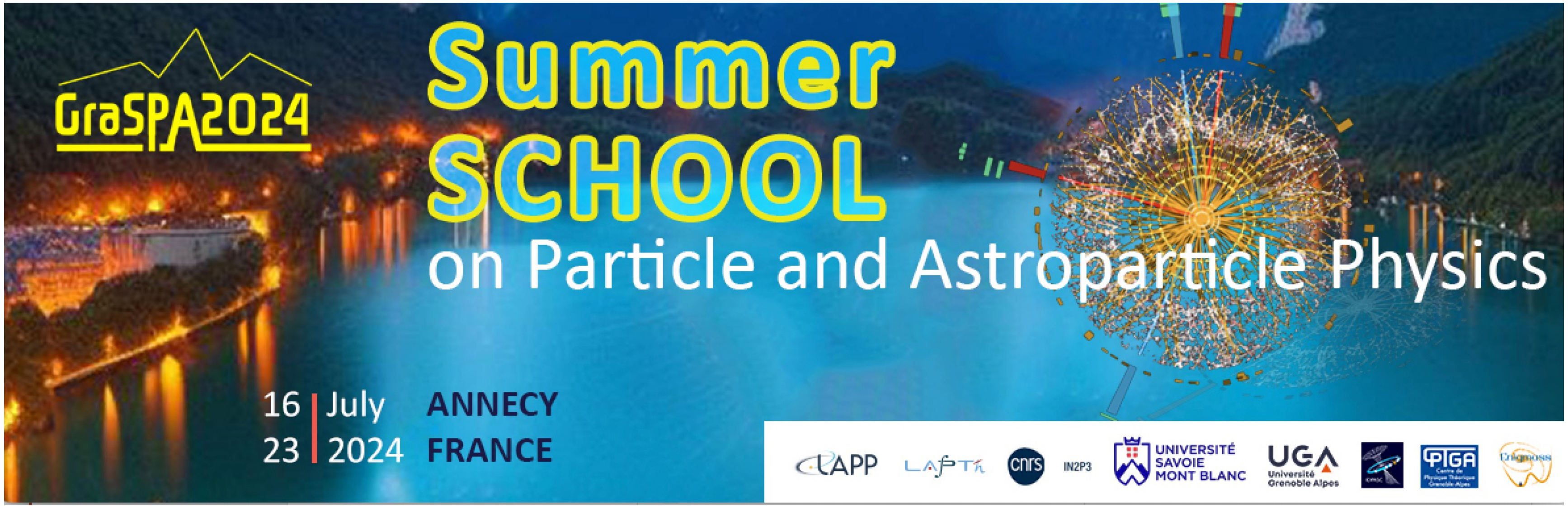


A computing exercise using ROOT

Aim: give a taste of data analysis @ LHC

- What is ROOT ?
  - ROOT is an object-oriented C++ analysis package
  - User-compiled code can be called to produce 1-d, 2-d, and 3-d graphics and histograms…

https://root.cern.ch

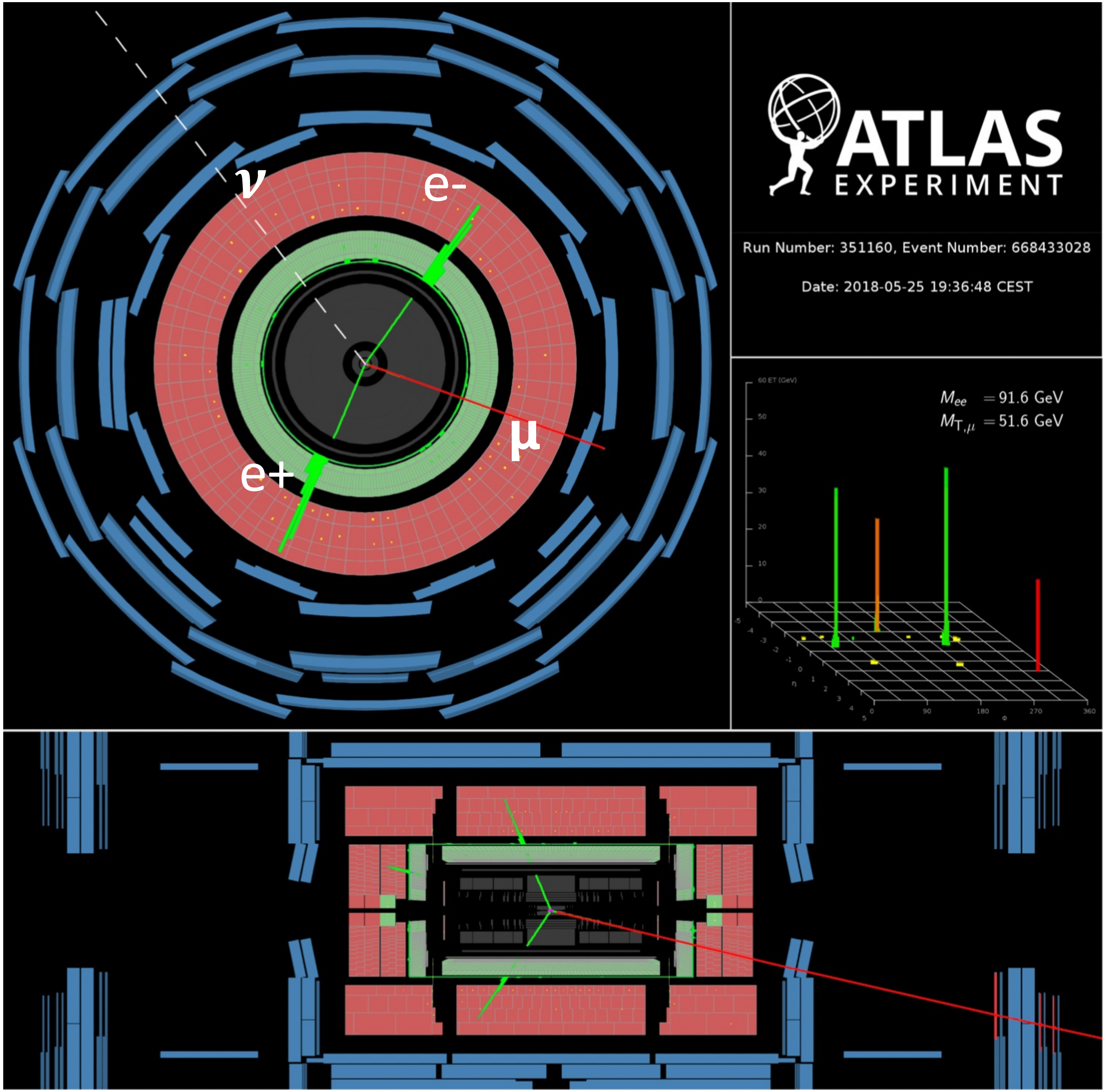
"open-source data analysis framework used by high energy physicist and others"

What

is

that?

