



Particle Detection

the ATLAS Detector as an Example

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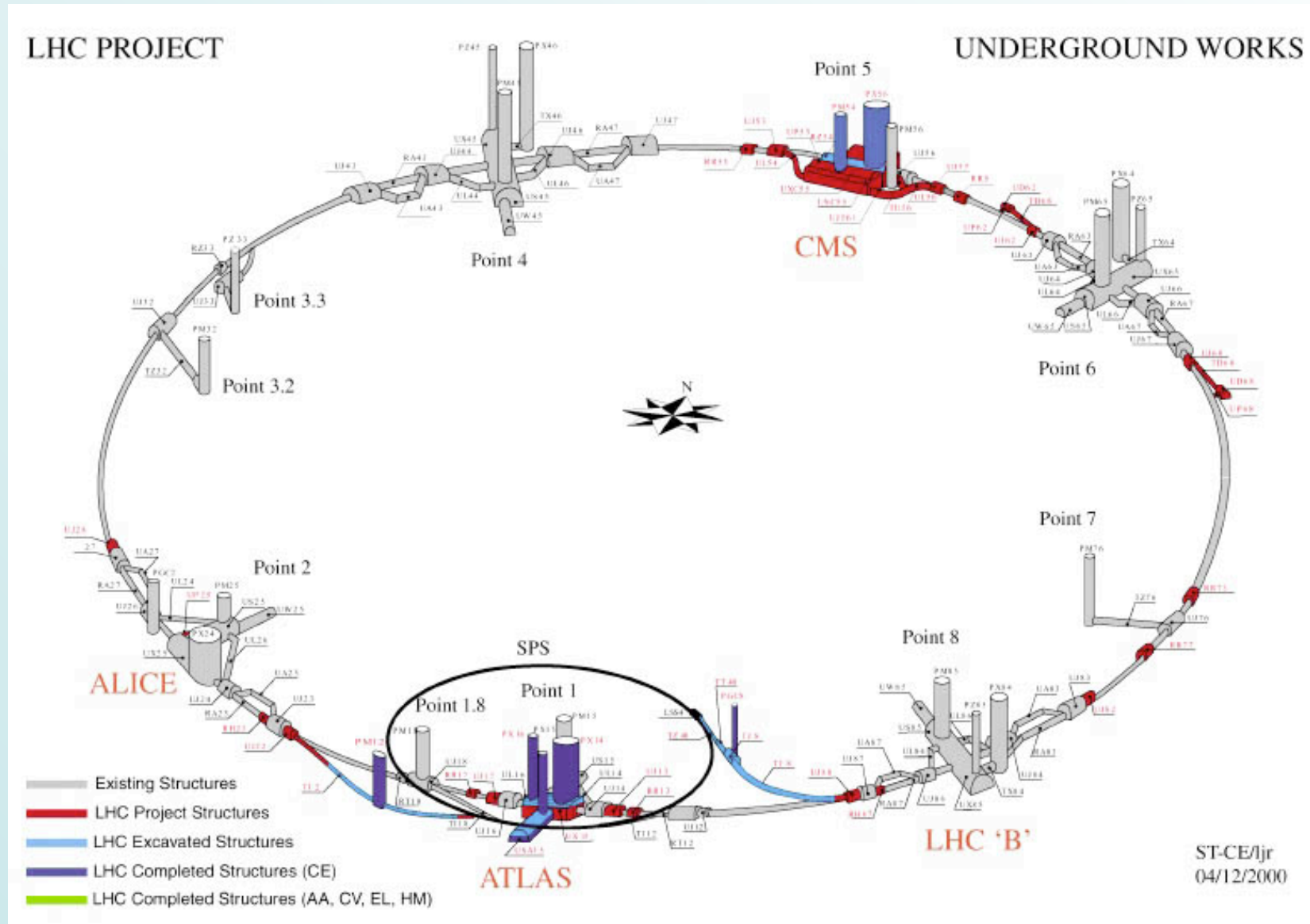
What's Happening in this Bucolic Place?

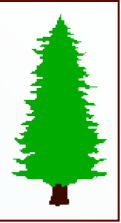


Arial View of CERN and the Geneva Countryside



Exciting New Physics at the LHC!





ATLAS – Objectives and Design

This talk will attempt to be complementary to other talks you will hear about the recent and future discoveries at the LCH. I will stress aspects of the detector, in particular particle detection, and hopefully not repeat most of the physics motivation and LHC descriptions.

The stated purpose of ATLAS:

A search for new physics:

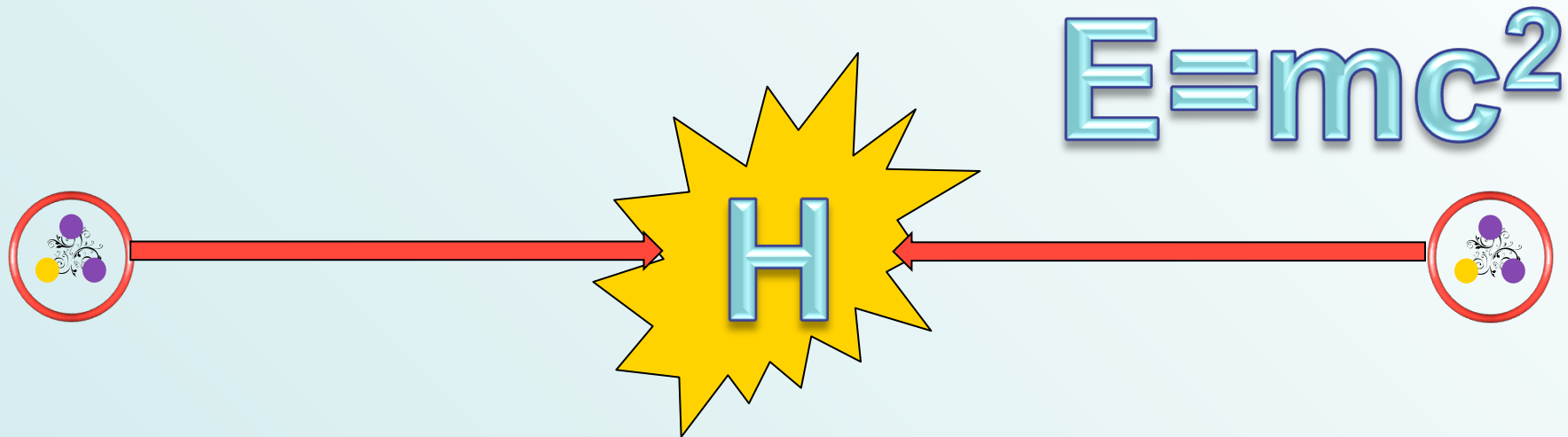
- Search for the Standard Model Higgs particle.
- Search for Supersymmetric particles.
- What new surprises might show up at a new energy regime.

Detailed studies of known sectors at higher energies with high luminosity:

- Study Top-quark Physics.
- Study B-quark Physics.



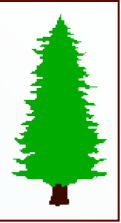
How Do We Look for these Discoveries?



We bang two protons together hoping a quark or gluon in each will annihilate to form something new.

It happens very rarely so we collide two very high intensity beams of protons.

We expect that anything new that is created will be very short lived. We, therefore, will likely see only the decay products and not the original new object.



As an Example – Higgs Production

At hadron colliders, the relevant processes are

$$gg \rightarrow h^0 \rightarrow \gamma\gamma,$$

$$gg \rightarrow h^0 \rightarrow VV^{(*)}, \quad [V = W \text{ or } Z]$$

$$qq \rightarrow qqV^{(*)}V^{(*)} \rightarrow qqh^0, \quad h^0 \rightarrow \gamma\gamma, \tau^+\tau^-, VV^{(*)},$$

$$q\bar{q}^{(\prime)} \rightarrow V^{(*)} \rightarrow Vh^0, \quad h^0 \rightarrow b\bar{b}, WW^{(*)},$$

$$gg, q\bar{q} \rightarrow t\bar{t}h^0, \quad h^0 \rightarrow b\bar{b}, \gamma\gamma, WW^{(*)}.$$

Note all the decay channels.

Heavy particles like Ws & Zs are also short lived and decay into other objects.

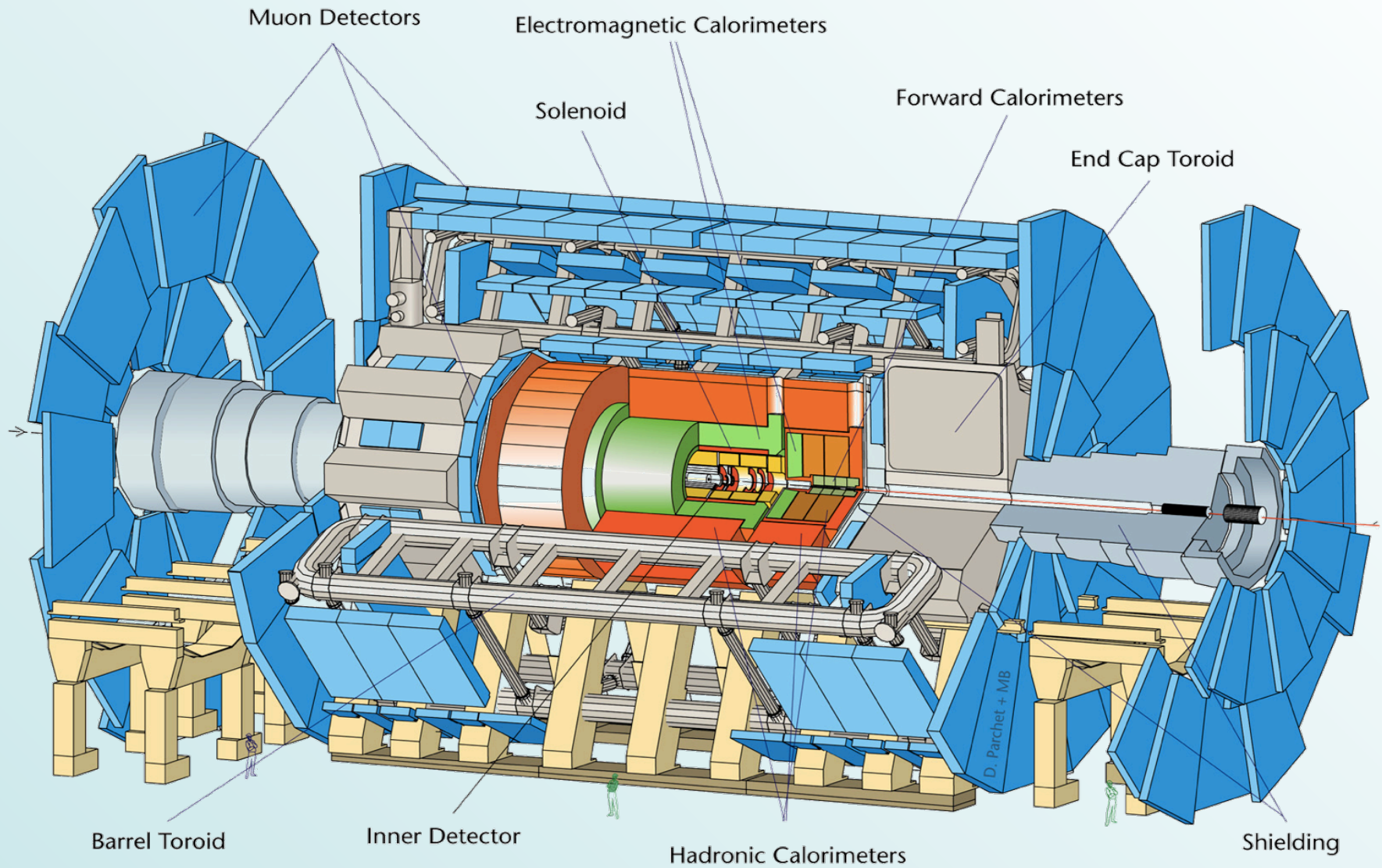
Detection of γ s and leptons is crucial as well as reconstruction of Ws.

