Characteristics of the ATLAS and CMS Detectors

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Outline

- Physics Goals.

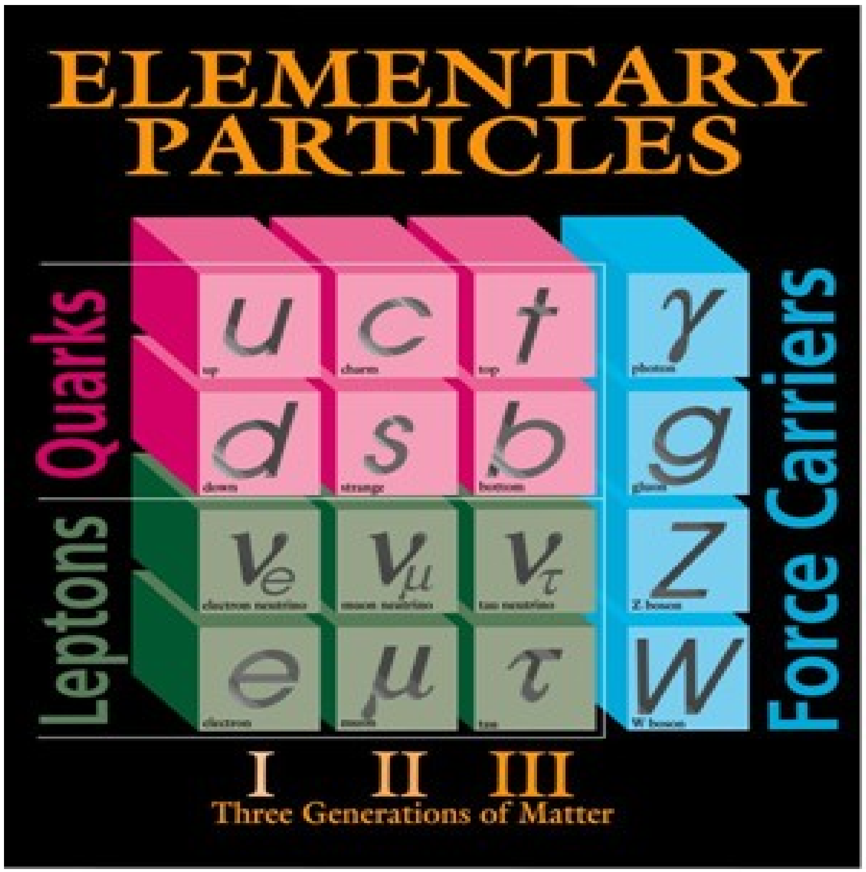
  You have heard about this, I will just re-emphasize a few general issues that strongly impact detector design.
- What do we actually see in the LHC collisions?
- What do we want to detect by examining the events?
- Translating this into a detector design.

  I will mention some of the design choices.
- Trade-offs made in designing the detector, some of the ATLAS and CMS choices.
- What's next?

General Comment: Detectors are performing well and both collaborations publishing many papers based on initial data collected.

Periodic Table of the Very Early Universe: these are the Particles Produced at the LHC.

Standard Model of Particle Physics: Matter and Forces.



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Many of these particles decay (e.g., W, Z, τ) to lighter mass particles in the table. Quarks and gluons carry color and are only seen as constituents of colorless particles such as protons and pions. At high energies they give “jets” of such particles, which are large numbers of particles closely spaced in the detector. Some of the quarks (b and c) and the τ produce detectable displaced decay locations (vertices) near the initial collision, resulting from weak interaction decay.

Presently undiscovered particles (“new physics”) are expected to decay to the known particles or to be non-interacting. The LHC detectors will search for “new physics” at energies well beyond previous accelerators. They will explore the TeV energy scale.

Three Missing Ingredients of the Standard Model

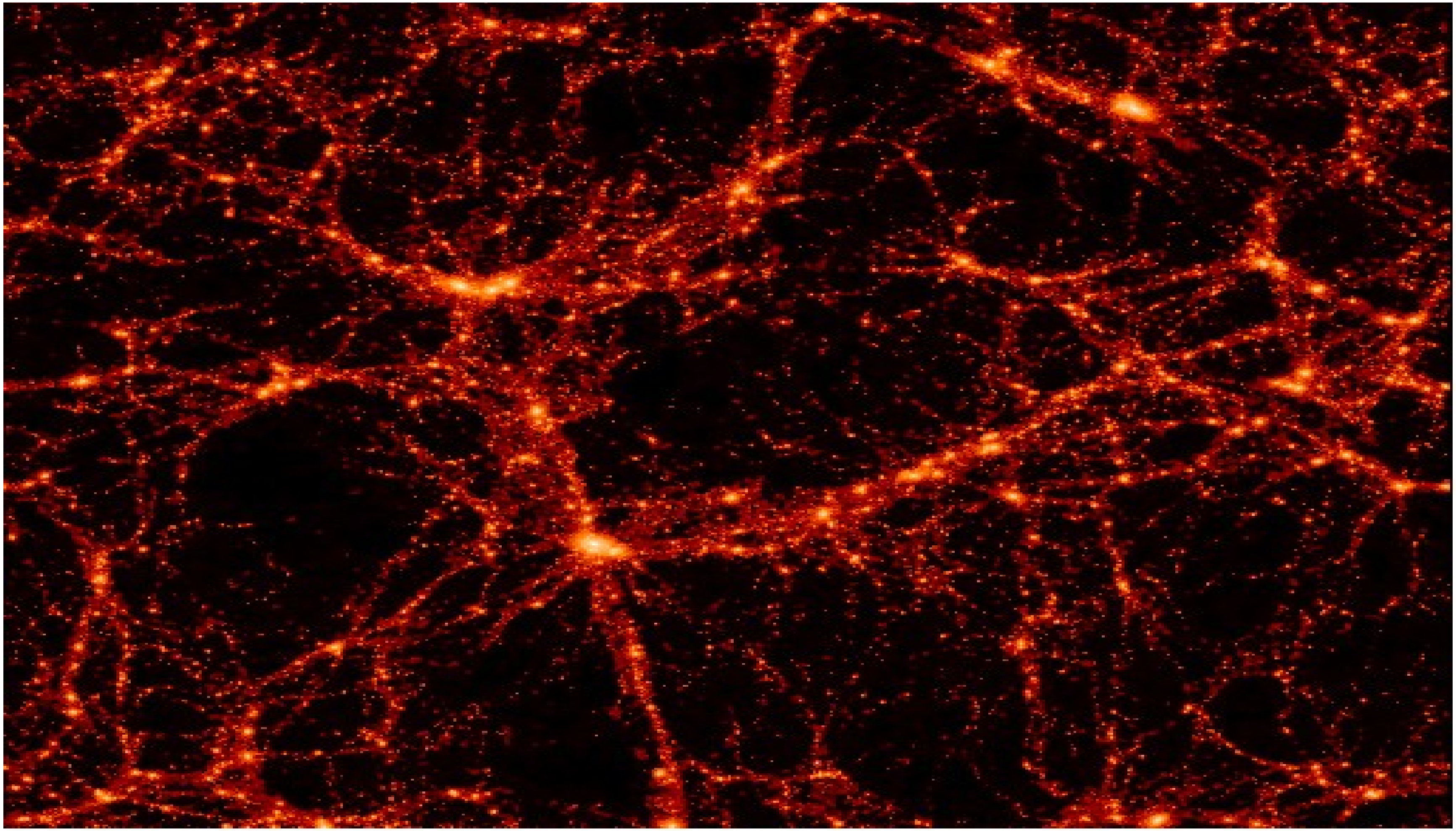
1) **Dark Matter**: made of particles coming out of the big bang, whose gravitational behavior is similar to the other particles. However, weakness of any other interactions (besides gravity probably only has weak interactions) has so far allowed the dark matter to evade direct detection on earth. A good target for the LHC.

2) **Dark Energy**: a form of energy that affects the geometry of space and time and seems unrelated to any particular particle type. So far it can only be studied with telescopes, so the LHC will likely not have an impact on this.

3) **Higgs Field**: A field that uniformly permeates space, provides particles with their mass, and is needed to make the Standard Model equations mathematically consistent. The consistency condition requires that we find evidence within the LHC energy window! Simplest example: single particle called the Higgs boson. The Higgs boson decay pattern depends on its mass, provides the first specification for the detector: **need to be able to discover the Higgs over the full range of possible masses. Requires very broad detection capabilities.**

Also would like to know: is there a more general physics framework for the missing ingredients? Will this lead to additional particles discovered and then incorporated into the "Periodic Table"?

Simulation of Universe's Large Scale Structure: Very small initial fluctuations seen in the cosmic microwave background grow into spectacular structure 13 billion years later due to gravity. **Dark Matter: Invisible hand gathering luminous matter into galaxies**. **Second specification: critical to be able to measure missing energy in events if we are to discover invisible particles at the LHC.**



Scale for plot: 300 million light years on a side.

What do we actually detect?

At a most basic level a particle detection element in a medium measures the local deposition of ionization, collected on electrodes because of electric fields in the medium, resulting in an electrical signal to be read out into a data stream. The ionization may be the result of the traversal of the medium by a charged particle, light produced because of the traversal, or ionization created by showers of particles resulting from interaction of the particle we wish to detect. The detection elements are arrayed to allow us to discern a pattern of energy deposits, which we attribute to the particles produced in the collision. The signals and detectors are organized so we can measure the energy and momentum of the various particles either by a reconstructed trajectory or for showers by proportionality of the signal to the energy (after typically a number of corrections that are based on models and calibration data). Different particles that traverse the detector are distinguished by the type of interactions they have with the medium: strong, electromagnetic, or weak (undetectable, unless the particle decays spontaneously).

