Brunel University
Queen Mary, University of London
Royal Holloway, University of London
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Intercollegiate post-graduate course in High Energy Physics

Paper 2 : Current HEP Projects

Friday, 8 February 2013

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

i. Quasi-elastic interactions have played an important role in neutrino history. Draw the Feynman diagram of the reaction that led to the experimental discovery of neutrinos and explain which particles could be detected and how. **[4]**

ii. Name an experiment at accelerator which uses quasi-elastic interactions to measure θ_{13}. How does this experiment distinguish electrons and positrons from muons in the far detector ? Would you expect tau leptons to be produced from the interaction of neutrinos in the beam ? Justify your answer. **[5]**

iii. What are the constraints on the ν_τ mass ? Is ν_τ effectively heavier than ν_e ? Which information would a signal of neutrinoless double-β decay in SuperNemo give on the neutrino mass nature and hierarchy ? **[5]**

iv. Imagine you were to design an experiment optimised for the search of ν_e to ν_μ oscillation in the region of $\Delta m^2 = 1\,\mathrm{eV}^2$ with an electron neutrino beam peaked at 2 GeV.

a) Which facilities could produce such a beam ?

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

c) If 90 ν_μ events due to oscillations are observed in the far detector, how many events would you expect in a second far detector, identical to the first one, placed at a distance from the source $L_2 = 3 \times L_1$? **[6]**

[Total Marks = 20]

Question 2 : CP violation

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

ii. Draw the Feynman diagram for the amplitude responsible for $B^0 - \overline{B}^0$ mixing, and indicate the dominant contribution to the mixing amplitude. Note CKM matrix elements on vertices where appropriate. **[3]**

iii. The decay $B^0 \to J/\psi\,\pi^0$ can be used to measure $\sin 2\beta$. Draw the tree and loop Feynman diagrams for this decay. Where does the decay pick up a factor of $V_{\rm td}$ from in order for it to be sensitive to $\sin(2\beta)$? Note CKM matrix elements on vertices where appropriate. What is the importance (if any) of a measurement of $\sin 2\beta$ in $B^0 \to J/\psi\,\pi^0$ being significantly different from $\sin 2\beta$ in $B^0 \to J/\psi\,K^0_s$? **[7]**

iv. The γ angle of the Unitarity Triangle 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 ? 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 = 20]

Question 3 : Hadron colliders and LHC physics

i. Given a boosted W (assume $m_W = 80\,\text{GeV}$) with transverse momentum of $320\,\text{GeV}$, decaying into two jets with direction perpendicular to that of the W, calculate their opening angle in the laboratory frame. **[5]**

ii. The resolution for reconstructing the decay of a Higgs boson into a photon pair at the LHC is given by

$$\frac{\sigma_m}{m} = \frac{1}{\sqrt{2}} \left(\frac{\sigma_1}{E_1} \oplus \frac{\sigma_2}{E_2} \oplus \frac{\sigma_\theta}{\tan\theta/2} \right)$$

Calculate energies and the mass resolution for two photons coming from the decay of a Higgs boson with a mass of $126\,\text{GeV}$, and emitted at 90° in the lab frame (use $\sigma(E)/E = 5\%/\sqrt{E}$ and $\sigma(\theta) = 50\,\text{mrad}/\sqrt{E}$). **[3]**

Considering that after the selection cuts, about 400 Higgs events are selected for a luminosity of $10\,\text{fb}^{-1}$ and that the background in this region can be approximated as

$$N_{\text{ev}} = 25000 - 20 \cdot m$$

where m is the diphoton mass, calculate the statistical significance of a Higgs signal given by counting the events within two sigma of the mass peak. To improve the significance, would it be better to halve the resolution on energy or that on the angular measurement?

