Introduction to ROOT

Summer Students Lecture
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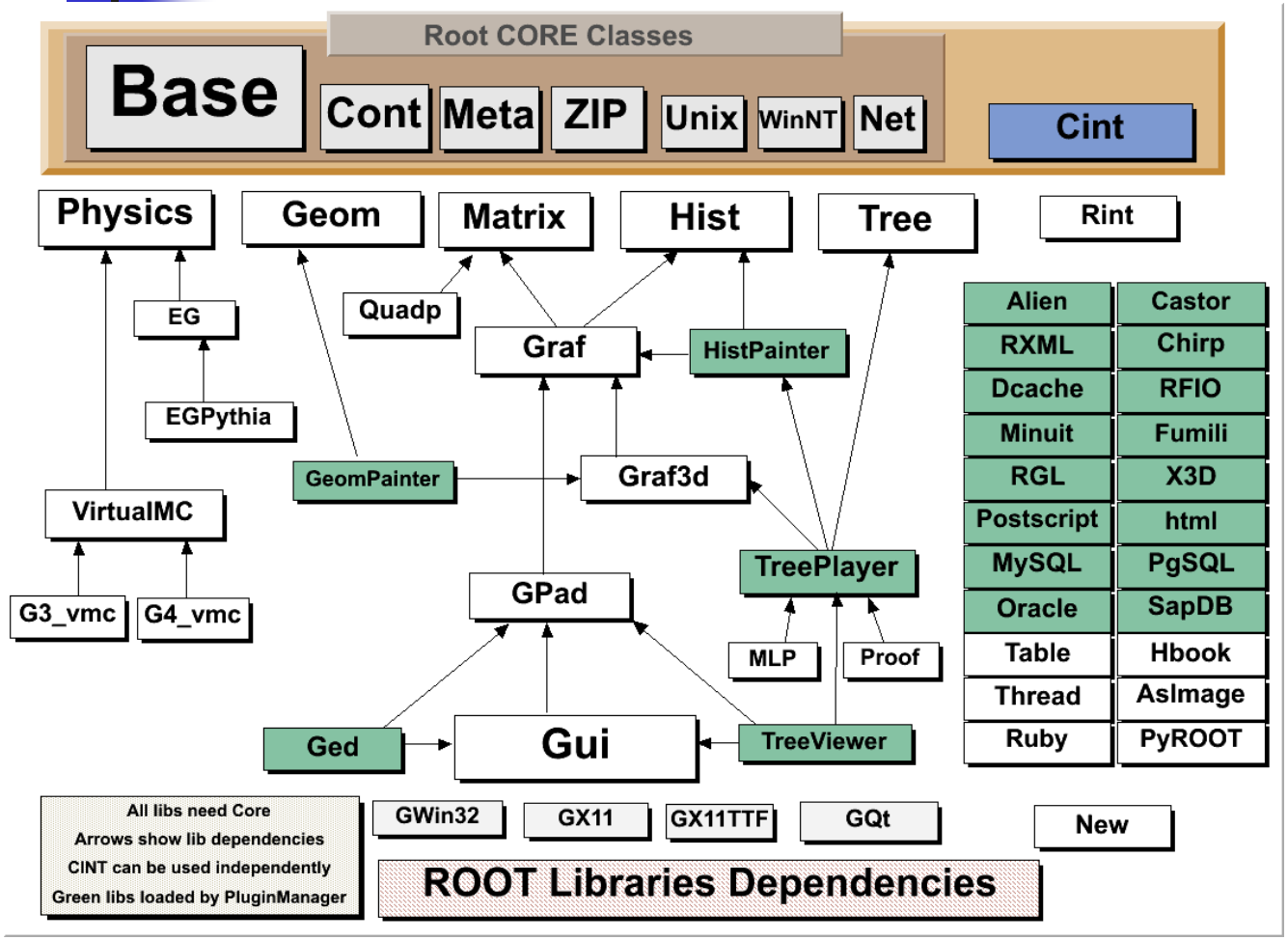
Fons Rademakers (PH/SFT)
Jan Fiete Grosse-Oetringhaus (PH/AIP)

http://root.cern.ch

ROOT in a Nutshell

- ROOT is a large Object-Oriented data handling and analysis framework
  - Efficient object store scaling from KB's to PB's
  - C++ interpreter
  - Extensive 2D+3D scientific data visualization capabilities
  - Extensive set of multi-dimensional histograming, data fitting, modeling and analysis methods
  - Complete set of GUI widgets
  - Classes for threading, shared memory, networking, etc.
  - Parallel version of analysis engine runs on clusters and multi-core
  - Fully cross platform, Unix/Linux, MacOS X and Windows
- The user interacts with ROOT via a graphical user interface, the command line or scripts
- The command and scripting language is C++, thanks to the embedded CINT C++ interpreter, and large scripts can be compiled and dynamically loaded

The ROOT Libraries



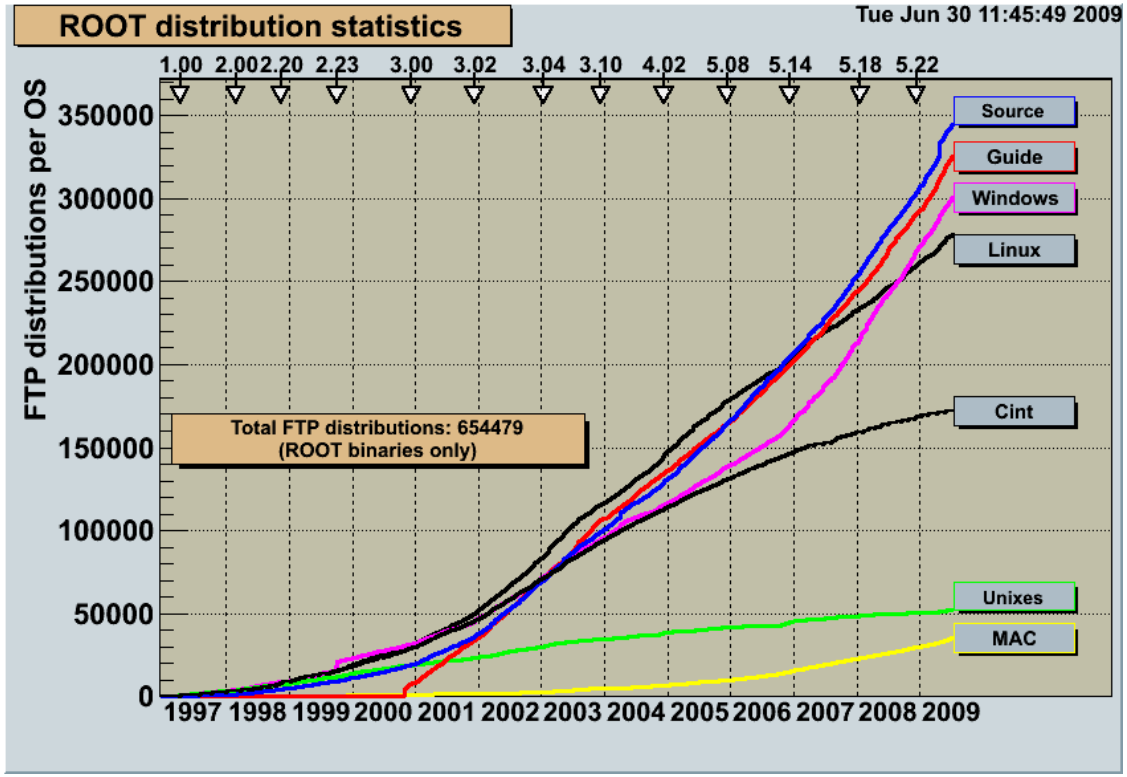
- Over 1500 classes
- 2,000,000 lines of code
- CORE (8 Mbytes)
- CINT (2 Mbytes)
- Green libraries linked on demand via plug-in manager (only a subset shown)
- 100 shared libs

ROOT: An Open Source Project

- The project was started in Jan 1995
- First release Nov 1995
- The project is developed as a collaboration between:
  - Full time developers:
    - 8 people full time at CERN (PH/SFT)
    - 2 developers at Fermilab/USA
  - Large number of part-time contributors (160 in CREDITS file)
  - A long list of users giving feedback, comments, bug fixes and many small contributions
    - 3870 registered to RootTalk forum
    - 10,000 posts per year
- An Open Source Project, source available under the LGPL license
- Used by all HEP experiments in the world
- Used in many other scientific fields and in commercial world

ROOT Stats

- ROOT binaries have been downloaded more than 650000 times since 1997
- The estimated user base is about 20000 people



ROOT: a Framework and a Library

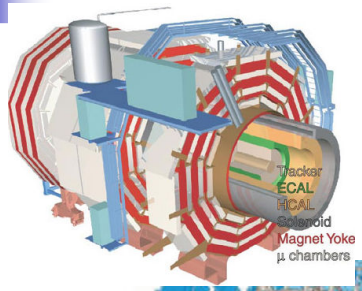
- User classes
  - User can define new classes interactively
  - Either using calling API or sub-classing API
  - These classes can inherit from ROOT classes
- Dynamic linking
  - Interpreted code can call compiled code
  - Compiled code can call interpreted code
  - Macros can be dynamically compiled & linked

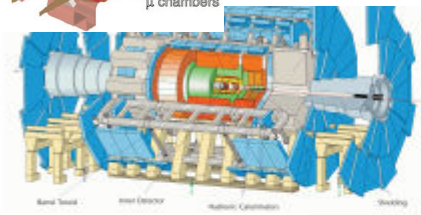
This is the normal operation mode

Interesting feature for GUIs & event displays

Script Compiler
root > .x file.C++

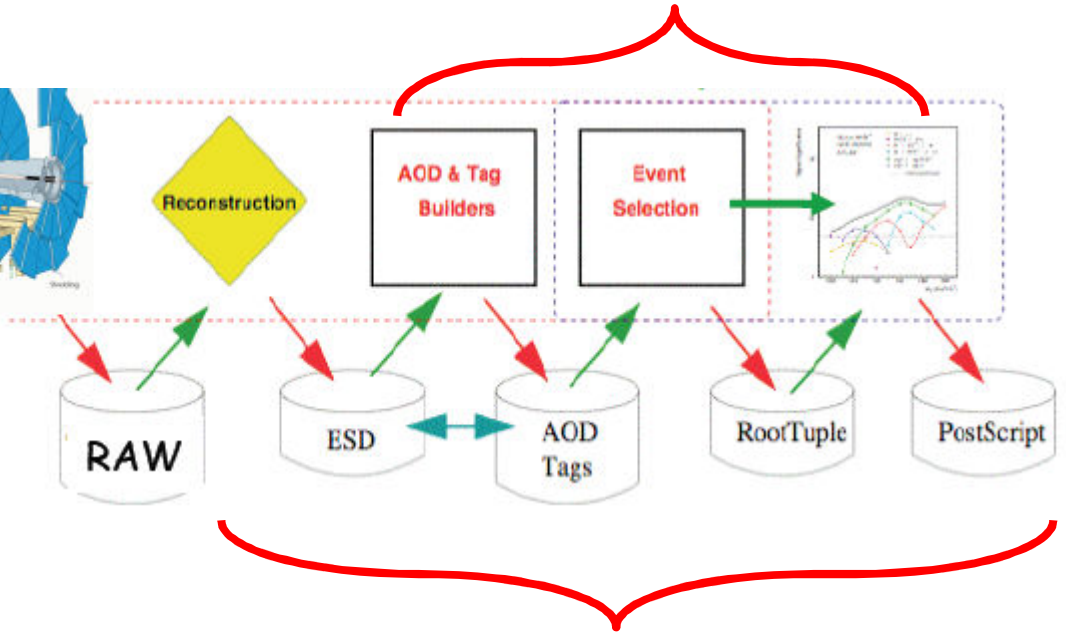
ROOT Application Domains





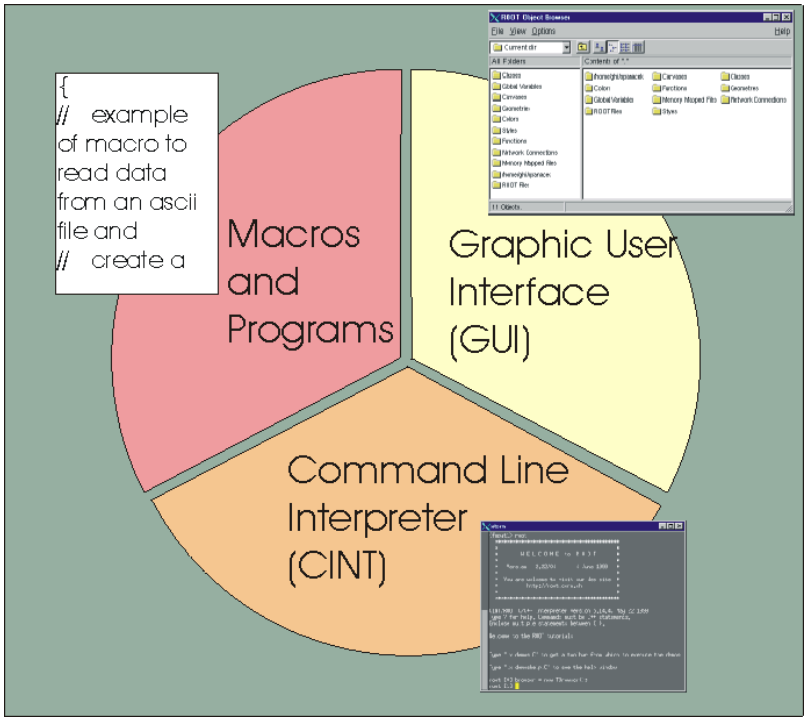
General Framework

Data Analysis & Visualization



Data Storage: Local, Network

Three User Interfaces



- GUI
  windows, buttons, menus
- Command line
  CINT (C++ interpreter)
- Macros, applications, libraries (C++ compiler and interpreter)

CINT Interpreter

CINT in ROOT

- CINT is used in ROOT:
  - As command line interpreter
  - As script interpreter
  - To generate class dictionaries
  - To generate function/method calling stubs
  - Signals/Slots with the GUI
- The command line, script and programming language become the same
- Large scripts can be compiled for optimal performance

Compiled versus Interpreted

- Why compile?
  - Faster execution, CINT has some limitations…
- Why interpret?
  - Faster Edit → Run → Check result → Edit cycles ("rapid prototyping"). Scripting is sometimes just easier.
- Are Makefiles dead?
  - No! if you build/compile a very large application
  - Yes! ACLiC is even platform independent!

Running Code

To run function mycode() in file mycode.C:

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

Equivalent: load file and run function:

```
root [1] .L mycode.C
root [2] mycode()
```

All of CINT's commands (help):

```
root [3] .h
```

Running Code

Macro: file that is interpreted by CINT (`.x`)

```
int mymacro(int value)
{
  int ret = 42;
  ret += value;
  return ret;
}
```

Execute with `.x mymacro.C(42)`

Unnamed Macros

No functions, just statements

```
{
  float ret = 0.42;
  return sin(ret);
}
```

Execute with `.x mymacro.C`

No functions thus no arguments

Named macro recommended!

Compiler prefers it, too…

Running Code – Libraries

"Library": compiled code, shared library

CINT can call its functions!

Building a library from a macro: ACLiC
(**A**utomatic **C**ompiler of **Li**braries for **C**INT)

```
.x mymacro.C(42)+
```

Use "+" instead of writing a Makefile…

CINT knows all functions in mymacro_C.so/.dll

```
mymacro(42)
```

My First Session

root

```
root [0] 344+76.8
(const double)4.20800000000000010e+002
root [1] float x=89.7;
root [2] float y=567.8;
root [3] x+sqrt(y)
(double)1.13528550991510710e+002
root [4] float z = x+2*sqrt(y/6);
root [5] z
(float)1.09155929565429690e+002
root [6] .q
```

root

See file $HOME/.root_hist

root [0] try up and down arrows

My Second Session

root

```
root [0] .x session2.C
for N=100000, sum= 45908.6
root [1] sum
(double)4.59085828512453370e+004
Root [2] r.Rndm()
(Double_t)8.29029321670533560e-001
root [3] .q
```

unnamed macro executes in global scope

session2.C

```
{
   int N = 100000;
   TRandom r;
   double sum = 0;
   for (int i=0;i<N;i++) {
      sum += sin(r.Rndm());
   }
   printf("for N=%d, sum= %g\n",N,sum);
}
```

My Third Session

root

```
root [0] .x session3.C
for N=100000, sum= 45908.6
root [1] sum
Error: Symbol sum is not defined in current scope
*** Interpreter error recovered ***
Root [2] .x session3.C(1000)
for N=1000, sum= 460.311
root [3] .q
```

Named macro
Normal C++ scope rules

session3.C

```
void session3 (int N=100000) {
   TRandom r;
   double sum = 0;
   for (int i=0;i<N;i++) {
      sum += sin(r.Rndm());
   }
   printf("for N=%d, sum= %g\n",N,sum);
}
```

My Third Session with ACLIC

```
root [0] gROOT->Time();
root [1] .x session4.C(10000000)
for N=10000000, sum= 4.59765e+006
Real time 0:00:06, CP time 6.890
root [2] .x session4.C+(10000000)

for N=10000000, sum= 4.59765e+006
Real time 0:00:09, CP time 1.062
root [3] session4(10000000)
for N=10000000, sum= 4.59765e+006
Real time 0:00:01, CP time 1.052
root [4] .q
```

File session4.C
Automatically compiled and linked by the native compiler.
Must be C++ compliant

session4.C

```
#include "TRandom.h"
void session4 (int N) {
   TRandom r;
   double sum = 0;
   for (int i=0;i<N;i++) {
      sum += sin(r.Rndm());
   }
   printf("for N=%d, sum= %g\n",N,sum);
}
```

Macros With More Than One Function

```
root [0] .x session5.C >session5.log
root [1] .q
```

```
root [0] .L session5.C
root [1] session5(100); >session5.log
root [2] session5b(3)
sum(0) = 0
sum(1) = 1
sum(2) = 3
root [3] .q
```

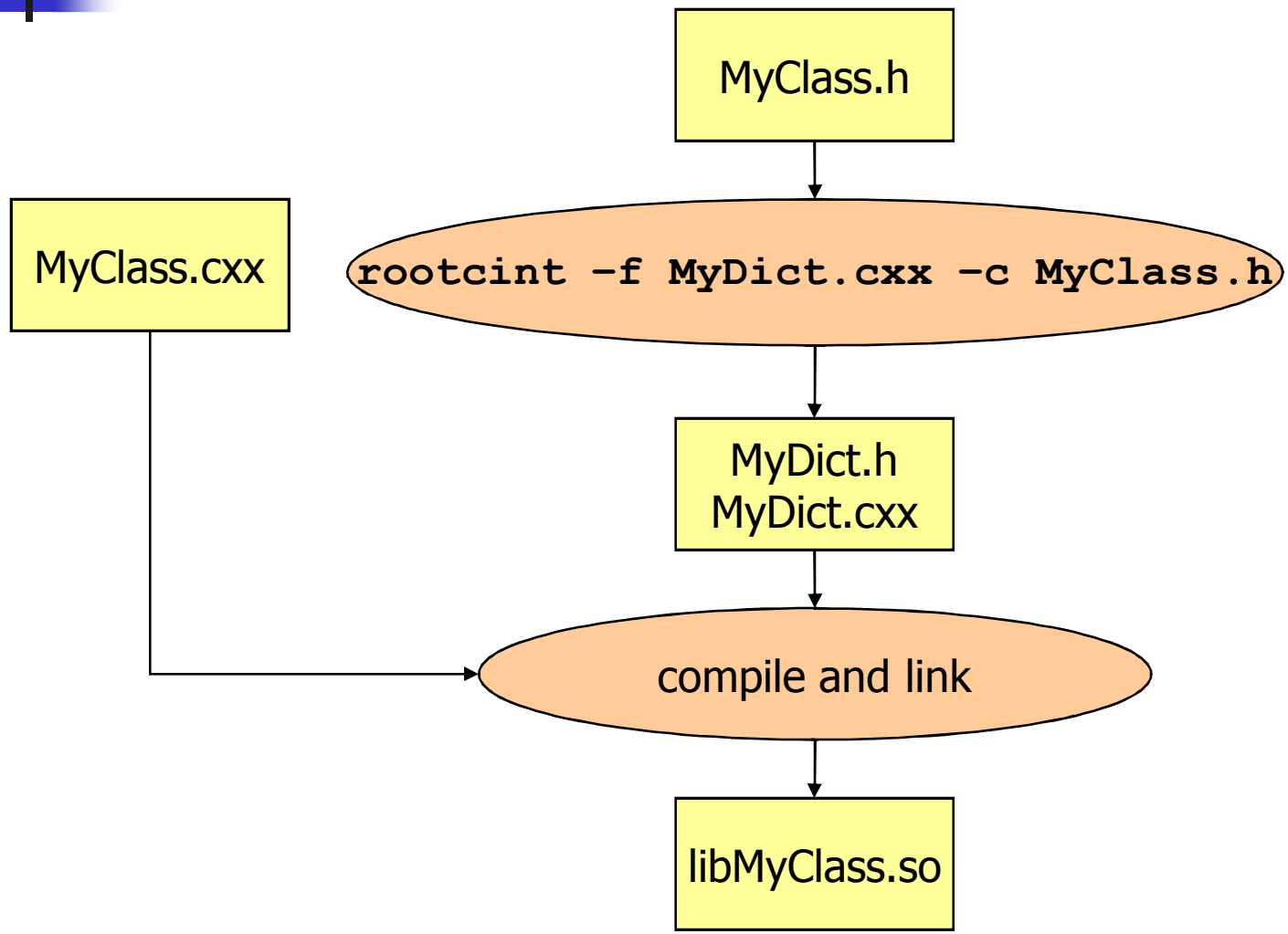
.x session5.C
executes the function session5 in session5.C

use gROOT->ProcessLine to execute a macro from a macro or from compiled code

session5.C

```
void session5(int N=100) {
   session5a(N);
   session5b(N);
   gROOT->ProcessLine(".x session4.C+(1000)");
}
void session5a(int N) {
   for (int i=0;i<N;i++) {
      printf("sqrt(%d) = %g\n",i,sqrt(i));
   }
}
void session5b(int N) {
   double sum = 0;
   for (int i=0;i<N;i++) {
      sum += i;
      printf("sum(%d) = %g\n",i,sum);
   }
}
```

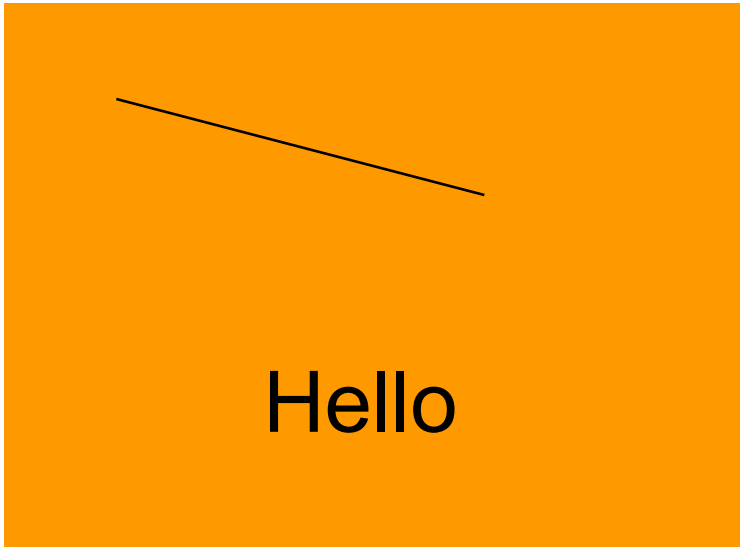
Generating a Dictionary



Graphics & GUI

TPad: Main Graphics Container

```
Root > TLine line(.1,.9,.6,.6)
Root > line.Draw()
Root > TText text(.5,.2,”Hello”)
Root > text.Draw()
```



