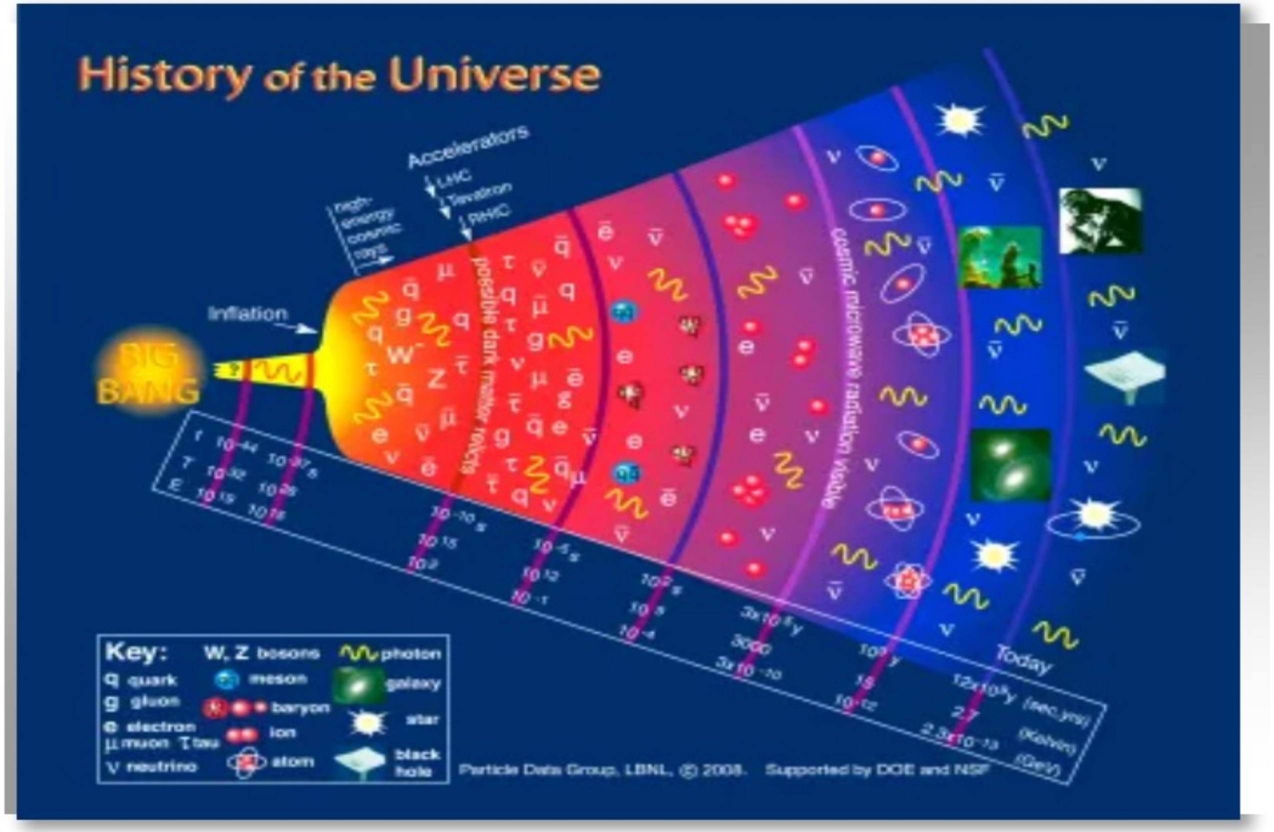
A computing exercise for Experimental Particle Physics



Fundamental particle and interactions at the base of evening !

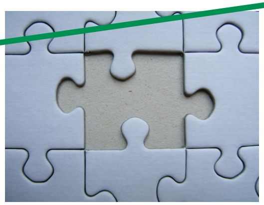
Accelerator physics: controlled and known initial conditions

→ big advantage ☺

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

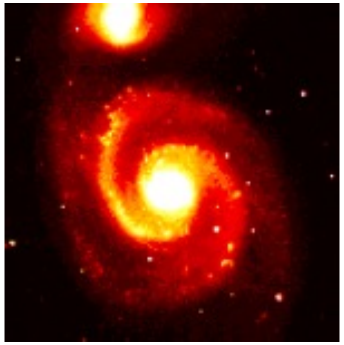
Particle physics : still many things to discover (very simplifyed)

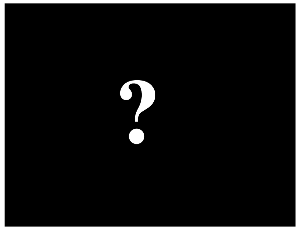
- ~~Origin of particle masses :
  Higgs bosons, the missing piece ?~~

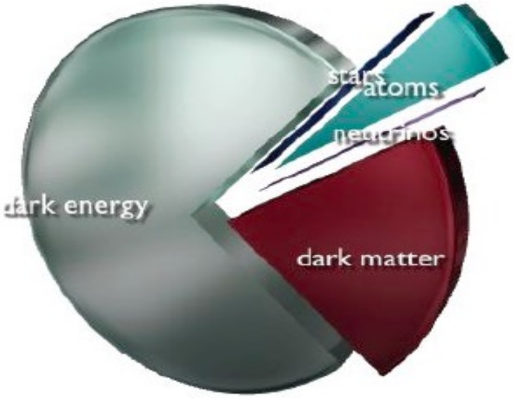


✓DONE

- Nature of Dark Matter / Dark Energy ?







