

MINERVA Masterclass

Teachers Manual

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Fundamental Particles - theoretical background of using Minerva for teachers

1. Standard Model of Fundamental Particles
2. Fermions and Bosons
3. Brief Description of Fermions
4. Brief Description of Bosons
5. Decay of W and Z bosons
6. Missing Energy
7. The Higgs Boson

1. Standard Model of Fundamental Particles

The Standard Model of particle physics is a theory of three of the four known fundamental interactions and the elementary particles that take part in these interactions. These particles make up all visible matter in the Universe.

Every high energy physics experiment carried out since the mid-20th century has eventually yielded findings consistent with the Standard Model. Still, the Standard Model falls short of being a complete theory of fundamental interactions because it does not include gravity or dark matter. It isn't quite a complete description of leptons either, because it does not describe nonzero neutrino masses.

2. Fermions and Bosons

All observed particles are either fermions or bosons.

In particle physics, fermions are particles which obey Fermi-Dirac statistics, bosons are particles which obey Bose-Einstein statistics.

Fermions have half-integer spin, bosons have integer spin.

Fermions respect the Pauli Exclusion Principle: only one fermion can occupy a quantum state at a time. In contrast to fermions, several bosons can occupy the same quantum state. Thus, bosons with the same energy can occupy the same

place in space. Therefore bosons are often force carrier particles while fermions are usually associated with matter.

In the Standard Model there are two types of elementary **fermions**: quarks and leptons. In total, there are 24 different fermions; 6 quarks and 6 leptons, each with a corresponding antiparticle:

- **12 quarks** - 6 particles ($u \cdot d \cdot s \cdot c \cdot b \cdot t$) with 6 corresponding antiparticles ($\bar{u} \cdot \bar{d} \cdot \bar{s} \cdot \bar{c} \cdot \bar{b} \cdot \bar{t}$);
Quarks make up protons, neutrons and other baryons, which are composite fermions; they also comprise mesons, which are composite bosons. Composite fermions, such as protons and neutrons, are essential building blocks of matter.
- **12 leptons** - 6 particles ($e^- \cdot \mu^- \cdot \tau^- \cdot \nu_e \cdot \nu_\mu \cdot \nu_\tau$) with 6 corresponding antiparticles ($e^+ \cdot \mu^+ \cdot \tau^+ \cdot \bar{\nu}_e \cdot \bar{\nu}_\mu \cdot \bar{\nu}_\tau$).

Forces in physics are the ways that particles interact and influence each other. The standard model explains forces as resulting from matter particles exchanging other particles, known as force mediating particles. When a force mediating particle is exchanged, at a macro level the effect is equivalent to a force influencing both of them, and the particle is therefore said to have been the agent of that force. Force mediating particles are believed to be the reason why the interactions between particles observed in the laboratory and in the universe exist. In the Standard Model, there are four **bosons**: photon, gluon, Z-boson, and W-bosons.

Three Generations of Matter (Fermions)				
	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	u up	c charm	t top	γ photon
Quarks	4.8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ d down	104 MeV $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4.2 GeV $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 g gluon
	$\ll 2.2$ eV 0 $\frac{1}{2}$ ν_e electron neutrino	$\ll 0.17$ MeV 0 $\frac{1}{2}$ ν_μ muon neutrino	$\ll 15.5$ MeV 0 $\frac{1}{2}$ ν_τ tau neutrino	91.2 GeV 0 1 Z weak force
	0.511 MeV -1 $\frac{1}{2}$ e electron	105.7 MeV -1 $\frac{1}{2}$ μ muon	1.777 GeV -1 $\frac{1}{2}$ τ tau	80.4 GeV ± 1 1 W weak force
Leptons				Bosons (Forces)

Weakly interacting fermions can also display bosonic behaviour, as in superconductivity.

3. Brief Description of Fermions

In the Standard Model, fermions are defined as elementary particles having half-integer spin, and that respect the Pauli Exclusion Principle. They are classified according to how they interact - in other words, by what charges they carry.

Fermions						
	Charge	First <u>generation</u>		Second generation		Third generation
Quarks	$+\frac{2}{3}$	Up	u	Charm	c	Top
	$-\frac{1}{3}$	Down	d	Strange	s	Bottom
Leptons	-1	Electron	e^-	Muon	μ^-	Tauon
	0	Electron neutrino	ν_e	Muon neutrino	ν_μ	Tauon neutrino

There are six quarks (up, down, charm, strange, top, bottom), and six leptons (electron, muon, tauon, and their corresponding neutrinos).

The defining property of the **quarks** is that they carry color charge, and hence, interact via the strong force. The infrared confining behavior of the strong force results in quarks being perpetually (or at least since very soon after the start of the Big Bang) bound to one another, forming color-neutral composite particles (hadrons) containing either a quark and an antiquark (mesons) or three quarks (baryons). The familiar proton and the neutron are the two baryons having the smallest mass. Quarks also carry electric charge and weak isospin. Hence they interact with other fermions both electromagnetically and via the weak nuclear interaction.

The remaining six fermions do not carry color charge and are called **leptons**. The three neutrinos do not carry electric charge either, so their motion is directly influenced only by the weak nuclear force, which makes them notoriously difficult to detect. However, by virtue of carrying an electric charge, the electron, muon and the tauon interact electromagnetically.

Each member of a generation has greater mass than the corresponding particles of lower generations. The first generation charged particles do not decay; hence all ordinary (baryonic) matter is made of such particles. Specifically, all atoms consist of electrons orbiting atomic nuclei ultimately constituted of up and down quarks. Second and third generations charged particles, on the other hand, decay with very short half lives, and are observed only in very high-energy environments. Neutrinos of all generations also do not decay and pervade the universe, but rarely interact with baryonic matter.

4. Brief Description of Bosons

In the Standard Model, bosons are defined as elementary particles having integer spin.

Bosons				
Electromagnetic Force		Weak Nuclear Force		Strong Nuclear Force
Photon	γ	W^+ , W^- , and Z Bosons	W^+ , W^- , Z	8 Gluons

Two kinds of **W bosons** exist with +1 and -1 elementary units of electric charge; the W^+ is the antiparticle of the W^- . The **Z boson** is electrically [neutral](#) and is its own antiparticle. All three particles are very short-lived with a mean life of about 3×10^{-25} s.

All three types have a spin of 1. The emission of a W^+ or W^- boson either raises or lowers the electric charge of the emitting particle by 1 unit, and alters the spin by 1 unit. At the same time a W boson can change the generation of the particle, for example changing a strange quark to an up quark. The Z boson cannot change either electric charge nor any other charges (like strangeness, charm, etc.), only spin and momentum, so it never changes the generation or flavour of the particle emitting it.

