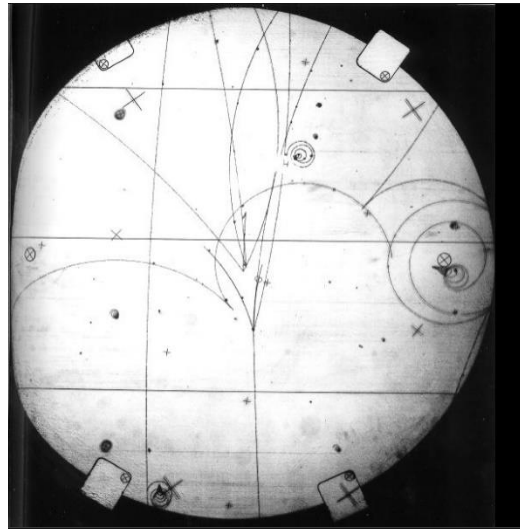
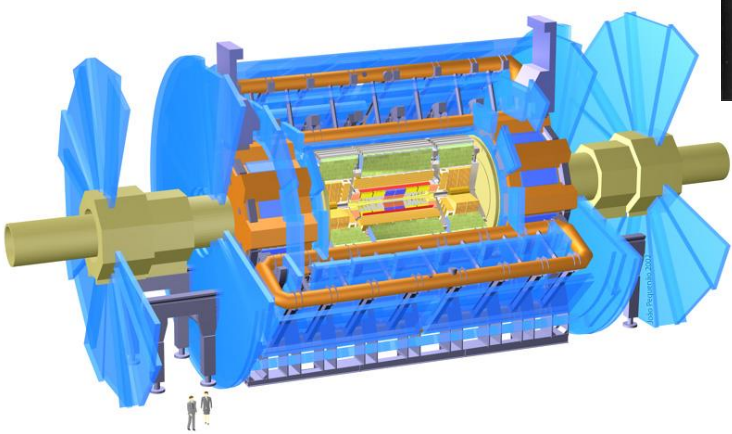
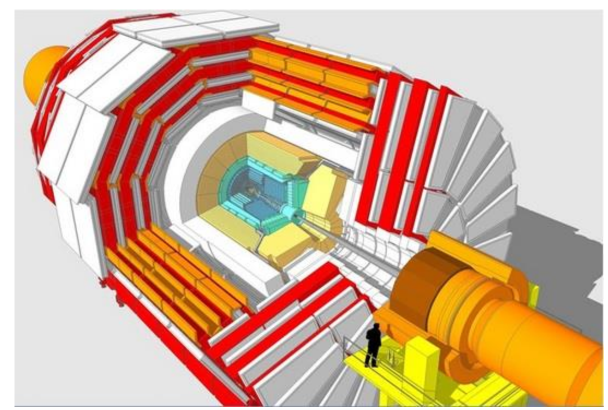
Detectors in Particle Physics





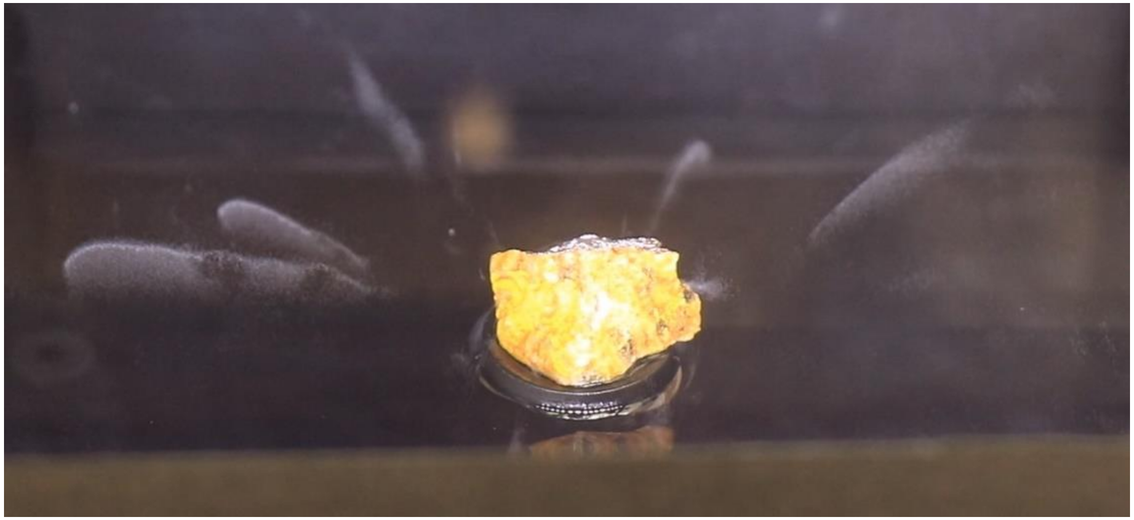


Agostinho Gomes
LIP and FCUL

OCJF LIP, 22 Jul 2022

Detectors

Particle detectors are devices where the particles interact allowing us to measure some quantities – position, time, momentum, electric charge, energy, etc



Tracks of alpha particles seen in a cloud chamber at LIP

Track of a cosmic ray seen in a spark chamber at LIP

Detectors

Emulsions used to record the tracks of particles

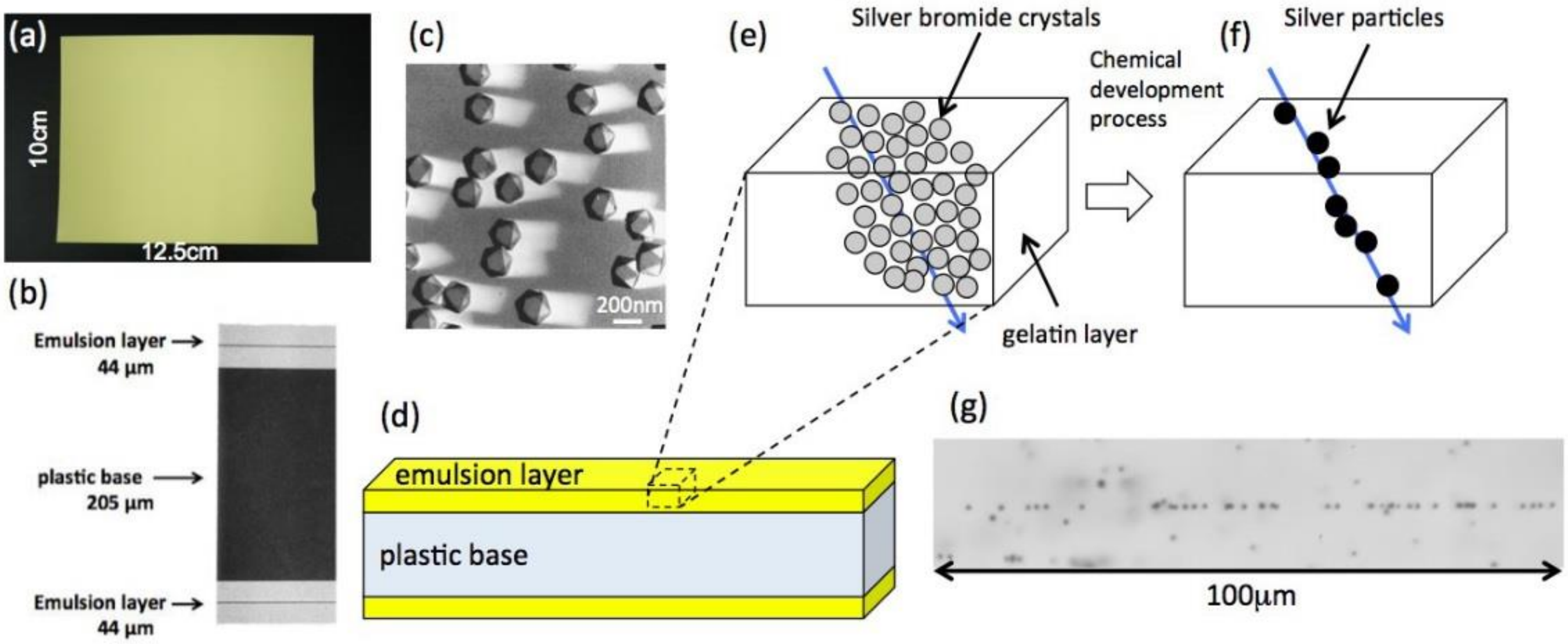


Fig. 1. (a) A picture of OPERA film; (b) An electro microscope image of cross section of OPERA film; (c) An electron microscope image of silver bromide crystals of OPERA film. The diameter of crystals is about 200 nm; (d) An Illustration of the structure of OPERA film; (e) and (f) The principle of detection of charged particle; (g) A microscope image of track of minimum ionizing particle in OPERA film.

Emulsions at OPERA experiment

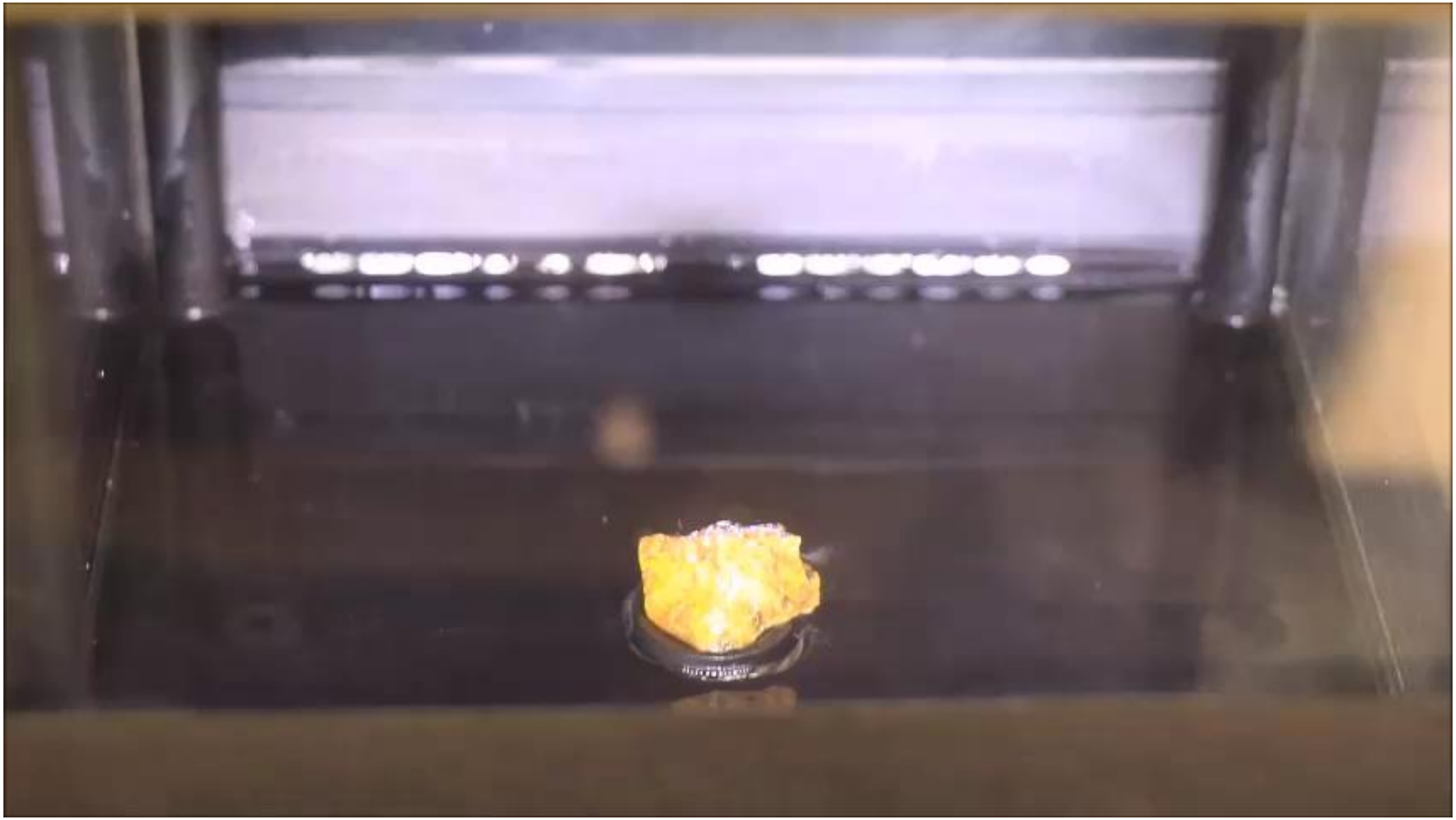
Detectors

Similar detectors can see very different pictures

Pictures of Hubble and James Webb

Pictures in different wavelengths

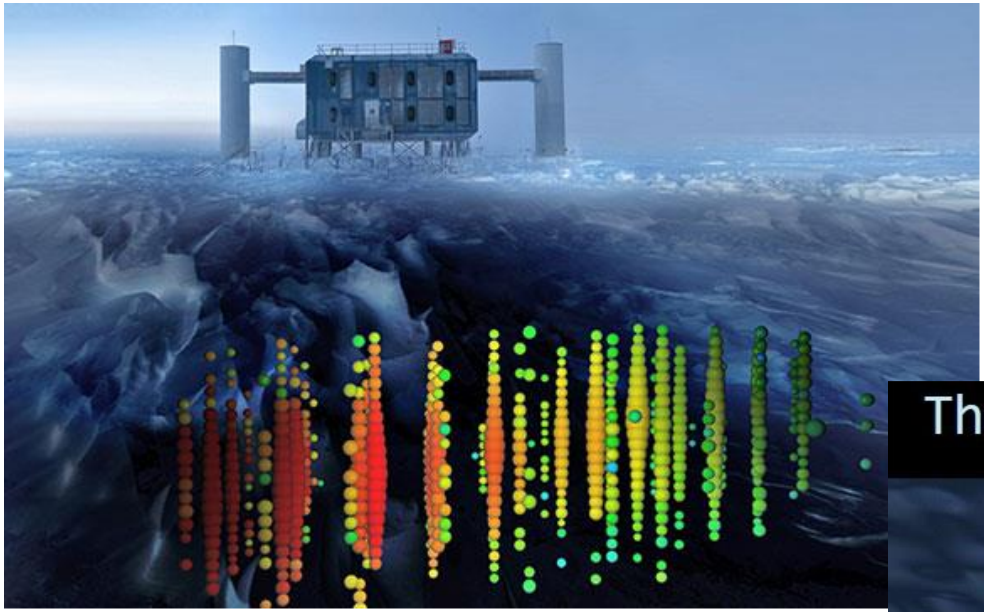
A detector in action



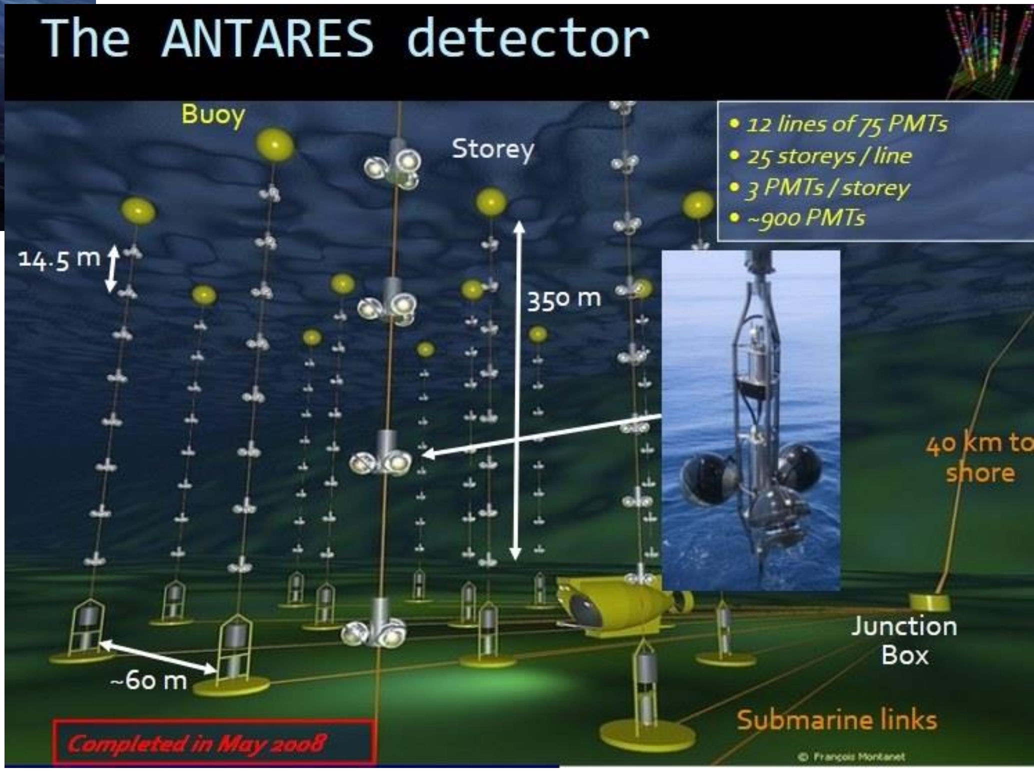
Cloud chamber at LIP

Detectors – large and deep neutrino detectors

Examples of Ice Cube in Antartica using the ice as detector and Antares in the Mediterranean using the sea water as detector

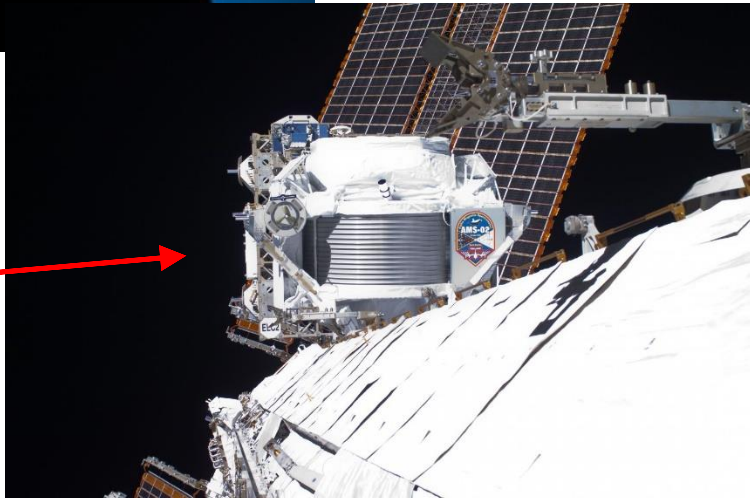


Ice Cube



Both detectors use photmultiplier tubes as photosensors

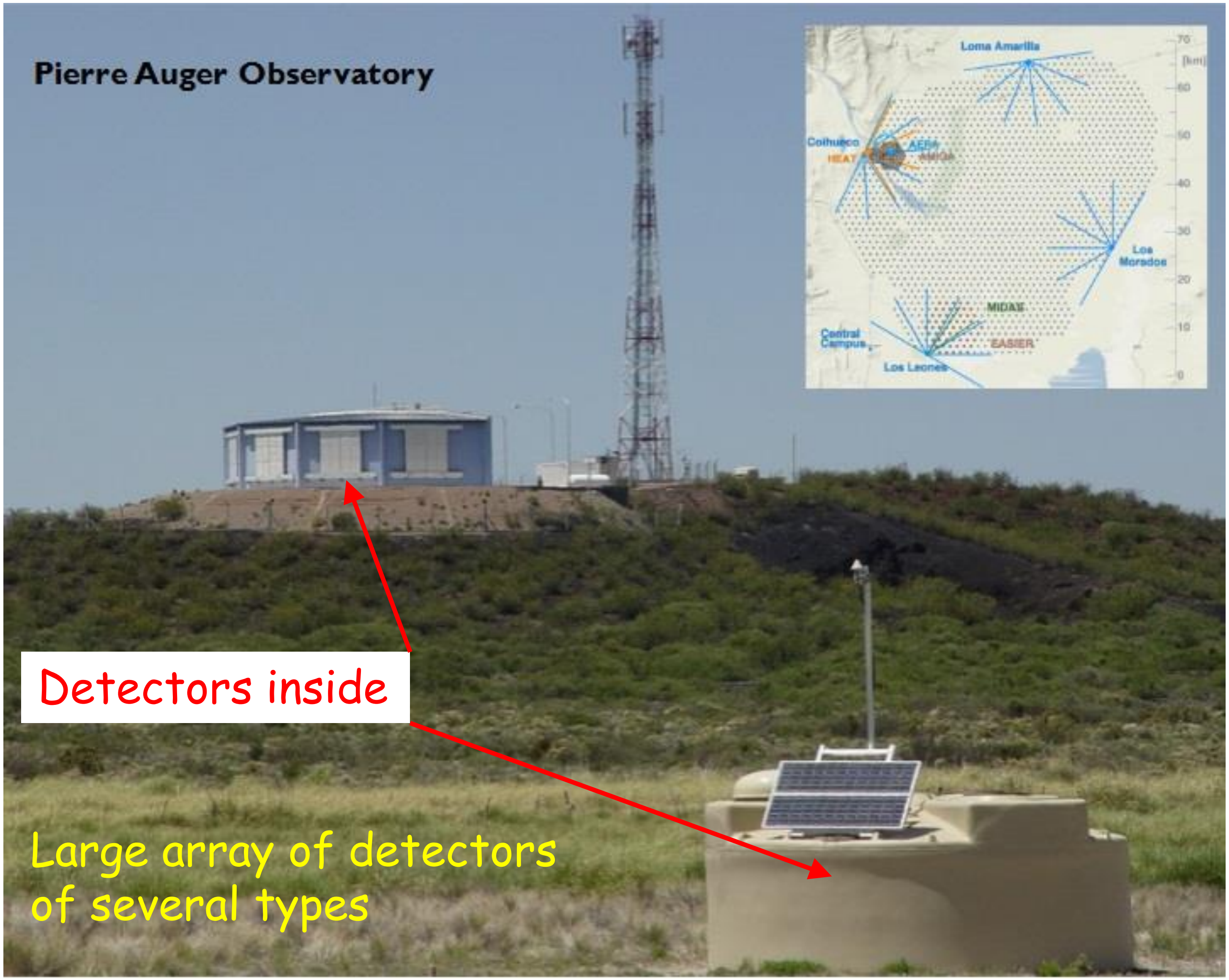
Detectors for cosmic rays - the atmosphere and above



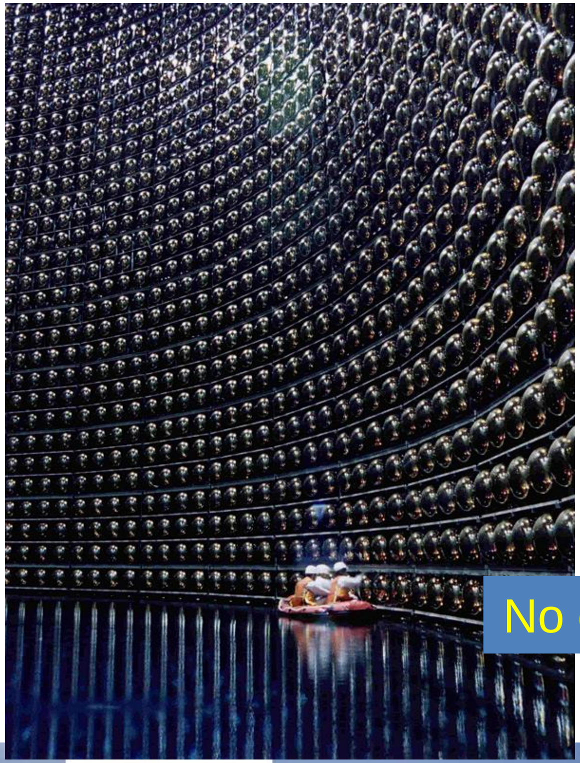
Can send detectors in balloons, put them in orbit (example AMS at the ISS) or lay them in the ground or underground in deep mines (neutrinos again)

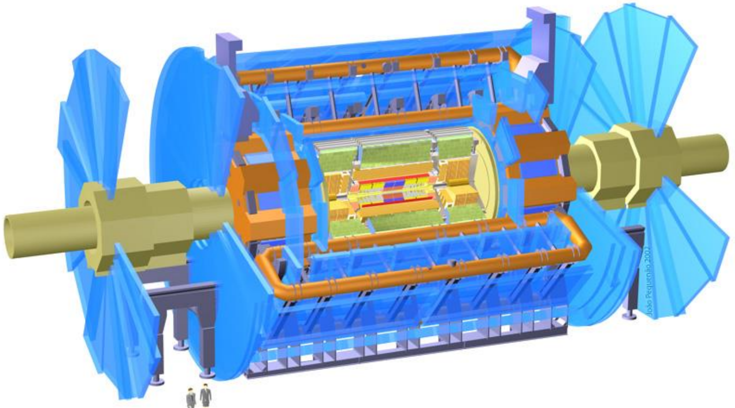
Detectors – a large detector atmosphere based

Auger detector in Argentina uses the atmosphere as a component to study extreme energy cosmic rays



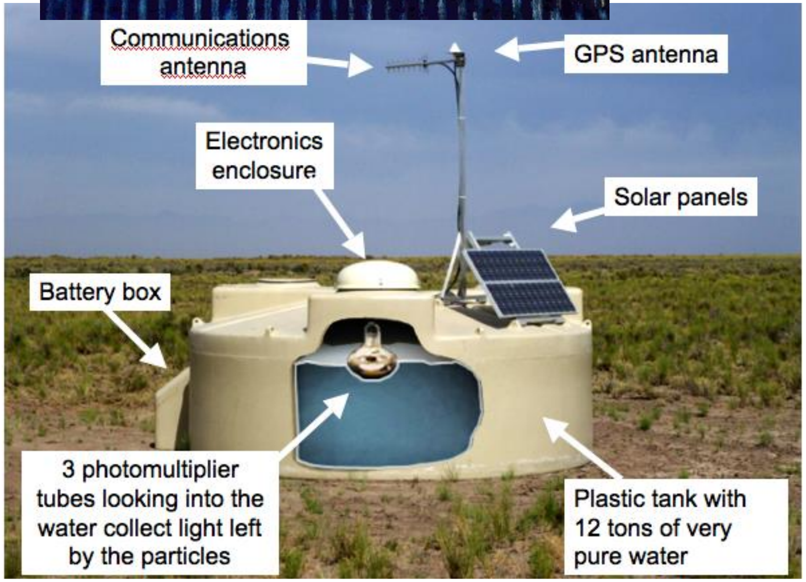
Collider or no collider?

