Tutorial on Data Analysis with Root
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Identifying and studying the Z boson

Using real ATLAS data to study the Z boson in the ROOT framework (http://root.cern.ch/drupal/). For this tutorial, we're going to work in pairs, so please team up with someone next to you.

IMPORTANT: You need to go through this tutorial in order: i.e. you need to finish each step before going on to the next one.

1 Setup

You need to download three files:

- muons.root: A ROOT ntuple file containing real ATLAS data. This file was produced by selecting events containing two muons.
- electrons.root: A ROOT ntuple file containing real ATLAS data. This file was produced by selecting events containing two electrons.
- readEvents.C: An example ROOT macro which reads this data file and produces histograms

You need the program ROOT in order to look at this data and to run the macro. Luckily ROOT has already been installed on the computers in the lab. So to get started open a terminal and type root.

If everything works ok, you should see a white and blue window pop up saying root and then the following output:

```
Heather-Grays-MacBook-Pro% root
  *******************************************
  *                                         *
  *        W E L C O M E  to  R O O T       *
  *                                         *
  *   Version   5.27/04      29 June 2010   *
  *                                         *
  *  You are welcome to visit our Web site  *
  *          http://root.cern.ch            *
  *                                         *
  *******************************************
```

```
ROOT 5.27/04 (trunk@34195, Jun 30 2010, 06:36:24 on macosx64)

CINT/ROOT C/C++ Interpreter version 5.17.00, Dec 21, 2008
Type ? for help. Commands must be C++ statements.
Enclose multiple statements between { }.

Applying ATLAS style settings...
```

Now run the macro you downloaded in the ROOT command prompt:

```
root [0] .x readEvents.C
```

You should see some print out and once the macro is done (maybe 30s or so) a histogram should pop up on your screen. This histogram show the pseudorapidity distribution of the electrons in your data file.

Next open up the readEvents.C file in your favourite text editor. You will see lines of C++ code, which are used to produce the histogram. Look through these lines and try to understand a little bit what they mean. The comments in the code (indicated by //) are there to help you understand a bit what the code is doing. The code selects events containing 2 muons and then fills some histograms with the properties of the muons.

1.1 Setting up ROOT on your Laptop

You only need this section if you are using your laptop instead of the computers in the lab.

- download the ROOT v5.34 for your O/S from http://http://root.cern.ch/drupal/content/production-version-534 and install it following the instructions on the site and in the ROOT instruction manual (found on the ROOT site)
- to get python to be able to read the ROOT libraries you need to set some environment variables, here is what I set on my Mac (for Windows I think you use "set" instead of "export", and the paths will be different):

  ```
  %# set up ROOT
  %export ROOTSYS=/Applications/root
  %export PATH=$ROOTSYS/bin:$PATH
  %export DYLD_LIBRARY_PATH=$ROOTSYS/lib:$DYLD_LIBRARY_PATH
  ```

To set environment variables, you need to go into the terminal and type in the commands above. To check they worked, simply type: echo $ROOTSYS.

2 Z-boson Plot

A Z-boson is particle that only lives for a very short time before decaying. We can observe a Z-boson by looking at its decay products. The decay modes of the Z are here

- http://pdg.lbl.gov/2012/tables/rpp2012-sum-gauge-higgs-bosons.pdf

It decays to two muons and two electrons 3.4% of the time.

Modify the example to calculate the invariant mass of the first muon pair in each event and then plot the invariant mass in a histogram. Only look at events which contain at least two muons and those which have both muons with transverse momentum, pt ¿ 20 GeV. Make sure that the two selected muons have opposite charge. The charge is encoded in the data in the sign of the transverse momentum. As pT is by definition always positive, it is encoded by setting the pT of muons with negative charge to negative values and those with positive charge to positive values. Why ? This is because we need to always save as much space as we can in the data we make because it becomes enormous very quickly.

Locate the Z boson in the histogram.

Hint: The TLorentzVector class (http://root.cern.ch/root/html/TLorentzVector.html) is very nice. If you have two particles and want to know the properties of the particle which produced them, you can simply add them together:

```
TLorentzVector Particle1;
TLorentzVector Particle 2;
// set up the properties of particle 1 and particle 2
TLorentzVector MotherParticle = Particle1 + Particle2;
```

Bonus: Can you expand the code to include events with the Z-boson decaying into two electrons as well as muons ? You would want to use the electrons.root file for this.

3 Z-boson Properties

Now that you have some Z-bosons, let's explore some of it's properties.

- Estimate the mass of the Z-boson
- Estimate the number of events containing a Z-boson
- Add additional plots showing its properties. Do these look like the original plots we made for the muons ?

Hint1: If you right click on the histogram, you will find an option that allows you to fit the distribution. The default option, a Gaussian, will work quite well to begin with, especially if you set it to only work in a restricted range.

Hint2: You can integrate a histogram very simply using the Integral(minBin, maxBin) function. Here you need to tell it the number of the first and last bins that you want included in the integral. Bins in root are numbered sequentially from left to right with the first bin being bin 1.

4 Cross-section Measurement

A cross-section of a particle is a measurement of how often a particle is produced. Even with our simple code, we can actually already measure this.

- Background estimate. Add another histogram to your code and fill it in exactly the same way as the Z boson but ensure that the muons have opposite charge. This picks out events containing fake leptons in a very nice way. Plot both of the histograms in the same canvas (using Draw(”same”) for the second histogram). You will see that it follows the same shape but has a slightly different scale. Try scaling the background histogram a little until it lines up nicely with the signal (use the Scale(myscale) function for this).
- Use the Integral(minBin, maxBin) function to estimate the number of events under the peak. Also estimate the number of background events. A useful function is also FindBin(80): this tells you the bin number you need for the Integral function. A good range for the integral could be something like 70 - 110 GeV.
- If you're told that the detector efficiency is 60% to accept muons from a Z-decay and the data corresponds to 50 pb^{-1} luminosity, what is the cross-section to produce Z-bosons the LHC ? Remember that $N_{events} = \sigma \times L$, where L is the luminosity and σ is the cross-section. Also remember that the detector efficiency is defined as: $\epsilon = N_{rec}/N_{true}$.
- Bonus: How does your result compared to the published ATLAS value ?
- Bonus: Can you estimate the difference between the electron and muon reconstruction efficiency from the plot of the Z boson mass.

5 More Information

- ROOT website: http://root.cern.ch/drupal/
- Intro to ROOT: http://root.cern.ch/drupal/content/discovering-root
- Tutorials: http://root.cern.ch/root/html/tutorials/
- Reference guide for all classes: http://root.cern.ch/root/html534/ClassIndex.html
- ATLAS Z cross-section: http://arxiv.org/pdf/1010.2130v1.pdf