These bosons are heavyweights among the elementary particles. With a mass of $80.4 \text{ GeV}/c^2$ and $91.2 \text{ GeV}/c^2$, respectively, the W and Z particles are almost 100 times as massive as the proton. The masses of these bosons are significant because they act as force carriers; their masses thus limit the range of the weak interaction.

Photon is the force carrier for the electromagnetic force. The photon has no rest mass; this allows for interactions at long distances.

The **gluon** has a spin of 1. In theory, gluons have zero mass (experiment limits the gluon's mass to less than a few MeV). The gluon is its own antiparticle. There are eight independent types of gluons.

The strong force is thought to be mediated by gluons, acting upon quarks, antiquarks, and the gluons themselves. This is detailed in the theory of quantum chromodynamics (QCD).

5. Decay of W and Z bosons

The W and Z bosons decay to fermion-antifermion pairs.

- **W bosons** can decay to a lepton and a neutrino or to an up-type quark and a down-type quark. The W cannot decay to the higher-mass top quark.
- **Z bosons** decay into a fermion and its antiparticle.

6. Missing Energy

Missing energy refers to energy which is not detected in a particle detector, but is expected because of conservation of energy and conservation of momentum. For example, if an electron and a positron collide head-on at equal speeds in the lab frame, any net momentum of outgoing particles indicates missing energy in the opposite direction. Missing energy is generally attributed to particles which escape the detector without being detected

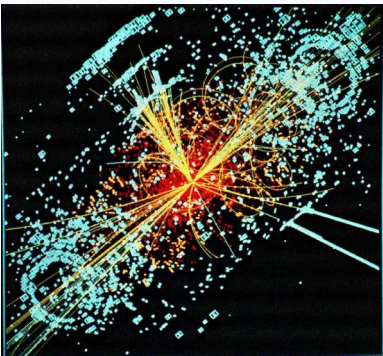
7. The Higgs boson

The Higgs particle is a massive elementary particle predicted by the Standard Model. It has no intrinsic spin, and for that reason is classified as a boson. The Higgs boson is its own antiparticle.

Because an exceptionally large amount of energy and beam luminosity are required to create a Higgs boson in high energy colliders, it is the only fundamental particle predicted by the Standard Model that has yet to be observed.

The Higgs boson plays a unique role in the Standard Model, by explaining why the other elementary particles, the photon and gluon excepted, are massive. In particular, the Higgs boson would explain why the photon has no mass, while the W and Z bosons are very heavy. Elementary particle masses, and the differences between electromagnetism and the weak force, are critical to many aspects of the structure of microscopic matter. In electroweak theory, the Higgs boson generates the masses of the fermions.

As yet, no experiment has directly detected the existence of the Higgs boson, but there is some indirect evidence for it. It is hoped that the Large Hadron Collider at CERN will confirm the existence of this particle.



A simulated event at the LHC. This simulation depicts the decay of a Higgs particle following a collision of two protons in the CMS experiment.

PARTICLE DETECTION

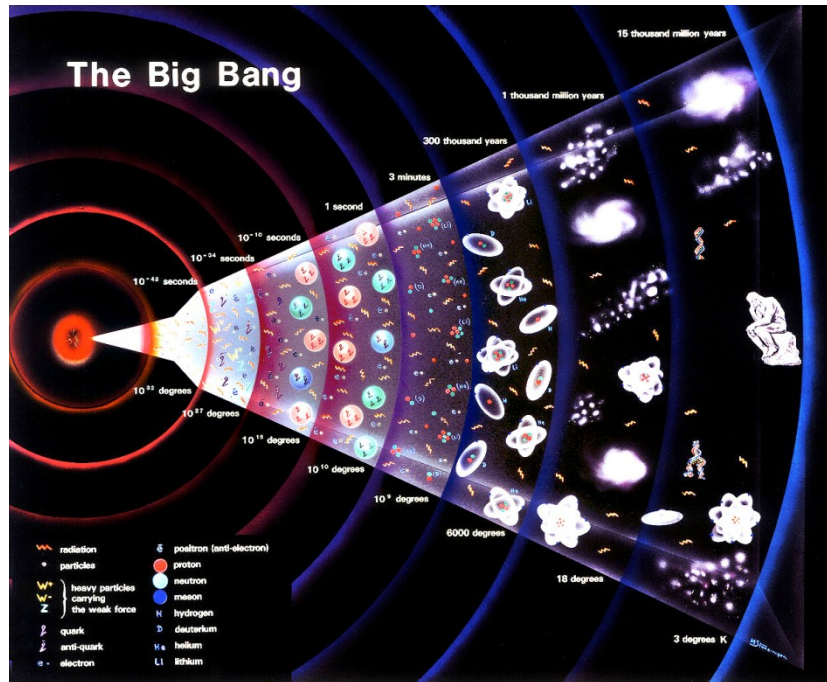
1. Introduction
2. Experiments
3. ATLAS detector

1. Introduction

Scientists at CERN do research on elementary particles. They do it for a better understanding of the (evolution of the) universe. In more detail, they hope to find the answers for the following questions:

- The Standard Model does not give any information about the masses of the elementary particles. Theoretical physicists described the answer to that question: the Higgs boson. But... does the Higgs boson exist?
- 95% of our universe is made of dark matter. But... what is dark matter?
- Theoretical physicists think our universe is symmetric. This means that there is an equal amount of matter and anti-matter. But... where has the anti-matter gone to?
- The previous symmetry raises another questions: if there is symmetry, also quarks should have a symmetrical partner (the “squarks”). But... is this true?
- Leptons and quarks are said to be fundamental particles. But... is this all there is?
- There are three “generations” of leptons and quarks. But... is this all there is?
- There are four forces: the strong force, the weak force, the electromagnetic force and gravity. The weak force and the electromagnetic force were already unified into the electroweak force. But... can we unify these other forces into one Grand Unified Theory?
- We live in a three dimensional space. Theoretical physicists applying String Theory think there must be more dimensions. But... is this true?

