



Introduzione alle misure di fisica delle alte energie:

La ricerca del bosone Z e del bosone di Higgs

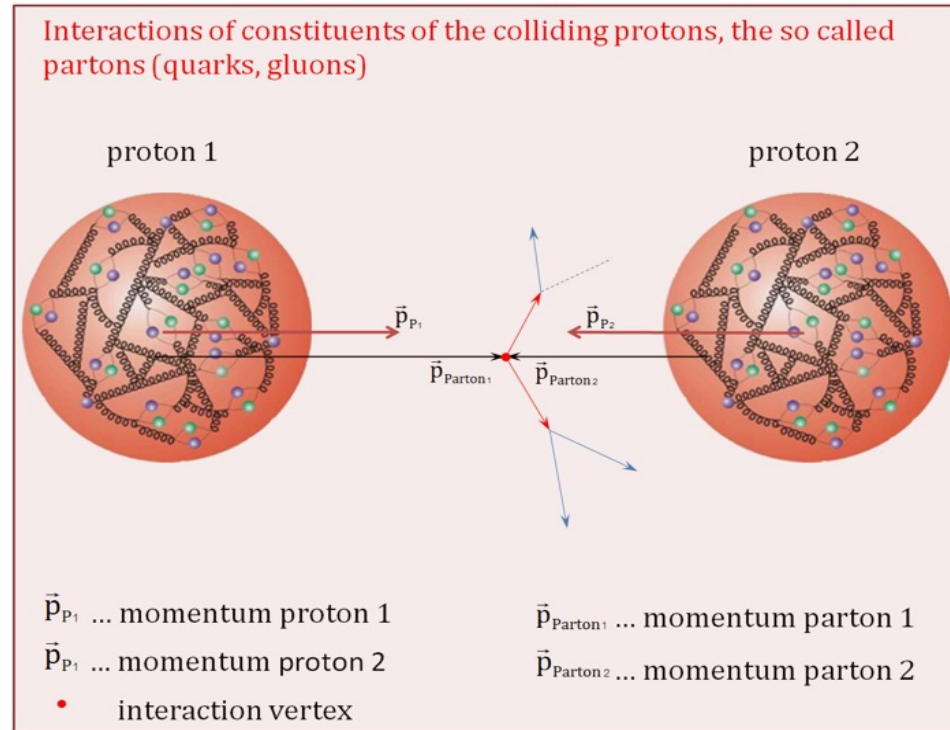
*Francesco Giuli
11/02/2025*

- **What is an “event”?**
- **Z boson: production and decays**
- **How one can identify the particles produced?**
 - ... in ATLAS
- **The “Particle Physics Giant”: the ATLAS detector**
- **Example of a real analysis: signal and backgrounds**
- **Hands-on session**

The event

Every time two beams (10^{11} protons in each beam) collide in the Interaction Point (every 25 ns), on average we have about 40-50 primary vertexes

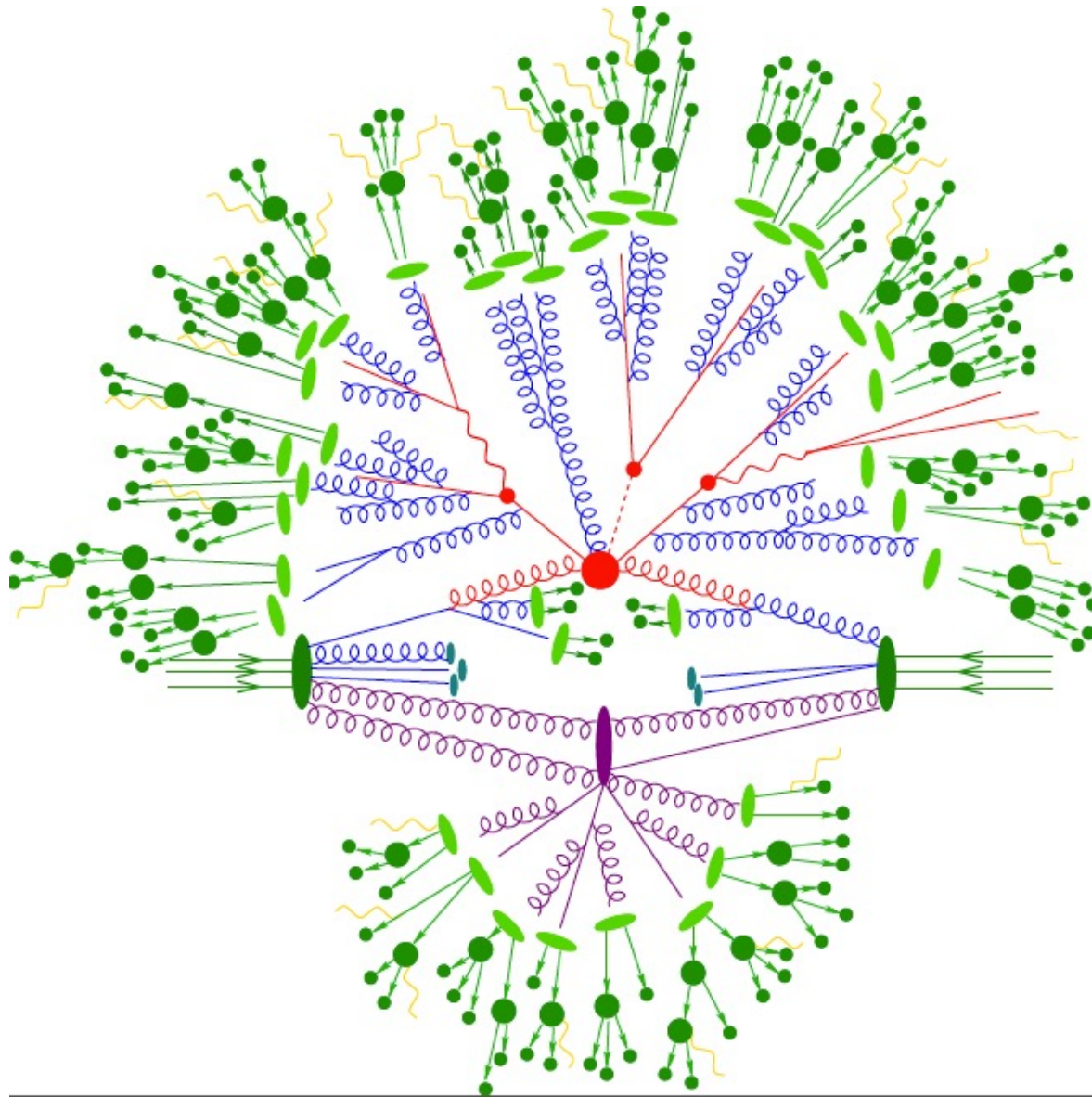
The rest of these collisions are not very interesting ($pp \rightarrow pp$)



Protons collide with protons at high speed:
lots of energy ($E_1 + E_2 = mc^2$) which can be used to create **new particles**

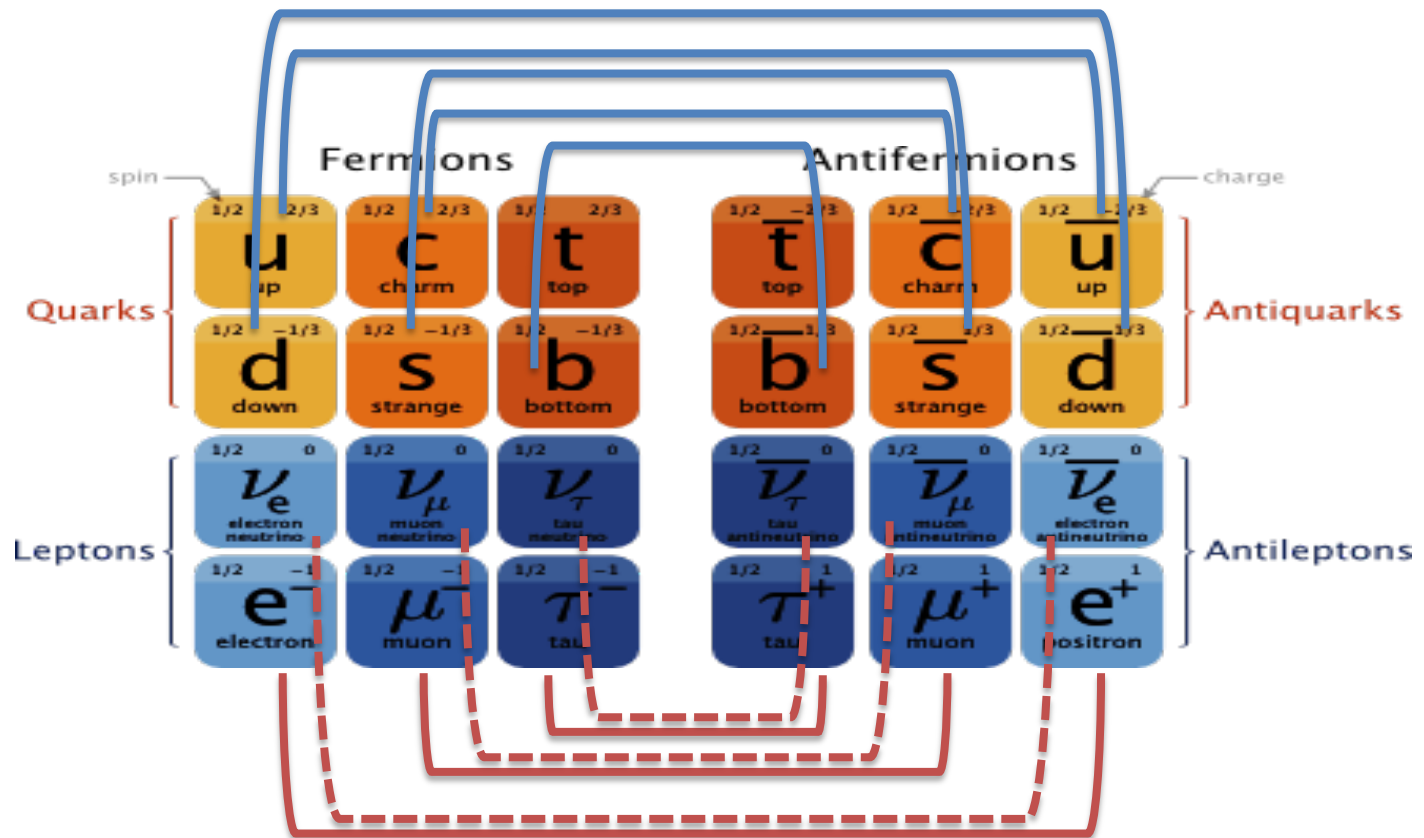
Sometimes a **Z boson** ($m = 91.2 \text{ GeV}/c^2$) or a **Higgs boson** ($m = 125.1 \text{ GeV}/c^2$) is created

Things are a bit more complex...