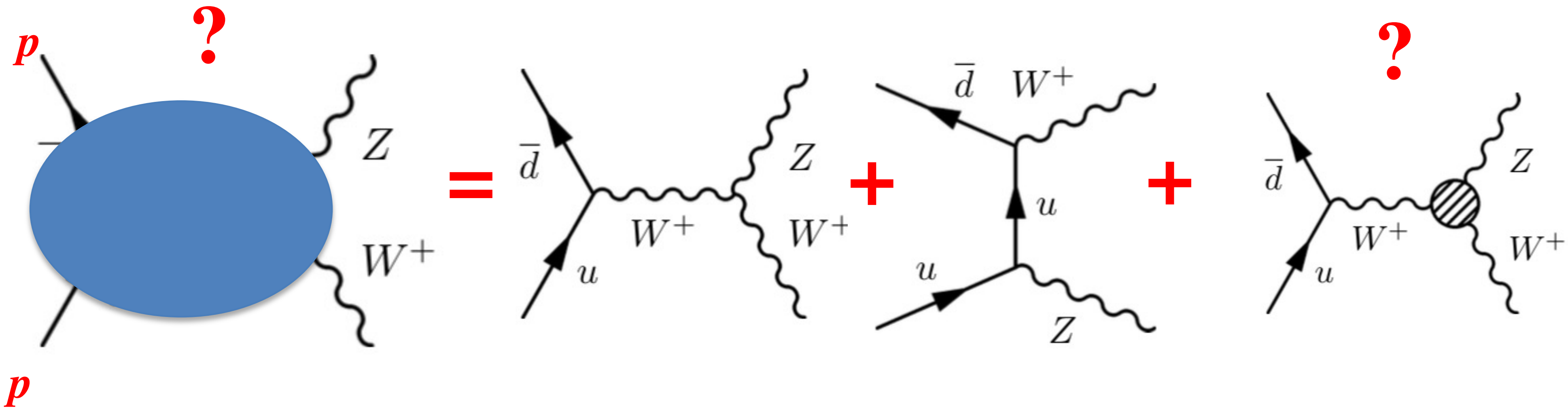
(we know
that from
theory
AND
experiments)



Z → e+e-

W→ $\mu\nu$

Hands-on on diboson physics  topic @ LHC



Test of SM
(measure interaction probability)

Discover New Physics
(look inside the blob)

Advantage of accelerator physics: controlled and known initial conditions

☺

→ most of things discovered about <u>fundamental interactions</u> so far thanks to accelerator physics

Outline of the presentation

- **Kinematic variables used in the analysis of *p - p* collisions**
- **Useful relations**
- **Concept of invariant mass** (example: 'inclusive' Z boson production)
- **Example of analysis in *p - p* collisions :**
  - * Signal: Production of a W and a Z *p - p* → W Z X
  - * Background: Production of a pair of top-antitop
- **Example: Macro.C**

p – p = proton - proton

X = additional undetected particles (X) = part1, part2, part3, ...

In all the following slides we assume the speed of the light

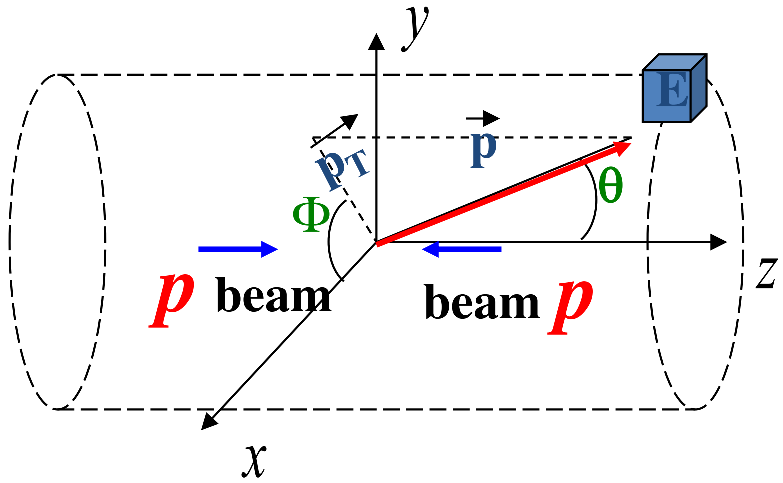
c=1

Variables used in the analysis of *p - p* collisions

A particle (**Z, W, e+, e-, etc …**) is described by its **four-momentum**:

$\tilde{p} = (E, px, py, pz)$

The particle mass is $m = \sqrt{E^2 - p_x^2 - p_y^2 - p_z^2}$



When dealing with ***p-p*** collisions the following variables are used:

For each particle (Z, W, e+, e-, etc …):

- **1. Transverse momentum/energy :** $p_T = p \sin\theta$ $\quad E_T = E \sin\theta$
- **2. Rapidity** $Y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$

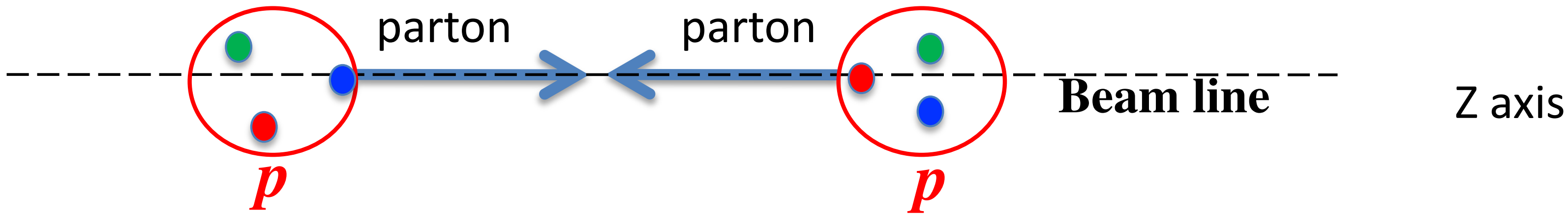
  or Pseudorapidity $\eta = -\ln(\tan\frac{\theta}{2})$
- **3. Azimuthal angle** Φ

Why?