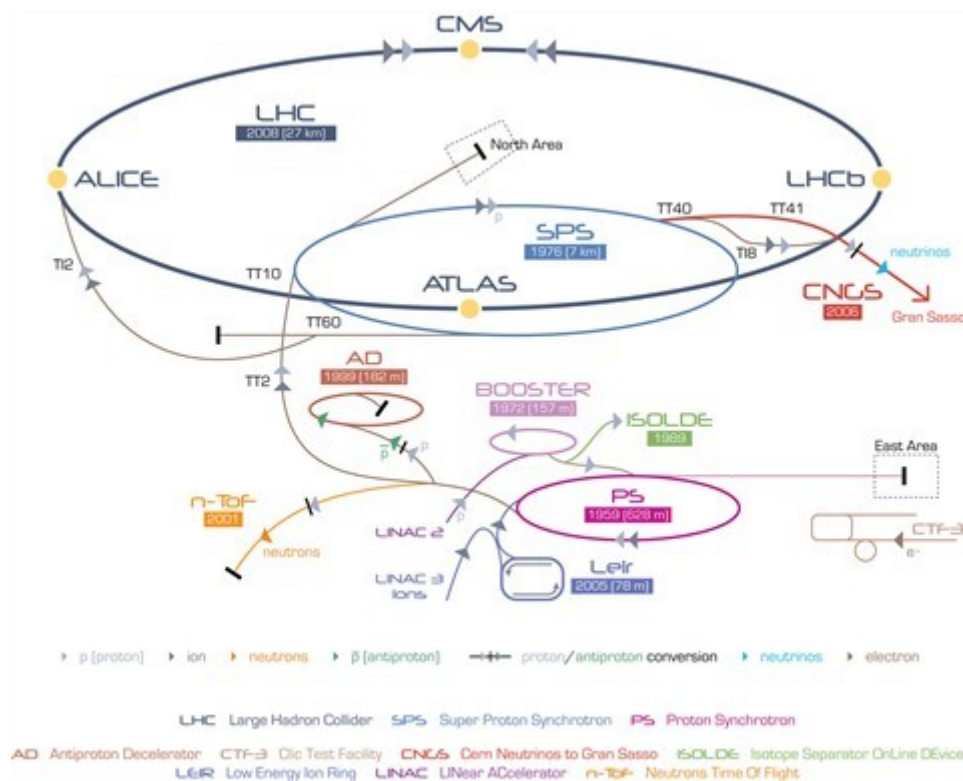
Scientists at CERN hope to find the answers experimentally. Therefore they use particle accelerators and particle detectors. To find the answers to these questions, they have “to go back in time” towards 10^{-25} seconds after the Big Bang. By then, the universe had a radius of 300 000 000 km and a temperature of $10^{17} \text{ }^{\circ}\text{C}$.



They constructed a particle accelerator for this purpose: the Large Hadron Collider. This circular accelerator has a circumference of 27 km and is therefore the largest accelerator on earth. It is located 100 m below surface at CERN (mostly under Switzerland and partly under France).

The accelerator will work with two parallel beams of protons that will travel in opposite directions. To keep the beams in the desired locations, the accelerator is using 1624 magnets. These magnets have a magnetic field of 8.33 Tesla and they require a current of 11,700 Ampère (this is 117 times more than the average total current for a family house). The materials have to be superconductive (this means that their resistance should be nearly 0 Ohm below a certain temperature), hence there is an operational temperature of -271.3°C . This results in an energy of 7 TeV (7 000 000 000 000 eV, this equals the kinetic energy at 99.999,999,1% of the speed of light) for the protons to collide. This results in the conditions of 10^{-25} seconds after the Big Bang.

To reach this huge amount of energy, the particles are accelerated in multiple accelerators before entering the Large Hadron Collider.



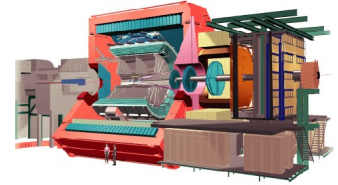
- Hydrogen atoms are taken from a hydrogen bottle. The orbiting electrons are stripped of the atom. The protons remain. This is done in LINAC2 at an energy of 50 MeV.
- The beam is then injected into the PS Booster [PSB]. The booster accelerates the beam to an energy of 1.4 GeV.
- The beam is then injected into the Proton Synchrotron [PS]. This accelerates the beam to an energy of 25 GeV.
- The beam is then injected into the Super Proton Synchrotron [SPS]. This accelerates the beam to an energy of 450 GeV.
- Finally the beam is transferred into the Large Hadron Collider [LHC]. The beams go in both clockwise and anticlockwise directions, where they are accelerated to 7 TeV. (This takes about 20 minutes.)

2. Experiments

There are six experiments installed at the Large Hadron Collider:

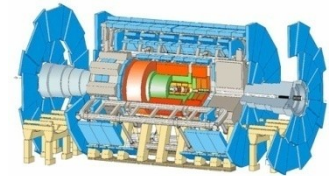
- **ALICE: A Large Ion Collider Experiment**

ALICE is a detector specialized in analysing lead ion collisions. It will study the properties of quark-gluon plasma. This is a state of matter where quarks and gluons are no longer confined inside hadrons. This state existed just after the Big Bang, before protons and neutrons were formed.



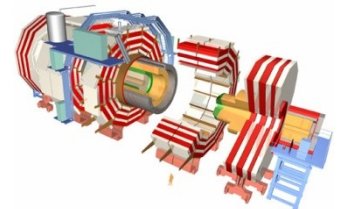
- **ATLAS: A Toroidal LHC ApparatuS**

ATLAS is a general purpose detector designed to cover the widest possible range of physics at the Large Hadron Collider. It will search for the Higgs boson, supersymmetry and extra dimensions.



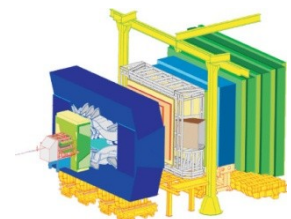
- **CMS: Compact Muon Solenoid**

CMS is a general purpose detector that will do the same research as ATLAS. The difference between ATLAS and CMS are their technical solutions and their design.



- **LHCb: Large Hadron Collider beauty**

LHCb is a detector specialized in the study of the slight asymmetry between matter and antimatter that is present in interactions of b-particles. These particles contain the bottom/beauty-quark.



- **LHCf: Large Hadron Collider forward**
LHCf is a small specialized experiment that will measure particles that are produced very close to the direction of the beams. LHCf will only work for the proton-proton collisions.