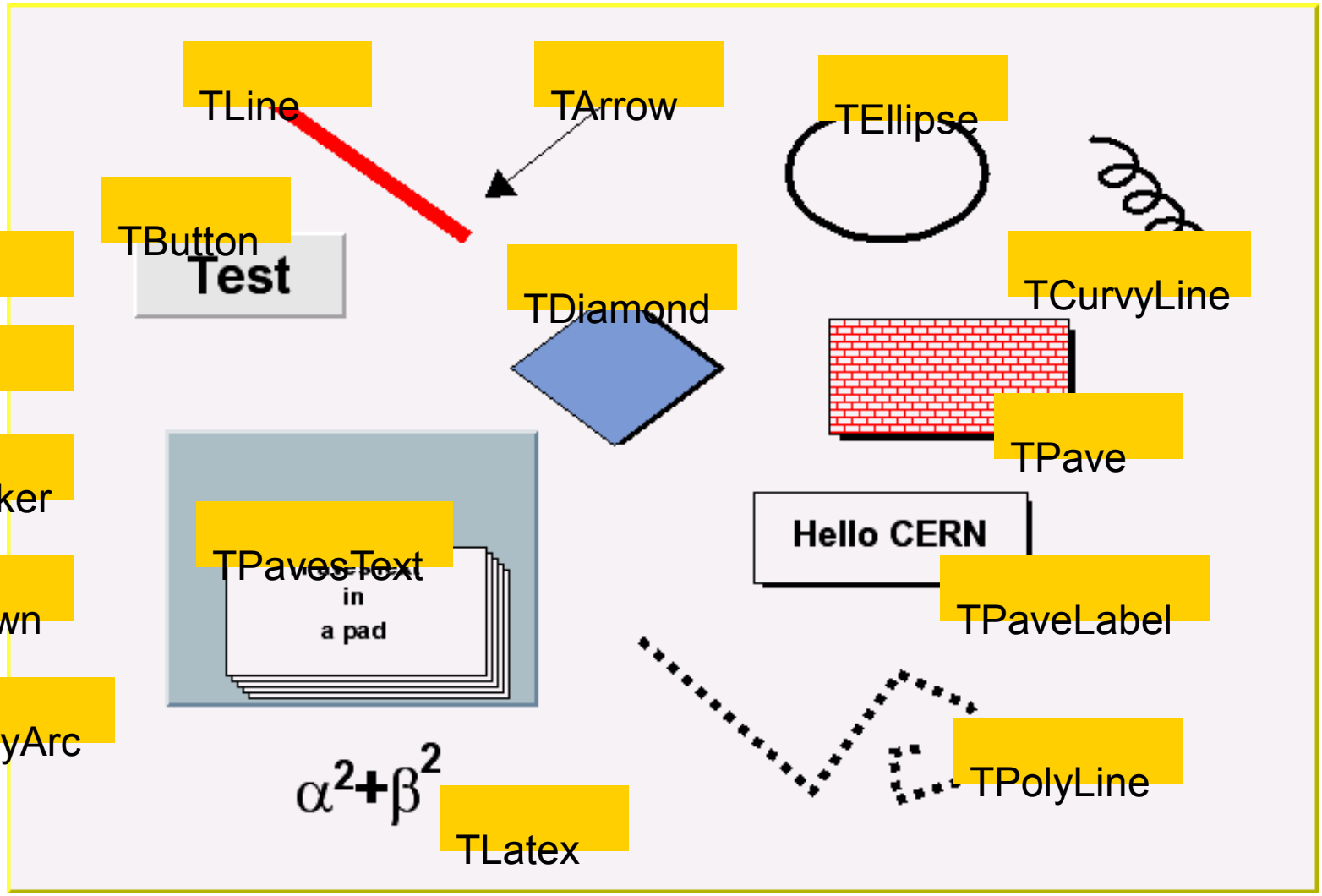
The Draw function adds the object to the list of primitives of the current pad.

If no pad exists, a pad is automatically created with a default range [0,1].

When the pad needs to be drawn or redrawn, the object Paint function is called.

Only objects deriving from TObject may be drawn in a pad
ROOT Objects or User objects

Basic Primitives



Full LateX support on screen and postscript

latex3.C

Born equation

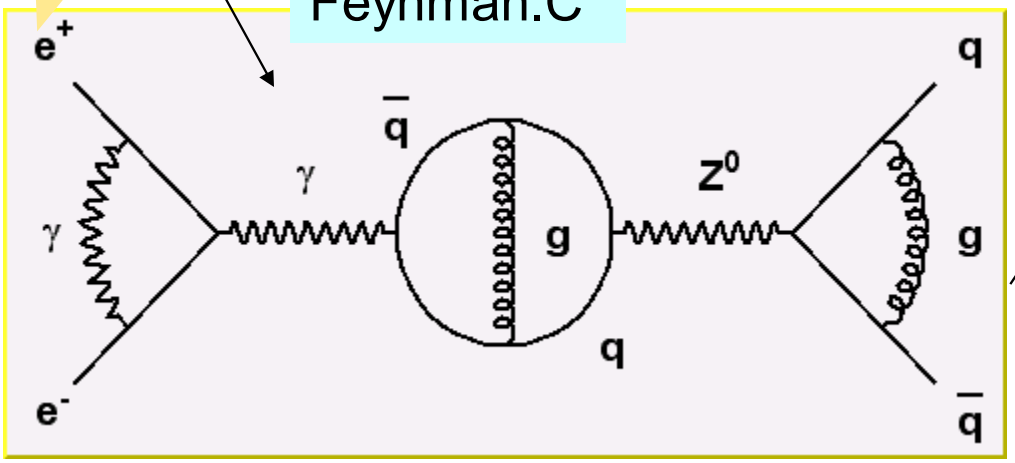
$$\frac{2s}{\pi\alpha^2}\frac{d\sigma}{d\cos\theta}(e^+e^- \to f\bar{f}) = \left|\frac{1}{1-\Delta\alpha}\right|^2 (1+\cos^2\theta)$$

$$+ 4\,\mathrm{Re}\left\{\frac{2}{1-\Delta\alpha}\chi(s)\left[\tilde{g}_v^{e}\tilde{g}_v^{f}(1+\cos^2\theta) + 2\,\tilde{g}_a^{e}\tilde{g}_a^{f}\cos\theta\right]\right\}$$

$$+ 16\left|\chi(s)\right|^2\left[(\tilde{g}_a^{e2} + \tilde{g}_v^{e2})(\tilde{g}_a^{f2} + \tilde{g}_v^{f2})(1+\cos^2\theta) + 8\,\tilde{g}_a^{e}\tilde{g}_a^{f}\tilde{g}_v^{e}\tilde{g}_v^{f}\cos\theta\right]$$

Formula or diagrams can be edited with the mouse

Feynman.C



TCurlyArc
TCurlyLine
TWavyLine
and other building blocks for Feynmann diagrams

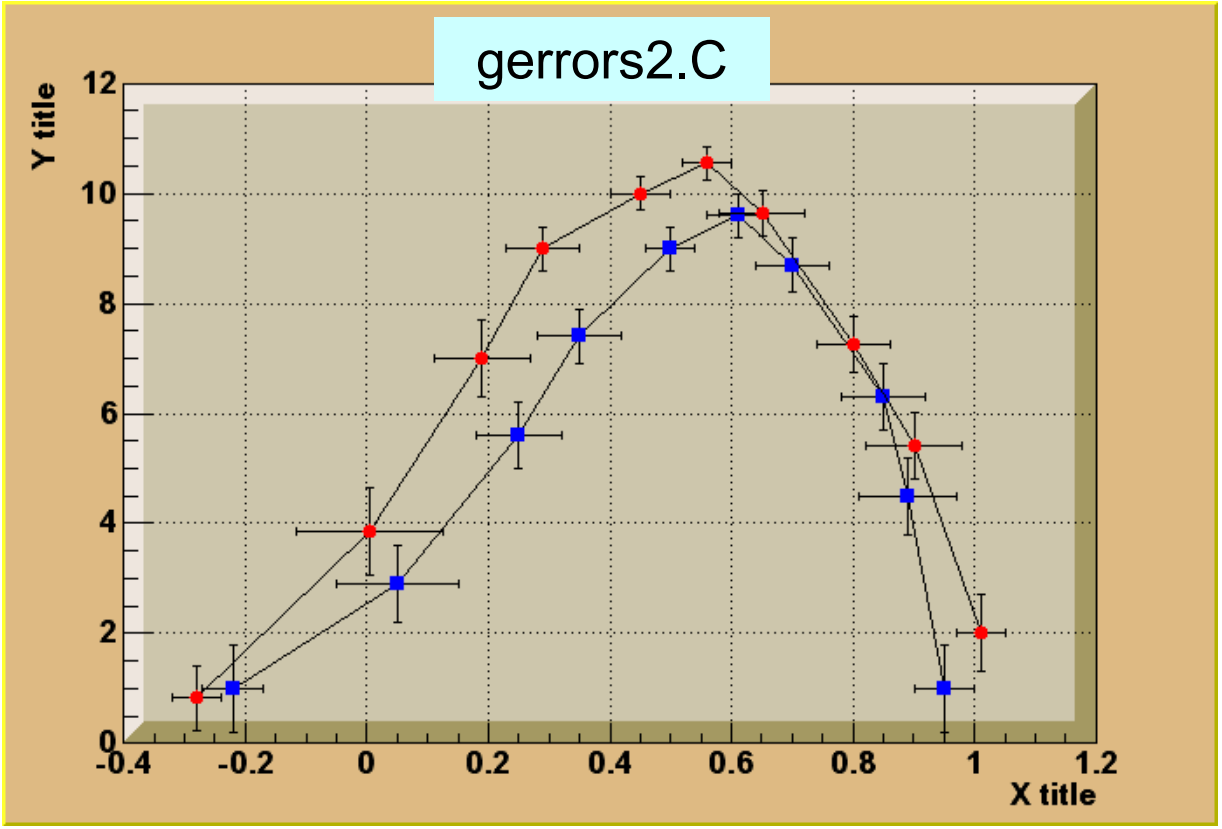
Graphs

TGraph(n,x,y)

TCutG(n,x,y)

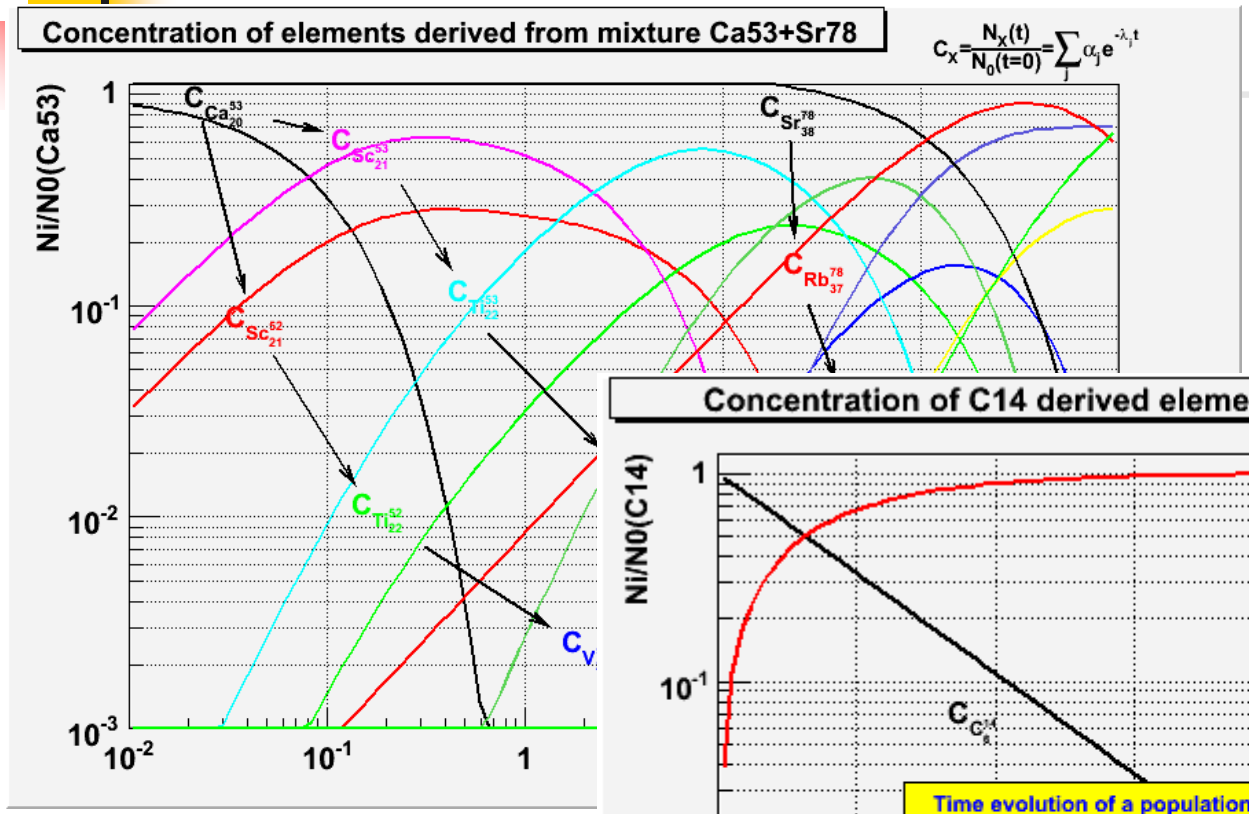
TMultiGraph

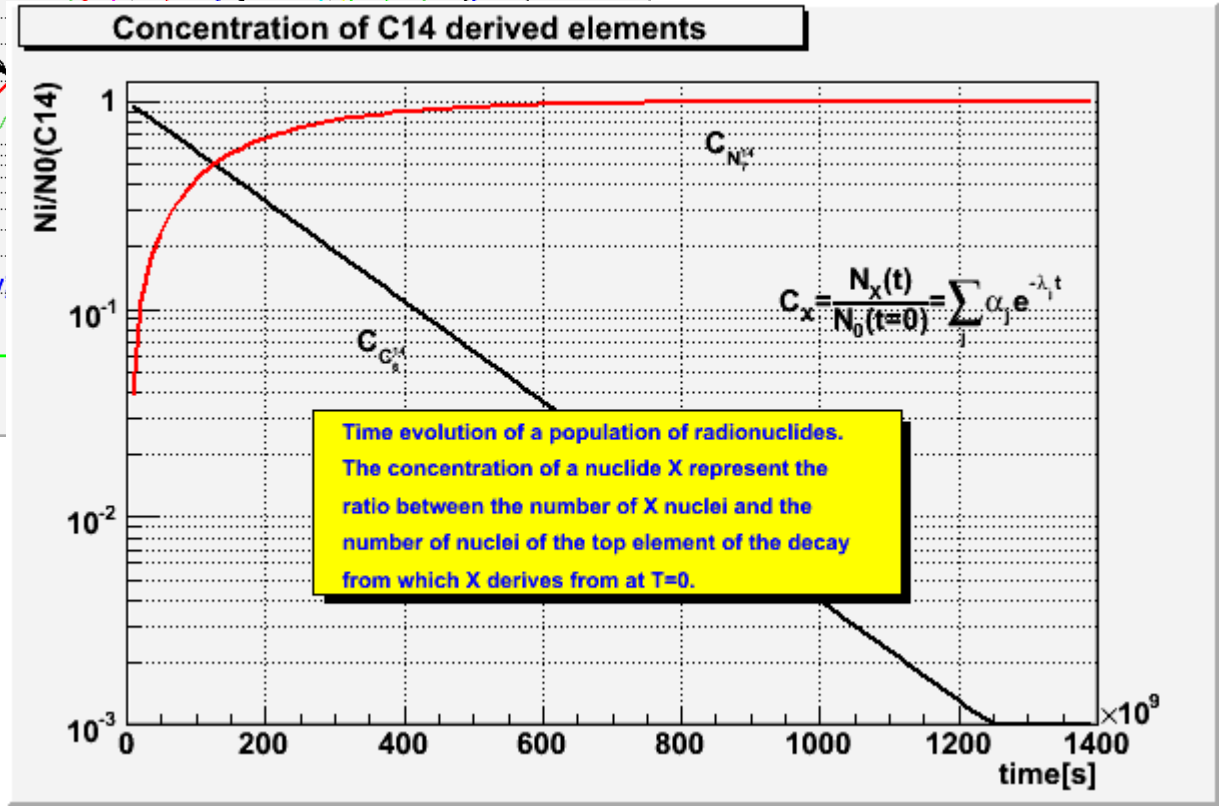
TGraphErrors(n,x,y,ex,ey)



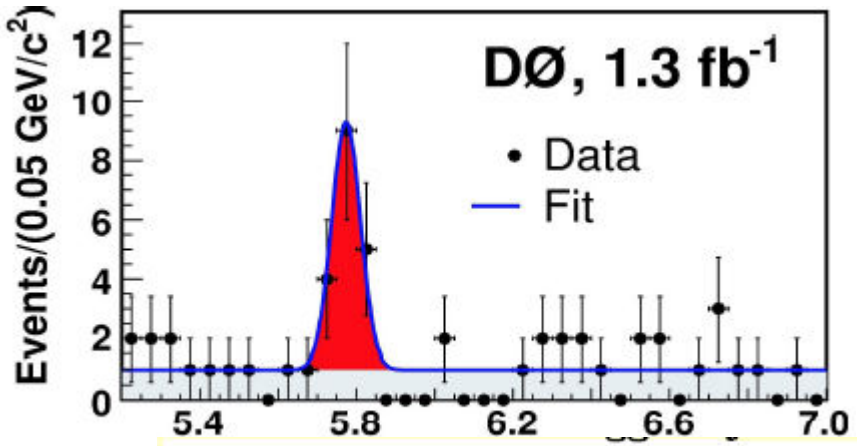
TGraphAsymmErrors(n,x,y,exl,exh,eyl,eyh)

