Candidacy Exam - October 3, 2017

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. 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?

2. 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

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

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

3. At the Fermilab Tevatron protons and antiprotons are 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?

4. 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.

   (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.

   (e) List at least two ways in which the jet reconstruction approach taken by ATLAS differs from that used by CMS.

5. Statistics plays an increasingly important role in the interpretation of particle physics results, especially searches for new particles like the Higgs boson or supersymmetry.

   (a) Define the following commonly used statistical terms

      i. p-value

      ii. Nuisance parameter

      iii. Profiling

      iv. Test statistic

      v. MVA

   (b) A typical analysis approach on CMS begins with the construction of a binned likelihood function for a particular reconstructed distribution (say a reconstructed invariant mass or an MVA output). Write an expression for a binned likelihood for a distribution with N bins. You may assume there is a single signal process of interest (s) as well as one relevant background (b). The amount of signal should be characterized by a signal strength parameter μ which is a multiplicative factor that scales the up or down the expected amount of signal. You should also write the signal and background expectation as functions of a set of arbitrary nuisance parameters (θ_i). For simplicity, assume that Gaussian constraints are applied to each nuisance parameter. You may find the following statistical functions helpful:

$$p(n;\nu) = \frac{\nu^n e^{-\nu}}{n!} \qquad \text{(Poisson)}$$

$$p(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \qquad \text{(Guassian)}$$

6. (a) What are the quark contents of the charmed D^0 and D^{*+} mesons? A D^{*+} meson has a mass of 2010 MeV/c^2 and it decays into a D^0 and a π^+ meson with masses of $m_{D^0} = 1865.$ MeV/c^2 and $m_\pi = 139.6$ MeV/c^2, respectively. Calculate the energy of the π^+ in the rest frame of the D^{*+}.

   (b) The K^0 meson has a mass of 497.6 MeV/c^2 and it decays into two charged pions of mass 139.6 MeV/c^2. What is the energy of a pion observed in the rest frame of the K^0? The K^0 lifetime is 0.89×10^{-10} s. State what interaction is responsible for the decay, and justify your answer.

7. With increasingly large $t\bar{t}$ samples being collected at the LHC, it is interesting to study the production of a top quark pair in association with other particles. The table below shows the cross sections for inclusive $t\bar{t}$ production as well as for a variety of associated production modes:

Process	8 TeV	13 TeV	Ratio
$t\bar{t}H$	133 fb	507 fb	3.8
$t\bar{t}Z$	206 fb	840 fb	4.1
$t\bar{t}W$	232 fb	570 fb	2.5
$t\bar{t}$	246 pb	816 pb	3.3

Table 1: Cross sections for various top pair production processes at 8 and 13 TeV.

(a) Draw a representative Feynman diagram for each production. (You can leave top quarks, and W, Z, and H bosons in the final state; no need to draw the those decays as part of the diagram.)

(b) Why does the $t\bar{t}W$ cross section grow noticeably less than the others?

(c) How do each of these four processes manifest (or not) themselves in the following final states? Explain how each process can contribute the objects listed in the signature, making sure to explain a particular object may be misidentified. If objects have to be missed for the process to match a particular signature, please note that as well.

i. One charged lepton, missing transverse momentum, and multiple jets, of which four are b-quark jets.

ii. Three charged leptons, missing transverse momentum, and multiple jets, or which two are b-quark jets.

iii. Six charged leptons, missing transverse momentum, and two b-quark jets.

8. The cosmological evidence for dark matter gives us one clear evidence of physics beyond the standard model.

(a) Based on what we know from cosmological observations, what basic particle properties would a suitable dark matter candidate need to have?

(b) Why can't the dark matter be composed of standard model neutrinos?

(c) What are the experimental challenges to detecting dark matter particles produced in LHC collisions?

(d) Explain the possible connection between dark matter and supersymmetry.