

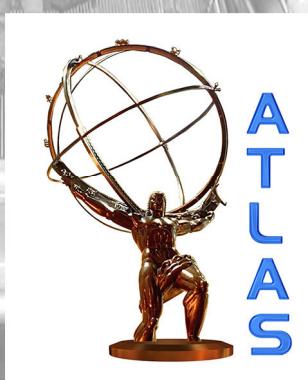
HY.P.A.T.I.A.

HYbrid Pupil's Analysis Tool
for Interactions in ATLAS

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ΕΘΝΙΚΟΝ & ΚΑΠΟΔΙΣΤΡΙΑΚΟΝ
ΠΑΝΕΠΙΣΤΗΜΙΟΝ ΑΘΗΝΩΝ



INTRODUCTION

The LHC – The Large Hadron Collider and ATLAS

The accelerator is located at CERN, in a tunnel at a depth of around 100m beneath the French-Swiss border near Geneva. The protons used in the experiments are accelerated in opposite directions in the underground circular accelerator which has a circumference of 27 km. Given the wide variety of research objectives of the LHC, 6 different types of detectors are placed in four caves around the four points of intersection of the beams,

Two of them (ATLAS and CMS) are large general purpose detectors, the other two (ALICE and LHCb) have specific goals, while the TOTEM and LHCf are much smaller and have much more specific purposes.

The ATLAS detector (A Toroidal LHC ApparatuS), which is the focus of this exercise, was designed to cover the widest possible range of investigations. Its main objectives are to discover the Higgs boson, to confirm (or not) the theory of supersymmetry, to study matter and antimatter, the formation of dark matter and to search for extra dimensions and new phenomena.

Involved in the experiment are 3000 physicists from 170 universities and laboratories in 37 countries

The detector with 44m length and 25m height is the largest in volume for any detector ever built (see **Figure 1**).

The size of the detector stems from the need for great accuracy in detecting the nature and trajectory of the particles resulting from the particle collisions.

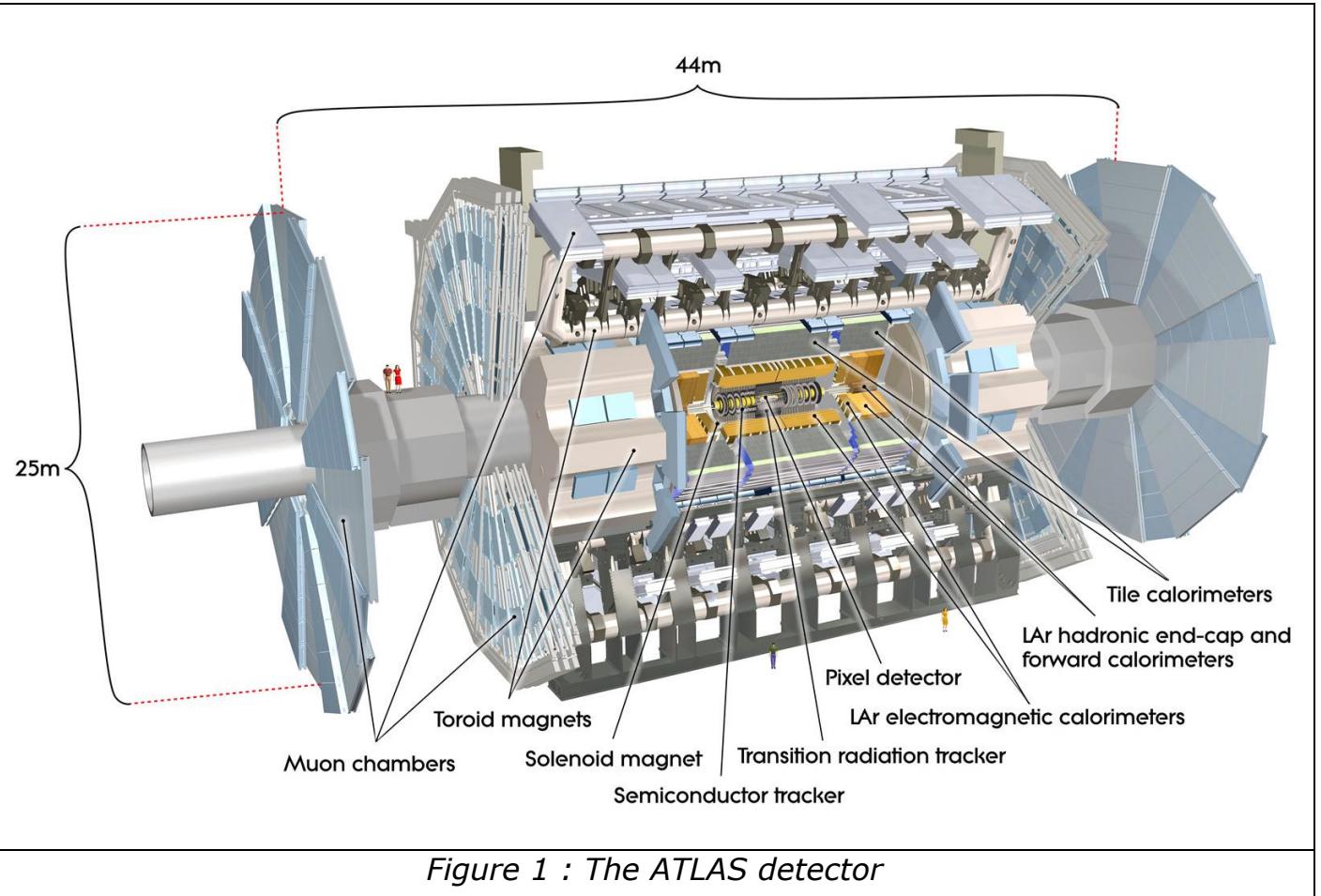


Figure 1 : The ATLAS detector

The sections of ATLAS

The ATLAS detector consists of a series of concentric cylinders mounted so that the beams collide in the center. The particles resulting from the collision pass through the detectors in turn and either stop at one of them or continue on their way out of the detector.

The different layers allow us to identify the particles and measure their direction, charge, momentum, energy, etc. An example of how different particles interact with different layers of the detector is shown in **Figure 2**.

