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, 3 February 2012

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

(a)

i. Briefly describe the T2K experiment : main purpose and first results;

ii. Describe the main characteristics of the neutrino beam used by T2K highlighting the differences compared to older long baseline neutrino beams (e.g. NUMI beam line to MINOS);

iii. Which neutrino interaction process has the largest cross-section at the T2K peak energy ? How does that cross-section depend on the energy ?

iv. What are the main sources of background to the oscillation search in the appearance channel ?

v. Draw the ν_μ survival probability as a function of the detector-source distance, L, for $\sin^2 2\theta = 1$, $\Delta m^2 = 2.5 \times 10^{-3}\,\mathrm{eV}^2$, and $E = 0.6\,\mathrm{GeV}$. [Only an approximate plot is requested. Start by calculating and plotting the value of $\mathrm{P}(\nu_\mu \to \nu_\mu)$ at five different values of L, between 0 and 1200 km, then interpolate between the chosen points in a sensible way. Use the simple formalism for oscillation between two neutrino species and neglect matter effects].

- To which values of L do the first and second minima of $\mathrm{P}(\nu_\mu \to \nu_\mu)$ correspond to ?
- Imagine a detector like superK could be positioned at the point corresponding to the second minimum, how would the sensitivity to $\sin^2 2\theta$ of this detector compare to that of a similar detector placed at the first minimum ? [Hint : compute the ratio of the 90% confidence levels at the two distances, using the known dependence of $\sin^2 2\theta_{\mathrm{min}}$ on the maximum number of detectable events at "high" Δm^2 (i.e. $\Delta m^2(\mathrm{eV}^2) \gg E\,(\mathrm{GeV})/L\,(\mathrm{km})$.] **[10]**

(b)

i. What is a Majorana particle ?

ii. Describe a process which, if observed, would unambiguously establish that neutrinos are Majorana particles. Draw the Feynman diagram and explain why the process is forbidden in the Standard Model.

iii. The Cuore and SuperNemo experiments use two different experimental techniques to search for Majorana neutrinos. Which are the main merits of each of the two different approaches ?

iv. Which information about the neutrino mass hierarchy could the above experiments give ?

v. How can one determine whether the mass hierarchy is normal or inverted if neutrinos are Dirac particles ? **[10]**

[Total Marks = 20]

Question 2 : CP violation

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

(b) In which meson systems has CP violation been seen experimentally ? Describe which of the three types of CP violation has been measured in each system. [**6**]

(c) Define direct CP violation and describe under which conditions it manifests itself. Briefly describe one example of measured direct CP violation in the B system. [**4**]

(d) Draw two diagrams contributing to the $B^0 \to \pi^+\pi^-$ decay. Discuss what kind of CP violation and what quantity can be measured in this case (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.) [**8**]

[**Total Marks = 20**]

Question 3 : Hadron colliders and LHC physics

(a) Based on their mass and their decay mode, estimate rough hadronic branching fractions of tau leptons, W bosons and Z bosons, and explain the results. **[5]**

(b) Assuming that the number of pileup events in a collision is distributed according to a Poissonian with mean value of 10, and assuming that each pileup event has an average total energy of 10 GeV, spread uniform in P_T over the rapidity range $|\eta| < 5$, what is the offset that has to be subtracted on average to a circular jet with radius 0.4 ? What is the probability that more than 3 GeV is added to the jet ? **[3]**

(c) The measured distance of a reconstructed secondary vertex in a LHC experiment can be described as the sum of a Gaussian (due to the resolution of light-quark decays) plus a falling exponential (due to B-meson decays, for which resolution effects are neglected) :

$$\frac{dN}{dx} = A\exp(-Bx^2) + C\exp(-Dx)$$

Calculate b-tagging efficiency and purity :

i. if the impact parameter is required to be positive, knowing that $\frac{1}{\sigma\sqrt{2\pi}} \int e^{-x^2/2\sigma^2} = 1$;

ii. as a function of the value x of the cut on the measured secondary vertex distance (you can leave the result in integral form for the Gaussian part). **[4]**

(d) Quote some reasons why the SM may be inadequate as a final theory of nature, and some of the main theories aiming at solving these issues, with a specific emphasis on their experimental signatures at the LHC. **[8]**

[Total Marks = 20]

Question 4 : QCD phenomenology

(a)

i. For an e^+e^- collision draw two Feynman diagram which include some strong coupling vertices but correspond to two-jet final states. Explain why they can correspond to two jets even if there are more than two strongly interacting partons in the final state. **[3]**

ii. Compare the cone-type and cluster-type algortithms for defining jets, briefly explaining advantages of the latter. **[4]**

iii. Parton showers produce a large number of final state partons. Explain very briefly why the parton showering in Monte Carlo generators changes the details of jet shapes, such as thrust, but does not have much effect on the total number of final states with a given number of high-energy jets. **[3]**

(b)

i. Consider the asymmetry in W^+ and W^- production as a function of rapidity y,

$$A_W(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy}.$$

Explain why this is zero at zero rapidity in proton-antiproton collisions at the Tevatron and positive for positive y, if positive y is aligned with the proton beam direction. **[3]**

ii. If at the Tevatron $\sqrt{s} = 1.96\,\text{TeV}$ find the x value corresponding to $y = 0$, i.e. $x = x_0$, and the maximum possible y value. The LHC is a proton-proton collider operating at $\sqrt{s} = 7\,\text{TeV}$. Find x_0 and the maximum y at the LHC. **[4]**

iii. Using the assumption that all antiquarks are equal (which is reasonable for x_0 at the LHC), show that rather than vanishing at $x = x_0$ the asymmetry becomes

$$A_W(y) = \frac{u_V(x_0) - d_V(x_0)}{u(x_0) + d(x_0)},$$

where $u_V(x)$ and $d_V(x)$ are the valence distributions and we ignore contributions from strange, charm, bottom and top quarks. **[3]**

[Total Marks = 20]

Question 5 : Accelerator physics

The parameters for the LHC at the ATLAS interaction point are

Parameter	Value	Unit
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
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	11.245	kHz

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

(b) Calculate the total beam power in a full storage of the LHC and briefly discuss why this might cause difficulties for detectors and accelerator. **[4]**

(c) Discuss the factors that limit the luminosity of the LHC. **[4]**

(d) Discuss how the LHC luminosity or energy could be upgraded, whilst keeping the same circumference ring. **[6]**

[Total Marks = 20]

END OF PAPER