Exercises to Lectures 5/6: Experimental Basics

Exercise 13 (Luminosity):

The luminosity $\mathcal{L}$ of the LHC can be calculated from its beam parameters by:

$$\mathcal{L} = \frac{fN^2}{4\pi\sigma^2}F(\theta)$$

with the following parameters:

- f corresponding to the bunch crossing frequency (→ $40\ \mathrm{MHz}$),
- N corresponding to the number of protons per bunch (→ 10^{11}),
- σ corresponding to the mean diameter of the beam (→ $17\ \mu\mathrm{m}$).
- $F(\theta)$ corresponding to a reduction function, which depends e.g. on the crossing angle of the two beams (→ 0.85).

(Values given for nominal running in design configuration at 14 TeV.)

a)
Calculate the nominal luminosity of the LHC at a center of mass energy at 14 TeV. (Cross sections in particle physics are calculated in “barn”. One barn corresponds to $1\mathrm{b} = 10^{-24}\mathrm{cm}^2$. Give the value of the luminosity in $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and in $\mu\mathrm{b}^{-1}\mathrm{s}^{-1}$.)

b)
The total inelastic cross section at 14 TeV is $\sigma_{\mathrm{inel}}(pp) \approx 85\,\mathrm{mb}$. Calculate the number of pp collisions per second. How many pp collisions does this correspond to per bunch crossing?

c)
In the following the cross section for a few more interesting inelastic scattering processes are given:

- $\sigma(pp \to Z + X, Z \to \ell\ell) = 3380\,\mathrm{pb}$ (cross section per lepton flavor),
- $\sigma(pp \to W + X, W \to \ell\nu) = 21872\,\mathrm{pb}$ (cross section per lepton flavor),
- $\sigma(pp \to t\bar{t}) = 880\,\mathrm{pb}$ (inclusive),
- $\sigma(pp \to H + X) = 53\,\mathrm{pb}$ (gluon fusion only, for a SM Higgs boson with $m_H = 125\,\mathrm{GeV}$).

A typical beam lifetime during physics data taking is 15 hours. Calculate how many of the corresponding particles are produced during one beam cycle in the collision point at CMS.

d)
Assume that you have simulated 100'000 events of type $pp \to H + X$ (gluon fusion only, for a SM Higgs boson with $m_H = 125\,\mathrm{GeV}$) and 100'000 events of type $pp \to Z + X, Z \to \ell\ell$ with a MC event generator. To what integrated luminosity do these numbers of generated events correspond to? What normalization factors would you have to apply to normalize them to a luminosity of 300/fb? How many events would you have to simulate to arrive at an event weight of ≈1?

Exercise 14 (Monte Carlo Event Generation):

In this exercise you will install and use the event generator pythia to study distributions of signal and background processes. The environment to run this and other event generators is readily provided in the form of a “virtual machine” based on the operating system Linux (Ubuntu 14.04). Some documentation on the Monte Carlo event generator pythia will be provided together with this exercise.

a)
Download the virtual machine from the web page:

http://www-ekp.physik.uni-karlsruhe.de/~quast/VMroot/

and follow the instructions in the file Vmroot.pdf. You should now be able to start your virtual machine and to log in. This virtual machine already contains an installed version of the data analysis package root and some examples in the subdirectory

~/root.

The next step is the installation of the pythia8 Monte Carlo event generator. From within the virtual machine, open the web browser and change to:

http://www-ekp.physik.uni-karlsruhe.de/~quast/VMroot/addons/pythia/

Download all packages and files in this directory (pythia8.help, install_pythia8.tgz, userdata_pythia8.tgz). Follow the instructions in pythia8.help to install the pythia8 Monte Carlo event generator in the directory

/usr/local

and the files needed to execute it in the user-directory

~/generators.

In order to set the paths to all libraries, execute the configuration file with the command

```
source setpythia.
```

b)
In your virtual machine, change to the directory

~/generators/examples.

This directory contains some examples (mainNN.cc) and a Makefile to produce the executable files. Type

```
make main01.
```

This will compile the program main01.cc, link it against the pythia8 libraries to produce an executable file main01.exe.

