Particle detection

Recall

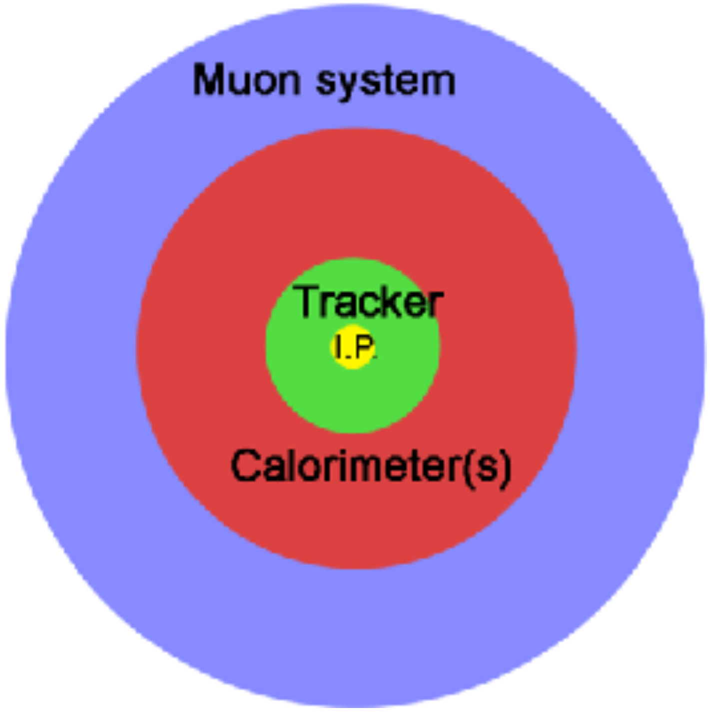
Particle detectors

- Detectors usually specialize in:
  - Tracking: measuring positions / trajectories / momenta of charged particles, e.g.:
    - Silicon detectors
    - Drift chambers
  - Calorimetry: measuring energies of particles:
    - Electromagnetic calorimeters
    - Hadronic calorimeters
  - But they can also be a combination.

Basic concept of a general purpose detector
Remarks

- A strong magnetic field is used to bend the trajectories of charged particles.
- Hermetic coverage:
  - The detector systems cover a large solid angle around the interaction point.
  - The calorimeters are able to fully contain and measure high energy particles.
- Design driven by performance goals, cost, but also radiation hardness.

- A reconstructed "physics event" requires the combination of measurements from all sub-detectors.



wikipedia.org

Recall

Ionization

Bethe energy loss formula

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right) - \beta^2\right]$$

$-\frac{dE}{dx}$ Energy loss per distance traveled

$\beta = \frac{v}{c}$ Particle velocity

z Particle charge (in units of electron charge)

n Density of electrons in material

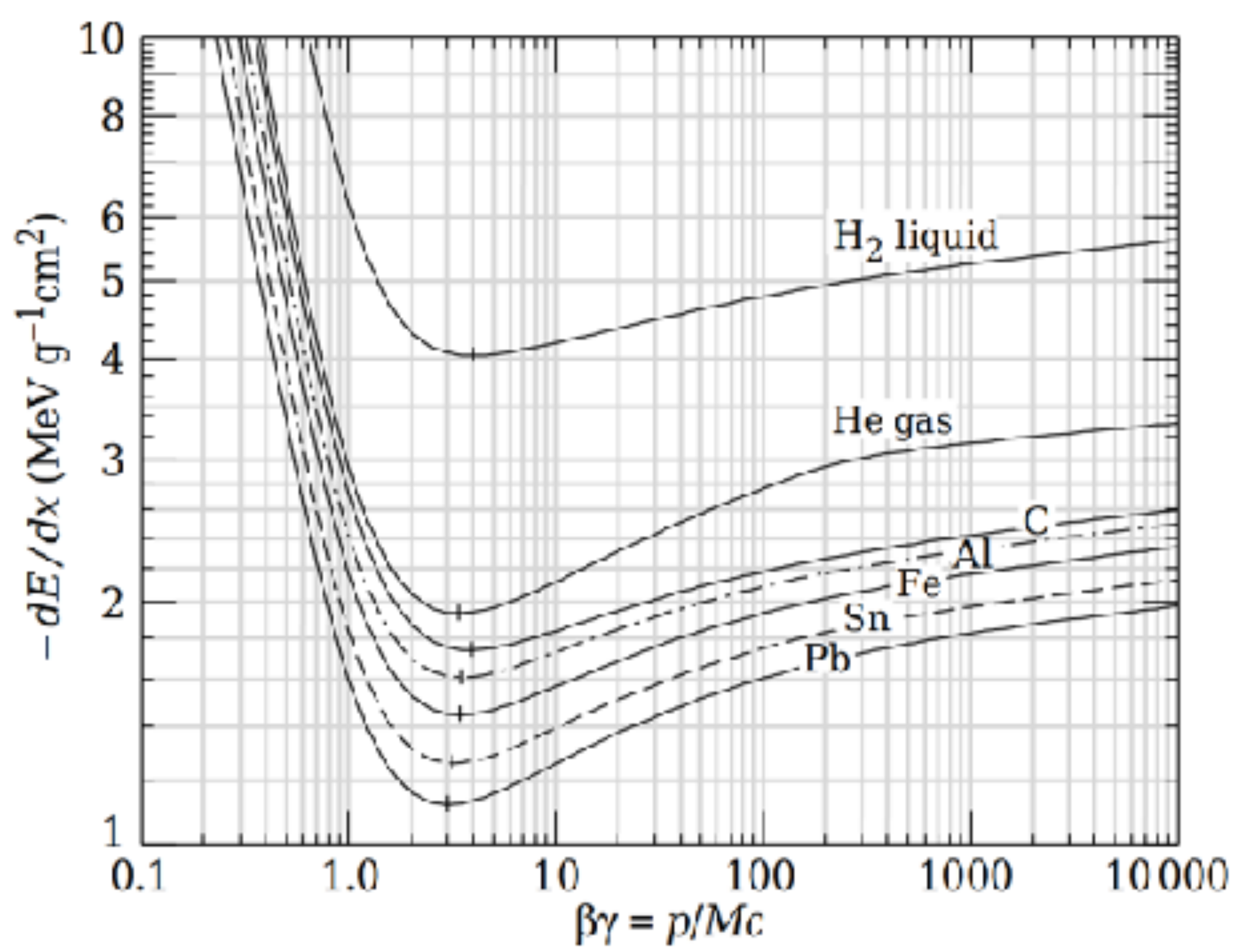
I Mean excitation potential of material

ϵ_0 Vacuum permittivity

e Electron charge

m_e Electron mass

c Speed of light in vacuum



Recall

Ionization

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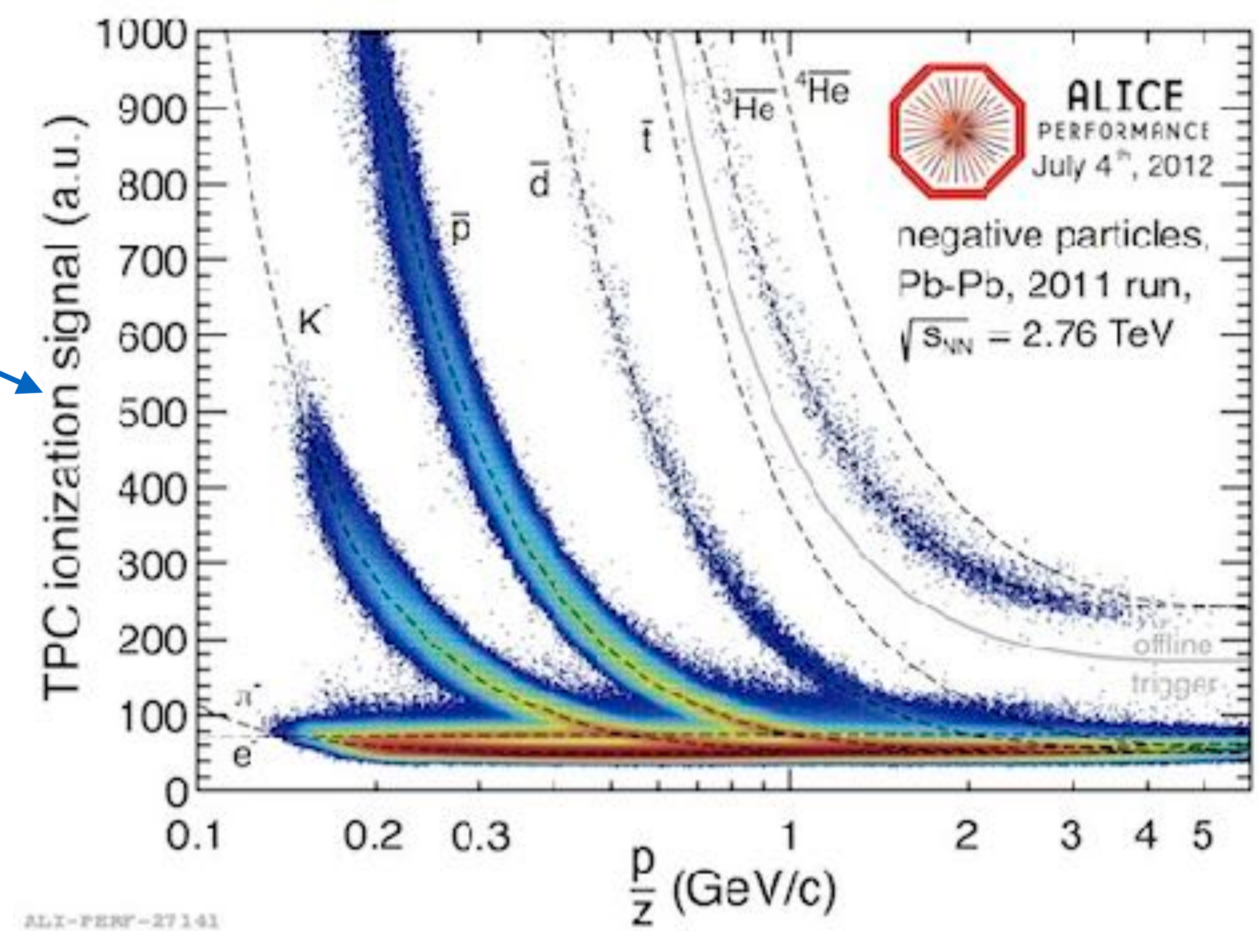


Recall

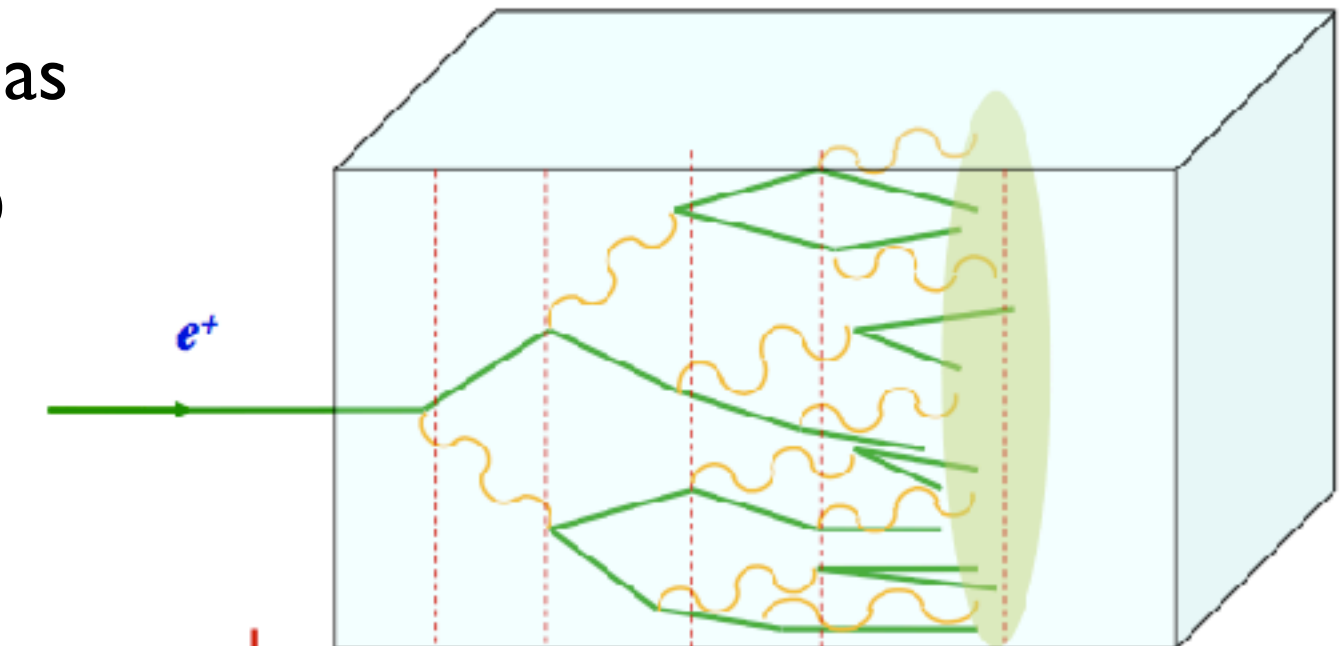
Scintillation

- Scintillators produce light when excited by ionization radiation.
- Depending on the particular energy loss of a certain particle (dE/dx) different relative intensities in the light output are observed.

Recall

Electromagnetic showers

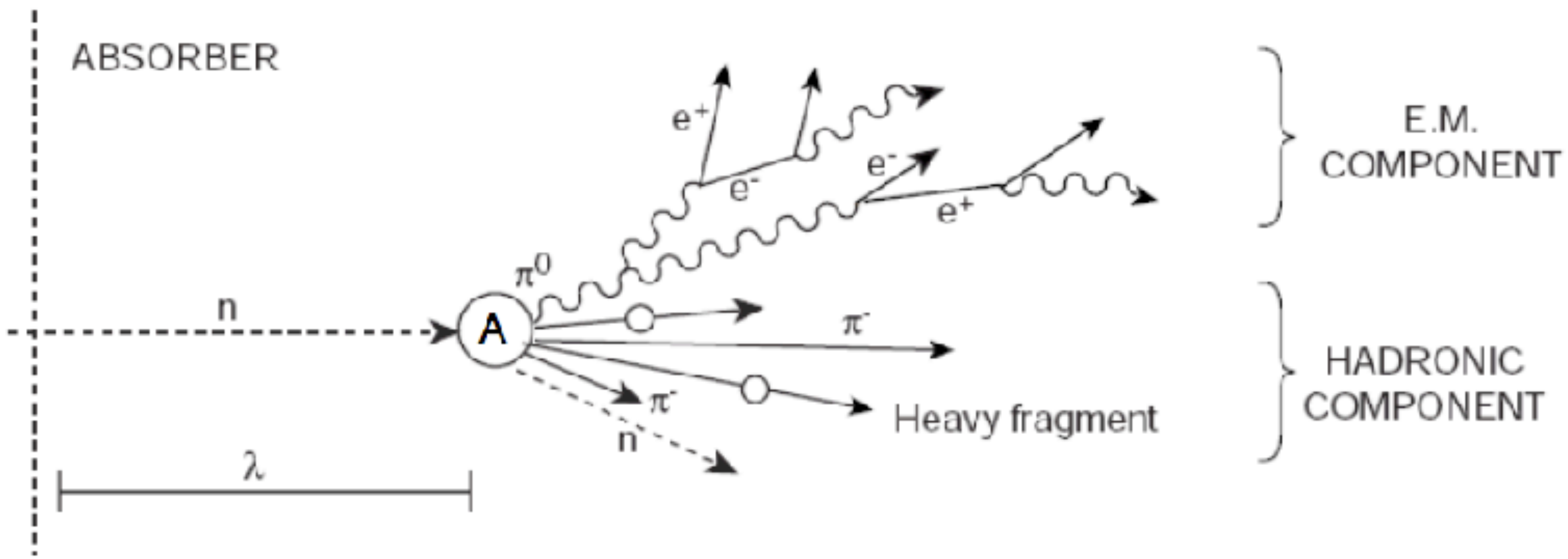
- The number of particles increases as a 2^N, where N is the number of X_0 over which the shower has developed.
- X_0 is the "radiation length".
- The length of the shower depends on the primary electron energy.



x	0	X_0	$2X_0$	$3X_0$	$4X_0$	
N	1	2	4	8	16	0
$\langle E \rangle$	E_0	$E_0/2$	$E_0/4$	$E_0/8$	$E_0/16$	$<E_c$

Recall

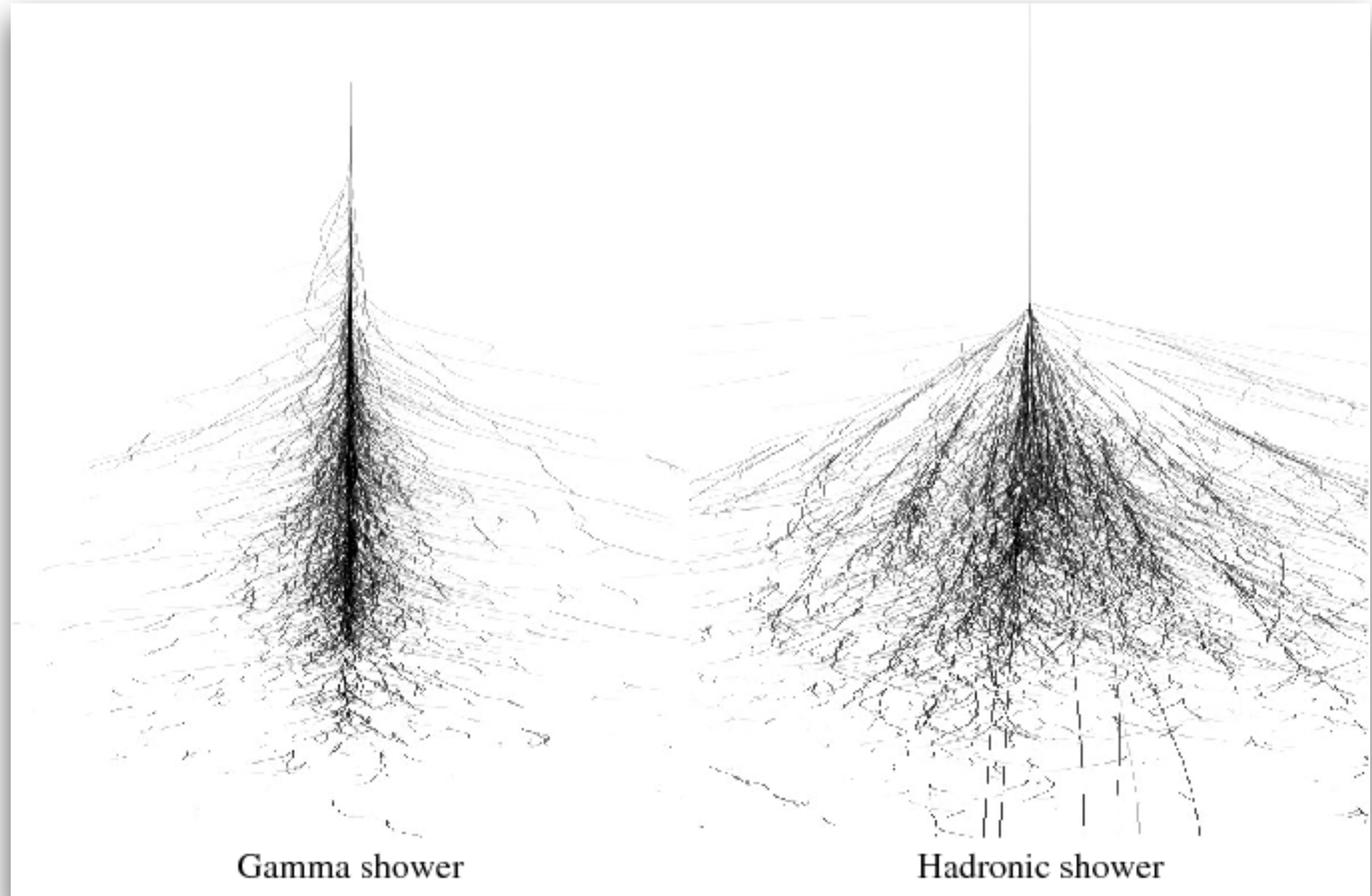
Hadronic showers



- Hadronic interactions have high multiplicity:
  - Shower is to 95% contained in ~7λ at 50 GeV (1.2 m of iron).
- Hadronic interactions produce π^0:
  - $\pi^0 \rightarrow \gamma\gamma$, leading to local EM showers.
- Some energy loss in nuclear breakup and neutrons ("invisible energy")
- Stronger fluctuations in a hadronic shower:
  - Worse energy resolution.