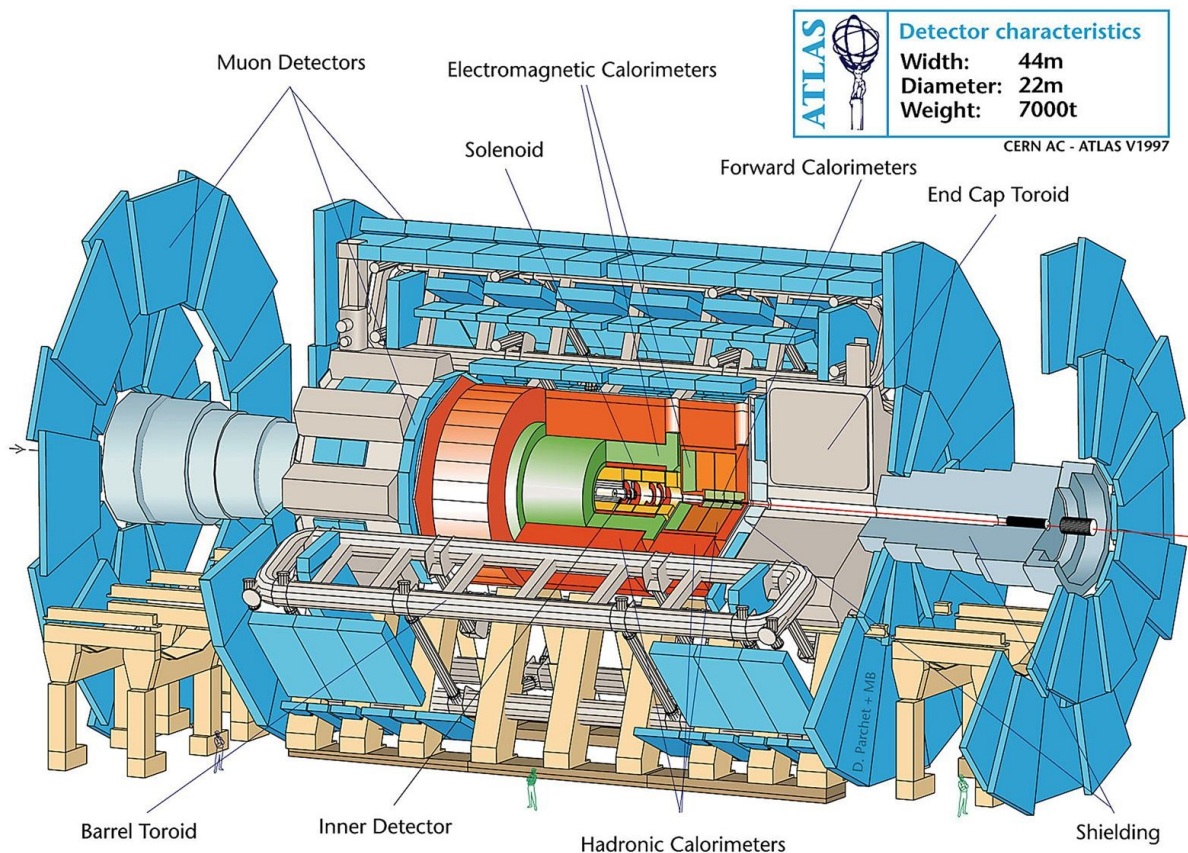
This experiment will be installed near the ATLAS experiment.

- **TOTEM: TOTal Elastic and diffractive cross section Measurement**
TOTEM is a small specialised experiment that will measure the size (cross-section) of the proton at the LHC.

This experiment will be installed near the CMS experiment.

3. Atlas detector

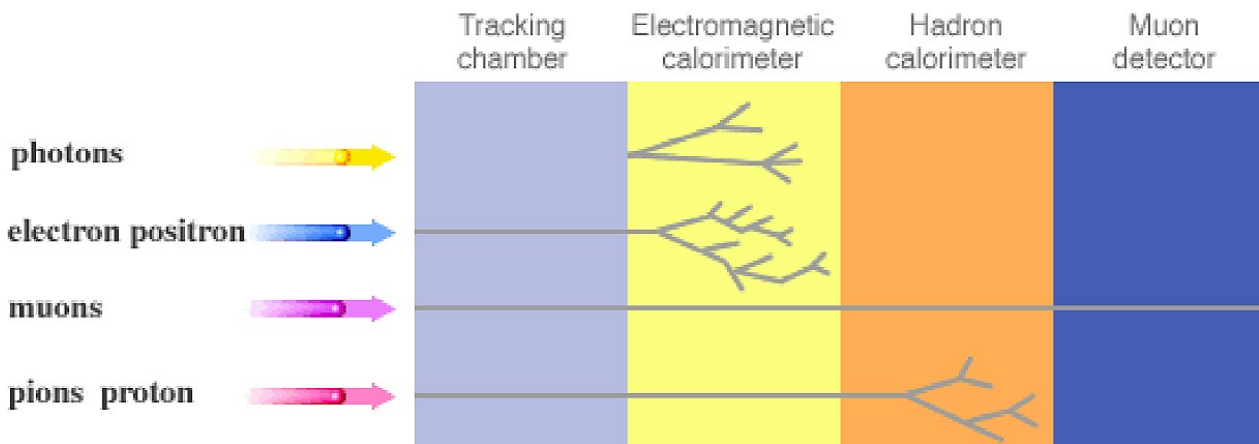
ATLAS is a general purpose detector designed to cover the widest possible range of physics at the Large Hadron Collider. It will search for the Higgs boson, supersymmetry and extra dimensions. The collaboration consists of more than 1,900 members from 164 institutes in 35 countries.



The ATLAS detector consists of four major components:

- The inner tracker (yellow) measures the momentum of the charged particles. This is done by measuring the curvature in the magnetic field.
- The calorimeters (orange and green) measure the energies of the particles. This is done by the light amount and the penetration depth.
 - The electromagnetic calorimeter (orange) measures the energies carried by particles that interact via the electromagnetic interaction.
 - The hadron calorimeter (green) measures the energies carried by particles that interact via the strong nuclear force.
- The muon spectrometer (blue) identifies and measures the momentum of the muons. This is done by measuring the curvature in the magnetic field.
- By measuring the missing energy, they can calculate the existence and the properties of the undetected neutrinos.

Which particle will be detected by which part of the ATLAS detector?



- All charged particles leave tracks in the tracking chamber.
- Neutral particles (like a photon) can deposit energy in the electromagnetic calorimeter, but leave no track in the tracking chamber.
- Electrons and positrons are small charged particles. The electromagnetic calorimeter stops these particles and the deposited energy is measured.
- Muons pass through all detector layers. They leave tracks and are the only particle that deposits a small amount of energy in each of the detectors.

You can find an introductory video online at www.atlas.ch.

On the same website, you can find a lot of extra information and multimedia.

TUTORIAL ON MINERVA PROGRAM

1. Introduction
2. Explanations of different sections
3. How to read the different parts due to collisions
 - a. $W \rightarrow e + \nu_e$
 - b. $W \rightarrow \mu + \nu_\mu$
 - c. $Z \rightarrow e + e$

1. Introduction

MINERVA is the abbreviation for **Masterclass INvolving Event Recognition Visualized with Atlantis**.

MINERVA has been trailed as a master-class tool for students to learn more about the ATLAS experiment at CERN. It is based on a simplified set-up of the ATLAS event display, Atlantis, which allows users to visualize what is happening in the detector. The aim is to look at ATLAS events and try to recognize what particles are seen in the detector.