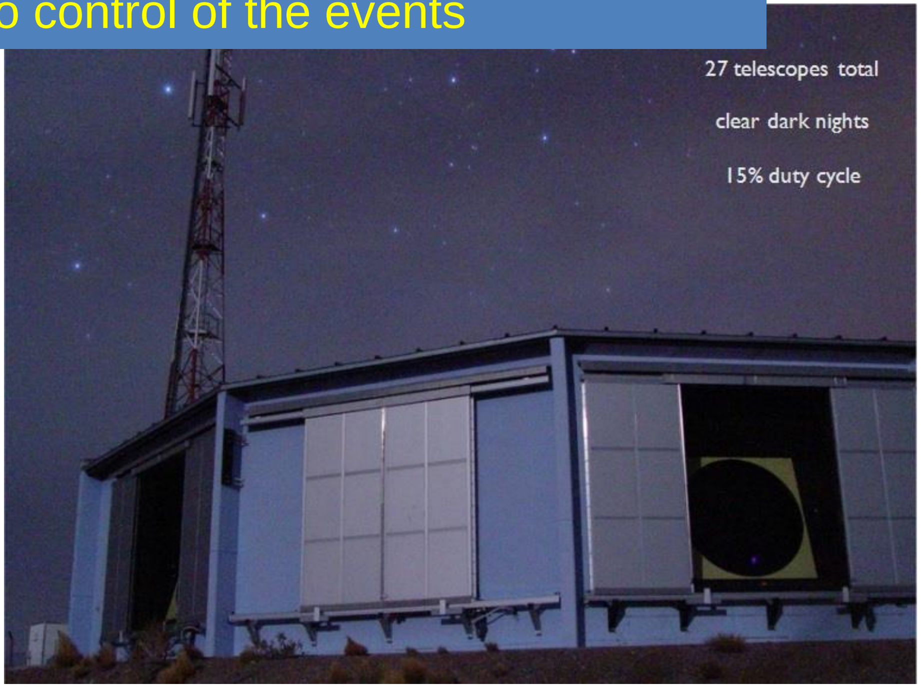




ATLAS@LHC collider – full control of the events

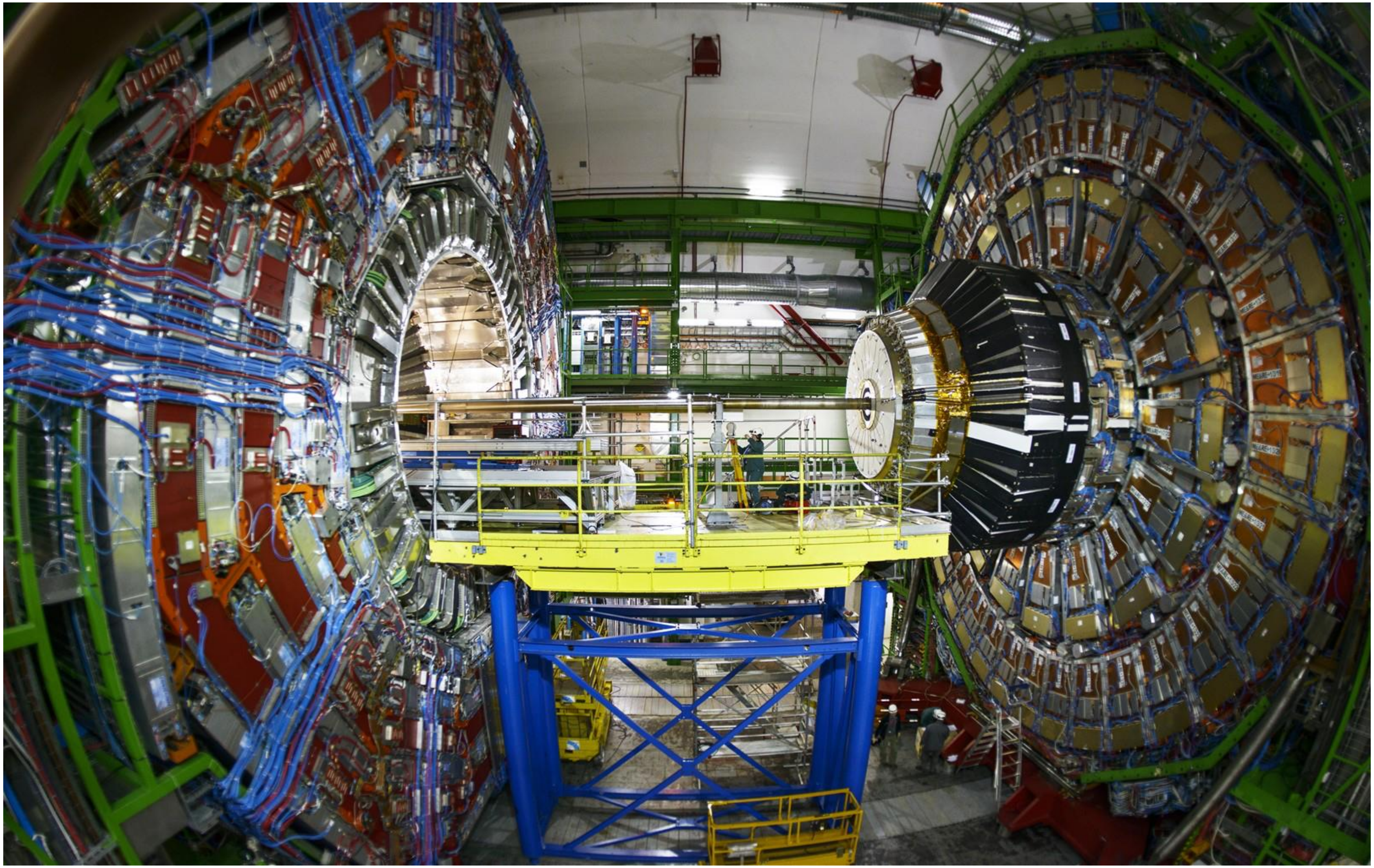
No collider - no control of the events





Timing, position and detector size and granularity need to be adequate for the subject

Focus on LHC and its general purpose detectors ATLAS and CMS

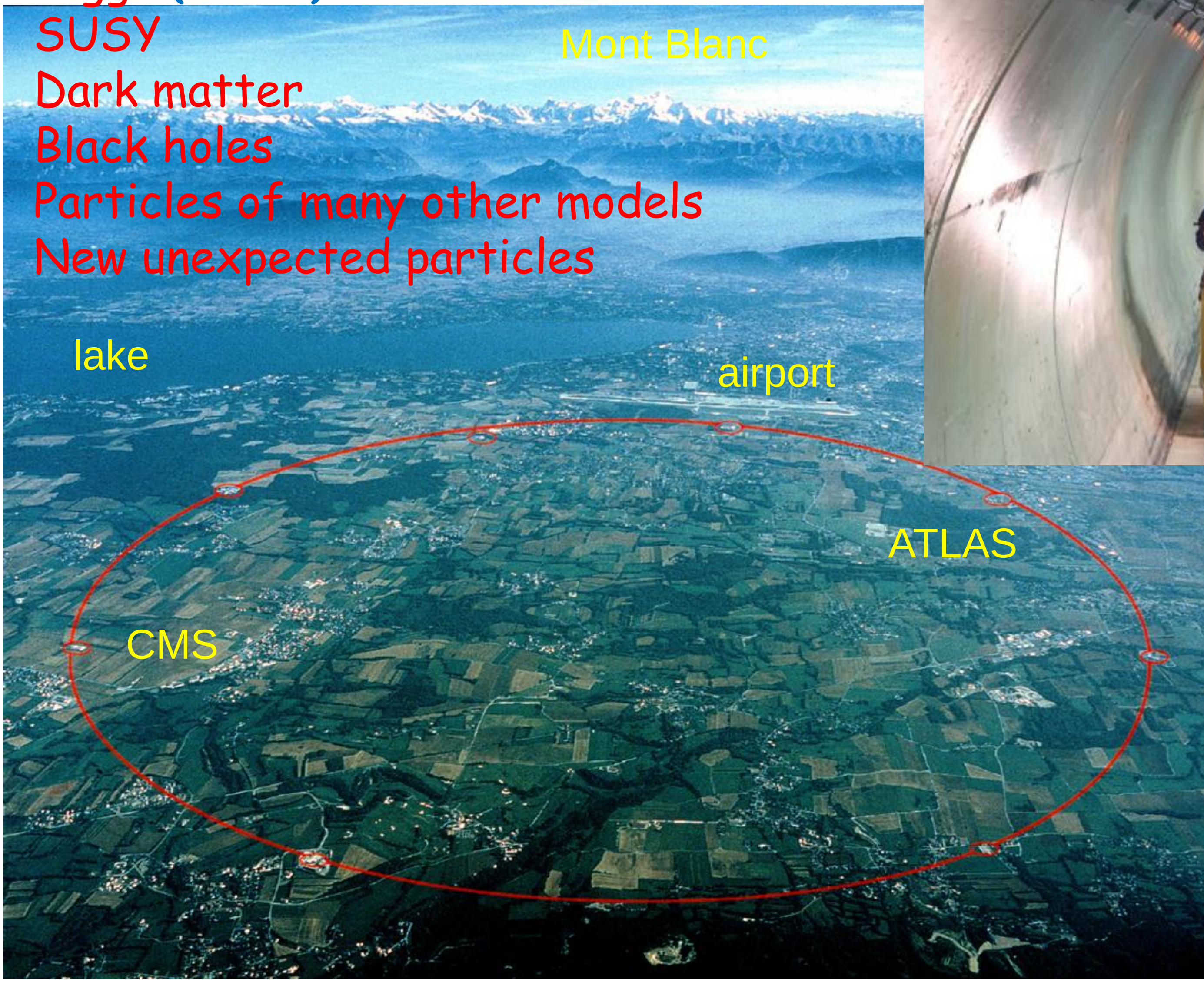


CMS detector open for maintenance

Large Hadron Collider (LHC)

It is a discovery machine, projected to search for:

Higgs (found)
SUSY
Dark matter
Black holes
Particles of many other models
New unexpected particles

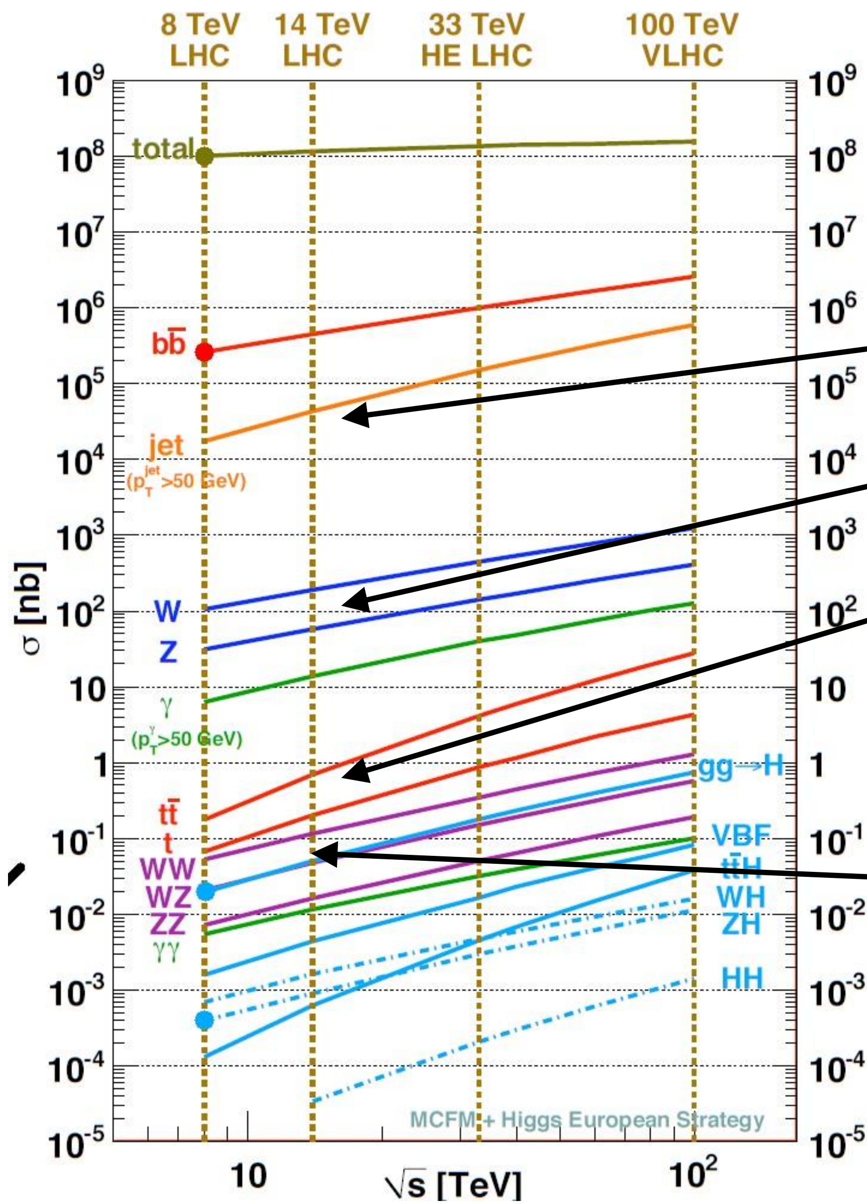


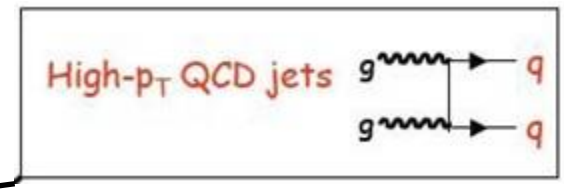
p-p collider
27 km perimeter
Designed for:
7 TeV/beam
Luminosity $10^{34} cm^{-2} s^{-1}$

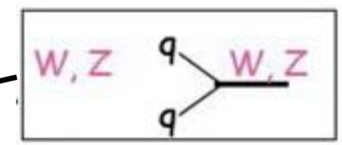
These parameters set the working environment for these HEP detectors

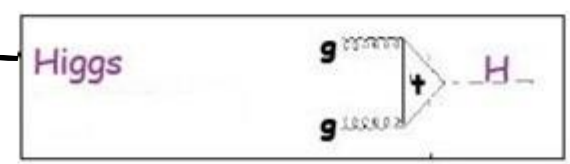
Signal and background in the LHC package

LHC generates trash at huge rates



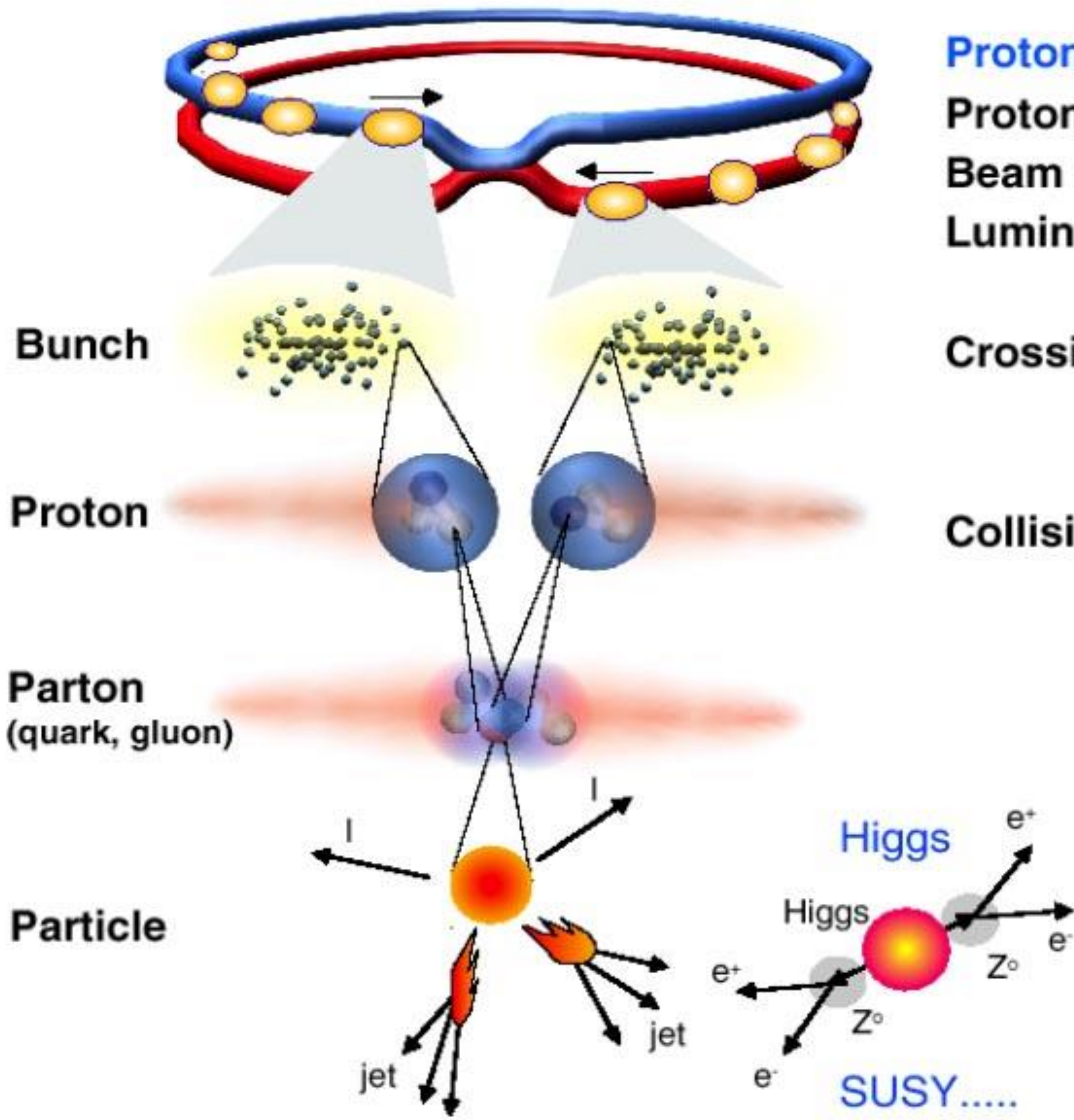






And the interesting particles we are looking for are rare

Collisions at the LHC: nominal values



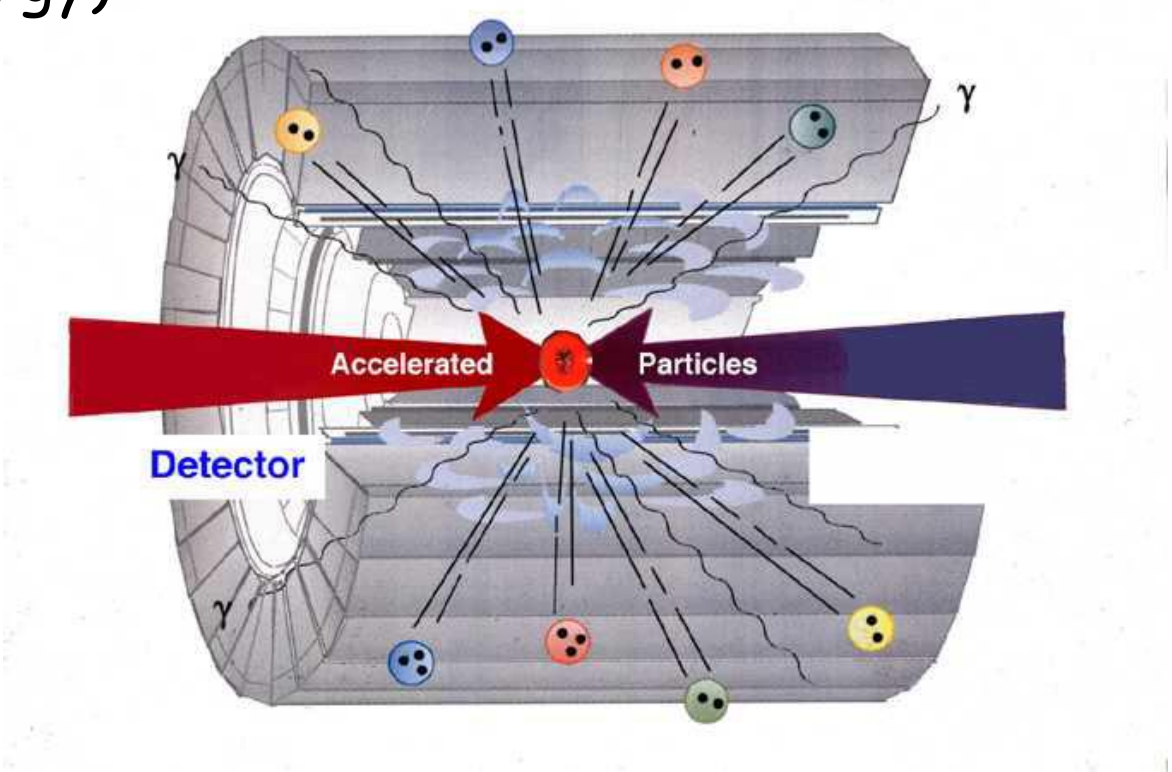
Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^7 - 10^9 Hz

