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

Intercollegiate post-graduate course in High Energy Physics

Paper 3 : Current HEP Projects

Tuesday, 3 February 2015

Time allowed for Examination : 3 hours

Answer **ALL** questions

Books and notes may be consulted

The paper is split into the following sections each carrying 20 marks :

1. Neutrino physics
2. CP violation
3. Hadron colliders and LHC physics
4. QCD phenomenology
5. Accelerator physics

Please start a new piece of paper for each question

Question 1 : Neutrino physics

1. What are the experimental evidences that there are at least three neutrino mass eigenstates? **[2]**

2. The PMNS matrix has been introduced in the context of a 3-neutrinos oscillation framework.

   a) Explain which role it plays and describe its main properties.

   b) Which parameters of the PMNS matrix have been measured with solar and atmospheric neutrino experiments?

   c) Briefly describe a $\bar{\nu}_e$ disappearance experiment that has measured θ_{12}. **[8]**

3. Neutrino factories provide the best sensitivity to the CP violation parameter δ.

   a) Explain which are the characteristics of the neutrino factory beam which make it ideal for CP violation studies.

   b) Mention the most important requirements on the far detector to study $\nu_e \rightarrow \nu_\mu$ oscillations at a neutrino factory and name a suitable detection technique.

   c) A 28 kton detector placed at L=1000 km on a neutrino-factory beamline observes 20 ν_μ events due to $\nu_e \rightarrow \nu_\mu$ oscillation in one year of data-taking. Determine the ν_e flux using the following: neutrino energy E = 10 GeV; deep-inelastic cross-section $\sigma(\nu_\mu) = 6.7\times10^{-38}$ cm^2 per nucleon; $\sin^2 2\theta_{23} = 1$ and $\Delta m^2_{23} = 2.4 \times 10^{-3}$ eV^2.

   Assume detection efficiency $\epsilon = 40\%$. (Hint: neglect CP violation and matter effects, and use an approximate formula for P($\nu_e \rightarrow \nu_\mu$) valid for experiments sensitive to Δm^2_{atm}). d) How many $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ events would the experiment in c) detect? (Make plausible assumptions on the anti-neutrino flux and assume for the cross-section $\sigma(\bar{\nu}_\tau) = 0.15\times\sigma(\nu_\mu)$). **[10]**

[Total Marks = 20]

Question 2 : CP violation

1) Describe the three discrete transformations for a Lagrangian, their operators and their properties.

(3 marks)

2) List the types of CP violation, and the minimum requirements for each of these effects to be manifest.

(3 marks)

3) Write down the CKM unitarity relation corresponding to the Unitarity Triangle relative to b physics, and explain briefly why this particular triangle is significant.

(3 marks)

Connect each of the angles of the Unitarity Triangle with at least one decay that can lead to its measurement.

(3 marks)

4) Draw the main Feynman diagram which contributes to the $B^0 \to J/\psi K_s$ decays. Discuss what kind of CP violation can be measured in these decays and what quantity this measurement is sensitive to (draw any additional diagram if necessary).

(3 marks)

Draw the Feynman diagram corresponding to a higher order contribution to this decay. Demonstrate why this extra amplitude does not spoil the measurement.

(3 marks)

How is this similar to the $B^0 \to \pi^+\pi^-$ case? How is it different?

(2 marks)

(In all your answers: note CKM matrix elements on vertices where appropriate and if any CKM matrix element in the diagram is related to a weak phase.)

[Total Marks = 20]

Question 3 : Hadron colliders and LHC physics

1. Outline the main advantages and disadvantages of a proton-proton collider with respect to a proton-antiproton one. **[2]**

2. Suggest a hypothetical new particle where a proton-antiproton collider would be superior to a proton-proton one, and state why. **[5]**

3. Calculate rapidity y and pseudo-rapidity η of an electron of $p_T = 200$ GeV emitted at an angle of 30° from the beam axis. **[2]**

4. Calculate the same quantities for a top quark emitted in the same kinematical configuration. **[2]**

5. What is the expected increase of cross-section for top quark pair production between the LHC run 1 ($\sqrt{s} = 8$ TeV) and run 2 ($\sqrt{s} = 13$ TeV)? **[2]**

6. Explain why the ratio of increase between Run 1 and Run 2 is larger for top quarks than for b-quark.

   [2]

7. Do supersymmetric particles have the same mass as their corresponding SM companions? How can it be explained in theory?

   [2]

8. What are the main differences between the approach to new physics of SuperSymmetry and those of the Hidden Sector approach?

   [3]

[Total Marks = 20]

Question 4 : QCD phenomenology

1. The value of the strong coupling constant at scale M_Z^2 is given by $\alpha_S(M_Z^2) = 0.118$. Using the leading order expression for the coupling running and assuming a fixed value of 5 quark flavours find the value of Λ_{QCD}. **[2]**

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. The initial particle has large virtuality $p^2 = t$ and the subsequent particles are massless and on shell, i.e. we assume $p_1^2 = p_2^2 = 0$. The angle of separation of the two resultant particles, θ, is very small. Show that

$$t = 2E_1E_2(1-\cos\theta) \approx E_1E_2\theta^2. \quad (1)$$

[2]

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

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

[4]

In the Monte Carlo generator k_t^2 is sometimes used as the argument of the strong coupling constant, i.e. one has $\alpha_S(k_T^2)$. If $t = 100$ GeV^2 what limits does this impose on z or $(1-z)$ for perturbation theory to be reliable? **[2]**

2. Write matrix elements for LO expressions for the production of W^+, W^- and Z bosons in proton-proton collisions. Overall normalisation is not required, but the full and correct parton content (ignoring Cabibbo mixing and any contribution from top quarks) should be included. **[3]**

Do you expect the cross section at the LHC to be larger for W^+ or W^- production, and why? **[2]**

What are the standard means of obtaining information about the strange (and antistrange) quark content in the proton? Draw a Feynman diagram to illustrate the dominant process. **[3]**

Use your expressions for W, Z production explain why each provides some useful information on strange quarks, and why using both in conjunction can provide even more information. **[2]**

[Total Marks = 20]

Question 5 : Accelerator physics

The Future Circular Hadron-Hadron Collider (FCC-hh) is a proposed new hadron collider that will, like the LHC, collide protons with protons. Some important parameters of the FCC-hh, compared with those for the LHC, are given in the following table

Parameter	LHC	**FCC-hh**	Unit
Beam energy E_{beam}	7	50	TeV
Circumference	27	100	km
Luminosity $\mathcal{L}$	1	5	10^{32} cm^{-2} s^{-1}
Bunch spacing	25	25	ns
Dipole field B	8.33	16	T
Bunch population N	1.15	1.00	10^{11}
Normailised emittance ϵ	3.75	2.2	μm
Interaction point β_*	0.55	1.1	m

1. Given the proposed dipole field for FCC-hh compute the magnetic radius of the accelerator and then calculate the machine circumference. Explain the difference between your calculated value and the value in the table. [4]
2. What limits going to higher energies than 100 TeV? [3]
3. Assuming all bunches are filled around the ring, compute the total stored beam energy in Joules. [3]
4. Compute the interaction point beam size and hence the machine luminosity. [6]
5. Briefly discuss possible limits on the maximum achievable luminosity using both detector and accelerator considerations. [4]

[Total Marks = 20]

END OF PAPER