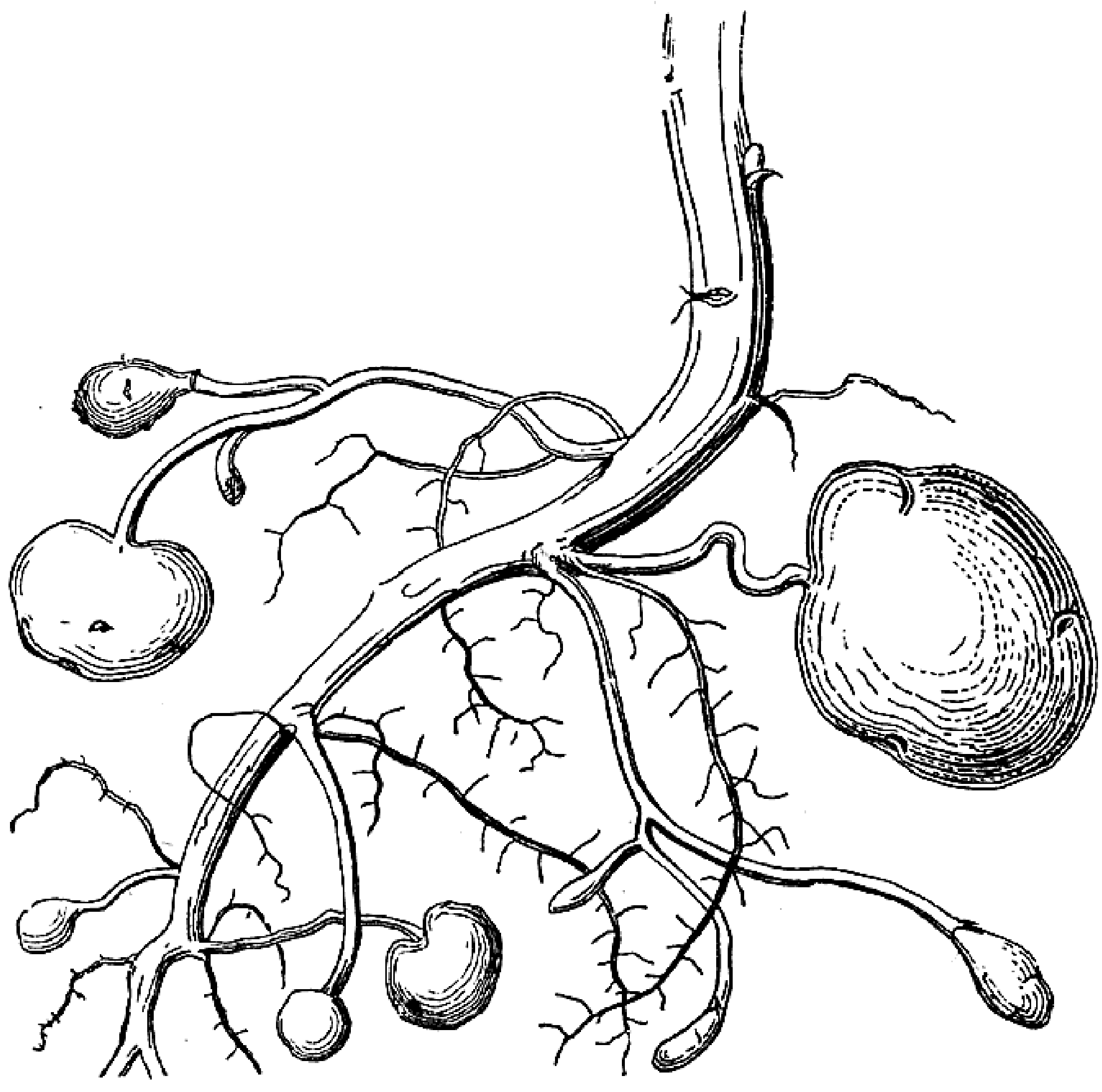
ROOT

Bertrand Bellenot, Axel Naumann
CERN

What's ROOT?

What's ROOT?



What's ROOT?

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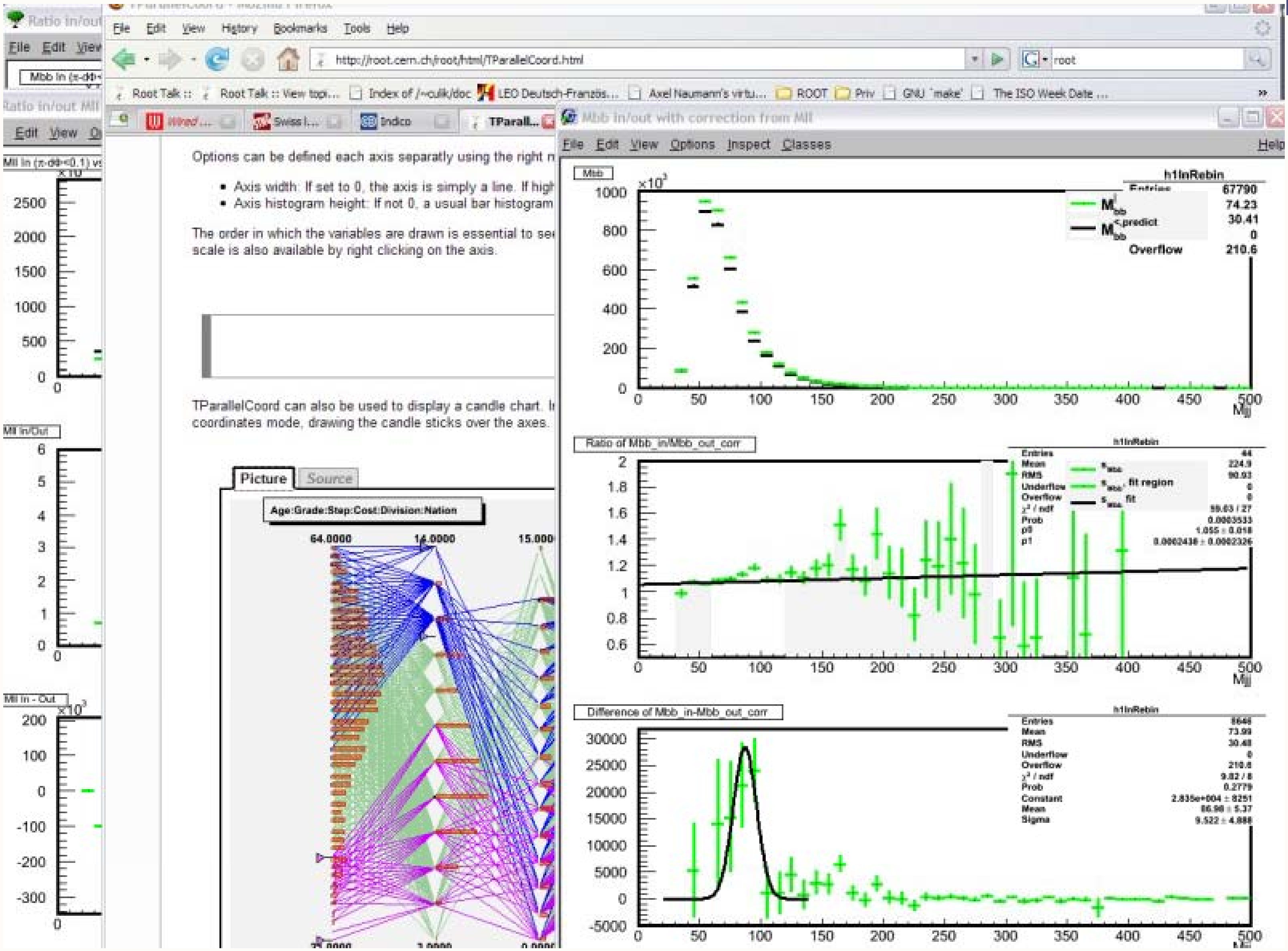


Options can be defined each axis separatly using the right
Axis width: If set to 0, the axis is simply a line.
Axis histogram height: If not 0, a usual bar histogram
The order in which the variables are drawn is essential to see
scale is also available by right clicking on the axis.
TParallelCoord can also be used to display a candle chart.
coordinates mode, drawing the candle sticks over the axes.
Picture
Source
Age:Grade:Step:Cost:Division:Nation
Mbb in/out with correction from Mll
File Edit View Options Inspect Classes
h1InRebin
Ratio of Mbb_in/Mbb_out_corr
Difference of Mbb_in-Mbb_out_corr

ROOT: An Open Source Project

- Started in 1995
- 11 full time developers at CERN, plus Fermilab, Agilent Tech, Japan, MIT (one each)
- Large number of part-time developers: let users participate
- Available (incl. source) under GNU LGPL

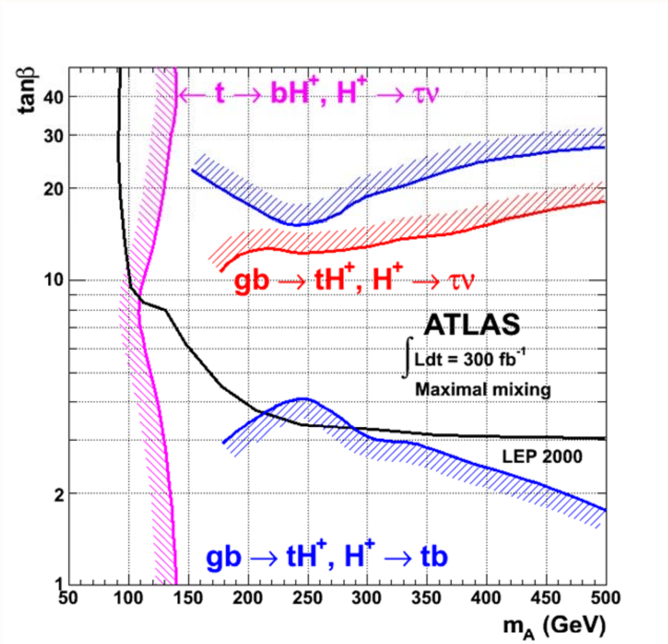
ROOT in a Nutshell

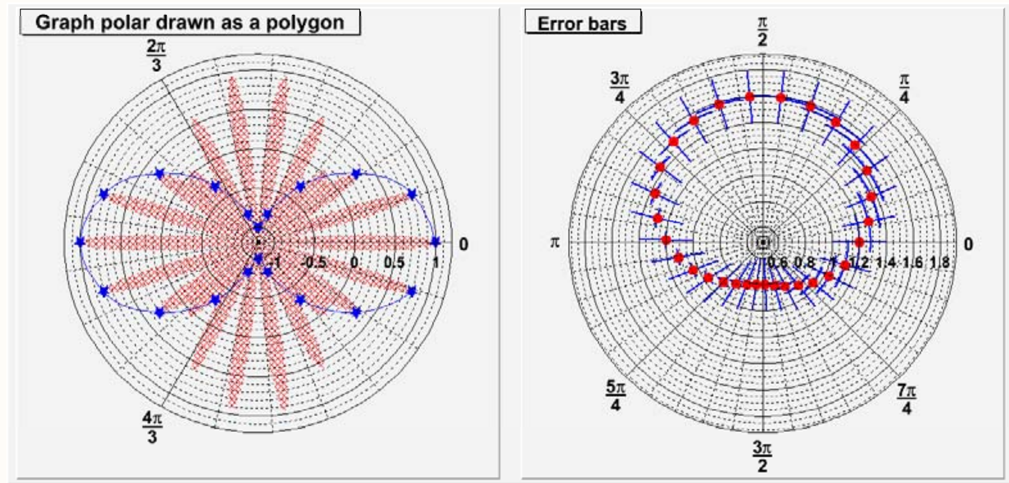
Framework for large scale data handling

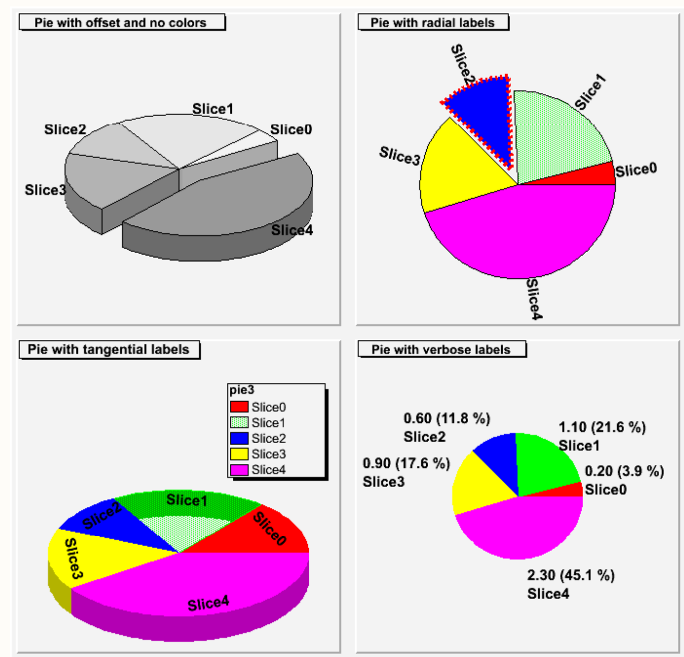
Provides, among others,

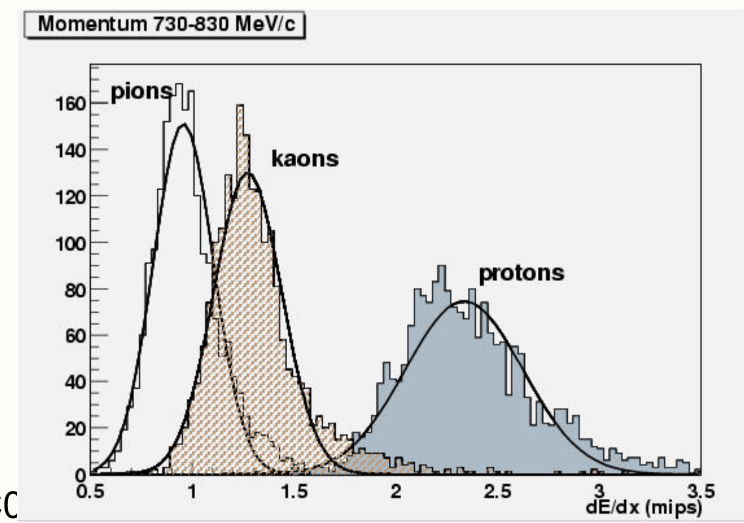
- an efficient data storage, access and query system (PetaBytes)
- advanced statistical analysis algorithms (multi dimensional histogramming, fitting, minimization and cluster finding)
- scientific visualization: 2D and 3D graphics, Postscript, PDF, LateX
- geometrical modeller
- PROOF parallel query engine

Graphics


tanβ
t → bH+, H+ → τν
gb → tH+, H+ → τν
ATLAS
∫Ldt = 300 fb-1
Maximal mixing
LEP 2000
gb → tH+, H+ → tb
mA (GeV)

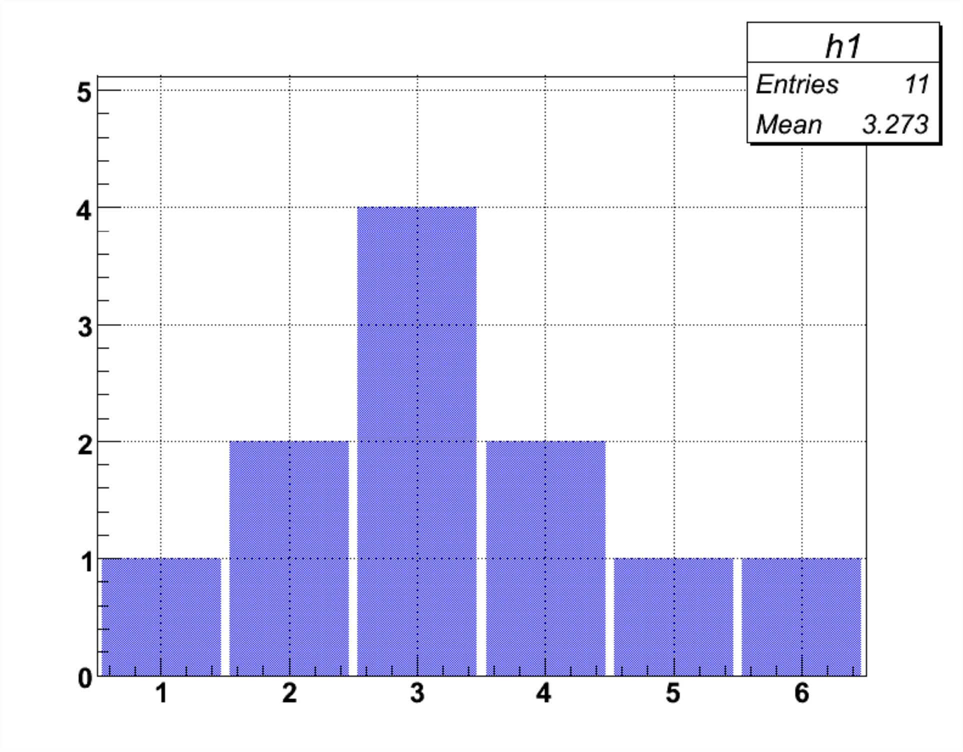

Graph polar drawn as a polygon
Error bars


Pie with offset and no colors
Pie with radial labels
Pie with tangential labels
Pie with verbose labels
pie3
Slice0
Slice1
Slice2
Slice3
Slice4
0.60 (11.8 %)
1.10 (21.6 %)
0.90 (17.6 %)
0.20 (3.9 %)
2.30 (45.1 %)


Momentum 730-830 MeV/c
pions
kaons
protons
dE/dx (mips)

Histogramming

- Histogram is just occurrence counting, i.e. how often they appear
- Example: {1,3,2,6,2,3,4,3,4,3,5}



Histogramming

- **How is a Real Histogram Made?**
  Lets consider the age distribution of the participants:

Ages
26.93
23.03
29.66
33.74
32.19
31.40
24.88
27.56
26.99
26.65
[illegible]

Age	Number
20-22	1
22-24	5
24-26	14
26-28	14
28-30	10
30-32	5
32-34	5
34-36	1
36-38	1
38-40	1

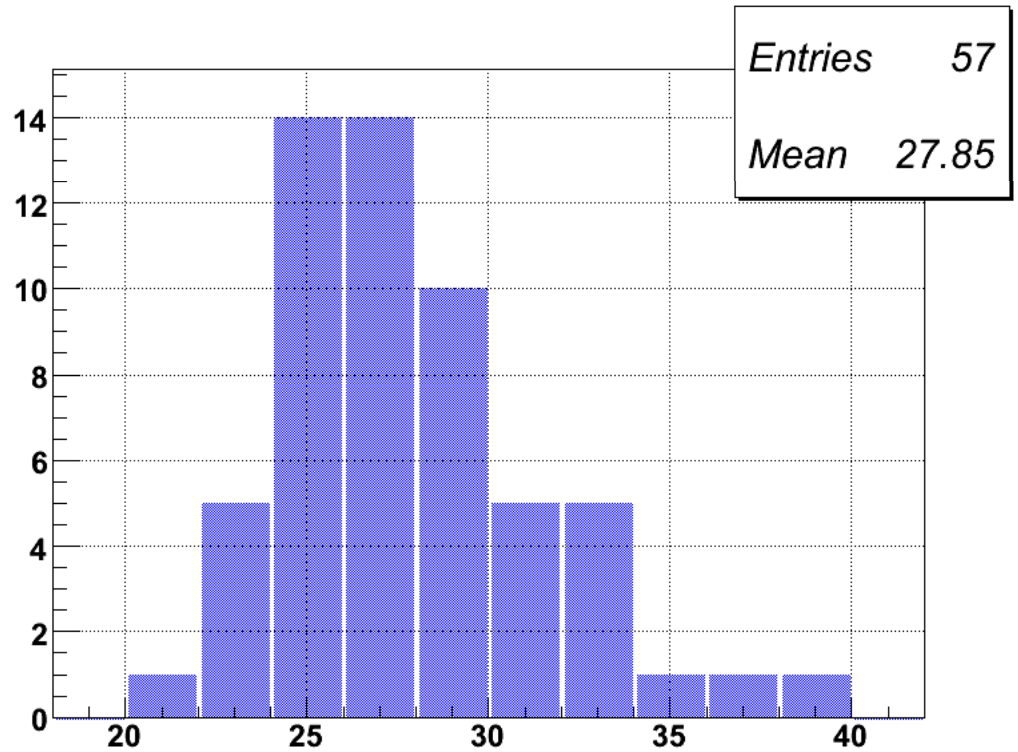
Binning:

Grouping ages of participants in several categories (bins)

Histogramming

Table of Ages (binned)

Age	Number
20-22	1
22-24	5
24-26	14
26-28	14
28-30	10
30-32	5
32-34	5
34-36	1
36-38	1
38-40	1

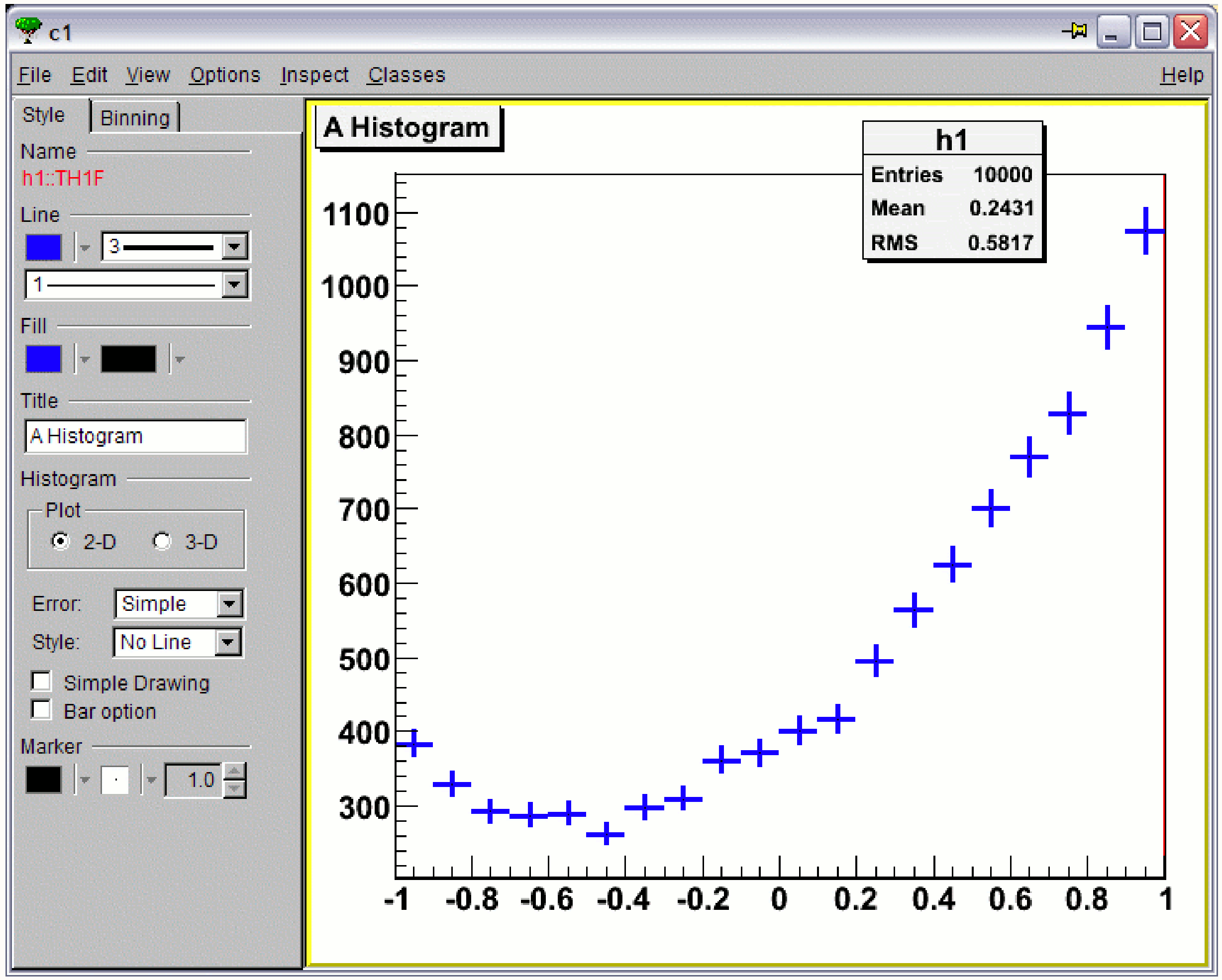


Shows distribution of ages, total number of entries (57 participants) and average: 27 years 10 months 6 days…

