Challenges

Basics
- Magnet
- Tracking
- Calorimetry
- Muons
- Particle ID

CMS Design

CMS Detectors
- Tracker
- ECAL
- HCAL
- Solenoid
- MUON
- Triggering

Installation

Collaboration

Higgs → γγ

Status

The CMS Detector

Exploring Nature at its smallest scales

Dave Barney, CERN

CMS Detector Overview

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Higgs → $\gamma\gamma$

Status

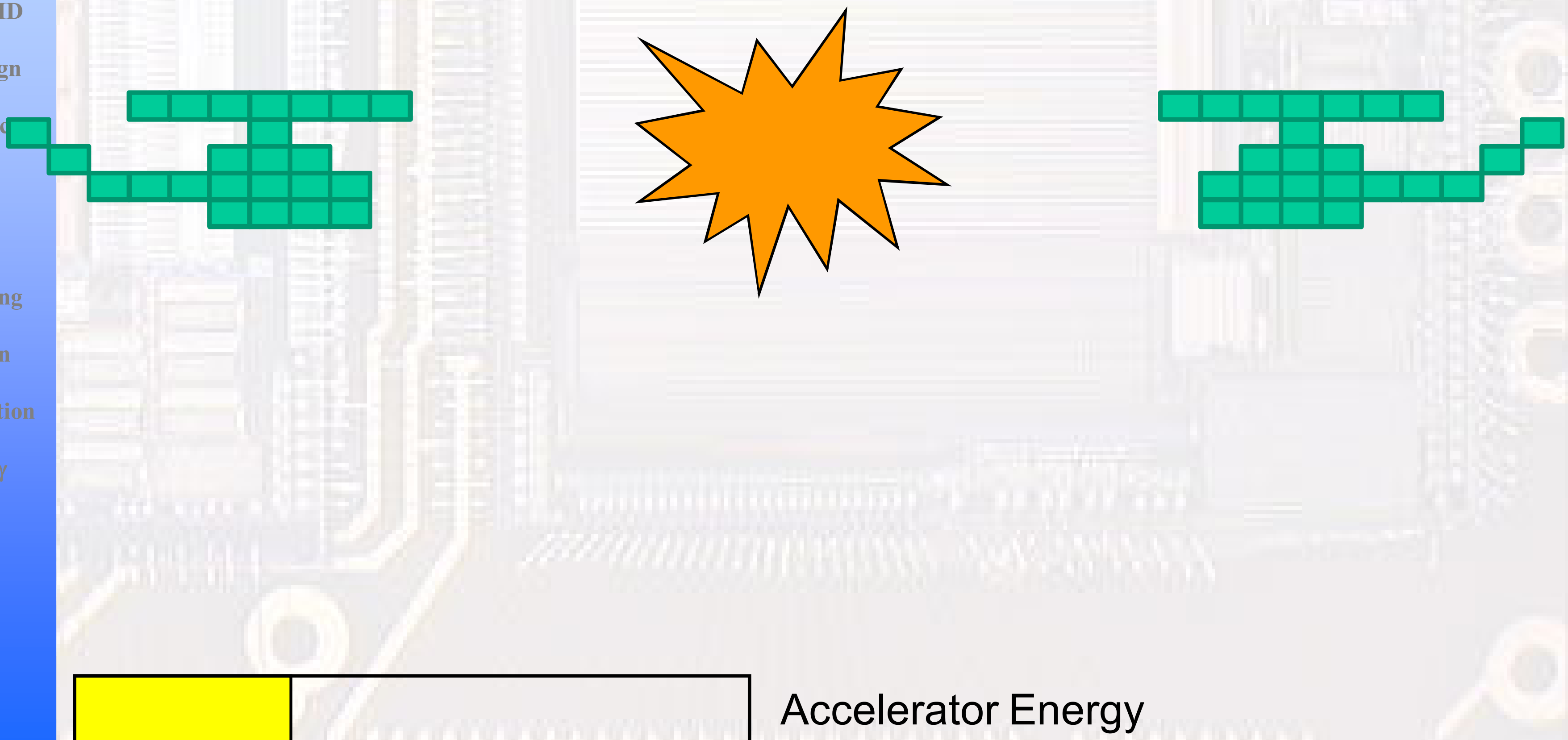
- **Personal Background**
- **Challenges of modern particle detectors**
- **Detector basics**
- **Design principles of the CMS detector**
- **The CMS sub-detectors**
- **Installation**
- **CMS Collaboration**
- **Example: discovering the Higgs boson!**
- **Status and prospects**

Personal Background

- **1987-1990: BSc Physics at Imperial College London**
- **1990-1993: PhD Particle Physics at Imperial College**
- **1993: CERN Fellow → staff – always working on the CMS detector**
  - Design (simulation) → prototyping → construction → assembly → testing → installation → **commissioning** → operation → performance
- **Currently: CMS Preshower Project Coordinator**
  CMS Outreach Coordinator

Digression (already!)

Animations prepared for 10-11 year olds


Accelerator Energy

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Accelerator Energy

$$E=mc^2$$

The collision energy was used
to create something new, that
did exist but does not any more!

Accelerator Energy

Challenges of Modern Detectors

What we do at CERN: Smash things together and see what happens!

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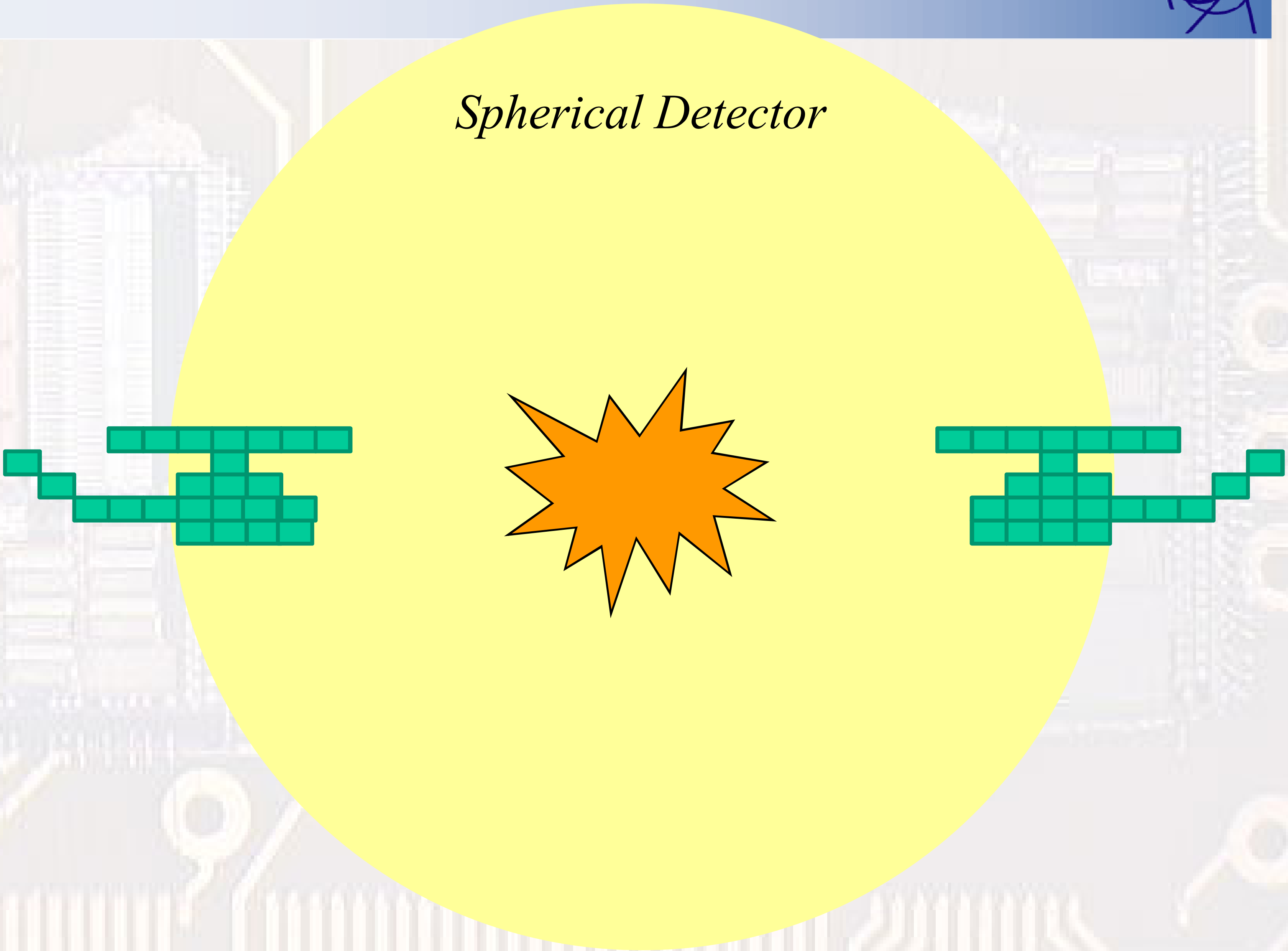
Spherical Detector



What does a particle detector need to do?

- **Need to determine:**
  - What particles do we see?
  - Where did they come from and where do they go?
  - What were their energies and momenta?
- **In order to understand:**
  - What happened in a collision between particles?
  - Has something interesting been created?

- **We don't really know what we are looking for!**
- **The "interesting" things we are looking for are very rare**
  - Like looking for a needle in a million haystacks
  - Need to make millions of collisions every second
  - Cannot use conventional photography
  - The interesting particles are also unstable…..

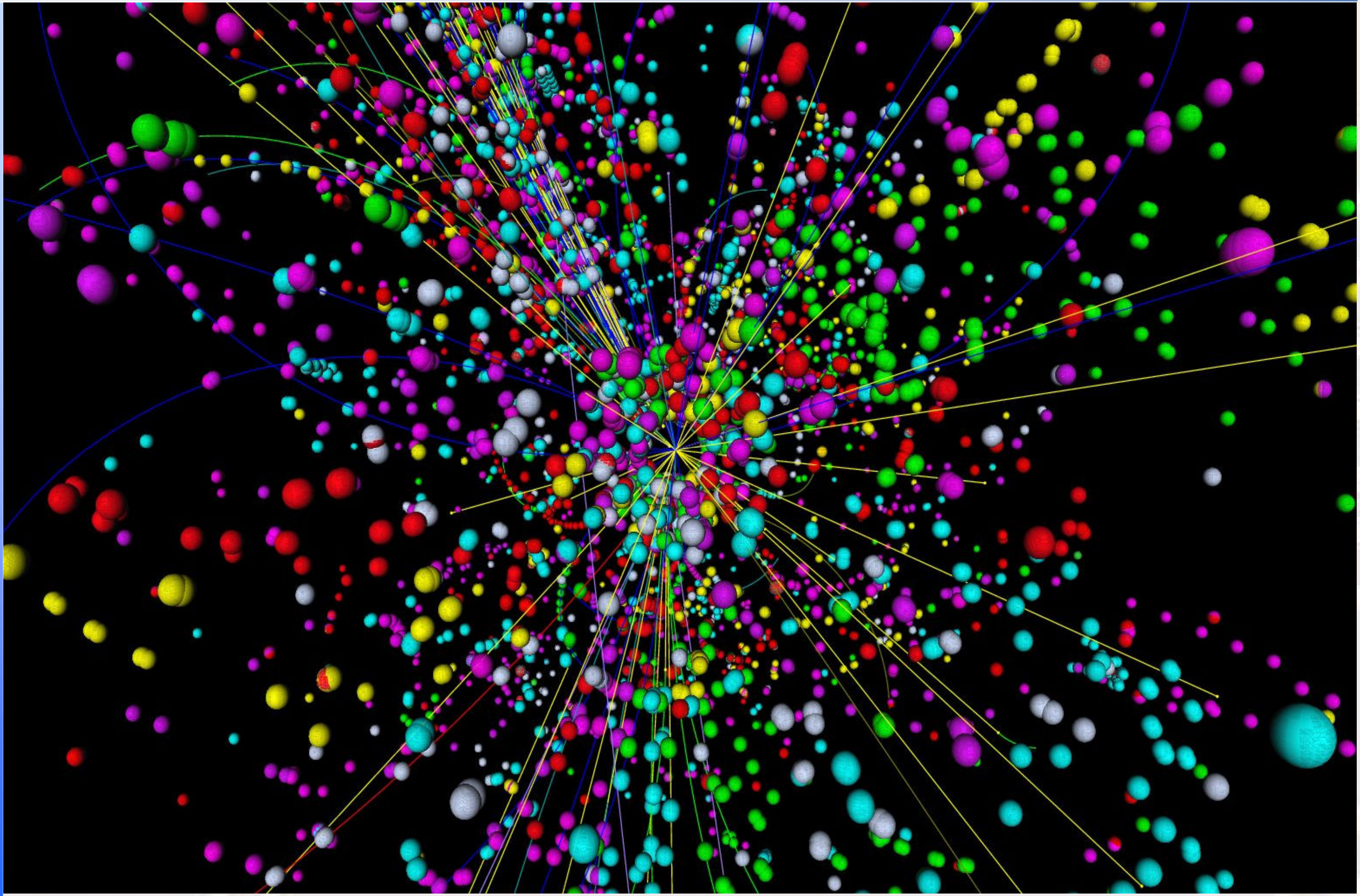
Unstable Interesting Particles

The interesting things (the dinosaurs!) disappear almost instantly. We "see" the resulting particles – so we have to be like detectives – look at the evidence to see what happened!

The challenges of modern detectors

- **Each collision produces many hundreds of particles**
- **The energies/momenta of the particles involved are huge**
  - The detectors are very complex and have many layers
  - They also need to be big! ***VERY BIG!!***

The challenges of modern detectors



Have to understand this sort of image 40 million times per second!

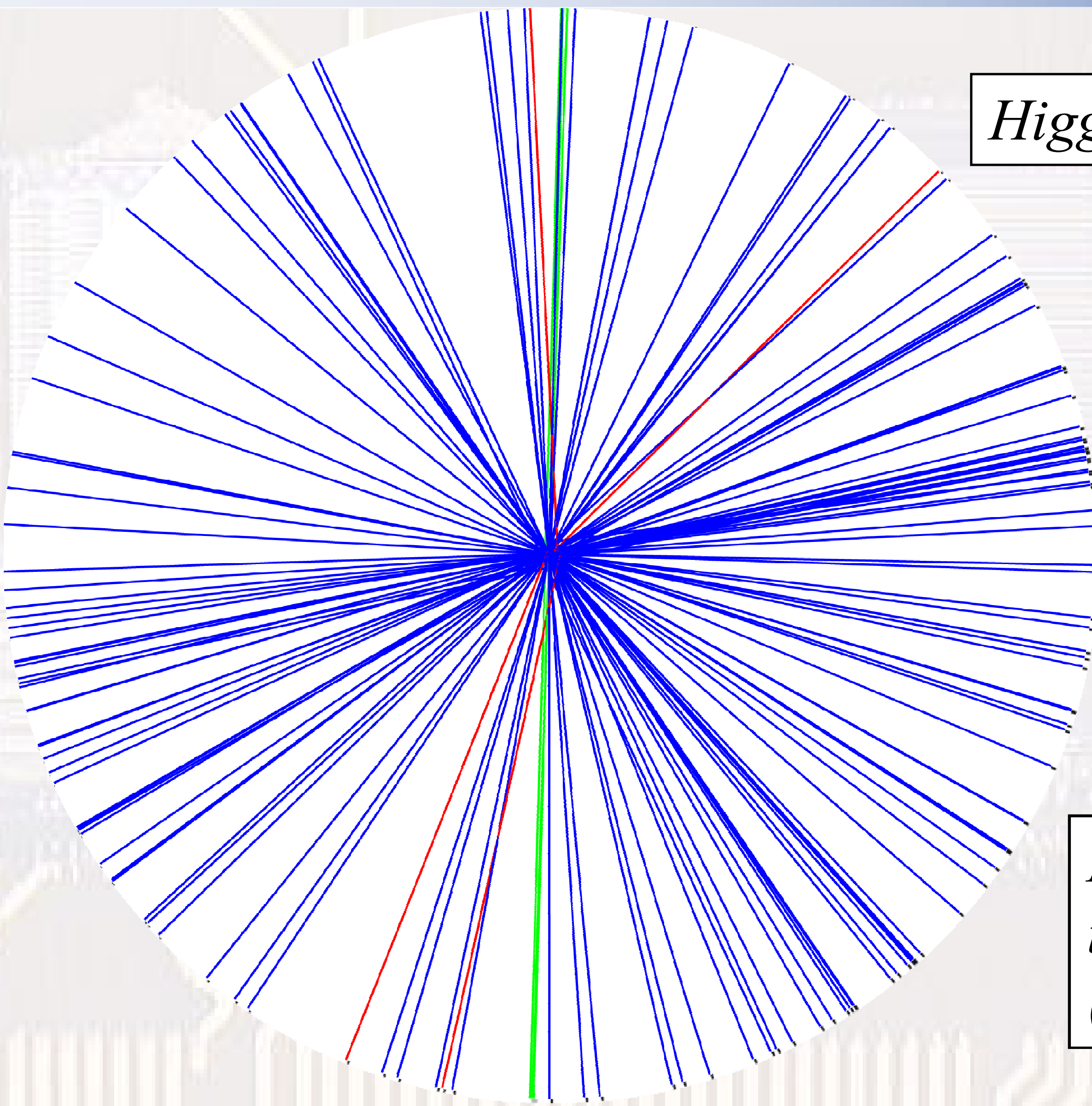
Challenging environment

- **Detectors and electronics have to withstand massive amounts of radiation**
  - Over ten years the accumulated dose is comparable to being in the middle of a nuclear bomb blast!
- **Operating temperatures may be very low (e.g. for silicon detectors) or need to be kept very stable (e.g. for calorimeters)**
- **Need to survive for >10 years with no intervention**

Detector Basics

- *The Magnet*
- *Tracking*
- *Calorimetry*
- *Muon Detectors*
- *Putting it all together*
  → *Particle identification*

A “simple” collision at LHC (simulation)



Higgs → 4 muons

Where are the muons? They are high momentum compared to the majority of the particles…

Red lines show the muons (cheating!)

Let's add a magnetic field!

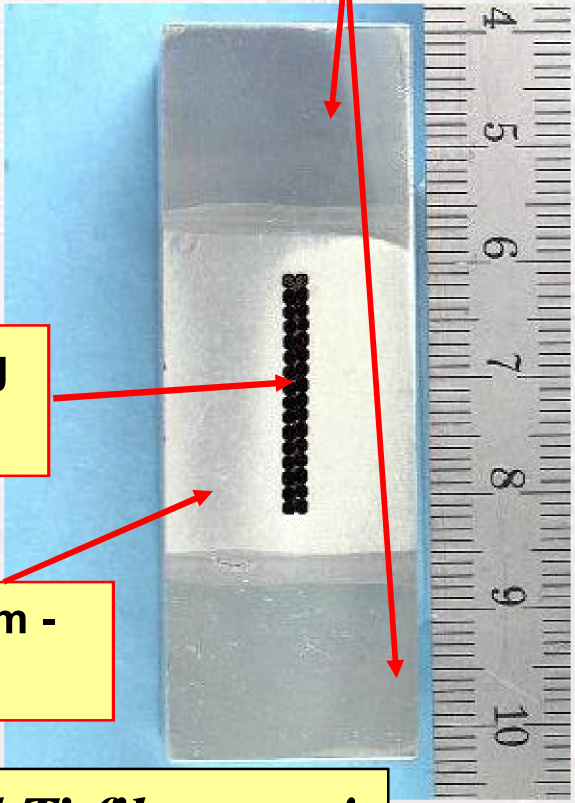
Charged particles bend in the magnetic field

The lower the particle momentum the more they bend

$R = p/0.3B$

Now the muons are clear!