Variables used in the analysis of *p - p* collisions

Why p_T , Y ?

Many reasons (*p* = proton)



1. p_T and ΔY are <u>invariants for Lorentz transformations along the z a</u>xis

2. The longitudinal momentum of the initial partons is 'unknown', while we know that $\vec{p}_T^{\text{ initial parton}} \sim 0$

   → Exploit momentum conservation in the plane ⊥ to the beam using *transverse* quantities → Example:

$$\sum^{\text{initial partons}} \vec{p}_T = \sum_{vis}{}^{fin} \vec{p}_T + \sum_{invis}{}^{fin} \vec{p}_T \approx 0$$

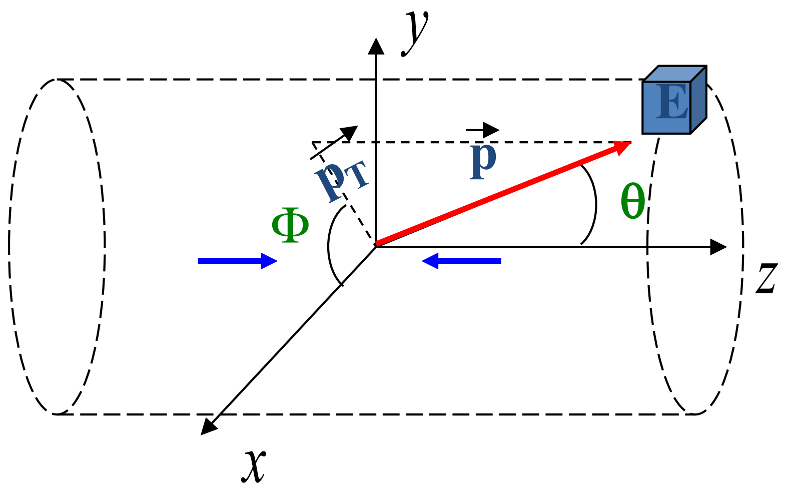
→ Allows to evaluate the p_T of not detected (ν) particles

$$\sum_{invis}{}^{fin} \vec{p}_T = - \sum_{vis}{}^{fin} \vec{p}_T$$

$|\sum_{invis} p_T|$ is the "missing E_T (MET)"

3. The "interesting" physics is in the hard scattering processes → high p_T particles (selection of high p_T particles ensures "interesting" physics)

Useful relations



$p_T = p \sin\theta$

px = p_T*cos(Φ);
py = p_T*sin(Φ);
pz = E*tanh(η);

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

NB:

- **m « E** → **Y ≈ η** **(η doesn't require particle identification)**
- **m « E** → $p_T \approx E_T$ $E_T = E \sin\theta$

Concept of *invariant* mass M_A

Particle A decays to B and C

A → B C

$$M^2_A = \tilde{p}_A^{\,2} = (\tilde{p}_B + \tilde{p}_C)^{2}$$

The invariant mass is the same in all frames of reference related by Lorentz transformations

Concept of *invariant* mass: inclusive Z boson production

p - p --> **Z** (**X**) with **Z** → e+e-

(**X**) = part1, part2, part3, …

M_{ee} = Invariant mass of ee system
(it allows to measure the Z mass, $\mathbf{M_Z}$):

from the 4-momentum conservation

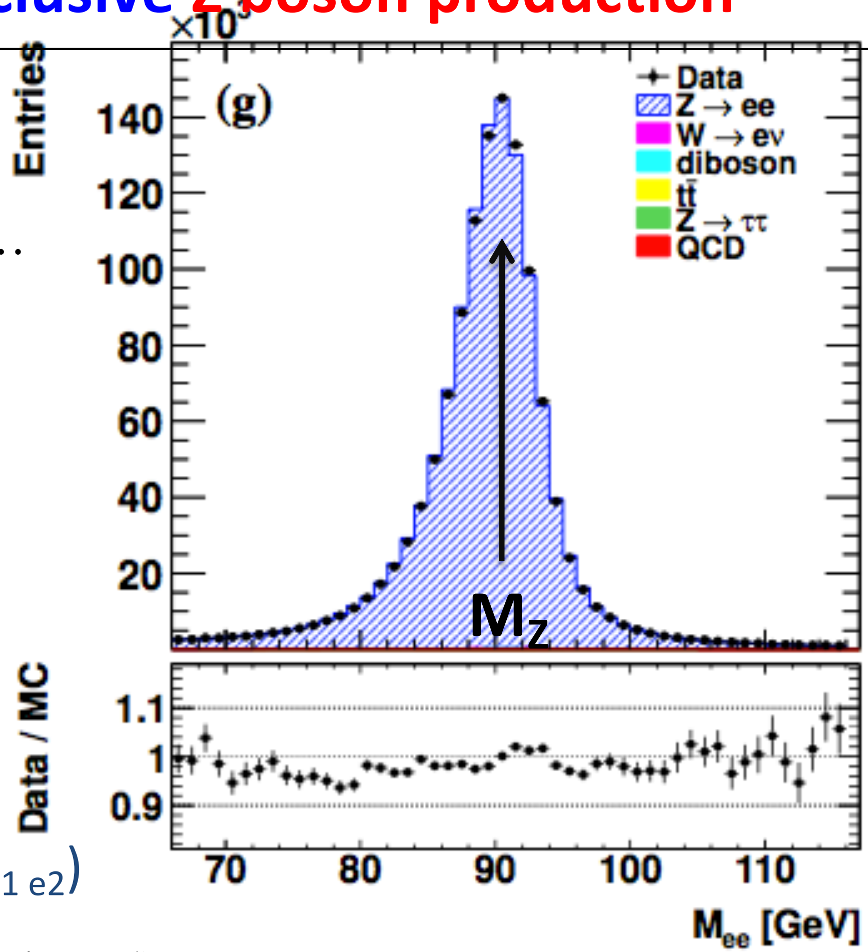
$$\tilde{p}_Z^{\,2} = (\tilde{p}_{e1} + \tilde{p}_{e2})^{\,2}$$

$$M_{ee}^{\,2} = (\tilde{p}_{e1} + \tilde{p}_{e2})^{\,2} \approx 2\,(E_{e1} E_{e2} - |\vec{p}_{e1}|\,|\vec{p}_{e2}| \cos \vartheta_{e1\,e2})$$

$$M_{ee} \approx \sqrt{2\, E_{e1} E_{e2}\, (1 - \cos \vartheta_{e1\,e2})}$$ (electron mass is neglected)

Very 'clean' distribution (low bkg)!!