The Z boson

- Responsible for mediating the weak interaction (with the W boson)
- It is not a stable particle – lifetime 3×10^{-25} (0.0000000000000000000000003s) → no hope to measure the Z directly!
- Z bosons decay into a pair of fermion and anti-fermion



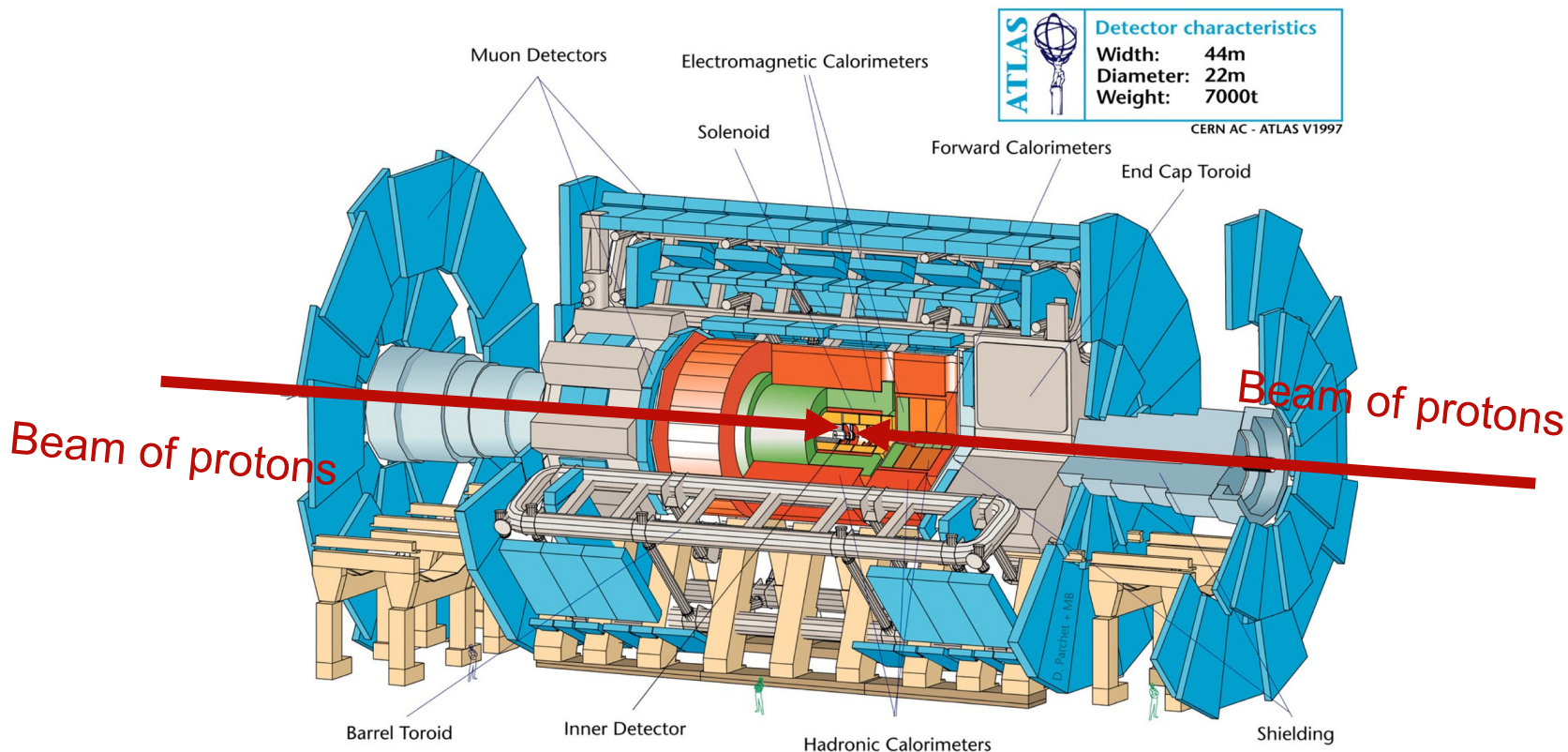
The Z boson

- The possible decays are:
 - 5 types of quark pairs (the top is too heavy to be produced)
 - A pair of taus
 - **A pair of muons**
 - **An electron-positron pair**
 - **3 types of neutrinos**
- Quarks are not observed free in nature, they *hadronise* which means they produce a collimated “jet” of particles
- Leptons have unique signature which we will explore
 - Taus are more complex, so we only look at muons and electrons
- Neutrino do not interact* with matter, so they escape the detector
 - * they do interact, but the probability is so low we assume it is zero in ATLAS

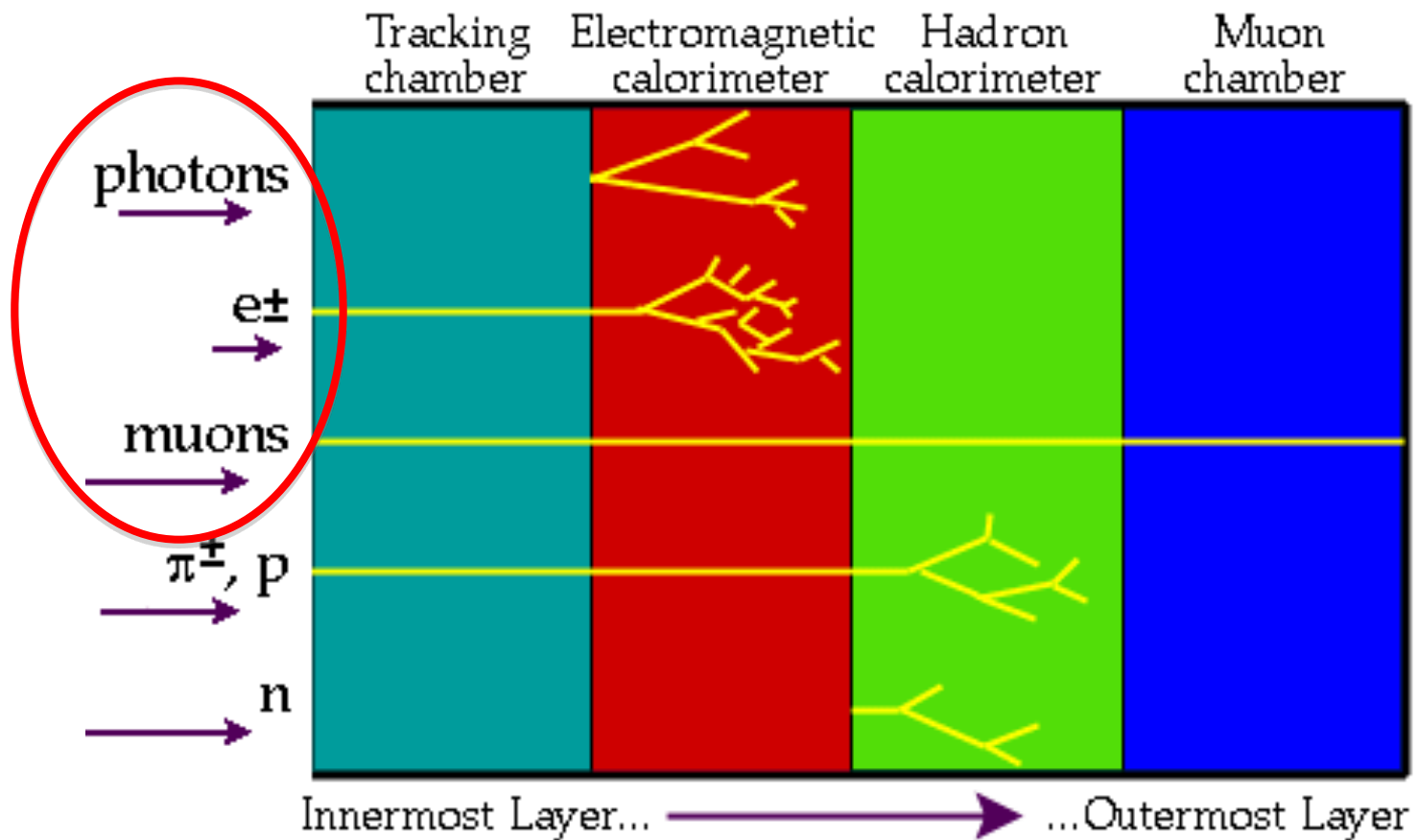
ATLAS

We surround the place where particles collide with a set of detectors.

Different types of particles leave different signals in the various detectors



How particles interact with detectors



The Inner Detector (tracking detector)

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- detects electrically charged particles traversing the detector

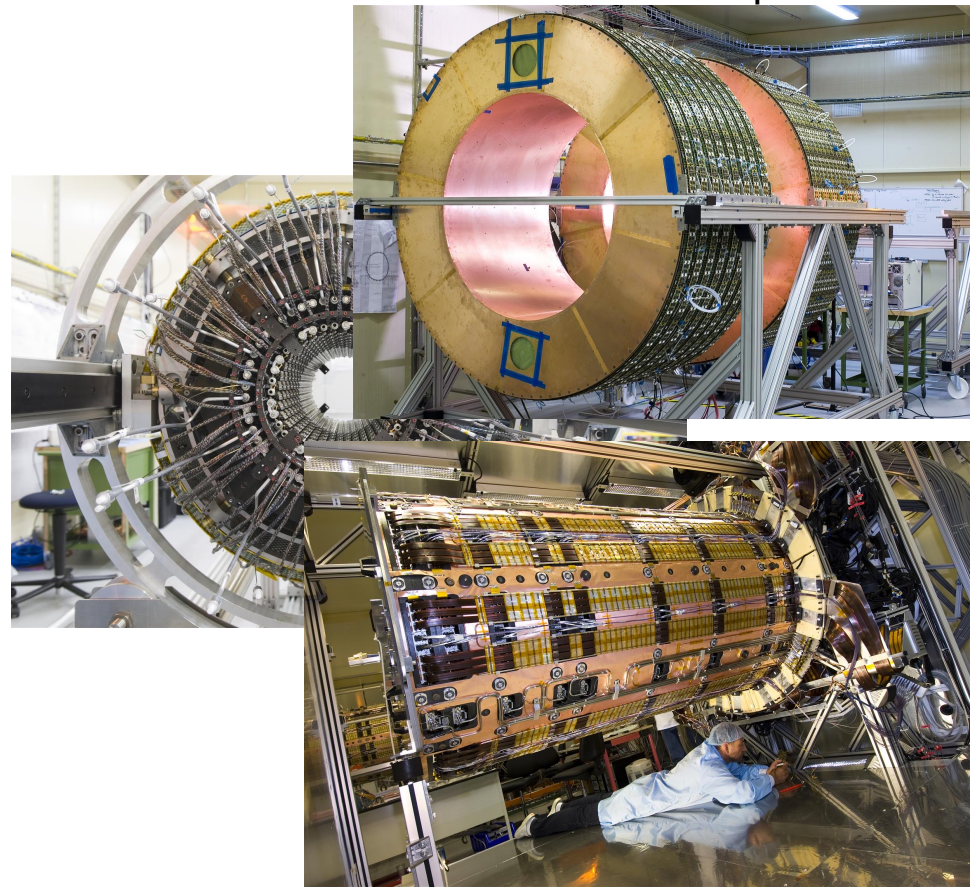
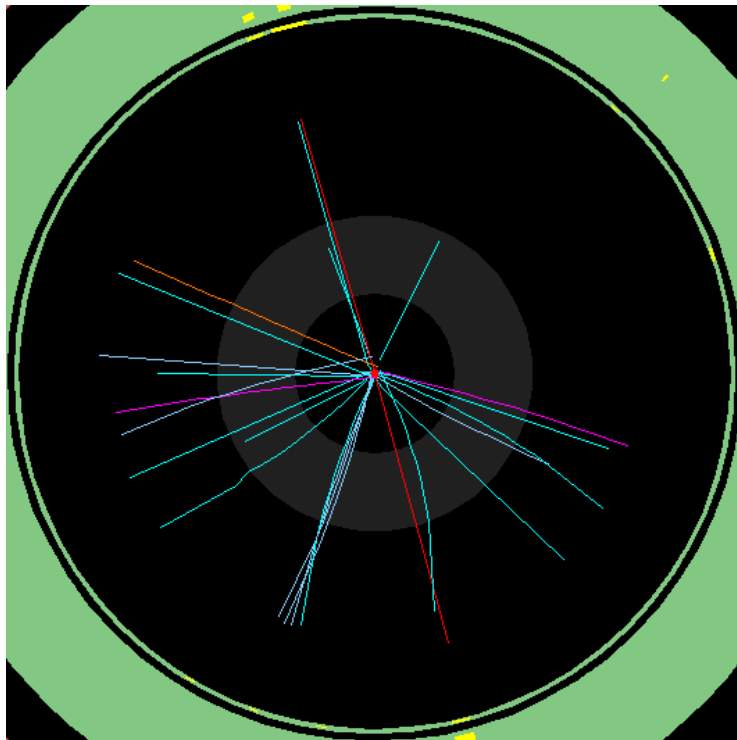
- electrons, muons, protons, quarks (jets) ...

- it is not sensitive to electrically neutral particles

- photons, neutrons, neutrinos...