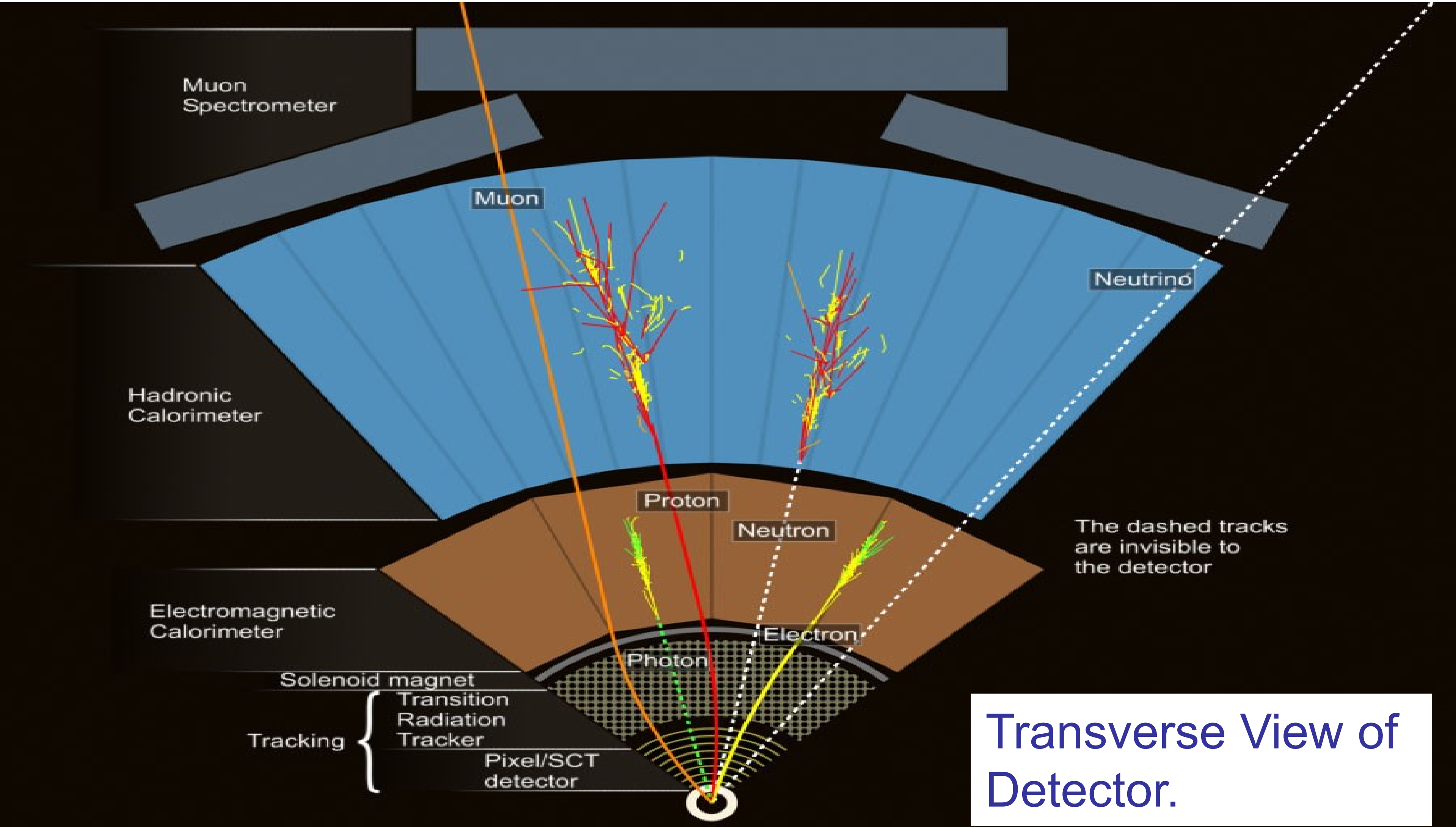
What do we really want to detect?

Based on Table of the Particles: want to reconstruct the passage through the detector of:

1) Jets of particles, signaling the creation of quarks or gluons.
2) Leptons: e, μ, τ, typically signaling a weak decay, for example production of *W* or *Z* bosons, since the leptons are mainly not produced directly in proton-proton collisions.
3) Photons, the only force carrier that we can directly detect.
4) Decay vertices, which indicate the generation number of the particles produced. The third generation is heaviest and in many physics models is an indicator of "new physics" processes.
5) Missing transverse momentum. Neutrinos contribute, but "new physics" is expected to produce much larger values, reflecting a large mass.

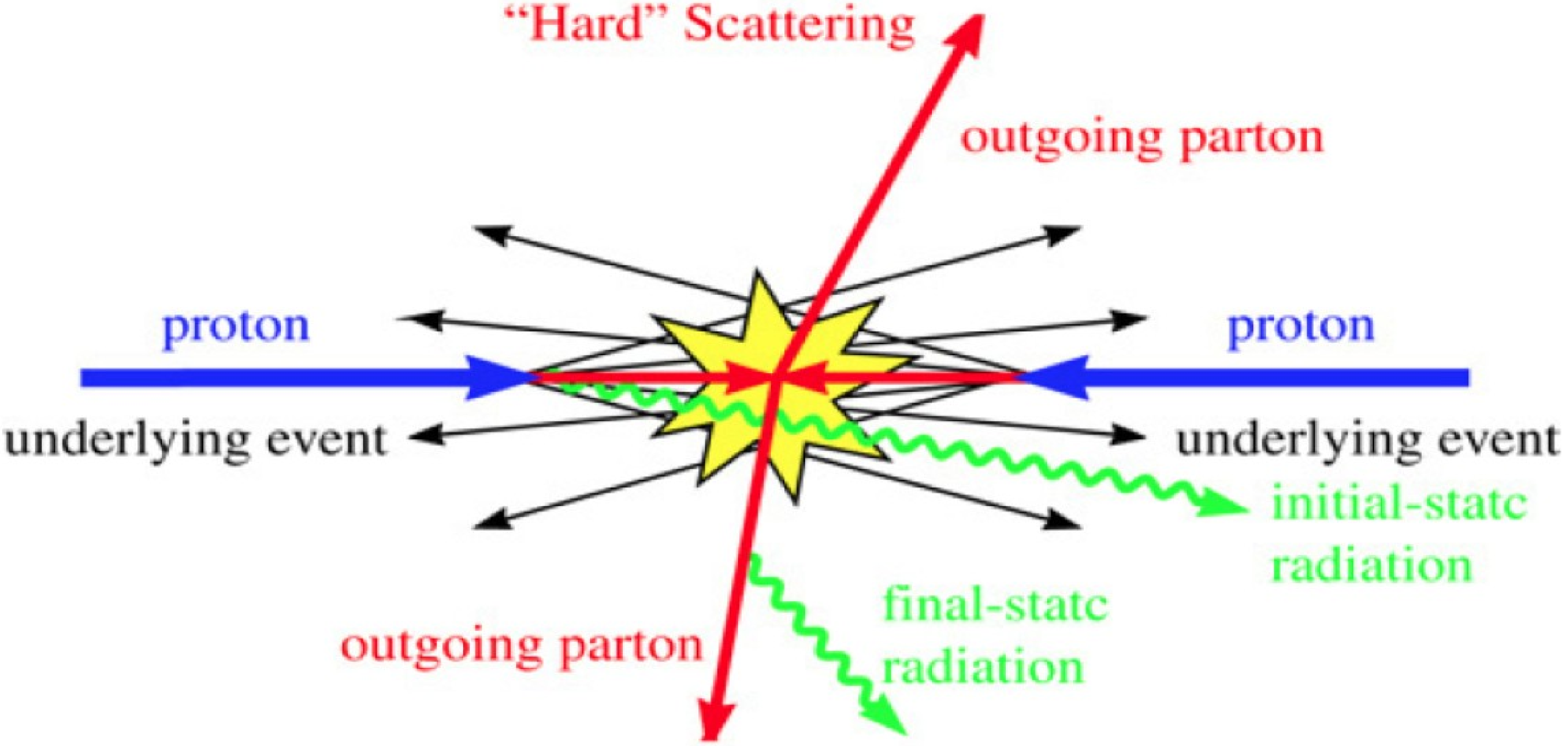
In general a number of signatures are combined to indicate that we are not just looking at typical ordinary events. The mass scale that we are interested in, larger than typically 100 GeV, makes it possible to see signals above background in many model of "new physics" and in particular for the single Higgs boson. Which of the above signatures can be used to find the Higgs boson depends on its mass.