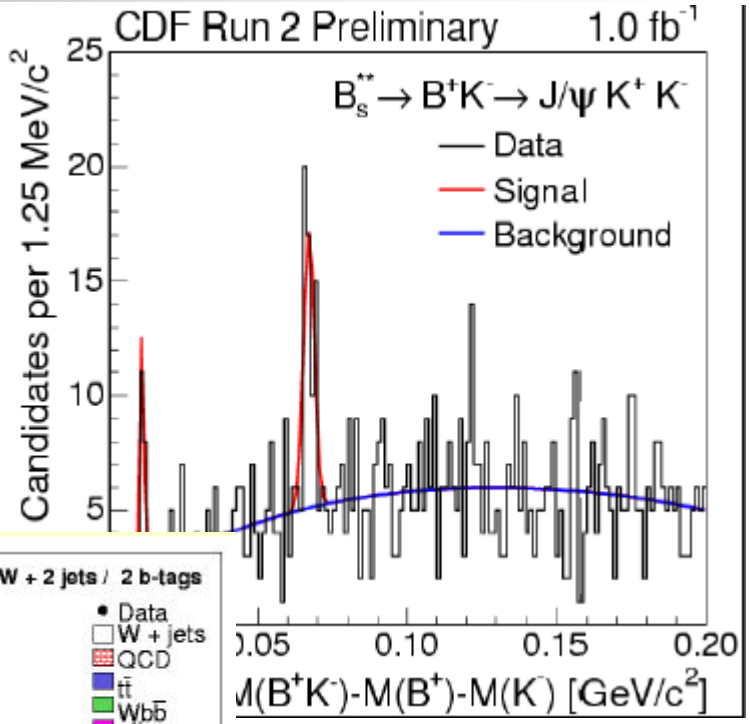
Graphics Examples

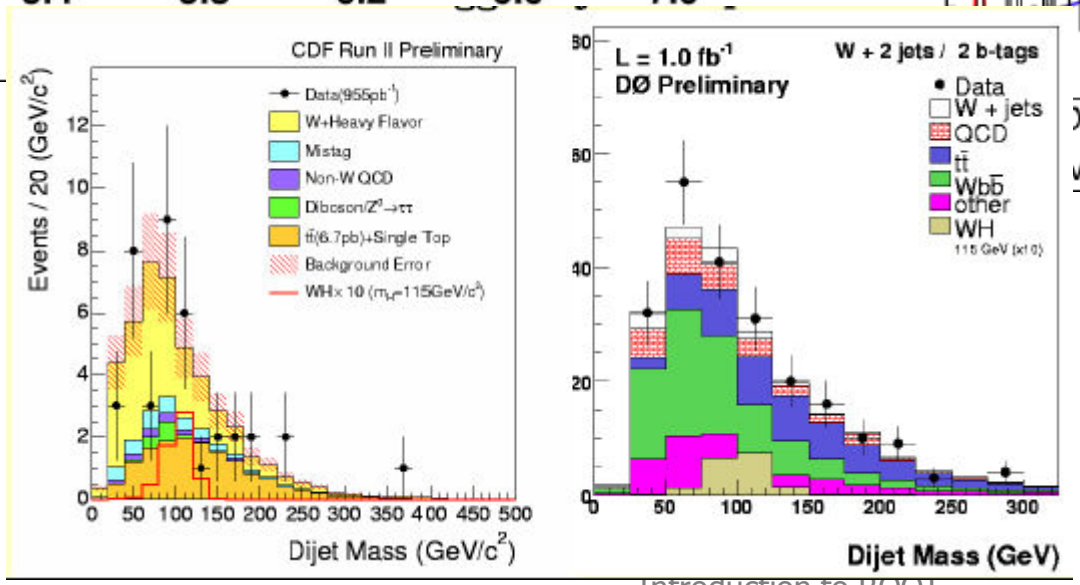




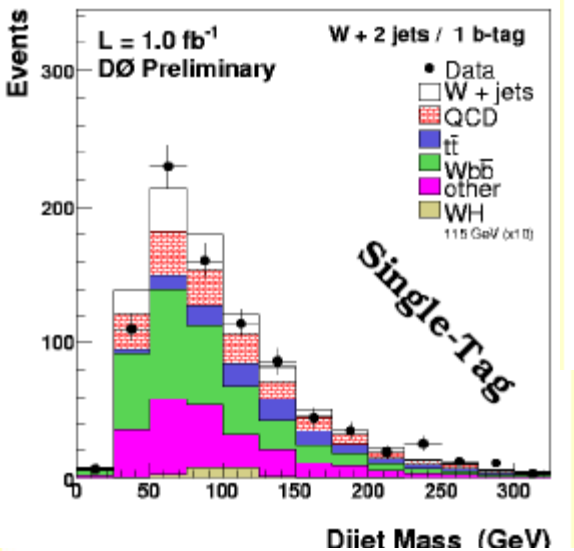
More Graphics Examples

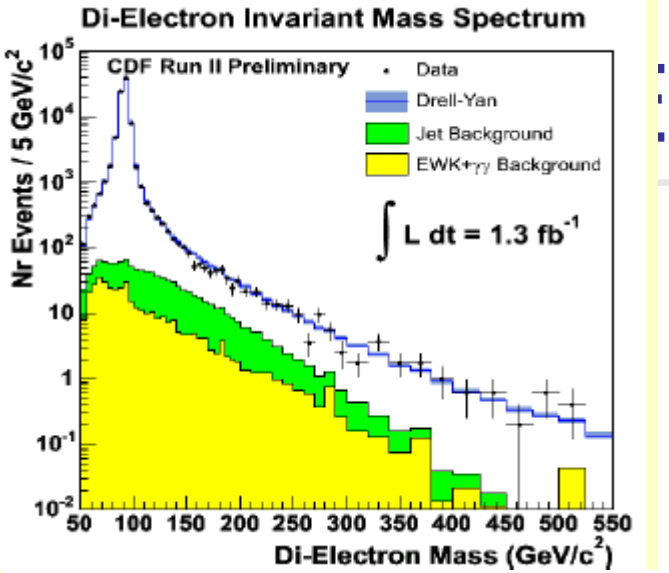


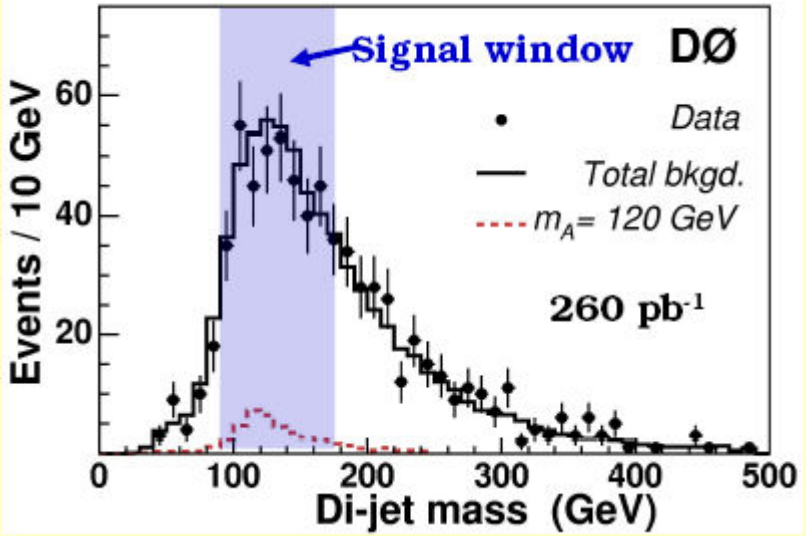


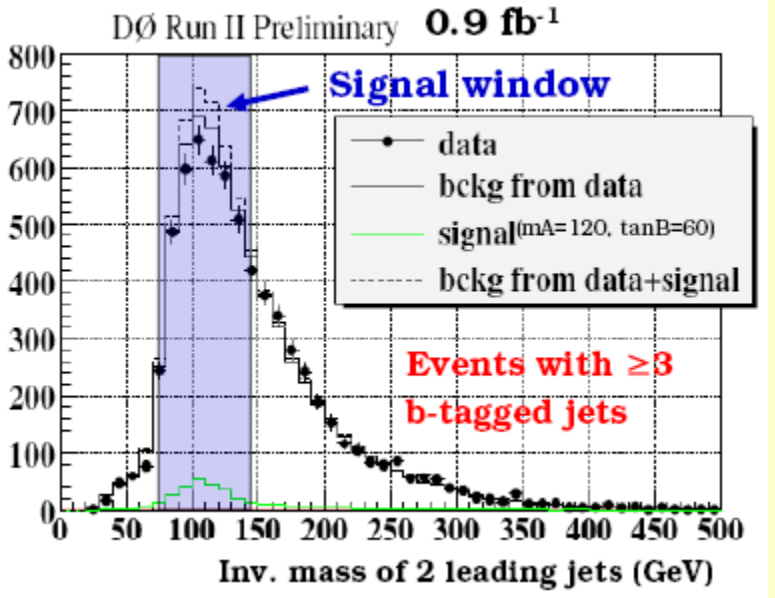


Even M … Examples

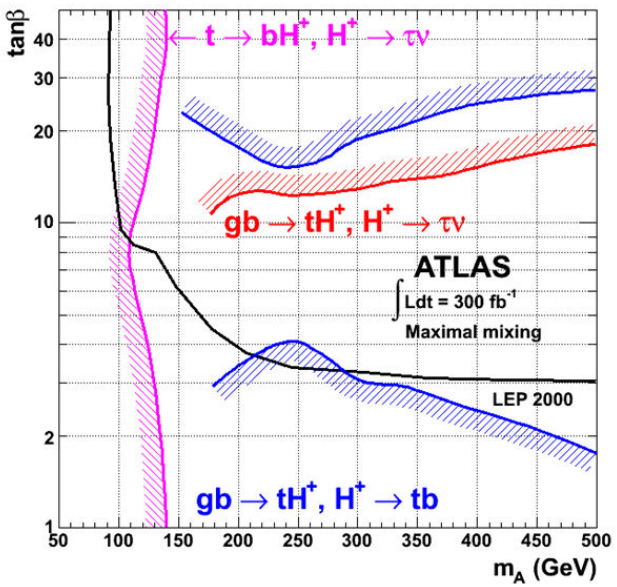


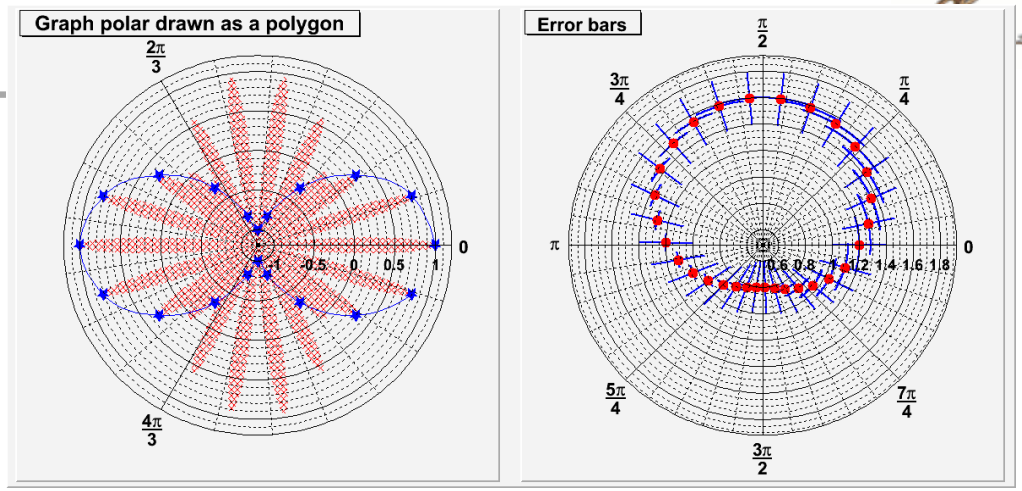


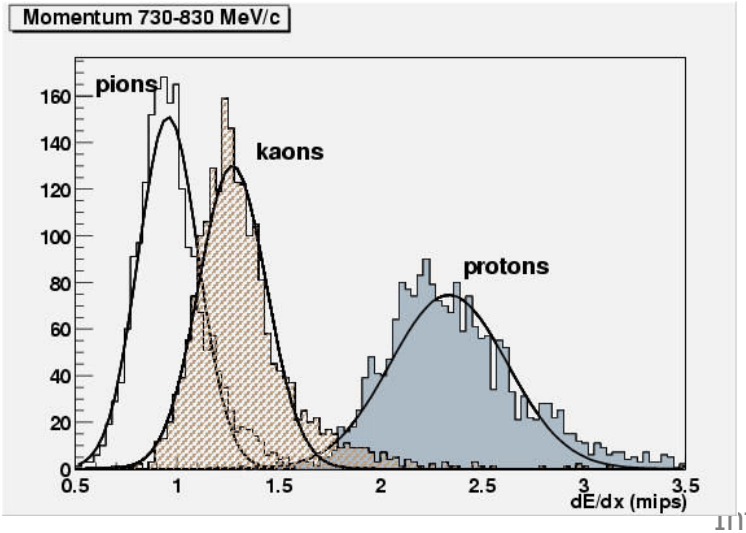


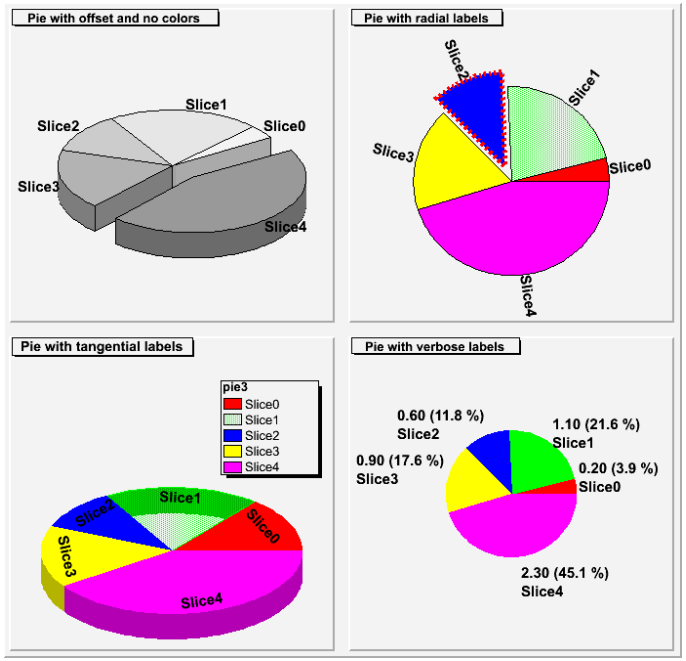


Special Graphics

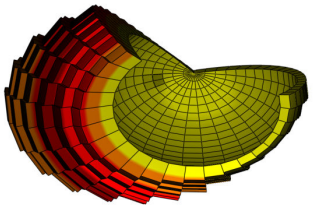


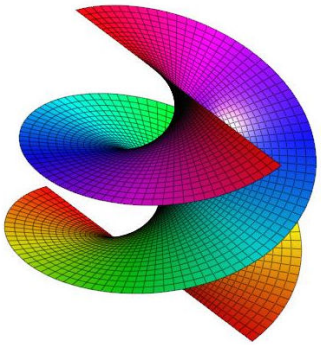


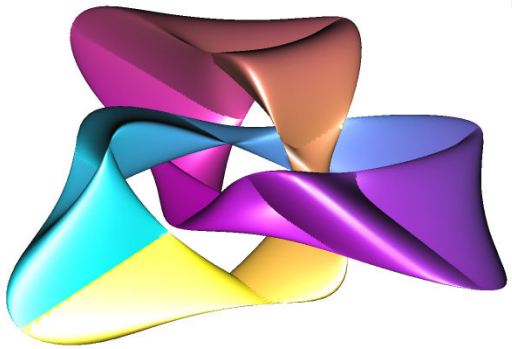


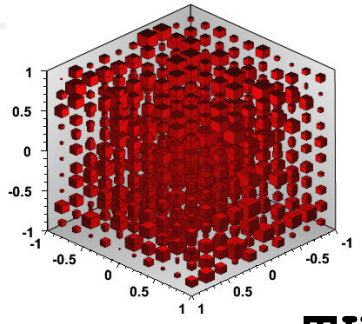


Graphics (2D-3D)



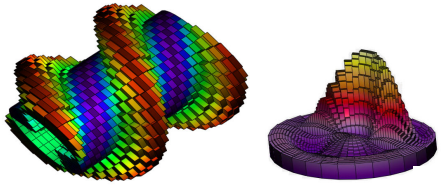


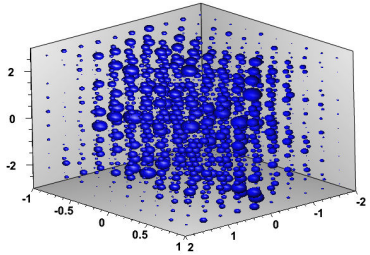


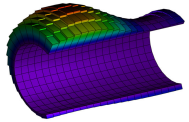


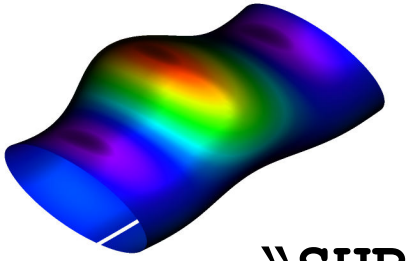
TH3

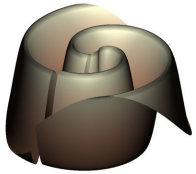
TGLParametric



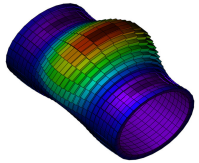




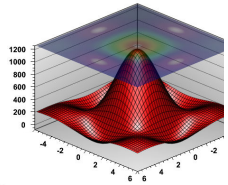


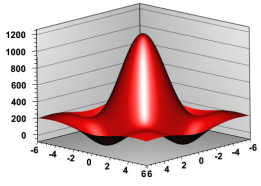


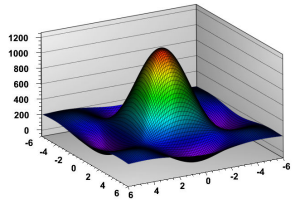
"LEGO"

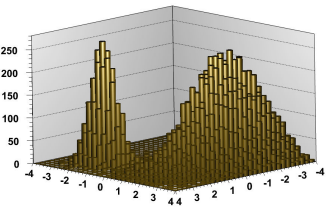


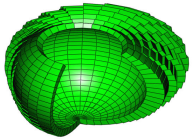
"SURF"

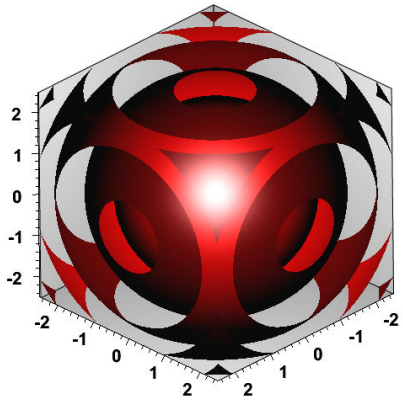






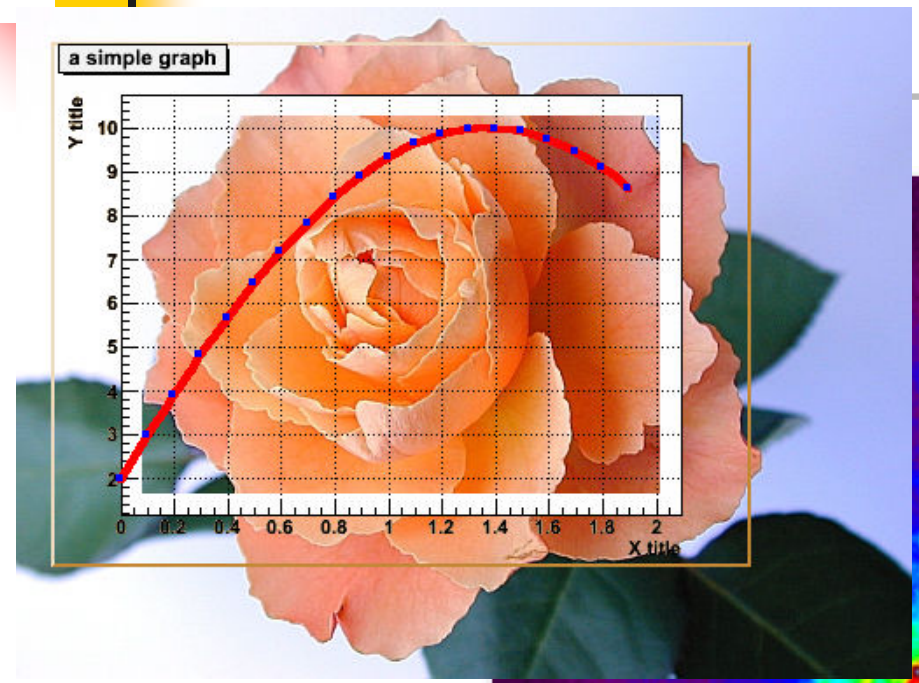


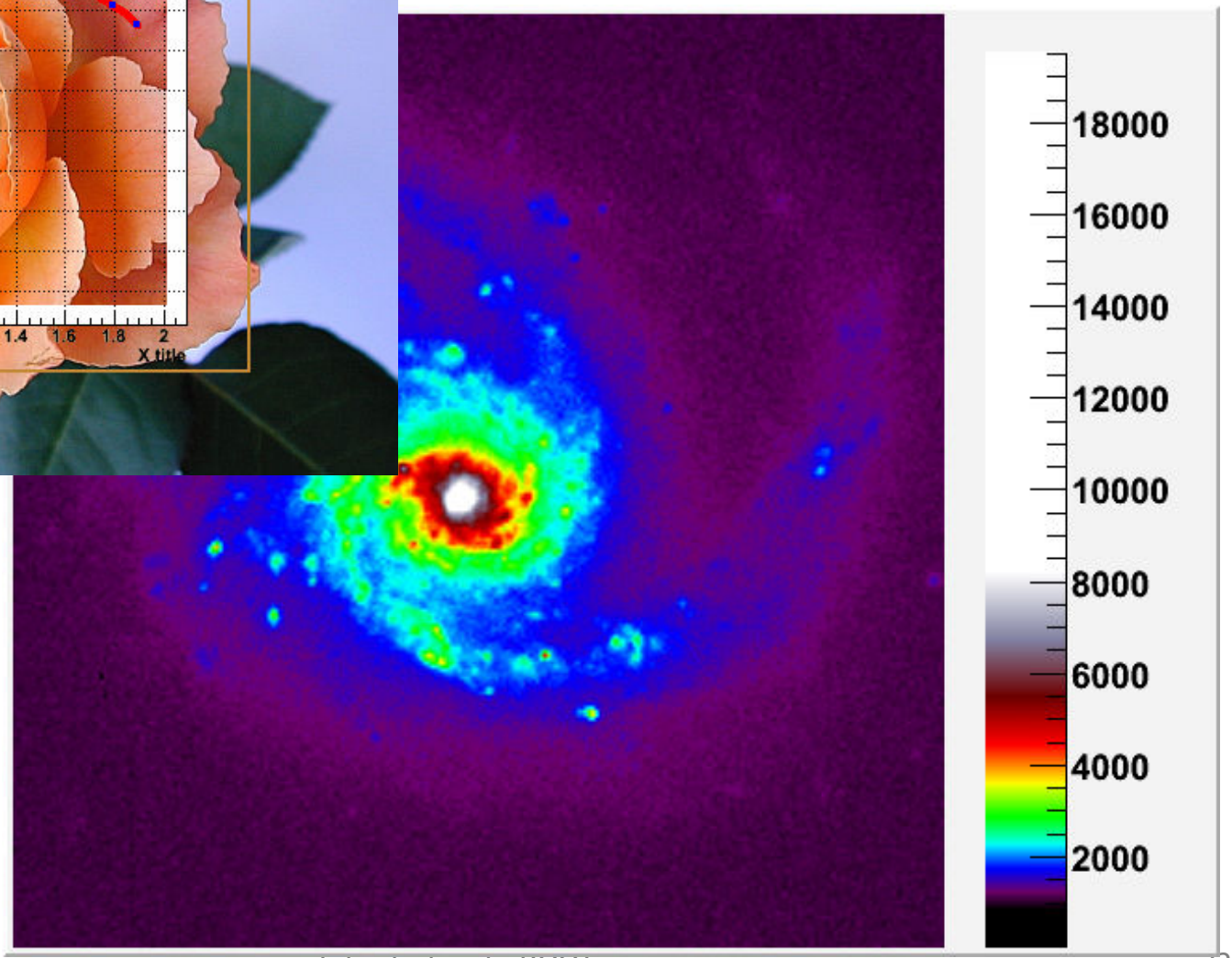




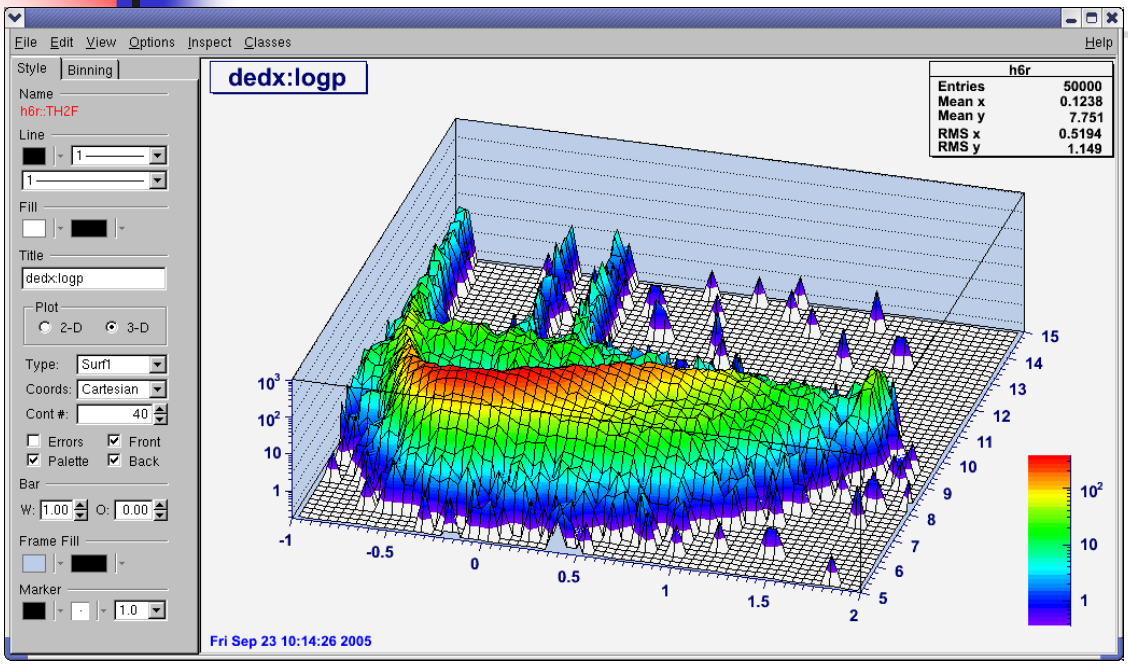
TF3

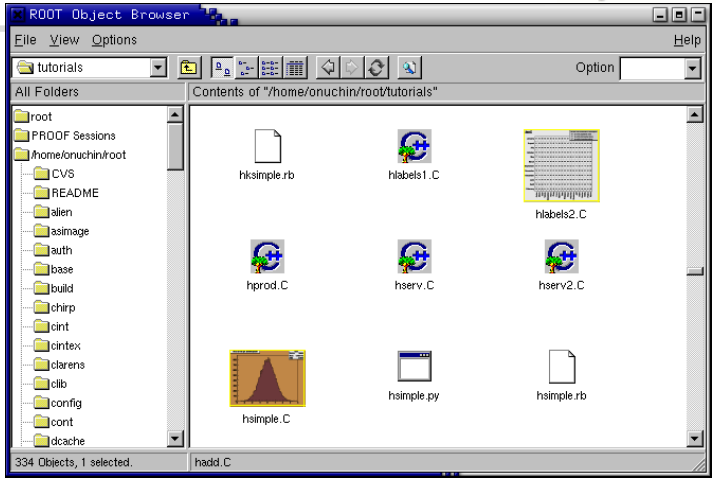
ASImage: Image processor

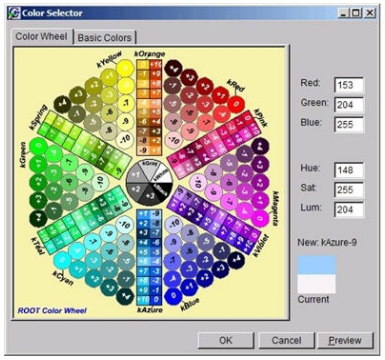


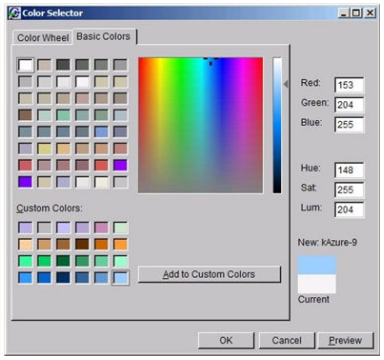


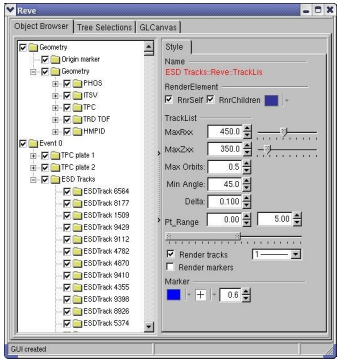
GUI (Graphical User Interface)

