CMS: a personal journey

Dave Barney, CERN, 7th July 2023

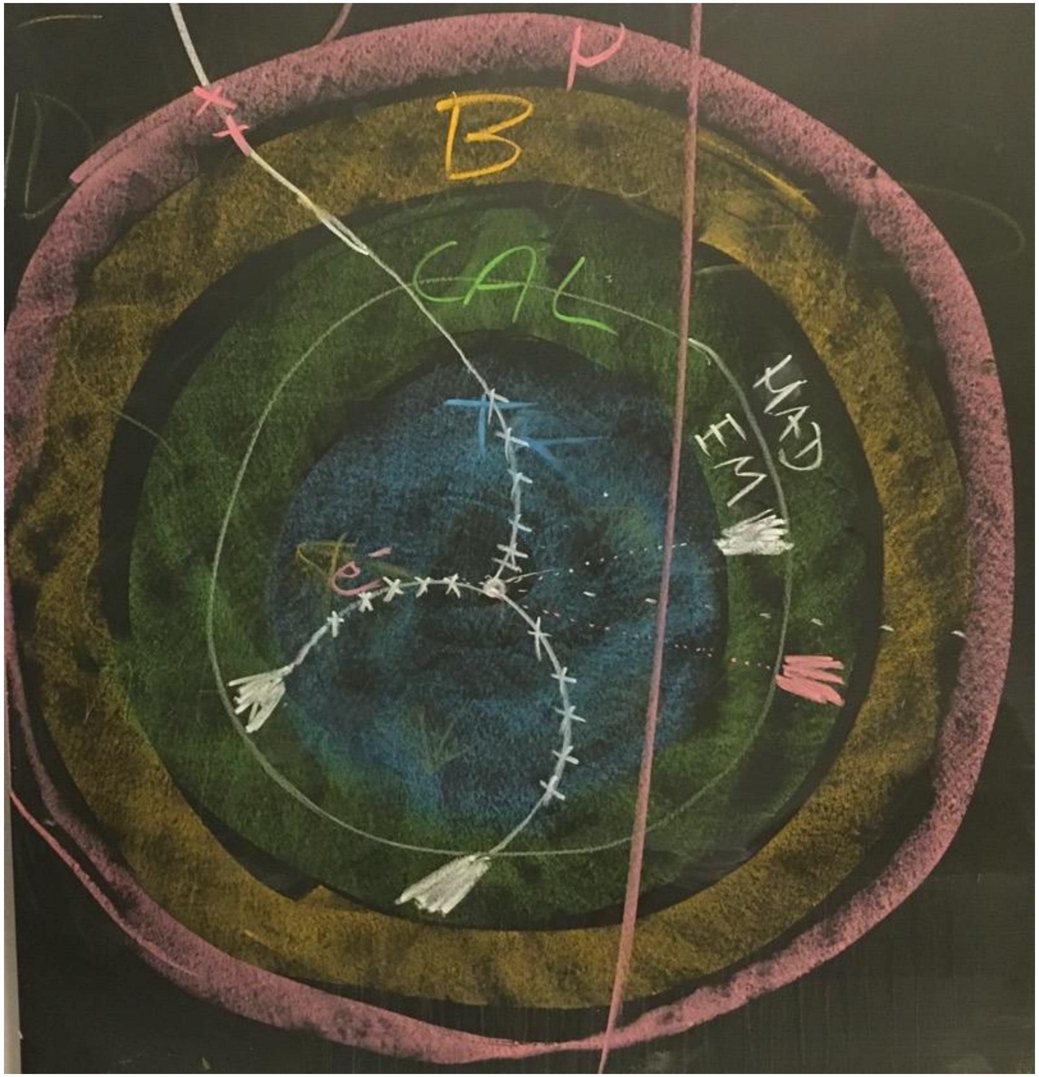
What do we do at CERN?

We smash things together and see what happens!

The Large Hadron Collider…

Needs *Detectors*

Overall detector design is so simple you can do it with students on a blackboard!



The challenge is to decide **how** to build it, with **what technologies**, and **with whom**!

