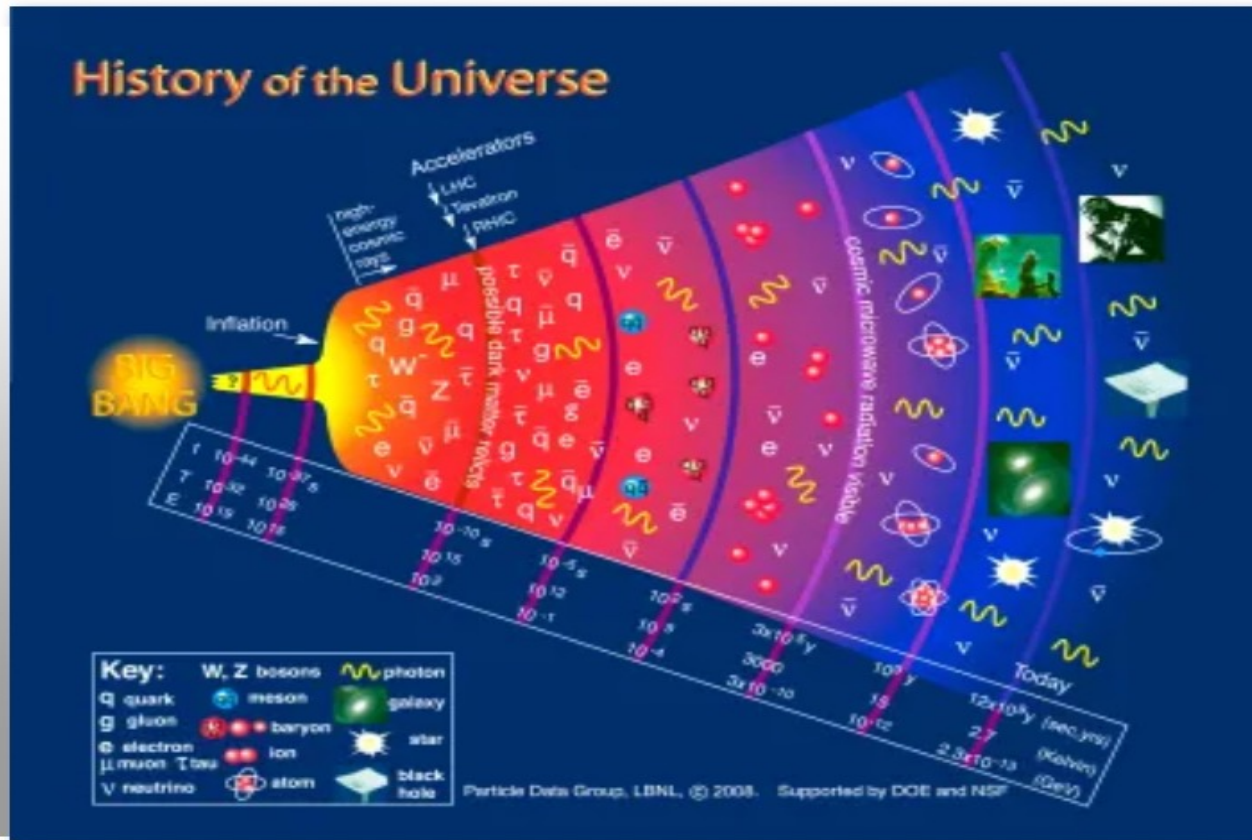


A computing exercise for Experimental Particle Physics



**Fundamental particle
and interactions at the
base of evening !**

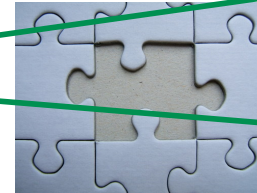
Accelerator physics: controlled and known initial conditions

→ big advantage 😊

→ most of the discoveries about fundamental interactions so far thanks to
accelerator physics

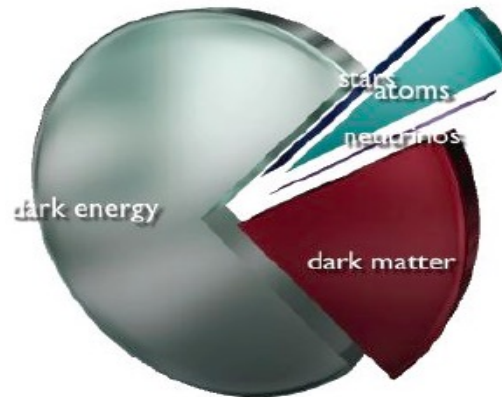
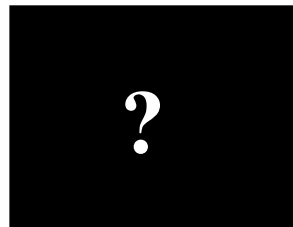
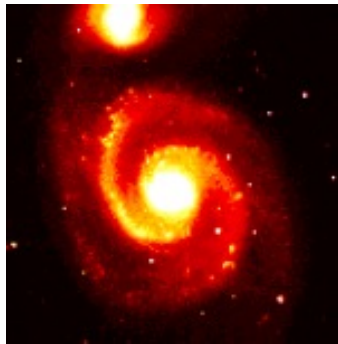
Particle physics : still many things to discover (very simplified)

- ✦ Origin of particle masses :
Higgs bosons, the missing piece ?



✓ DONE

- ✦ Nature of Dark Matter / Dark Energy ?



- ✦ Can we “describe” gravitation in a similar way as the other the other forces (Electromagnetism, Weak force, Strong force)?