Common elements to ATLAS and CMS: Detector organized as "concentric shells" with end caps, each shell with specific detection tasks. **Another major requirement at the LHC: need to fully absorb energies in calorimeters; this defines transverse dimensions of these large and expensive parts of the detector. Outermost dimension, however, determined by how muon detection is handled.**

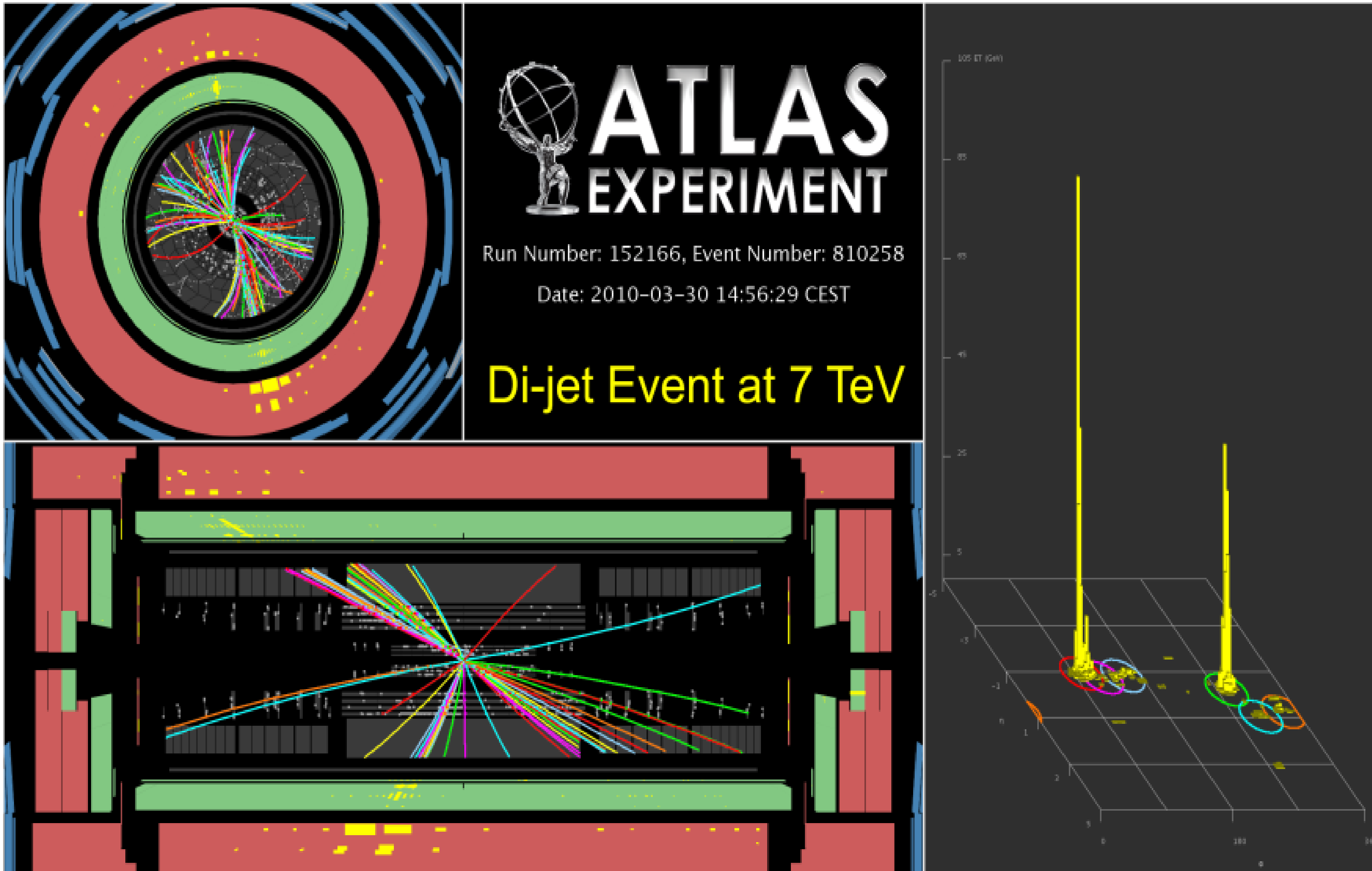


Transverse View of Detector.

Complex events, plus need to detect "invisible particles" carrying large transverse momentum, leads to very long detectors (what goes down the beam directions, and appears as missing energy, is constrained by detector geometry to carry very little transverse momentum). **Both detectors are hermetic down to about 1^0 scattering from beam directions.**



Importance of the Calorimeters in frequently providing a simplified but clear view of the event characteristics. **Feature used in event trigger for both detectors!**

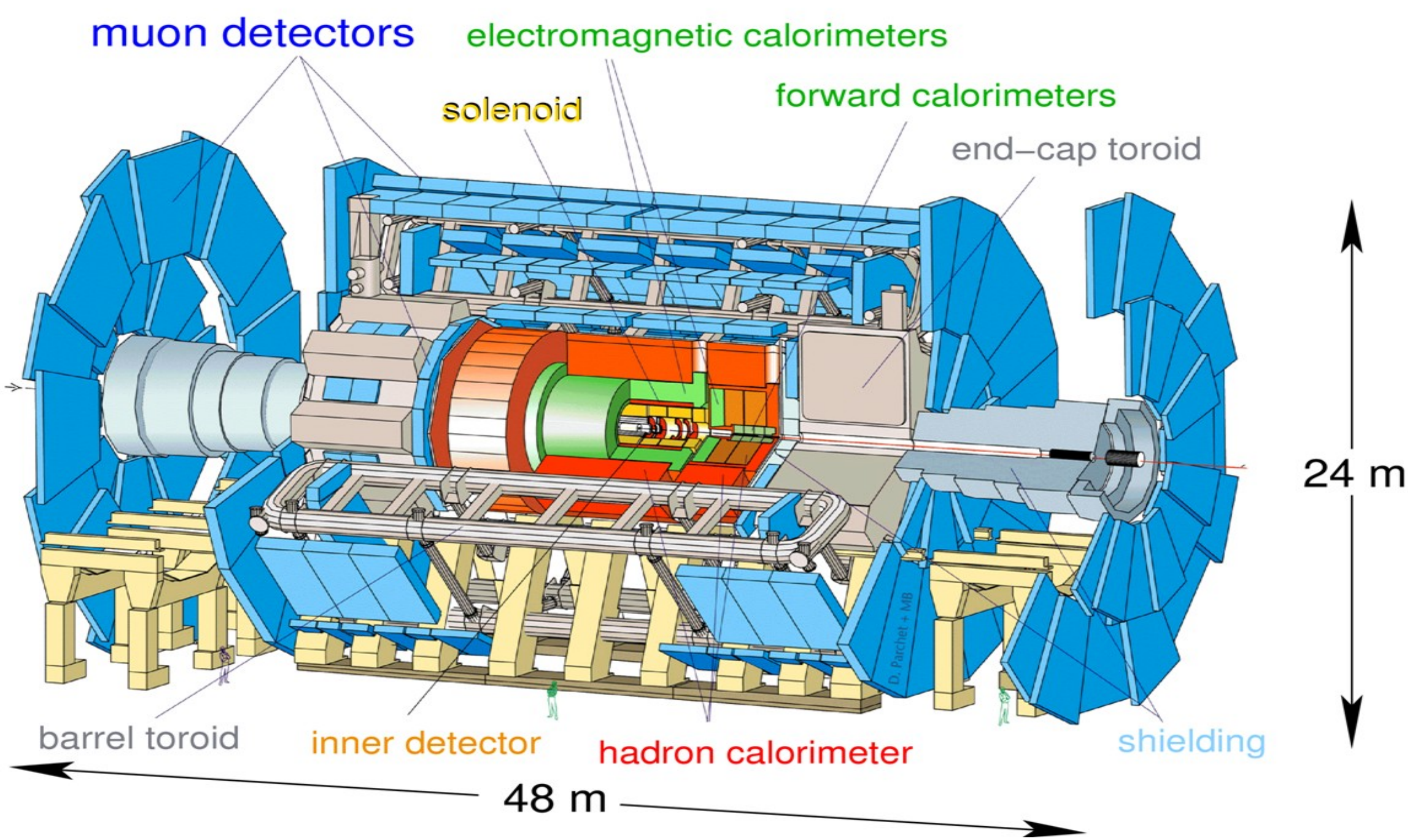


Besides a common detector strategy, many trade-offs are required to reach a final detailed detector design. Examples:

- Choice of granularity of detection elements and how many measurement layers are needed to pin down the particles and their energy and momentum in an event. Example: the charged particle tracking detector is made of layers. Based on event simulations, have to choose the number of layers, what type, the outer radius of the tracker, as well as the size of the magnetic field. Goal: efficient recognition of charged tracks and a targeted momentum and angular resolution after many years of irradiation and with many tracks present.
- Choice of detection medium. Example: choice of an electromagnetic calorimeter material. Here the full shower can occur in an active material (typically crystals) or one where the shower is sampled (detection medium is interspersed with heavy radiator, energy deposited in radiator is not measured). These have different advantages.
- Precision desired for all the different kinds of measurements has to be chosen, guided by our physics goals.
- Strategies for background rejection have important implications for the detector design.
- Cost limitations affect how funds are invested in different parts of the detector.