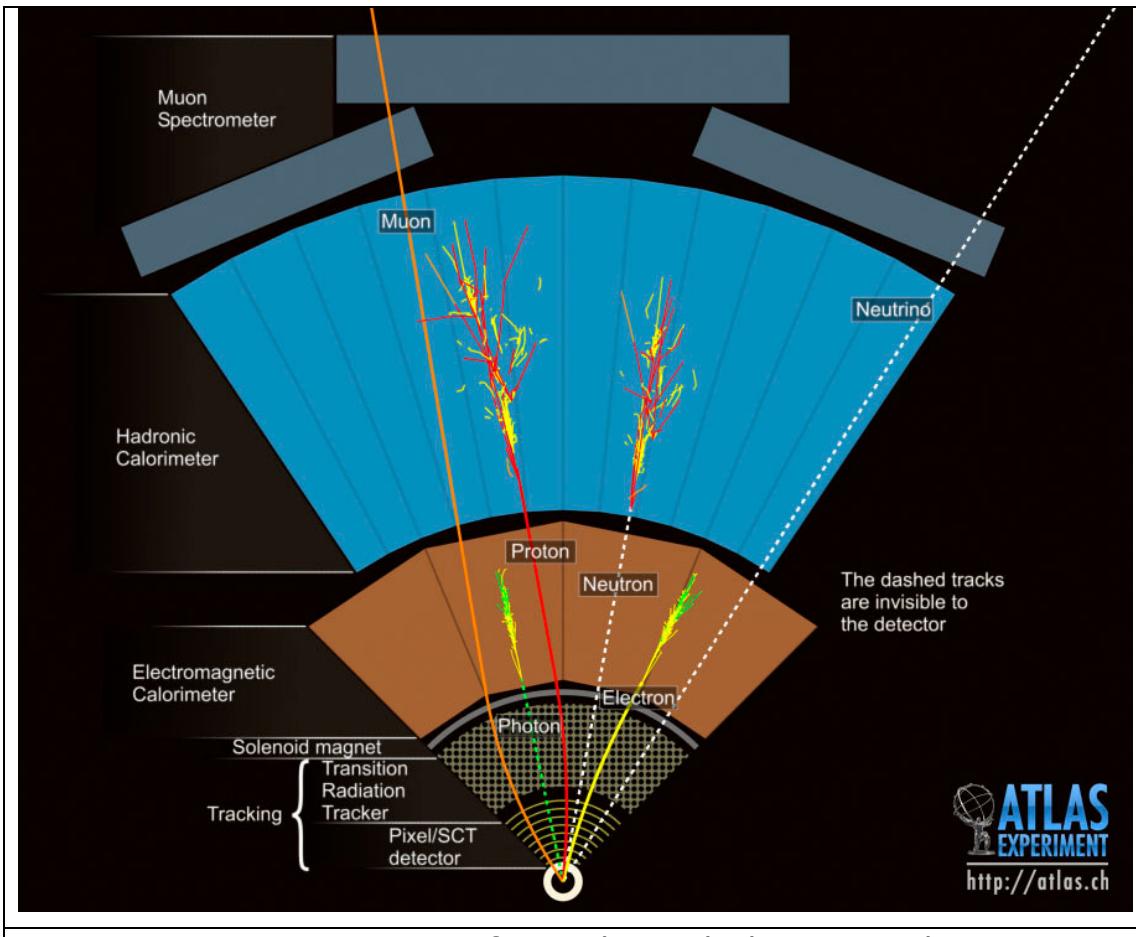


Figure 2 : Interaction of particles with the ATLAS detector

The individual detectors are four. **The tracking chamber, the electromagnetic calorimeter and the hadronic calorimeter, the muon chambers and the magnet system.**

During the exercise you will see various "events" that occur when there is a proton-proton collision. The events that you will examine are the result of collisions that produce many particles. Some of these particles have very short lifetimes and decay immediately into more stable particles. The collision products are not always detected (because there is incomplete coverage of the detector, gaps, etc.). In general however, the particles interact with the detector and produce traces in various parts. The traces are called "tracks". If all tracks come from the decay of the same particle, then they should meet in (i.e. come from) the same place, called vertex. Each particle leaves a different signature in the detector, as will be explained later.

Tracking Chamber

The detector is located in the center of the device and consists of three different sub-detectors, all designed to **detect charged particles**. The neutral particles (e.g. photons) pass through the detectors unnoticed. All charged particles interact with the detector, but exit with about the same energy and direction as before entering.



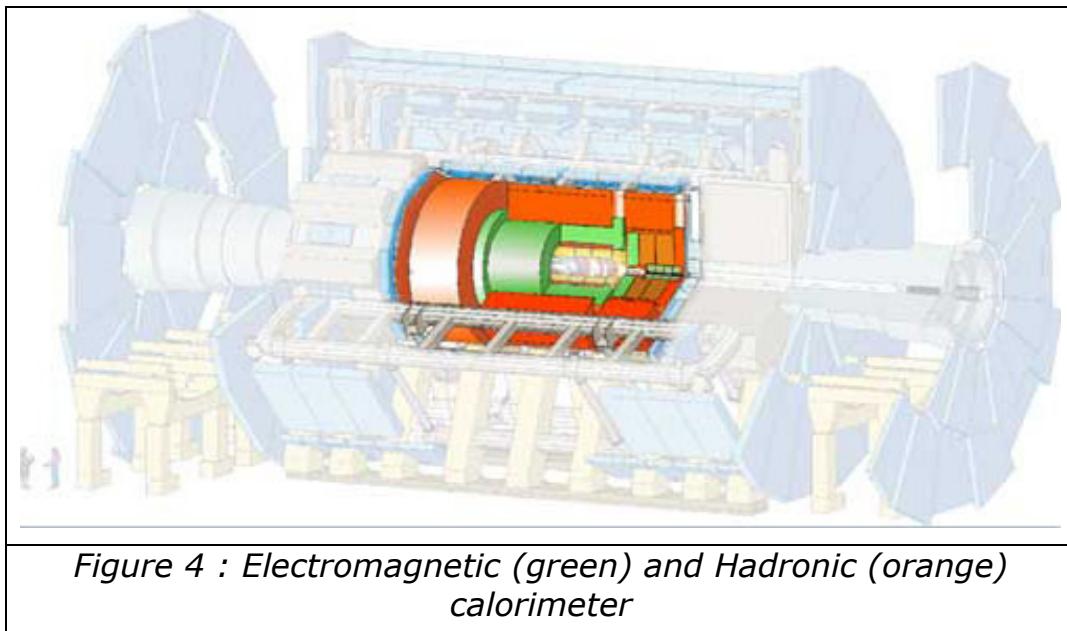
Figure 3 : Tracking Chamber

In the innermost part are high-resolution semiconductor detectors while the outer parts are gas detectors. All elements are mounted inside the central solenoid which creates a magnetic field with 2 Tesla intensity.

The internal diameter of the detector is 1.15 m while its total length is 7m.

