions performed at each level. **4 marks**

(c) What is deadtime? Explain how deadtime can arise in experiments and the methods used to avoid it at each level of a three-level trigger system. **3 marks**

(d) Discuss, giving examples, the uses of look-up-tables in trigger selection. What are the advantages and disadvantages of using look-up- tables? **3 marks**

(e) Discuss the role of buses in data acquisition systems, highlight their merits and limitations. **3 marks**

(f) Compare the merits of inclusive and exclusive triggers. **3 marks**

Question 5

The attached figure shows a schematic view of the CMS (Compact Muon Solenoid) experiment for the LHC. It has a length of about 20m and a diameter of about 15m. The solenoid produces a field of 4T. The electromagnetic calorimeter consists of lead tungstate crystals and the active part of the hadron calorimeter is made of layers of scintillator "tiles" between copper plates.

Some of the important physics aims of CMS are searches for the Higgs boson and for supersymmetry, and b-physics. Particular emphasis is placed on the possible Higgs boson decay $\mathrm{H} \to \gamma\gamma$.

With reference to the physics aims, comment on the major design features of the CMS detector and sub-detectors as shown by the figure and the above description.

Propose possible solutions for the central tracking system and the muon system.