CMS' history goes back to ~1990

First LHC & detector concepts: 1990-1992

CMS Letter of Intent: 1992 and Technical Proposal: 1994

Summary of CMS/ATLAS/LHCb/ALICE as-built detectors & performance: 2009

80cm

More to come!

Technical & Engineering Design Reports for CMS subsystems: 1997-2006

Technical Proposal and
Technical Design Reports
for UPGRADES to CMS subsystems: 2015-

And my history in CMS goes back to 1994

Technical Proposal: 1994
When I joined the CMS experiment

80cm

More to come!

I joined CERN as a “fellow” – a 2 year contract. And have been here ever since!

CMS: a truly global project

CMS Collaboration

~~~4000 members~~

~~~40 countries~~

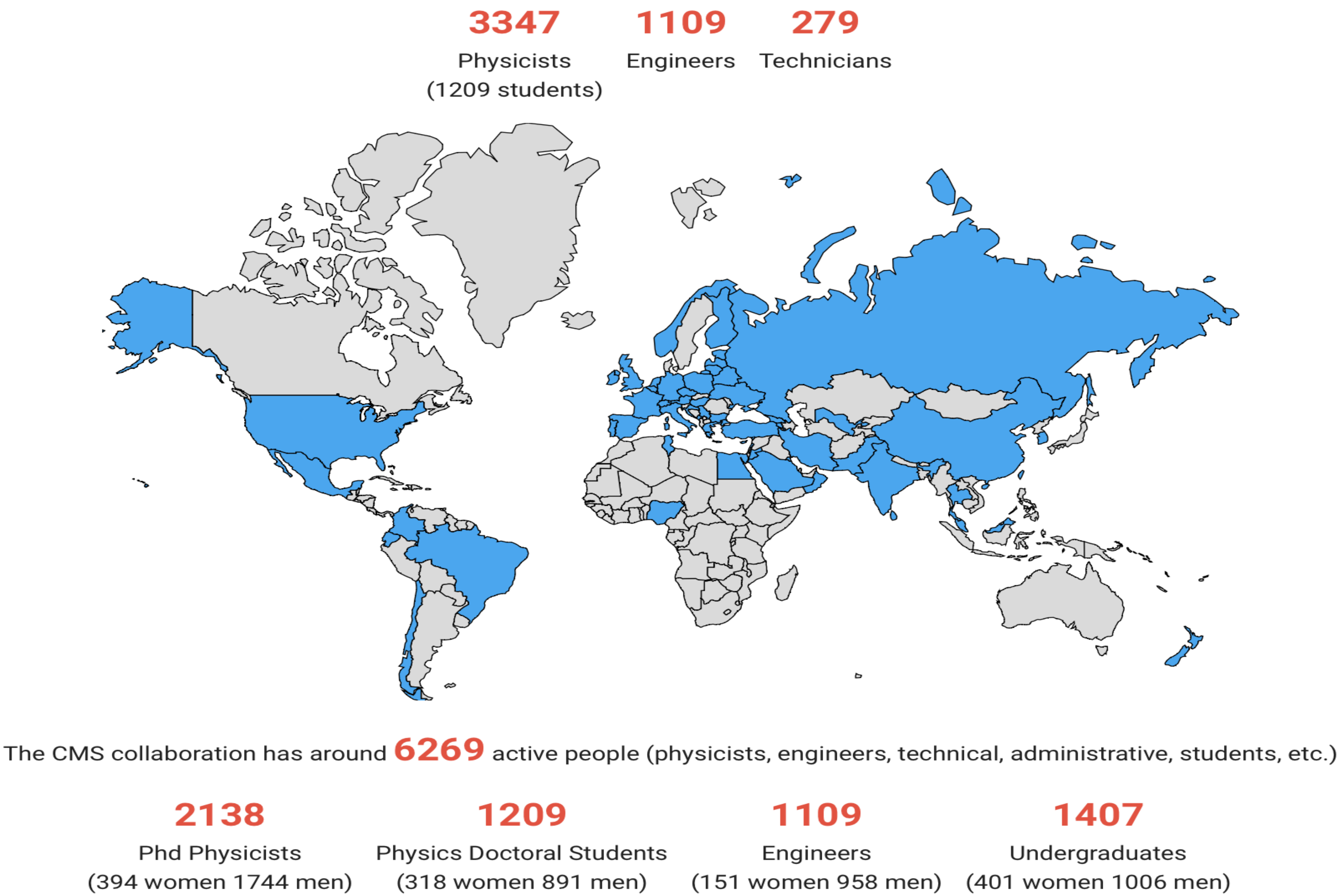
~~~200 Institutes~~

Inc. about 700 students


