CPP Part 2 Endsem

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- Question 1:Using the ROOT file exam.root:
- a. Find the number of events (or entries) stored in the file and include that information in your report.
- b. Plot the number of muons, number of electrons, p_T (up to 150 GeV), eta, phi of the particles.

  a) Number of events in the file

```
root [7] std::cout << ((TTree*)TFile::Open("exam.root")->Get("Events"))->GetEntries() << std::endl;
1497445
```

Figure 1: Figure shows the number of events in the file displayed in root command line.

There are 1497445 events in the file. [1]

[1] ***NOTE : Instead of considering only the leading lepton from each event as is shown by the TBrowser of the file, here I consider all the leptons. Since the leptons in an event can be 0,1,2,3 or 4, the Y axis is labeled accordingly. Here I am not considering the gross number of events but total number of concerned particles in events and plotted accordingly.**

***Note: For plotting, I used inline root commands for convenience and haven't made a separate macro for the same. Hence the codes for q1 don't have a macro.**

- **Histograms for Muon data**:
- Muon eta plot:

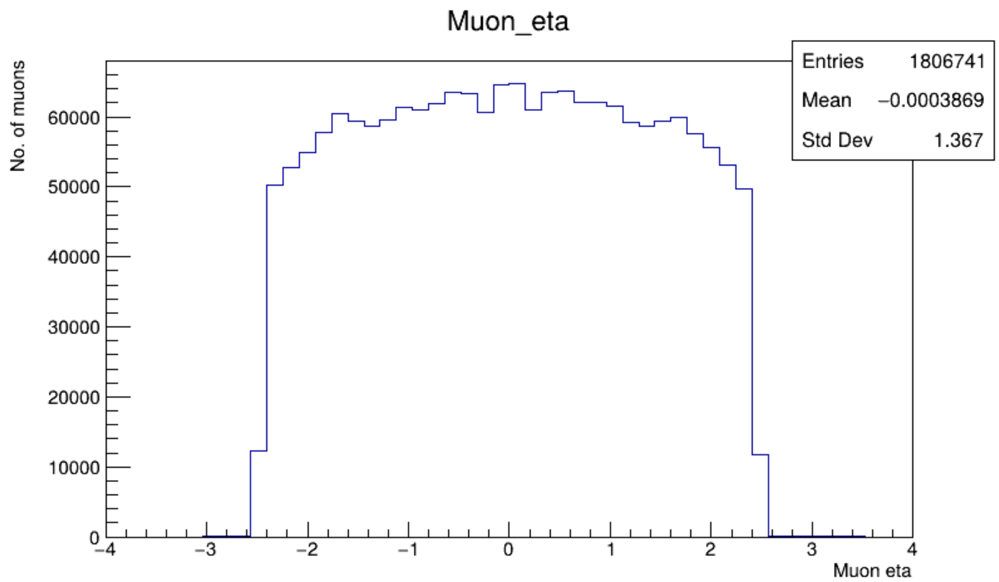


Figure 2: Muon Eta plot for exam.root file data

- nMuon plot:

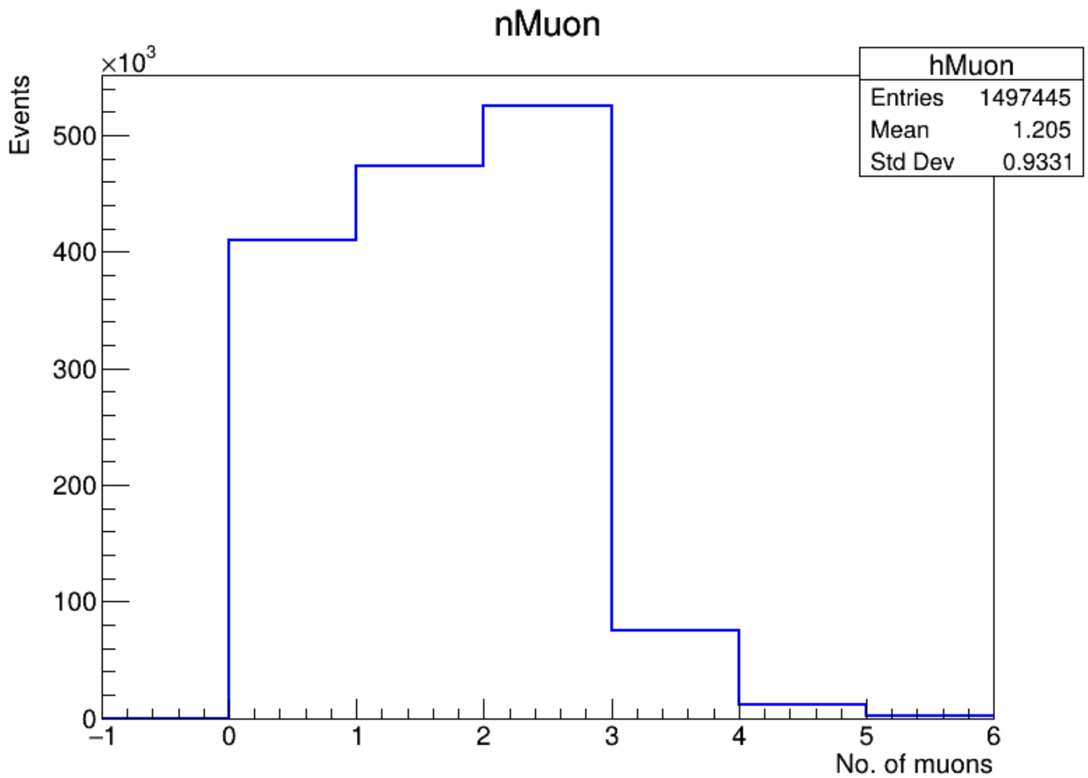


Figure 3: Number of muon events plot for exam.root file

- Muon Phi plot:

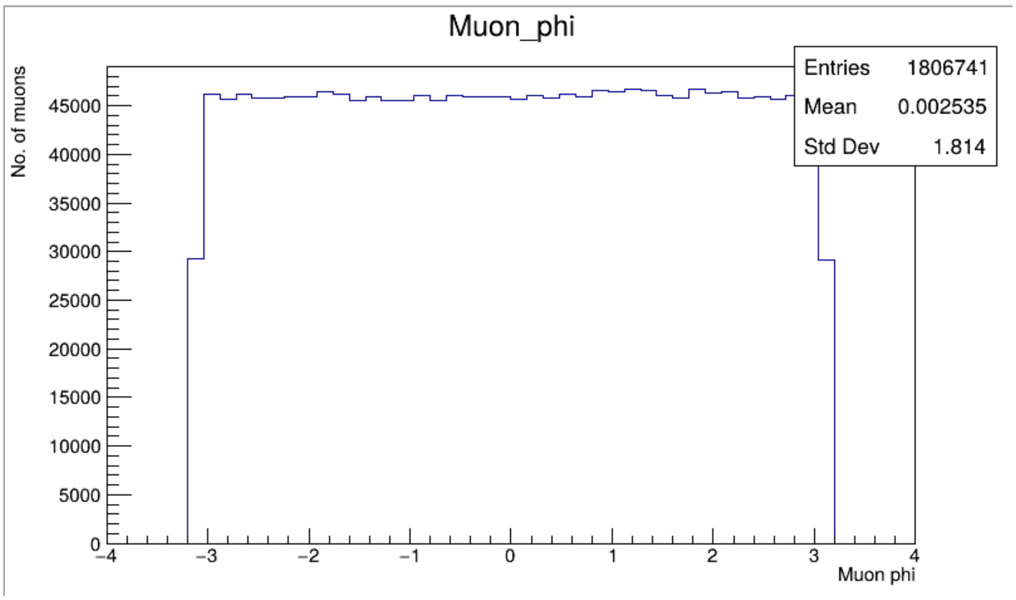


Figure 4: Muon Phi plot for exam.root data.