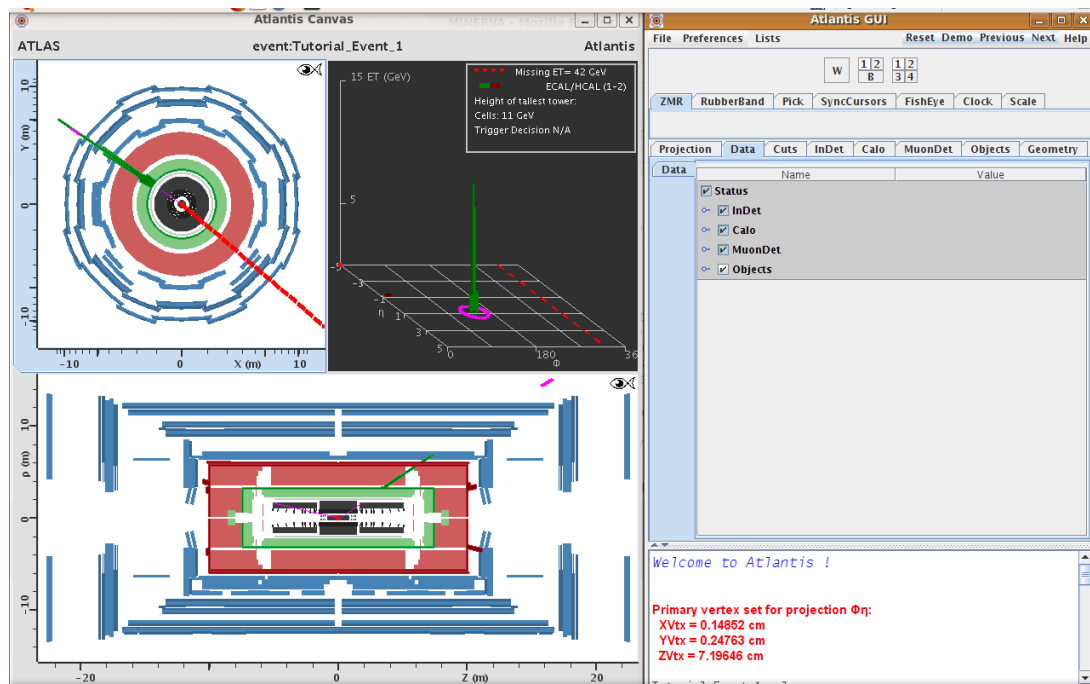
To do this we use the ATLAS event display called **ATLANTIS**. The setup was tailored to make it simpler and better looking for the students. Typically two students would work together on this exercise. The aim is to classify events in the different categories: $W \rightarrow e\nu$, $W \rightarrow \mu\nu$, $Z \rightarrow ee$, $Z \rightarrow \mu\mu$ and background events from jet production.

This will teach the student some basics about how the detector works, e.g. what kind of 'traces' the different particles leave in the various detectors (e, μ , jet, missing transverse energy). They will need to learn how to select events via their signatures.

MINERVA can be run either directly from the website, or if more groups of events are needed then it needs to be installed on each computer, running under Windows, Mac, or linux. [Here's](#) the link to run MINERVA directly from the web site.

To run MINERVA you need a recent version of Java installed on your computer, version 1.5 or later. If you need Java installing please go to www.java.com and download the software from the website.

When the program starts it looks like this screen shot:



2. Explanations of different sections

THE DETECTOR

ATLAS is a particle physics experiment at the Large Hadron Collider at CERN.

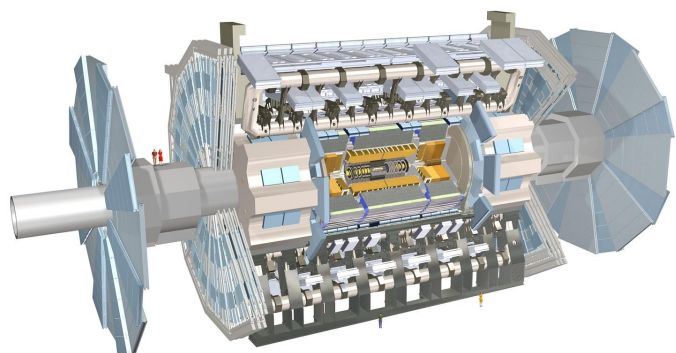
This detector will search for new discoveries in the head-on collisions of protons of extraordinarily high energy.

ATLAS will learn about the basic forces that have shaped our Universe since the beginning of time and that will determine its fate.

Among the possible unknowns are the origin of mass, extra dimensions of space, microscopic black holes, and evidence for dark matter candidates in the Universe.

ATLAS is about 45 meters long, more than 25 meters high, and weighs about 7,000 tons.

It is about half as big as the Notre Dame Cathedral in Paris and weighs the same as the Eiffel Tower or a hundred 747 jets (empty).



MINERVA END ON VIEW

The upper left plot shows the end on view of the ATLAS detector.

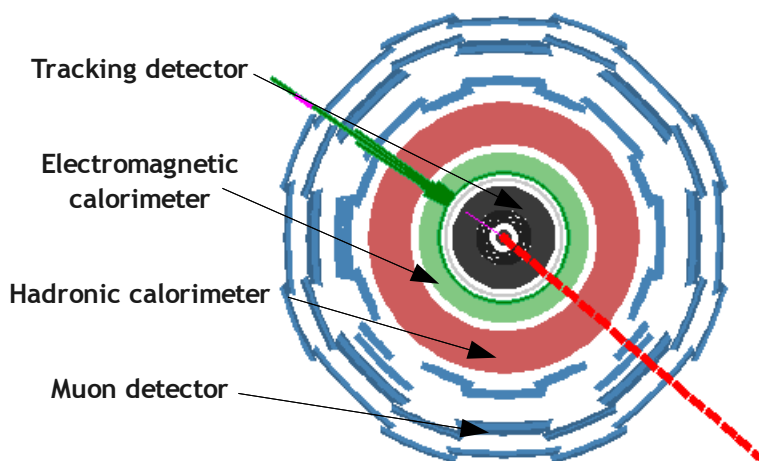
In this plot you ONLY see particles in the central region (barrel) of the detector.

Tracking detector

Measure charge and momentum of charged particles in magnetic field.

Electro-magnetic calorimeter

Measure energy of electrons, positrons and photons.



SIDE VIEW

In the lower plot you see particles produced in the barrel as well as the forward (end cap) region.

