PHYS 575, HW #7

Due: 4/8/20

Top quark production with MadGraph and PYTHIA. In this HW you will get familiar with some of the standard software packages of high-energy physics, the event generator `MadGraph` (developed here at UIUC by Tim Stelzer!) and the parton shower package `PYTHIA`. You may find the following references useful:

- Les Houches Events (LHE) numbering scheme:
  `http://pdg.lbl.gov/2019/reviews/rpp2019-rev-monte-carlo-numbering.pdf`
- Python parser for LHE file format:
  `https://github.com/lukasheinrich/pylhe`
- HEPMC file format: Ch. 6 of
  `http://lcgapp.cern.ch/project/simu/HepMC/20400/HepMC2_user_manual.pdf`

There are also plenty of `MadGraph` tutorials on the web which you should feel free to peruse. In your solutions, you may use the formulas in Peskin appendix E without derivation.

Note: Thanks to the amazing Matthew Feickert, a fully "containerized" package containing all the software tools you will need for this HW set is available as a Docker image. You'll need to download the Docker client from `https://www.docker.com` and set up an account, after which you can follow the instructions in the README here:
`https://github.com/matthewfeickert/MadGraph5_aMC-NLO/tree/feat/PHYS575`.
Please feel free to contact Matthew for technical help: `matthew.feickert@cern.ch`. Of course, you are welcome to download and install these software packages on your own if you find that easier.

1. **(10 points.)** Generate the process $pp \to t\bar{t}$ in `MadGraph` and look at the `index.html` file. Which Feynman diagrams appear? Are the diagrams different for $p\bar{p} \to t\bar{t}$?
2. **(20 points.)** Determine the total cross section for $p\bar{p} \to t\bar{t}$ at the Tevatron, and for $pp \to t\bar{t}$ at the LHC (make sure you use the correct beam energies and beam particle types for both). Give an analytic estimate for the cross section using only the diagram $u\bar{u} \to t\bar{t}$ (you will want to use information about the PDF's that `MadGraph` is using to compute the cross section) and compare to the result that `MadGraph` gives you.

3. **(20 points.)** Generate 10,000 events (do *not* decay the top quarks yet) for $p\bar{p} \to t\bar{t}$ at both the Tevatron and the LHC, and plot the angular distributions for the t and $\bar{t}$ with respect to the beam axis for both sets of events. How do they compare to the distribution if only $q\bar{q} \to t\bar{t}$ contributed, and can you explain the differences between the Tevatron and LHC distributions? You may find the discussion in Peskin Section 13.5 useful. Also make a histogram of the partonic center-of-mass energy; how does the average center-of-mass energy compare to the total center-of-mass energy at both colliders?

4. **(15 points.)** Now generate 10,000 events at the Tevatron where all unstable on-shell final-state particles decay. Which particles appear in the final state, after all the unstable particles have decayed? Show that for each event, you can reconstruct the top quark mass by computing the invariant mass of a suitable combination of final-state particles. (Note that some of these particles, like neutrinos, will be invisible to the detector, so this won't actually work in practice. We'll get to what the detector sees in the next part.) Make a histogram of the invariant mass of the top quark constructed in this way, and explain the shape qualitatively.

5. **(20 points.)** For the Tevatron events where the W decays to two quarks (a "fully hadronic" decay), there are six jets in the final state: one from the b quark from $t \to Wb$, and two from the W, for both the top and the anti-top. Without further information, we can't tell which jets came from t versus $\bar{t}$, but for each event, we can blindly try to form combinations of 3 jets. There are jet-finding algorithms which can take the output from `PYTHIA` and cluster the hadrons into jets, but for this problem, you can pretend that the 4-vector of the jet is the same as the 4-vector of each final-state quark. There are $\binom{6}{3} = 20$ such 3-jet combinations for each 6-jet event. Compute the invariant mass for all such 3-jet combinations for each event, and make a histogram over all the 6-jet events. Can you identify the top quark mass from this histogram? (This channel is not typically used for searches for new particles because generic QCD events often produce a background of lots of jets, swamping the signal; this is why the CDF experiment used a lepton as a signature of the W to claim discovery of the top quark.)

6. **(15 points.)** Finally, generate 1000 events at the Tevatron with `PYTHIA` turned on to shower and hadronize the final-state quarks. (Note that the output file is quite large so 1000 events is plenty!) Inspect the output and identify the following:

   - Find a hadronic W decay in the event list, and describe the first 5 vertices in the branching process (i.e. which daughter particles came from which parent particles). Attach a printout of the relevant lines from the event file.
   - Look towards the end of one of the events and find a heavy flavored meson (K, K^*, D, D^*, etc.). Describe its decay chain and attach a printout of the relevant lines from the event file.