~~~

CMS: a truly global project

https://icms.cern.ch/statistics/overview



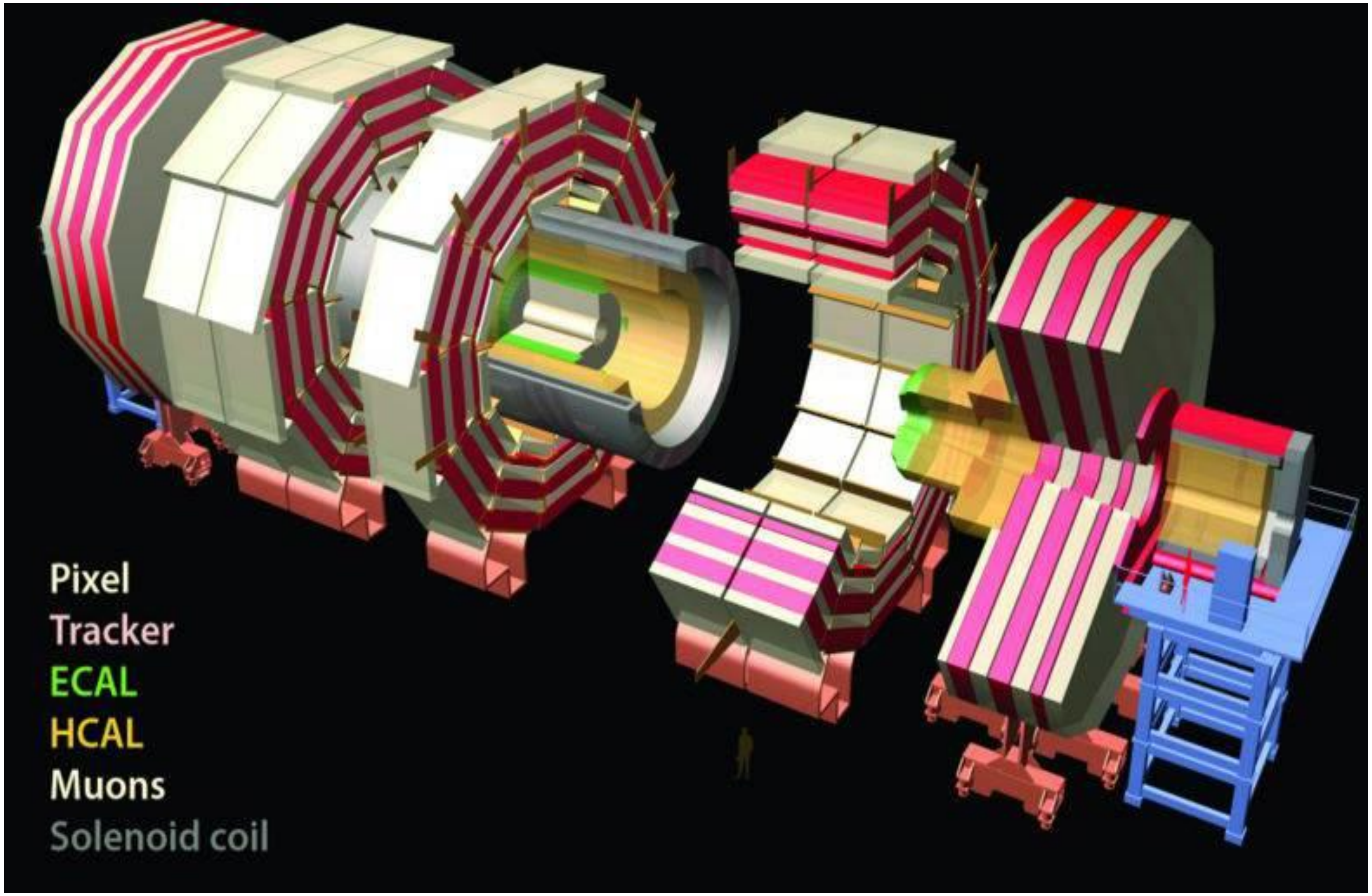
CMS in a nutshell

Took ~**2500 scientists and engineers** more than **20 years** to design and build