Calorimeters

Calorimeters measure the energy of both charged and neutral particles. They consist of absorbers and active parts. The collision of particles with the absorbers creates a shower of secondary particles that are collected and recorded by the sensors. The energy of the initial particle in most cases is absorbed by the calorimeter. Because of this, the calorimeters are located outside the inner detector, so that the track of the charged particle is recorded before being absorbed by the calorimeter.



The ATLAS calorimeters consist of two different sections:

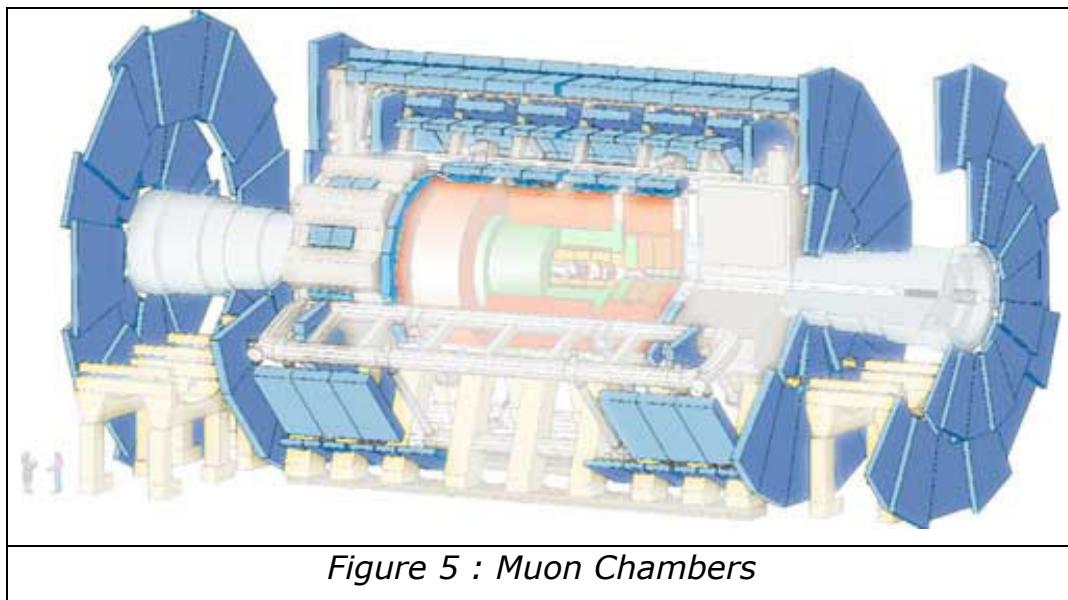
- The electromagnetic calorimeter (green area) in which the hadrons leave a small portion of their energy. In contrast, the electromagnetic calorimeter absorbs the full energy of e^+ , e^- and photons.
- The hadronic calorimeter (orange area) measures the total energy of hadrons (like protons, neutrons).

Only muons (and neutrinos) have the ability to penetrate the detector first, and then the calorimeters, leaving little energy, and continue to the muon chambers.

Muon Chambers

The muons are particles like electrons, but they are about 200 times heavier. They are the only charged particles that can pass through the calorimeters without losing very much and reach the muon chambers located in the outside layer of ATLAS. **The muon chambers measure the momentum and the trajectory of muons that cross them with great precision.**

The only particles that pass through ATLAS undetected are neutrinos.



The muon chambers consist of thousands of tubes which detect charged particles (the University of Athens alone built 30,000 tubes) positioned in the magnetic field created by huge superconducting toroidal coils.



Figure 6 : Muon chamber construction at the University of Athens

Magnet System

ATLAS uses two types of magnets, solenoid and toroidal with eight coils each. The detector is in a strong magnetic field which bends the trajectories of charged particles. The magnetic field generated by four different magnets: three toroidal (one large central and two smaller pieces in front) and a solenoid. Positively and negatively charged particles are curved in opposite directions from the same magnetic field. The radius of curvature and direction of the particles used to determine the momentum and the charge of particles.

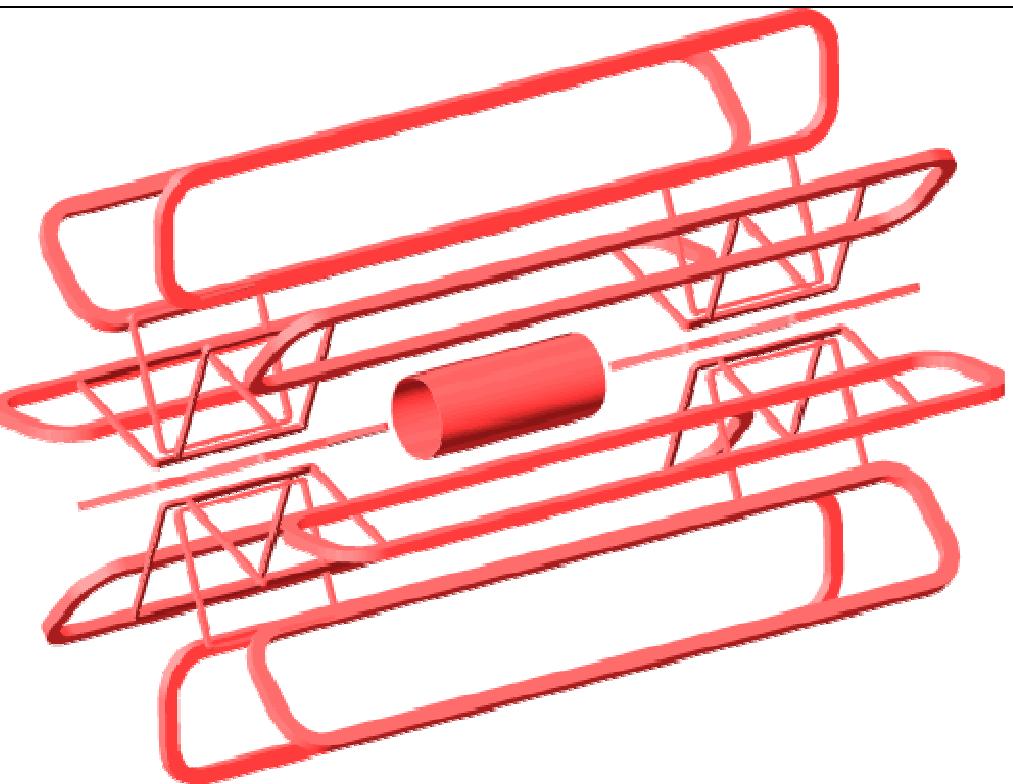
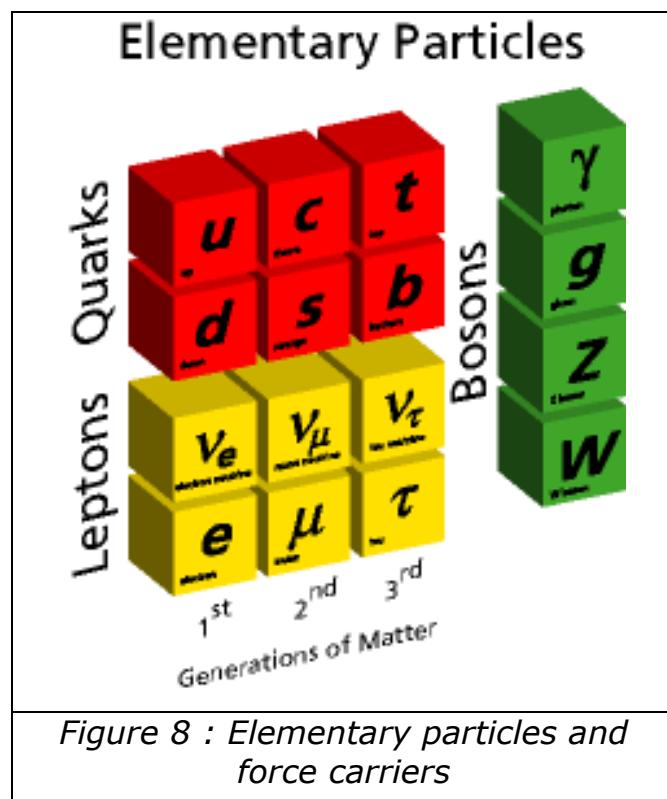