- the whole detector "swims" in a magnetic field, that deflects charged particles' trajectories

- Amount of deflection depends on mass and speed



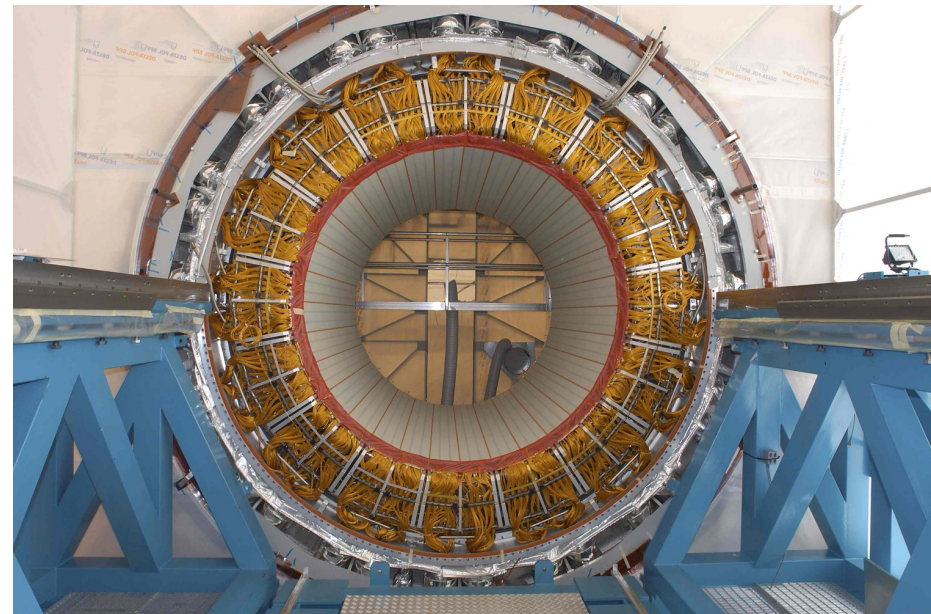
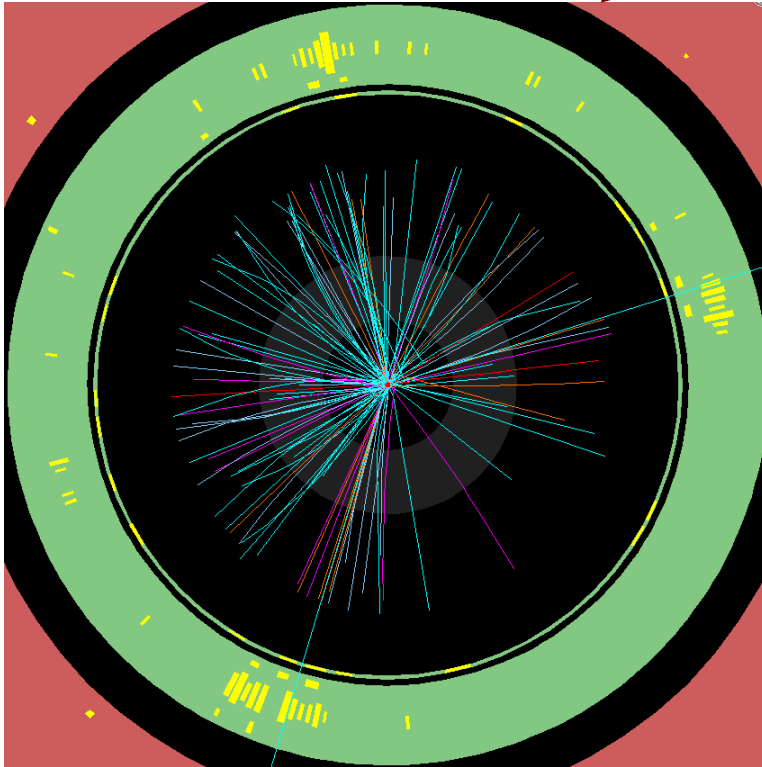
Electromagnetic calorimeter (ECAL)

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■ detects all particles interacting electromagnetically

■ such as electron, positron, photon, ...

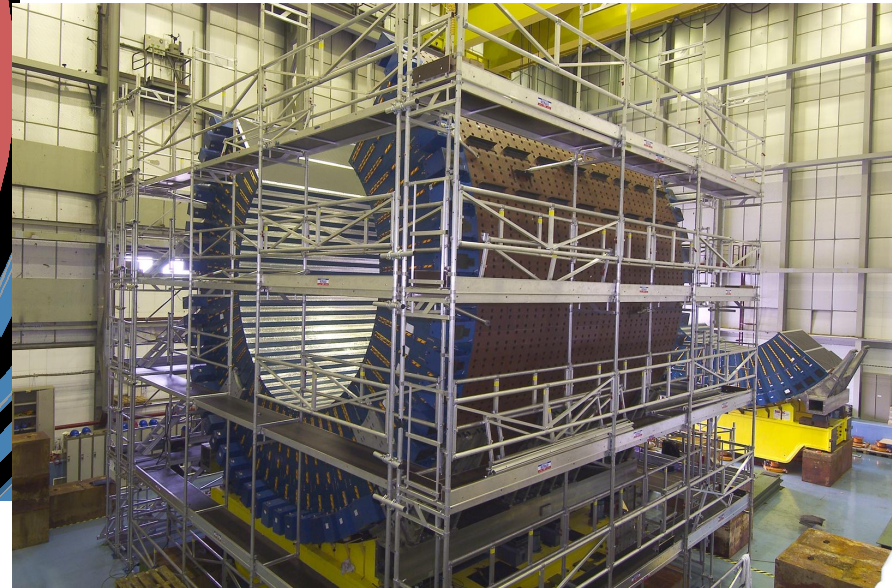
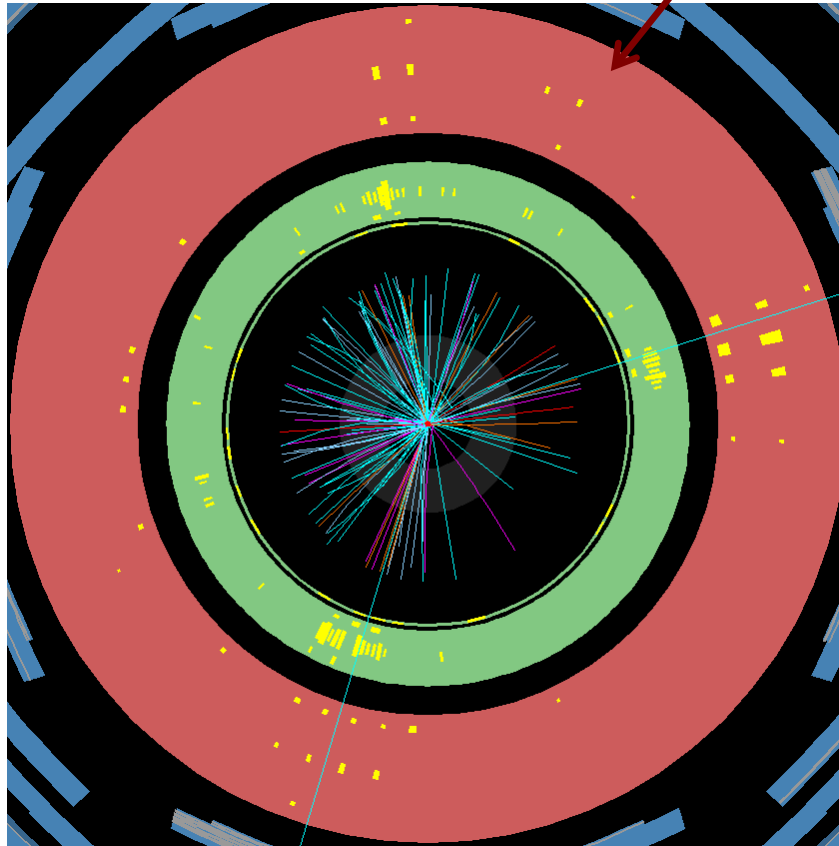
■ these particles deposit energy in the ECAL and this energy is measured



Hadronic calorimeter (HCAL)

- detects particles subject to strong interactions

- mainly particles made of various flavours of quarks

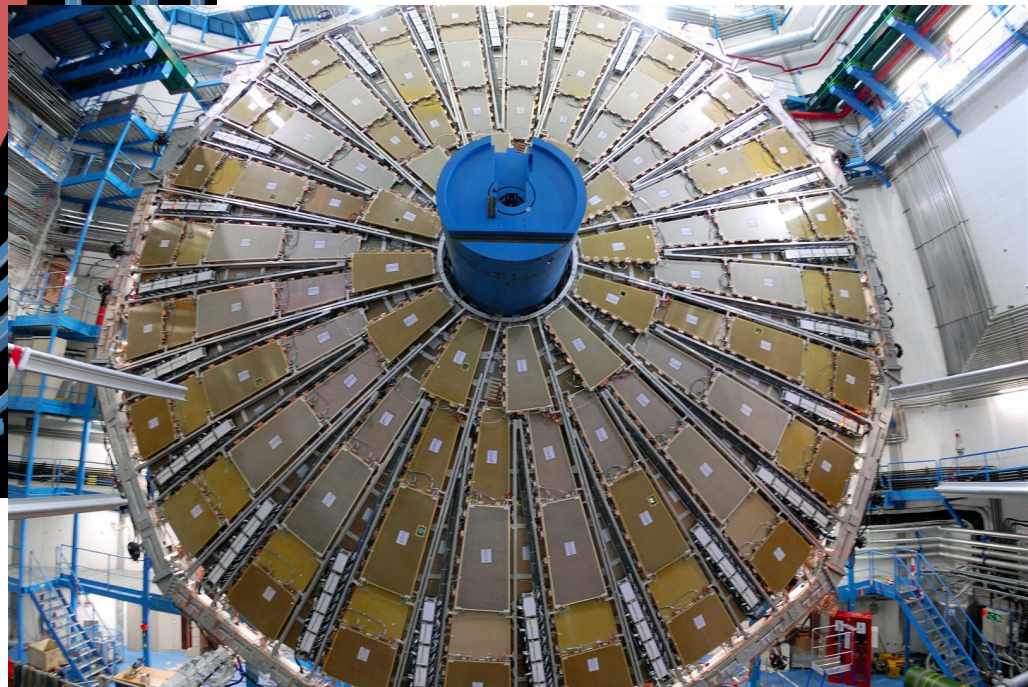
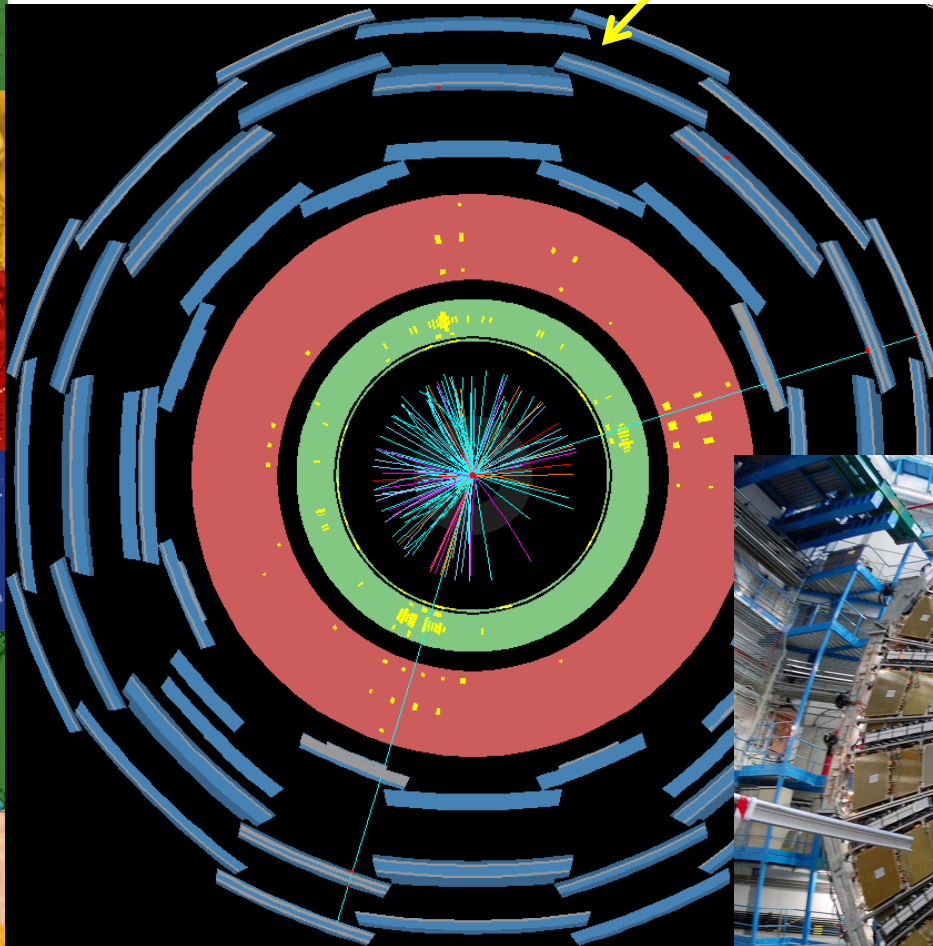