- Muon p_T plot:

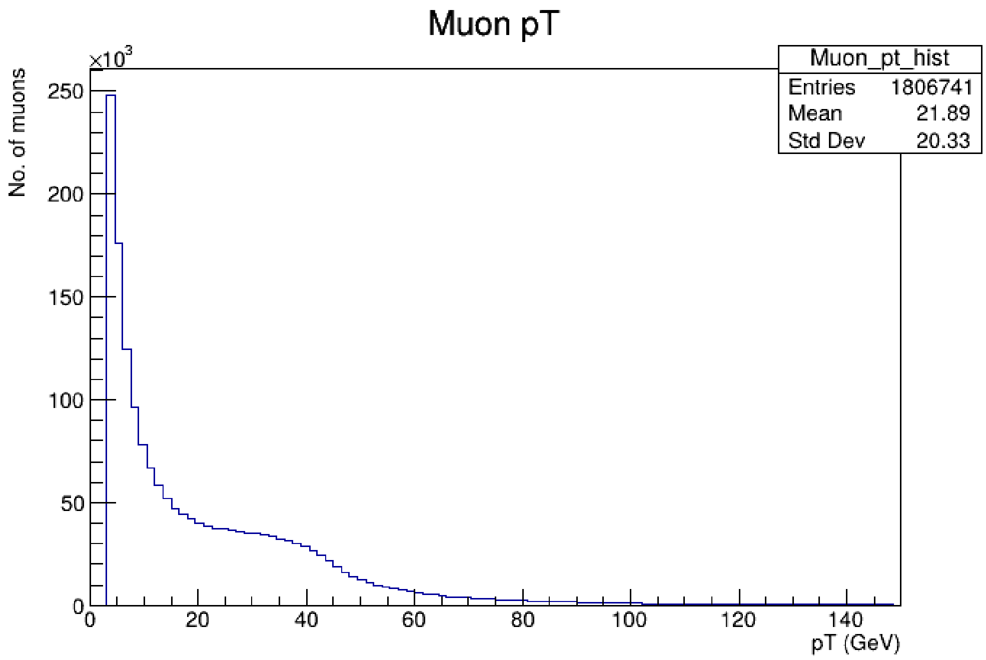


Figure 5: Muon p_T plot for exam.root data.

- **Histograms for electrons data**:
- Electron eta plot:

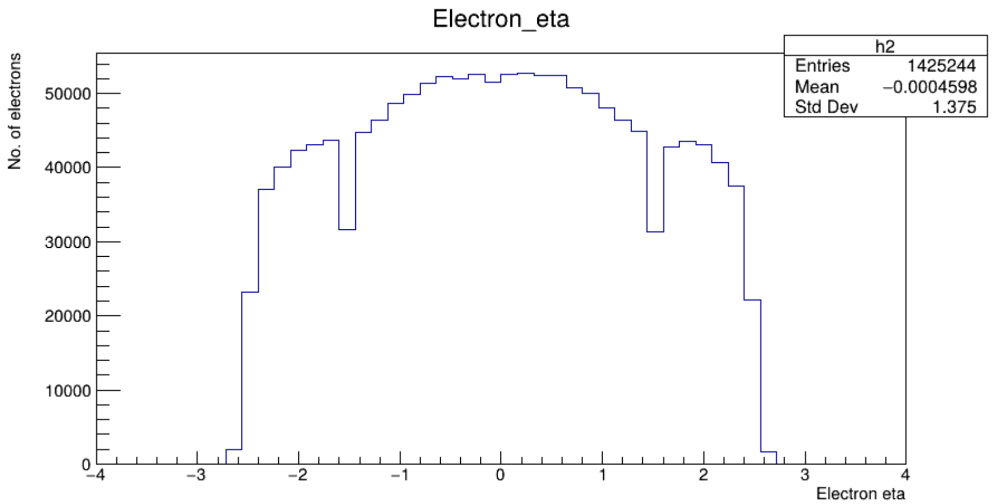


Figure 6: Electron Eta plot for exam.root data.

- nElectron plot:

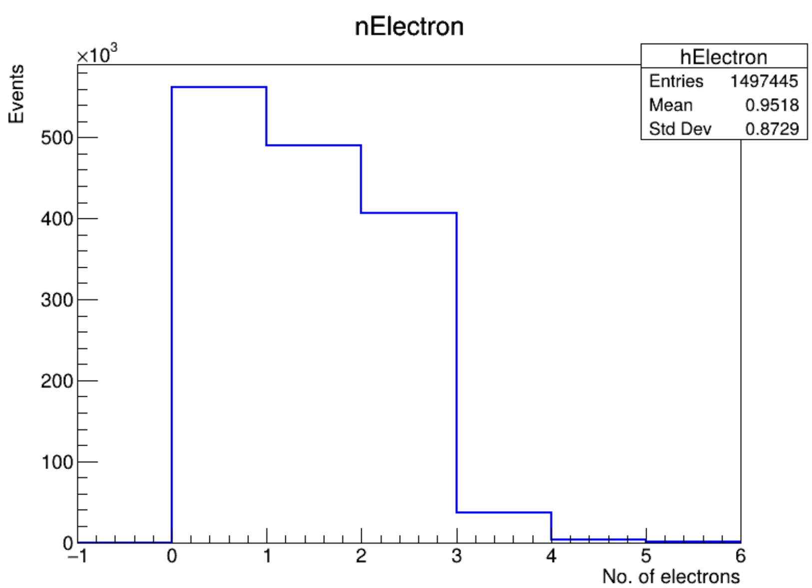


Figure 7: No of electrons plot for exam.root data.

