Andrew Brinkerhoff
March 2012

Candidacy Exam - March 21th, 2012

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. Consider a generic detector on a hadron collider, which consists of a tracking chamber, surrounded by electromagnetic and hadronic calorimeters, and finally muon chambers surrounding the calorimeter. CMS, Atlas, CDF, and D0 are all examples of this type of detector. In terms of the signals in the tracking chamber, EM and hadronic calorimeter, and muon chambers, describe the signatures for the following particles:

   (a) i. electron
   ii. photon
   iii. muon
   iv. proton
   v. neutron
   vi. charged kaon
   vii. charged pion

   (b) Which of these signatures are indistinguishable from one another, and what kind of measurement would you have to add to tell them apart?

2. At the Stanford Linear Accelerator Center we collide electrons (e^-) with energy E_- and positrons (e^+) with energy E_+ to produce pairs of B mesons via the reaction

$$e^+ + e^- \to \Upsilon(4s) \to B\overline{B}$$

   The $\Upsilon(4s)$ is a shortlived state with mass 10.58 GeV. $M_B = M_{\overline{B}} = 5.279$ GeV. The electrons are moving along the z-axis in the +z direction and the positrons in the -z direction.

   (a) If $E_- = 9.0$ GeV what is the minimum E_+ required to produce the $\Upsilon(4s)$. ($E_+, E_- \gg m_e$ so $|E| = |p|$)?

   (b) What is the Lorentz factor γ for the produced $\Upsilon(4s)$?

   (c) In the rest frame of the $\Upsilon(4s)$ what is the energy and momentum of the B and the $\overline{B}$?

   (d) In the lab frame (i.e the frame in which $E_- = 9.0$ GeV) suppose the $B\overline{B}$ are produced collinear with the e^+e^-. What is the energy and momentum of the B and $\overline{B}$?

3. The cross-section for the process $e^+e^- \to \mu^+\mu^-$ is given by

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s^2} \tag{1}$$

   where α is the electromagnetic coupling constant and s is the center of mass energy.

(a) Draw the Feynman Diagram for Electro-Magnetic process $e^+e^- \to q\bar{q}$.

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

(c) The ratio R is given by

$$R = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} \quad (2)$$

Show that at

i. s=2 GeV R=2

ii. s=8 GeV R=10/3

iii. s=11 GeV R=11/3

4. In a collider experiment at the LHC or the Tevatron, a typical interaction might produce a number of pions. The charged pions have a mass of 139.6 MeV and a mean life of 2.6×10^{-8} seconds, while the neutral o has a mass of of 135.0 MeV and a mean life of 8.4×10^{-17} seconds.

(a) Explain the large difference in lifetime between the charged and neutral pions.

(b) If a charged and neutral pion are each produced in an LHC collision with an energy of 10 GeV, calculate how far they will "typically" travel in the detector before decaying. Will these decays be visible in the detector? Explain.

(c) The π^+ decays nearly 100% of the time via: $\pi^+ \to \mu^+\nu_\mu$ and only a small fraction of the time via: $\pi^+ \to e^+\nu_e$.

Explain why the decay into electron-neutrino is so small relative to muon-neutrino even though there is more phase space available for the electron decay.

(d) Write down the Feynman diagrams for $\pi^+ \to \mu\nu_\mu$ and for $\pi^0 \to \gamma\gamma$.

(e) A π^0 is produced at the interaction point of the CMS detector with an energy of 10 GeV. Assume that, in the center of mass of the π^0, the two decay photons are in the plane transverse to the direction of the π_0. Estimate the spatial separation of the two photons as they hit the electromagnetic calorimeter 1.8 meters from the interaction point. Will the detector be able to separate these two photons? Explain.

5. As the most massive quark (discovered so far), the top quark exhibits a range of interesting phenomenology. Please answer the following questions related to the production, decay, and experimental observation of the top quark:

(a) Top decays predominantly to a W boson and a b quark. Why is this decay so dominant?

(b) At hadron colliders, top quarks are predominantly produced in pairs. Write down at least two Feynman diagrams for top quark production. One diagram should involve quarks in the initial state while the other should involve gluons.

(c) In terms of jets, leptons (e, μ, or τ), and missing energy, describe the three general categories of experimental signature for top pair production. How many leptons and how many jets are in each category? How many jets will originate from a b quark in each category?

(d) Estimate the branching fraction for top pair production into each of the three final states above. Hint: Assume that the W decays only to $e\nu_e$, $\mu\nu_\mu$, $\tau\nu_\tau$, ud, and cs, and that $|V_{ud}| \sim |V_{cs}| \sim 1$.

(e) One important experimental technique for identify top pair production is b-quark tagging. Describe the primary technique(s) for b quark identification at CMS.

(f) Top quarks can also be produced singly via the electroweak interaction. Draw at least three Feynman diagrams for electroweak single top production. Which is the dominant production mechanism at the LHC?

6. The primary decay modes available to the Higgs boson depend on the (currently unknown) Higgs mass. Likewise the strategy for searching for the Higgs, and which backgrounds have to be dealt are different for different Higgs mass ranges.