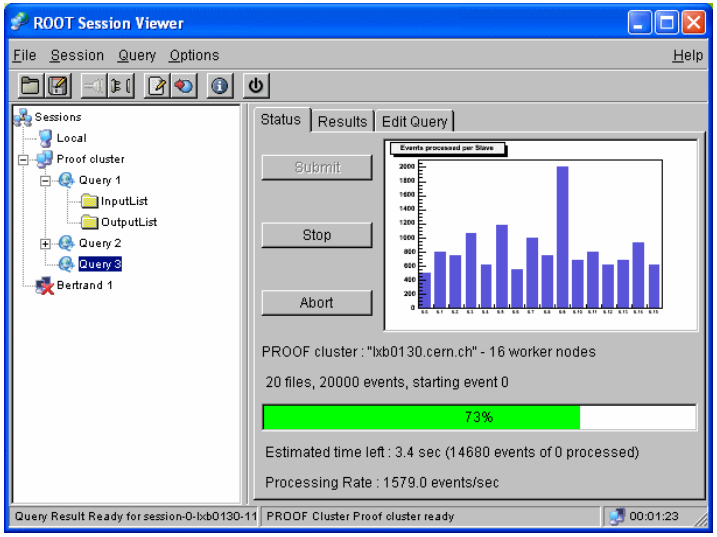




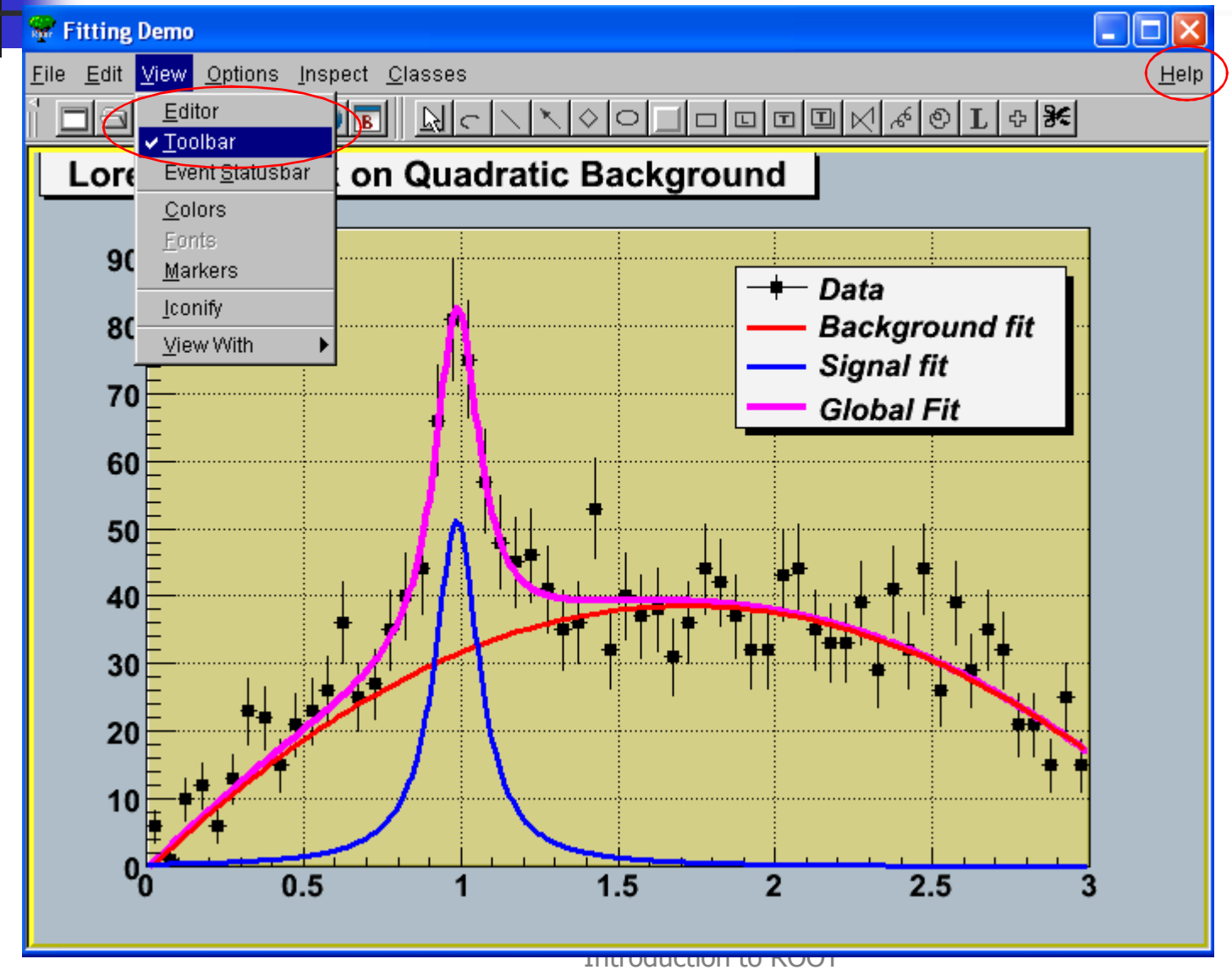




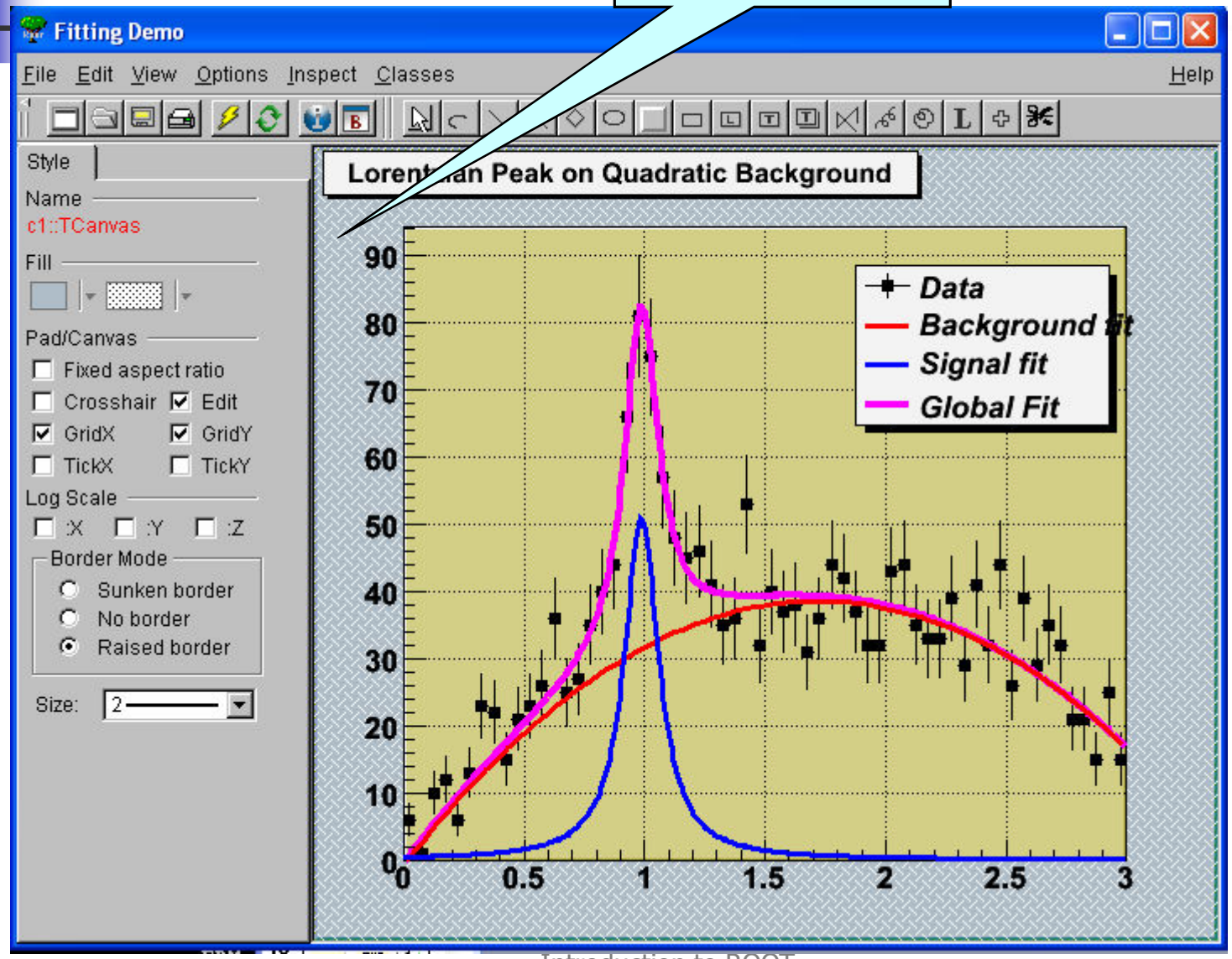




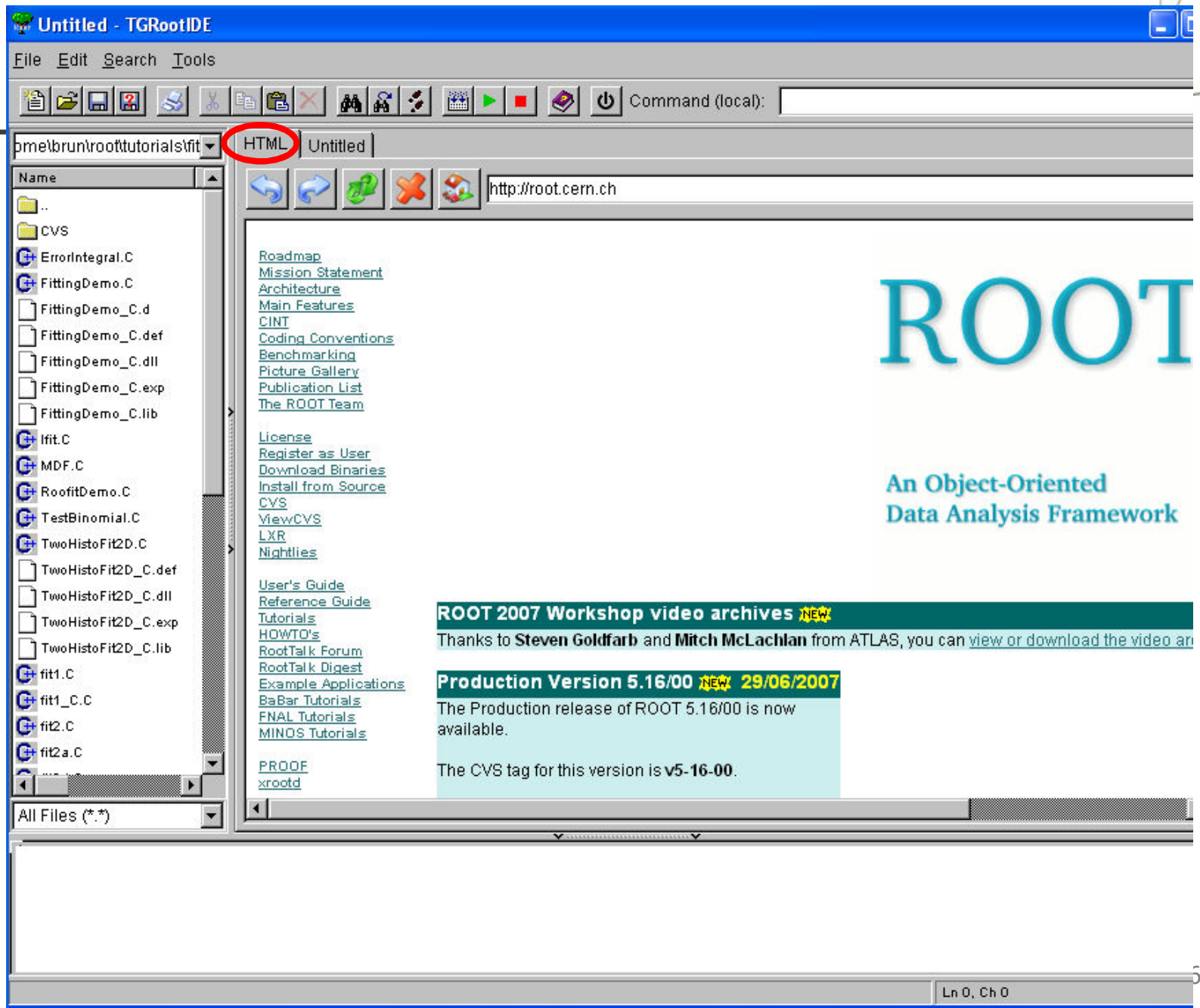
Canvas tool bar/menus/help



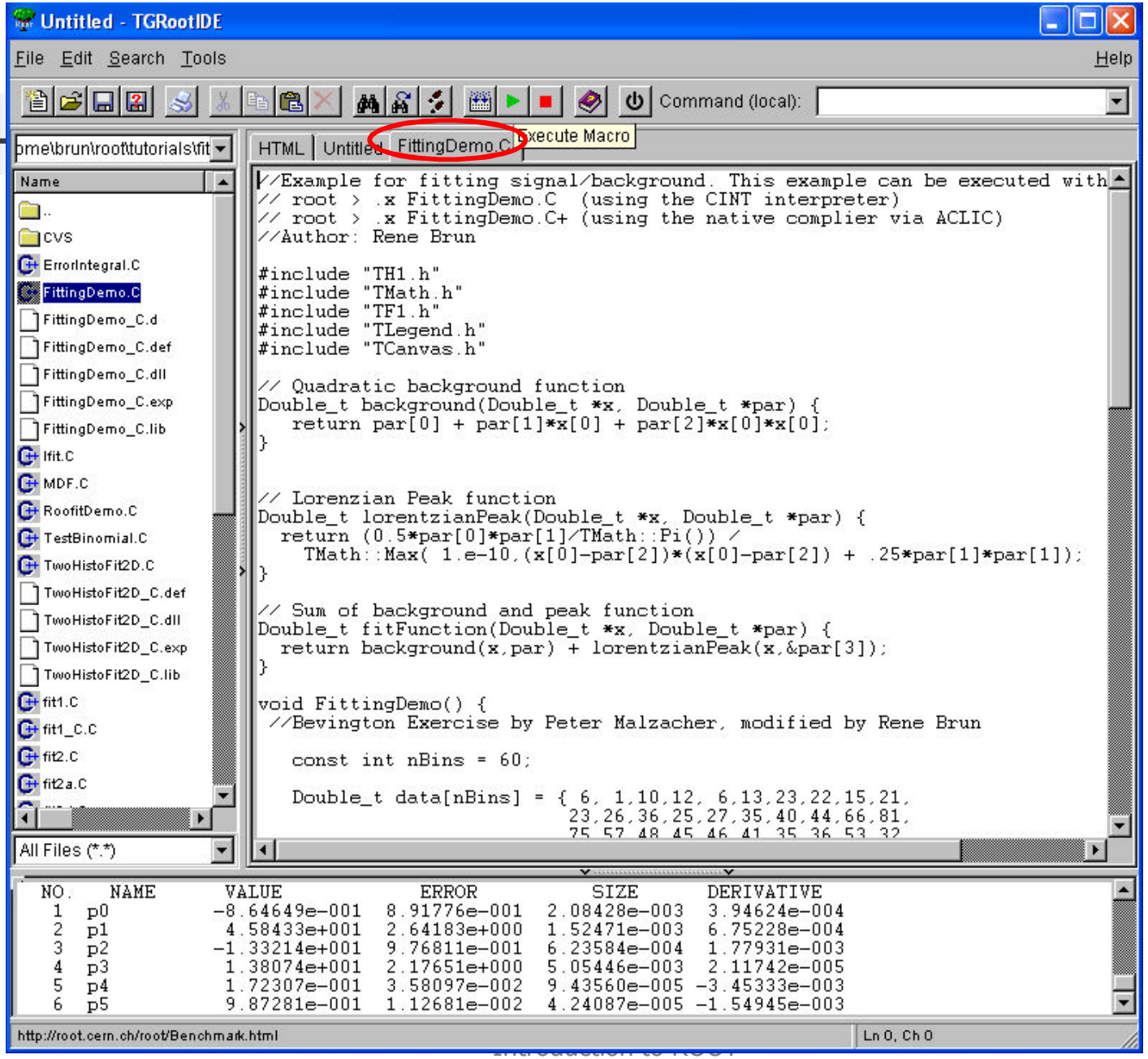
Object Editor



ROOT Browser

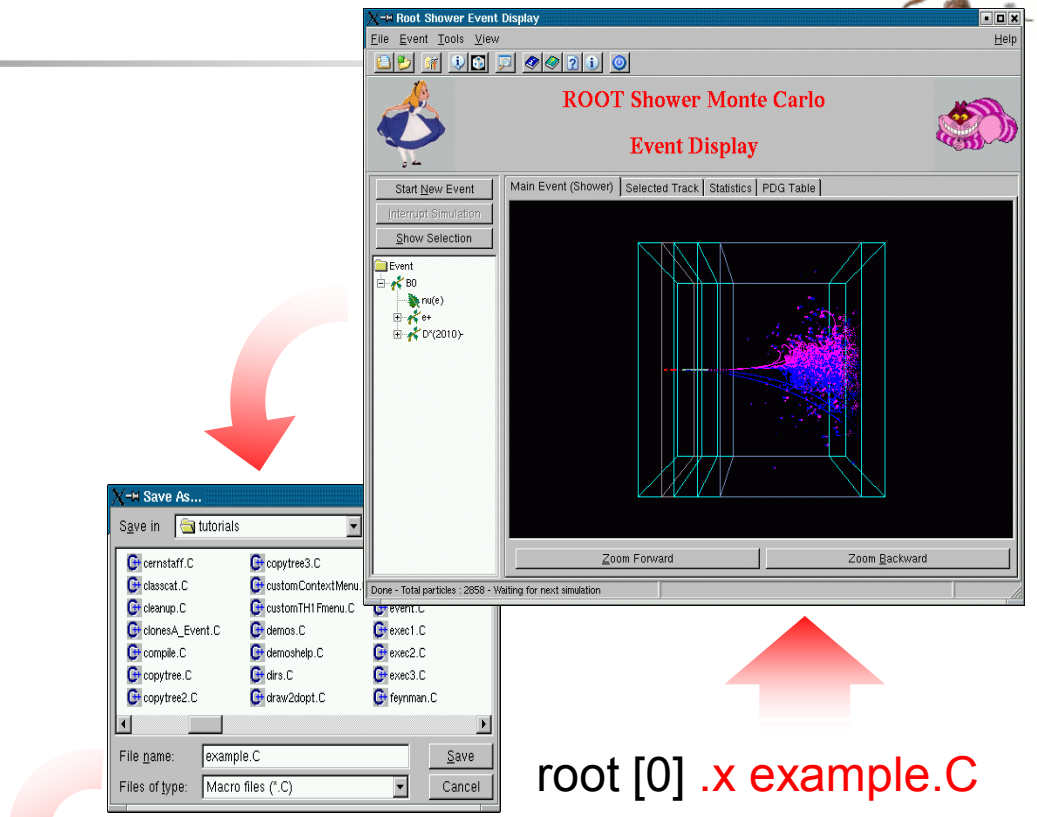


ROOT Browser



GUI C++ Code Generator

- When pressing *ctrl+S* on any widget it is **saved as a C++ macro file** thanks to the *SavePrimitive* methods implemented in all GUI classes. The generated macro can be edited and then executed via CINT
- Executing the macro restores the complete original GUI as well as all created signal/slot connections in a global way

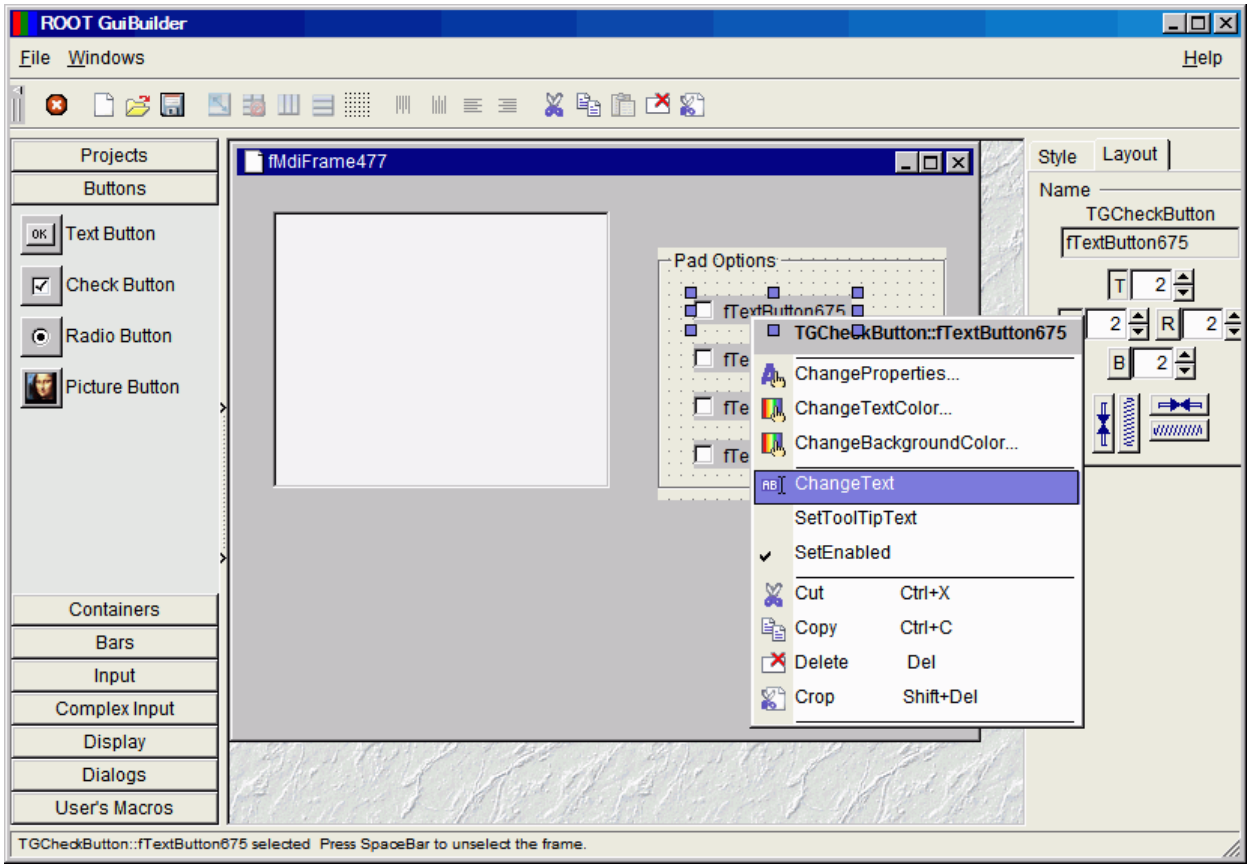



```
 // transient frame
 TGTransientFrame *frame2 = new TGTransientFrame(gClient-
>GetRoot(),760,590);
 // group frame
 TGGroupFrame *frame3 = new TGGroupFrame(frame2,"curve");

 TGRadioButton *frame4 = new TGRadioButton(frame3,"gaus",10);
 frame3->AddFrame(frame4);
```

The GUI Builder

- The GUI builder provides GUI tools for developing user interfaces based on the ROOT GUI classes. It includes over 30 advanced widgets and an automatic C++ code generator.