Figure 7 : The magnets used by ATLAS

What we currently know about the nature of subatomic particles and the forces that govern them

The following **figure 8** shows (on the left with red and yellow) all the known elementary particles today. According to the most successful theoretical model, the Standard Model, all particles can be described on the basis of the six quarks and six leptons that are the fundamental building blocks. The forces that govern the interactions of particles are four and are transmitted via the force mediating particles (the right column in figure 8).



The photon that has zero mass is the mediating particle of the electromagnetic force, the gluons (also massless) are the carriers of the strong interaction, the Z particles and W (which will be studied in this exercise), are the mediating particles of weak interactions. Finally the graviton for which we know very little, but it is different from other mediating particles, is gravity's mediating particle.

The Standard Model tries to describe with a similar mathematical formalism the first three forces, namely to unify the electroweak with the strong force. Also this model has allowed us to explain the existence of the different elementary particles that we have so far discovered. But there are questions which the Standard Model has not answered.

The first of the unanswered questions is the mechanism that gives mass to particles. Why do particles have the measured mass, and why do some not have mass?

The best explanation to date was given in 1964 by Peter Higgs, who assumed the existence of a particle, the boson which bears his name, which is the mediating particle of the Higgs field. This field gives mass to each particle it interacts with.

This particle along with the theories beyond the Standard Model are being investigated using the new LHC accelerator.

Particle Collision Products

Some particles are very short-lived and decay almost immediately to more stable particles. In most proton collisions, the protons have gentle interactions, and the majority of the particles continue in the direction of the original particles (rather than perpendicular to the beam). However, rarely few very massive particles are produced. If particles originate from the decay of a parent particle, their tracks should join together at the same original point, called a "vertex".

Most massive particle's decays often give rise to several high-energy particles going out at large angles, more or less perpendicular to the original protons in the beam. For this reason we measure the momentum, the transverse momentum (p_T), and we use it to pick up interesting events. By adding up the decay products which come from the same vertex we reconstruct the original "invisible" particle. In this exercise you will reconstruct the Z^0 particle which is the carrier of the weak force responsible for the energy from the sun and radioactivity.

Decay of Z bosons

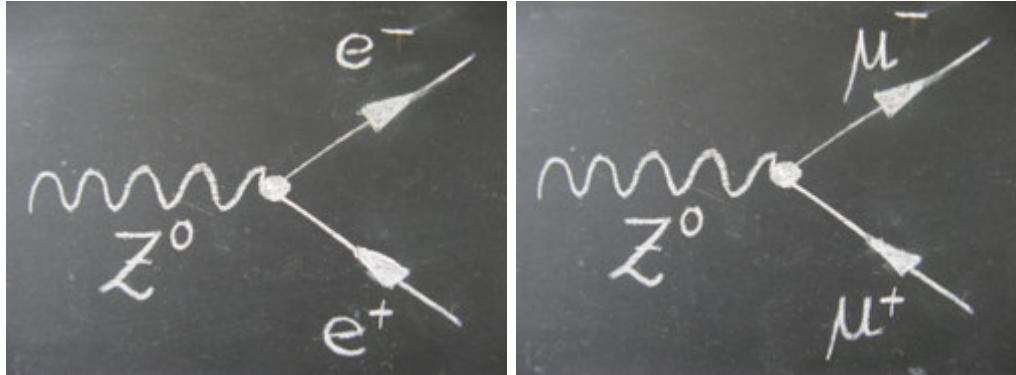
Since Z is neutral the sum of the charges of its decay products must be 0. This is because in nature charge is conserved.

Therefore Z must decay into a particle, antiparticle pair. The 100% probability of Z to decay is divided between groups of particles according to additional conservation laws.

- In 10% of the Z -decays, charged lepton-antilepton pairs are produced. The three possible charged lepton pair types are electron-positron, muon-antimuon, and tau-antitau pairs. Each pair is approximately equally probable. This gives 3 decay possibilities.
- The Z boson decays in 20% of the cases into a neutrino-antineutrino pair. Our detector is not capable of detecting neutrinos since they almost don't interact with anything (no electric charge). The neutrinos are therefore invisible to us and the only way we can "see" them is when we measure that there is some energy or transverse momentum missing after the collision (since we know

that both transverse momentum and energy should be conserved in the collision)

- In 70% of Z decays, a quark-antiquark pair is produced. These appear as particle showers called “jets” in the detector.



In your exercise you will have to deal only with Z decays into lepton pairs (electron – positron or muon – antimuon).

Decay of Higgs bosons

The Higgs boson was discovered by the ATLAS and CMS experiments in July 2012 with a mass ~ 125.5 GeV and published in Physics Letter B in September 2012. This concluded a nearly 50-year search, since Prof. Higgs and others introduced the Higgs mechanism to explain why the elementary particles Z and W have non-zero mass.

The Higgs bosons in the LHC are mainly produced by the “fusion of two gluons”, each one originating from each colliding proton, as shown below.