Selection of 1 in 10,000,000,000,000

Collisions at the LHC: the detectors

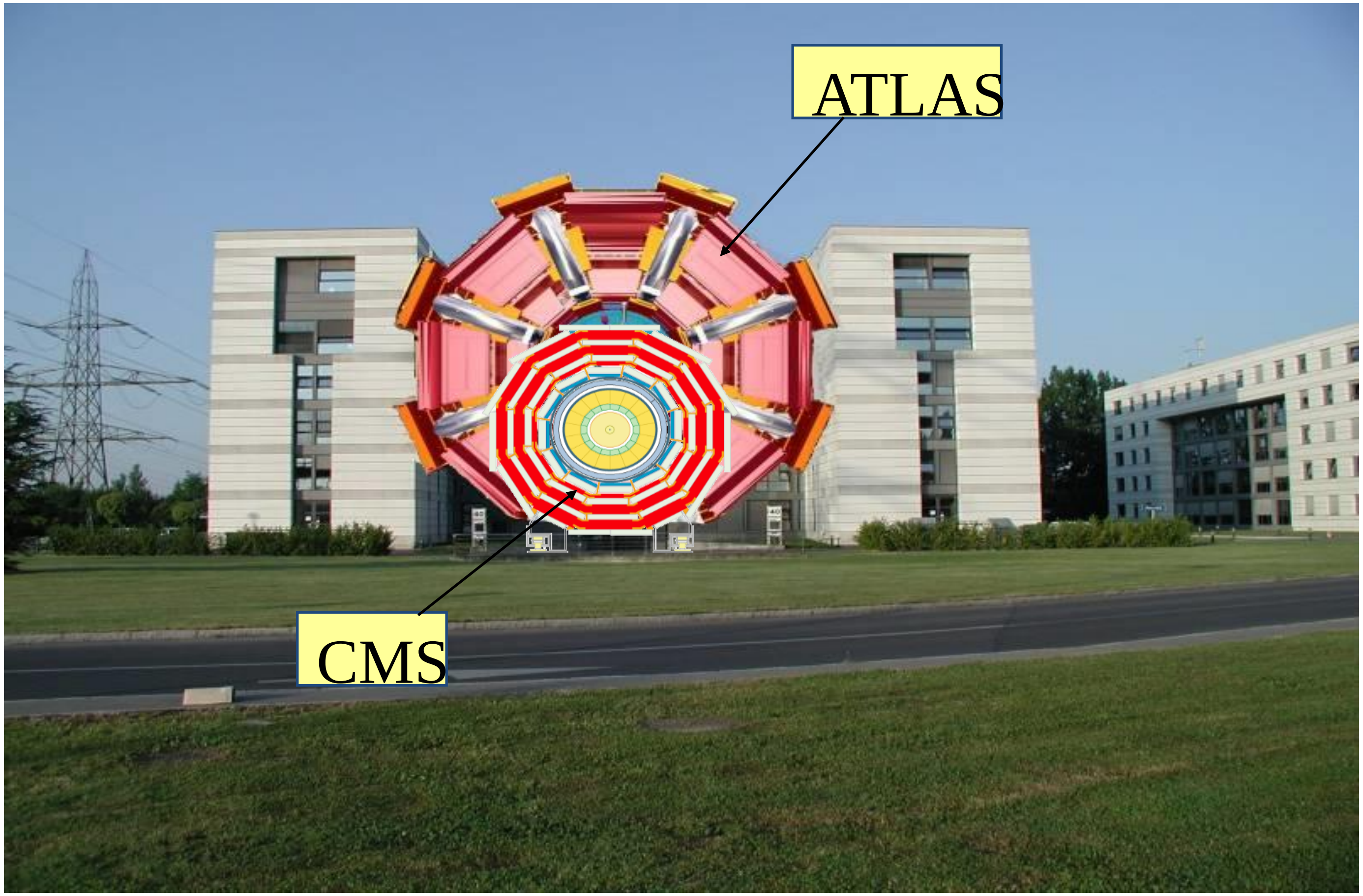
Want to see what happens (result) in the collision

Detector built around the collision point, covering as much as possible (depending on the center of mass energy)



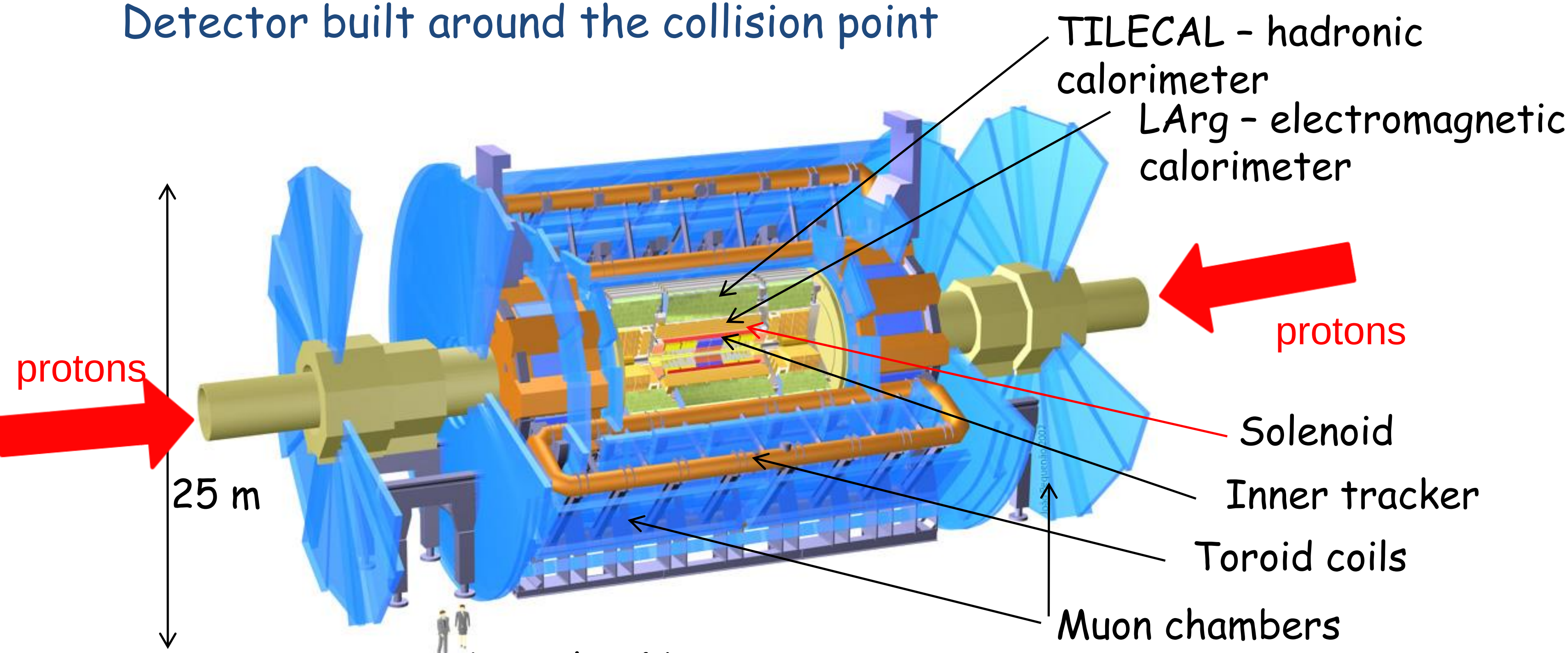
Collisions at the LHC: the detectors

At the LHC center of mass energy the detectors to contain most of the particles produced in the collisons need to be huge.
Even the “compact” CMS is quite big.



ATLAS detector

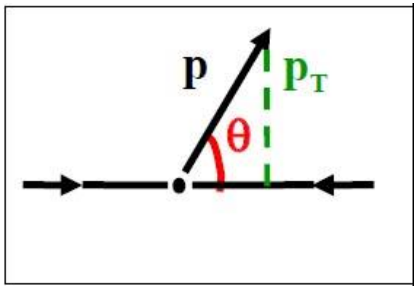
Detector built around the collision point

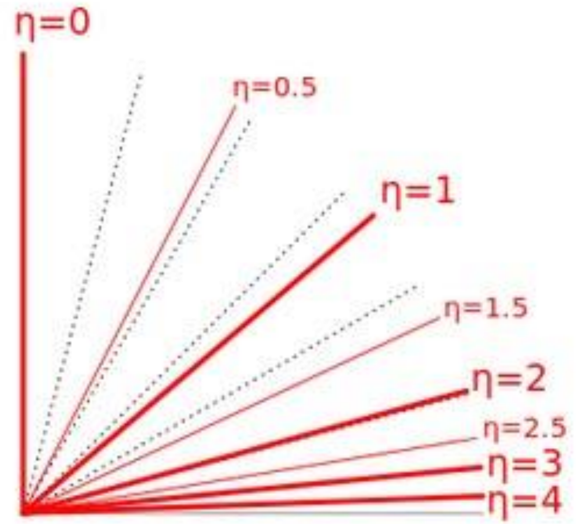


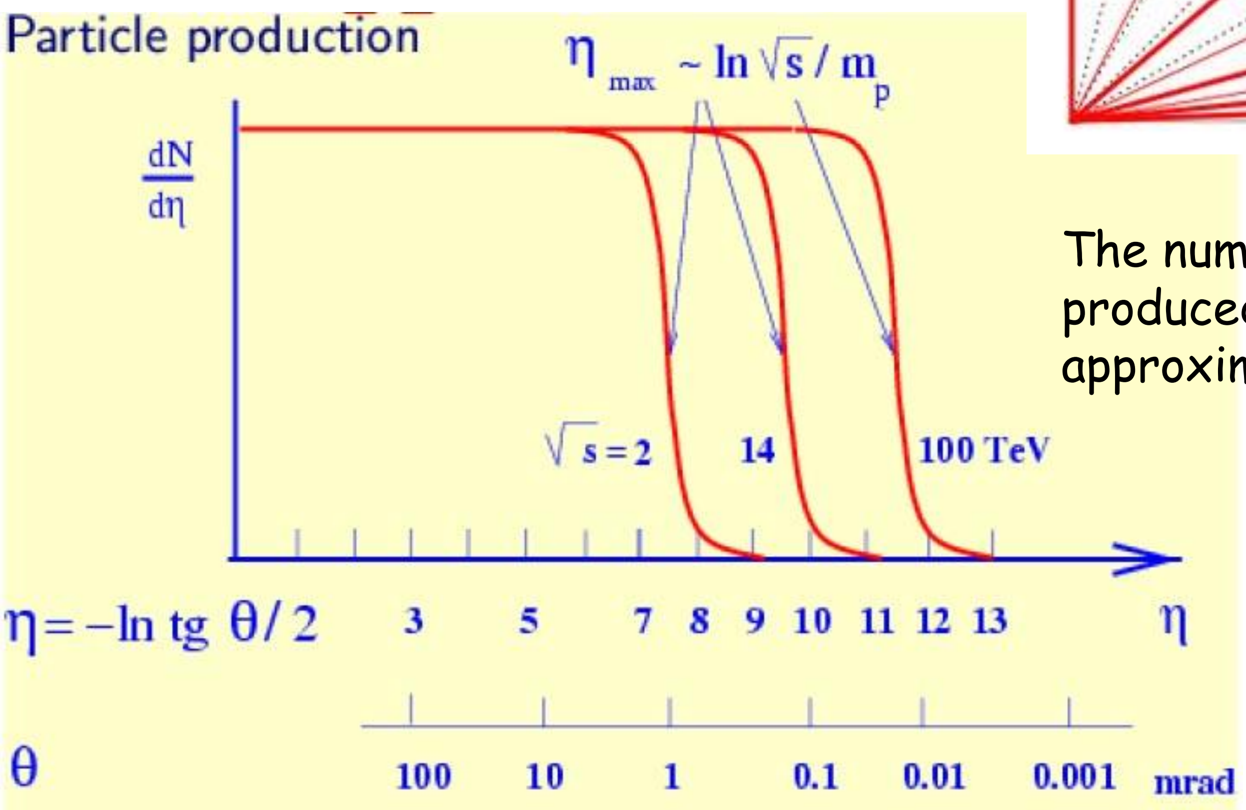
Length: 46 m
Weight: 7000 tons
Electronic chanels: ~100 million

Based on track detectors in magnetic fields
and energy detectors (calorimeters)

Transverse momentum (p_T) and eta (η)







The number of particles produced per unit of η is approximately constant

LHC environment

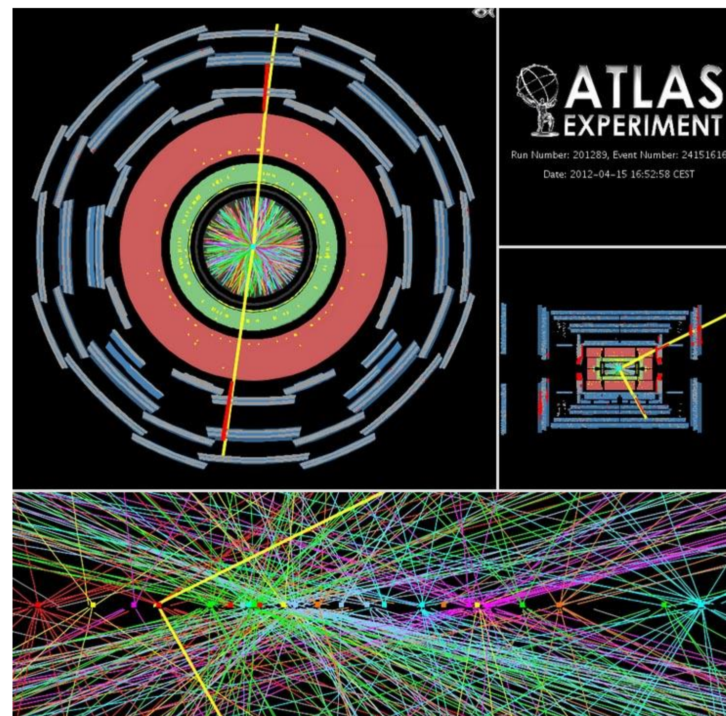
What do we expect roughly speaking at $L = 10^{34}\ cm^{-2}s^{-1}$?

Assume detector with coverage over $-3 < \eta < 3$ ($\theta = 5.7^o$) for tracks and $-5 < \eta < 5$ ($\theta = 0.8^o$) for calorimetry:

- ✓ Most of the energy is not seen! (300000 GeV down the beam pipe)
- ✓ ~ 900 charged tracks every 25 ns through inner tracking
- ✓ ~ 1400 GeV transverse energy (~ 3000 particles) in calorimeters every 25 ns

Pile-up

Pile-up is the name given to the impact of the 10-40 uninteresting (usually) interactions occurring in the same bunch crossing as the hard-scattering process which generates



About neutrinos

One word about neutrinos in hadron colliders:

- since most of the energy of the colliding protons escapes down the beam pipe, one can only use the energy-momentum balance in the transverse plane

  -> concepts such as E_T^{miss}, missing transverse momentum are used everywhere
- the detector must therefore be quite hermetic

  -> no neutrino escapes undetected

  -> no human enters without major work (fast access to some parts of the detectors is difficult)

Detector shape and parameters

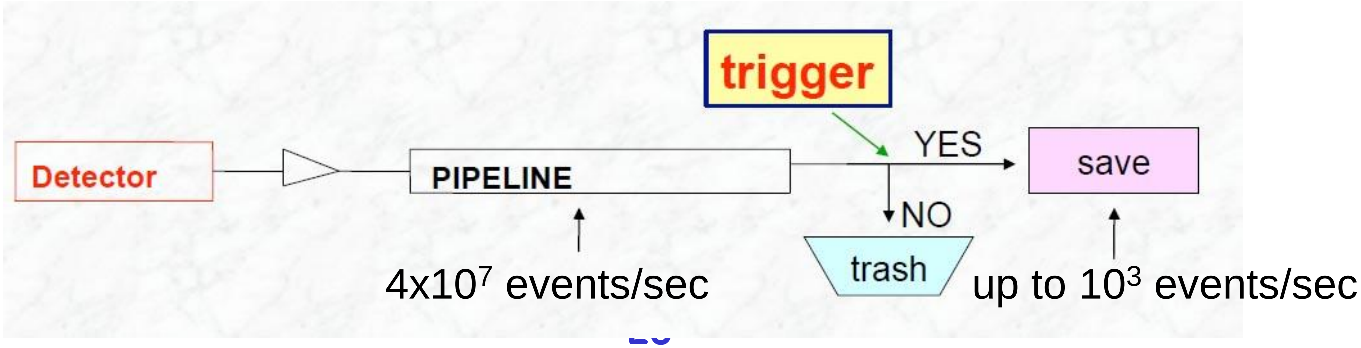
Needs very fine granularity near the collision point to identify isolated tracks of each charged particle

Needs coverage to very near the beam pipe to be able to identify missing transverse energy (momentum)

Needs to be radiation hard

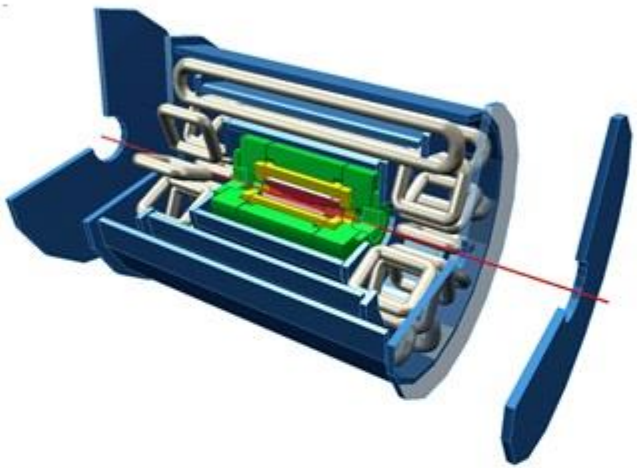
Needs to be very fast producing a manageable volume of data to record. It is impossible to record all events.

Needs a trigger system able to select the few interesting events to record and reject the uninteresting ones

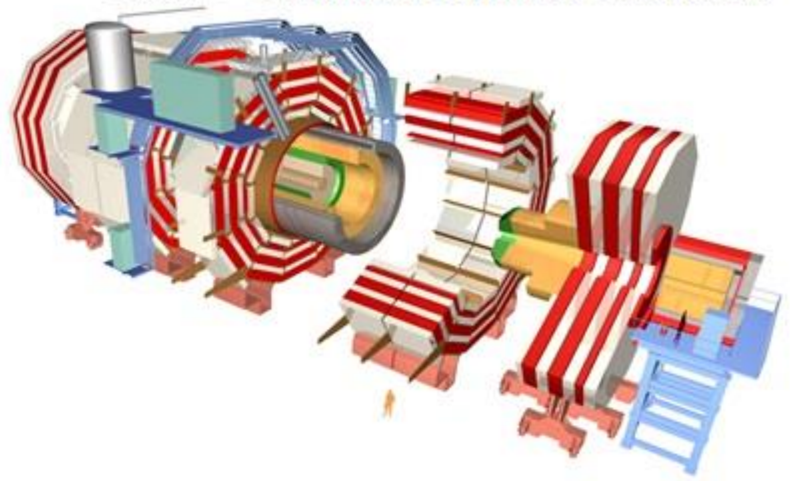


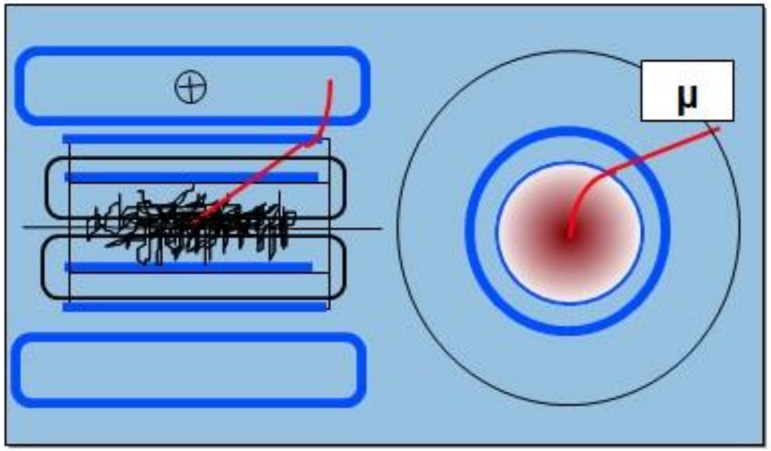
Measuring momentum – bending path of charged particles in magnetic field

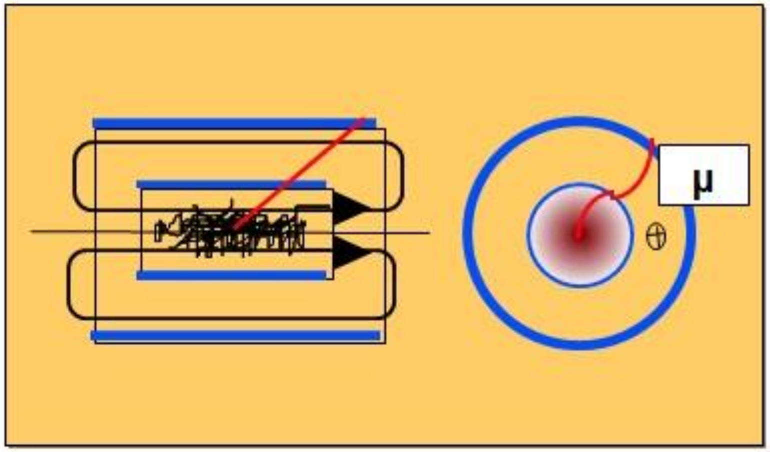
ATLAS A Toroidal LHC Apparatus



CMS Compact Muon Solenoid

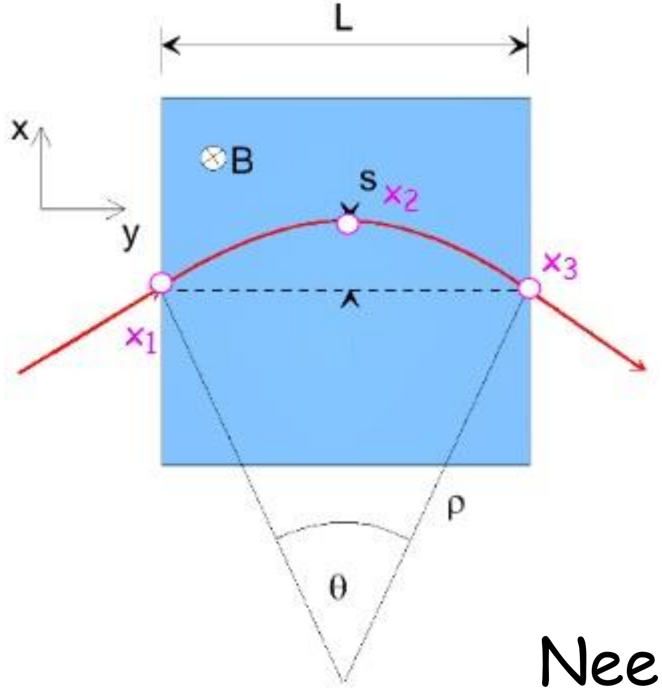






CMS advantage: 4T (vs 2T in ATLAS inner tracker); much easier to visualize
CMS disadvantage: huge amount of iron for return flux produces multiple scattering for the muons decreasing resolution in momentum measurement

