Version 11.3.2

Geant4 Tutorial Course

Jefferson Lab, Newport News, VA, USA

August 18-22 2025

Analysis

Maurizio Ungaro

Jefferson Lab

Inspired by the original slides of Lorenzo Pezzotti

Jefferson Lab
Thomas Jefferson National Accelerator Facility

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Introduction

The default Geant4 simulation flow sets up the geometry, the physics list and the primary generator, transports particles and… *that's it, no output!*

Bash - exampleB1 execution

```
$ source <geant4>/install/bin/geant4.sh
$ cp -r <geant4>/examples/basic/B1 .
$ cd B1
$ cmake .
$ make -j 12 -f Makefile
$ ./exampleB1 run1.mac
```

```
**************************************************************
 Geant4 version Name: geant4-11-02-patch-01 [MT]   (16-February-2024)
  << in Multi-threaded mode >>


$ ls


CMakeCache.txt  CMakeLists.txt  History   README                exampleB1     exampleB1.in   include
run1.mac  src
CMakeFiles      GNUmakefile     Makefile  cmake_install.cmake   exampleB1.cc  exampleB1.out
init_vis.mac  run2.mac  vis.mac
```

…no data permanently stored

g4analysis

- In Geant4 the user is responsible for storing the variables of interest
- The Geant4 analysis category g4analysis (geant4/source/analysis/) provides a unique interface:
  - to write **histograms** and **n-tuples** (the so-called *primitive types*), and
  - to specify the format (**`ROOT, XML, CSV, HDF5`**)
- Good choice to support the large and heterogeneous user community that adopts different tools (`Python, ROOT in HEP, …`) to run the analysis *a posteriori… or 'inline' using* **`ToolsSG`**

g4analysis

- g4analysis is available in Geant4 since December 2011
  - It is an active area of development with new features added at every release
  - It ensures input/output (I/O) thread-safe capability in multi-threaded simulations (take a second to appreciate how cool is that…)

API:

- Users access the g4analysis tools via the G4AnalysisManager

NOTE: Users can still link their applications against external libraries to handle I/O (typically `ROOT::TTree` for small applications and Event Data Models for large applications)

G4AnalysisManager

- G4AnalysisManager is a singleton (users must access it with static method ::Instance())
- handles output file(s) creation
- owns and handles histos and n-tuples

It provides:

- uniform user interface to different formats (ROOT, XML, CSV, HDF5), i.e. the user is not required to know how to handle any of them,
- with high-level memory management and access to low-level objects (e.g. n-tuples columns)

And is fully integrated in the Geant4 framework (e.g. it is accessible via user commands and uses G4-units)

NOTE: using **HDF5** format requires HDF5 libraries installation and Geant4 build with:

```
-DGEANT4_USE_HDF5=ON
```

Using G4AnalysisManager

Step 1

The G4AnalysisManager usage consists of three steps

1. Create the manager, book n-tuples/histos and open a file, to be done at the begin of each run (`RunAction::BeginOfRunAction()`)

NOTE: since Geant4-11.0 the file format is chosen via the extension (.root, .xml, .csv, .hdf5)

RunAction.cc

```
#include "G4AnalysisManager.hh"

void RunAction::BeginOfRunAction(const G4Run* run) {
    auto analysisManager = G4AnalysisManager::Instance(); //get the manager

    std::string runnumber = std::to_string( run->GetRunID() );

     G4String fileName = "Run" + runnumber + ".root";  //select root format
    //G4String fileName = "Run" + runnumber + ".xml"; //or select xml format
    //G4String fileName = "Run" + runnumber + ".csv"; //or select csv format
    //G4String fileName = "Run" + runnumber + ".hdf5";//or select hdf5 format -> requires hdf5 installation

    analysisManager->OpenFile(fileName);

    //Create histogram(s)
    analysisManager->CreateH1("Edep","Energy deposit",100,0.*MeV,10*GeV); //h1 - energy deposited

    // Create ntuple(s)
    analysisManager->CreateNtuple("Ntuple", "Ntuple");
    analysisManager->CreateNtupleDColumn("Energy");
    analysisManager->FinishNtuple();
}
```