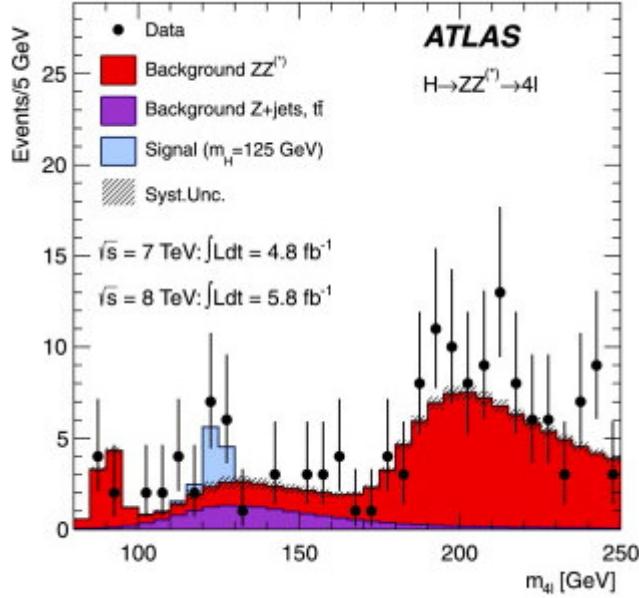


Higgs production in proton-proton accelerators by the fusion of two gluons

One of the easiest -to detect- decays of the Higgs boson is to a pair of Z bosons. Afterwards, each Z decays into two leptons of opposite charge but of the same flavor, so as observable final states we have the following:

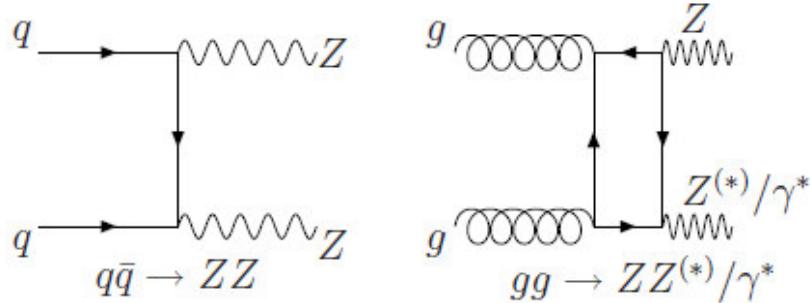
- $H \rightarrow 2 e^+ + 2 e^-$
- $H \rightarrow 2 \mu^+ + 2 \mu^-$
- $H \rightarrow e^+ + e^- + \mu^+ + \mu^-$

The figure below shows the invariant mass of the four leptons from data measurements, showing a peak at ~ 125 GeV (Higgs mass) along with the distribution of the background (calculated or estimated from data).



Four lepton mass

The background is primarily from the direct production of two Z , i.e. a ZZ pair which does not originate from Higgs resonance decays.



ZZ^* background production mechanisms

Because now we know that the Higgs boson has a mass less than the sum of the masses of the two Z , we say that it decays into a real Z and a "virtual" Z (Z^*).

For the exercise below we have elected to use events that include a superposition of two Z boson decays instead of real Higgs decays. This is done because there are easier to identify. Therefore, the mass of the "Higgs" bosons will be 180 GeV i.e. twice that of the Z boson.

Invariant Mass

The invariant mass is also called the "rest mass", and is characteristic of a particle. According to Einstein's theory, the invariant mass is a quantity which does not change with velocity or frame of reference. If the units are chosen in such a way that the velocity of light is $c=1$, then the invariant mass is defined as

$$m = \sqrt{E^2 - p^2}$$

where E is the energy and $p = m*v$ the momentum of the particle. To determine the invariant mass of a particle which decays almost instantaneously, one has to look at its decay products. One has to measure the energy and momentum of each decaying particle and then sum all their energies

$$E = E_1 + E_2 + E_3 + \dots$$

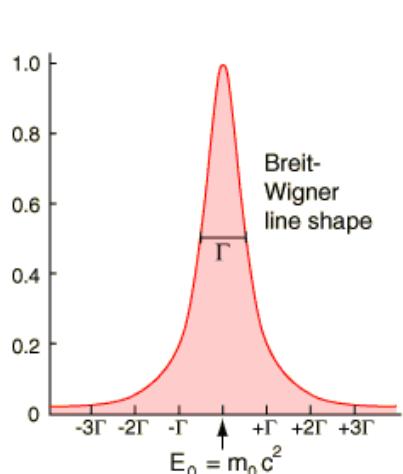
and their momenta

$$\vec{p} = \vec{p}_1 + \vec{p}_2 + \vec{p}_3 + \dots$$

The result is the invariant mass and if you are looking at one particle, then the mass calculated in each event should be "almost" the same, so if you make the distribution of masses for various events you will see a peak around the particle's mass.

Measurement of the width of a particle

If an extremely short-lived particle is produced in a high energy collision, Heisenberg's uncertainty principle:



$$\Delta E * \Delta t > \frac{\hbar}{2}$$

suggests that there will be a significant uncertainty in its measured energy (which means its invariant mass). The measurement of the invariant mass of an unstable particle gives a distribution (histogram) of masses called a Breit-Wigner distribution.

The width of this distribution at half-maximum is labeled Γ , $\Gamma=1/\tau$, where the particle lifetime τ is taken as the uncertainty

in time $\tau = \Delta t$. Γ is often referred to as the "natural line width" gives very valuable information and has to be measured. As an example we quote that the measurement of the width of the Z particle in LEP (CERN's previous big accelerator which was replaced by LHC) gave a very good determination of the number of different neutrino types which exist.

Missing Transverse Momentum

This is the momentum/energy which is not detected in the detector, but is expected because of energy and momentum conservation in the transverse plane.

The ETMiss is generally attributed to particles which escape the detector without being detected such as the neutrinos (although apparent missing energy may be caused by mismeasurement of the momentum/energy of detected particles).

In LHC, the initial momentum of the colliding constituents along the beam axis is not known (because the energy of each hadron is split, and constantly exchanged, between its constituents), so the amount of missing energy cannot be determined. However, the initial energy and momentum in a plane transverse to the beam axis is zero, so any net momentum indicates missing transverse momentum/energy (ETMiss). It is represented (in the event display) with a dashed red line which in addition to the value (which is the magnitude of the transverse missing momentum/energy) shows the direction of the missing transverse momentum vector.

Laboratory Exercises

For this part you will use real events that were collected by the ATLAS experiment. Among the events from the ATLAS detector, there are some which contain decays of the Z particle (The Z itself can not be seen because it has a very short lifetime and decays immediately). In this exercise you are looking for Z decays into electron – positron or muon – antimuon pairs. You have to distinguish these events from other events called background events.

The proton-proton collisions produce too many particles, and at a very fast pace: 40 million events / sec. Very few of those events are interesting and the experiment uses selections (triggers) to record only the events of interest at a rate of 200 events / sec.

