Indian Institute of Technology Kanpur

PHY-683 Experimental Techniques in High Energy Physics

Midsem Exam, Date: September 21, 2023

Timing: 1.00 PM to 3.00 PM Max marks: 60

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1. (a) What is rapidity? Suppose the particle is moving in the z-direction; we want to construct observable that are boost invariant along the z-direction. The momentum is boosted in the longitudinal direction (z-direction) by

$$q'^{\mu} = k_z q^{\mu}$$

The boost generator k_z is given by

$$k_z = \begin{pmatrix} \cosh\beta & 0 & 0 & \sinh\beta \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \sinh\beta & 0 & 0 & \cosh\beta \end{pmatrix}$$

Get the rapidity expression from these boost generators and demonstrate the Lorentz invariance of the difference in rapidity between two particles. **(7)**

(b) Obtain the expression of rapidity for a massless particle. **(3)**

2. (a) The LHC at CERN will collide proton beams with a maximum of $p = 7$ TeV/c per beam. The LHC parameters are the following:

Circumference	26658.9 m
Particle momentum	7 TeV/c
Dipole magnetic field	8.392 T
Length of dipole magnet, l_b	14.2 m

Calculate the beam rigidity of the design beam and the bending radius of the dipole magnet in the arc. Also calculate the number of dipole magnets required for the machine. **(6)**

(b) Determine the formula for cyclotron frequency and explain why the cyclotron cannot function at relativistic velocities. Additionally, provide an overview of the underlying concept behind synchrotrons. **(4)**

3. (a) Consider following pion decay at rest:

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

Calculate the magnitude of muon momentum, assume $m_\nu = 0$. Given: $m_{\pi^+} = 140$ MeV, $m_{\mu^-} = 106$ MeV. **(7)**

(b) Write down the expressions for Mandelstam variables s, u, and t. Show that

$$s + u + t = m_1^2 + m_2^2 + m_3^2 + m_4^2$$

(3)

4. (a) What is the phenomena of neutrino oscillation? Derive two-flavor neutrino oscillation formula using basic quantum mechanics. **(7)**

   (b) In this context, explain why charged leptons do not oscillate (**Hint:** assume propagation eigenstate as wave packet.) **(3)**

5. (a) Using pure classical arguments, calculate the energy loss per unit distance, $\frac{dE}{dx}$, for a massive, charged particle as it traverses a material. **(6)**

   (b) When a heavy charged particle moves thorough the material, most of its energy loss is due to interactions with the atomic electrons and not with the nuclei, why? **(2)**

   (c) Explain the Bragg peak phenomenon when a heavy charged particle deposits energy in a material. And subsequently, outline the advantages of proton therapy over X-ray therapy in cancer treatment. **(2)**

6. (a) Compare the energy available for particle production in Fixed Target & collider experiments. Obtain the expression for energy available for particle production in both scenarios. **(6)**

   (b) Using one mass scale dominance ($m_1 \sim m_2$) and the following parametrization, get two flavor probability equations for $P(\nu_\mu \to \nu_\mu)$:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R(\theta_{23})R(\theta_{13}, \delta)R(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

   What is the leading order term in oscillation frequency and amplitude? What kind of experiments are useful to measure these all the mixing angles and mass-squared difference parameters? **(4)**