Histograms

Analysis result: often a histogram

Menu:
  View / Editor



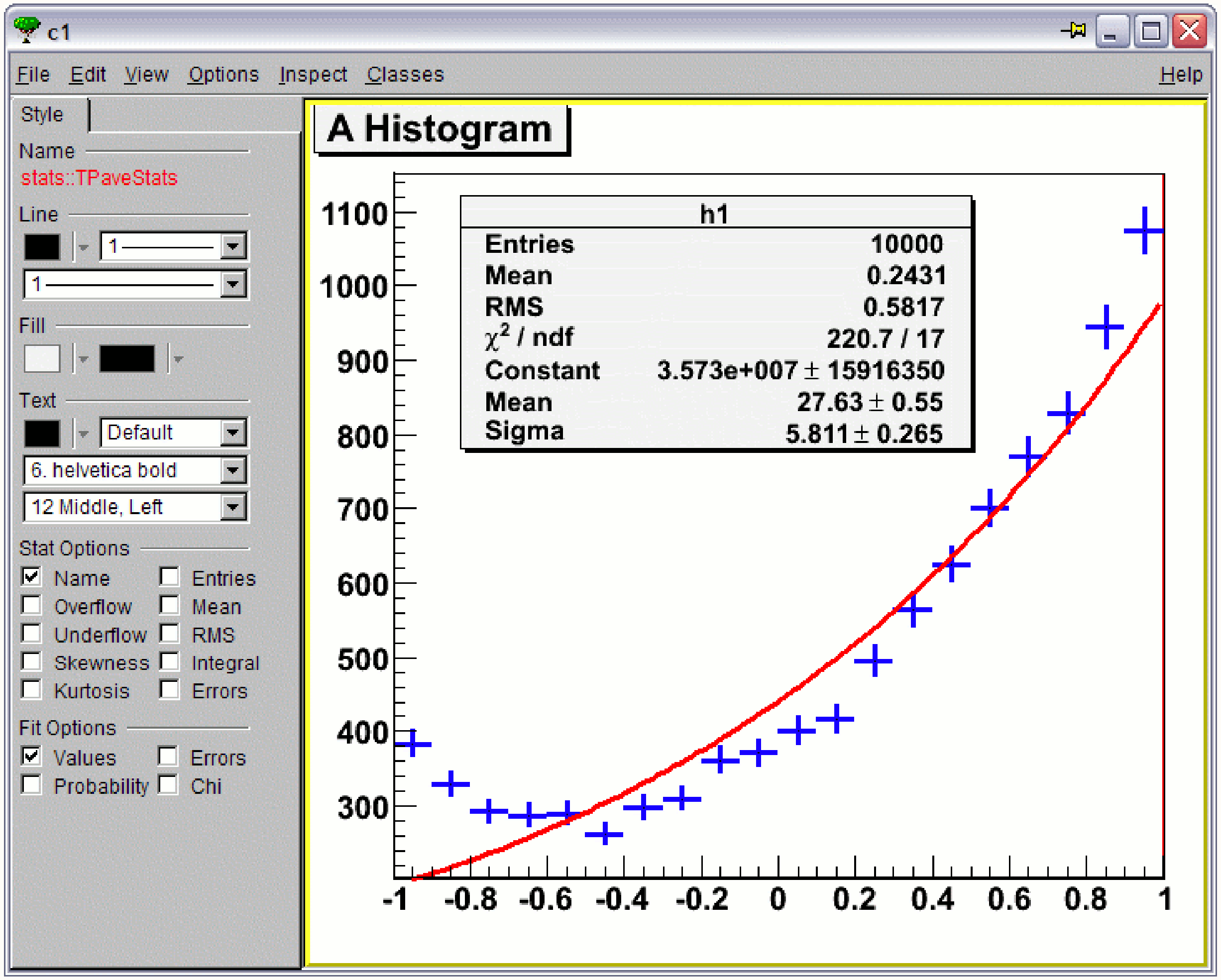
Fitting

Analysis result:

often a ***fit***

based on a

histogram



Fit

Function describing the distribution of data

Fit = optimization in parameters,

e.g. Gaussian $f(x) = [0] \cdot e^{-\frac{(x-[1])^2}{2 \cdot [2]^2}}$

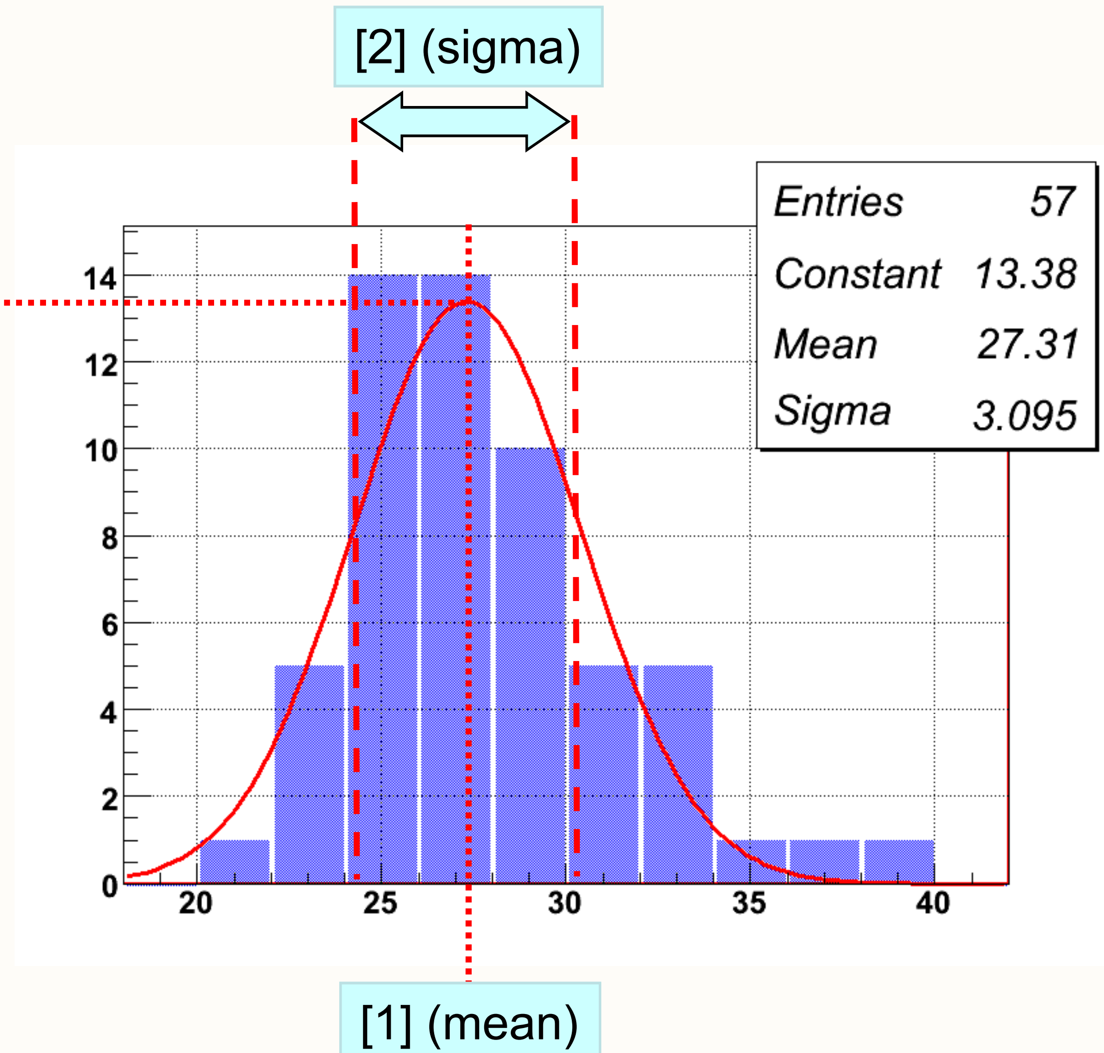
For Gaussian: [0] = "Constant"
[1] = "Mean"
[2] = "Sigma" / "Width"

Objective: choose parameters [0], [1], [2] to get function as close as possible to histogram

Fit

Gaussian fit over our histogram:

$$f(x) = [0] \cdot e^{-\frac{(x-[1])^2}{2 \cdot [2]^2}}$$



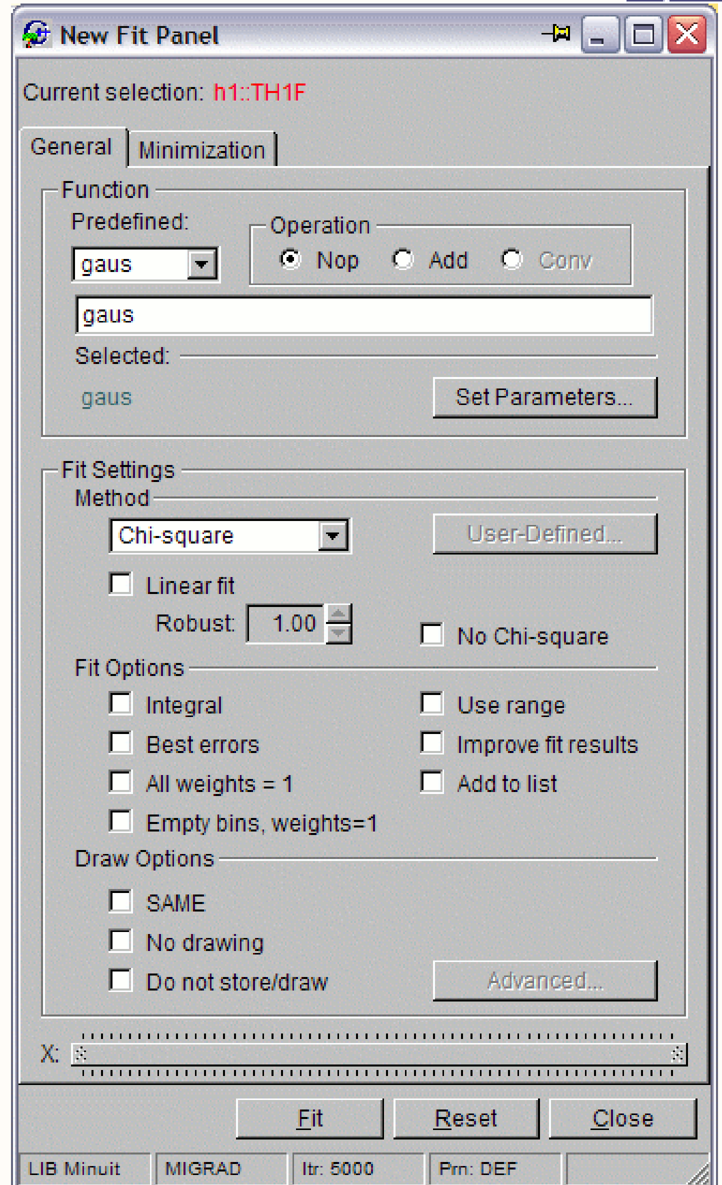
Fit Panel

To fit a histogram:

right click histogram,

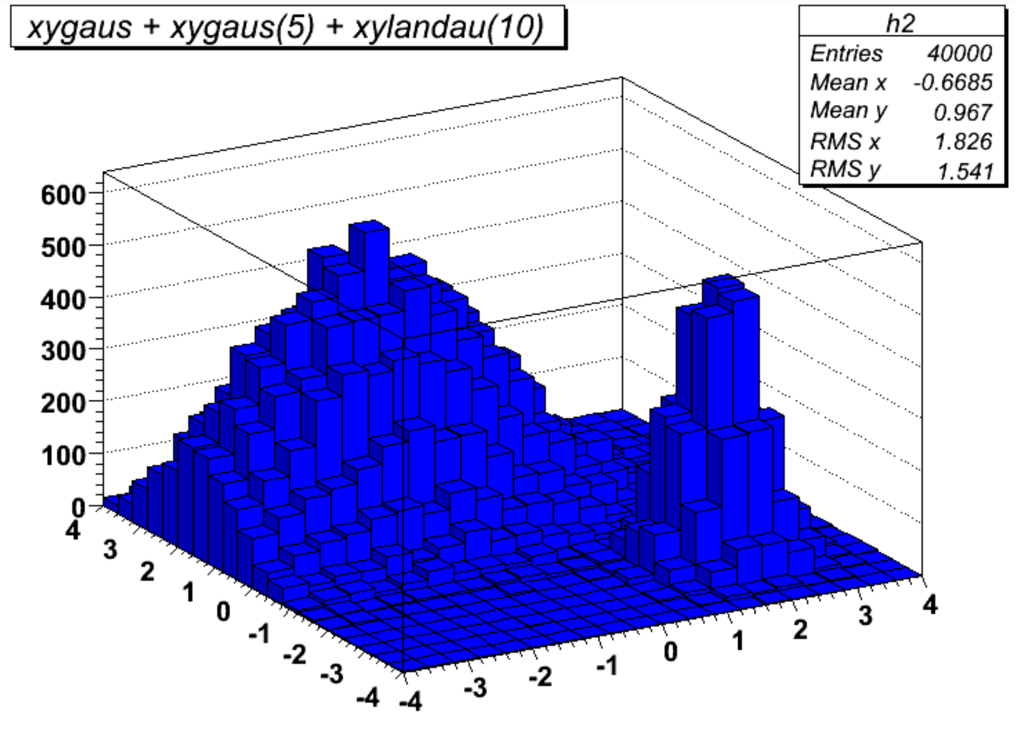
"Fit Panel"

Straightforward interface for fitting!

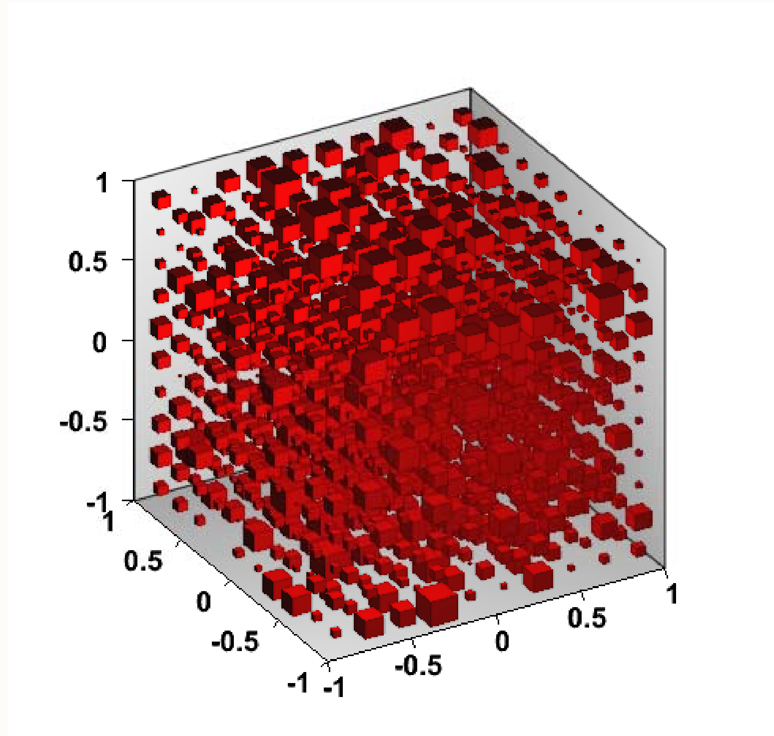


2D/3D

We have seen 1D histograms, but there are also histograms in more dimensions.



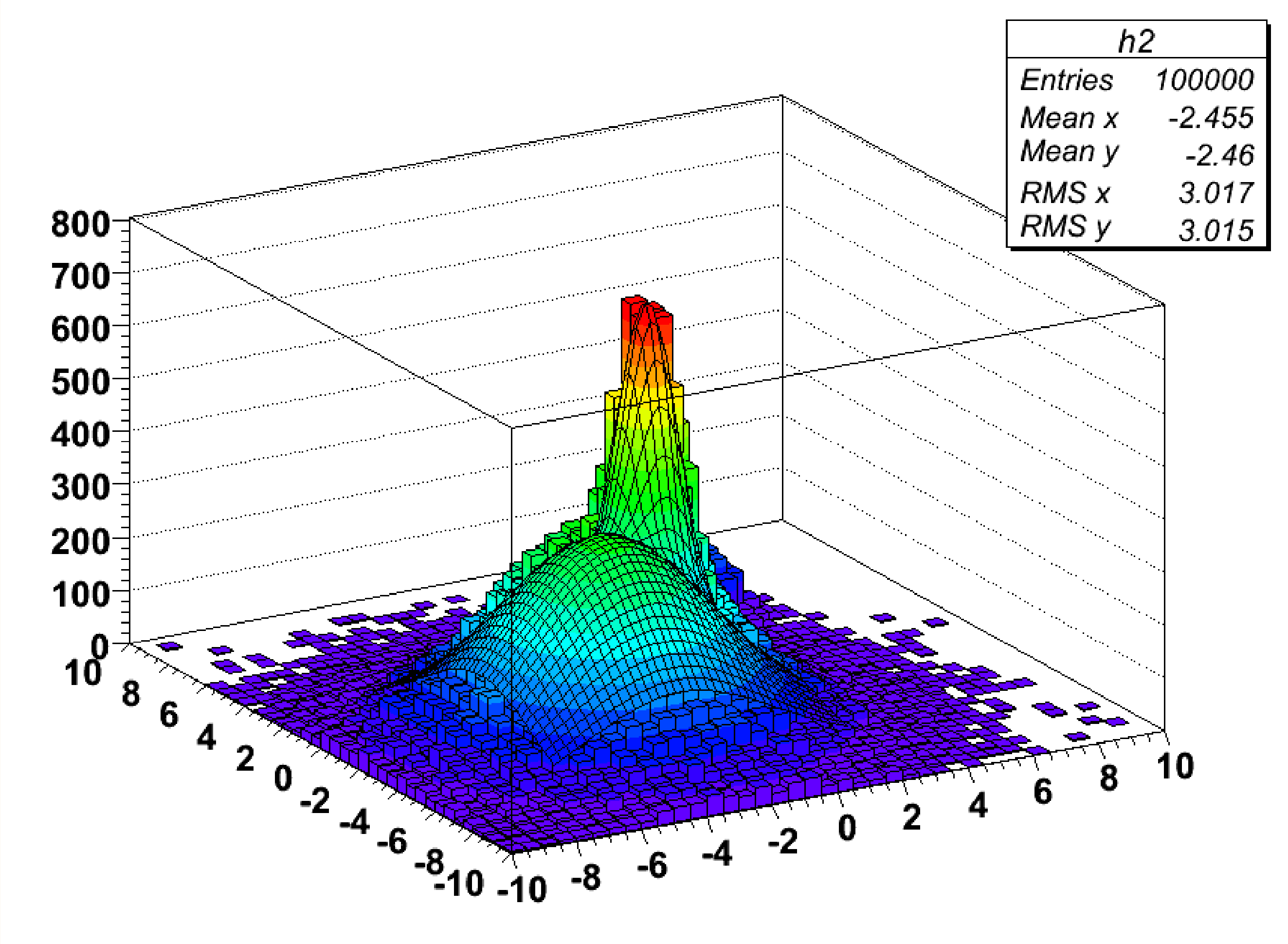
2D Histogram



3D Histogram

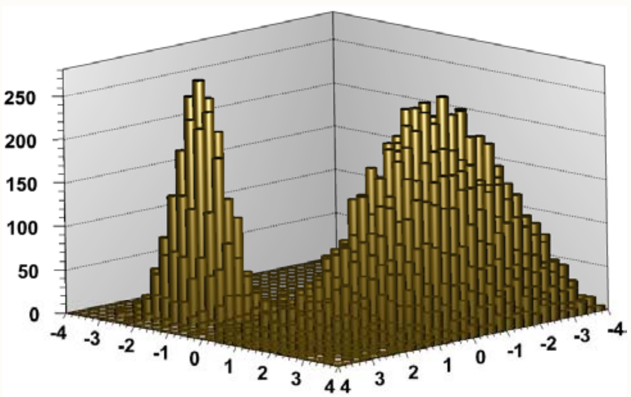
2D Fitting

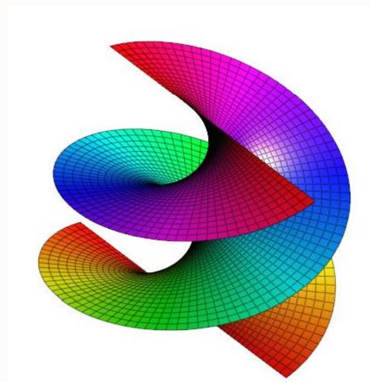
Example of a fit over a 2D histogram

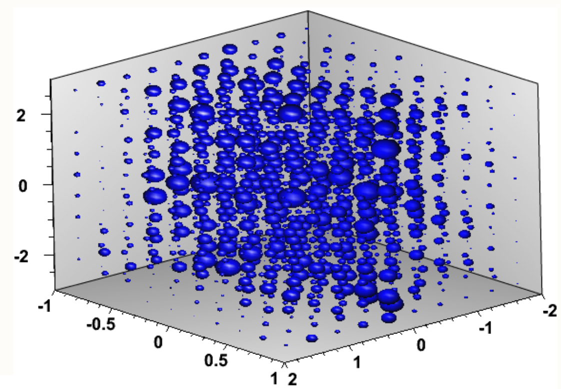


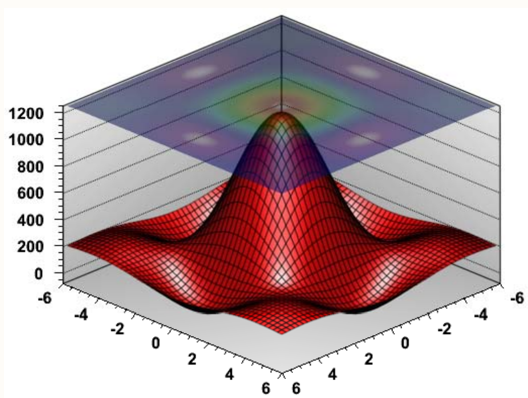
OpenGL

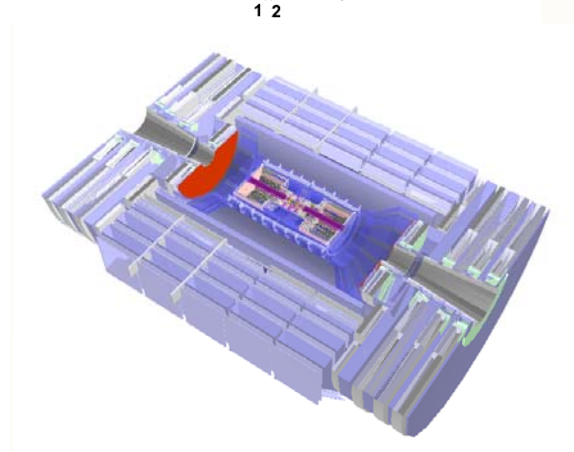
- OpenGL can be used to render 2D & 3D histograms, functions, parametric equations, and to visualize 3D objects (geometry)



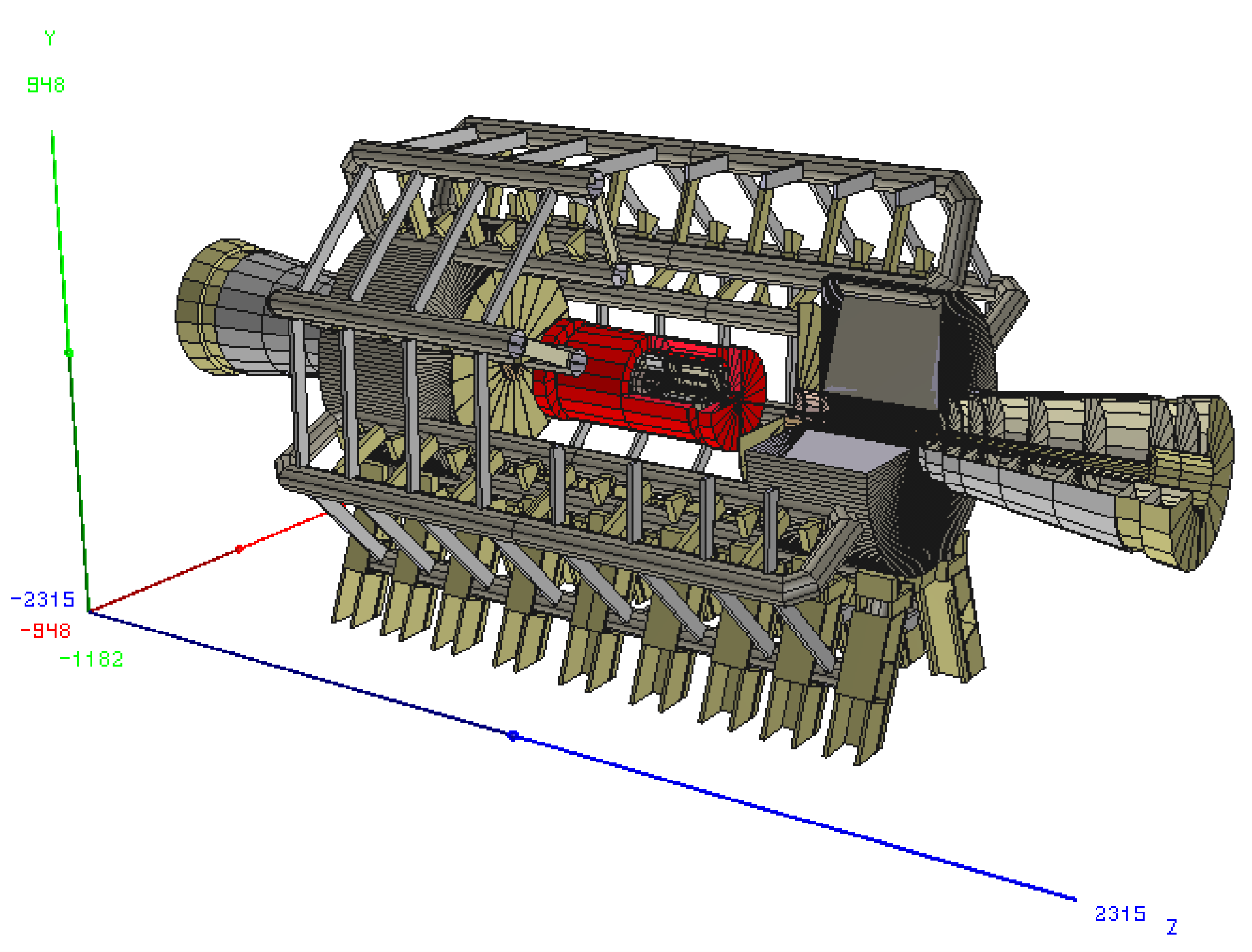








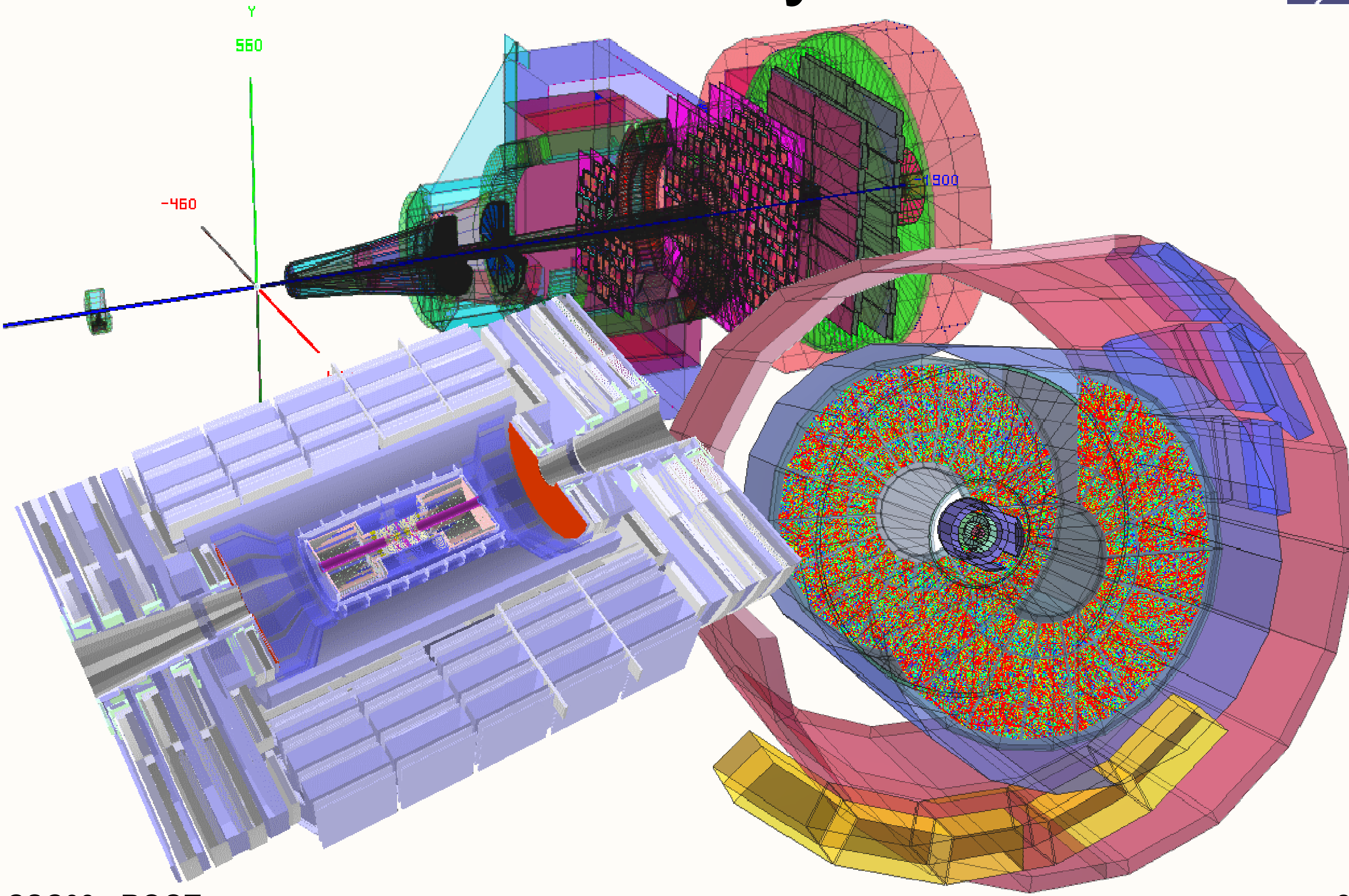
OpenGL



Geometry

- Describes complex detector geometries
- Allows visualization of these detector geometries with e.g. OpenGL
- Optimized particle transport in complex geometries
- Working in correlation with simulation packages such as GEANT3, GEANT4 and FLUKA