- Electron Phi plot:

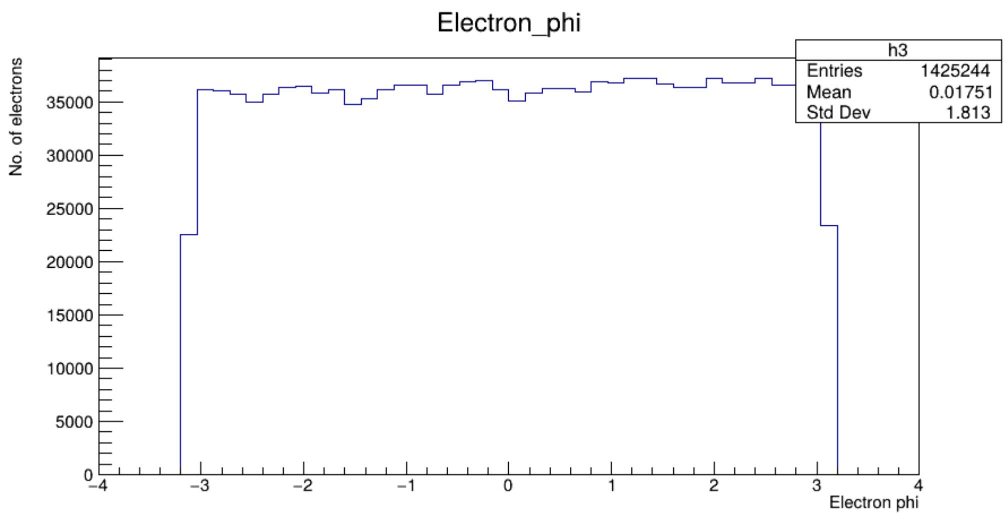


Figure 8: Electron Phi plot for exam.root data.

- Electron p_T plot:

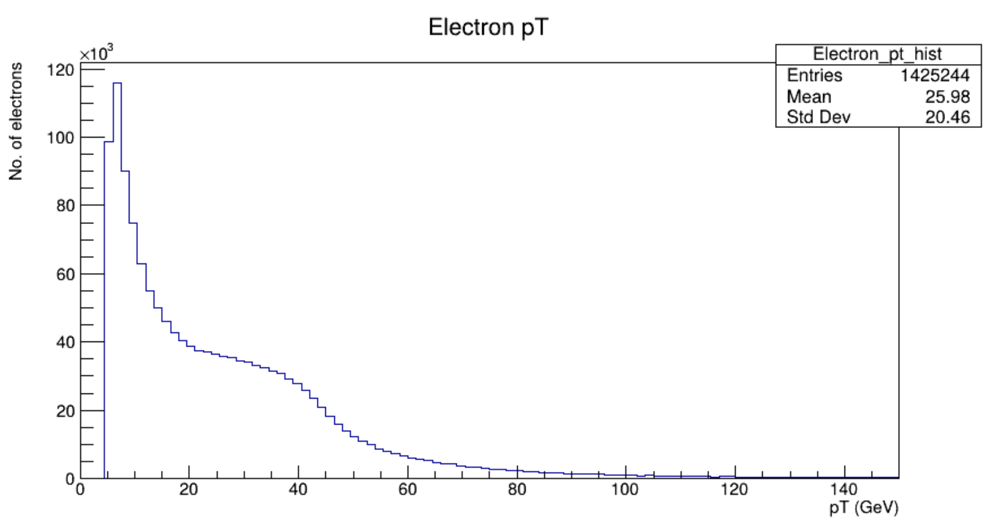


Figure 9: Electron p_T plot for exam.root data.

- Question 2:Using the ROOT file exam.root:
- a. Produce an output ROOT file containing only the muon pT information stored in a branch with name the same as your name and the output file should also have the same name.
- b. In the report, note the difference in size between the two files.

  a) Output root file with only pT information stored

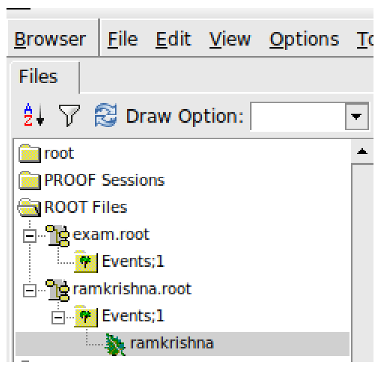


Figure 10: Output root file with my name i.e ramkrishna.root and branch with my name ramkrishna with muon pT information stored

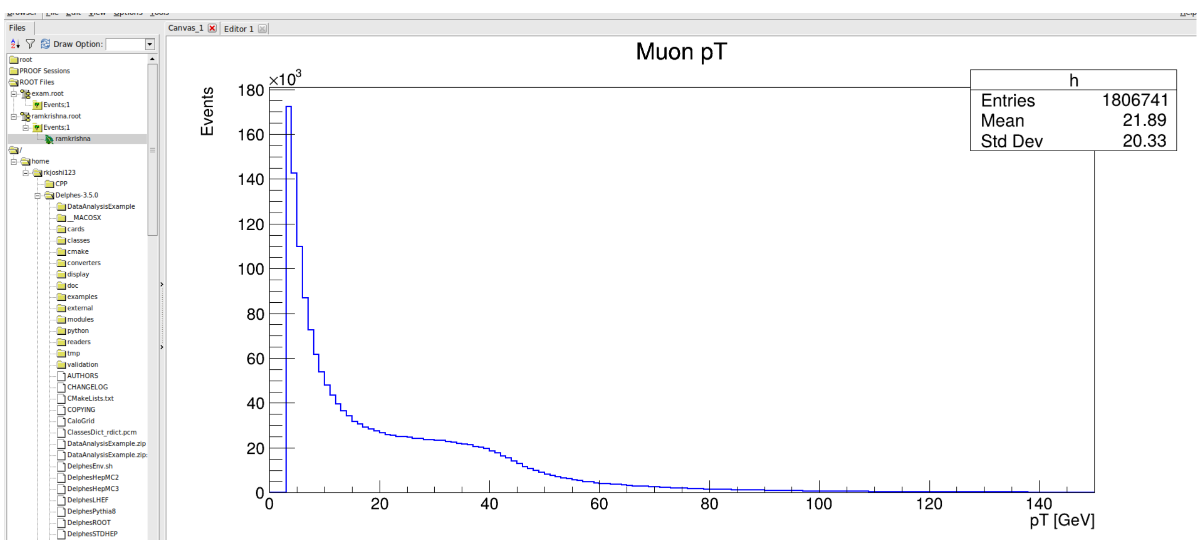


Figure 11: Muon pT drawn from the ramkrishna branch in the ramkrishna.root confirms that the muon pT values are stored correctly in this branch. The number of entries for the plot match with the muon pT plot from exam.root as can be seen in Q1.

```
rkjoshi123@DESKTOP-M7HQSN7:~/Delphes-3.5.0$ ls -lh exam.root ramkrishna.root
-rw-r--r-- 1 rkjoshi123 rkjoshi123 166M Apr 28 04:09 exam.root
-rw-r--r-- 1 rkjoshi123 rkjoshi123  14M Apr 28 07:31 ramkrishna.root
```

Figure 12: Size difference between exam.root and ramkrishna.root files

- Question 3: Using the ROOT file exam.root:
- a. Create the invariant mass of two leading (in pT) muons if they are of opposite charge and have a PT of above 10 GeV and store the distribution as a histogram. Fit the histograms in a suitable range around the Z mass using a gaussian function and note the resolution and resolution error. Include the plots in your report.
- b. Do the same for Muons and Electrons for events that have both at least 2 muons and 2 electrons. Can you guess which kind of events are simulated here?