How to measure the momentum of large momentum particles



Momentum resolution

$$\frac{dp}{p} \propto \frac{p}{BL^2}$$

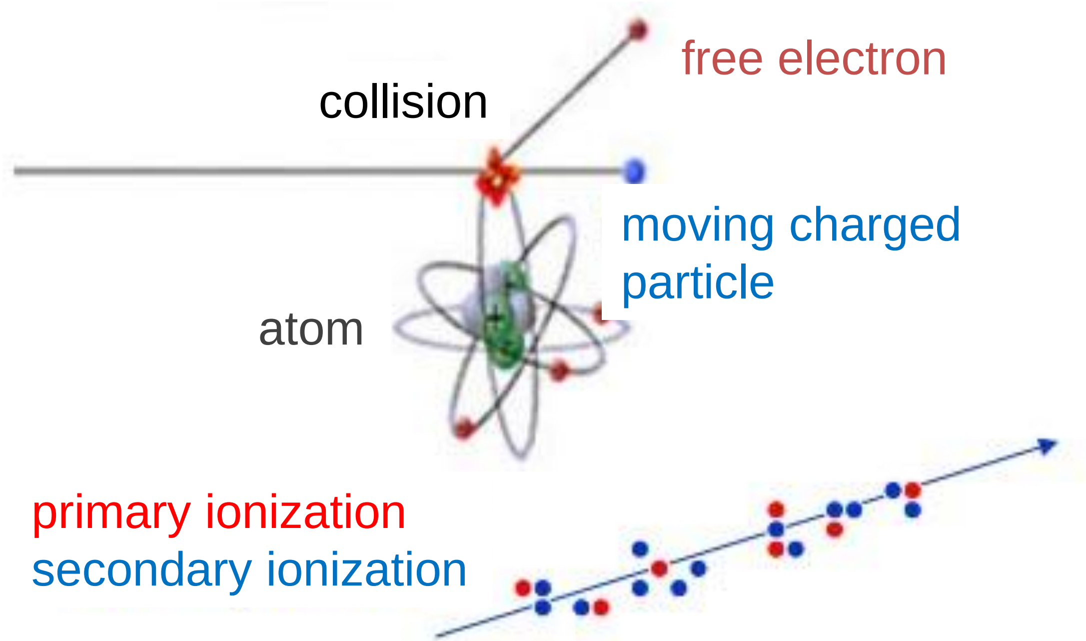
So, optimize BL^2

Need a large lever arm L
(choice of ATLAS)

or

a large magnetic field B
(choice of CMS, B = 4 T)

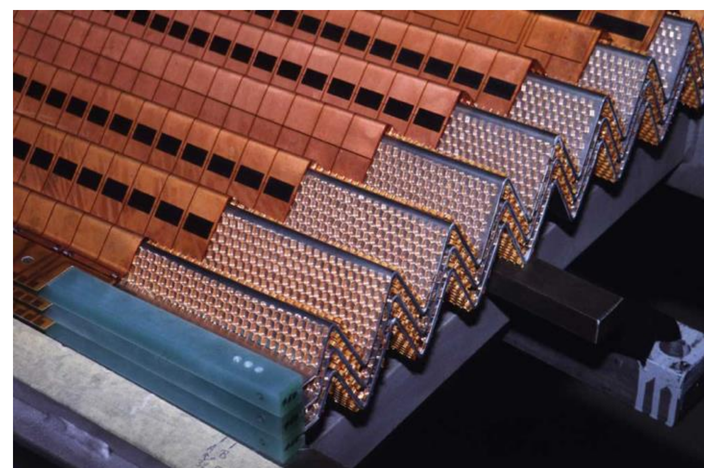
How detectors work - ionization



Passage of a charged particle through matter releases electrons from the atoms along its path producing ionization

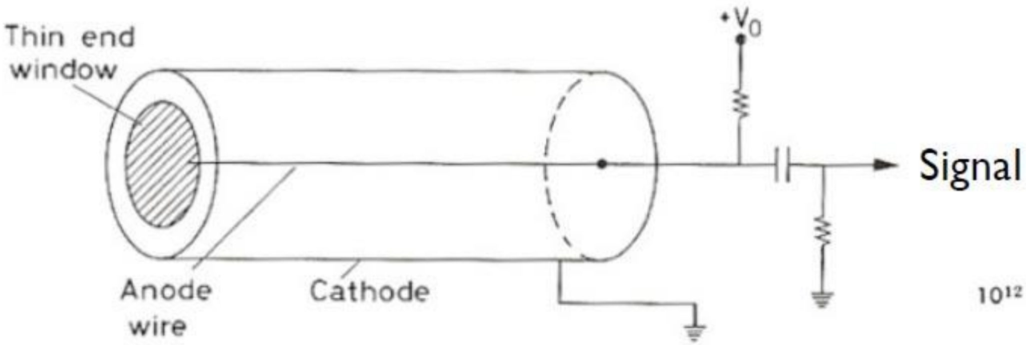
total ionization is the sum of primary and secondary

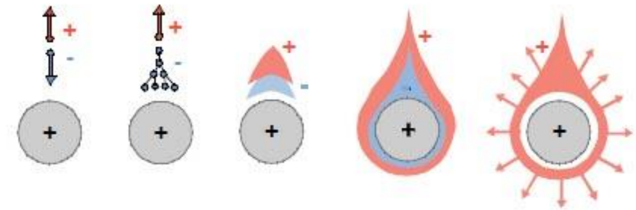
ATLAS Liquid Argon calorimeter
LArg + Pb

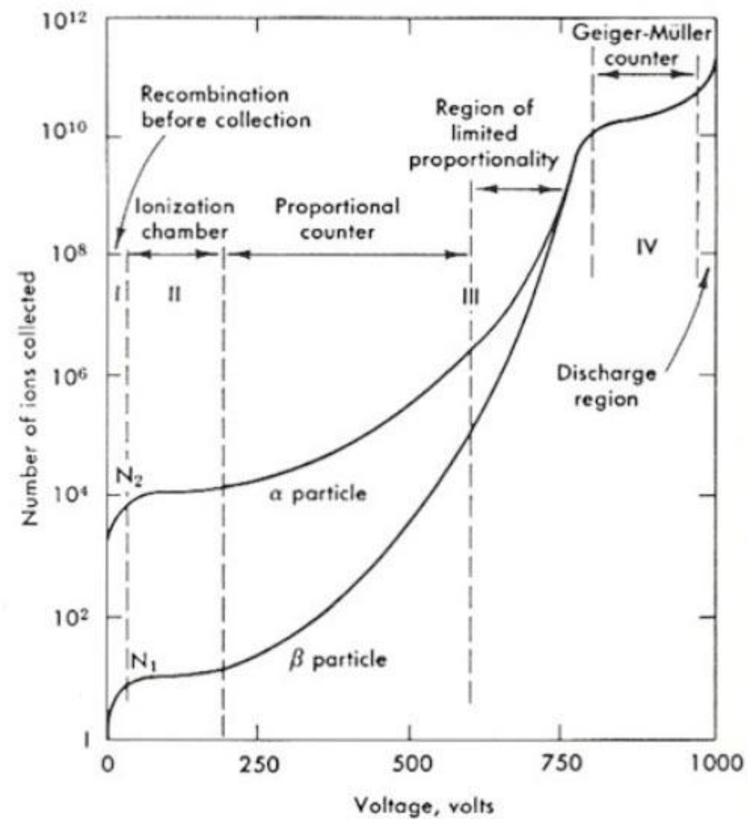


How detectors work

Ionization in a gas filled tube

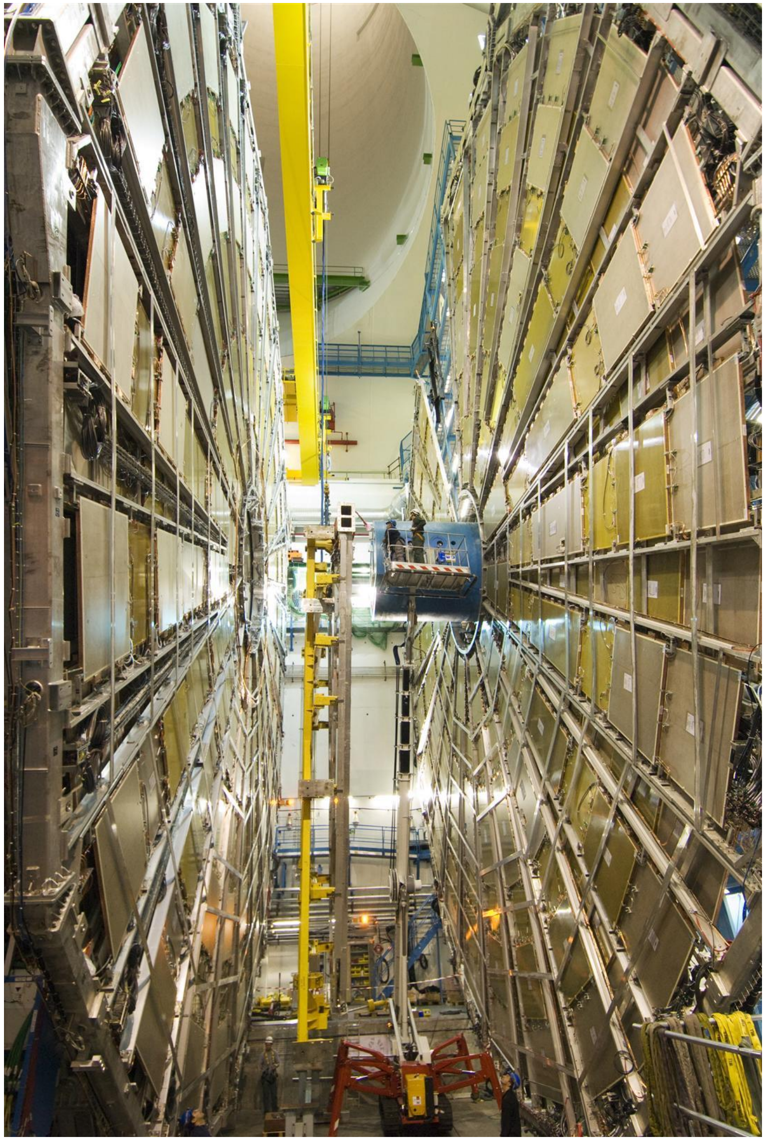




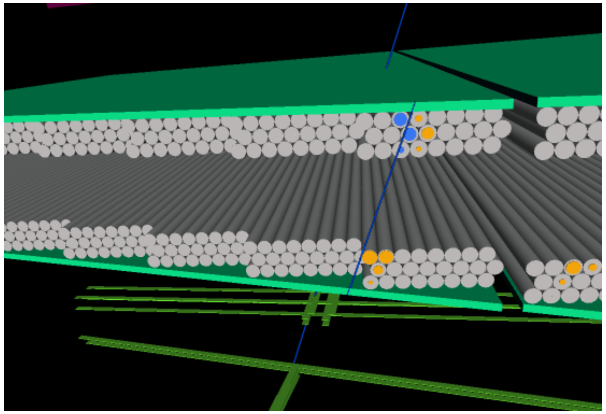


- Passage of particles creates within the gas volume electron-ion pair
- Electrons are accelerated in a strong electrics field -> amplification
- The signal is proportional to the original deposited charge or is saturated (depending on the voltage)

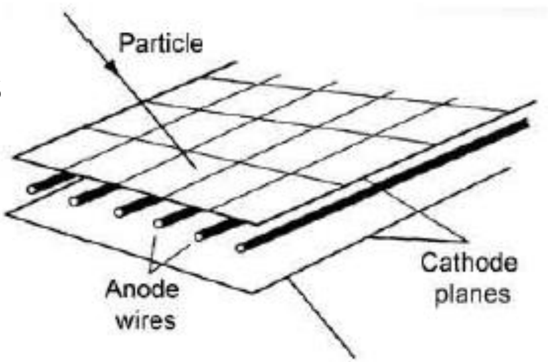
Muon chambers:



- **In general, only muons (and neutrinos that are not detected) arrive here**



They leave tracks in stacked long gas filled tubes of the muon detector.

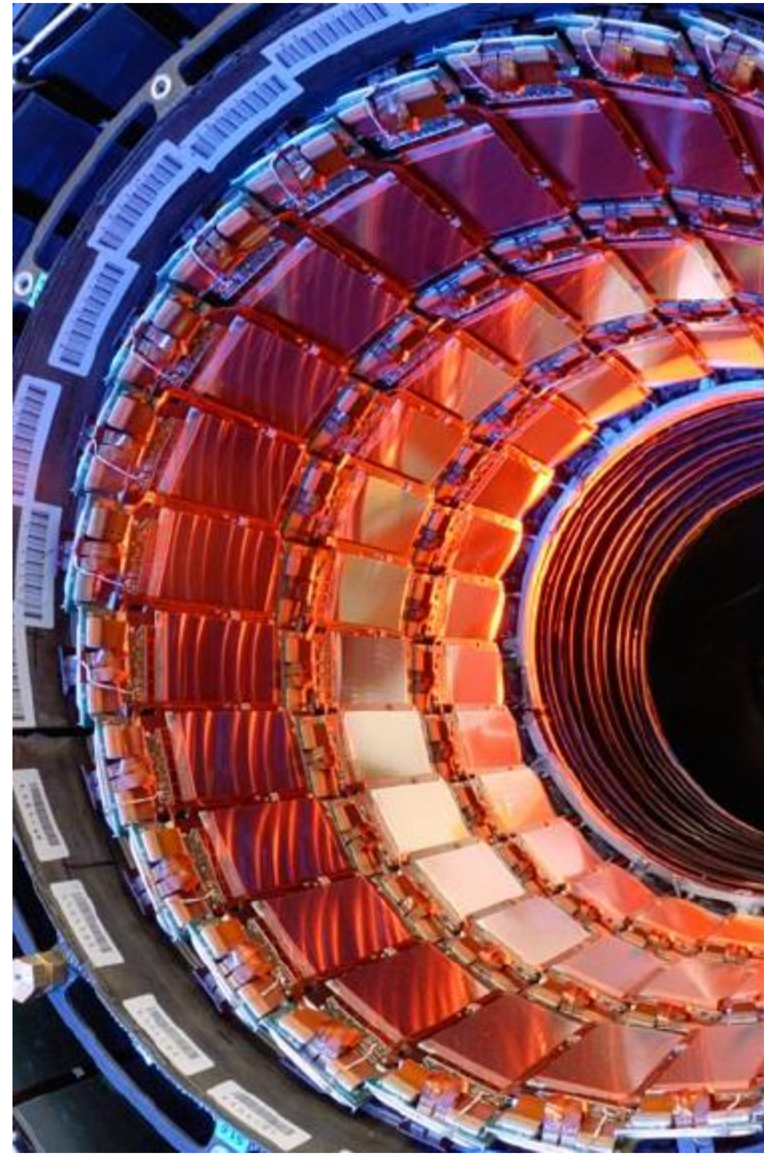


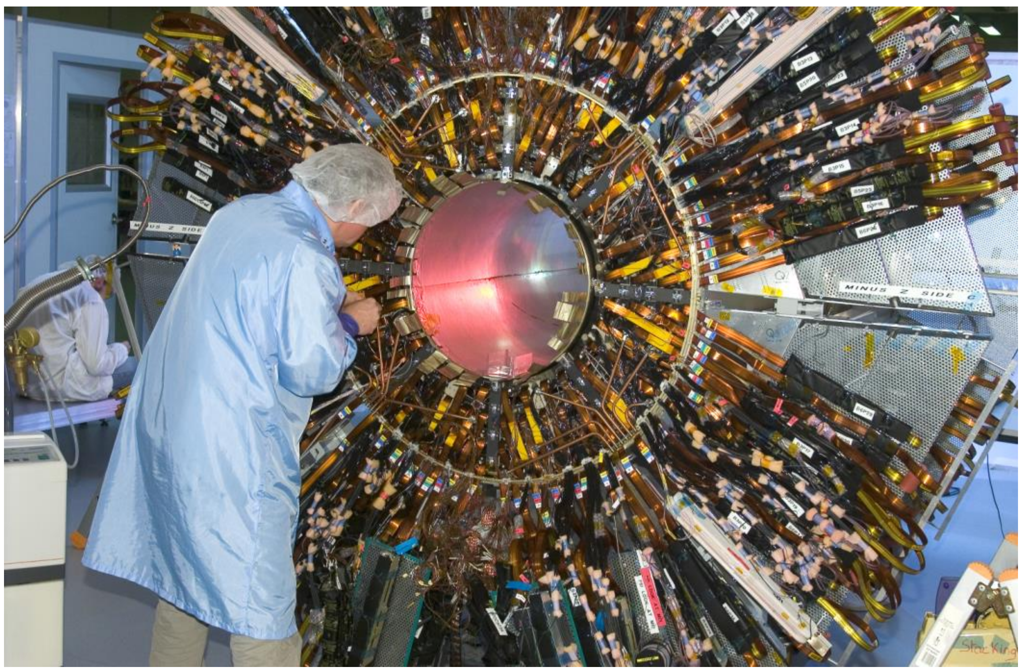
Several planes of chambers allow to reconstruct the track of the particle

Inner trackers

Inner trackers

CMS – all silicon detector (pixels and strips)

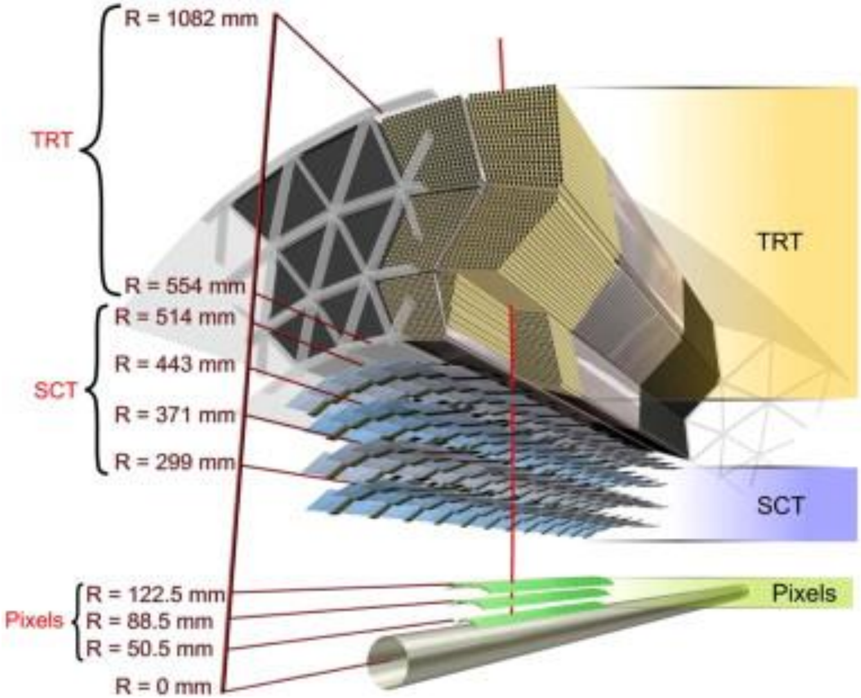


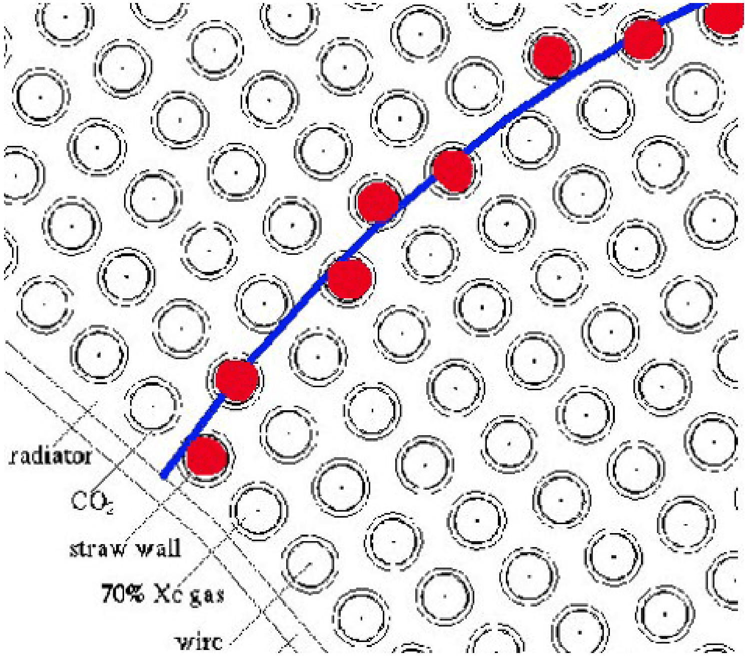


ATLAS – pixels and strips at inner radii followed by a gaseous transition radiation detector at larger radii

Tracking detector

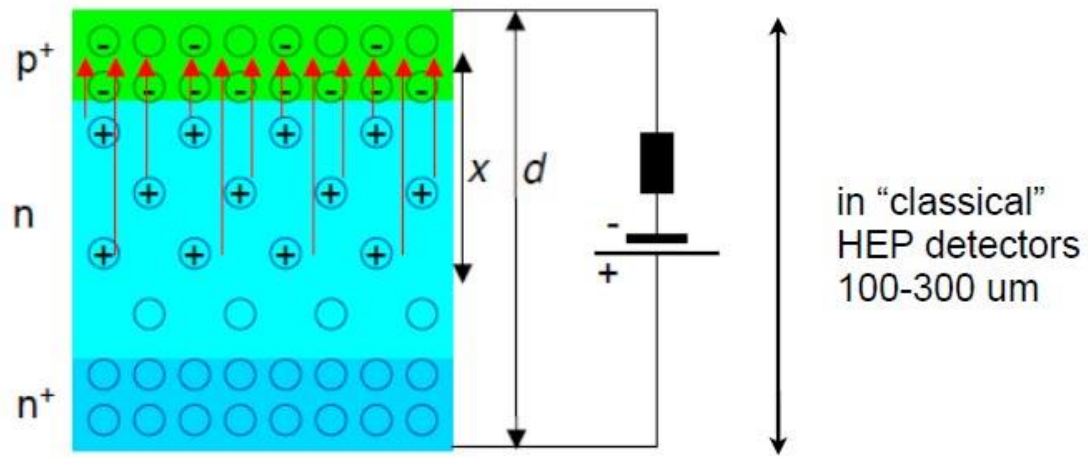
- Immerse in a solenoidal magnetic field
- Allows the "visualization" of the charged particles tracks
- Allows the determination of the collision point
- Gives information about secondary vertices
- Inner layers made of semiconductors. In ATLAS, outer layer is transition radiation detector and a ionization tracker