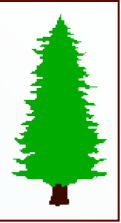
Each event yields many particles. They must be identified along with their energy or momentum.

What two channels did ATLAS report on the 4th?



The ATLAS Detector





Some ATLAS Specifications

Detector Diameter: 25 meters

Overall Weight: 7000 tons

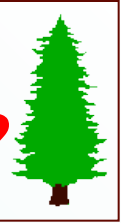
Target Luminosity: 10^{34} particles/cm²-s

Energy: 7 TeV protons on 7 TeV protons
(heavy ions in the future)

Collision Rate: One bunch crossing collision every 25 ns (40 MHz)
Approximately 20-25 proton-proton collisions per bunch crossing

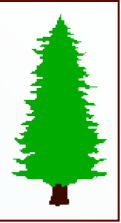
Trigger Rates: 150 kHz - Level 1
1 kHz - Level 2
100 Hz - Level 3 (written to storage)

Data Size: ~1 Mbytes/event
~1 “interesting” event per 40 million collisions



Why so Many Detector Components– Why so Big?

- The produced particles decay into many different types of known particles.
- These particles carry some fraction of the initial beam energy. Therefore, most have relatively high energy – typically 10s of GeV.
- At these energies, different particle types require different detection schemes.
- High energy charged particles require a large volume of magnetic field to bend them and thus measure their momentum.
- Measuring the energy of these particles requires sufficient volume to capture all their energy.



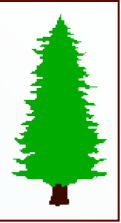
What Can We Measure for Each Particle?

- **For charged particles:**
 - What is its charge?
 - What is its momentum?
 - Where is its origin (i.e. primary interaction point or displaced decay point)?
 - What type of particle? (e, μ , p, π , k, etc.) – referred to as “Particle ID”
- **For neutral particles:**
 - What is its energy?
 - What are possible origins? (We will see that without a track we can only guess at a trajectory of possible origins.)
 - What type of particle? (n, π^0 , k_S , k_L , etc.)
- **With all this information, we can attempt to reconstruct what sequence of particle production and decays took place.**



Trackers and Calorimeters

- **Tracking charged particles:**
 - If we can measure the trajectory of a charged particle in a magnetic field, we will measure the sign of its charge and its momentum.
 - If we can measure the trajectory precisely enough, we can determine where the particle track originated.
 - Typically charged particle detectors are contained in a strong magnetic field.
- **Calorimeters:**
 - Neutral particles don't interact with a magnetic field. We need measure their energy by absorbing all their energy and measuring the energy deposited – a calorimeter.
 - Some calorimeters are segmented such that the direction of the deposited energy can be measured thus giving a trajectory of the incoming neutral.
 - If we place the tracking detector in front of the calorimeter, then the absence of a charged track pointing to the deposited energy in the calorimeter implies the energy came from a neutral.



Particle ID

- Particle ID is often the most difficult task – many schemes measure velocity in addition to momentum.
- Time of Flight (TOF):
 - TOF + distance \Rightarrow velocity; combined with momentum \Rightarrow mass
 - This will often isolate the ID of charged particles.
 - At LHC energies & ATLAS sizes, TOF differences are too small.
- Cherenkov Radiation Detector:
 - The angle of the radiation cone is dependent upon particle velocity.
 - Measuring this angle is often difficult in a multi-particle detector.
- Transition Radiation Detector:
 - The energy of emitted photons by a charged particle transitioning a change of media is again dependent upon its velocity.
- Often ID is accomplished by a process of elimination, for example:
 - e^- , e^+ and γ produce a characteristic shower in a segmented calorimeter.
 - Knowledge of a track or missing track plus this shower makes this ID.



The ATLAS Inner Detector

The Inner Detector (ID) is organized into three sub-systems:

Pixels

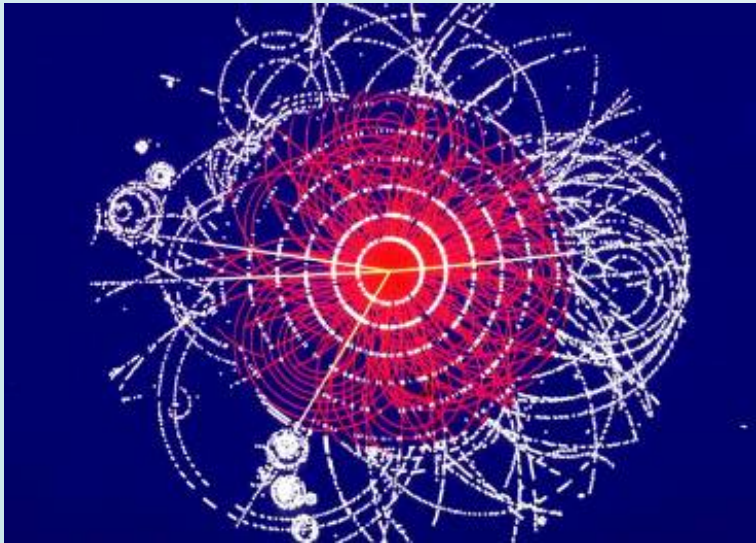
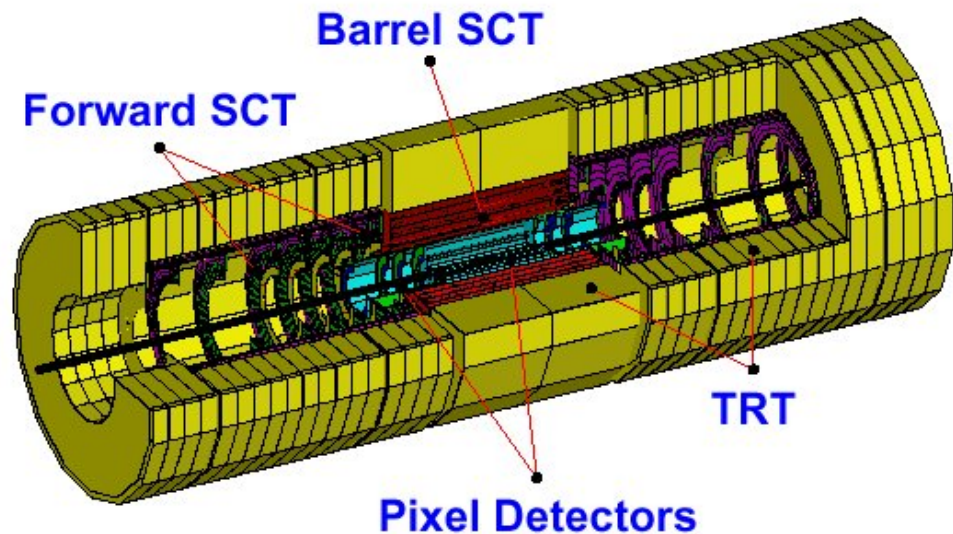
$(0.8 \times 10^8 \text{ channels})$

Silicon Tracker (SCT)

$(6 \times 10^6 \text{ channels})$

Transition Radiation Tracker (TRT)

$(4 \times 10^5 \text{ channels})$

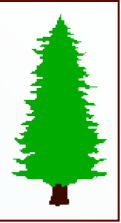


Tracking information is provided by the Inner Detector.