Besides the $Z \rightarrow \mu^+ \mu^-$ events, in the sample there are also events in which the muons come from quark decays and also events where the muons come from cosmic rays.

- The quark decay muons are **not** isolated (they are in jets of particles) and often they are accompanied by missing energy in the transverse plane (ETMiss) because the leptons are accompanied by neutrinos in order to preserve the lepton number.
- The muons coming from cosmic rays appear as two tracks as they cross the detector from side to side. The "two" reconstructed tracks in reality are one, the angle formed between them is 180° and they are seen to pass far from the point of interaction, which is the beginning of most of the other tracks.

- The leptons from the Z decays should have high transverse momentum so that the sum of the transverse momenta gives at least roughly half the mass of the Z. Whether two tracks belong to the same Z (which must be also have opposite charge) can be checked by putting the tracks (double click) in the "Invariant Mass Window" table where the relativistic invariant mass of those tracks is calculated.
- The mass should be around 91.2 GeV which is the mass of the Z, but which has a range of few GeV derived firstly from the natural width of the particle and secondly from the resolution of the detectors.

The mass can also be calculated directly from the known relativistic formula

$$m = \sqrt{E^2 - \vec{p}^2}$$

Where E is the total energy

$$E = \sum_i E_i$$

And p the total momentum

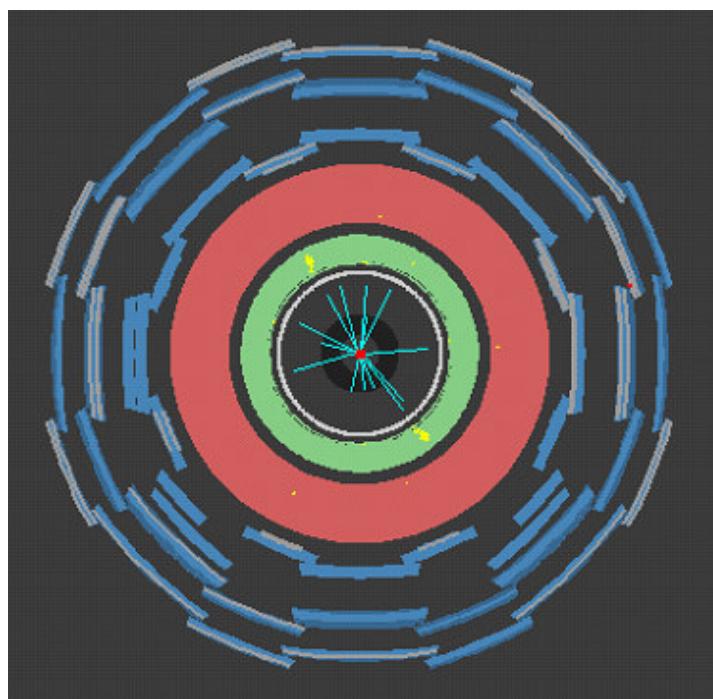
$$p = \sum_i p_i$$

Exercise 1

For the first exercise you need to select 'Group_1' from the first drop down box which contains the first event group.

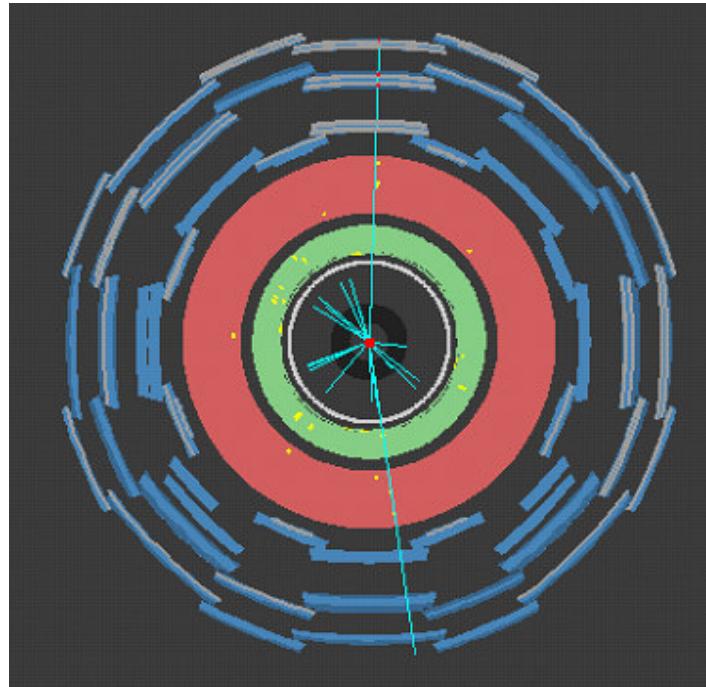
eV	Group	eta [rad]
1	Group_1	0.888
4	Group_2	-1.04
7	Group_3A	-0.70
9	Group_3B	-0.84
9	Group_3C	1.594
93	Higgs	0.801
93	Conservation	-2.08
93	B_Field	21.83
78	Applet_events_2012	0.769
9		-1.30
90		2.212

This group contains 10 events. The first 5 are from Z decays into electron – positron pairs and the other 5 are Z decays into muon – antimuon pairs. Let's see some examples of electron tracks.



Electron tracks are shown as short lines at the center of the detector, since electrons stop at the electromagnetic calorimeter (green area) and deposit their energy there (yellow marks).

Muons, on the other hand, are the only particles (which can be seen) to reach the muon chambers (blue area) and are shown as long lines. Neutrinos can also pass through all layers of the detector as they are not absorbed by any of its sections, but they can not be detected directly, so they are not shown.



Exercise 2

For this exercise you need to select the 'Askisi_2' group of events. This group contains 10 events from Z decays as the previous exercise, but this time they are mixed. You need to identify which events belong to each group and complete the following table.

Exercise 3

For this exercise you need to select the 'Askisi_3' group. This contains 50 events which are either Z decays into electron – positron or muon – antimuon pairs, or background events which come from other sources (cosmic rays, different Z decays, decays of other particles etc).

You need to identify which of these events contain Z decays into electron – positron or muon – antimuon pairs. Then you need to insert those two tracks from each event into the invariant mass table (look at column m_{\parallel}) and thus create a histogram of the invariant mass of the Z boson. Background events are simply ignored in this process.