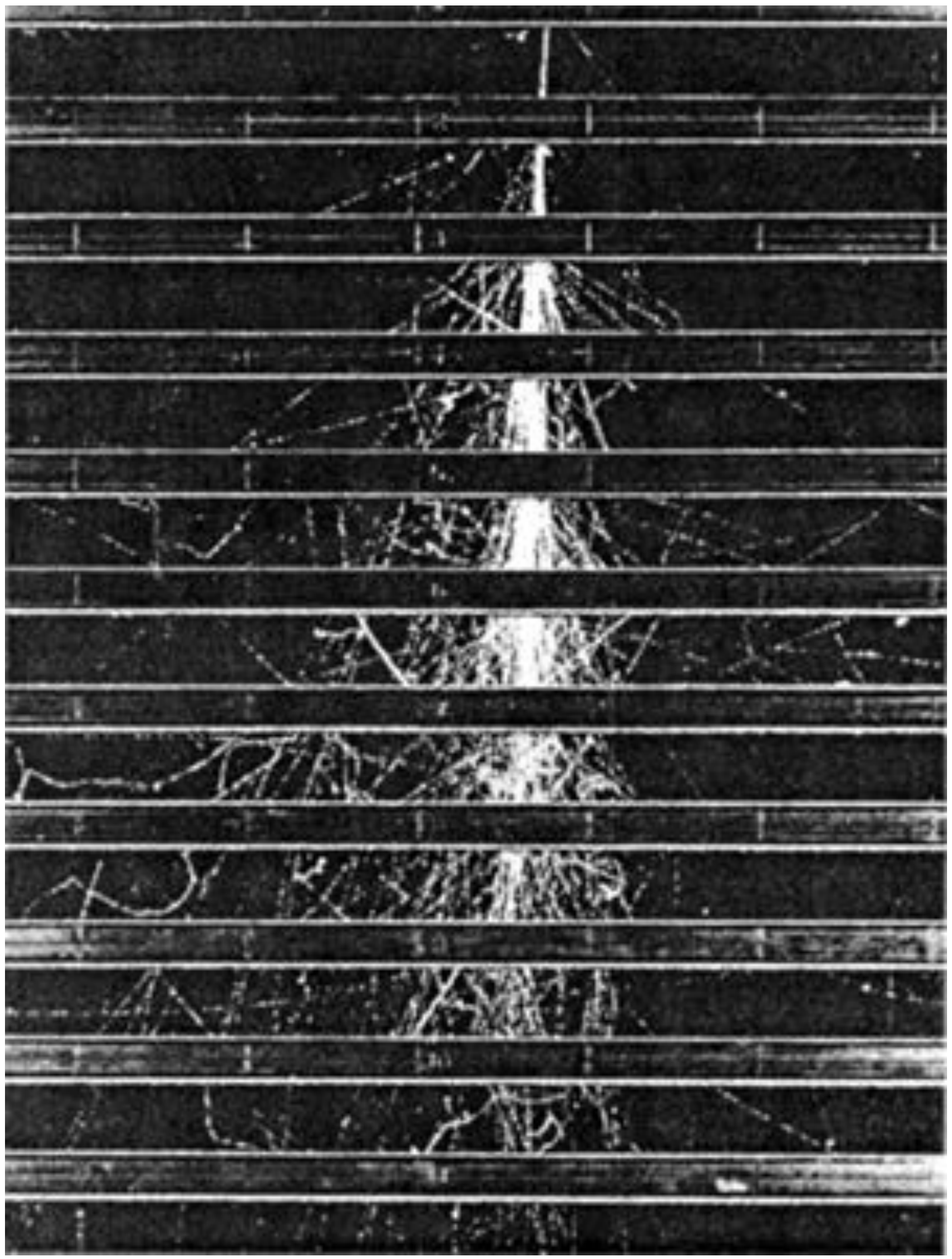
Recall

Hadronic vs EM showers



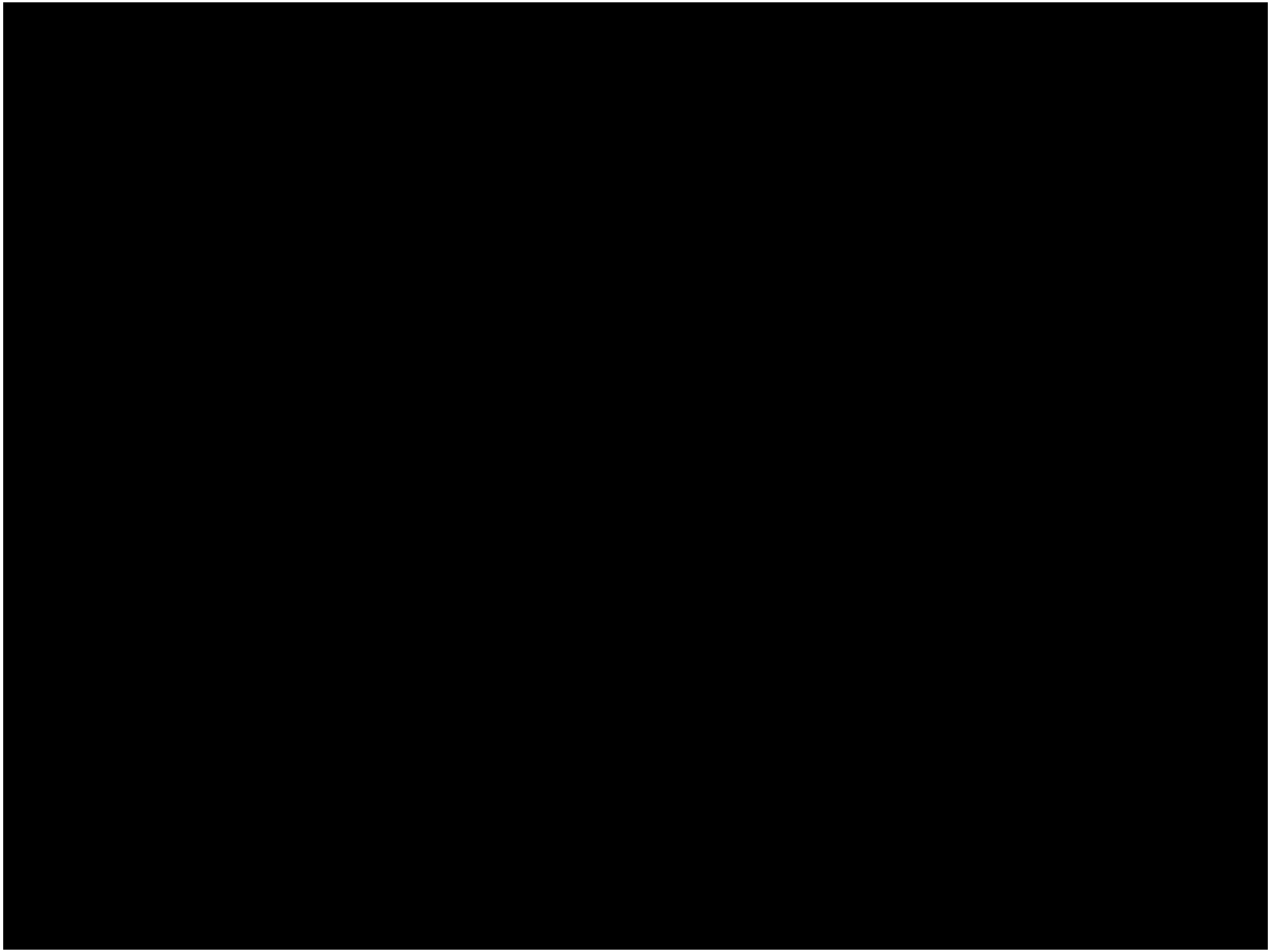
Recall

Hadronic vs EM showers

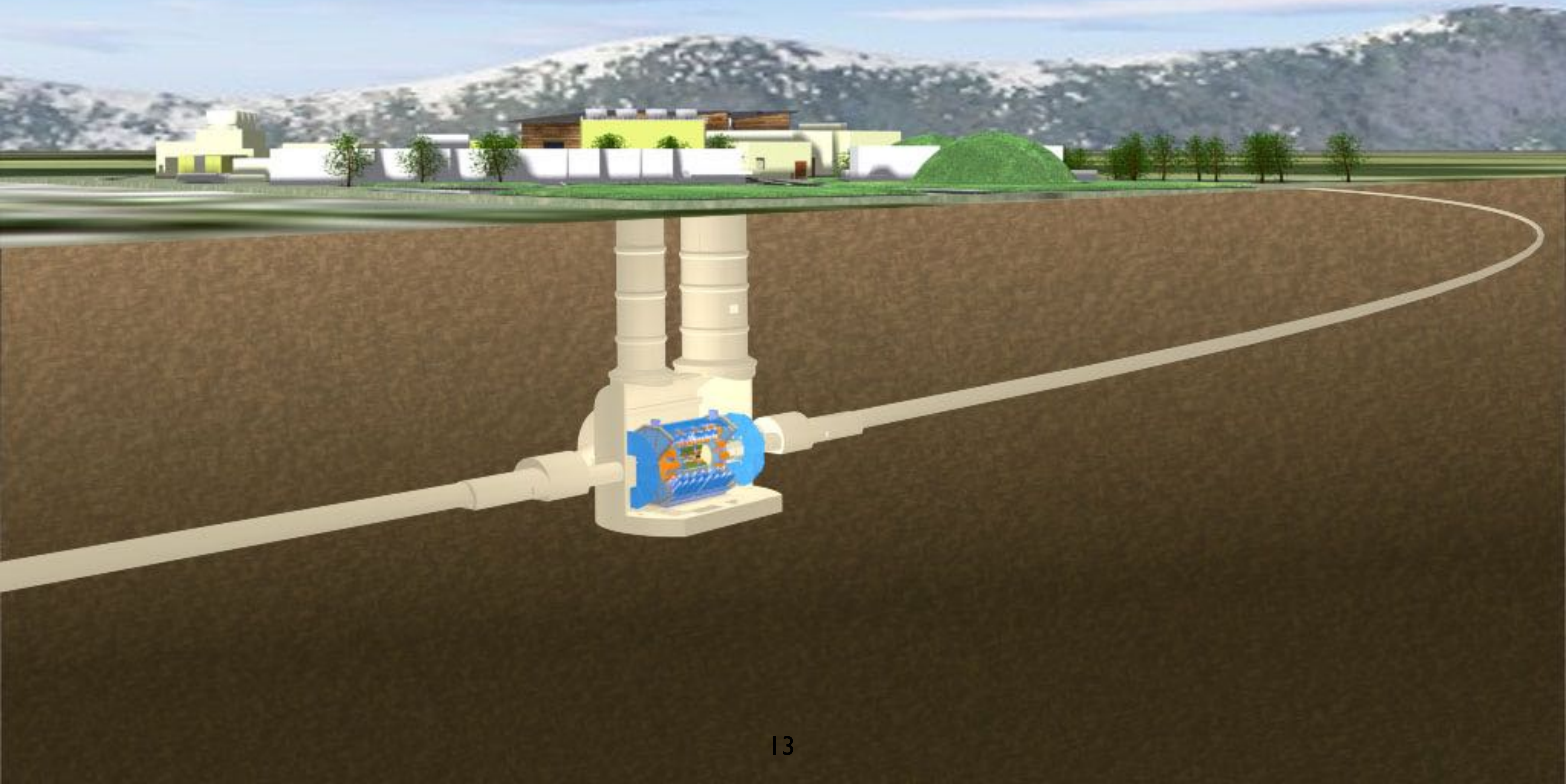


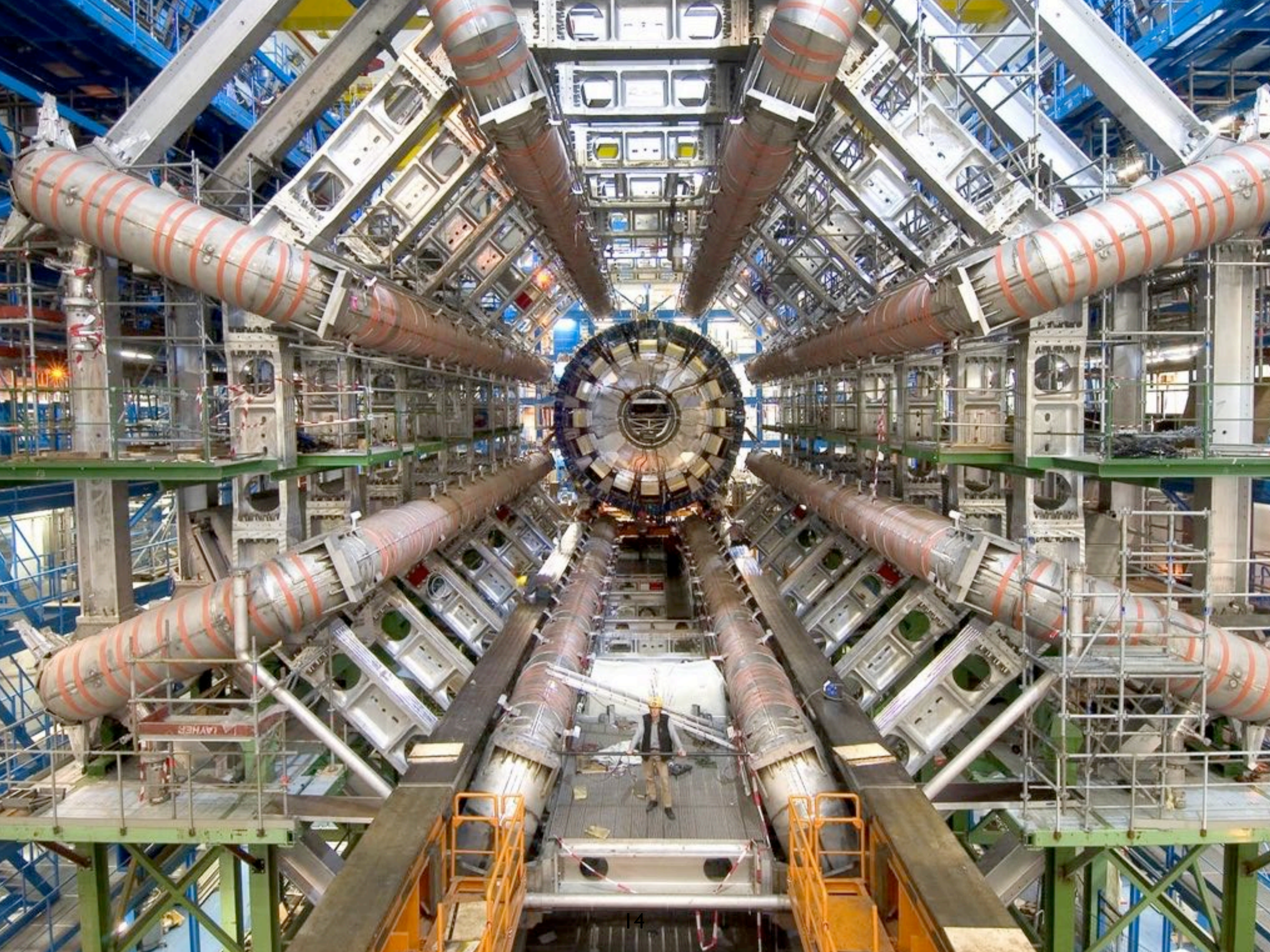
The ATLAS experiment

From Space to ATLAS

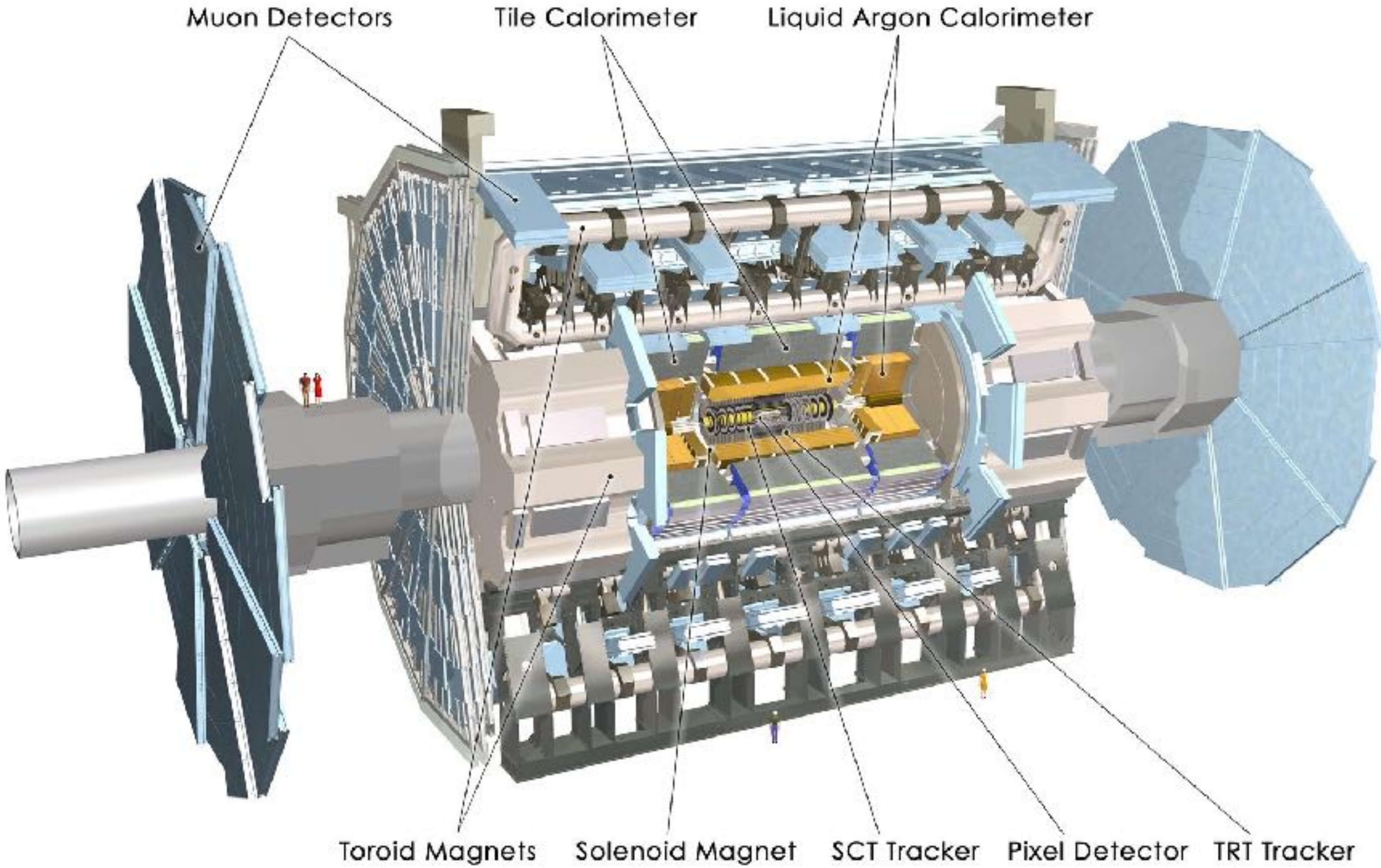


The ATLAS detector

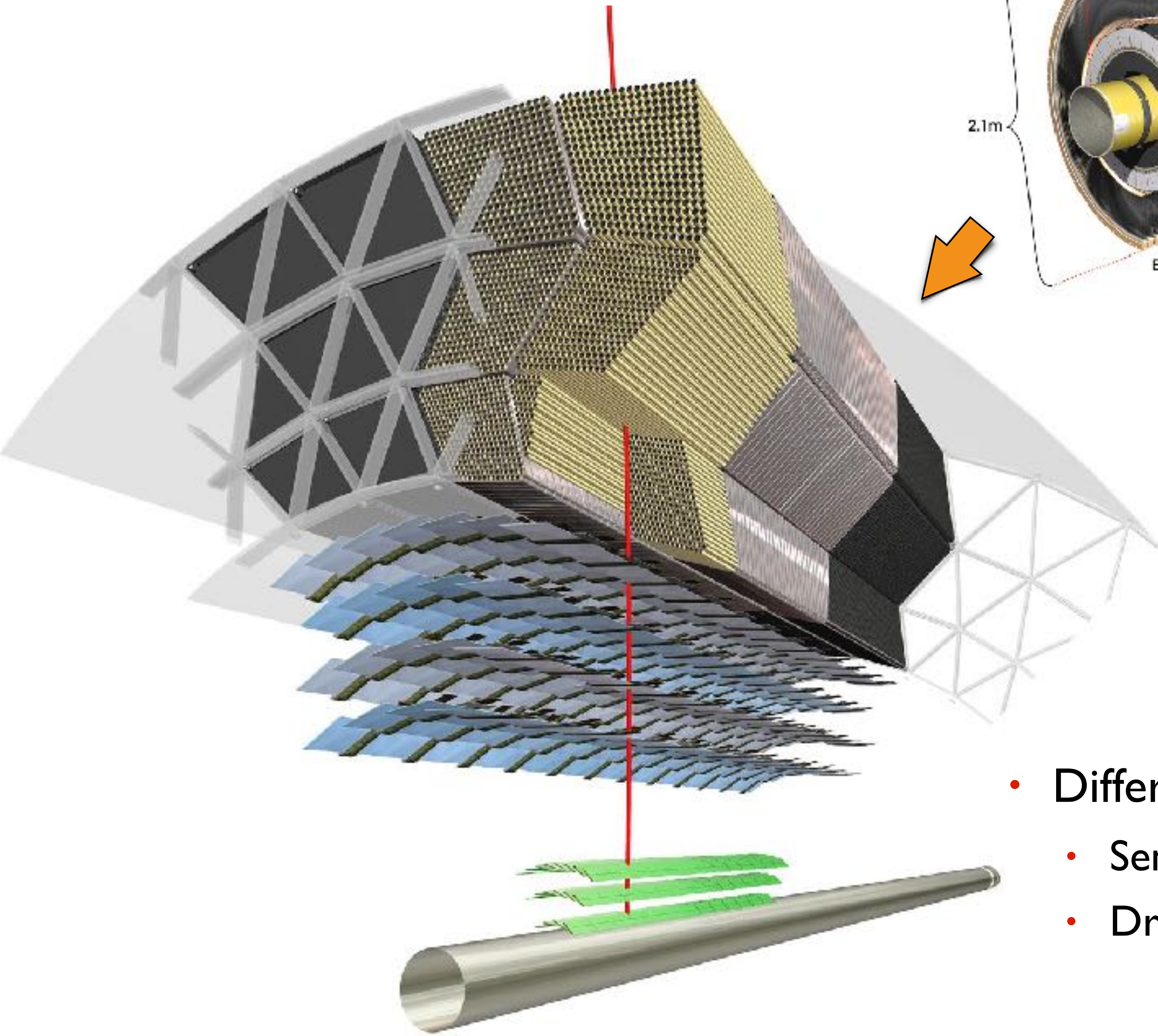


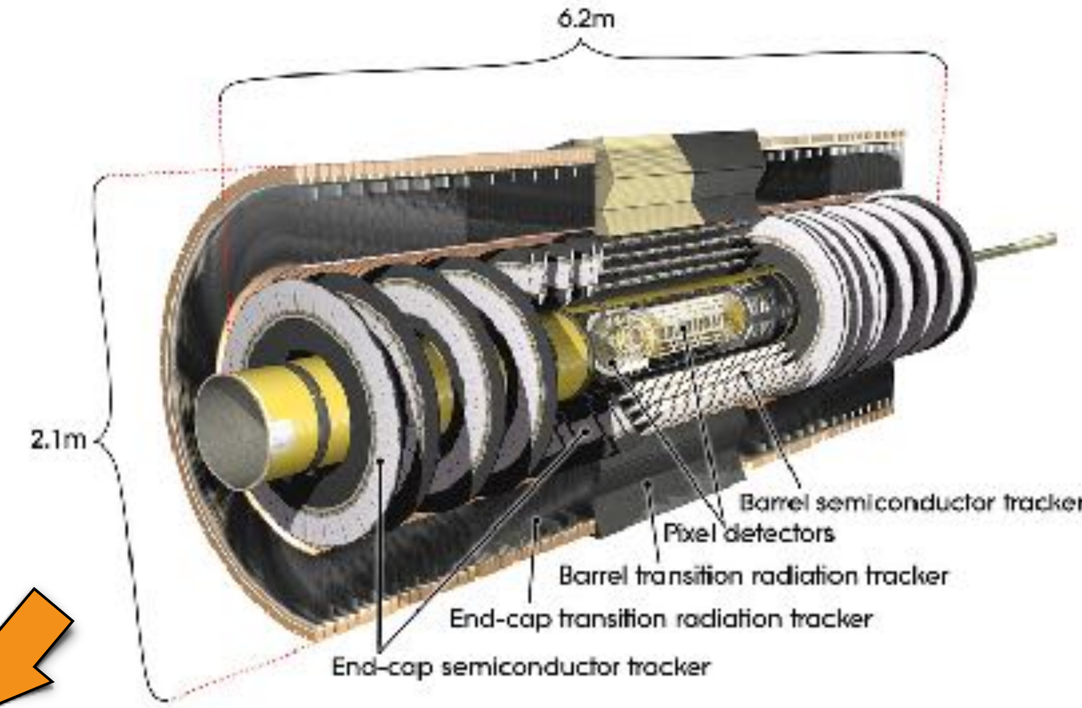


The ATLAS detector



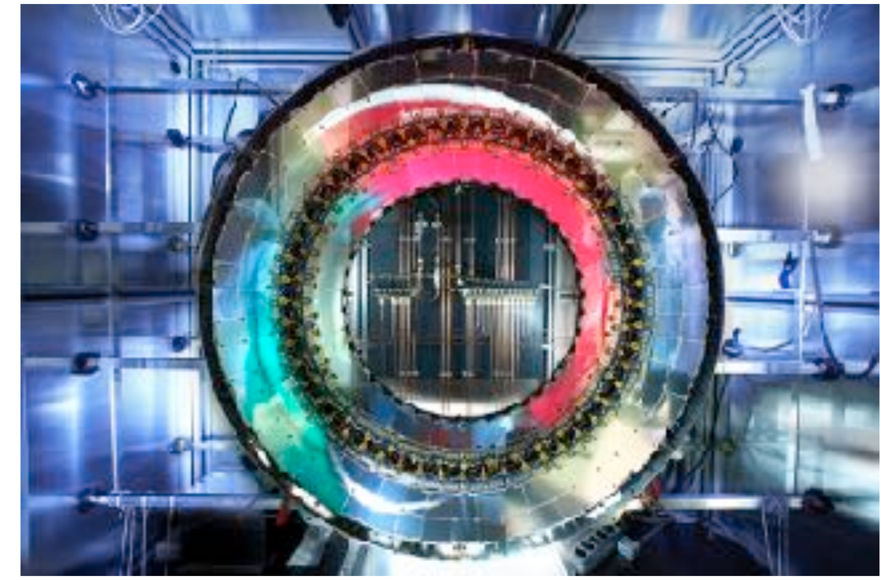
Tracking and vertexing



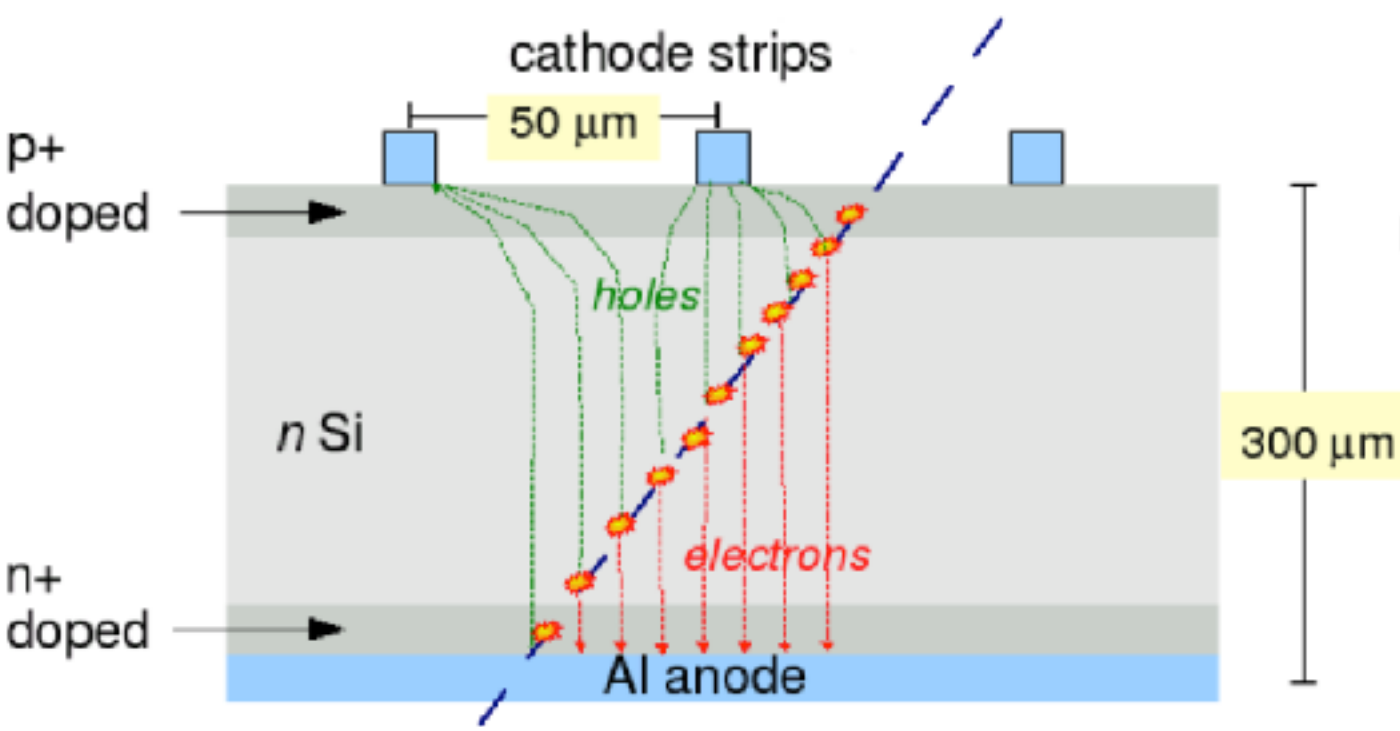


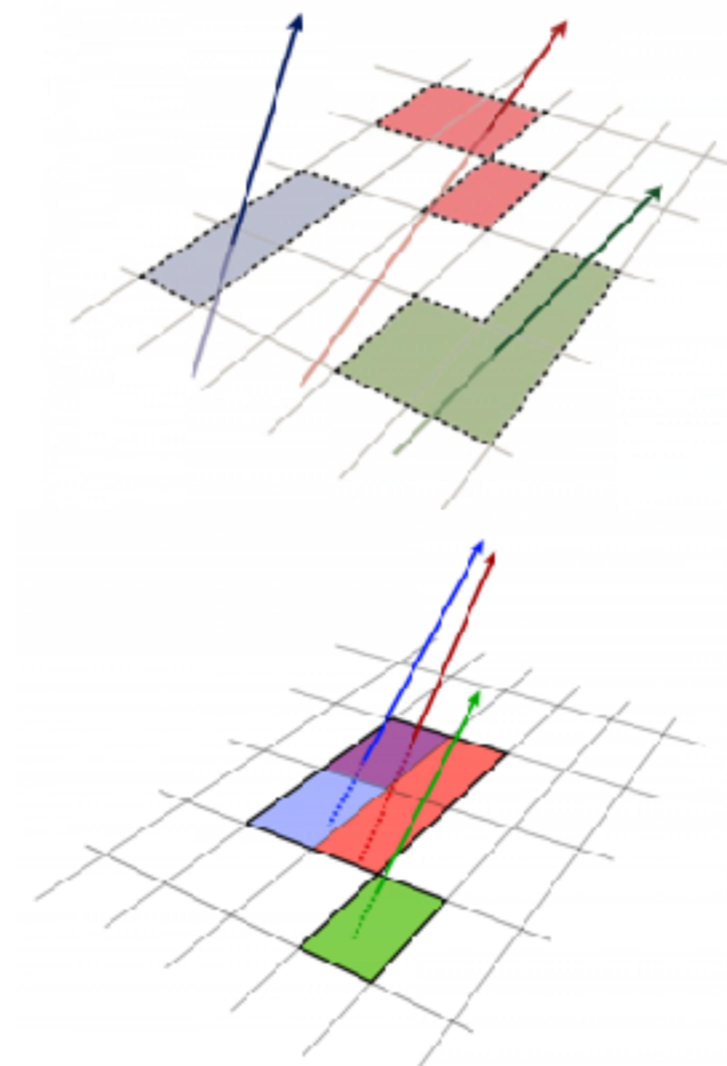
- Different technologies:
  - Semiconductor detectors
  - Drift tubes

Tracking and vertexing



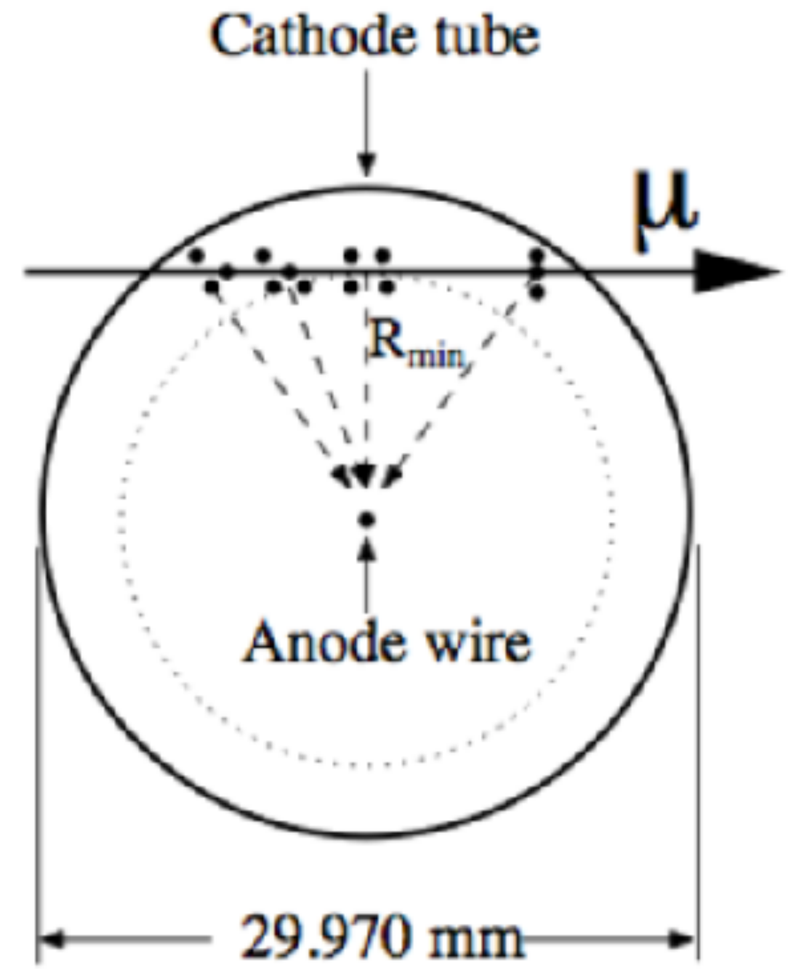
- Semiconductor (Si) detectors:
  - Ionizing radiation sets "charge carriers" free and an electric signal can be measured.
  - Thin detectors and high charge mobility: fast charge collection

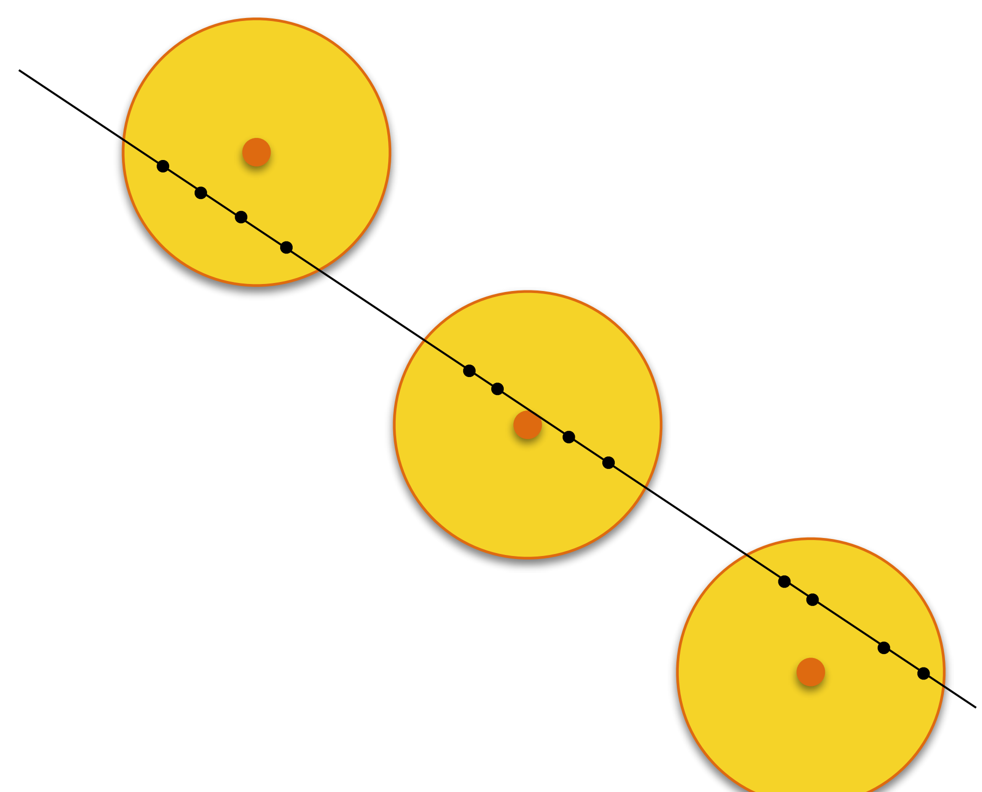




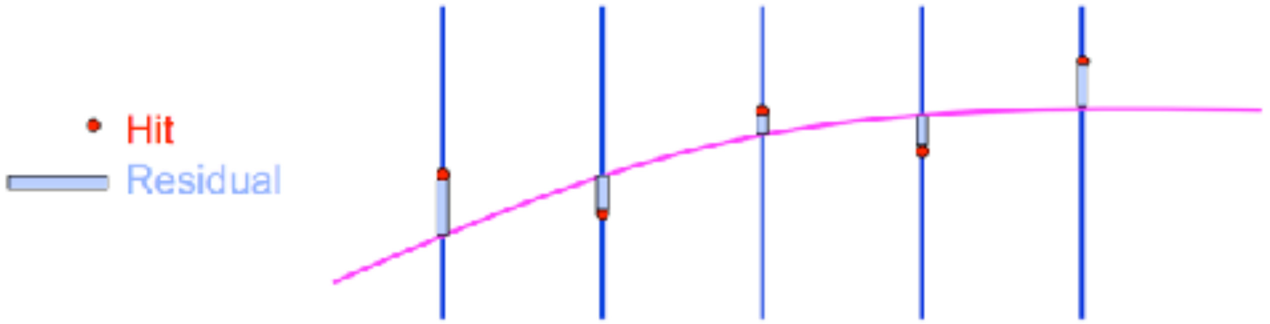
Tracking and vertexing

- **Drift tube:**
  - Gas ionization under a strong electric field.
- A characteristic drift time can be measured with respect to a time t_0:
  - Taking into account "LHC clock" and the original particle's time of travel
  - Can be used to define a set of possible "hits" for the particle's trajectory: the other detectors will help constrain the position.
- Also PID, with transition radiation:
  - When a charged particle travels through the boundary of two different media, it emits electromagnetic radiation.