Why M_{ee} gives a distribution
and not a single value?



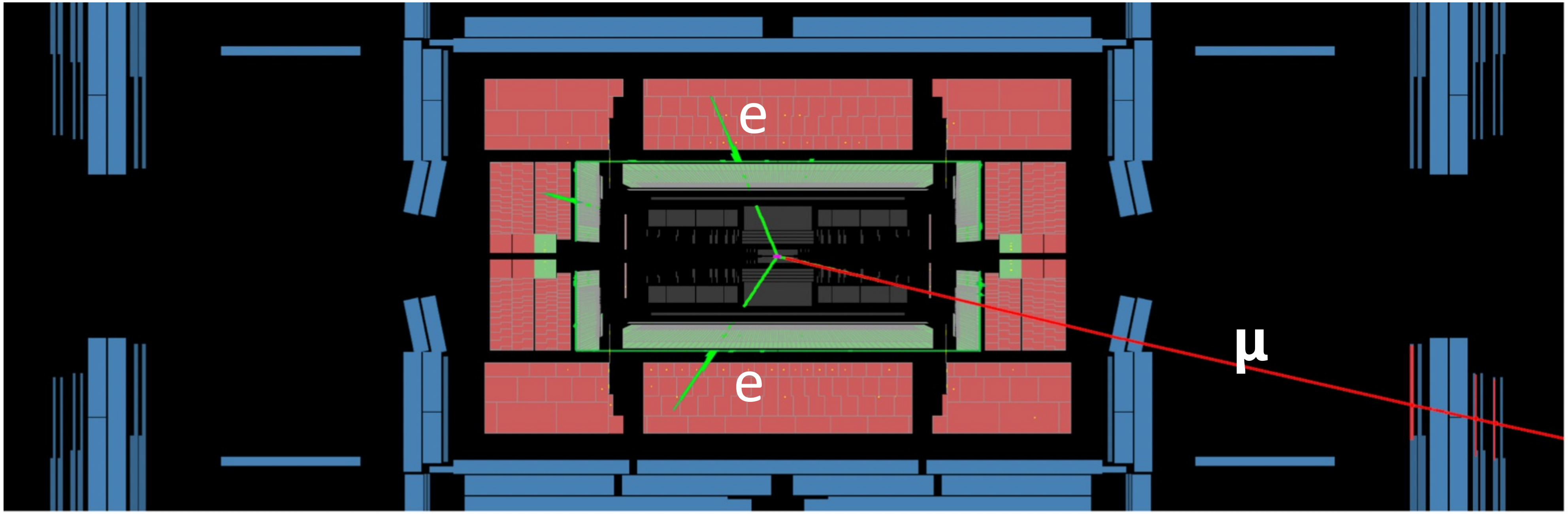
1. $\Delta E * \Delta t > \hbar/2$ $\Delta m * \tau > \hbar/2$

   $\Gamma * \tau > \hbar/2$

   width lifetime

2. Experimental resolution

What is that?



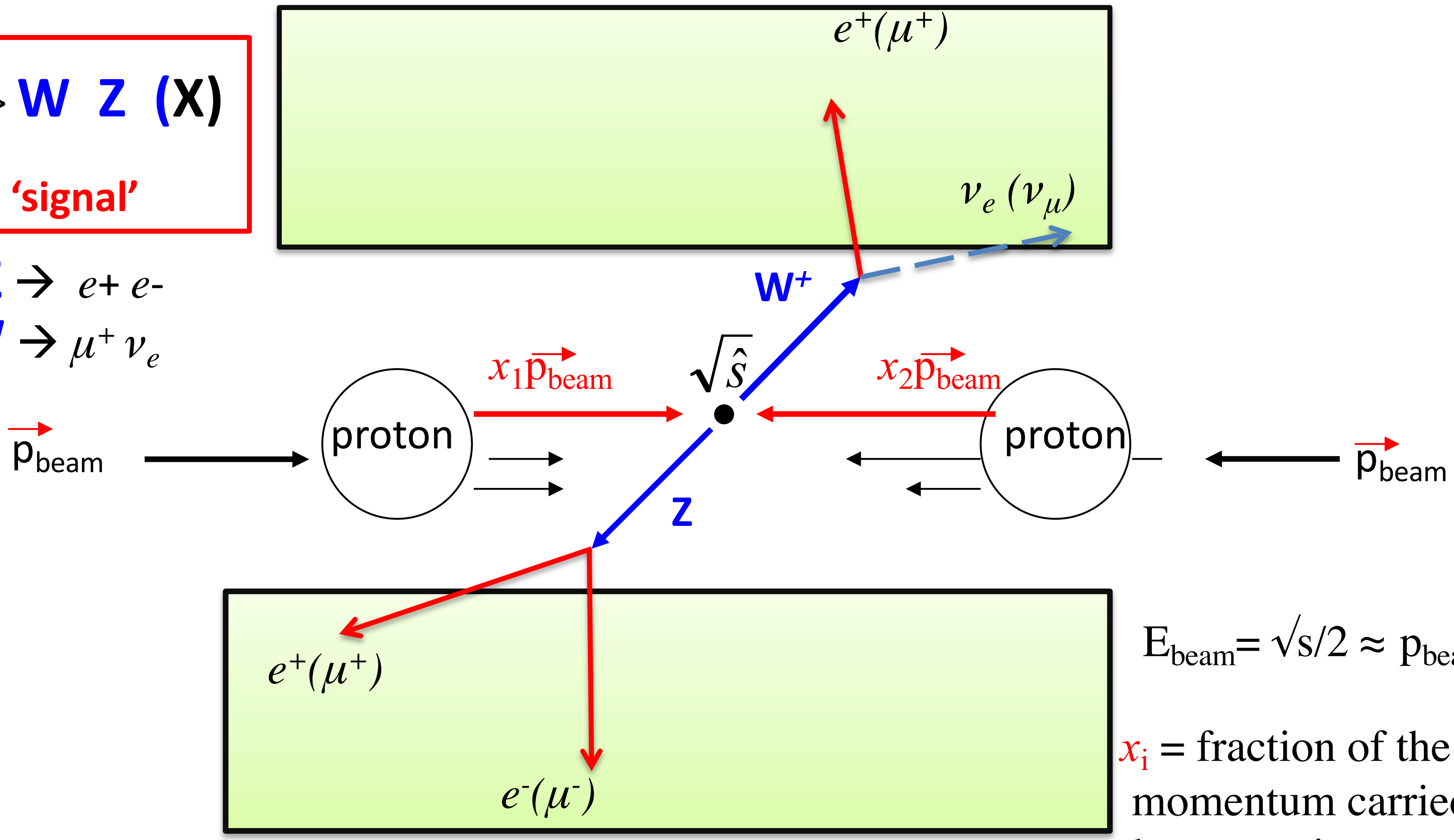
Our signal : production of a W and a Z (decaying leptonically)