  a) Invariant mass of two leading muons and electrons with all events

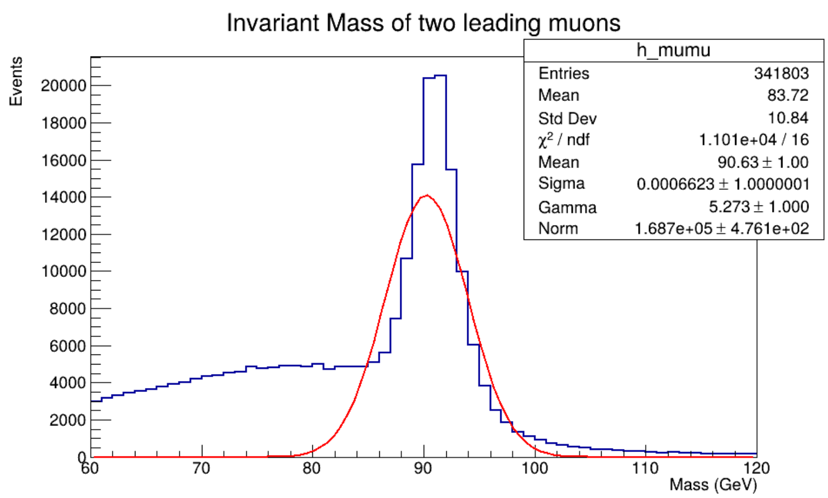


Figure 13: Invariant mass of two leading muons with pT and charge cuts applied plotted with a gaussian fit.

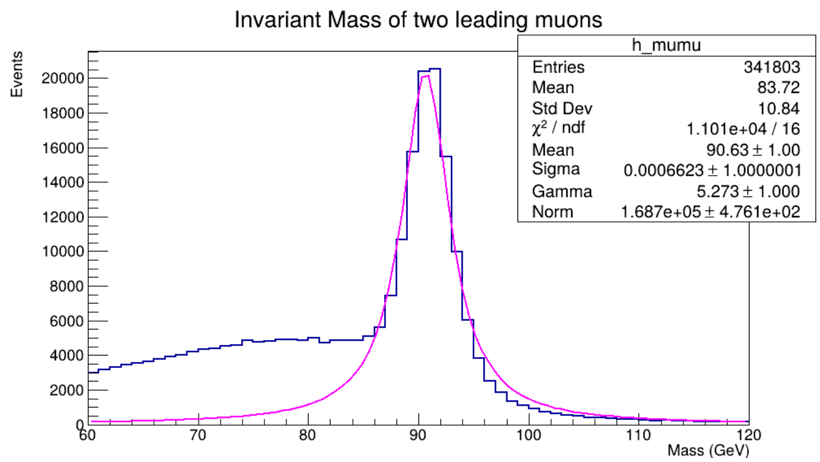


Figure 14: Invariant mass of two leading muons with pT and charge cuts applied plotted with a voigtian fit.

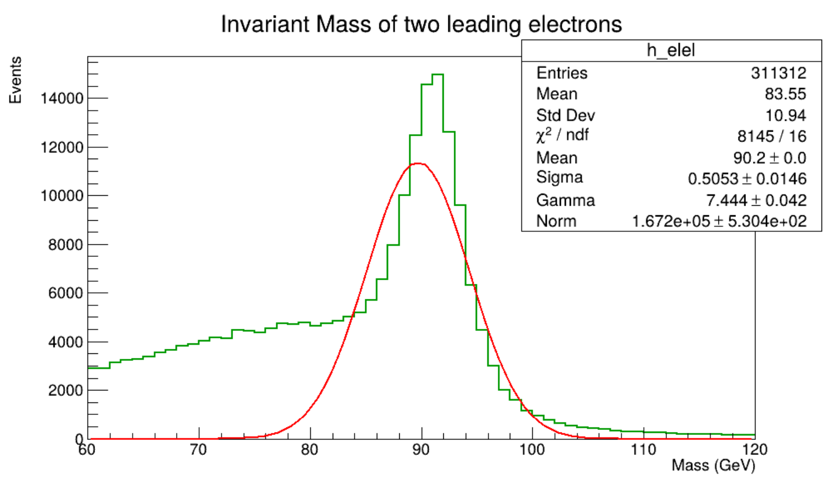


Figure 15: Invariant mass of two leading electrons with cuts applied plotted with a gaussian fit.

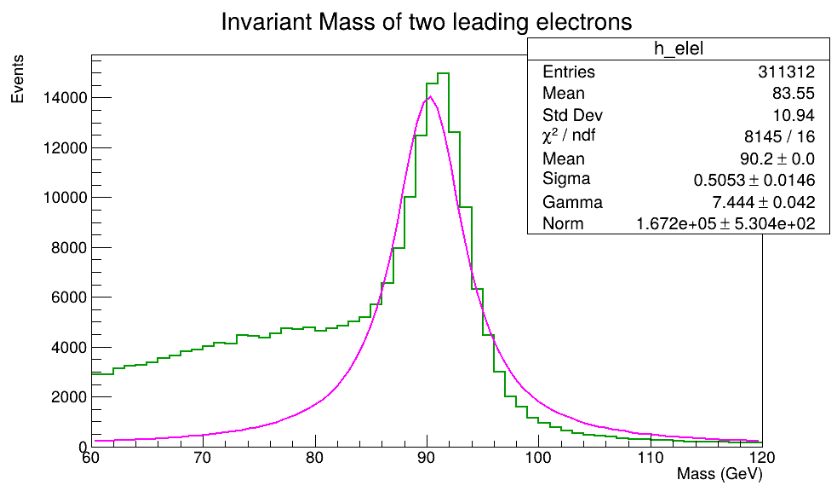


Figure 16: Invariant mass of two leading electrons with cuts applied plotted with a voigtian fit.

b) Selecting only 4 lepton events and plotting the invariant mass of electrons and muons

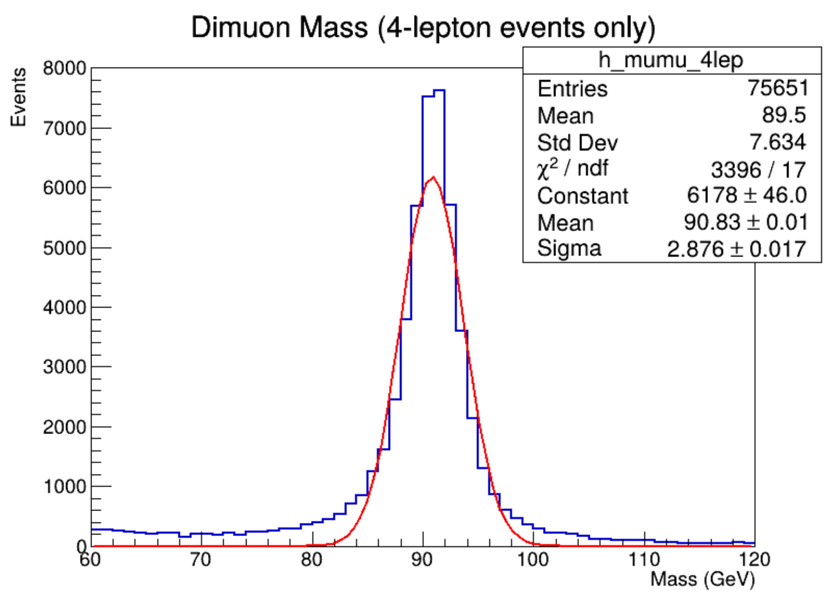


Figure 17: Invariant mass of two muons in 4 lepton events. The background has significantly reduced as expected since we are selecting only 4l events.