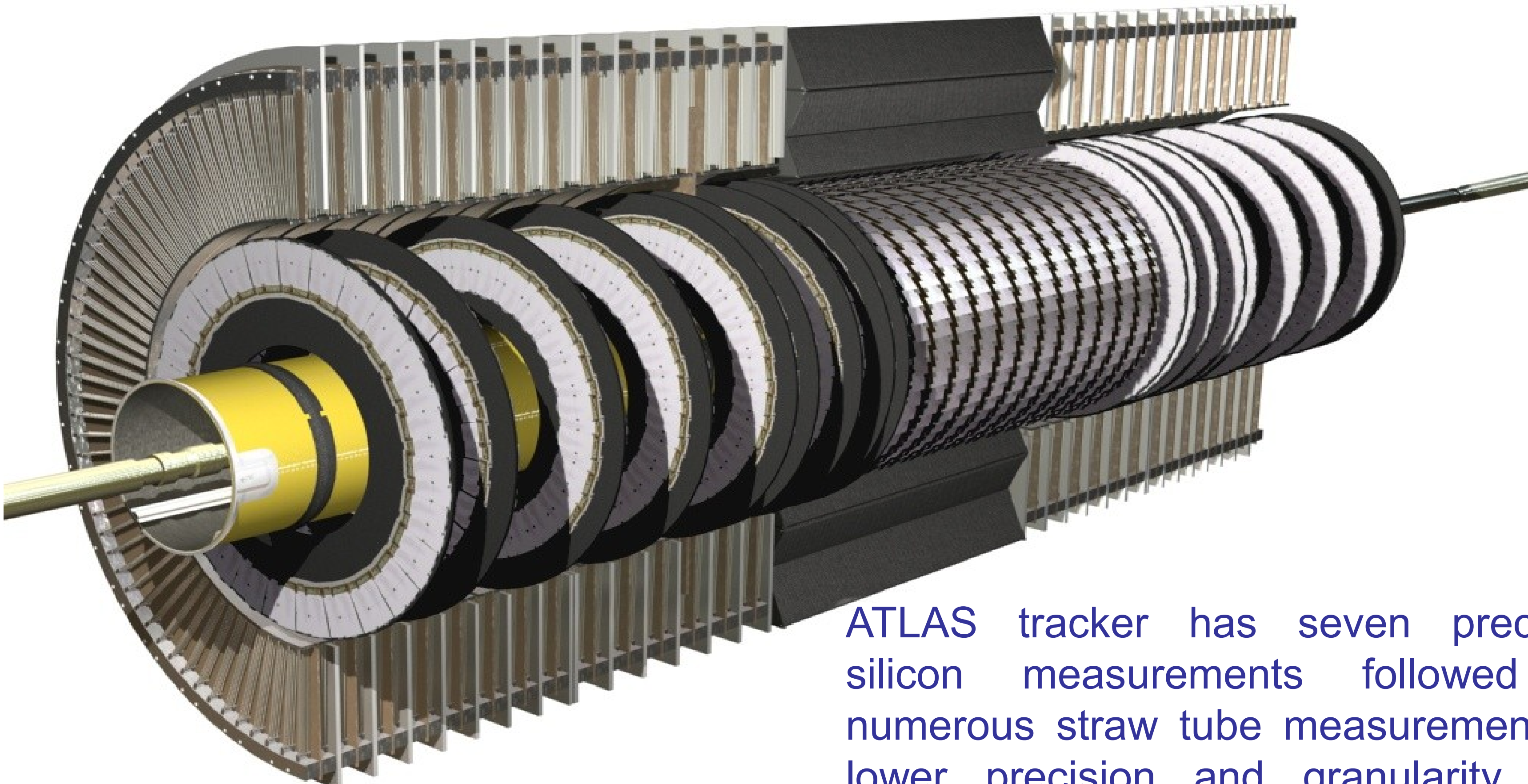
ATLAS and CMS have largely the same physics objectives yet the final detectors are quite different as the balance between the above items has been chosen differently. The performance of both detectors, however, goes well beyond what has been achieved in previous experiments and many elements in the experiments are completely new to the field.

ATLAS Experiment



Other than inner charged particle tracking detector, the other devices are outside the thin solenoid coil, which provides a 2 T field. Muon identification and measurement provided by additional very large toroidal magnet systems. All coils made of superconducting material.

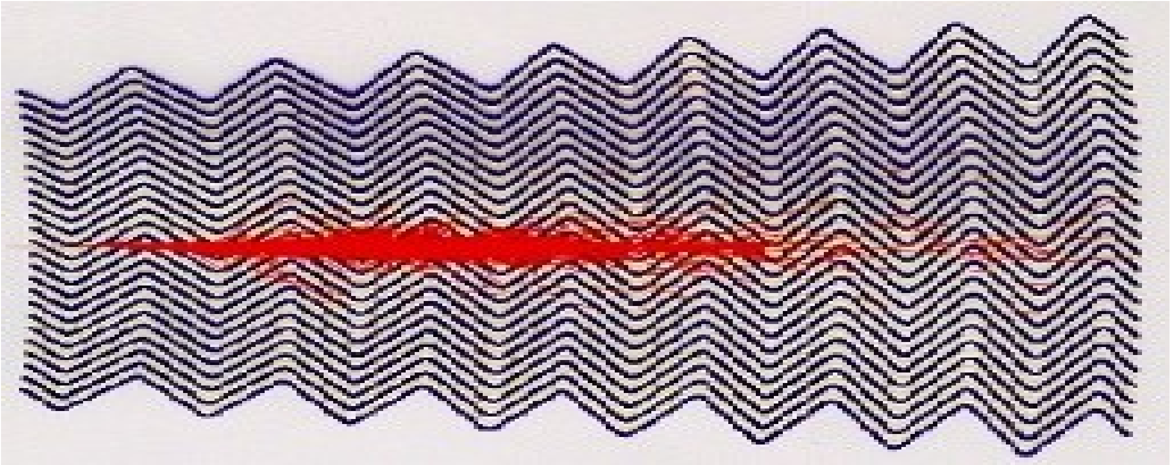
ATLAS Inner Tracking Detector: As for CMS, inner most (precision) layers are made of arrays of silicon pixels, followed by silicon strip detectors (out to 60 cm); outside layers, specific to ATLAS, are made of small diameter straw tubes.



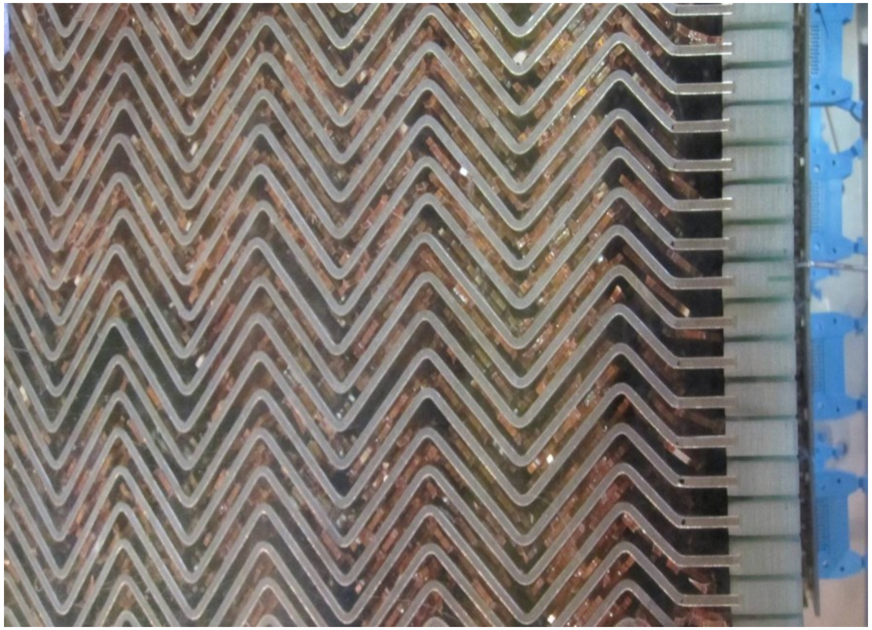
ATLAS tracker has seven precision silicon measurements followed by numerous straw tube measurements of lower precision and granularity. The latter provide a nearly continuous picture of the tracks and help with electron identification by registering large signals for electrons due to transition radiation

ATLAS Electromagnetic Calorimeter

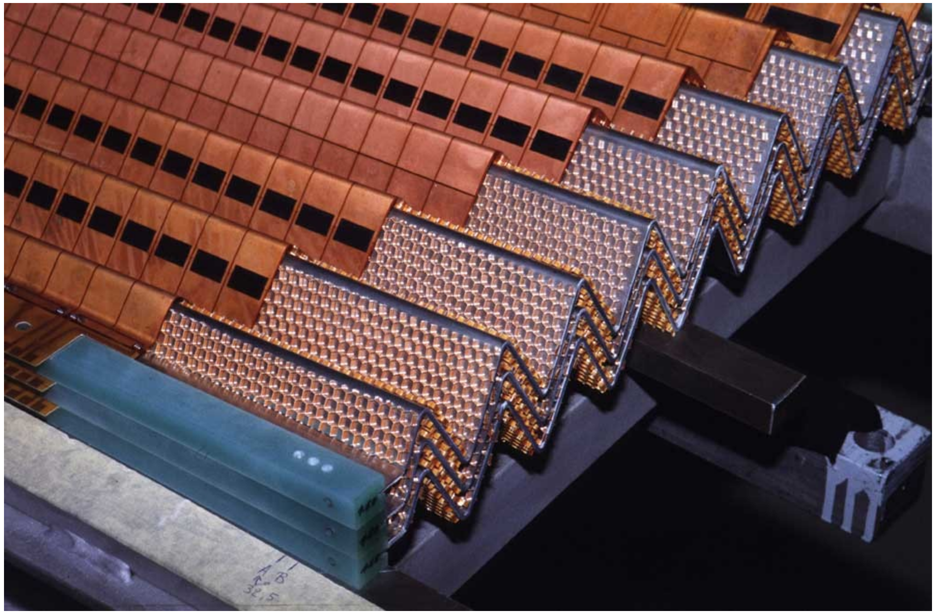
Calorimeter concept: novel design, using an accordion-like radiator structure. Good uniformity in sampling the shower using ionization in Liquid Argon.



