Introduction to ROOT

remoll Simulation Workshop – May 26th 2023

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Exploring the Nature of Matter

Outline of this introductory talk

- What is ROOT?
- What are ROOT Files
- What can you do with ROOT?
- Command Line Interface
  - I'll be painting in broad strokes as you'll have a formal hands-on session in the afternoon
- Macros/Scripting
  - Again, broad strokes.

GOAL: (Hopefully) Leaving you with a feeling for what you can do with ROOT and give you a conceptual leg up for the hand-on portion of the workshop.

What is ROOT? (cont'd)

- General framework for data analysis developed for particle physics
  - Based on data structure we call a ROOT file.
- C++ based OOP for scalable data and simulation-data analysis
  - Remoll automatically outputs ROOT files.
  - Importing CSV data into root is very easy.
    - Great option for data collected from in-lab hardware or EPICS data at JLab.
  - Available ROOT libraries to connect to databases and dataframes.
  - If you're a data-junkie bored on weekends ROOT is a great tool to churn through datasets.
- Main tool that will be used for Remoll simulation analysis and MOLLER data analysis.
  - ROOT is designed to handle large amounts of data

What is ROOT? (cont'd)

- Installation is *generally* straight forward
  - Pre-compiled binaries available on ROOT website for many, but not all Linux OS
    - !!! Ubuntu 22 pre-compiled binaries have given me issues; you may have to compile from scratch; after installing dependencies I had zero problems.
  - ⭐ Already available for you in the ifarm

- When you compile remoll you'll also get reroot which includes certain remoll class definitions
  - 👉 Use reroot for remoll simulation analysis...

What is ROOT? (cont'd)

- (Opinion) It's a extraordinarily easy-to-use framework for both data analysis and data presentation

- One can convert many data types of data files into ROOT files.
    - At the end of these slides is a very simple script for converting CSV file to ROOT

- I prefer to use ROOT for data visualization and plotting for many different types of data (not just particle physics).

In other words ⇒ A VALUABLE SKILL TO HAVE ⇐

What is ROOT? (cont’d)

- (Truth) There is a learning curve.
    - Familiarity with C++ will make learning ROOT easier.
        - There is PyRoot for the python-inclined.
    - Doing things in ROOT is how you’ll learn.
        - Don’t be shy asking for help.
        - Plenty of online resources.
    - You’ll learn what you need to know as you go and eventually you’ll become a ROOT ‘expert’.
    - This is your tool to interpret simulation results and extract interesting physics from experimental data.

What are ROOT files?

Hierarchical structure of data.

⇒ Base of data structure is 'tree'
⇒ Data tree broken into 'branches'
⇒ Branches further divided into 'leaves'

- ROOT File
  - ↳ Data Tree #1
    - ↳ Branch 1
      - ↳ Leaves
    - ↳ Branch 2
      - ↳ Leaves
    - ↳ Branch 3,4,5…

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ROOT files can contain multiple trees

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  - ↳ Data Tree #1
    - ↳ Branch 1
      - ↳ Leaves
    - ↳ Branch 2
      - ↳ Leaves
    - ↳ Branch 3,4,5…
  - ↳ Data Tree #2
    - ↳ Branches
      - ↳ Leaves

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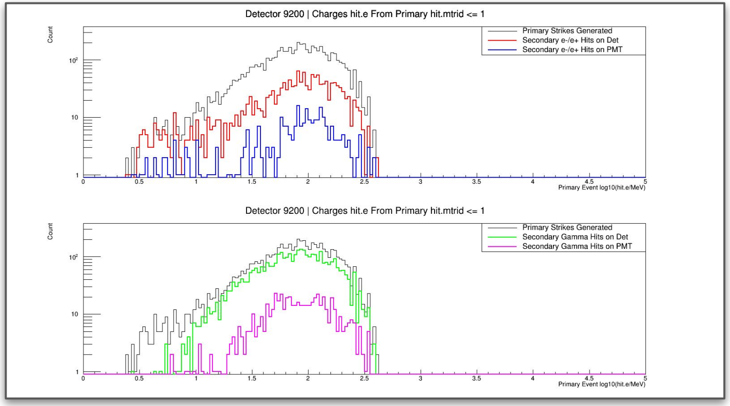
ROOT files can hold other objects as well:

- Histograms
- Canvases
- Graphs
- etc

- ROOT File
  - ↳ Data Tree #1
    - ↳ Branch 1
      - ↳ Leaves
    - ↳ Branch 2
      - ↳ Leaves
    - ↳ Branch 3,4,5...
  - ↳ Data Tree #2
    - ↳ Branches
      - ↳ Leaves
  - ↳ Object(s) ...

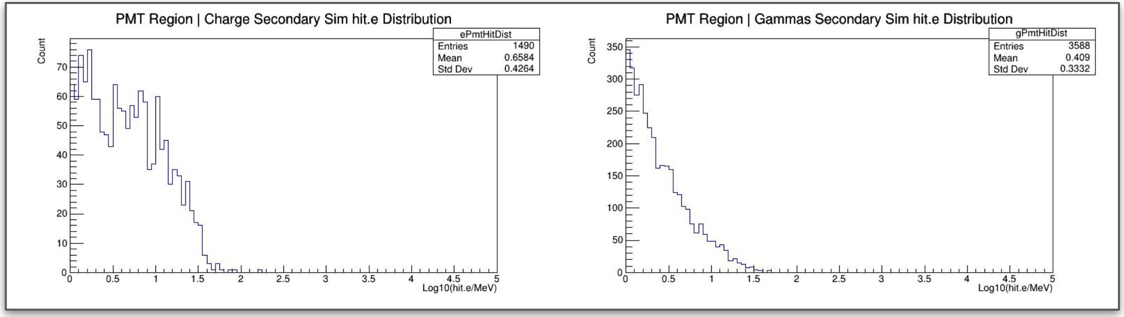
What can you do with ROOT? [Data Visualization]

- Draw histograms



remoll simulation data from ferrous materials studies.