Using G4AnalysisManager

Step 2

2. Fill values in histos and n-tuples, likely at the end of each event (`EventAction::EndOfEventAction()`)

EventAction.cc

```
#include “G4AnalysisManager.hh"

void EventAction::EndOfEventAction(const G4Event*){

    auto analysisManager = G4AnalysisManager::Instance();

    //Fill histograms
    analysisManager->FillH1(0, Edep); // Fill value as MeV

    //Fill ntuples
    analysisManager->FillNtupleDColumn(0, Edep);
    analysisManager->AddNtupleRow();
}
```

Index of histogram.

Auto-incremented by Geant4 at creation.

Index of Ntuple Variable.

Auto-incremented by Geant4 at creation.

Using G4AnalysisManager

Step 3

3. Write and close file, at the end of each run (`RunAction::EndOfRunAction()`)

RunAction.cc

```
#include "G4AnalysisManager.hh"

void RunAction::EndOfRunAction(const G4Run*) {

    auto analysisManager = G4AnalysisManager::Instance();

    // Write and close file
    analysisManager->Write();
    analysisManager->CloseFile();

}
```

NOTE: performing the steps in the suggested classes/methods is not mandatory but guarantees correct execution in multi-threaded applications

Output: ROOT

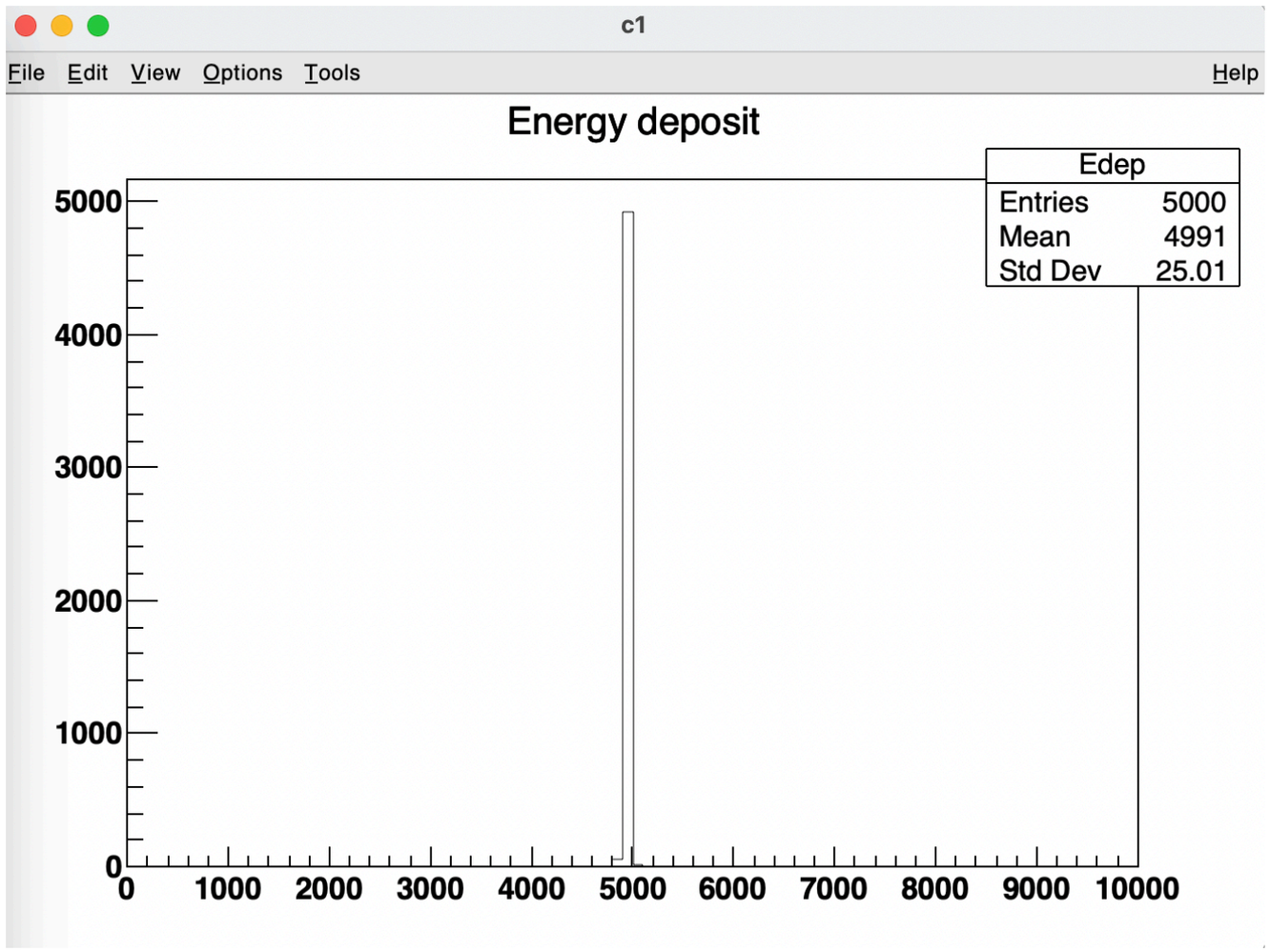
RunAction.cc

```
G4String fileName = "Run" + runnumber + ".root";
```