- **B-field needs to be uniform and large (few teslas)**
- **Use superconductors**



CMS uses approx: 1 million km of NbTi filaments!

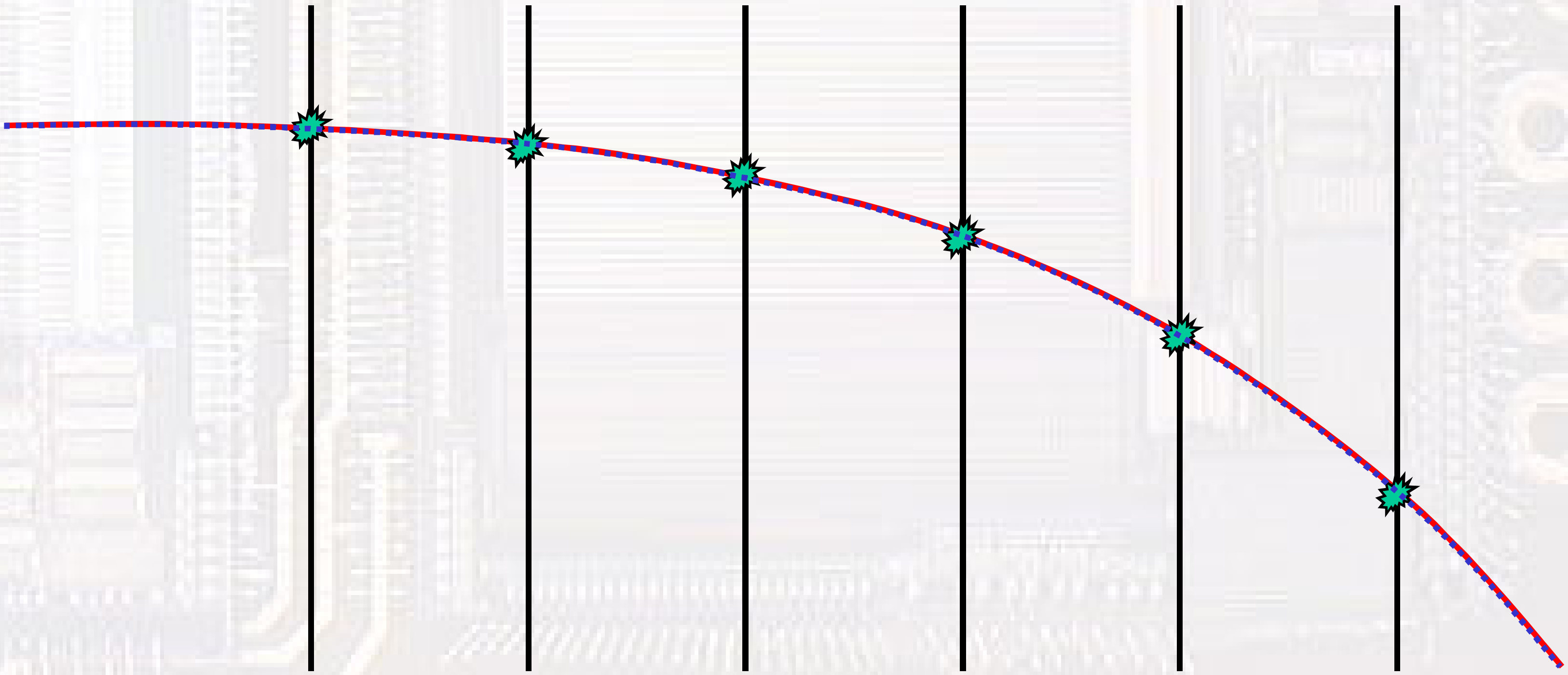
Tracking Detectors

To measure the direction and momenta of charged particles

Thin sensors: must not disturb the trajectories of the particles

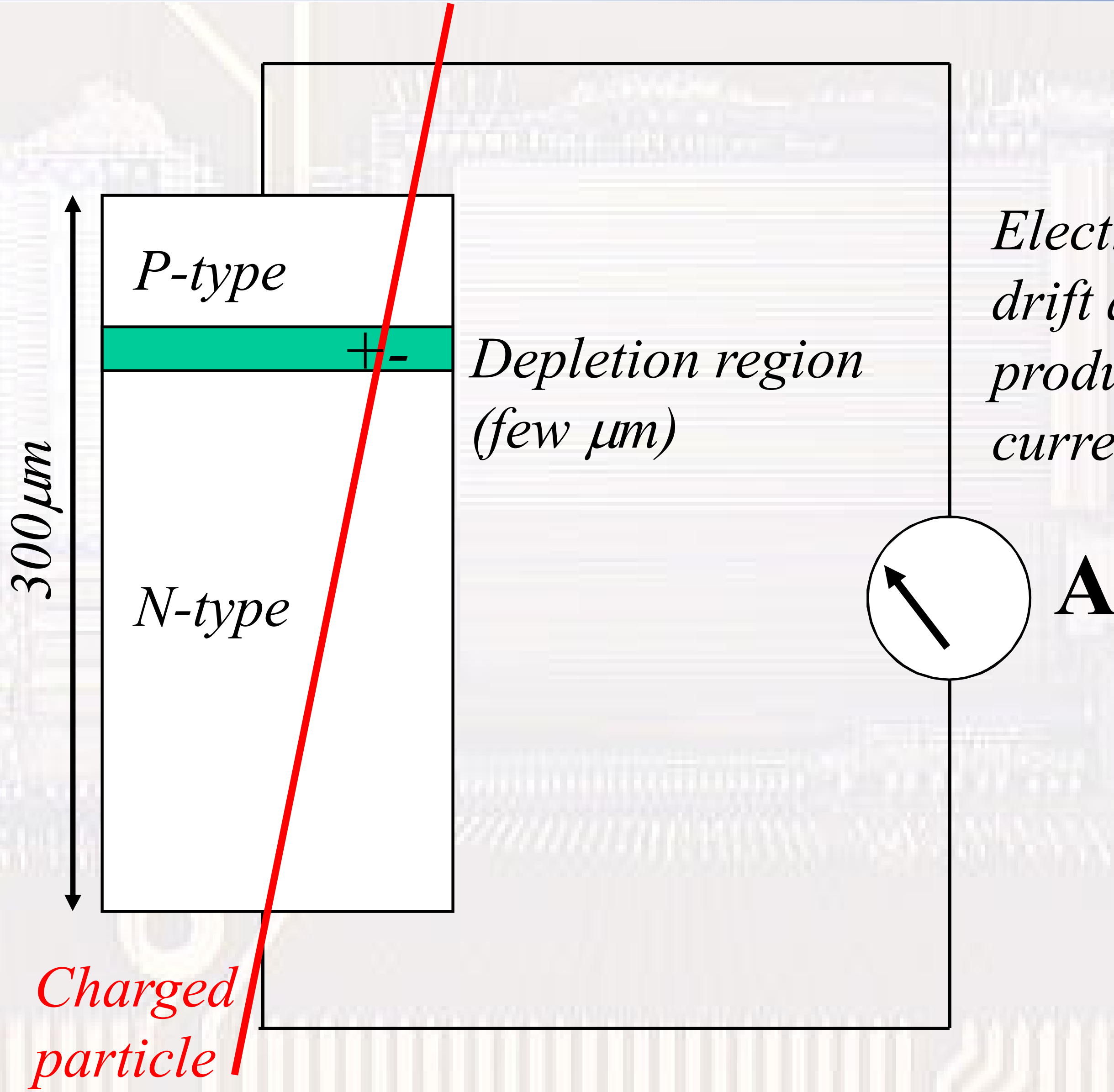
The tracker must be the first layer in a detector – closest to the interaction point

A basic "Tracker"

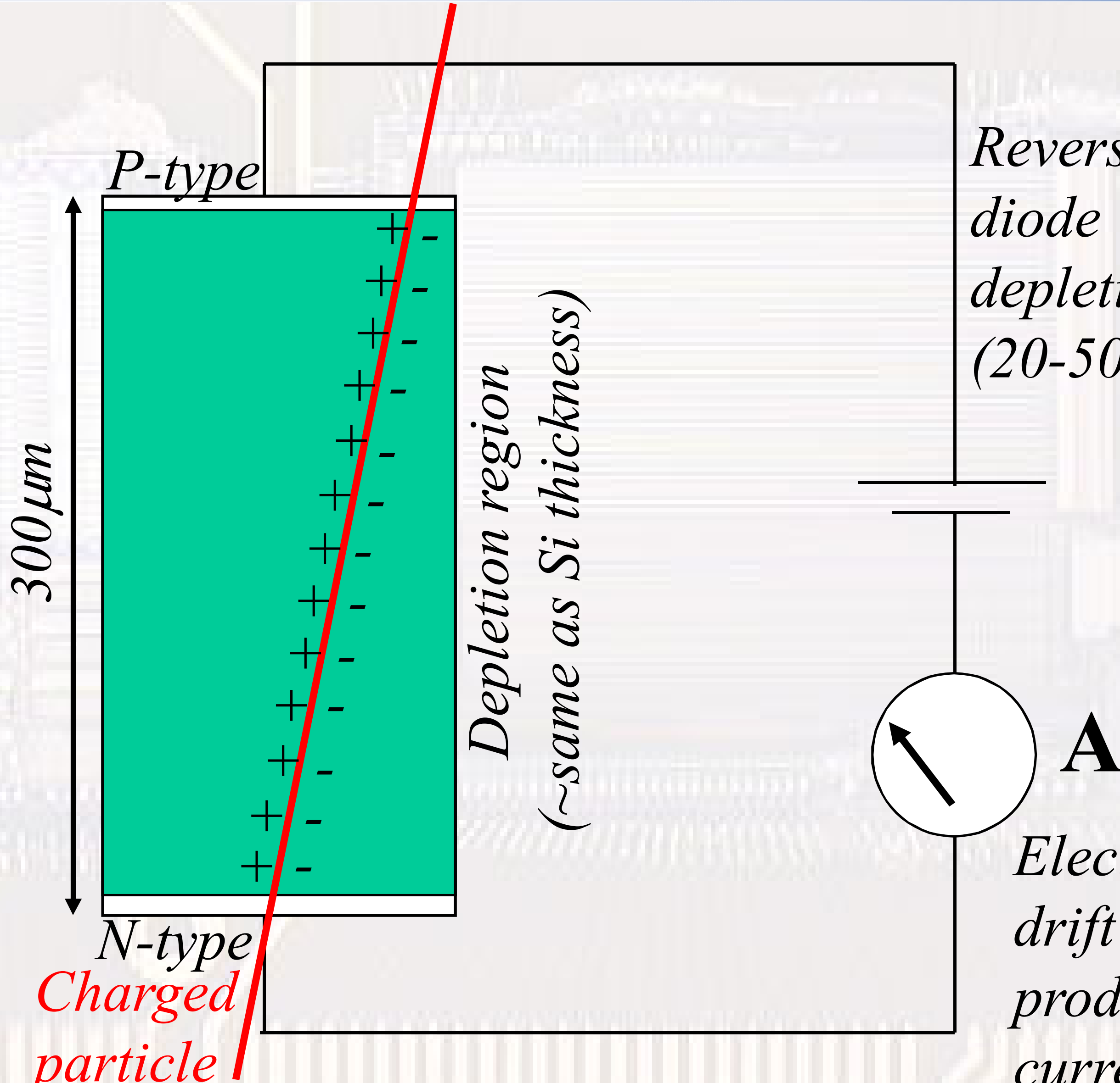


*Multiple thin layers of, for example, **silicon** sensors*

Silicon Sensors (1)



Electrons & holes drift apart and produce a small current

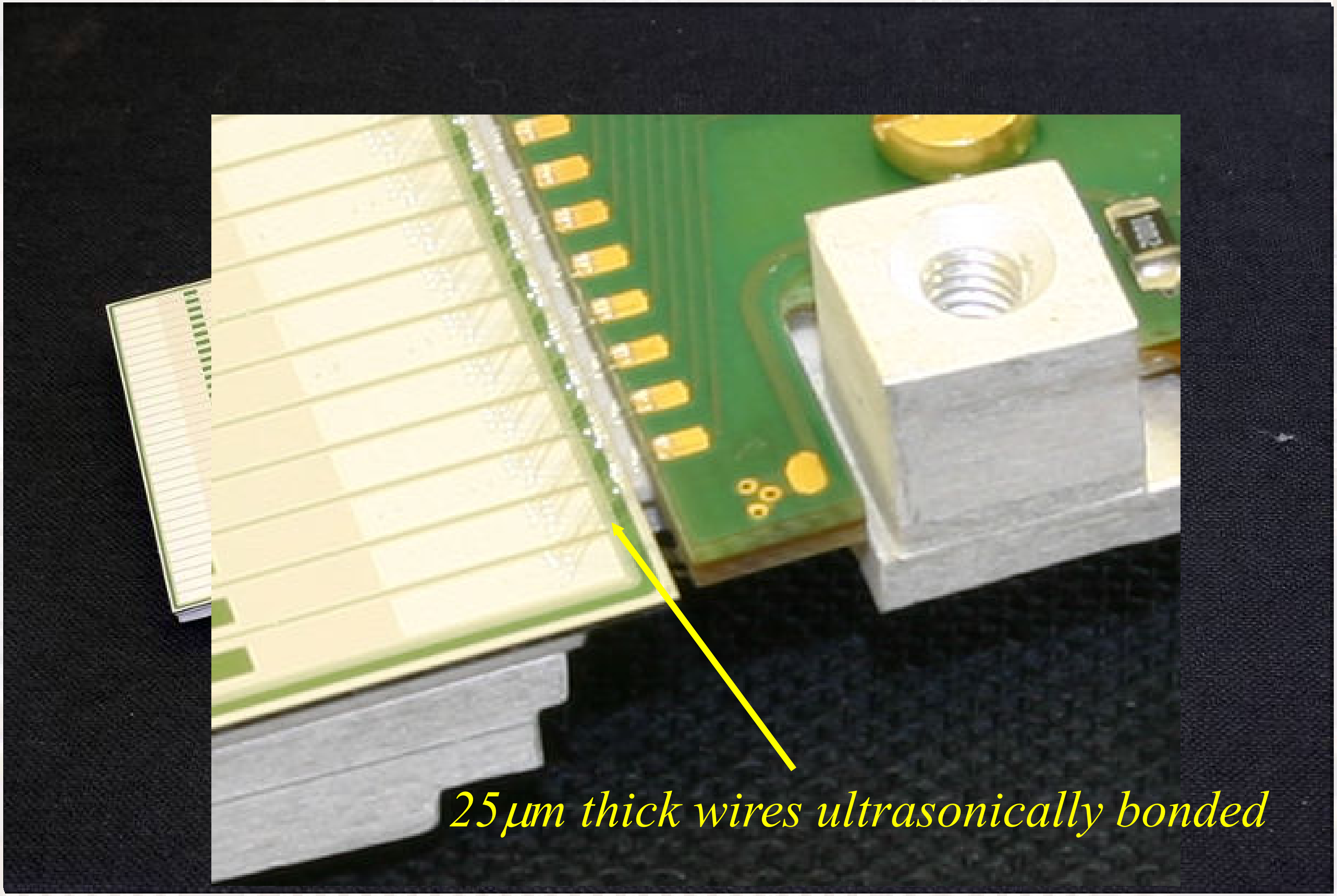


Reverse-biasing the diode "grows" the depletion region (20-500 V required)

*Electrons & holes drift apart and produce a **large** current*

Example Silicon Detector Construction

300μm thick Silicon sensor divided into 2mm-wide strips



Calorimeters

To measure the energies of different types of particle

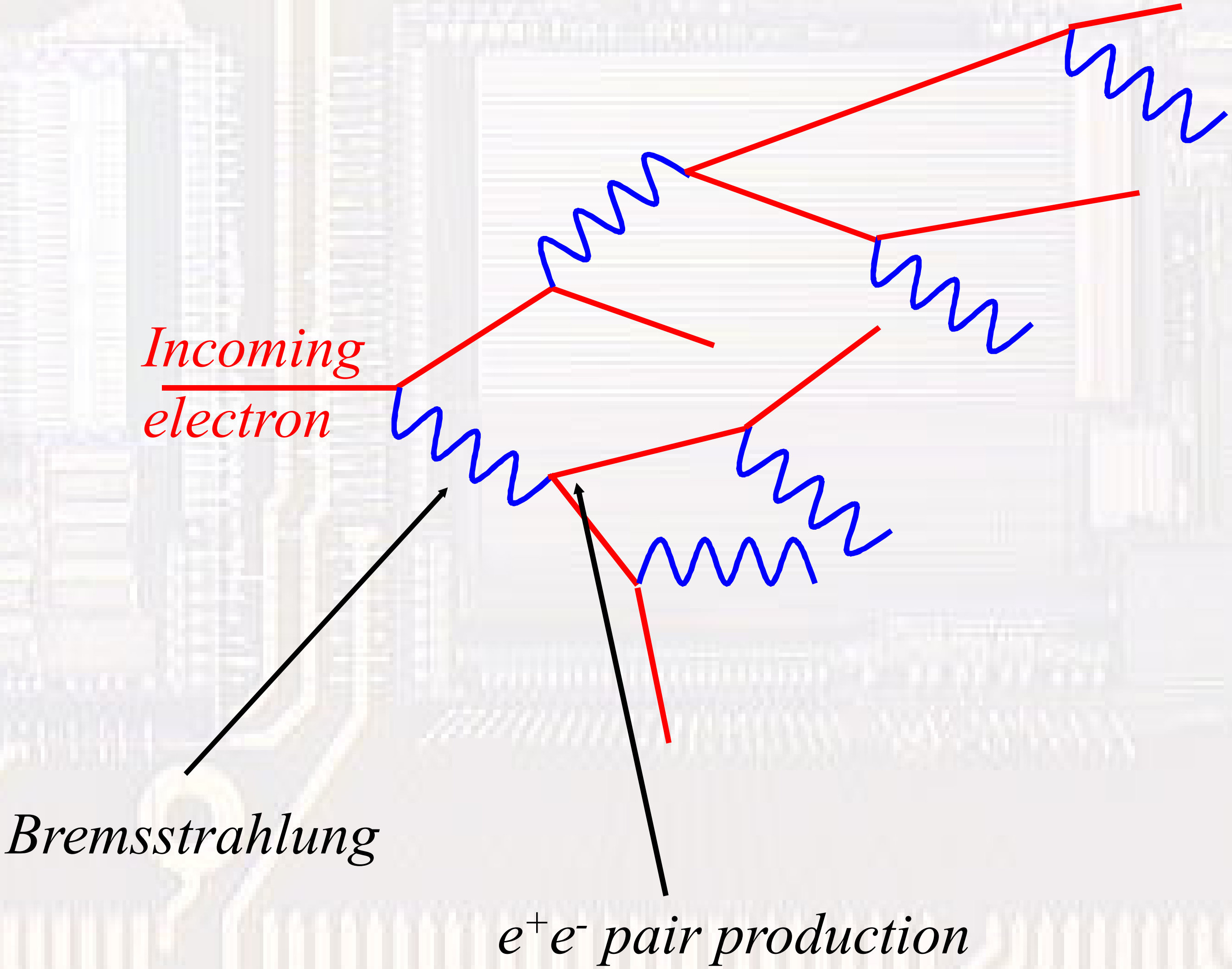
Electromagnetic Calorimeters – sensitive to photons, electrons, positrons

Hadronic Calorimeters – sensitive to “hadrons” (particles containing quarks) such as protons, neutrons, pions etc.