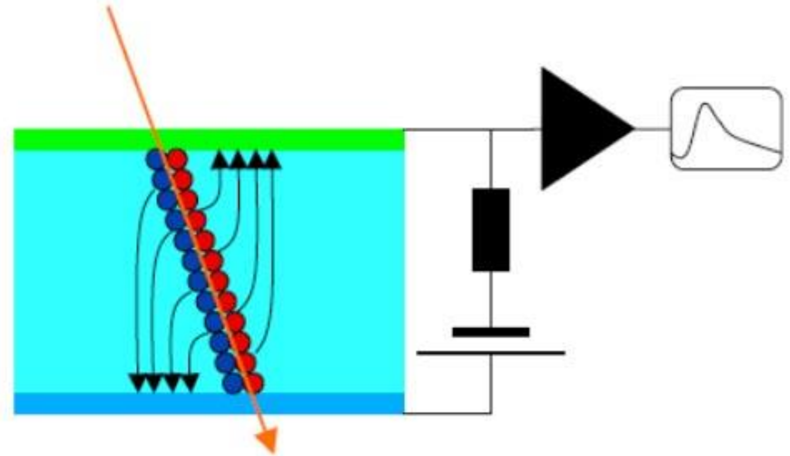


Principle of semiconductor detectors

- **Apply voltage to deplete charges in thickness d**



- **Ionizing particles create free charge carriers (electrons and holes)**
- **Charge carriers drift to electrodes and induce signal**

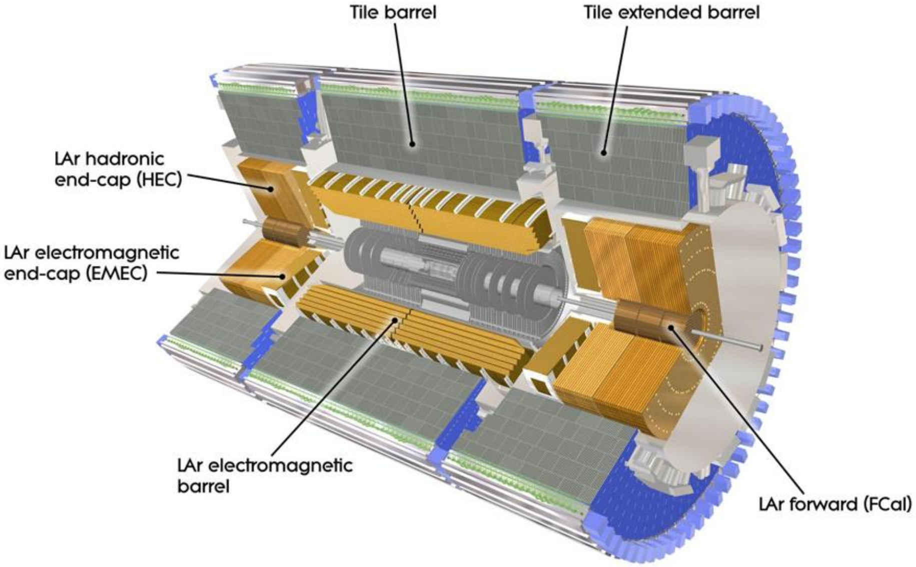


Typical dimension of a pixel in HEP large detectors is ~100μm

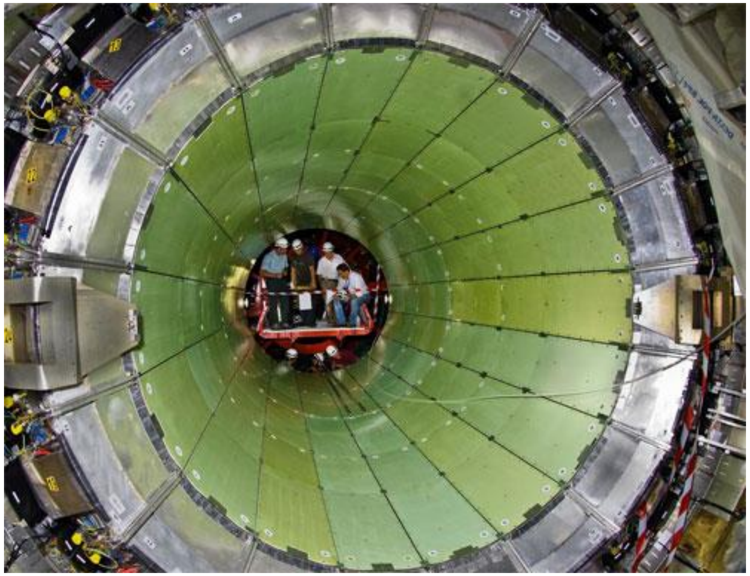
Calorimeters

Calorimeters:

- Participate in the identification of particles
- The e.m. calorimeter measures the energy of electrons and photons
- The hadronic calorimeter measures the energy of hadrons



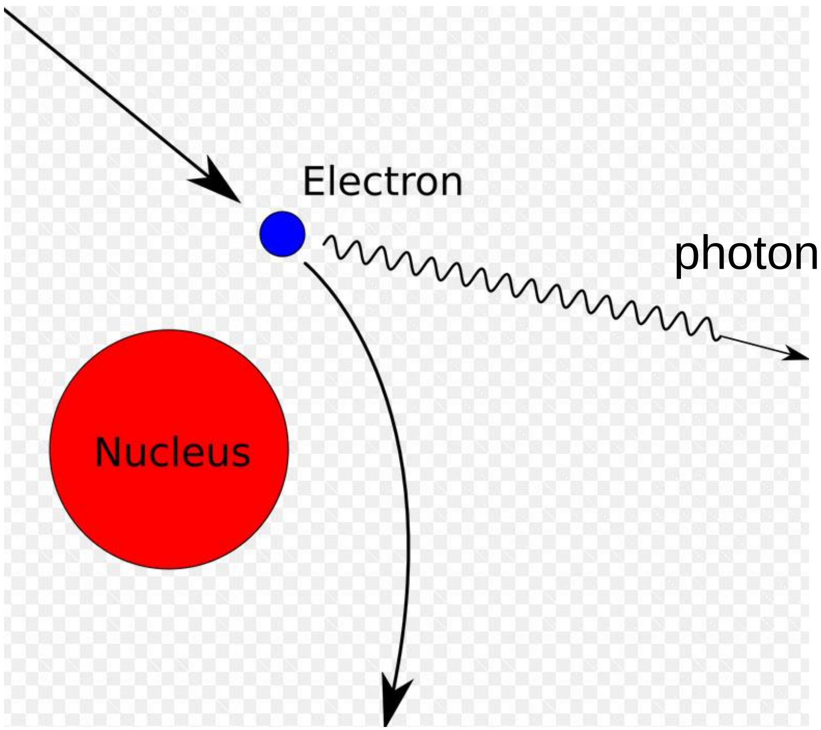
ATLAS calorimeters



CMS ECAL

Interactions of high energy electrons/positrons

The main way of energy loss for high energy electrons/positrons is bremsstrahlung (braking radiation)



Strong deceleration happens when the particle passes near a nucleus

there is emission of photons

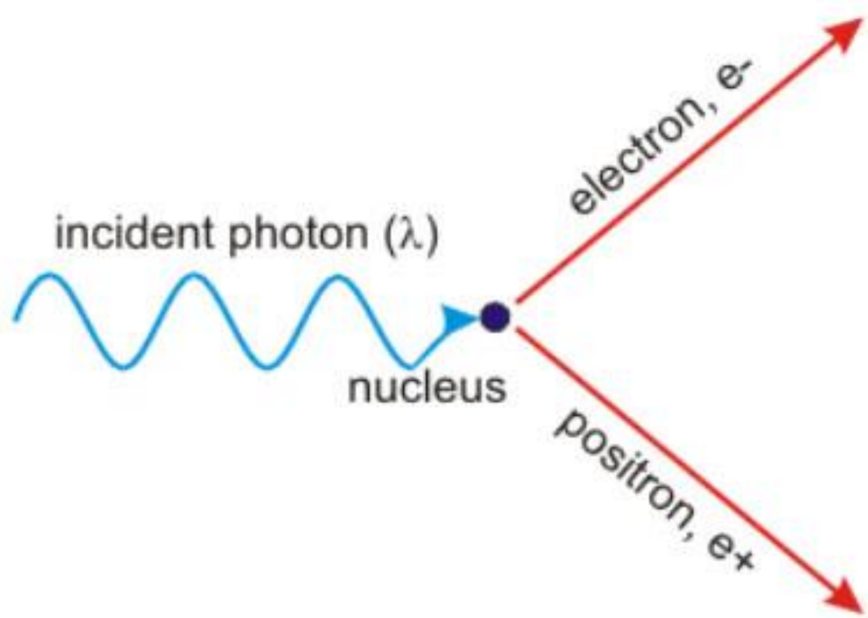
energy of the electron that is loosing energy by bremsstrahlung:

$E = E_0 \exp(-x/X_0)$

X_0 is the radiation length

Interaction of high energy photons

The main interaction of high energy photons is the production of electron-positron pairs

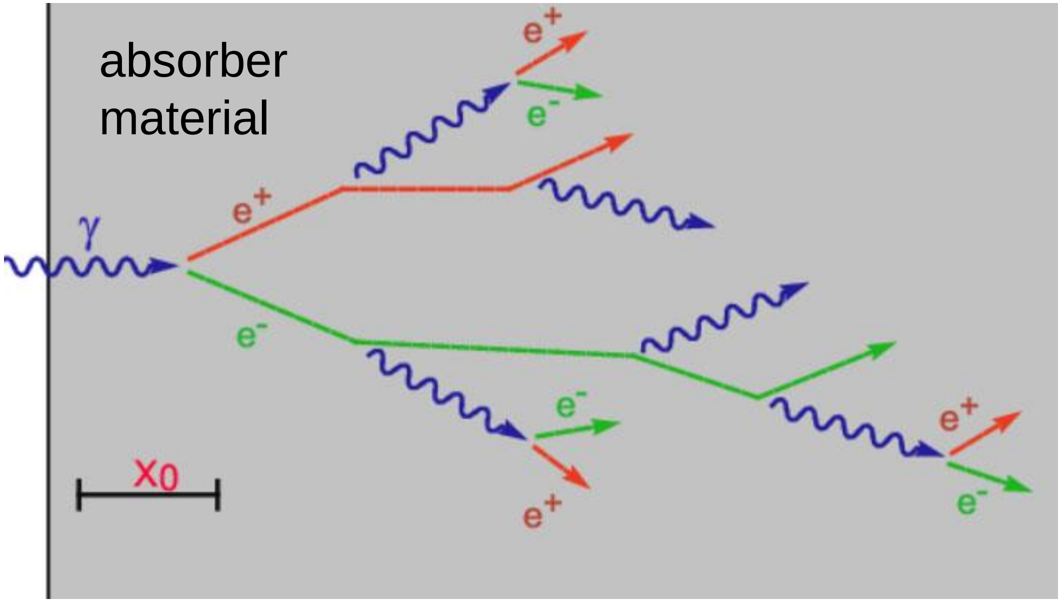


happens near a nucleus

photon energy needs to be above 2 x 511 keV

Electromagnetic shower

For high energy photons or electrons/positrons, pair production and bremsstrahlung are respectively the most probable way to loose energy. They will alternate in a particle shower.



photon origins e+ e- pair

electron/positron radiates photon

proccess repeats when particle energy is high enough

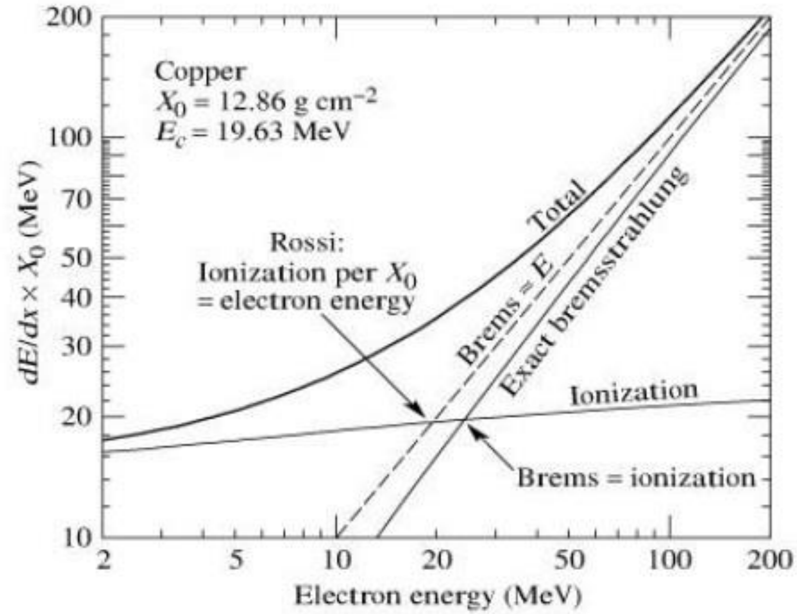
Electromagnetic showers allow the absorption of photons/electrons/positrons in calorimeters

number of particles in the shower grows with time

Electromagnetic shower

Critical energy:

$$\frac{dE}{dx}(E_c)\Big|_{\mathrm{Brems}} = \frac{dE}{dx}(E_c)\Big|_{\mathrm{Ion}}$$



Approximations:

$$E_c^{\mathrm{Gas}} = \frac{710\ \mathrm{MeV}}{Z+0.92} \qquad \left[E_c^{\mathrm{Sol/Liq}} = \frac{610\ \mathrm{MeV}}{Z+1.24}\right]$$

$$\left(\frac{dE}{dx}\right)_{\mathrm{Brems}} \Big/ \left(\frac{dE}{dx}\right)_{\mathrm{Ion}} \approx \frac{Z\cdot E}{800\ \mathrm{MeV}}$$

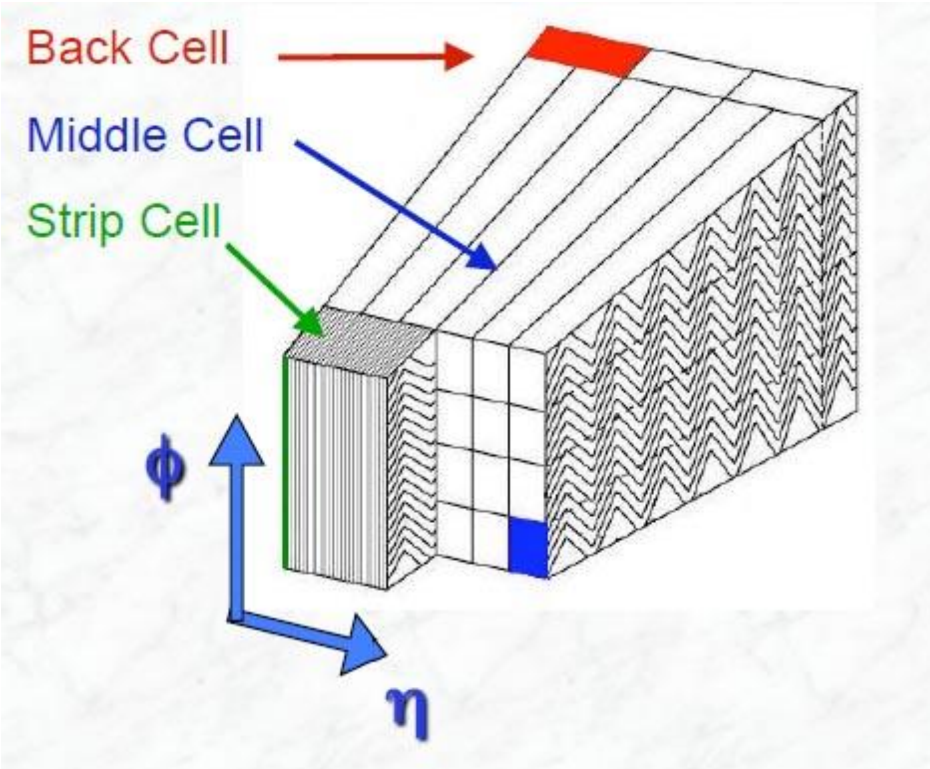
with:

$$\frac{dE}{dx}\Big|_{\mathrm{Brems}} = \frac{E}{X_0} \quad \& \quad \frac{dE}{dx}\Big|_{\mathrm{Ion}} \approx \frac{E_c}{X_0} = \mathrm{const.}$$

After the critical energy shower does not grow.

Shower maximum at $x_{max} \propto \ln(\frac{E0}{EC})$

ATLAS Liquid Argon e.m. calo



Absorber is lead

Active medium is liquid argon

Shape is accordion to avoid particles crossing only absorber or only active medium

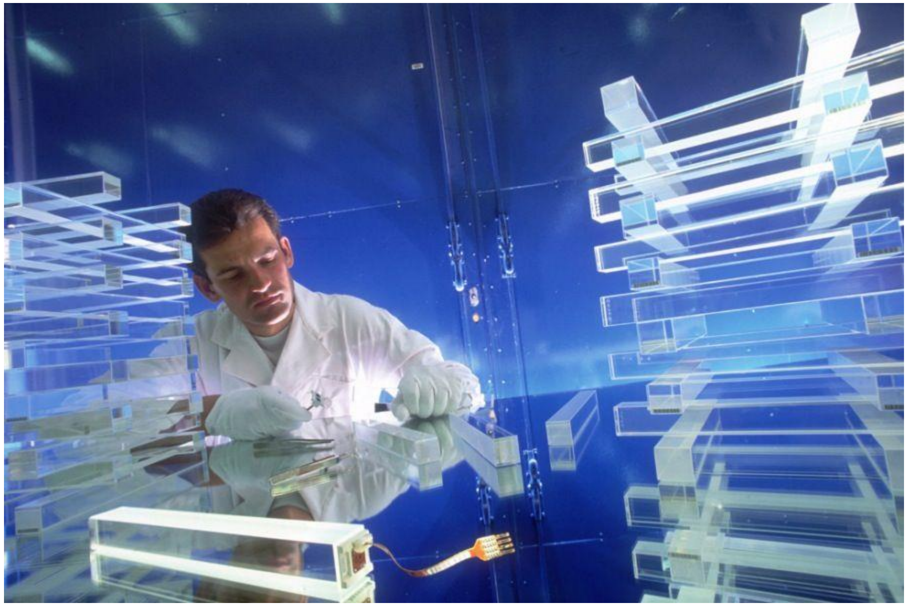
Located inside a cryostat

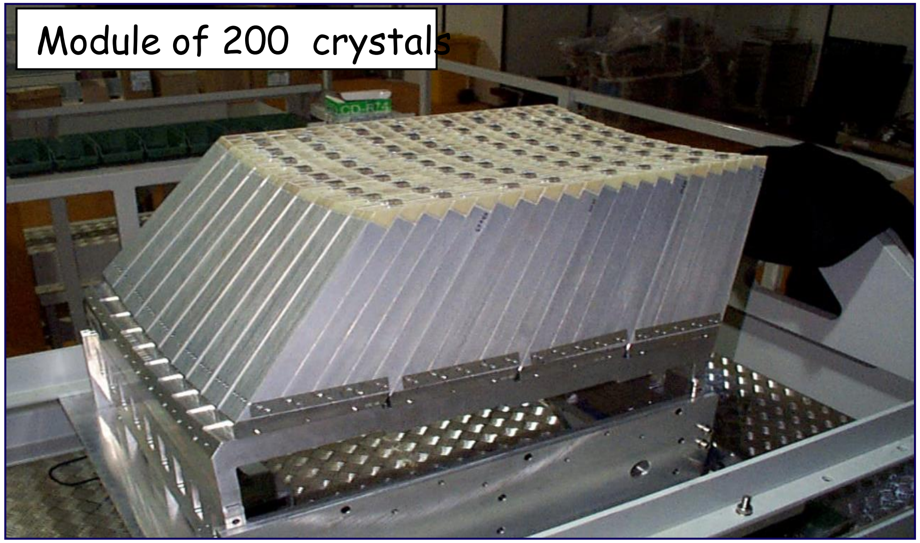
It is radiation hard

High granularity in front and longitudinal segmentation for better e/gamma identification

Relatively small back cells to be sensitive to energy lost in cryostat

CMS crystal electromagnetic calo





Homogeneous calorimeter

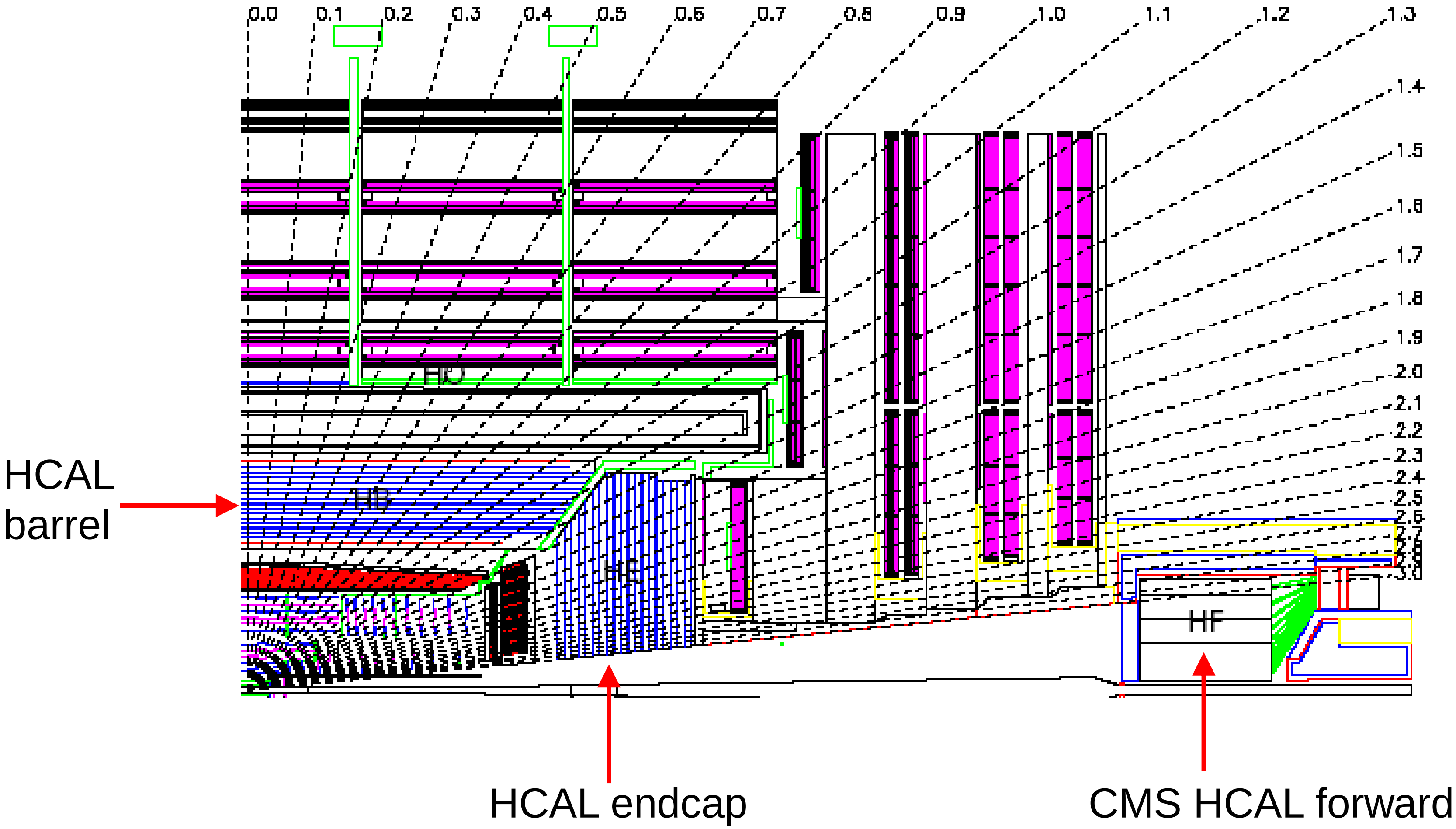
Lead tungstate ($PbWO_4$) crystals create electromagnetic showers and produce scintillation light