Bash - after execution

```
$ root -l Run0.root
root [0]
Attaching file Run0.root as _file0...
(TFile *) 0x1258cc990
root [1] .ls
TFile**         Run0.root
 TFile*         Run0.root
  KEY: TTree    Ntuple;1  Ntuple
  KEY: TH1D     Edep;1    Energy deposit
root [2] Edep->Draw("histo")
root [3] Ntuple->Scan()

************************
*    Row   * Energy.En *
************************
*        0 * 4986.2465
*        1 * 4988.8028
*        2 *      5000
*        3 * 4996.4155
```



Output: AIDA XML & CSV

RunAction.cc

```
G4String fileName = "Run" + runnumber + ".xml";
G4String fileName = "Run" + runnumber + ".csv";
```

Bash - after execution

```
$ open Run0_nt_Ntuple.csv
$ open Run0.xml
```

Run0.xml — Edited

Run0 〉 histogram1d "Energy deposit"

```
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE aida SYSTEM "http://aida.freehep.org/schemas/3.2.1/aida.dtd">
<aida version="3.2.1">
  <implementation package="tools" version="5.6.0"/>
  <histogram1d path="/" name="Edep" title="Energy deposit">
    <annotation>
      <item key="axis_x.title" value=""/>
    </annotation>
    <axis direction="x" numberOfBins="100" min="0" max="10000"/>
    <statistics entries="5000">
      <statistic direction="x" mean="4991.163651377722089819144" rms="25.00646158764153881293169"/>
    </statistics>
    <data1d>
      <bin1d binNum="44" entries="1" height="1" error="1" weightedMean="4451.520478311058468534611"/>
      <bin1d binNum="45" entries="3" height="3" error="1.7320508075688771931766 04"
          weightedMean="4576.961659167744073783979" weightedRms="22.328554700306483482563 64"/>
      <bin1d binNum="46" entries="2" height="2" error="1.4142135623730951454746 22"
          weightedMean="4621.246948266485560452566" weightedRms="15.712966417564876664414 44"/>
      <bin1d binNum="47" entries="6" height="6" error="2.4494897427831778813356 32"
          weightedMean="4756.059668558203156862874" weightedRms="25.498484724997929617984 48"/>
      <bin1d binNum="48" entries="55" height="55" error="7.4161984870956629833926 85"
          weightedMean="4866.724766711570737243164" weightedRms="28.309935867661234709657 95"/>
      <bin1d binNum="49" entries="4921" height="4921" error="70.149839629182338285318 11"
          weightedMean="4993.326701671887349220924" weightedRms="12.664306018189465774526 07"/>
      <bin1d binNum="50" entries="12" height="12" error="3.4641016151377543863532 08"
          weightedMean="5002.203202368423262669239" weightedRms="0.573165332769643542931 7035"/>
    </data1d>
</aida>
```