The calorimeters “stop” the incoming particles so must go outside of the “tracker”

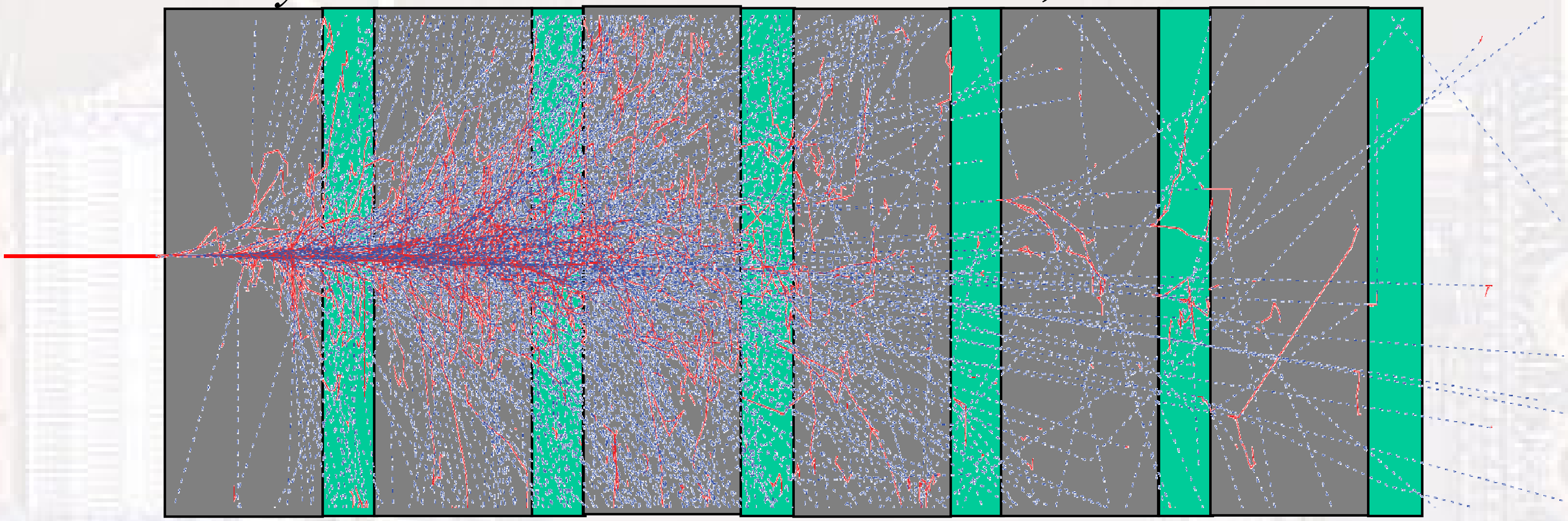
Calorimeters: “Shower production”

In a dense medium….



Calorimeters: A basic "sampling" calorimeter

Grey materials are dense and inert, such as lead

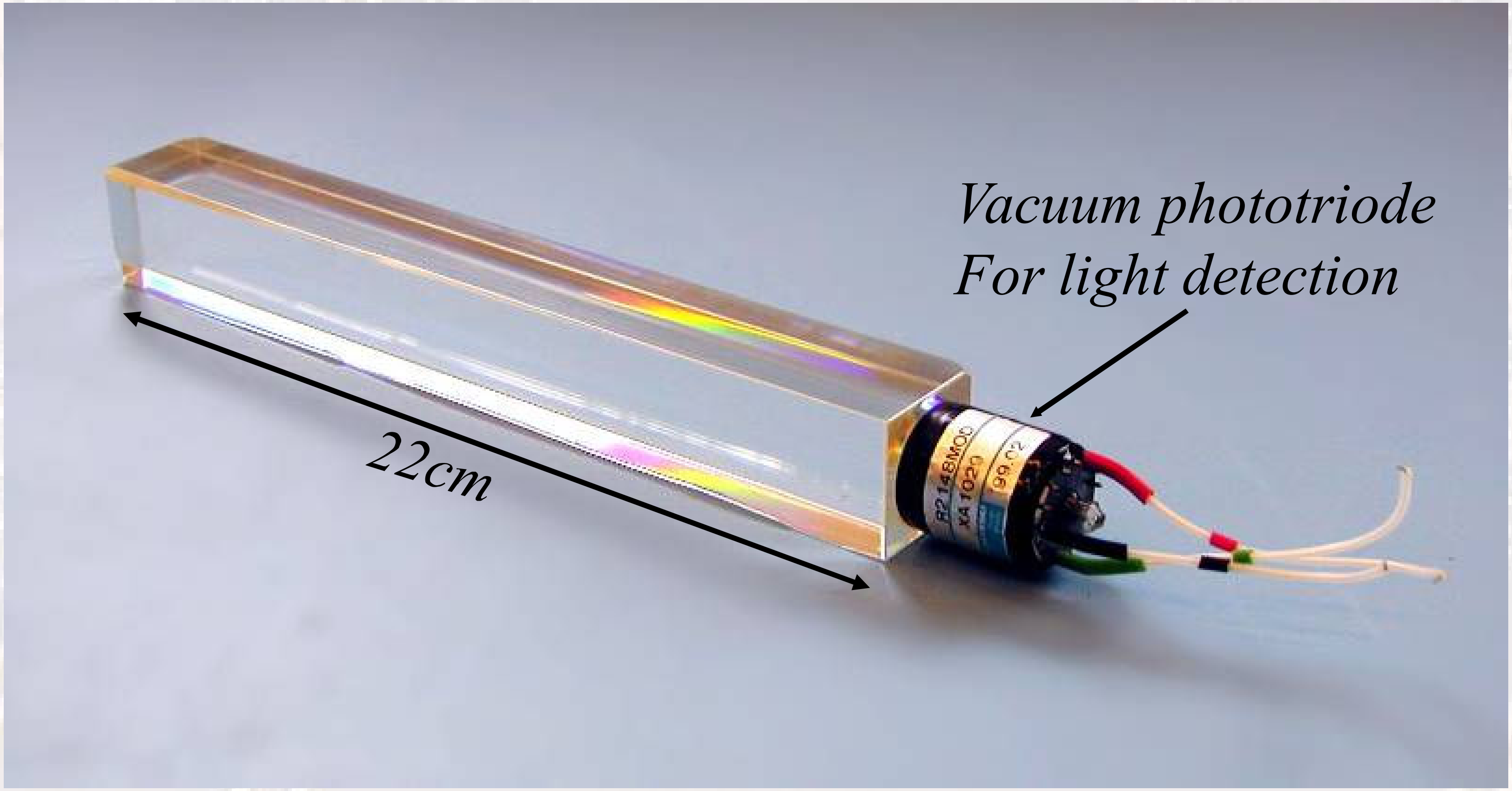


Total # of particles in the shower proportional to energy of incoming particle

Light materials (green) produce a signal proportional to the number of charged particles traversing the layer. This signal can be from ionization, scintillation or Cerenkov light production

Alternative: Homogeneous calorimeter – single substance to produce shower and ionization/light

- **One dense substance – $PbWO_4$ - produces the shower and scintillation light**



Muon Detectors

Specifically to detect Muons

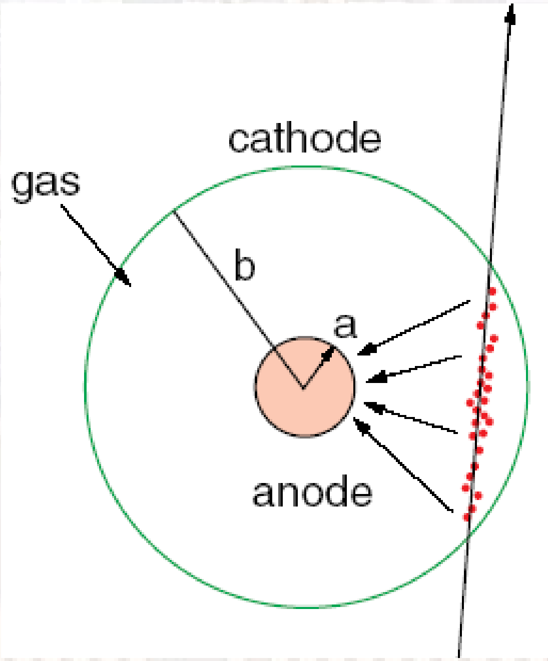
Only charged particles to travel all the way through the calorimeters are Muons (~heavy electrons)

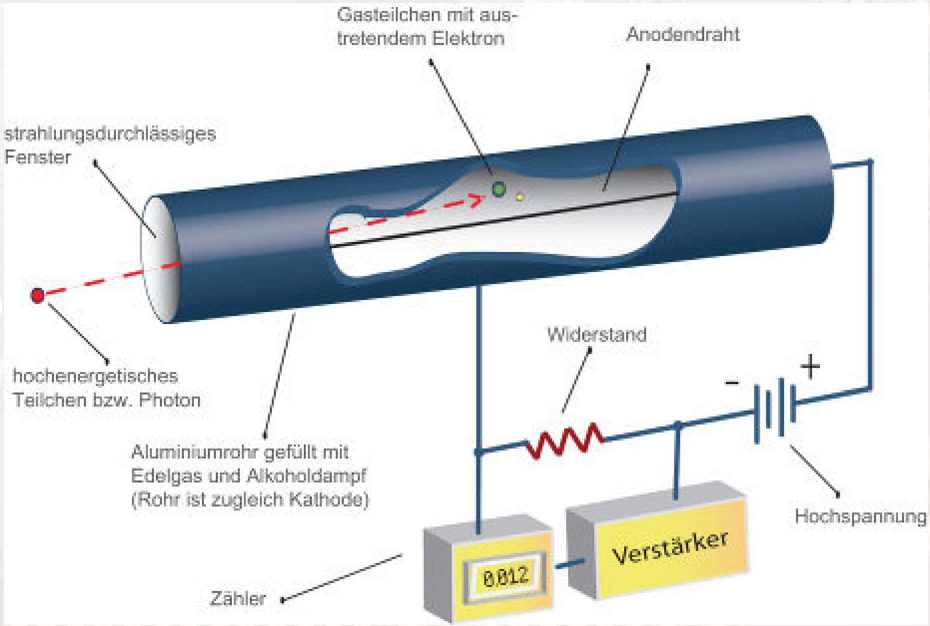
If we see any signal in these detectors we ~know that it is due to a passing Muon

Muons signify that something **interesting** has happened (e.g. production of a Higgs boson!)

Muon Detectors

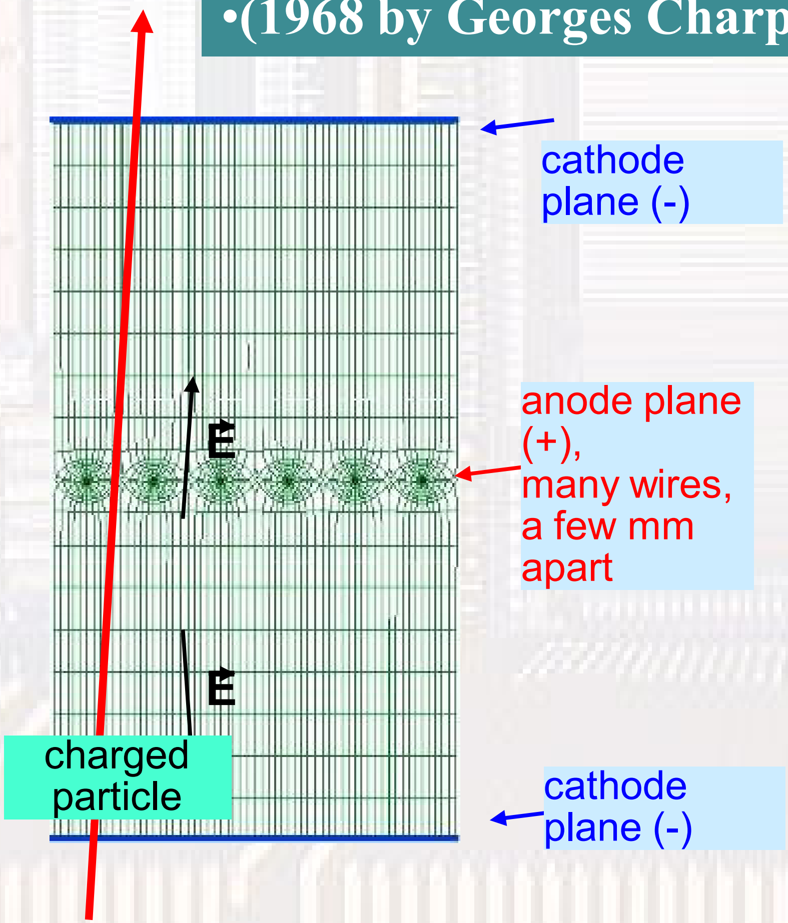
- **Could, in principle, use any detector sensitive to the passage of charged particles**
- **Need to cover a large surface area**
  - Silicon too expensive
  - Use, for example, “wire chambers” like G-M tubes





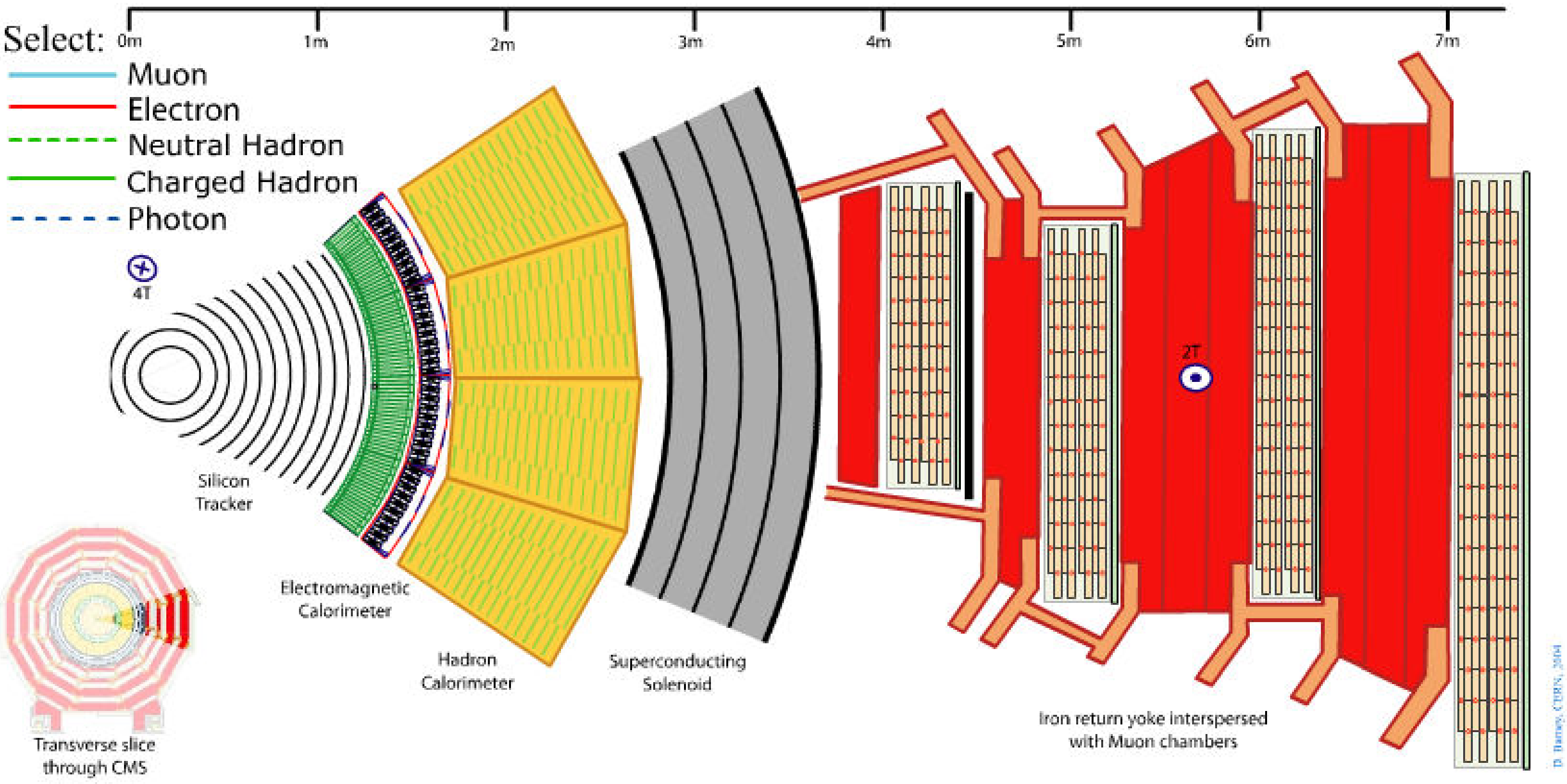
Muon Detectors: MWPC

- Geiger-Müller tube just good for single tracks with limited precision (no position information)
- Multi Wire Proportional Chamber (MWPC)
- (1968 by Georges Charpak, Nobel Prize 1992)



Large Area Muon Detector

Particle Identification



Design Principles of the CMS Detector

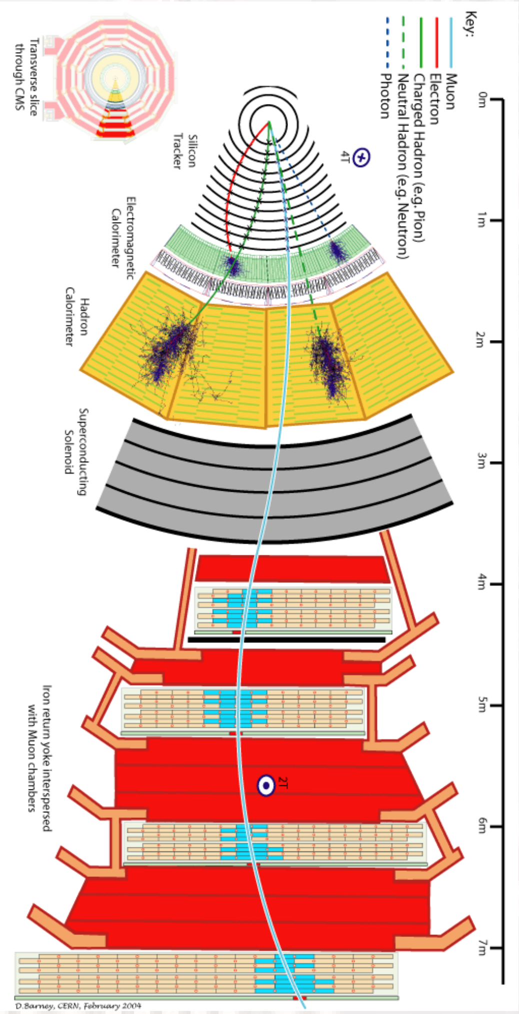
CMS Design Principles

- **Use one single superconducting solenoid to provide uniform axial magnetic field**
  - Largest coil that can be transported to CERN by road
  - Place tracking and calorimeters inside the coil
- **Best possible electromagnetic calorimeter**
  - Use $PbWO_4$ crystals
- **Best possible tracking system**
  - Based completely on silicon sensors
- **Large and *redundant* muon system**
- **Construct large pieces on the surface and then lower them underground for final assembly**
- **Affordable! (cost ~350 million Euros)**