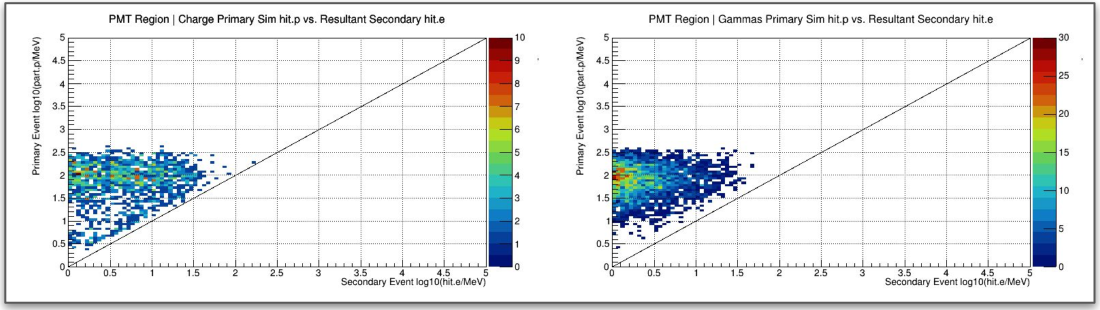
Multiple histograms can be overlaid to produce more informative plots.



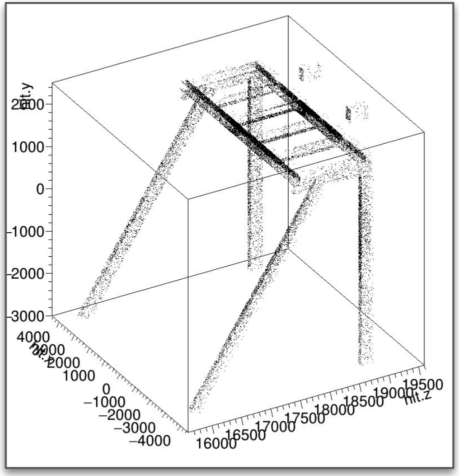
Or you can be very basic...

What can you do with ROOT? [Data Visualization]

- Draw histograms
- Draw scatter plots and heatmaps (2D hist with color!)



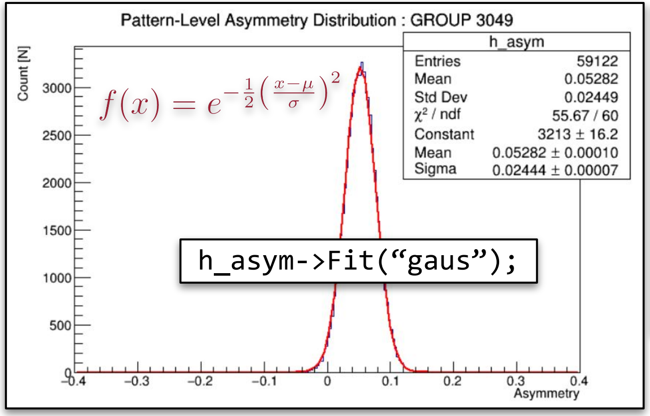
2D Heatmap of ferrous materials scattering PMT region backgrounds from collar 2 barite wall support (prelim' simulation).



3D Scatter plot of remoll simulation data of events that strike the collar 2 barite wall support structure for ferrous materials background studies.

What can you do with ROOT? [Data Visualization]

- Draw histograms
- Draw scatter plots and heatmaps (2D hist with color)
- **Data Fitting**
  - Predefined or custom functions



Experimental data fit; here to a gaussian.

f(x) = p0*exp(-0.5*((x-p1)/p2)^2)

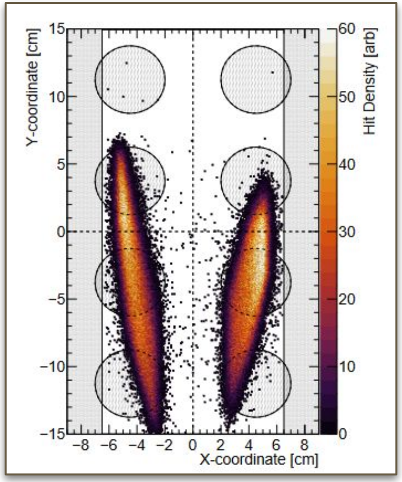
Fit returns:
$\chi 2$ / ndf
P0 ⇒ Constant: Amplitude of Gaussian
P1 ⇒ (Gaussian) Mean
P2 ⇒ (Gaussian) Sigma

```
root [8] H->Fit("gaus")
 FCN=32.6596 FROM MIGRAD    STATUS=CONVERGED      63 CALLS       64 TOTAL
                     EDM=2.2785e-09 STRATEGY= 1      ERROR MATRIX ACCURATE
  EXT PARAMETER                                    STEP         FIRST
  NO.   NAME    VALUE          ERROR          SIZE      DERIVATIVE
   1  Constant        1.78988e+02   4.07137e+00   9.47909e-03  -1.50266e-05
   2  Mean            3.50379e-02   1.82819e-04   5.11155e-07  -1.29829e-01
   3  Sigma           9.57978e-03   1.26021e-04   1.00540e-05  -1.77126e-02
```

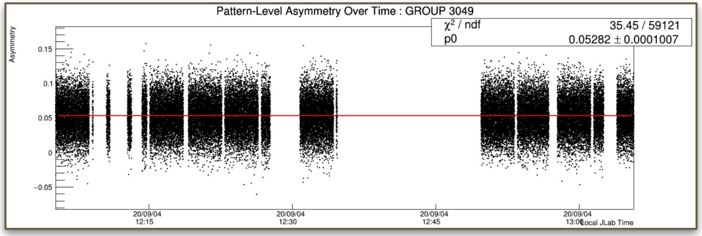
Note: Plot and text fit data not the same

What can you do with ROOT? [Data Visualization]

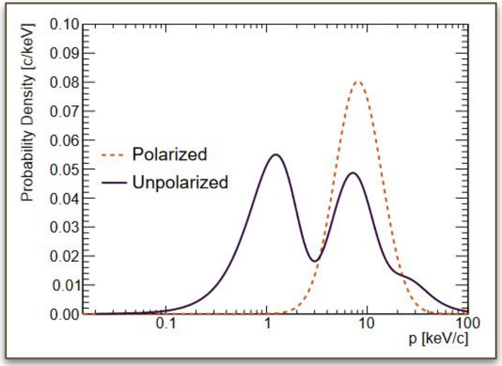
- Draw histograms
- Draw scatter plots and heatmaps
- Data Fitting
  - Predefined or custom functions
- **Data Visualization**
  - **Actual data**
  - **Simulated data**
  - **Imported data**
- **>> Publication ready plots <<**



