Candidacy Exam

There are eight questions. Answer 5 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. Exam is close book and no laptops, cellphones etc should be used except for a standard calculator. A Formula sheet is attached. Time allowed is 4 hours.

1. 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 one specific measurement you would need to make?

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

2. 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 and ATLAS are 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

3. At the SLAC National Accelerator Laboratory, the PEP-II accelerator collided 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 short-lived 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 are moving in the $-z$ direction.

(a) If $E_- = 9.0$ GeV, what is the minimum E_+ required to produce the $\Upsilon(4s)$? Take (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 along the z axis. What is the energy and momentum of the B and the $\overline{B}$ in the lab frame?

4. 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) The top quark 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 jet, leptons (e, μ, or τ), and missing energy, describe the three general categories of experimental signatures 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 technique for indentifying top pair production is b quark tagging. Describe the primary technique(s) for b quark identification in 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?

5. The following reactions or decay processes may or may not be allowed. Comment on each. If allowed, under what conditions would each happen? If not allowed, give reasons why not.

(a) $p + \bar{p} \to \Delta^+_{(1232)} + \Delta^-_{(1232)}$

(b) $\nu_\mu \to \nu_e$

(c) $\tau^- \to \rho^+ \nu_\tau$

(d) $t \to H^+ b$

(e) $t \to W^+ b$

(f) $H^0 \to \gamma\gamma$

(g) $e^+e^- \to W^+W^-$

(h) $\rho^0 \to \pi^0\pi^0$

(i) $\phi \to K^0_s K^0_s$

(j) $\mu^+ \to e^+\gamma$

(k) $\mu^- \to e^-\bar{\nu}_\mu\nu_e$

6. Recently, ATLAS and CMS announced that they had reached 5σ significance for the observation of the Higgs boson decaying to $b\bar{b}$. The following questions explore the techniques used in this analysis.

   (a) Write down at least two Feynman diagrams for Higgs production at the LHC.

   (b) For the diagrams you drew, above, discuss their suitability for observing $H \to b\bar{b}$. In particular, discuss how CMS could trigger (or not) on each of the production modes, the particles produced, and their decay products.

   (c) Discuss which sub-detectors are critical to making this measurement, and why. Include both the triggering and reconstruction of these events, and as many suitable decay modes as you can.

   (d) What are the primary background processes that can appear similar to $H \to b\bar{b}$ in the production modes you discussed?

   (e) Make a rough estimate of the sub-detector (tracker, EM and hadronic calorimeter) resolutions required to make this measurement and distinguish the Higgs decays from backgrounds.

7. Consider the scattering of *spinless* electrons ($e^+e^- \to e^+e^-$).

   (a) What is perturbation theory and how do we use it calculate particle interactions (a one paragraph summary of the basic assumptions and technique is all that is required).

   (b) Draw the leading order Feynman diagram(s). (The Feynman rules for spinless leptons are attached)

   (c) Use the Feynman Rules to Write down the matrix element in terms of the four momenta of the ingoing and outgoing particles

   (d) Give the expression for the differential cross-section $d\sigma$ in terms of the matrix element M, the flux F and the Lorentz invariant phase space dLips.

   (e) The electron and positron are collided in the center of mass frame (i.e equal and opposite momenta). In this frame show that $F = 4|p|s$ where $|p|$ is the magnitude of the 3-momentum of either the electron or the positron and s is the center of mass energy.

   (f) In this frame let θ be the angle between the beamline and the outgoing electron or positron. dLips is given by

   $$dLips = \frac{|p_{out}|d(\cos\theta)}{8\pi s}$$

   where $|p_{out}|$ is the outgoing 3-momentum of either the electron or the positron. Find an expression for $\frac{d\sigma}{d(\cos\theta)}$ in terms of s and $\cos\theta$ alone.

   (g) A free photon has $p^2 = 0$ yet the photon exchanged in the interaction of the electron and the positron above has $p^2 \neq 0$ where p is the 4-momentum. Explain why this can happen.

8. 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?