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, 4 February 2011

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)

i. Why are neutrino oscillations not allowed in the Standard Model ?

ii. Do neutrino oscillation measurements give information on the absolute mass scale ? Is there any lower bound on the neutrino mass ?

iii. Which is the current upper bound on the ν_e mass and how was it determined ?

iv. Briefly describe an experiment which aims to improve the current upper bound.

v. Is ν_e lighter than ν_τ ?

vi. No neutrinos are emitted, yet neutrino-less double-β decay, if observed, would allow experiments to determine the neutrino mass. Draw the Feynman diagram of this process and explain why its decay rate is sensitive to the neutrino mass if neutrinos are Majorana particles. **[6]**

(b)

i. Describe briefly the LSND experiment (beam, detection method, main results).

ii. What are the main differences with MiniBoone ? What is similar ?

iii. If you could place a neutrino detector at a distance, L, of your choice on the CNGS (CERN Neutrino beam to Gran Sasso), which distance would you choose to maximise the sensitivity to oscillations in the region of parameters indicated by LSND ? (Assume an average energy of 20 GeV for the CNGS.)

iv. Which fundamental symmetry can be assumed to relate the probability of $\nu_e \to \nu_\mu$ oscillations to that of $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations ?

v. Explain which are the most important requirements on the far detector to study $\nu_e \to \nu_\mu$ oscillations at a neutrino factory, and name a suitable detection technique.

vi. If $\sin^2 2\theta_{13} = 0.05$ and a detector could be placed at $L = 2\,000\,\text{km}$ on a neutrino factory beam line, which detector mass would be needed to observe 10 ν_μ events due to $\nu_e \to \nu_\mu$ oscillation in one year of data-taking ?
Use the following : neutrino energy, $E = 20\,\text{GeV}$; deep-inelastic cross-section, $\sigma(\nu_\mu) = 13.5 \times 10^{-38}\,\text{cm}^{-2}$ per nucleon; ν_e flux $\phi(\nu_e) = 10^7\,\text{cm}^{-2}\text{year}^{-1}$; detection efficiency, $\epsilon = 20\%$; $\Delta m^2_{23} = 2.4 \times 10^{-3}\,\text{eV}^2$, and $\sin^2 2\theta_{23} = 1$. (Hint : neglect CP violation and matter effects, and use an approximate formula for $\text{P}(\nu_e \to \nu_\mu)$ valid for experiment sensitive to Δm^2_{atm}.)

vii. How many $\bar{\nu}_\mu \to \bar{\nu}_\tau$ events would the experiment in vi. detect ? (Make plausible assumptions on the anti-neutrino flux and assume for the cross-section $\sigma(\bar{\nu}_\tau) = 0.25 \times \sigma(\nu_\mu)$.)

[9]

[Total Marks = 15]

Question 2 : CP violation

(a) Describe the three discrete transformations, including the properties of their operators. **[3]**

(b) From which *golden* decay can the angle β be easily extracted ? What kind of CP violation is exploited in this case ? Which is the minimum requirement for this type of CP violation ? Explain briefly why the asymmetric B factories have been a perfect ground for this measurement. **[5]**

(c) One of the angles of the unitarity triangle is called γ and it is measured through $B^+ \to DK^+$ decays, where D represents an admixture of D^0 and $\overline{D}^0$ states. Draw the Feynman tree diagrams for these $B^+ \to DK^+$ decays. Then considering the D decay to $K\pi$, discuss how CP violation can arise when we look at $B^+ \to [K^-\pi^+]_D K^+$ decay chain. What kind of CP violation is this and which is its minimum requirement ? Note CKM matrix elements on vertices where appropriate and which CKM matrix element in the diagram is related to the weak phase (γ). **[7]**

[Total Marks = 15]

Question 3 : Hadron Colliders

CDF has recently measured the forward-backward asymmetry of top quarks (A_{FB}) in $\mathrm{t\bar{t}}$ events in the $\mathrm{t\bar{t}}$ rest-frame and observes a 3.4σ discrepancy with respect to the SM prediction.

(a) Draw the two leading order Feynman diagrams for $\mathrm{t\bar{t}}$ production at the Tevatron. Which one has the highest rate and why ? **[4]**

(b) Explain why at leading order A_{FB} is expected to be zero. **[2]**

(c) Beyond leading order, interference diagrams produce a non zero A_{FB}. Draw two ($\mathrm{t\bar{t}}$) NLO diagrams that interfere and which are not invariant under charge conjugation. **[2]**

(d) The CDF $\mathrm{t\bar{t}}$ sample is selected where one top (or $\mathrm{\bar{t}}$) decays semi-leptonically (lepton) and one purely hadronically (jets). Calculate the fraction of the $\mathrm{t\bar{t}}$ sample expected to produce this lepton+jets signature. In this sample how is the t-quark system differentiated from the $\mathrm{\bar{t}}$ system. **[4]**