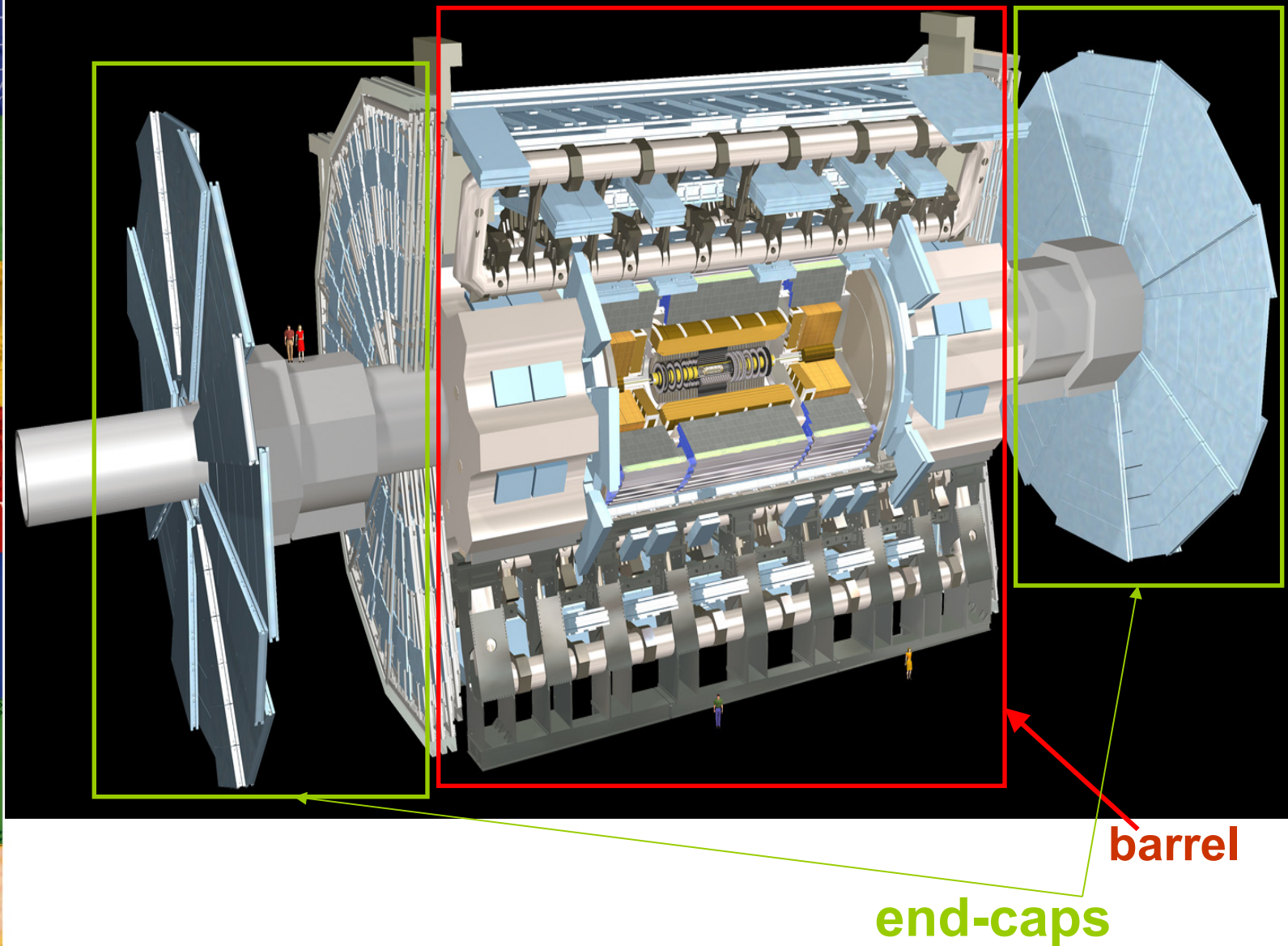
Muon spectrometer (MS)

■ is the outermost part of the detector

■ detects muons

■ a strong magnetic field deflects the muon's trajectory allowing a measure of the momentum





■ In order to detect as many particles as possible after each collision, the detector is built such that it covers nearly the full solid angle

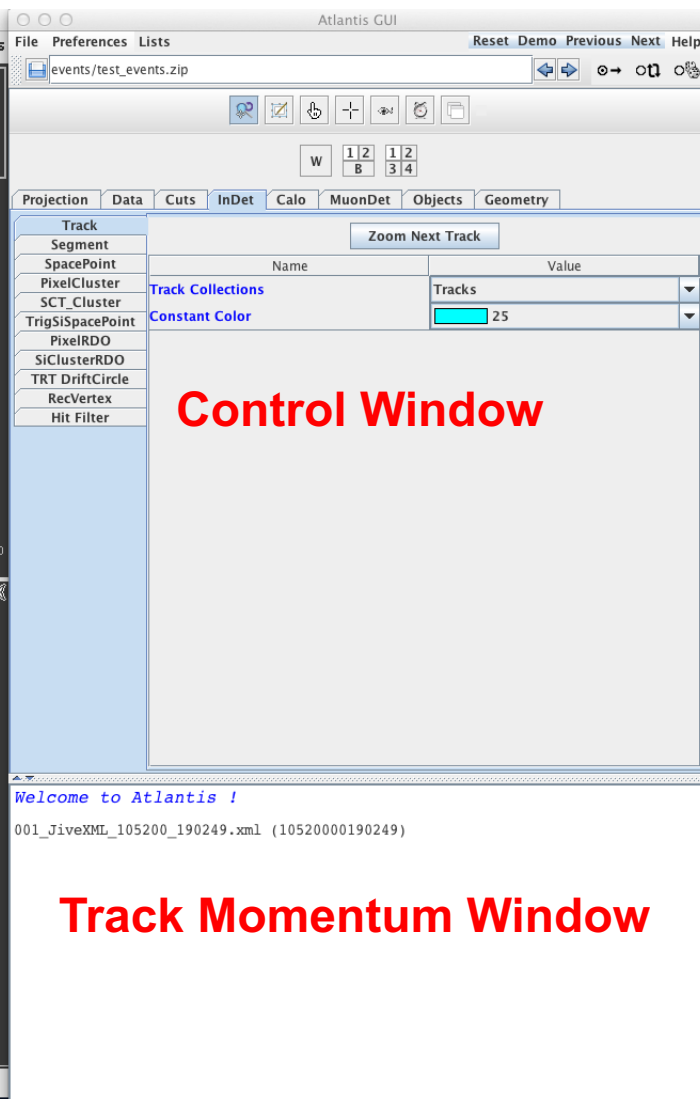
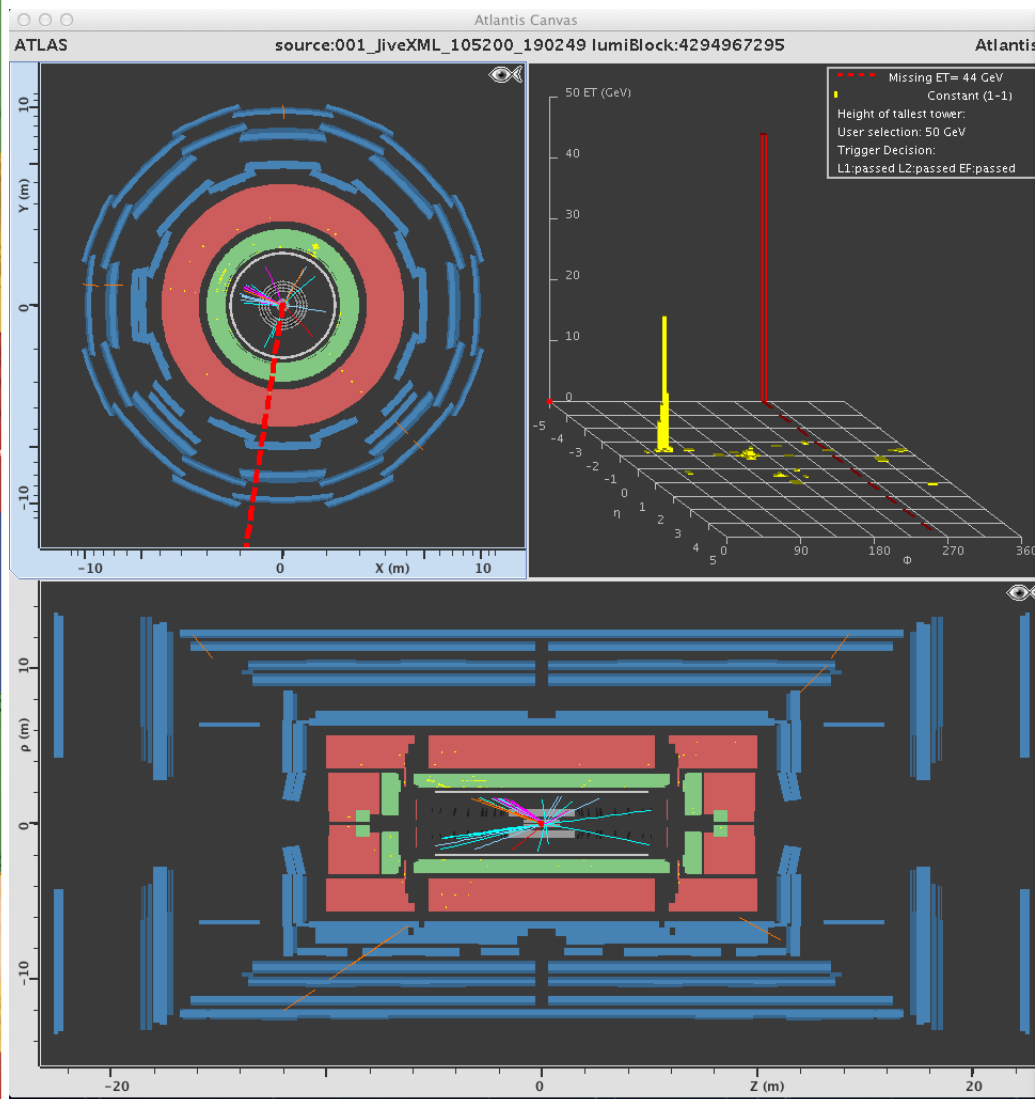
You will:

- **1. Get to know the ATLANTIS event display: a visualisation program for particle collisions in ATLAS**
 - Identify particles in a detector
 - Identify a decay process
 - Find as many correct answers as possible? *
- **2. Work with real data from LHC**
 - Identify decays of the Z boson from background

*: Can we answer this? What about for real data?