Salvataggio automatico

Home Inserisci Disegno Layout di pagina Formule Dati

Incolla Calibri (Corpo) 12

Possibile perdita di dati Alcune caratteristiche della cartella di lavoro potre

A1 #class tools::wcsv::ntuple

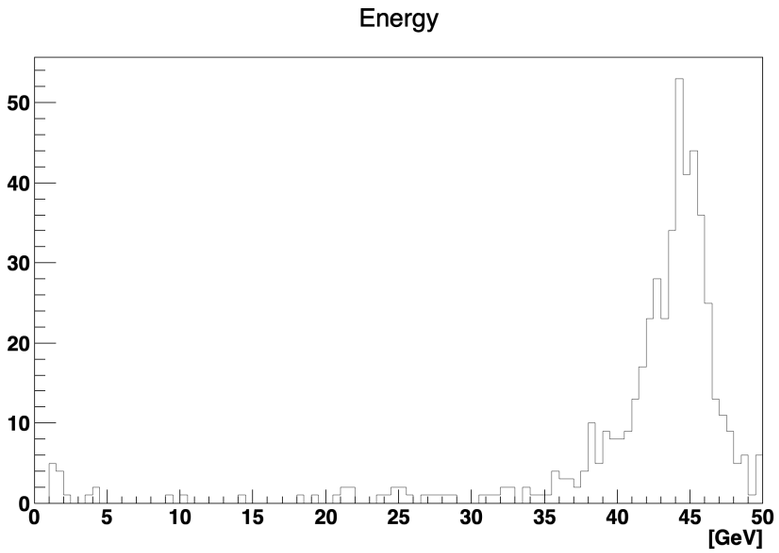
	A	B	C	D	E	F	G
1	#class tools::wcsv::ntuple						
2	#title Ntuple						
3	#separator 44						
4	#vector_separator 59						
5	#column double Energy						
6	4986.25						
7	4988.8						
8	5000						
9	4996.42						
10	4985.11						
11	4998.78						
12	4988.71						
13	5000						
14	5000						
15	5000						
16	5000						
17	4979.43						
18	4998.82						
19	5000						
20	4996.43						
21	4998.83						
22	5000						
23	4988.8						
24	5000						
25	4988.8						
26	5000						
27	4969.2						
28	5000						
29	5000						
30	5000						