Geometry



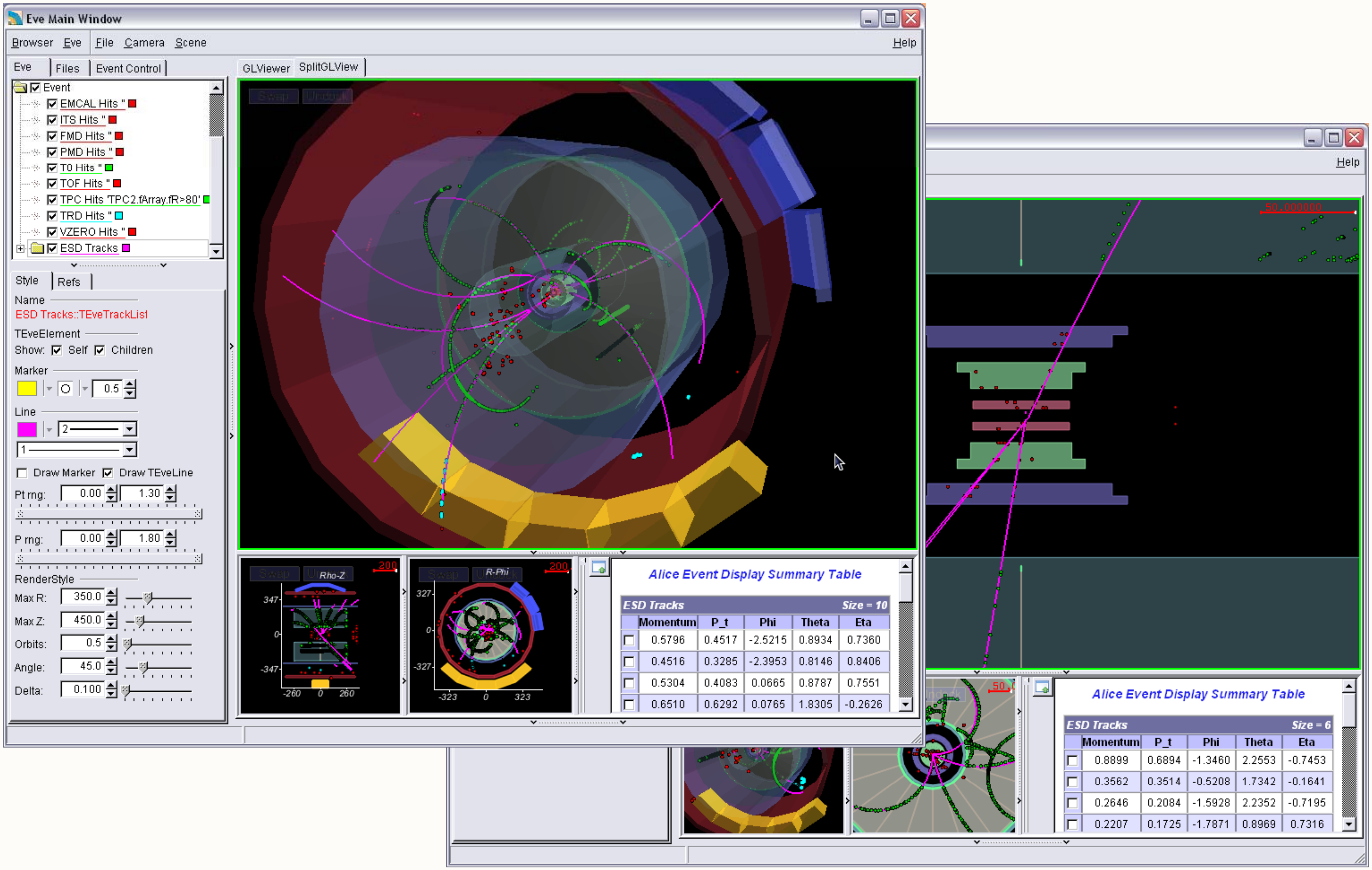
EVE (Event Visualization Environment)

- Event: Collection of data from a detector (hits, tracks, …)

Use EVE to:

- Visualize these physics objects together with detector geometry (OpenGL)
- Visually interact with the data, e.g. select a particular track and retrieve its physical properties

EVE


Eve Main Window
Browser Eve File Camera Scene
Help
Eve
Files
Event Control
GLViewer
SplitGLView
Event
EMCAL Hits "
ITS Hits "
FMD Hits "
PMD Hits "
T0 Hits "
TOF Hits "
TPC Hits 'TPC2.fArray.fR>80'
TRD Hits "
VZERO Hits "
ESD Tracks
Style
Refs
Name
ESD Tracks::TEveTrackList
TEveElement
Show: Self Children
Marker
0.5
Line
2
1
Draw Marker
Draw TEveLine
Pt rng: 0.00 1.30
P rng: 0.00 1.80
RenderStyle
Max R: 350.0
Max Z: 450.0
Orbits: 0.5
Angle: 45.0
Delta: 0.100
Rho-Z
R-Phi
Alice Event Display Summary Table
ESD Tracks Size = 10
Momentum P_t Phi Theta Eta
0.5796 0.4517 -2.5215 0.8934 0.7360
0.4516 0.3285 -2.3953 0.8146 0.8406
0.5304 0.4083 0.0665 0.8787 0.7551
0.6510 0.6292 0.0765 1.8305 -0.2626
Help
Alice Event Display Summary Table
ESD Tracks Size = 6
Momentum P_t Phi Theta Eta
0.8899 0.6894 -1.3460 2.2553 -0.7453
0.3562 0.3514 -0.5208 1.7342 -0.1641
0.2646 0.2084 -1.5928 2.2352 -0.7195
0.2207 0.1725 -1.7871 0.8969 0.7316

Math

Histogram library
- TH1
- TF1

MathMore
- Random Numbers
- Extra algorithms
- Extra Math functions
- GSL and more

MathCore
- Function interfaces
- Physics Vectors
- Basic algorithms
- Basic Math functions

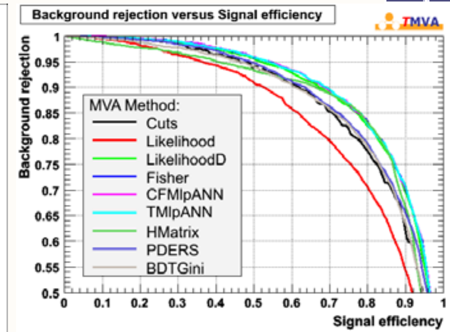
Statistical Libraries
- Statistical Utilities
- TMVA
- MLP

Fitting and Minimization
- New Fitter
- RooFit
- TMinuit
- TFumili
- Linear Fitter
- Minuit2 (new C++ Minuit)

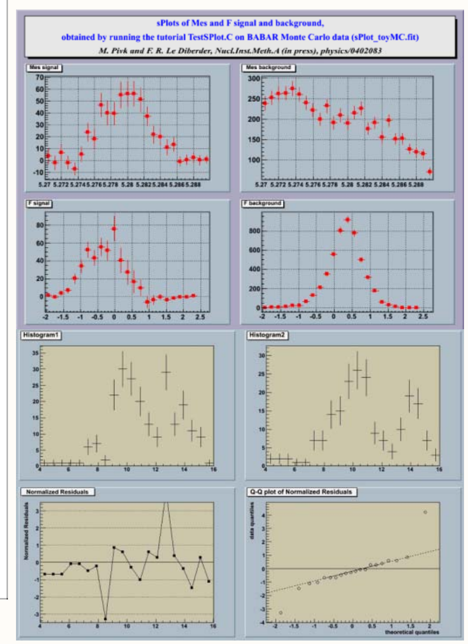
Linear Algebra
- TMatrix
- SMatrix

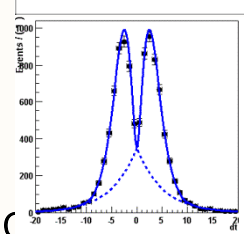
libCore
- TMath
- TRandom

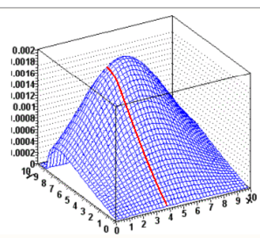
TMVA

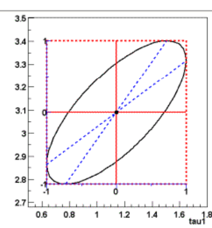


SPlot



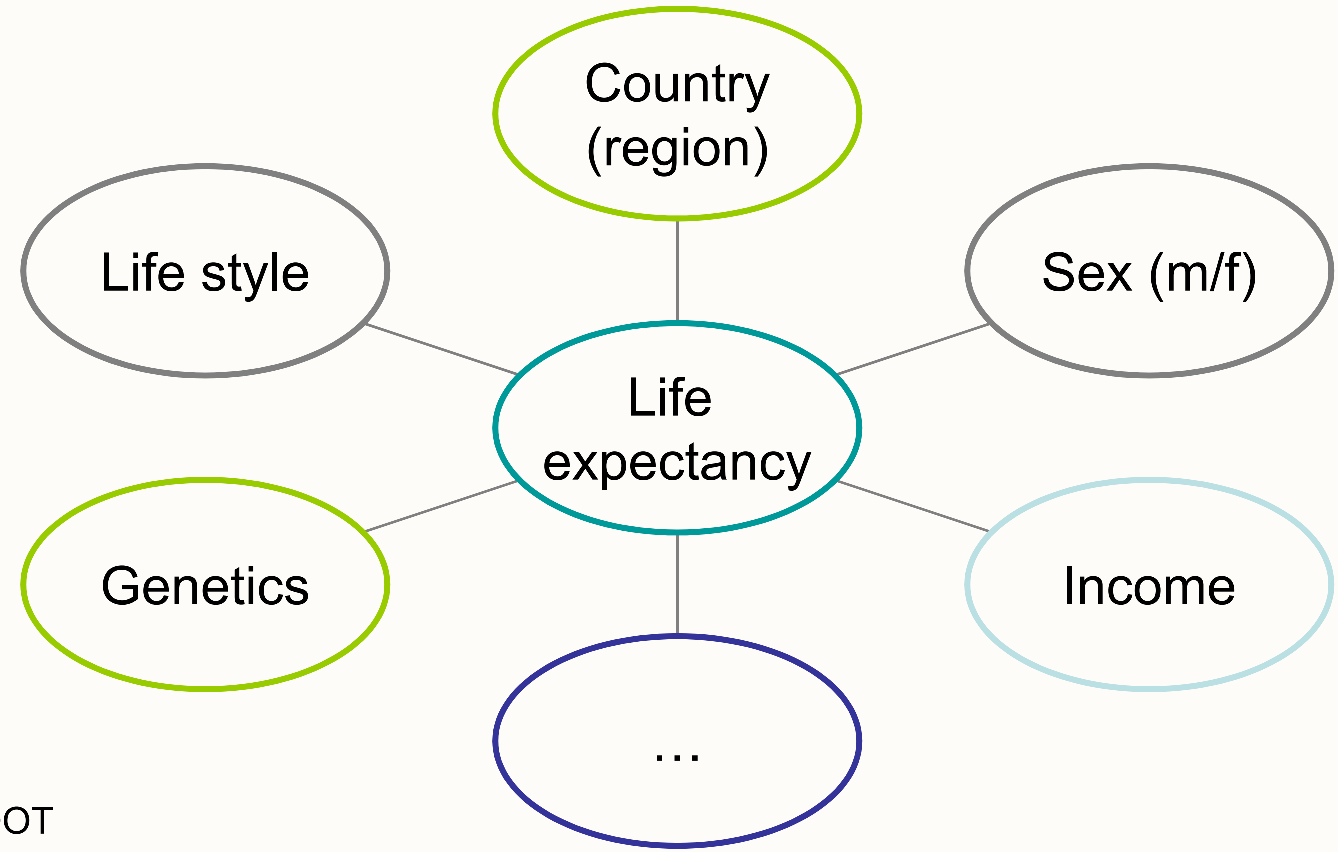






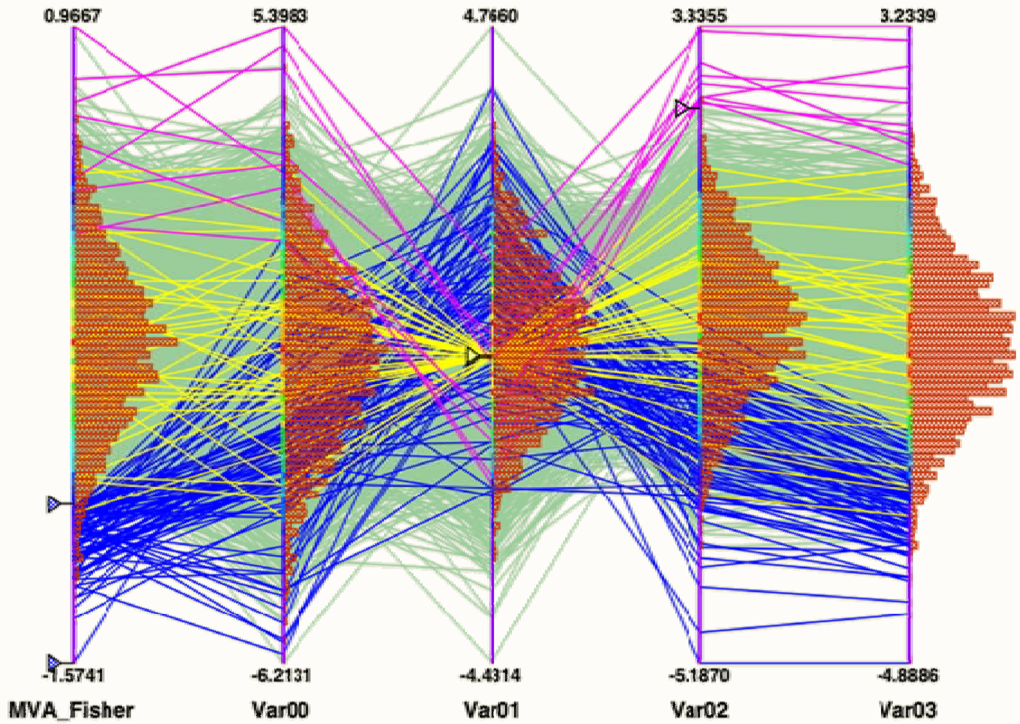
Multivariate Analysis

- Consider this simple question: How to estimate someone's life expectancy?
- This depends on many variables:



Multivariate Analysis

- Many variables? *Parallel Coordinates*

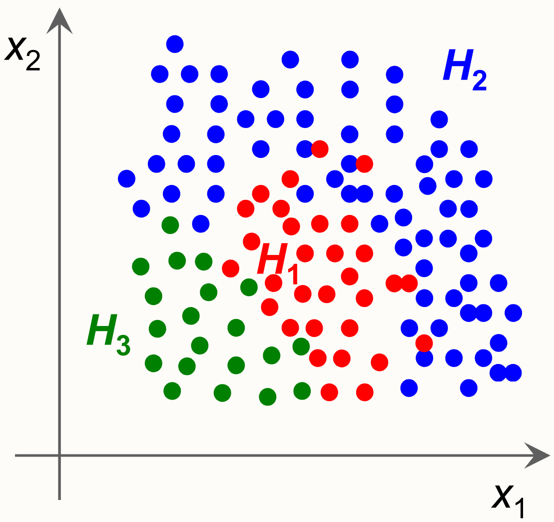


- This will not help to solve the problem, it only allows to visualize multiple variables

Multivariate Analysis

- Sample described by k variables (that are found to be discriminating)
- Samples can be classified into n categories: $H_1 \ldots H_n$
- E.g.
  - H_1 : life exp. < 40
  - H_2 : life exp. 40..60
  - H_3 : life exp. > 60
- Example: k=2 variables x_1, x_2

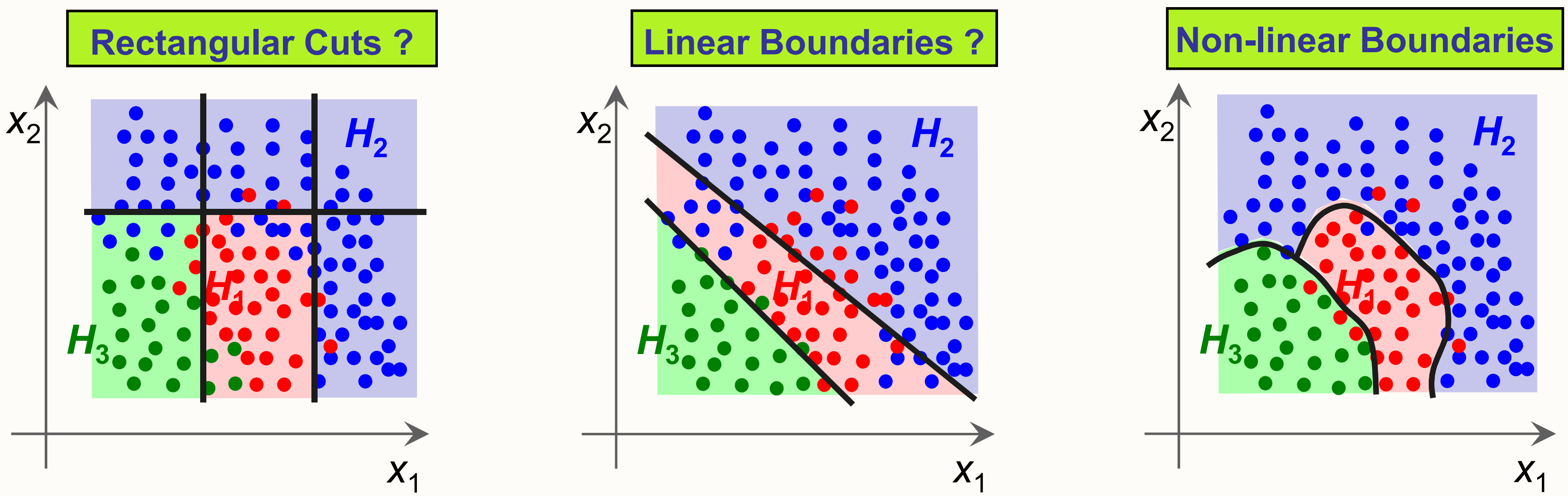
  n=3 categories H_1, H_2, H_3



Example: k=2, n=3

Multivariate Analysis

Problem: Find boundaries between H_1, H_2, and H_3 such that f(***x***) returns the category of ***x*** with maximum correctness



Simple example → I can do it by hand.

Large input variable space, complex correlations: manual optimization very difficult

Multivariate Analysis

Generic problem: find category for set of values

To make such an estimation, we need two phases:

- (Supervised) learning / training phase:
  - Take samples for which categories are known
  - Machine adapts to give the smallest classification error on training sample
- Processing phase:
  - The trained system can now analyze and produce output for any new sample

TMVA

- Framework offering a collection of data mining tools, e.g. NN (Neural Network), GA (Genetic Algorithm), …
- In HEP mostly two class problems – signal (S) and background (B)
  - Physics processes
  - Finding physics objects
  - Detector readout
  - ...

Interlude: HELP!

ROOT is a framework – only as good as its documentation.

User's Guide (it has your answers!)

http://root.cern.ch

"What is TNamed? What functions does it have?"

Reference Guide

http://root.cern.ch/root/html

Let's fire up ROOT!

Setting Up ROOT

Before starting ROOT:

setup environment variables $PATH, $LD_LIBRARY_PATH

Go to where ROOT is:

```
$ cd /path-to/root
```

(ba)sh:
```
$ . bin/thisroot.sh
```

(t)csh:
```
$ source bin/thisroot.csh
```

Starting Up ROOT

ROOT is prompt-based

```
$ root
root [0] _
```

Prompt speaks C++

```
root [0] gROOT->GetVersion();↵
(const char* 0x5ef7e8)"5.16/00"
```

ROOT As Pocket Calculator

Calculations:

```
root [0] sqrt(42)
(const double)6.48074069840786038e+00
root [1] double val = 0.17;
root [2] sin(val)
(const double)1.69182349066996029e-01
```

Uses C++ Interpreter CINT

Running Code

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

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

Equivalent: load file and run function:

```
root [0] .L mycode.C
root [1] mycode()
```

Quit:

```
root [0] .q
```

All of CINT's commands (help):

```
root [0] .h
```

ROOT Prompt

? Why C++ and not a scripting language?!

! You'll write your code in C++, too. Support for python, ruby,… exists.

? Why a prompt instead of a GUI?

! ROOT is a programming framework, not an office suite. Use GUIs where needed.

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)`

Compiling Code: ACLiC

Load code as shared lib, much faster:

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

Uses the system's compiler, takes seconds

Subsequent `.x mymacro.C+(42)` check for changes, only rebuild if needed

Exactly as fast as e.g. Makefile based stand-alone binary!

CINT knows types, functions in the file, e.g. call

```
mymacro(43)
```

Compiled versus Interpreted

- ? Why compile?
- ! Faster execution, CINT has limitations, validate code.

- ? Why interpret?
- ! Faster Edit → Run → Check result → Edit cycles ("rapid prototyping"). Scripting is sometimes just easier.

- ? Are Makefiles dead?
- ! Yes! ACLiC is even platform independent!

A Little C[++]

Hopefully many of you know – but some don't.

- Object, constructor, assignment
- Pointer, reference
- Scope, destructor
- Stack vs. heap
- Inheritance, virtual functions

If you use C++ you *have* to understand these concepts!