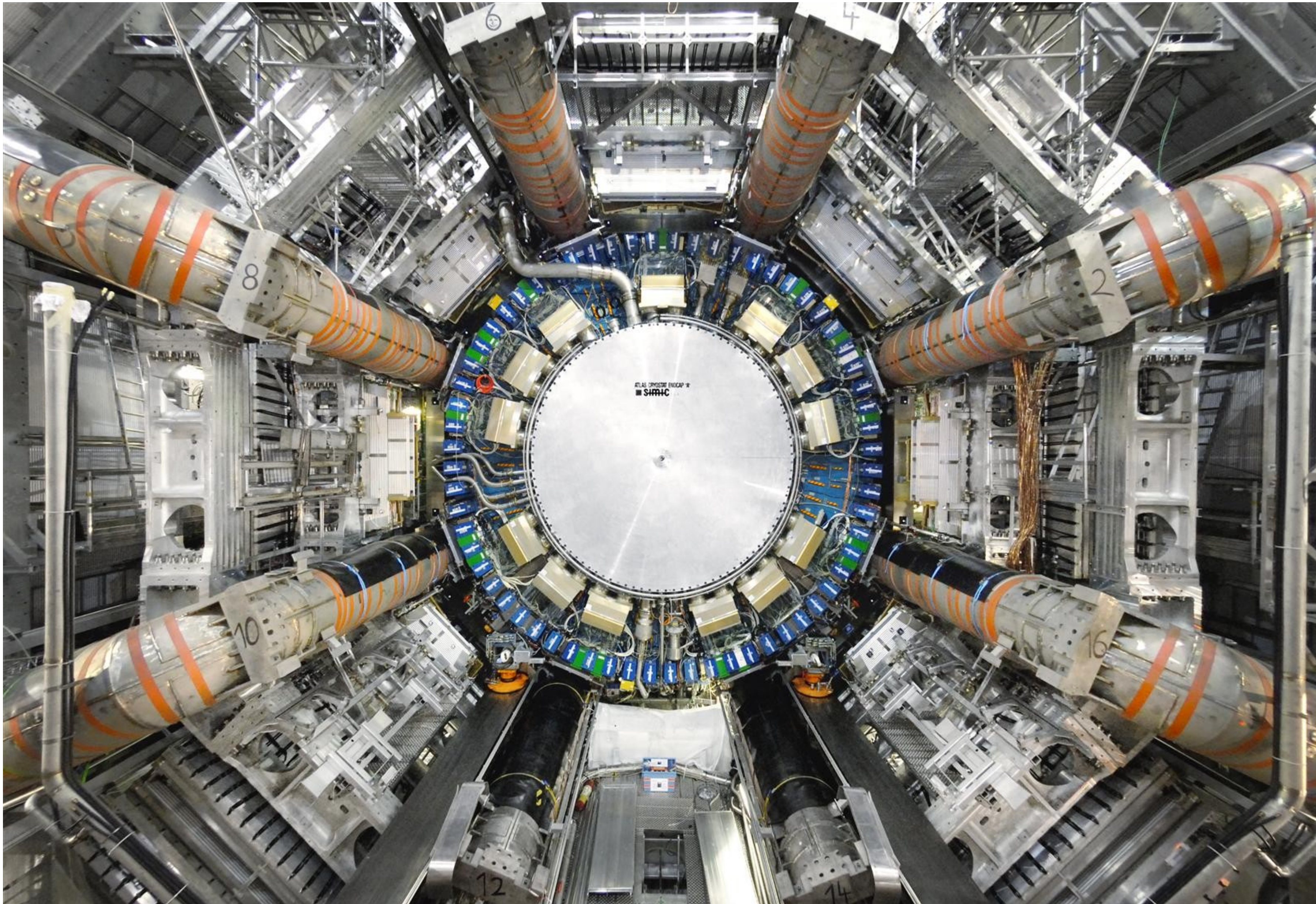
Lead Radiator Material



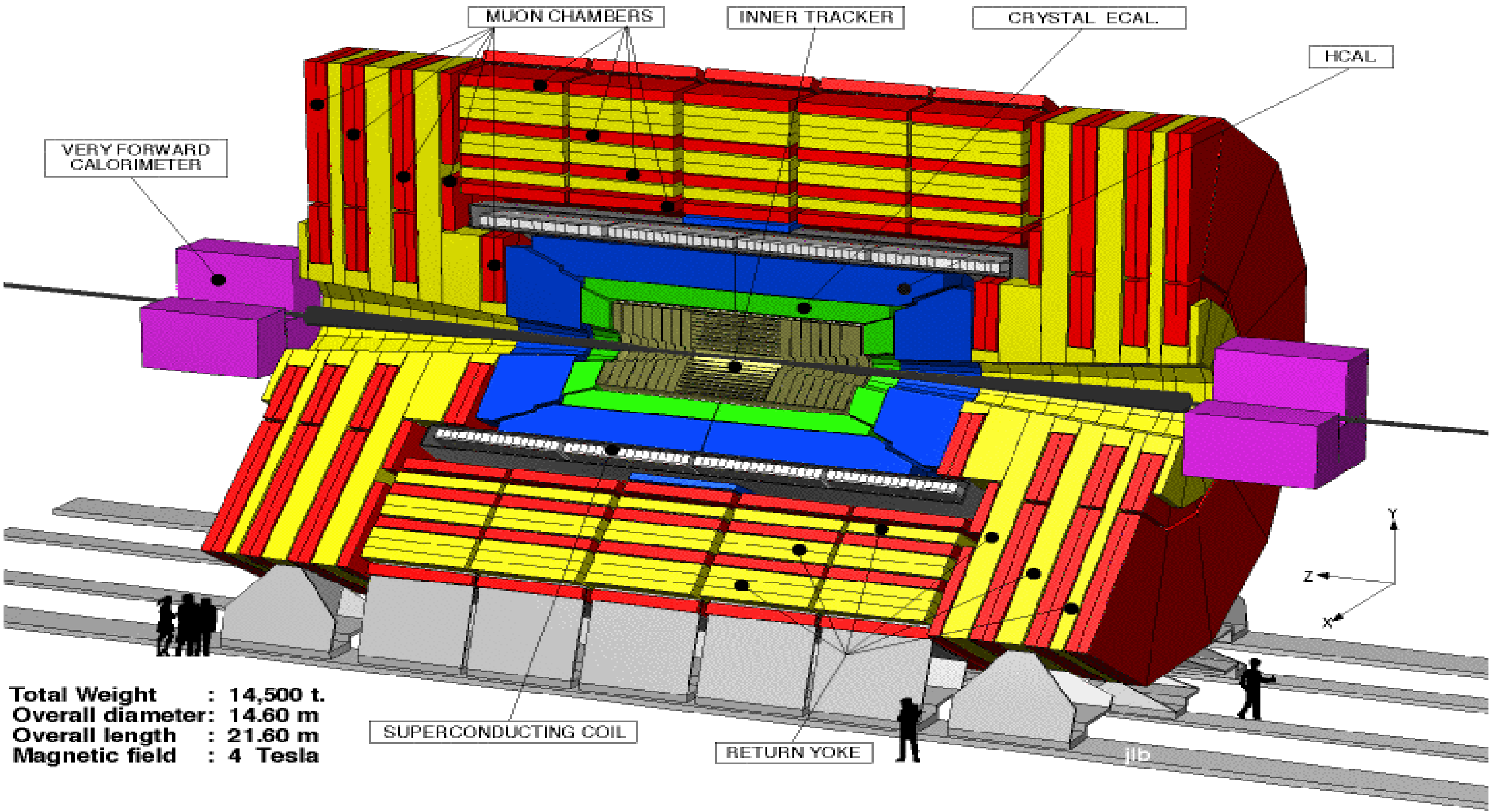
Electrodes for Collection of Ionization



Muon Toroids While ATLAS is Being Assembled



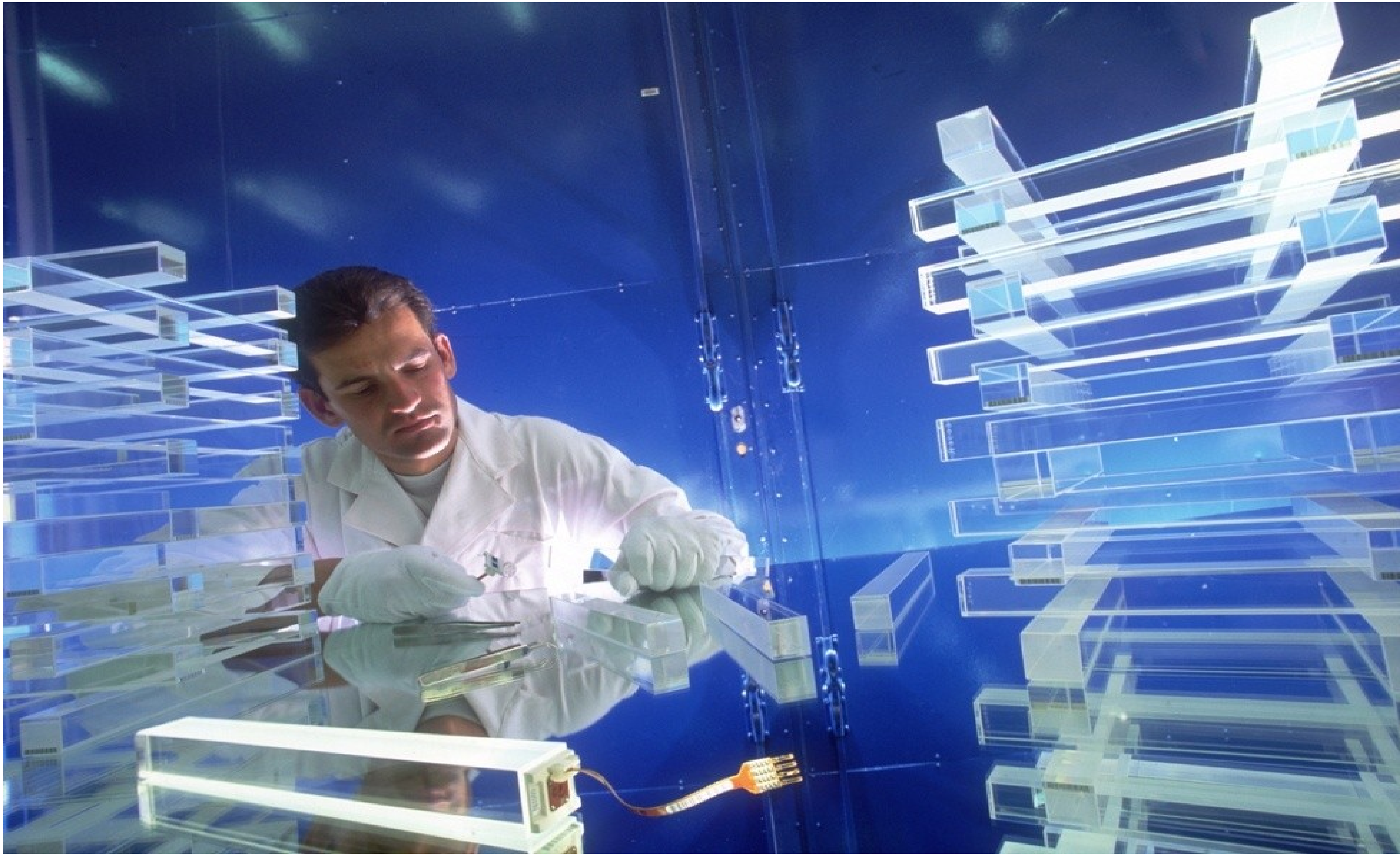
CMS Experiment



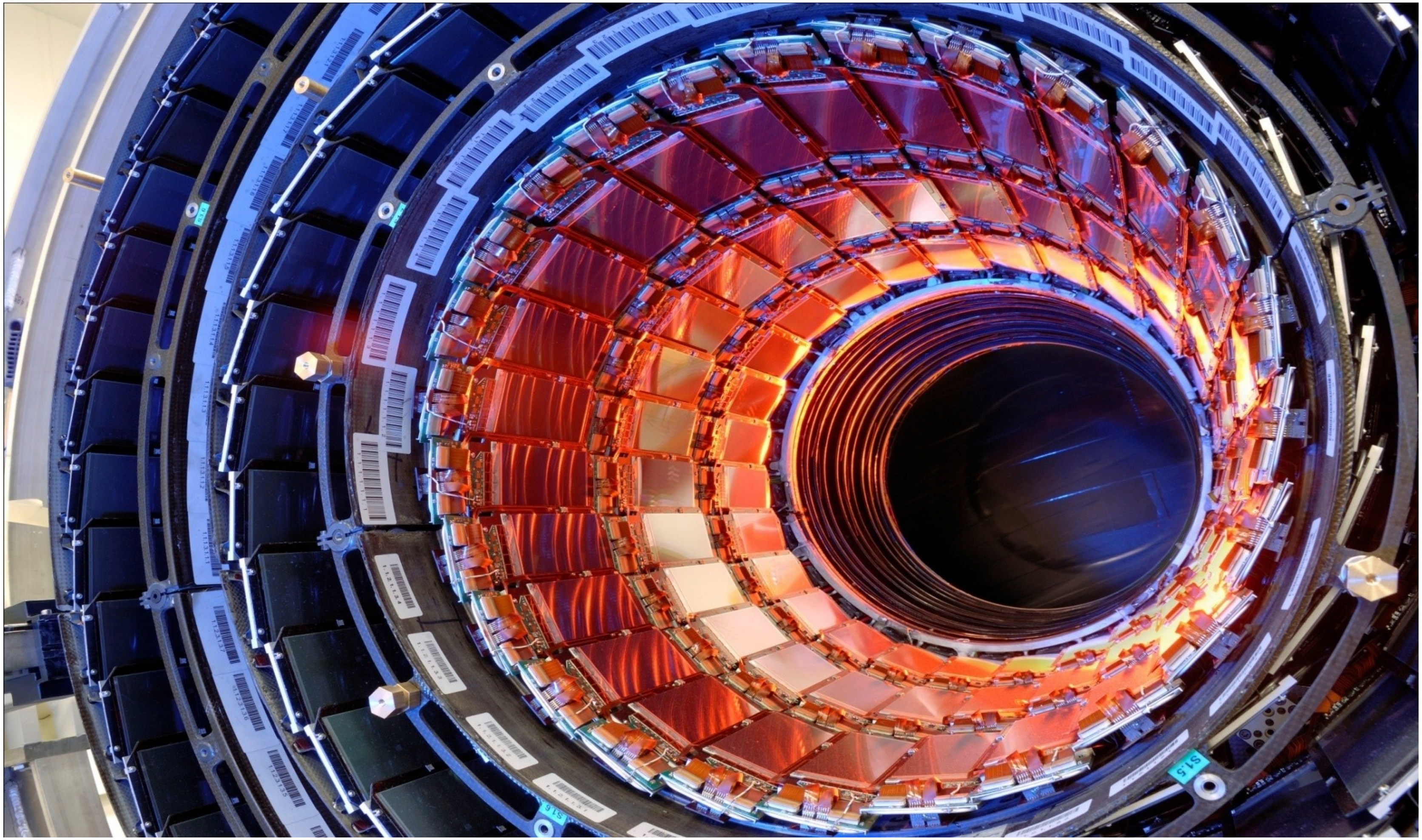
Most of the detectors, other than the muon detection system, which uses an instrumented flux return, and the forward detectors, are inside the thick solenoid coil, which provides a 4 T field. Having the coil outside most of the detectors avoids un-instrumented material in the path of particles.

CMS Large Magnet Coil and Flux Return with Muon Detectors.

Novel Lead Tungstate Scintillating Crystals for Electromagnetic Calorimeter: Very dense, about 25cm long, very fast signals. About 76,000 crystals in the detector.



Part of the CMS Inner Tracker, Showing Individual Silicon Detectors.



CMS has an all silicon tracker made of individual wafers, which provide 13 precision measurements spaced out along a track trajectory. Precision varies from about 10 microns for inside layers to about 65 microns on the outside. Outer radius is 110 cm.

Some Special Emphases

- A special emphasis of CMS is excellent energy resolution for charged particles, photons and electrons. For charged particles this is a result of a large magnetic field (4 Tesla) and large tracking volume (1.1 meters) for the inner tracker; for photons and electrons this is a result of using crystals for the calorimeter material. These result in a single particle resolution a few times better than for ATLAS. Muon detection is provided by instrumenting the iron magnetic flux return with chambers that track muons in the field in the iron. Precision measurement for muons is provided by the inner tracker and at high momentum by the inner tracker and muon system combined. This is a cost effective way to do the muon measurement.