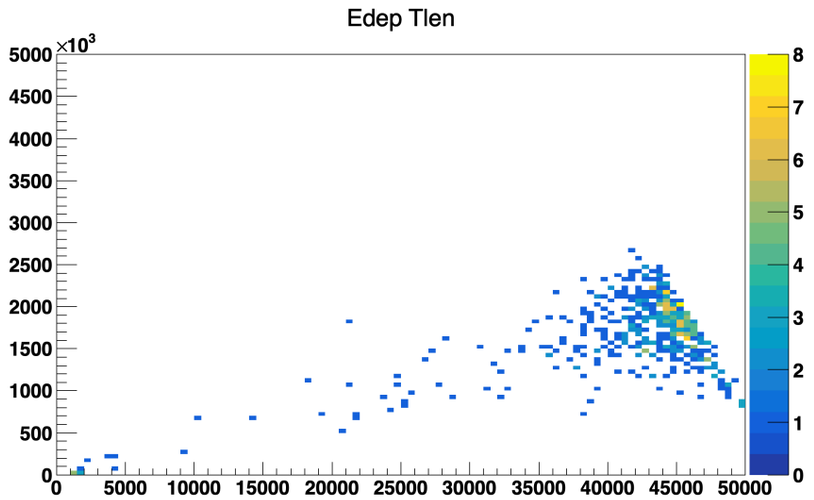
Histograms

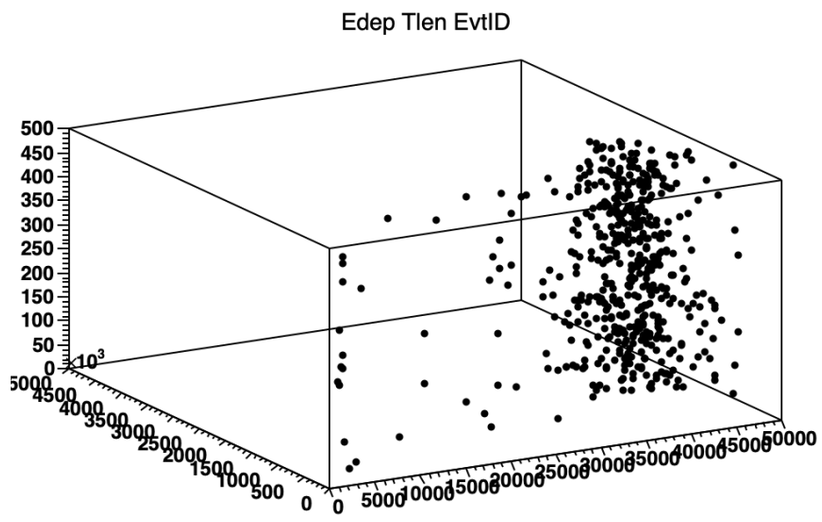
- It is possible to create 1D (CreateH1()), 2D (CreateH2()), 3D (CreateH3()) histograms as well as 1D (CreateP1()) and 2D (CreateP2()) profile histograms

- **IDENTIFIERS**: each histo ID is automatically generated when the histo is created and its value returned by creating function (histo names are not related to IDs and cannot be used for filling)

  - Default start value is 0, it can be changed with `G4AnalysisManager::SetFirstHistoId(G4int)`
  - IDs for H1, H2, H3, P1 and P2 are defined independently







Histograms

- It is possible to access histogram objects via the G4AnalysisManager

RunAction.cc - accessing histogram(s) mean and rms

```
void RunAction::EndOfRunAction(const G4Run* /*run*/) {

  auto analysisManager = G4AnalysisManager::Instance();

  G4cout << G4endl << " ----> print histograms statistic ";
  if(isMaster) {
     G4cout << "for the entire run " << G4endl << G4endl;
  } else {
     G4cout << "for the local thread " << G4endl << G4endl;
  }

  G4cout << " Edep : mean = "
         << G4BestUnit(analysisManager->GetH1(0)->mean(), "Energy")
         << " rms = "
         << G4BestUnit(analysisManager->GetH1(0)->rms(),  "Energy")
         << G4endl;

}
```

Terminal - Geant4 execution on 2 threads

```
**************************************************************
 Geant4 version Name: geant4-11-01 [MT]   (9-December-2022)
  << in Multi-threaded mode >>
     Copyright  : Geant4 Collaboration
     References : NIM A 506 (2003), 250-303
                : IEEE-TNS 53 (2006), 270-278
                : NIM A 835 (2016), 186-225
                  WWW : http://geant4.org/
**************************************************************



// some output


G4WT0 >  ----> print histograms statistic for the local thread
G4WT0 >  Edep : mean = 41.117 MeV rms = 9.2968 MeV
G4WT1 >  ----> print histograms statistic for the local thread
G4WT1 >  Edep : mean = 41.906 MeV rms = 7.36116 MeV
----> print histograms statistic for the entire run
Edep : mean = 41.5036 MeV rms = 8.41347 MeV
```

Histograms

Additional histogram properties can be defined via the `G4AnalysisManager`

- Unit: if defined, filled values are automatically converted to it

```
analysisManager->CreateH1("Tlen", "Tracks length", 100, 0.*km, 5.*km, "km")
```

- Function: if defined, the function is automatically executed on the filled value (can be `log`, `log10`, `exp`)

```
analysisManager->CreateH1("Tlen", "Tracks length", 100, 0.*km, 5.*km, "km", "exp")
```

(if both unit and function are defined, unit is applied first)