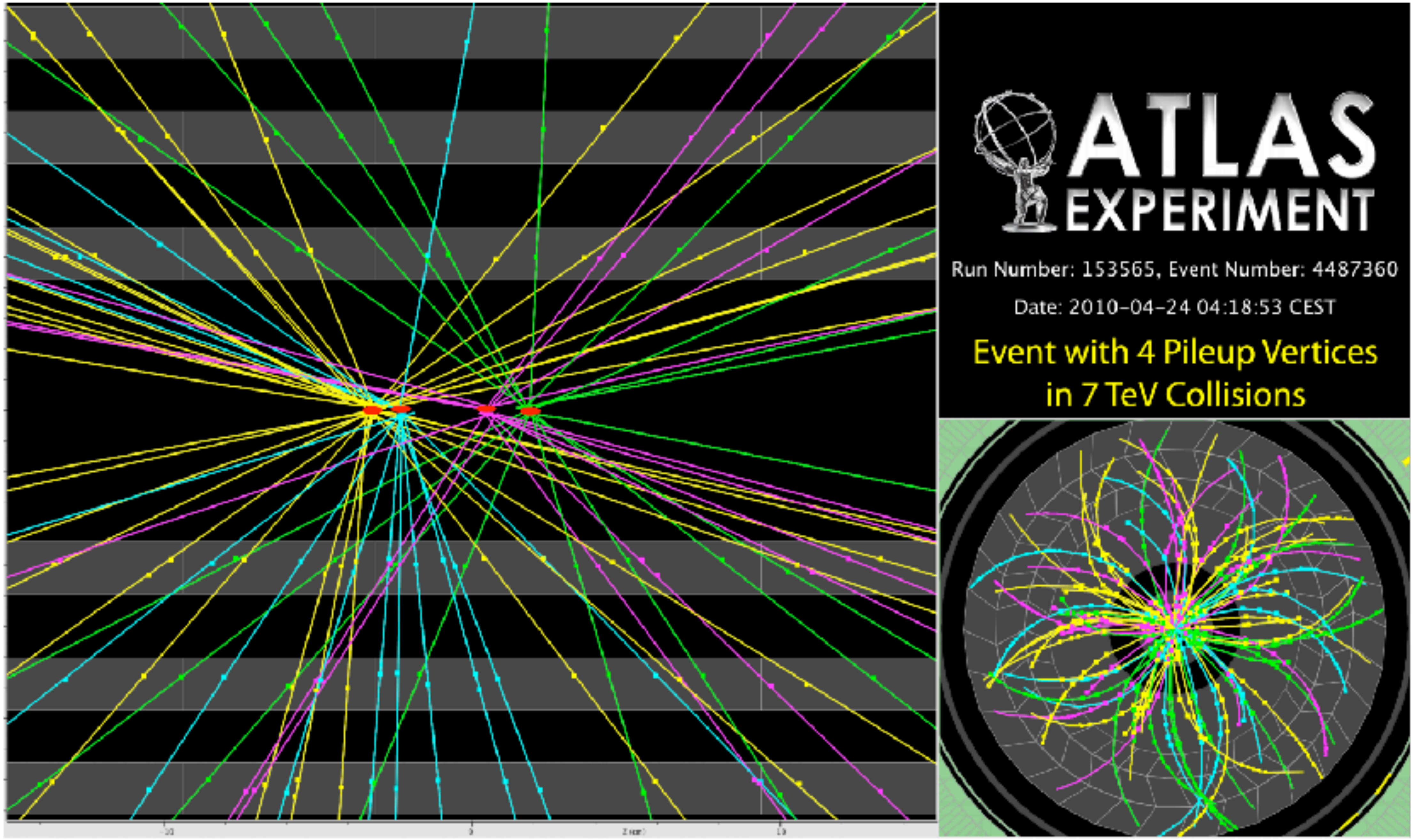




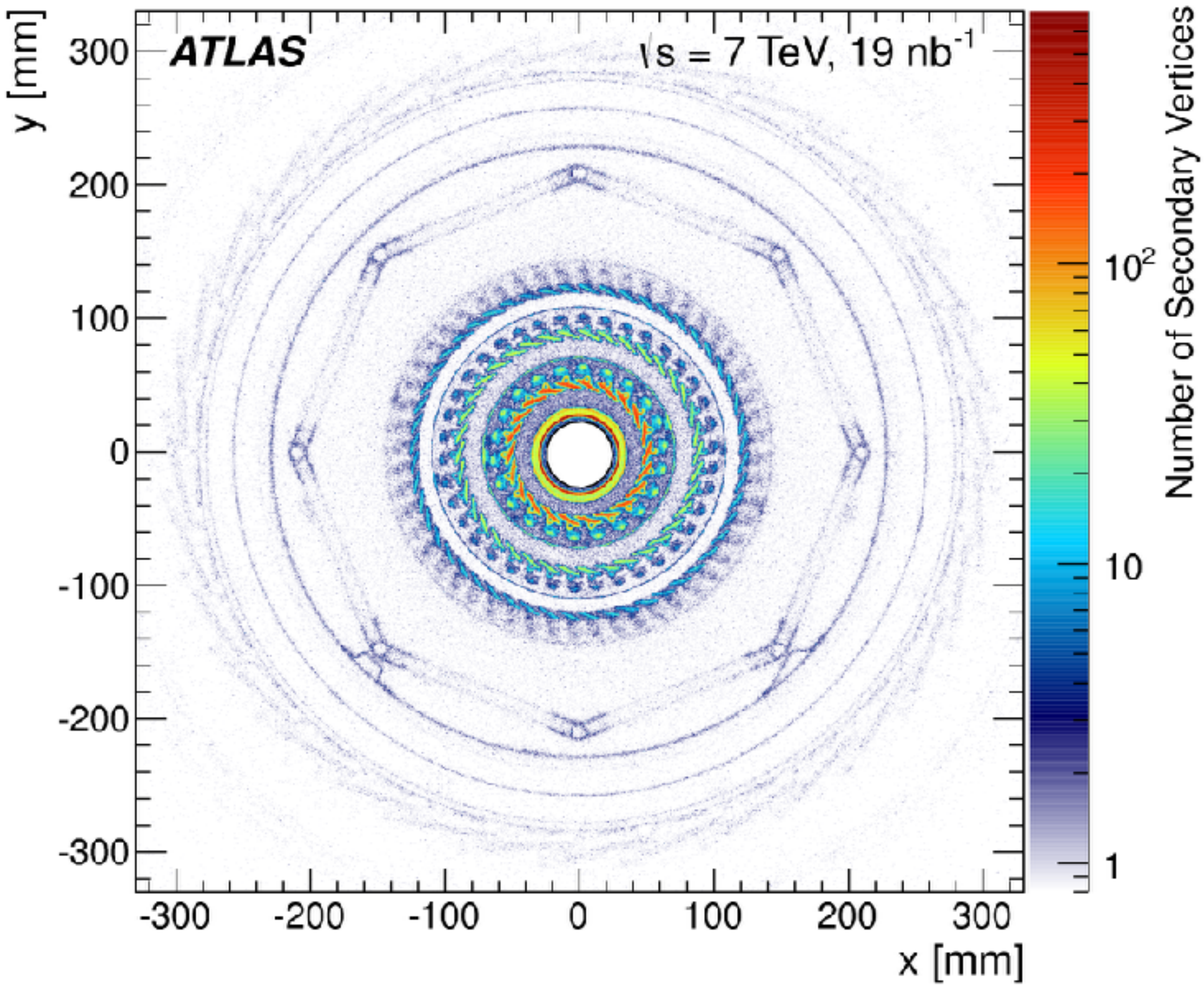
Tracking and vertexing



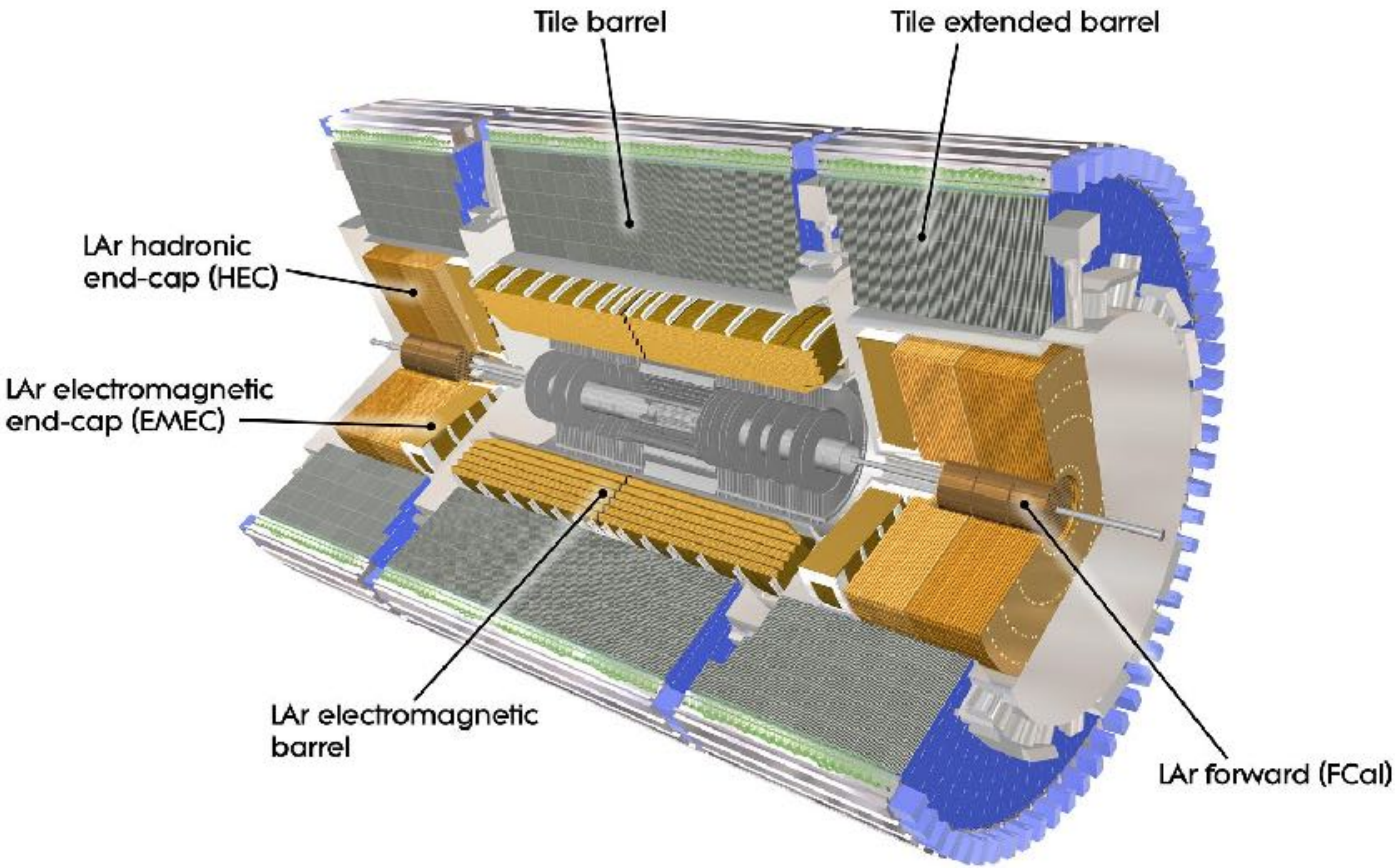
from F. Meier



Tracking and vertexing



Calorimeters



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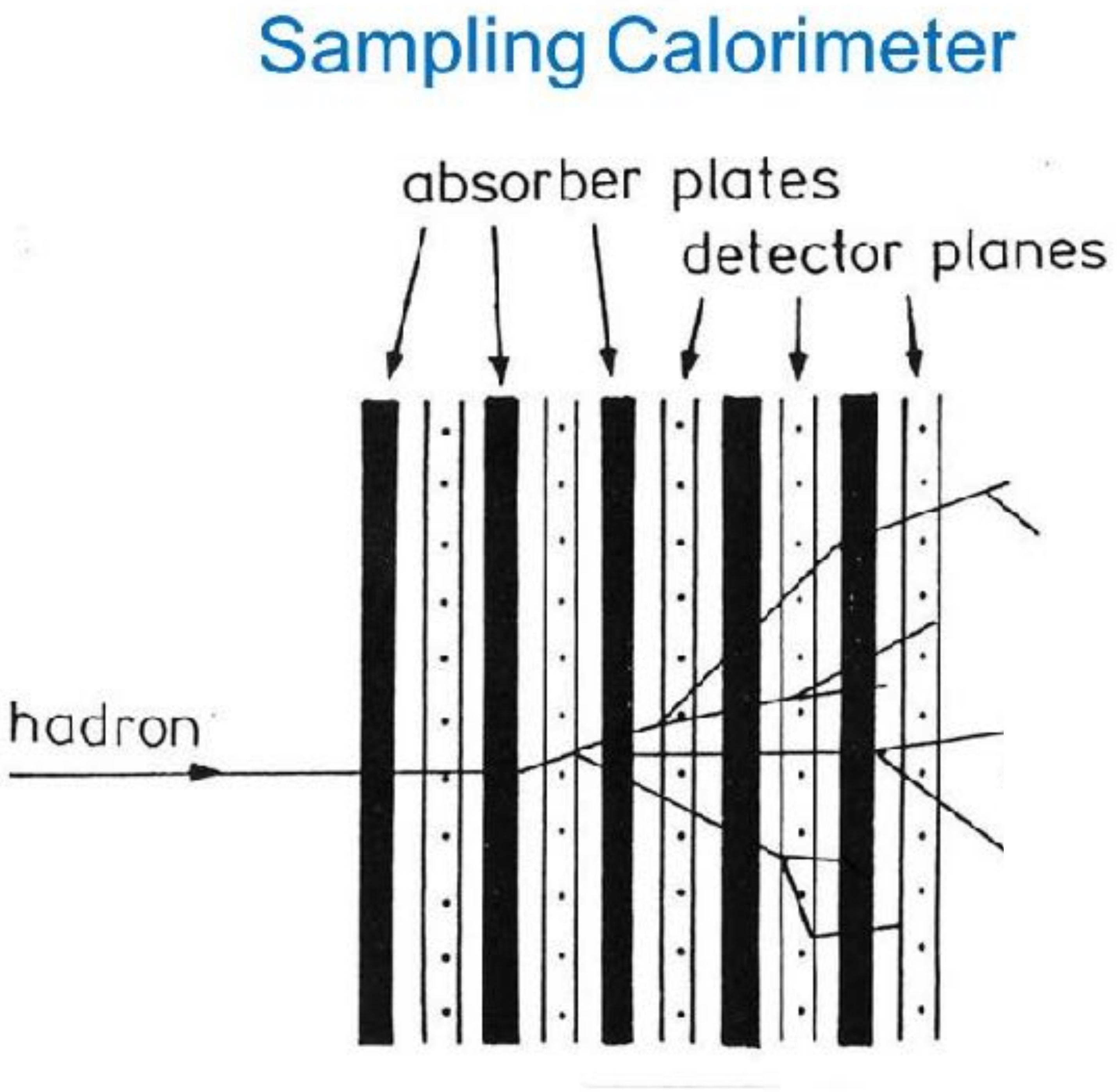
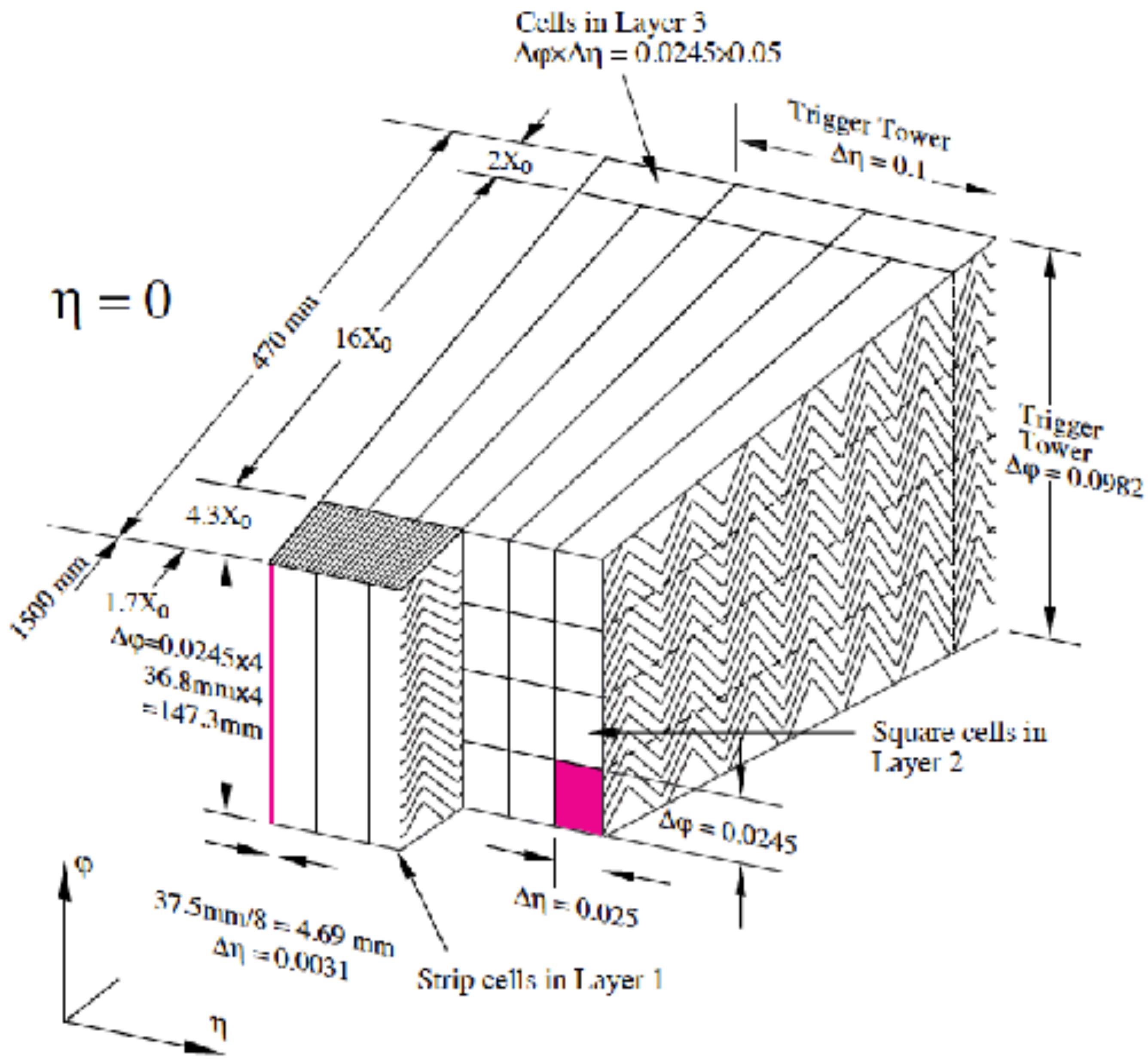
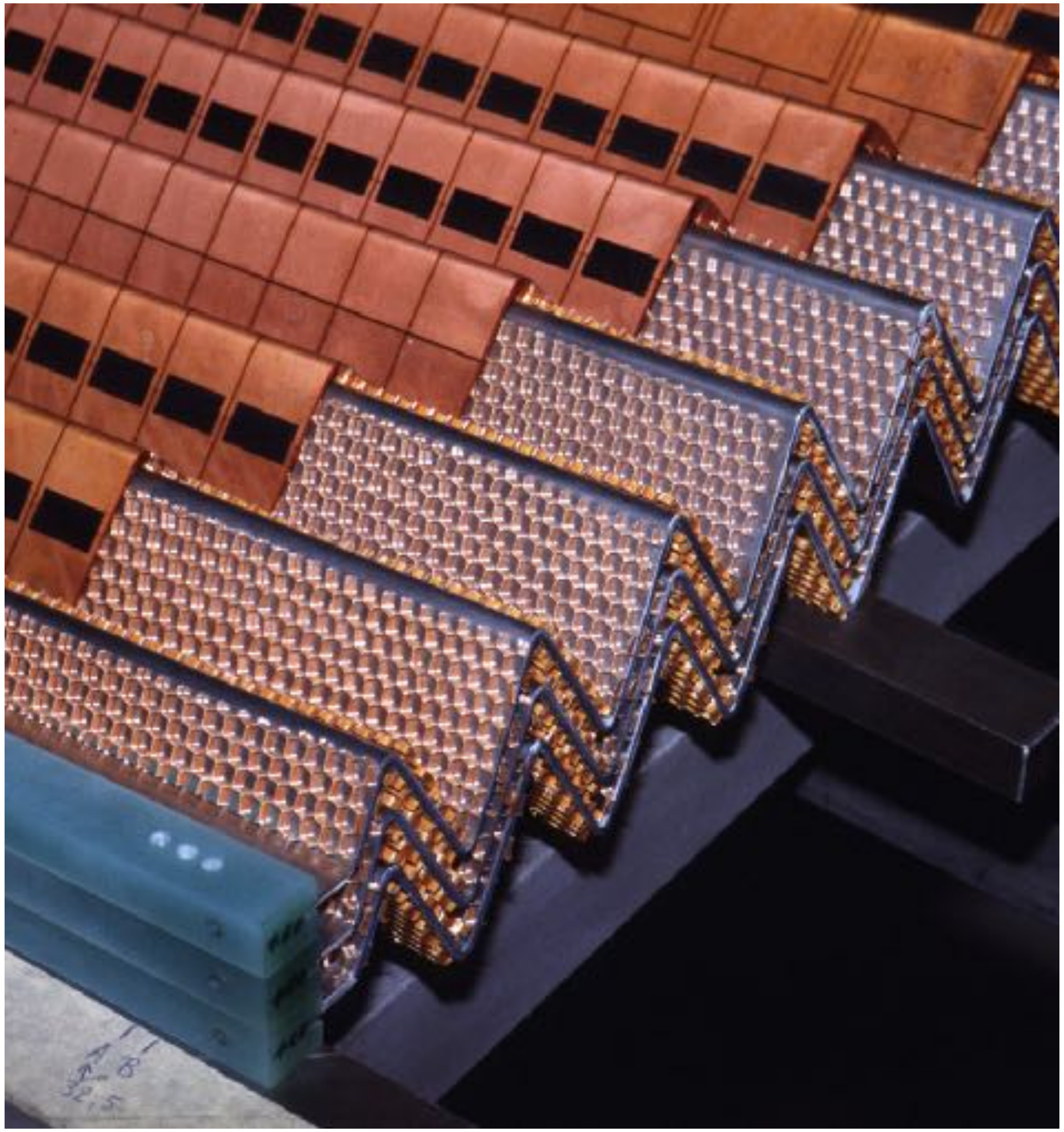