- For ATLAS a special emphasis is excellent background rejection through redundant measurements, excellent muon measurement, and good calorimeter resolution. For electrons, transition radiation in the straw tube tracker can be combined with the momentum and energy measurement in the tracker and calorimeter for identifying electrons and rejecting background. The electromagnetic calorimeter is very fine grained in the transverse direction and has four longitudinal measurements for sampling the shower, the hadronic calorimeter has three samples, to allow careful examination of showers. The muon measurement using the outer air-core toroids (to avoid multiple scattering limitations to the momentum measurement) can be compared to the reasonably high precision inner tracker measurement for excellent background rejection.

Another Example of Trade-offs: Hadron Calorimeters Choices

The electromagnetic calorimeters are about 25 to 30 radiation lengths in depth. For jet measurements each detector has about 10 interaction lengths. These numbers keep fluctuations due to energy leakage to values consistent with resolution goals. These choices are based on detailed simulations.

Detection medium for the hadron calorimeter is scintillator for both ATLAS and CMS (fast, moderate cost). Resolution depends on the sampling fraction and sampling frequency for the scintillator versus the inactive material. Larger for both provides better resolution.

For CMS the hadron calorimeter is inside the magnetic field so the radiator has to be non-magnetic and would like the calorimeter to be as compact as possible since the coil radius will grow with the radius of the calorimeter. The choice of radiator is copper.

For ATLAS the hadron calorimeter is outside the coil and material chosen is iron for cost minimization. The resulting plate thicknesses for ATLAS and CMS are shown below, in units of both radiation length and interaction length:

	Thickness (Radiation Length)	Thickness (Interaction Lengths)
ATLAS (FE)	1.0	0.11
CMS (Cu)	3.5	0.33

Some Approximate Resolution Numbers Which Result from Design Choices

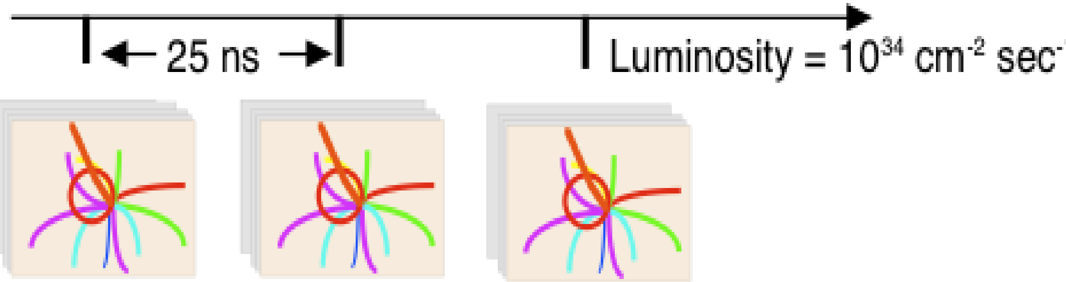
For a 100 GeV particle or jet, percentage measuring error:

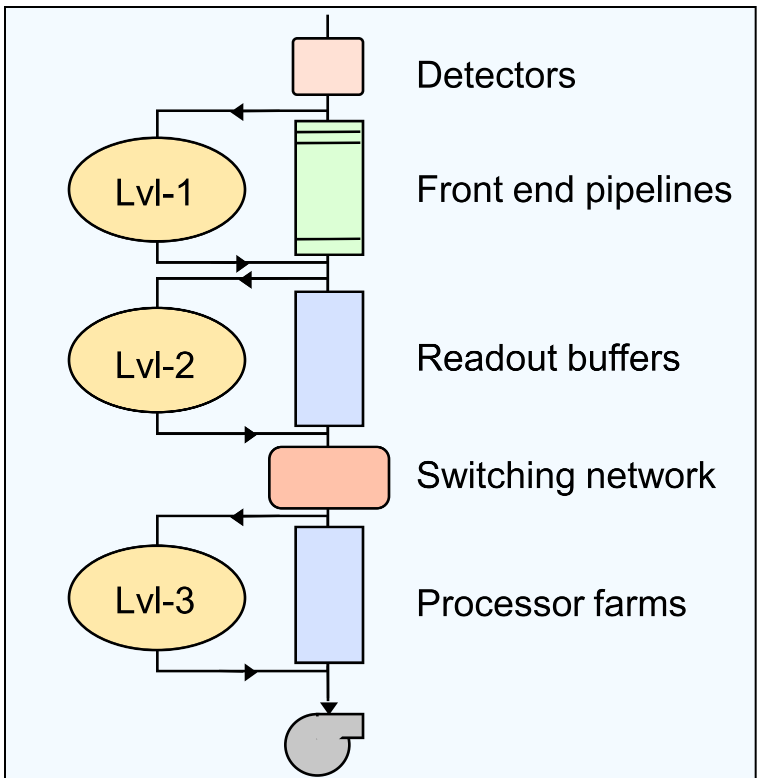
	ATLAS	CMS
Inner Tracker: (Charged Particle)	3.8%	1%
EM Calorimeter: (Electron or Photon)	1.1%	0.5%
Hadronic Calorimeter (Jet of hadrons)	6%	11%
Muon System (Single muon)	1%	1%

Crucial Item: ATLAS and CMS Trigger.

