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, 6 February 2009

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

Section 1: Neutrino physics

Question 1

The Opera experiment has recently presented its first results from a short period of data-taking on the CERN to Gran Sasso neutrino beamline: out of 38 observed neutrino interactions, 29 have been classified as ν_μ CC events and 9 as NC events; no ν_τ CC event was observed. The detector target mass for this period corresponded to 0.5 kton.

(a) Briefly describe the purpose of experiment and its sensitivity.

(b) Draw the Feynman diagram of the ν_τ events that are searched for. What is the characteristic signature of this kind of interaction in the Opera detector target?

(c) Given the expected numbers of: 2900 ν_μ CC/kton/year and 2 ν_τ CC/kton/year (for $\Delta m^2 = 2.5 \text{ x } 10^{-3}$ at maximal mixing), which values of Δm^2 can be excluded by the first Opera results? (**HINT**: use the expected number of events to infer a ratio of cross-sections times detection efficiencies)

[7 marks]

Question 2

(a) Explain how CP violation (CPV) can arise in the lepton sector. How many neutrino families are needed for CPV to manifest in neutrino oscillations? Which parameter(s) of the MNS matrix should be different from zero for its observation? Could an experiment observe a CPV effect if all neutrinos had identical mass? Justify all your answers.

(b) What are the experimental evidences that there are at least three different mass eigenstates?

(c) Describe briefly one of the experiments under construction which can measure or improve the limit on the mixing angle θ_{13} (detectors, beam/baseline main parameters, sensitivity). Which CPV effect can it look for (if any)?

[8 marks]

[Total Marks = 15]

Section 2: CP violation

Question 1

Describe the significance of Kobayashi and Maskawa's work that led to them being awarded half of the 2008 Nobel Prize for physics. Also note how this differs from the quark-mixing model proposed by Cabibbo.

[5 marks]

Question 2

What are the Sakharov conditions, and what is their physical consequence?

[3 marks]

Question 3

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

[7 marks]

[Total Marks = 15]

Section 3: Hadron Colliders

Question 1

Draw the two Feynman diagrams which illustrate why precision measurements of the W boson and top-quark mass can be used to place a limit on the Higgs mass. What is the present experimental lower bound on the Higgs mass? What is the approximate upper limit (at 95% CL) implied by the W, top-quark mass and other precision electroweak measurements?

[4 marks]

Question 2

Draw the rapidity distribution of Z bosons produced at the Tevatron. Explain why the distribution has the shape it does. Explain how the distribution is expected to change at the LHC (at nominal beam energy) for the same integrated luminosity and approximately what is the maximum rapidity at which Z bosons can be produced at the LHC?

[7 marks]

Question 3

Considering the production of a Higgs boson ($m_H = 120$ GeV) in association with a Z boson at the Tevatron. Show that the energy of the Higgs (E_H) is given by:

$$E_H = \frac{x^2 s + m_H^2 - m_Z^2}{2x\sqrt{s}},$$

where m_Z is the mass of the Z boson, m_H is the mass of the Higgs boson, $\sqrt{s}$ is the Tevatron's centre of mass energy and both the interacting partons carry the same momentum fraction, x, of the proton and anti-proton's 4-momenta.

[4 marks]

[Total Marks = 15]

Section 4: LHC Physics

Question 1

Define R-parity (R_p). Which values does R_p take for Standard Model and for SUSY particles, respectively? Discuss some of the consequences of R_p conservation at the LHC, including how R_p conserving SUSY models support the existence of a good Dark Matter candidate.

[4 marks]

Question 2

Draw a lowest order Feynman diagram for gluino pair production at the LHC.

[3 marks]

Question 3

What is a typical inclusive SUSY selection (both leptonic and non-leptonic) for R_p-conserving SUSY decays at the LHC? Explain. (Consider the case where the sparticle mass ordering is such that $m_{\tilde{g}} > m_{\tilde{q}} > m_{\tilde{\chi}_2^0} > m_{\tilde{l}}$).

[5 marks]

Question 4

With the help of a Feynman diagram, discuss how real graviton emission in ADD models with extra spatial dimensions could "fake" a SUSY signature in the final state.

[3 marks]

[Total Marks = 15]

Section 5: QCD phenomenology

Question 1

Consider e^-e^+ annihilation in the centre-of-mass frame with total energy $\sqrt{s}$. We produce a quark, antiquark and gluon with four-momenta p_1, p_2 and p_3 respectively. Defining $x_i = 2E_i/\sqrt{s}$ (where E represents energy), using energy and momentum conservation show that

$$(1 - x_1) = 1/2 x_2 x_3 (1 - \cos\theta_{\bar{q}g})$$

where $\theta_{\bar{q}g}$ is the angle between the antiquark and gluon.

[4 marks]

The three jet cross-section diverges as $x_1 \to 1$. By reference to the above equation describe the cuts required to avoid this happening. Discuss how this matches our idea of the requirements for measuring a three jet event in practice.

[4 marks]

Question 2

The structure function F_2 for neutral current scattering is given by

$$F_2(x) = x \sum_i e_i^2 (q_i(x) + \bar{q}_i(x)),$$

where e_i is the electric charge weighting. Show that the integral

$$\int_0^1 dx\, (F_2^p(x) - F_2^n(x))/x,$$

where p represents proton and n neutron, is equal to 1/3 if $\bar{u} = \bar{d}$, and calculate the correction term if this is not the case. (Assume isospin symmetry, i.e. in going from proton to neutron swap up and down quarks and antiquarks).

[4 marks]

The experimental measurement is 0.23 ± 0.03. Suggest another experiment which would give more information on $\bar{u}, \bar{d}$ differences.

[3 marks]

[Total Marks = 15]

Section 6: Introduction to machine physics

The parameters for the LHC at the ATLAS interaction point are

Parameter	Value	Unit
Proton energy (E_p)	7000	GeV
Relativistic γ	7461	
Number of particles per bunch (N_b)	1.15×10^{11}	
Number of bunches (n)	2808	
Normalised transverse emittance	3.75	μm rad
Beta function (β)	0.55	m
Bunch length (σ_z)	7.55	cm
RMS bunch size ($\sigma_x = \sigma_y = \sigma^*$)	16.7	μm
Crossing angle (θ_c)	285	μrad

Some general LHC parameters are

Parameter	Value	Unit
Ring circumference	26658.9	m
Revolution frequency	11.245	kHz

Question 1

Calculate the peak luminosity of the LHC in cm^{-2}s^{-1} with and without a crossing angle.

[5 marks]

Question 2

Calculate the total beam power in a full storage of the LHC and briefly discuss why this might cause difficulties.

[3 marks]

Question 3

Discuss the factors which limit the luminosity of the LHC.

[3 marks]

Question 4

Discuss how the LHC luminosity and energy could be upgraded, whilst keeping the same circumference ring, with as much reference as possible to your answers to previous questions.

[4 marks]

[Total Marks = 15]