p- p 'hard' collisions in the $q_1\,\bar{q}_2$ center of mass:

p- p -> W Z (X)

Our 'signal'

With **Z** → $e+\ e-$
and **W** → $\mu^+\,\nu_e$



$E_{beam} = \sqrt{s}/2 \approx p_{beam}$

x_i = fraction of the beam momentum carried by the parton i

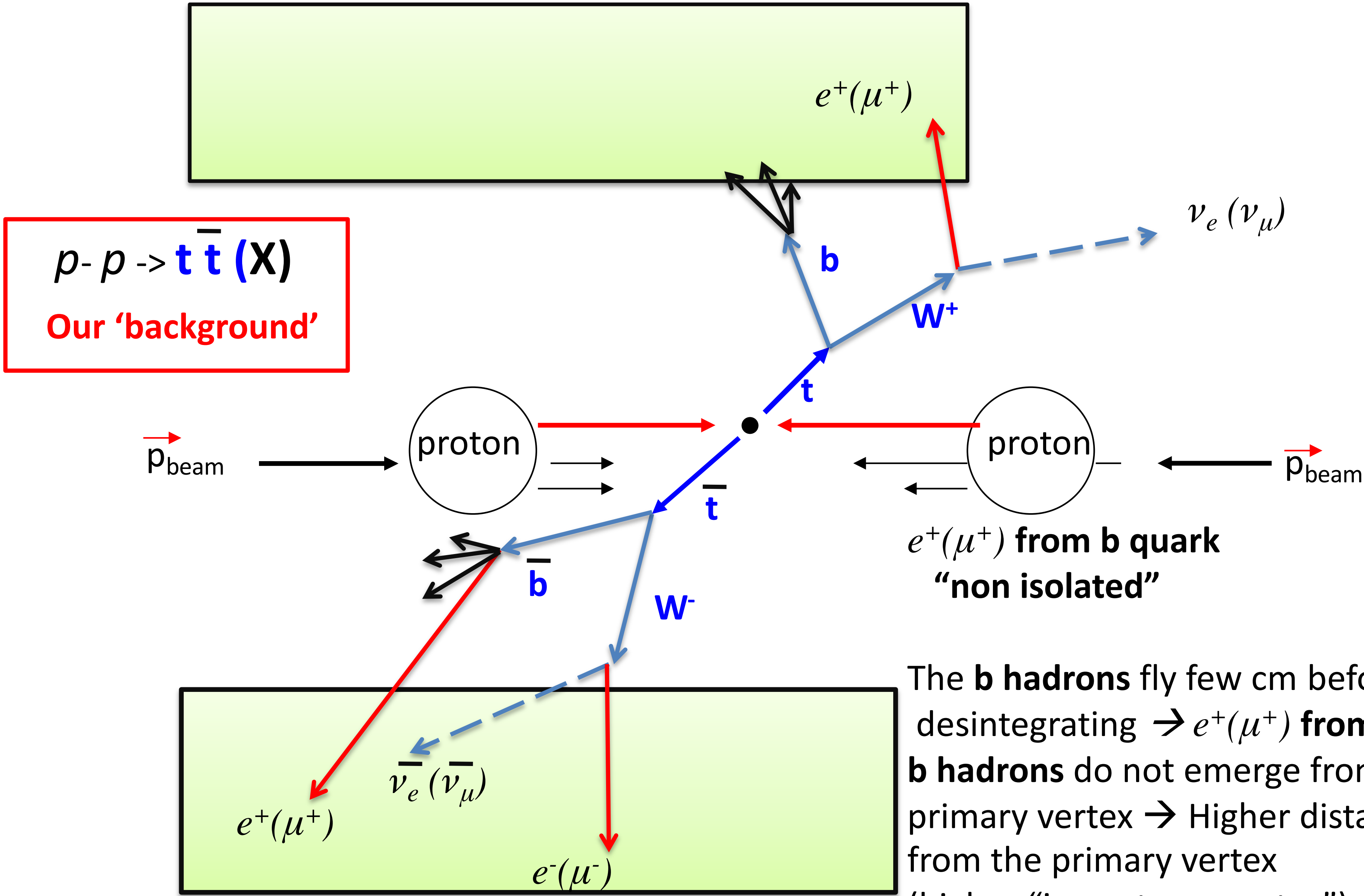
$0 < x_{1,2} < 1$

Kinematics of p - p collisions

- **4-mom of the initial partons** : $[\ (x_1+x_2)E_{beam},\ 0,\ 0,\ (x_1-x_2)\ p_{beam}]$

Our background: Production of a pair of top-antitop

p- p 'hard' collisions. In the $\bar{q}_1$ q_2 center of mass:



The **b hadrons** fly few cm before desintegrating → $e^+(\mu^+)$ **from b hadrons** do not emerge from the primary vertex → Higher distance from the primary vertex (higher "impact parameter")

Aim of the exercise (note, this are the first steps of an analysis):

1) look at some important variables,
2) build the Z invariant mass,
3) how one can discriminate between the 'signal' and the 'background' ?