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”

Experimental
probe:

Dibosons:

What

is

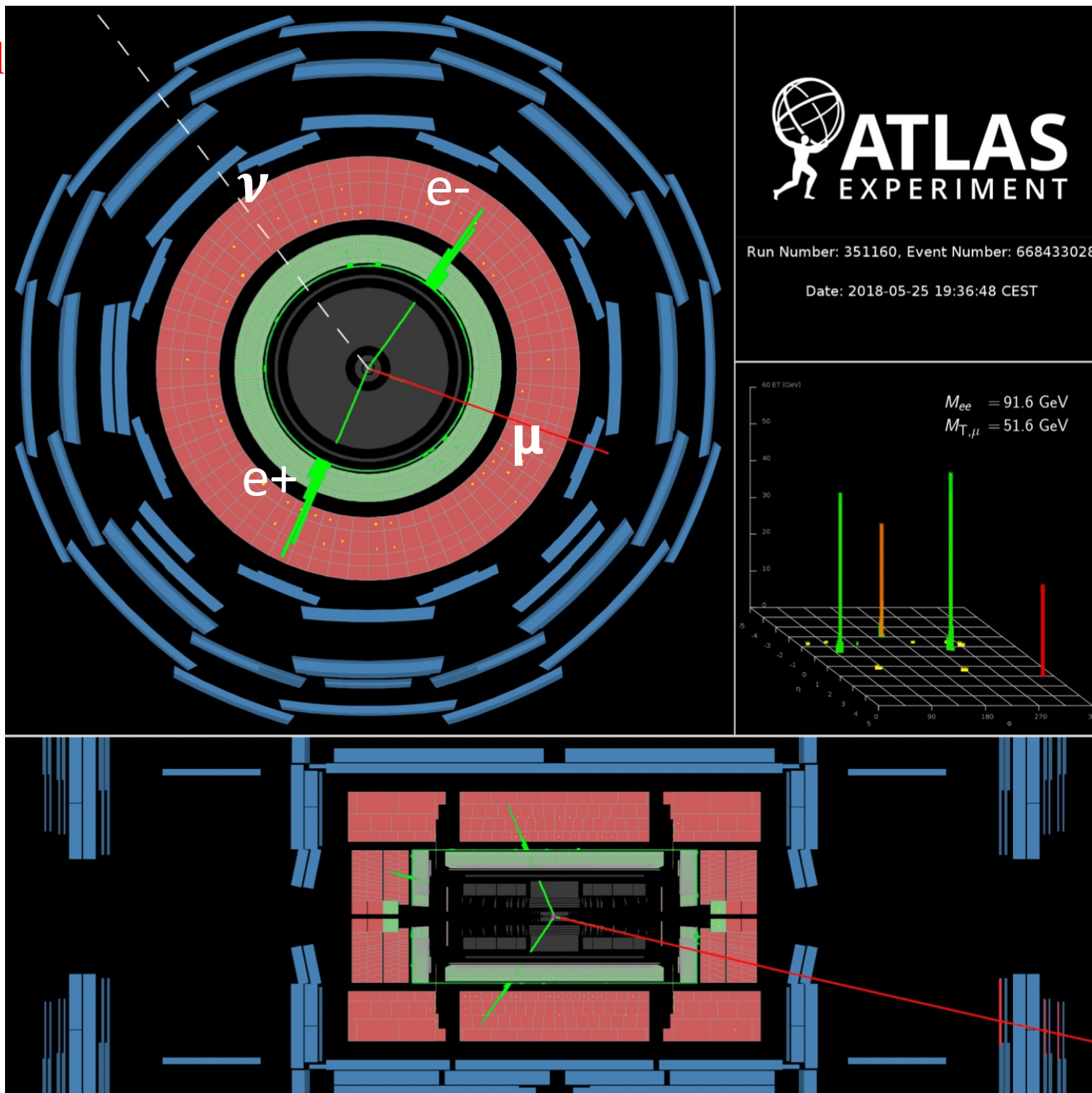
that?

We know

from theory
AND **previous
experiments**)
that

$Z \rightarrow e^+e^-$

$W \rightarrow \mu\nu$



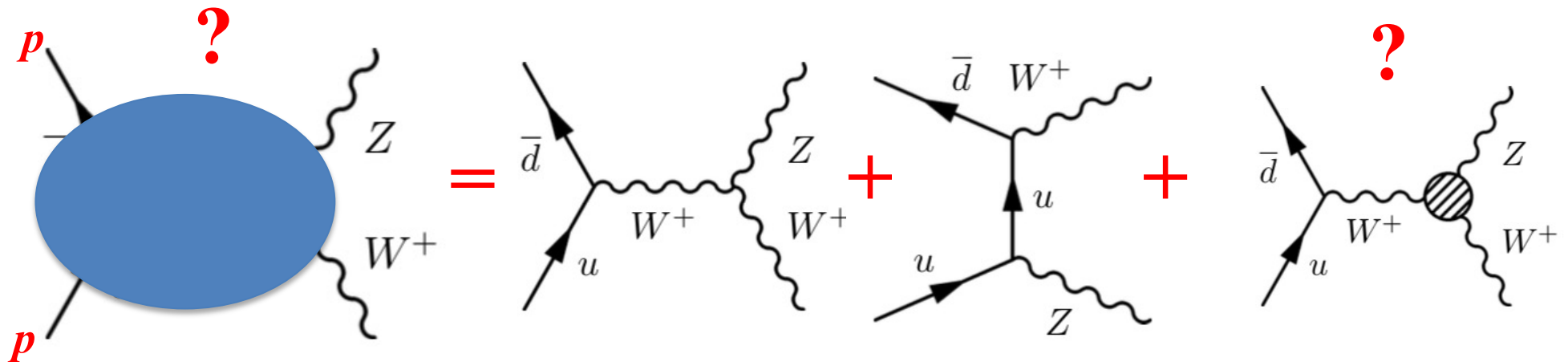
Hands-on on diboson physics



topic @ LHC

Theory:

The “interesting” physics is in the **hard scattering** processes



Test of SM
(measure interaction
probability)

Discover New Physics
(look inside the blob)

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 $p - p \rightarrow W Z X$
 - * **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
 $c=1$

