Candidacy Exam - Dec. 16, 2019

There are eight questions. Answer five of them as completely as you can. Each question should be answered on a different sheet of paper as the grading is distributed among the HEP faculty. The exam is closed book and no laptops, cellphones etc should be used except for a standard calculator. A Formula sheet is attached. The time allowed is 4 hours.

1. At the Fermilab Tevatron protons and antiprotons were collided together at nearly 2.0 TeV center-of-mass energy.

   (a) Compare and contrast the proton and antiproton.

   (b) The anti-proton was first seen experimentally at Berkeley in the 1950s. In the experiment a beam of protons hit a stationary metal target, and the subsequent reaction was: $p + p \to p + p + p + \bar{p}$.

   Calculate the minimum beam energy necessary for this production reaction.

   (c) In a certain experiment various pions, kaons, protons and anti-protons are routinely produced. Describe how one could experimentally identify the anti-protons and distinguish them from the other hadrons.

   (d) Although several experiments have looked, there has never been an observation of proton decay. Explain why the proton is stable (or at least very long lived).

   (e) Currently the lower limit on the mean lifetime of the proton is about 10^{34} years. If the mean lifetime was 10^{36} years and the prominent decay mode was $p \to e^+ + \pi^0$, calculate how many protons would be required in an experiment such that about 10 events per year are observed.

   (f) Describe how such an experiment could make this measurement.

   (g) What conservation law(s) would be violated by such a decay?

2. CMS uses the anti-k_T jet clustering algorithm to cluster particle flow (PF) candidates into jets.

   (a) Give a brief overview of PF reconstruction. In particular, list the different types of objects reconstructed using PF and explain which detectors subsystems are used in the reconstruction of each. Here we're asking about the objects (i.e. PF candidates) that are then used to perform jet clustering, etc.

   (b) Give a brief description of how the anti-k_T jet clustering algorithm works. In particular, you should address the following points: How does the algorithm decide whether a particular PF candidate is included in the jet? What is k_T and why is the algorithm called "anti-k_T"?

   (c) Pile-up (PU) collisions can contribute in an unwanted way to jet reconstruction. List at least two approaches that CMS uses to mitigate the impacts of PU on jet reconstruction. Describe briefly how each approach you list works.

(d) A $t\bar{t}$ event produced in the so-called "lepton+jets" final state which includes the following particles: $\ell^{\pm}\nu b\bar{b}q\bar{q}'$. Ideally this signature should produce four jets (one for each of the four quarks, including the two bottom quarks). However, in a real experiment, the actual number of reconstructed jets varies, with most events having 3–5 jets. Explain what factors might contribute to reconstructing a number of jets different from the four expected.

3. (a) Explain why jets are formed formed from quarks and gluons in proton-proton collisions.

   (b) Describe how jets are detected and reconstructed in the CMS detector.

   (c) How is the jet energy scale calibrated in the CMS detector.

   (d) The evidence that established the existence of color came from the measurement of R in e^+e^- collisions.

$$R = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} \tag{1}$$

   where the cross-section for $e^+e^- \to \mu^+\mu^-$ is given by

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s^2} \tag{2}$$

   α is the electromagnetic coupling constant and s is the center of mass energy. Draw the Feynman Diagram for Electro-Magnetic process $e^+e^- \to q\bar{q}$.

   (e) If the quark has mass m_q what is the center of mass energy required to produce $q\bar{q}$ pairs.

   (f) Using the expression for the ratio R given above, show the following:

   i. At $\sqrt{s} = 2\,\text{GeV},\ R = 2.$

   ii. At $\sqrt{s} = 8\ \text{GeV},\ R = 10/3.$

   iii. At $\sqrt{s} = 11\ \text{GeV},\ R = 11/3.$

4. (a) Explain how an electromagnetic shower is formed from a high energy (> 1 GeV) photon or electron in an electromagnetic calorimeter.

   (b) The CMS electromagnetic calorimeter was designed to detect $H \to \gamma\gamma$. Describe the technology used and the important design considerations that led to the choice of that technology.

   (c) The resolution of the EM calorimeter is given by

$$(\frac{\Delta E}{E})^2 = (\frac{A}{\sqrt{E}})^2 + (\frac{B}{E})^2 + C^2 \tag{3}$$

   Describe qualitatively what determines the value of the three constants A,B and C

   (d) How is the CMS electromagnetic calorimeter calibrated.

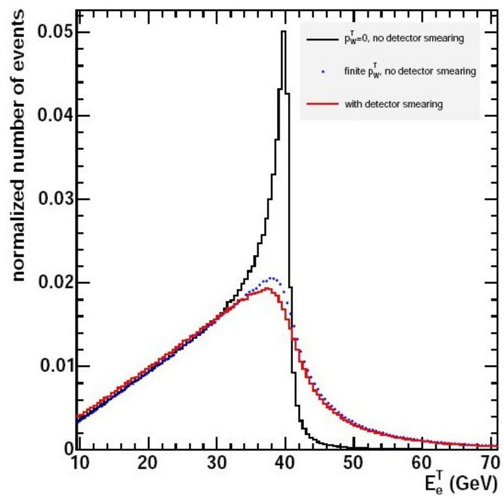
(e) Derive an expression for the reconstructed mass of the Higgs boson candidate in terms of the energy of the two photons and the opening angle between them and use this expression to explain what determines the mass resolution of the candidate.