Is about **15 metres wide** and **21.5 metres long**

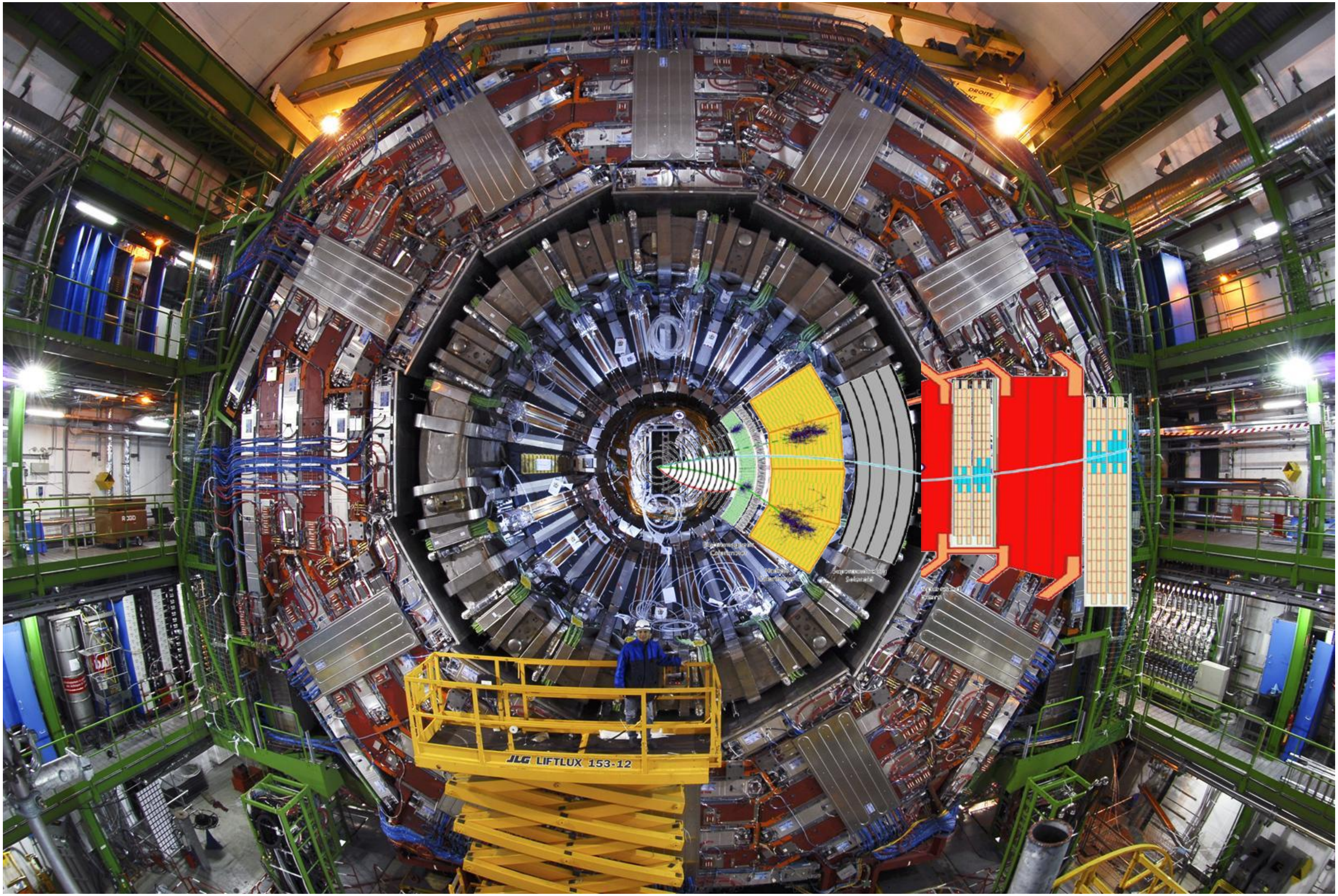
Weighs **twice as much as the Eiffel Tower** – about 14000t