Moller polarimeter simulated data. (almost publication plot)



Polarimetry – Moller QED asymmetry over time during CREX



Imported CSV data of computed bulk Fe wavefunctions turned into TGraph object. (publication plot)

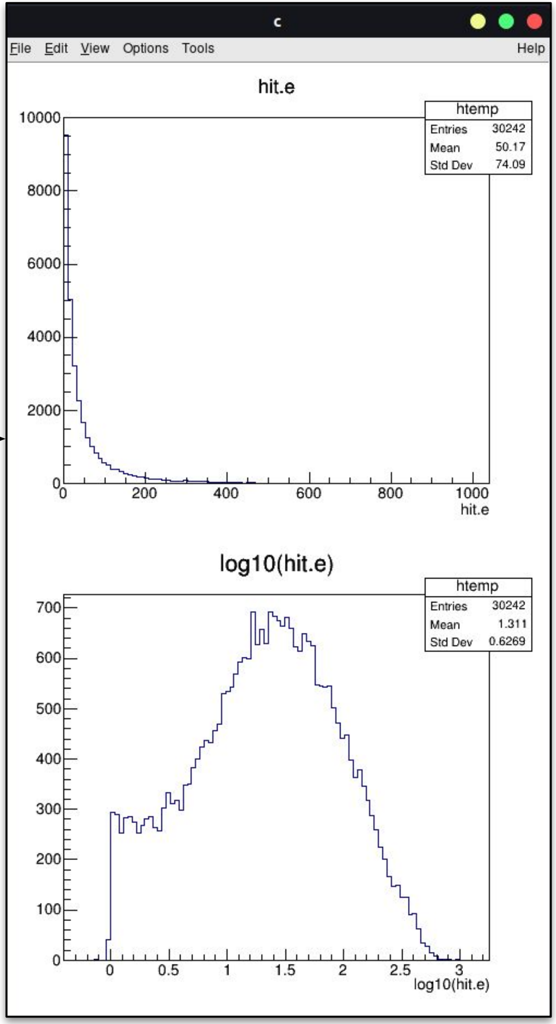
DE King, DC Jones, et al. – Moller Polarimetry for PREX-2 and CREX
10.1016/j.nima.2022.167506

Using ROOT

Three ways of using ROOT:

- Command Line Interface
  - Quick and dirty method of looking at data.
  - Make basic data cuts.
  - Make basic plots.

```
ifarm1802.jlab.org> ./reroot -l o_remollSkimTree9098_1.root
re-root [0]
Attaching file o_remollSkimTree9098_1.root as _file0...
(TFile *) 0x2380910
re-root [1] TCanvas* C = new TCanvas("c","c",500,900)
(TCanvas *) 0x2f15e10
re-root [2] C->Divide(1,2)
re-root [3] C->cd(1)
(TVirtualPad *) 0x3004570
re-root [4] T->Draw("hit.e")
re-root [5] C->cd(2)
(TVirtualPad *) 0x28fae00
re-root [6] T->Draw("log10(hit.e)")
re-root [7]
```



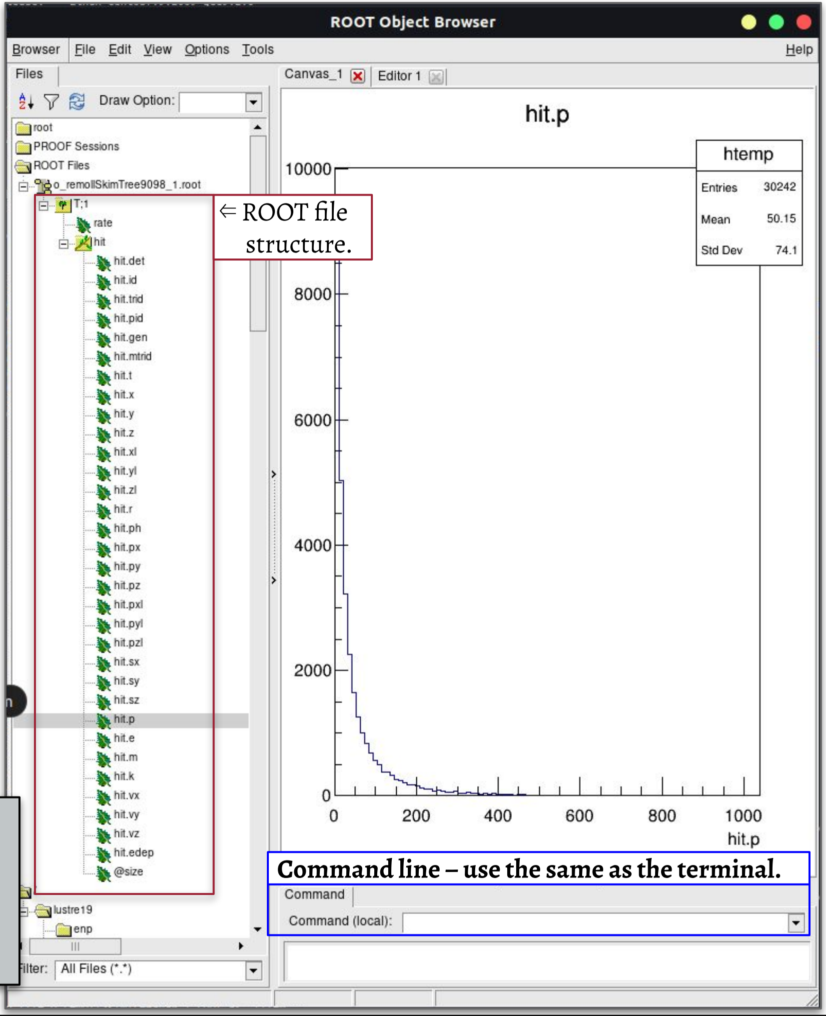
Using ROOT

Three ways of using ROOT:

- Command Line Interface
  - Quick and dirty method of looking at data.
  - Make basic data cuts.
  - Make basic plots.
- There is a GUI File Browser
  - This is perfectly fine when working locally, but a total nuisance over X11.
  - ☆ It's an easy way to see file structure and plot uncut data distributions.
  - Perhaps good for beginners.

I'll note that this is a thing that one can do.

I don't care for it much but it has its a couple perks; you may like it.