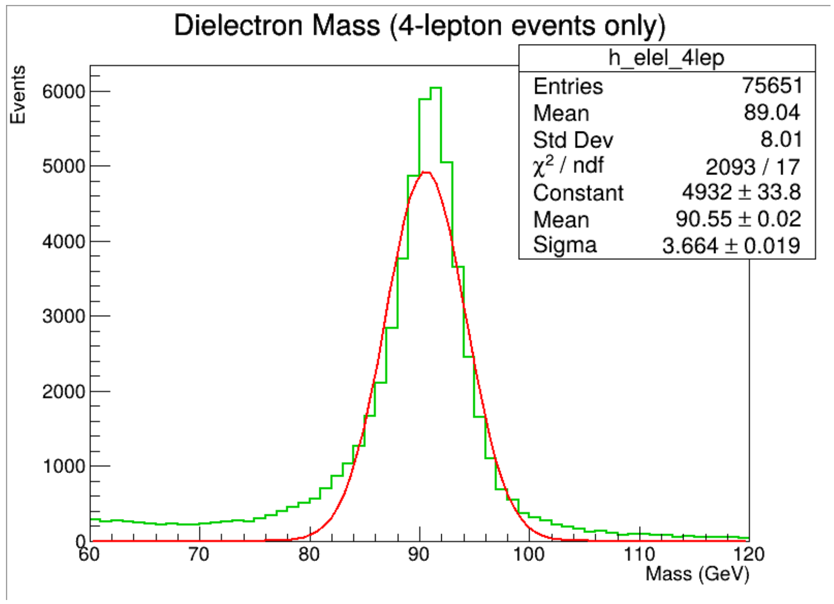


Figure 18: Invariant mass of two electron in 4 lepton events. The background has significantly reduced as expected since we are selecting only 4l events.

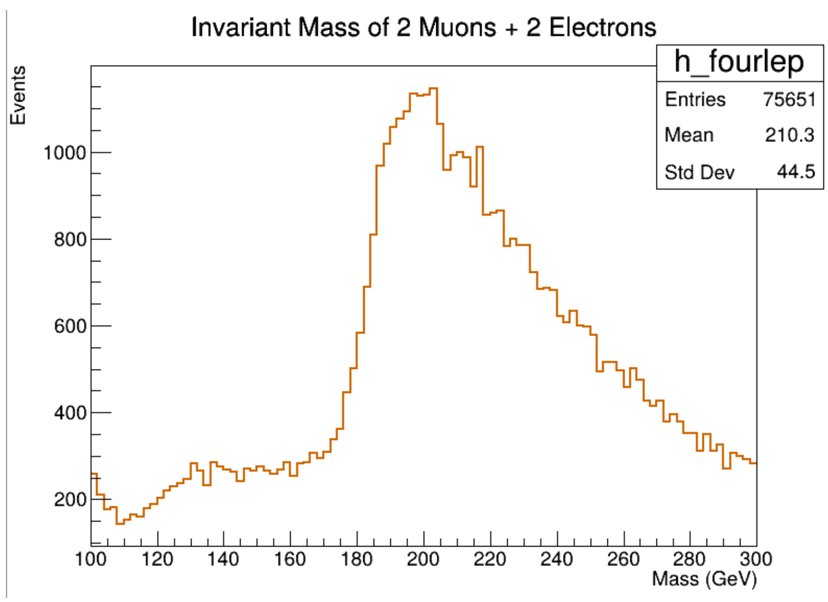
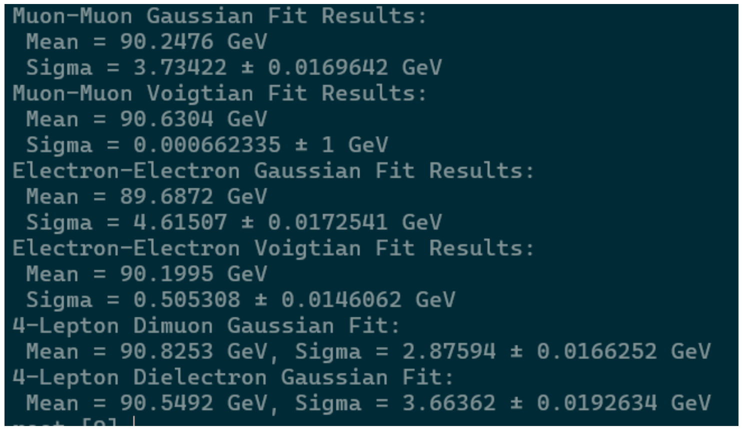


Figure 19: Invariant mass of 4 leptons in the selected events. Since we are reconstructing 2 Z bosons from here, we expect a peak at $\approx 182\ GeV$



```
Muon-Muon Gaussian Fit Results:
 Mean = 90.2476 GeV
 Sigma = 3.73422 ± 0.0169642 GeV
Muon-Muon Voigtian Fit Results:
 Mean = 90.6304 GeV
 Sigma = 0.000662335 ± 1 GeV
Electron-Electron Gaussian Fit Results:
 Mean = 89.6872 GeV
 Sigma = 4.61507 ± 0.0172541 GeV
Electron-Electron Voigtian Fit Results:
 Mean = 90.1995 GeV
 Sigma = 0.505308 ± 0.0146062 GeV
4-Lepton Dimuon Gaussian Fit:
 Mean = 90.8253 GeV, Sigma = 2.87594 ± 0.0166252 GeV
4-Lepton Dielectron Gaussian Fit:
 Mean = 90.5492 GeV, Sigma = 3.66362 ± 0.0192634 GeV
```

Figure 20: Summary of mean,sigma and sigma-error for all the plots above.

c) Type of process

From the $n_{electron}$, n_{muon} and invariant mass plots it is clear that the process simulated here is Drell-Yan production with the Z channel as;

$$ZZ \rightarrow e^+e^-\mu^+\mu^-$$

- Question 4: Use the exam.lhe file attached with DELPHES to simulate the detector reconstruction of the events in

- a. CMS detector using the card: cards/delphes-card-CMS.tcl in your Delphes directory. Use DELPHES ROOT based visualization to visualize the event number corresponding to the final digit of your roll number in the CMS detector and attach screenshots in your report.