You will have:

GRASPA2024explanation.pptx.pdf (this slides)

Exercise2024.pdf (what we ask to do)
Selected_All_EEM.root (« data file » (simulated data))
macro.C (draft of an analysis program)

macro_final.C (solution: final analysis program)

https://root.cern.ch/root/htmldoc/guides/primer/ROOTPrimer.html

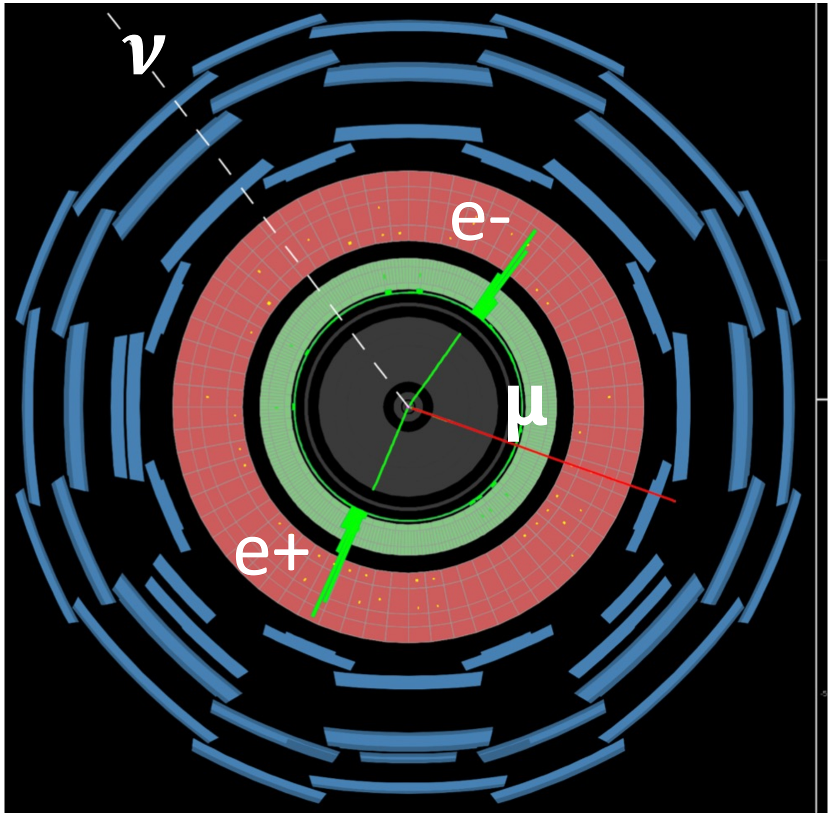
1) The input file containing the physics: Selected_All_EEM.root

List of variables given per each collision event (kinematics of the final state leptons)

=== MOST ENERGETIC LEPTON FROM THE Z
Br 4 :pt1 : pt1
Br 5 :eta1 : eta1
Br 6 :phi1 : phi1
Br 7 :E1 : E1

=== SECOND ENERGETIC LEPTON FROM THE Z
Br 8 :pt2 : pt2
Br 9 :eta2 : eta2
Br 10 :phi2 : phi2
Br 11 :E2 : E2

=== LEPTON FROM W
Br 12 :pt3 : pt3
Br 13 :eta3 : eta3
Br 14 :phi3 : phi3
Br 15 :E3 : E3



List of Variables in the ntuple (Br 0,1.. means "Branch 0, 1, ...")