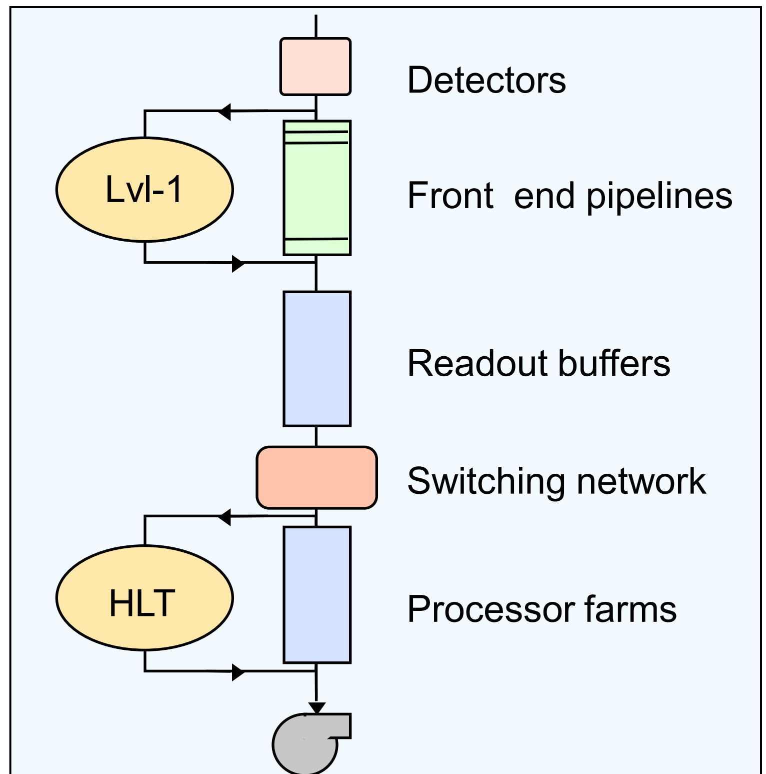
≈ 30 Collisions/25ns
(10^9 event/sec)

10^7 channels
(10^{16} bit/sec)





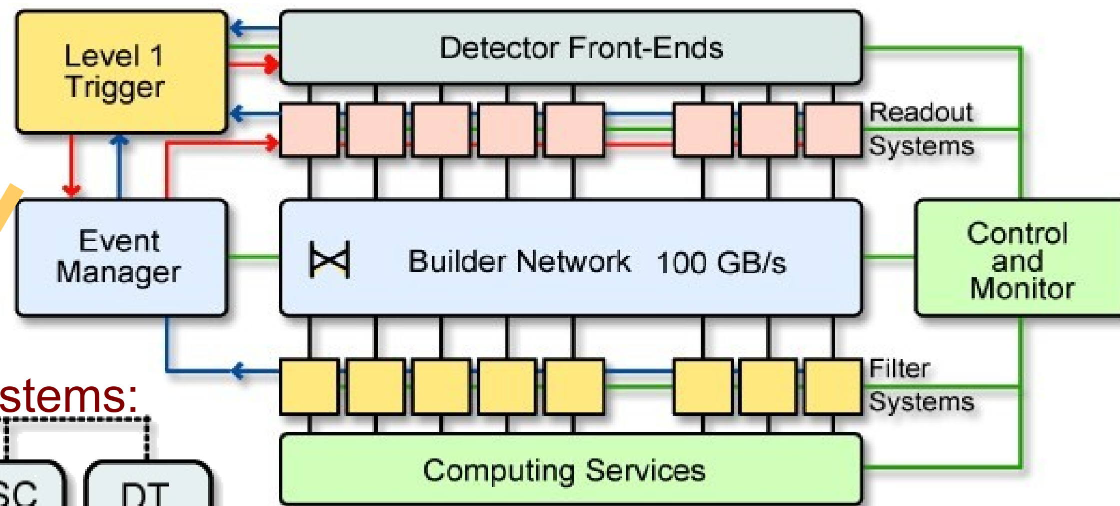
ATLAS: 3 physical levels

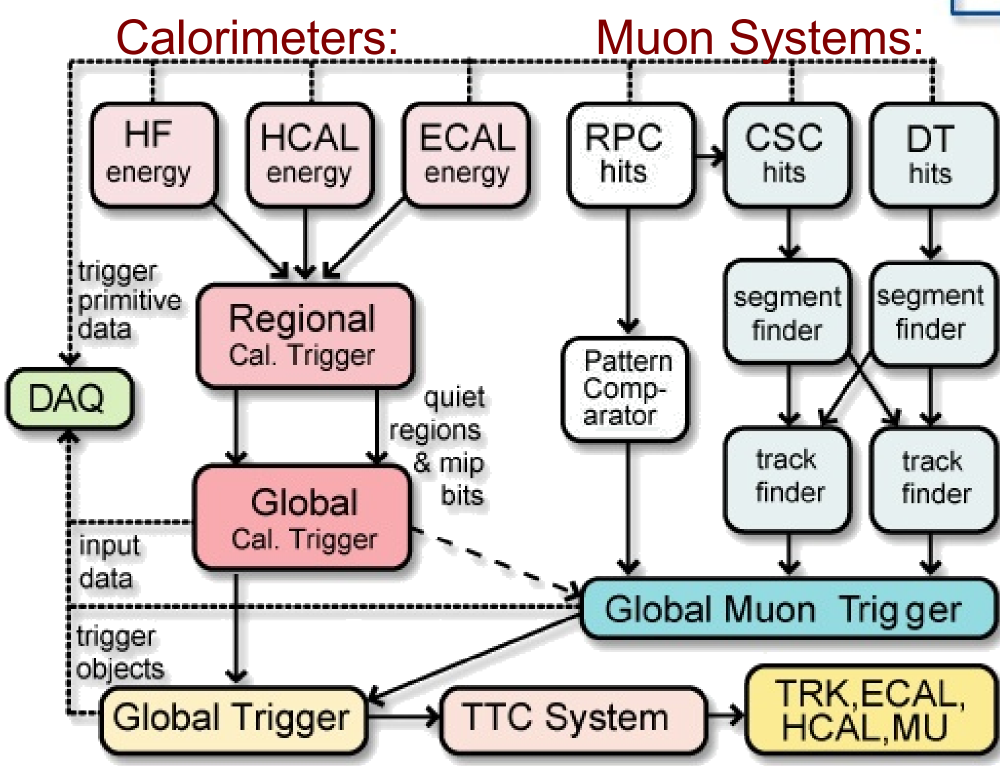


CMS: 2 physical levels

CMS Trigger & Data Acquisition System

Level 1 Trigger fully experiment specific electronics. Higher Level Trigger uses commercial devices to profit over time from advances in industry.





Interaction rate: 1 GHz

Bunch Crossing rate: 40 MHz

Level 1 Output: 100 kHz (50 kHz initial)

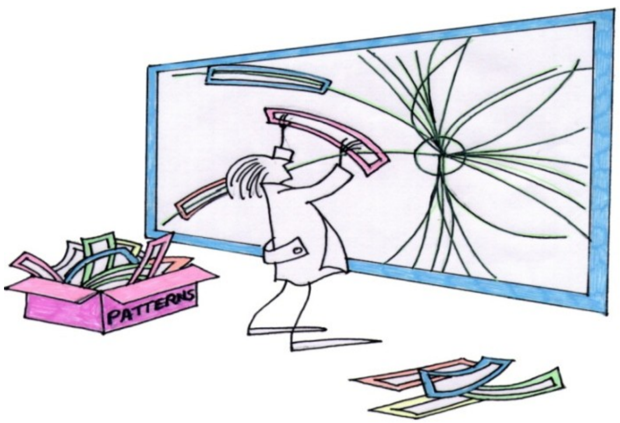
Output to Storage: 100 Hz was design, run at few hundred Hz.