- Can we "describe" gravitation in a similar way as the other
  the other
  forces (Elecromagnetism, Weak force, Strong force)?

GraSPA 2025

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"

Experiment:

Dibosons:

What

is

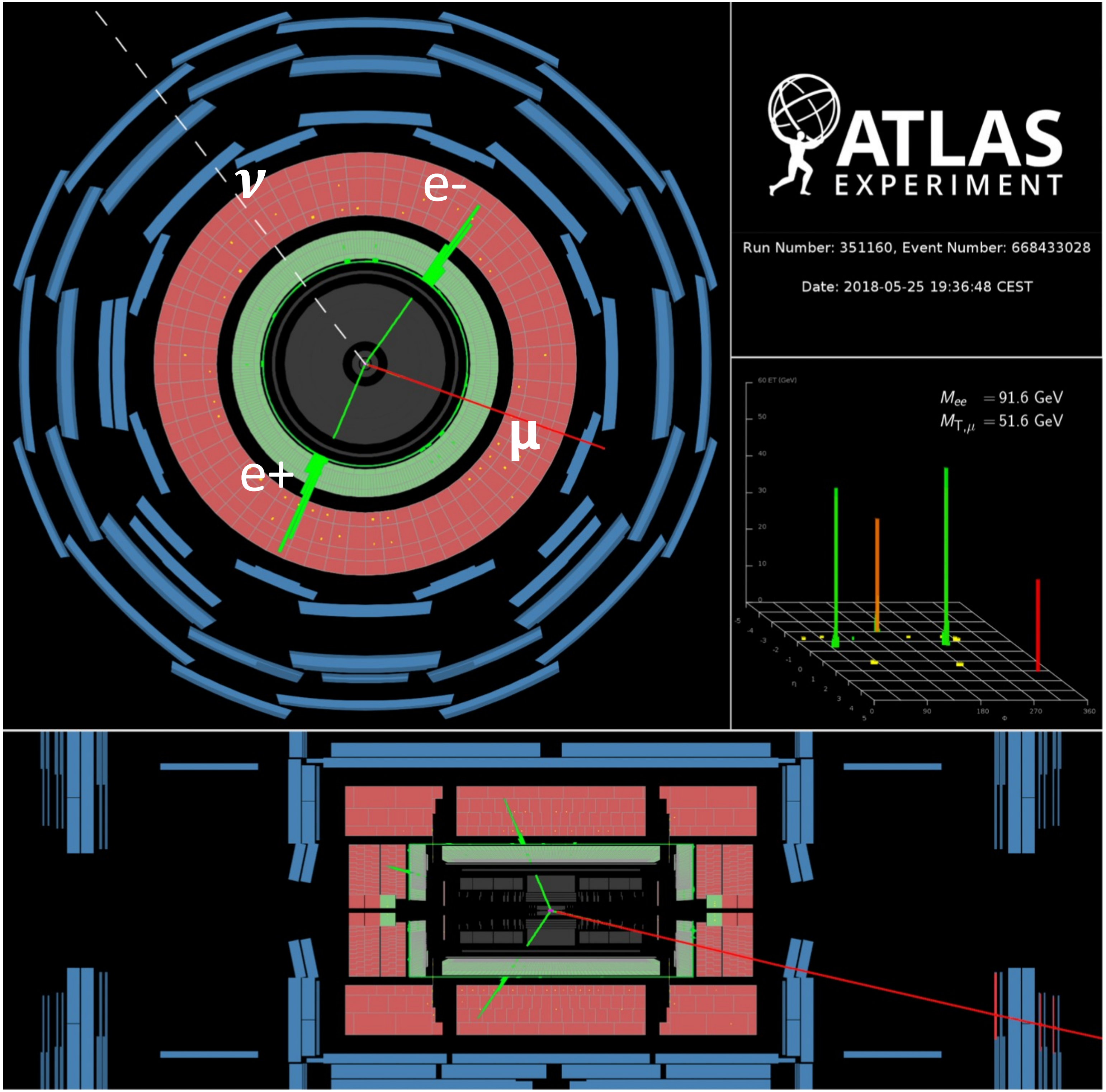
that?