== IMPACT PARAMETER and ISOLATION of the lepton from W

Br 0 :Trackd0cutWMu : Trackd0cutWMu

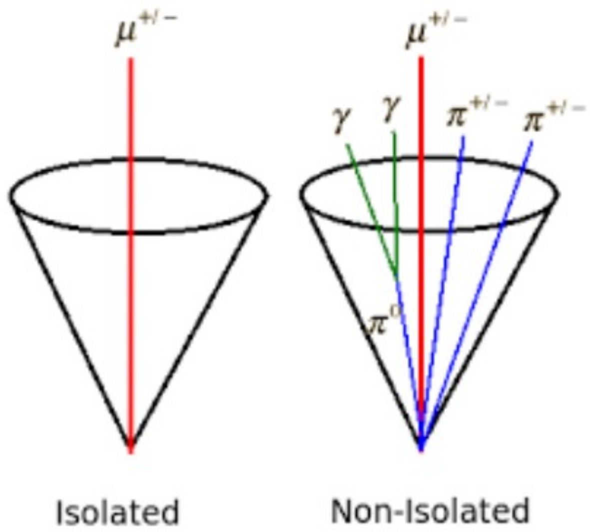
Br 1 :TrackIsoWmu : TrackIsoWmu

== MISSING TRANSVERSE ENERGY

Br 2 :MET : MET

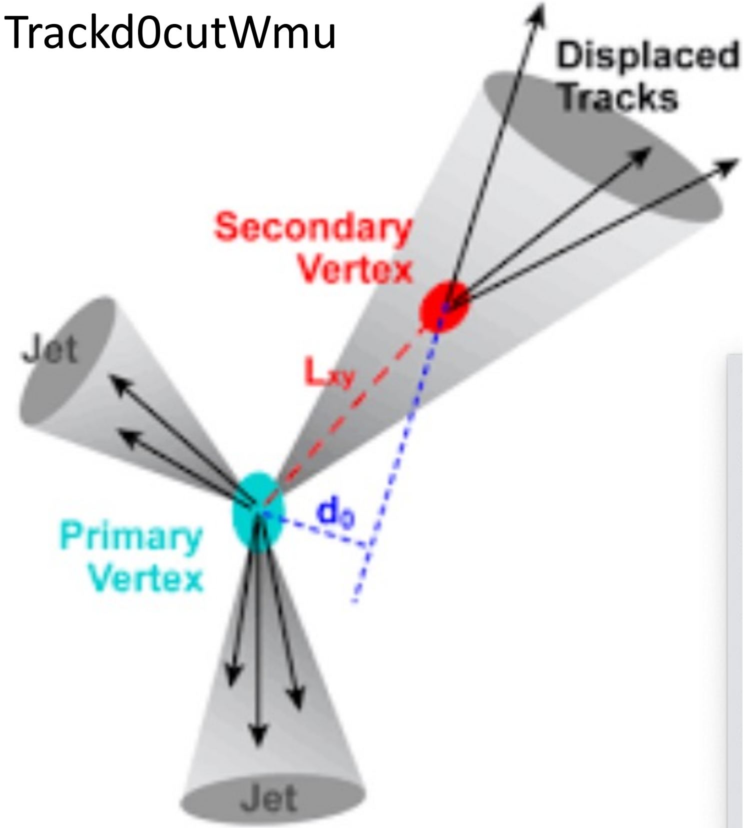
=== MASS of Z

Br 3 :MZ : MZ



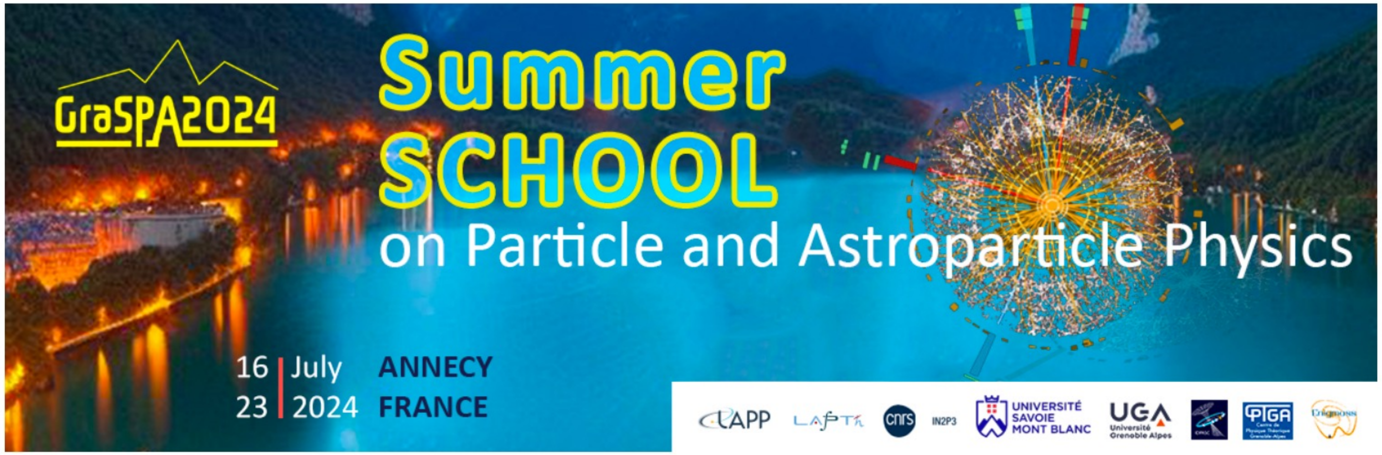
TrackIsoWmu
Energy in the cone

Trackd0cutWmu



2) Instructions to make the computing exercise : Exercise2024.pdf

GRASPA 2024 **16-23 July 2024**



COMPUTING EXERCISE

Study of the production of a pair of gauge bosons (W and Z) at the LHC

The data to analyse are organised into a **'Root n-tuple'** which we will provide to you. The Root n-tuple is a file containaining information about the kinematics of "events", each resulting from a **proton-proton interaction**.
These events have three leptons (electrons or muons) and are of two kinds:

1) SIGNAL EVENTS: corresponding to $pp \to W\ Z\ X$ with both bosons disintegrating leptonically (X stands for non identified generic particles),
2) BACKGROUND EVENTS: top-antitop events $pp \to t\bar{t}X$.

We remind that the leptonic decays of the W and Z are:
$W \to \ell\nu$ and $Z \to \ell^+\ell^-$ with $\ell =$ e or μ.

3) A skeleton of an analysis program using ROOT: macro.C

```
#include "TCanvas.h"
#include "TROOT.h"
#include "TFile.h"
#include "TTree.h"
#include "TBrowser.h"
#include "TH2.h"
#include "TRandom.h"

void tree1r()
{
  // Read Selected_All_EEM.root file
  //Root file
  TFile *f = new TFile("Selected_All_EEM.root");

  // Signal events
  TTree *sig = (TTree*)f->Get("WZSignal");
  Double_t pt1, eta1, phi1, E1;
  Double_t pt2, eta2, phi2, E2;
  Double_t pt3, eta3, phi3, E3;
  Double_t MZ, MET, trackd0cutWMu, TrackIsoWmu;
  Double_t Weight;

  //get some variables for SIGNAL EVENTS
  sig->SetBranchAddress("pt1",&pt1);
```

Example of analysis program


```
#include "TCanvas.h"
#include "TROOT.h"
#include "TFile.h"
#include "TTree.h"
#include "TBrowser.h"
#include "TH2.h"
#include "TRandom.h"

void tree1r()
{
  // Read Selected_All_EEM.root file
  //Root file
  TFile *f = new TFile("Selected_All_EEM.root");

  // Signal events
  TTree *sig = (TTree*)f->Get("WZSignal");
  Double_t pt1, eta1, phi1, E1;
  Double_t pt2, eta2, phi2, E2;
  Double_t pt3, eta3, phi3, E3;
  Double_t MZ, MET, trackd0cutWMu, TrackIsoWmu;
  Double_t Weight;

  //get some variables for SIGNAL EVENTS
  sig->SetBranchAddress("pt1",&pt1);
  sig->SetBranchAddress("eta1",&eta1);
  sig->SetBranchAddress("phi1",&phi1);
  sig->SetBranchAddress("E1",&E1);
  sig->SetBranchAddress("MZ",&MZ);
  sig->SetBranchAddress("Weight",&Weight);
  // add other variables ...
```