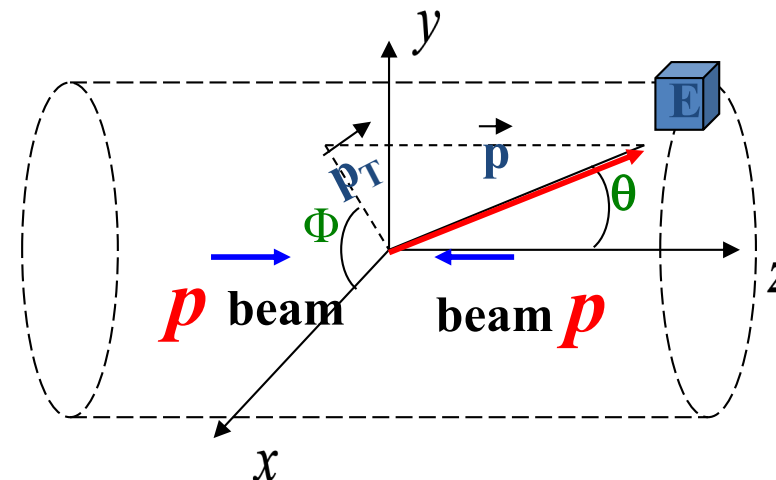
Variables used in the analysis of $p - p$ collisions

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

$$\tilde{p} = (E, p_x, p_y, p_z)$$

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** : $p_T = p \sin \theta$ $E_T = E \sin \theta$

• 2. **Rapidity** $Y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$

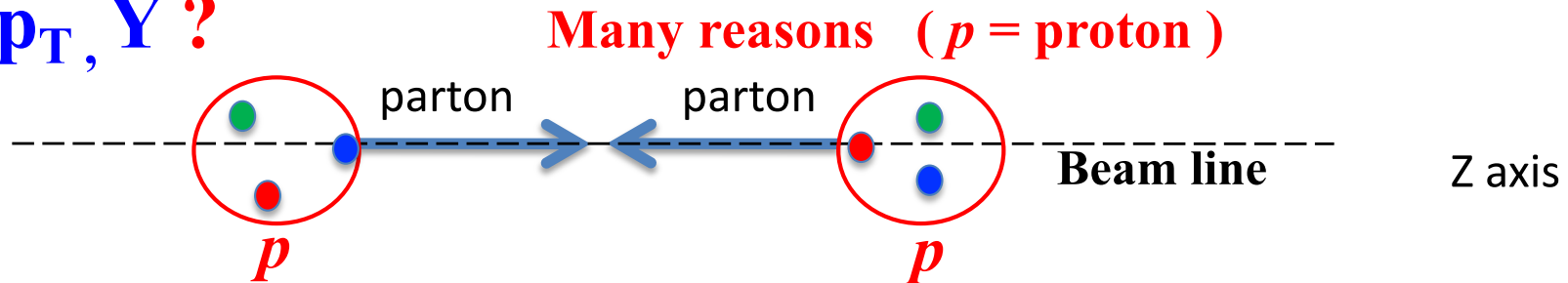
or **Pseudorapidity** $\eta = - \ln \left(\tan \frac{\theta}{2} \right)$

• 3. **Azimuthal angle** Φ

Why?

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

Why p_T, Y ?

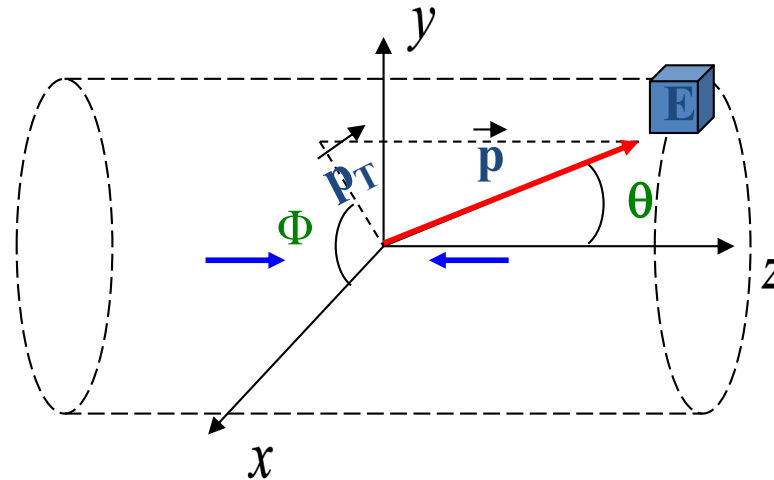


1. p_T and ΔY are invariants for Lorentz transformations along the z axis 😊
2. The **longitudinal** momentum of the initial partons is ‘**unknown**’, while we know that $\vec{p}_T^{\text{initial parton}} \sim 0$
 → Exploit **momentum conservation in the plane $\perp$ to the beam** using *transverse* quantities

$$\sum^{\text{initial partons}} \vec{p}_T = \sum_{\text{vis}}^{\text{fin}} \vec{p}_T + \sum_{\text{invis}}^{\text{fin}} \vec{p}_T \approx 0 \quad \rightarrow \text{Allows to evaluate the } p_T \text{ of not detected (v) particles}$$

$$\sum_{\text{invis}}^{\text{fin}} \vec{p}_T = - \sum_{\text{vis}}^{\text{fin}} \vec{p}_T \quad | \sum_{\text{invis}} p_T | \text{ is the “missing } E_T \text{ (MET)”}$$
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



$$p_T = p \sin \theta$$

$$p_x = p_T \cos(\Phi);$$

$$p_y = p_T \sin(\Phi);$$

$$p_z = E \tanh(\eta);$$

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

NB:

- if $m \ll E \rightarrow Y \approx \eta$ (η doesn't require particle identification)
- if $m \ll E \rightarrow p_T \approx E_T \quad E_T = E \sin \theta$

Concept of *invariant* mass M_A

Particle A decays to B and C

$$A \rightarrow B \ C$$

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

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

Concept of *invariant* mass: inclusive Z boson production

$$p - p \rightarrow Z (X) \text{ with } Z \rightarrow e^+e^-$$

(X) = part1, part2, part3, ...