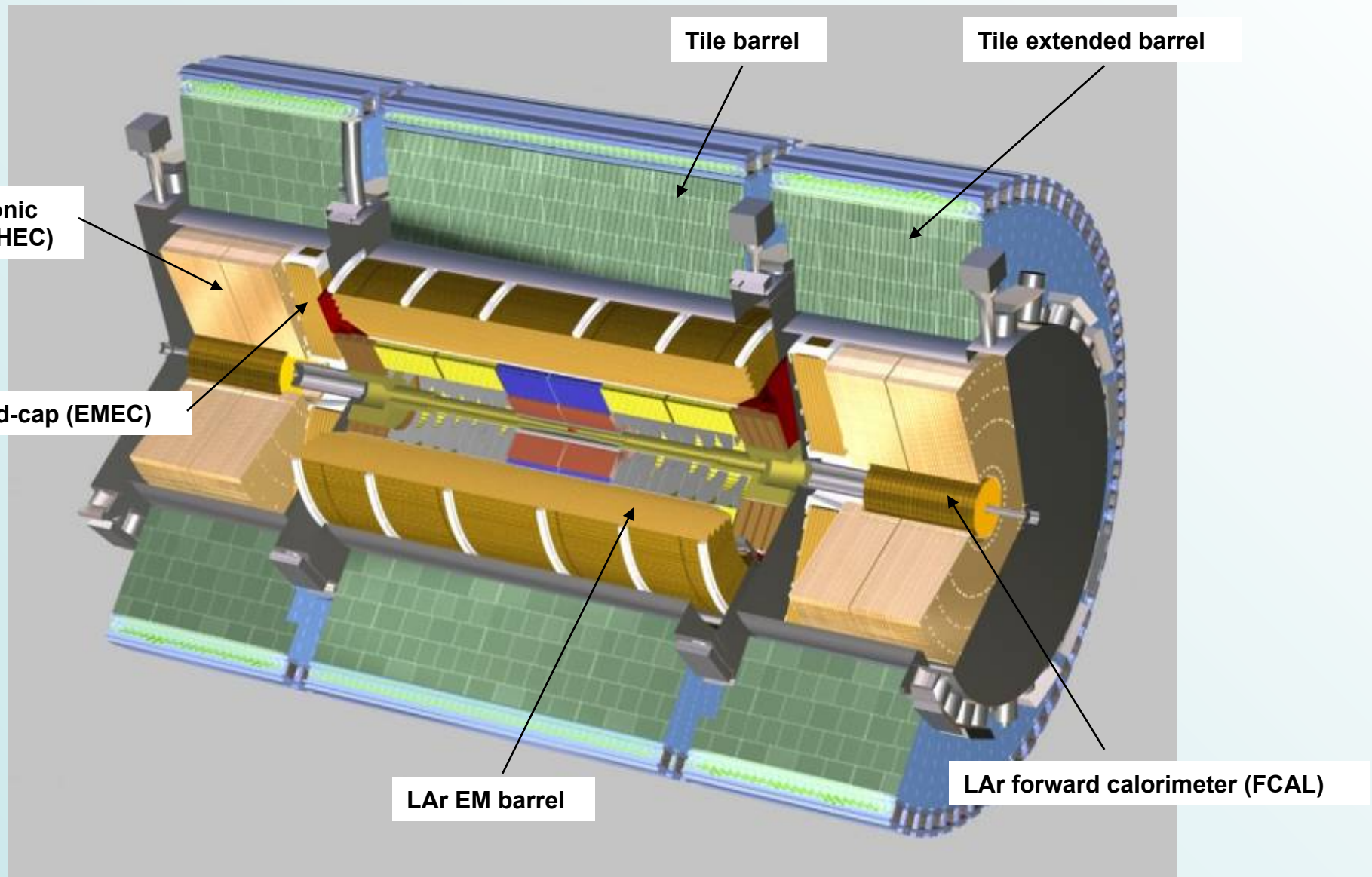
Radially starting from the Interaction Point (IP):

- Pixel Detector
- silicon strip Semiconductor Tracker (SCT)
- straw tubes Transition Radiation Tracker (TRT)

The entire ID is enclosed in a 2 Tesla solenoid magnet to bend charged particles for momentum measurement.

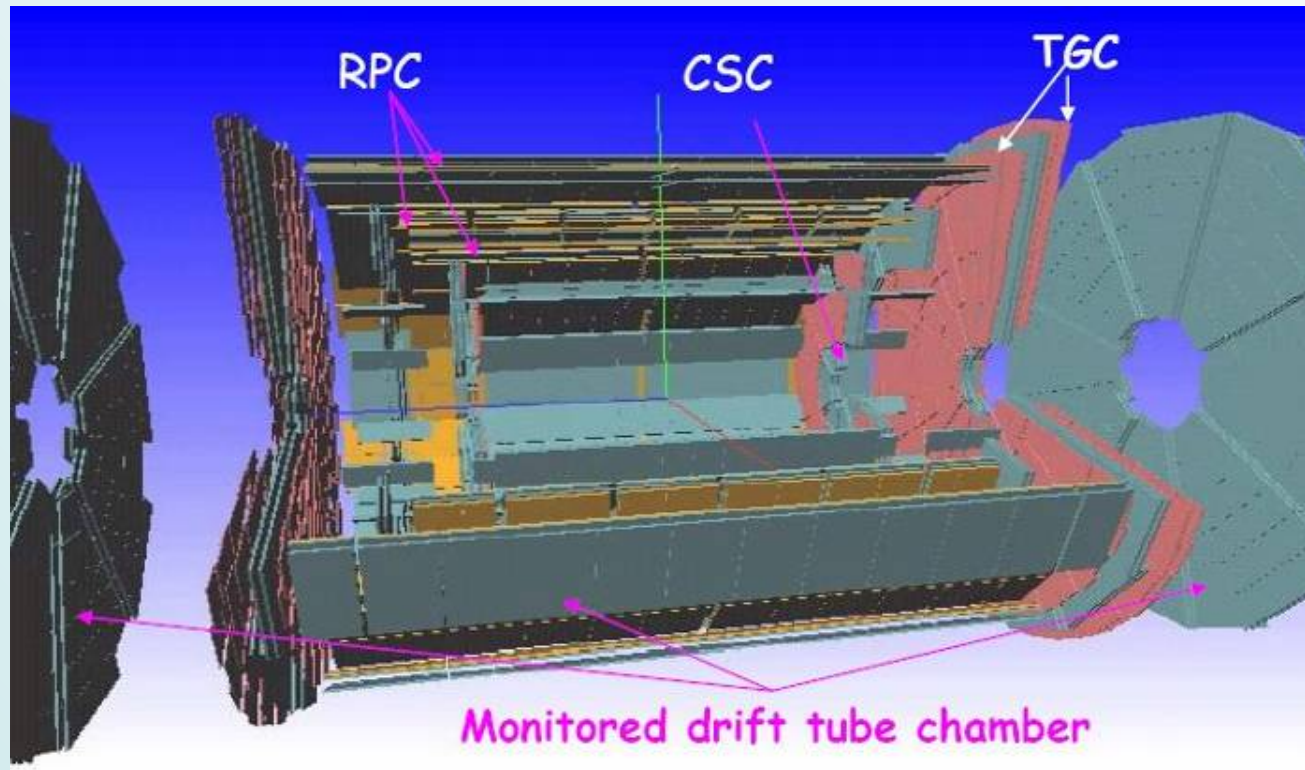


Liquid Argon & Tile Calorimeters





Muon Spectrometer



The Muon Spectrometer is instrumented with precision chambers and fast trigger chambers

A crucial component to reach the required accuracy is the sophisticated alignment measurement and monitoring system

Precision chambers:

- MDTs in the barrel and end-caps
- CSCs at large rapidity for the innermost end-caps

Trigger chambers:

- RPCs in the barrel
- TGCs in the end-caps



Charged Particle Detectors

- Almost all charged particle detectors are based upon the particle ionizing some material (creating $e^- + \text{ion pairs}$) and then measuring the ionization.
- The first example probably was the cloud chamber.
 - Charged cosmic rays traverse a tank of super cooled, super saturated vapor. The ionized molecules act as condensation nuclei such that the trail is visible.
- The bubble chamber provided a controlled method to synchronize the formation and clearing of visible tracks with an accelerator beam.
 - Still the filmed tracks needed to be measured by hand to analyze.
- Wire chambers stretch closely spaced wires across a planar gas volume.
 - With high voltage on the wires, charge is collected and sent to a computer.
 - Each wire measures the position of the traversing particle.
 - Wire spacing establishes position measurement resolution of the chamber.
 - Typically a few millimeters.
 - Examples: Geiger counter, spark chamber, multi-wire proportional chamber, drift chamber, straw tube chamber.
 - Drift chambers improve accuracy by measuring drift time to the wire.
 - No more manual measuring of tracks!



Scintillation Detectors

- Another type of detector makes use of the property of some material to “scintillate” when exposed to ionizing radiation.
 - The passing ionizing particle excites certain molecules to an excited state. The transition back to ground state emits light, typically in the visible.
 - There exist inorganic scintillators (e.g. NaI) and organic (e.g. doped plastics).
 - The emitted light is typically collected at a photo-multiplier tube which converts the photons to electrons (photo-cathode) and then amplifies the electron signal to be analyzed by other electronics.
- Advantages:
 - Fast signals (ns rise-times) – good for timing applications (e.g. TOF).
 - Self triggering with discriminator – good for trigger signals.
- Disadvantages:
 - Typical large size limits position measurement resolution.
 - Photo-multiplier tubes are expensive.
- Recent advances:
 - Scintillating fibers.
 - Solid state photo detectors.



Example of a Photomultiplier Tube

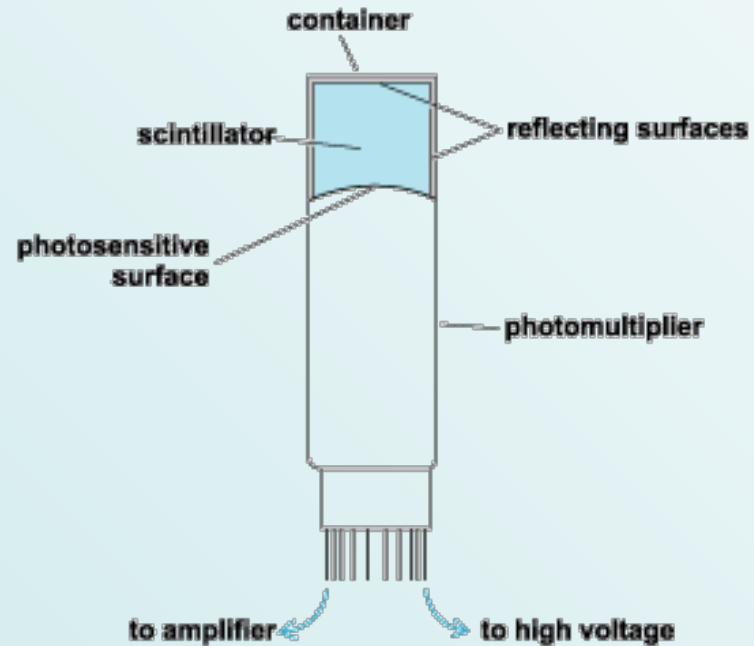
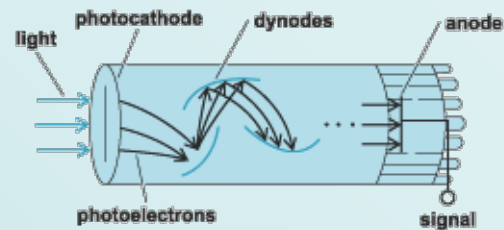
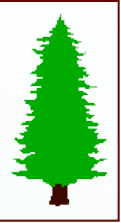


Diagram of a scintillation counter.