Divided into **5 main detecting layers**

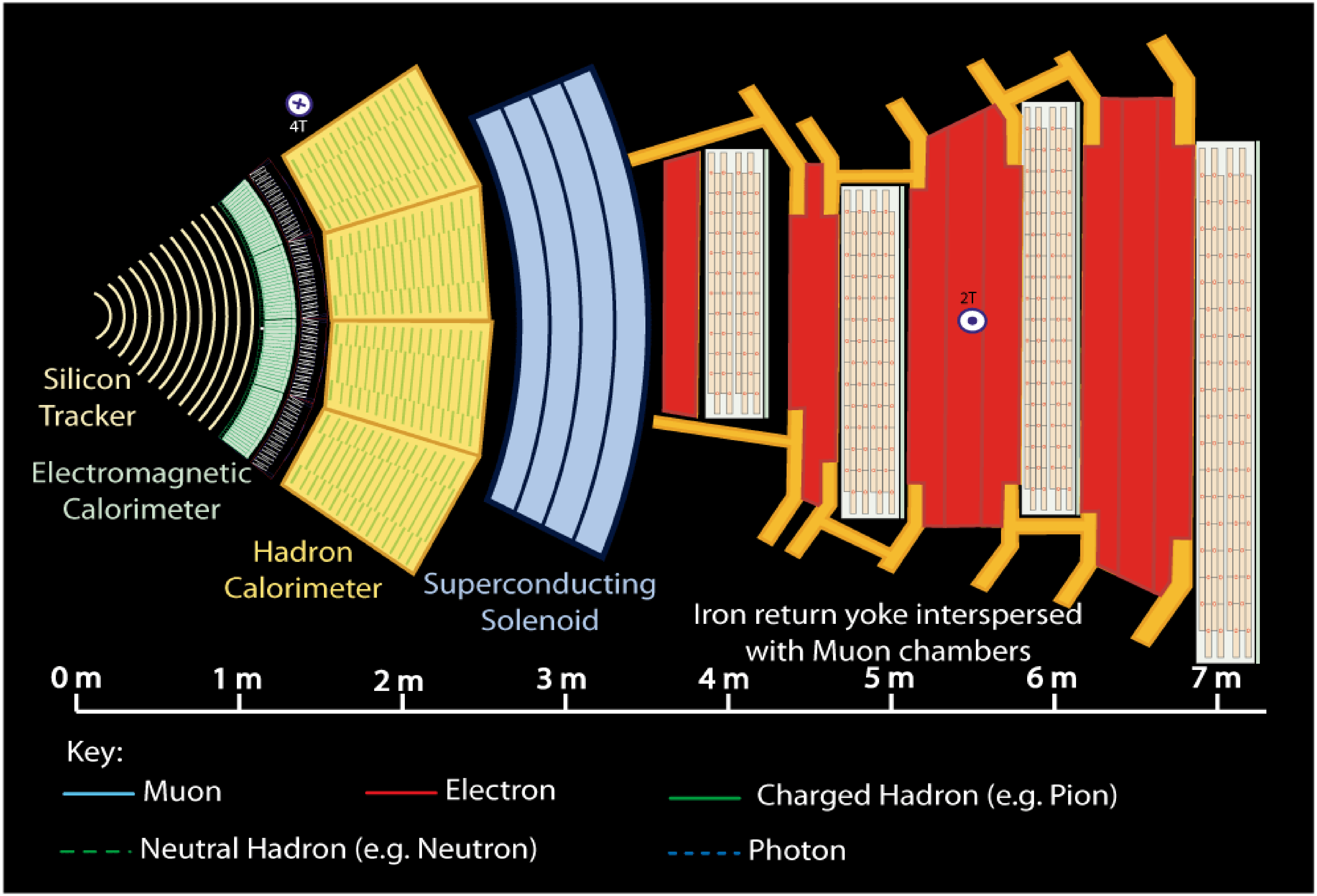


It has been performing excellently during the past 15 years, but we need it to work for another ~20! **Need to upgrade…**