5. This question explores the W mass measurement one might make at the LHC.

   (a) Draw the lowest-order Feynman diagram you can for production of a single W boson in a pp collison.

   (b) At the LHC, what would the typical η distribution for the produced W direction look like? Explain why you made this prediction? Sketch your prediction for the η distribution for W^+ production direction at the LHC.

   (c) A typical way of measuring the W mass is to look at the shape of the "Jacobian" peak of the transverse energy of the W decay electron, shown in the figure below.



   There are two questions to ask about this figure. First, why is there a very sharp edge at the right hand side of the unsmeared distribution? Second, why might the position of this edge versus energy tell you about the W mass?

   (d) Another issue in the W mass measurement is that of understanding the p_T spectrum of the W. Its importance is also shown in the figure. Why might the W be produced with non-zero p_T? Sketch a Feynman diagram showing your thoughts on the dominant process to generate p_T in single-W production.

   (e) Assume you cannot measure the energy from the neutrino in the W decay. How would you measure the neutrino momentum? What are several effects that might complicate this measurement at the LHC? List as many as you can think of, both in terms of the collision environment and detector performance.

6. Suppose there were a massive, stable charged particle that could be pair produced at the LHC. Also suppose this particle was uncolored–in other words, it does not interact via the strong force.

(a) Based on the above information, draw at least one Feynman diagram representing the leading production mechanism for this particle at the LHC.

(b) What is the minimum mass such a new particle would need to have not to have been detected at past collider experiments, like LEP?

(c) What sort of a signature would such a particle leave in the CMS detector?

(d) How would you distinguish this sort of particle from the known particles in the Standard Model? List at least two specific measurements you would need to make?

(e) Could this particle be a fourth-generation quark or lepton? Explain your reasoning?

7. K mesons and π mesons have negative parity and zero intrinsic spin, while ρ mesons have negative parity and intrinsic spin one.

(a) Explain why the weak interaction decay

$$K^+ \rightarrow \pi^+ + \pi^0$$

provides evidence that weak interactions violate parity and explain why the decay

$$\rho^+ \rightarrow \pi^+ + \pi^0$$

can proceed by the strong interaction.

(b) Draw the relevant Feynman diagrams for the semi-leptonic decay of the K^0 (quark content $\bar{s}d$) via $K^0 \rightarrow \pi^- + \mu^+ + \nu_\mu$ and the semileptonic decay of $\overline{K^0}$ via $\overline{K^0} \rightarrow \pi^+ + \mu^- + \overline{\nu_\mu}$

(c) What is meant by CP?

(d) From the fact that the weak interactions are (to a very good approximation) CP invariant explain why $|K^0>$ and $|\overline{K^0}>$ are *not* mass eigenstates, whereas the superposition states $|K_L>$ and $|K_S>$ are.

(e) Show that the superposition

$$|K_L>= \frac{1}{\sqrt{2}}(|K^0> + |\overline{K^0}>)$$

is CP-odd whereas the superposition

$$|K_S>= \frac{1}{\sqrt{2}}(|K^0> - |\overline{K^0}>)$$

is CP-even.

(f) Explain why K_S decays only into two pions whereas K_L can only decay into three pions.

(g) The mean lifetime of K_S, denoted by τ_S is much shorter than the mean lifetime of the K_L. A K^0 is produced at time $t = 0$, and after a time t which is much larger than τ_S, it decays semi-leptonically. Explain why in such case the decay $K^0 \to \pi^+\mu^-\overline{\nu_\mu}$ is just as likely as $K^0 \to \pi^-\mu^+\nu_\mu$

8. In the LHC, the collision frequency is approximately 40 MHz. The number of protons per bunch is approximately 1×10^{12}. For an instantaneous luminosity of 2×10^{34} cm^{-2}s^{-1}, find

   (a) the instantaneous luminosity per bunch crossing

   (b) the approximate cross-sectional area of the bunches at the collision point, assuming that both beams are the same size.

   (c) the number of pileup interactions per bunch crossing, assuming a total proton-proton inelastic cross section of 80 mb.

   These pileup interactions spray charged and neutral particles randomly into the detector. A characteristic of minimum bias interactions is that the distribution of charged particles $N_{\rm ch}$ is such that $dN_{\rm ch}/d\eta$ is constant and, at LHC energies, is about 6.0 at the center of the detector. Given what you know about Fermi motion in the proton and what this means for an average transverse momentum of collision products, estimate

   (d) on average, how much transverse energy is deposited per bunch crossing in the central region of CMS, $|\eta| < 2.0$, at this instantaneous luminosity. Don't forget about neutral particles!