Schematic of a photomultiplier. (After P. W. Engstrom, Photomultipliers—then and now, RCA Eng., 24(1):18-26, June-July 1978)



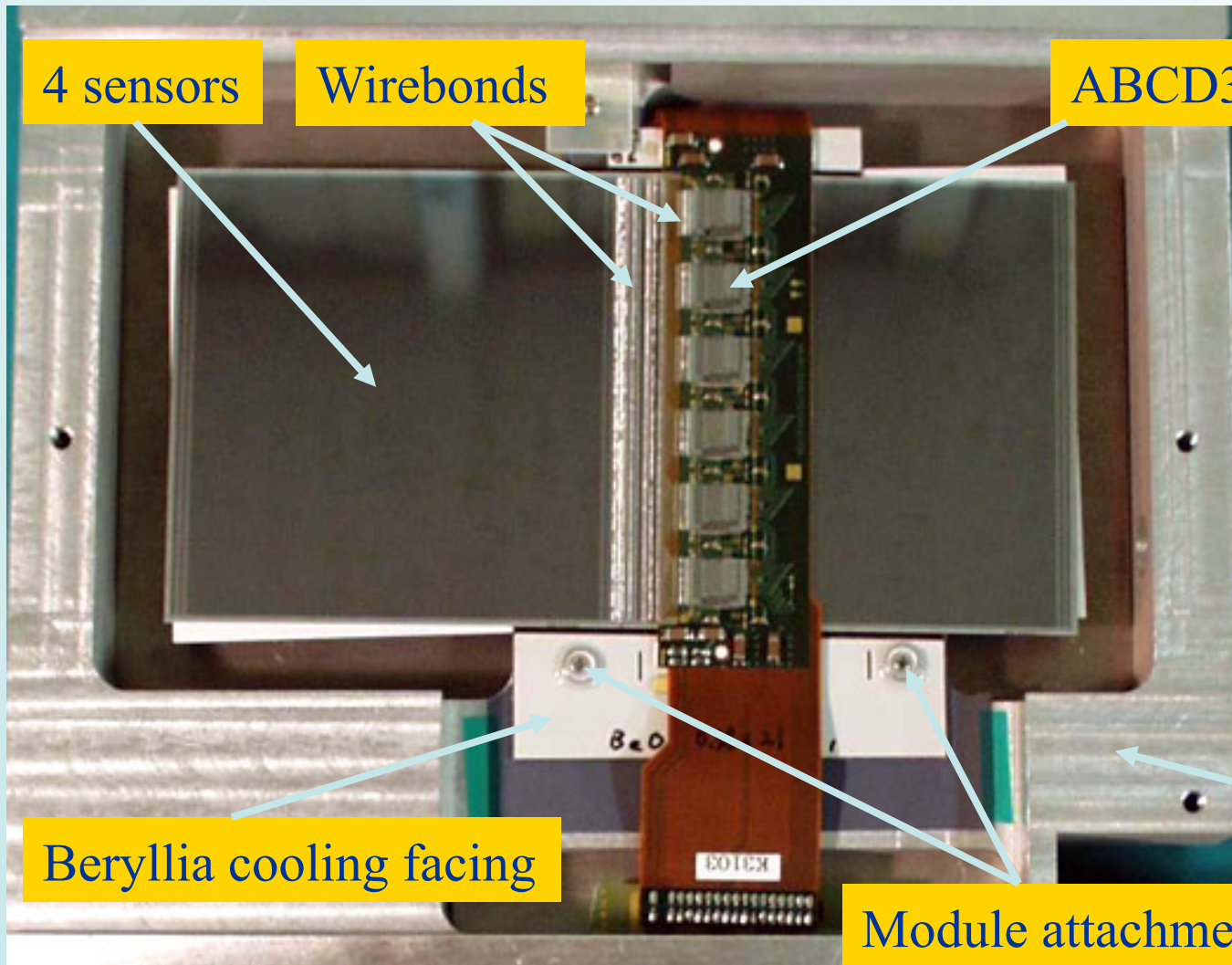


Advanced Charged Particle Detectors

- An advanced exploitation of wire chamber concept is the silicon strip detector.
 - The ionizing material is a silicon wafer.
 - The equivalent “wires” are strips of implant in the silicon to form strip diodes.
 - The diodes are reverse biased such that nearly zero leakage current flows except when a charged particle traverses the silicon.
 - Then e^- are collected by the anode and ions by the cathode of the strip diode.
 - This charge can be amplified and fed to a computer for analysis.
 - Spacing of diode strips is now limited by micro-electronics lithography (microns instead of millimeters).
- Silicon pixel detectors use the same principle except that the diode strips are cut into short pads giving a two dimensional measure in one plane.

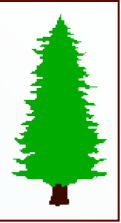


An SCT Barrel Detector Module



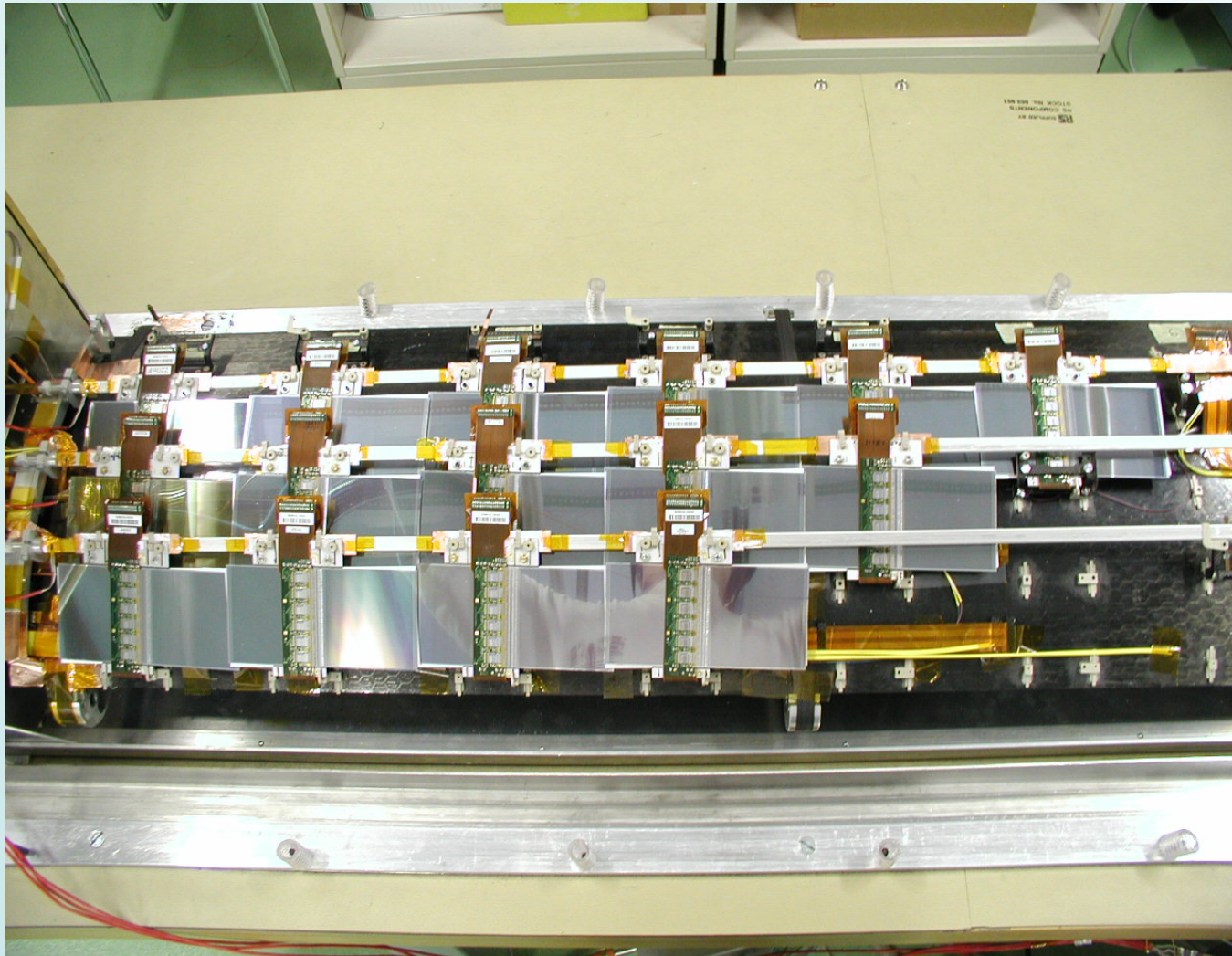
Features:

- 4 single-sided sensors at 40 mrad crossing angle
- 1536 strips with 80 μm pitch
- Multi-Chip Unit
- Large dimensions (12 cm x 6 cm x 1.1 mm)