   (a) Draw at least three Feynman diagrams for Higgs production at a pp collider like the LHC. Indicate the relative contribution from each diagram. In other words, how does the cross section for each process compare?

   (b) Consider a high mass Higgs (for example a Higgs with 135 GeV/c^2 $< M_H <$ 300 GeV/c^2). What is the dominant decay channel for a Higgs in this mass range? Which of the above processes is the most practical one to use for searching for Higgs in this mode (please explain)? What are some of the main backgrounds?

   (c) Now consider a "low-mass" Higgs (that is, one whose mass is $<$ 135 GeV/c^2). What is the dominant decay channel for the Higgs? Which production mechanism(s) listed above are most practical for looking for a Higgs boson in this mass range (again, please explain)? What are the main backgrounds for this signature?

7. This question pertains to the trigger on CMS:

   (a) Explain how the CMS trigger system works. Include in your answer a description of why CMS needs a trigger, how the different level triggers work,which subdetectors are used in the trigger at each level, approximately what event rates are at the output of each trigger level.

   (b) Compare and contrast the signatures for photons, electrons, and muons in the different levels of the trigger. What is the earliest level of the trigger at which each of these can be distriguished from the others?

   (c) Currently, CMS does not include any tracking information in the L1 part of the trigger. What advantages would CMS gain by including tracking at level 1?

8. Suppose we were to define:

$$\mathbf{F}^{\mu\nu} = \partial^\mu \mathbf{A}^\nu - \partial^\nu \mathbf{A}^\mu$$

   in Yang-Mills theory

A) Find the transformation for this $\mathbf{F}^{\mu\nu}$ under the gauge transformations

$$\mathbf{A}'_\mu \to \mathbf{A}_\mu + \partial_\mu \vec{\lambda} + \frac{2q}{\hbar c}(\vec{\lambda} \times \mathbf{A}_\mu)$$

with $\vec{\lambda}$ a color vector with the same number of components in color space as $\mathbf{A}_\mu$.

B) For $\mathbf{A}_\mu = (A^1_\mu, A^2_\mu, A^3_\mu)$ in a 3 dimensional representation of the gauge group how does the Lagrangian $\mathcal{L}_\mathbf{A}$ transform

$$\mathcal{L}_\mathbf{A} = -\frac{1}{16\pi} F_1^{\mu\nu} F_{\mu\nu 1} - \frac{1}{16\pi} F_2^{\mu\nu} F_{\mu\nu 2} - \frac{1}{16\pi} F_3^{\mu\nu} F_{\mu\nu 3}$$

$$\mathcal{L}_\mathbf{A} = -\frac{1}{16\pi} \mathbf{F}^{\mu\nu} \cdot \mathbf{F}_{\mu\nu}$$

Bryan Ostdiek

Candidacy Exam
Spring 2012

The exam has 6 questions. You must answer 4 of them correctly in order to pass. If you attempt more than 4, your best 4 answers will be kept. This is closed book. You have 4 hours to take the exam.

1. Calculate the total cross-section for $e^+e^- \to \bar{q}q$, keeping only the QED contributions to leading order. Ignore all masses.

2. Derive the renormalization group equation, at one loop, for the electron mass in QED.

3. Explain, using formulae and diagrams, why the photon mass is not quadratically divergent in QED.

4. What is a Kaluza-Klein tower? Give an explicit example of a situation where KK modes arise and do an explicit calculations of their masses.

5. Lets imagine a theory with a Z' that couples to both quarks and leptons in the same way as the usual Z. What would be the discovery strategy at the LHC? Explain the signals and the possible backgrounds.

6. If we couple the Standard Model to general relativity within the framework of QFT, what is wrong with the resulting theory? Give examples where it might be expected to fail.

De La Puente, Alejandro

Candidacy Exam
Fall 2010

The exam has 6 questions. You must answer 4 of them correctly in order to pass. If you attempt more than 4, your best 4 answers will be kept. This is closed book. You have 4 hours to take the exam.

1. Show all the Feynman diagrams that contribute to $e^- q \to e^- q$ in the Standard Model. Calculate the total cross-section including only QED contributions.

2. Calculate the one-loop renormalization group equation for the top quark Yukawa coupling in the MSSM. Be sure to get the basic structure correct even if you have trouble with the exact coefficients.

3. What is an anomaly in QFT? Explain the concept from as many angles as you can, and then prove that there are no gauge anomalies in the Standard Model.

4. Starting from the Higgs potential of the MSSM, show that the mass of the lightest scalar Higgs is always below m_Z at tree level.

5. Explain how a Higgs boson can decay to photons. In other words, write the effective operator for the decay, give the Feynman diagram(s) which contribute to the operator, explain why the diagrams are finite, and give an estimate for the width of this process.

6. The Fermi theory for the weak interactions is not renormalizable. Why is that so, and what does it imply about the theory? In particular, under what circumstances can the Fermi theory be used, and where does it fail? In what way does it fail?