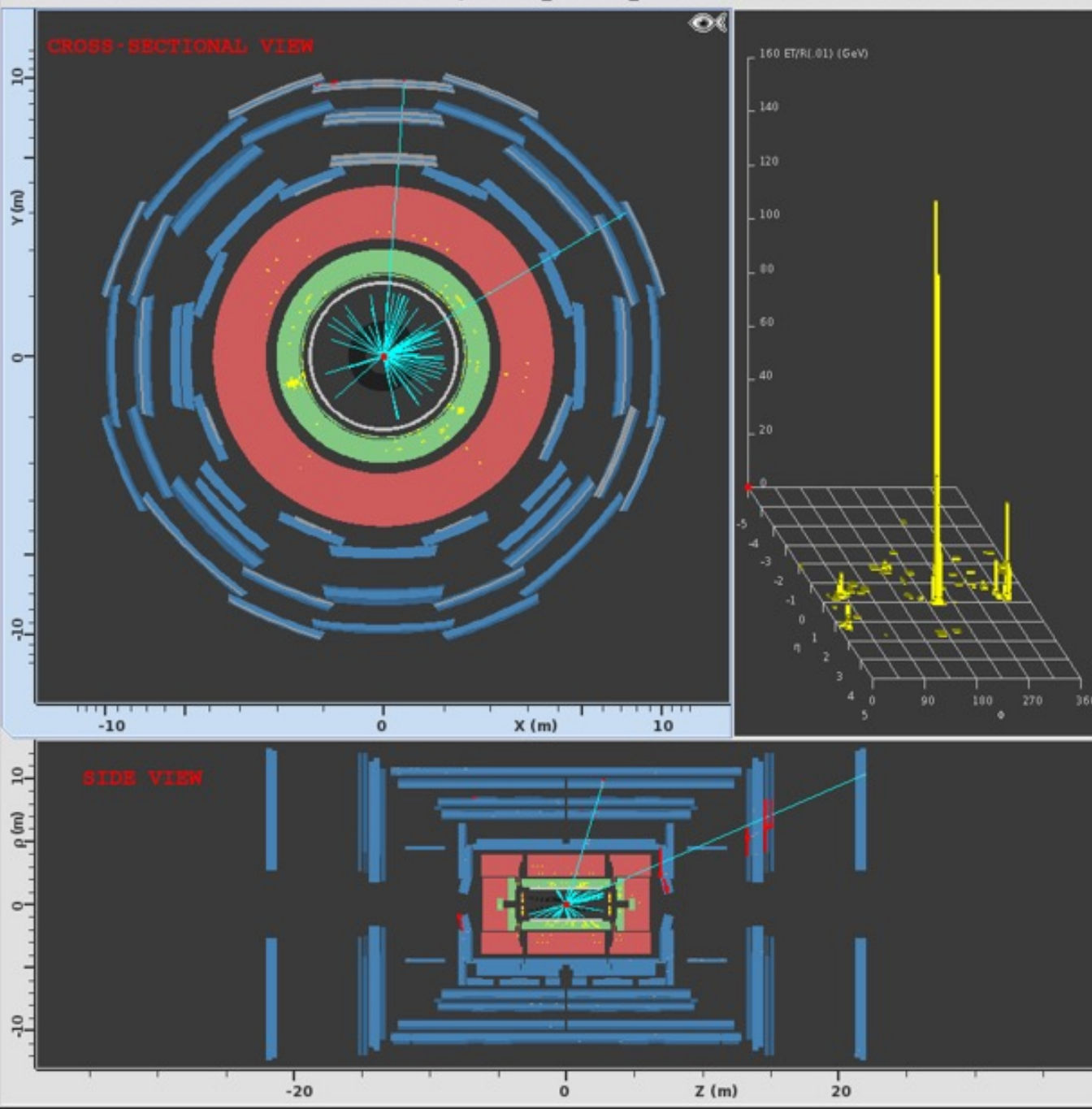
How it looks like...

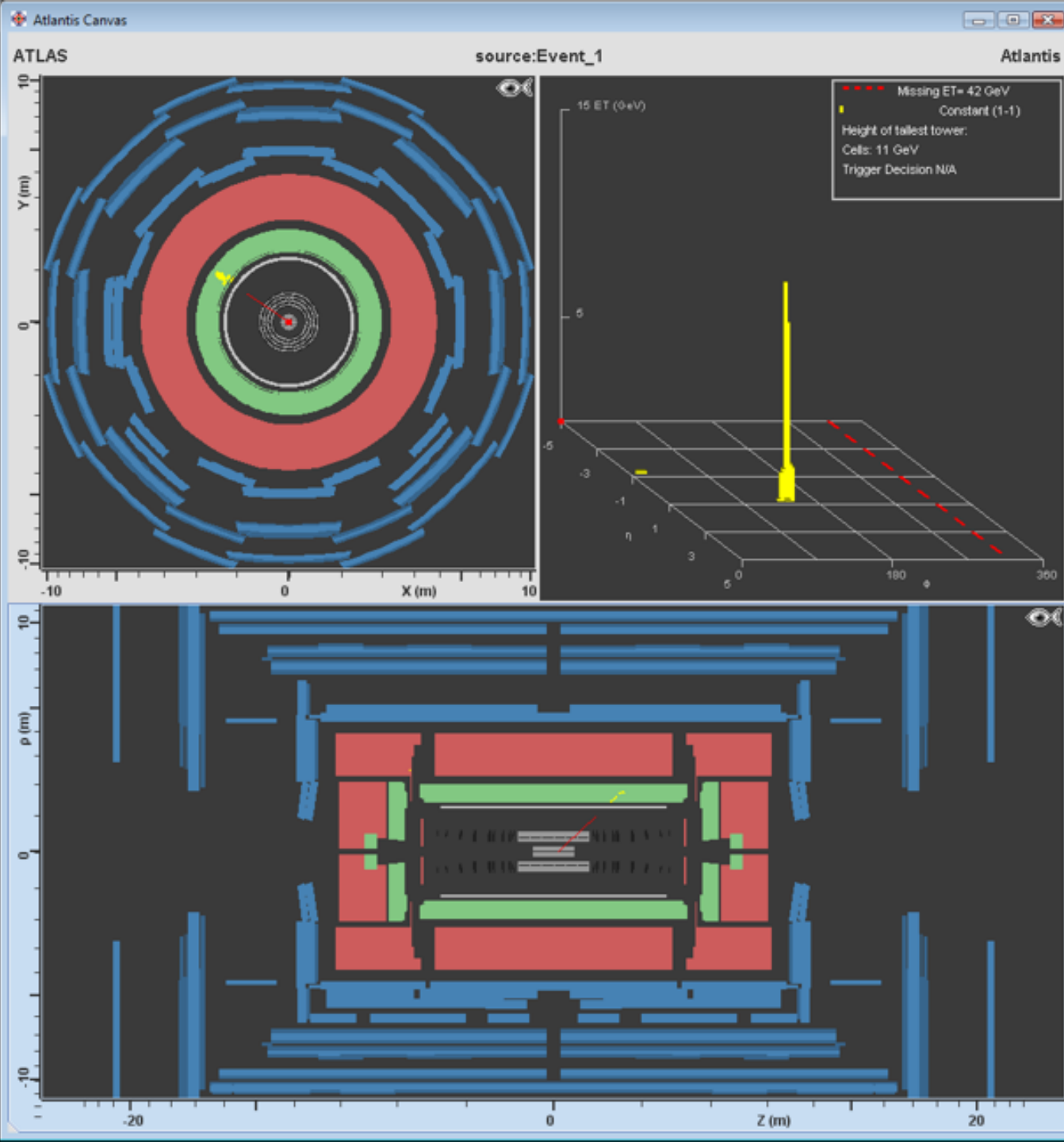
Canvas Window



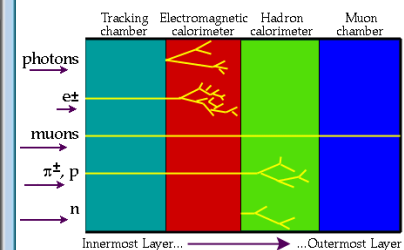
Detector views

Four sub-detector types, depicted in different colors



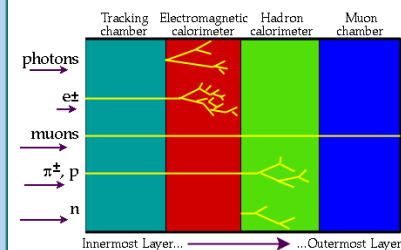


Electron



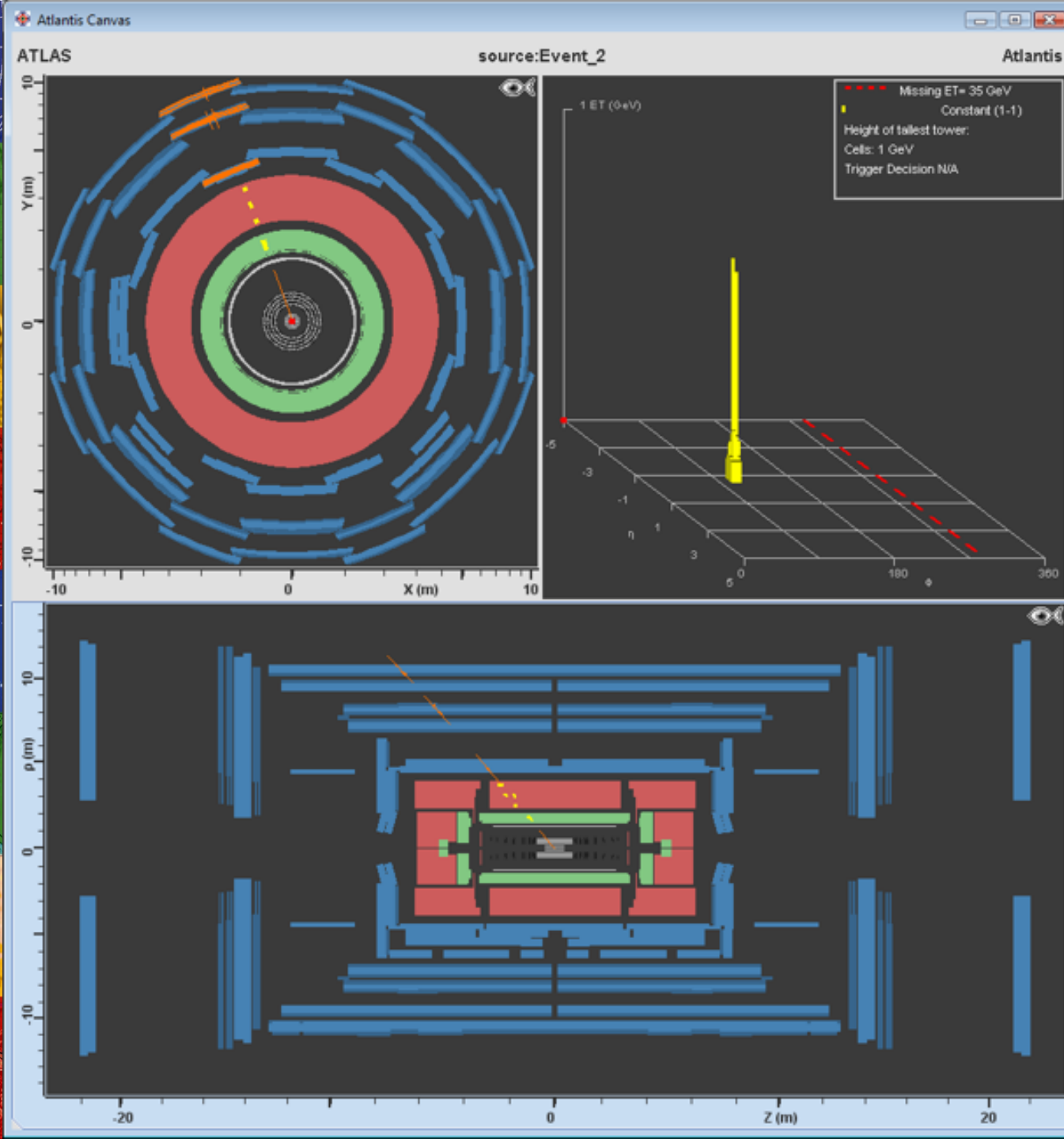
Electron clusters in the EM calorimeter look like yellow “towers” over a green background