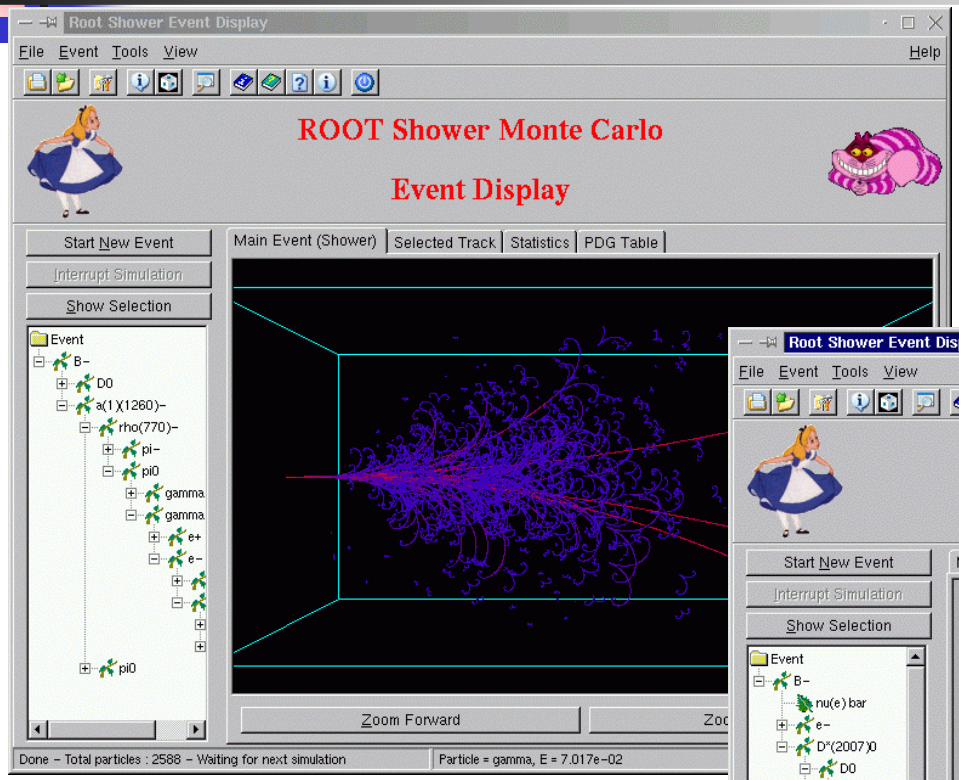


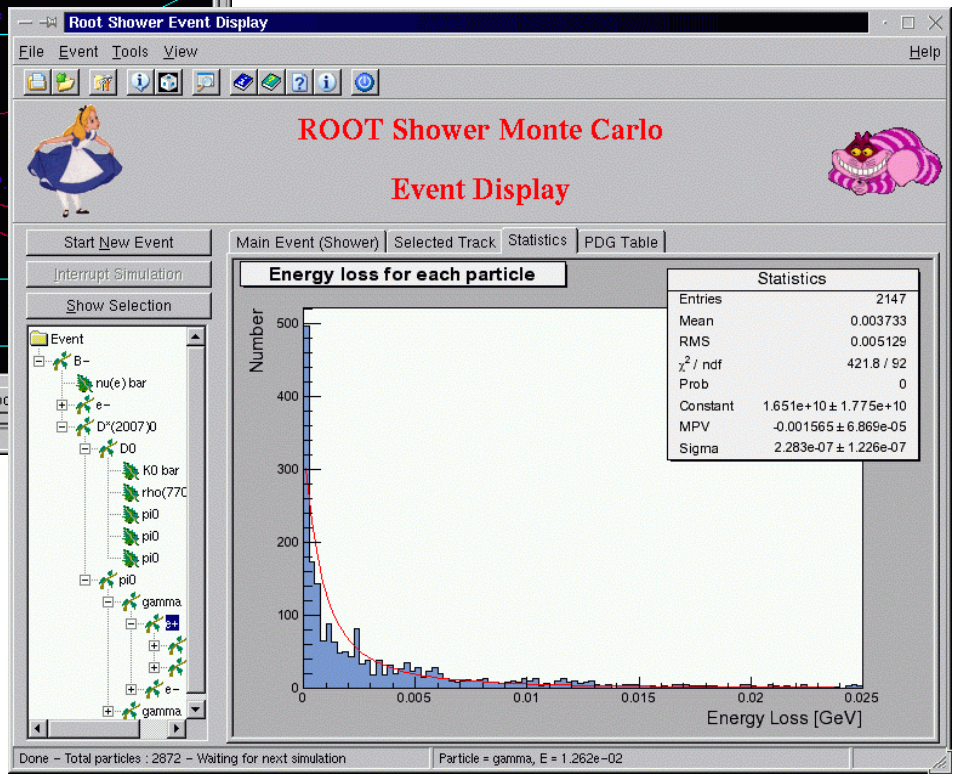
More GUI Examples

$ROOTSYS/tutorials/gui

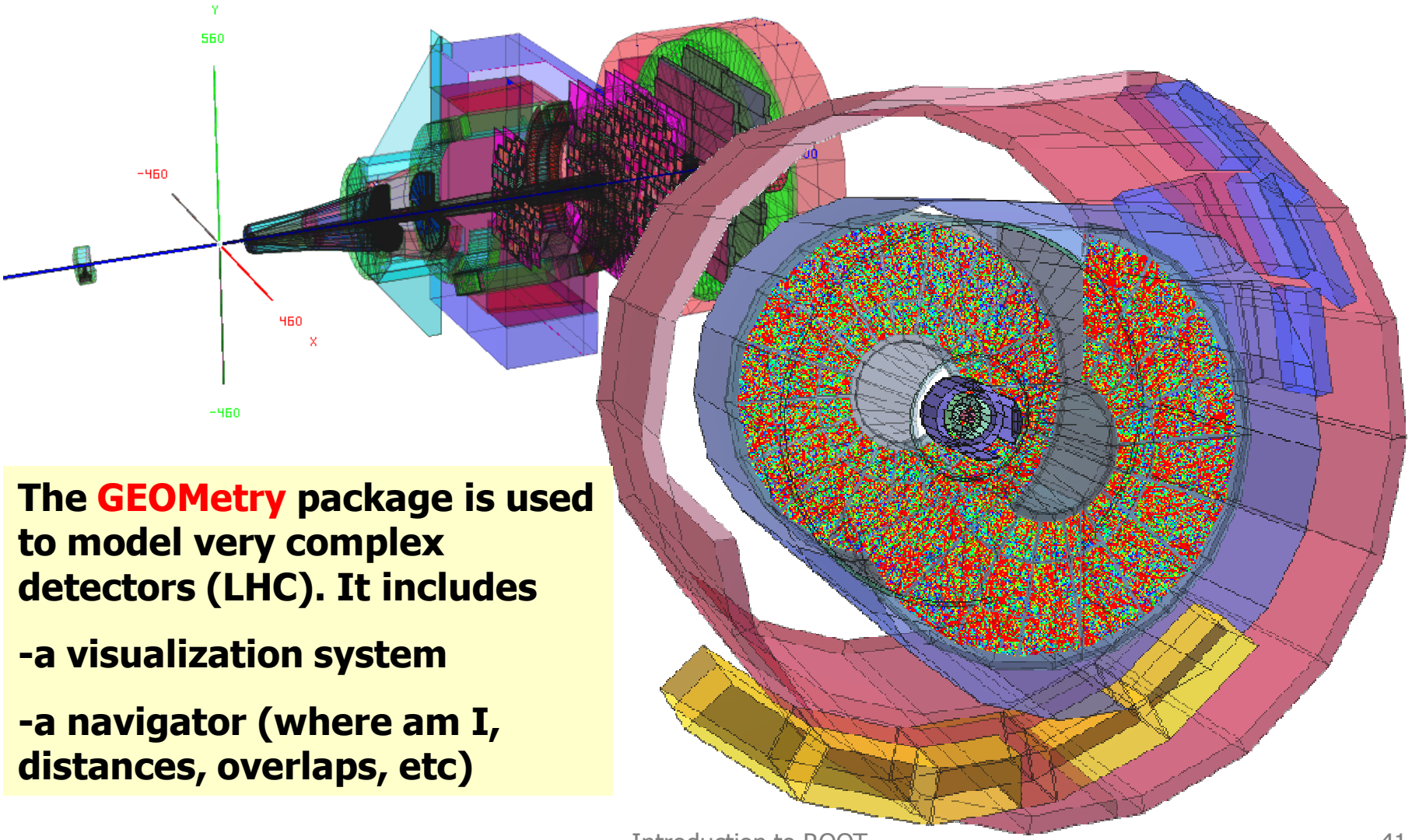
$ROOTSYS/test/RootShower

$ROOTSYS/test/RootIDE





Geometry

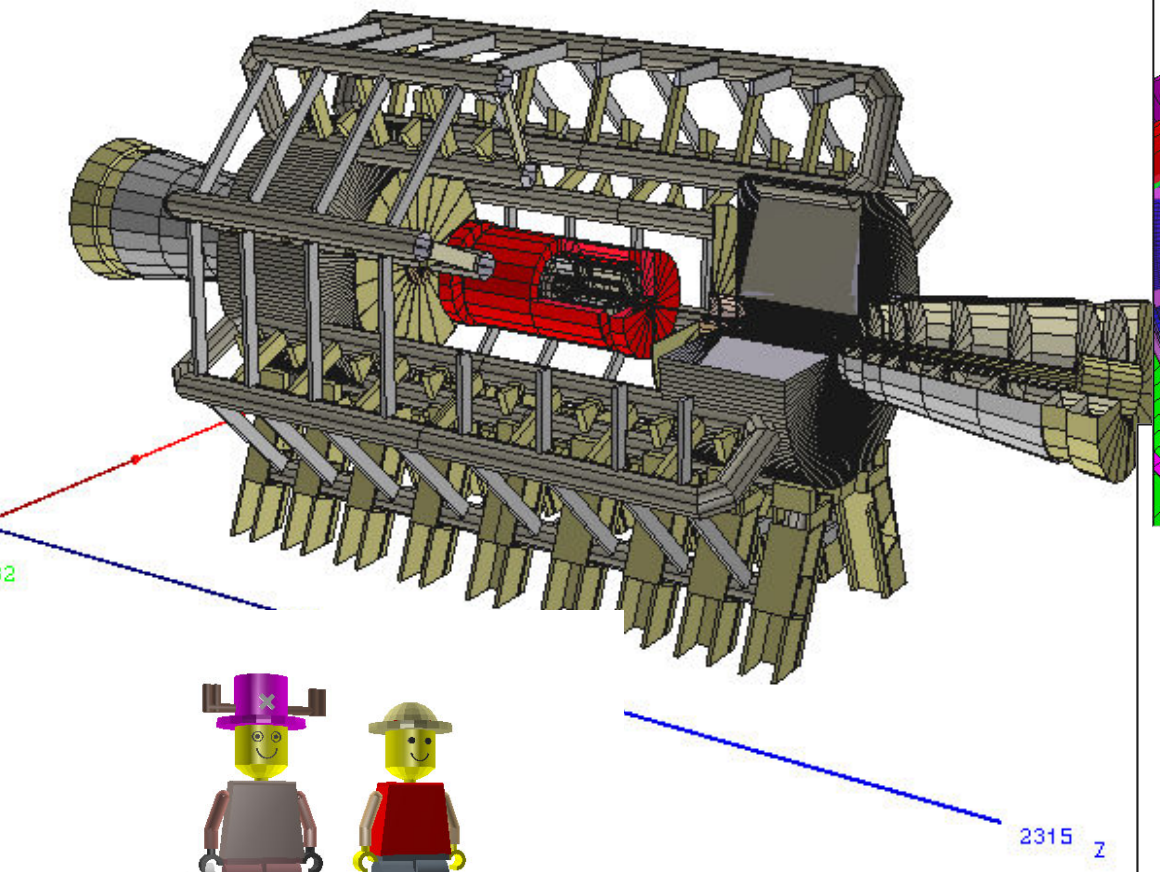


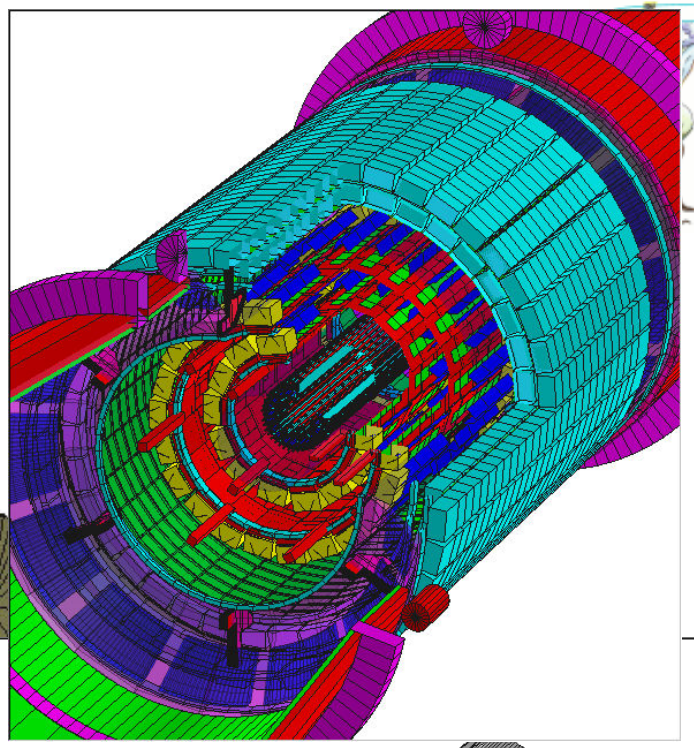
The GEOMetry package is used to model very complex detectors (LHC). It includes

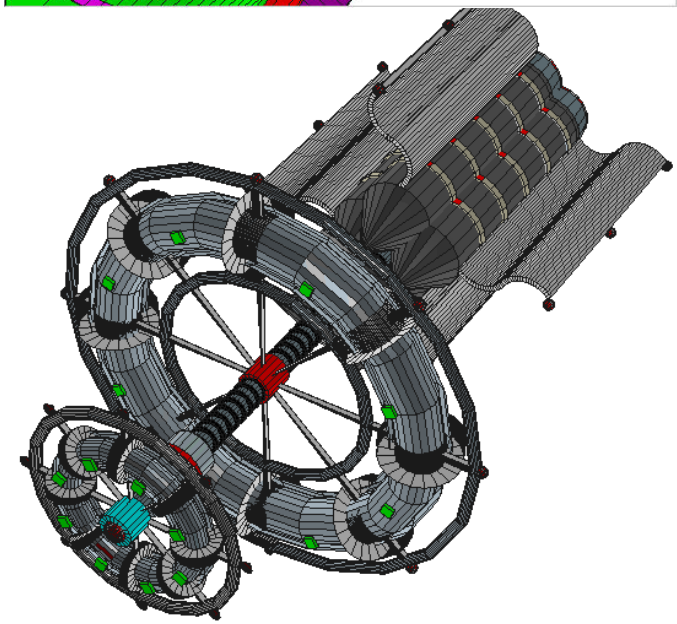
-a visualization system

-a navigator (where am I, distances, overlaps, etc)