- b. ATLAS detector using the card: cards/delphes-card-ATLAS.tcl in your Delphes directory. Attach visualisation similarly as for the previous part.

- c. Plot the invariant mass of the first two Muons for events with these objects separately for the two detectors and include the two in your report.

- d. Can you guess which kind of events are simulated here (you may take into account electron and muon information)?

  a) CMS DELPHES card:

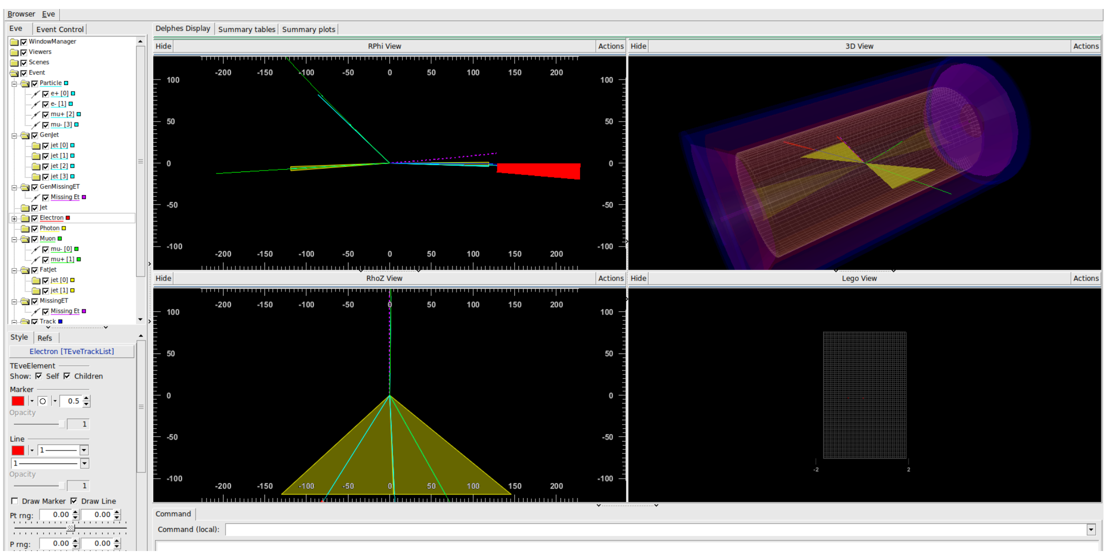


Figure 21: Event 9 from the exam.lhe visualized in CMS Delphes card.

  b) ATLAS DELPHES card:

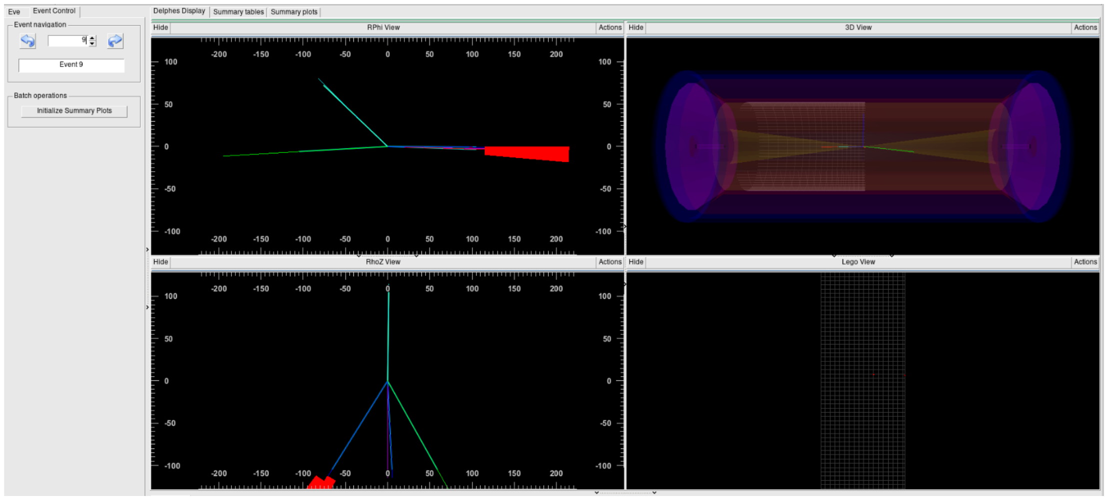


Figure 22: Event 9 from the exam.lhe visualized in ATLAS Delphes card.

c) Invariant mass of two leading muons

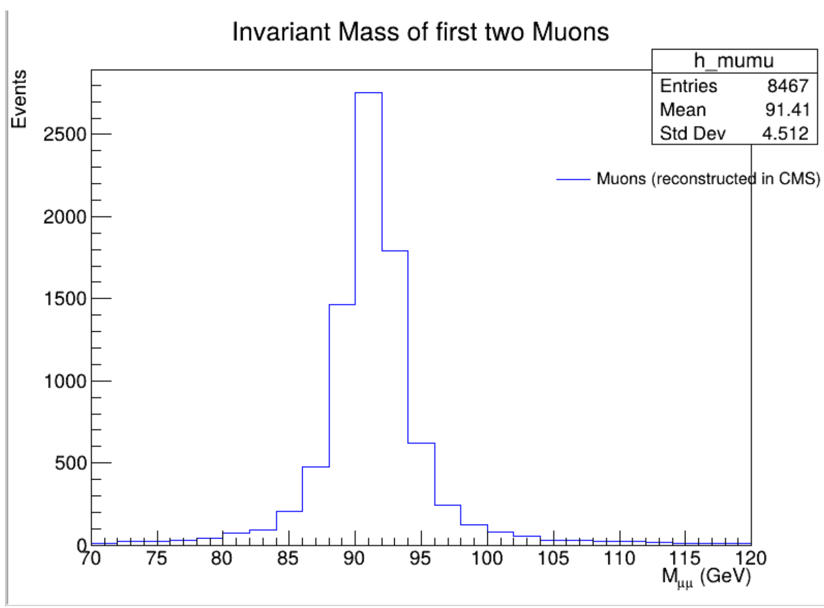


Figure 23: Histogram of reconstructed invariant mass of first two muons in CMS dephes card.