Running the program via

```
./main01.exe> out01
```

writes the output to the file out01. First, inspect the source code in main01.cc to understand:

- how pythia is set up;
- how a simple histogram is booked;
- how the "event loop" works;
- how variables in the generated event are accessed and filled into the histogram
- how to obtain the output at the end.

Now have a look at the result file out01. It contains details about the run that has been performed, the parameter settings and shows a full event listing with all generated intermediate and final state particles. At the end, there is information on the calculated cross section of each relevant sub-process, and finally the histogram showing the distribution of the number of stable charged particles.

Inspect some more of the examples and run them. The second one shows the distribution of the transverse momentum of Z bosons produced in collisions of protons and anti-protons. Example 03 uses a "configuration file" main03.cmnd to configure pythia. The configuration file defines the beam parameters (=initial particles) and the sub-processes of interest. In the C++ code a number of histograms are booked and filled. Example 03 is a good model of typical studies with pythia8 at "generator level".

c)
You are now ready for your first own exercise. The aim is to simulate a signal process, here the signal of super-symmetric Higgs bosons decaying to two muons, on top of a background of di-muon events originating from the decay of $\gamma^{*}/Z^{(*)}$ to two muons. The Higgs boson has an assumed mass of 150 GeV, and your task is to separate the signal from the background by looking at the distribution of a highly-discriminating variable, the invariant di-muon mass. To get started, download the templates from:

http://www-ekp.physik.uni-karlsruhe.de/~quast/vorlesung/TP2Higgs/Uebungen/pythia-exercise.tgz

and install it under your account by unpacking the archive. Now change to the work directory:

```
cd generators/pythia-exercise
```

and type

```
source setpythia.sh
```

to set up the necessary paths to root and pythia8. In the directory you find the Makefile for the three example programs provided. Type

```
make
```

to produce the executables runcmnd.exe, EventRecord.exe and NtupleProcuder.exe. The program runcmnd.cc is a variant of the program main03.cc, which accepts the name of a pythia configuration file as an argument on the command line and then starts pythia. Run it with the files Higgs.cmnd and DrellYan.cmnd as inputs and note down the cross sections of the two processes.

Now you have two choices: the analysis can be implemented completely inside the program runcmnd.cc, or you can use the program NtupleProducer.cc as an example. This program writes a root ntuple with relevant variables, which can then be analyzed using root. Depending on your choice, calculate the appropriate variables and store them in pythia histograms, or modify the source code NtupleProducer.cc to write out the variables of the event to an *n-tuple*, as indicated in the code. In practice, we mostly choose the latter option, as the *n-tuple* resembles the output format of the real experiment, which is passed to the same analysis program as the data. If you choose option two, you have to write a root *macro* that opens the *n-tuples* one after the other, calculates the invariant mass of muon pairs, and fills them into histograms. The first option is simpler, and also sufficient for this exercise.

Next, implement the detector acceptance, in this case given by a range in rapidity, $|y| < 2.4$, and a threshold of the transverse momentum, $p_T > 25$ GeV, for each muon. Fill the invariant mass distributions if both muons are within the acceptance.

Looking at the problem more carefully, you will notice that you need to generate a large number of background events to sufficiently populate the region where your expect the signal to be. Find a suitable number, modify the configuration file DrellYan.cmnd and re-run the background simulation.

In order to study the amount of signal expected on top of the Drell-Yan background, the invariant mass distributions of signal and background need to be scaled appropriately and displayed on the same *graph*. To do this correctly you need to scale both histograms to an identical integrated luminosity (as you did for **Exercise 13 d)**), which is obtained from (i) the number of events that you have produced and; (ii) the cross sections of the processes you are looking at. For Drell-Yan production you can use the cross section that has been given for **Exercise 13 c)**. For the signal process you can use a production cross section of 0.25 pb (!). This cross section corresponds to a real prediction of the next to minimal supersymmetric SM hMSSM scenario for the model parameters $m_A = 150$ GeV (corresponding to the mass of the new Higgs boson “A”) and $\tan\beta = 15$ (corresponding to the ratio of two vacuum expectation values for two Higgs boson doublets in this model). From the common graph estimate the expected signal significance for an integrated luminosity of 300/fb. To estimate the significance define your signal region within two standard deviations around the center of the signal peak at 150 GeV.