Candidacy Exam - Jun. 15, 2022

There are nine questions. Answer five of them as completely as you can. Be sure to answer the question that is required for students of your advisor. 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. Statistics plays an increasingly important role in the interpretation of particle physics results.

   (a) Define the following commonly used statistical terms

      i. p-value
      ii. Nuisance parameter
      iii. Profiling
      iv. Test statistic

   (b) A typical analysis approach begins with the construction of a binned likelihood function for a particular reconstructed distribution (for example an invariant mass or machine learning discriminant). Write an expression for a binned likelihood for a distribution with N bins. The observation in each bin is denoted as n_i. You may assume that in each bin there is a single signal process of interest $s_i(\theta_j)$ as well as one relevant background $b_i(\theta_j)$, where θ_j represents a set of M nuisance parameters that can modify the signal and/or background predictions. 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. (There is only a single signal strength r used in common across all bins.) The nuisance parameters are constrained by auxiliary measurements, calibrations, or theoretical predictions, and for simplicity, you may assume that these constraints can be expressed by Gaussian constraints where the nuisance parameters have been defined so that the mean of the Gaussian $\mu = 0$ and the standard deviation is $\sigma = 1$. You may find the following statistical functions helpful:

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

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

2. 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 1950's. 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 CMS 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?

   (h) Which theorem or conservation law guarantees that the proton and antiproton have the same mass and lifetime?

3. In the quark model a meson (any strongly interacting boson) is made up of a quark antiquark pair. QCD has an additional 8 degrees of freedom, the gluon octet. In addition to the gluons one can have a $q\,\bar{q}$ in a color octet. Both of these possibilities can enrich the meson spectrum. For historical reasons these additional strongly interacting bosons are called "exotic mesons".

   (a) What are the physical limitations on the QCD color composition of all mesons? What are the spin and parity of a gluon? How do the gluons transform under the QCD SU(3) symmetry? How do the quarks transform under the QCD SU(3) symmetry?

   (b) For pure quark antiquark states what are the allowed values for the meson spin J, as a function of the quarks spin S and orbital angular momentum L. Given L and S what is the parity P of a pure quark antiquark meson state?

   (c) For charge neutral quark antiquark states what are the allowed values of the charge conjugation operator C

   (d) What are the allowed quantum numbers J^{PC} for neutral $q\,\bar{q}$ states in the quark model? Restrict the answer to $J < 2$.

   (e) Describe two ways to find evidence for exotic mesons.

4. A pion has a rest energy of $E_0 = 139.568$ MeV and a mean lifetime of $\tau_0 = 26.029$ ns in its rest frame.

   (a) What are the life-times of a pion accelerated to kinetic energies T1 = 20 MeV and T2 = 100 GeV?

   (b) Assuming the pions decay exponentially according to $e^{-t/\tau}$, at what distance from the source will a population of N pions with kinetic energies T1 and T2 have fallen to 50% of its original value?

   (c) The pion decays to a muon (rest mass = 105.658 MeV/c^2) and a neutrino (essentially massless). What are the total energies of the neutrino and the muon in the pion's rest frame.

5. 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

6. The dominant decay modes of the η meson are as follows:

   - $\eta \to \gamma\gamma$ (39%)
   - $\eta \to 3\pi$ (56%)
   - $\eta \to \pi\pi\gamma$ (5%)

   It is classified as a "stable particle", so none of these is purely a strong interaction. This seems odd since the mass of the η is $549\,\mathrm{MeV/c^2}$ and has plenty of energy to decay strongly into 2π and 3π.

   (a) Explain why the 2π decay is forbidden for strong and electromagnetic interactions.

   (b) Explain why the 3π decay is forbidden as a strong interaction but allowed as an electromagnetic decay.

7. For each of the following types of detectors, describe how the detector works, i.e. what happens when a particle traverses the detector, what type of information is collected, and how that information is used to make measurements of particle properties.

   (a) Time projection chamber

   (b) Time of flight detector

   (c) Gas cherenkov detector

   (d) Silicon strip detector

   (e) Sampling calorimeter

8. (Required for Prof. Lannon's students) As of the date of this exam, experimentally, the only couplings between the Higgs boson and quarks that have been directly measured are the couplings to the top and bottom quarks. Let's consider how we've managed to make those measurements and consider how we might push things further.

   (a) Given that the top quark mass is larger than the Higgs boson mass, we cannot measure the coupling in $H \to t\bar{t}$ decays. Draw at least one Feynman diagram showing a process we can measure at the LHC that would *directly* probe the top-Higgs coupling. (By directly, we mean that there are one or more detectable top quarks in the final state.)

   (b) Is there an *indirect* way to measure the top-Higgs coupling? Explain.

   (c) For the bottom quark, we can measure the coupling via $H \to b\bar{b}$ decays. However, we cannot use the direct production of an individual Higgs boson (e.g. $pp \to H \to b\bar{b}$). Explain why this approach is experimentally infeasible.

   (d) Draw a Feynman diagram for at least one alternative Higgs production mechanism that *is* experimentally feasible for measuring the bottom-Higgs coupling.

   (e) The couplings of top and bottom quarks to Higgs have already been measured, but the coupling to the charm quark has not. Give at least two reasons why we haven't managed to measuring the coupling to charm quarks yet.

9. (Required for Prof. Fields' students)

   (a) Describe the basic elements of a conventional accelerator-based neutrino beam.

   (b) What are the major sources of uncertainty in the neutrino fluxes of conventional accelerator-based neutrino beams?

   (c) Neutrinos can interact in particle detectors via charged-current or neutral current interaction. Draw a Feynman diagram for each of these types of interaction. In each case, there are many different possible diagrams, but just one will suffice.

   (d) Charged current interactions are typically used as the signal process in neutrino oscillation experiments. Why is this?

   (e) Neutral current interactions did play a crucial role in the discovery of neutrino oscillations. What was that role?

   (f) Conventional accelerator-based neutrino beams can produce neutrino or antineutrino enhanced beam. What parameter of the beamline is changed to swap between these two configurations?

   (g) In a neutrino detector, how can we determine whether an interaction was initiated by a neutrino or an antineutrino?