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 : Current HEP Projects

Tuesday, 11 February 2014

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

- Draw the Feynman diagrams for ν_e and ν_μ elastic scattering on electrons and indicate whether they are neutral current (NC) or charge current (CC) processes. Which of these interactions were detected in the SNO experiment? **[4]**

- What is the MSW mechanism? Describe briefly a reactor experiment whose results supported a MSW solution to the solar neutrino problem. Explain why this experiment excluded the vacuum oscillation solution. **[5]**

- Imagine you were to design an experiment optimised for the search of ν_e to ν_τ oscillation at $\Delta m^2 = 1eV^2$ with a neutrino beam peaked at 10 GeV.

  a) Which facility could produce the neutrino beam?

  b) At which distance from the source, L_1 would you place the far detector to maximise the oscillation probability?

  c) List the most important requirement(s) for the far detector and name a suitable detection technique.

  d) If N_1 ν_τ events are observed in the far detector, how many events would you expect to observe in a second far detector, identical to the first one, placed at a distance from the source $L_2 = 2 \times L_1$? **[6]**

- Is ν_τ the heaviest neutrino? Which information would a signal of neutrinoless double-decay in SNO+ give on the neutrino mass nature and hierarchy? **[5]**

[Total Marks = 20]

Question 2 : CP violation

- State the CPT theorem and name at least one of its consequences. **[2]**

- List the types of CP violation, and the minimum requirements for each of these effects to be manifest. **[3]**

- Describe the process of meson mixing: specify which mesons can mix, define the eigenstates involved and mention the variables needed to describe their oscillations. **[4]**

- Draw the Feynman diagrams for the amplitudes responsible for $B^0_{d,s} - \overline{B}^0_{d,s}$ mixing, and indicate the dominant contributions to the mixing amplitudes. Indicate the CKM matrix elements appropriate to each vertex on your diagram. Quantitatively comment on the main differences between the two systems. **[5]**

- Draw the two Feynman diagrams which contribute to the $B^0 \to \pi^+\pi^-$ 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). Specify also what effect can spoil the measurement and what kind of analysis can recover the potential of the channel. (Note CKM matrix elements on vertices where appropriate and if any CKM matrix element in the diagram is related to a weak phase.) **[6]**

[Total Marks = 20]

Question 3 : Hadron colliders and LHC physics

- Describe the main decay modes of top quarks, and show how the approximate branching fractions are connected with the presence of quark colors. **[3]**

- Calculate the rapidity y and pseudo-rapidity η of an electron of $p_T = 100$ GeV emitted at an angle of 45° from the beam axis. **[2]**

- Calculate y and η for a top quark emitted in the same kinematical configuration as the electron in part 2). **[2]**

- Explain the main limitations on the energy of the LHC, and how it could be possible to overcome them. **[2]**

- Describe the advantages and disadvantages of a proton-proton compared to a proton-antiproton collider. **[2]**

- Assume the inclusive jet cross-section can be described by an exponential of the form $10^4 exp(-p_T/100GeV)$. What would be the consequence of a 3% uncertainty on the jet enegy scale on the cross-section measurement, for jet p_T of 100 GeV? **[4]**

- The branching fraction of the Higgs into $\gamma\gamma$ is about $2{\times}10^{-3}$, while that of $H \to ZZ$ is ten times larger. However the analysis performed at the LHC only considers decays of each Z into electrons or muons, for a toal branching fraction of 7% per Z boson.

  The background to the $\gamma\gamma$ case is about 10 times the signal, while in the ZZ case signal over background is about 1. If 200 signal events are present in the $\gamma\gamma$ peak, estimate the significance for this channel, as well as a relative selection efficiency of the ZZ channel such that its significance is the same as the $\gamma\gamma$ channel, despite the larger branching fraction and S/B ratio. **[5]**

[Total Marks = 20]

Question 4 : QCD phenomenology

- 1. For a proton-antiproton collision draw two Feynman diagrams which include at least two strong coupling vertices but correspond to two-jet final states. Explain how only two jets may be produced even when there are more than two strongly interacting partons in the final state. **[3]**

  2. Describe both the cone-type and cluster types algorithms for defining jets, briefly explaining advantages of the latter. **[4]**

  3. Experiments now look for sub-jets within larger jets by initially finding jets using a given jet cut then lowering the cut required to define a jet (e.g. defining a smaller cone radius) and repeating the procedure. Which is more likely to result in a large number of sub-jets, a high thrust or high sphericity event, and why? **[3]**

- 1. In a proton-proton collision the momentum four vectors of partons with momentum x_1 and x_2 in the two protons are given by

  $$p_1 = \frac{\sqrt{s}}{2}(x_1, 0, 0, x_1), \qquad p_2 = \frac{\sqrt{s}}{2}(x_2, 0, 0, -x_2), \tag{1}$$

  where $\sqrt{s}$ is the centre of mass energy. Show that when two gluons collide to form a Higgs boson of mass M_H and rapidity y_H

  $$x_1 x_2 \equiv x_0^2 = \frac{m_H^2}{s}, \tag{2}$$

  and

  $$x_1 = x_0 \exp(y_H). \tag{3}$$

  [5]

  2. What is the maximum rapidity of a Higgs boson of mass $m_H = 115$ GeV for LHC centre of mass energies of 7 TeV and 14 TeV. **[2]**

  3. In associated Higgs production a Higgs is produced by being radiated from a Z or W boson produced in quark-antiquark annihilation. Explain why the values of x_1 and x_2 for the incoming partons in this process have to be higher than those for Higgs produced via gluon-gluon fusion. **[3]**

[Total Marks = 20]

Question 5 : Accelerator physics

Important parameters and associated values for the Large Hadron Collider (LHC) at the ATLAS interaction point are as follows:

Parameter	Value	Unit
Beta function β	0.55	m
Bunch length σ_z	7.55	cm
r.m.s. bunch size $\sigma_x = \sigma_y = \sigma^*$	16.7	μm
Crossing angle θ_c	285	μrad

Some general LHC parameters are as follows:

Parameter	Value	Unit
Proton energy E_p	7000	GeV
Relativistic Lorentz factor γ	7461	
Number of particles per bunch N_b	1.15×10^{11}	
Number of bunches n	2808	
Normalised transverse emittance ϵ	3.75	μm rad
Ring circumference	26658.9	m
Revolution frequency f_{rev}	11.245	kHz

1. Calculate the total beam power in a full bunch store of the LHC and briefly discuss the consequences for the detectors and accelerator. **[4]**

2. Calculate the peak luminosity of the LHC in cm^{-2}s^{-1}. Explain why there is a crossing angle, and its impact on the achievable luminosity. **[6]**

3. Discuss the other factors (excluding the crossing angle) that limit the luminosity of the LHC. **[4]**

4. Discuss how the LHC luminosity and energy could be upgraded whilst keeping the same circumference ring. **[6]**

[Total Marks = 20]

END OF PAPER