Muon

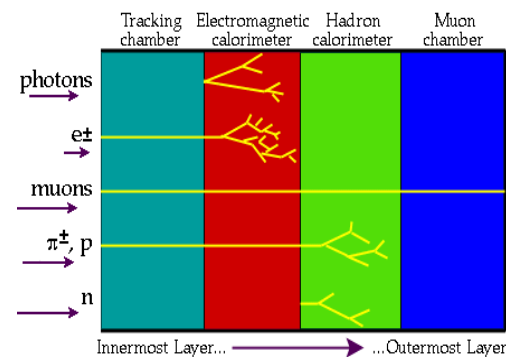


Muon chambers that are hit are colored orange

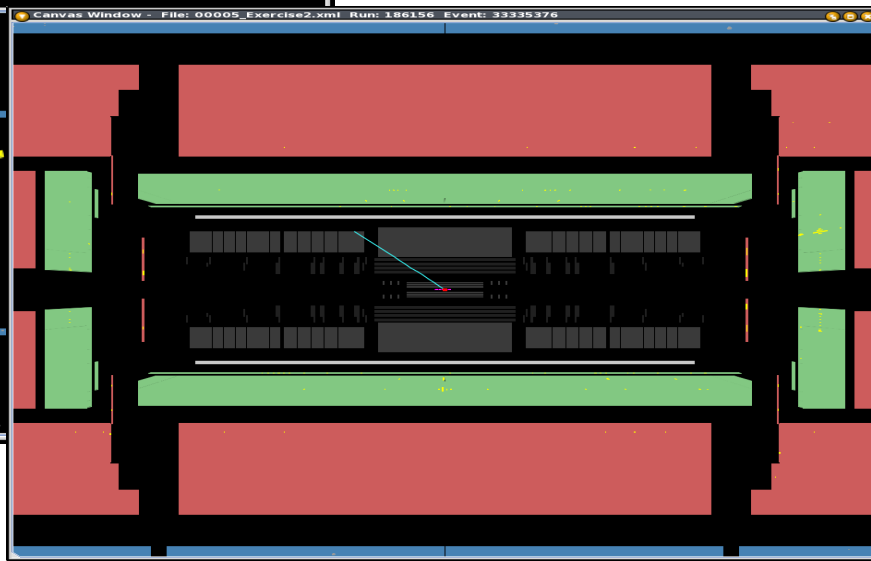
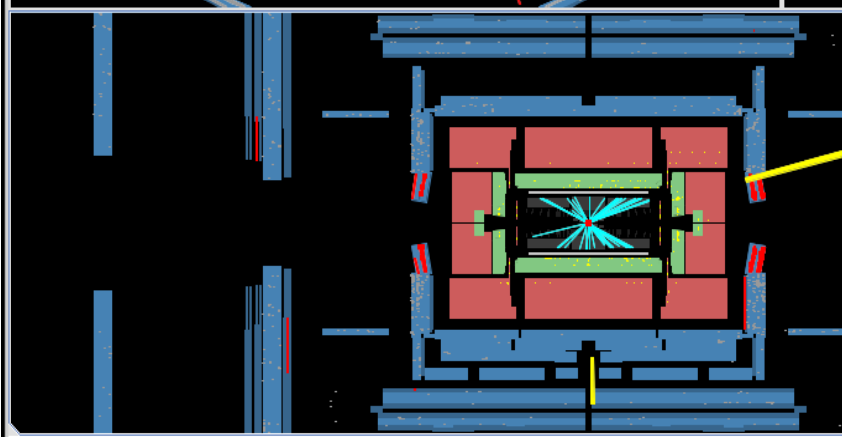
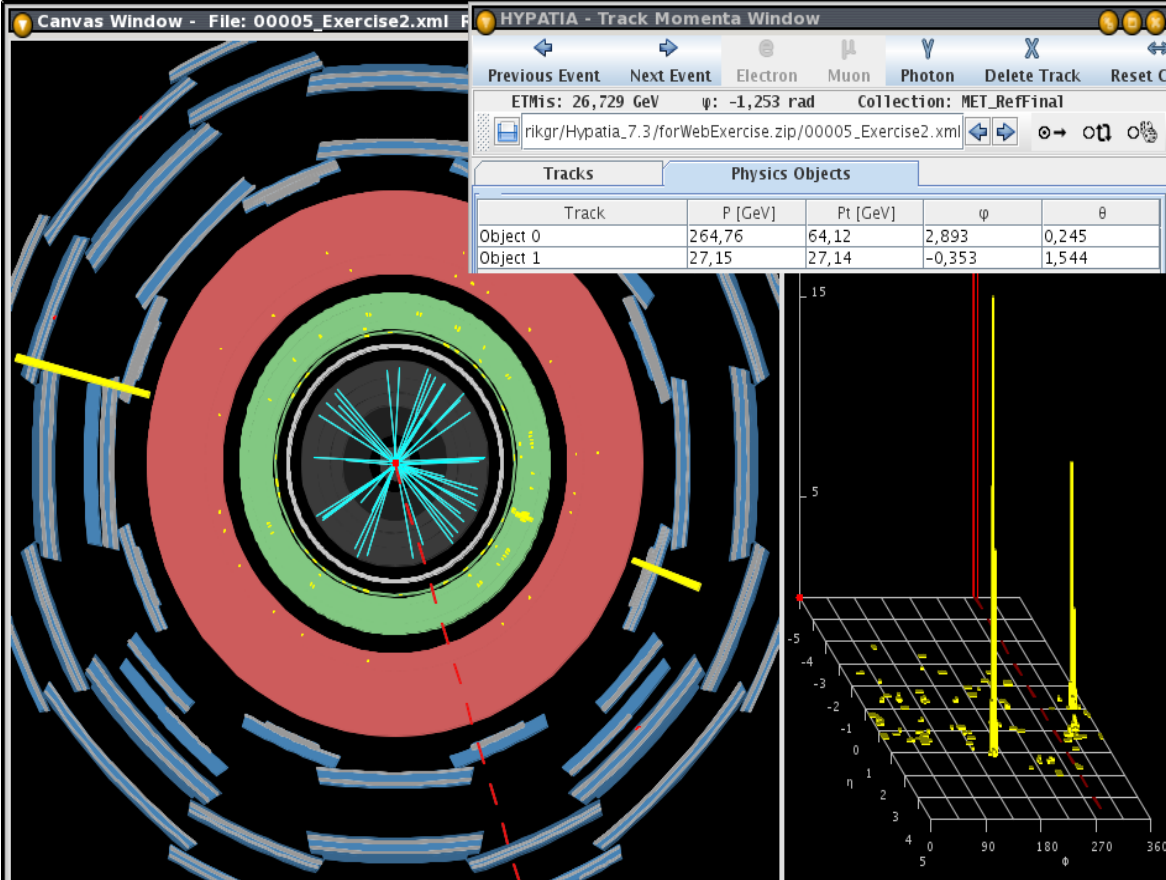
Some of the hits in the outer muon chambers are due to particles in the cavern