M_{ee} = Invariant mass of ee system

(it allows to measure the Z mass, M_Z):

from the 4-momentum conservation

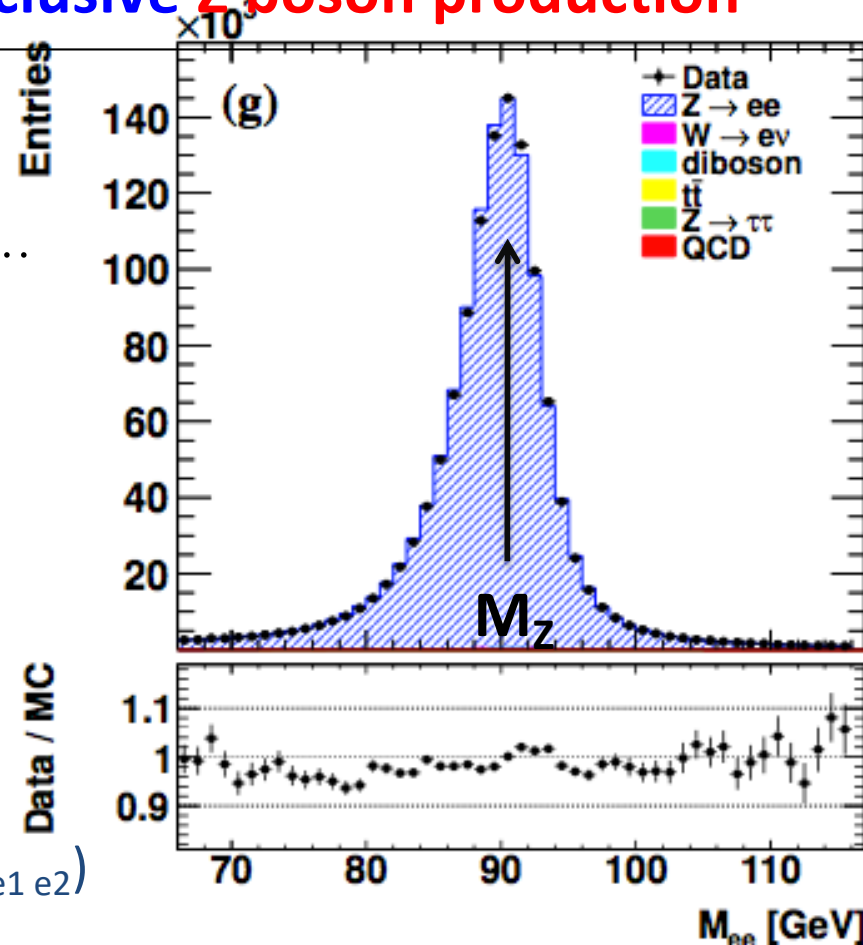
$$\tilde{p}_Z^2 = (\tilde{p}_{e1} + \tilde{p}_{e2})^2$$

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

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

Very ‘clean’ distribution (low bkg)!!

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



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

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

width

lifetime

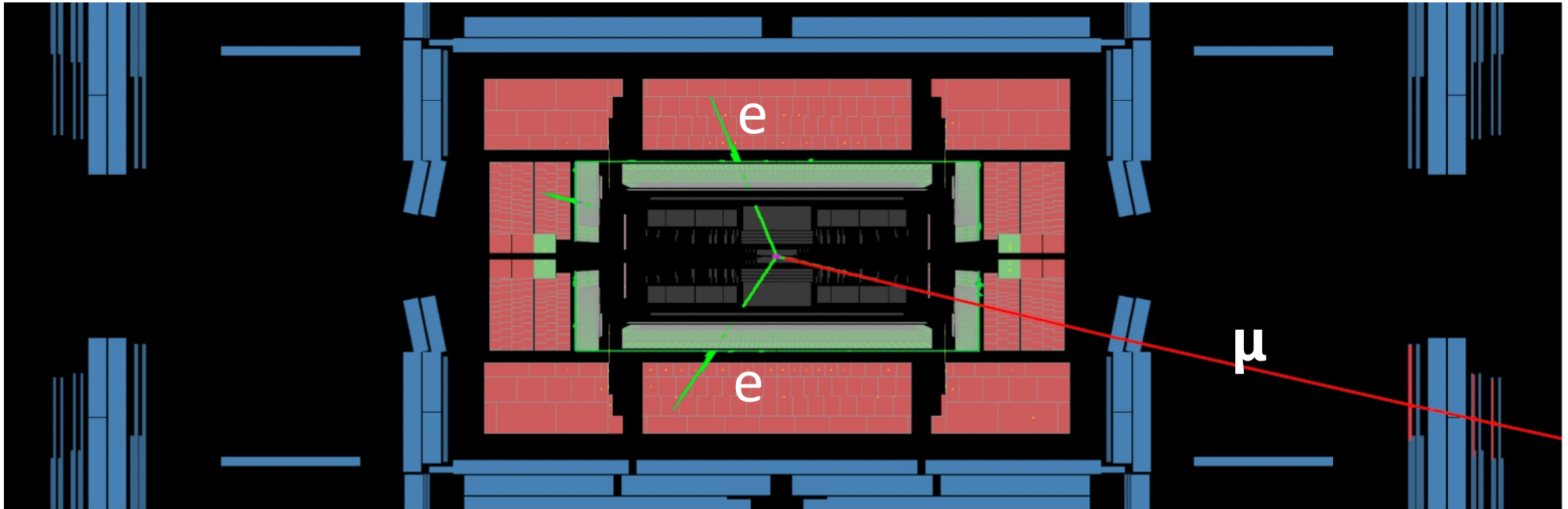
2. Experimental resolution

Non-relativistic Breit-Wigner (simplest formula)

$$f(E) = \frac{P_0}{(E - P_1)^2 + \frac{P_2}{2}},$$

Same mathematical shape of Cauchy distribution

What is that?