A Sector of One SCT Barrel

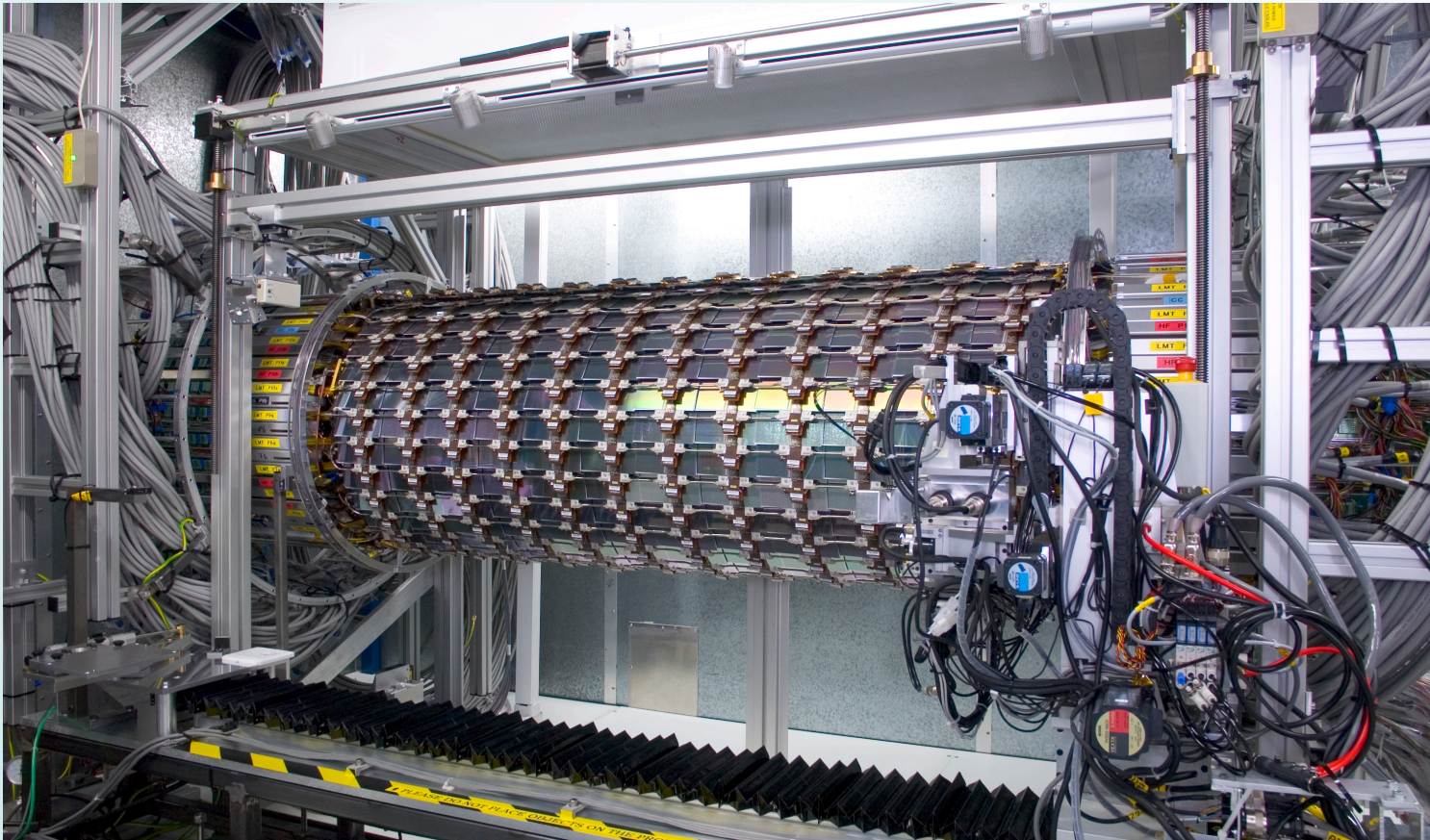
SCT System Test
with 15 modules
mounted on a barrel
sector at CERN.





Inner Most SCT Barrel Complete at Oxford

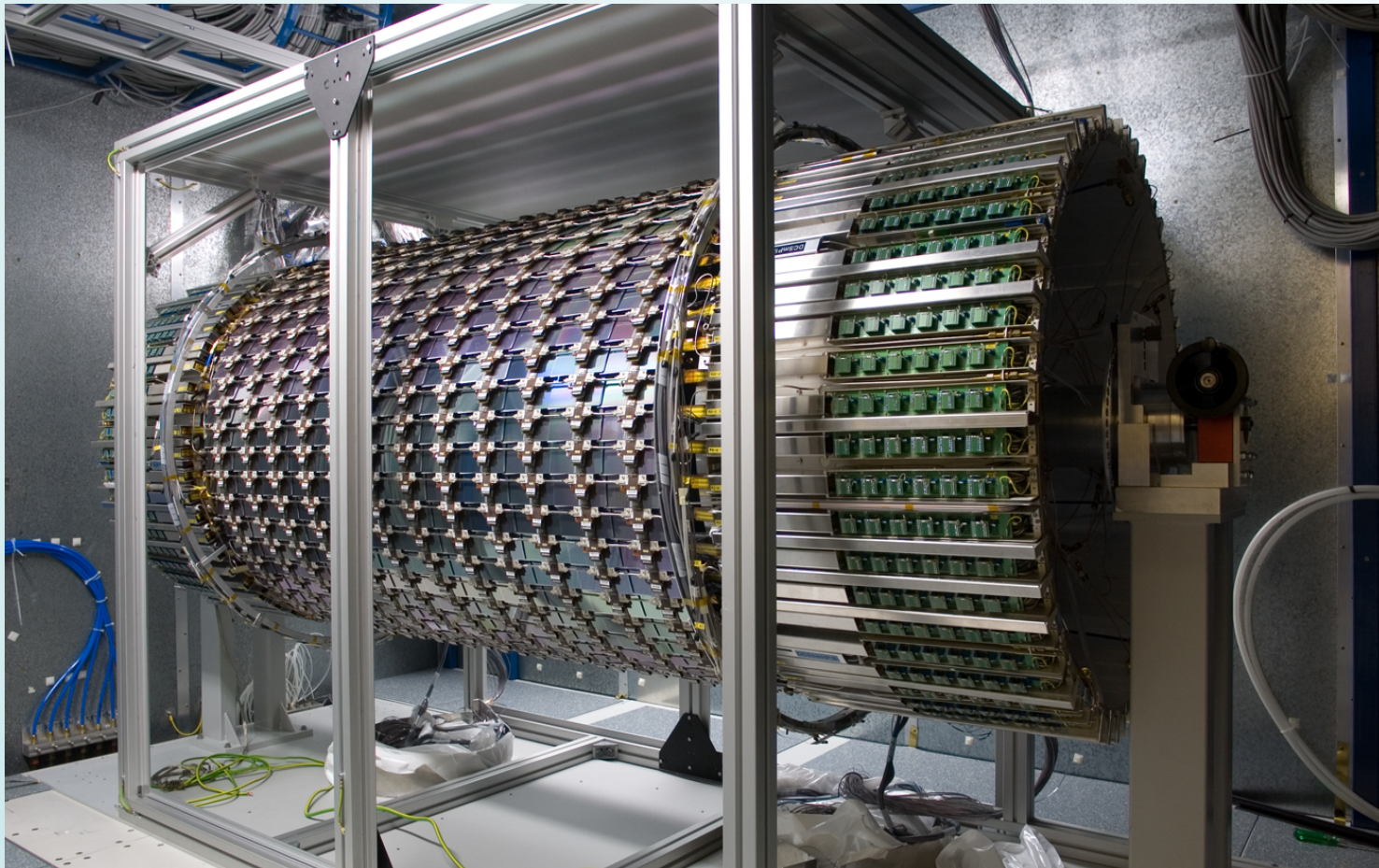
As it looked waiting for shipment from Oxford to CERN
384 modules mounted

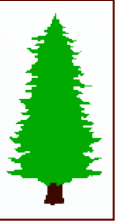




Outer Most SCT Barrel Complete at Oxford

The big sister of Inner Most Barrel
672 modules mounted





SCT plus TRT Barrel Prepared for Installation

- The SCT barrel assembly (all four barrels) was inserted into the TRT barrel assembly on 17-Feb-06.





The ATLAS Semi-Conductor Tracker

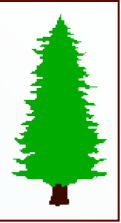
SCIPP's work has been focused on the
Semi-Conductor Tracker (SCT)

Features:

- 4 barrel layers, at 300, 373, 447, and 520 mm radii.
- 9 forward disks
- 60 m² of silicon strip sensors with 60,000,000 readout channels
- 4,000 modules and 50,000 front-end ASICs
- 16 μm (R- ϕ) and 580 μm (z) spatial resolution

Unique Requirements:

- Rad-Hard up to 10 MRad
- 25 ns bunch-crossing time
- Large-scale distributed project



Calorimeters Measure a Particle's Total Energy

- **Electromagnetic Calorimeters (e^- , e^+ , γ):**
 - As these particles traverse “high Z” material, they convert:
 - e^- and e^+ radiate γ s, γ s pair produce e^+e^- or knock out e^- s.
 - Traversing more material creates more of the same – a “shower” develops.
 - Sufficient material will eventually convert all the energy to low energy particles which are captured. Thus total energy is deposited in material.
 - By interleaving the radiating material with other material which can be ionized and subsequently collect the ionized charge, a measure of the total energy of the initial particle can be made.
 - ATLAS interleaves Pb and liquid argon with copper electrodes to collect the charge. The cells are segmented laterally and longitudinally so that a rough trajectory can be measured.
- **Hadronic calorimeters are similar with the goal of having the strongly interacting particle interact with a nucleus producing a hadronic cluster of particles which can then be measured in similar fashion.**
 - ATLAS interleaves steel and scintillating tiles.