OpenGL

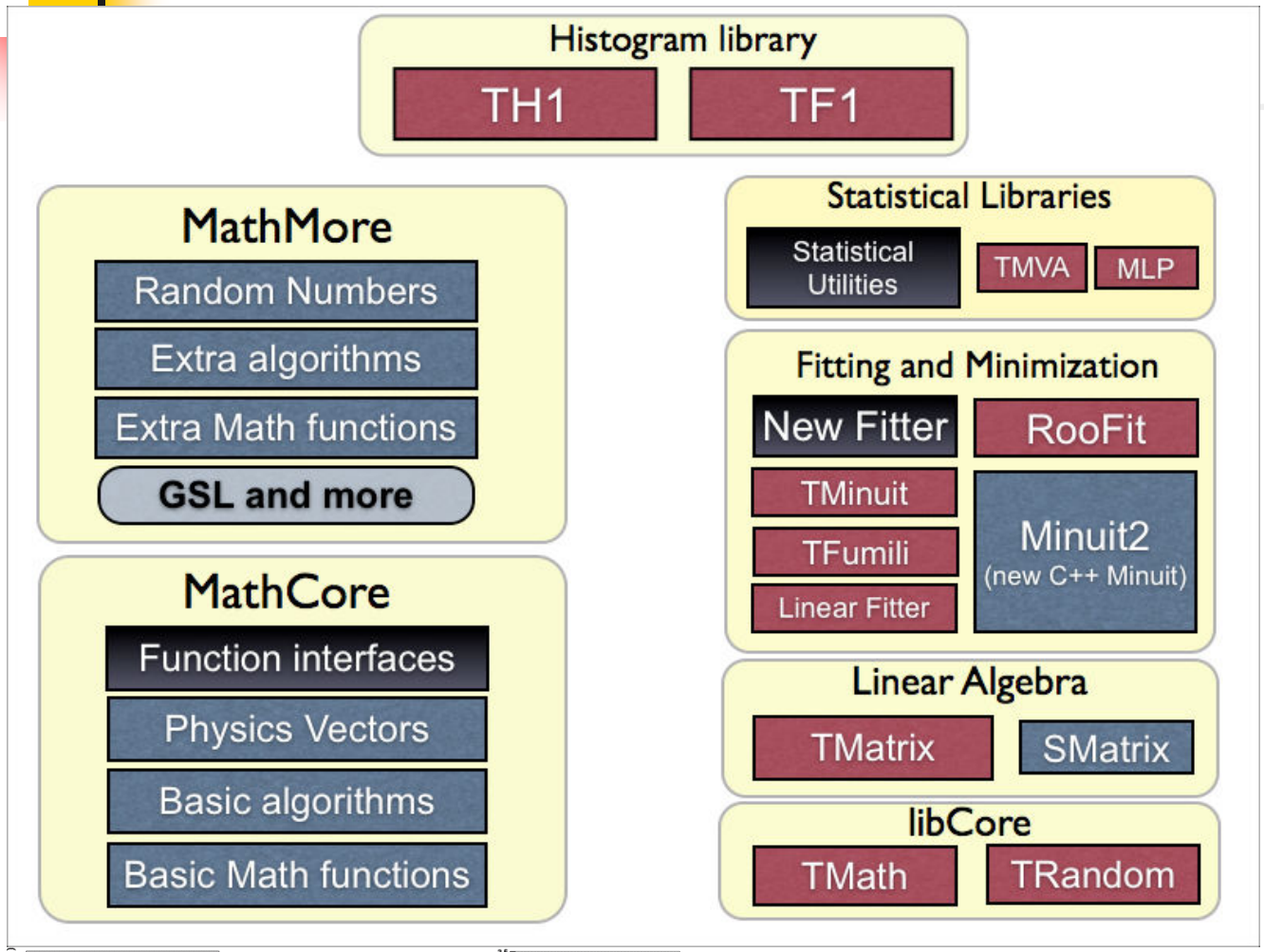


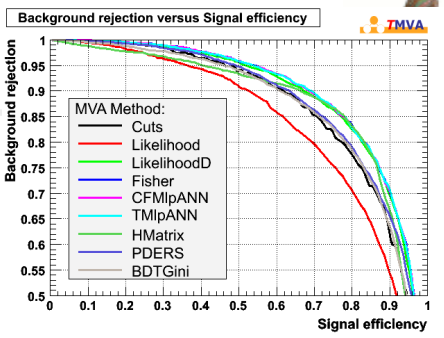


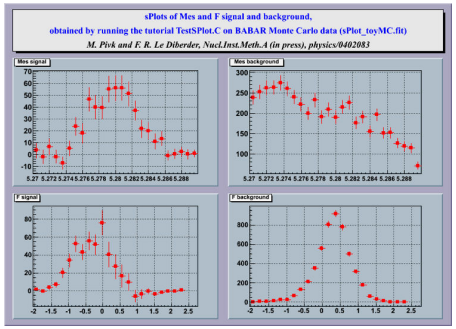


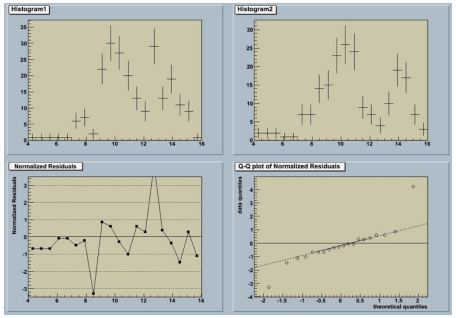
see $ROOTSYS/tutorials/geom

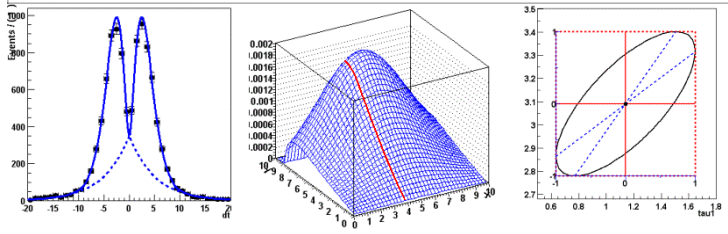
Math Libraries





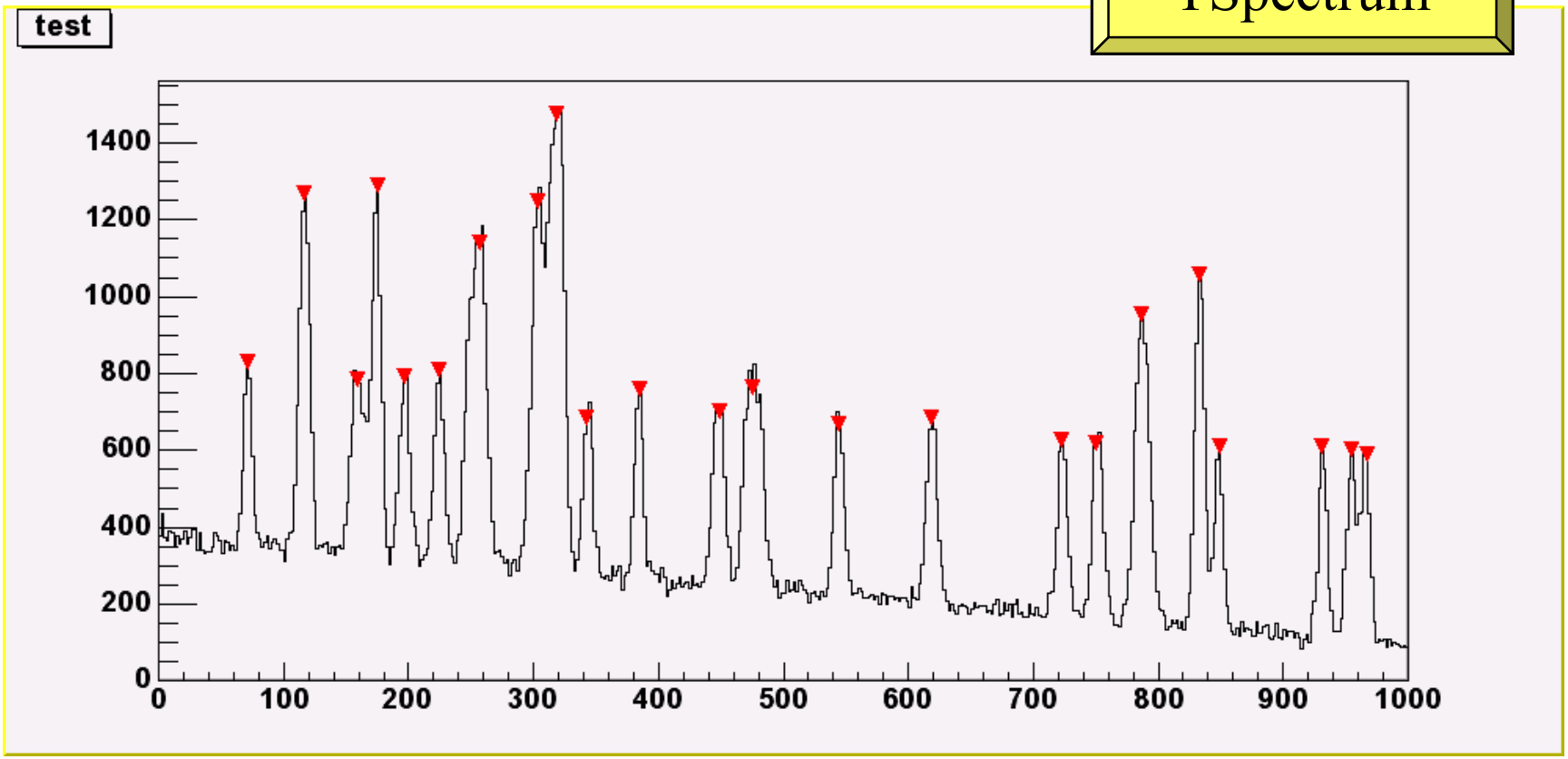




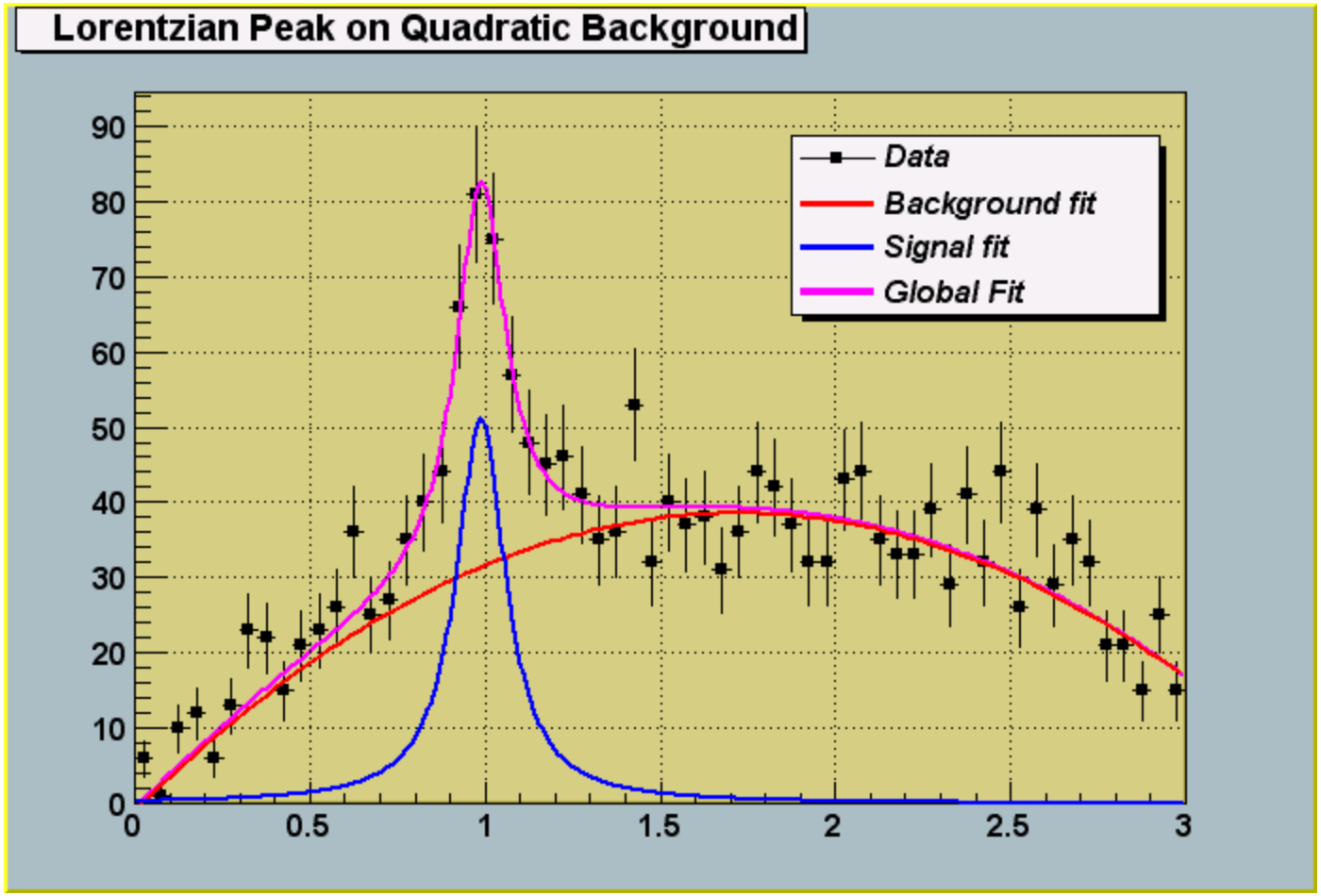


Peak Finder + Deconvolutions

TSpectrum

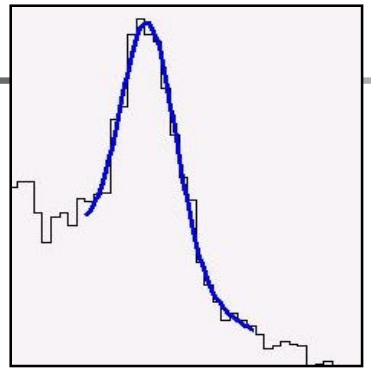


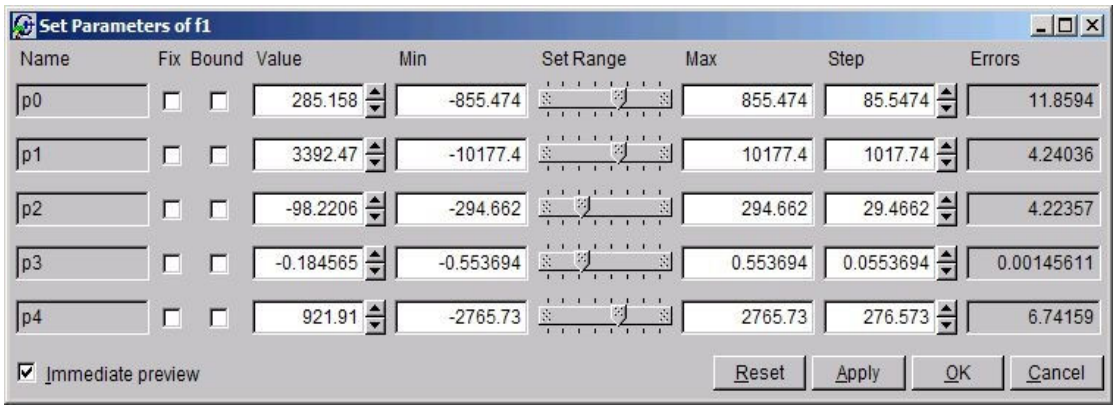
Fitters

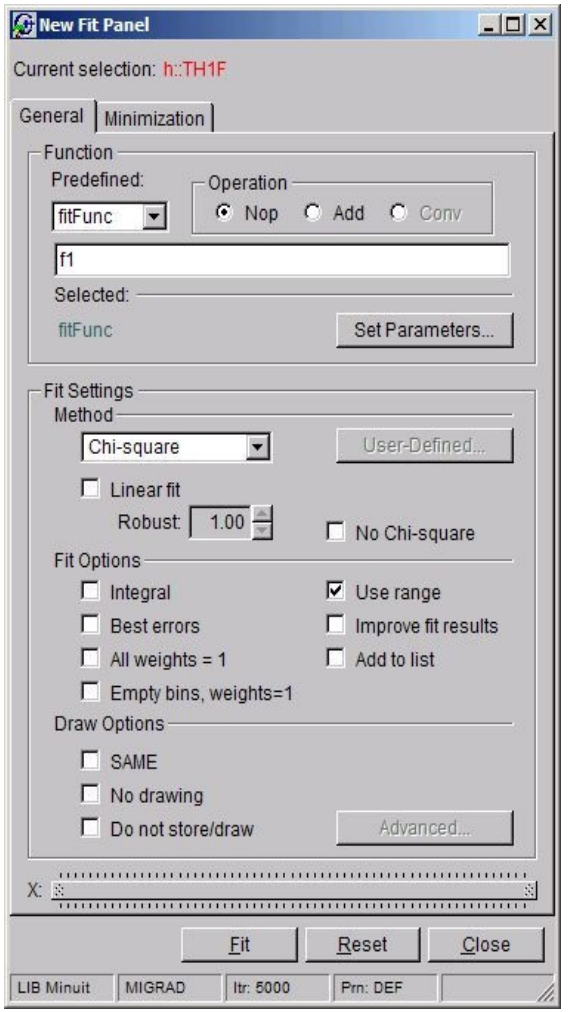


- Minuit
- Fumili
- LinearFitter
- RobustFitter
- RooFit

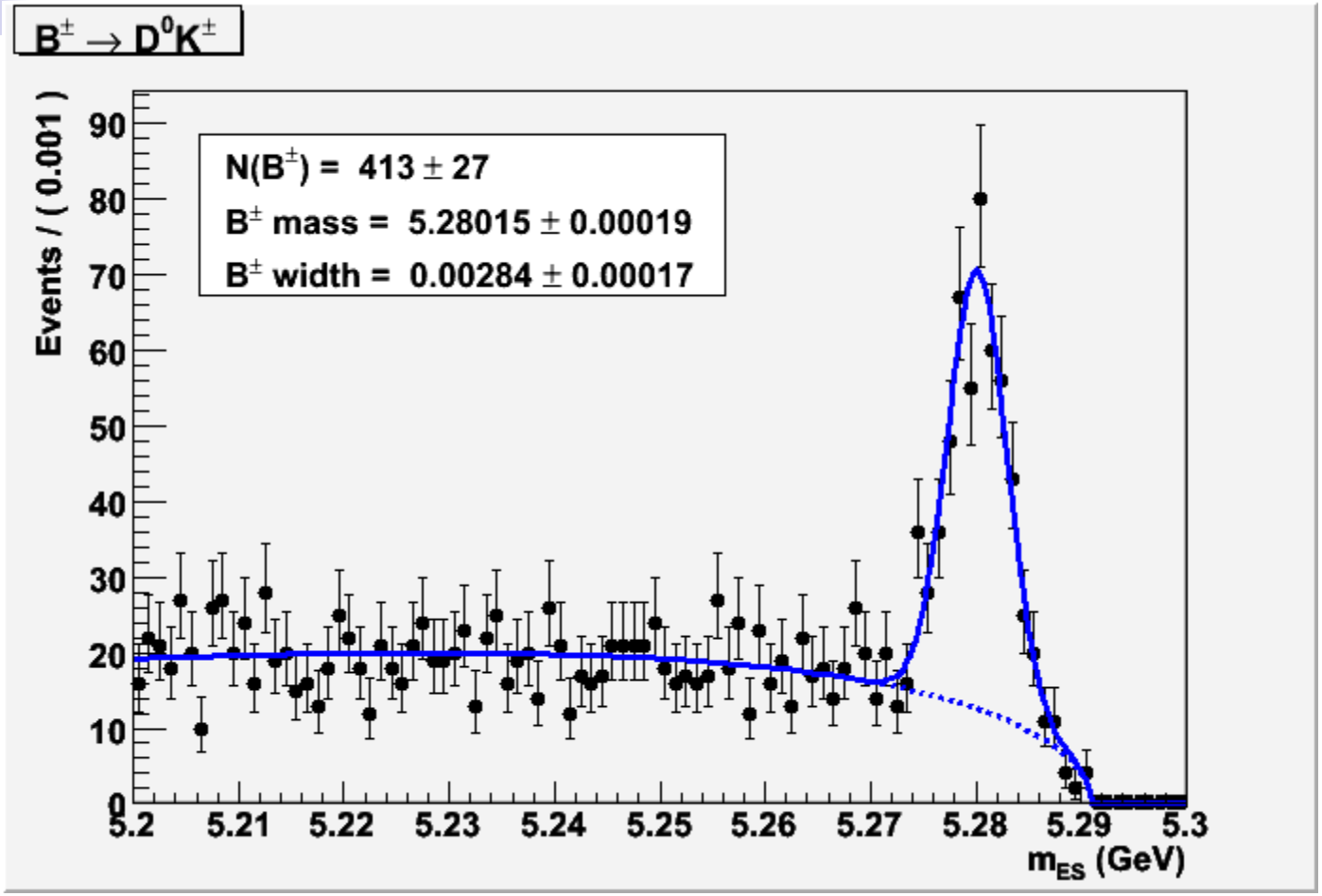
Fit Panel




Set Parameters of f1
Name Fix Bound Value Min Set Range Max Step Errors
p0 285.158 -855.474 855.474 85.5474 11.8594
p1 3392.47 -10177.4 10177.4 1017.74 4.24036
p2 -98.2206 -294.662 294.662 29.4662 4.22357
p3 -0.184565 -0.553694 0.553694 0.0553694 0.00145611
p4 921.91 -2765.73 2765.73 276.573 6.74159
Immediate preview
Reset Apply OK Cancel


New Fit Panel
Current selection: h::TH1F
General Minimization
Function
Predefined:
fitFunc
Operation
Nop Add Conv
f1
Selected:
fitFunc
Set Parameters...
Fit Settings
Method
Chi-square
User-Defined...
Linear fit
Robust: 1.00
No Chi-square
Fit Options
Integral
Best errors
All weights = 1
Empty bins, weights=1
Use range
Improve fit results
Add to list
Draw Options
SAME
No drawing
Do not store/draw
Advanced...
X:
Fit Reset Close
LIB Minuit MIGRAD Itr: 5000 Prn: DEF

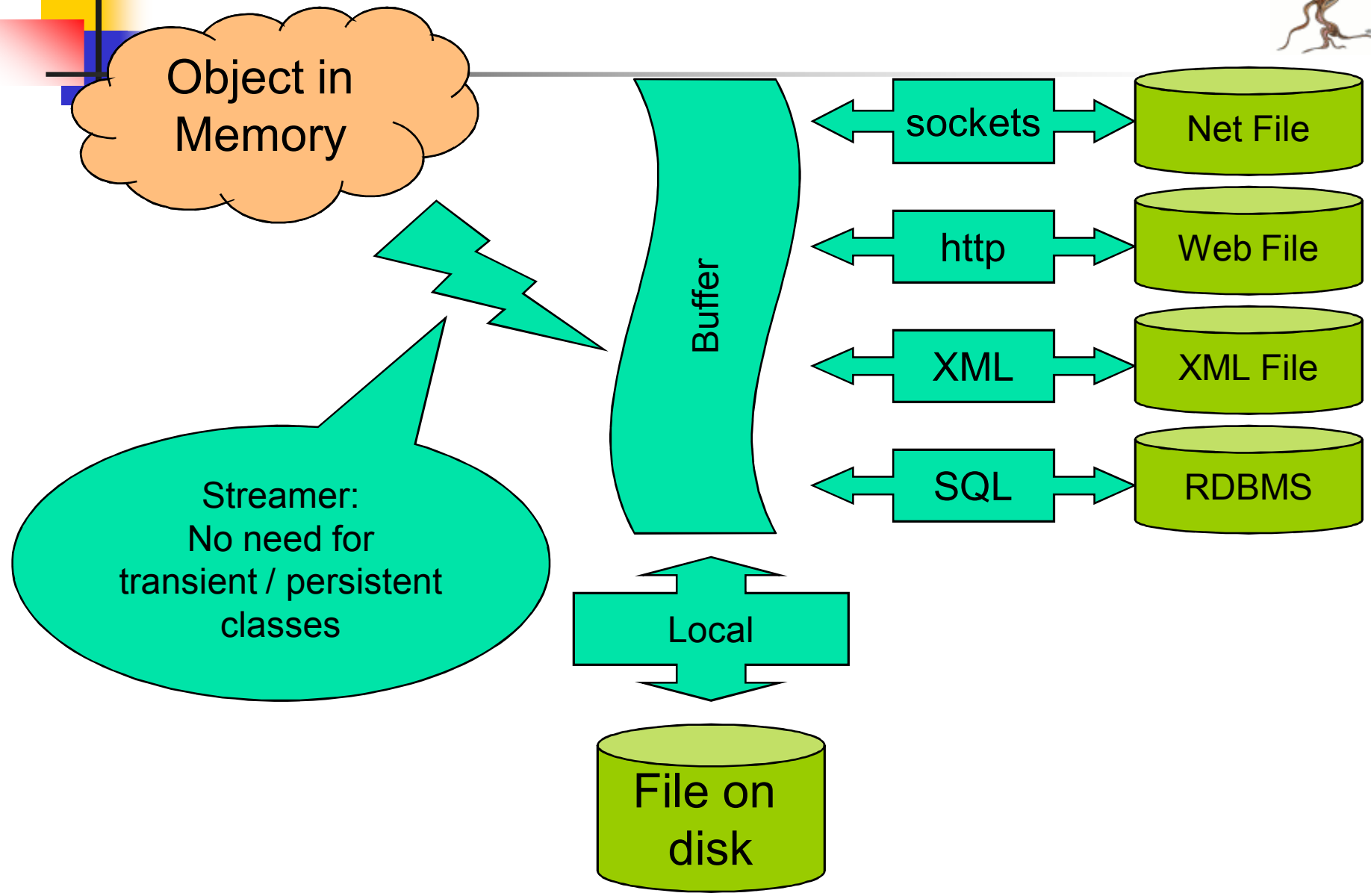
RooFit: a Powerful Fitting Framework



see $ROOTSYS/tutorials/roofit/RoofitDemo.C

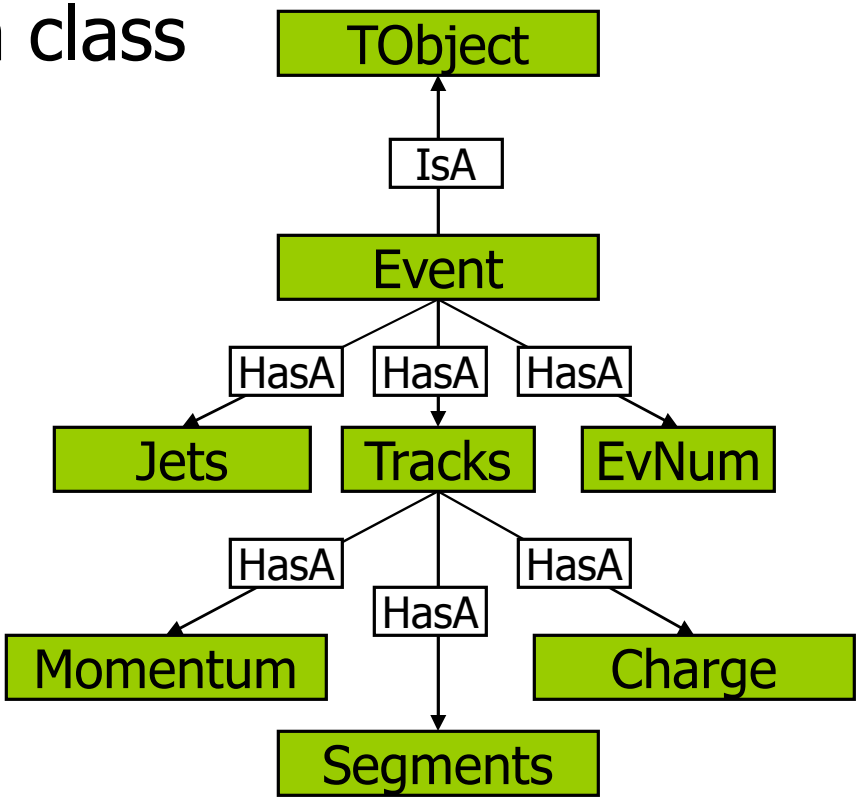
Input/Output

I/O


Object in Memory
Buffer
sockets
Net File
http
Web File
XML
XML File
SQL
RDBMS
Streamer:
No need for
transient / persistent
classes
Local
File on
disk

Object Oriented Concepts

- Class: the description of a "thing" in the system
- Object: instance of a class
- Methods: functions for a class
  - Members: a "has a" relationship to the class.
  - Inheritance: an "is a" relationship to the class.



TFile / TDirectory

- A TFile object may be divided in a hierarchy of directories, like a Unix file system.
- Two I/O modes are supported
  - Key-mode (TKey). An object is identified by a name (key), like files in a Unix directory. OK to support up to a few thousand objects, like histograms, geometries, mag fields, etc.
  - TTree-mode to store event data, when the number of events may be millions, billions.