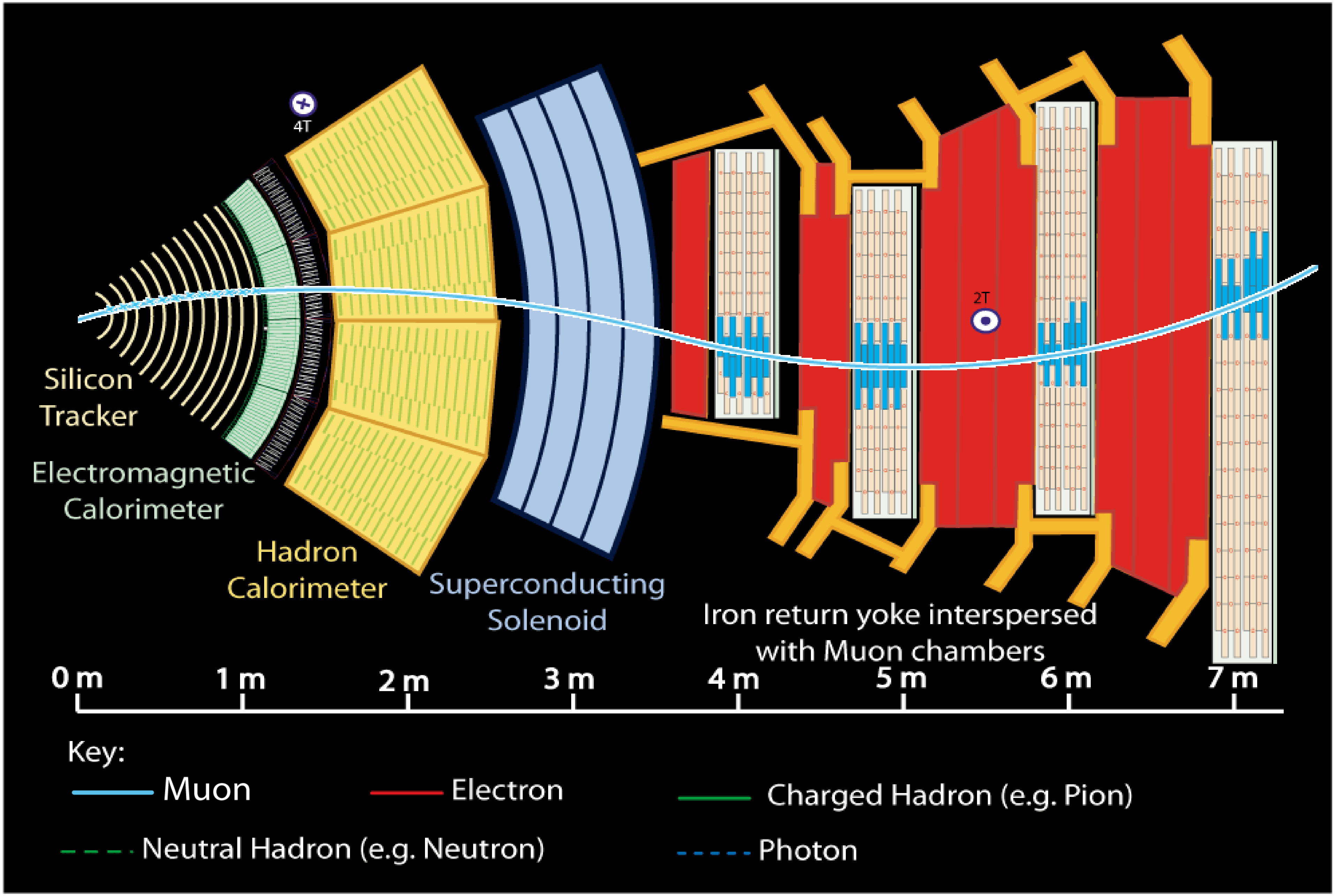
70 Mpix 3-D camera taking 40 million photos per second!



