Queen Mary, University of London
Royal Holloway, University of London
University College London

Intercollegiate post-graduate course in High Energy Physics

Paper 3: Current HEP Projects

Thursday, 22nd March 2018 – 14:30

Time allowed for Examination: 2.5 hours

Answer all questions

Books and notes may be consulted

This 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 phenomenolgy

Please begin each question on a new piece of paper.

Question A: Neutrino physics

1. For a 2 GeV neutrino beam, at what baseline would oscillations driven by the "atmospheric" mass splitting $\Delta m^2_{32} \approx 2.5 \times 10^{-3}\,\mathrm{eV}^2$ be maximized? **[1]**

2. Consider a neutrino beam produced by the decay $\pi^+ \to \mu^+ + \nu_\mu$.

   (a) Briefly, why do the π^+ preferentially decay to μ^+ rather than e^+? **[2]**

   (b) If the initial pion has energy E, what is the energy of the ν_μ and μ^+, assuming they are produced parallel to the pion's direction of travel? You may assume the neutrino is massless. **[2]**

   (c) Using conservation of energy and momentum, derive an exact expression for the energy of a neutrino produced at an angle θ from the pion direction. **[4]**

   (d) For small angles and in the relativistic limit, this expression simplifies to

   $$E_\nu = 0.43 E_\pi / (1 + \gamma^2 \theta^2),$$

   with $\gamma = E_\pi / m_\pi$. For initial pions distributed around 10 GeV, what off-axis angle will maximize the flux of 2 GeV neutrinos? **[1]**

3. This beam can also be configured to produce $\bar{\nu}_\mu$ from the decay of π^-. Is it possible in principle to detect CP-violation by comparing the oscillation probabilities $P(\nu_\mu \to \nu_\mu)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$? If so, how? If not, why not? How about $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$? **[2]**

4. What signature would the quasi-elastic interaction of a 2 GeV muon neutrino leave in a tracking calorimeter detector? What about an electron neutrino? And a neutrino interacting via a Neutral Current interaction? Compare and contrast to the same interactions in a water Cherenkov detector. **[4]**

5. Why would this experiment be unlikely to be able to directly observe $\nu_\mu \to \nu_\tau$? **[2]**

6. How is the energy spectrum of Neutral Current interactions observed in the Far Detector related to the same spectrum in the absence of neutrino oscillations? **[2]**

[Total Marks = 20]

Question 2 : CP violation

1) Describe the three discrete transformations for a Lagrangian, their operators and their properties.

(3 marks)

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

(3 marks)

3) Write down the CKM unitarity relation corresponding to the Unitarity Triangle relative to b physics, and explain briefly why this particular triangle is significant.

(3 marks)

Connect each of the angles of the Unitarity Triangle with at least one decay that can lead to its measurement.

(3 marks)

4) Draw the main Feynman diagram which contributes to the $B^0 \to J/\psi K_s$ decays. Discuss what kind of CP violation can be measured in these decays and what quantity this measurement is sensitive to (draw any additional diagram if necessary).

(3 marks)

Draw the Feynman diagram corresponding to a higher order contribution to this decay. Demonstrate why this extra amplitude does not spoil the measurement.

(3 marks)

How is this similar to the $B^0 \to \pi^+\pi^-$ case? How is it different?

(2 marks)

(In all your answers: note CKM matrix elements on vertices where appropriate and if any CKM matrix element in the diagram is related to a weak phase.)

[Total Marks = 20]

Question C: Hadron colliders and LHC physics

1. Explain the limiting factors on the LHC beam energy and how they could be overcome? **[2]**

2. Event Reconstruction and Particle Detectors.

   (a) The efficiency to reconstruct charged particle tracks from electrons at high pseudorapidity (η) degrades. Explain the main effects causing this degradation. **[2]**

   (b) Explain why the same does not typically hold for muons and how we reconstruct muons in a standard collider detector. **[2]**

   (c) What signature do neutrinos leave in a standard collider detector? Given their signature, explain how they are reconstructed in the detector. **[2]**

3. Higgs Physics

   (a) Calculate how many Higgs bosons we expect with 120 fb^{-1} in the $H \rightarrow \bar{b}b$ decay channel, for both the gluon fusion (ggH) and vector boson associated production channels ($WH + ZH$), given the branching ratios of $H \rightarrow \bar{b}b$, $W \rightarrow e\nu/\mu\nu$ and $Z \rightarrow ee/\mu\mu$ (given we only search for the e and μ decays of the W and Z). **[3]**

   (b) Explain why it was necessary to use the $WH + ZH$ production channel to find evidence for the $H \rightarrow \bar{b}b$ decay despite the much smaller yield. **[2]**

4. Standard Model Physics

   (a) When reconstructing electrons or muons, we typically require they have a transverse momentum (pT) greater than 20 GeV. Now, assume a Z boson is produced at rest at the LHC and decays to two muons. What coverage in polar angle (θ) is needed to identify all of the muons with pT $>$ 20 GeV? What is the equivalent coverage in pseudorapidity (η)? The mass of the Z boson is 91 GeV. **[3]**

   (b) Assuming we were to use the full acceptance of the ATLAS muon detectors ($|\eta| < 2.5$), how low in pT would the muon reconstruction have to go in order to find all muons hitting the muon detectors? Again, assume the Z boson is produced at rest **[2]**

   (c) Describe qualitatively how these numbers may change if the Z is produced with a boost i) in the z (beam) direction ii) in the transverse direction. **[2]**

[Total Marks = 20]

Question D: QCD phenomenolgy

1. (a) For an e^+e^- collision draw two Feynman diagrams (one tree diagram and one loop diagram) which include some strong coupling vertices but correspond to two-jet final states. Explain why they correspond to two jet diagrams even if there are more than two strongly interacting partons in the final state. **[3]**

   (b) Compare the cone-type and cluster types algorithms for defining jets, briefly explaining problems with the former and advantages of the latter. **[4]**

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

2. (a) Consider the Z production at hadron colliders as a function of rapidity y. Write all the contributing parton initial states to this process at both proton-antiproton and proton-proton colliders **[4]**

   (b) If at the Tevatron $\sqrt{s} = 1.96$TeV find the x value corresponding to $y = 0$, i.e. $x = x_0$, and also the maximum possible y value. Consider the LHC operating at $\sqrt{s} = 14$ TeV. Find x_0 and the maximum y at the LHC. **[3]**

   (c) Explain why precise measurements of the Z rapidity distribution can provide specific information on the strange quark content of the proton. What other types of experiment provide information on the strange quark, and in what ways is the interpretation of this information less direct than that from the Z boson measurements? **[3]**

[Total Marks = 20]