- Binning scheme: default is linear, possible to set it to logarithm (`lin`, `log`)

```
analysisManager->CreateH1("Tlen", "Tracks length",
100, 0.1*km, 5.*km, "none", "none", "log")
```

- Alternative binning scheme: alternative constructor available to set a non-equidistant binning scheme using a vector of bin edges

```
G4int CreateH1(const G4String& name, const G4String& title,
               const std::vector<G4double>& edges,
               const G4String& unitName = "none",
               const G4String& fcnName = "none");
```

NTuples

- IDENTIFIERS: ntuple and ntuple column IDs are automatically generated and returned by `G4AnalysisManager->CreateNtuple()` and `G4AnalysisManager->CreateNtupleXColumn()`

- IDs must be used to fill columns if more than one ntuple is created

```
void EventAction::EndOfEventAction(const G4Event* event){

    auto analysisManager = G4AnalysisManager::Instance();

    //Fill ntuple 0 and 1
    analysisManager->FillNtupleDColumn(0, 0, Edep); //ntuple ID, column ID, value
    analysisManager->FillNtupleDColumn(0, 1, TrackL);
    analysisManager->AddNtupleRow(0);

    analysisManager->FillNtupleDColumn(1, 0, ADC);
    analysisManager->FillNtupleDColumn(1, 1, TDC);
    analysisManager->AddNtupleRow(1);

}
```

- The following types can be saved in columns: int (I), float (F), double (D), string (S), std::vector of int (I), float (F), and double (D)

UI Commands

Several UI commands are available to interact with the G4AnalysisManager in your macro card

- General options and handling histos

```
/analysis/verbose 1                              # Set verbose level
/analysis/h1/set 0 100 0. 50. GeV                # set H1 nbins, min, max
```

(similar commands available for H2, H3, P1 and P2)

- Handling output file

```
/analysis/setFileName name                       # set output file name
/analysis/setHistoDirName histos                 # store hist in directory
/analysis/setNtupleDirName ntuples               # store ntuple in directory
```

- Example of a macro `gammaSpectrum.mac` in **TestEm5** example (`examples/extended/electromagnetic/TestEm5/gammaSpectrum.mac`)

UI Commands

Several UI commands are available to interact with the G4AnalysisManager in your macro card

- Histograms control (similar commands available for H2, H3, P1 and P2)

```
/analysis/h1/setAscii id true|false            # activate printing h1 on ASCII file
/analysis/h1/setTitle id title                 # Set title for the 1D histogram
/analysis/h1/setXaxis id title                 # Set x-axis, y-axis title for the 1D histogram
/analysis/h1/setYaxis id title
```

- Batch graphics (similar commands available for H2, H3, P1 and P2)

```
/analysis/h1/setPlotting id true|false         # Automatic plotting of h1
/analysis/h1/setPlottingToAll true|false
```