We know

from theory
AND
experiments)
that

Z → e+e-

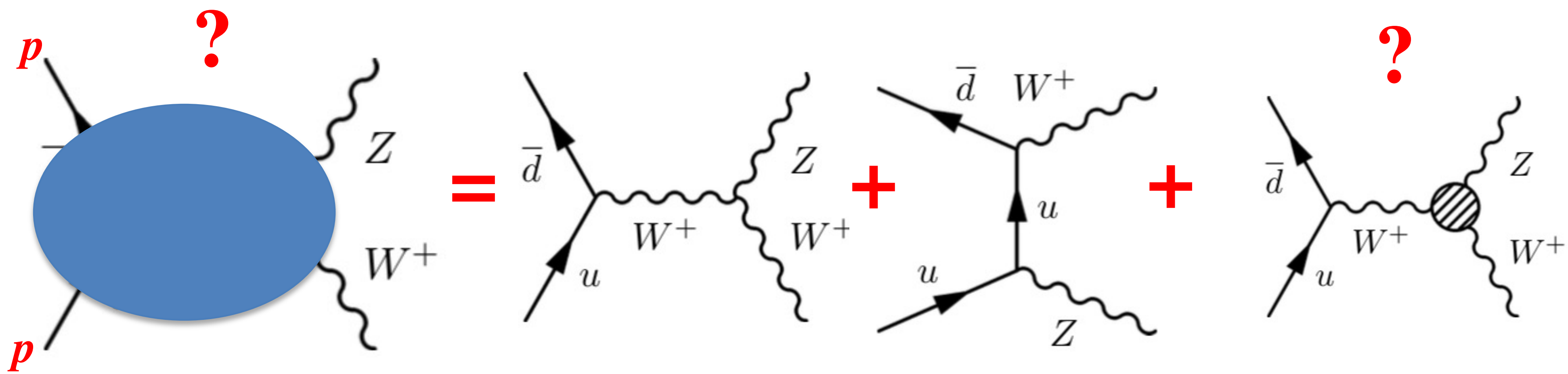
W→ $\mu\nu$



Hands-on on diboson physics HOT 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* → 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

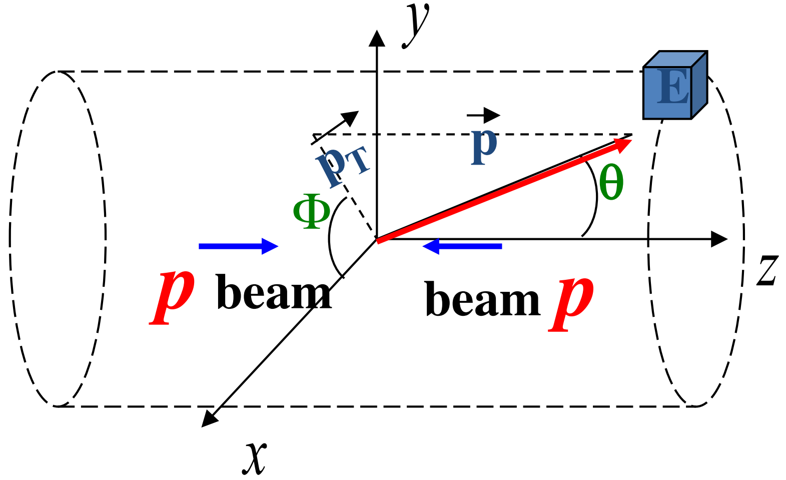
Variables used in the analysis of *p - p* collisions

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

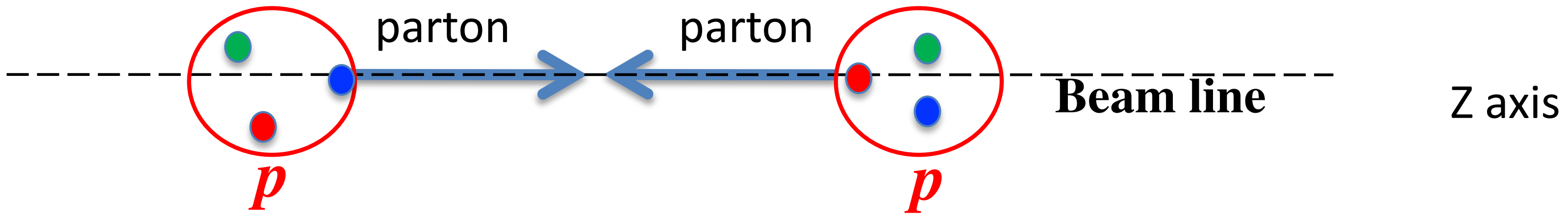
  or Pseudorapidity $\eta = -\ln(\tan\frac{\theta}{2})$
- **3. Azimuthal angle** Φ

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 axis</u>

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

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

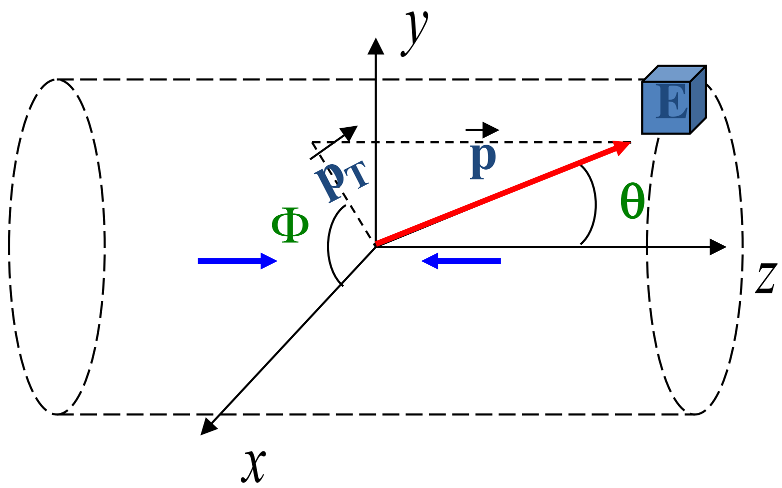
→ Allows to evaluate the p_T of not detected (ν) particles

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

$|\sum_{\text{invis}} p_T|$ 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:

- if m « E → $Y \approx \eta$ (η doesn't require particle identification)
- if 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

$$A \rightarrow B\ C$$

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

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

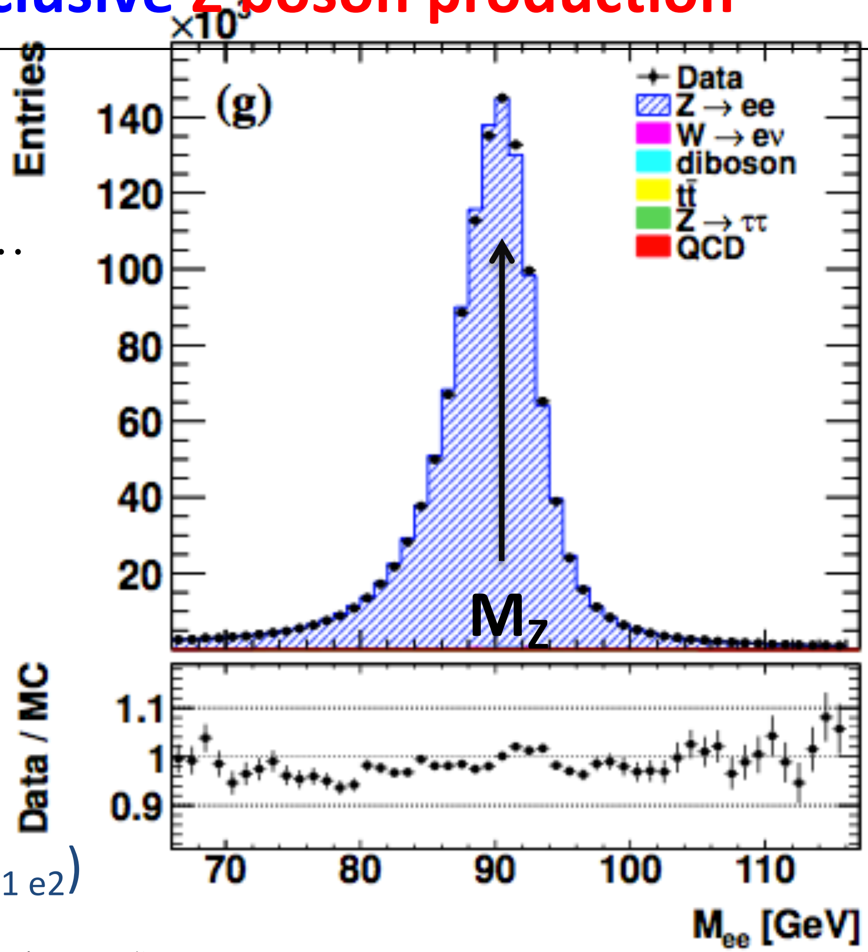
$$\tilde{p}_Z^{\,2} = (\tilde{p}_{e1} + \tilde{p}_{e2})^2$$

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

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

Very 'clean' distribution (low bkg)!!

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



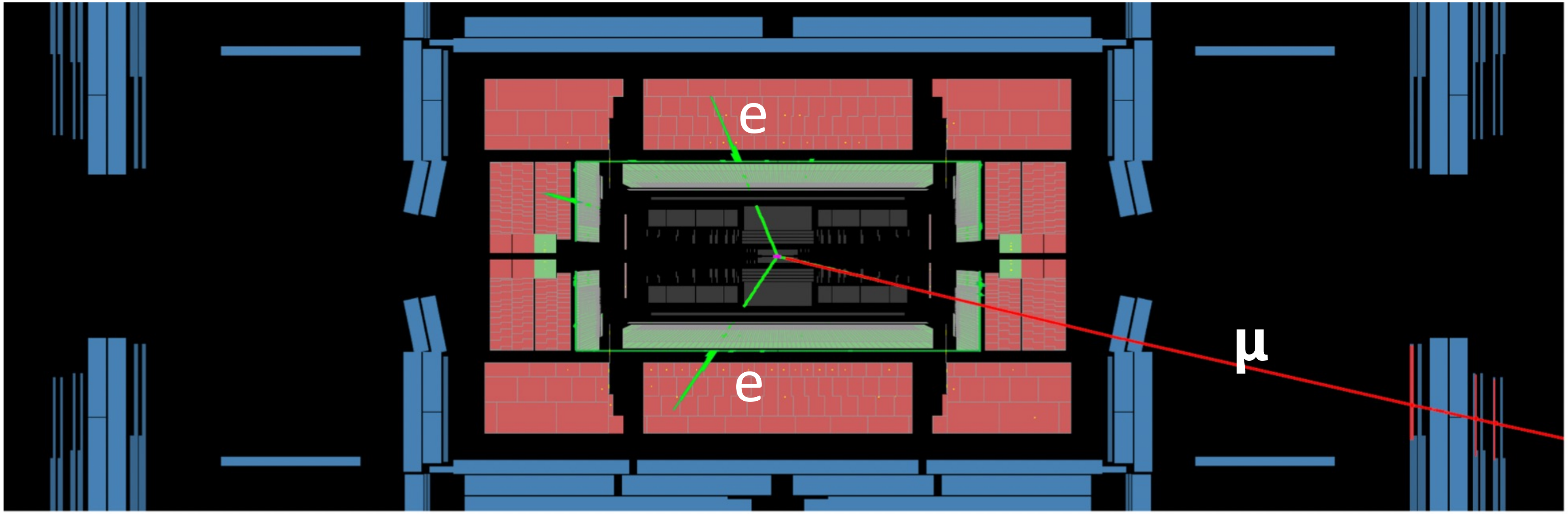
1. $\Delta E * \Delta t > \hbar/2$ $\Delta m * \tau > \hbar/2$