The criteria that you will need to make your selections are:

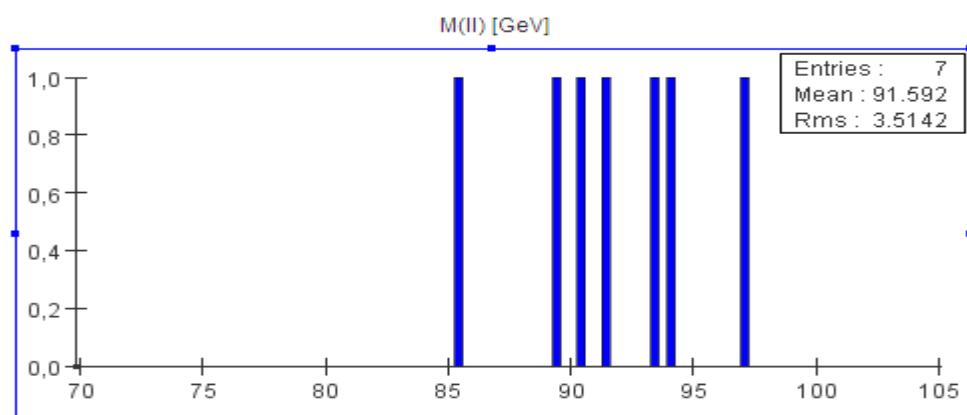
$$Z \rightarrow \mu^+ + \mu^- \quad Z \rightarrow e^+ + e^-$$

- 2 tracks with opposite charges
- Invariant mass of 91,2 GeV
- Small ETMiss <10 GeV

Background events

- Usually contain only one lepton ($W \rightarrow \text{lepton} + \nu$ decays)
- Cosmic rays : opposed tracks on both views
- Large ETMiss (existence of neutrinos)

Below is an example of a histogram which is made up of Z boson decays. The center of the histogram is around 91,2 GeV which is the invariant mass of the Z and as the number of events which are included increases, the histogram approaches the Breit-Wigner distribution as we mentioned



Exercise 4

For this exercise you need to select the ‘Higgs’ group. This contains 10 events, 3 of which are Higgs decays into Z and the other are background events. Each Higgs decays into two Z and each of those to two leptons. So the available Higgs decays are:

- $H \rightarrow 2 e^+ + 2 e^-$
- $H \rightarrow 2 \mu^+ + 2 \mu^-$
- $H \rightarrow e^+ + e^- + \mu^+ + \mu^-$

Using the previous criteria you need to identify the 3 Higgs decays and add their tracks (four from each event) into the invariant mass tale. This will calculate their mass at column m_{III} and the corresponding histogram. The events used in this exercise are not real.

HYPATIA web application

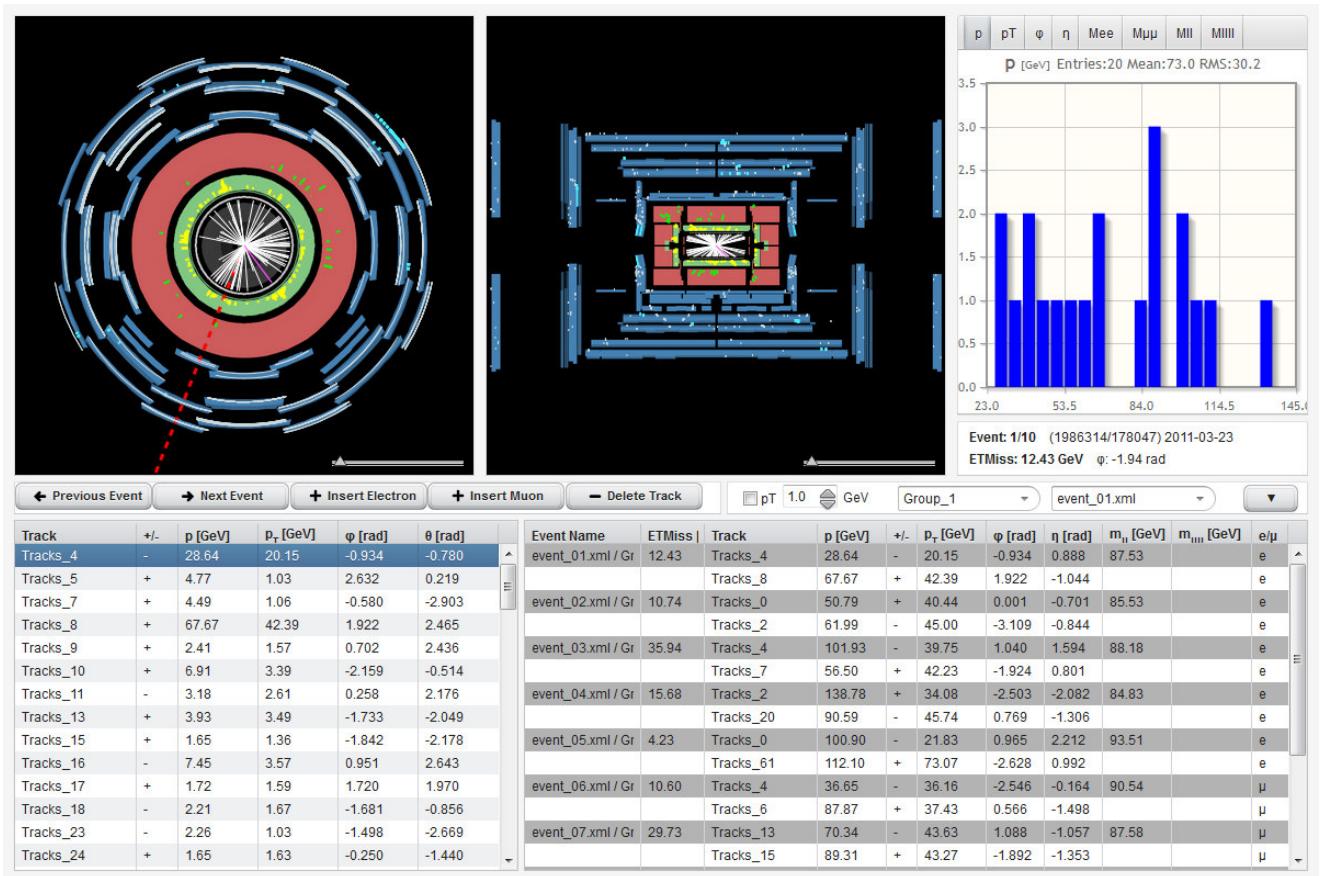
To use the web application you need to use a browser and navigate to:

<http://hypatia.iasa.gr/>

From there you can choose the language that you want to use as well as the version of the webapp that you need. In our case you need webapp 4.

When the webapp is first loaded, it displays the first of the available events. The tracks belonging to this event are listed in the table at the middle of the screen (Track Table). The two detector views show the front and side view of the ATLAS detector. Next to them are the histograms of the user selected tracks (empty for now). The bottom part of the webapp (Invariant Mass Table) lists the user selected tracks with their corresponding invariant masses (empty for now).