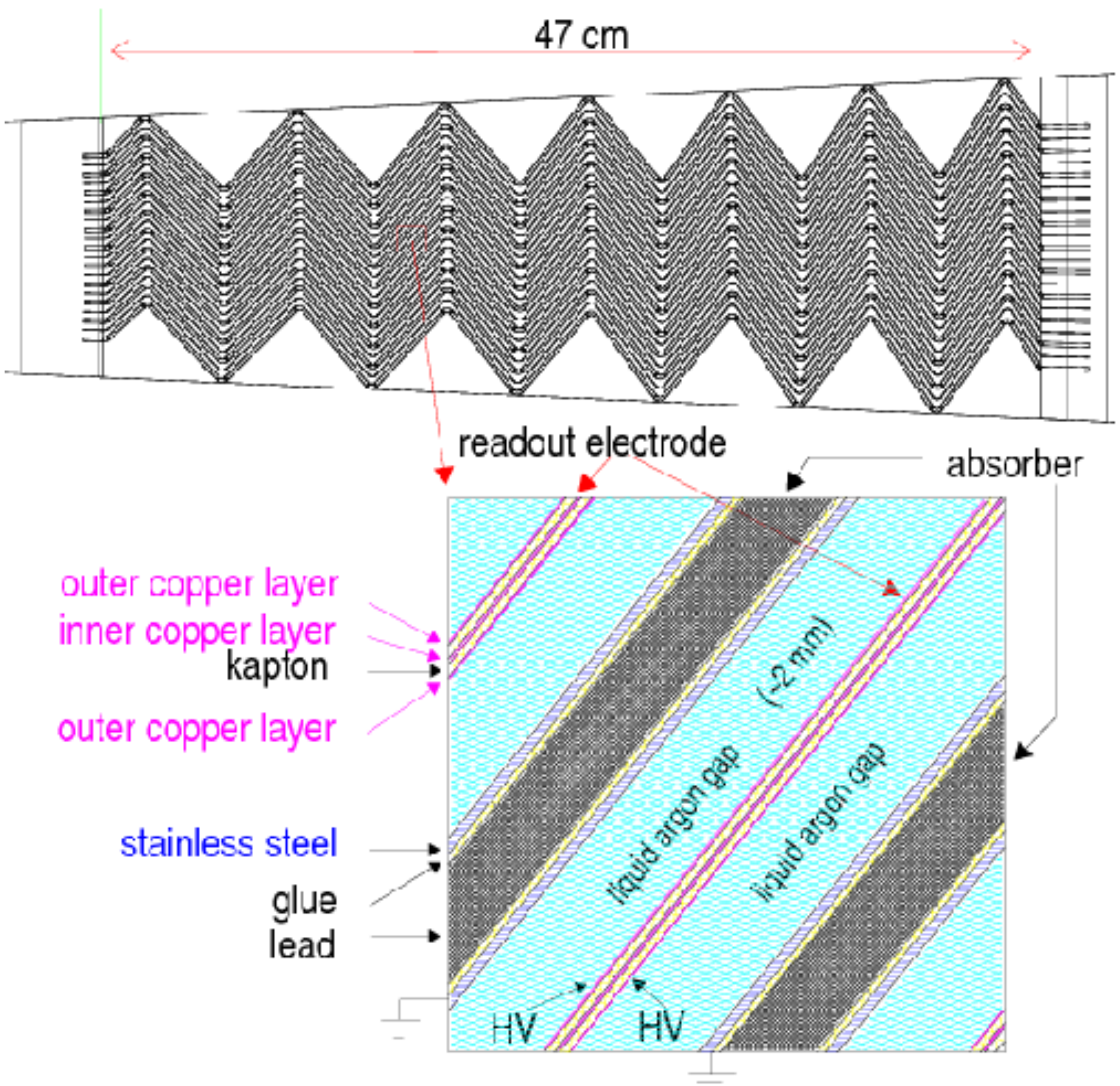
R.S. Orr 2009 TRIUMF Summer Institute

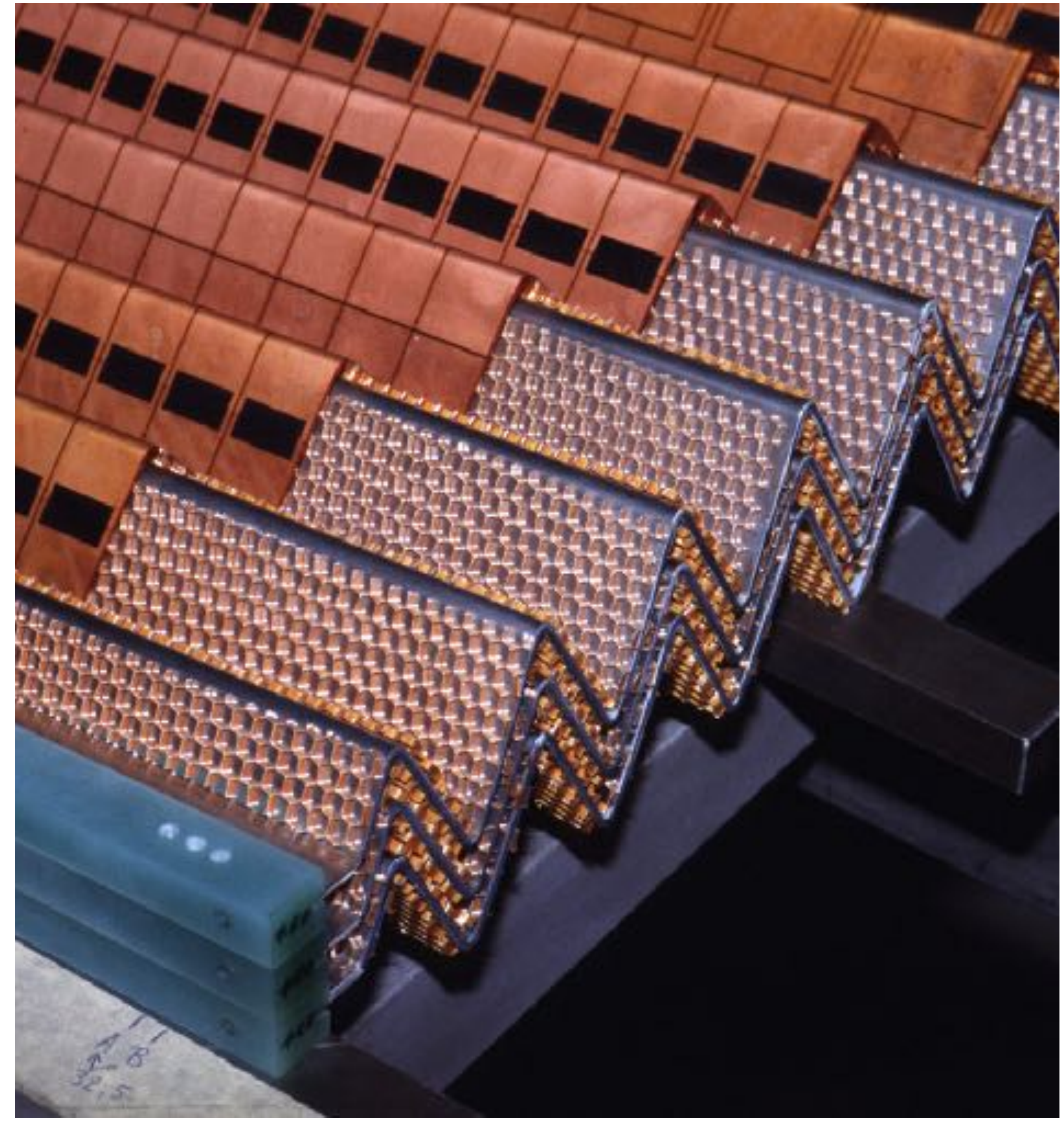
Calorimeters





Calorimeters





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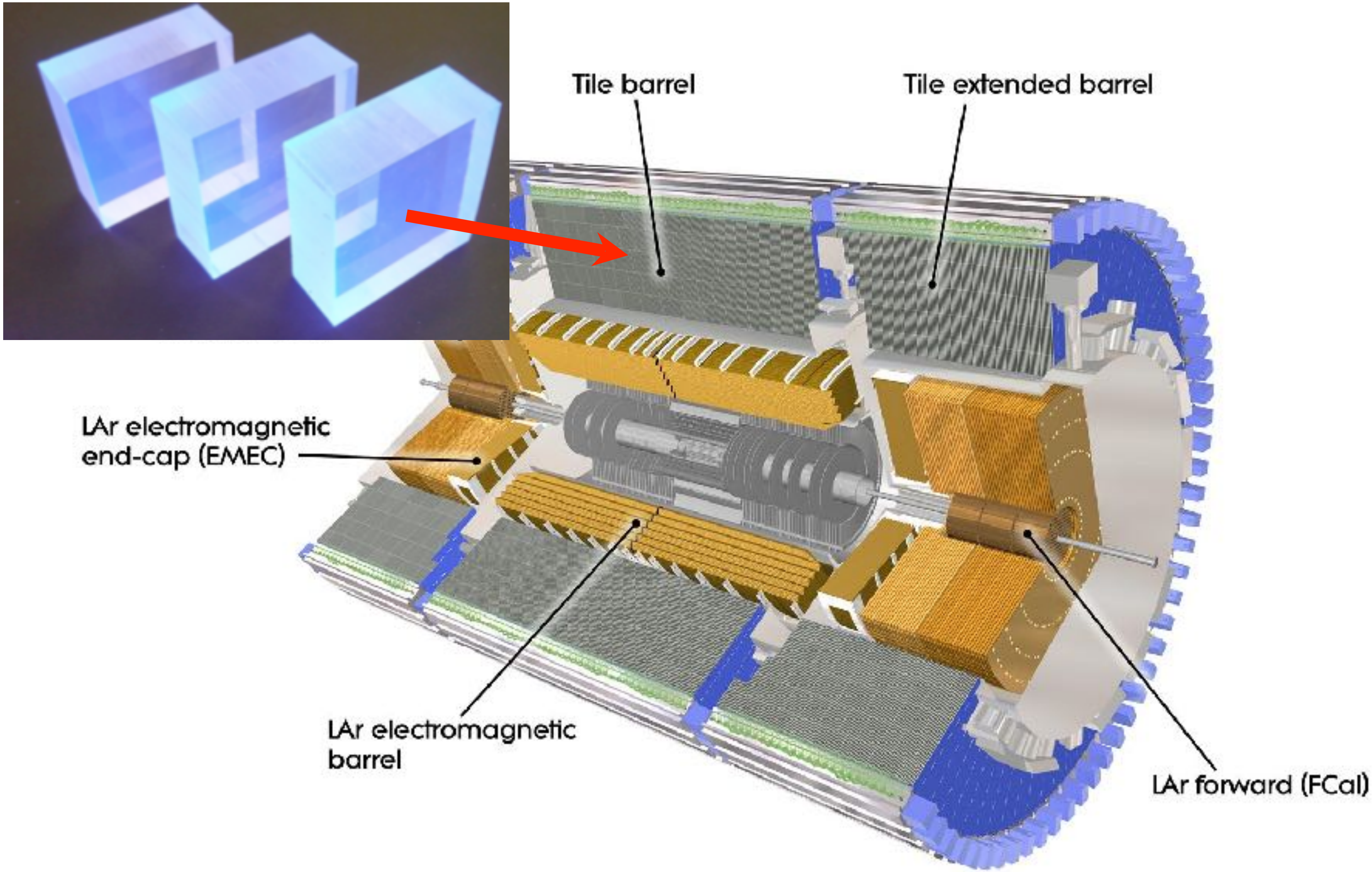
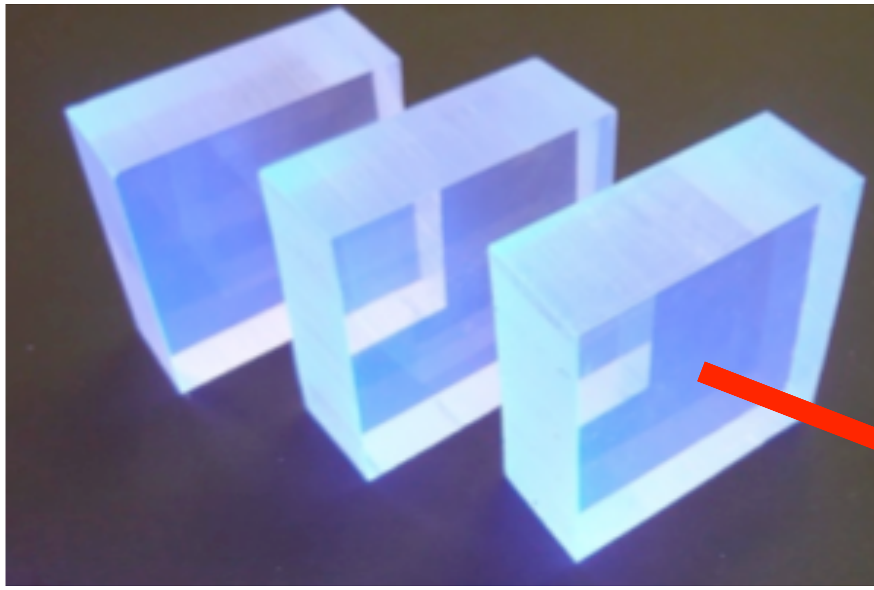
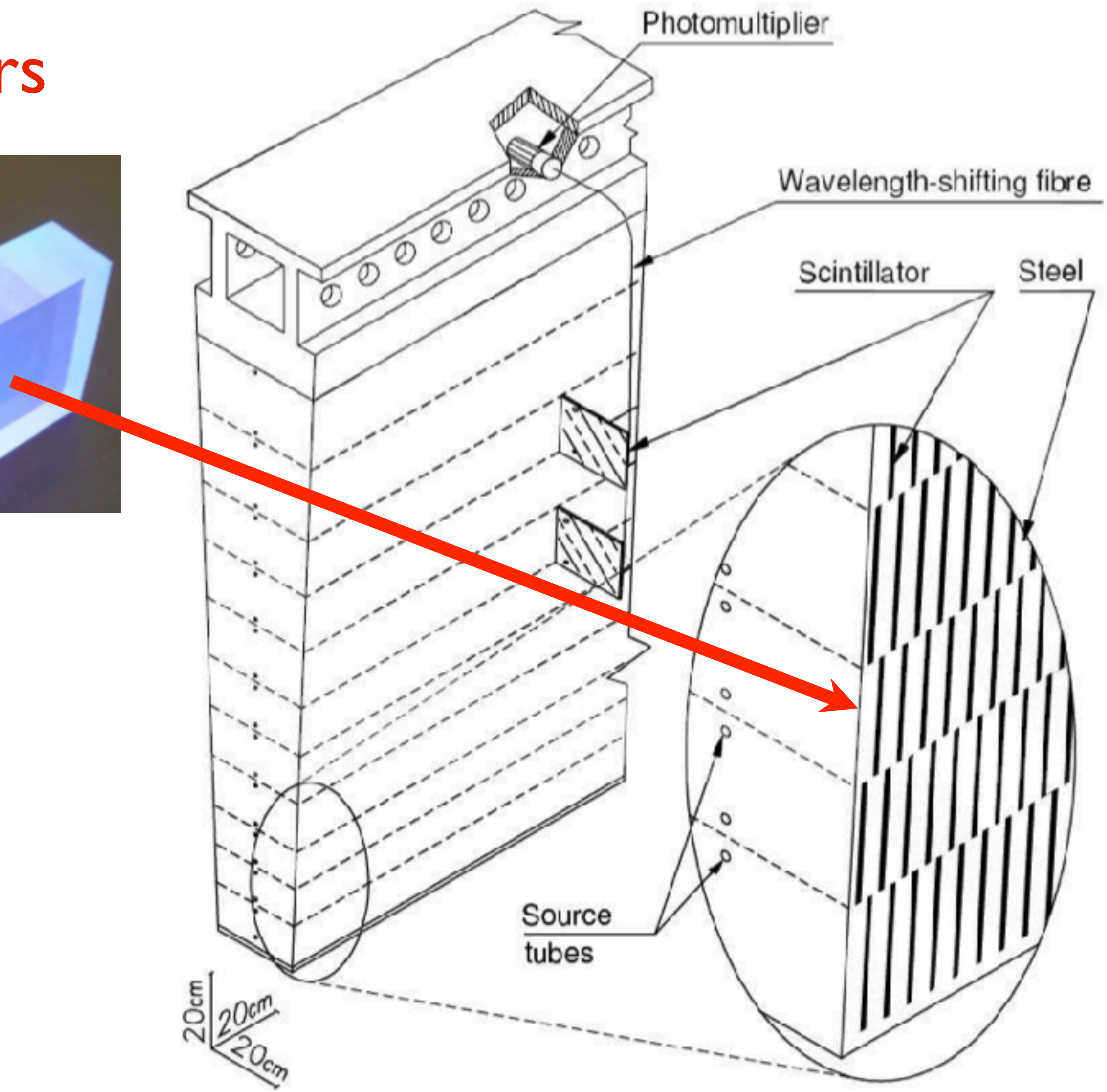


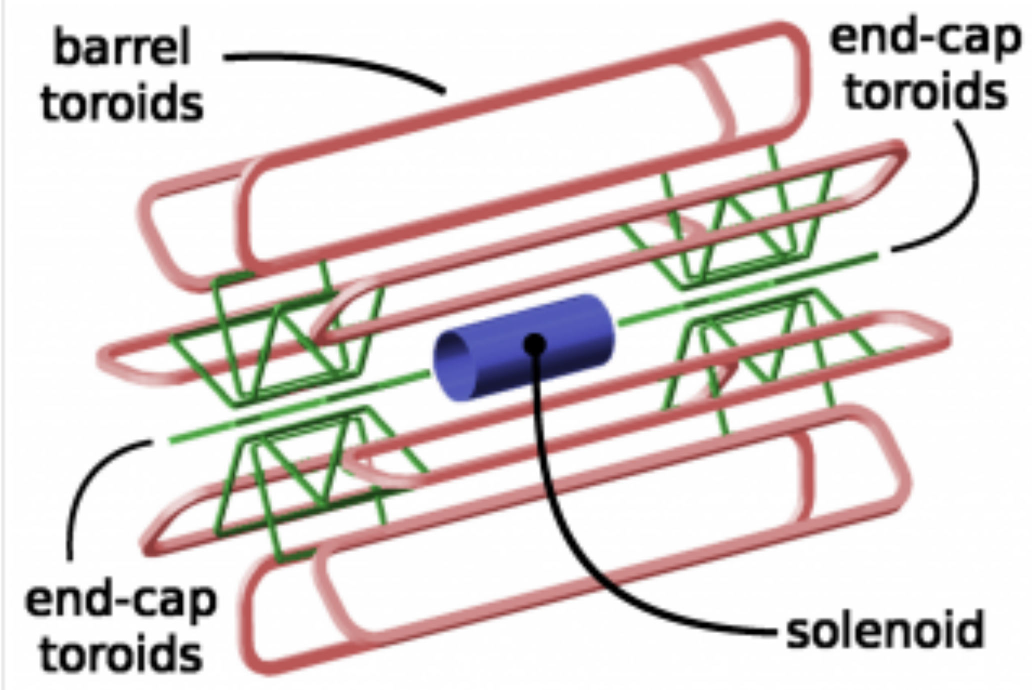
Calorimeters

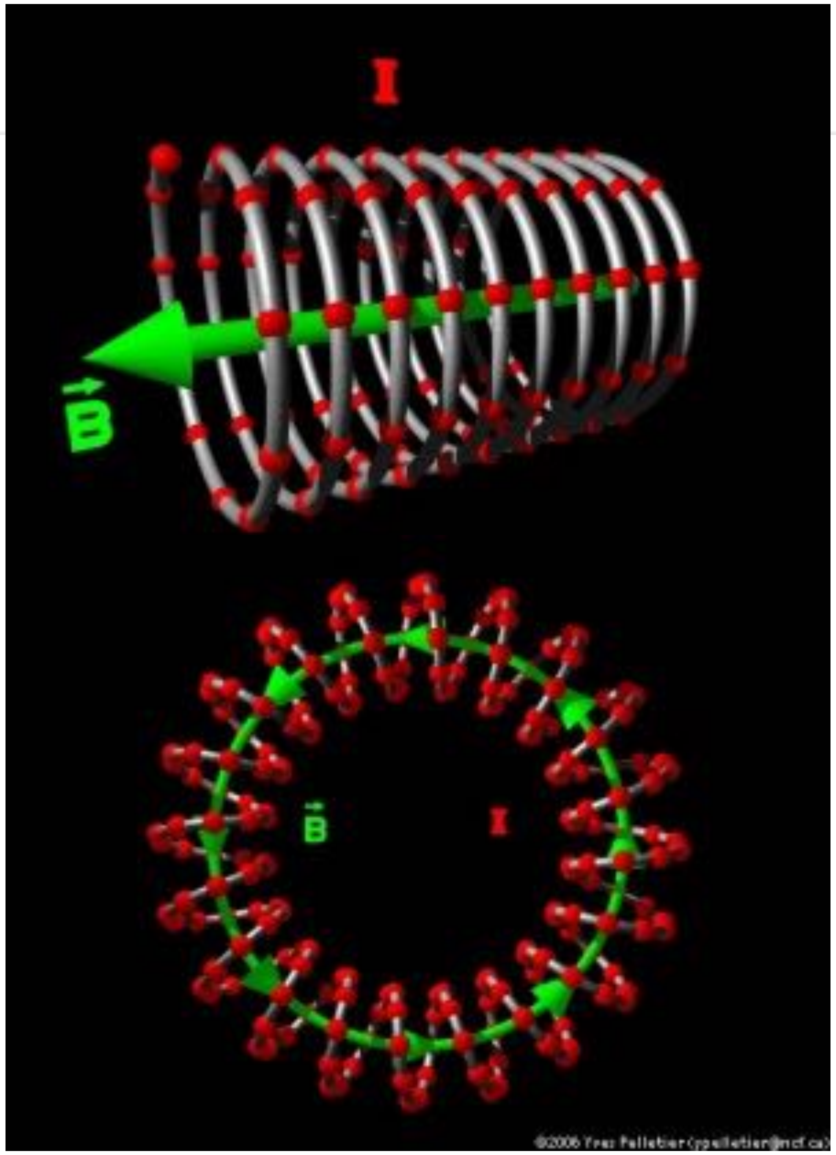




Magnet systems

- Solenoid coils in CMS and ATLAS:
  - Field direction along beam axis.
  - Homogenous field inside the coil.
  - e.g. CMS superconducting magnet
    - I = 20 kA, B = 4 T
    - Temperature 4K.
- Toroidal magnets in ATLAS.
- For comparison, Earth's magnetic field at surface is ~50 μT.



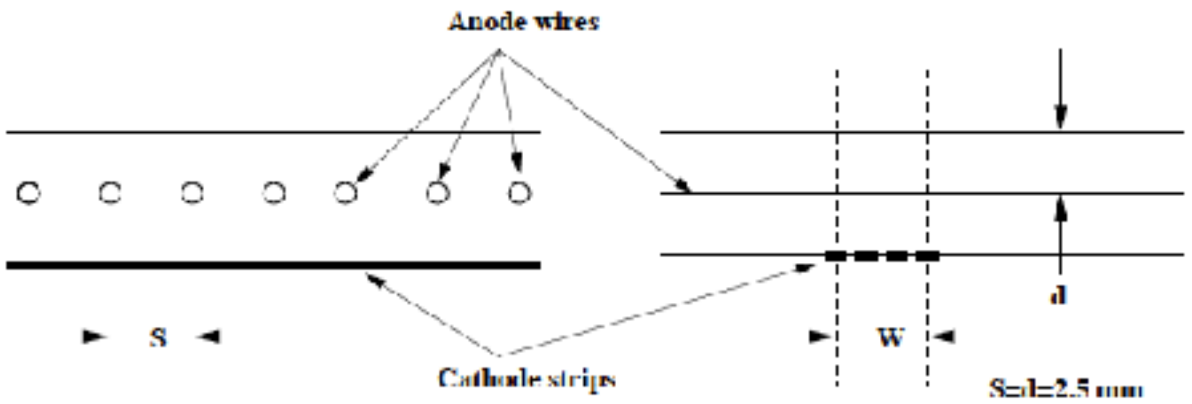


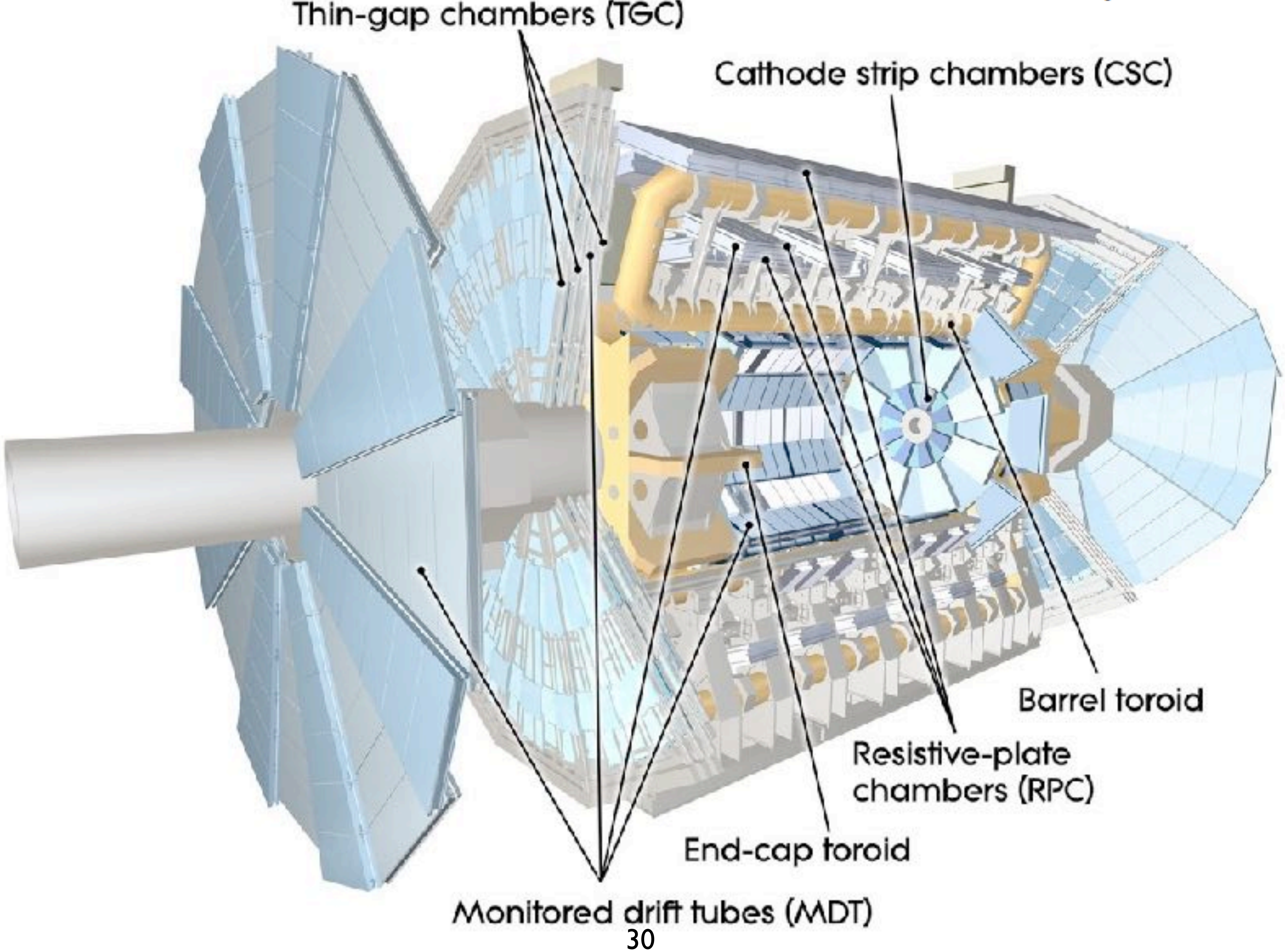
Muon detectors

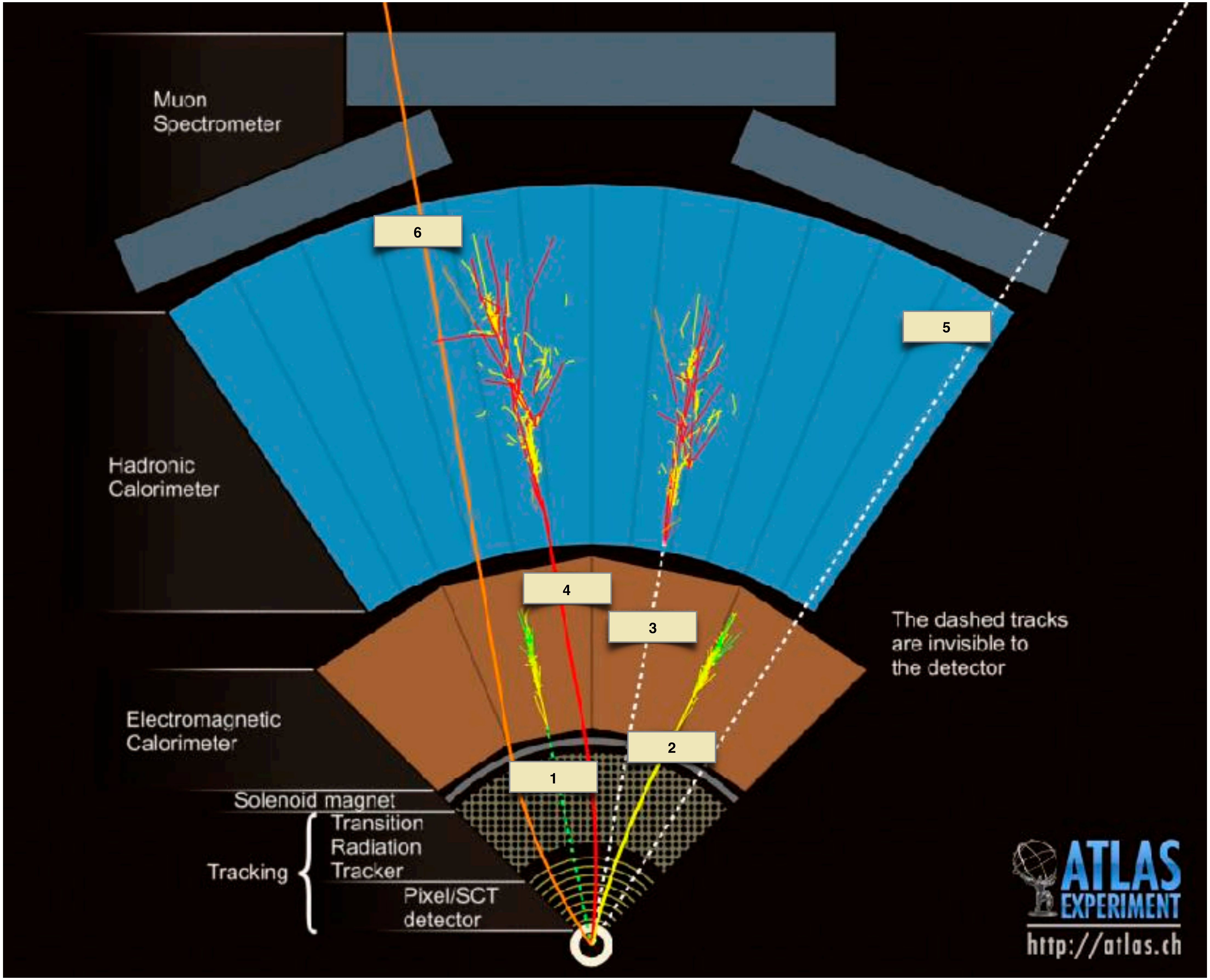
- Muons interact very little with matter: they will travel through several metres of dense material before coming to a stop.
- Momentum resolution: more bending → better resolution → bigger magnets!