CMS Sub-detectors

Starting from the interaction point and going outwards

- *Silicon Tracker*
  - *Pixels*
  - *Strips*
- *Electromagnetic Calorimeter (ECAL)*
- *Hadronic Calorimeter (HCAL)*
- *Solenoid Magnet*
- *Muon Detectors*



CMS Sub-detectors: Tracker

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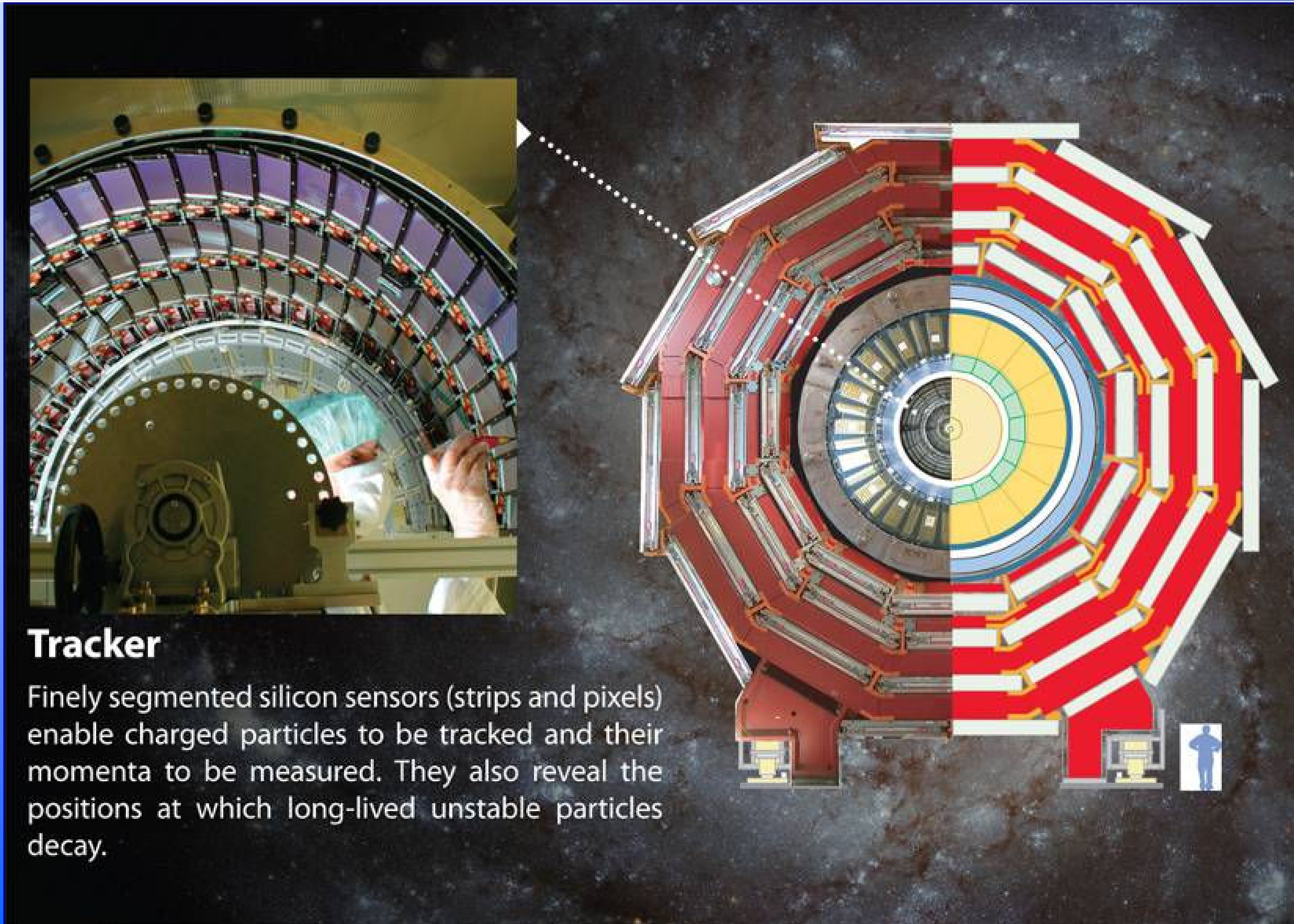
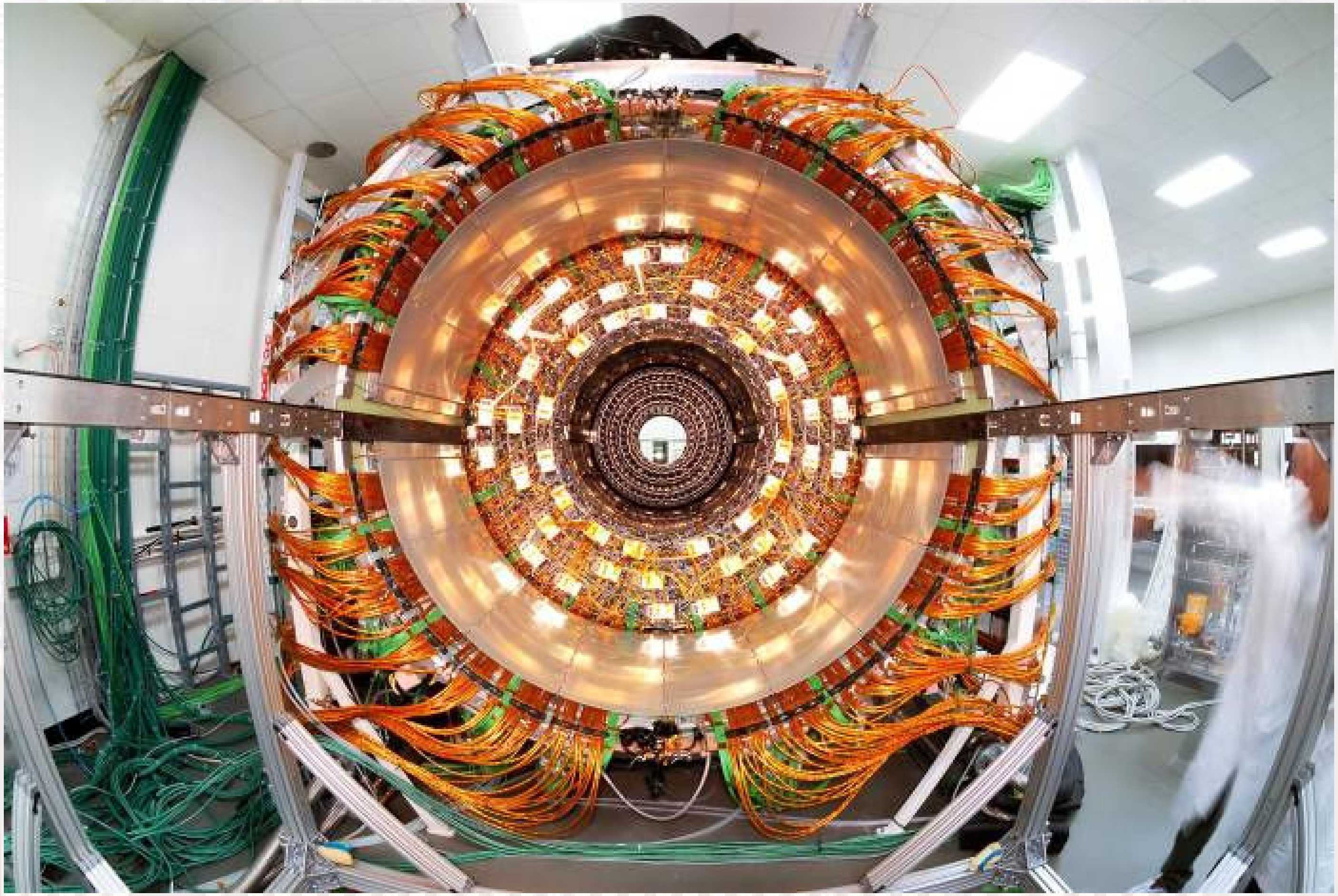
Higgs → γγ

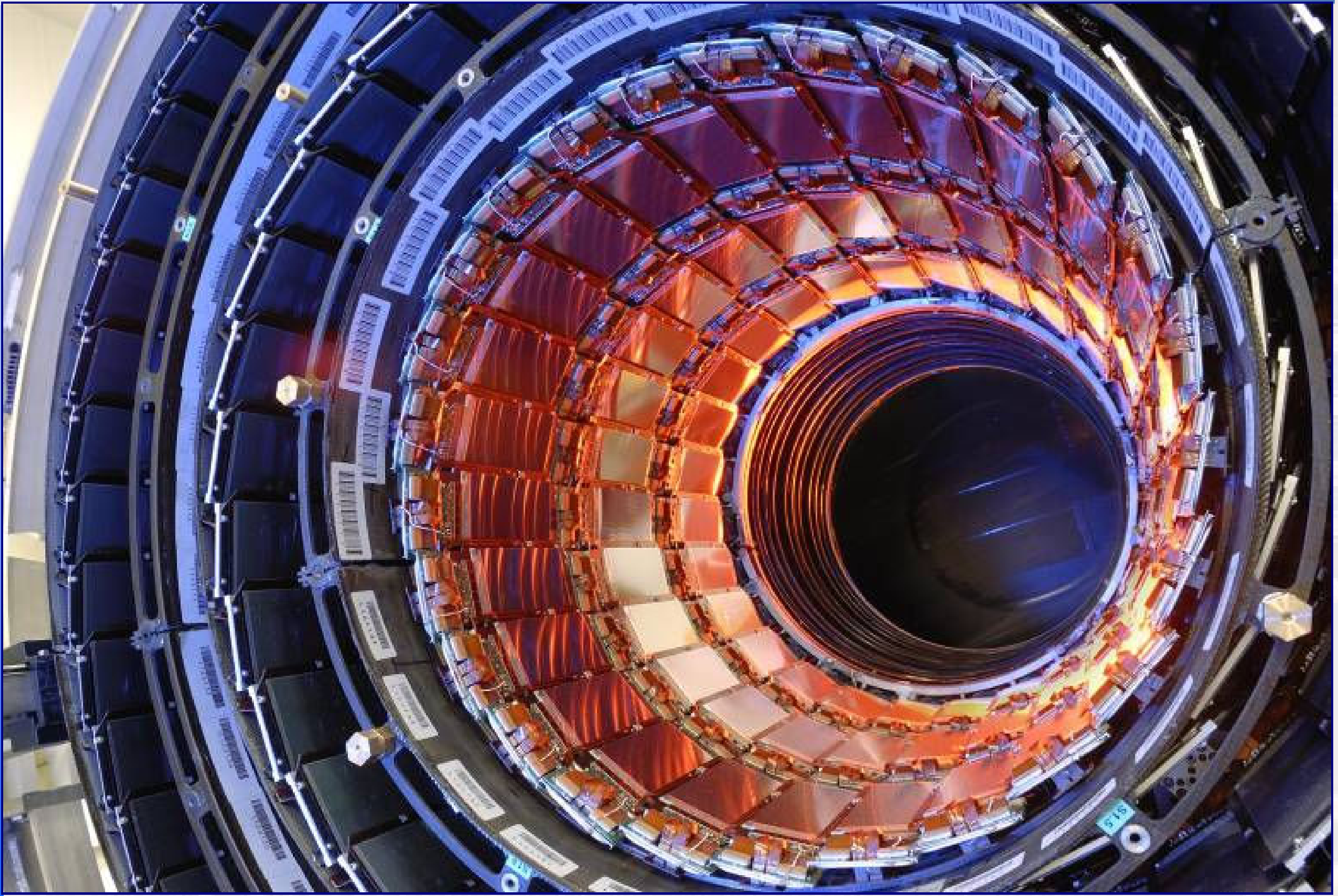
Status



- **Largest silicon-sensor system ever made**
  - 6m long, ~2.2m diameter, operates at -15°C
  - More than 220m^2 of sensors (65M pixels and 10M strips)



CMS Sub-detectors: Tracker



View of inner tracking layers of silicon sensors

CMS Sub-detectors: Tracker

Assembling (left) and installation (below) of part of the Pixel detector

CMS sub-detectors: ECAL

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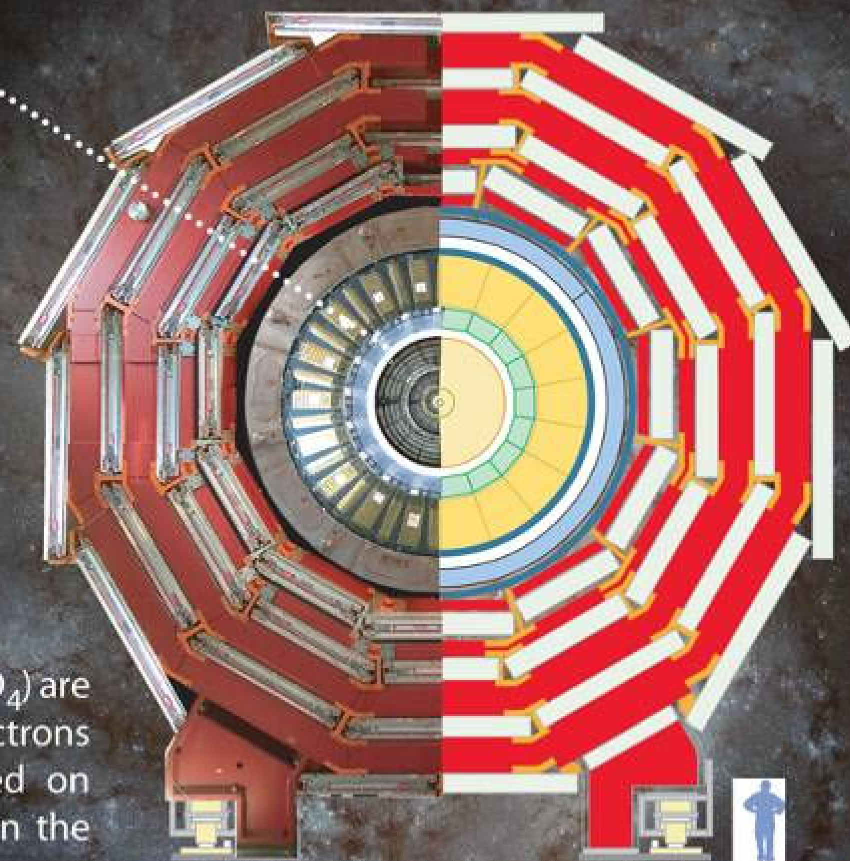
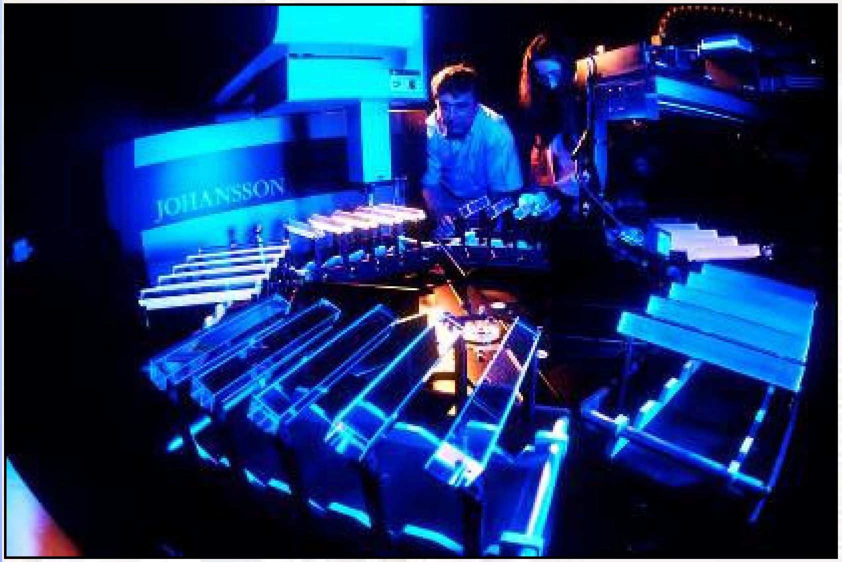
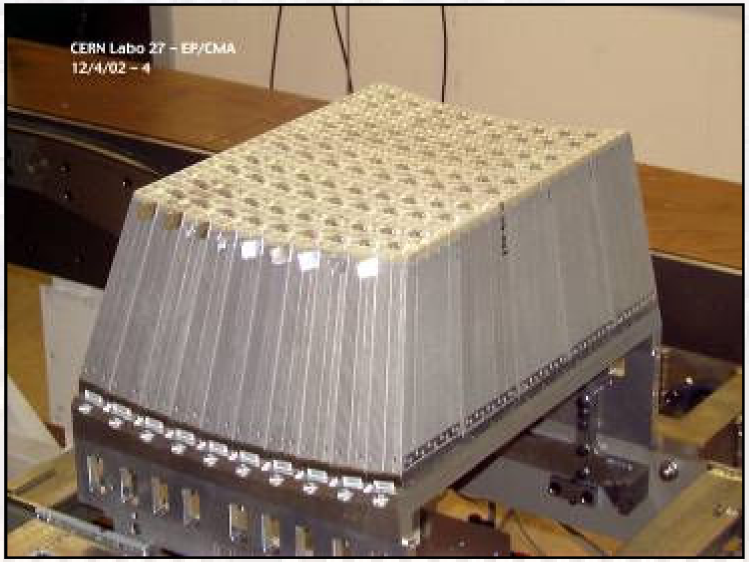


Electromagnetic Calorimeter

Nearly 80 000 crystals of lead tungstate ($PbWO_4$) are used to measure precisely the energies of electrons and photons. A 'preshower' detector, based on silicon sensors, helps particle identification in the endcaps.