Objects, Constructors, =

Look at this code:

```
TNamed myObject("name", "title");
TNamed mySecond;
mySecond = myObject;
cout << mySecond.GetName() << endl;
```

Objects, Constructors, =

Look at this code:

```
TNamed myObject("name", "title");
TNamed mySecond;
mySecond = myObject;
cout << mySecond.GetName() << endl;
```

Creating objects:

1. Constructor **`TNamed::TNamed(const char*, const char*)`**
2. Default constructor **`TNamed::TNamed()`**

Objects, Constructors, =

Look at this code:

```
TNamed myObject("name", "title");
TNamed mySecond;
mySecond = myObject;
cout << mySecond.GetName() << endl;
```

3. Assignment:

Objects, Constructors, =

Look at this code:

```
TNamed myObject("name", "title");
TNamed mySecond;
mySecond = myObject;
cout << mySecond.GetName() << endl;
```

3. Assignment: creating a twin

Objects, Constructors, =

Look at this code:

```
TNamed myObject("name", "title");
TNamed mySecond;
mySecond = myObject;
cout << mySecond.GetName() << endl;
```

4. New content

mySecond

TNamed:
fName "name"
fTitle "title"

output: **"name"**

Pointer, Reference

Modified code:

```
TNamed myObject("name", "title");
TNamed* pMySecond = 0;
pMySecond = &myObject;
cout << pMySecond->GetName() << endl;
```

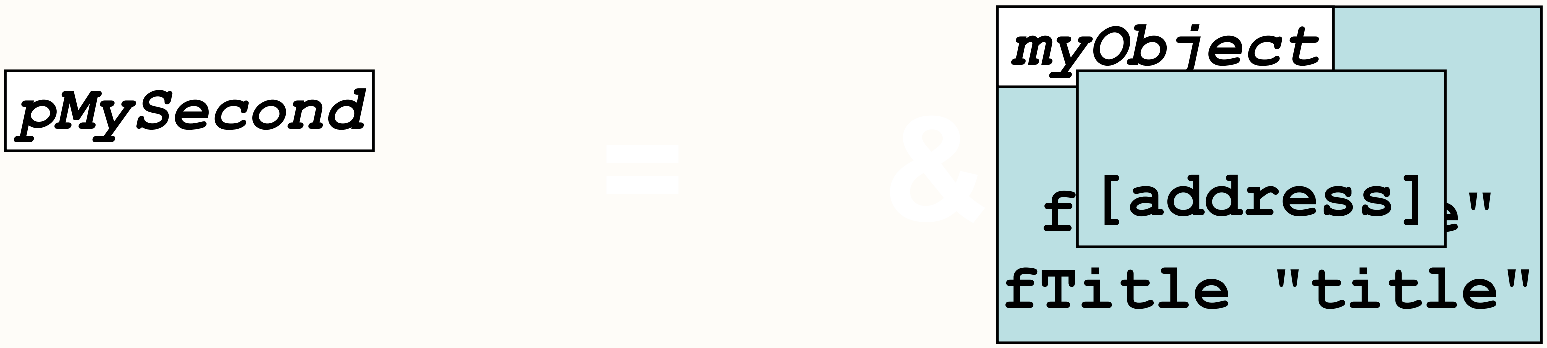
Pointer declared with "*", initialize to 0

Pointer, Reference

Modified code:

```
TNamed myObject("name", "title");
TNamed* pMySecond = 0;
pMySecond = &myObject;
cout << pMySecond->GetName() << endl;
```

Assignment: point to myObject; no copy



Pointer, Reference

Modified code:

```
TNamed myObject("name", "title");
TNamed* pMySecond = 0;
pMySecond = &myObject;
cout << pMySecond->GetName() << endl;
```

Assignment: "&" creates reference:

Pointer, Reference

Modified code:

```
TNamed myObject("name", "title");
TNamed* pMySecond = 0;
pMySecond = &myObject;
cout << pMySecond->GetName() << endl;
```

Access members of value pointed to by "`->`"

Pointer, Reference

Modified code:

```
TNamed myObject("name", "title");
TNamed* pMySecond = 0;
pMySecond = &myObject;
cout << (*pMySecond).GetName() << endl;
```

Or dereference pointer by "`*`"

and then access like object with "`.`"

Pointer, Reference

Changes propagated:

```
TNamed myObject("name", "title");
TNamed* pMySecond = 0;
pMySecond = &myObject;
pMySecond->SetName("newname");
cout << myObject.GetName() << endl;
```

Pointer forwards to object

Name of object changed – prints "newname"!

Object vs. Pointer

Compare object:

```
TNamed myObject("name", "title");
TNamed mySecond = myObject;
cout << mySecond.GetName() << endl;
```

to pointer:

```
TNamed myObject("name", "title");
TNamed* pMySecond = &myObject;
cout << pMySecond->GetName() << endl;
```

Object vs. Pointer: Parameters

Calling functions: object parameter obj gets copied for function call!

```
void funcO(TNamed obj);

TNamed myObject;
funcO(myObject);
```

Pointer parameter: only address passed, no copy

```
void funcP(TNamed* ptr);

TNamed myObject;
funcP(&myObject);
```

Object vs. Pointer: Parameters

Functions changing parameter: funcO can only access copy! **`caller`** not changed!

```
void funcO(TNamed obj){
  obj.SetName("nope");
}

funcO(caller);
```

Using pointers (or references) funcP can change **`caller`**

```
void funcP(TNamed* ptr){
  ptr->SetName("yes");
}

funcP(&caller);
```

Scope

Scope: range of accessibility and C++ "life".

Birth: constructor, death: destructor

```
{ // birth: TNamed() called
  TNamed n;
} // death: ~TNamed() called
```

Variables are valid / accessible only in scopes:

```
int a = 42;
{ int a = 0; }
cout << a << endl;
```

Scope

Functions are scopes:

```
void func(){ TNamed obj; }

func();
cout << obj << end; // obj UNKNOWN!
```

must not return pointers to local variables!

```
TNamed* func(){
  TNamed obj;
  return &obj; // BAD!
}
```

Stack vs. Heap

So far only stack:

```
TNamed myObj("n","t");
```

Fast, but often < 10MB. Only survive in scope.

Heap: slower, GBs (RAM + swap), creation and destruction managed by user:

```
TNamed* pMyObj = new TNamed("n","t");
delete pMyObj; // or memory leak!
```

Stack vs. Heap: Functions

Can return heap objects without copying:

```
TNamed* CreateNamed(){
  // user must delete returned obj!
  TNamed* ptr = new TNamed("n","t");
  return ptr; }
```

ptr gone – but TNamed object still on the heap, address returned!

```
TNamed* pMyObj = CreateNamed();
cout << pMyObj->GetName() << endl;
delete pMyObj; // or memory leak!
```

Inheritance

Classes "of same kind" can re-use functionality

E.g. TPlate, TBowl both dishes:

```
class TPlate: public TDish {...};
class TBowl: public TDish {...};
```

Can implement common functions in TDish:

```
class TDish {
 public:
  void Wash();
};
```

Inheritance: The Base

Use TPlate, TBowl as dishes:
- assign pointer of derived to pointer of base
- "every plate is a dish"

```
TDish *a = new TPlate();
TDish *b = new TBowl();
```

But not every dish is a plate, i.e. the inverse doesn't work. And a bowl is totally not a plate!

```
TPlate* p = new TDish(); // NO!
TPlate* q = new TBowl(); // NO!
```

Virtual Functions

Often derived classes behave differently:

```
class TDish { ...
  virtual bool ForSoup() const;
};
class TPlate: public TDish { ...
  bool ForSoup() const {return false;}
};
class TBowl: public TDish { ...
  bool ForSoup() const {return true;}
};
```

Pure Virtual Functions

But TDish cannot know! Mark as "not implemented"

```
class TDish { ...
  virtual bool ForSoup() const = 0;
};
```

Only for virtual functions.

Cannot create object of TDish anymore (one function is missing!)

Calling Virtual Functions

Call to virtual functions evaluated at runtime:

```
void FillWithSoup(TDish* dish) {
  if (dish->ForSoup())
    dish->SetFull();
}
```

Works for any type as expected:

```
TDish* a = new TPlate();
TDish* b = new TBowl();
FillWithSoup(a); // will not be full
FillWithSoup(b); // is now full
```

Virtual vs. Non-Virtual

So what happens if non-virtual?

```
class TDish { ...
  bool ForSoup() const {return false;}
};
```

Will now always call TDish::ForSoup(), i.e. false

```
void FillWithSoup(TDish* dish) {
  if (dish->ForSoup())
    dish->SetFull();
}
```

Congrats!

Fine print:

* comes with lifelong subscription,

this diploma is worth nothing if not exercised regularly

Summary

We know:

- why and how to start ROOT
- C++ basics
- that you run your code with ".x"
- can call functions in libraries
- can (mis-) use ROOT as a pocket calculator!

Lots for you to discover during next two lectures and especially the exercises!

Saving Data

Streaming, Reflection, TFile, Schema Evolution

Saving Objects

Cannot do in C++:

```
TNamed* o; TNamed* p;
o = new TNamed("name", "title");
std::write("file.bin", "obj1", o);
p = std::read("file.bin", "obj1");
p->GetName();
```

E.g. LHC experiments use C++ to manage data

Need to write C++ objects and read them back

std::cout not an option: 15PetaBytes / year of processed data (i.e. data that will be read)

Saving Objects – Saving Types

What's needed?

```
TNamed* o;
o = new TNamed("name", "title");
std::write("file.bin", "obj1", o);
```

Store *data members* of TNamed; need to know:

1) type of object

2) data members for the type

3) where data members are in memory

4) read their values from memory, write to disk

Serialization

Store *data members* of TNamed: serialization

1) type of object: runtime-type-information RTTI

2) data members for the type: reflection

3) where data members are in memory: introspection

4) read their values from memory, write to disk: raw I/O

Complex task, and C++ is not your friend.

Reflection

Need type description (aka *reflection*)

1. types, sizes, members

TMyClass is a class.

```
class TMyClass {
  float fFloat;
  Long64_t fLong;
};
```

Members:

- "fFloat", type float, size 4 bytes
- "fLong", type Long64_t, size 8 bytes

Platform Data Types

Fundamental data types (int, long,…):
 size is platform dependent

Store "long" on 64bit platform, writing 8 bytes:
 00, 00, 00, 00, 00, 00, 00, 42

Read on 32bit platform, "long" only 4 bytes:
 00, 00, 00, 00

Data loss, data corruption!

ROOT Basic Data Types

Solution: ROOT typedefs

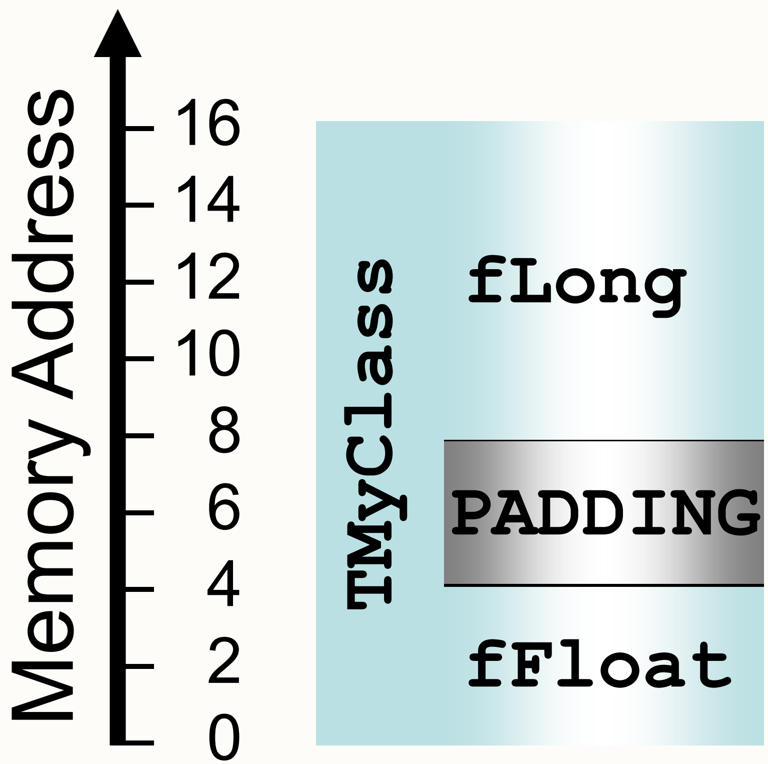
Signed	Unsigned	sizeof [bytes]
`Char_t`	`UChar_t`	1
`Short_t`	`UShort_t`	2
`Int_t`	`UInt_t`	4
`Long64_t`	`ULong64_t`	8
`Double32_t`		float on disk, double in RAM

Reflection

Need type description (platform dependent)

1. types, sizes, members
2. offsets in memory

```
class TMyClass {
  float fFloat;
  Long64_t fLong;
};
```

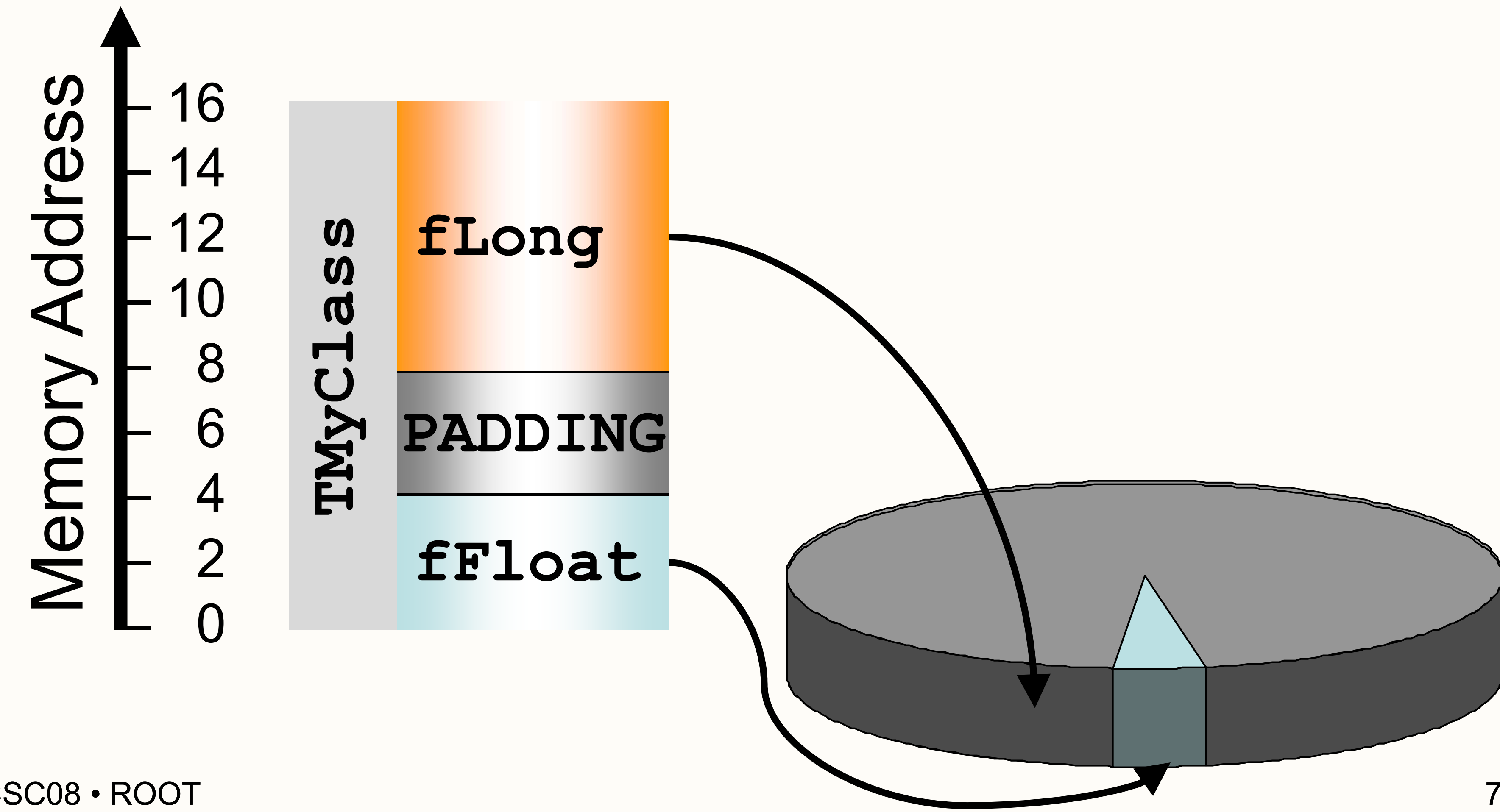


"fFloat" is at offset 0

"fLong" is at offset 8

I/O Using Reflection

members → memory → disk



C++ Is Not Java

Lesson: need reflection!

Where from?

Java: get data members with

```
Class.forName("MyClass").getFields()
```

C++: get data members with

– oops. Not part of C++.

BE CAREFUL

THIS LANGUAGE HAS NO BRAIN USE YOUR OWN

ROOT And Reflection

Simply use ACLiC:

```
.L MyCode.cxx+
```

Creates library with reflection data ("dictionary") of all types in MyCode.cxx!

Dictionary needed for interpreter, too

ROOT has dictionary for all its types

Back To Saving Objects: TFile

ROOT stores objects in TFiles:

```
TFile* f = new TFile("file.root", "NEW");
```

TFile behaves like file system:

```
f->mkdir("dir");
```

TFile has a current directory:

```
f->cd("dir");
```

TFile compresses data ("zip"):

```
f->GetCompressionFactor()
2.6144216060384277e00
```

Saving Objects, Really

Given a TFile:

```
TFile* f = new TFile("file.root", "RECREATE");
```

Write an object deriving from TObject:

```
object->Write("optionalName")
```

"optionalName" or `TObject::GetName()`

Write any object (with dictionary):

```
f->WriteObject(object, "name");
```

"Where Is My Histogram?"

TFile owns histograms, graphs, trees (due to historical reasons):

```
TFile* f = new TFile("myfile.root");
TH1F* h = new TH1F("h","h",10,0.,1.);
h->Write();
TCanvas* c = new TCanvas();
c->Write();
delete f;
```

h automatically deleted: owned by file.

c still there. → *names unique!*

TFile acts like a scope for hists, graphs, trees!

Risks With I/O

Physicists can loop a lot:

For each particle collision

For each particle created

For each detector module

Do something.

Physicists can loose a lot:

Run for hours…

Crash.

Everything lost.

Name Cycles

Create snapshots regularly:

- MyObject;1
- MyObject;2
- …
- MyObject; 5427
- MyObject

Write() does not replace but append!

- but see documentation TObject::Write()

The "I" Of I/O

Reading is simple:

```
TFile* f = new TFile("myfile.root");
TH1F* h = 0;
f->GetObject("h", h);
h->Draw();
delete f;
```

Remember:

TFile owns histograms!

file gone, histogram gone!

Ownership And TFiles

Separate TFile and histograms:

```
TFile* f = new TFile("myfile.root");
TH1F* h = 0;
TH1::AddDirectory(kFALSE);
f->GetObject("h", h);
h->Draw();
delete f;
```

… and h will stay around.

Changing Class – The Problem

Things change:

```
class TMyClass {
  float fFloat;
  Long64_t fLong;
};
```

Changing Class – The Problem

Things change:

```
class TMyClass {
  double fFloat;
  Long64_t fLong;
};
```

Inconsistent reflection data, mismatch in memory, on disk

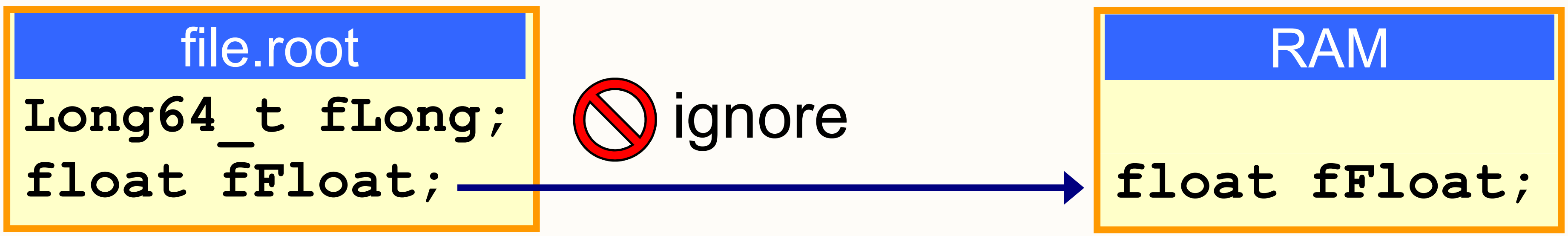
Objects written with old version cannot be read

Need to store reflection with data to detect!

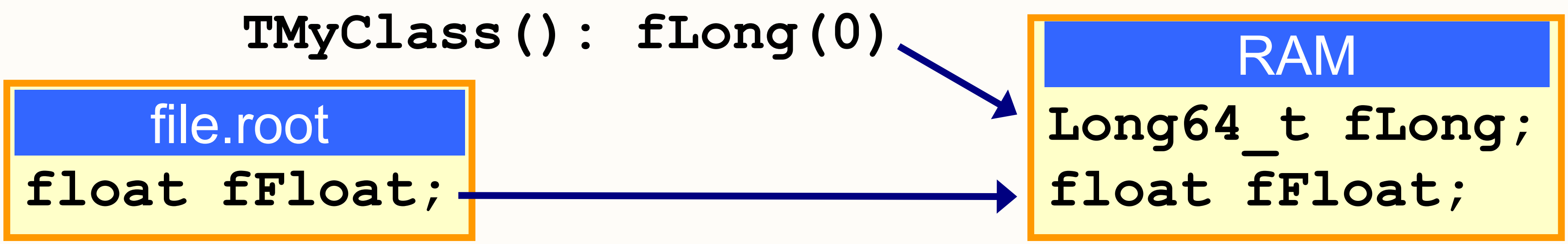
Schema Evolution

Simple rules to convert disk to memory layout

1. skip removed members



2. default-initialize added members



3. convert members where possible

Class Version

ClassDef() macro makes I/O faster, needed when deriving from TObject

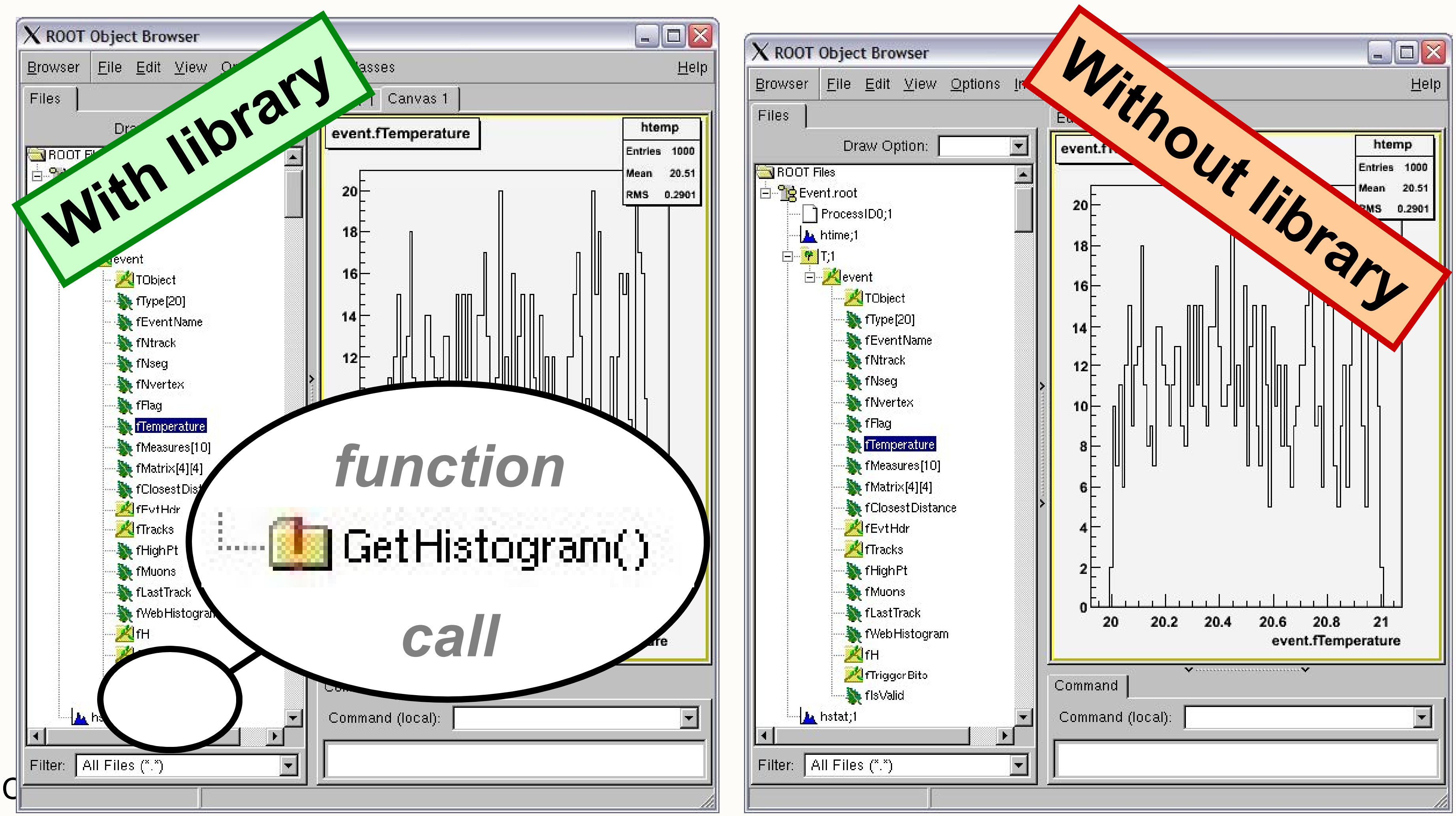
Can have multiple class versions in same file

Use version number to identify layout:

```
class TMyClass: public TObject {
public:
  TMyClass(): fLong(0), fFloat(0.) {}
  virtual ~TMyClass() {}
  ...
  ClassDef(TMyClass,1); // example class
};
```

Reading Files

Files store reflection and data: need no library!