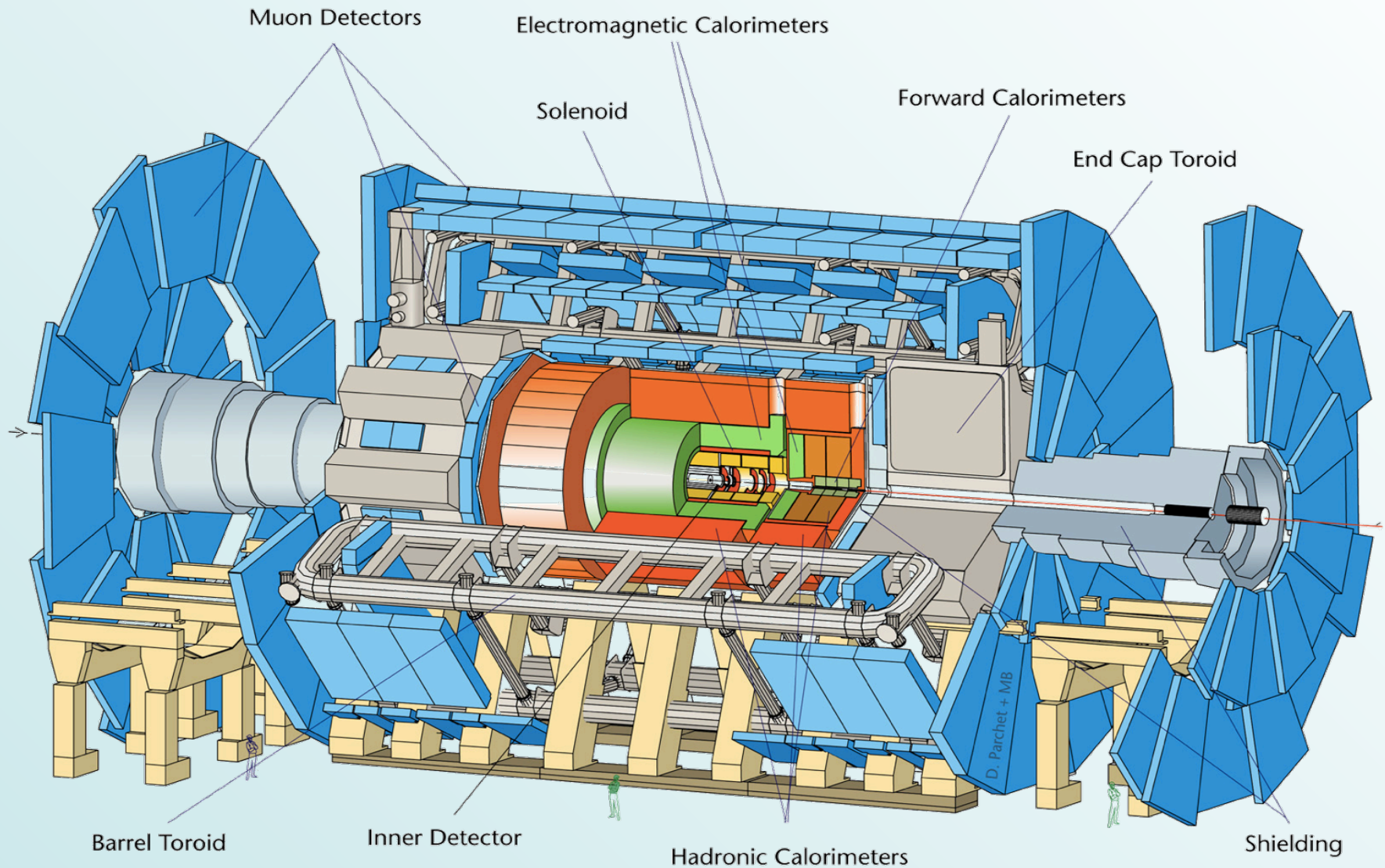


Muon Detection

- **Muons are too heavy to shower in the EM calorimeter. They also don't readily interact in the hadronic calorimeter since they don't interact strongly.**
 - As a result, they exit the ID and both calorimeters – any charged particle detected outside the calorimeters must be a muon.
- **The ATLAS Muon Detector consists of typical charged particle detectors arrayed to cover the entire outer surface of ATLAS!**
 - Actually fast detectors are used for triggering and precision detectors are used for accurate track measurement.
- **Special toroidal magnets are also positioned there so that a final measure of the muon's momentum can be made.**
- **Note that neutrinos completely escape the entire detector!**
 - Any event containing neutrinos will have missing energy and momentum which complicates the analysis.
 - But such missing energy or momentum could be a sign of new physics!