The user can interact with the webapp using the buttons and controls that are available. He can also click on the tables to highlight the desired track, or click on the detector displays to pick a track.



Select an event

The user can select the event that he wants to view either by using the "Previous/Next" buttons or by selecting it from the drop-down list. The number of the selected event along with the total number of available events is displayed to the left of the list. Next to this, the missing energy (ETMiss) of the event is also displayed.

Pick a track

When the user clicks on a track (white line) on either of the two detector views the track is selected on both views with purple color. The corresponding line on the Track table is also selected.

The reverse is also true. Selecting a track on the Track table also selects it on both detector views.

If the track is inserted into the Invariant Mass table then it is selected there as well.

Insert track

Since the user is trying to "discover" the Z particle from its decays into pairs of muon/antimuon or electron/positron he has to insert the selected track into the Invariant Mass table as either electron/positron by clicking the "insert electron" button or muon/antimuon by clicking the "insert muon" button. Of course in order to do that, electron and muon tracks have to be recognized first in the previous step.

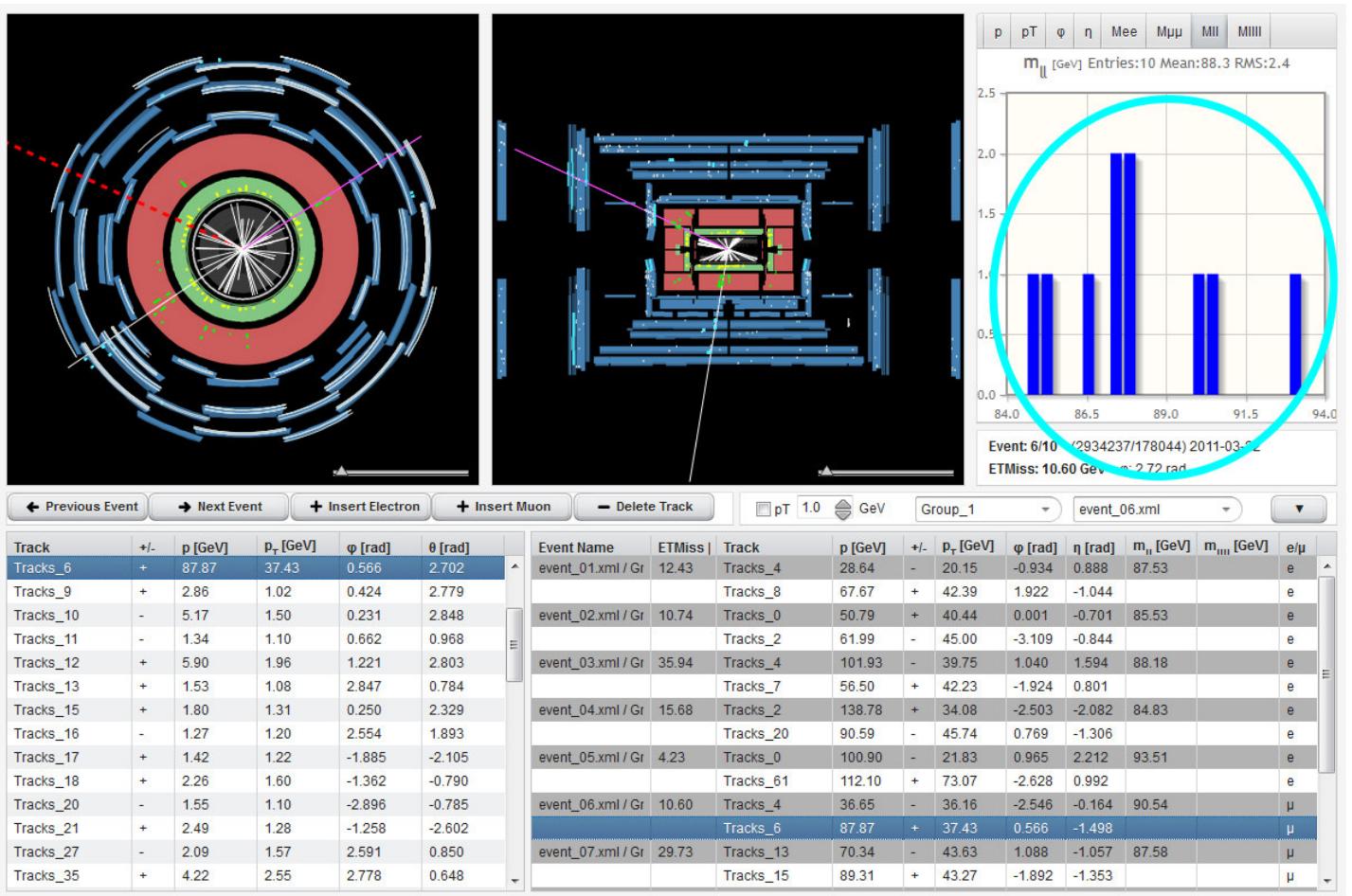
By clicking the appropriate button, the selected track is copied into the Invariant Mass table and when two compatible tracks (either both electron tracks or both muon tracks) are inserted from the same event, their Invariant Mass is calculated automatically.

Another valid combination, dedicated to the Higgs discovery, is two electron tracks and two muon tracks or four electron or four muon tracks. Only four tracks from each event can be inserted and each track can only be used once. The user can remove a track by selecting it and clicking on the "Delete track" button.

The histograms with the tracks that are inserted into the Invariant Mass table are also updated automatically. When the user clicks on a track on the Invariant Mass table the corresponding event is automatically loaded and the track is selected on both the Track table and the Detector Views.

Histograms

The histograms corresponding to the tracks of the Invariant Mass table are always automatically calculated when the user inserts or removes a track.



The first three histograms represent the Energy, Transverse Energy and θ angle distribution of the tracks. The next two show only the Invariant Masses calculated from Electron or Muon tracks. The next displays all Invariant Masses of pairs of tracks regardless of their type and the last histogram shows the Invariant Mass of groups of four tracks (either four electrons, four muons or two electrons and two muons).

Cuts

Cuts are limits the user can place on the displayed tracks.

The user can select the threshold of energy of the displayed tracks. By checking the checkbox and entering a value into the corresponding field the user can remove all tracks whose energy is below the limit. Note that after entering the value, Enter must be pressed.

This can be very helpful in events with a large number of tracks where usually the low energy tracks are of no interest.

Zoom

The user can change the zoom level to get a better view of the tracks. This can be done by dragging the zoom slider. Each view can be zoomed to a different level.

Zooming can be very helpful in events with a large number of tracks that overlap.