$$p-p \rightarrow \mathbf{W} \mathbf{Z} (\mathbf{X})$$

Our 'signal'

With $\mathbf{Z} \rightarrow e^+ e^-$
and $\mathbf{W} \rightarrow \mu^+ \nu_e$

OR

$$p-p \rightarrow \mathbf{t} \bar{\mathbf{t}} (\mathbf{X})$$

Our 'background'

$$\begin{aligned} \mathbf{t} &\rightarrow \mathbf{b} \mathbf{W} \rightarrow (\mathbf{X}) e^- \\ \bar{\mathbf{t}} &\rightarrow \mathbf{b} \mathbf{W} \rightarrow e^+ (\mathbf{X}) \mu^+ \end{aligned}$$

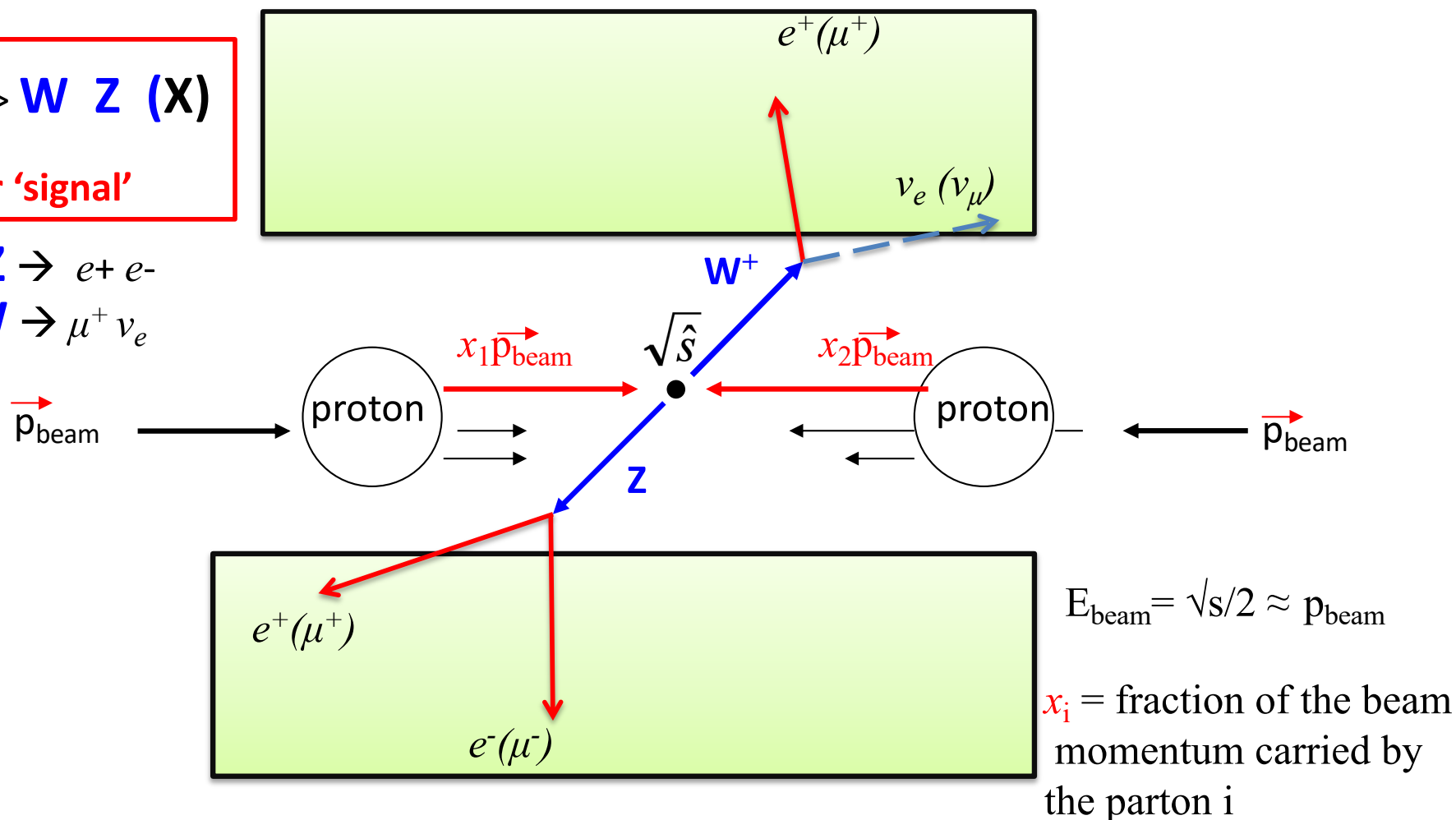
Our signal : production of a W and a Z (decaying leptonically)

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

$$p-p \rightarrow W Z (X)$$

Our 'signal'