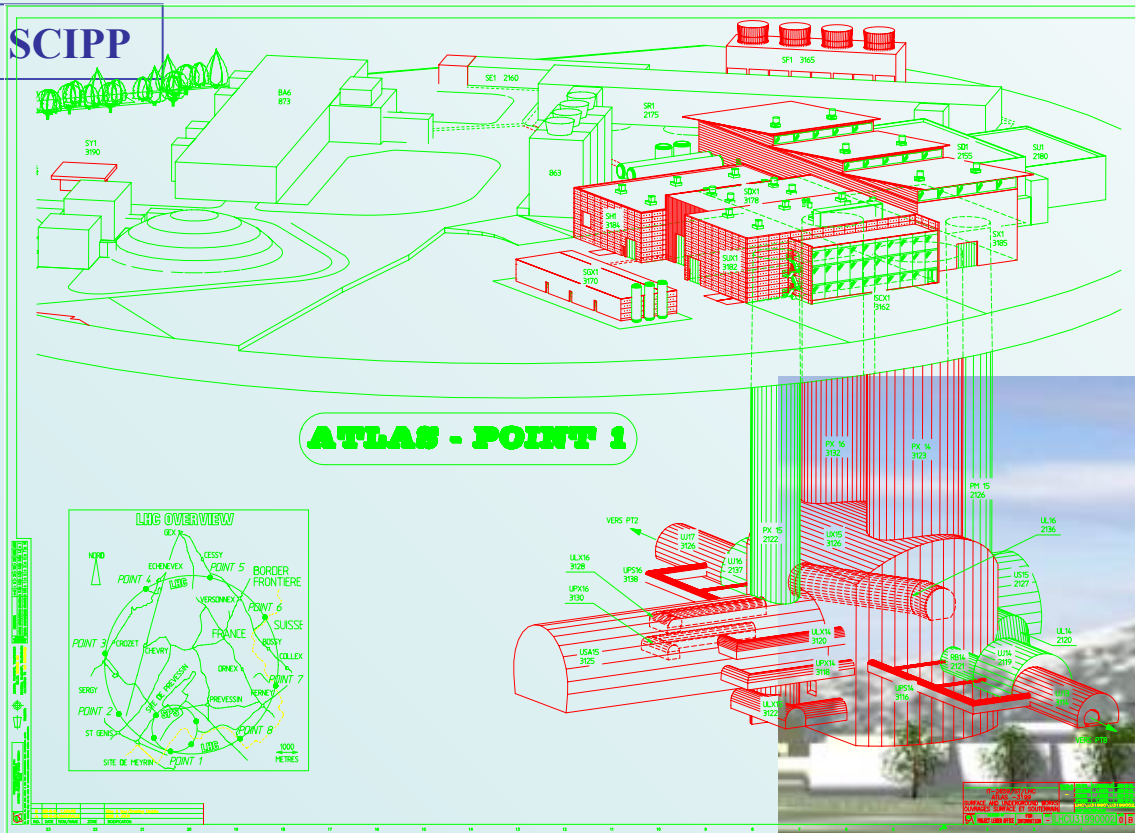


One More Look at the Pieces of the ATLAS Detector

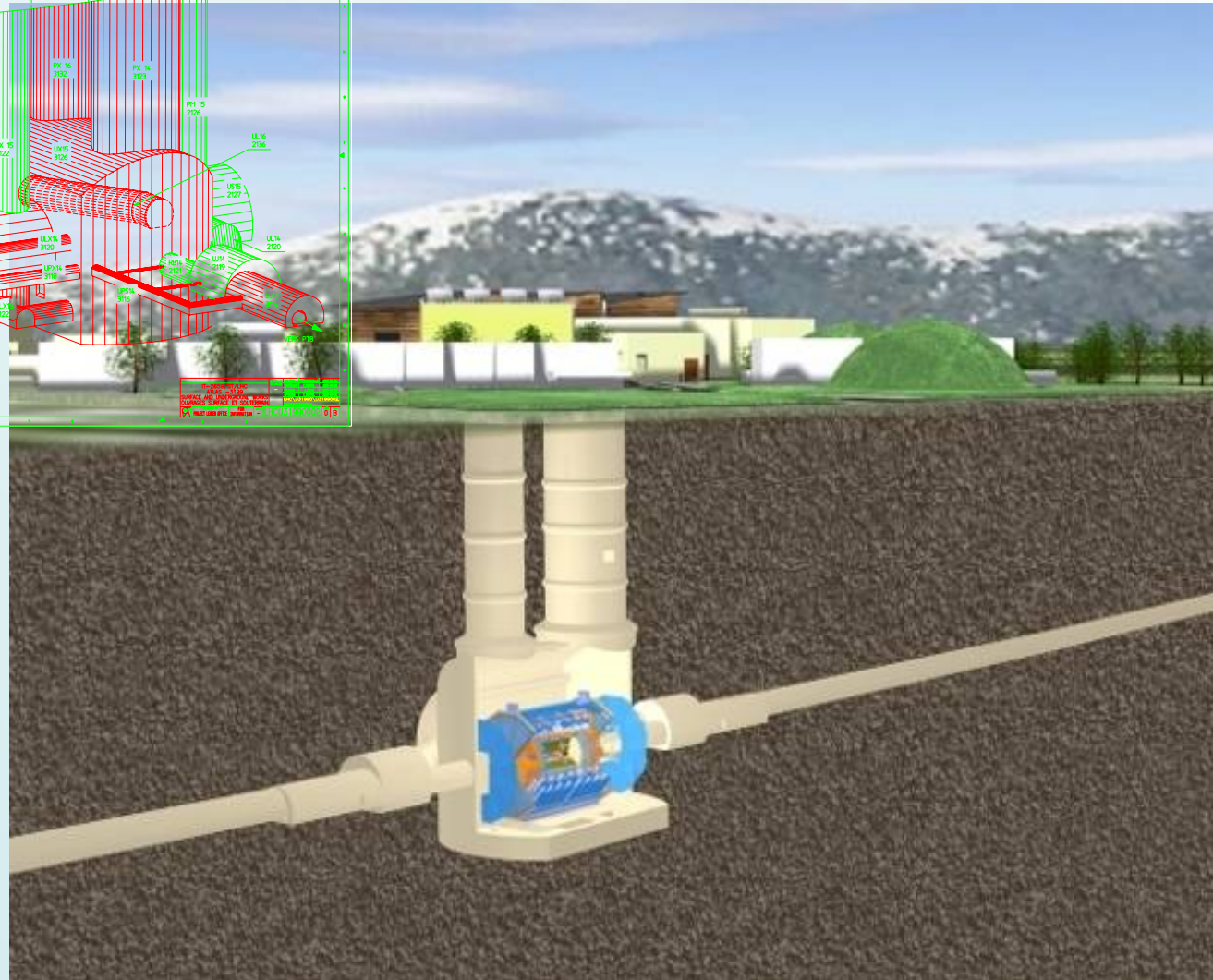




Underground Cavern for the ATLAS Detector



Length = 55 m
Width = 32 m
Height = 35 m





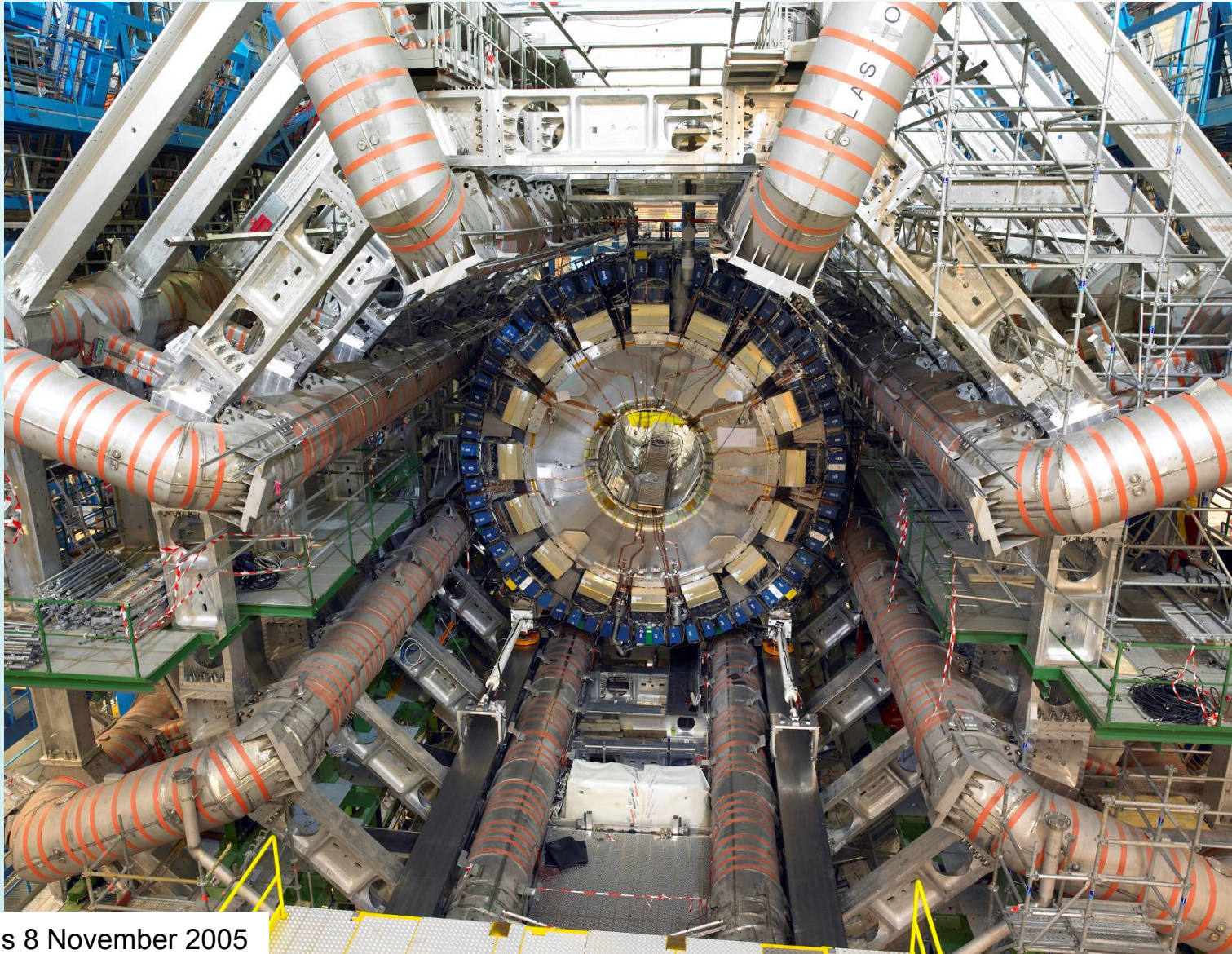
Installation Starts with the Lower Toroid Coils



Status 10 December 2004



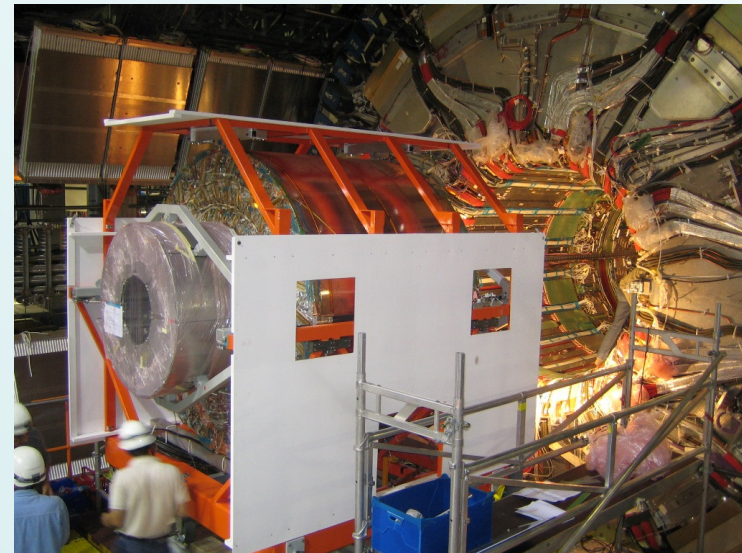
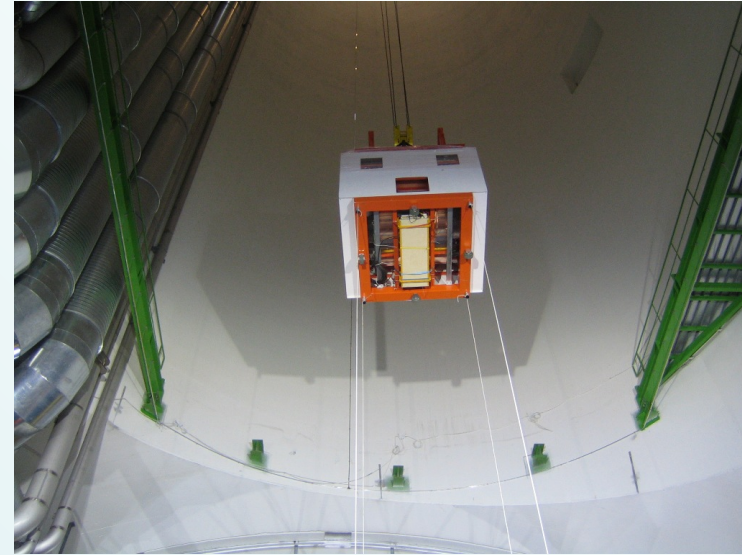
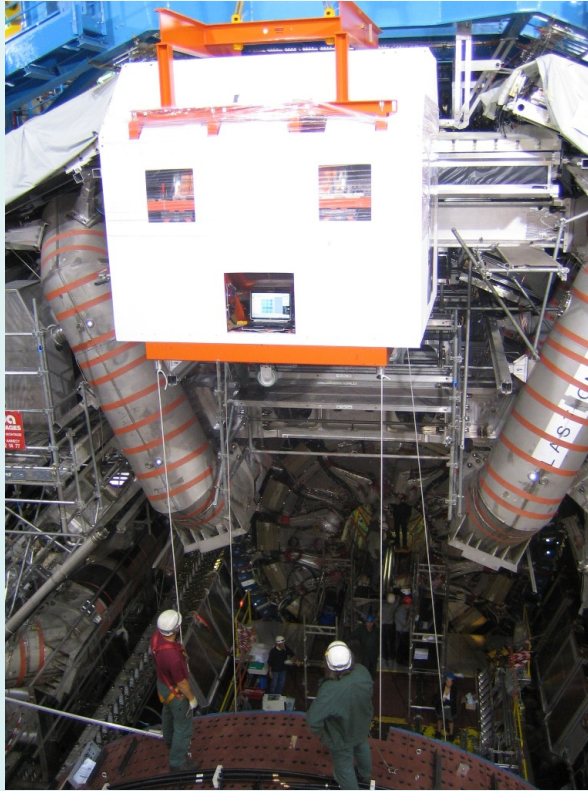
Barrel TileCal and Liquid Argon Calorimeter



