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

Friday, 5 February 2010

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 15 marks :

1. Neutrino physics
2. CP violation
3. Hadron Colliders
4. LHC physics
5. QCD phenomenology
6. Introduction to machine physics

Please start a new piece of paper for each question

Question 1 : Neutrino physics

(a) Neutrino beams

Different kinds of neutrino beams can be made using particle accelerators. The so-called "conventional" neutrino beams were historically the first ones. Recently, "super-beams", "neutrino factories", "beta-beams" have been proposed.

1) Briefly describe a conventional neutrino beam : main beam characteristics and beamline components.

2) What are the origins and the typical levels of the intrinsic ν_e and ν_τ contaminations in a conventional beam ? Discuss their relevance for $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ appearence experiments.

3) Discuss ways to reduce the energy spread of the ν_μ component using super-beams.

    i. What are the advantages and disadvantages of such a beam ?

    ii. Name an experiment which runs or plans to run with it.

4) Is there a way to produce pure $\nu_e/\bar{\nu}_e$ beams ? How ? What can they be used for ?

[7 marks]

(b) Solar Neutrino detection in SNO

In the last phase of operation, the SNO collaboration added proportional counters to its apparatus to enhance the detection of neutrons.

1) Why is neutron detection important for detecting solar neutrino interactions in SNO?

2) Compute the total neutrino flux from the number of events (983 ± 77 in 385.17 live days) recorded with the neutron counters, the measured detection efficiency (21%), the detector mass (1 t), and the solar neutrino cross-section for the appropriate process, σ, which is given below for both Neutral Current (NC) and Charged Current (CC) processes (choose the correct one) :

$$\sigma(\mathrm{NC}) = 0.4 \times 10^{-42}\,\mathrm{cm}^2$$
$$\sigma(\mathrm{CC}) = 0.6 \times 10^{-42}\,\mathrm{cm}^2$$

3) Using the total neutrino flux computed in 2) and assuming electron neutrinos oscillate in the propagation from the sun surface to the earth ($\mathrm{L} = 10^{11}\,\mathrm{m}$) , with oscillation parameters from the best fit to all solar experiments [$\theta = (34.4 \pm 1.2)^\circ$ and $\Delta m^2 = (7.6 \pm 0.2) \times 10^{-5}\mathrm{eV}^2$], compute the *surviving* ν_e flux in the SNO detector.

4) Is the ν_e flux computed in 3) compatible with the value measured by SNO using CC events [$(1.7 \pm 0.1) \times 10^{-6}\mathrm{cm}^{-2}\mathrm{s}^{-1}$] ? Justify your answer.

[8 marks]

[Total Marks = 15]

Question 2 : CP violation

(a)

Write down the CKM matrix in the Wolfenstein parameterisation. Given this, determine the 6 triangle relations that can be used to study CP violation, and indicate which of these is the Unitarity Triangle.

[5 marks]

(b)

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

[3 marks]

(c)

Draw the Feynman diagram for $B\overline{B}$ mixing, and indicate on this diagram what the dominant contribution to the total mixing amplitude is. Note CKM matrix elements on vertices where appropriate. Also note which CKM matrix element in the mixing diagram is related to β.

[7 marks]

[Total Marks = 15]

Question 3 : Hadron Colliders

(a)

The maximum LHC magnetic field strength is 8.3 T. Show given an LHC circumference of 27 km that this is more than sufficient to keep protons of energy 7 TeV moving in a circle. What is the circumference of the LHC from the perspective of one of the 7 TeV protons ?

[4 marks]

(b)

Consider the LHC running at the same centre of mass energy as the Tevatron i.e. $\sqrt{s} \sim 2$ TeV. Draw the leading order Feynman diagram for WH associated production and explain why the cross section at the Tevatron is larger for $m_H = 120$ GeV. Explain with reference to a Feynman diagram why single top production is a significant background to WH production and draw an additional Feynman diagram that produces a background to both WH and single-top production.