With $Z \rightarrow e^+ e^-$
and $W \rightarrow \mu^+ \nu_e$



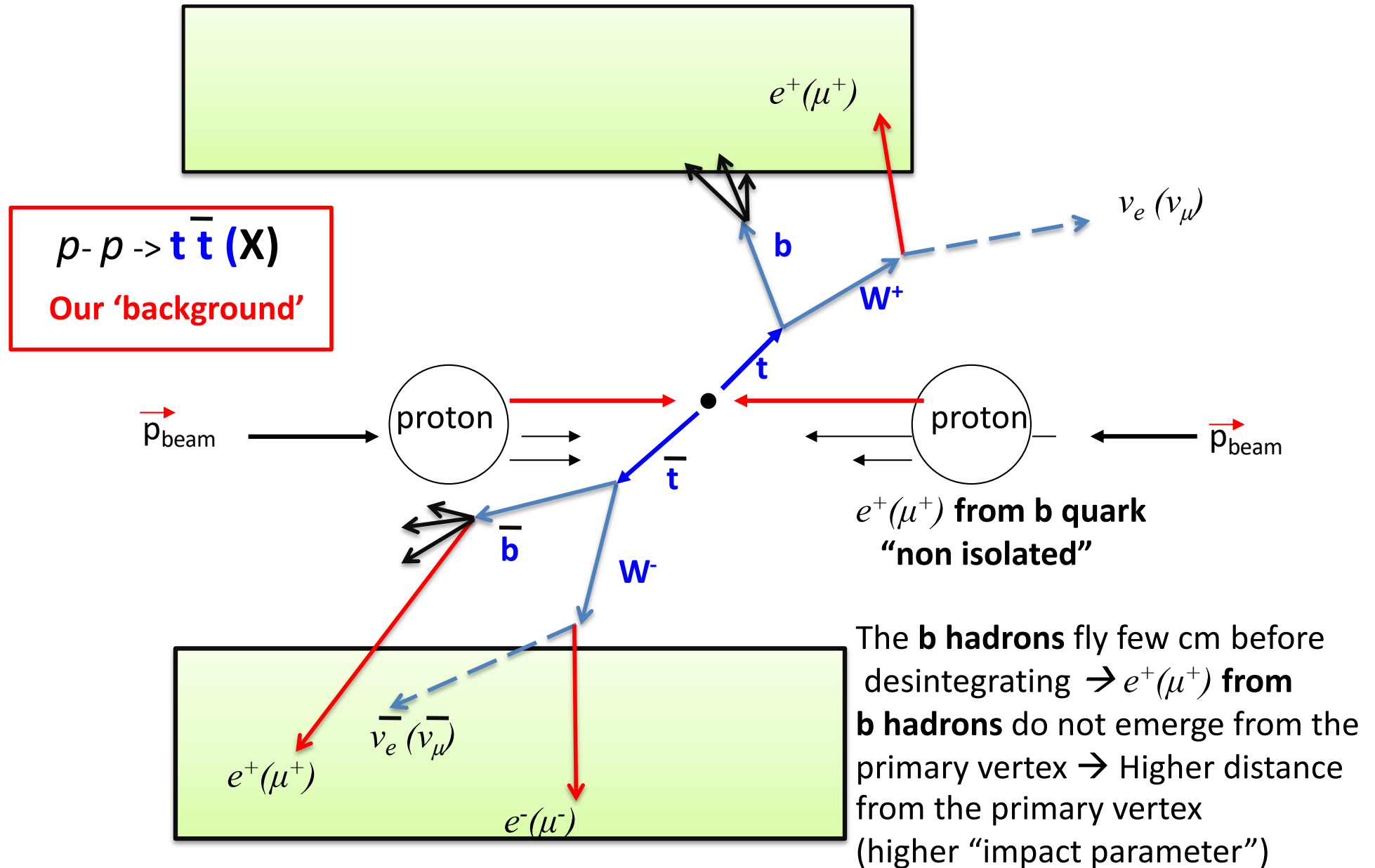
Kinematics of p - p collisions

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

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

Our background: Production of a pair of top-antitop

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



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

In practice:

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

You will have:

GRASPA2026explanation.pptx.pdf (this slides)

Exercise2026.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/html/doc/guides/primer/ROOTPrimer.html>

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

=== 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

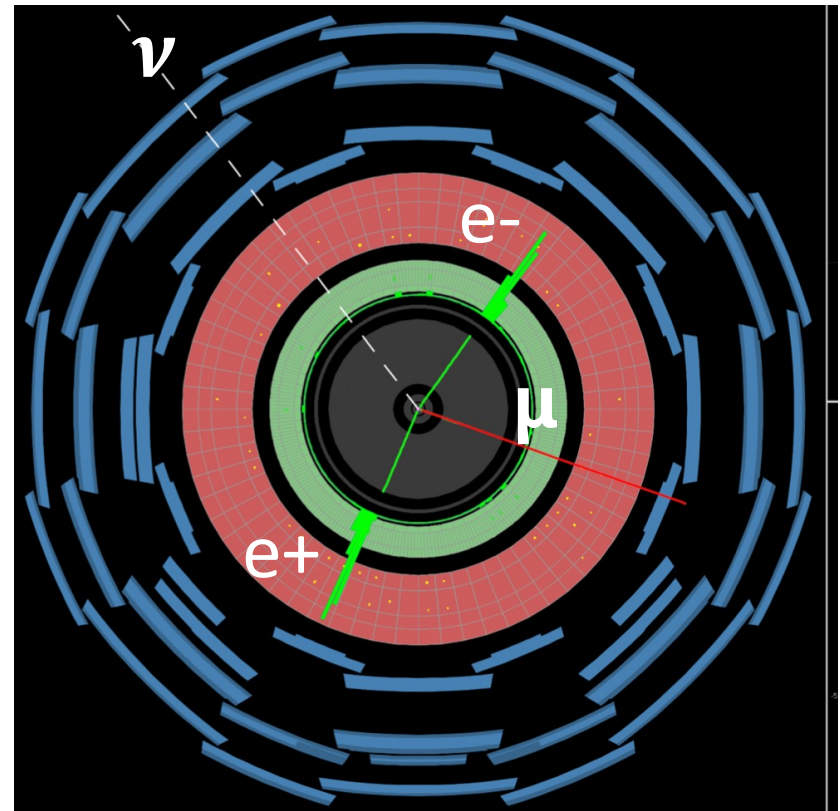
Br 12 :pt3 : pt3

Br 13 :eta3 : eta3

Br 14 :phi3 : phi3

Br 15 :E3 : E3

List of variables given
per each collision event
(kinematics of the final
state leptons Br='branch')



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

```
#include "TCanvas.h"
#include "TR00T.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->SetBranchAddresses("pt1",&pt1);
```