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- There is a GUI File Browser
  - This is perfectly fine when working locally, buta total nuisance over X11.
  - ☆ It's an easy way to see file structure and plot uncut data distributions.
  - Perhaps good for beginners.
- Macros/Scripting
  - Formal analysis – capable of complex data cuts.
  - Allows analysis work to be repeated easily.
  - Will require you to be comfortable with C++.

```
void skimTreeMulti(string fileList, string DetNums, Int_t gencut=0, int beamGen=1, int test=0){
  startTime = std::clock();
  std::ofstream fout;
  fout.open("ferrous_skimTree_results.txt");

  testRun    = test;
  generation = gencut;

  //////////////////////////////////////////////////////////////
  //// Detectors to be looked at
  std::stringstream ss(DetNums);
  while(ss.good()){
    string ss_parse;
    getline(ss,ss_parse,',');
    detectorNumbers.push_back( std::atoi(ss_parse.c_str()) );
    vector<Int_t> tempVec;
    for(Int_t g=0; g<=generation; g++) tempVec.push_back(0);
    detectorHitN.push_back( tempVec );
  }
  cout << "Detectors to be examined: ";
  for(Int_t k=0; k<detectorNumbers.size(); k++){
    if(k==0 && detectorNumbers.size()==1){
      cout << "{" << detectorNumbers[k] << "}";
    }else if(k==0){
      cout << "{" << detectorNumbers[k];
    }else if(k==(detectorNumbers.size()-1)){
      cout << "," << detectorNumbers[k] << "}" << endl;
    }else{
      cout << "," << detectorNumbers[k];
    }
  }
  cout << "Recording all particles whose mother is <=" << generation << endl;

  long nTotHits(0);
  int nFiles(0);

  if(fileList==""){
    cout<<"\t did not find input file. Quitting!"<<endl;
    return;
  }

  //////////////////////////////////////////////////////////////
  //// Create output files and trees
  otree     = new TTree("T", "ferrous skim tree");
  b_rate    = otree->Branch("rate", &newrate);
  b_hit     = otree->Branch("hit",  &newhit );
  for(Int_t i = 0; i < detectorNumbers.size(); i++){
    cout << "Creating pointer to TFile named " << Form("o_remollSkimTree%d_%i.root",detectorNumbers[i],gencut) << endl;
    outputFiles.push_back( new TFile(Form("o_remollSkimTree%d_%i.root",detectorNumbers[i],gencut),"RECREATE") );
    otree->SetObject("T",Form("ferrous skim tree %i",detectorNumbers[i]));
    //otree->SetObject(Form("T%i",detectorNumbers[i]),Form("ferrous skim tree %i",detectorNumbers[i])); //for debugging
    outputTrees.push_back( otree->CloneTree(0) ); //Create a clone of tree and copy 0 entries
  }
  otree->SetObject("T","ferrous skim tree");

  //////////////////////////////////////////////////////////////
  / Keep code from original script
    fileList.find(".root") < fileList.size() ){
   /cout<<"Processing single file:\n\t"<<fileList<<endl;
   f(beamGen){
    scaleRate = getEvents(fileList);

    nTotHits+=processOne(fileList);
    nFiles=1;
  }else{
```

Showing example with skimmed simulated hit data from my work.
remoll files contain much more information

Using ROOT – Command Line Interface

Command line interface uses CLING (a C++ interpreter)

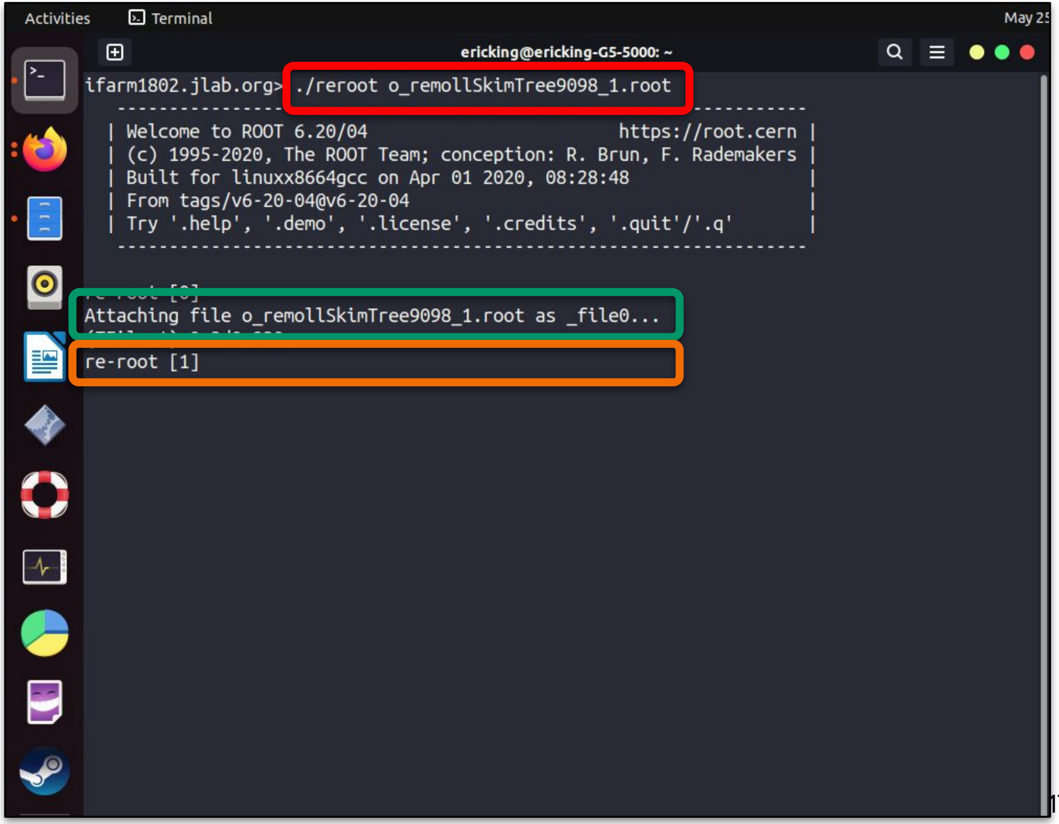
From the terminal command line you can open a ROOT session

We execute the command *root* and pass it a filename as an argument.

```
./reroot o_remollSkimTree.root
```

ROOT starts and we see that the file has successfully opened.