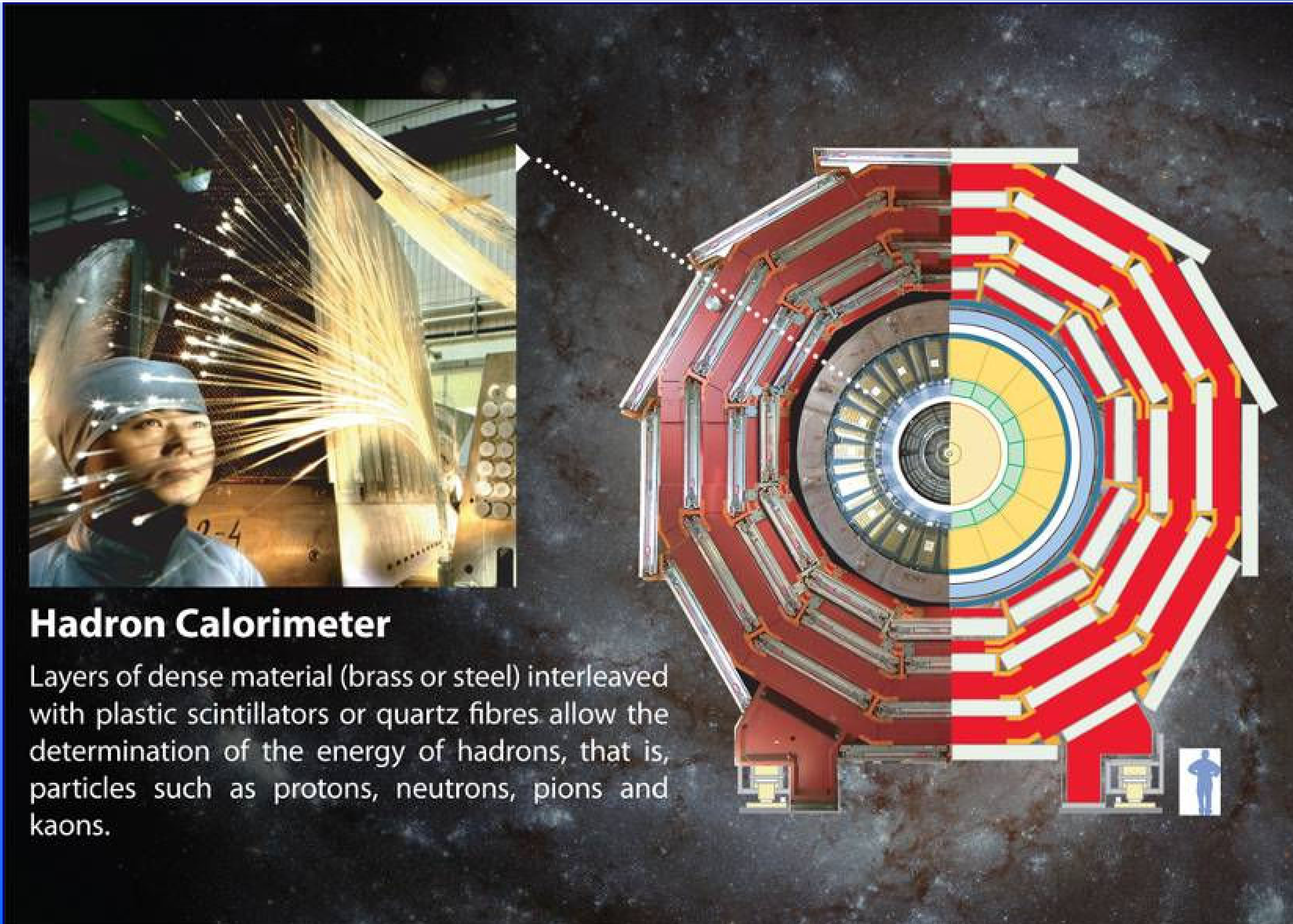
CMS Sub-detectors: ECAL



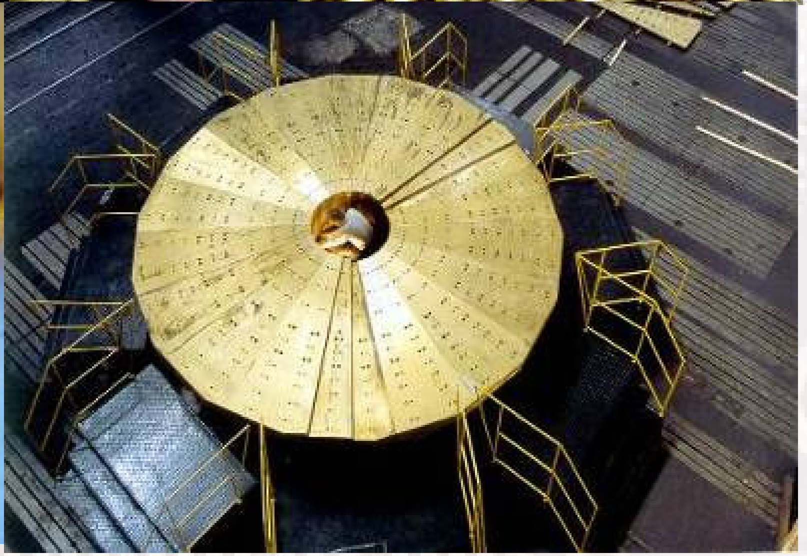


CMS Sub-detectors: ECAL

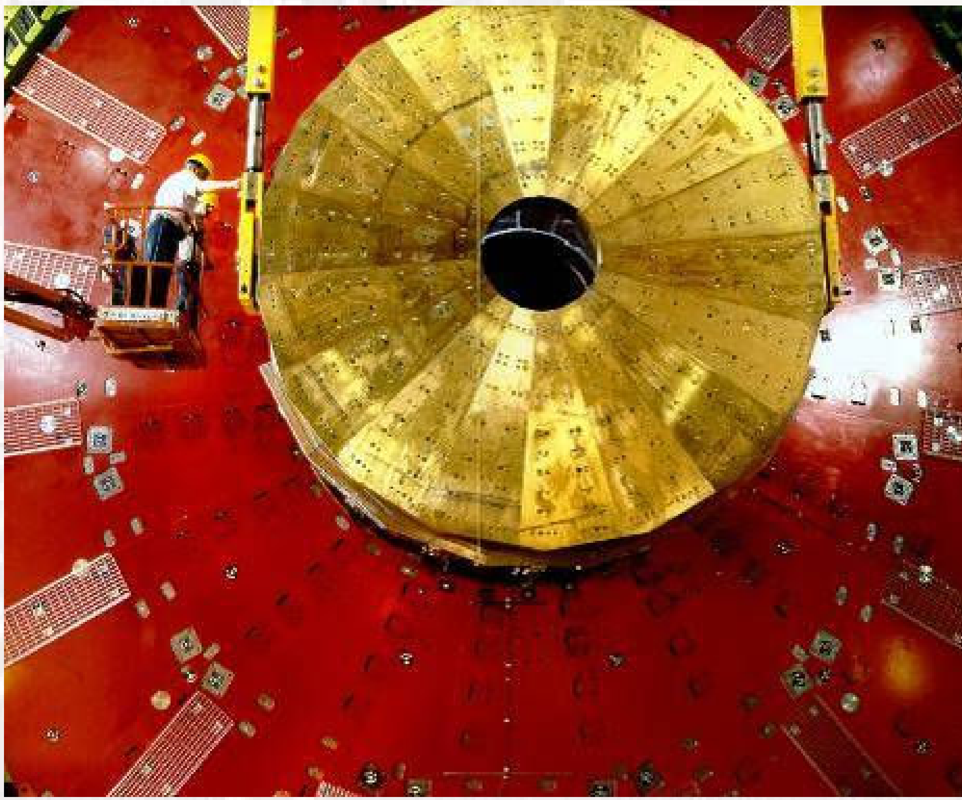
CMS Sub-detectors: HCAL

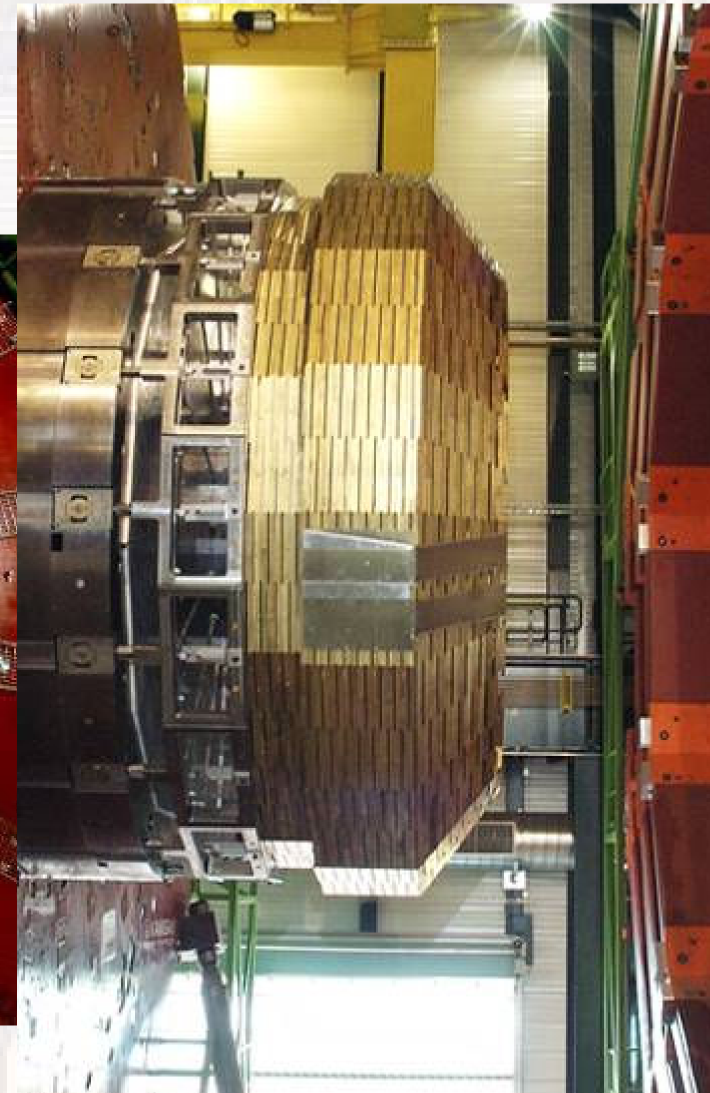


Weapons to ploughshares: Brass for HCAL recuperated from Russian warships!



Installed Endcap HCAL

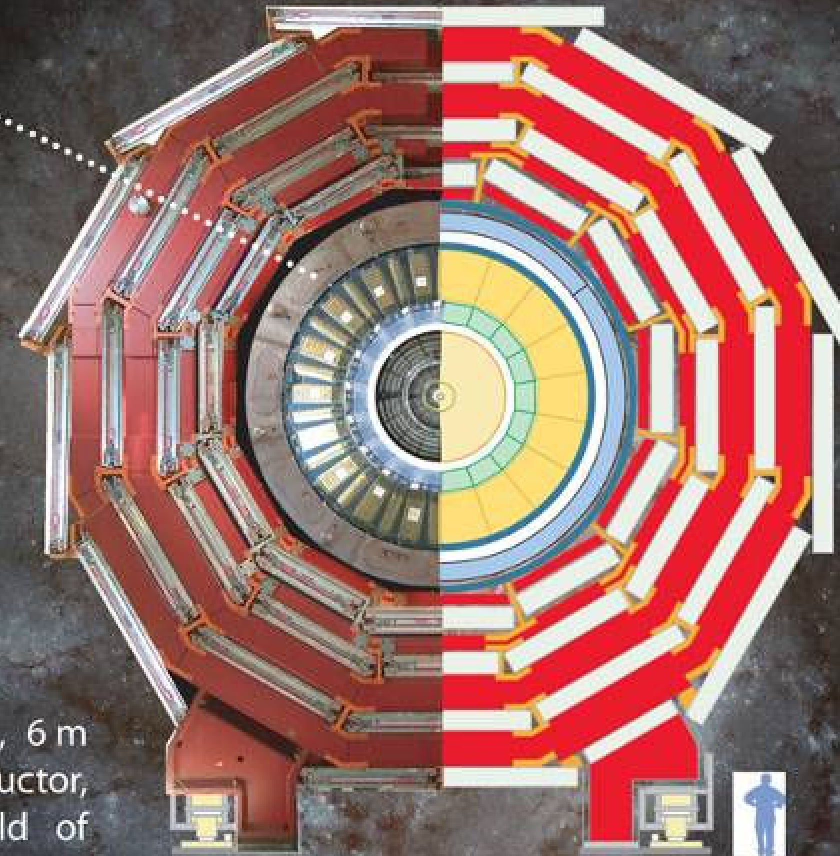




CMS Solenoid

Superconducting Solenoid

Passing 20 000 amperes through a 13 m long, 6 m diameter coil of niobium-titanium superconductor, cooled to –270°C, produces a magnetic field of 4 teslas (about 100 000 times stronger than that of the Earth). This field bends the trajectories of charged particles, allowing their separation and momenta measurements.



CMS Solenoid

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CMS Solenoid

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Higgs → γγ

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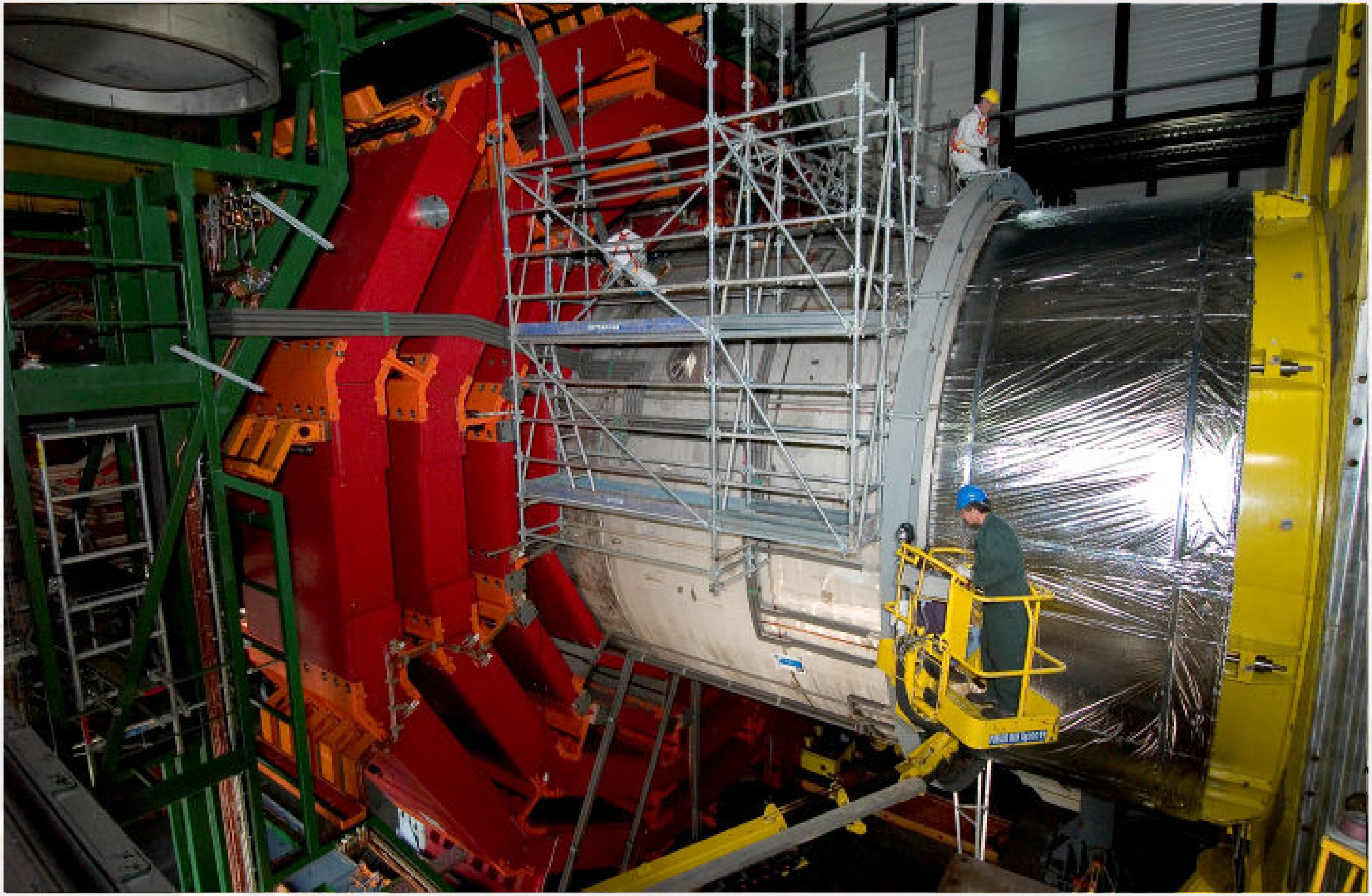
Coil is constructed vertically but needs to be horizontal!

CMS Solenoid



CMS Solenoid at 100K !

CMS sub-detectors: Muon Chambers

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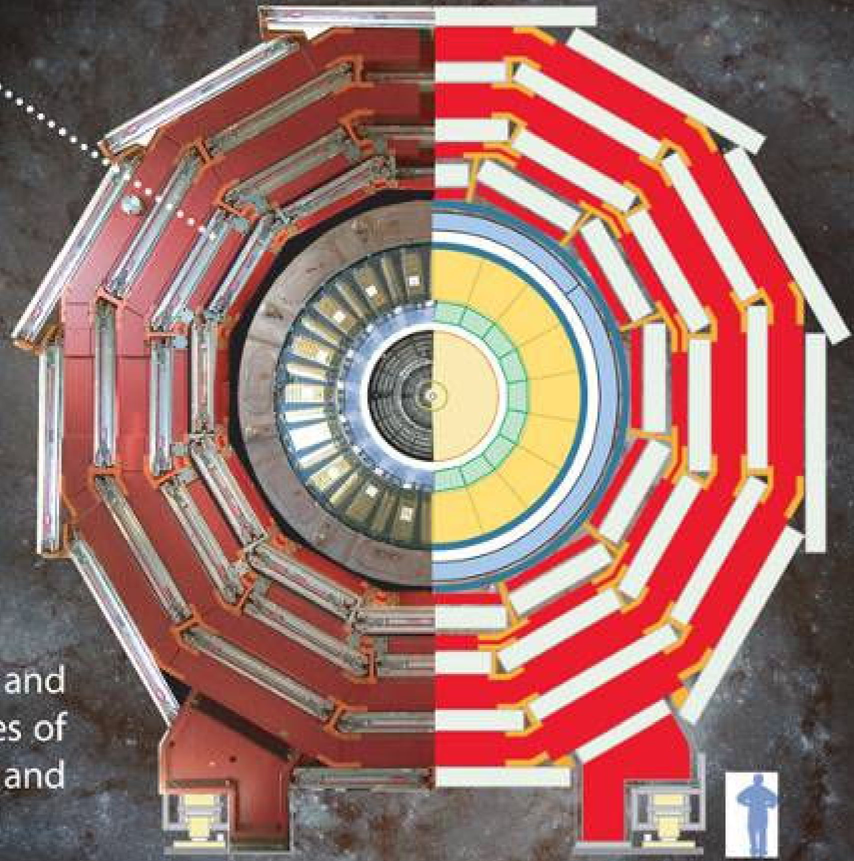
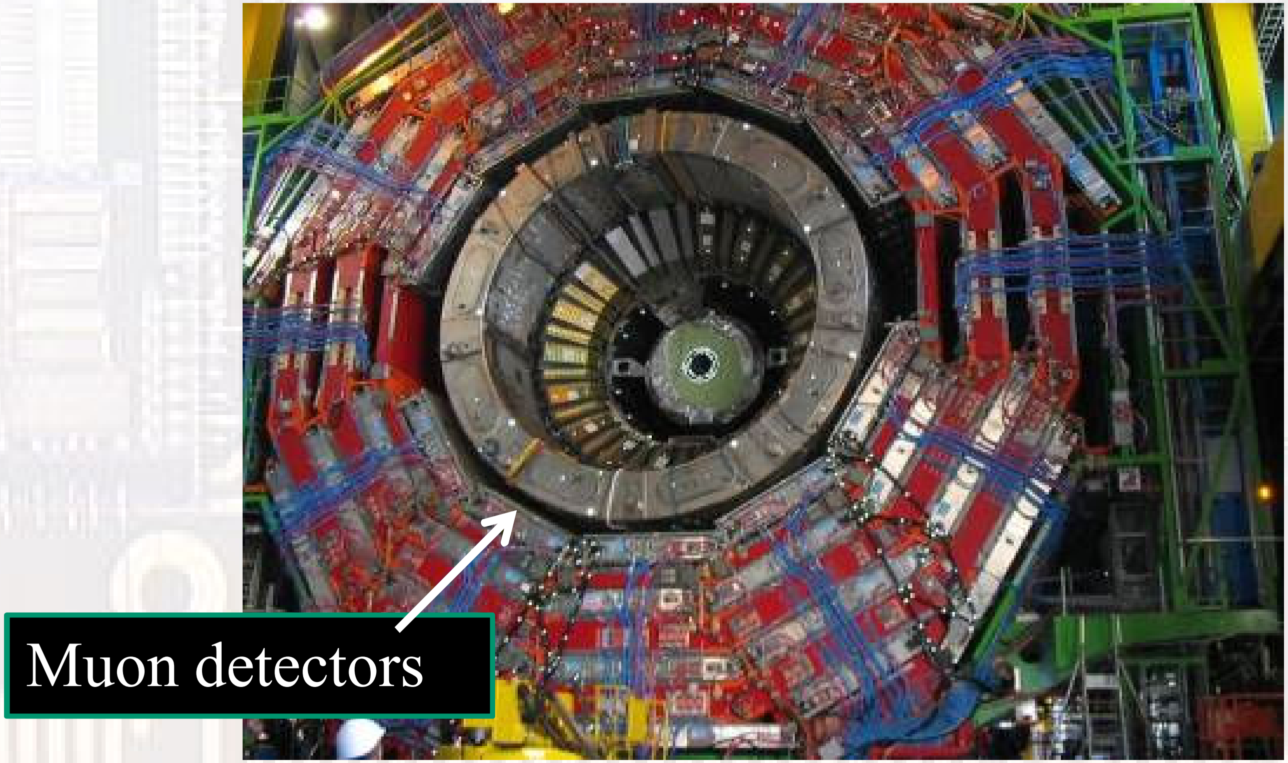