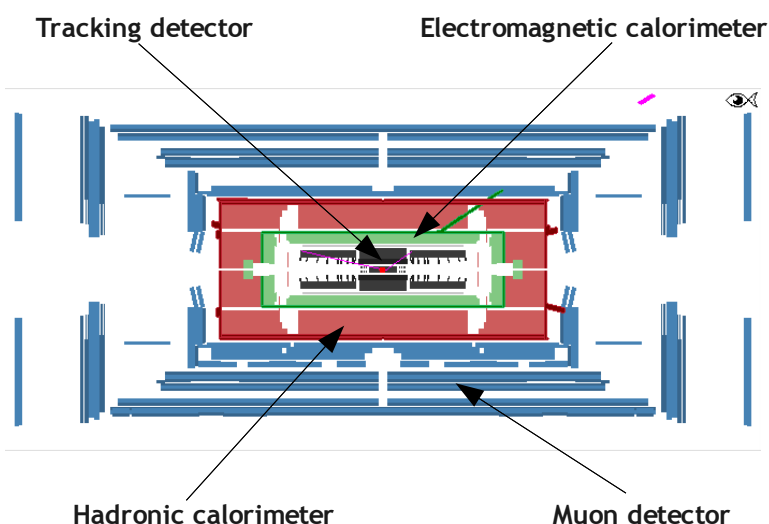
Hadronic calorimeter

Measure energy of hadrons (particles containing quarks), such as protons, neutrons, pions, etc.

Muon detector

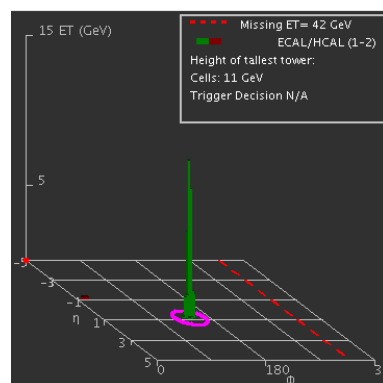
Measure charge and momentum of muons.

Neutrinos are only detected indirectly via 'missing energy' not recorded in the calorimeters.



ROLLED OUT CALORIMETERS

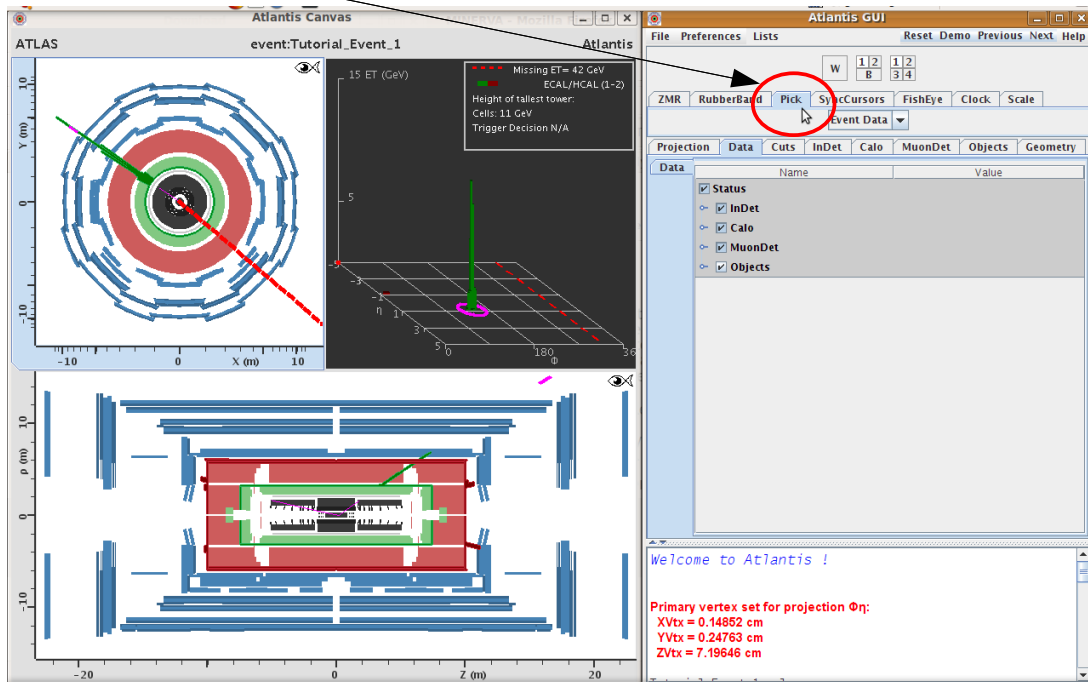
In the upper right plot you can see the calorimeter deposits of energy (E.M. in green, Hadronic in red and so on).



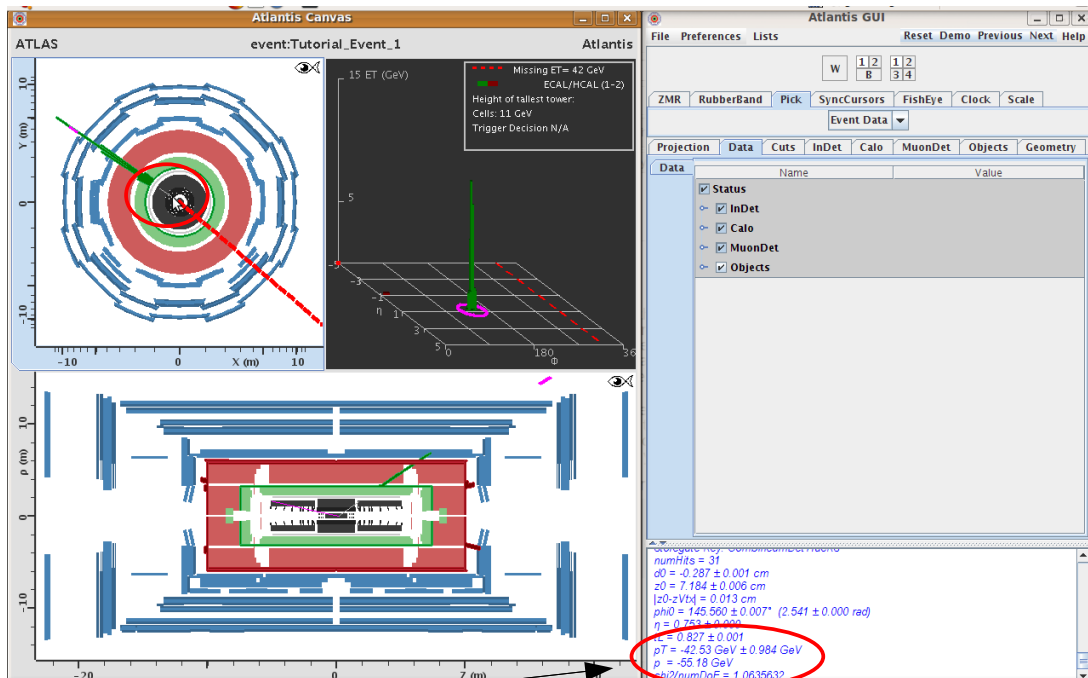
3. How to read the different parts due to collisions

First example: $W \rightarrow e + \nu_e$

Click on 'Pick'.



Now move the pointer to the track and click on it. Selected track becomes grey.

