Brunel University
Queen Mary, University of London
Royal Holloway, University of London
University College London

Intercollegiate post-graduate course in High Energy Physics

Paper 2

Wednesday, 30 January 2008

Time allowed for Examination: 2.5 hours

Answer **ALL** questions

Books and notes may be consulted

The paper is split into the following sections with their weights in brackets:

1. Neutrino physics (32%)
2. CP violation (12%)
3. Hadron Colliders (12%)
4. LHC physics (16%)
5. QCD phenomenology (16%)
6. Future colliders (12%)

Please answer different sections in different answer books as they will be marked by different people.

Section 1: Neutrino physics

Question 1

Neutrinoless double-β decay ($2\beta_{0\nu}$) searches are actively pursued in several laboratories with different techniques.

(a) Why is this decay forbidden in the Standard Model?

(b) Which are the most important neutrino properties that this phenomenon would determine?

(c) Which are the two main experimental approaches? Highlight advantages and disadvantages and give examples of experiments adopting them.

(d) If measured, would the value of the neutrino mass from these experiments be the same as that measured in the β decay of tritium? Justify your answer.

[8 marks]

Question 2

(a) Describe briefly the MiniBoone experiment (purpose, experimental apparatus, main results).

(b) What are the main differences with the LSND experiment? What is similar?

(c) Infer the upper bound on the oscillation probability measured by MiniBoone using the fact that the experiment is sensitive to $\sin^2 2\theta \approx 5 \cdot 10^{-3}$ at large Δm^2.

(d) An excess of 96 events was observed over the background in the "low energy" region (below 475 MeV). If this excess was due to oscillations, what would the corresponding probability be? (Assume: a ν_μ detection efficiency of 60%, a ν_e detection efficiency of 20%, and 10^5 observed ν_μ interactions). If $\sin^2 2\theta = 0.2$, what value of Δm^2 would be allowed? Would this value be compatible with the LSND results?

(e) Name an experiment which looks for $\nu_\mu \rightarrow \nu_e$ oscillations in the region of $\Delta m^2 \approx 2 \cdot 10^{-3} eV^2$. Which fundamental parameter of the MNS matrix can it measure?

[12 marks]

[Total Marks = 20 : to be scaled to 32%]

Section 2: CP violation

Question 1

Draw the Feynman diagram for the amplitude responsible for $B^0 - \overline{B}^0$ mixing, and indicate the dominant contribution to the mixing amplitude. Note CKM matrix elements on vertices where appropriate.

[3 marks]

Question 2

The decay $B^0 \to J/\psi\pi^0$ can be used to measure $\sin 2\beta$. Draw the tree and loop Feynman diagrams for this decay. Where does the decay pick up a factor of $V_{\rm td}$ from in order for it to be sensitive to $\sin(2\beta)$? (**HINT:** The quark content of J/ψ is $c\overline{c}$). Note CKM matrix elements on vertices where appropriate.

[5 marks]

Question 3

What is the importance (if any) of a measurement of $\sin 2\beta$ in $B^0 \to J/\psi\pi^0$ being significantly different from $\sin 2\beta$ in $B^0 \to J/\psi K_s^0$?

[2 marks]

[Total Marks = 10 : to be scaled to 12%]

Section 3: Hadron Colliders

Question 1

Estimate, showing your reasoning, what you expect the value for the cross section ratio for the production of W^+ bosons at $Y = 0.0$ and $Y = 3.0$ to be at (i) the LHC and (ii) the Tevatron.

[5 marks]

Question 2

Explain how the cross section ratio of W^+/W^- production at the LHC differs from that at the Tevatron.

[3 marks]

Question 3

Estimate, to leading order, the branching fraction for a W^- decay to a tau-lepton.

[2 marks]

Question 4

Draw a Feynman diagram for the decay $\tau^- \to K^- K^+ \pi^-$. Experimentally how could one distinguish this final state from a $\tau^- \to \pi^- \pi^+ \pi^-$ decay.

[3 marks]

[Total Marks = 13 : to be scaled to 12%]

Section 4: LHC Physics

Question 1

Draw a Feynman diagram for Standard Model Higgs production at the LHC via the "Vector Boson Fusion" mechanism.