Muon Detectors

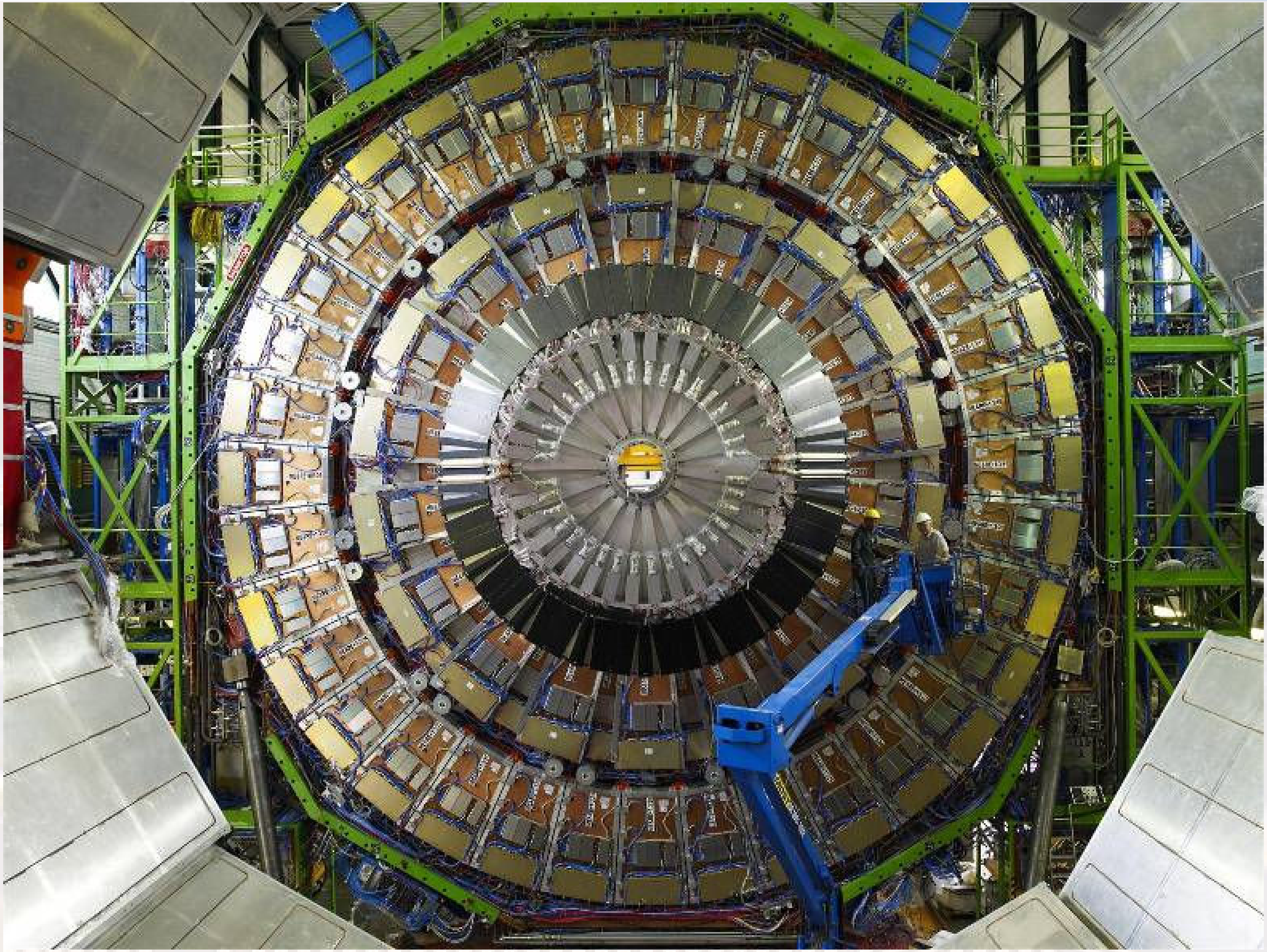
To identify muons (essentially heavy electrons) and measure their momenta, CMS uses three types of detector: drift tubes, cathode strip chambers and resistive plate chambers.

CMS sub-detectors: Muon Chambers

- **Position measurement**
  - Drift Tubes (DT) in barrel
  - Cathode Strip Chambers (CSC) in endcaps
- **Trigger**
  - Resistive Plate Chambers (RPCs) in barrel and endcaps



CMS sub-detectors: Muon Chambers



Triggering

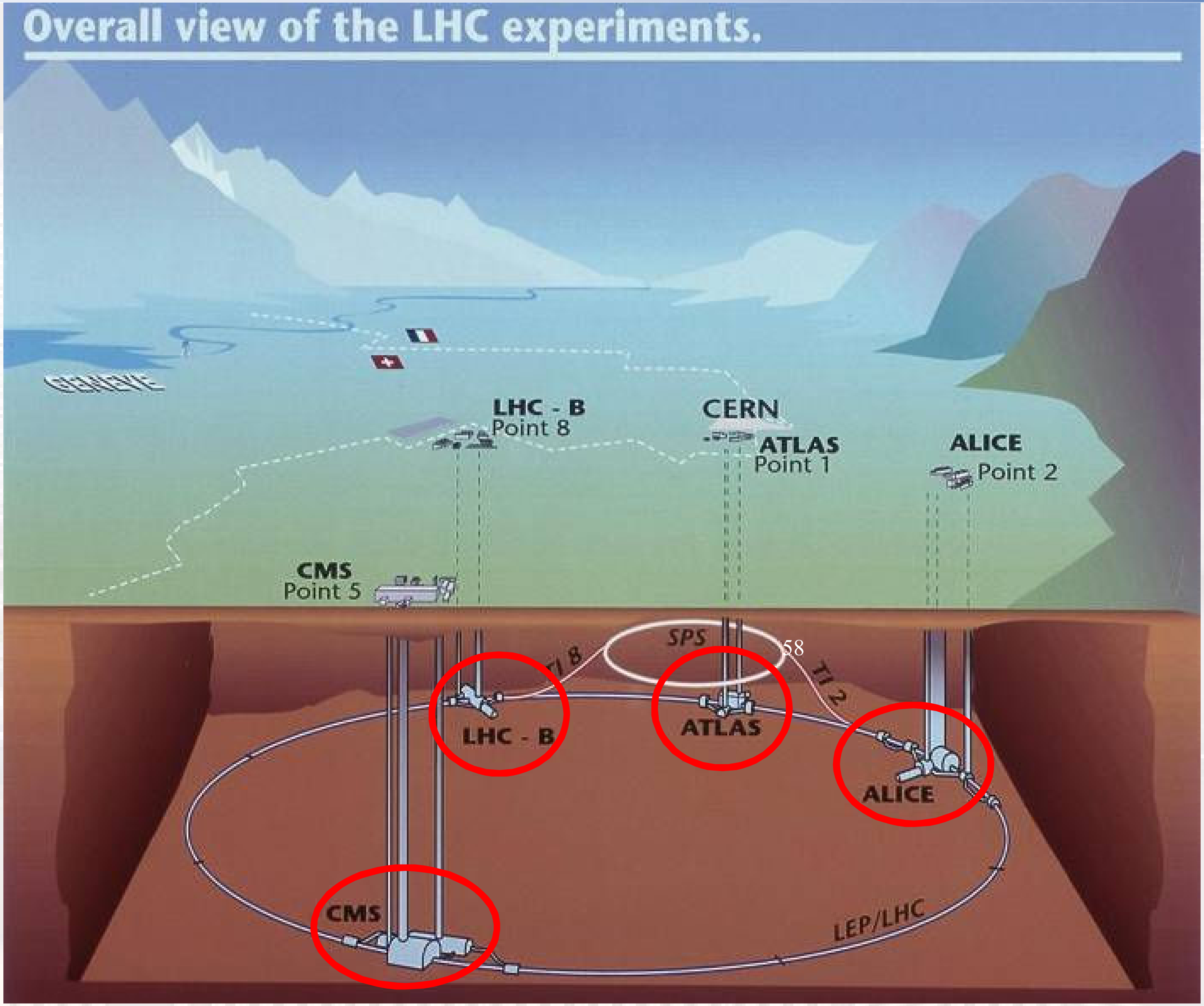
- **Bunches of protons collide 40 million times per second in the LHC**
  - Cannot possibly store all information from all collisions
  - Most collisions do not produce anything "interesting"
- **Need to select the most interesting ~100 "events" per second (this is the maximum rate of data storage – equivalent to about 100 Mbytes/second – or about a Petabyte per year!)**
- **Two stages:**

1. Select ~100000 "potentially interesting" events per second
   - Based on simple information, such as:
     - High-energies in the calorimeters
     - Presence of one or more muons
   - Analogous to "scanning the headlines" of thousands of newspapers and selecting only the interesting articles
2. From these 100000 select the best 100
   - Use all possible information from all sub-detectors
   - Equivalent to analysing 10000 Encyclopaedia Britannica per second
   - Analogous to reading the complete articles from the newspapers

Installation

Large pieces of CMS constructed on the surface and then lowered underground for final assembly and testing

LHC Detectors



Fire Safety Underground

Challenges

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Higgs → γγ

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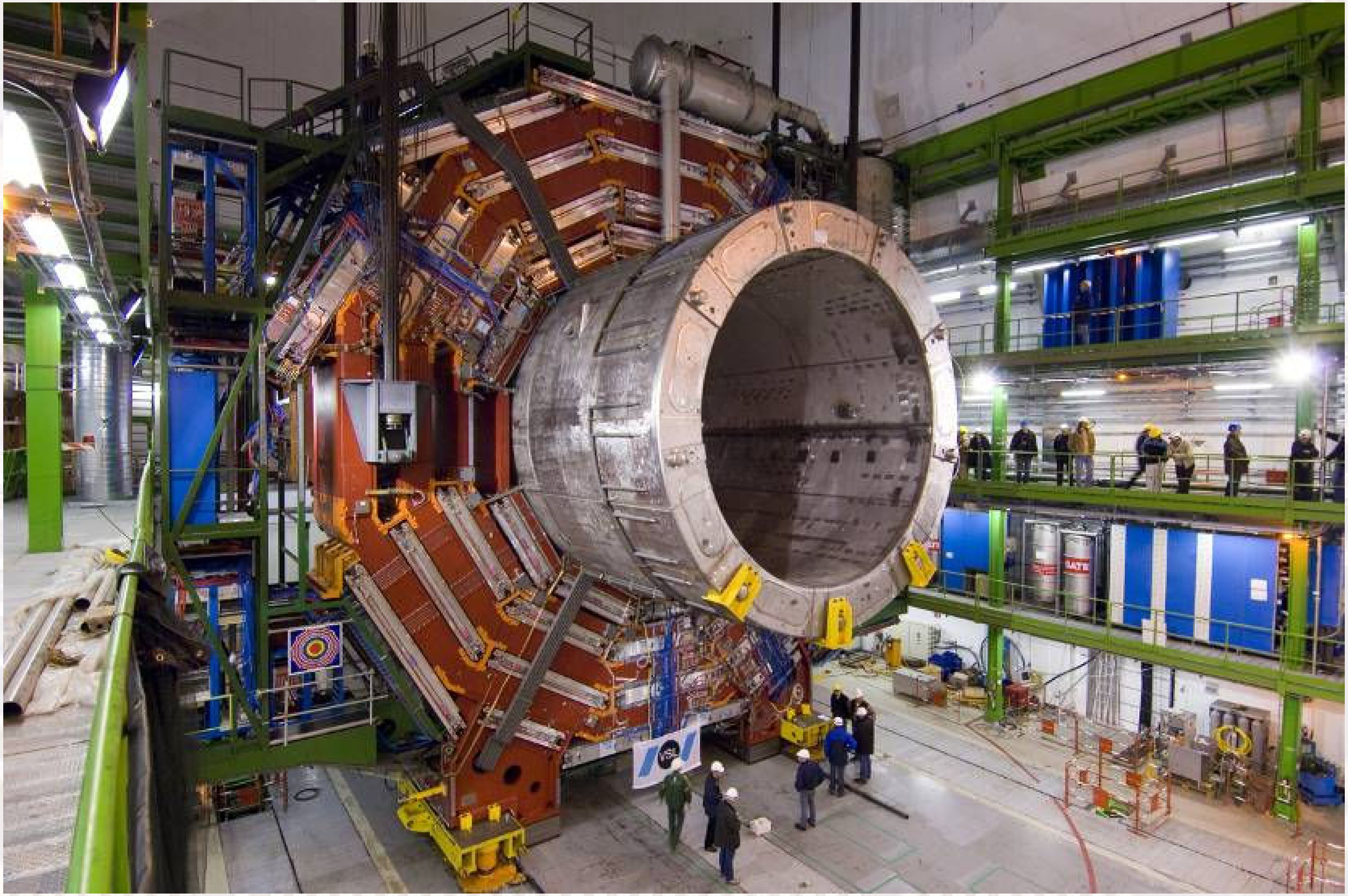
Can fill the experimental cavern with foam in 7 minutes!

Lowering CMS underground

Lowering CMS underground



In the CMS cavern

In the CMS cavern

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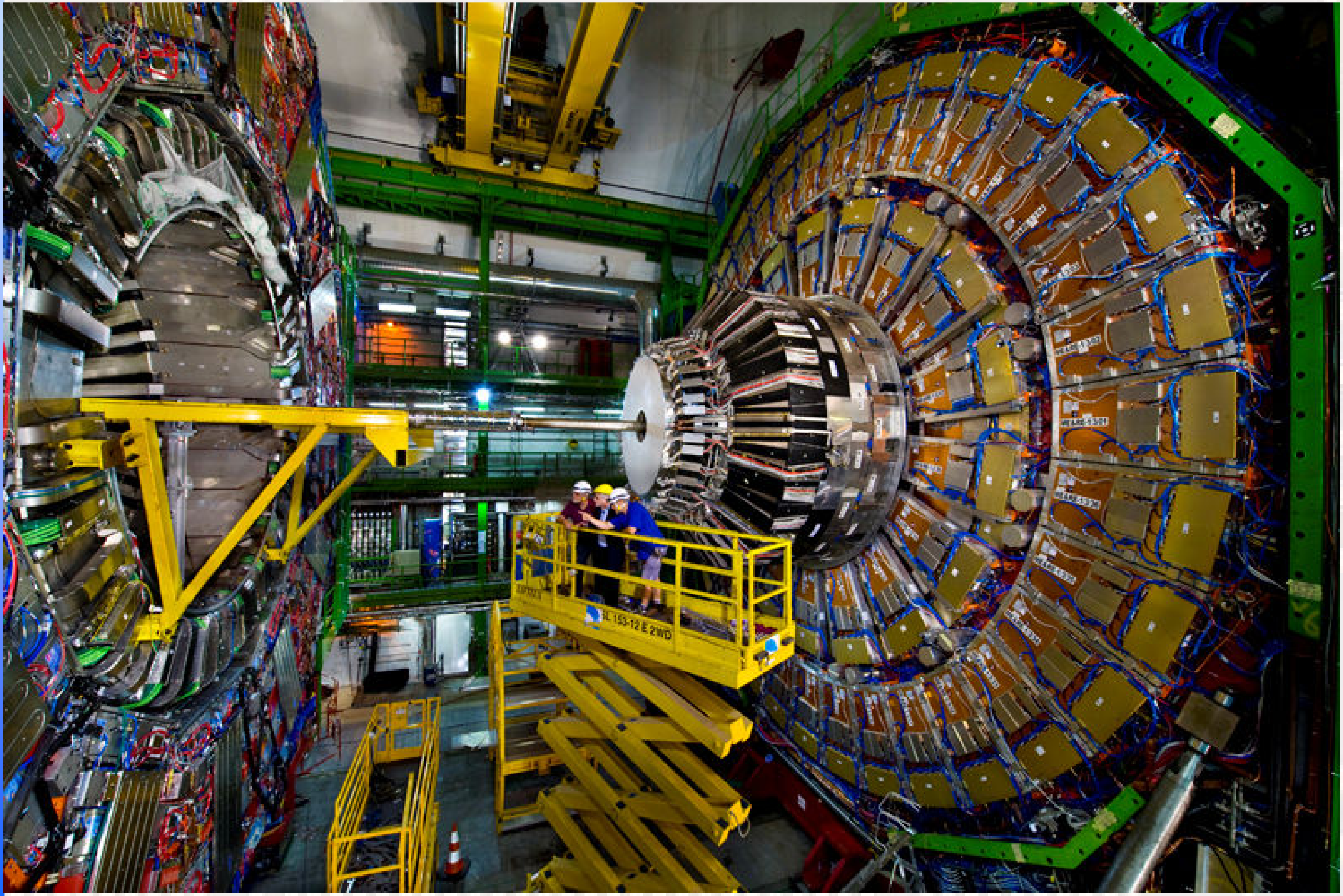
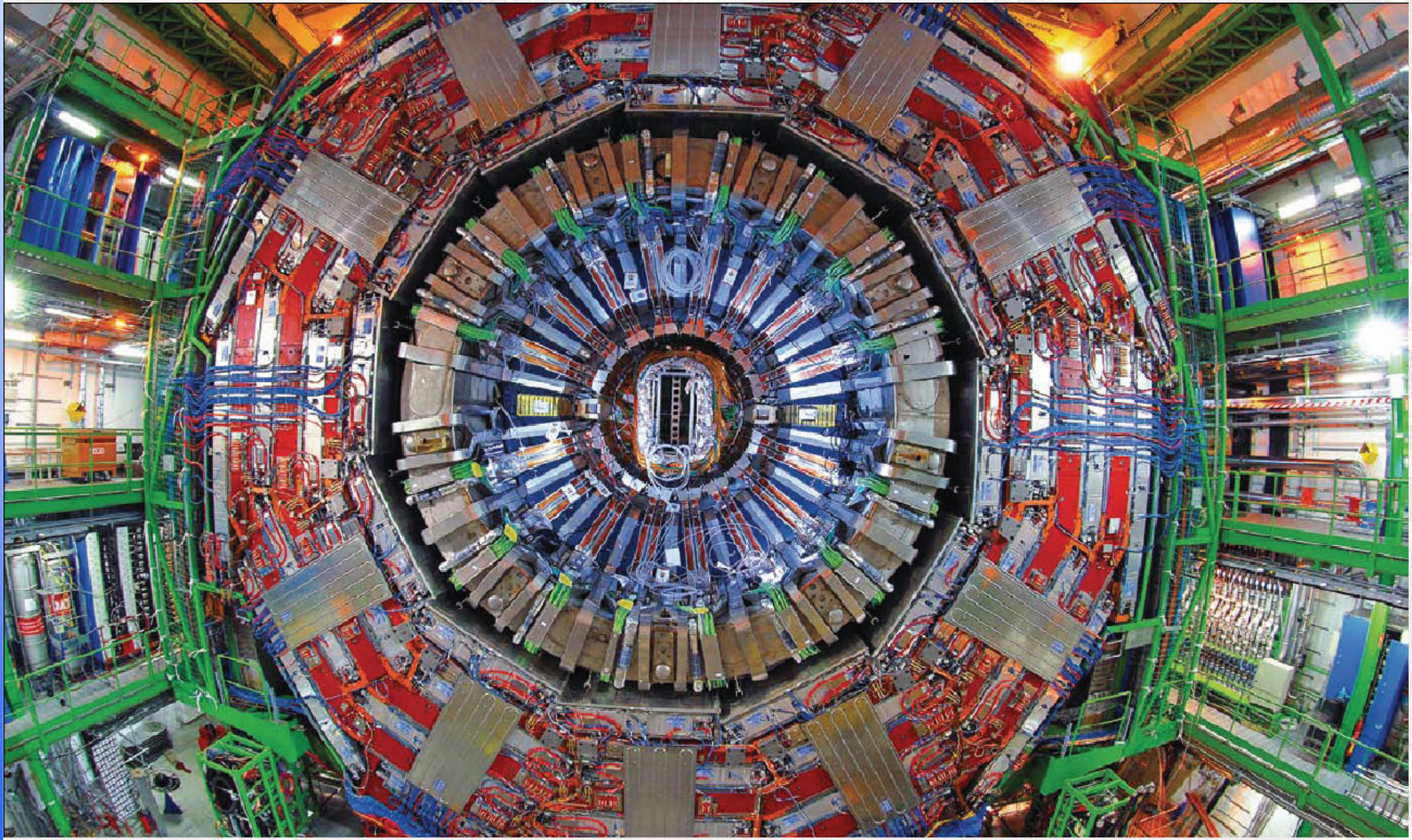
Once underground, all cabling, piping etc. took place – 250km and 50000 man-hours for the central part alone!