High density (8.3 g/cm3), fast decay time allows to collect 80% of light in 25 ns

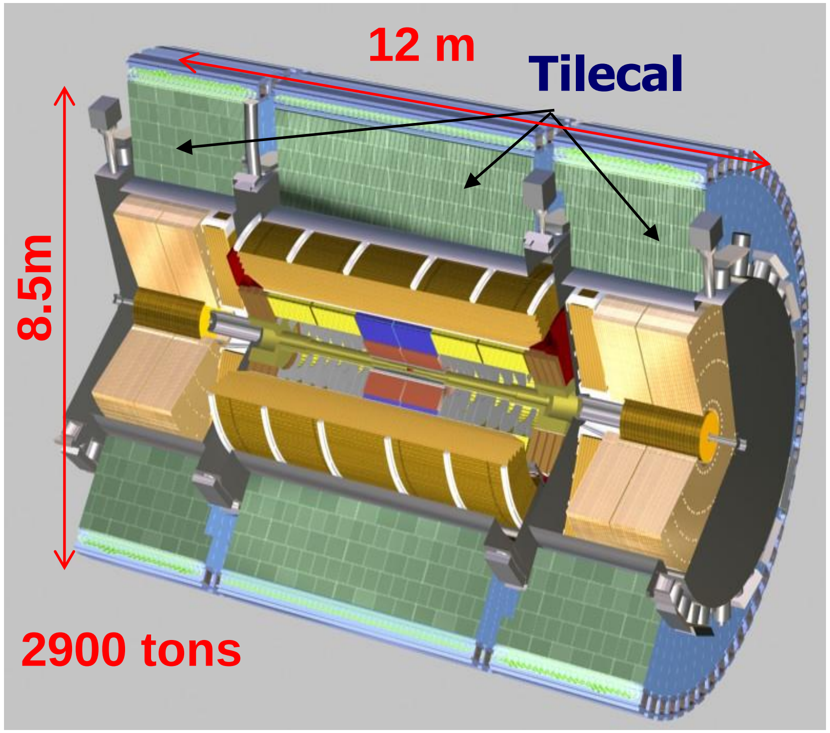
Radiation hard

Allows excellent energy resolution

Hadron calorimeter



ATLAS TileCal hadron calorimeter

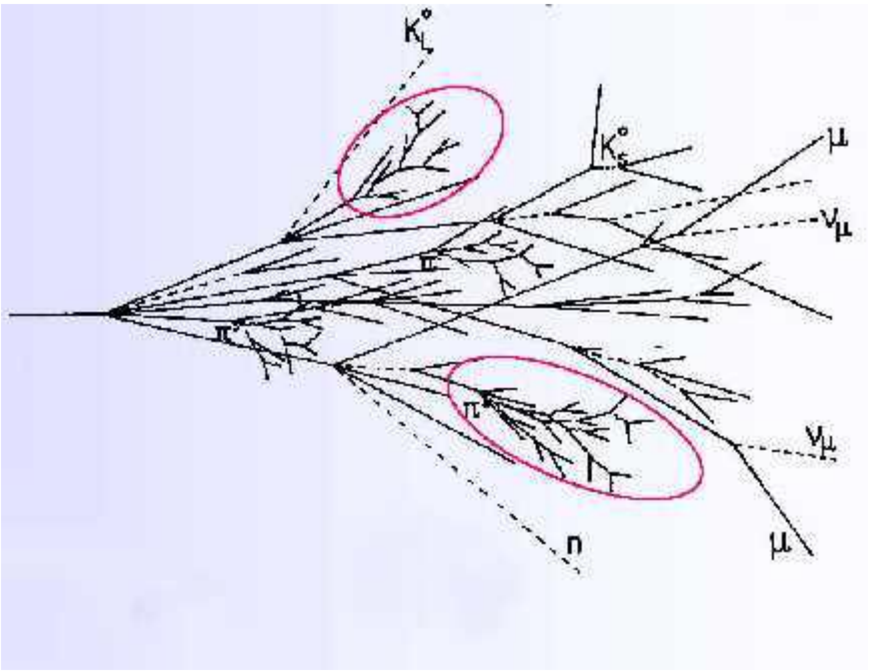


Hadron calorimeter with good performance at low cost

- Scintillating Tiles and WLS optical fibres
- Photomultiplier tubes (PMTs)
- Steel/Tiles, ratio 4.7 : 1 (λ = 20.7 cm)
- 10 k channels (5000 cells)
- Transversal granularity $\Delta\eta \times \Delta\phi$=0.1x0.1
- Longitudinal segmentation: 3 layers
- Containment ~ 98% TeV hadrons, jets
- ATLAS jet resolution: $\sigma_E/E \sim 50\text{-}60\%/\sqrt{E} \oplus 3\%$

Robust technology for barrel region, but not suited for end-caps (radiation damage)
In end-caps use Liquid Argon technology

Hadronic showers and jets



Hadronic showers originate jets of particles

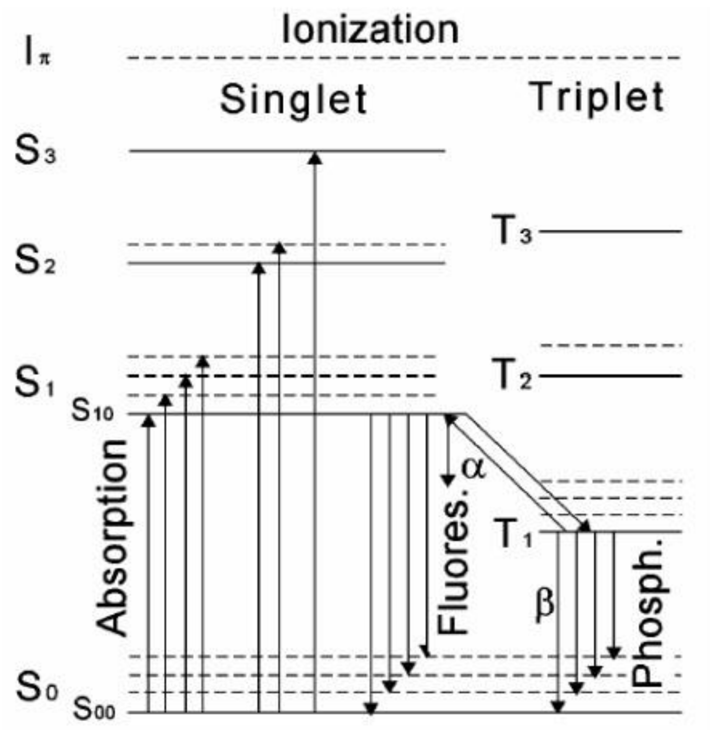
Hadronic showers are similar to electromagnetic ones but much more complex

They originate from the interaction of particles made of quarks or gluons

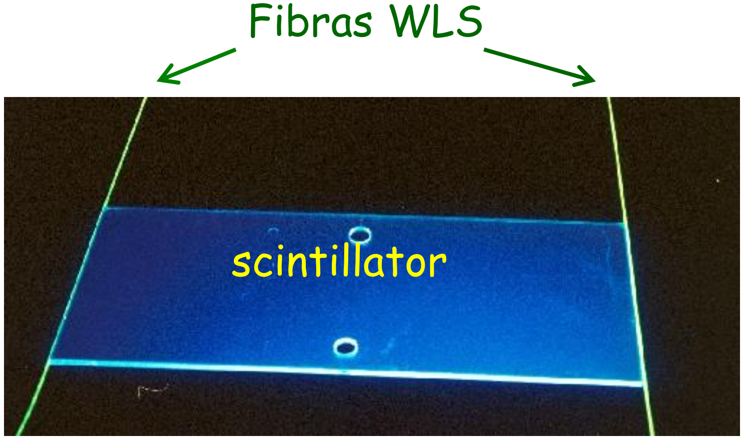
They have larger intrinsic fluctuations in energy detectable by detectors:
there are nuclear interactions taking energy, it may include neutrinos, muons, neutrons, etc that may escape totally or partially, etc

How detectors work

Scintillation – organic scintillators

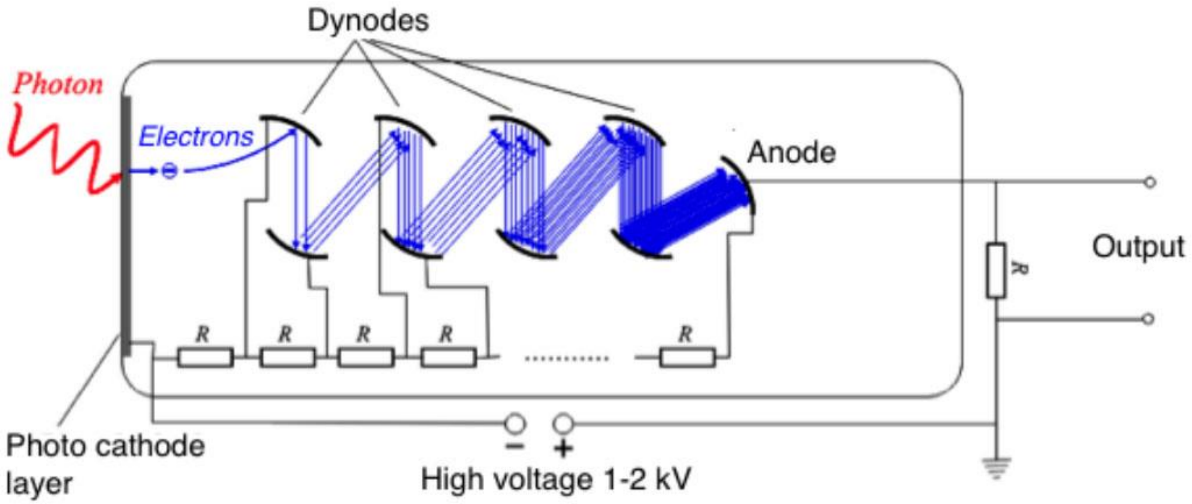


Charged particles deposit energy causing excitation of solvent and dopants molecules. Fast de-excitation by fluorescense. Light collected by photodetector.

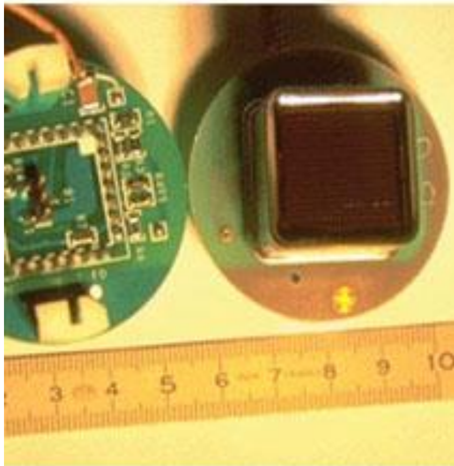


Hadronic calorimeter Tilecal

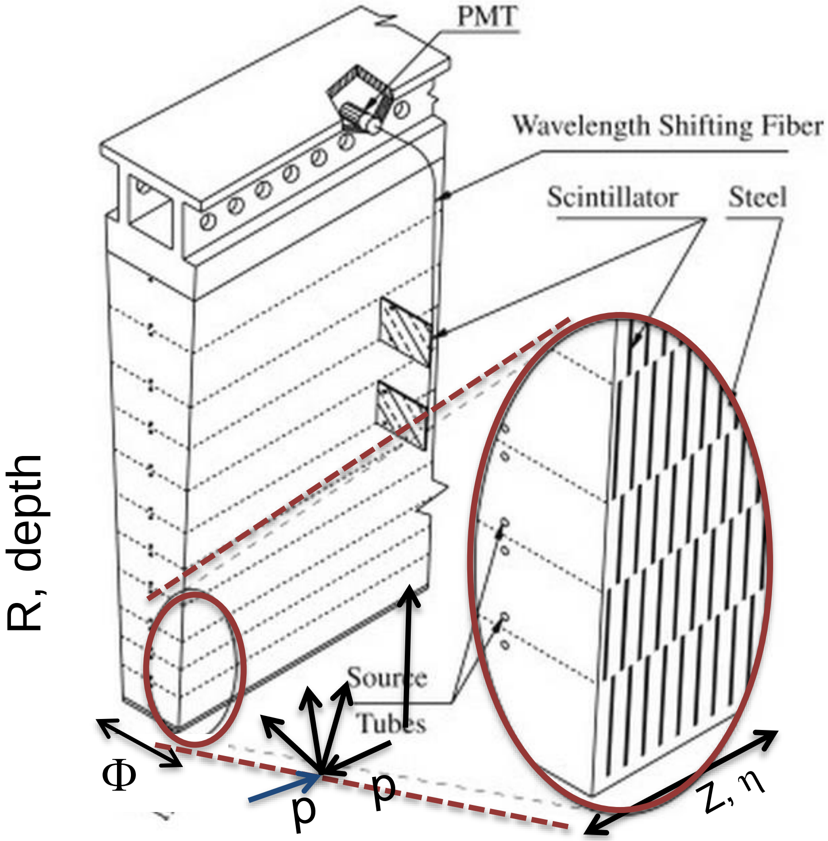
Photodetector – PMT example



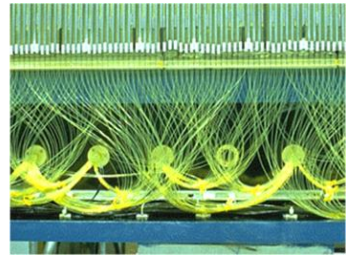
Photons hitting the photo cathode release electrons (photoelectric effect).
Electric fields accelerate electrons to dynodes, multiplying the number of electrons that arrive at the anode.

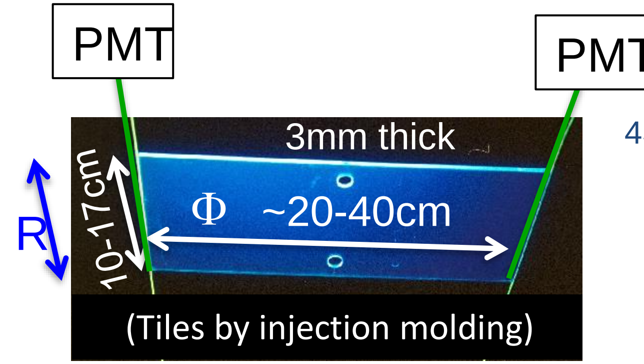


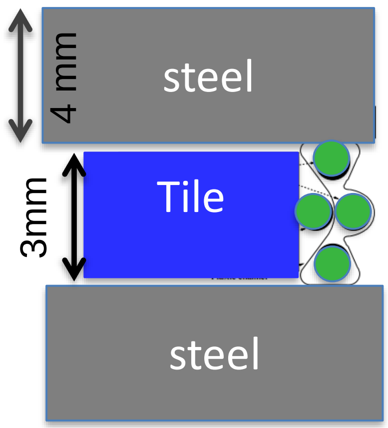
Tilecal layout



Fibre bundles
(at outer radius)

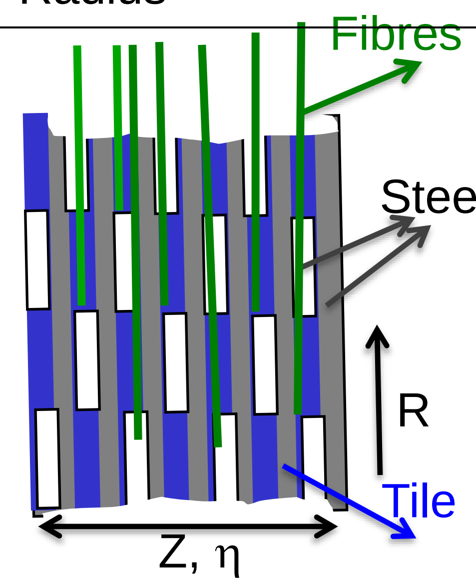






Fibres start at different R and go radially out =>

- No cracks in ϕ
- depth segmentation
- PMTs at outer Radius



ATLAS Tile cells $\Delta\eta x\Delta\phi$=0.1x0.1 (0.2x0.1 in outer layer) and 3 layers driven by LHC requirements and electronics readout costs

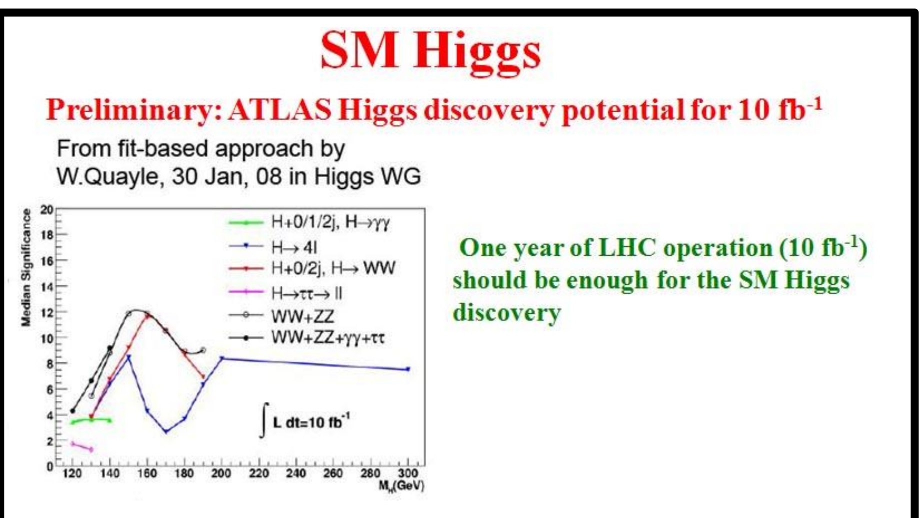
Optics granularity (~ 620k fibres 400k tiles):

- $\Delta\eta$: 3mm tiles every 9-18mm in Z
- ΔR: 11 tiles and 8 fibres in R
- $\Delta\Phi$: 20 cm tiles

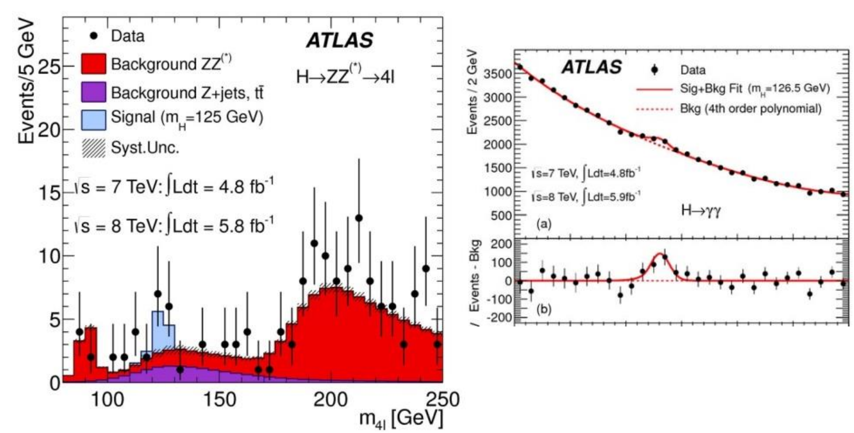
HEP detectors are quite complex systems

But many times they deliver what we are expecting from them
(example of Higgs at ATLAS)

Slide 2008 - forecast



Discovery 2012, ~10 fb^{-1}



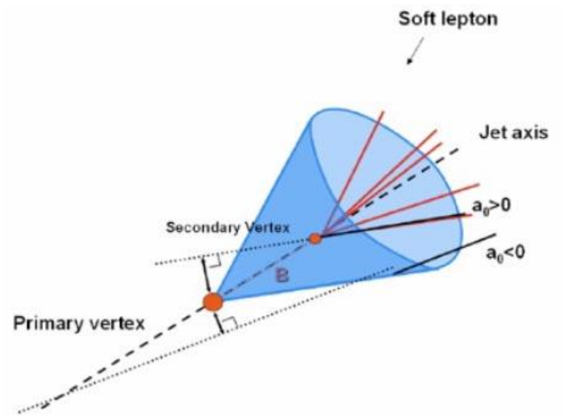
BACKUP

Detector shape and parameters

LHC environment (circular collider of 7 TeV protons at a huge rate) and the Physics searched motivated the design of the multi-purpose detectors ATLAS and CMS

Need to measure/identify:

Muons
Electrons
Photons
Taus
Jets
B tagged jets (requires identification of secondary vertices)
Neutrinos and other non-interacting particles



In an environment of pile-up of collisions (seen in next slide)
With a lot of radiation that damages the detectors

Trigger and Data Acquisition (TDAQ)

Trigger – online selection

Much of LHC physics means cross sections at least ~10^6 times smaller than total cross section