Powers of ROOT I/O

- Can even open
  `TFile("http://myserver.com/afile.root")`
  including read-what-you-need!
- Nice viewer for TFile: `new TBrowser`
- Combine contents of TFiles with
  `$ROOTSYS/bin/hadd`

Summary

Big picture:

- you know ROOT files – for petabytes of data
- you learned what schema evolution is
- you learned that reflection is key for I/O

Small picture:

- you can write your own data to files
- you can read it back
- you can change the definition of your classes

ROOT Collection Classes

Collection Classes

ROOT collections polymorphic containers: hold pointers to **TObject**, so:

- Can only hold objects that inherit from **TObject**
- Return pointers to **TObject**, that have to be cast back to the correct subclass

```
void DrawHist(TObjArray *vect, int at)
{
   TH1F *hist = (TH1F*)vect->At(at);
   if (hist) hist->Draw();
}
```

TObjArray

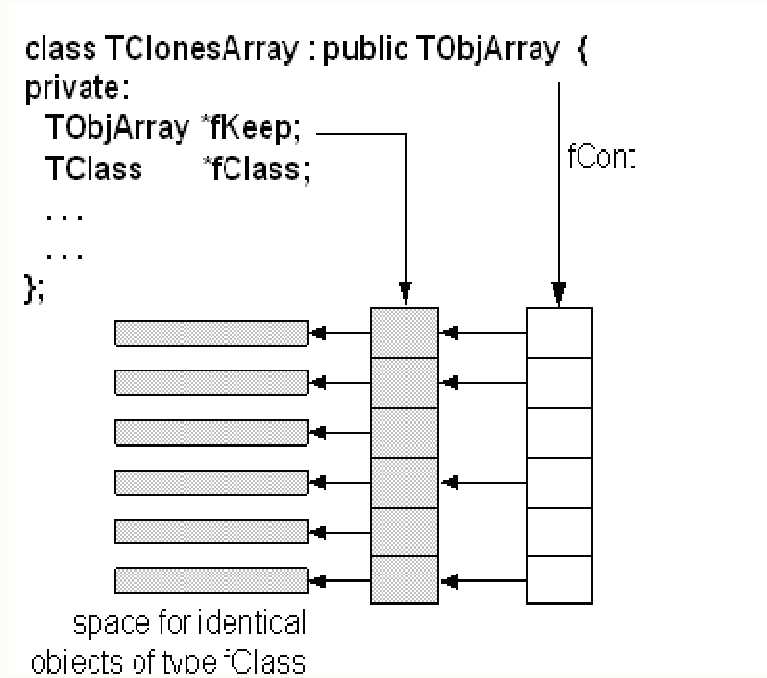
- Like vector<**TObject** *>, supports traditional array semantics:
  - Objects can be directly accessed via an index with the operator[]
  - Expands automatically when objects are added

TClonesArray

Array of objects of the same class ("clones")

Designed for repetitive data analysis tasks: same type of objects created and deleted many times.

No comparable class in STL!



The internal data structure of a TClonesArray

Traditional Arrays

Very large number of new and delete calls in large loops like this (N(100000) x N(10000) times new/delete):

N(100000)

```
TObjArray a(10000);
while (TEvent *ev = (TEvent *)next()) {
   for (int i = 0; i < ev->Ntracks; ++i) {
      a[i] = new TTrack(x,y,z,...);
      ...
   }
   ...
   a.Delete();
}
```

N(10000)

You better use a **TClonesArray** which reduces the number of new/delete calls to only N(10000):

```
TClonesArray a("TTrack", 10000);
while (TEvent *ev = (TEvent *)next()) {
   for (int i = 0; i < ev->Ntracks; ++i) {
      new(a[i]) TTrack(x,y,z,...);
      ...
   }
   ...
   a.Delete();
}
```

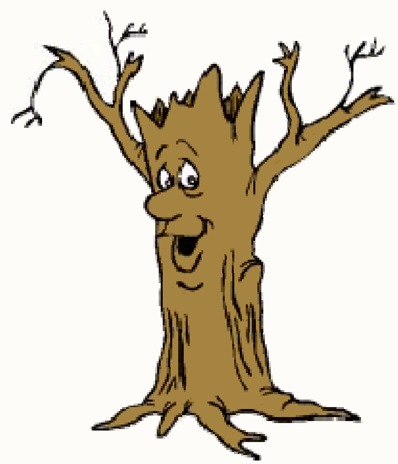
N(100000)

N(10000)

Pair of new / delete calls cost about 4 μs

Allocating / freeing memory NN(10^9) times costs about 1 hour!

ROOT Trees

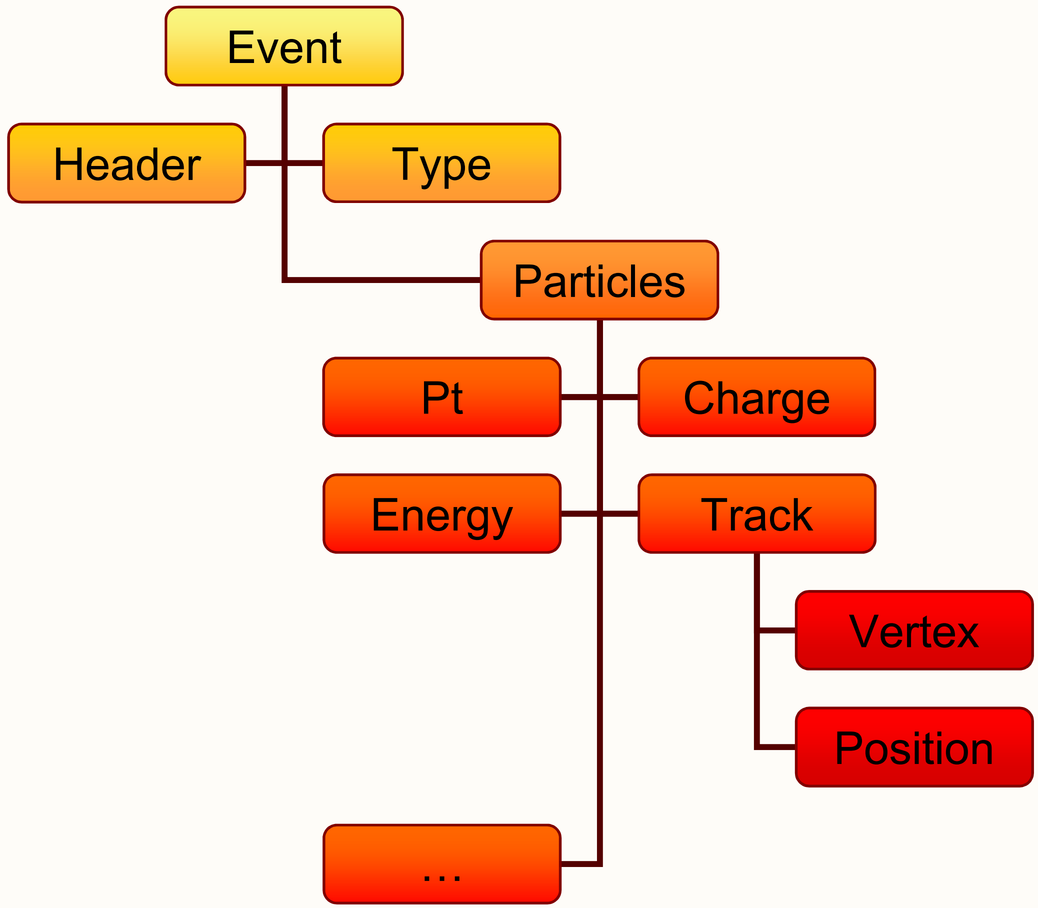


Trees

From:
Simple data types
(e.g. Excel tables)

x	y	z
-1.10228	-1.79939	4.452822
1.867178	-0.59662	3.842313
-0.52418	1.868521	3.766139
-0.38061	0.969128	1.084074
0.552454	-0.21231	0.350281
-0.18495	1.187305	1.443902
0.205643	-0.77015	0.635417
1.079222	-0.32739	1.271904
-0.27492	-1.72143	3.038899
2.047779	-0.06268	4.197329
-0.45868	-1.44322	2.293266
0.304731	-0.88464	0.875442
-0.71234	-0.22239	0.556881
-0.27187	1.181767	1.470484
0.886202	-0.65411	1.213209
-2.03555	0.527648	4.421883
-1.45905	-0.464	2.344113
1.230661	-0.00565	1.514559
		3.562347

To:
Complex data types
(e.g. Database tables)



Trees

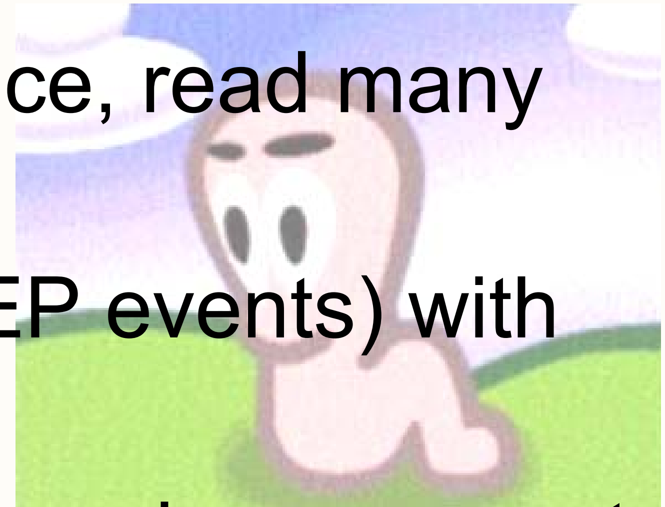
- Databases have row wise access
  - Designed to store complete objects.
  - Data clustering is organized around objects and containers of objects.
  - Can only access the full object (e.g. full event)
- ROOT trees have column wise access
  - Direct access to any event, any branch or any leaf even in the case of variable length structures
  - Designed to access only a subset of the object attributes (e.g. only particles' energy)

Why Trees ?

object.Write() convenient for simple objects like histograms, inappropriate for saving collections of events containing complex objects

- Reading a collection: read all elements (all events)
- With trees: only one element in memory, or even only a part of it (less I/O)

Why Trees ?



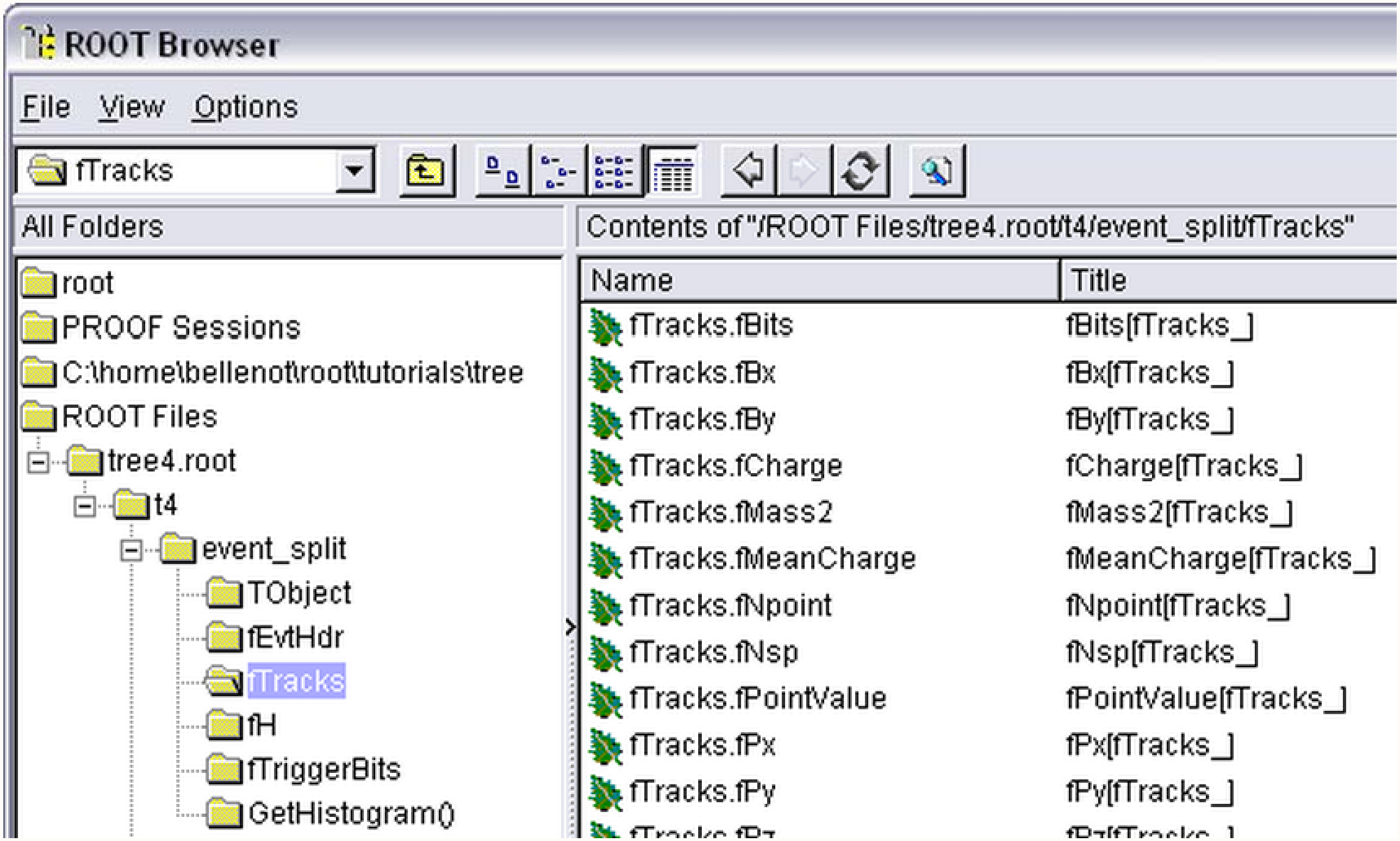
- Extremely efficient write once, read many ("WORM")
- Designed to store $>10^9$ (HEP events) with same data structure
- Trees allow fast direct and random access to any entry (sequential access is the best)
- Optimized for network access

Building ROOT Trees

Overview of
- Trees
- Branches

5 steps to build a TTree

Tree structure

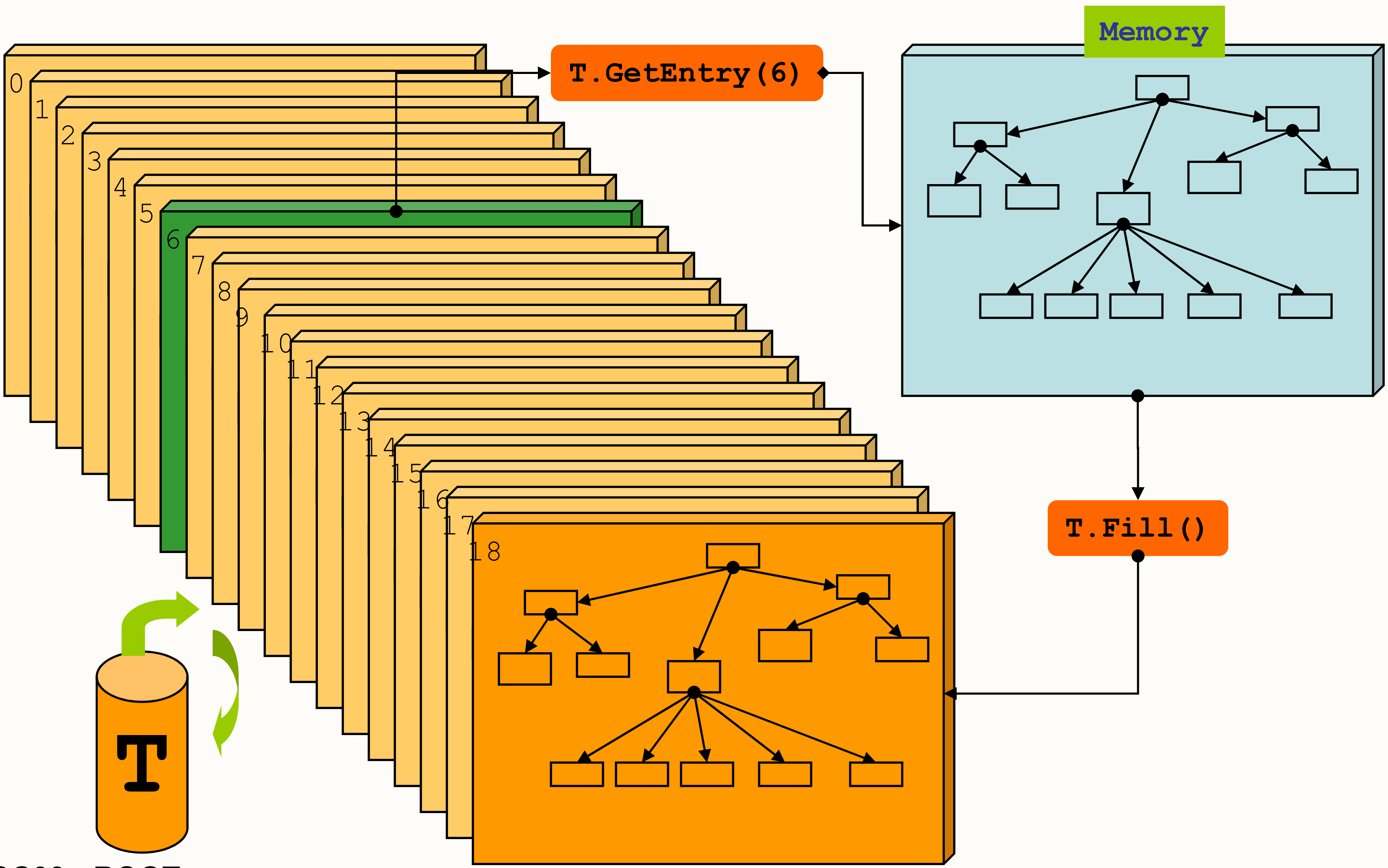


Tree structure

- Branches: directories
- Leaves: data containers
- Can read a subset of all branches – speeds up considerably the data analysis processes
- Tree layout can be optimized for data analysis
- The class for a branch is called **TBranch**
- Variables on **TBranch** are called leaf (yes - **TLeaf**)
- Branches of the same **TTree** can be written to separate files

Memory ↔ Tree

Each Node is a branch in the Tree



Five Steps to Build a Tree

Steps:

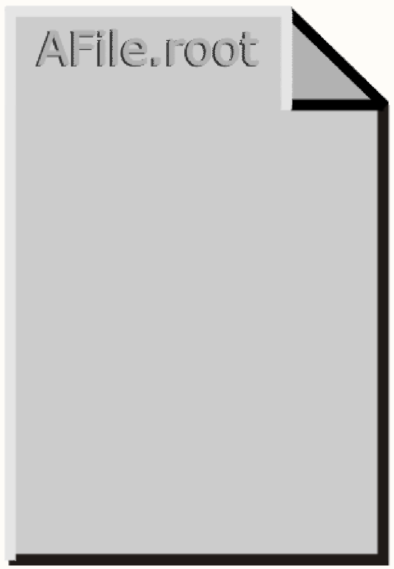
1. Create a TFile
2. Create a TTree
3. Add TBranch to the TTree
4. Fill the tree
5. Write the file

Example macro

```
void WriteTree()
{
   Event *myEvent = new Event();
   TFile f("AFile.root");
   TTree *t = new TTree("myTree","A Tree");
   t->Branch("EventBranch", myEvent);
   for (int e=0;e<100000;++e) {
      myEvent->Generate();  // hypothetical
      t->Fill();
   }
   t->Write();
}
```

Step 1: Create a TFile Object

Trees can be huge → need file for swapping filled entries

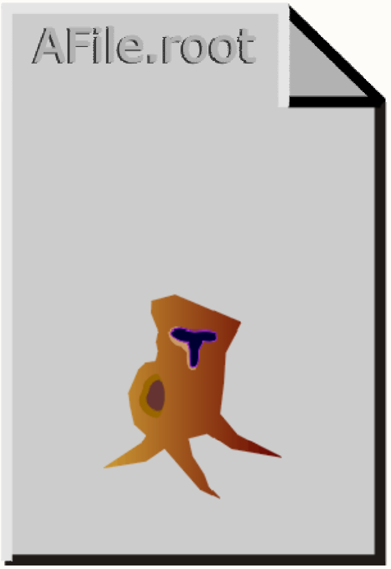



```
TFile *hfile = new TFile("AFile.root");
```

Step 2: Create a TTree Object

The TTree constructor:

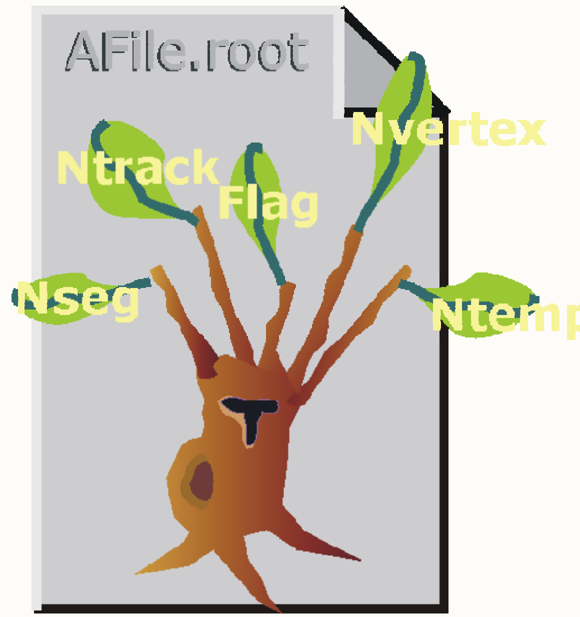
- Tree name (e.g. "myTree")
- Tree title




```
TTree *tree = new TTree("myTree","A Tree");
```

Step 3: Adding a Branch

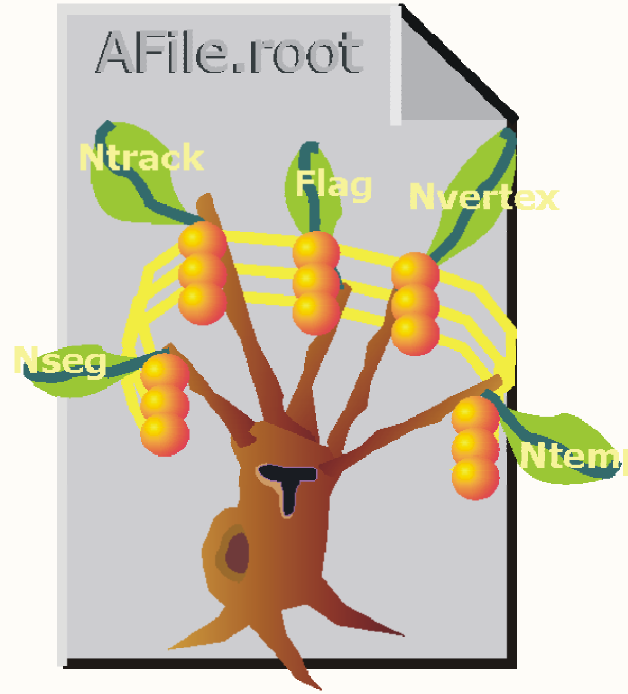
- Branch name
- Pointer to the object




```
Event *myEvent = new Event();
myTree->Branch("eBranch", myEvent);
```

Step 4: Fill the Tree

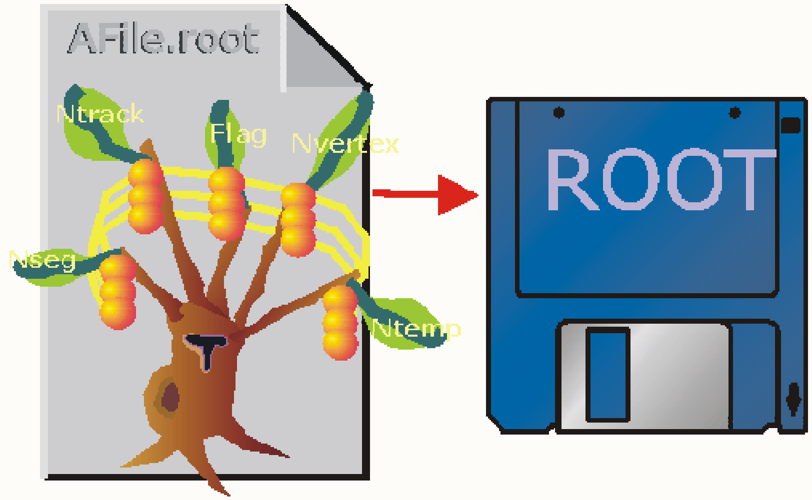
- Create a for loop
- Assign values to the object contained in each branch
- TTree::Fill() creates a new entry in the tree: snapshot of values of branches' objects




```
for (int e=0;e<100000;++e) {
   myEvent->Generate(e); // fill event
   myTree->Fill();       // fill the tree
}
```

Step 5: Write Tree To File

```
myTree->Write();
```



Reading a TTree

- Looking at a tree
- How to read a tree
- Friends and chains

Example macro

```
void ReadTree()
{
  Event *myEvent = 0;
  TFile f("AFile.root");
  TTree *myTree = (TTree*)f->Get("myTree");
  myTree->SetBranchAddress("EventBranch",
                           myEvent);
  for (int e=0;e<100000;++e) {
     myTree->GetEntry(e);
     myEvent->Analyze();
  }
}
```

The pointer (myEvent) MUST be set to 0

How to Read a TTree

Example:

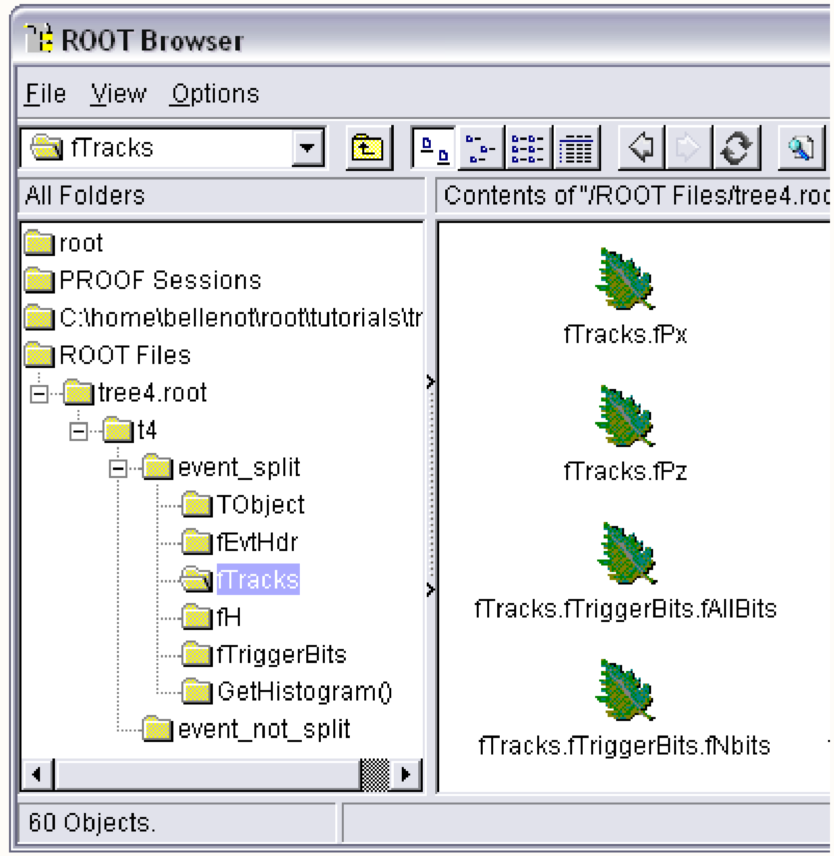
1. Open the Tfile

```
TFile f("AFile.root")
```

2. Get the TTree

```
TTree *myTree = 0;
f.GetObject("myTree",
myTree)
```

OR



How to Read a TTree

3. Create a variable pointing to the data

```
root [] Event *myEvent = 0;
```

4. Associate a branch with the variable:

```
root [] myTree->SetBranchAddress("eBranch", myEvent);
```

5. Read one entry in the TTree

```
root [] myTree->GetEntry(0)
root [] myEvent->GetTracks()->First()->Dump()
==> Dumping object at: 0x0763aad0, name=Track,
  class=Track
fPx              0.651241    X component of the momentum
fPy              1.02466     Y component of the momentum
fPz              1.2141      Z component of the momentum
[...]
```

Branch Access Selection

- Use TTree::SetBranchStatus() to activate only the branches holding wanted variables.
- Speed up considerably the reading phase

```
TClonesArray* myMuons = 0;
// disable all branches
myTree->SetBranchStatus("*", 0);
// re-enable the "muon" branches
myTree->SetBranchStatus("muon*", 1);
myTree->SetBranchAddress("muon",myMuons);
// now read (access) only the "muon" branches
myTree->GetEntry(0);
```

Looking at the Tree

TTree::Print() shows the data layout

```
root [] TFile f("AFile.root")
root [] myTree->Print();
******************************************************************************
*Tree    :myTree    : A ROOT tree                                            *
*Entries :       10 : Total =          867935 bytes  File  Size =     390138 *
*        :          : Tree compression factor =   2.72                       *
******************************************************************************
*Branch  :eBranch                                                        *
*Entries :       10 : BranchElement (see below)                              *
*............................................................................*
*Br    0 :fUniqueID :                                                        *
*Entries :       10 : Total  Size=        698 bytes  One basket in memory    *
*Baskets :        0 : Basket Size=      64000 bytes  Compression=   1.00     *
*............................................................................*
…
…
```

Looking at the Tree

TTree::Scan("leaf:leaf:….") shows the values

```
root [] myTree->Scan("fNseg:fNtrack"); > scan.txt

root [] myTree->Scan("fEvtHdr.fDate:fNtrack:fPx:fPy","",
                "colsize=13 precision=3 col=13:7::15.10");
```

```
******************************************************************************
* Row * Instance * fEvtHdr.fDate * fNtrack *           fPx *             fPy *
******************************************************************************
*   0 *        0 *        960312 *     594 *          2.07 *     1.459911346 *
*   0 *        1 *        960312 *     594 *         0.903 *   -0.4093382061 *
*   0 *        2 *        960312 *     594 *         0.696 *    0.3913401663 *
*   0 *        3 *        960312 *     594 *        -0.638 *     1.244356871 *
*   0 *        4 *        960312 *     594 *        -0.556 *   -0.7361358404 *
*   0 *        5 *        960312 *     594 *         -1.57 *   -0.3049036264 *
*   0 *        6 *        960312 *     594 *        0.0425 *    -1.006743073 *
*   0 *        7 *        960312 *     594 *          -0.6 *    -1.895804524 *
```

TTree Selection Syntax

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

Prints the first 8 variables of the tree.