[5]

iii. Why does Supersymmetry provide a natural candidate for dark matter, and is there a difference between R-parity violating and R-parity conserving SUSY ? **[4]**

iv. The cross section for producing two W bosons with the same sign from vector-boson scattering is of the order of $1\,\text{fb}$, while the cross section for inclusive W plus a forward jet is about $10^2\,\text{pb}$. Considering that $1\,\text{pb} = 10^{36}\,\text{cm}^2$, and the accelerator is run at $10^{34}\,\text{s/cm}^2$, with about 10^7 bunch crossings per second, what percentage of same-sign WW events will be due to two W bosons being produced in the same bunch-crossing ? **[3]**

[Total Marks = 20]

Question 4 : QCD phenomenology

(a)

i. Explain briefly why the coupling constant α_S of QCD is said to run with the energy scale of the process. **[4]**

ii. What is meant by "renormalisation scale dependence" ? A physical quantity which is a function only of centre of mass energy $\sqrt{s}$, where $\sqrt{s} = 20$ GeV, has a cross section calculated up to $\mathcal{O}(\alpha_S^2)$ of

$$\sigma(s) = \alpha_S(\sqrt{s}) + 2\alpha_S^2(\sqrt{s})$$

when expressed at $\mu^2 = s$. Plot the scale dependence if μ is varied between $\mu = 0.25\sqrt{s}$ and $\mu = 4s$ (the β-function $\beta_0 = 0.663$ and $\Lambda_{\rm QCD} = 150$ MeV). **[5]**

iii. Why is the scale dependence generally worse if the number of jets in a final state process increases ? **[2]**

(b)

i. Write down the evolution equation for a flavour non-singlet quark distribution function and the equation relating the distribution to the flavour non-singlet structure function. (Explain what the convolution symbol $\otimes$ means if using this in your answer.) **[2]**

ii. One can eliminate the parton distribution completely and simply write an evolution equation for the structure function in this case, i.e.

$$\frac{dF^{NS}(x,Q^2)}{d\ln Q^2} = \Gamma^{NS}(x,\alpha_s(Q^2)) \otimes F^{NS}(x,Q^2)$$

Find an expression for $\Gamma^{NS}(x,\alpha_s(Q^2))$. **[3]**

iii. Why is a precise measurement of the non-singlet structure function in principle a better means of determining the strong coupling constant than the measurement of the very rapid evolution of the structure function at small-x at HERA ? **[2]**

iv. In what ways is it limited in practice ? **[2]**

[Total Marks = 20]

Question 5 : Accelerator physics

The interaction point machine parameters for the 3 TeV Compact Linear Collider (CLIC) are shown in the table below.

Parameter	Value	Unit
Beam energy E	1.5	TeV
Train repetition frequency f_{train}	50	Hz
Bunches per train N_b	312	Bunches/train
Bunch charge N_e	3.7×10^9	$e^{+/-}$/bunch
Horizontal beta function β_x^*	10	mm
Vertical beta function β_y^*	0.07	mm
Horizontal bunch size σ_x^*	40	nm
Vertical bunch size σ_y^*	1	nm
Bunch length σ_z^*	44	μm

Table 1: Parameters for 3 TeV, CLIC accelerator taken from the CLIC Conceptual Design Report 2012. The starred quantities mean the value at the interaction point.

i. Calculate the beam power (in Watts) for a single beam. Guess a reasonable value for the conversion efficiency of electrical energy into beam power and calculate the *wall-plug* power required per beam. **[4]**

ii. Given typical beam sizes of order micrometers calculate the energy density in J/cm^3 if a beam train is lost into a detector or collimator. Calculate the temperature rise of a kilogram of tungsten (specific heat of 0.13 kJ kg^{-1}K^{-1} and density 193.0 kg m^{-3}) if a train deposits all its energy. **[4]**

iii. Calculate the luminosity of CLIC in units of cm^{-2}s^{-1}. Explain why this luminosity might not be achieved so easily. **[6]**

iv. CLIC proposes to use a novel two beam acceleration system, briefly explain (possibly with reference to your other answers) why such a system is used. **[6]**

[Total Marks = 20]

END OF PAPER