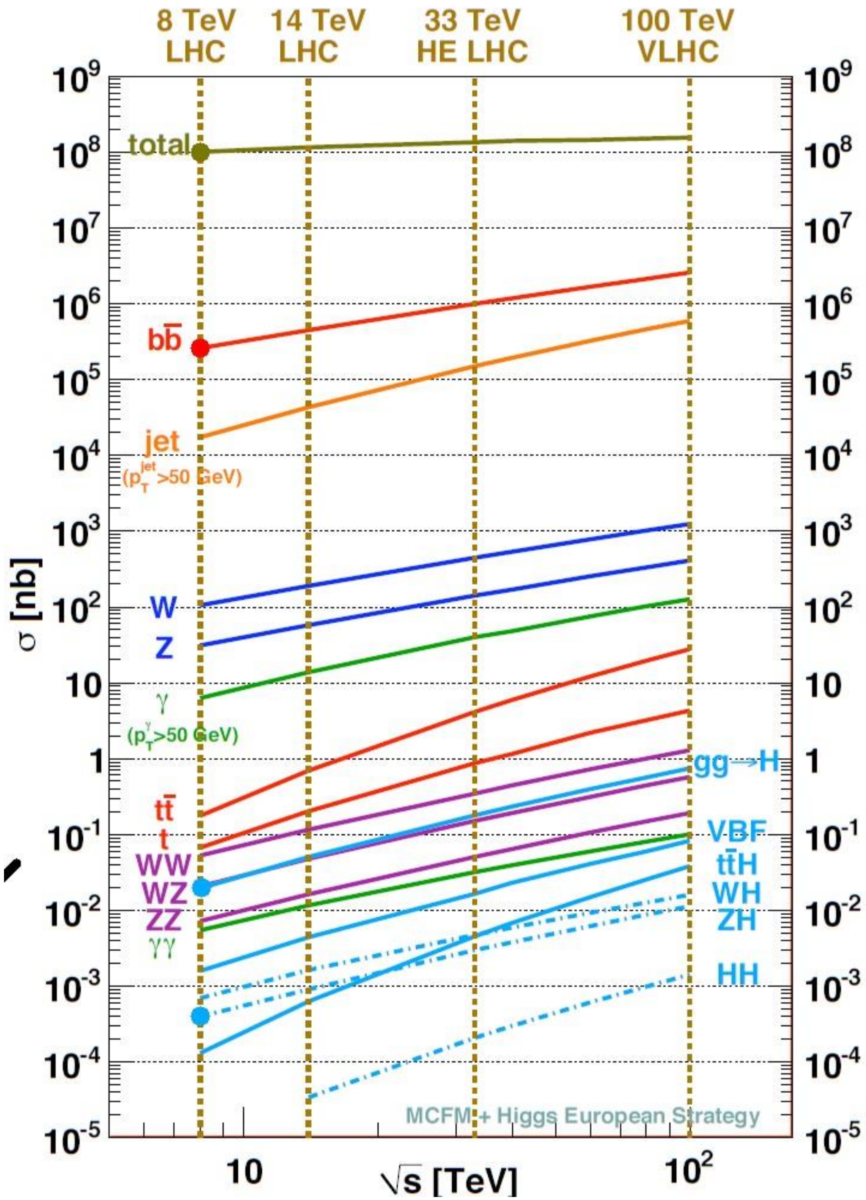
25ns bunch crossing interval (40 MHz)

Offline storing/processing: ~1000 Hz

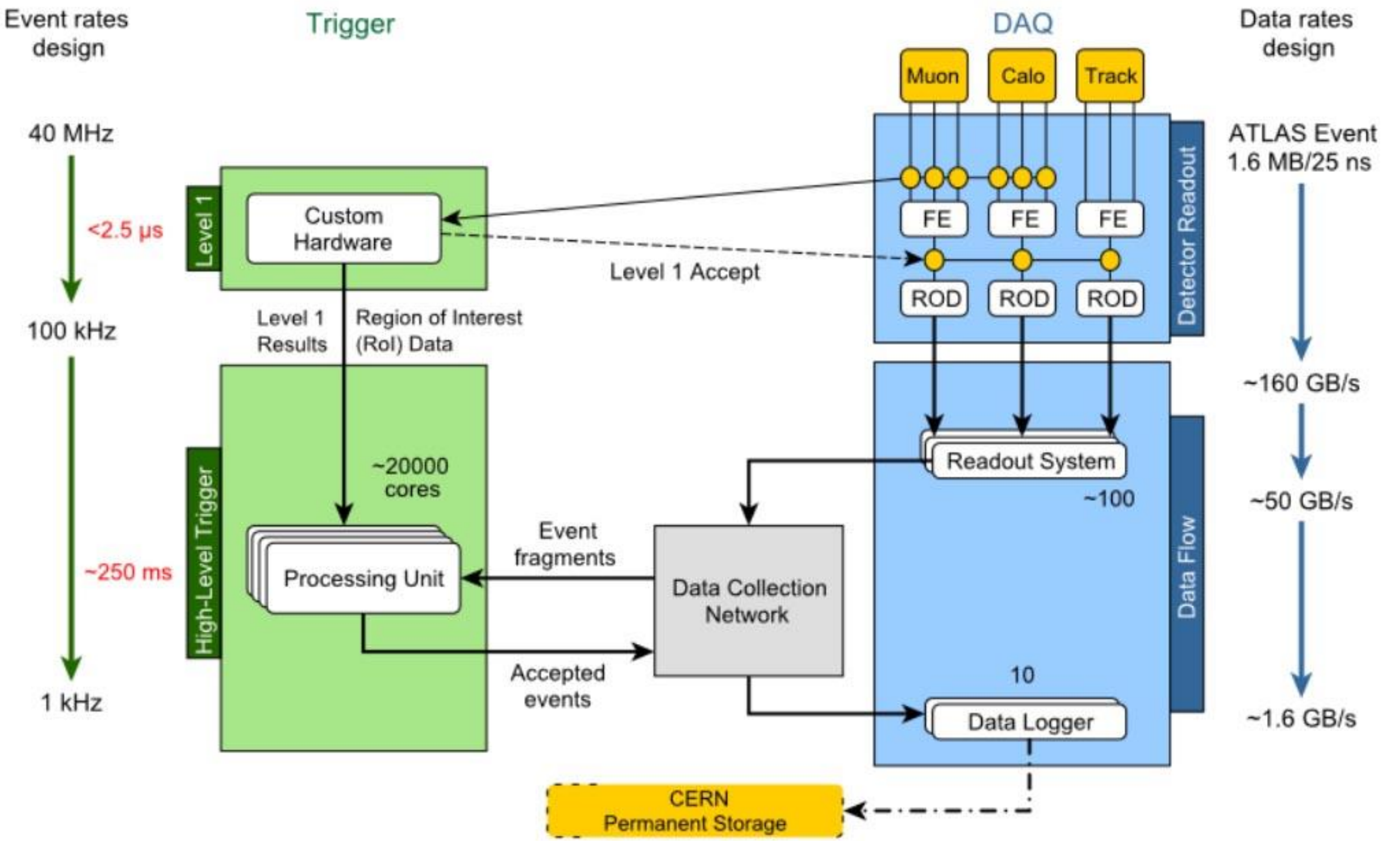
In one second at design luminosity:

- 40 000 000 bunch crossings
- ~2000 W events
- ~500 Z events
- ~10 top events
- ~0.1 Higgs events
- **1000 events written out**

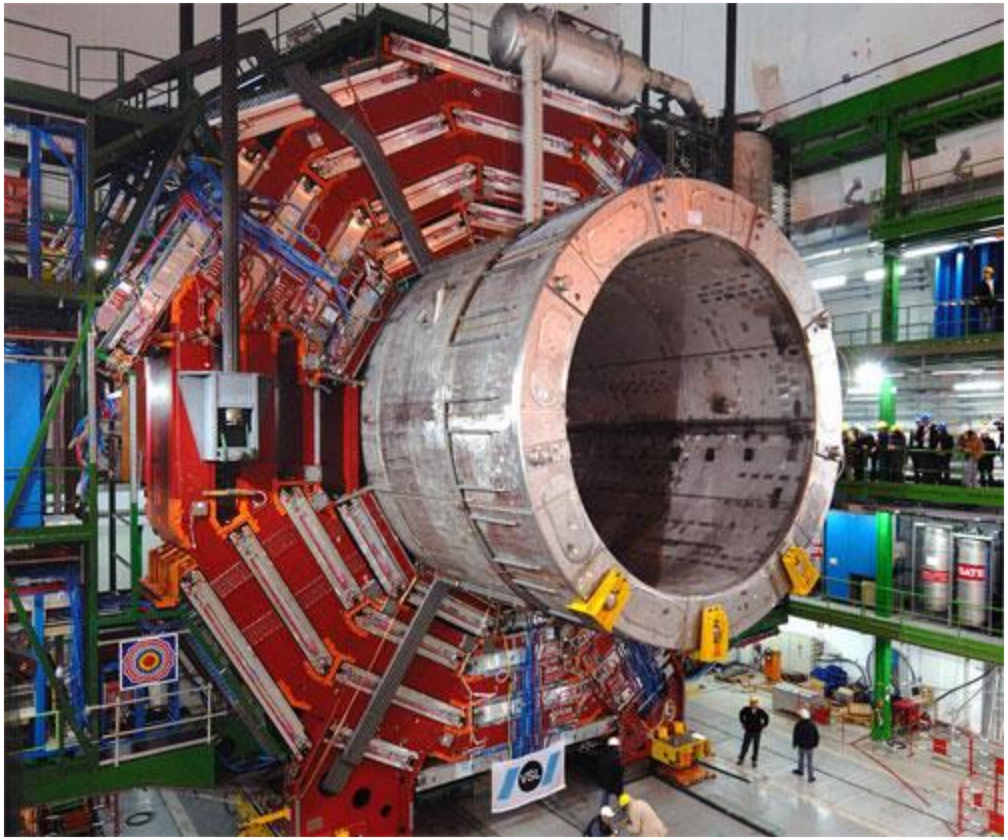
The right 1000 events should be written out!



ATLAS Trigger and Data Acquisition (TDAQ) Run 2



CMS solenoid



Huge solenoid

Length: 12.5 m

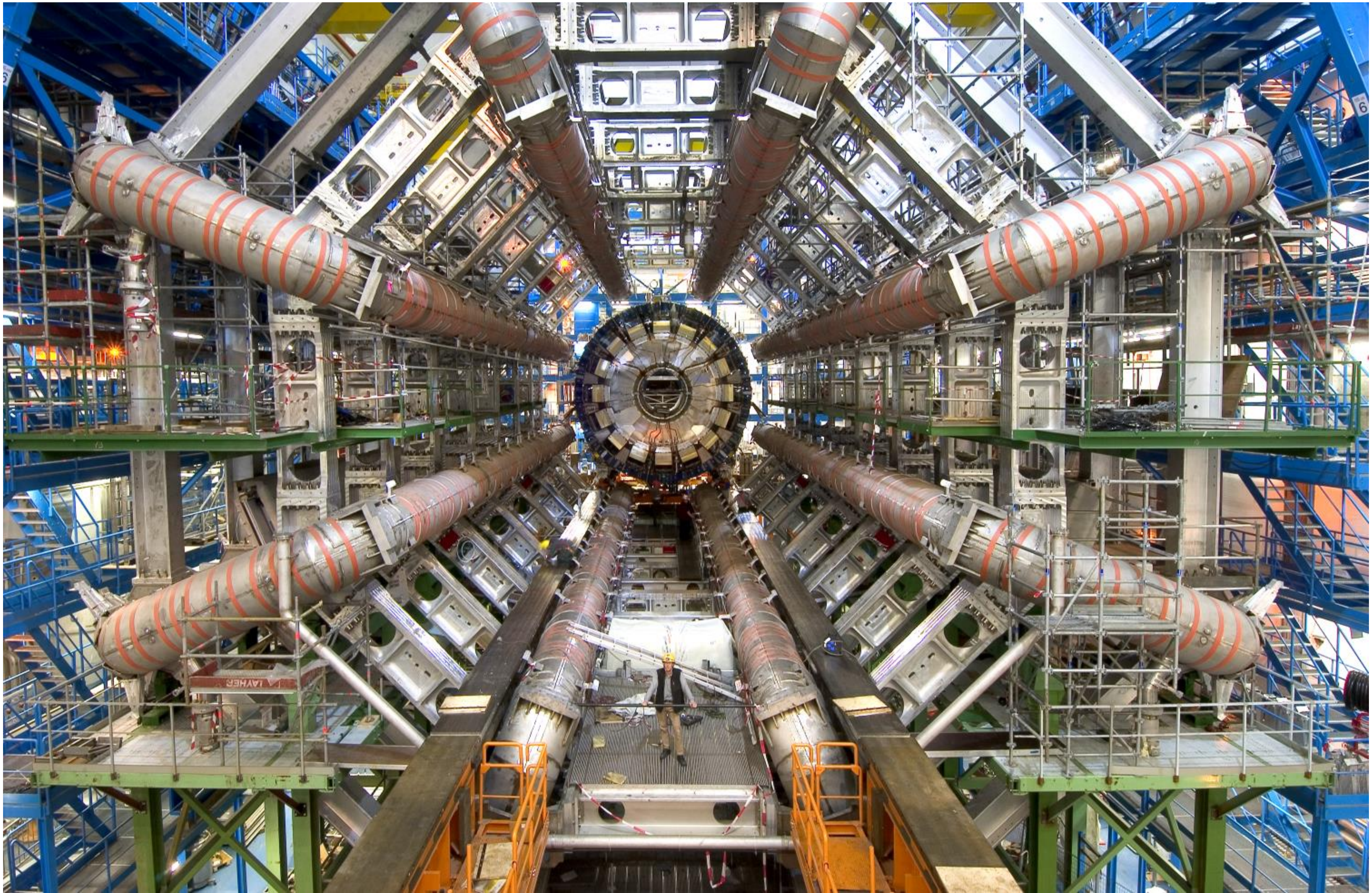
B = 4 T

I = 19500 A

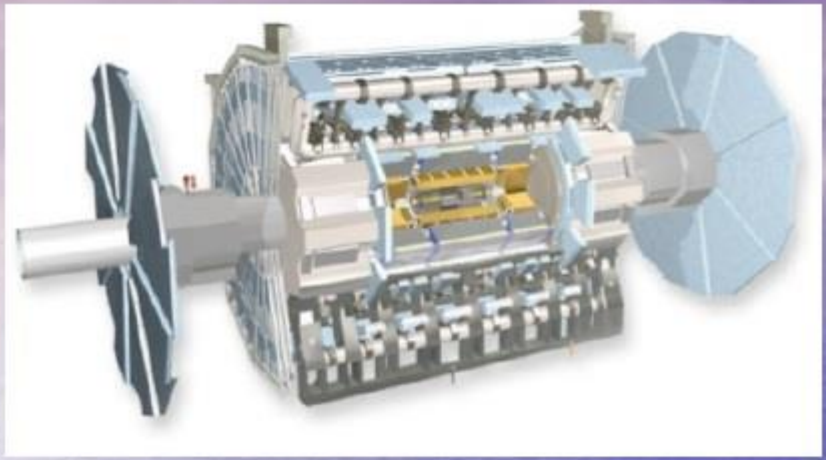
Stored energy
E = 2.3 GJ
(half-a-tonne of TNT equivalent)

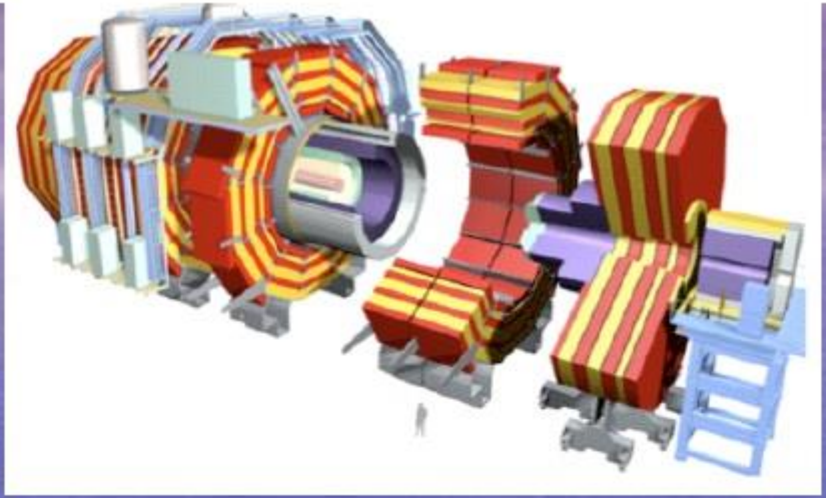
ATLAS muon spectrometer

ATLAS toroid coils – they are huge and produce the toroidal magnetic field of the muon spectrometer



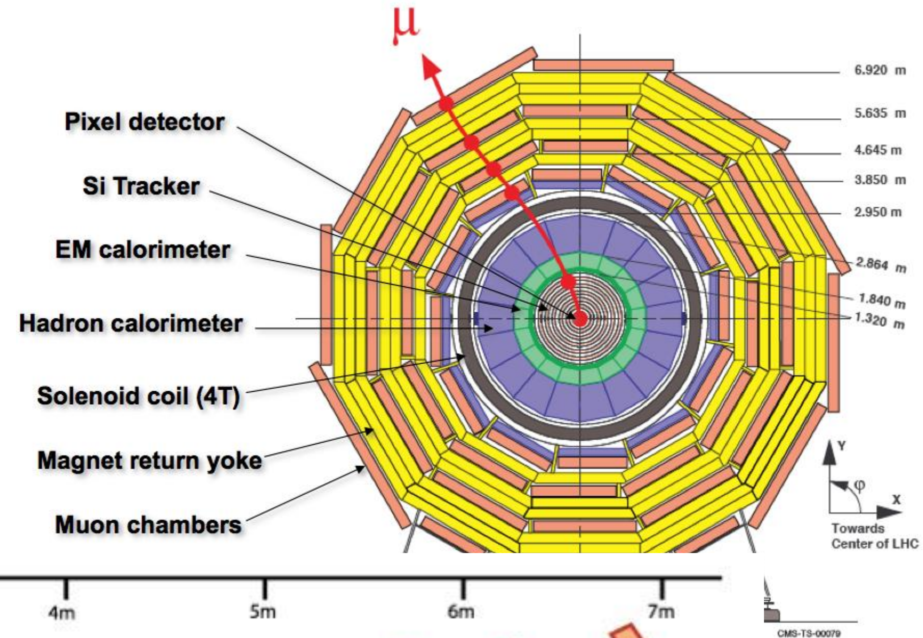
ATLAS and CMS subdetctor design parameters

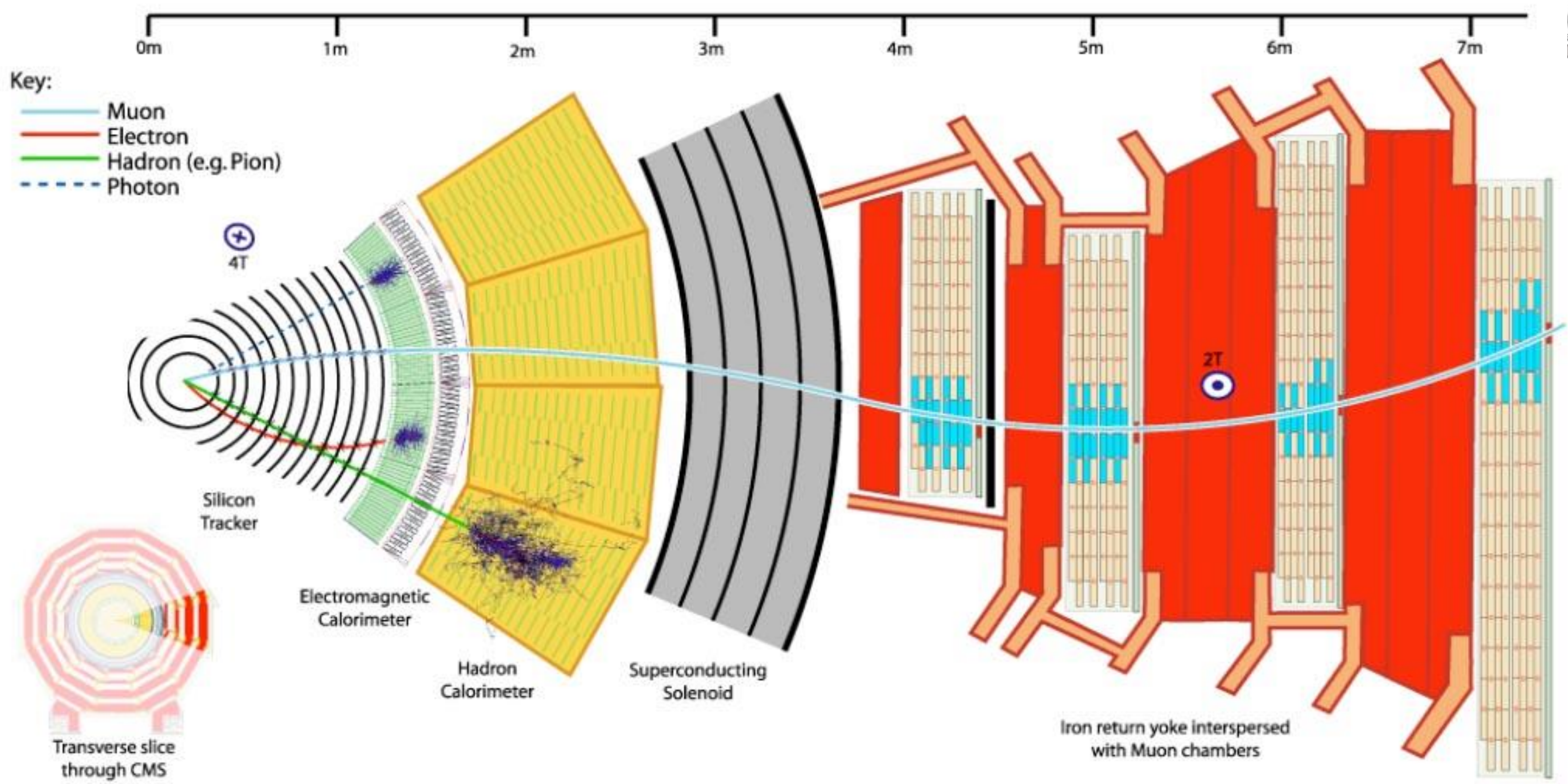




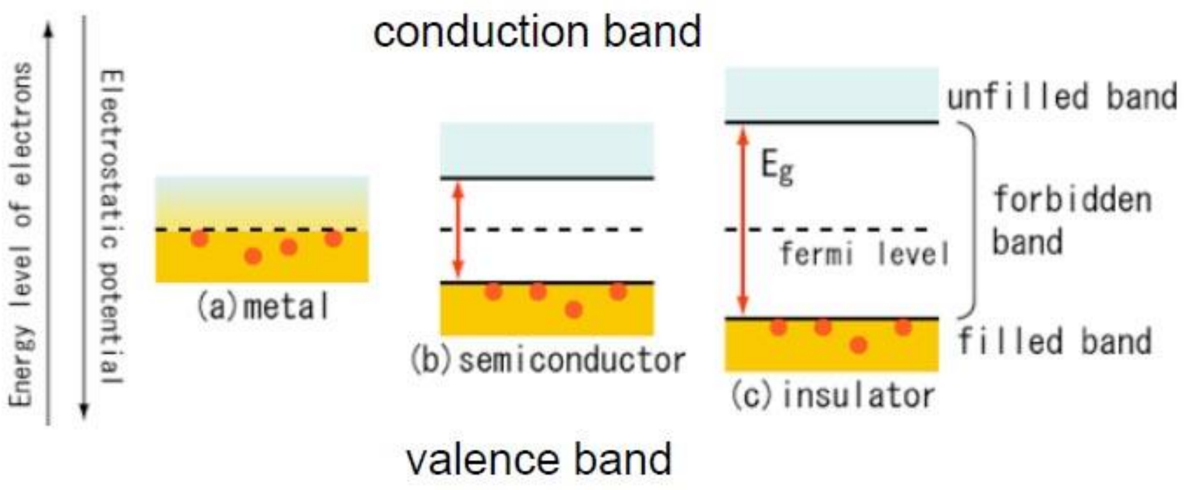
	ATLAS	CMS
Tracker	|η|<2.5 coverage $\sigma / p_T \approx 5 \cdot 10^{-5} p_T \oplus 0.01$ [GeV]	|η|<2.6 coverage $\sigma / p_T \approx 1.5 \cdot 10^{-5} p_T \oplus 0.005$
EM Calorimeter	|η|<4.9 coverage $\sigma / E \approx 10\% / \sqrt{E}$ [GeV]	|η|<4.9 coverage $\sigma / E \approx 2-5\% / \sqrt{E}$
HAD Calorimeter	|η|<4.9 coverage $\sigma / E \approx 50\% / \sqrt{E} \oplus 0.03$ [GeV]	|η|<4.9 coverage $\sigma / E \approx 100\% / \sqrt{E} \oplus 0.05$
Muon Spectrometer	|η|<2.7 coverage: $\sigma / p_T \approx 0.07$ *(1TeV muons)*	|η|<2.6 coverage: $\sigma / p_T \approx 0.10$ *(1TeV muons)*

Where and how do we see the particles?