[3 marks]

Question 2

If the Higgs boson decays to $\tau^+\tau^-$ and the two tau leptons decay to $e^+\nu_e\bar{\nu}_\tau$ and $\mu^-\bar{\nu}_\mu\nu_\tau$ respectively, discuss which experimental signatures could be used in a general purpose detector such as ATLAS or CMS to select Higgs events in this channel.

[3 marks]

Question 3

Missing transverse energy ("Etmiss") is an important kinematical variable in many new physics searches at the LHC. Discuss briefly how this quantity could be calculated experimentally. Justify your answer.
Explain why Etmiss is a crucial variable in the search for R-parity conserving supersymmetry at the LHC.

[4 marks]

[Total Marks = 10 : to be scaled to 16%]

Section 5: QCD phenomenology

Question 1

Consider the process of a single particle of energy E splitting into two particles of energy $E_1 = (1-z)E$ and $E_2 = zE$, as happens in Monte Carlo event generators. If we let the initial particle have large virtuality $p^2 = t$ and the subsequent particles are massless and nearly on shell, i.e. we assume $p_1^2 = p_2^2 = 0$, show that the virtuality of the original particle is given by

$$t = 2E_1E_2(1-\cos\theta) \approx E_1E_2\theta^2, \tag{1}$$

where θ is the angle between the two resultant particles, and in the final expression we have assumed this is small.

[3 marks]

Staying in the small-angle limit show that the transverse momentum of each particle relative to the original particle direction is given by

$$k_T^2 = z^2(1-z)^2E^2\theta^2 \equiv z(1-z)t. \tag{2}$$

[5 marks]

In the Monte Carlo generator k_T^2 is sometimes used as the argument of the strong coupling constant, i.e. one has $\alpha_S(k_T^2)$. State what problem this introduces if z is very small.

[2 marks]

Question 2

At leading order the proton structure function $F_2(x)$ is given by the sum of the contributions $\kappa_i x f_i(x)$, where $f_i(x)$ is the parton distribution for quarks and anti-quarks, x is the momentum fraction and κ_i is the relative coupling of the vector boson to the quark. Explain why for neutral current scattering via the exchange of a photon with virtuality $Q^2 \approx 10$ GeV^2

$$F_2^{\gamma^\star}(x)/x \propto 4/9(u(x)+\bar{u}(x)+c(x)+\bar{c}(x)) + 1/9(d(x)+\bar{d}(x)+s(x)+\bar{s}(x)), \tag{3}$$

[2 marks]

and for neutrino scattering via the exchange of a W^+ boson

$$F_2^{\nu}(x) \propto (d(x)+s(x)+\bar{u}(x)+\bar{c}(x)). \tag{4}$$

[2 marks]

For the parity-violating structure function $F_3(x)$ possible for charged-current interactions anti-quark contributions pick up a relative minus sign. Show that with some stated assumption we obtain

$$F_3^{\nu}(x) + F_3^{\bar{\nu}}(x) \propto u_V(x) + d_V(x) \tag{5}$$

[4 marks]

where $q_V(x)$ is the valence quark combination which represents the difference of quarks and anti-quarks. What value would the integral of the right-hand side of this equation over all x give?

[2 marks]

[Total Marks = 20 : to be scaled to 16%]

Section 6: Future Colliders

Question 1

Calculate the energy loss of a single electron due to synchrotron radiation in a 100 GeV beam energy accelerator, given its magnetic bending radius is 3 km and the total circumference is 27 km. Given each beam contains 4 bunches of population 45×10^{10} particles calculate the total power loss in Watts.

[5 marks]

Question 2

Describe briefly what limits the maximum achievable energy and luminosity of a proton synchrotron, such as the Large Hadron Collider.

[5 marks]

Question 3

A possible design for high energy electron-positron colliders uses linear electron-positron accelerators. Estimate the required vertical interaction point beam size needed to provide a luminosity of 2×10^{34} cm^{-2}s^{-1} given a bunch charge of 2×10^{10}, horizontal beam sizes of 500 nm and a bunch repetition rate of 1.2×10^{4} Hz. Explain why this beam size might be difficult to achieve.

[5 marks]

Question 4

Muon colliders could be another possible solution to achieving TeV lepton beam energies. What major technical challenges must be overcome before building a high energy muon collider?

[5 marks]

[Total Marks = 20 : to be scaled to 12%]