Self-describing Files

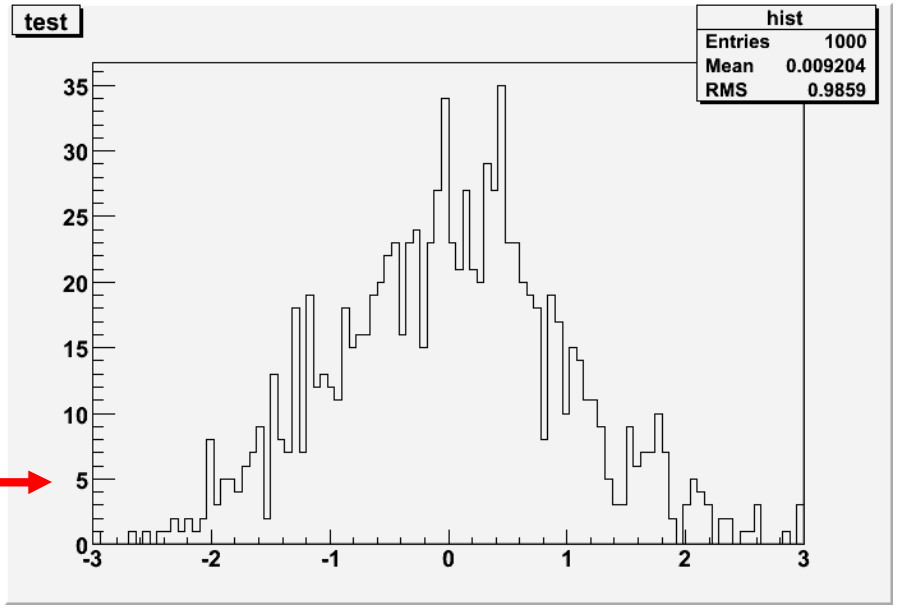
- Dictionary for persistent classes written to the file
- ROOT files are self describing
- Support for Backward and Forward compatibility
- Files created in 2001 must be readable in 2015
- Classes (data objects) for all objects in a file can be regenerated via TFile::MakeProject

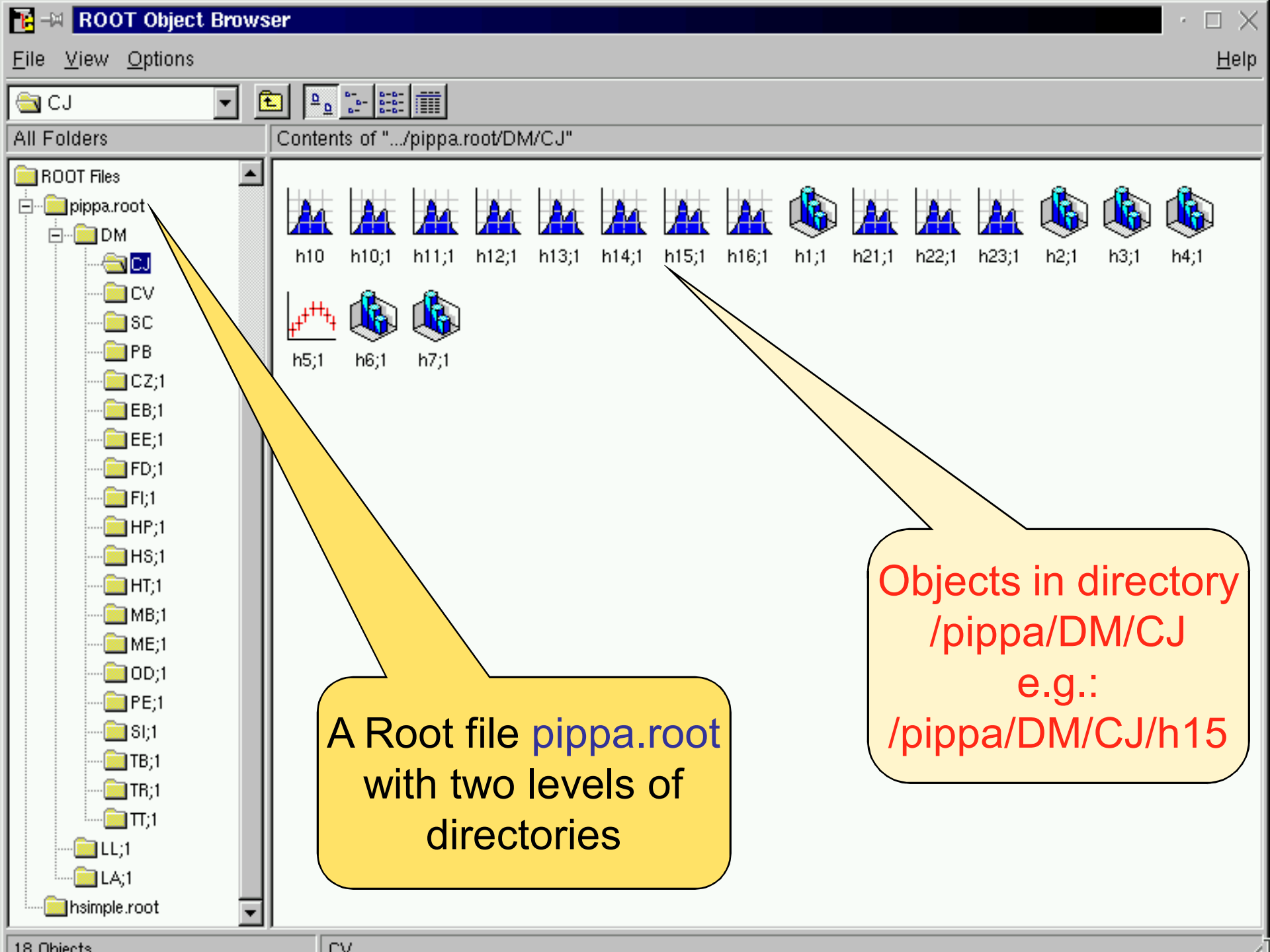
```
Root >TFile f("demo.root");
Root > f.MakeProject("dir","*","new++");
```

Example of Key Mode

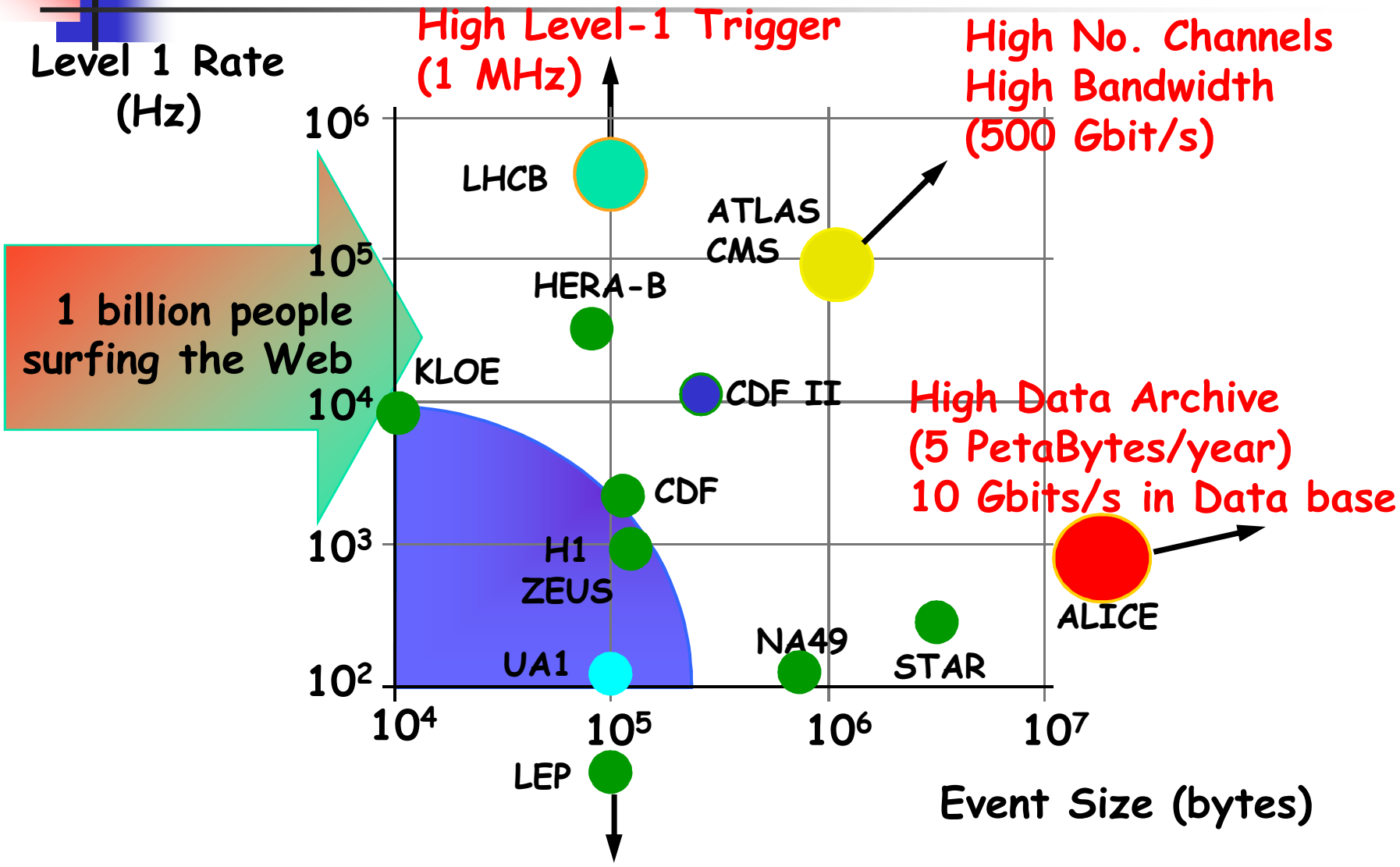
```
void keywrite() {
   TFile f("keymode.root","new");
   TH1F h("hist","test",100,-3,3);
   h.FillRandom("gaus",1000);
   h.Write()
}
```

```
void keyRead() {
   TFile f("keymode.root");
   TH1F *h = (TH1F*)f.Get("hist");;
   h.Draw();
}
```

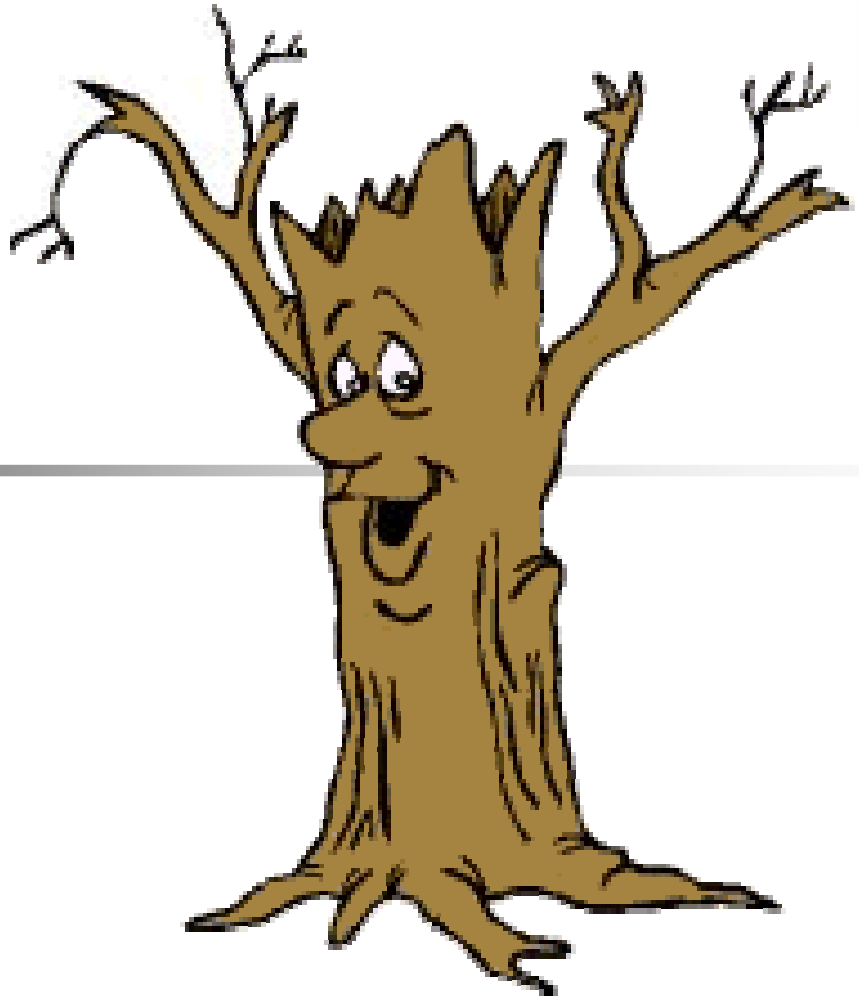



ROOT Object Browser
File View Options Help
CJ
All Folders
Contents of ".../pippa.root/DM/CJ"
ROOT Files
pippa.root
DM
CJ
CV
SC
PB
CZ;1
EB;1
EE;1
FD;1
FI;1
HP;1
HS;1
HT;1
MB;1
ME;1
OD;1
PE;1
SI;1
TB;1
TR;1
TT;1
LL;1
LA;1
hsimple.root
h10
h10;1
h11;1
h12;1
h13;1
h14;1
h15;1
h16;1
h1;1
h21;1
h22;1
h23;1
h2;1
h3;1
h4;1
h5;1
h6;1
h7;1
A Root file pippa.root with two levels of directories
Objects in directory /pippa/DM/CJ e.g.: /pippa/DM/CJ/h15

LHC: How Much Data?



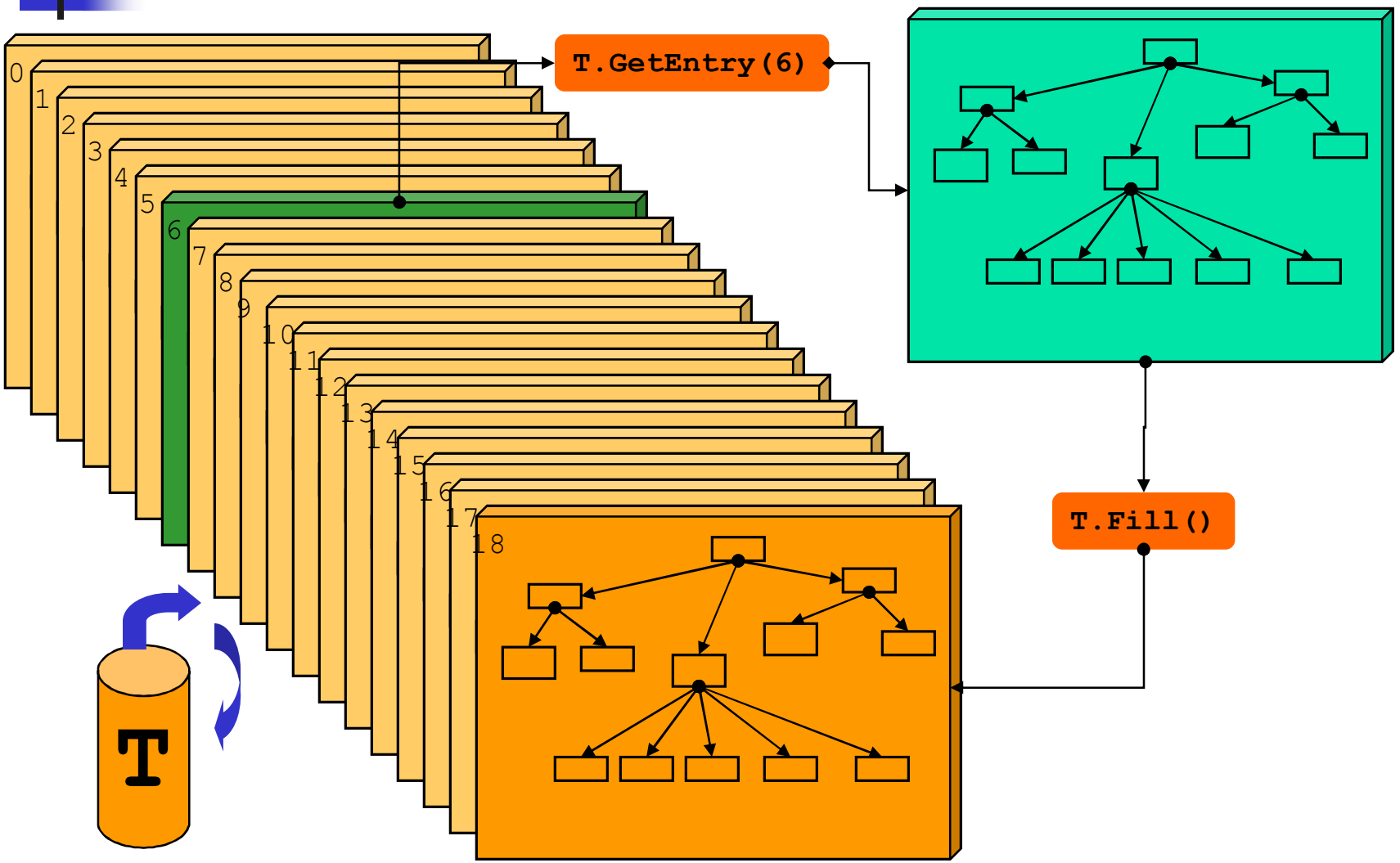
ROOT Trees



Why Trees ?

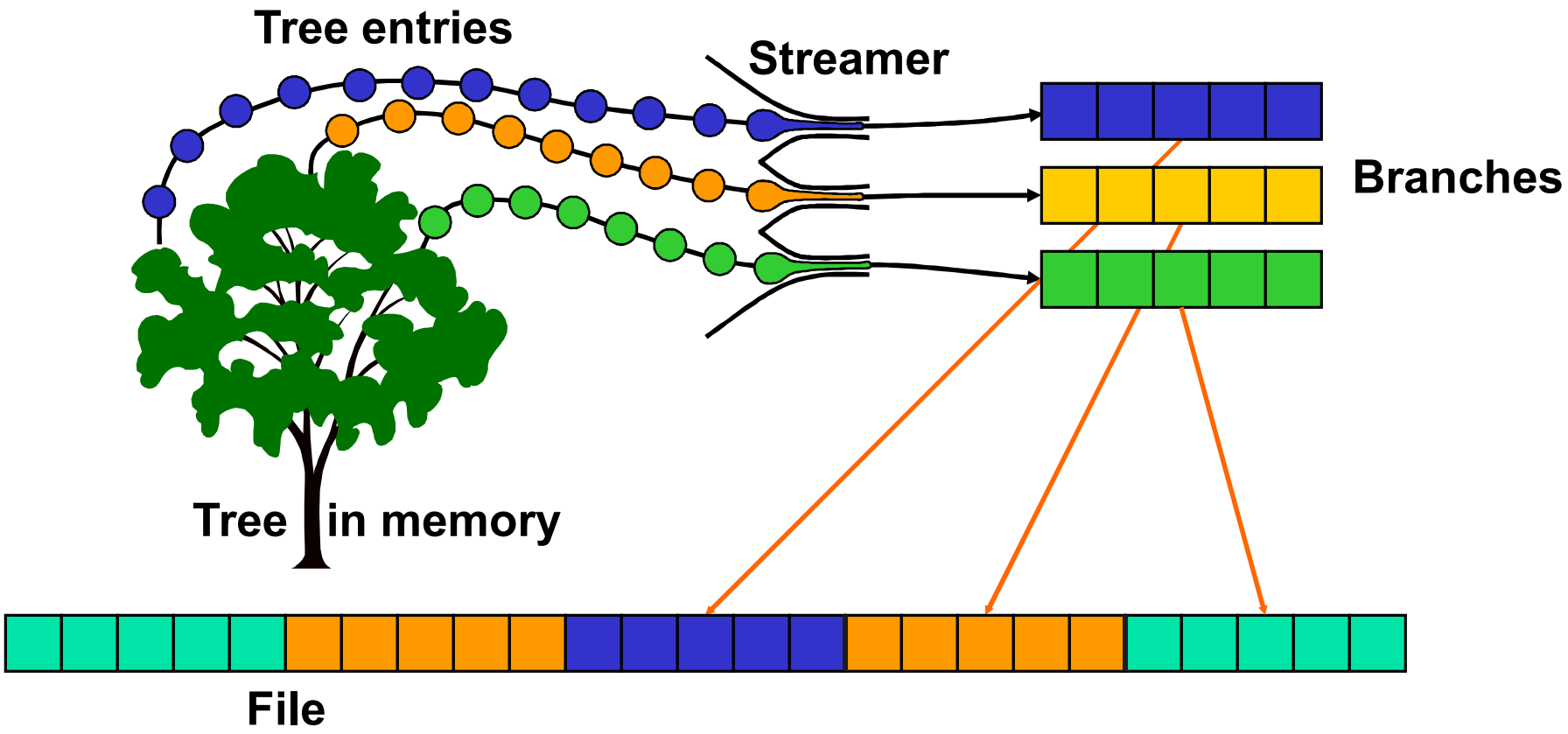
- Trees have been designed to support very large collections of objects. The overhead in memory is in general less than 4 bytes per entry.
- Trees allow direct and random access to any entry (sequential access is the best)
- Trees have branches and leaves. One can read a subset of all branches.
- High level functions like TTree::Draw loop on all entries with selection expressions.
- Trees can be browsed via TBrowser
- Trees can be analyzed via TTreeViewer

Memory <--> Tree
Each Node is a Branch in the Tree



ROOT I/O -- *Split/Cluster*

Tree version



Writing/Reading a Tree

Event.h

```
class Event : public Something  {
 Header                fHeader;
 std::list<Vertex*> fVertices;
 std::vector<Track> fTracks;
 TOF                   fTOF;
 Calor                *fCalor;
}
```

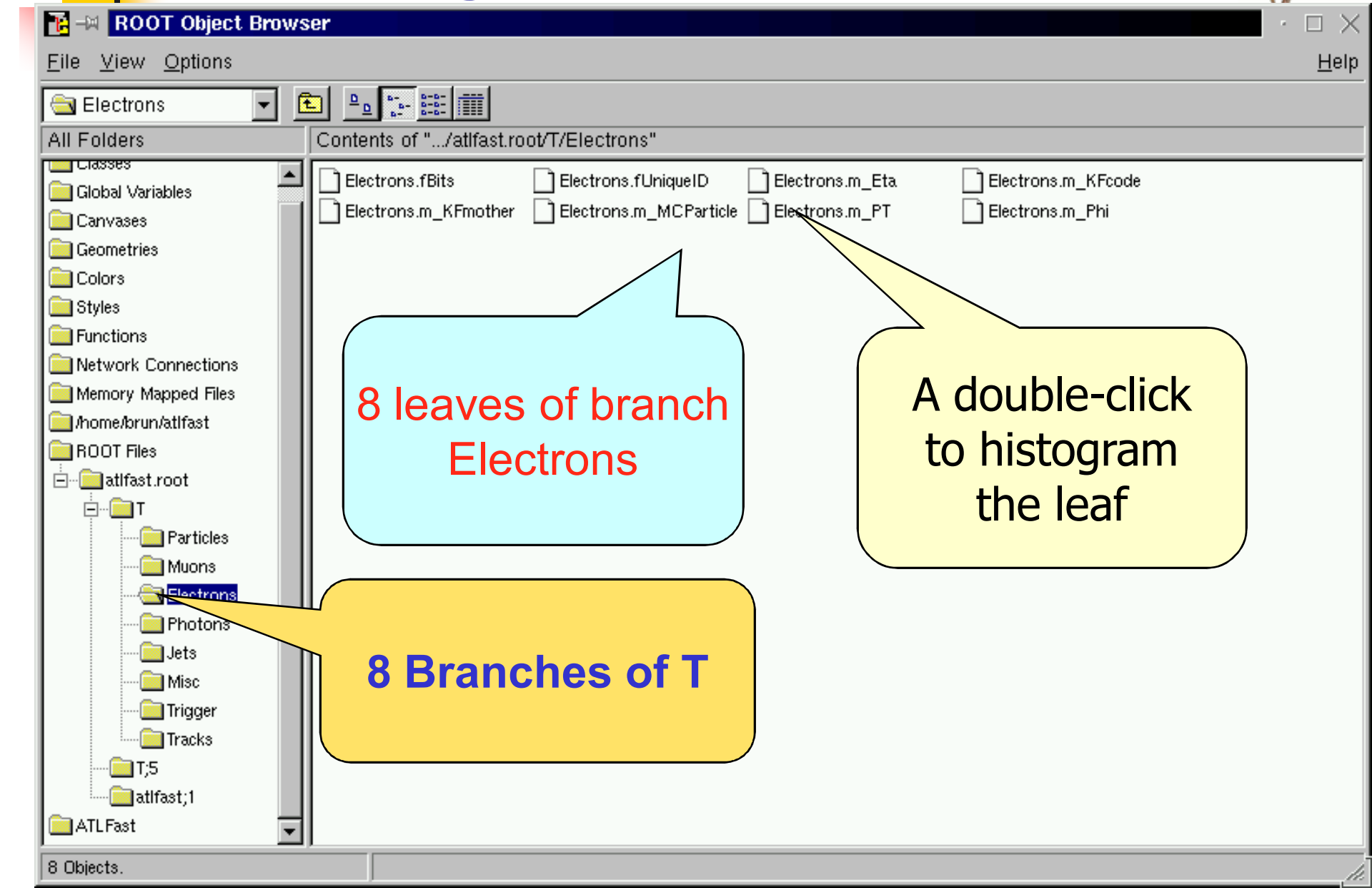
Write.C

```
main() {
   Event *event = 0;
   TFile f("demo.root", "recreate");
   int split = 99;  //maximnum split
   TTree *T = new TTree("T","demo Tree");
   T->Branch("event", "Event", &event, split);
   for (int ev = 0; ev < 1000; ev++) {
      event = new Event(…);
      T->Fill();
      delete event;
   }
   t->AutoSave();
}
```