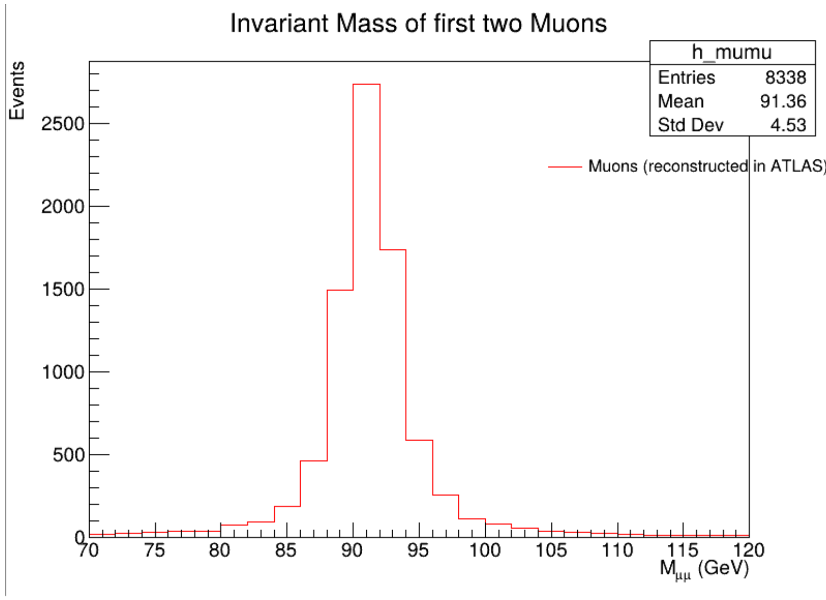
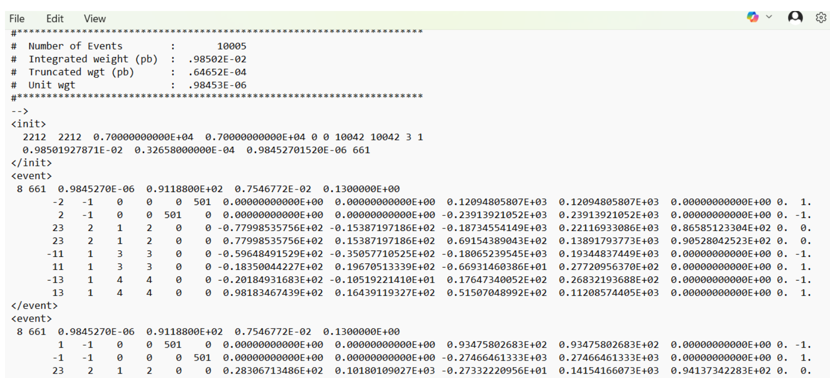


Figure 24: Histogram of reconstructed invariant mass of first two muons in ATLAS dephes card.



File Edit View

```
#*********************************************************************
#  Number of Events        :       10005
#  Integrated weight (pb)  :  .98502E-02
#  Truncated wgt (pb)      :  .64652E-04
#  Unit wgt                :  .98453E-06
#*********************************************************************
-->
<init>
  2212  2212  0.70000000000E+04  0.70000000000E+04 0 0 10042 10042 3 1
  0.98501927871E-02  0.32658000000E-04  0.98452701520E-06 661
</init>
<event>
 8 661  0.9845270E-06  0.9118800E+02  0.7546772E-02  0.1300000E+00
       -2   -1    0    0    0  501  0.00000000000E+00  0.00000000000E+00  0.12094805807E+03  0.12094805807E+03  0.00000000000E+00 0.  1.
        2   -1    0    0  501    0  0.00000000000E+00  0.00000000000E+00 -0.23913921052E+03  0.23913921052E+03  0.00000000000E+00 0. -1.
       23    2    1    2    0    0 -0.77998535756E+02 -0.15387197186E+02 -0.18734554149E+03  0.22116933086E+03  0.86585123304E+02 0.  0.
       23    2    1    2    0    0  0.77998535756E+02  0.15387197186E+02  0.69154389043E+02  0.13891793773E+03  0.90528042523E+02 0.  0.
      -11    1    3    3    0    0 -0.59648491529E+02 -0.35057710525E+02 -0.18065239545E+03  0.19344837449E+03  0.00000000000E+00 0. -1.
       11    1    3    3    0    0 -0.18350044227E+02  0.19670513339E+02 -0.66931460386E+01  0.27720956370E+02  0.00000000000E+00 0.  1.
      -13    1    4    4    0    0 -0.20184931683E+02 -0.10519221410E+01  0.17647340052E+02  0.26832193688E+02  0.00000000000E+00 0. -1.
       13    1    4    4    0    0  0.98183467439E+02  0.16439119327E+02  0.51507048992E+02  0.11208574405E+03  0.00000000000E+00 0.  1.
</event>
<event>
 8 661  0.9845270E-06  0.9118800E+02  0.7546772E-02  0.1300000E+00
        1   -1    0    0  501    0  0.00000000000E+00  0.00000000000E+00  0.93475802683E+02  0.93475802683E+02  0.00000000000E+00 0. -1.
       -1   -1    0    0    0  501  0.00000000000E+00  0.00000000000E+00 -0.27466461333E+03  0.27466461333E+03  0.00000000000E+00 0.  1.
       23    2    1    2    0    0  0.28306713486E+02  0.10180109027E+03 -0.27332220956E+01  0.14154166073E+03  0.94137342283E+02 0.  0.
```

Figure 25: Snapshot of exam.lhe file to examine the structure and the process

Z DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
e^+e^-		(3.3632 ± 0.0042) %		45594
$\mu^+\mu^-$		(3.3662 ± 0.0066) %		45594
$\tau^+\tau^-$		(3.3696 ± 0.0083) %		45559
$\ell^+\ell^-$	[c]	(3.3658 ± 0.0023) %		–
$\ell^+\ell^-\ell^+\ell^-$	[i]	(4.55 ± 0.17) $\times 10^{-6}$		45594
invisible		(20.000 ± 0.055) %		–
hadrons		(69.911 ± 0.056) %		–

Figure 26: Z decays to electron-antielectron and muon-antimuon pairs nearly 3.4% of the times which explains the invariant mass peak at $\approx 91GeV$. Source: PDG documentation

QUARKS	
d	1
u	2
s	3
c	4
b	5
t	6
b'	7
t'	8

LEPTONS	
e^-	11
ν_e	12
μ^-	13
ν_μ	14
τ^-	15
ν_τ	16
τ'^-	17
$\nu_{\tau'}$	18

GAUGE AND HIGGS BOSONS	
g	(9) 21
γ	22
Z^0	23
W^+	24
h^0/H_1^0	25
Z'/Z_2^0	32
Z''/Z_3^0	33
W'/W_2^+	34
H^0/H_2^0	35

Figure 27: Particle ID listings. From the PIDs one can cross verify the type of process encoded in the exam.lhe file. The first events represent quark, antiquark incoming pairs, 23 represents intermediate Z boson. 11,-11 represent electron-antielectron pair and 13,-13 represent muon-antimuon pair. Source: PDG monte carlon particle numbering scheme

d) Process simulated

As can be seen from the peaks in the invariant mass as well as from the lhe file, the events generated here are,

$$q\bar{q} \to ZZ \to e^+e^-\mu^+\mu^-$$

- Question 5: Using the DELPHES interface with PYTHIA8:
- a. Simulate the number of events corresponding to the last 4 digits of your roll number for the ttbar (top-antitop) production process at the LHC at the center of mass energy of 14 TeV and run it through the ATLAS detector simulation.
- b. Use DELPHES ROOT based visualization to visualize the event number corresponding to the final digit of your roll number in the ATLAS detector and attach screenshots in your report.

```
! Number of events to be generated (Since my roll no. is PH23MSCST11029, I generate 1029 events)
Main:numberOfEvents = 1029

! Energy of 14 TeV as mentioned in the question
Beams:idA = 2212
Beams:idB = 2212
Beams:eCM = 14000.

! Process simulation for ttbar production at LHC at 14 TeV
Top:gg2ttbar = on
Top:qqbar2ttbar = on

! setting up the Monash 2013 Tune for pp collisions for realism
Tune:pp = 14
```