Now, the ROOT command line is waiting for instructions. :)



Using ROOT – Command Line Interface

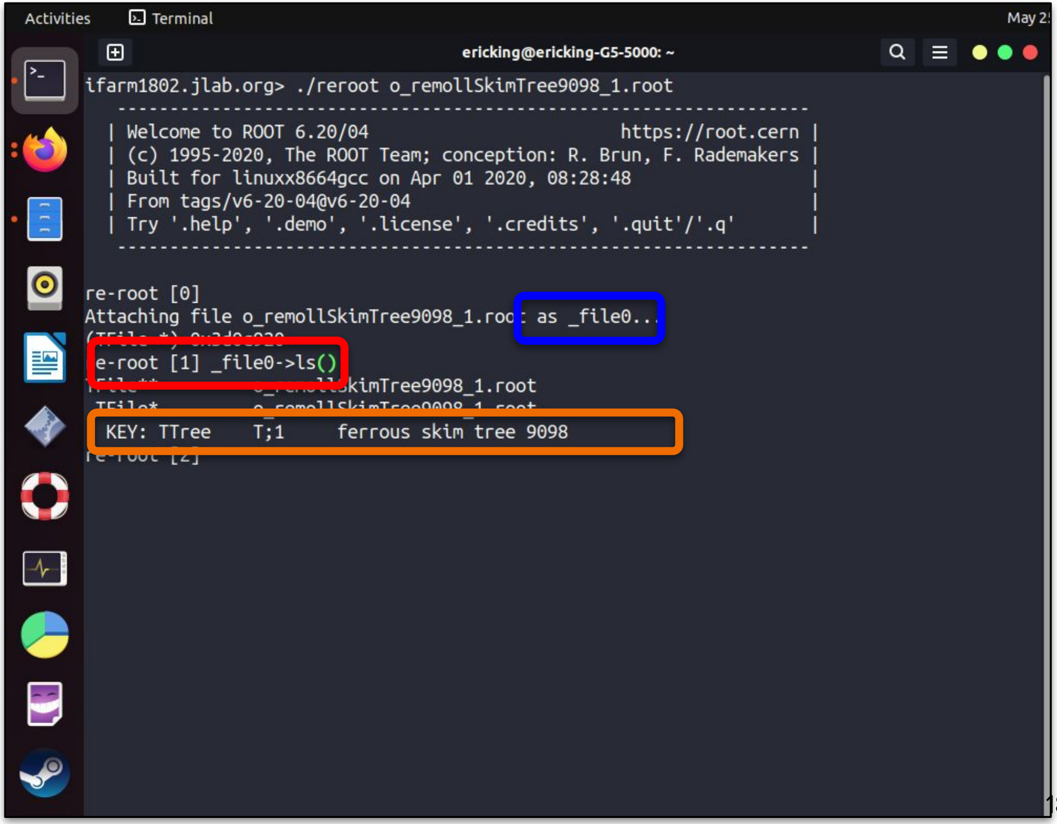
We can look at the contents of the ROOT file…

ROOT opened up the file and has auto-named the object **_file0**

Similar to the basic Linux command we can list the file contents using the ls() method of TFile.

```
_file0->ls()
```

☆ We have a data tree named “T” with the description “ferrous skim tree 9098”



Using ROOT – Command Line Interface

We can examine the structure of the data tree

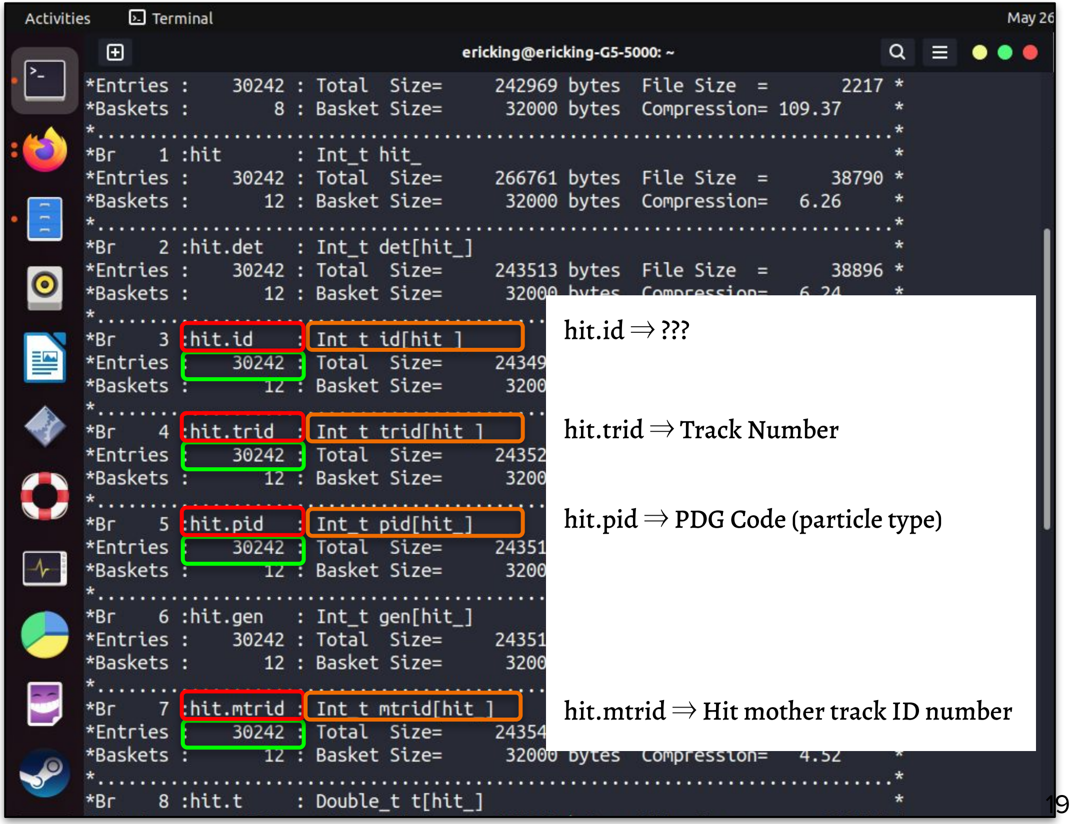
```
T->Print()
```

We can see branch names in red squares.

Total number of entries in green.