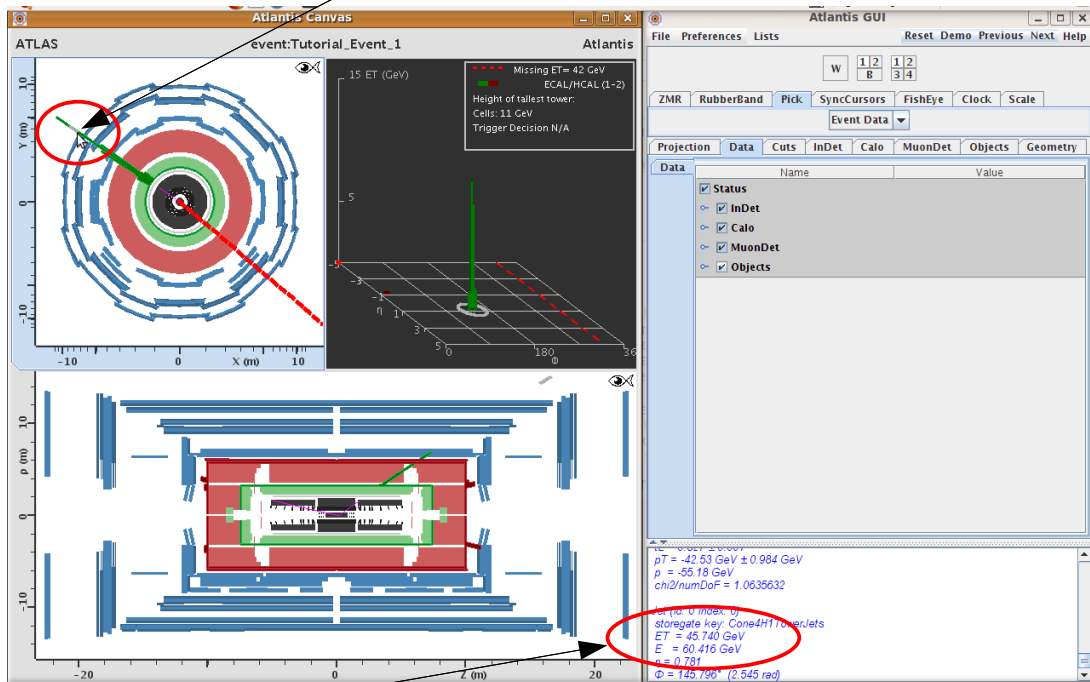


pT is shown here.

Electron track in tracking detector has high “side-ways” or transverse momentum ($p_T > 10 \text{ GeV}$)

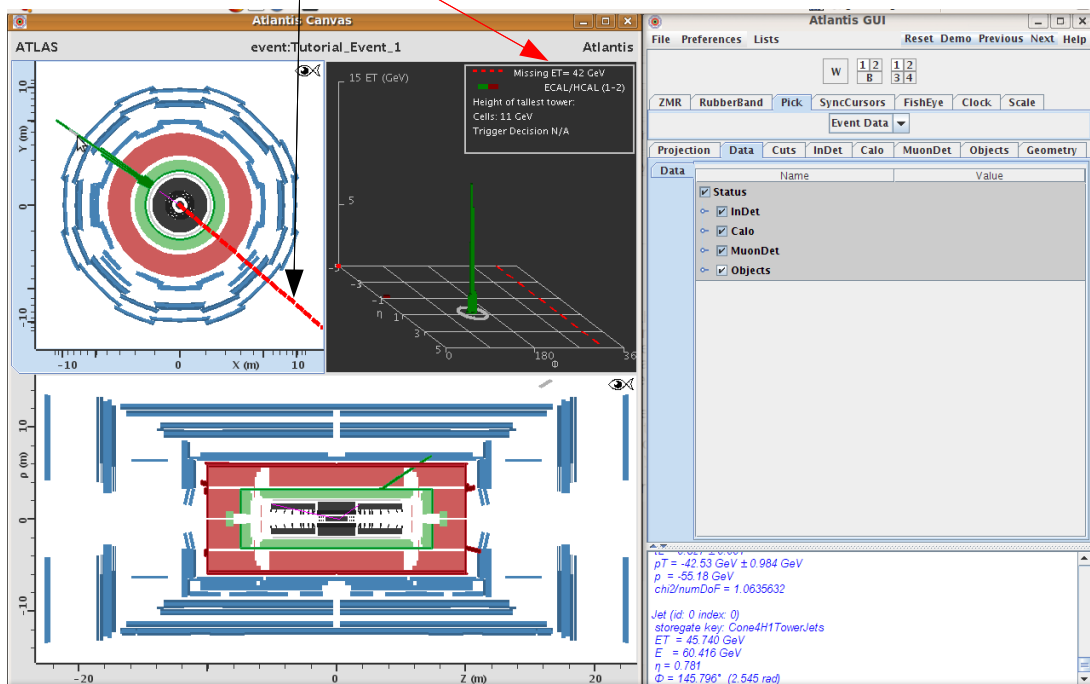
Electron deposits large “side-ways” energy (ET) in electro-magnetic calorimeter (ET>10GeV)

Move the pointer to the ‘purple square’ and click on it. Selected ‘square’ becomes grey.

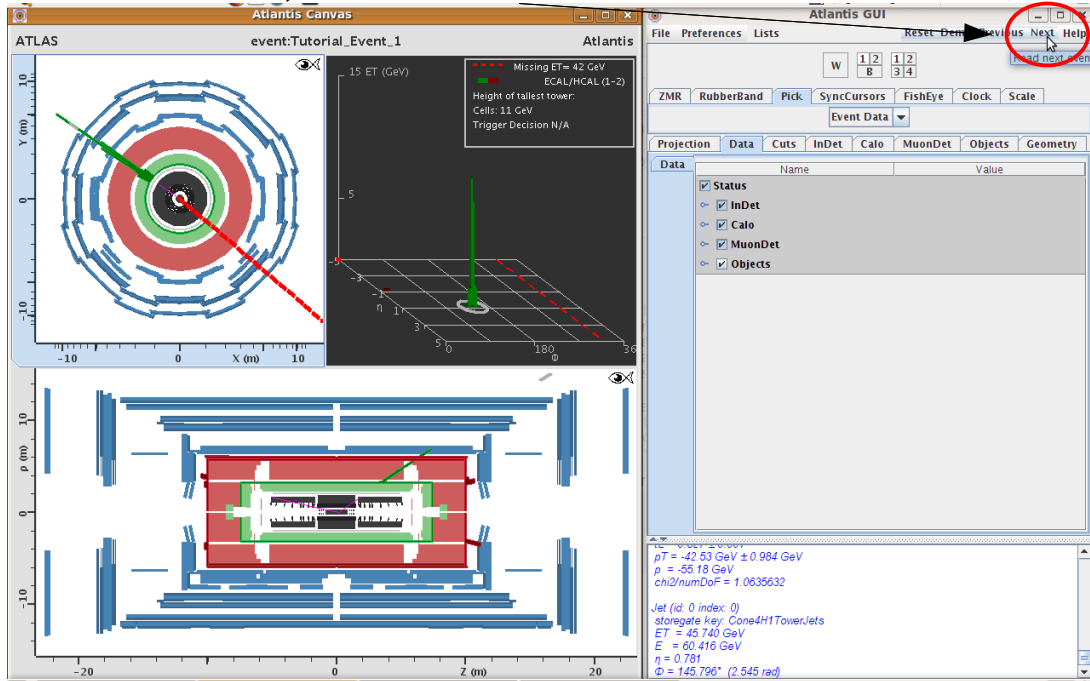


ET is shown here.