Muon detectors

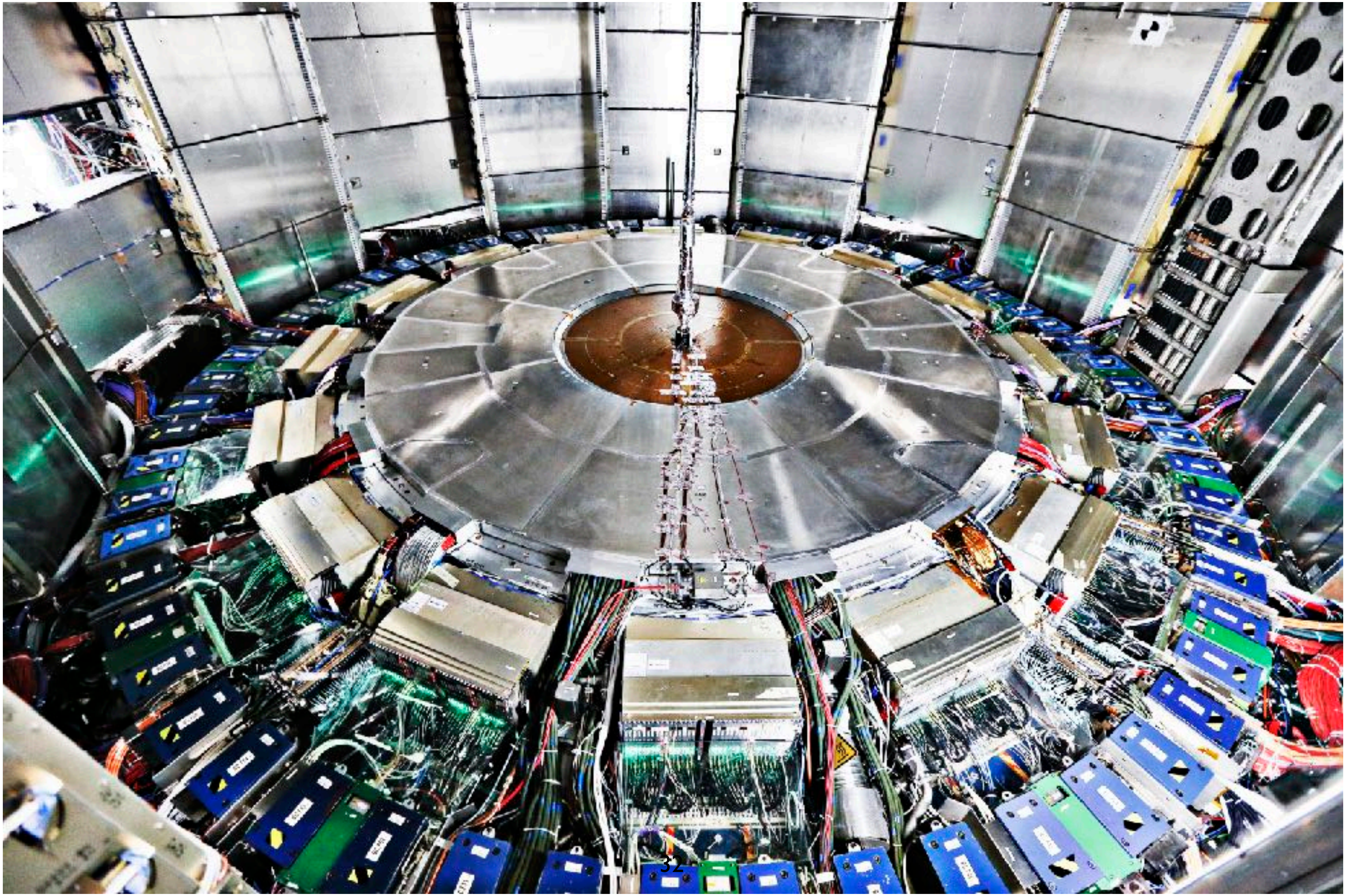
Muon detectors



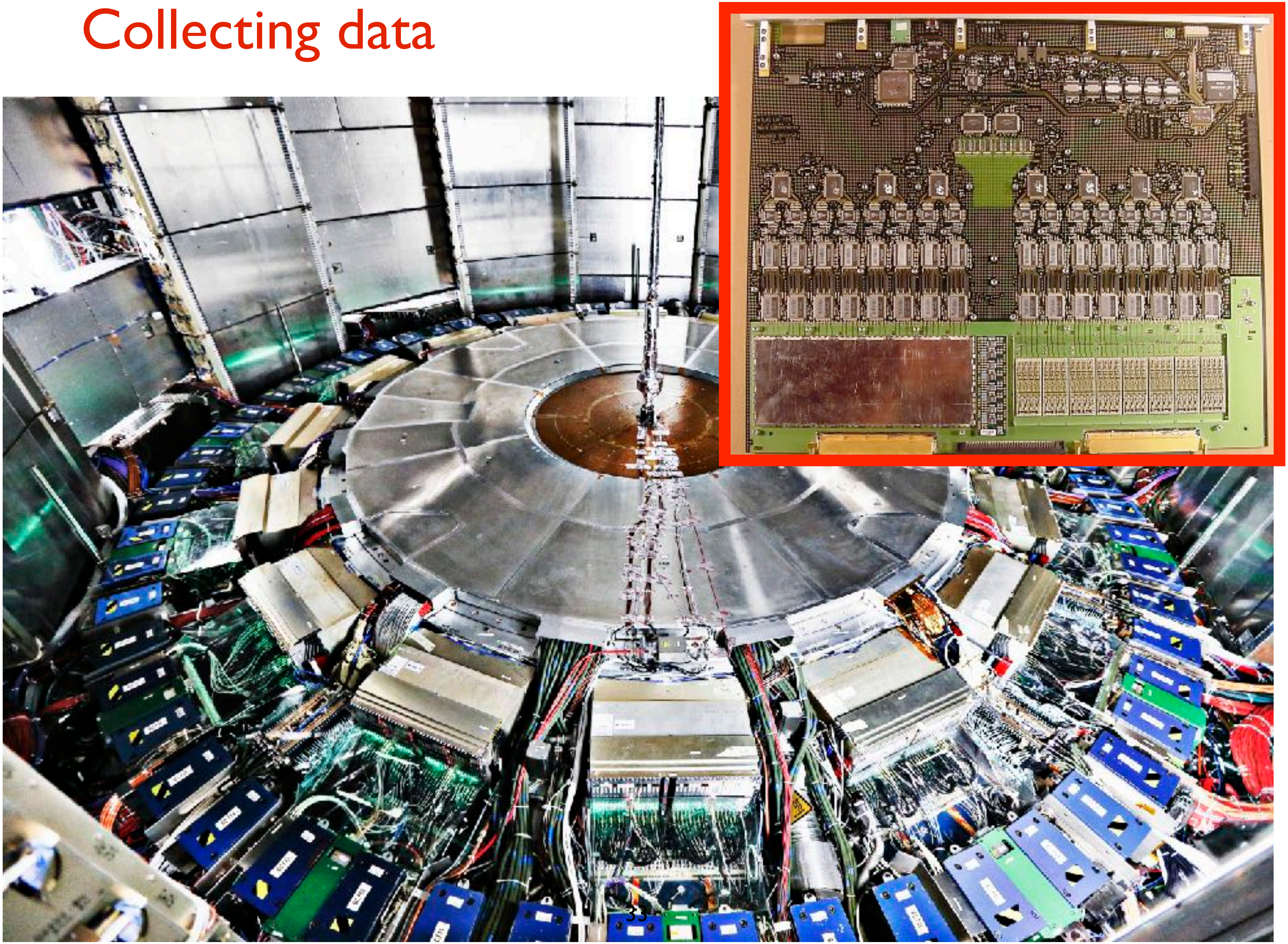



Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
6
5
4
3
2
1
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch

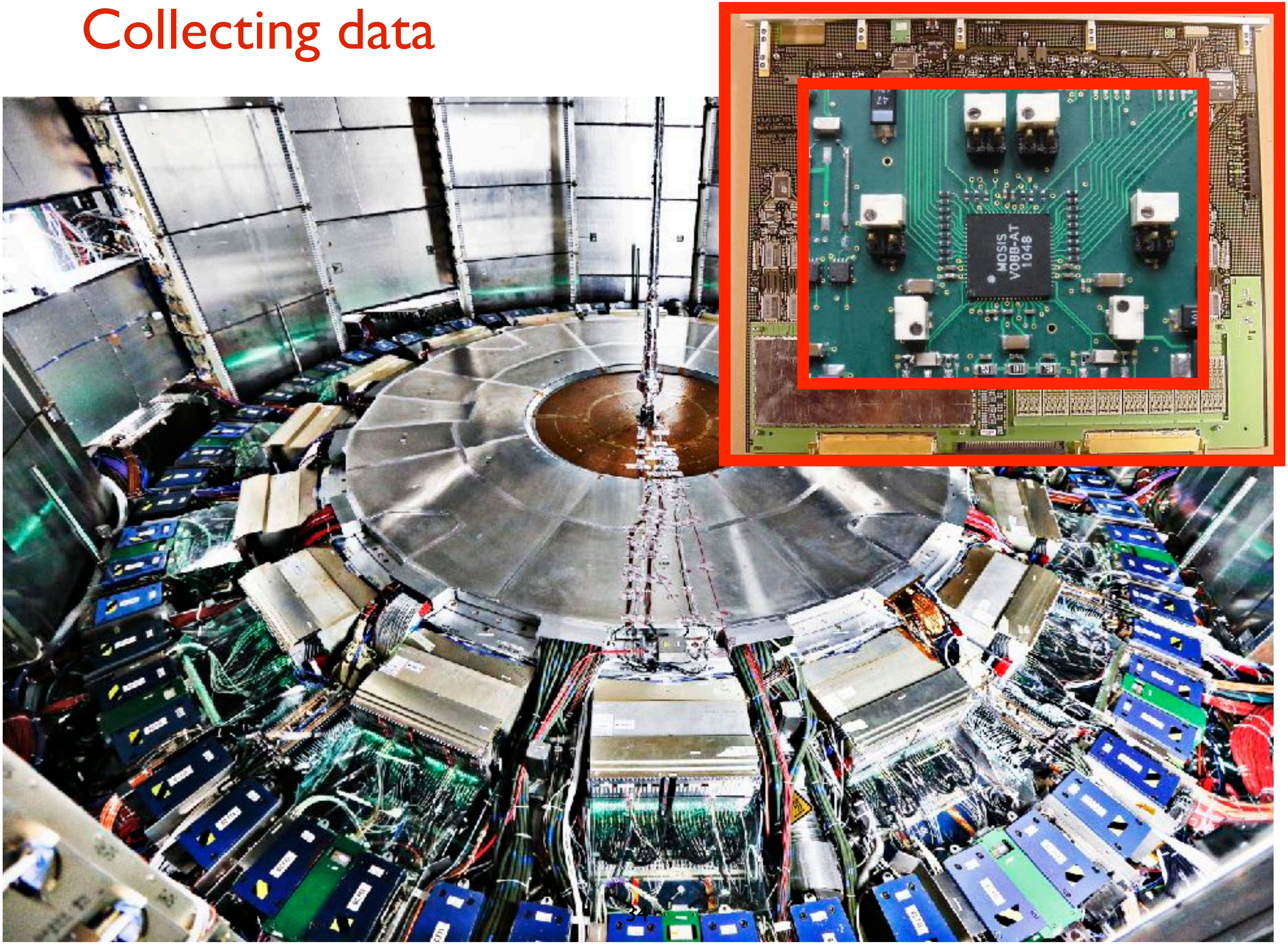
Collecting data



Collecting data

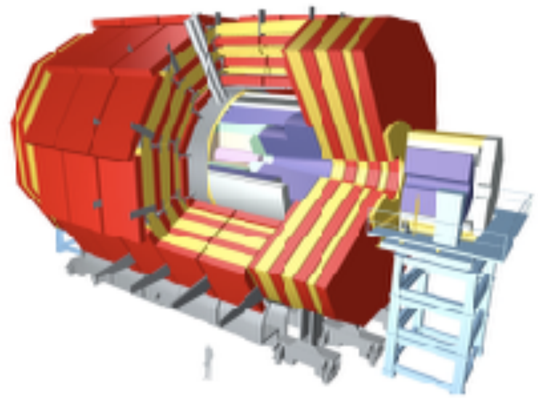


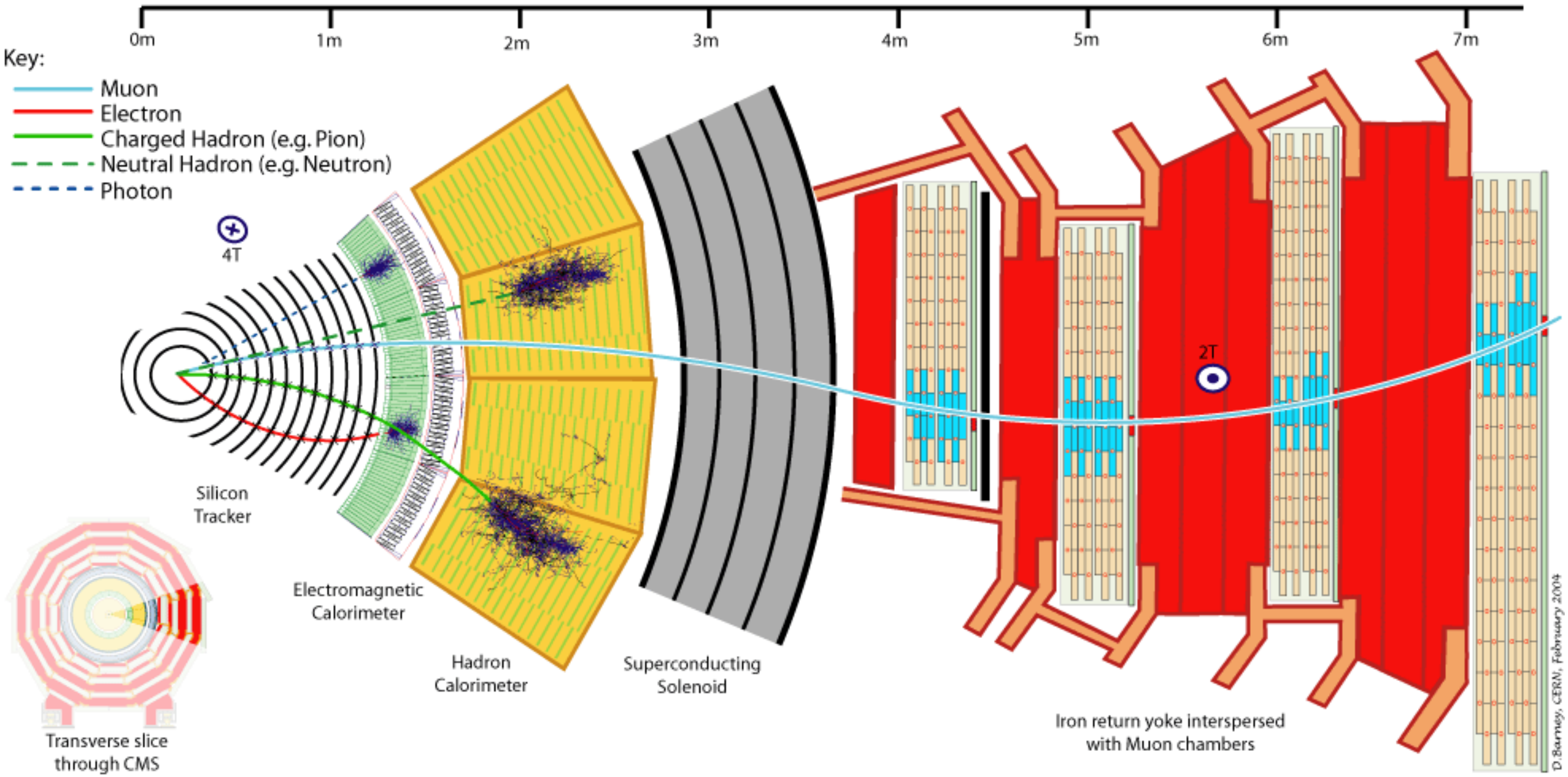
Collecting data



The CMS experiment

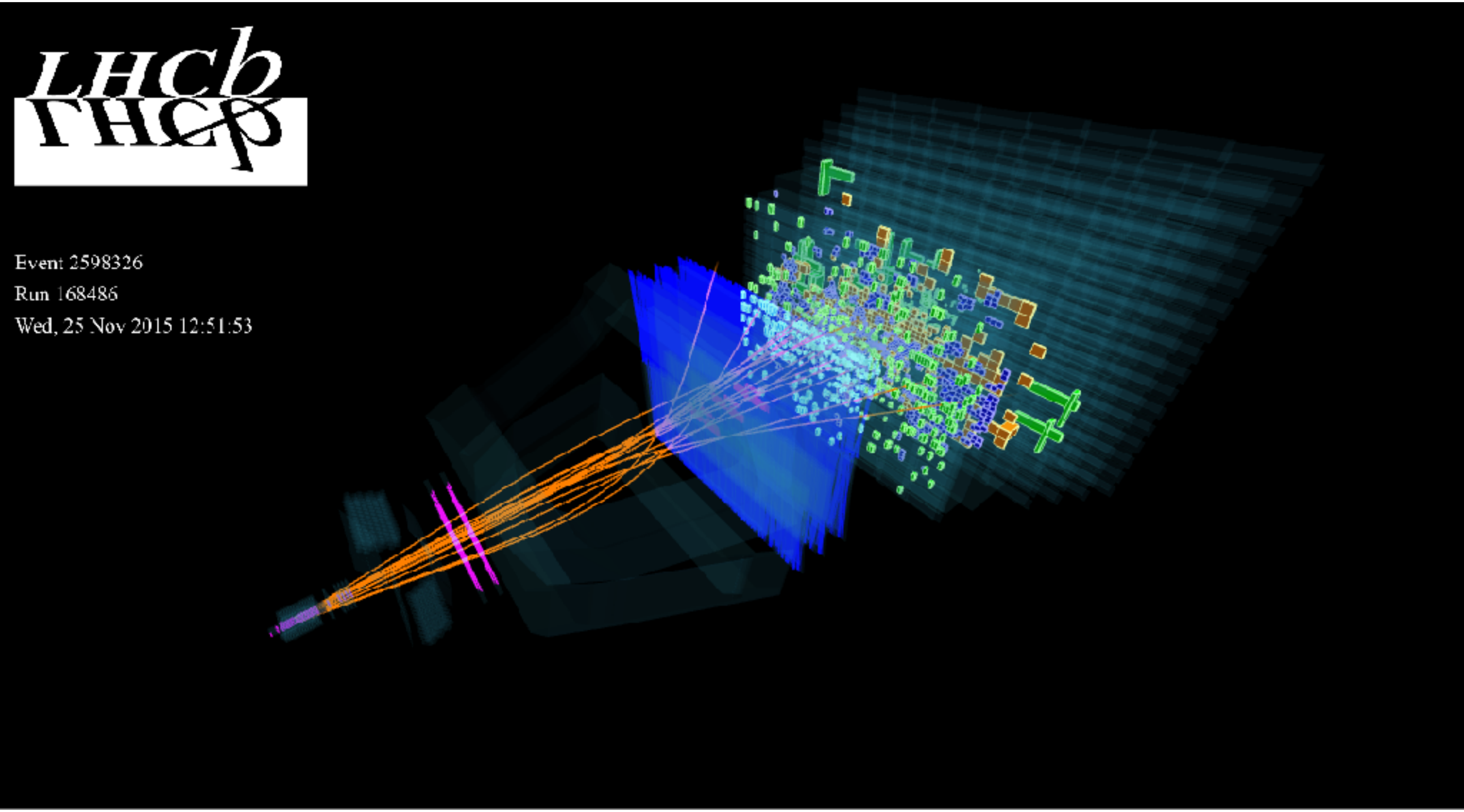
The CMS detector



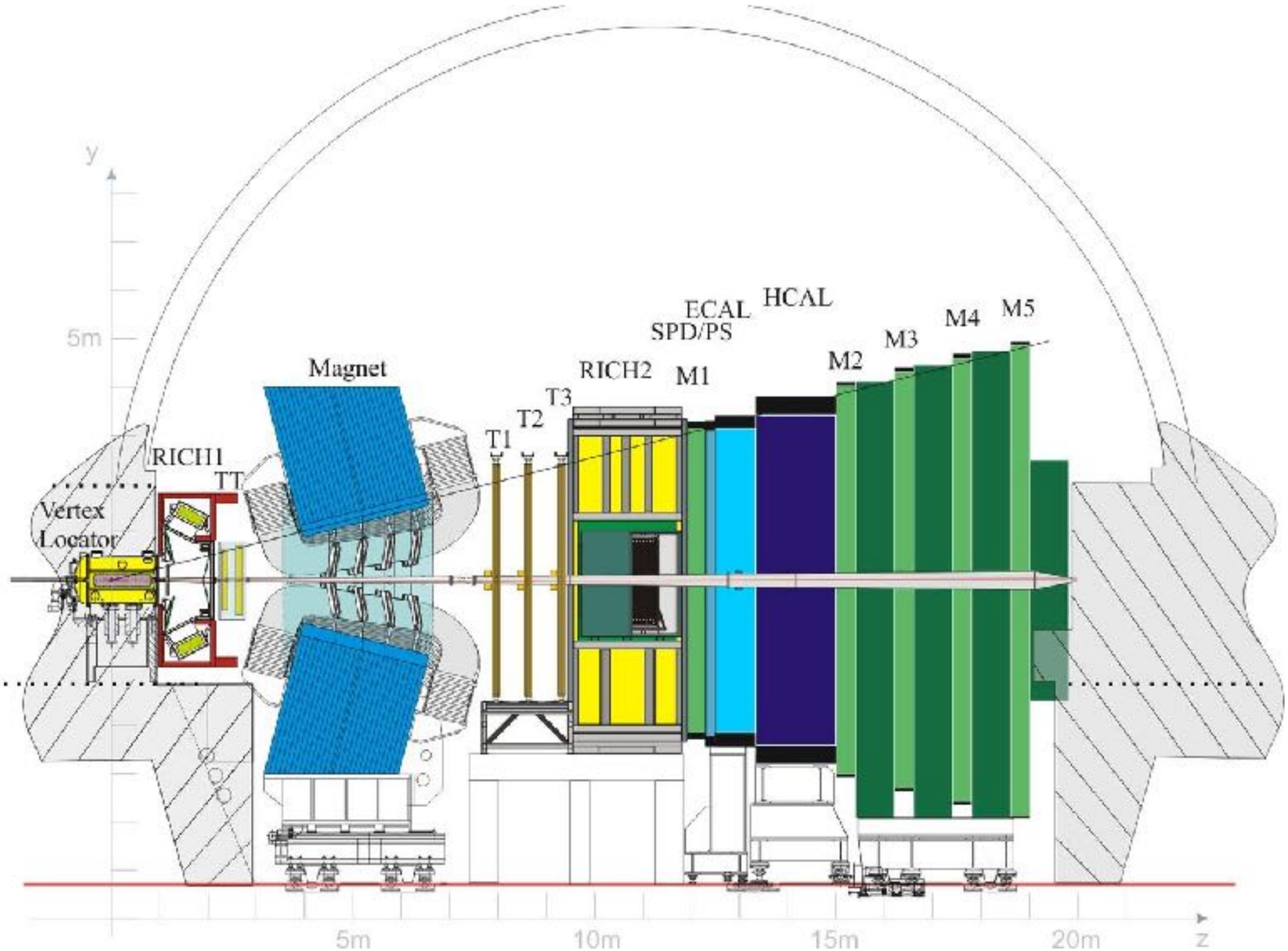


ALICE and LHCb

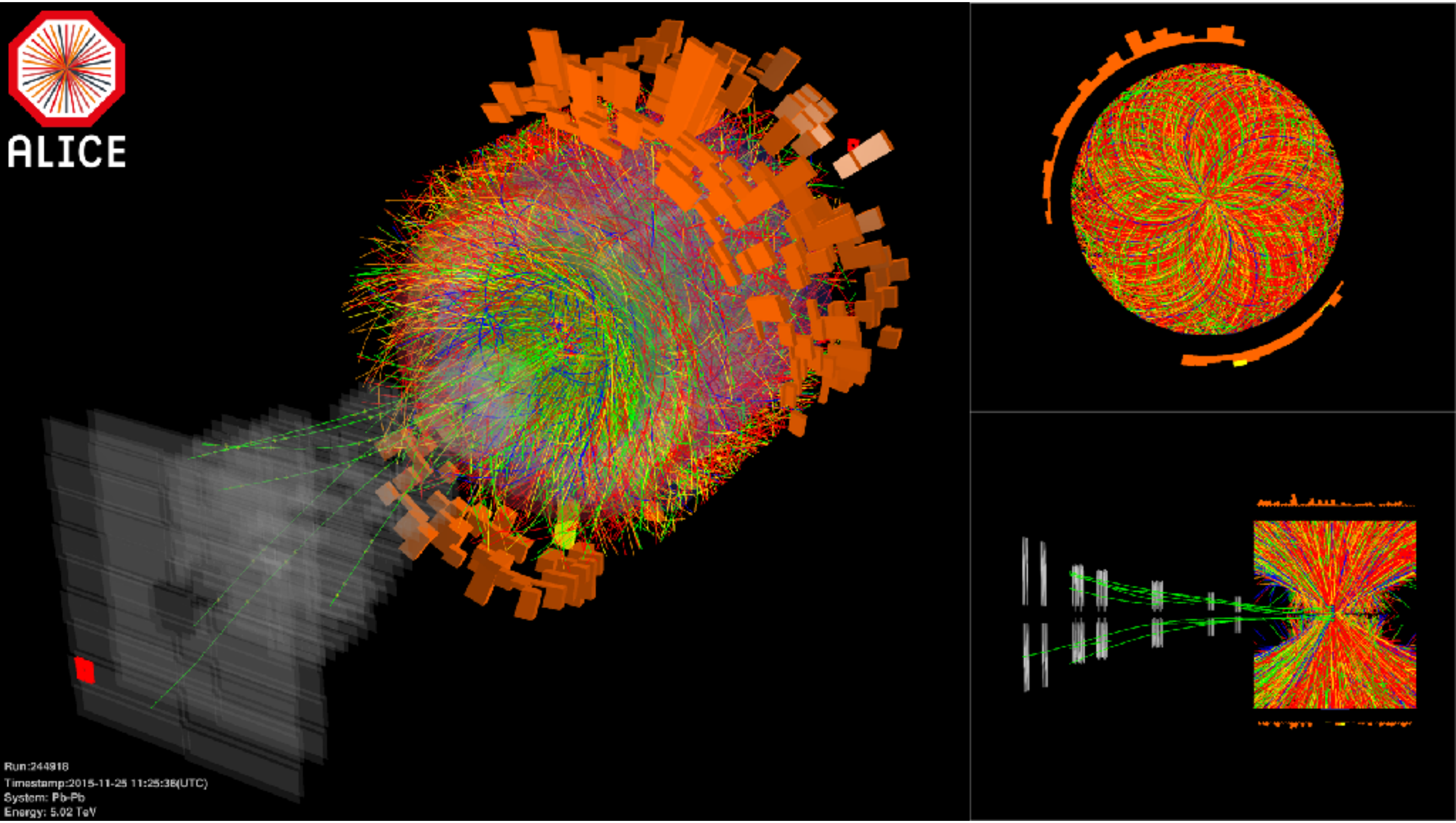
LHCb: flavor physics



LHCb: flavor physics



ALICE: the quark-gluon plasma



Challenges

- Some of the challenges associated with operating an experiment such as ATLAS, are:
  - Engineering challenges: magnets, cryostats.
  - High levels of radiation.
  - Collision and trigger rates.
  - Complex detector consisting of many individual systems.
  - Event reconstruction, calibration.
  - High complexity of simulating collision events.
  - …many more.