Details about the data structure in orange.

```
hit.trid    ⇒ Integer data type array
            ⇒ 30242 Entries
```



Using ROOT – Command Line Interface

We can perform a sampling (scan) of the data:

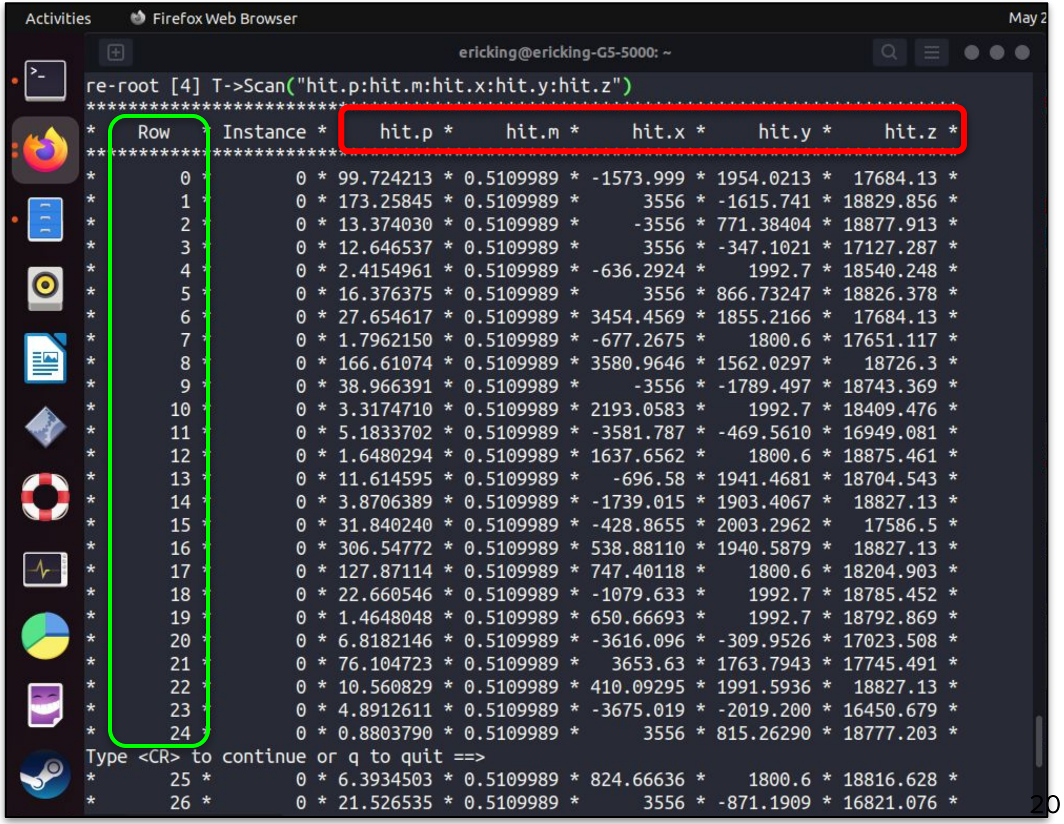
```
T->Scan(“hit.p:hit.m:hit.x …”)
```

We see our branches:

- hit.p
- hit.m
- hit.x
- hit.y
- hit.z

Entries are the row numbers

Not seen here is the fact that you can have multiple values per entry.



```
re-root [4] T->Scan("hit.p:hit.m:hit.x:hit.y:hit.z")
***********************************************************************************
*    Row   * Instance *    hit.p *    hit.m *    hit.x *    hit.y *    hit.z *
***********************************************************************************
*        0 *        0 * 99.724213 * 0.5109989 * -1573.999 * 1954.0213 *  17684.13 *
*        1 *        0 * 173.25845 * 0.5109989 *      3556 * -1615.741 * 18829.856 *
*        2 *        0 * 13.374030 * 0.5109989 *     -3556 * 771.38404 * 18877.913 *
*        3 *        0 * 12.646537 * 0.5109989 *      3556 * -347.1021 * 17127.287 *
*        4 *        0 * 2.4154961 * 0.5109989 * -636.2924 *    1992.7 * 18540.248 *
*        5 *        0 * 16.376375 * 0.5109989 *      3556 * 866.73247 * 18826.378 *
*        6 *        0 * 27.654617 * 0.5109989 * 3454.4569 * 1855.2166 *  17684.13 *
*        7 *        0 * 1.7962150 * 0.5109989 * -677.2675 *    1800.6 * 17651.117 *
*        8 *        0 * 166.61074 * 0.5109989 * 3580.9646 * 1562.0297 *   18726.3 *
*        9 *        0 * 38.966391 * 0.5109989 *     -3556 * -1789.497 * 18743.369 *
*       10 *        0 * 3.3174710 * 0.5109989 * 2193.0583 *    1992.7 * 18409.476 *
*       11 *        0 * 5.1833702 * 0.5109989 * -3581.787 * -469.5610 * 16949.081 *
*       12 *        0 * 1.6480294 * 0.5109989 * 1637.6562 *    1800.6 * 18875.461 *
*       13 *        0 * 11.614595 * 0.5109989 *   -696.58 * 1941.4681 * 18704.543 *
*       14 *        0 * 3.8706389 * 0.5109989 * -1739.015 * 1903.4067 *  18827.13 *
*       15 *        0 * 31.840240 * 0.5109989 * -428.8655 * 2003.2962 *   17586.5 *
*       16 *        0 * 306.54772 * 0.5109989 * 538.88110 * 1940.5879 *  18827.13 *
*       17 *        0 * 127.87114 * 0.5109989 * 747.40118 *    1800.6 * 18204.903 *
*       18 *        0 * 22.660546 * 0.5109989 * -1079.633 *    1992.7 * 18785.452 *
*       19 *        0 * 1.4648048 * 0.5109989 * 650.66693 *    1992.7 * 18792.869 *
*       20 *        0 * 6.8182146 * 0.5109989 * -3616.096 * -309.9526 * 17023.508 *
*       21 *        0 * 76.104723 * 0.5109989 *   3653.63 * 1763.7943 * 17745.491 *
*       22 *        0 * 10.560829 * 0.5109989 * 410.09295 * 1991.5936 *  18827.13 *
*       23 *        0 * 4.8912611 * 0.5109989 * -3675.019 * -2019.200 * 16450.679 *
*       24 *        0 * 0.8803790 * 0.5109989 *      3556 * 815.26290 * 18777.203 *
Type <CR> to continue or q to quit ==>
*       25 *        0 * 6.3934503 * 0.5109989 * 824.66636 *    1800.6 * 18816.628 *
*       26 *        0 * 21.526535 * 0.5109989 *      3556 * -871.1909 * 16821.076 *
```