[7 marks]

(c)

If the mean number of minimum bias interactions at the LHC at a luminosity of $10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ is 20, what is the ratio of the fraction of events with 10 minimum bias interactions at $10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ and $10^{33}\,\text{cm}^{-2}\text{s}^{-1}$?

[4 marks]

[Total Marks = 15]

Question 4 : LHC Physics

(a)

Outline an example case where a seeded cone jet reconstruction algorithm would be unstable under infrared emission. Explain why a recombination algorithm like k_T is intrinsically stable.

[5 marks]

(b)

One of the main search channels for the low-mass Higgs boson at the LHC is the decay into two photons. Draw the main Feynman diagram responsible for this process, and explain how it is possible given that the Higgs does not couple to massless particles. What sub-detector characteristics are important for its detection ?

[5 marks]

(c)

Using the plot of the pp cross section versus $\sqrt{s}$, estimate the average number of pile-up events as a function of the instantaneous luminosity. Calculate the probability that two independent Z bosons are produced in the same bunch crossing by the effect of pile-up for a typical LHC instantaneous luminosity.

[5 marks]

[Total Marks = 15]

Question 5 : QCD phenomenology

(a)

Show that the leading order differential equation for the running of the strong coupling constant

$$\frac{d\alpha_S}{d\ln\mu^2} = -\beta_0\alpha_S^2, \qquad \beta_0 = \frac{(11 - 2/3N_f)}{4\pi} \tag{1}$$

is satisfied by

$$\alpha_S(\mu^2) = \frac{4\pi}{(11 - 2/3N_f)\ln(\mu^2/\Lambda_{QCD}^2)}. \tag{2}$$

[2 marks]

The ratio R of the cross-section for $e^+e^- \to$ hadrons to the cross-section for $e^+e^- \to \mu^+\mu^-$ as a function of centre-of-mass energy squared s is at leading order in QCD,

$$R(s) = 3\sum_q Q_q^2\Big(1 + \frac{\alpha_S(\mu^2)}{\pi}\Big), \tag{3}$$

where the sum is over different quark flavours and Q_q is the quark charge. Plot approximately the dependence of $R(s) - 3\sum_q Q_q^2$ on renormalisation scale μ^2 for $s/4 < \mu^2 < 4s$ if $s = M_Z^2$, and $\alpha_S(M_Z^2) = 0.12$.

[2 marks]

At next-to-leading order the ratio becomes

$$R(s) = 3\sum_q Q_q^2\Big(1 + \frac{\alpha_S(\mu^2)}{\pi} + (1.41 + A\ln(s/\mu^2))\Big(\frac{\alpha_S(\mu^2)}{\pi}\Big)^2\Big). \tag{4}$$

By differentiating the right-hand side with respect to $\ln(\mu^2)$ and using the equation for the running of the coupling in the first part of the question determine the value of A required so that the $\ln(\mu^2)$-dependence of $R(s)$ is order α_S^3.

[3 marks]

(b)

Describe briefly a series of experiments which will allow you to obtain information on firstly the total valence quark composition of the proton, will then give additional information on the separation of the valence contributions at high x into the up and down quark contributions, and finally will also provide information on the high-x antiquark distributions.

[6 marks]

Once this information has been obtained with reasonable accuracy how might one also gain information on the gluon distribution at high x ?

[2 marks]

[Total Marks = 15]

Question 6 : Accelerator physics

At present there is no planned future colliding facility beyond the Large Hadron Collider (LHC). Describe what **you consider** to be the most reasonable future facility that will provide high energy beams beyond the LHC. In your answer you may wish to include discussion of the following :

1. Energy and luminosity reach.
2. Particle species and polarisation.
3. Benefit to scientific progress and possible important measurements.
4. Technical challenges, including the most important areas of research and development required to achieve a viable machine.
5. The possible upgrade path for such a facility.
6. Other possible, less important, factors (cost, location).

In your answer you can draw on your own research project, interests or general knowledge and of course the lecture material. Examples are LHC upgrades, super and normal conducting linear collider, neutrino factories and muon colliders. In your answer try to include as much technical and scientific detail to make your argument.

[Total Marks = 15]

END OF PAPER