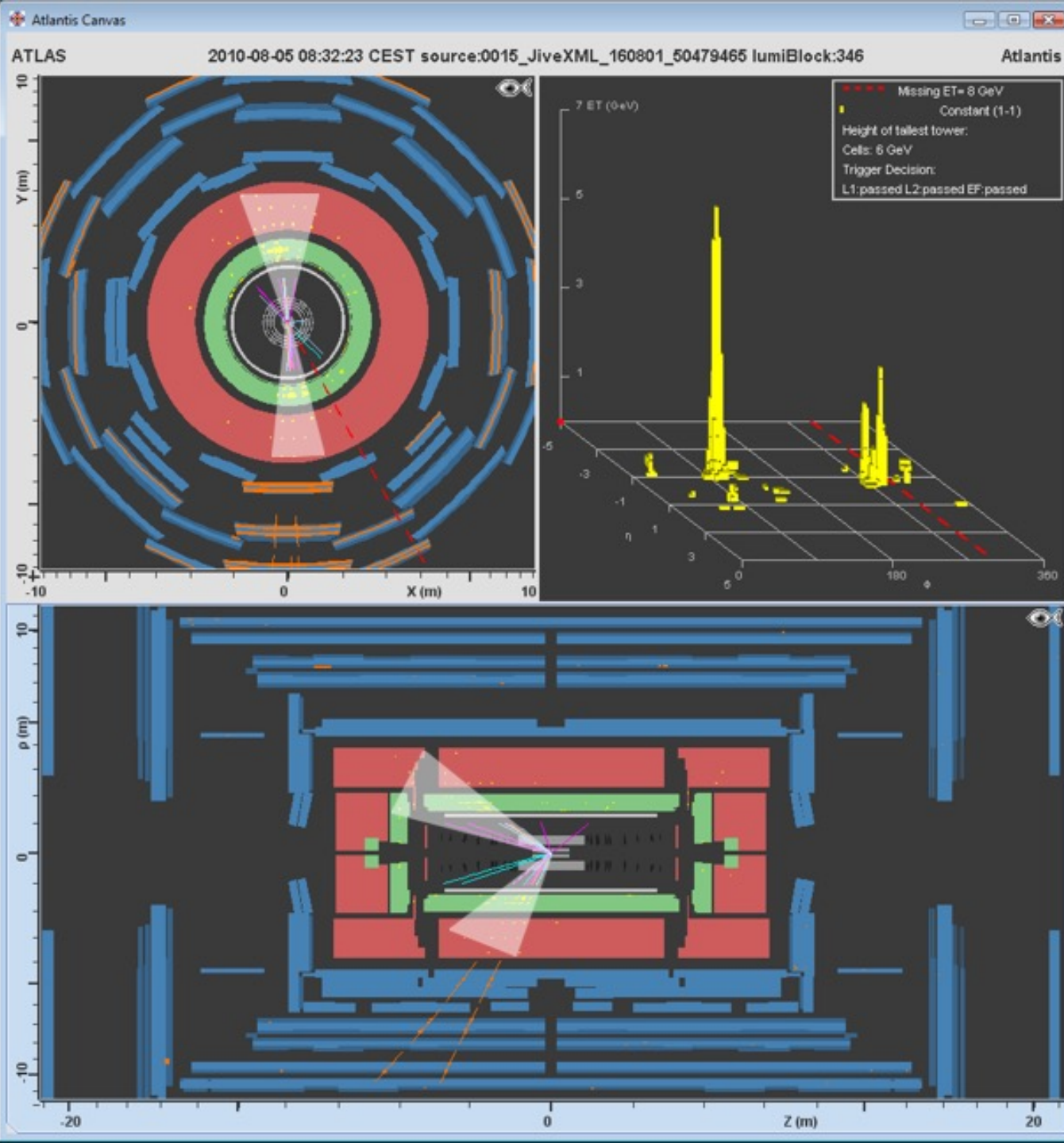


Photon

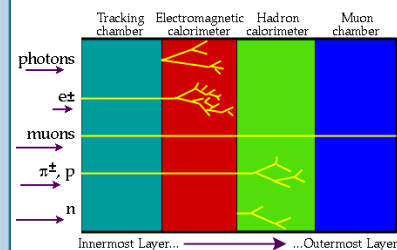


Electromagnetic
calorimeter cells
fired are
marked in yellow



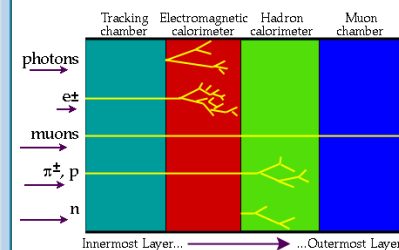


Jets of hadrons



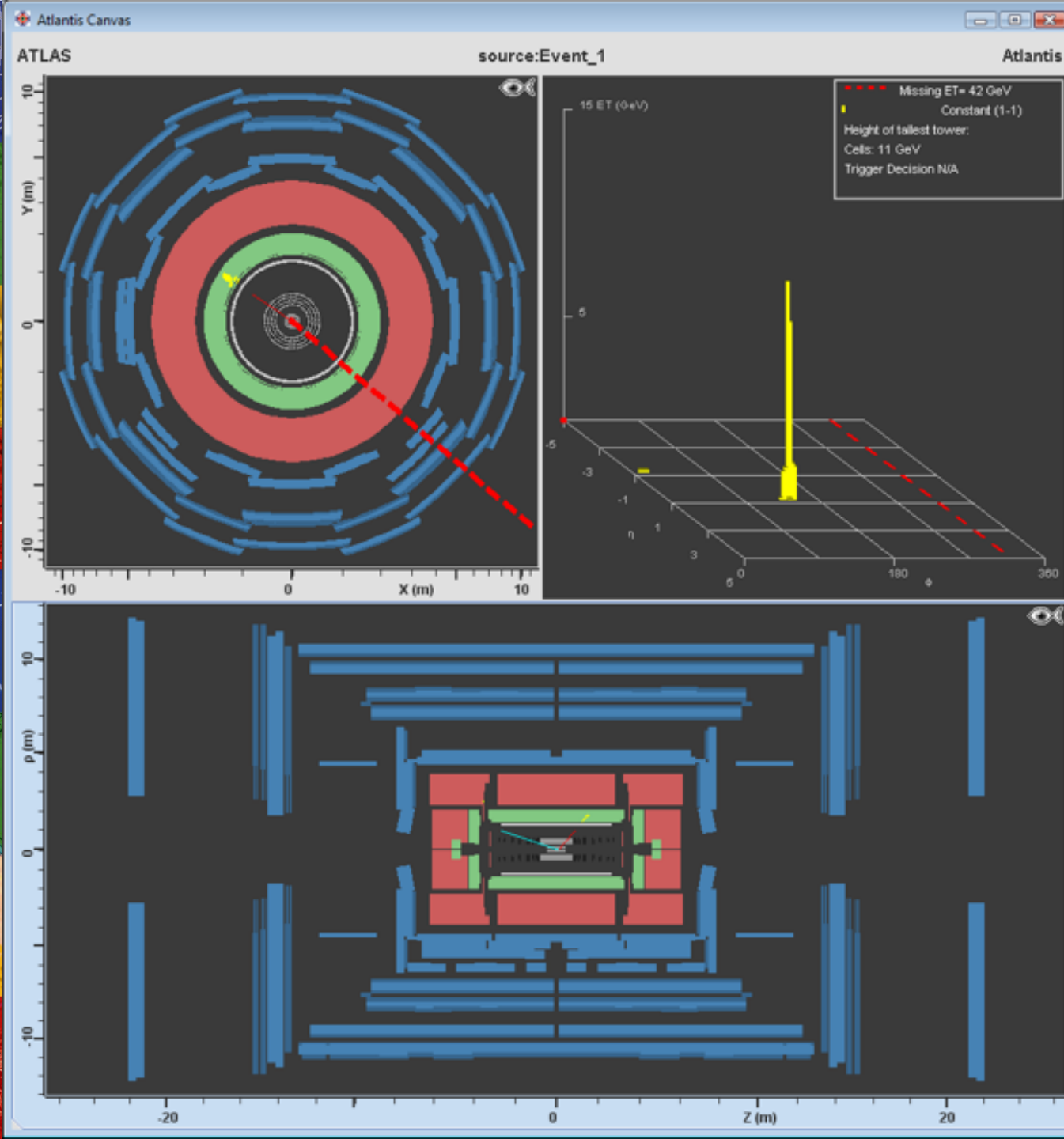
A bundle of several particles flying in one direction. It is the result of quark or gluons being ejected.

Neutrino

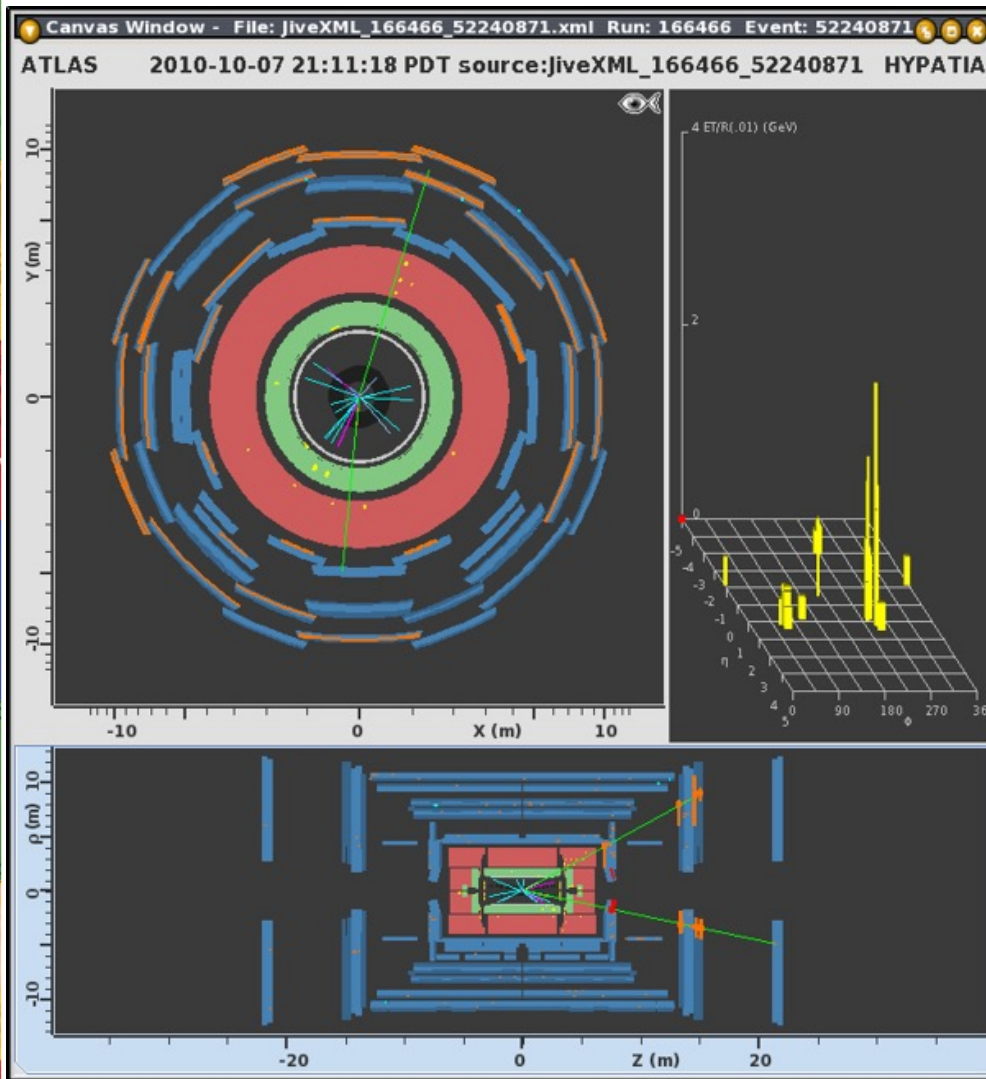


Neutrinos are not directly detected, but inferred from energy imbalance

Indicated by a dashed line, thicker line corresponds to larger missing energy

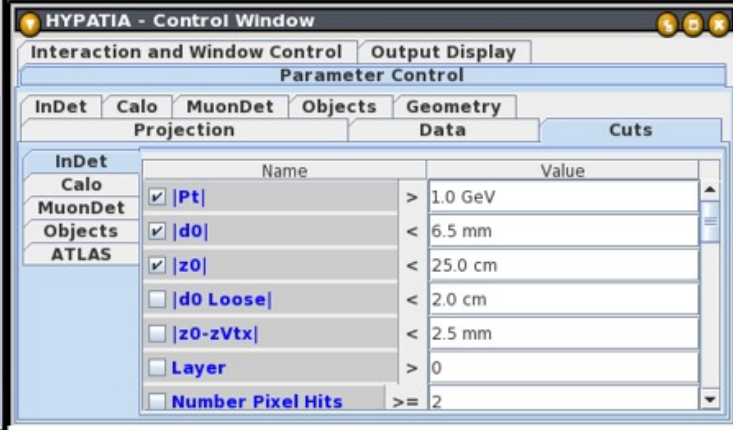


Signal: $Z \rightarrow \mu^+ \mu^-$



The screenshot shows the 'HYPATIA - Track Momenta Window' interface. At the top, there are navigation buttons (back, forward, home, search) and a status bar with 'Previous Event', 'Next Event', 'Insert Electron', 'Insert Muon', and 'Delete'. Below this, event details are displayed: 'ETMis: 0.568 GeV', 'φ: -0.573 rad', and 'Collection: MET RefFinal'. A file path is shown: 'asterClass/zpath/Mus/jiveXML_166466_52240871.xml'. The main section is titled 'Reconstructed Tracks' and contains a table with 6 columns: Track, +/-, P [GeV], Pt [GeV], φ, and θ.

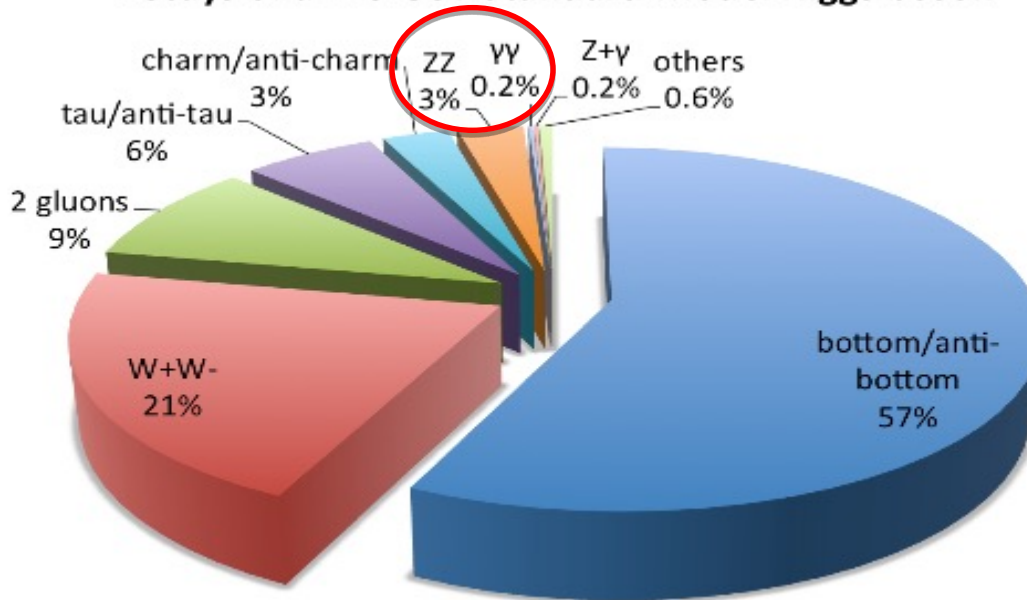
Track	+/-	P [GeV]	Pt [GeV]	φ	θ
Tracks 0	+	126.71	29.23	-1.659	0.233
Tracks 3	+	7.78	4.24	-1.928	0.577
Tracks 5	-	120.76	61.66	1.257	0.536
Tracks 6	+	2.97	1.31	-0.477	2.686
Tracks 7	-	2.83	1.06	-0.062	2.757
Tracks 9	-	2.99	1.20	-2.356	0.415
Tracks 10	+	8.03	1.47	-2.472	2.958
Tracks 11	+	5.87	1.19	-2.757	0.204
Tracks 15	+	6.06	2.69	-0.771	2.681
Tracks 17	-	8.08	4.16	-2.043	0.540
Tracks 24	-	1.50	1.36	2.582	2.002
Tracks 25	+	1.57	1.00	-1.943	0.689
Tracks 26	-	2.69	1.16	-0.327	2.697
Tracks 57	-	3.42	2.15	0.765	0.679
Tracks 58	-	1.09	1.09	2.206	1.510
Tracks 65	+	1.97	1.34	-2.065	0.745
Tracks 72	+	28.08	7.80	2.460	0.281