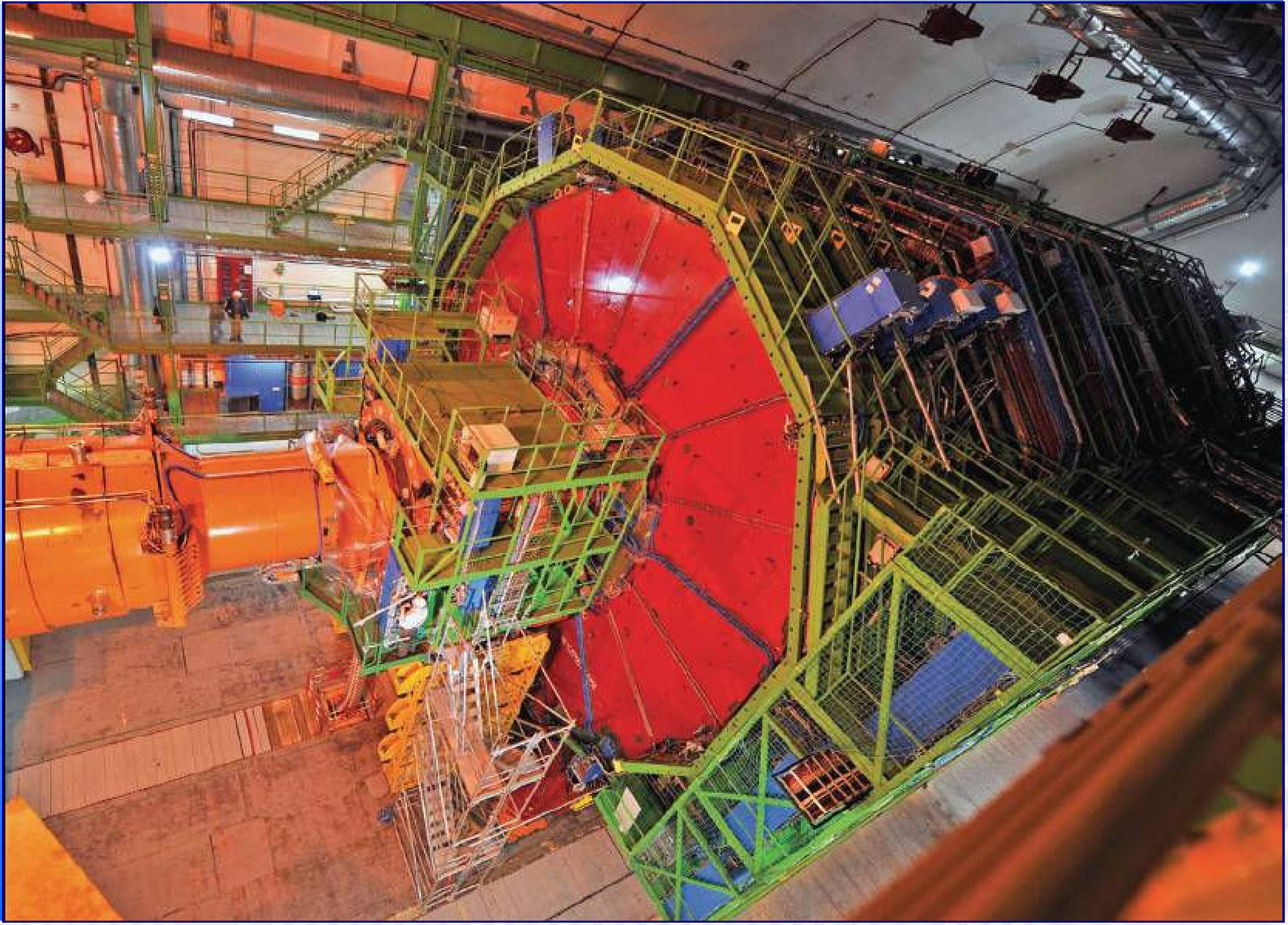
CMS in the cavern



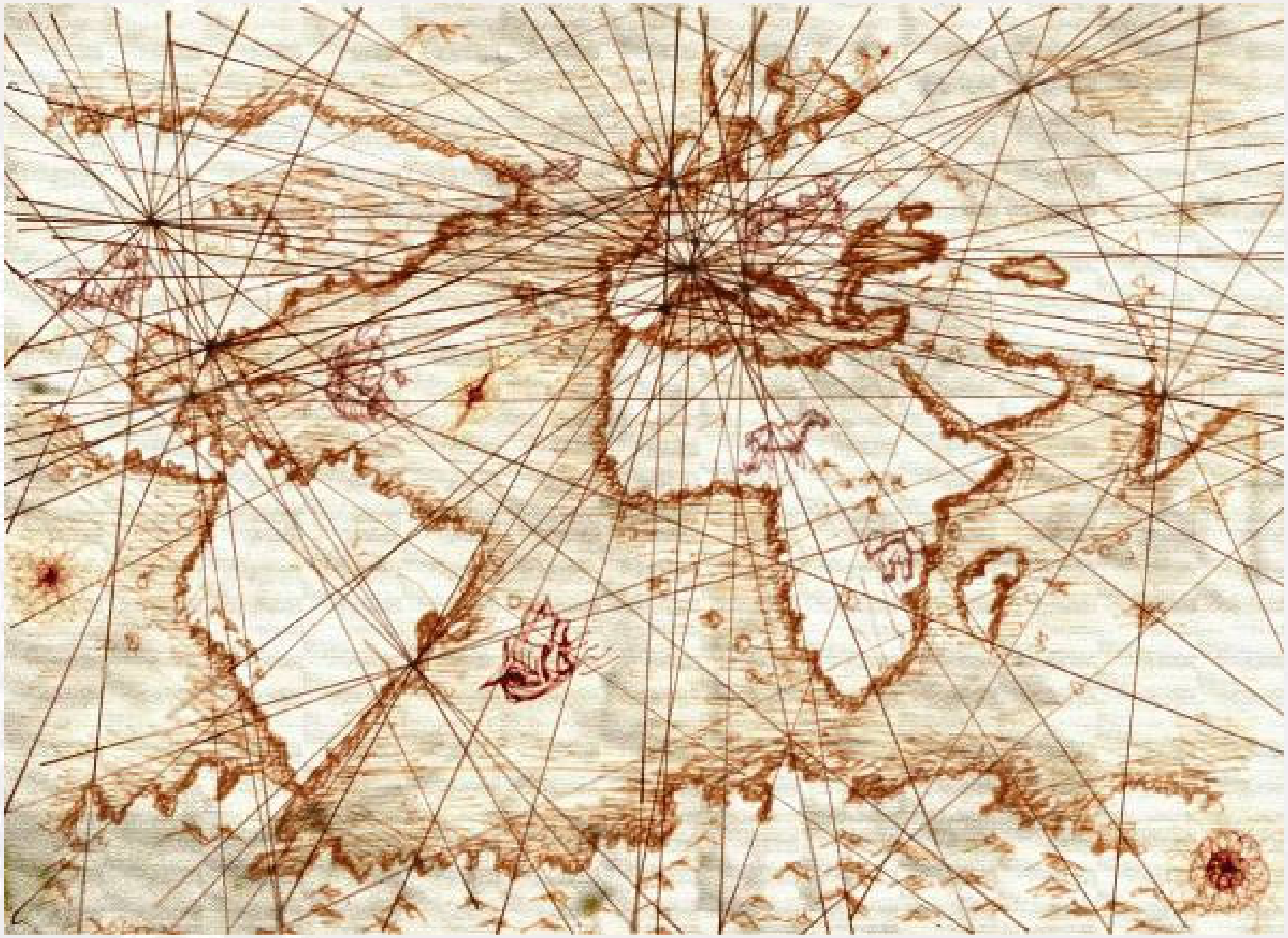
CMS in the cavern



CMS in the cavern today – fully closed



CMS Collaboration



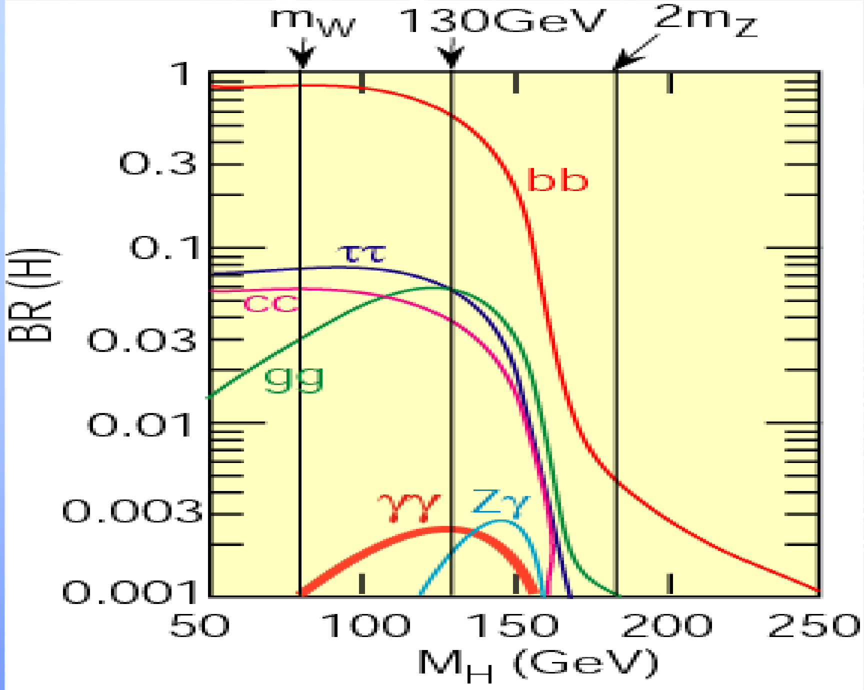
38 Countries;   182 Institutes

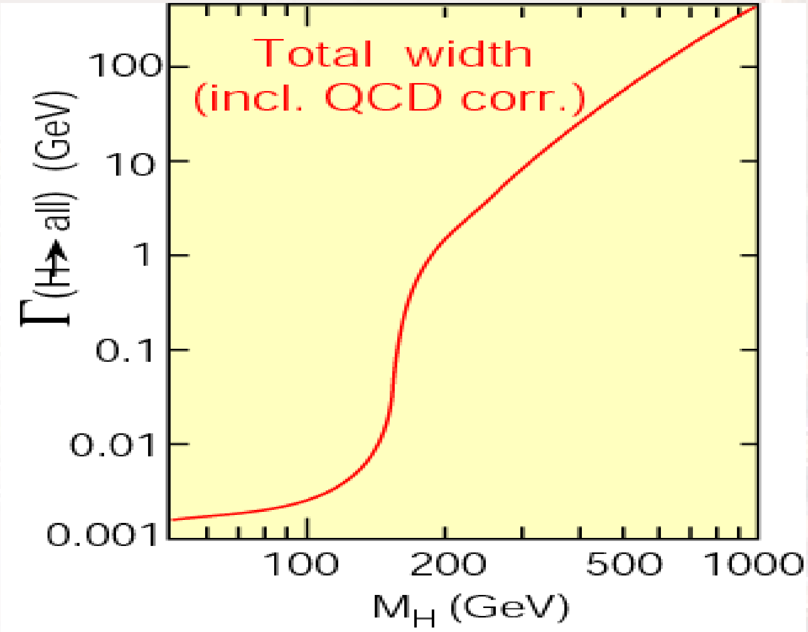
More than 2500 scientists and engineers

About 450 students

Example: Discovering the Higgs Boson

From theory.....





~0.2% BR into γγ
But γ are high p_T and isolated

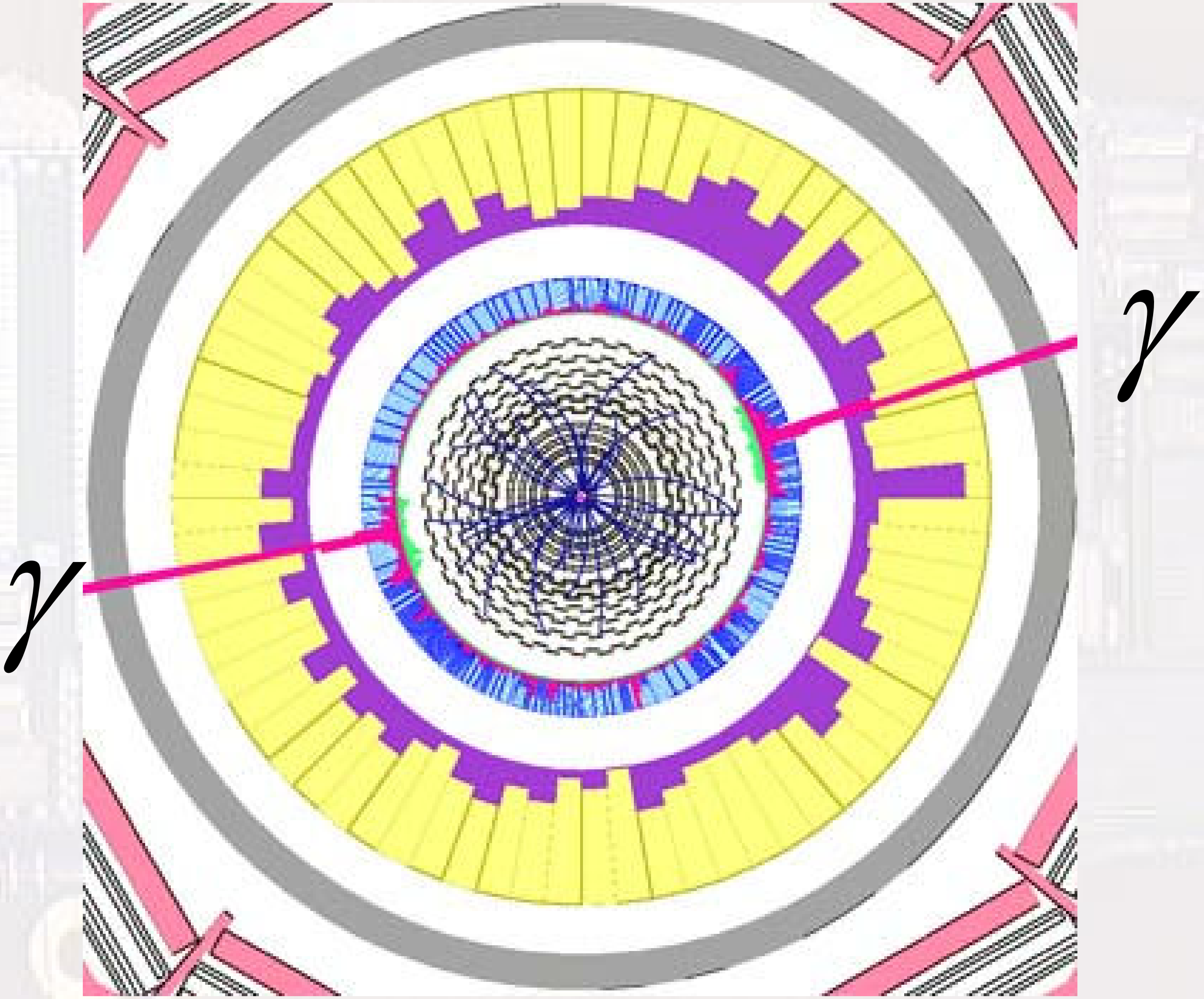
Natural width of H (m_H<150 GeV) is very small
→ Dominated by **detector mass resolution**

Although H→γγ is rare, it is "gold-plated"

What might a Higgs look like in CMS?

Prof. Peter Higgs (left) and CMS Spokesperson Jim Virdee

What might a real Higgs → γγ look like?