Neutrino is measured indirectly via large missing “side-way” or transverse energy (ET_{miss} > 10GeV). Red dashed line in end-on view. Note the thickness corresponds to the magnitude of ET_{miss}



To see the next event, click on 'Next' and remains in the 'Pick' view.



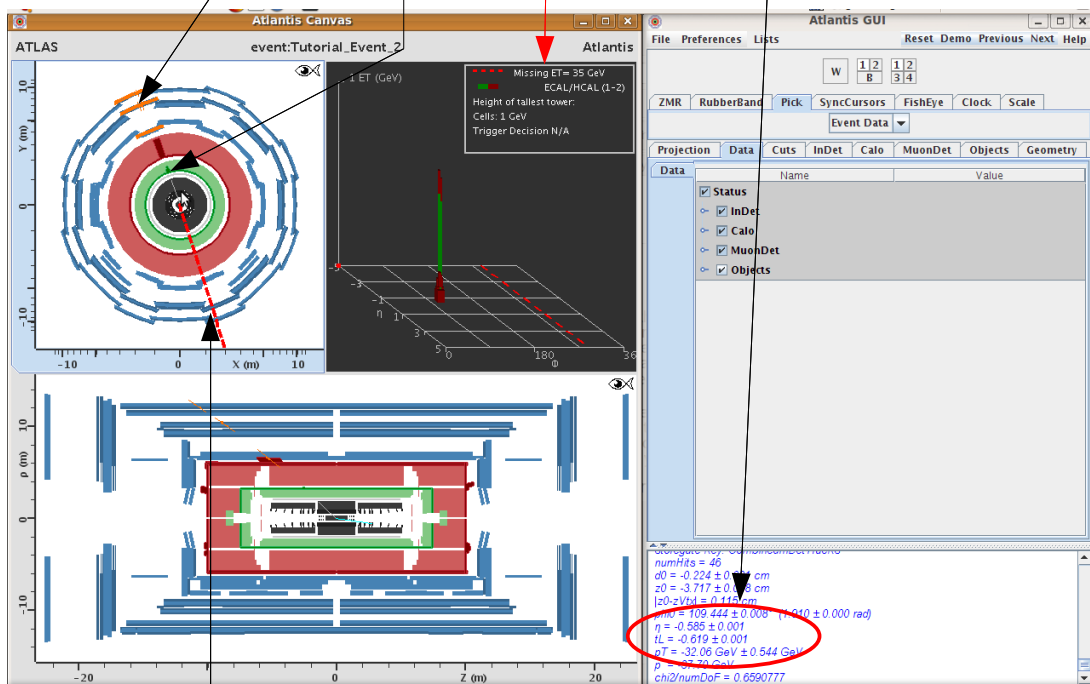
Second example: $W \rightarrow \mu + \nu_\mu$

Characteristics:

- Large missing “side-way” energy (ETmiss > 10 GeV)
- 1 muon with high track “side-way” momentum ($p_T > 10 \text{ GeV}$)

Muon identification:

- Track in tracking detector
- Track in muon detector

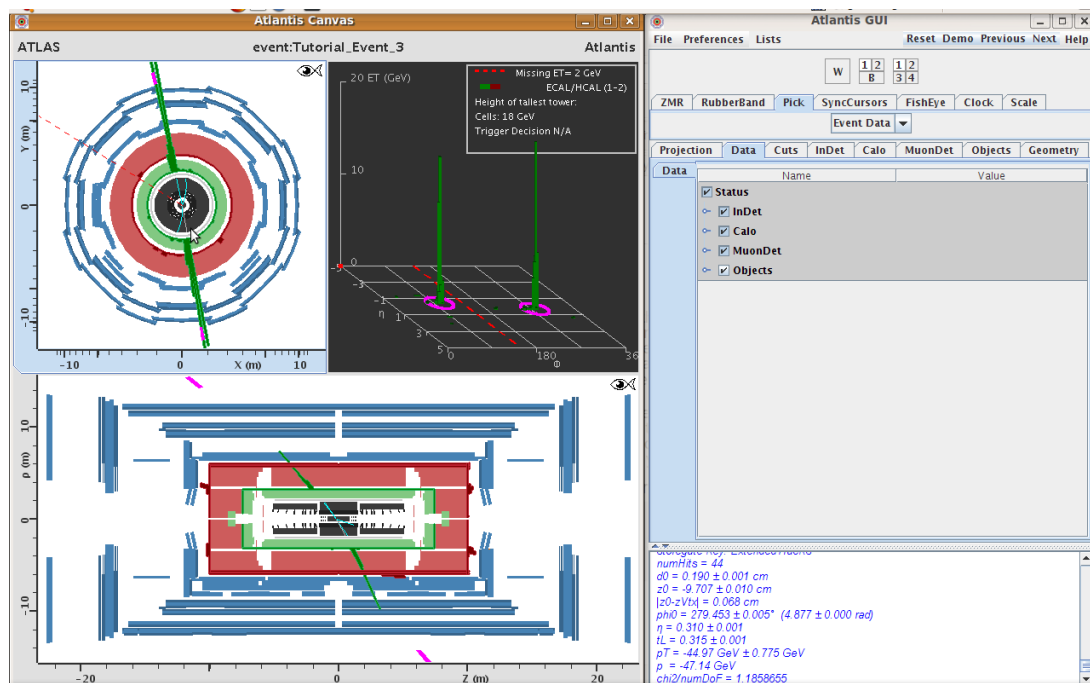


This is the neutrino.

Last example: $Z \rightarrow e+e$

Characteristics:

- 2 electrons in the event
- here also some other low momentum tracks around from collision fragments



Remember:

- Sometimes it's not so obvious if it's a jet or an electron
- Electron stops in electro-magnetic calorimeter, so has ONLY electro-magnetic component
- Jet goes also in hadronic calorimeter, so has electro-magnetic AND hadronic component
- Missing "side-ways" energy also present in background events but typically it's small

Also note:

- sometimes jets might be produced in addition to the W and Z bosons. In this case this is not a background event!