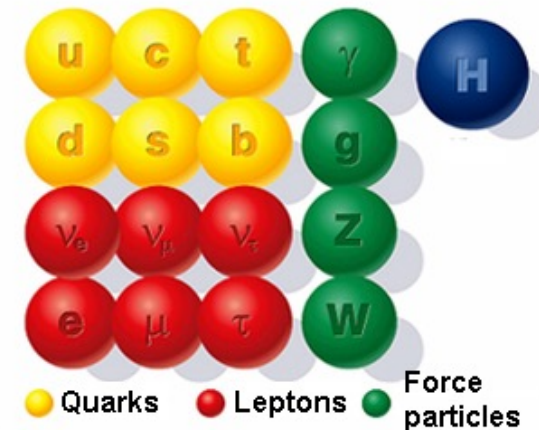
The Higgs Boson

- Responsible for the mass of all particles
- It is not a stable particle – lifetime 1.5×10^{-22} (0.000000000000000000000015s) → no hope to measure H directly!
- H bosons decay either into:
 - a pair of fermion and anti-fermion
 - a pair of gauge bosons (W^+W^- , ZZ , gg , $\gamma\gamma$)

Decays of a 125 GeV Standard-Model Higgs boson



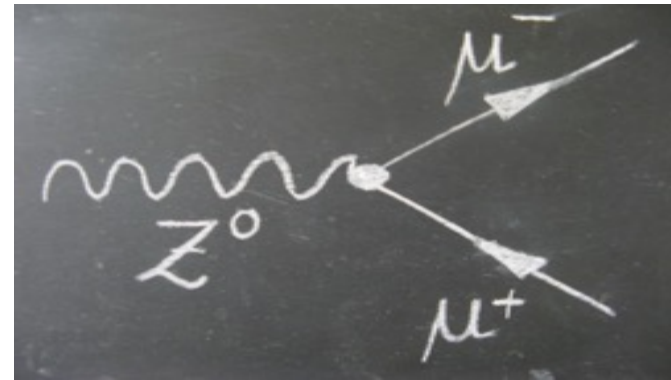
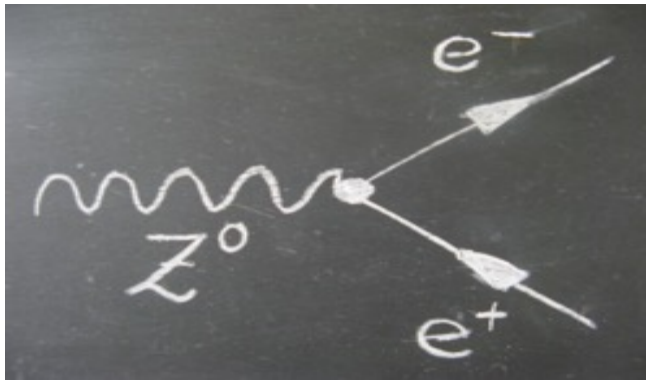
Standard Model particles



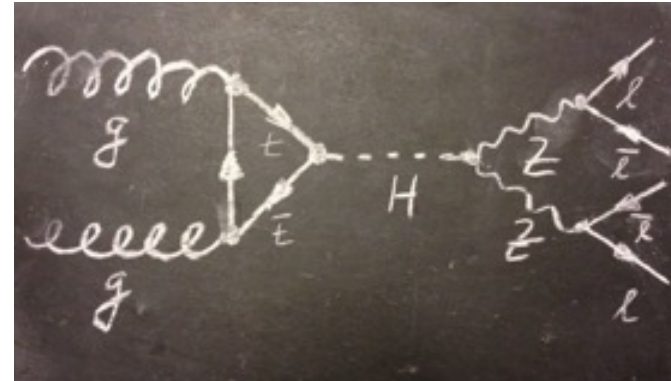
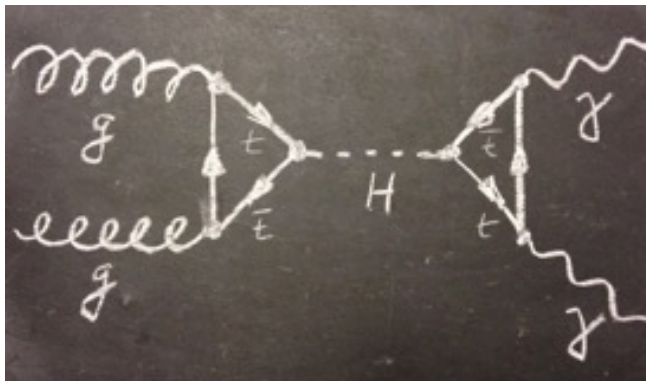
Today we are interested only in two decays: ZZ (and $\gamma\gamma$, if you want)
 Why these two decays and not the most probable one in bb ?

Signals summary

Z boson – electrically neutral mediator of the weak force

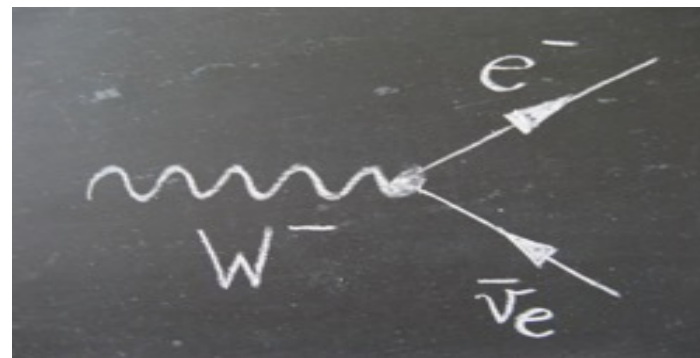
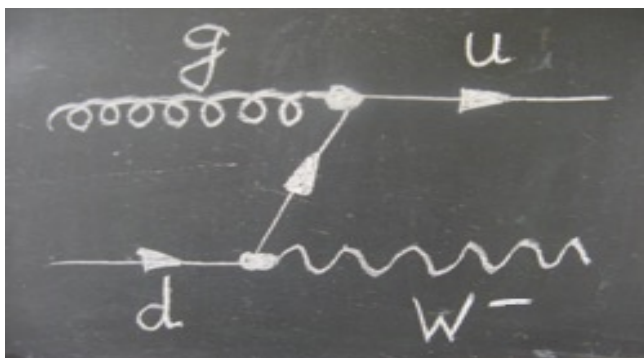


H boson – electrically neutral responsible of the mass of all elementary particles

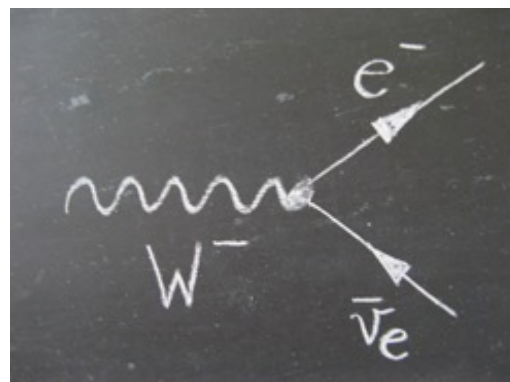
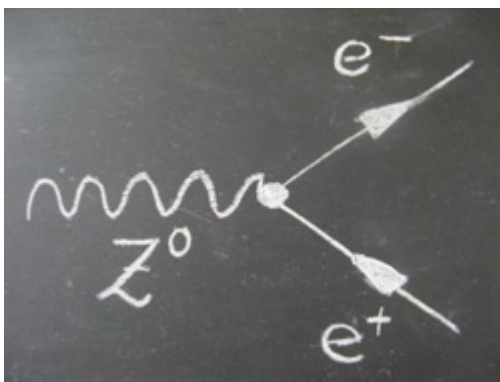


Background (fondo) events

- In any pp collision, a lot of particles are produced! Not only Z and H...
- But we reconstruct Z and H (**signals**) based on their decay products: **muons, electrons and photons**
- All other physics processes producing muons, electrons and photons are called background events



- How can we distinguish background events from signal events?
- By looking at **ALL particles** we want in the final state!



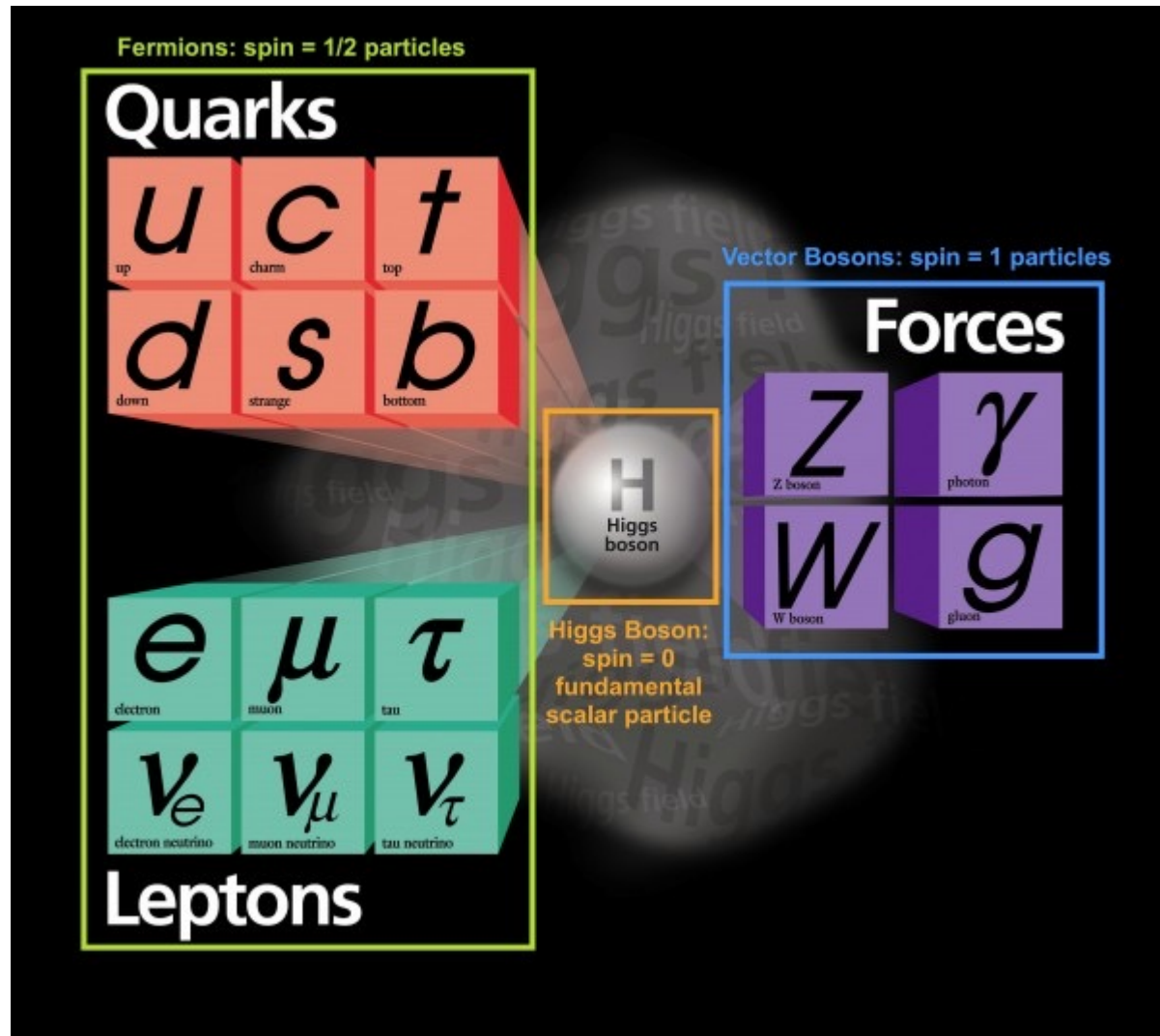
Are they the same??

And now

Hands-on!



Reminder: the Standard Model



Which of these is stable (i.e. can travel for ~100m) ?