also available as plain C++ `analysisManager->SetH1Plotting(id, true)`

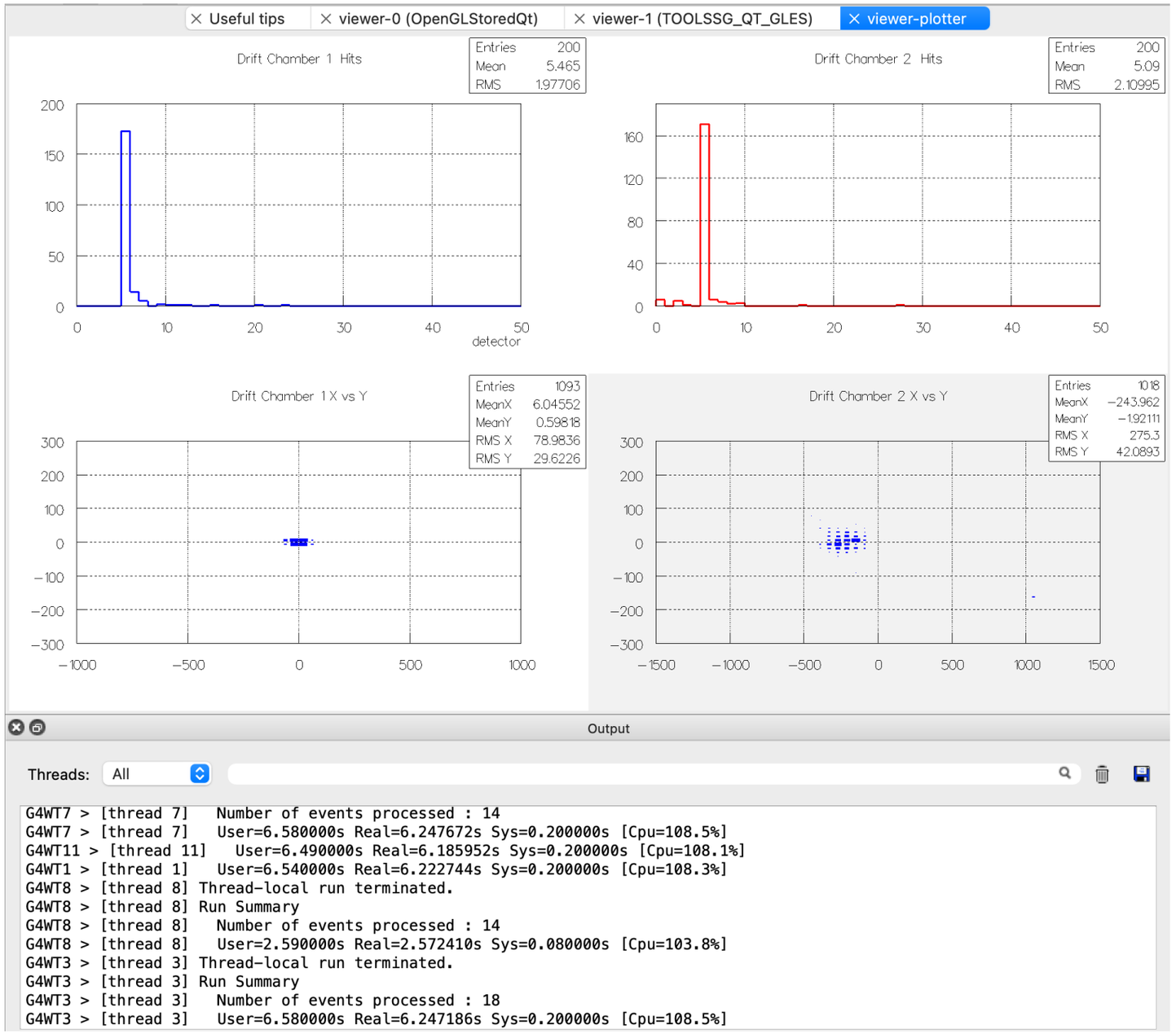
- The selected objects will be automatically plotted in a single (.ps) file with page size fixed to A4 format

ToolsSG Driver

- Introduced in 2021, now part of g4tools

- Binds to various renderer: OpenGL, X11, Xt, Windows, Qt5, Qt6
- Permits some plotting
- Used in G4/analysis for batch plotting
- See plotter.mac in B5

```
/vis/open TSGQt
/control/execute plotter.mac
/run/beamOn 200
```



Summary

Geant4 provides a *lightweight* analysis tool

- It handles the histograms and ntuples creation and storage in ROOT, (AIDA) XML, CSV and HDF5 format
- It is fully integrated in the Geant4 framework (units, UI commands)
- It is specifically designed to deliver thread-safe solutions in multi-threaded simulations

All basic and extended examples, as well as several advanced examples, use the `G4AnalysisManager`

- Examples that address data persistence in Geant4 (`examples/extended/analysis`)
  - **AnaEx01**, demonstrates how to use `g4analysis` tools for ntuples and histograms creation
  - **AnaEx02**, achieves same results by linking ROOT to a `Geant4` application
  - **AnaEx03**, use of AIDA interface classes, requires linking with an AIDA compliant tool, eg. OpenScientist

NOTE: Much more information in the Geant4 Analysis Documentation