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

width lifetime

2. Experimental resolution

What is that?



p- p -> **W Z (X)**

Our 'signal'

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

OR

p- p -> **t $\bar{t}$ (X)**

Our 'background'

t → **b W** → **(X)** e-
$\bar{t}$ → **b W** → e+ **(X)** μ^+

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

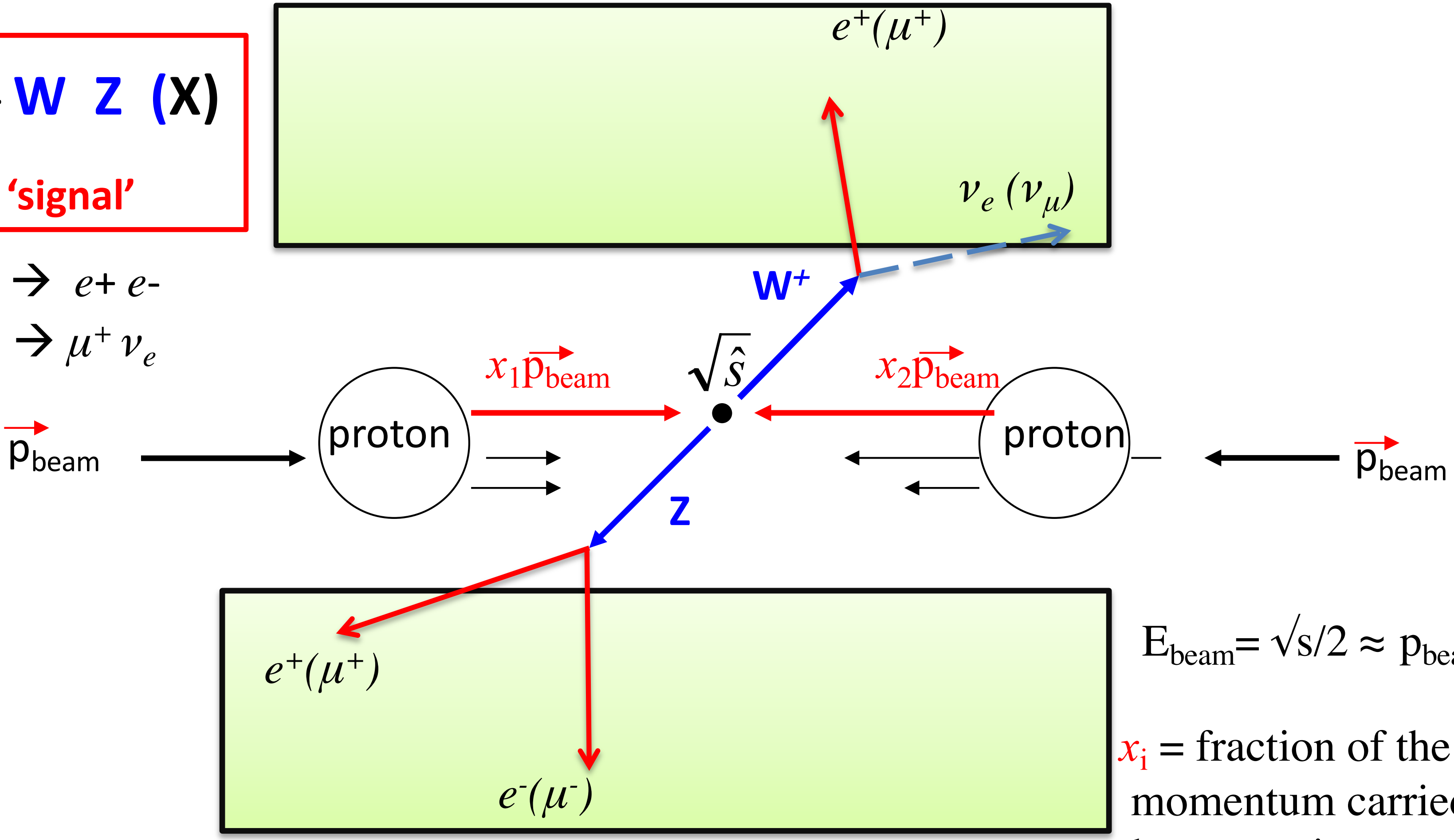
p- p ‘**hard**’ **collisions in the** $q_1\,\overline{q}_2$ **center of mass:**

