Modern Experimental Particle Physics FYST17
Problem set 2, VT2020

Deadline: February 27th, 2020, 23:59

Problem 1: The Greisen-Zatsepin-Kuzmin cut-off

Assume that ultra high energy protons in cosmic rays can interact with the photons from the cosmic microwave background via:

$$p + \gamma \rightarrow n + \pi^+$$

a) Draw a Feynman diagram for the process
b) What is the energy of the photons? (you can assume T = 3K)
c) What energy should the proton have in the lab frame (defined by the cosmic microwave background) for this process to be possible?
Assume a head-on collision, and that $E_p >> m_p$.

Problem 2: Detectors for lifetime measurements

Describe which methods could be used to measure lifetimes of the order
a) 10^9 years
b) 10^{-12} seconds
c) 10^{-22} seconds

Problem 3: Quark mixing

Consider the decays $D^0 \rightarrow \bar{K}^0\pi^0$ and $D^0 \rightarrow K^0\pi^0$.
a) Draw Feynman diagrams for the decays. Indicate for each quark vertex which CKM element that describes the coupling. (V_{ud} etc).

b) Using the CKM matrix, estimate the ratio between the two decay amplitudes.

Problem 4: Time of Flight

Time-of-flight detectors are often used for particle identification. Figure 1 shows a sketch of a time-of-flight detector. For two particles of the same momentum p, but with different masses, m_1 and m_2 (and thus different energies and velocities) the difference in time-of-flight can be calculated as:

$$\Delta t = L(\frac{1}{v_1} - \frac{1}{v_2})$$

where L is the distance between the counters.

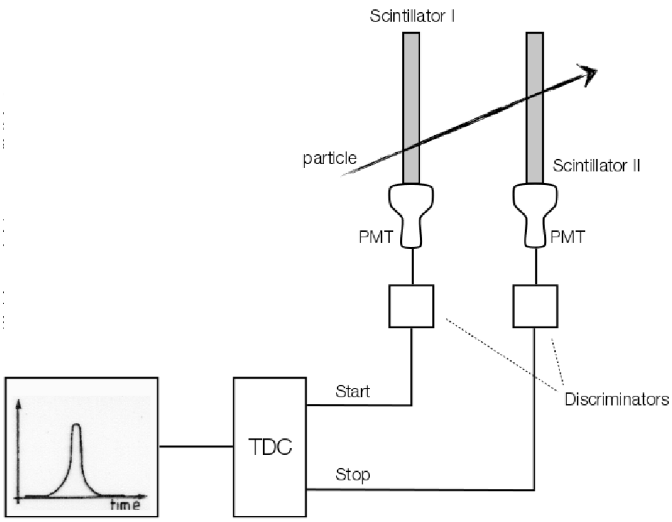

Figure 1: Sketch of a simple time of flight detector

a) What is Δt in the case of highly relativistic particles?
b) Calculate Δt in the case the particles are kaons and pions. Assume p = 1 GeV and L = 2m.
c) The mass resolution can be written as:

$$\sigma(m^2) = 2\sqrt{m^4\left(\frac{\sigma_p}{p}\right)^2 + E^4\left(\frac{\sigma_\tau}{\tau}\right)^2 + E^4\left(\frac{\sigma_L}{L}\right)^2}$$

, where τ is the time, $\beta = L/\tau$ in natural units.
  c1) Show this. (*Hint:* write m^2 in terms of p, L, τ.)
  c2) Which resolution term would you expect to dominate and why?

Problem 5: Significance of counting experiment

A detector is searching for dark matter particles by measuring a variable x, x ϵ [0,1], here x could for instance be the relative missing energy.
Assume that the probability density function for the Standard Model (i.e. "background") hypothesis is: $f(x|b) = \frac{2}{(x+1)^2}$ and that the alternate hypothesis (dark matter) has a probability density function $f(x|s) = 3x^2$

a) To investigate whether an observation is consistent with the Standard Model or not it is decided to reject the Standard Model hypothesis it if x $>$ some x_{cut}. Following standard procedure experimenters want to reject when the probability to reject the background hypothesis even though it is true (a type I error) is relatively small, $\alpha = 0.05$. What value of x_{cut} should they use?

b) Using the value you found in a) what is then the signal efficiency? (the power of the test)?

c) Assume that the final counting experiment applying the cut $x > x_{cut}$ gives an observed number of events $n_{obs} = 4$, with an expected Standard Model background of 0.5 events. What is the corresponding p-value?

d) Calculate or estimate the significance of the result. How many observed events would be necessary for a discovery of dark matter?