(a)

```
rkjoshi123@DESKTOP-M7HQSN7:~/Delphes-3.5.0$ ./DelphesPythia8 cards/delphes_card_ATLAS.tcl examples/Pythia8/ttbar.cmnd en
dsem_q5.root
```

(b)

```
*-------  PYTHIA Process Initialization  --------------------------*
|                                                                  |
| We collide p+ with p+ at a CM energy of 1.400e+04 GeV            |
|                                                                  |
|------------------------------------------------------------------|
|                                                    |             |
| Subprocess                                    Code |   Estimated |
|                                                    |    max (mb) |
|                                                    |             |
|------------------------------------------------------------------|
|                                                    |             |
| g g -> t tbar                                  601 |   9.089e-06 |
| q qbar -> t tbar                               602 |   1.084e-06 |
|                                                    |             |
*-------  End PYTHIA Process Initialization -----------------------*

*-------  PYTHIA Multiparton Interactions Initialization  ---------*
|                                                                  |
|                   sigmaNonDiffractive =    57.17 mb              |
|                                                                  |
|    pT0 =  2.65 gives sigmaInteraction =   328.57 mb: accepted    |
|                                                                  |
*-------  End PYTHIA Multiparton Interactions Initialization  -----*
```

(c)

```
------------
** 999 events processed
 Pythia::next(): 1000 events have been generated
** 1029 events processed

 *-------  PYTHIA Event and Cross Section Statistics  -------------------------------------------------------------*
 |                                                                                                                 |
 | Subprocess                                    Code |            Number of events       |      sigma +- delta    |
 |                                                    |       Tried   Selected   Accepted |     (estimated) (mb)   |
 |                                                    |                                   |                        |
 |-----------------------------------------------------------------------------------------------------------------|
 |                                                    |                                   |                        |
 | g g -> t tbar                                  601 |       15477        900        900 |   5.434e-07  9.067e-09 |
 | q qbar -> t tbar                               602 |        1822        129        129 |   7.646e-08  3.494e-09 |
 |                                                    |                                   |                        |
 | sum                                                |       17299       1029       1029 |   6.199e-07  9.717e-09 |
 |                                                                                                                 |
 *-------  End PYTHIA Event and Cross Section Statistics ----------------------------------------------------------*

 *-------  PYTHIA Error and Warning Messages Statistics  ----------------------------------------------------------*
 |                                                                                                                 |
 |  times   message                                                                                                |
 |                                                                                                                 |
 |      0   no errors or warnings to report                                                                        |
 |                                                                                                                 |
 *-------  End PYTHIA Error and Warning Messages Statistics  ------------------------------------------------------*
```

(d)

Figure 28: Summary of different stages: (a)ttbar event initialization file named ttbar.cmnd, (b) initial command to start event generation, (c) PYTHIA initialization, and (d) PYTHIA event run with 1029 events.

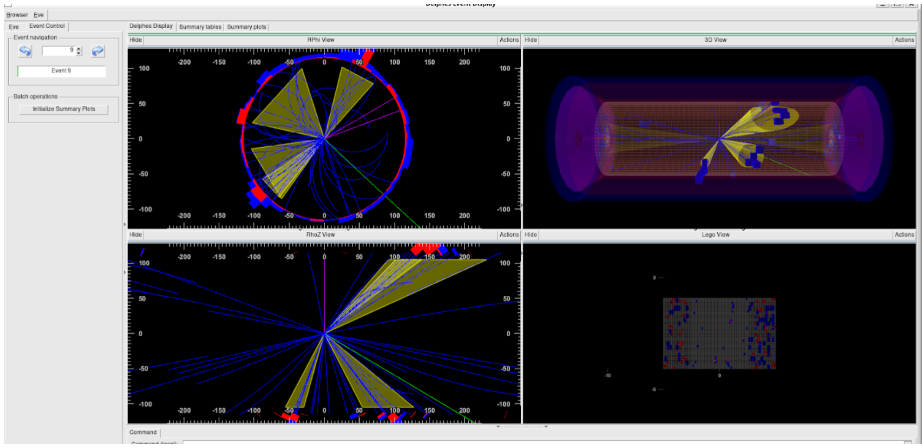


Figure 29: ATLAS event display of event 9 without enabling particles tab

NOTE : I have also performed the analysis with the available ttbar.lhe file and got the same results. In the report I have mentioned only one methods so as to avoid repetition

References

[1] ROOT Team, *TLorentzVector Class Documentation*, `https://root.cern/doc/master/classTLorentzVector.html`

[2] Andrei Gritsan, *Introduction to ROOT and TLorentzVector*, YouTube, `https://www.youtube.com/watch?v=KwV4DqG9gBQ`

[3] ROOT Team, *ROOT Users Guide*, `https://root.cern.ch/root/htmldoc/guides/users-guide/ROOTUsersGuide.html`

[4] ROOT Forum, *Initializing Muon Vectors - How To?*, `https://root-forum.cern.ch/t/initializing-muon-vectors-how-to/37980`

[5] ROOT Forum, *Extracting TLorentzVectors for Mass Reconstruction*, `https://root-forum.cern.ch/t/extracting-tlorentzvectors-for-mass-reconstruction/29916/10`

[6] ROOT Team, *RooFit Manual and Overview*, `https://root.cern/manual/roofit/`

[7] W. Verkerke and D. P. Kirkby, *The RooFit Toolkit for Data Modeling*, arXiv:physics/0306116

[8] RooFit Team, *RooFit Tutorial Collection*, `https://roofit.sourceforge.net/docs/tutorial/index.html`

[9] ROOT Team, *RooFit Main Tutorials*, `https://root.cern/doc/master/group__tutorial__roofit__main.html`

[10] ROOT Team, *Fitting Histograms - ROOT User's Guide*, `https://root.cern.ch/root/html534/guides/users-guide/FittingHistograms.html`

[11] ROOT Team, *Fitting - ROOT Manual*, `https://root.cern/manual/fitting/`

[12] ROOT Team, *ROOT Fit Tutorials*, `https://root.cern/doc/master/group__tutorial__fit.html`

[13] Mattia Lopresti, *Advanced Visualization and Data Fitting in ROOT*, `https://www.mattialopresti.com/advanced-visualization-and-data-fitting-in-root/`

[14] Nevis Labs, Columbia University, *Walkthrough: Fitting a Histogram*, `https://www.nevis.columbia.edu/~seligman/root-class/2022/basics/FittingHistograms.html`

[15] ROOT Team, *Linear Fit Example using TGraphErrors*, `https://root.cern.ch/doc/v612/fitLinear_8C.html`