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

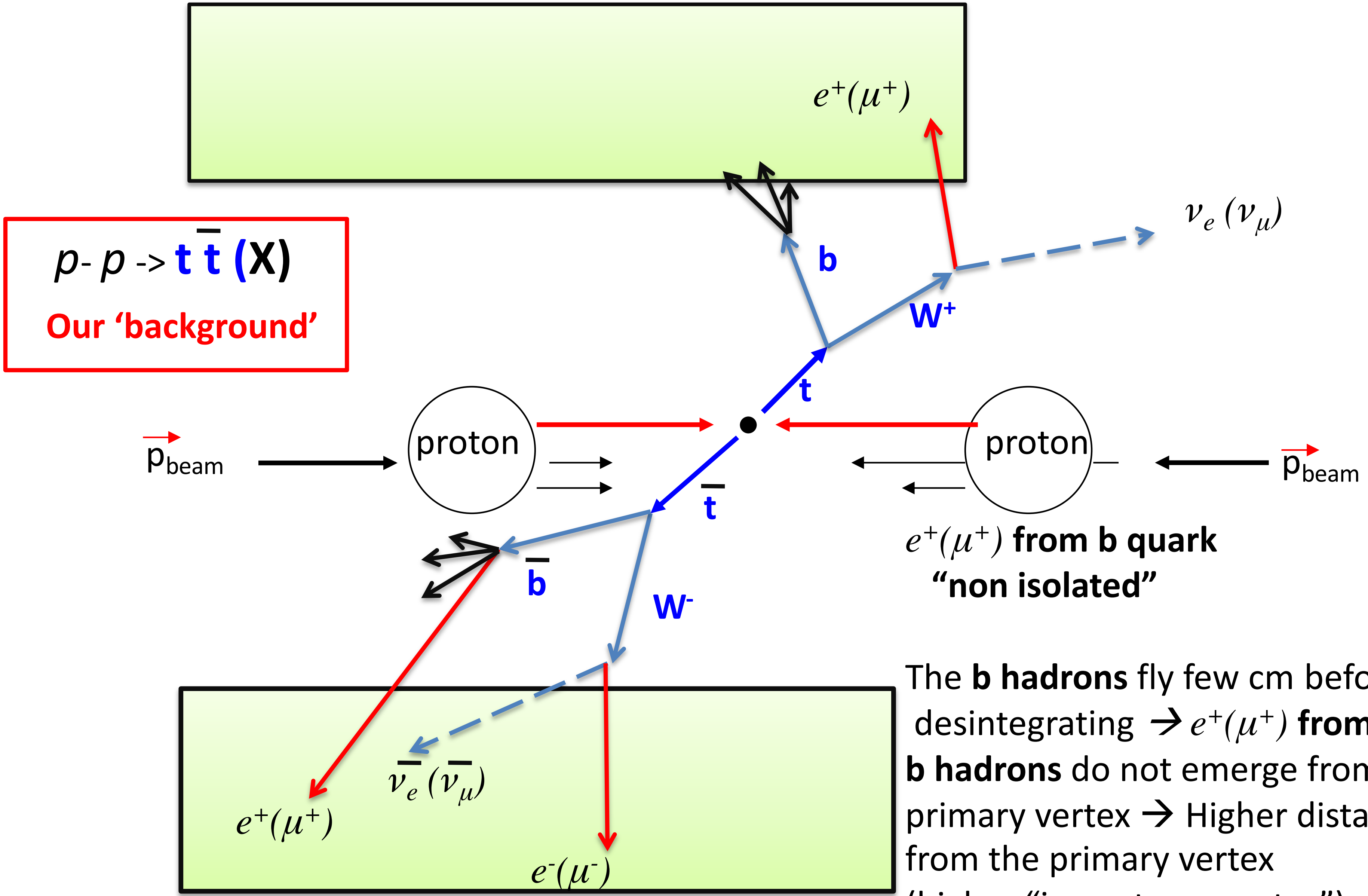
$0 < x_{1,2} < 1$

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):
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:

GRASPA2025explanation.pptx.pdf (this slides)

Exercise2025.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

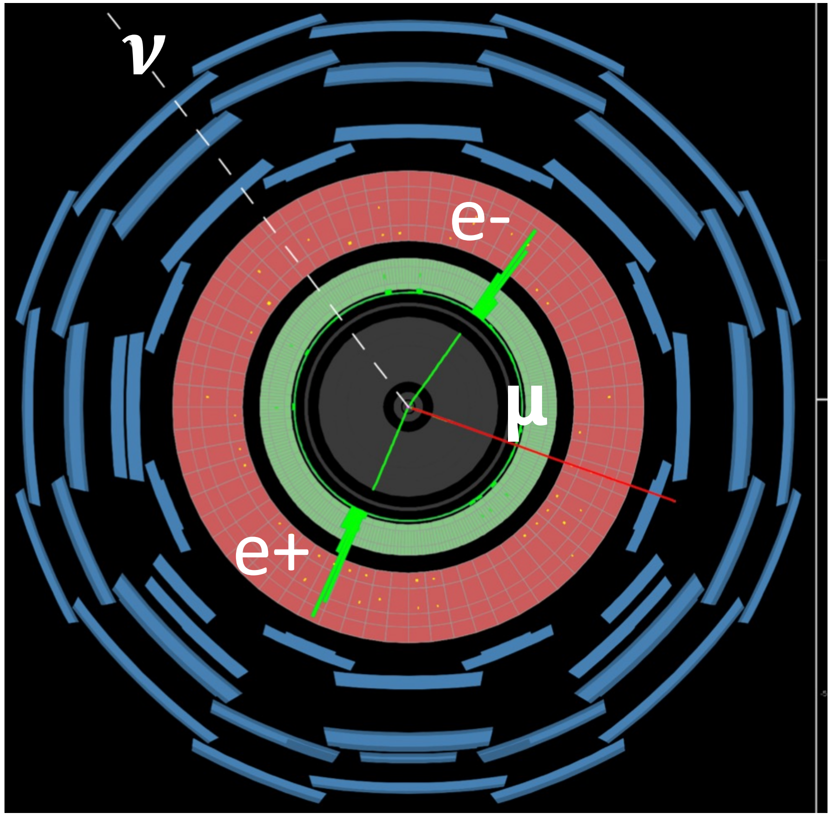
1) The input file containing the physics: Selected_All_EEM.root