Principle of semiconductor detectors



- Large gap: the solid is an insulator.
- No gap: it is a conductor.
- Small band gap: semiconductor

- For silicon, the band gap is 1.1 eV, but it takes 3.6 eV to ionize an atom. The rest of the energy goes to phonon exitations (heat).

Principle of semiconductor detectors

Silicon can be doped with donors of electrons (e.g. Phosphorus, group V) creating n-type semiconductor

Donors introduce energy levels near the conduction band, almost fully ionized

Electrons are the major carriers

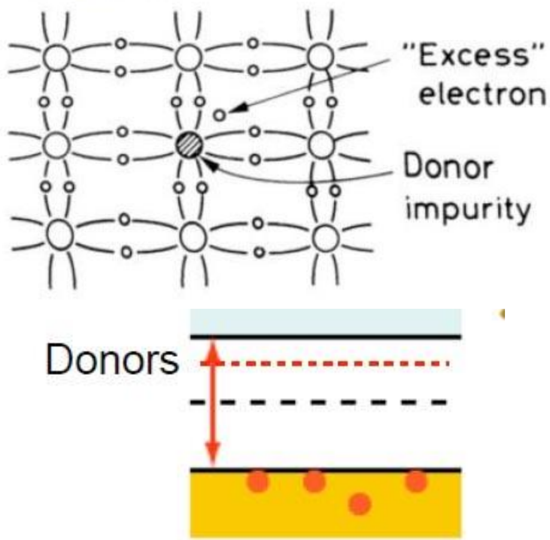
Or

Silicon can be doped with acceptors of electrons (e.g. Boron, group III) creating p-type semiconductor

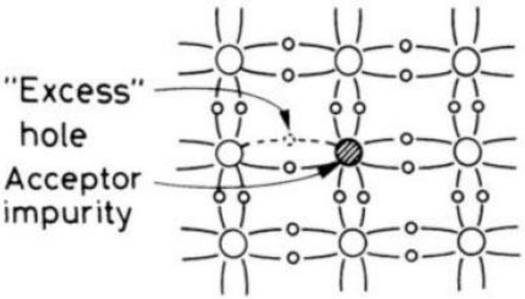
Acceptors introduce energy levels close to valence band 'absorbing' electrons from it, creating holes

Holes are the major carriers

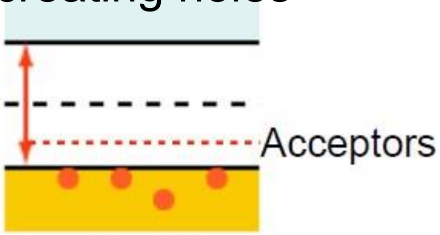
n-doping



(b) semiconductor



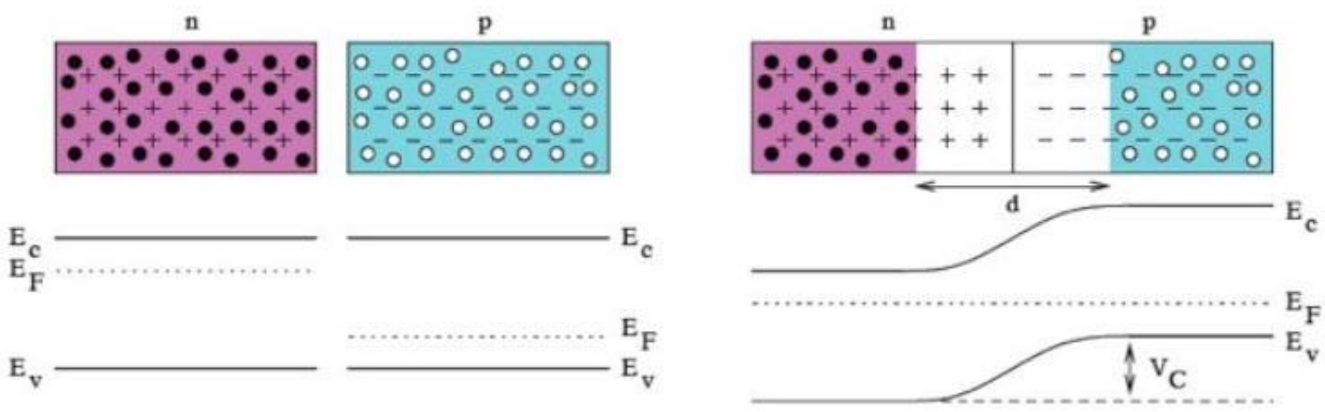
p-doping



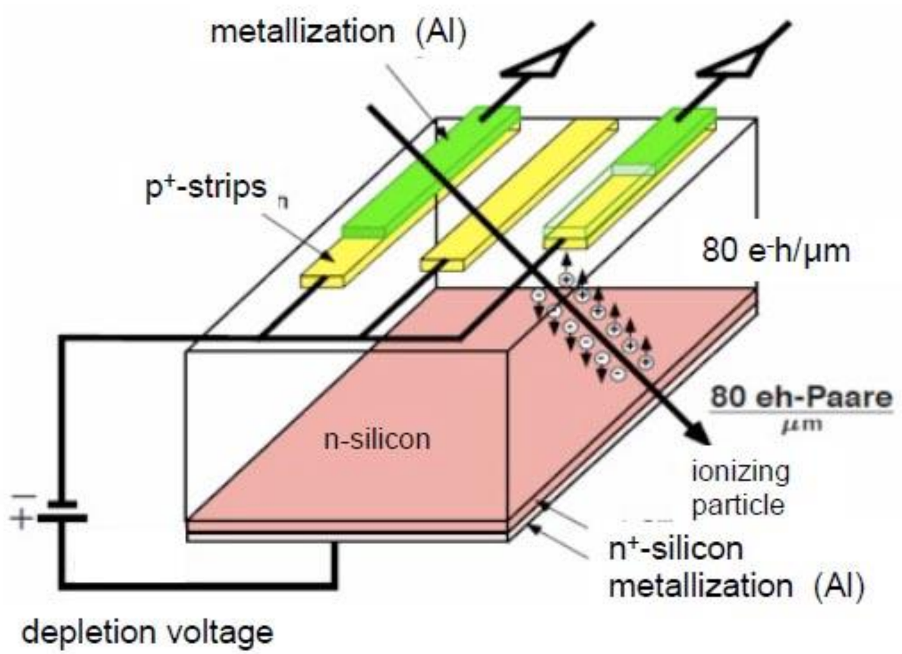
(b) semiconductor

Semiconductors p-n junction

- p- and n-doted semiconductor combined
- Gradient of electron and hole densities results in a diffuse migration of majority carriers across the junction.
- Migration leaves a region of net charge of opposite sign on each side, called the depletion region (depleted of charge carriers).



Semiconductor strip detectors



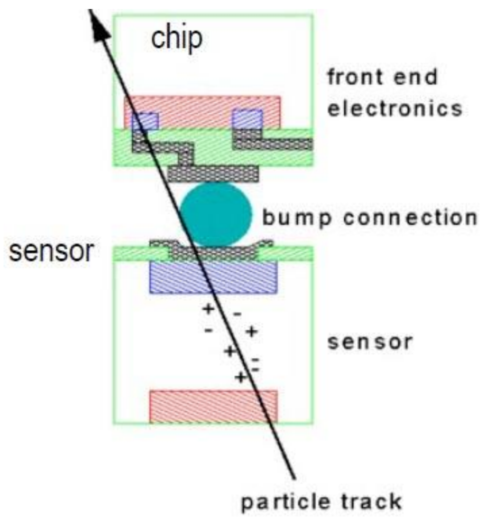
If the number of particles arriving simultaneously to the detector is small, using strips (in 2 perpendicular directions) allows to know where the particles cross the detector

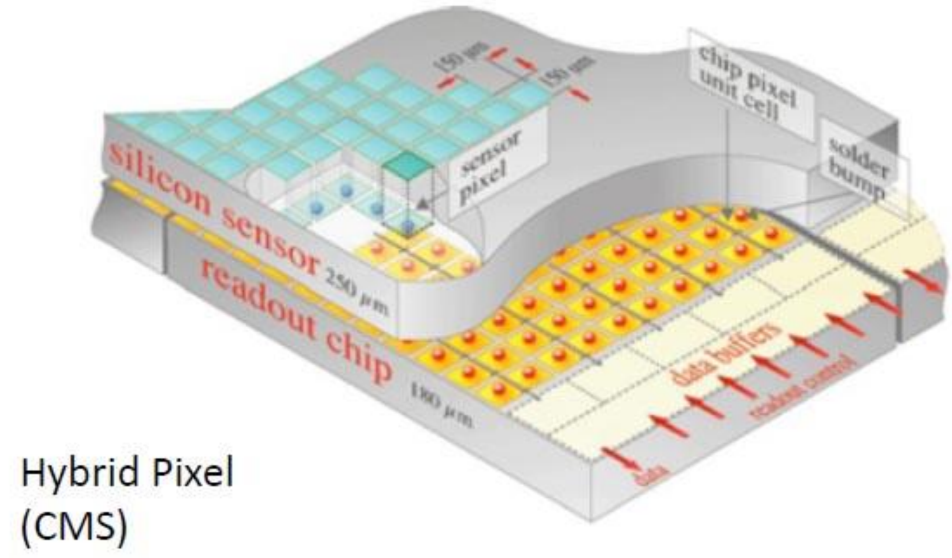
ATLAS SCT has 7 million channels with 10 μm precision

CMS strip detector has 10 million channels

In case of high particle fluences, ambiguities cause difficulties in the tracks reconstruction, another kind of detector (pixels) is needed

Semiconductor pixel detectors





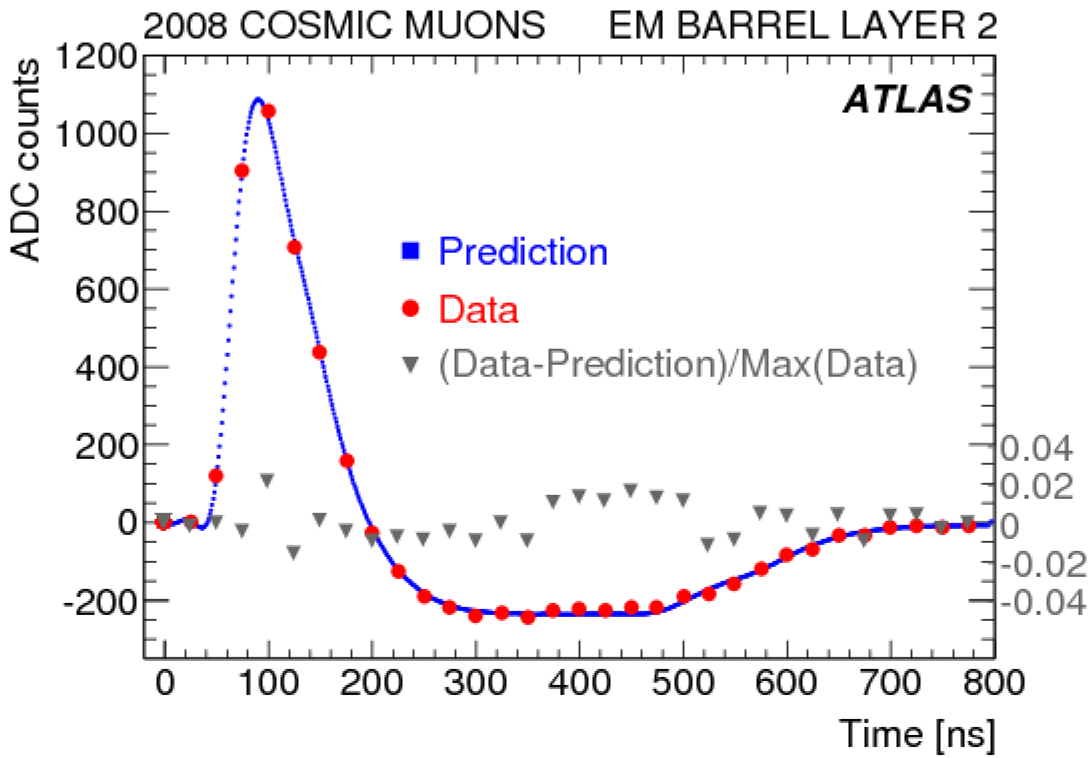
ATLAS pixel has 80 million channels – readout is complex

Readout chip mounted on top of pixels – defines the size of the pixel (50 x 400 μm)

CMS pixel has 66 million channels, size 100 x 150 μm

Pixel detectors allow track reconstruction at high particle rate without ambiguities

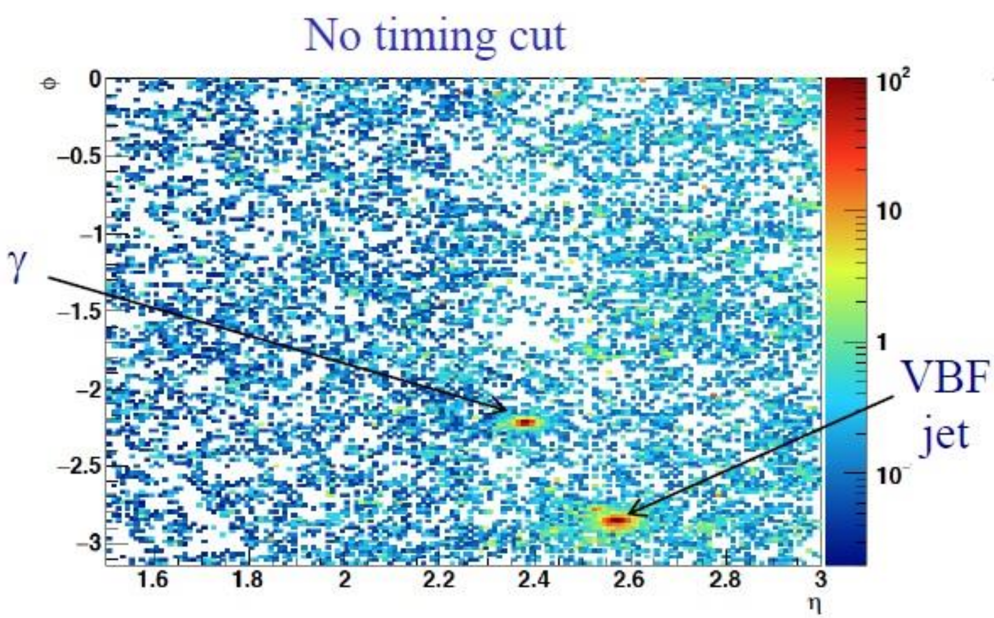
ATLAS Liquid Argon e.m. calo

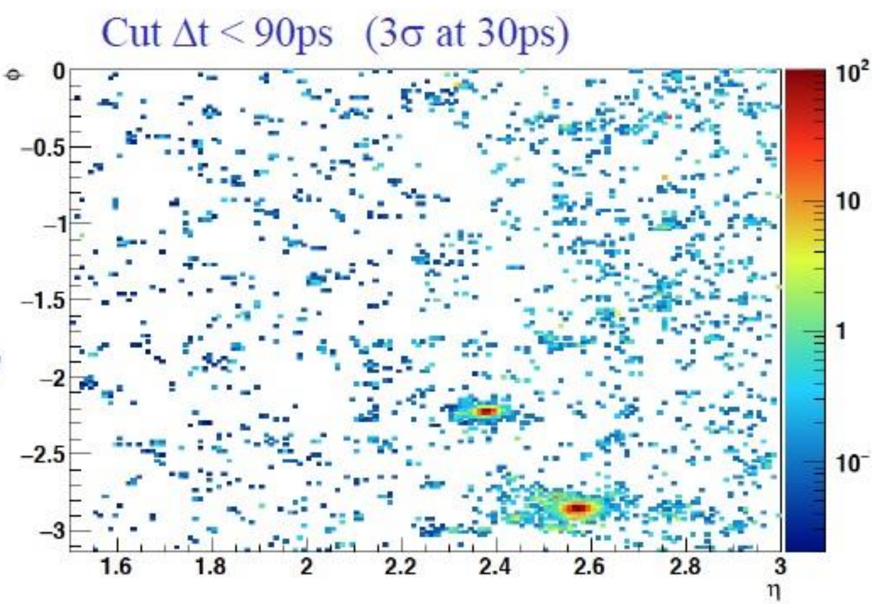


Larg calo response is relatively slow
ATLAS LArg calorimeter uses bipolar shaping

Remember that LHC collisions happen every 25 ns

Timing to help in pile-up rejection





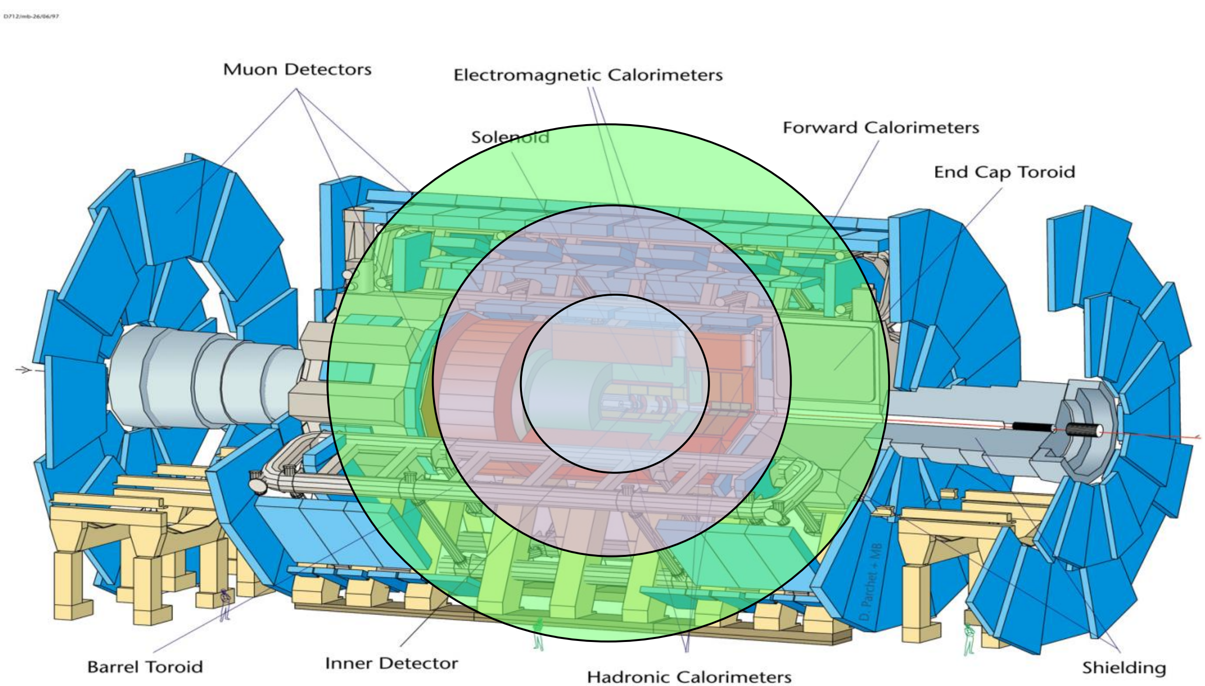
If the timing precision is of the order of ps then pile-up coming from different times during the bunch crossings can be removed

Timing alignment

When particles are leaving the detector at the speed of light there were already a few more collisions at the center of the detector.

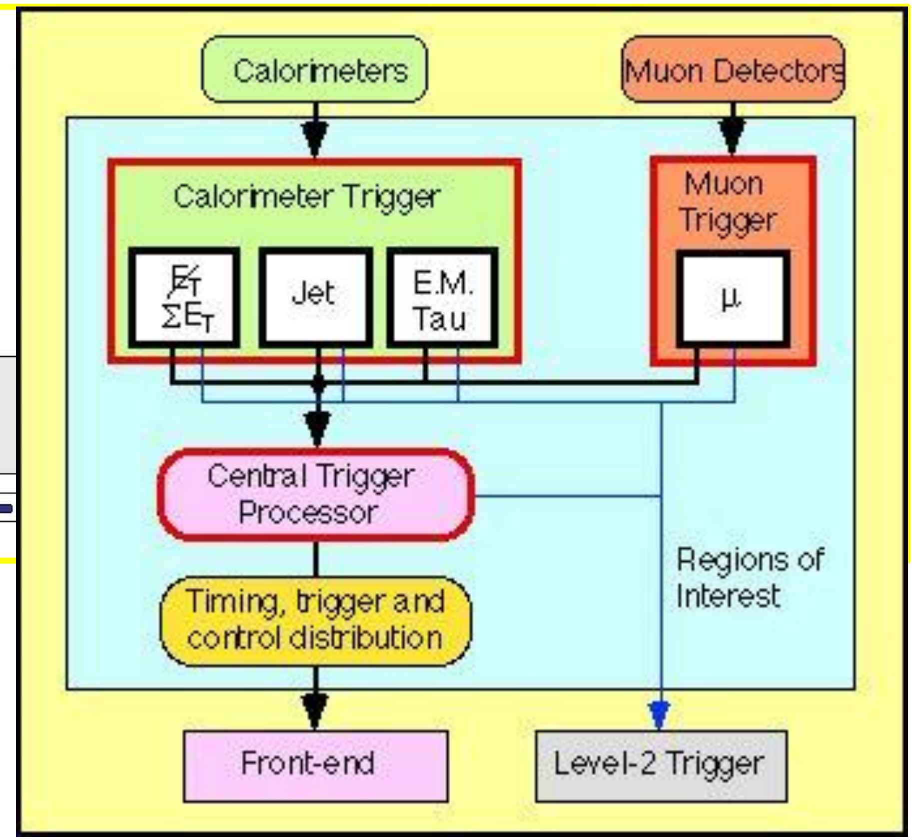
Correct timing in the event is crucial for trigger and offline analysis

c=30cm/ns; in 25ns, s=7.5m



ATLAS Level 1 architecture

Level 1 uses calorimeter and muon systems only to decide in 2.5 μs



Muon spectrometer:

- Dedicated trigger chambers
  - Thin Gap Chambers (endcap) – TGC
  - Resistive Plate Chambers (barrel) – CSC

Calorimeter:

- Trigger towers group calorimeter cells in coarse granularity: $\Delta\eta\times\Delta\varphi = 0.1\times0.1$ (EM/Tau); $\Delta\eta\times\Delta\varphi = 0.2\times0.2$ (Jets)

Identify regions of interest (RoI) and classify them as MU, EM/Tau, Jet

Relevant information is passed to Level 2 / High Level Trigger (in Run 1 / Run 2) where much more detector information is available for decision