**Declaration of
variables given
per each collision event**

Retrieve these variables

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

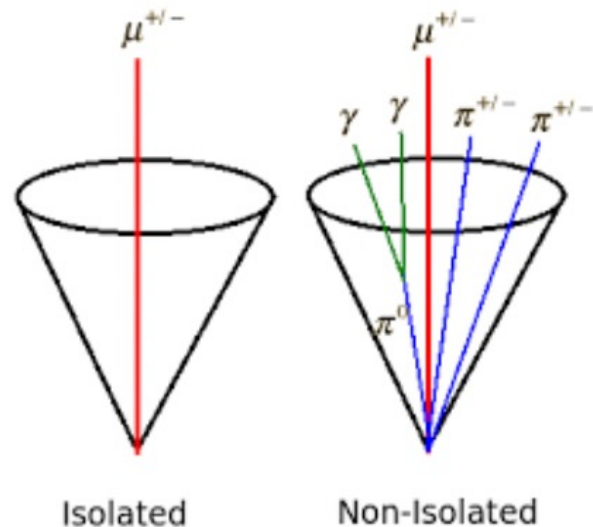
Br 1 :TrackIsoWmu : TrackIsoWmu

== MISSING TRANSVERSE ENERGY

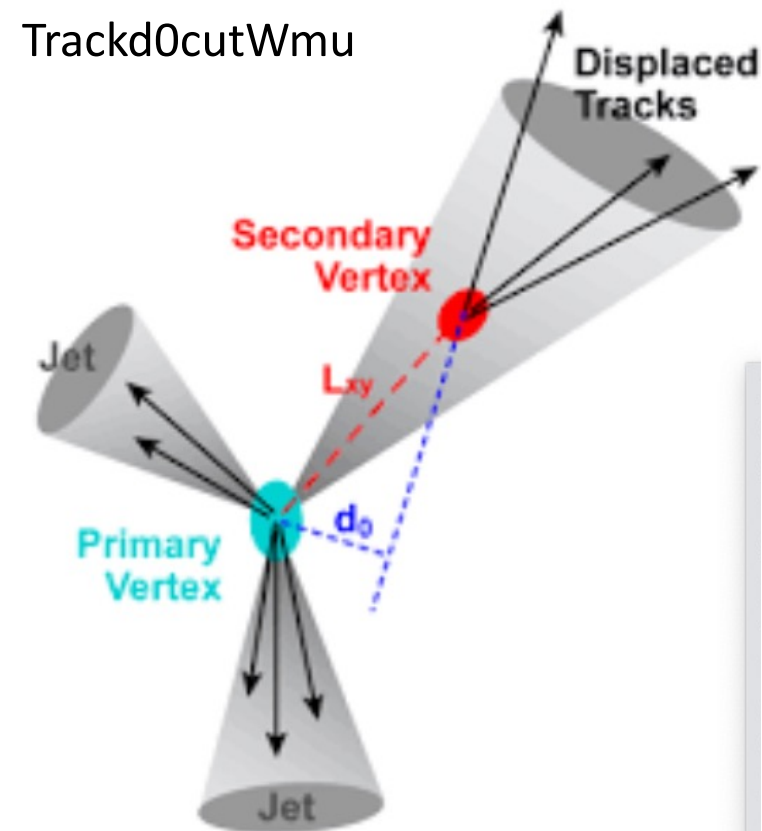
Br 2 :MET : MET

=== MASS of Z

Br 3 :MZ : MZ



TrackIsoWmu
Energy in the
cone



2) Instructions to make the computing exercise : [Exercise2025.pdf](#)

GRASPA 2026

16-23 July 2026



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

We remind that the leptonic decays of the W and Z are:

$W \rightarrow \ell\nu$ and $Z \rightarrow \ell^+\ell^-$ with $\ell = e$ or μ .

Exercise:

- Open the Root file (the name of the file is *Selected_All_EEM.root*)
- Access the 'branch' WZSignal and $t\bar{t}$ (follow, as guide the macro *Macro.C*) The list of variables describing the event are given in the next page of this document.
- Plot the **transverse momentum** of the most energetic lepton (**pt1**) 'from the Z', for signal ($\rightarrow$ Get" WZSignal") and from the background ($\rightarrow$ Get("ttbar")). (Note the average value and the shape of each distribution. Has this variable a good discriminating power?)
- Compute and plot the **invariant mass** of the Z for ALL events (using the two most energetic leptons). **Suggestion:** look at the slides: how to compute the invariant mass ? how to compute px, py and p from the variables of the ntuple: E , pt , η and ϕ ? how to compute the angle between two 'spatial' vectors (px, py and pz) ?
- Plot the isolation variable called **TrackIsoWmu** separately for signal and bkg. Is there a difference? How can one discriminate between signal and background?
- Plot the impact parameter variable called **Trackd0cutWMu** for signal and bkg. Is there a difference? How can one discriminate between signal and background?
- Plot the Z invariant mass for ALL events requesting that the lepton from W has a small impact parameter and is isolated.