(e) Draw the Feynman diagram for the dominant background to $\mathrm{t\bar{t}}$ production in the lepton+jets channel. **[2]**

(f) Experimentally the asymmetry is measured in terms of the sign of the difference of the lepton rapidity and the rapidity of the "jet" system, Δy_{lj}. Why is this a useful quantity ? **[1]**

[Total Marks = 15]

Question 4 : LHC Physics

(a) We can approximate the fully hadronic cross section at the LHC in the central rapidity region ($|y| < 0.3$) as an exponential distribution of the form $d\sigma/dp_T = A\exp(-Bp_T)$. Considering that this curve has a value 3×10^4 at $60\,\mathrm{GeV}$, and 10 at $360\,\mathrm{GeV}$, determine A and B, as well as the total cross section above $100\,\mathrm{GeV}$. **[5]**

(b) In fitting the top mass in the semi-leptonic channel (when the W from the decay of the first top decays hadronically and the other leptonically), only the transverse mass of the top quark can be measured. Explain why, and why on the other hand the use of the knowledge of the W mass also over-constrains the system. **[5]**

(c) The Minimum Bias trigger of an experiment is run for the equivalent of one full month of data taking at the rate of $10\,\mathrm{Hz}$. During that period, the accelerator has collected $10\,\mathrm{pb}^{-1}$, and we make the approximation that the instantaneous luminosity is constant during the whole period. Knowing that the Minimum Bias cross section is $70\,\mathrm{mb}$, how much is the average prescale factor of this trigger ?

This trigger is used to calculate the efficiency of a second trigger, that runs unprescaled with a cross section of $100\,\mathrm{pb}$. This second trigger is uncorrelated to the Minimum Bias, and all events passing the second trigger would be taken by an unprescaled Minimum Bias trigger. How many events are supposed to be taken by both triggers ? Are they sufficient for an efficiency determination ? **[5]**

[Total Marks = 15]

Question 5 : QCD phenomenology

(a) The evolution equation for the running strong coupling constant at leading order is

$$\frac{d\,\alpha_S}{d\,\ln\mu_R^2} = -\beta_0\alpha_S^2, \qquad \beta_0 = \frac{(11-2/3n_f)}{4\pi},$$

where n_f is the number of active quark flavours at a given scale μ_R^2.

i. Show that $\alpha_S(\mu_R^2) = 4\pi/((11-2/3n_f)\ln(\mu_R^2/\Lambda^2))$ is a solution to this equation if Λ is a constant. **[2]**

ii. Taking $m_b^2 = 20\,\mathrm{GeV}^2$, then n_f changes from 4 to 5 at $\mu_R^2 = 20\,\mathrm{GeV}^2$. For continuity of the coupling constant we must have Λ depending on the number of flavours. If $\Lambda_4 = 250\,\mathrm{MeV}$ what is the value of Λ_5 ? **[3]**

iii. What happens to the coupling constant at the hypothetical transition between 16 and 17 active quarks ? **[2]**

(b)

i. Draw three Feynman diagrams where two partons undergo an annihilation process to form two jets in the final state. **[3]**

ii. With possible reference to these diagrams explain why the production of very high-E_T jets at the LHC is more sensitive to the gluon distribution than very high-E_T jets at the Tevatron (once the jet energies have been scaled by the overall energy factor for the colliders, e.g. we compare a 200 GeV jet at the Tevatron with one of 700 GeV at the LHC). **[3]**

iii. Also show two diagrams where jets may be produced by the exchange of an intermediate parton rather than annihilation. **[2]**

[Total Marks = 15]

Question 6 : Accelerator physics

(a) The parameters for a future electron positron linear collider at 3 TeV centre of mass energy could be the following :

Parameter	Value	Unit
Beam energy	1.5	TeV
Bunch population	3.72×10^9	electrons or positrons
Number of bunches	312	per machine pulse
Train repetition frequency	50	Hz
Beam size x (y) at IP	45 (1)	nm
Luminosity	5.9×10^{34}	$\mathrm{cm^{-2}s^{-1}}$

i. Calculate the average beam power in Watts for this linear collider.

ii. Check the luminosity value given in the table above, explaining the source of any discrepancy. **[4]**

(b) The similar parameters for a 3 TeV muon collider could something like :

Parameter	Value	Unit
Beam energy	1.5	TeV
Bunch population	2×10^{12}	muons or anti-muons
Repetition frequency	12	Hz
Bunches / fill	4	per fill
Beam size x (y) at IP	3 (3)	μm
Magnetic bending radius	955	m

i. Calculate the synchrotron energy loss per bunch per turn.

ii. Approximately calculate the stored beam lifetime (muon lifetime at rest is $\tau_0 = 2.2 \times 10^{-6}$ s.) **[4]**

(c) Outline the benefits and technical challenges in building one of the machines above, in the answer please include all relevant aspects of beam production, acceleration and finally collision. **[7]**

[Total Marks = 15]

END OF PAPER