Using ROOT – Command Line Interface

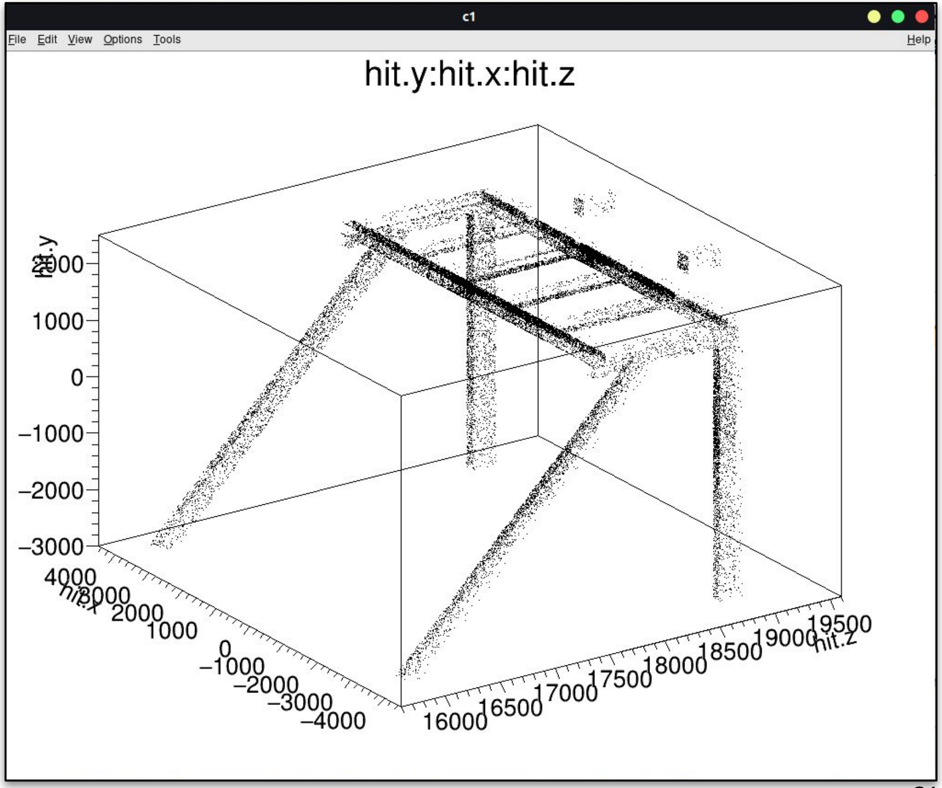
We can draw a sample scatter plot from the tree

```
T->Draw(“hit.y:hit.x:hit.z”)
```

Here we are drawing the locations of the hits on the sensitive detector in the simulation.

This scatterplot output is a TGraph object; it'll look nice and clean.

In a previous slide I created a TCanvas so I could specify a size and divide it. If you don't do that you'll get a default canvas object c1.



Using ROOT – Command Line Interface

We can do a little more:

```
T->Draw("hit.y:hit.x:hit.z>>H","hit.e > 100")
```

We store the contents of the draw in an object called "H"

```
T->Draw("hit.y:hit.x:hit.z>>H2","hit.e < 100")
```

We store the contents of the draw in a histogram object called "H2"

```
H->SetMarkerColor(kRed)
H2->SetMarkerColor(kBlue)
```

We set marker colors.

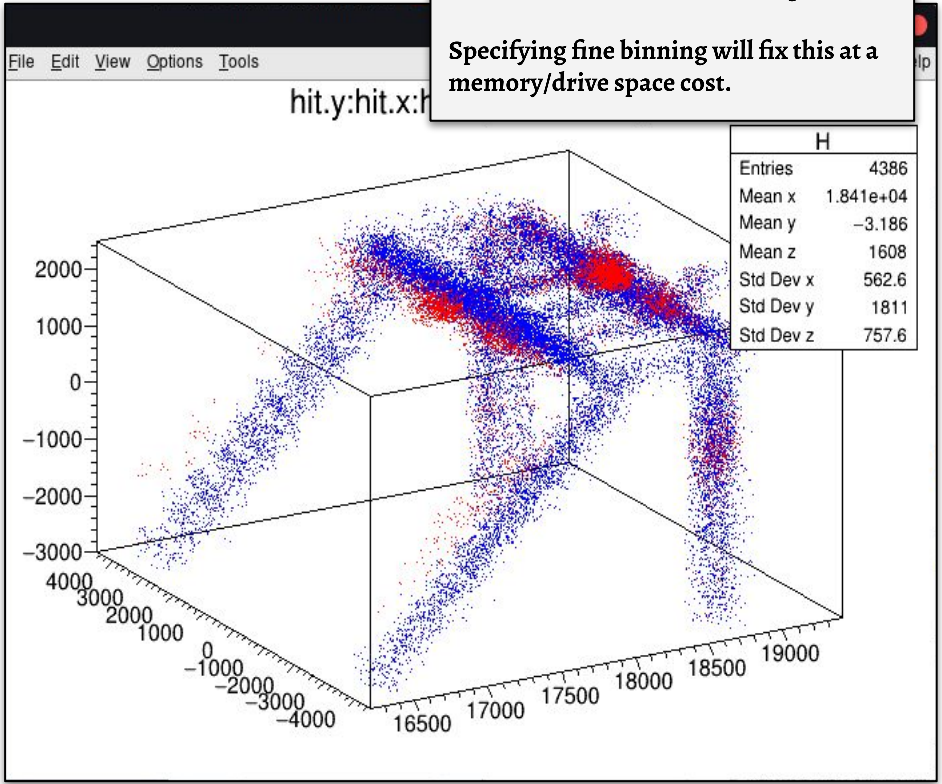
```
H2->Draw()
H->Draw("SAME")
```

And we Draw() – the second one we pass the argument "SAME"

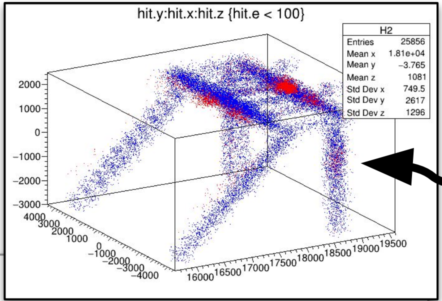
Previous plot was TGraph which is a point-by-point plotting.