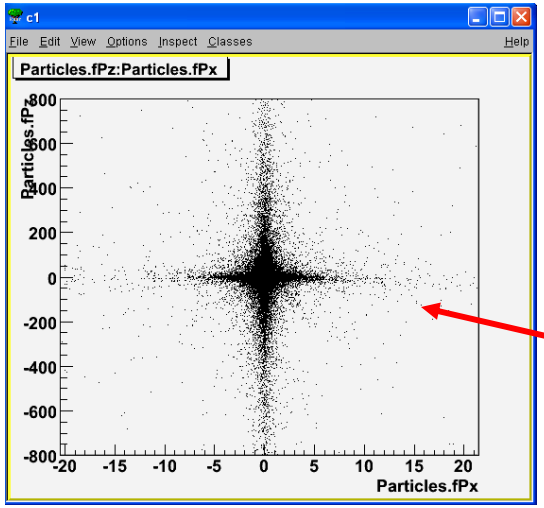
Read.C

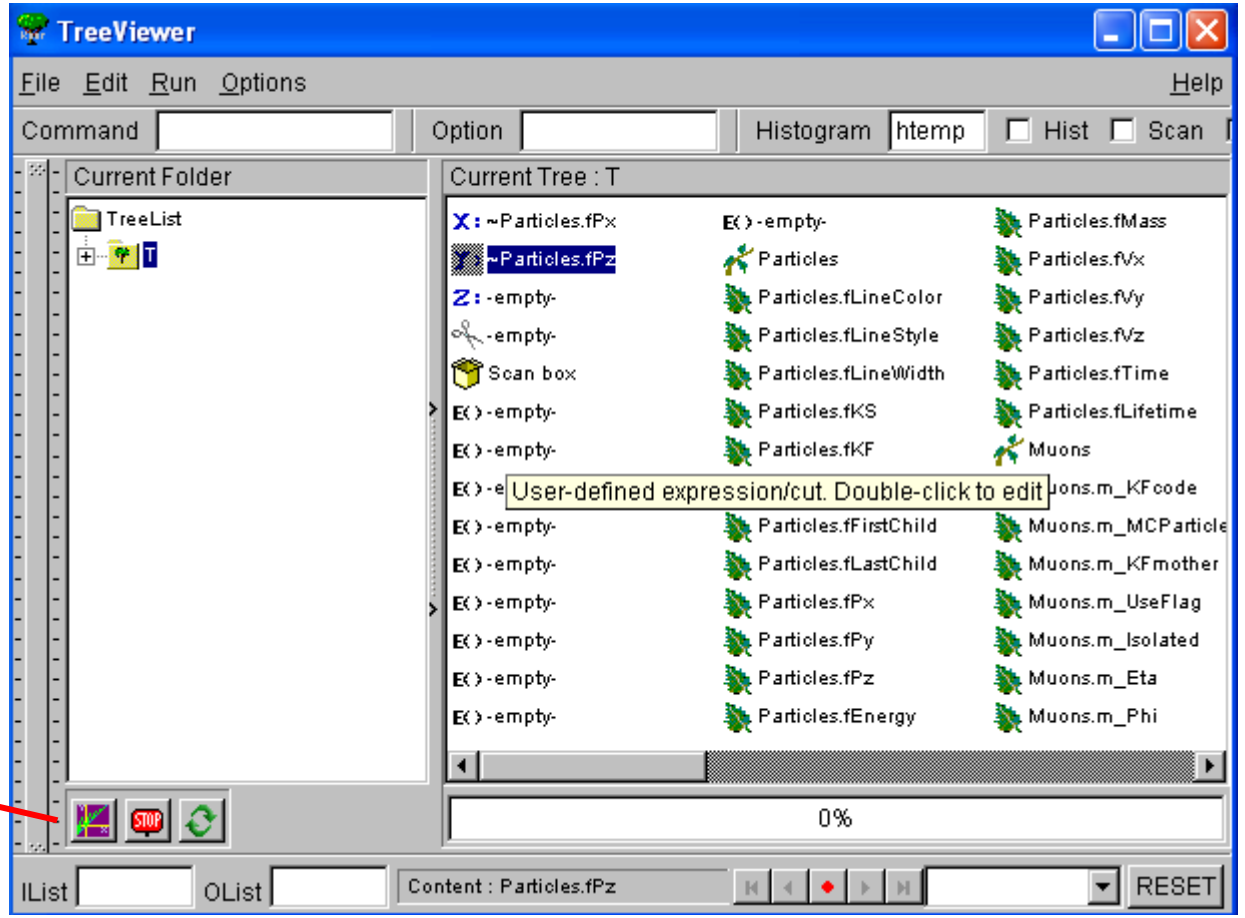
```
main() {
   Event *event = 0;
   TFile f("demo.root");
   TTree *T = (TTree*)f.Get("T");
   T->SetBranchAddress("event", &event);
   Long64_t N = T->GetEntries();
   for (Long64_t ev = 0; ev < N; ev++) {
      T->GetEntry(ev);
      // do something with event
   }
}
```

Browsing a Tree



The TTreeViewer





TTree Selection Syntax

Print the first 8 variables of the tree.

```
MyTree->Scan();
```

Print all the variables of the tree.

```
MyTree->Scan("*");
```

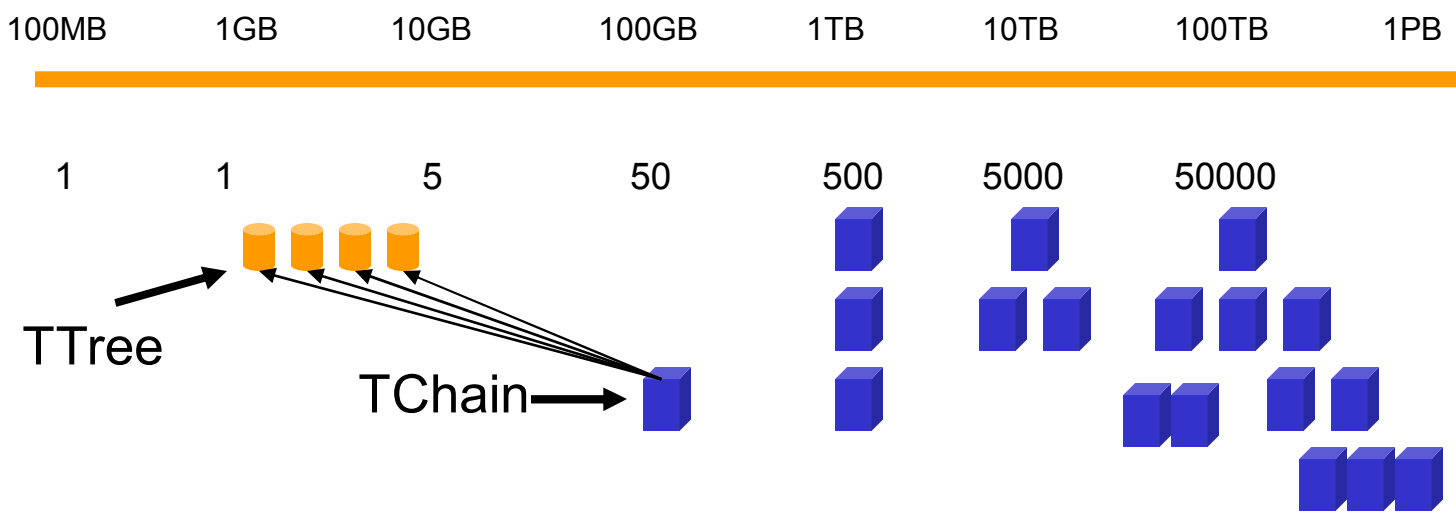
Print the values of var1, var2 and var3.

```
MyTree->Scan("var1:var2:var3");
```

Print the values of var1, var2 and var3 for the entries where var1 is exactly 0.

```
MyTree->Scan("var1:var2:var3", "var1==0");
```

Data Volume & Organisation



A TFile typically contains 1 TTree

A TChain is a collection of TTrees or/and TChains

A TChain is typically the result of a query to the file catalogue

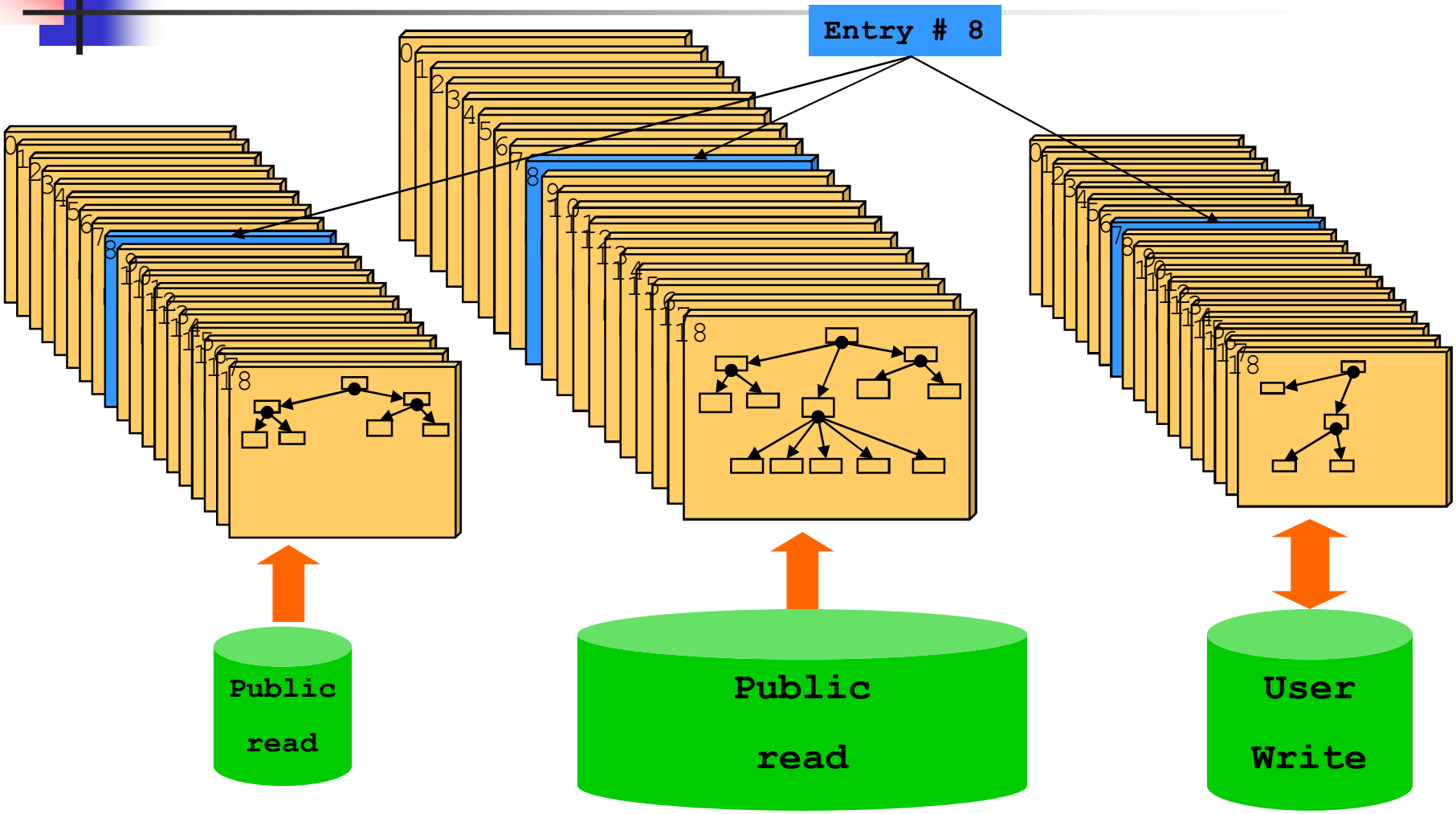
Chains of Trees

- A TChain is a collection of Trees.
- Same semantics for TChains and TTrees
  - root > .x h1chain.C
  - root > chain.Process("h1analysis.C")

```
{
  //creates a TChain to be used by the h1analysis.C class
  //the symbol H1 must point to a directory where the H1 data sets
  //have been installed

  TChain chain("h42");
    chain.Add("$H1/dstarmb.root");
    chain.Add("$H1/dstarp1a.root");
    chain.Add("$H1/dstarp1b.root");
    chain.Add("$H1/dstarp2.root");
}
```

Tree Friends



GRIDs & Multi-Cores & PROOF

From the desktop to the GRID

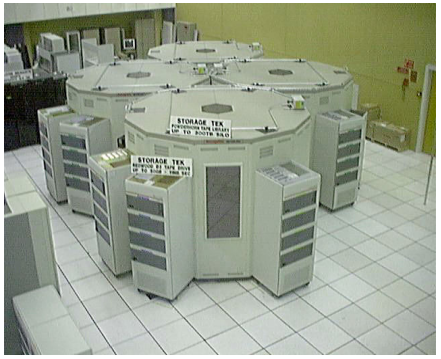
Online/Offline

Local/remote

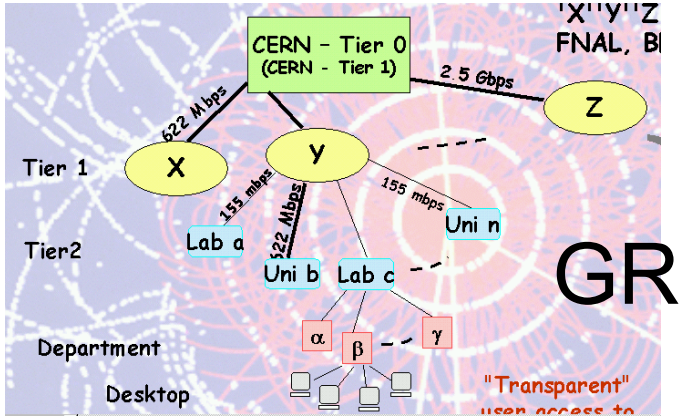
Desktop

Farms

Storage



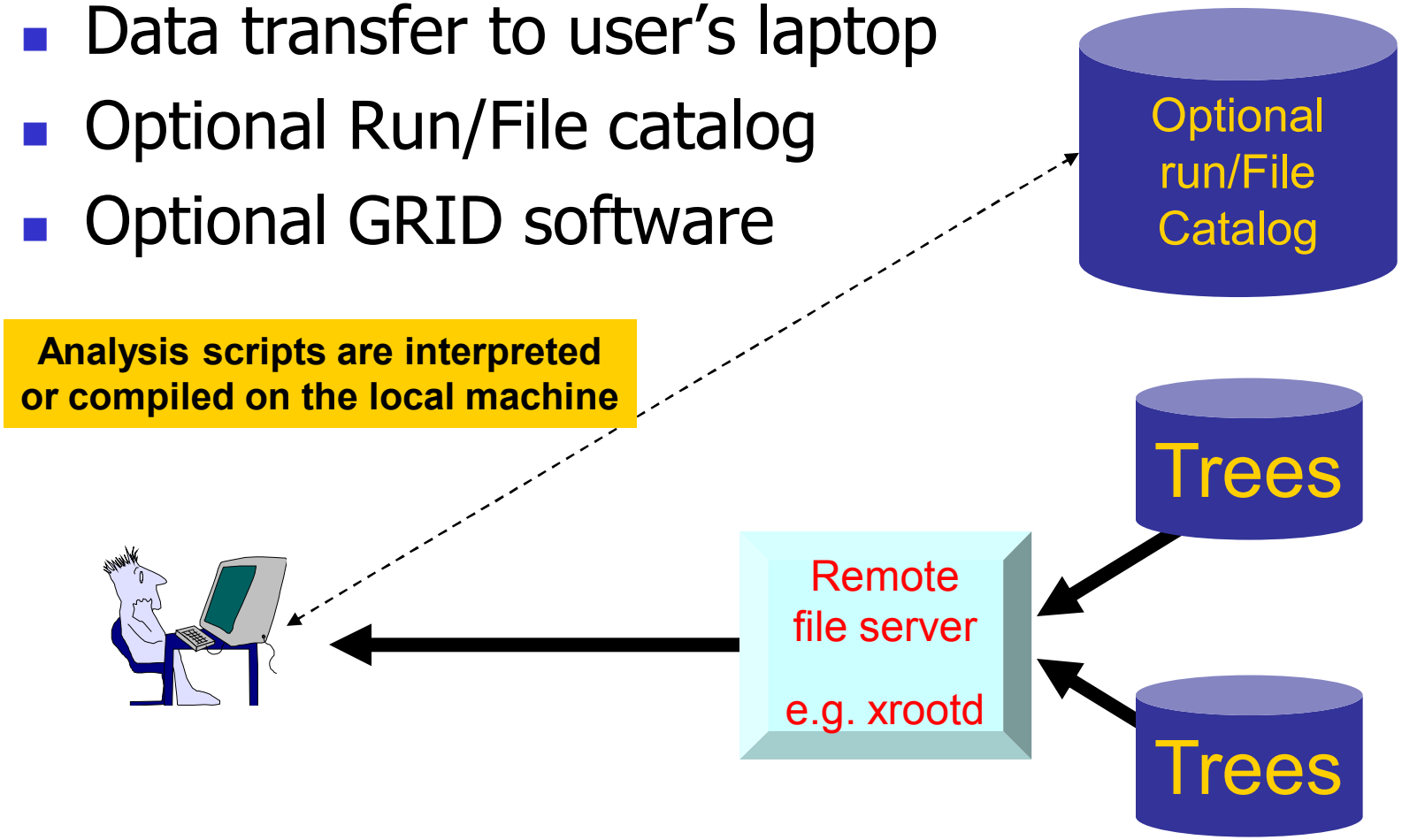
New data analysis tools must be able to use in parallel remote CPUS, storage elements and networks in a transparent way for a user at a desktop



GRID

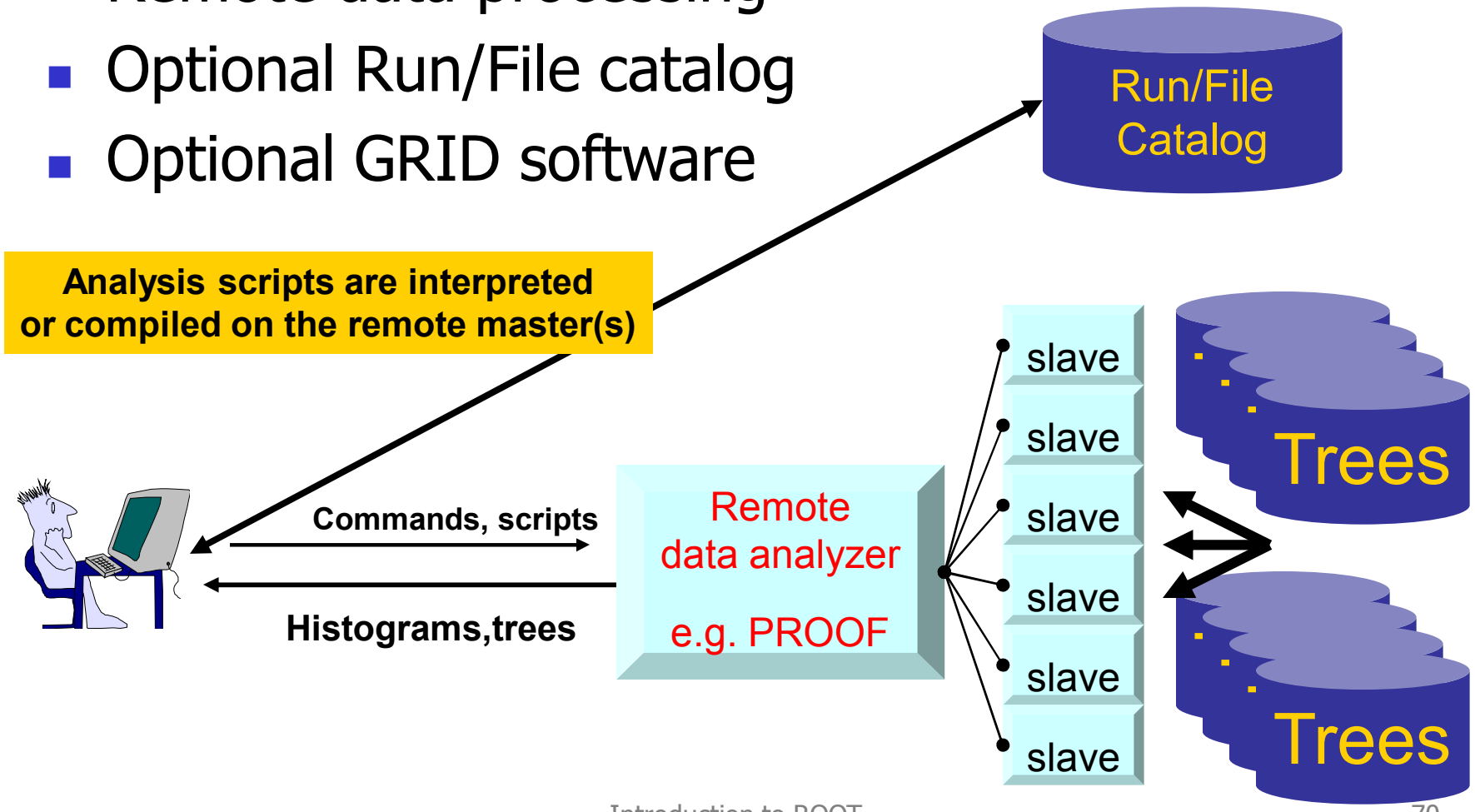
GRID: Interactive Analysis Case 1

- Data transfer to user's laptop
- Optional Run/File catalog
- Optional GRID software



GRID: Interactive Analysis Case 2

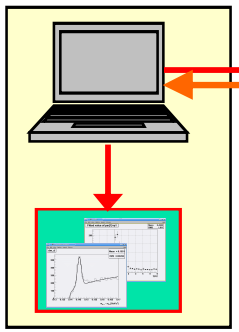
- Remote data processing
- Optional Run/File catalog
- Optional GRID software



Parallel ROOT Facility

- A system for running ROOT queries in parallel on a large number of distributed computers or many-core machines
- PROOF is designed to be a transparent, scalable and adaptable extension of the local interactive ROOT analysis session
- Extends the interactive model to long running "interactive batch" queries
- Uses xrootd for data access and communication infrastructure
- For optimal CPU load it needs fast data access (SSD, disk, network) as queries are often I/O bound
- Can also be used for pure CPU bound tasks like toy Monte Carlo's for systematic studies or complex fits

PROOF

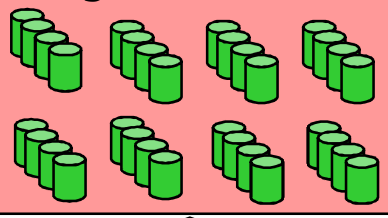


commands, scripts

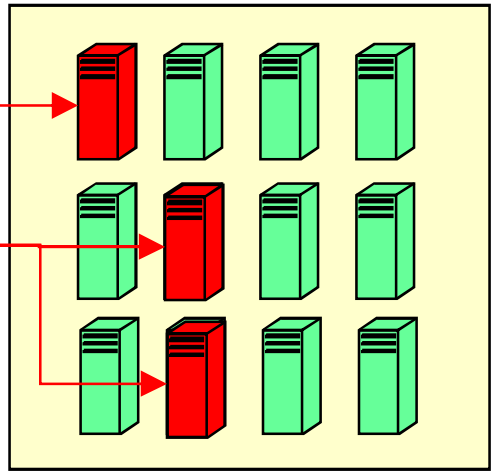
list of output objects (histograms, ...)

PROOF cluster

Storage



MASTER



- Cluster perceived as extension of local PC
  - *Same macro and syntax* as in local session
- More *dynamic* use of resources
- Real-time feedback
- Automated *splitting* and *merging*

ROOT is MORE….

- In this talk, I presented the most basic classes typically used during Physics Analysis.
- ROOT contains many more libraries, e.g.
  - FFT library
  - Oracle, MySQL, etc interfaces
  - XML drivers
  - TMVA (Multi Variate Analysis)
  - GRID, networking and thread classes
  - Interfaces to Castor, Dcache, GFAL, xrootd
  - Interfaces to Pythia, Geant3, Geant4, gdml
  - Matrix packages, Fitting packages, etc

Documentation

- Users Guide and Reference Manuals are available at http://root.cern.ch

Tomorrow Jan Fiete will demo in his session many of the features I've presented today