Basic idea: detect pairs of photons and calculate the mass of the object that created them (which may or may not be a Higgs)

ECAL Energy and Angular Resolution

Higgs mass resolution (for H→γγ) is given by:

$$\frac{\sigma_m}{m} = \frac{1}{2}\left[\frac{\sigma_{E1}}{E1} \oplus \frac{\sigma_{E2}}{E2} \oplus \frac{\sigma_\theta}{\tan(\theta/2)}\right]$$

i.e. energy resolution of each photon and the resolution of the angle between them (negligible in CMS)

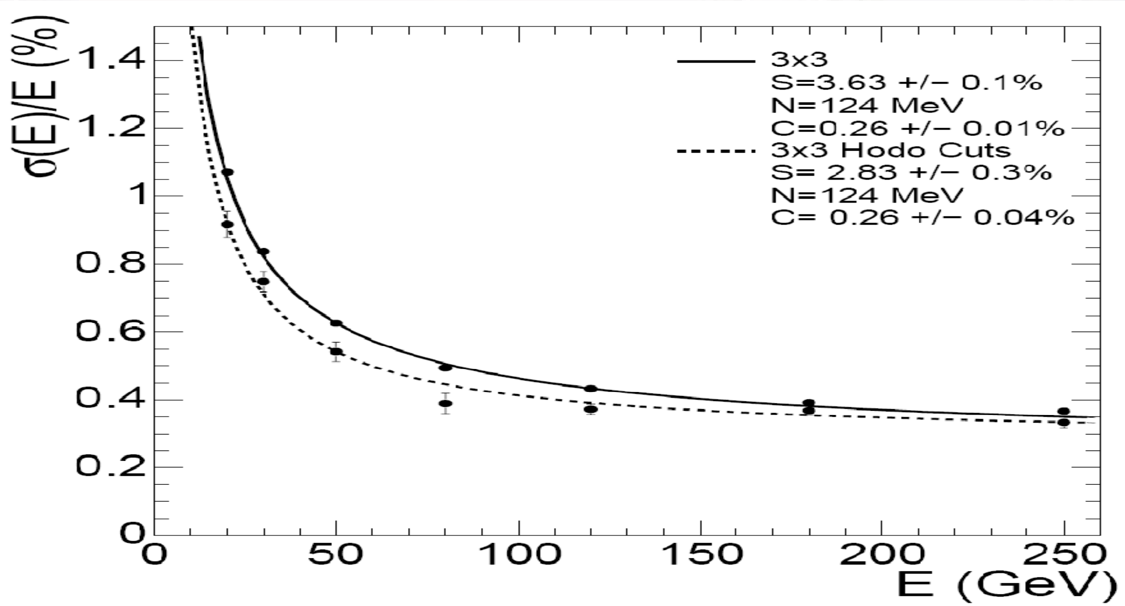
And the energy resolution is given by:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{\sigma_N}{E} \oplus c$$

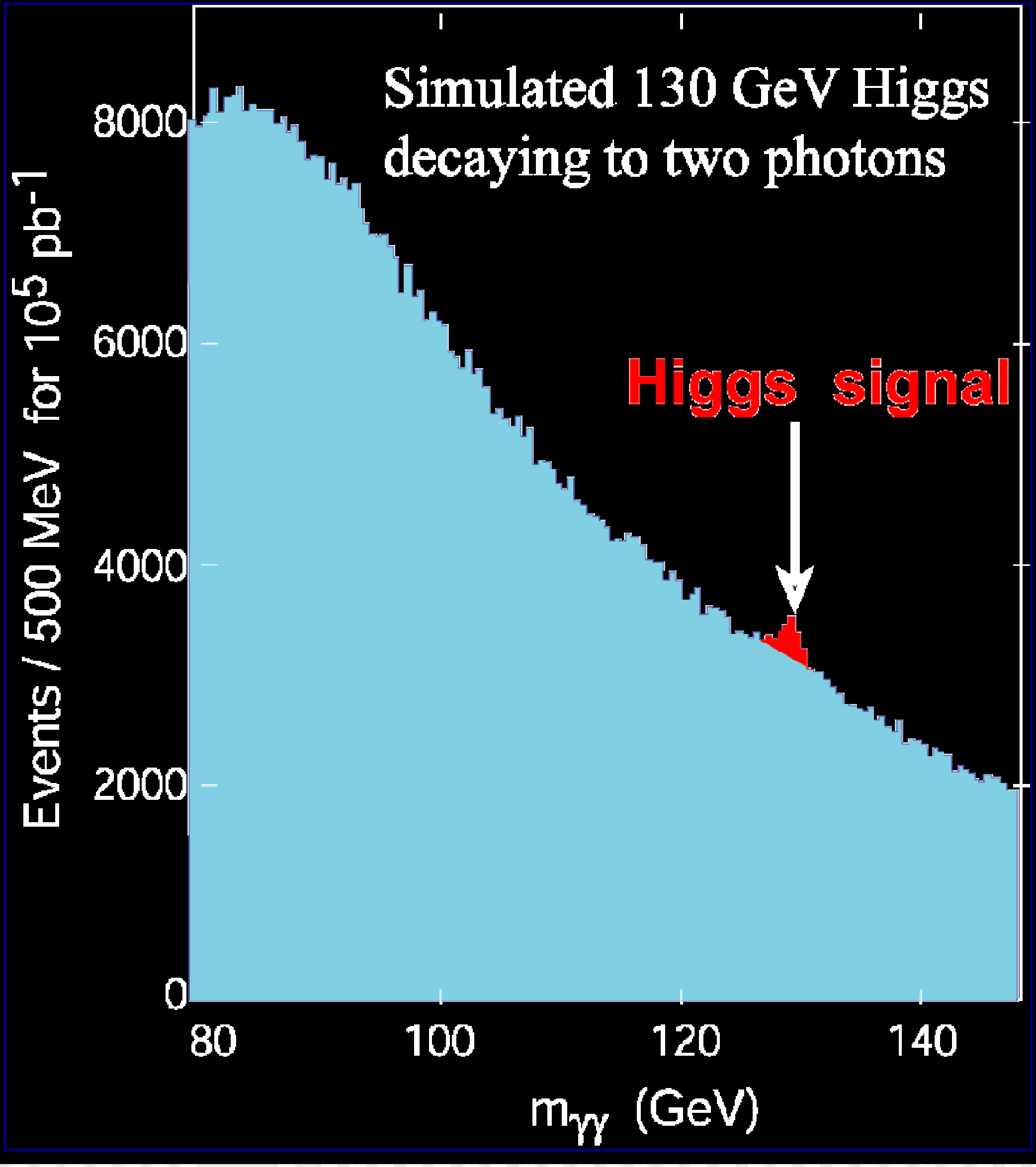
a = stochastic term – photoemission/sampling fluctuations
σ_N = "noise term" – electronics and pileup energy
c = "constant term" – non-uniformities, shower containment etc.

For CMS crystals:

- $a = 2.8\%$
- $\sigma_N = 120$ MeV
- $c = 0.25\%$



Higgs Discovery



IF the Higgs particle exists & IF it has a mass around 130 GeV

This is the signal we will see after about a year of running!

Status and Prospects

Cosmic Rays in CMS

Challenges

Basics
- Magnet
- Tracking
- Calorimetry
- Muons
- Particle ID

CMS Design

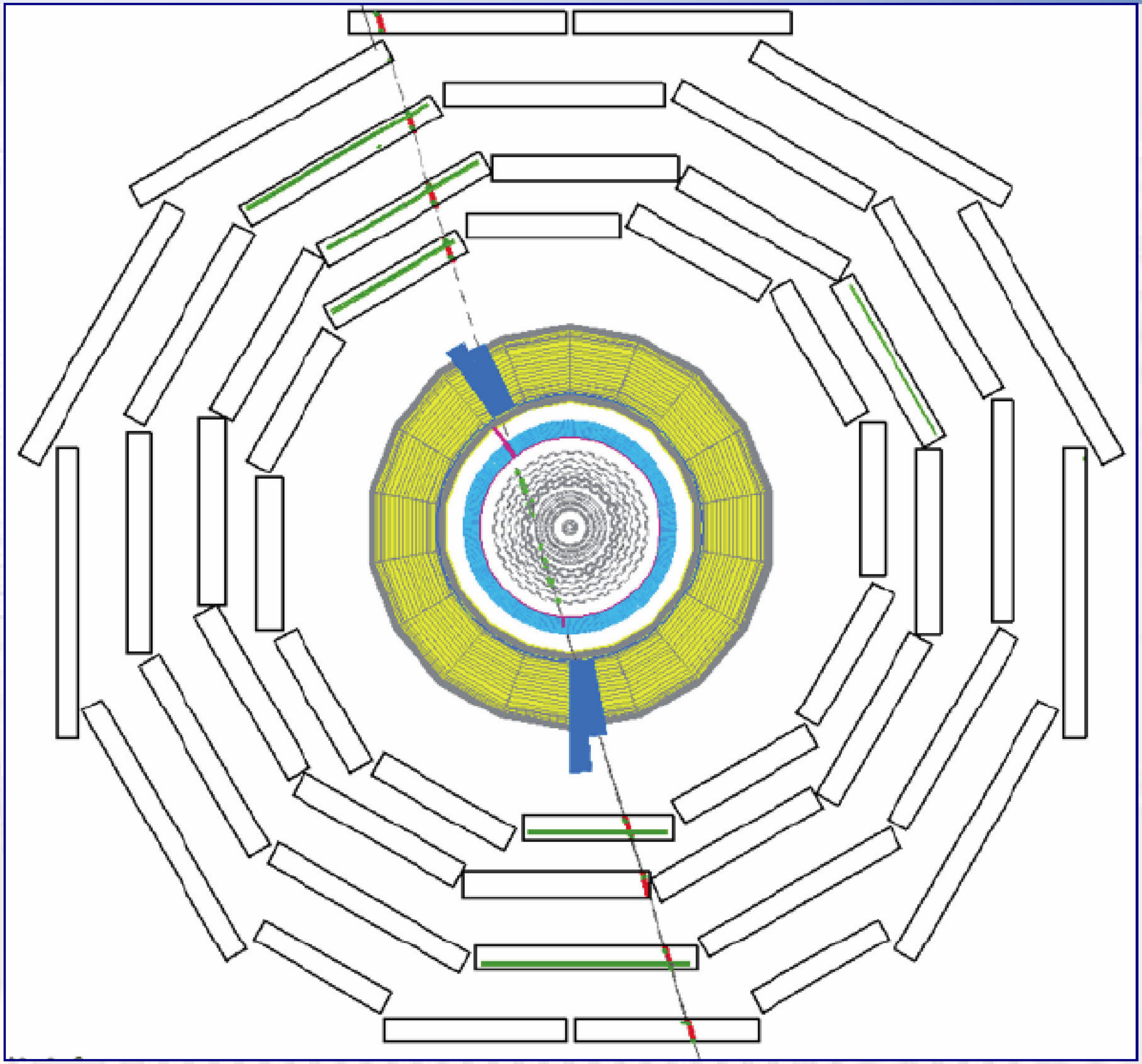
CMS Detectors
- Tracker
- ECAL
- HCAL
- Solenoid
- MUON
- Triggering

Installation

Collaboration

Higgs → γγ

Status



10th September 2008

Challenges

Basics
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CMS Design

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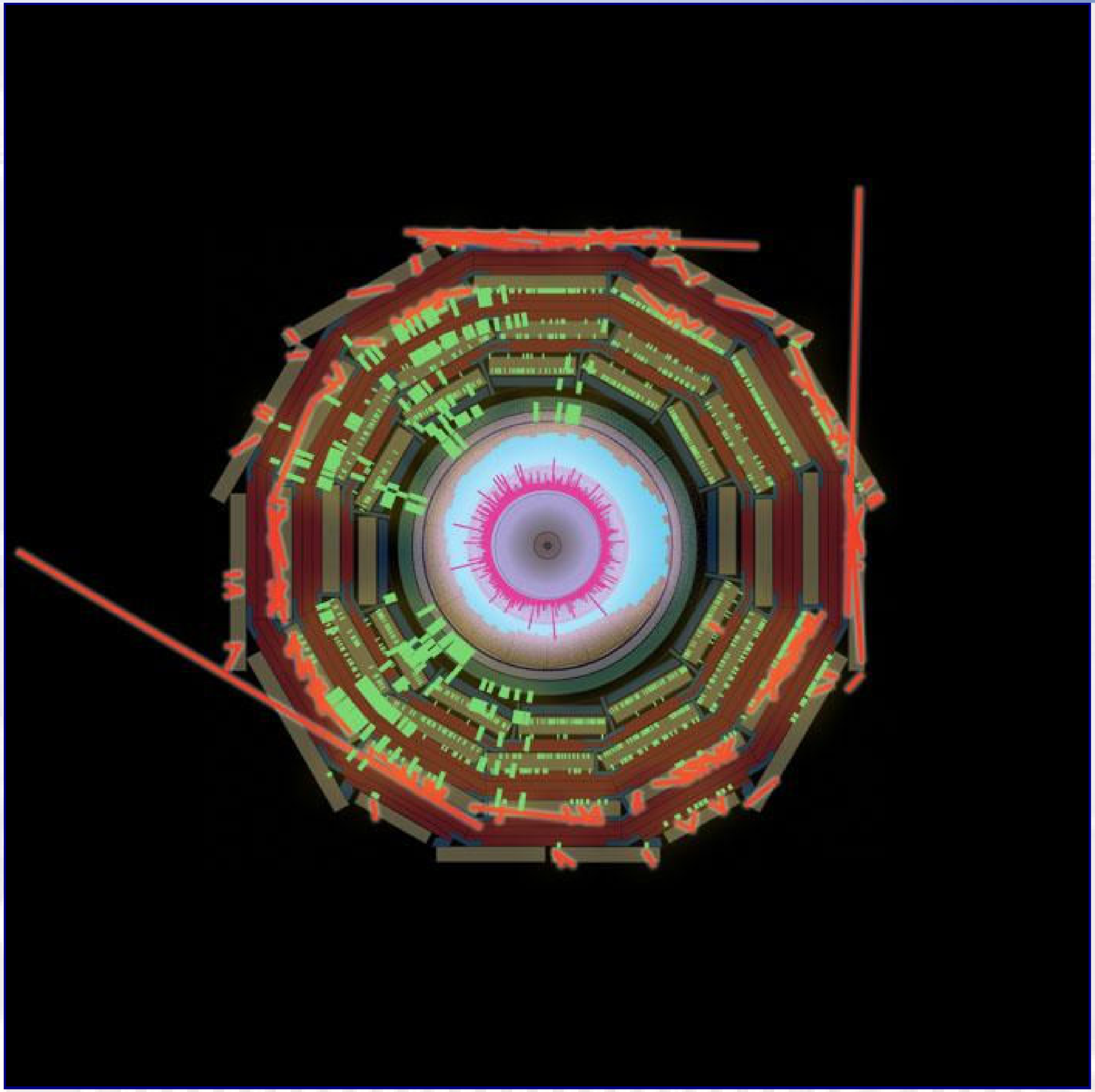
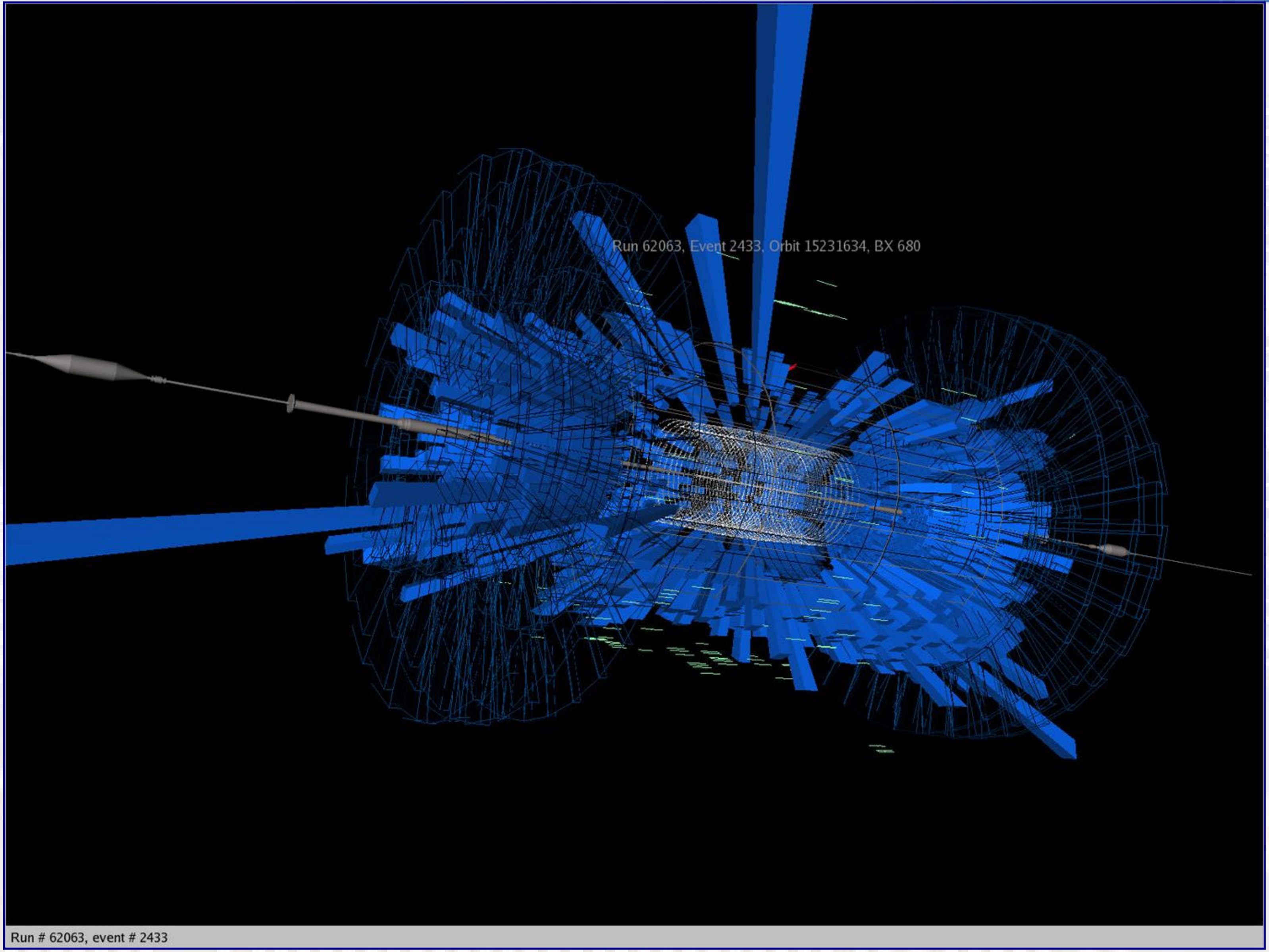
Higgs → $\gamma\gamma$

Status



10th September 2008



Status and Prospects

- **CMS has been more than 20 years in the making**
- **The CMS detector is complete, installed and operational**
- **Currently detecting cosmic rays**
  - Used for sub-detector calibration, alignment etc.
- **Ready for LHC re-start later in the year**
- **Will operate for at least 10 years, with little chance of intervention**
  - Cutting-edge technologies
- **Upgrades (particularly to the inner detectors) already being planned**
- **CMS is ready for whatever secrets Nature is hiding!**

More info

- CMS: http://cms.cern.ch
- ATLAS: http://atlas.ch
- ALICE: http://aliceinfo.cern.ch/Public
- LHCb: http://lhcb-public.web.cern.ch

Spares

Invariant mass of two photons

- **Photon 1: E_1, P_{1x}, P_{1y}, p_{1z}**
- **Photon 2: E_2, P_{2x}, P_{2y}, P_{2z}**
- **Quantities:**
  - $E_{tot} = E_1+E_2$
  - $P_{xtot} = P_{1x}+P_{2x}$
  - $P_{ytot} = P_{1y}+P_{2y}$
  - $P_{ztot} = P_{1z}+P_{2z}$
- **Mass = sqrt(E_{tot}*E_{tot} - P_{xtot}*P_{xtot} - P_{ytot}*P_{ytot} - P_{ztot}*P_{ztot})**