Below are two overlaid histograms; you can see how the bins 'fuzz' things out.

Specifying fine binning will fix this at a memory/drive space cost.



Using ROOT – Command Line Interface



Quick Note:

Done something in the command line that you've found useful? You can turn it into a macro command by looking at ~/.root_hist

At the end of that file you'll find your latest commands.

- Copy these to a new text file
- Enclose in **curly braces**
- Add **semicolons** to the line ends.
- ROOT/CLING may be cranky about some other minor things.

```
./reroot  -l  root-file.root
(TFile *) 0x0000000
re-root [1] .x macro.txt
```

```
{
  T->Draw("hit.y:hit.x:hit.z>>H","hit.e > 100");
  T->Draw("hit.y:hit.x:hit.z>>H2","hit.e < 100");
  H->SetMarkerColor(kRed);
  H2->SetMarkerColor(kBlue);
  H2->Draw();
  H->Draw("SAME");
}
```

Quick notes:

kRed and kBlue are variables in ROOT that are Int_t values. ROOT won't like those in the macro itself.

kRed = 2 ; kBlue = 4

Using ROOT – Macros/Scripting

We can also write macros with more ‘complicated’ rules for data selection.

- This can be done for drawing data.
  - Perhaps data you pull from database.
- This can be done for performing more complicated calculations on raw data and creating a new ROOT file with calculated data.
- This can be done to data skim the information you want to move from one ROOT file into a separate smaller ROOT file.

```
#define molpol_plot_for_paper_cxx
#include "molpol_plot_for_paper.h"
#include <TH2.h>
#include <TStyle.h>
#include <TCanvas.h>

void molpol_plot_for_paper::Loop(){

  TH2F * hCoin = new TH2F("hcoin",";X-coordinate [cm];Y-coordinate

  if (fChain == 0) return;

  Long64_t nentries = fChain->GetEntriesFast();

  Long64_t nbytes = 0, nb = 0;
  for (Long64_t jentry=0; jentry<nentries;jentry++){
    Long64_t ientry = LoadTree(jentry);
    if (ientry < 0) break;
    nb = fChain->GetEntry(jentry);   nbytes += nb;

    Bool_t trkCoin(false);
    Bool_t trk1hit(false);
    Bool_t trk2hit(false);
    Bool_t trkCoinA(false);
    Bool_t trk1hitA(false); //All coincidence on detector face
    Bool_t trk2hitA(false); //All coincidence on detector face
    for(Int_t i=0;i<hitN;i++){
      if(hitDet[i]==9 && hitTrid[i]==1) trk1hitA=true;
      if(hitDet[i]==9 && hitTrid[i]==2) trk2hitA=true;
    }
    if(trk1hitA&&trk2hitA) trkCoinA=true;
    //Fill Coincidence
    for(Int_t j=0; j<hitN; j++){
      if( hitDet[j]==9 && hitTrid[j]==1 ){
        if(trkCoinA==true)  hCoin->Fill(100*hitX[j],100*hitLy[j]);
      }
    }
  }

  gStyle->SetPalette(kSunset);
  gStyle->SetNdivisions(28,"z");

  Float_t topMargin = 0.025;
  Float_t rightMargin = 0.175;
  Float_t bottomMargin = 0.075;
  Float_t leftMargin = 0.125;

  gStyle->SetPadTopMargin(topMargin);
  gStyle->SetPadRightMargin(rightMargin);
  gStyle->SetPadBottomMargin(bottomMargin);
  gStyle->SetPadLeftMargin(leftMargin);
```

⇒ Specific code here is unimportant (not remoll).

What’s important to note is:

1. Data doesn’t contain all the immediate information we may need.
   a. Need to know if for any recorded Entry$ if each of the two generated electrons makes it to the detector.
2. Command line plotting is limited if you need compound data selection rules.

Using ROOT – Macros/Scripting

Creating macros by hand:

Be sure to include remolltypes.hh, this defines the hit, part, etc. data types.

- Open your ROOT file and your tree.

```
TFile * f = new TFile("yourFile.root","<Read/Write Option>");
TTree * t  = new TTree("YourTree","Some Name");
```

- Declare variables to hold branch data and set your branch addresses:

```
Float_t someValue;
T->SetBranchAddress("branchName",&someValue);
… … …
```

- Proceed with your data selection, histogram filling, and canvas building.

Resources: Extensive Documentation By CERN

ROOT Manual: https://root.cern/manual/

ROOT Reference Documentation: https://root.cern/doc/master/
⇒ Although, it's just as easy to Google "cern root <insert-class> class reference"

ROOT Tutorials: https://root.cern/doc/master/group__Tutorials.html
⇒ Abundance of examples on histograms, graphs, data fitting, SQL-interfacing, and (for the Python-inclined) examples using PyROOT.
⇒ And more… [plenty of stuff from beginners to advanced]

ROOT Forum: https://root-forum.cern.ch
⇒ Someone has very likely asked your question before…

Additional Functionality

- Plenty of available extended functionality with ROOT
  - Machine Learning libraries [TMVA]
    - https://root.cern/manual/tmva/
  - PyRoot (Use ROOT with Python)
    - https://root.cern/manual/python/
  - JSroot (A Javascript Framework for looking at ROOT files)
    - https://root.cern.ch/js/

Simple script to read CSV into ROOT file

```
#include<TROOT.h>
#include<TFile.h>
#include<TTree.h>
#include<TString.h>
#include<iostream>

Int_t read_csv(TString input, TString desc, TString output){
	TFile * f = new TFile(output,"RECREATE");
	TTree * T = new TTree("T",desc);
	Long64_t nlines = T->ReadFile(input,"",',');
	cout << "Number of lines read: " << nlines << endl;
	f->Write();
	f->Close();
	return 1;
}
```

- Header information in CSV must contain data type information:

  `Event/I,Value1/F,Value2/F,Value3/I    etc…`

- Can be picky reading in csv data but is useful.
  - Data output from hardware
  - EPICS archive output
  - etc...

- *If this was written well it would just replace the substring .csv with .root*