Challenge: Trigger Rates

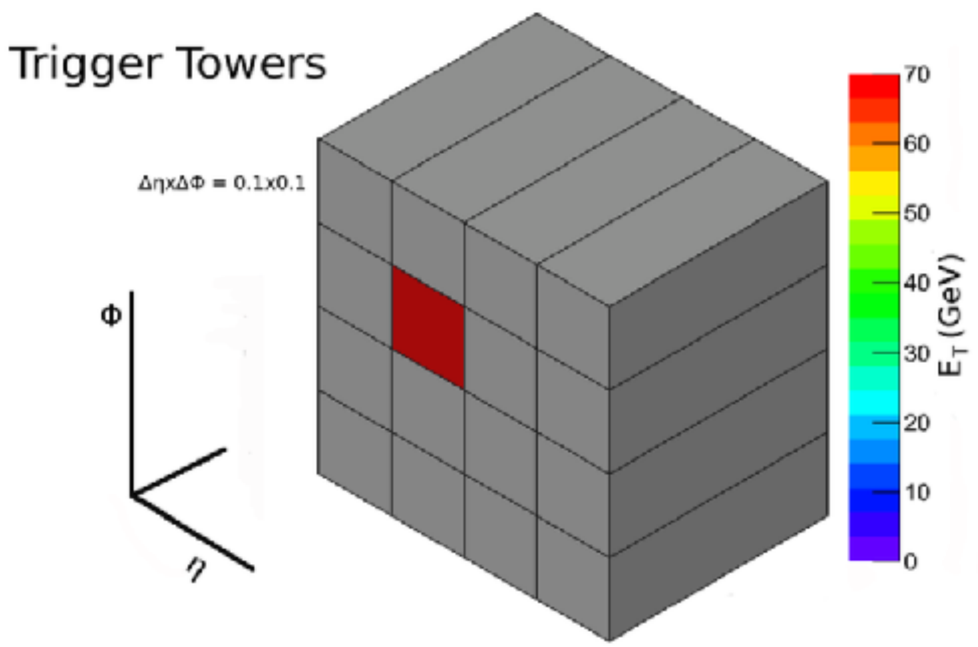
- Beams cross every 25 ns and each time several pairs of protons collide.
- Not all proton–proton collisions have interesting characteristics that lead to discoveries: those that do are **very rare**.
- The more data the better the chances of spotting something new, but we can only save about 400 events per second.
- The challenge is to catch the rare interesting event… if it is discarded, it is lost forever.

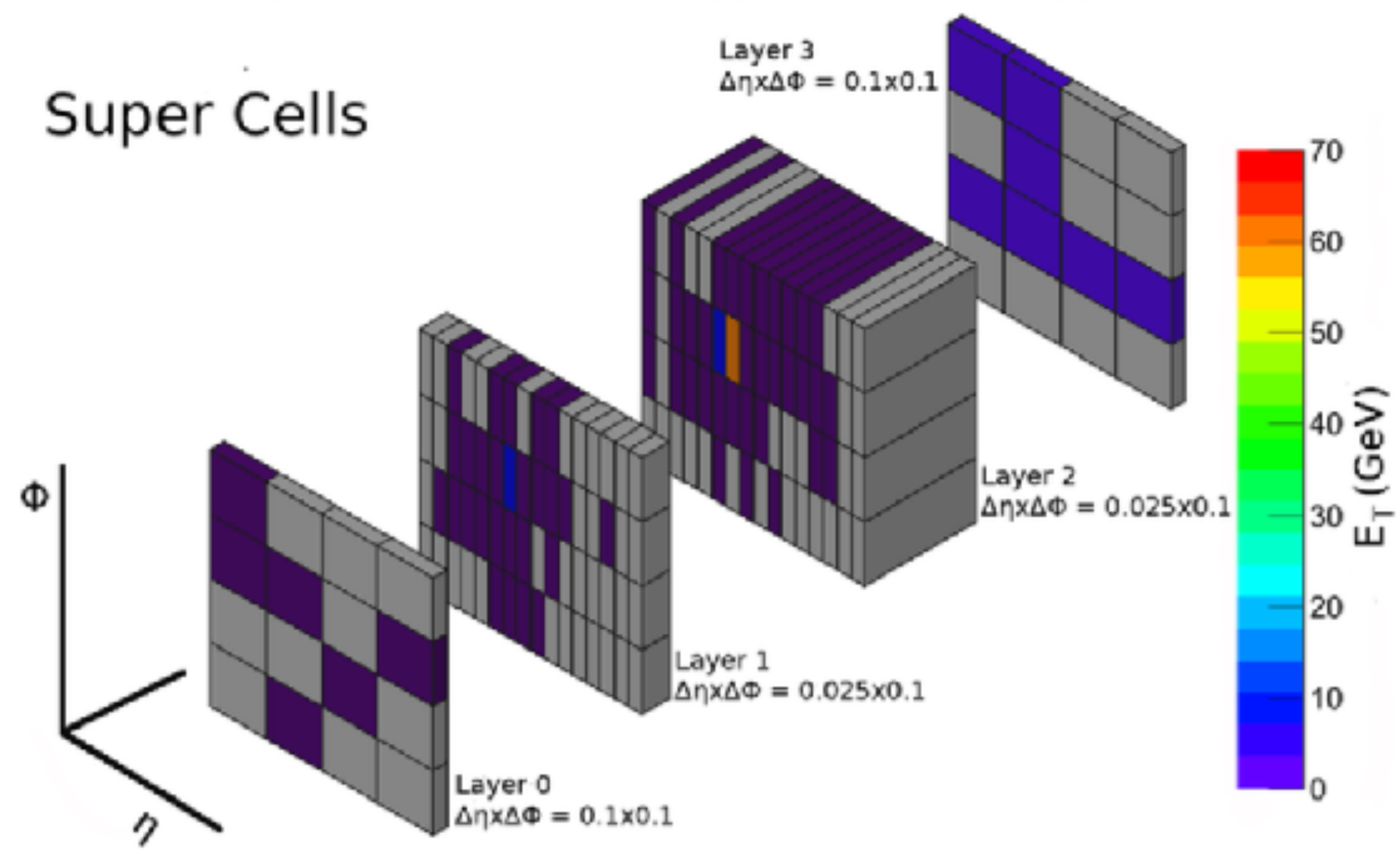
The ATLAS trigger system decides which events to keep, and has to do it very fast:

★ A first decision level decides within 2.5 microseconds after a collision has occurred.

Aside: detector upgrade

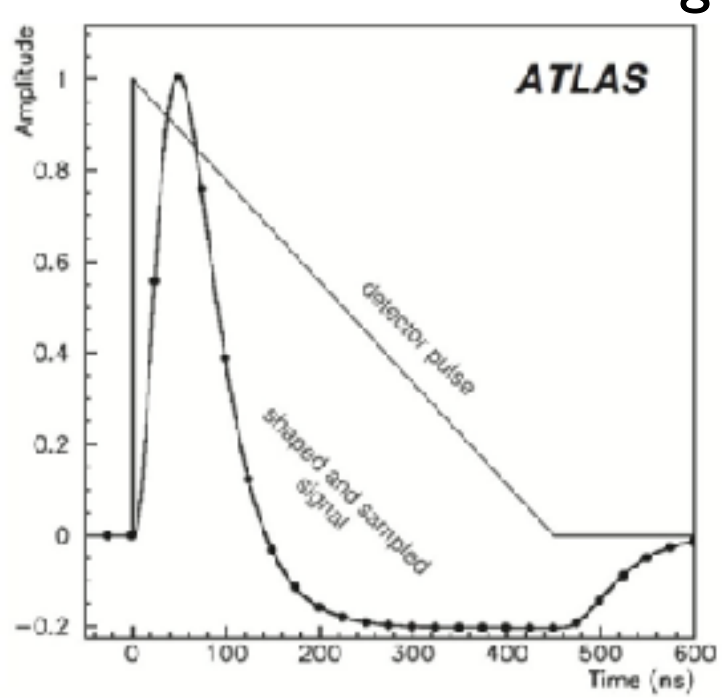
- Hardware triggers can be improved through finer granularity.

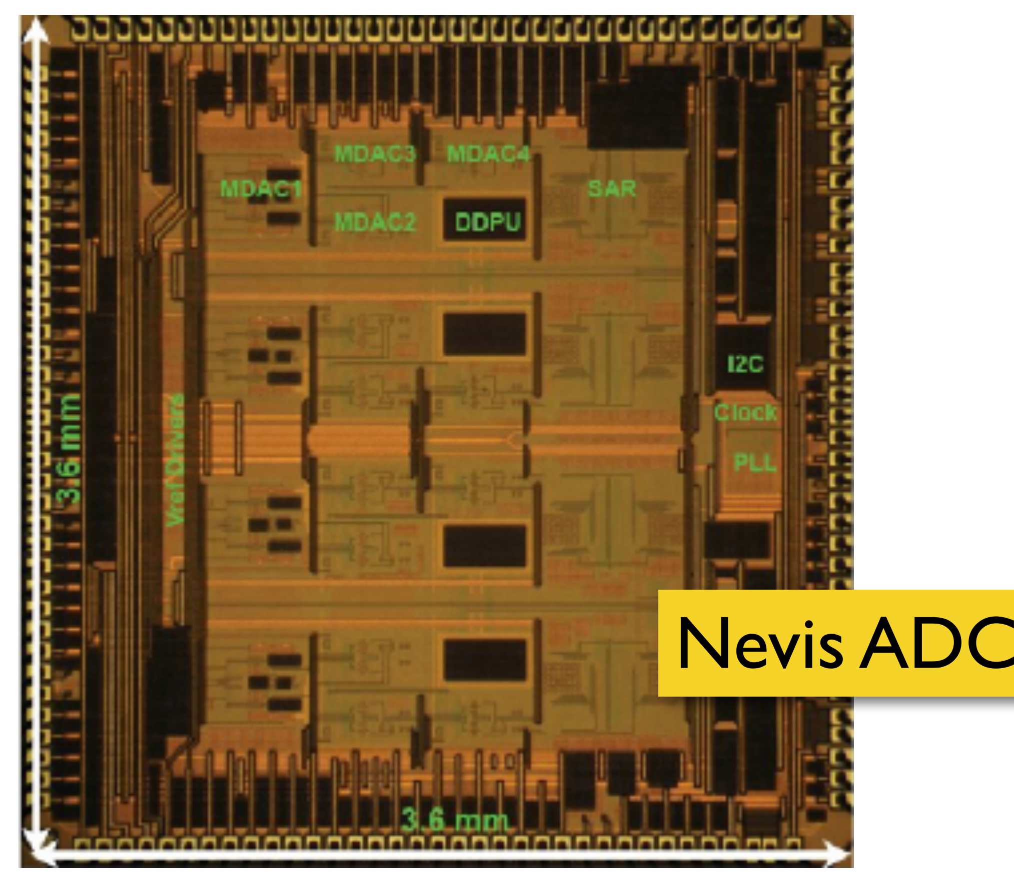




Aside: detector upgrade

- Nevis will contribute to the upgrade of the calorimeter front-end electronics.
- Calorimeter signals must be continuously sampled and digitized at a frequency of at least 40 MHz.
- **New ADCs are required and are being developed and tested at Nevis**
- Need to be radiation tolerant and high precision

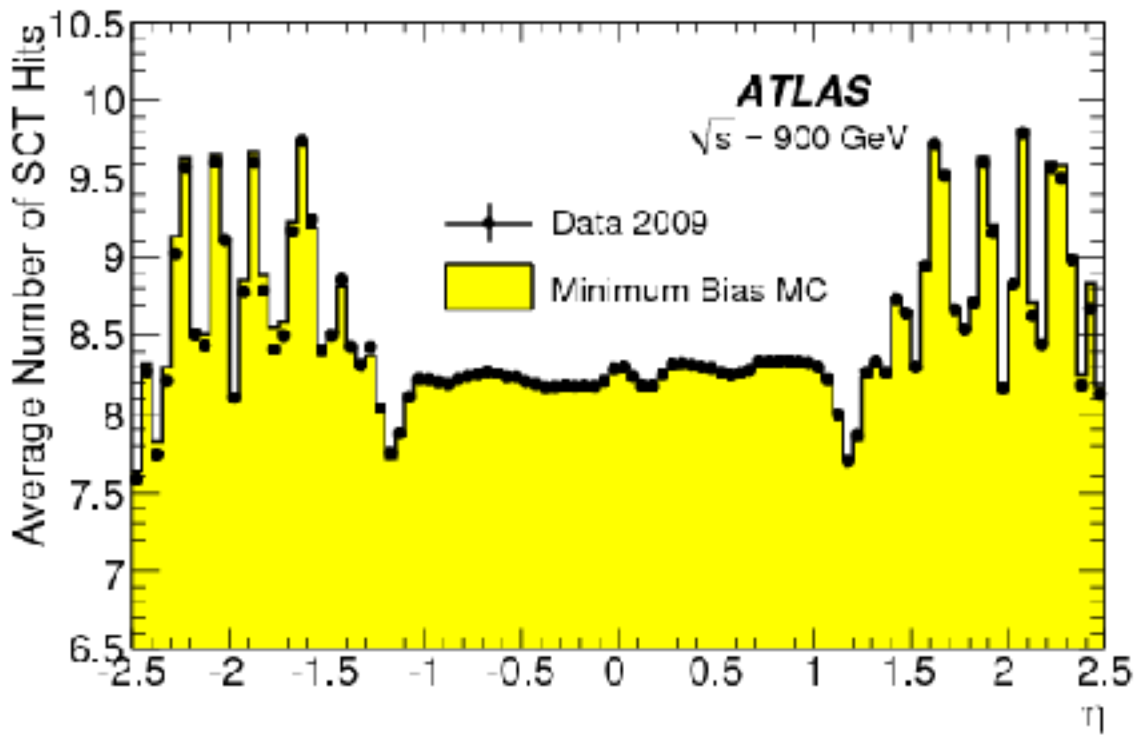




Challenge: Simulation

- Simulation of collisions in ATLAS is part of every step of the experiment:
  - Conception phase: decisions about optimal detector design.
  - Preparation phase: setting up reconstruction software, physics analyses, …
  - Data analysis: interpretation of physics results.

- Based on Monte-Carlo methods:
  - Processes randomly generated, within given cross-sections, detector resolutions, …

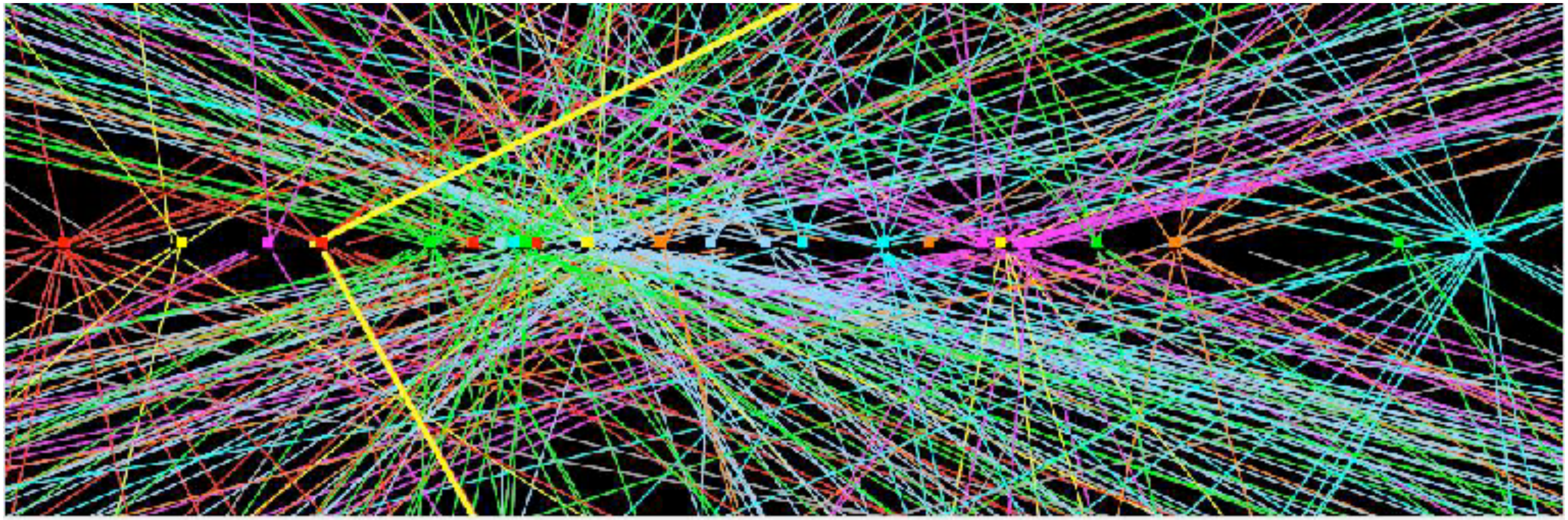


ATLAS simulation describes data extremely well!

Challenge: “pile-up" events

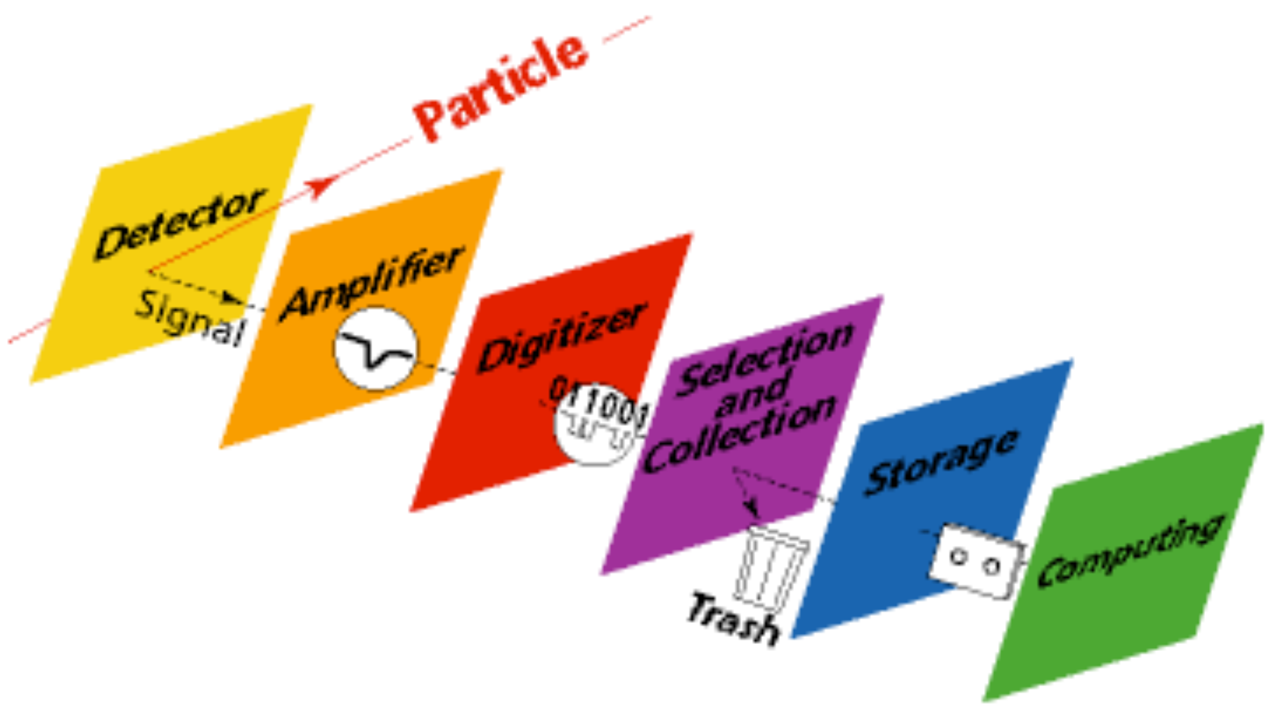
- In order to increase the number of collisions, protons travel around the LHC in bunches.
- Each time two bunches cross at an interaction point, however, not only one collision occurs, but several!
  - During 2016, an average of 25 collisions per crossing!