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

Prints all the variables of the tree.

Select specific variables:

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

Prints the values of var1, var2 and var3.

A selection can be applied in the second argument:

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

Prints the values of var1, var2 and var3 for the entries where var1 is greater than 0

Use the same syntax for TTree::Draw()

Looking at the Tree

TTree::Show(entry_number) shows the values for one entry

```
 root [] myTree->Show(0);
======> EVENT:0
 eBranch          = NULL
 fUniqueID        = 0
 fBits            = 50331648
 [...]
 fNtrack          = 594
 fNseg            = 5964
 [...]
 fEvtHdr.fRun     = 200
 [...]
 fTracks.fPx      = 2.066806, 0.903484, 0.695610, -0.637773,...
 fTracks.fPy      = 1.459911, -0.409338, 0.391340, 1.244357,...
```

TChain: the Forest

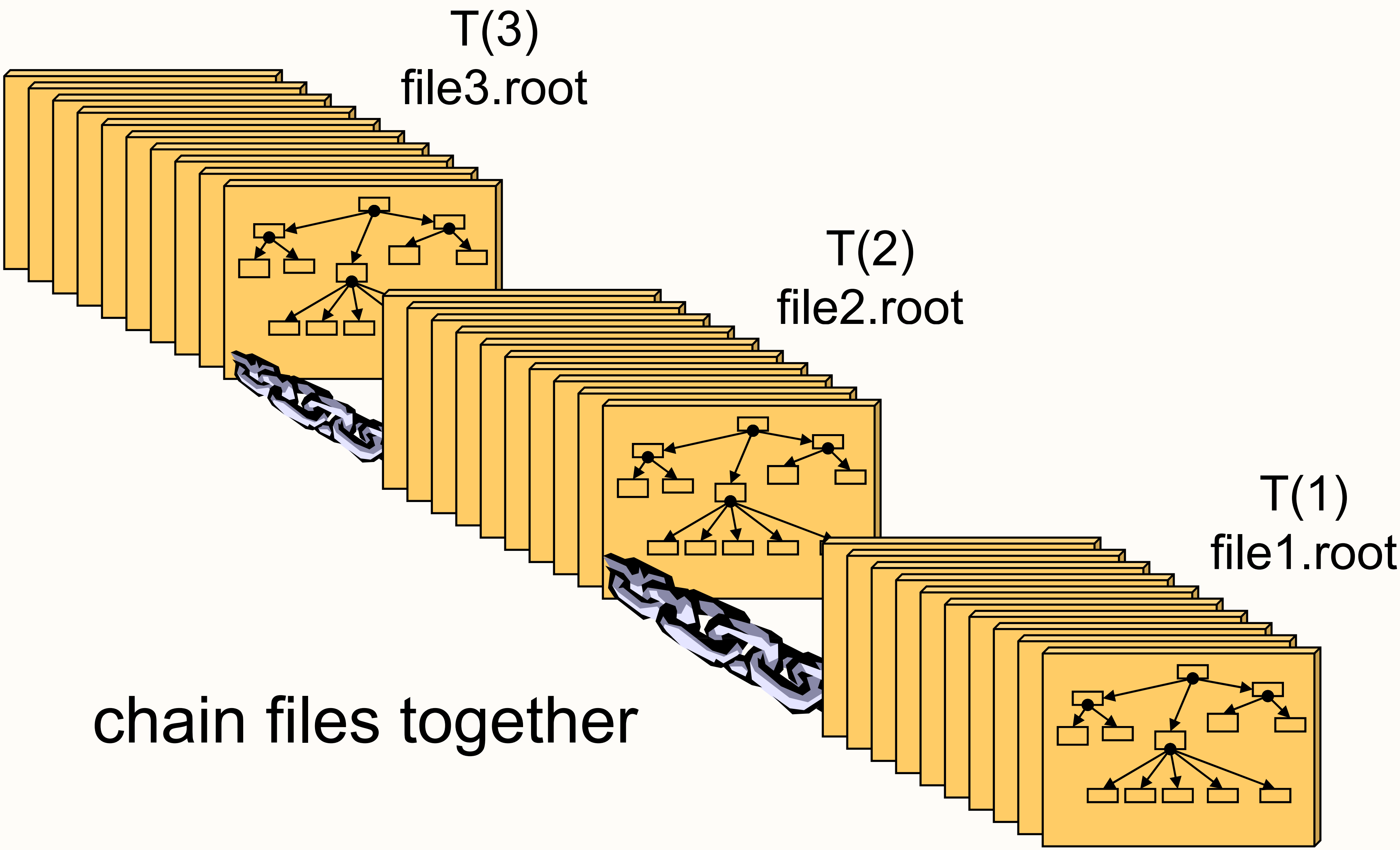
- Collection of TTrees: list of ROOT files containing the same tree
- Same semantics as TTree

As an example, assume we have three files called file1.root, file2.root, file3.root. Each contains tree called "T". Create a chain:

```
TChain chain("T"); // argument: tree name
chain.Add("file1.root");
chain.Add("file2.root");
chain.Add("file3.root");
```

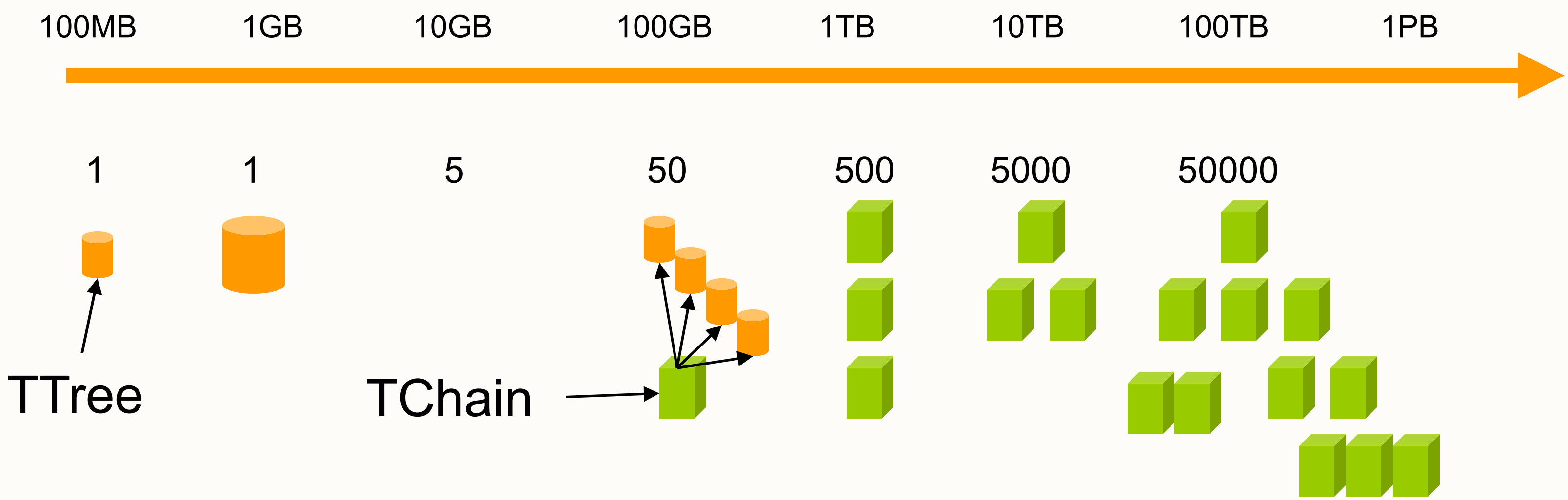
Now we can use the TChain like a TTree!

TChain



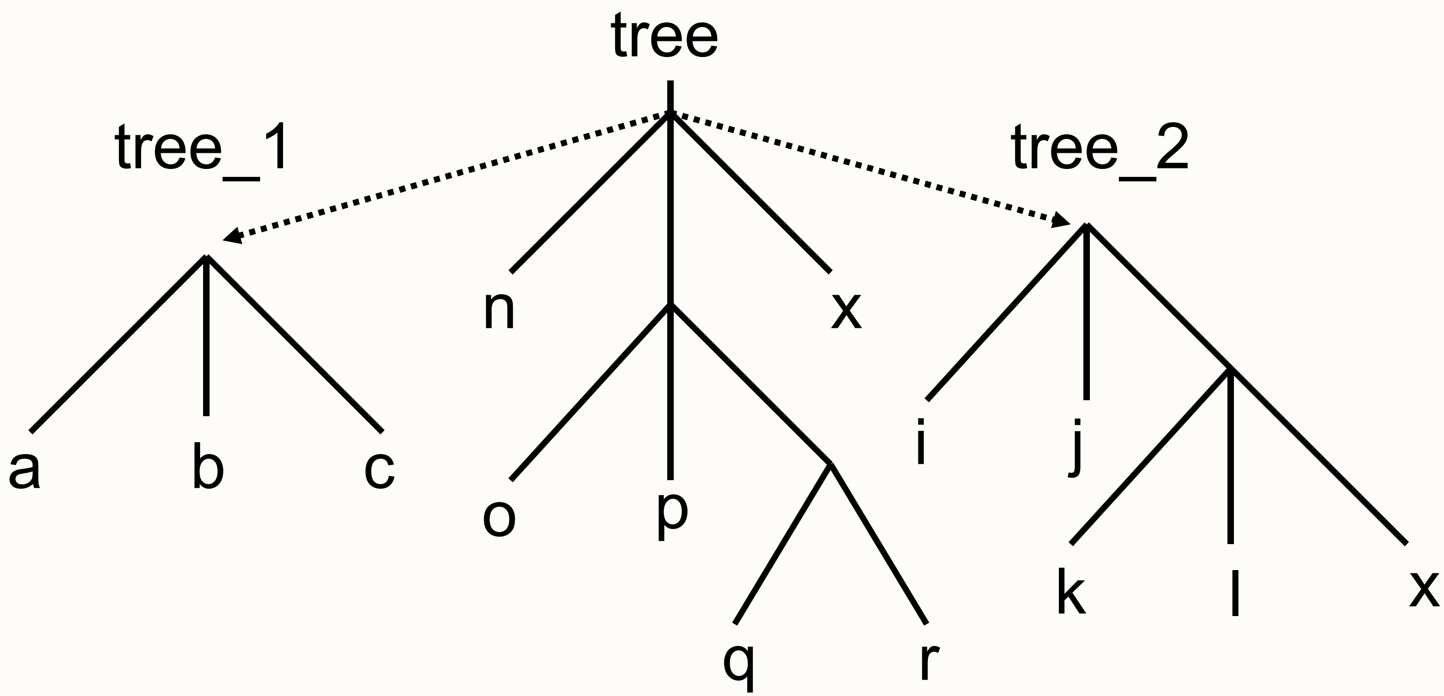
chain files together

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 a file catalog

Tree Friends

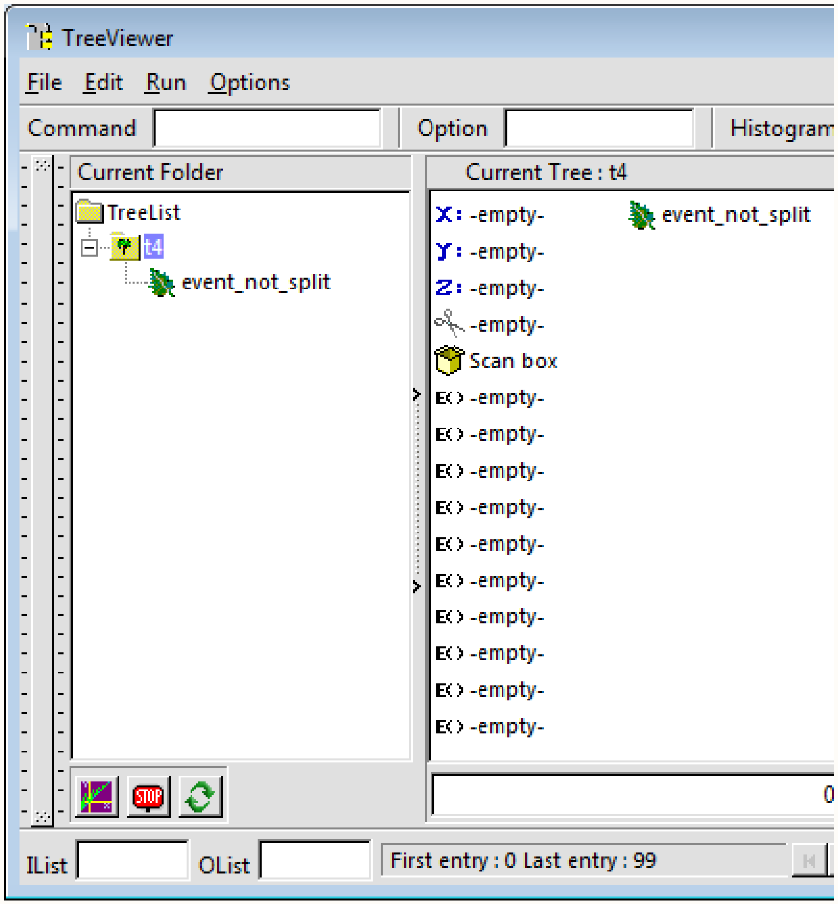



```
TFile f1("tree1.root");
tree.AddFriend("tree_1", "tree2.root")
tree.AddFriend("tree_2", "tree3.root");
tree.Draw("x:a", "k<c");
tree.Draw("x:tree_2.x", "sqrt(p)<b");
```

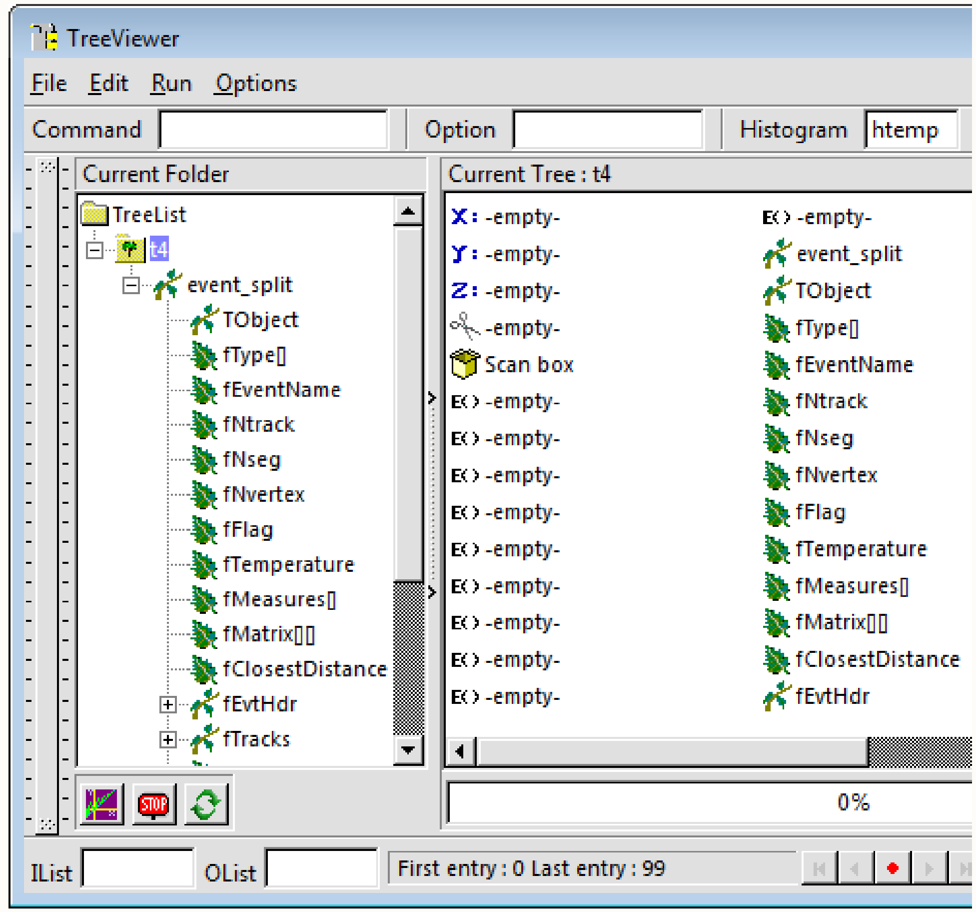
Summary: Trees, basics

- TTree is one of the most powerful collections available for HEP
- Extremely efficient for huge number of data sets with identical layout
- Very easy to look at TTree - use TBrowser!
- Write once, read many (WORM) ideal for experiments' data
- Still: extensible, users can add their own tree as friend

Splitting



Split level = 0



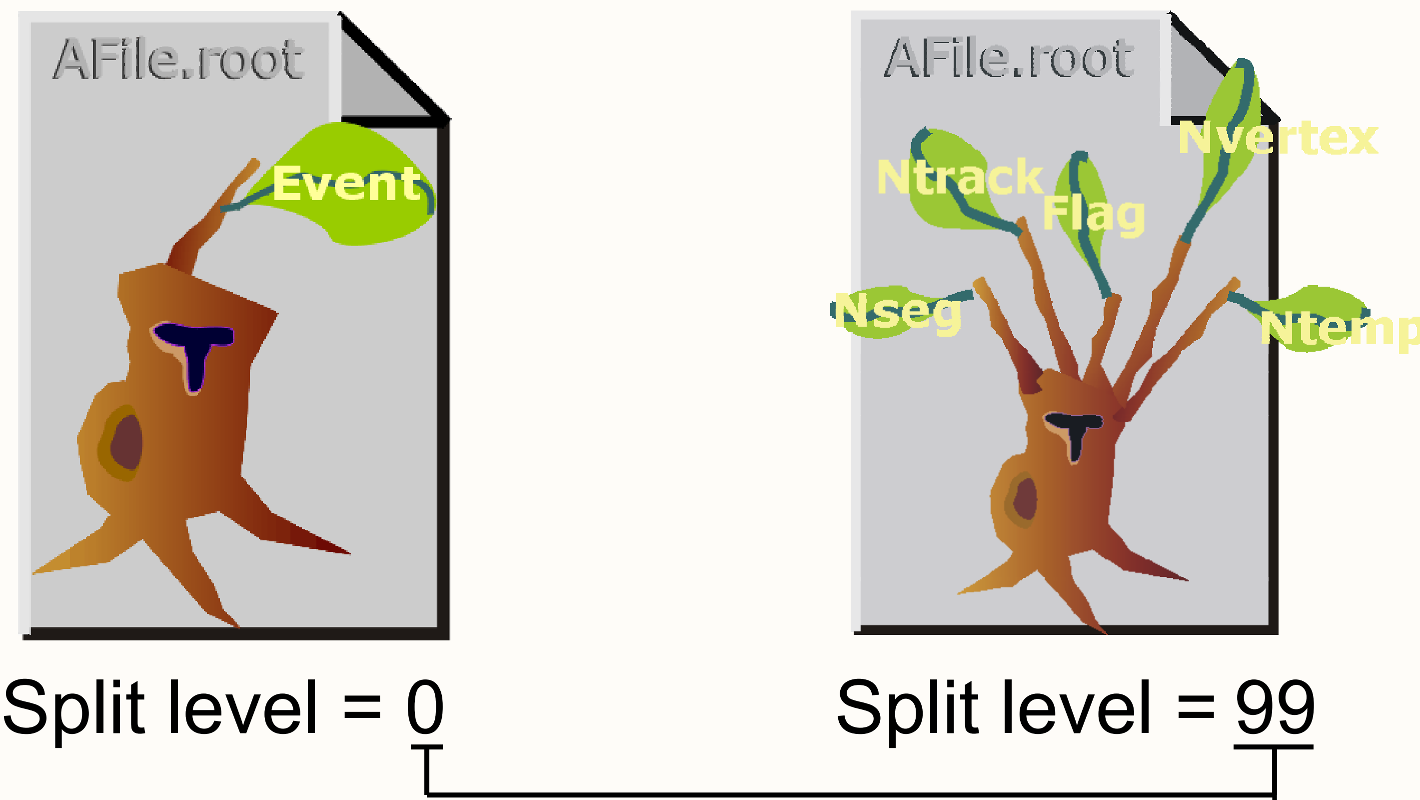
Split level = 99

Splitting

- Creates one branch per member – recursively
- Allows to browse objects that are stored in trees, even without their library
- Makes same members consecutive, e.g. for object with position in X, Y, Z, and energy E, all X are consecutive, then come Y, then Z, then E. A lot higher zip efficiency!
- Fine grained branches allow fain-grained I/O - read only members that are needed, instead of full object
- Supports STL containers, too!

Splitting

Setting the split level (default = 99)




```
tree->Branch("EvBr", &event, 64000, 0 );
```

Performance Considerations

A split branch is:

- Faster to read - the type does not have to be read each time
- Slower to write due to the large number of branches

Analyzing Trees

Selectors, Analysis, PROOF

Recap

TTree efficient storage and access
for huge amounts of structured data

Allows selective access of data

TTree knows its layout

Almost all HEP analyses based on TTree

TTree Data Access

TSelector: generic "TTree based analysis"

Derive from it ("TMySelector")

ROOT invokes TSelector's functions,

Used e.g. by tree->**Process**(TSelector*,…), PROOF

Functions called are virtual, thus TMySelector's functions called.