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

=== 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



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);
```

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

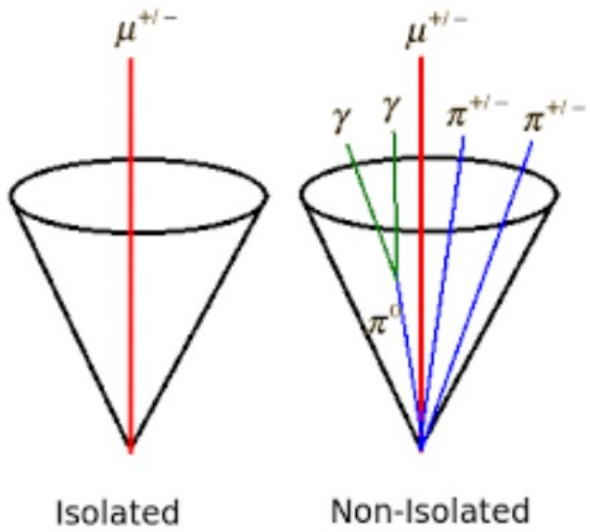
== MISSING TRANSVERSE ENERGY

Br 2 :MET : MET

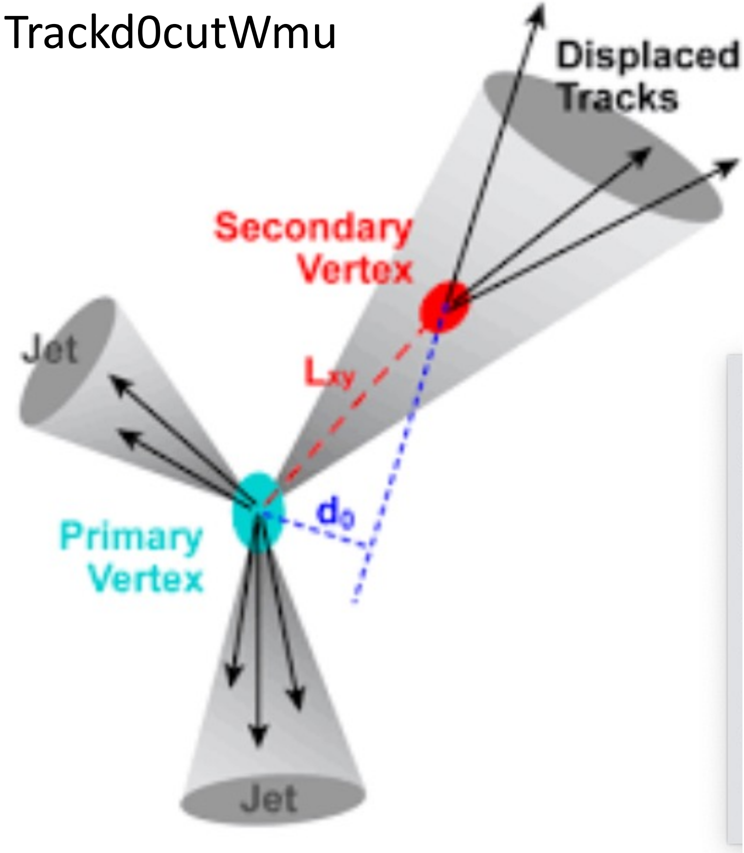
=== MASS of Z

Br 3 :MZ : MZ

Trackd0cutWmu



TrackIsoWmu
Energy in the cone



2) Instructions to make the computing exercise : Exercise2025.pdf

GRASPA 2025 **16-23 July 2025**

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.

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 (→ Get"WZSignal") and from the background (→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 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 "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

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"

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 'tree'

Declare the names of the variables per each SIGNAL lepton

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;

//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 ...
```

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

```
//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/htmldoc/guides/primer/ROOTPrimer.pdf