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

```
#include "TCanvas.h"
#include "TR00T.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

macro.C

23/07/2013 00:21

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

Header files

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

Open the input file

```
    // 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;
```

Access the SIGNAL 'tree'

**Declare the names of the
variables per each SIGNAL
lepton**

```
    //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 ...
```

Retrieve

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;

```

**Same steps as before
for BACKGROUND events
(Access, declare, retrieve)**

```

//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);

```

**Create
histograms**

```

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

```

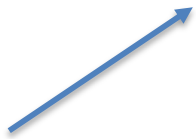
```

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);
}

```

**Loop
on background events**

**Fill
histograms**



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/html/doc/guides/primer/ROOTPrimer.pdf>

```

root [2] WZSignal->Print();
*****
*Tree      :WZSignal  : WZSignal
*Entries :      6725 : Total =      925932 bytes File Size =      714051 *
*          :          : Tree compression factor =      1.29
*****
*Br   0 :Trackd0cutWMu : Trackd0cutWMu/D
*Entries :      6725 : Total Size=      54493 bytes File Size =      51554 *
*Baskets :         2 : Basket Size=      32000 bytes Compression=      1.05 *
*.....
*Br   1 :TrackIsoWmu : TrackIsoWmu/D
*Entries :      6725 : Total Size=      54481 bytes File Size =      9659 *
*Baskets :         2 : Basket Size=      32000 bytes Compression=      5.59 *
*.....
*Br   2 :MET          : MET/D
*Entries :      6725 : Total Size=      54433 bytes File Size =      36250 *
*Baskets :         2 : Basket Size=      32000 bytes Compression=      1.49 *
*.....
*Br   3 :MZ           : MZ/D
*Entries :      6725 : Total Size=      54427 bytes File Size =      49876 *
*Baskets :         2 : Basket Size=      32000 bytes Compression=      1.08 *
*.....
*Br   4 :pt1          : pt1/D
*Entries :      6725 : Total Size=      54433 bytes File Size =      51094 *
*Baskets :         2 : Basket Size=      32000 bytes Compression=      1.06 *
*.....
*Br   5 :eta1         : eta1/D
*Entries :      6725 : Total Size=      54439 bytes File Size =      38421 *
*Baskets :         2 : Basket Size=      32000 bytes Compression=      1.40 *
*.....
*Br   6 :phi1         : phi1/D
*Entries :      6725 : Total Size=      54439 bytes File Size =      34701 *
*Baskets :         2 : Basket Size=      32000 bytes Compression=      1.55 *
*.....
*Br   7 :E1           : E1/D
*Entries :      6725 : Total Size=      54427 bytes File Size =      51216 *
*Baskets :         2 : Basket Size=      32000 bytes Compression=      1.05 *
*.....
*Br   8 :pt2          : pt2/D

```

```

root [0] TFile f("Selected_All_EEM.root");
root [1] f.ls();
TFile**      Selected_All_EEM.root
TFile*       Selected_All_EEM.root
KEY: TTree   WZSignal;1      WZSignal
KEY: TTree   ttbar;1 ttbar
root [2]

```

```

.....
root [3] WZSignal->Scan;
*****
*      Row      * Trackd0cu * TrackIsoW *      MET.MET *      MZ.MZ *      pt1.pt1 *      eta1.eta1 *      phi1.phi1 *      E1.E1 *
*****
*      0 * 0.2641882 *      0 * 253.64578 * 87.350410 * 61.601188 * -0.817877 * -1.500814 * 83.378844 *
*      1 * 0.9537003 *      0 * 92.529359 * 91.574428 * 71.422217 * -0.721660 * 1.9963139 * 90.841642 *
*      2 * 0.7880497 *      0 * 50.199683 * 85.517831 * 54.766218 * 1.2180694 * 1.9710001 * 100.67278 *
*      3 * 0.9396896 * 0.0497888 * 35.324738 * 90.074063 * 41.966772 * 0.5284444 * -0.339428 * 47.964093 *
*      4 * 0.3302549 *      0 * 21.890148 * 93.590557 * 78.954316 * -0.216677 * -2.845208 * 80.815003 *
*      5 * 0.1964478 * 0.5528677 * 6.8631630 * 90.617393 * 57.522515 * 1.6033705 * -0.483349 * 148.72366 *
*      6 * 0.0521366 *      0 * 22.399232 * 105.32648 * 32.583940 * 0.7230547 * -1.444287 * 41.479130 *
*      7 * 0.0158658 *      0 * 83.906039 * 85.514362 * 76.992449 * 0.6499663 * 2.5541749 * 93.836077 *
*      8 * 0.8594731 *      0 * 98.444078 * 95.427329 * 71.047542 * -1.592099 * 2.2048165 * 181.79483 *
*      9 * 0.7191259 *      0 * 55.521101 * 86.926958 * 39.746837 * 1.7523311 * -1.926207 * 118.07597 *
*     10 * 1.0504919 *      0 * 40.412230 * 83.049283 * 85.185360 * 1.2795817 * -2.562744 * 164.97378 *
*     11 * 0.2220973 * 0.0227451 * 137.98629 * 91.102069 * 78.362522 * 0.6634629 * -1.583802 * 96.251459 *
*     12 * 0.4516451 *      0 * 20.209451 * 92.144807 * 69.891041 * -0.805512 * 1.1507166 * 93.818284 *
*     13 * 0.0984018 *      0 * 69.865515 * 94.079940 * 77.923521 * 1.3334828 * 2.0610630 * 158.09875 *
*     14 * 1.1148476 *      0 * 49.904863 * 87.483494 * 46.311101 * 1.7198519 * -1.929639 * 133.44068 *
*     15 * 0.5134899 *      0 * 73.228976 * 92.536591 * 99.897442 * -1.168589 * 2.6775488 * 176.23183 *
*     16 * 1.6185537 *      0 * 80.422515 * 90.414728 * 71.959327 * -0.878087 * 2.2092824 * 101.52994 *
*     17 * 1.5021446 * 0.0326777 * 17.389455 * 87.855665 * 83.562489 * -1.221161 * -1.083674 * 154.00610 *
*     18 * 0.7095798 *      0 * 32.677386 * 75.58079 * 82.032108 * -2.051545 * 0.5421147 * 324.37359 *
*     19 * 2.8701089 * 0.0180627 * 5.0547876 * 91.270281 * 88.754800 * -0.668470 * 1.2492623 * 109.33448 *
*     20 * 2.4915679 *      0 * 62.205289 * 91.724654 * 68.497092 * -0.063284 * -2.382159 * 68.634302 *
*     21 * 0.6574025 *      0 * 20.827605 * 90.211062 * 55.085575 * 1.024565 * 2.0004816 * 88.716500 *

```

Have fun !!



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?