Header files

Open the input file

Access the Signal info

Define the name variables per each SIGNAL lepton

```
////get some variables for BACKGROUND EVENTS
TTree *ttbar = (TTree*)f->Get("ttbar");
Double_t pt1_bkg, eta1_bkg, phi1_bkg, E1_bkg;
Double_t MZ_bkg;
Double_t Weight_bkg;

//get some variables for ttbar
ttbar->SetBranchAddress("pt1",&pt1_bkg);
ttbar->SetBranchAddress("eta1",&eta1_bkg);
ttbar->SetBranchAddress("phi1",&phi1_bkg);
ttbar->SetBranchAddress("E1",&E1_bkg);
ttbar->SetBranchAddress("MZ",&MZ_bkg);
ttbar->SetBranchAddress("Weight",&Weight_bkg);
// add other variables ...

//create two histograms (for sig and ttbar)
TH1F *h_MZ   = new TH1F("h_MZ","MZ distribution All events",40,65,115);
TH1F *h_MZ_bkg   = new TH1F("h_MZ_bkg","MZ distribution BKG",40,65,115);
TH1F *h_MZ_sig   = new TH1F("h_MZ_sig","MZ distribution SIG",40,65,115);

//read all SIGNAL entries and fill the histograms
Int_t nentries = (Int_t)sig->GetEntries();

for (Int_t i=0;i<nentries_bkg;i++) {
  ttbar->GetEntry(i);
  h_MZ_bkg->Fill(MZ_bkg,Weight_bkg);
  h_MZ->Fill(MZ_bkg,Weight);
}
```

Access the background info

Define the name variables per each bkg lepton

Loop on events

Page 1 of 2

```
// example how Draw and  save histograms
 TCanvas *c = new TCanvas();
 c->cd();
 h_MZ_sig->Draw();
 h_MZ_bkg->SetLineColor(kRed);
 h_MZ_bkg->Draw("same");

 c->Print("test_MZ.eps");
}

void macro()
{
 tree1r();
}
```

Draw and save histograms

Main program

To start root you may type:

root –l
root [1] .x macro.C

and look at what you get ….

Useful in-line commands:

```
TFile f("Selected_All_EEM.root");
f.ls();
WZSignal->Scan();
WZSignal->Print();
```

Where to find help:

https://root.cern.ch/root/htmldoc/guides/primer/ROOTPrimer.pdf

Have fun !!

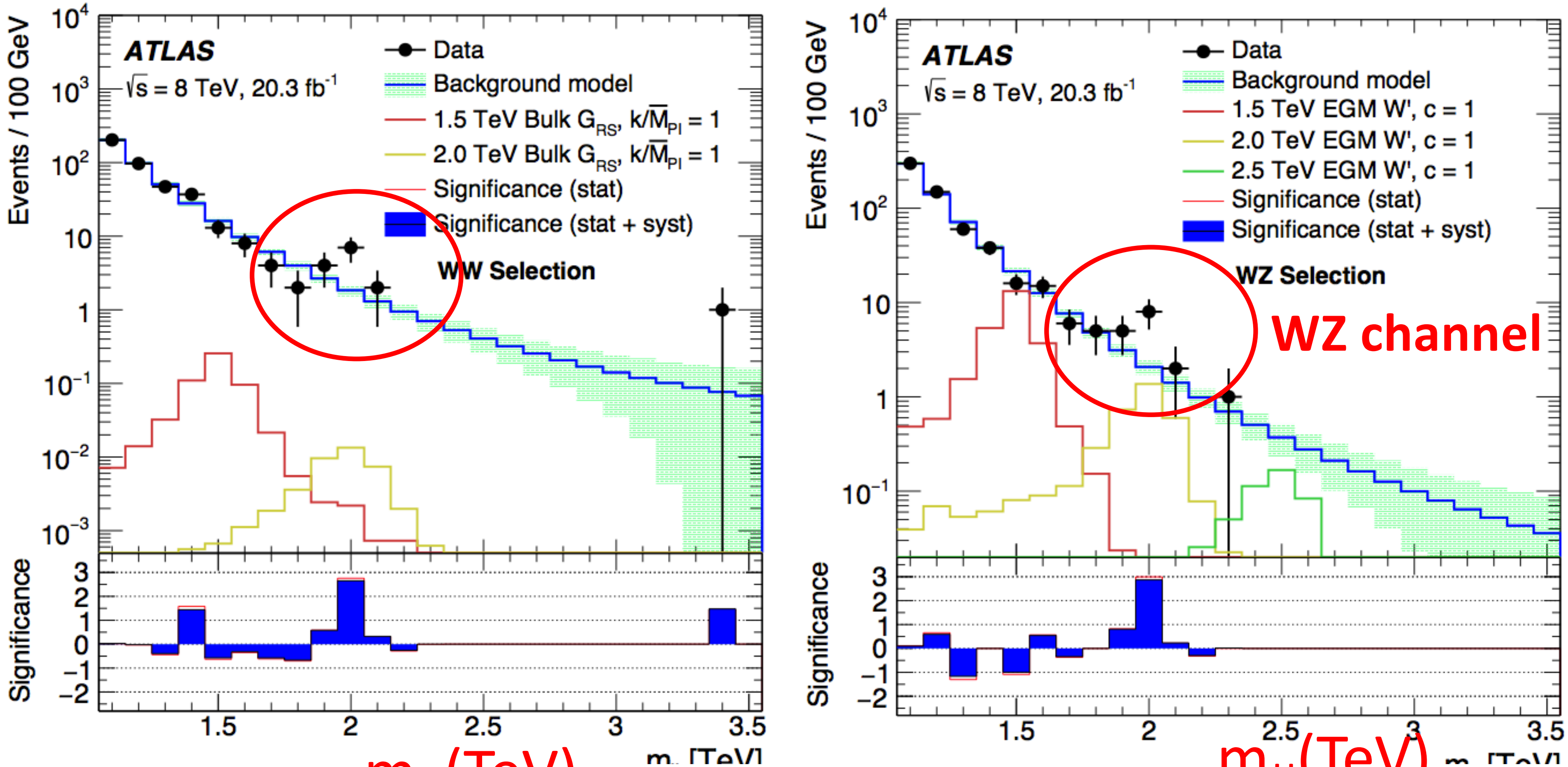

Are We Having Fun Yet ?
JIM DAVIS
GARFIELD: © 1978 United Feature Syndicate, Inc.

W(jj) Z (jj)

jj = J (1 fat jet)

Another example: search for di-boson resonances

- Is there something hiding in the data, waiting to be discovered?



m_{JJ}(TeV)

m_{JJ}(TeV)

WZ invariant mass