```
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 [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     *
*............................................................................*
 ,     2 :MET       : MET/D                                                  *
 ıtries :     6725 : Total  Size=      54433 bytes  File Size  =      36250 *
 ıskets :        2 : Basket Size=      32000 bytes  Compression=   1.49     *
 ............................................................................*
 '     3 :MZ        : MZ/D                                                   *
 ıtries :     6725 : Total  Size=      54427 bytes  File Size  =      49876 *
 ıskets :        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 [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 *
```

Have fun !!

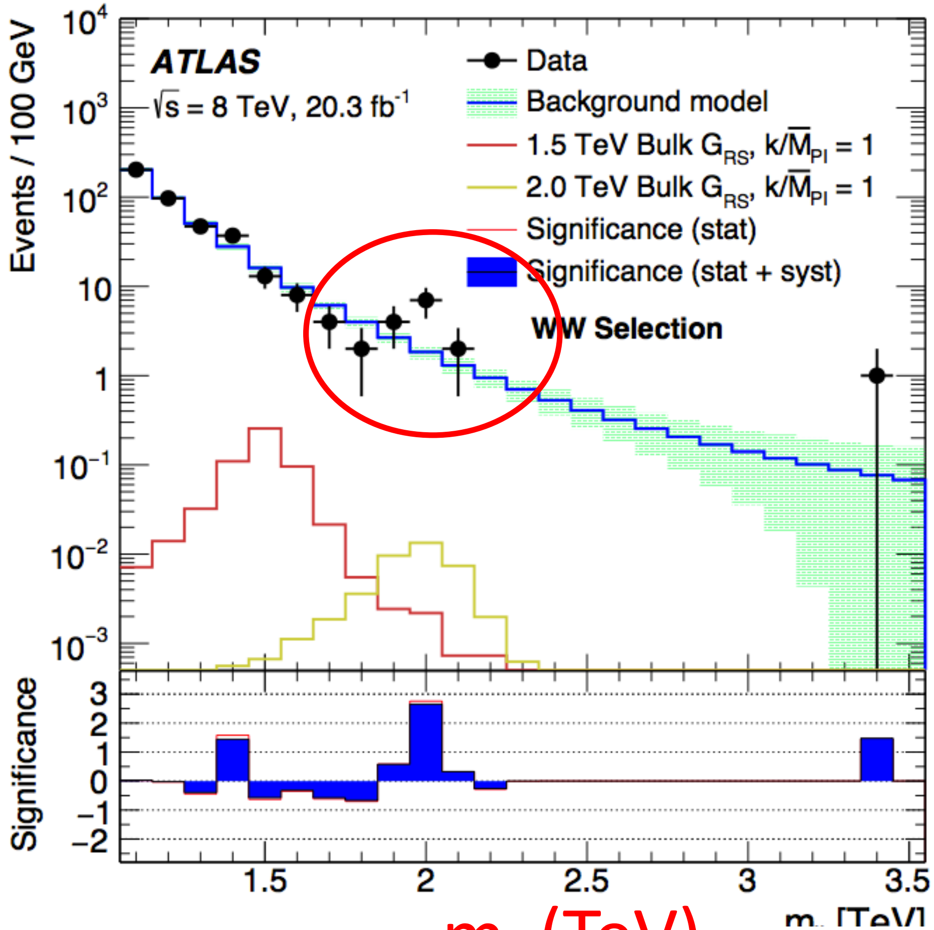

Are We Having Fun Yet ?
JIM DAVIS
GARFIELD: © 1978 United Feature Syndicate, Inc.

W(jj) Z (jj)

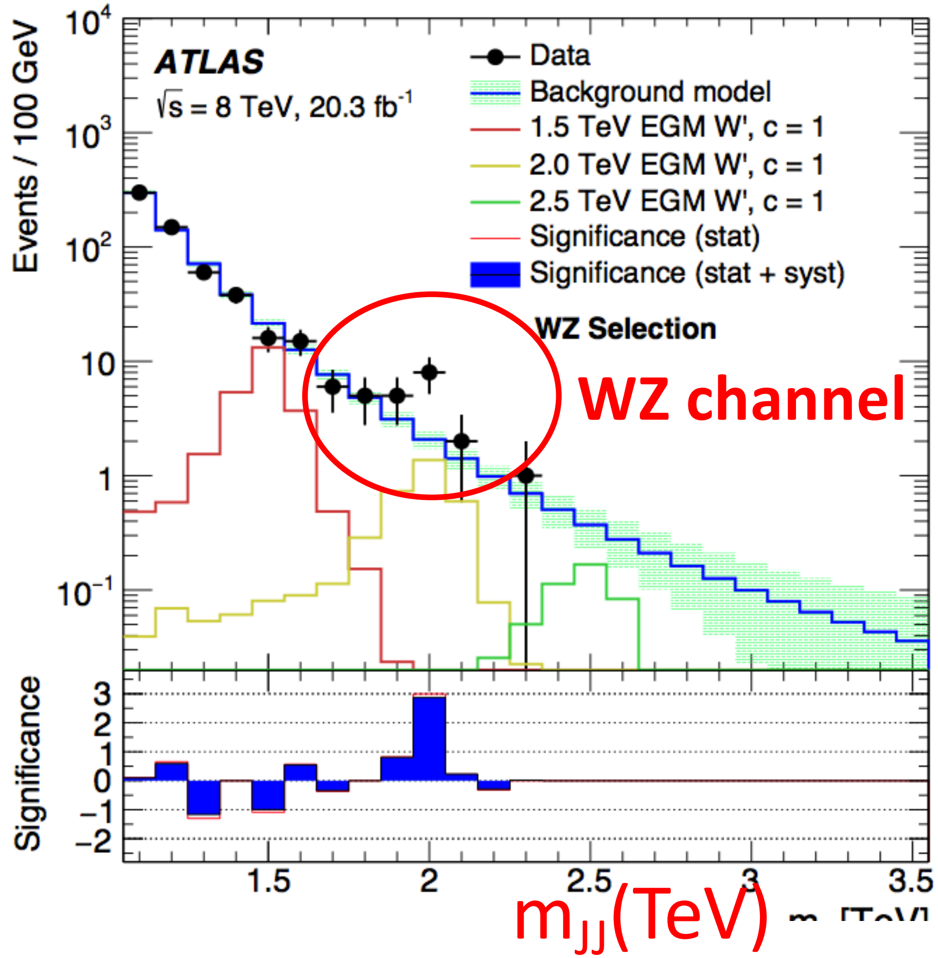
jj = J (1 fat jet)

Another example: search for di-boson resonances

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



m_{JJ}(TeV)



WZ invariant mass