Pile-up events in ATLAS



Challenge: Data Distribution

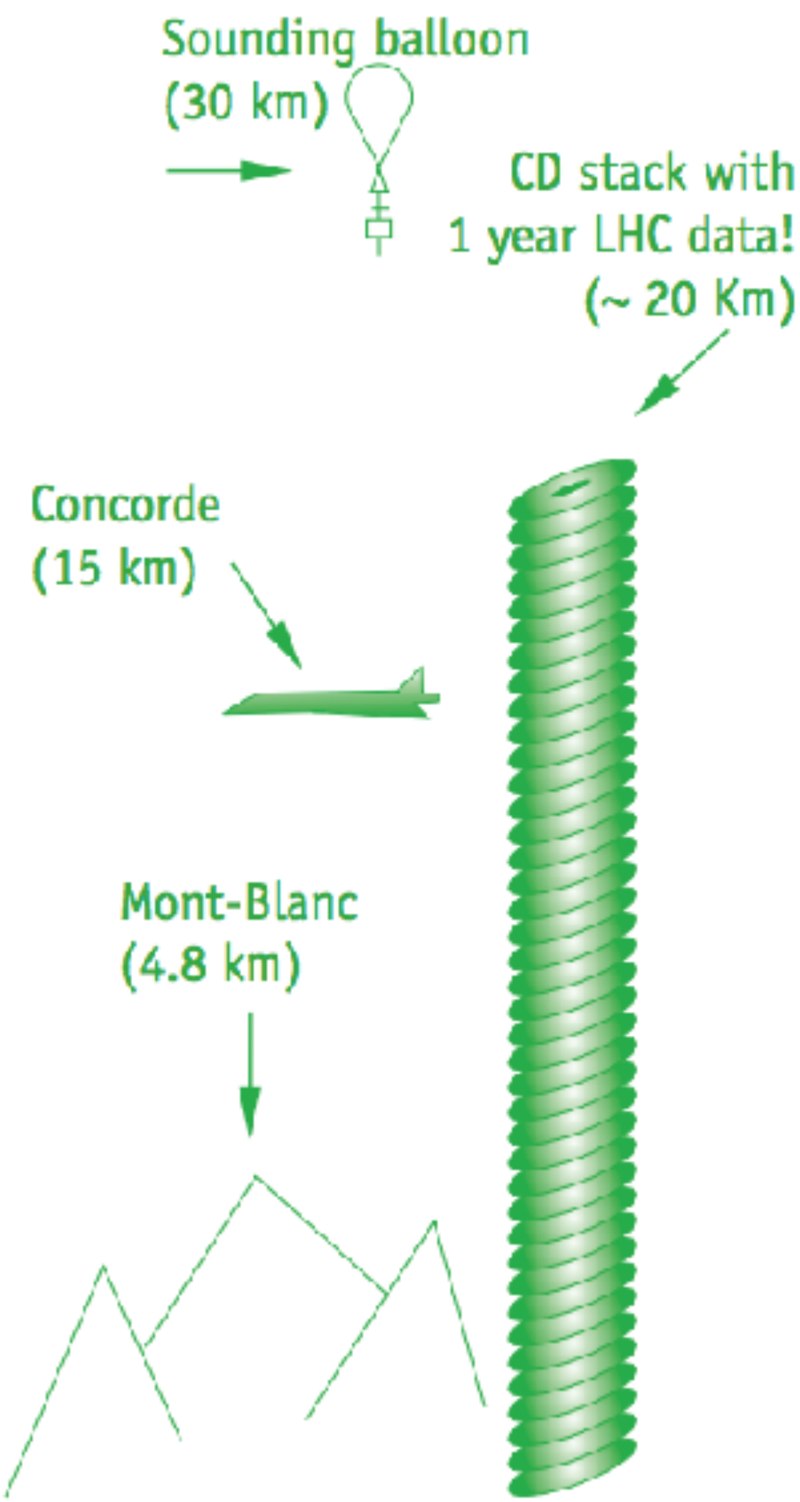
- The experiments at CERN generate an enormous amount of data.
- At the LHC, particles collide approximately 600 million times per second.



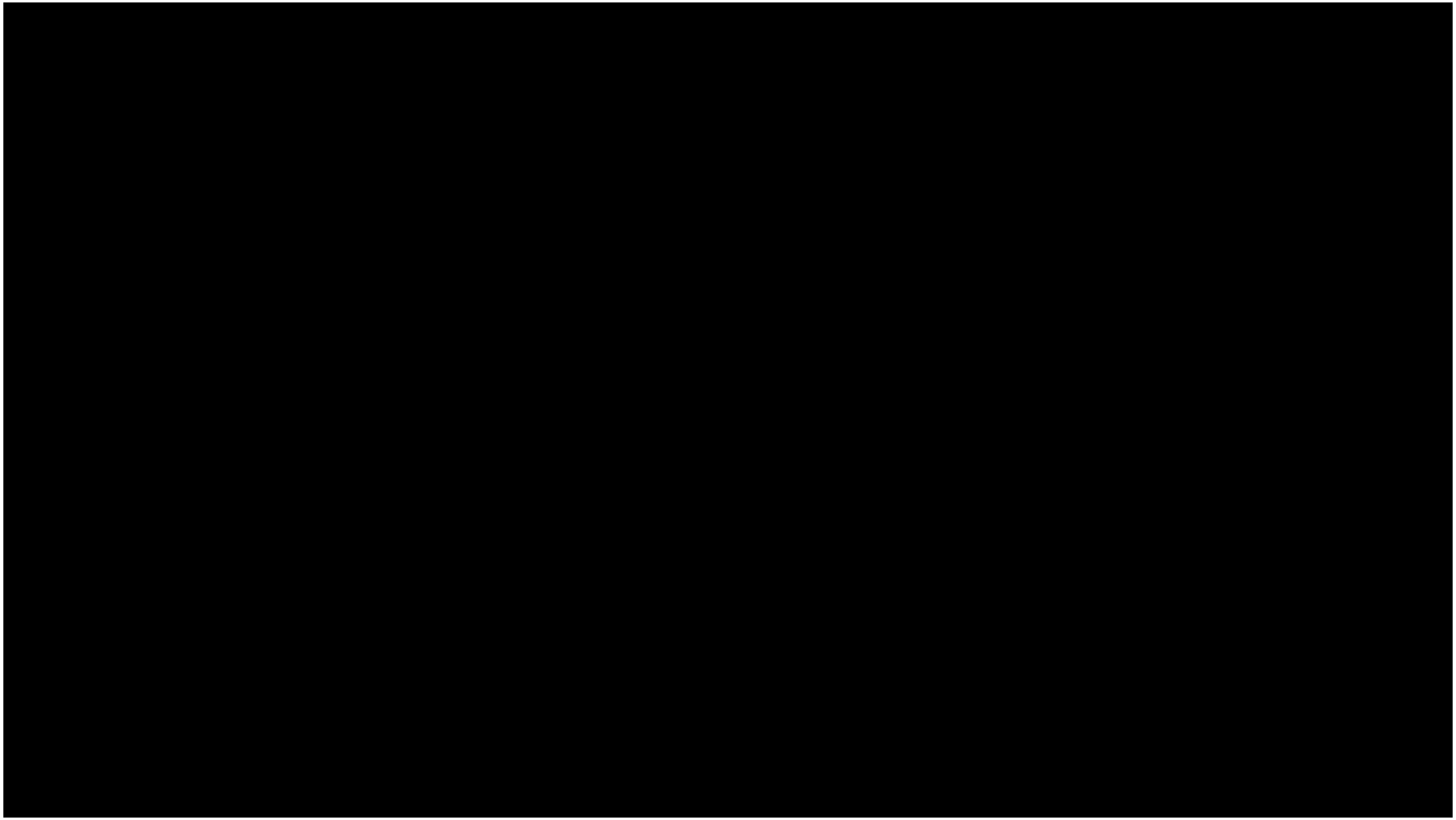
- CERN has local servers and data storages systems, but that is not enough…

Challenge: Data Distribution

- Every year, 30 petabytes of data are produced!
- In order to deal with this amount of data, for both storage and analysis, a global collaboration of computer centres was created and launched in 2002:
  - The Worldwide LHC Computing Grid, or simply, the Grid.
- It is the world's largest computer grid.
  - Over 170 cents across 41 countries, serving over 8000 physicists with near real-time access to LHC data.

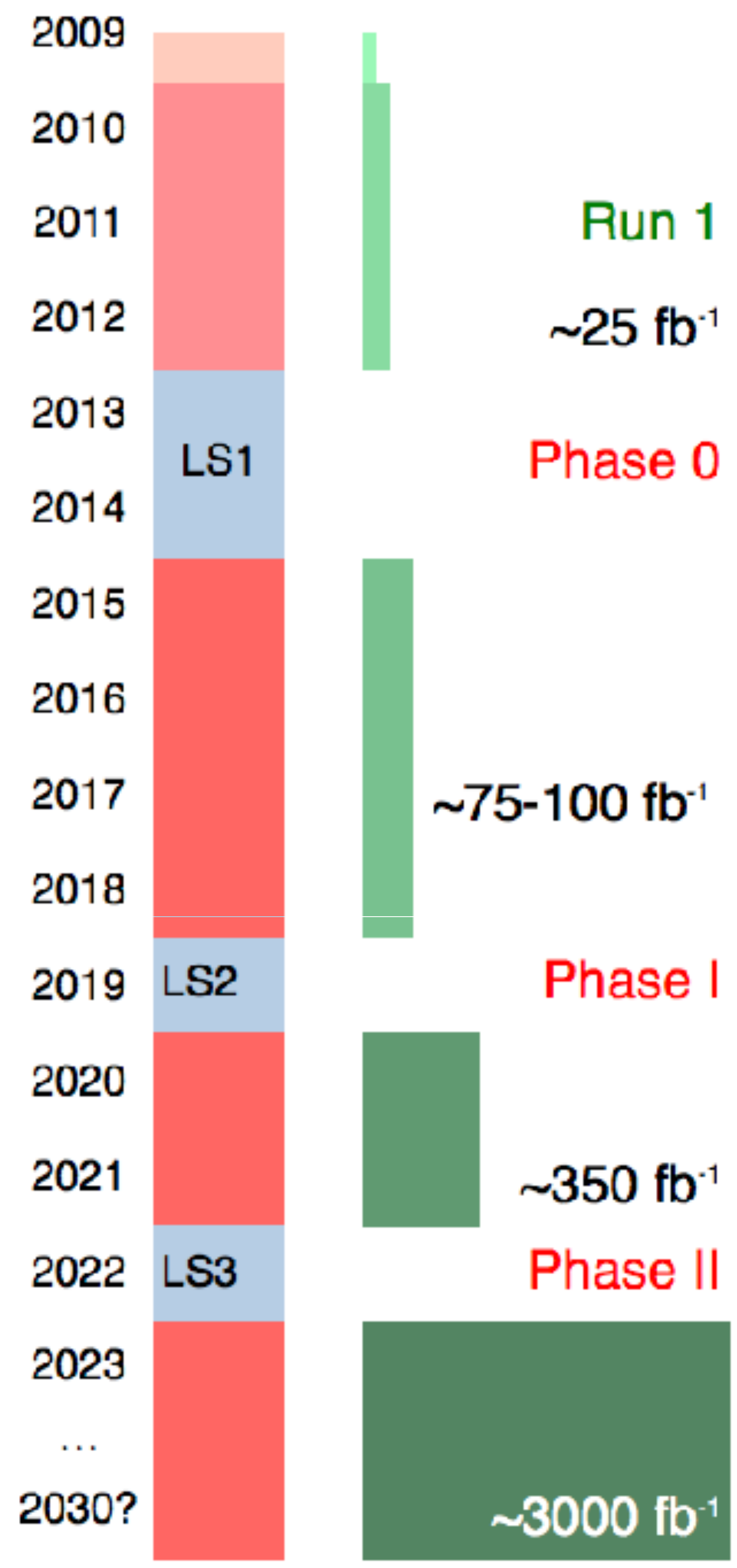


The Grid



What's next for the LHC?

- In 2019, the LHC will stop for a Long Shutdown.
- Detector upgrades are planned so as to maintain or improve on the present performance as the instantaneous luminosity increases.
- ATLAS Phase-I upgrades will take place to prepare for Run 3.



There is more to CERN than the LHC!

Nice TEDEd video here

CLOUD experiment

A day in the life of a physicist at CERN

Summary

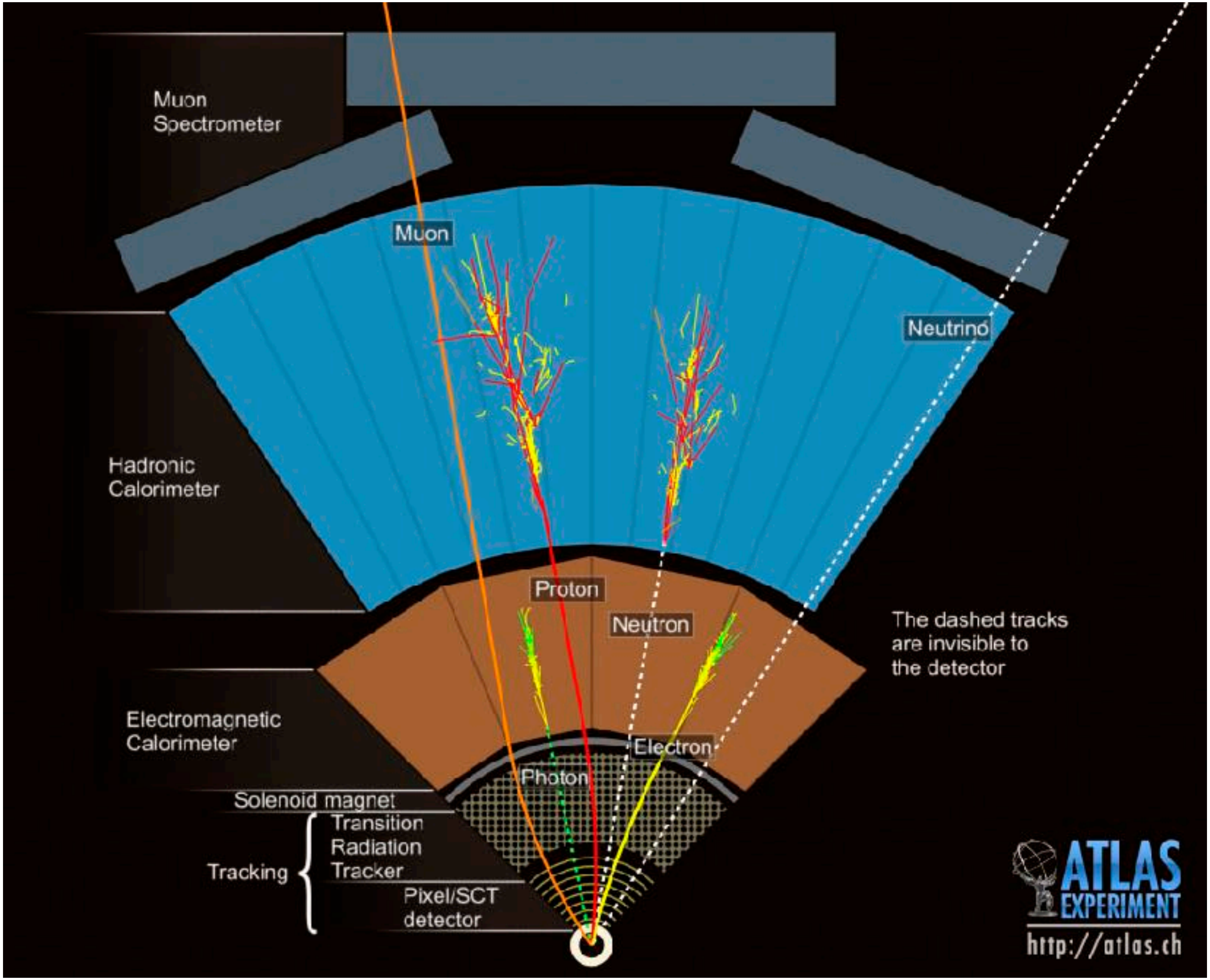
- The physics programme of the LHC experiments is vast and exciting!
- It presents several challenges, from engineering to computing, which put CERN at the forefront of technology.

That’s all for this week…

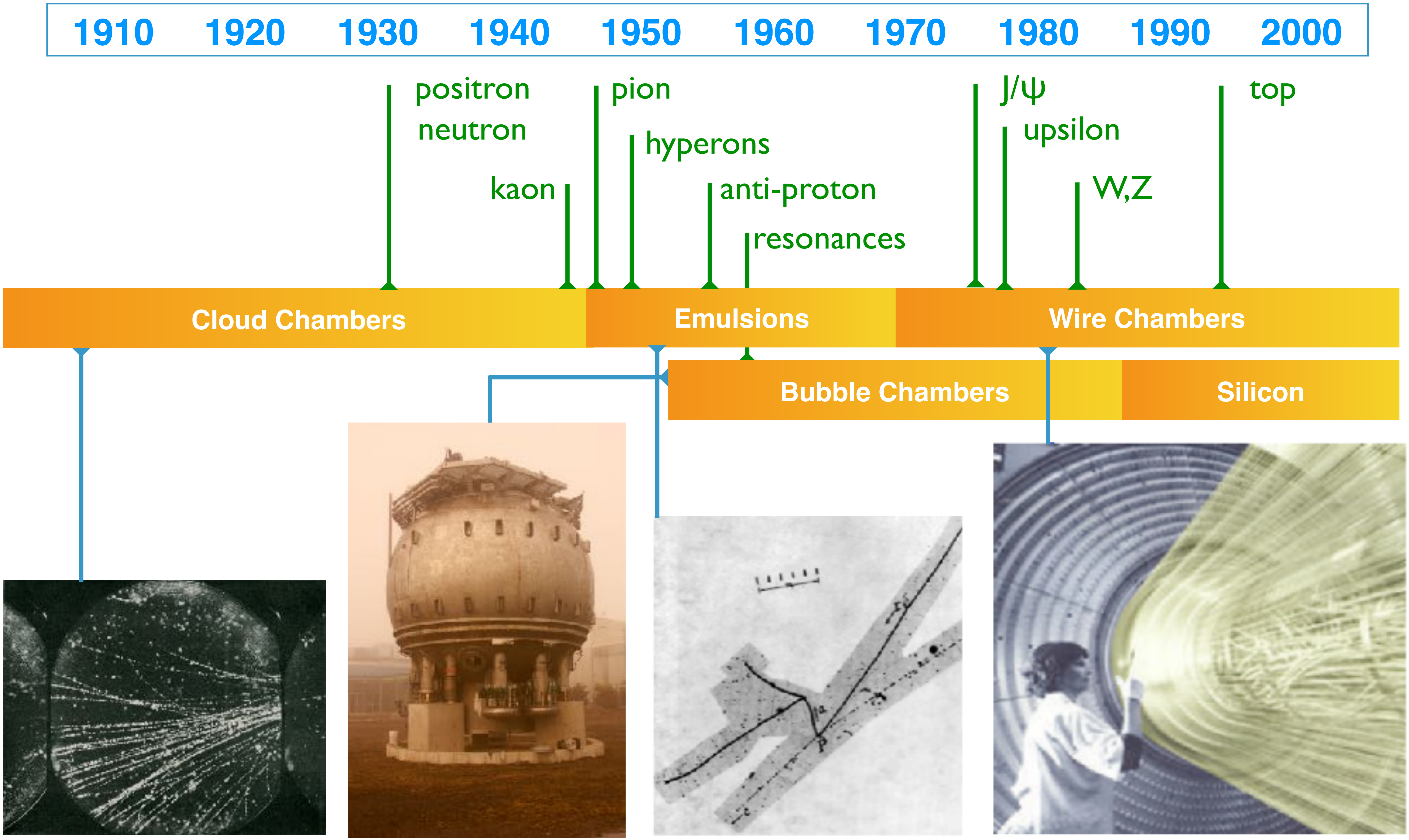
- **Next week:** The Higgs boson and beyond

- My email, if you have questions on the material covered so far:
  - miochoa@nevis.columbia.edu
  - Please add [SHP] to the email subject.

Bonus


Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch

A long history of discoveries

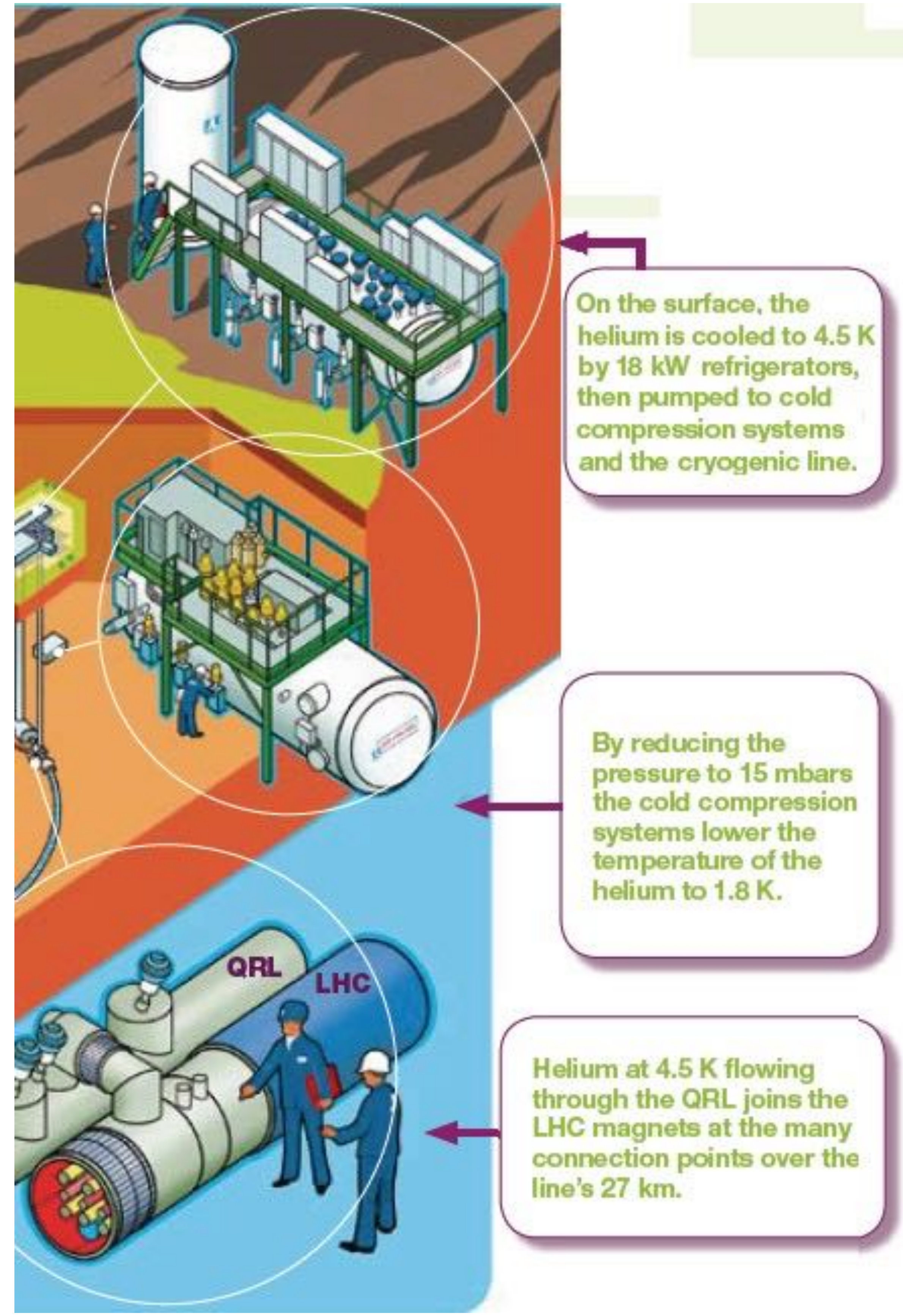


LHC cryogenics

When helium is cooled further it undergoes a second phase change at about 2.17 K (−271.0 °C) to its "**superfluid**" state. Among many remarkable properties, superfluid helium has a very high thermal conductivity, which makes it the coolant of choice for the refrigeration and stabilization of large superconducting systems

Routing the cold

The cold power generated is routed to the superconducting magnets via a cryogenic line which has been named **QRL**. To keep up the supply, the two helium flows (at 4.5 K and 1.8 K) coming from the 18 kW refrigerators and CCS compressors have first of all to be collected. Today, five cryogenic distribution boxes (**QUI**), five "cryogenic islands", are installed in the access shafts in the LHC tunnel. With their vacuum casing, valves and connections to upstream and downstream devices, they provide the connection between the refrigerated equipment and the accelerator itself.
Since the cryo-magnets are spread over 27 km, the QRL cryogenic distribution line follows the same layout.



lhc-closer.es