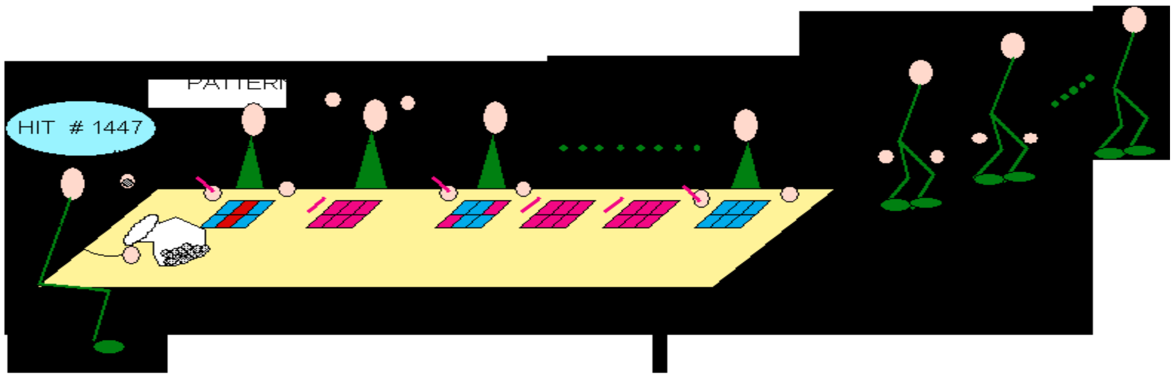
Average Event Size: 1 MB

Data production: few TB/day

Trigger evolves over time as we understand the detector, learn about the physics, and make use of latest available electronics. Example: proposed ATLAS Fast Tracker (FTK); electronics for very fast execution of two time-consuming stages in charged particle track finding.

- **Pattern recognition –** find track candidates with enough Si hits.





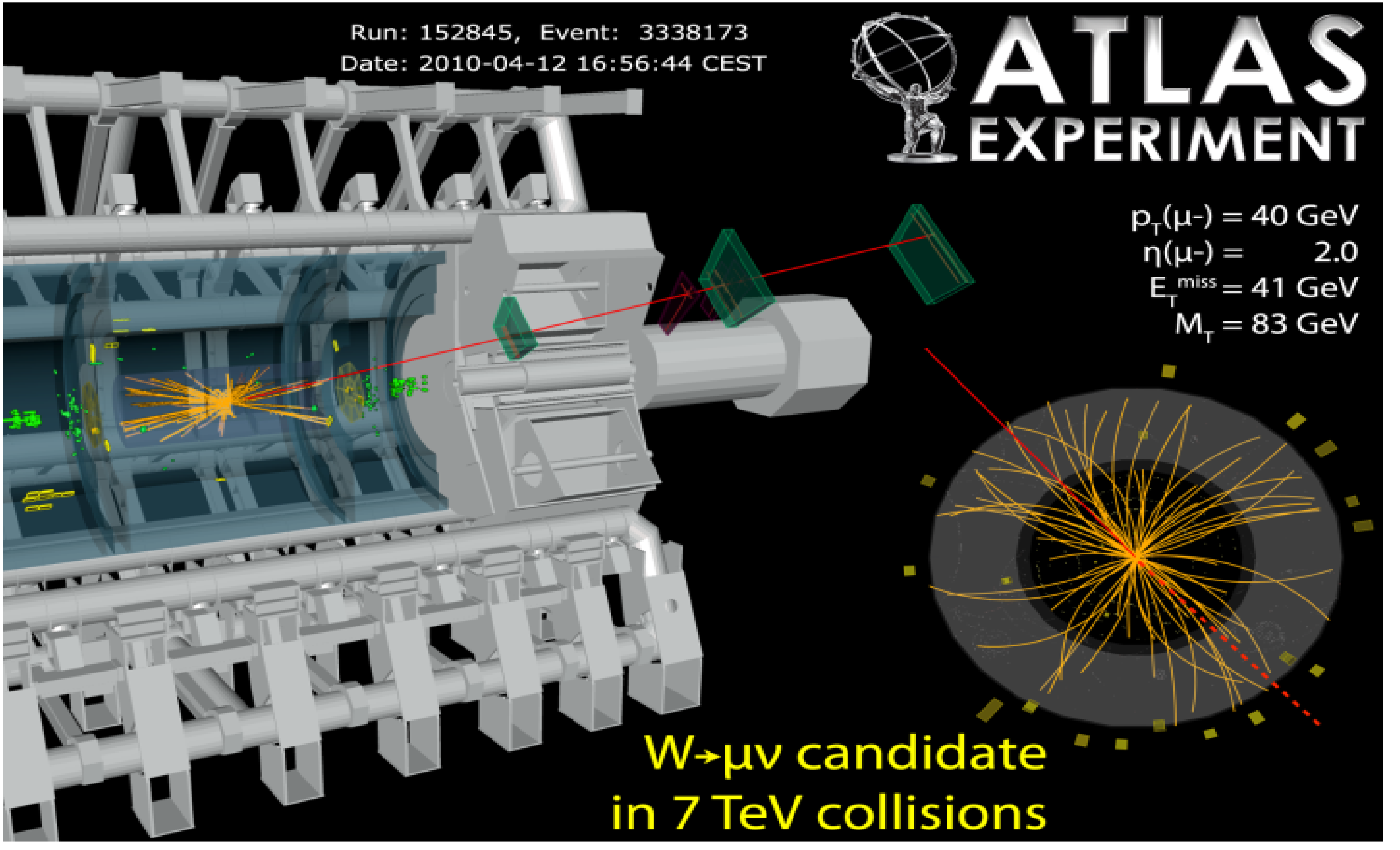
  - **10^9 prestored patterns used in FTK, simultaneously see each silicon hit leaving the detector at full speed.**

- **Track fitting –** precise helix parameter & χ^2 determination.
  - **Equations linearized in the 14 local hit coordinates, provided by the 7 precision inner tracker layers. Gives good resolution using pre-stored constants *a* & *b* (below). VERY fast in FPGA.**

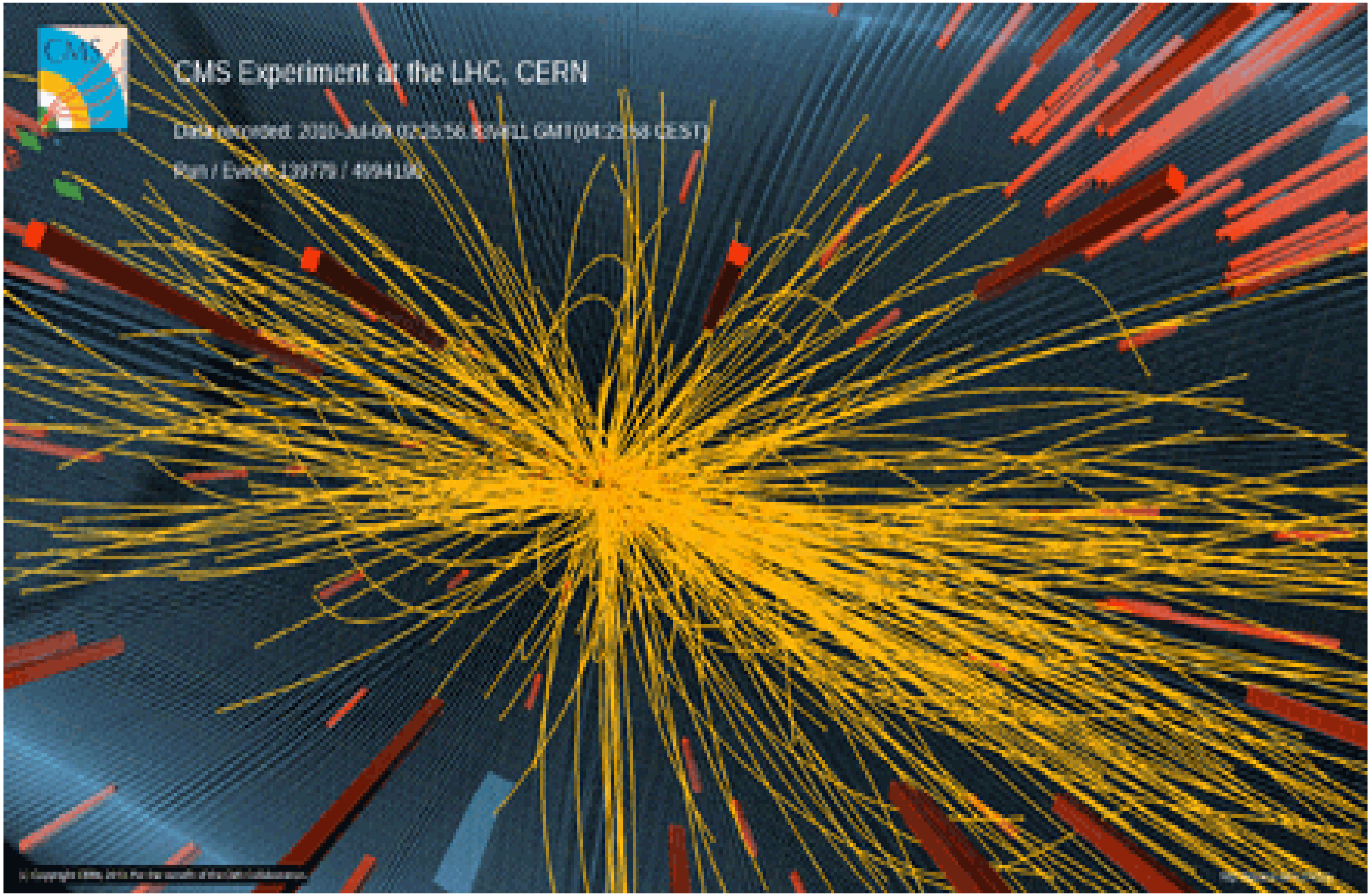
$$p_i = \sum_{j=1}^{14} a_{ij} x_j + b_i$$

Experiments are not static over time! However, easiest to make changes in electronics, rather than in large mechanical structures.

Experiments are Taking Data!



CMS Event with Over 100 Particles.



Angels and Demons at CERN. But will there be a Higgs boson detected? Good chance using 2011-2012 data.