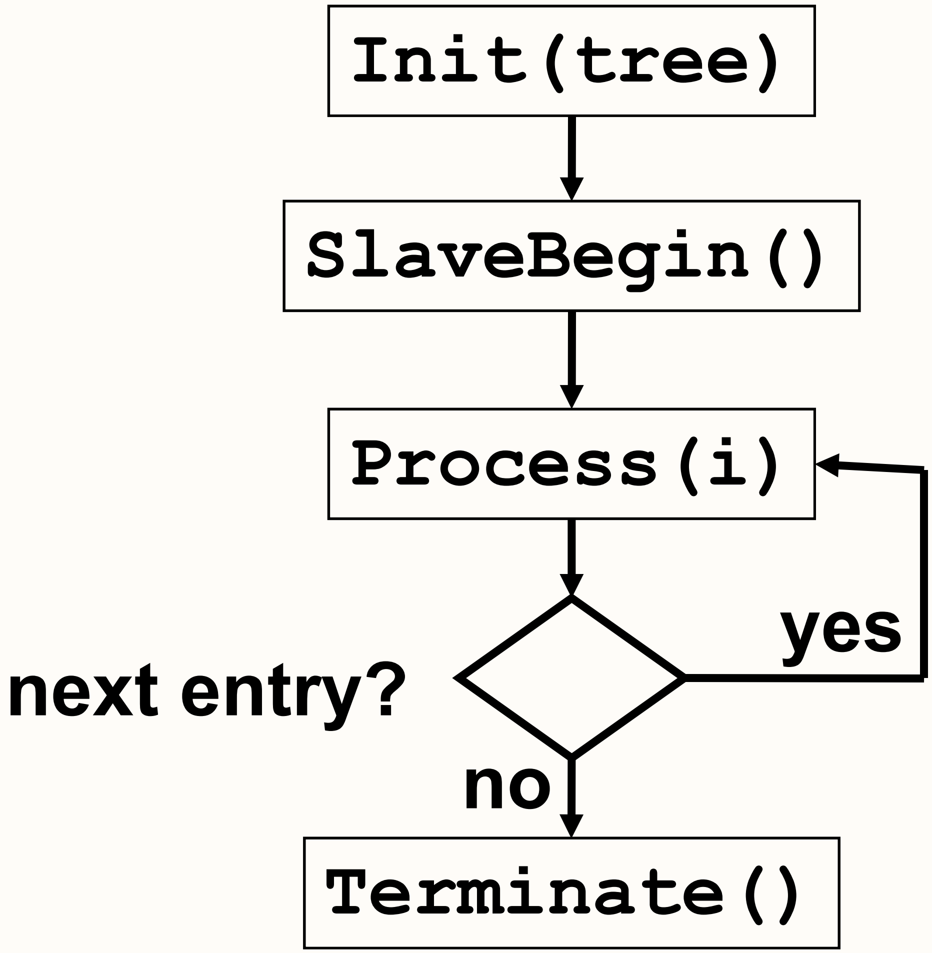
TSelector

Steps of ROOT using a TSelector:

1. ***setup*** Init(TTree*)
   called to inform selector about tree
2. ***start*** SlaveBegin()
   called to create histograms
3. ***run*** Process(Long64_t)
   called for each entry to load and analyze it
4. ***end*** Terminate()
   called to fit histograms, write them to files,…

TTree Data Access

E.g. `tree->Process("MySelector.C+")`



TSelector: Usage

- Init(TTree* tree):
  e.g. TMySelector::fChain = tree.
  Set branch addresses.
- SlaveBegin(): create histograms
- Process(Long64_t entry):
  fChain->GetTree()->GetEntry(entry);
  fill histograms
- Terminate(): fit; save histograms

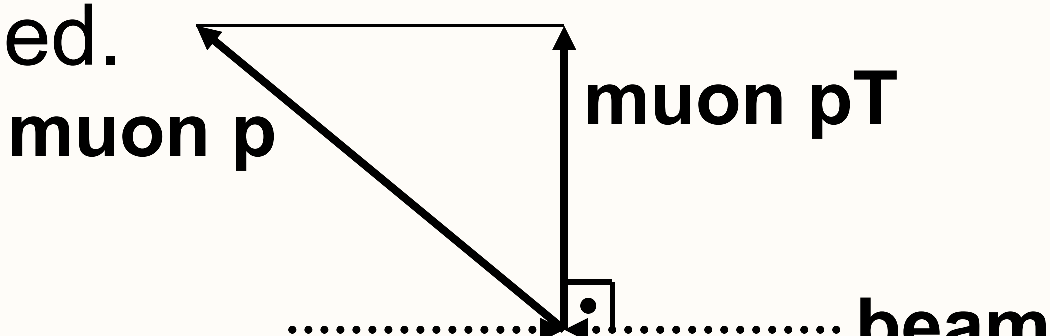
Analysis Example

Determine trigger efficiencies from data, typical ingredient in analyses

Trigger selection before writing data: not all events available

Usually higher energy is taken, lower is ignored

Example 15GeV muon trigger: events with a muon > 15GeV transverse momentum ("pT") are recorded.

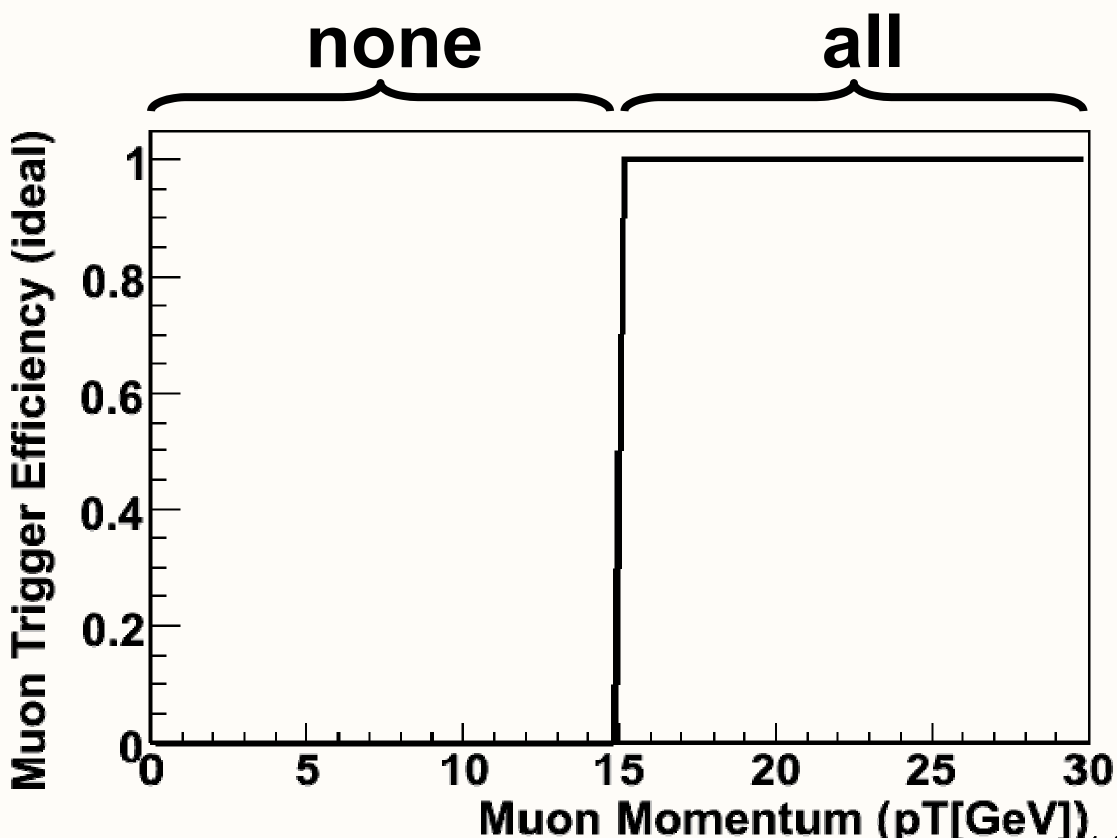


Ideal Trigger

Efficiency: probability to record an event with a given (transverse) muon momentum

eff = triggered/all

Ideal 15GeV muon trigger

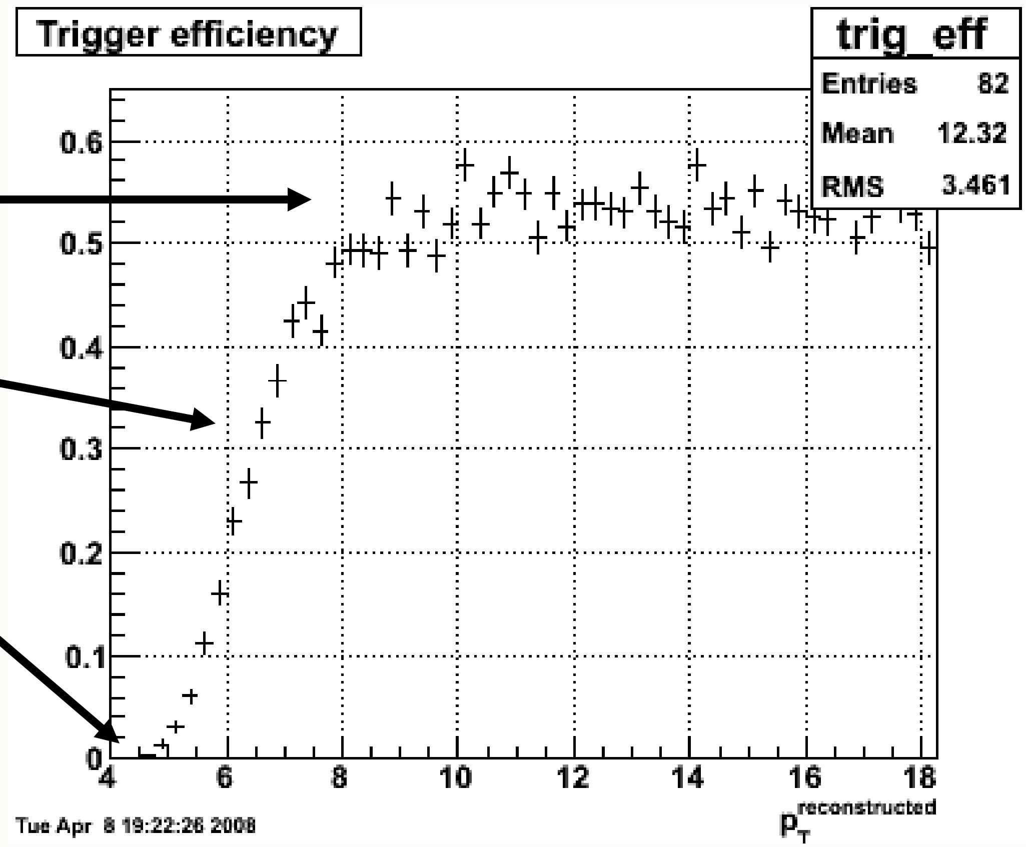


Trigger Example

Example for a trigger from STAR @ BNL

Main properties:

- plateau
- turn-on
- minimum



Trigger Efficiency From Data

Look at data triggered by 15GeV muon trigger:

for each event's muon:

  T=triggered, N=not triggered

  {T} {NTN}{TT}{TNT}{NT}{TT}…

But this sample doesn't see {N}, {NN}, {NNN},…

eff = |T| / all = |T| / (|T| + |N|)

But |N| unknown! Cannot determine efficiency!

Instead: need muons that are independent of trigger ("unbiased")

Dice And Tag / Probe

Think of two dice

Want probability for "6" ("6" trigger efficiency)

Have only triggered data, all results have >1 "6"

{1,6}, {6,4}, {6,6}, {1,6},…

Solution: one die has 6, the other is unbiased!

Result: N, N, T, N,… will yield 1/6

Muons And Tag / Probe

Solution: events with >1 muon

For each muon:

  if exists other muon causing trigger:

    this muon is unbiased!

Need trigger decision stored with data, as in:

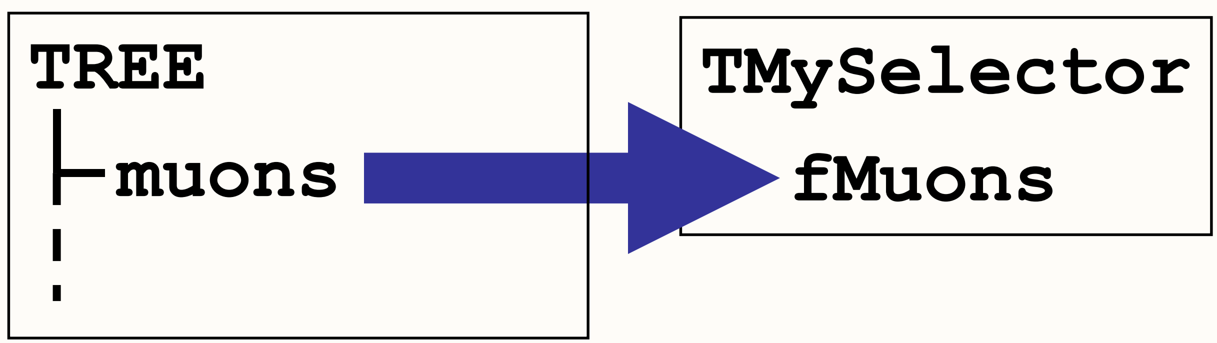
"other muon caused the 15GeV muon trigger"

Get Data From TTree

In TSelector::Init(tree) select branches and connect tree with our member fMuons:

```
TTree* t = fChain->GetTree();
t->SetBranchStatus("*", 0); // all off
t->SetBranchStatus("muons*", 1); // but muons
t->SetBranchAddress("muons", fMuons);
```

TTree::GetEntry(i) will load data from branch muons into fMuons; can access data via fMuons



TClonesArray

fMuons could be TClonesArray:

```
TClonesArray* fMuons; // array of TMuon
class TMuon: public TObject {
 public:
   ...
   float Pt() const;
   bool  Mu15() const; // triggered
};
```

Print pT of the i-th muon:

```
TMuon* muon = (TMuon*) fMuons->At(i);
cout << muon->Pt() << endl;
```

Determine Efficiency

Take a random muon number i ("probe")

Check that another muon ("tag") has caused trigger, then:

++ all[probe->pT()]

if probe muon has triggered:

++fired[probe->pT()]

efficiency[pT] = fired[pT] / all[pT]

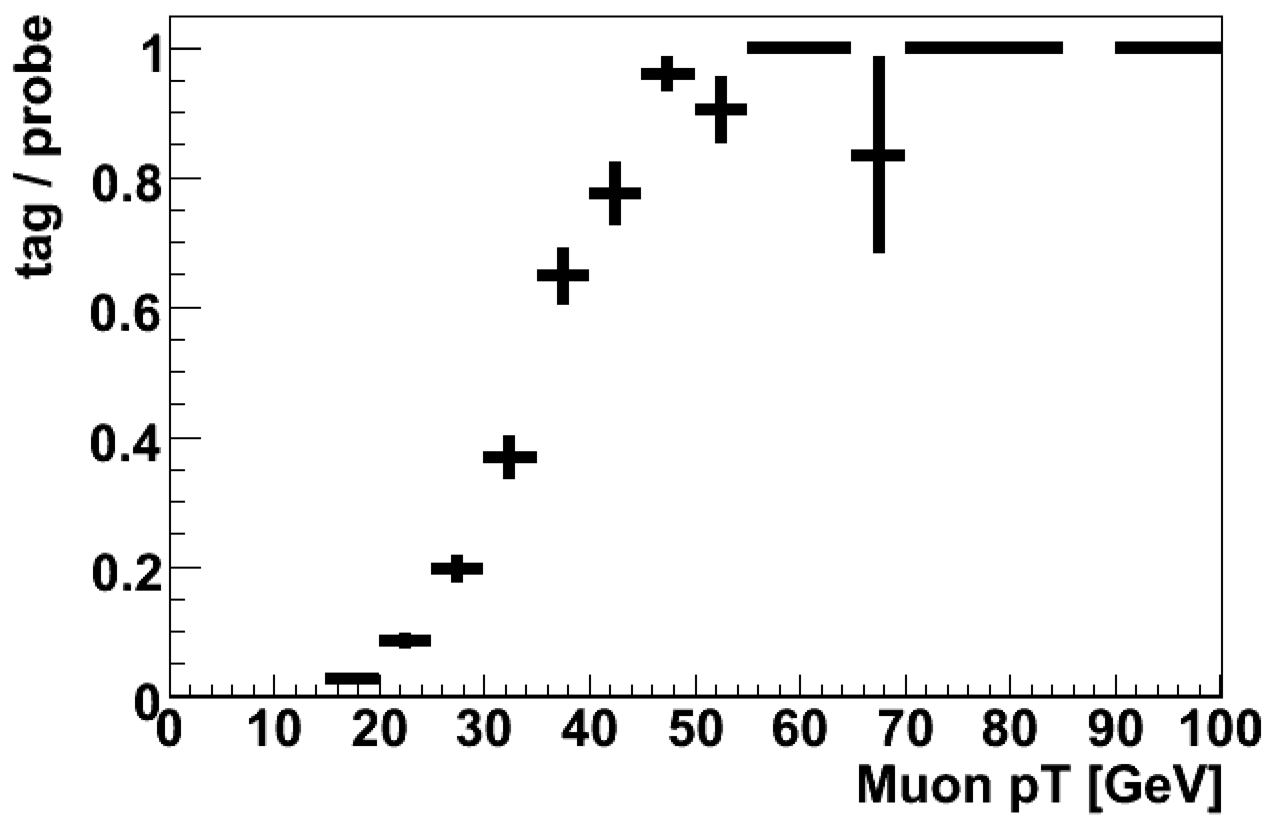
Counting in pT-bins – use histogram

Division: binomial errors, check Wikipedia ;-)

Result

Dividing probes / tags yields sampled efficiency

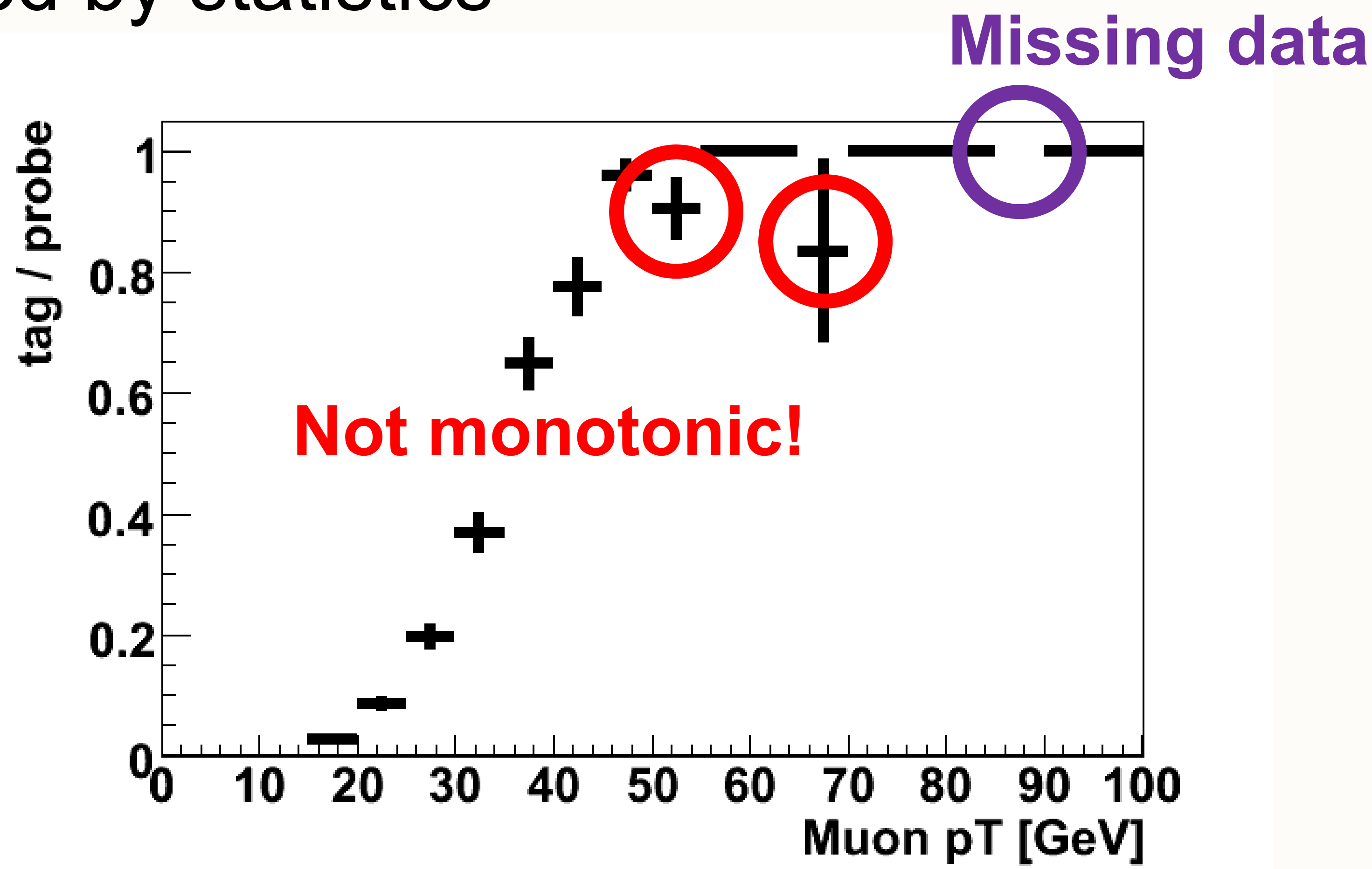
"Bumpy" because of low numbers of events



Statistics, Or: We Know Better!

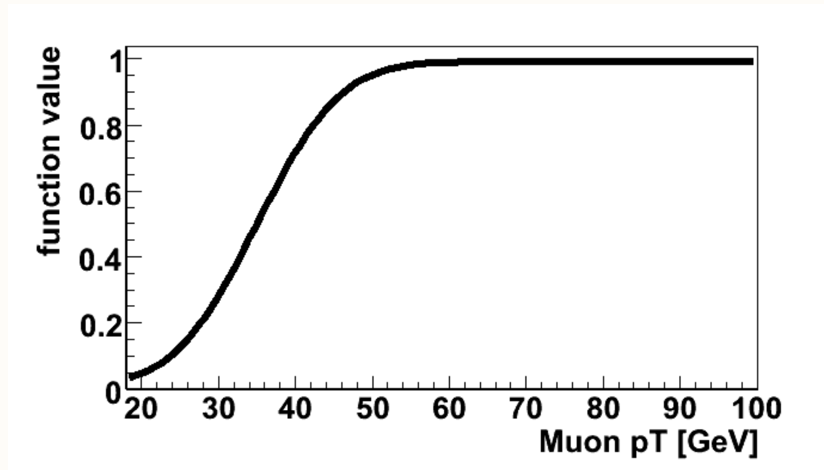
Sampling "known" distribution

Influenced by statistics

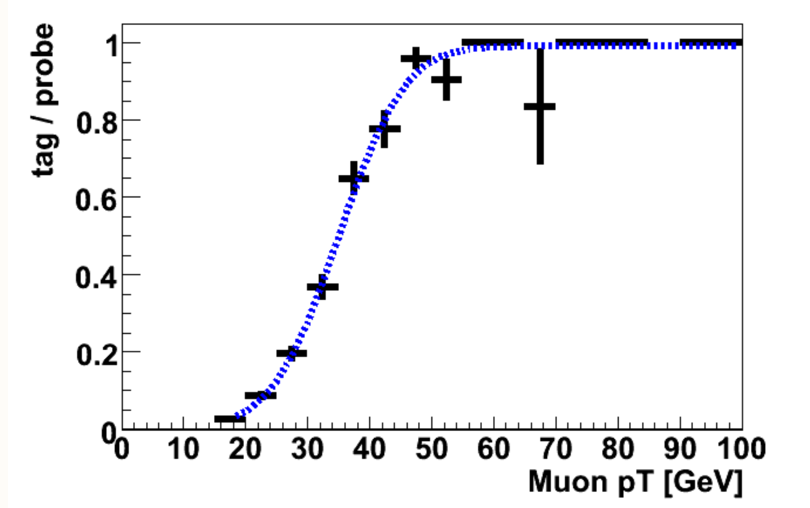


Fit

Combine our knowledge with statistics / data by fitting a distribution:



1. Find appropriate function with parameters



2. Fit function to distribution

Fitting: The Function

Finding the proper function involves:

- behavioral analysis:
  starts at 0, goes to constant, monotonic,…
- physics interpretation:
  "E proportional to sin^2(phi)"
- having a good knowledge of typical functions (see TMath)
- finding a good compromise between generalization ("constant") and precision ("polynomial 900th degree")

Fitting: The Function

Finding the proper function involves:

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  starts at 0, goes to constant, monotonic,…
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  "E proportional to sin^2(phi)"
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- finding a good compromise between generalization ("constant") and precision ("polynomial 900th degree")

MAGIC

Fitting: Parameters

Let's take "erf" `erf(x)/2.+0.5`

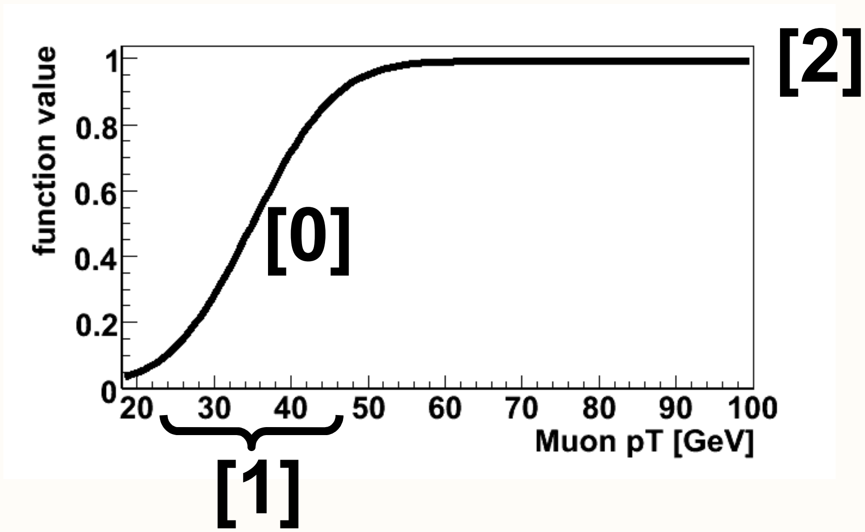
Free parameters:

```
(erf((x-[0])/[1])/2.+0.5)*[2]
```

[0]: x @ center of the slope

[1]: width of the slope

[2]: maximum efficiency



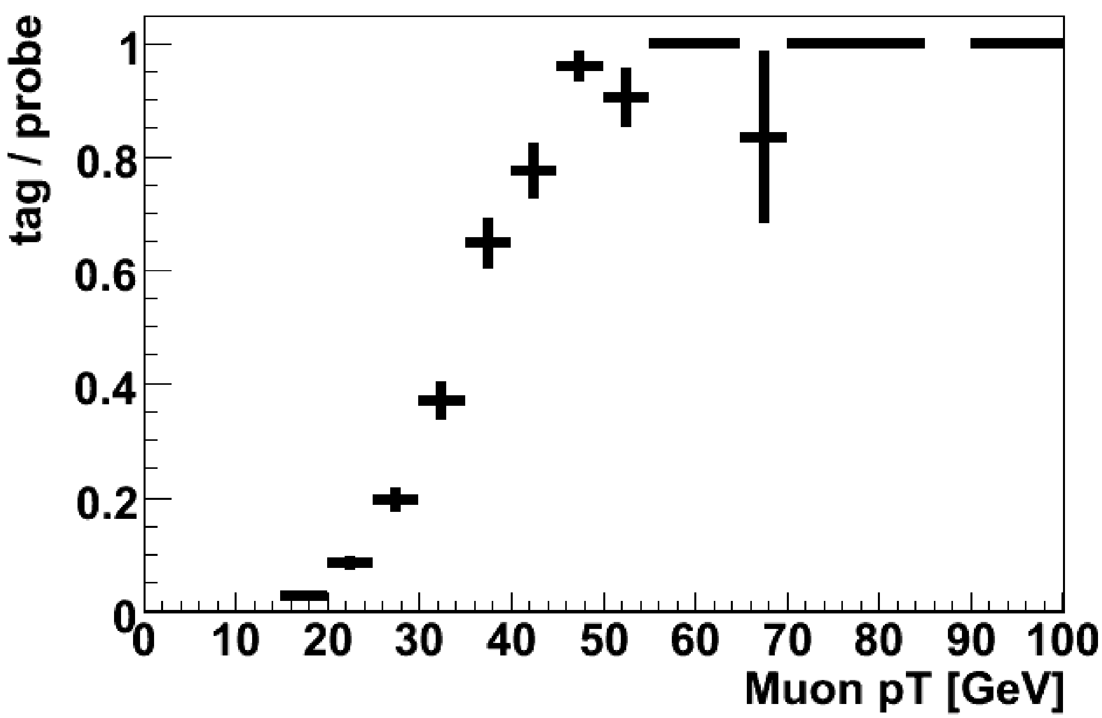
How do I know?