Status 8 November 2005



Installing the ATLAS Inner Detector



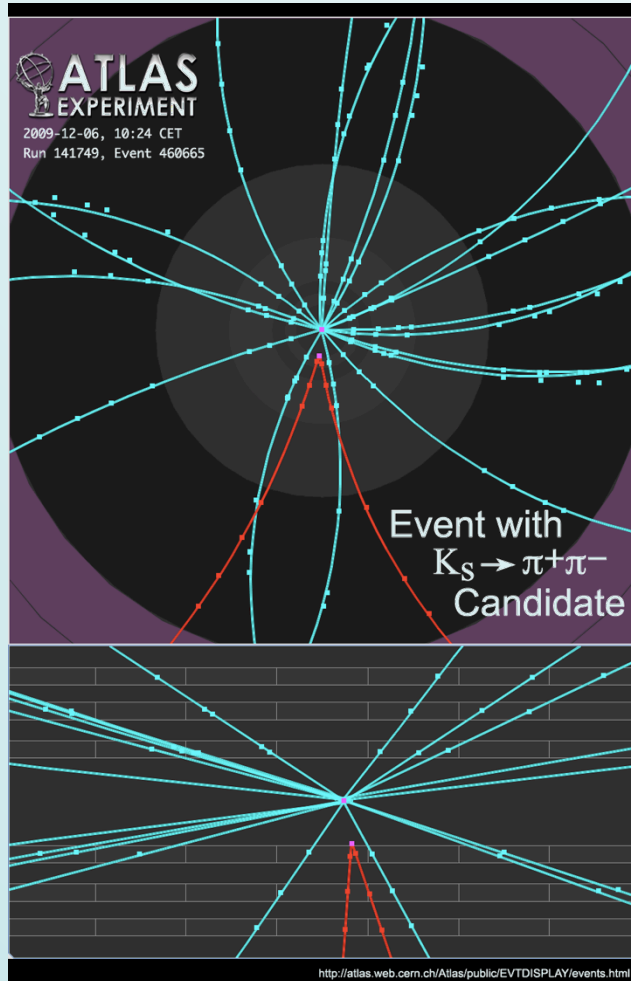
High School Students: 11-Jul-12

ATLAS & Particle Detection

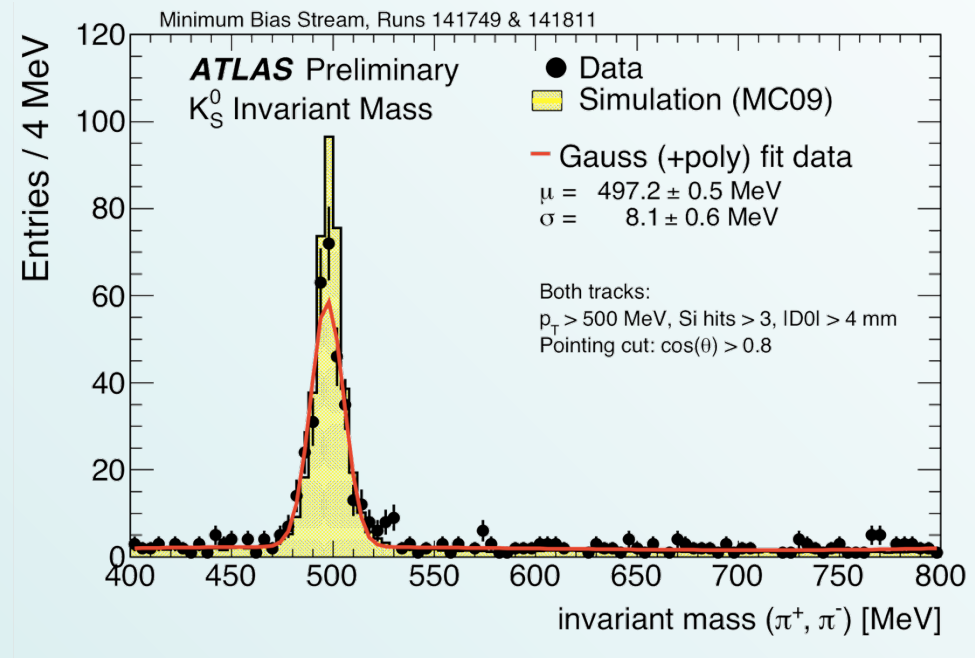


Finally the LHC Comes to Life!

- Examples of 900 GeV data taken Fall-09.
- Clear examples that the detector is performing well.
- Pixel and SCT alignment, calibration and timing well understood.



Clean K_S candidate in Pixels & SCT

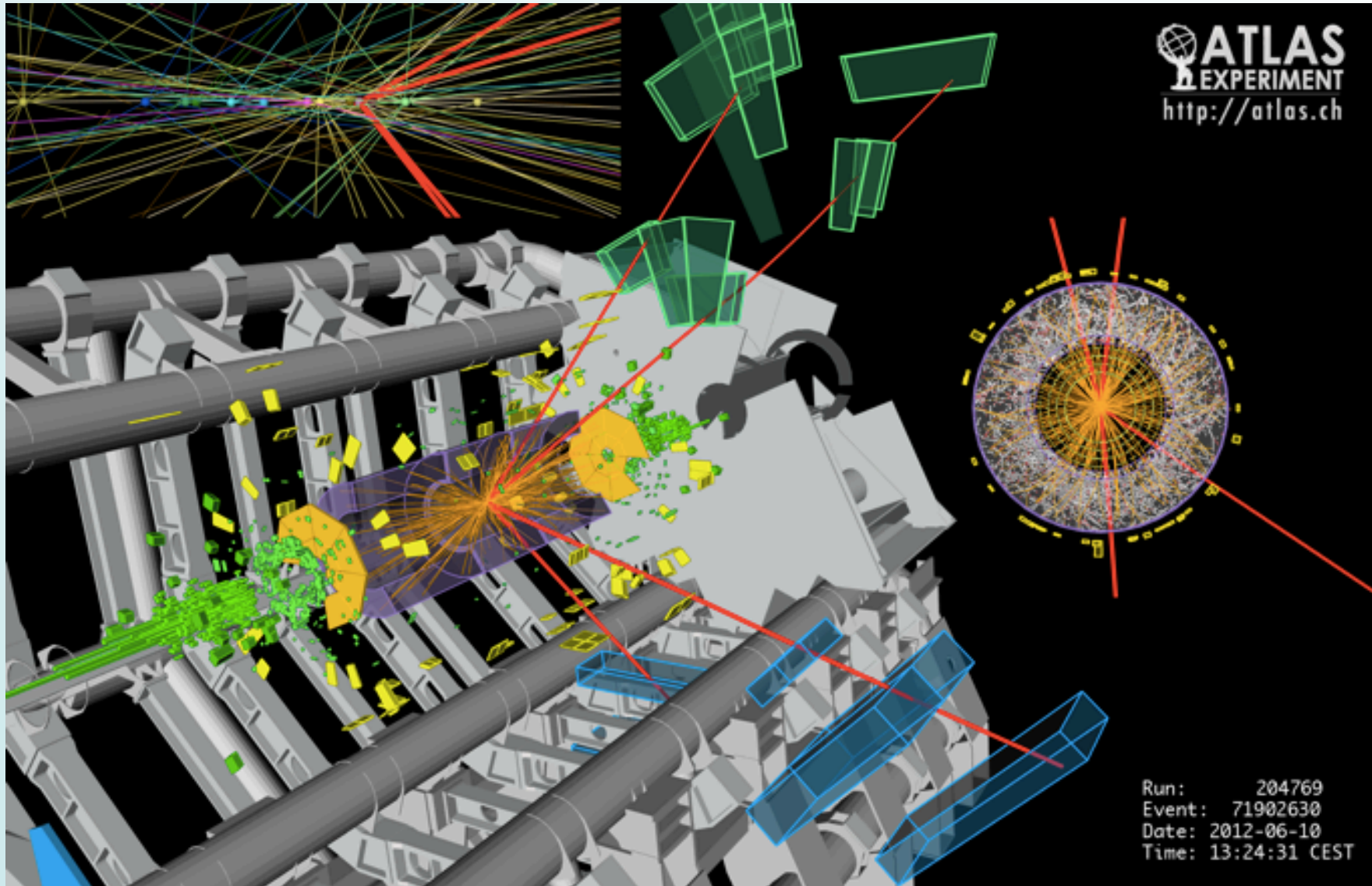


K_S^0 Mass Peak

- The mass peak is formed by plotting the invariant mass of each two-particle K_S candidate.



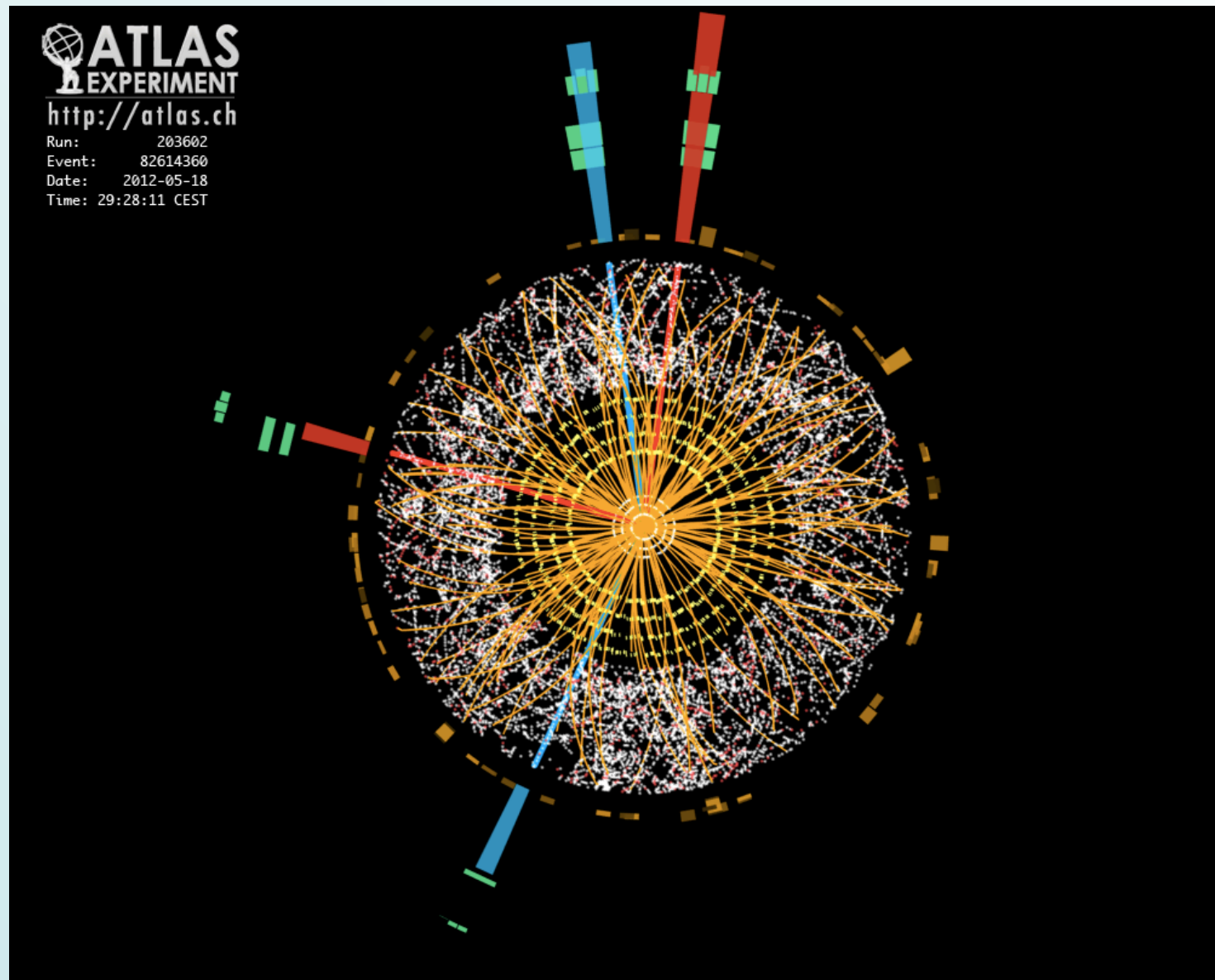
Is this a Higgs Event?



Candidate Higgs Boson decay into four muons recorded by ATLAS in 2012.



Another Possible Higgs Event?



Candidate Higgs Boson decay into four electrons recorded by ATLAS in 2012.