Study function behavior

Fitting: Parameter Init

Need to initialize parameters!

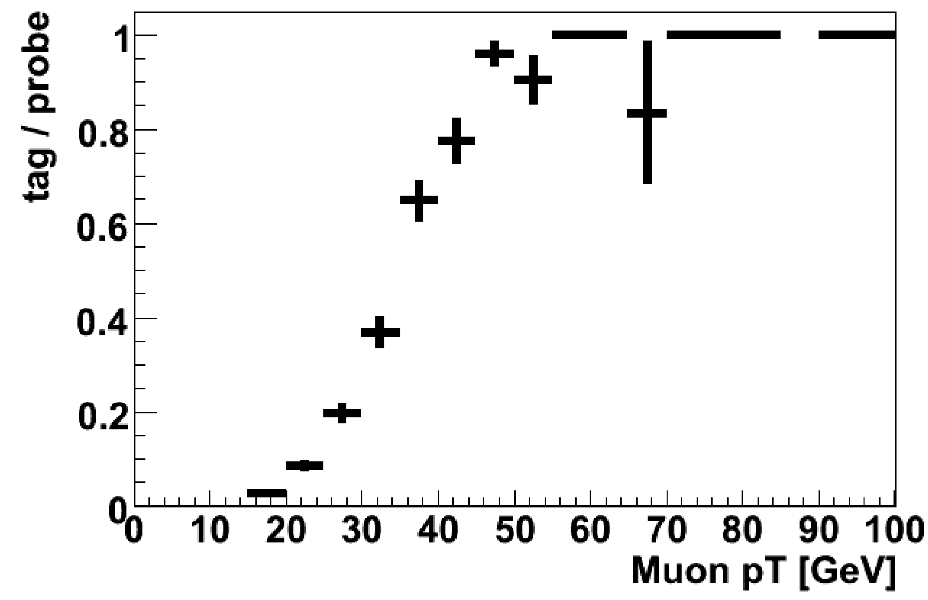
sensible: [0]: 35, [1]: 10, [2]: 1



Fitting: The Math

Fitting = finding parameters such that
  f(x) – hist(x)
minimal for all x [or any similar measure]

Histogram with errors:
  f(x) – hist(x) / err(x)
  [or similar]



Fitting In ROOT

Define fit function:

```
TF1* f = new TF1("myfit",
  "(TMath::Erf((x-[0])/[1])/2.+0.5)*[2]"
  0., 100.);
```

Set parameters:

```
f->SetParameter(0, 35.);
f->SetParameter(1, 10.);
f->SetParameter(2,  1.);
```

Fit it to the histogram:

```
hist->Fit(f);
```

Fitting Result

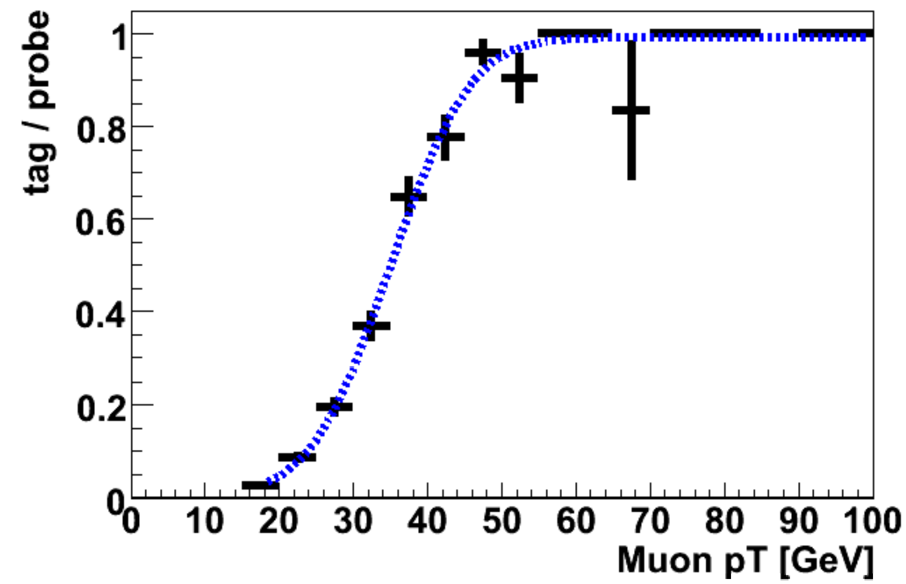
Result of fit printed or

```
cout << f->GetParameter(0) << endl;
```

[0]: 34.9

[1]: 12.1

[2]: 0.98



which means:

```
(TMath::Erf((x-34.9)/12.1)/2.+0.5)*0.98
```

Get efficiency at pT=42GeV:

```
f->Eval(42.)
```

Analysis: Recap

We started with the trigger problem – and ended with an answer

You now know

- how to determine trigger efficiency from triggered data
- why large samples are relevant
- what fitting is, how it works, when to do it, and how it's done with ROOT.

Interactive Data Analysis with PROOF

Bleeding Edge Physics with
Bleeding Edge Computing

Parallel Analysis: PROOF

Some numbers (from Alice experiment)

- 1.5 PB (1.5 * 10^{15}) of raw data per year
- 360 TB of ESD+AOD* per year (20% of raw)
- One pass at 15 MB/s will take 9 months!

Parallelism is the only way out!

* ESD: Event Summary Data   AOD: Analysis Object Data

PROOF

Huge amounts of events, hundreds of CPUs

Split the job into N events / CPU!

PROOF for TSelector based analysis:

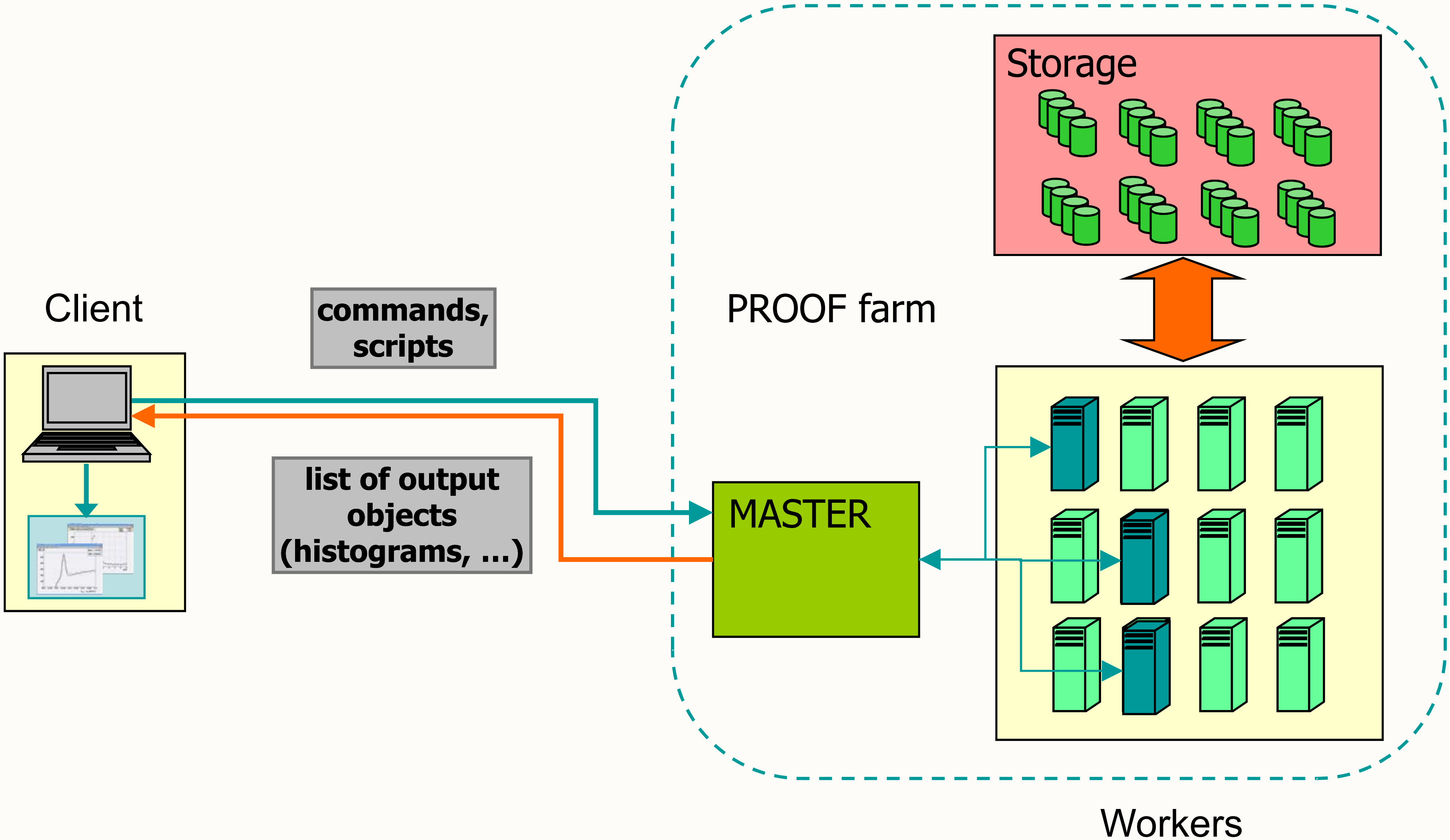
- start analysis locally ("client"),
- PROOF distributes data and code,
- lets CPUs ("workers") run the analysis,
- collects and combines (merges) data,
- shows analysis results locally
- More dynamic than a batch system

Including on-the-fly status reports!

Interactive!

- Start analysis
- Watch status while running
- Forgot to create a histogram?
  - Interrupt the process
  - Modify the selector
  - Re-start the analysis

PROOF



Storage
Client
commands, scripts
PROOF farm
list of output objects (histograms, …)
MASTER
Workers

Creating a session

To create a PROOF session from the ROOT prompt, just type:

```
TProof *p = TProof::Open("master")
```

where "master" is the hostname of the master machine on the PROOF cluster

PROOF Analysis

- Example of local TChain analysis

```
// Create a chain of trees
root[0] TChain *c = new TChain("myTree");
root[1] c->Add("http://www.any.where/file1.root");
root[2] c->Add("http://www.any.where/file2.root");

// MySelector is a TSelector
root[3] c->Process("MySelector.C+");
```

PROOF Analysis

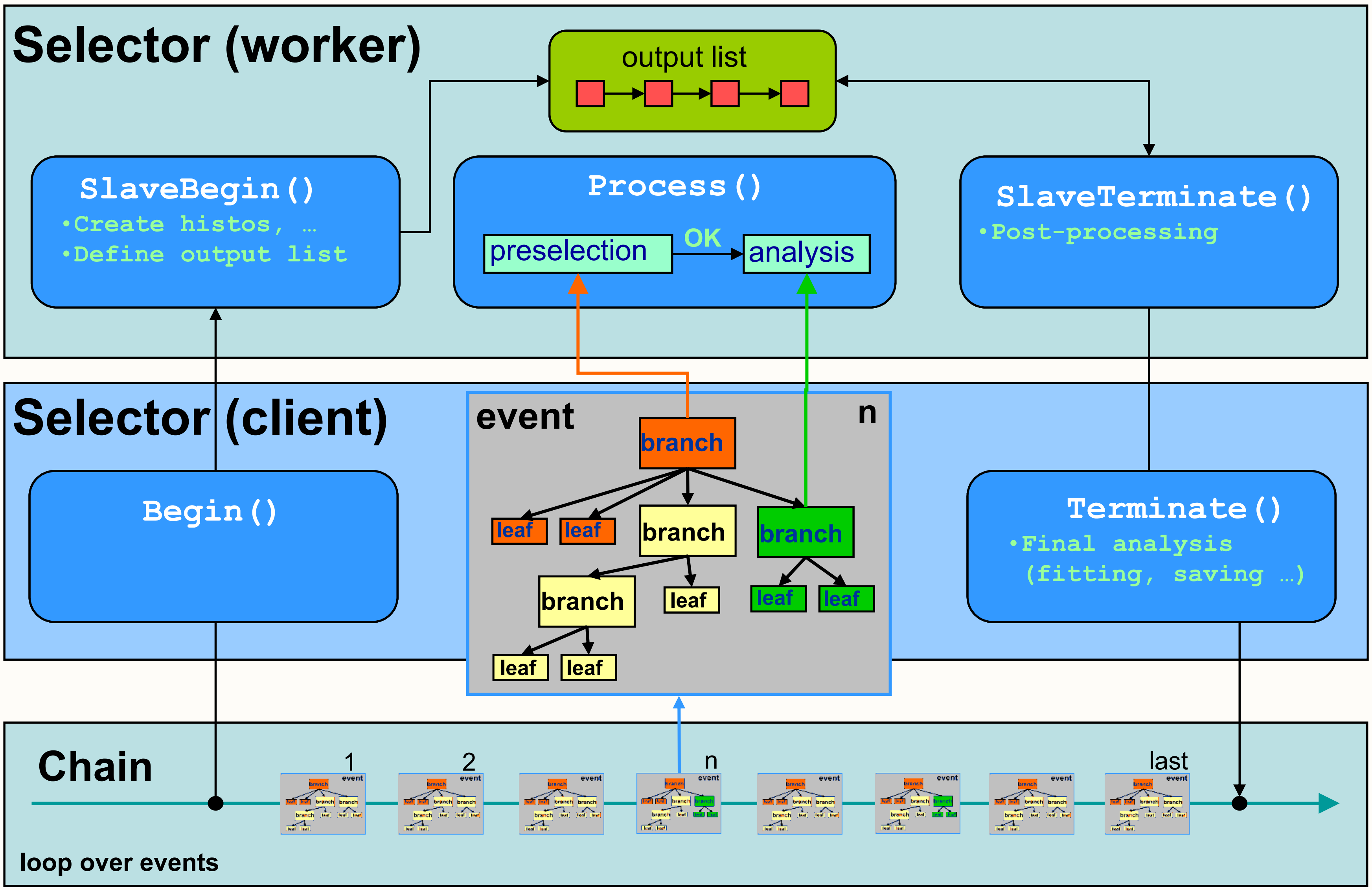
- Same example with PROOF

```
// Create a chain of trees
root[0] TChain *c = new TChain("myTree");
root[1] c->Add("http://www.any.where/file1.root");
root[2] c->Add("http://www.any.where/file2.root");

// Start PROOF and tell the chain to use it
root[3] TProof::Open("masterURL");
root[4] c->SetProof();

// Process goes via PROOF
root[5] c->Process("MySelector.C+");
```

TSelector & PROOF

- Begin() called on the client only
- SlaveBegin() called on each worker: create histograms
- SlaveTerminate() rarely used; post processing of partial results before they are sent to master and merged
- Terminate() runs on the client: save results, display histograms, …

PROOF Analysis



Output List (result of the query)

- Each worker has a partial output list
- Objects have to be added to the list in TSelector::SlaveBegin() e.g.:

```
fHist = new TH1F("h1", "h1", 100, -3., 3.);
fOutput->Add(fHist);
```

- At the end of processing the output list gets sent to the master
- The Master merges objects and returns them to the client. Merging is e.g. "Add()" for histograms, appending for lists and trees

Results

At the end of Process(), the output list is accessible via gProof->GetOutputList()

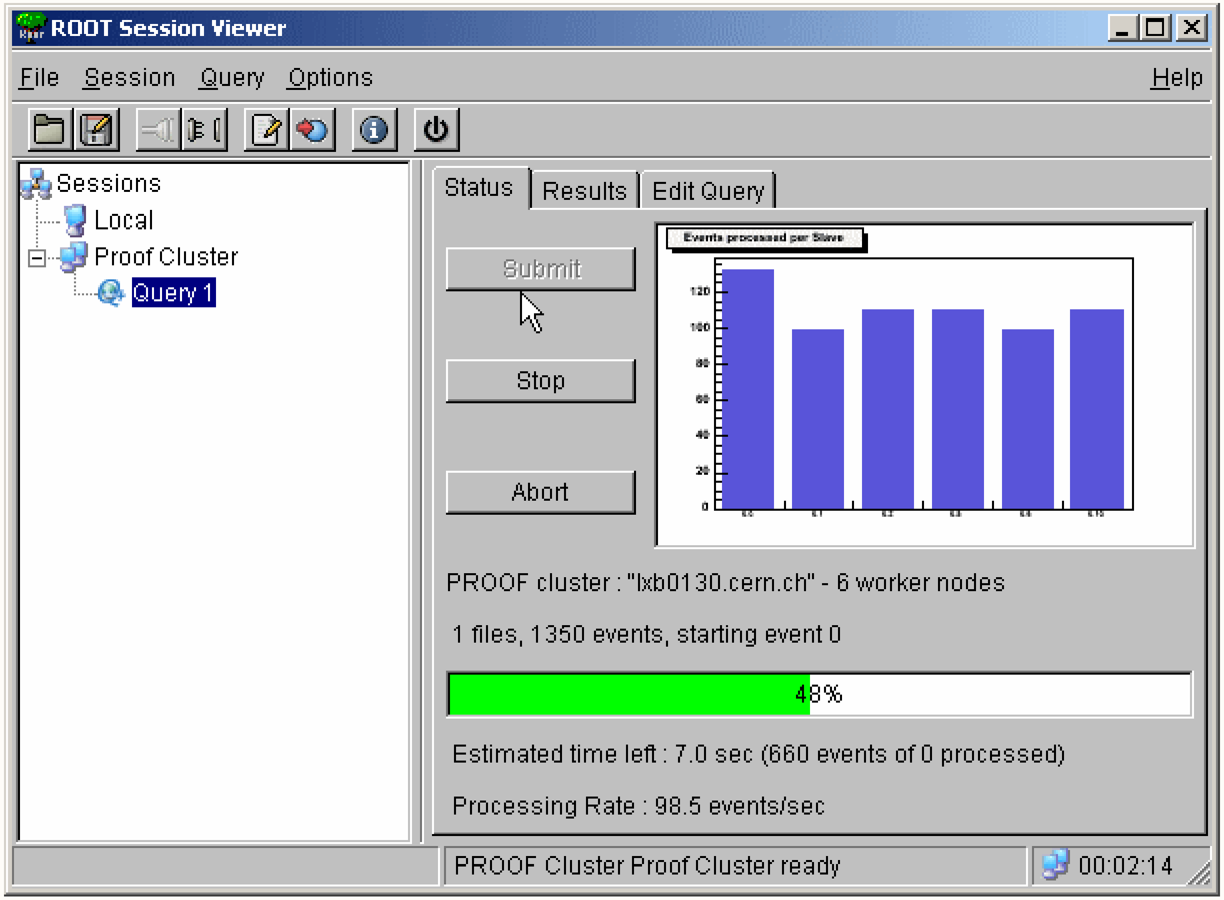
```
// Get the output list
root[0] TList *output = gProof->GetOutputList();
// Retrieve 2D histogram "h2"
root[1] TH2F *h2 = (TH2F*)output->FindObject("h2");
// Display the histogram
root[2] h2->Draw();
```

PROOF GUI Session

Starting a PROOF GUI session is trivial:

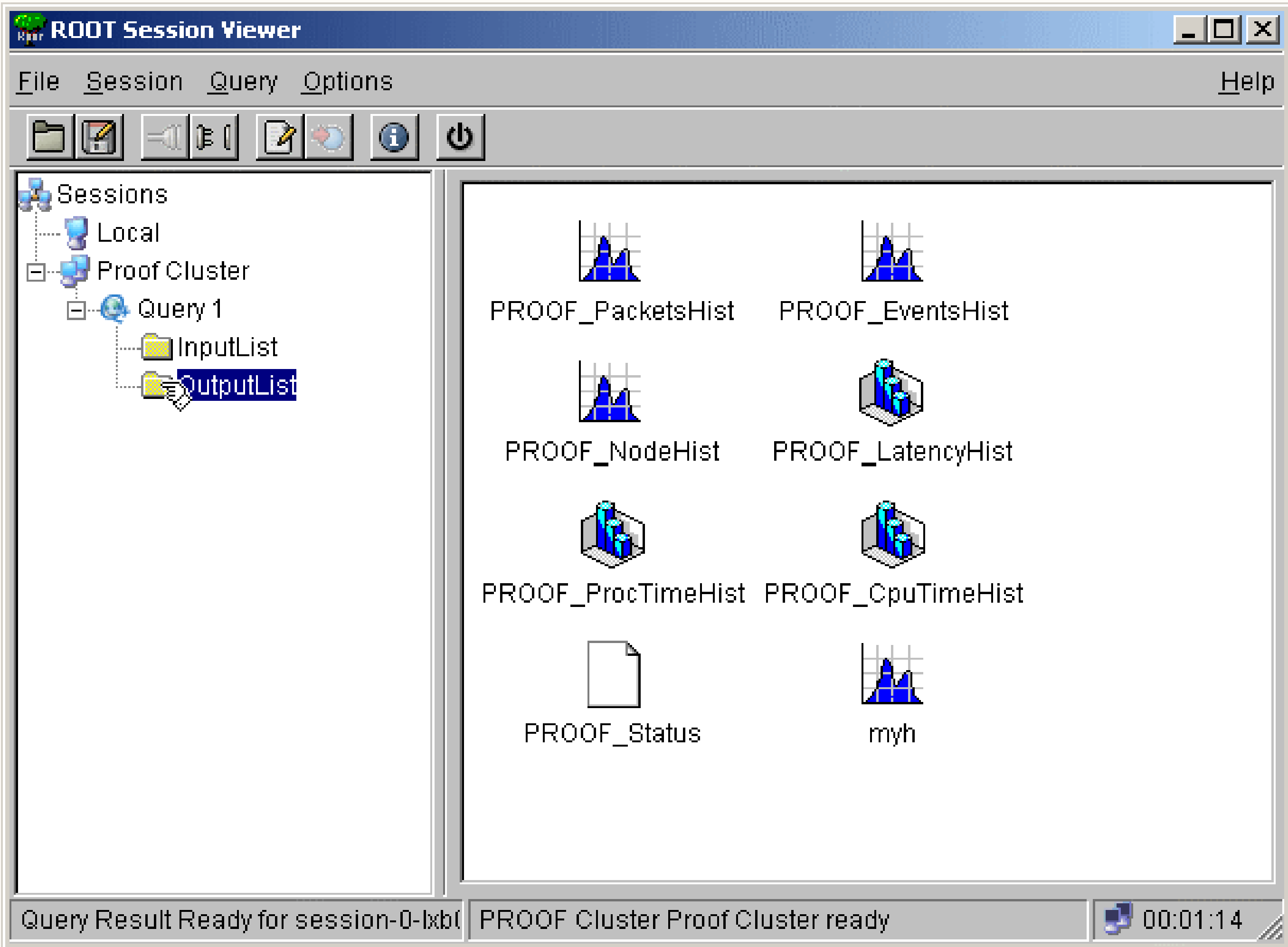
```
TProof::Open()
```

Opens GUI:



PROOF GUI Session – Results

Results accessible via TSessionViewer, too:



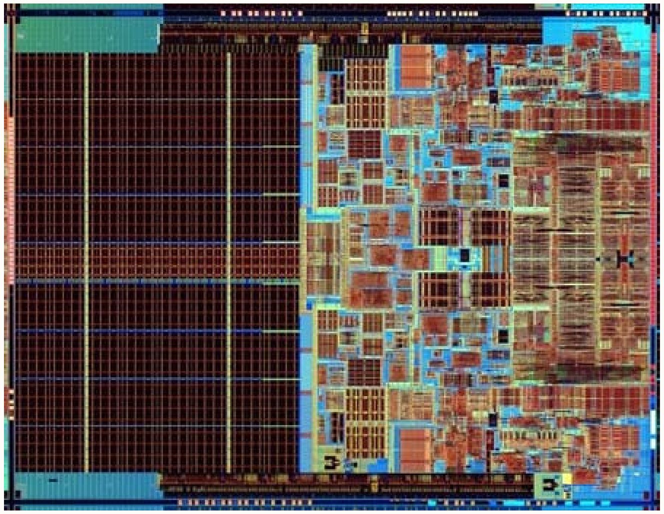
PROOF Documentation

Documentation available online at

root.cern.ch/twiki/bin/view/ROOT/PROOF

But of course you need a little cluster of CPUs

Like your multicore laptop!



Summary

You've learned:

- analyzing a TTree can be easy and efficient
- integral part of physics is counting
- ROOT provides histogramming and fitting
- > 1 CPU: use PROOF!

Looking forward to hearing from you:

- as a user (help! bug! suggestion!)
- and as a developer!