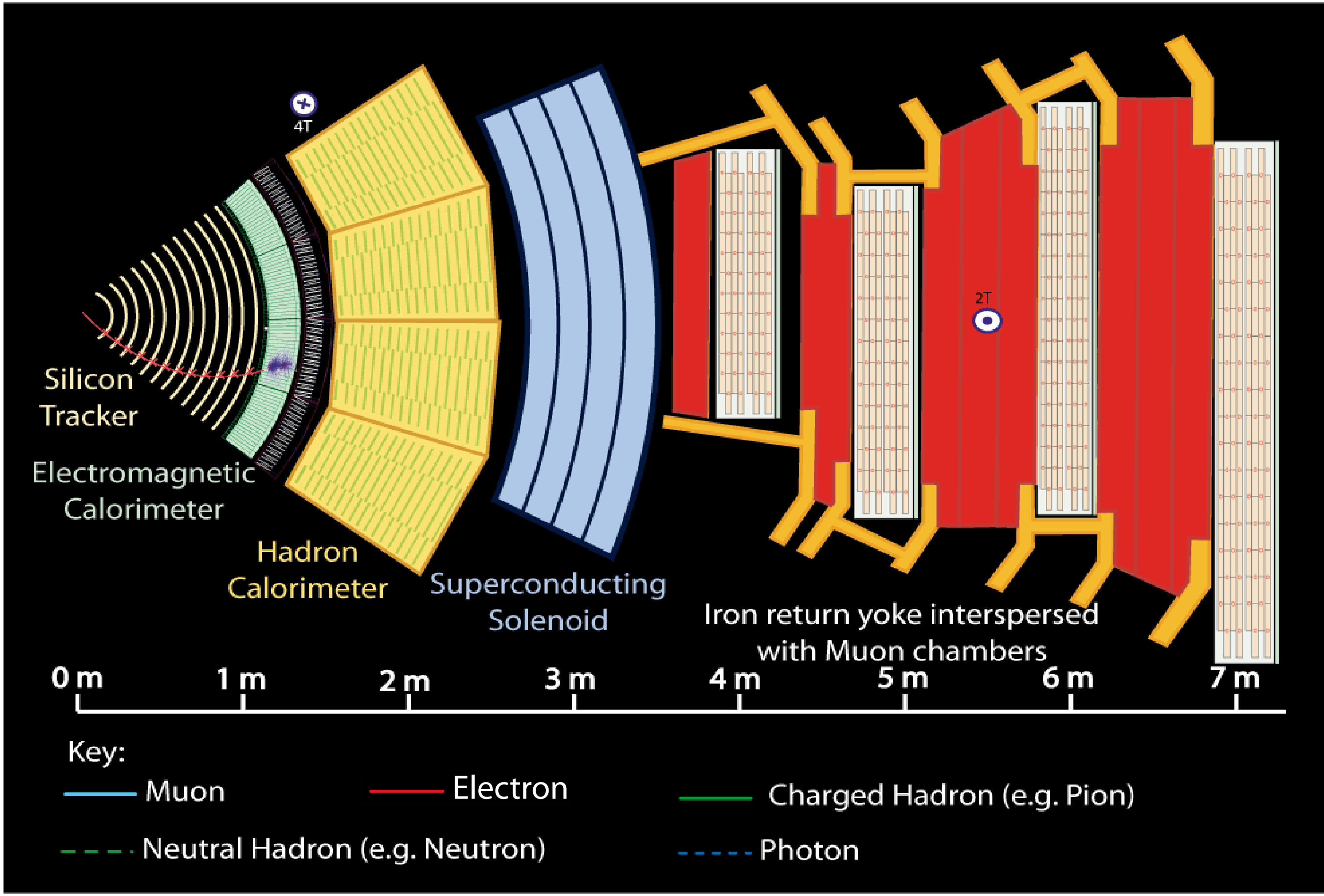
A slice through the CMS Detector



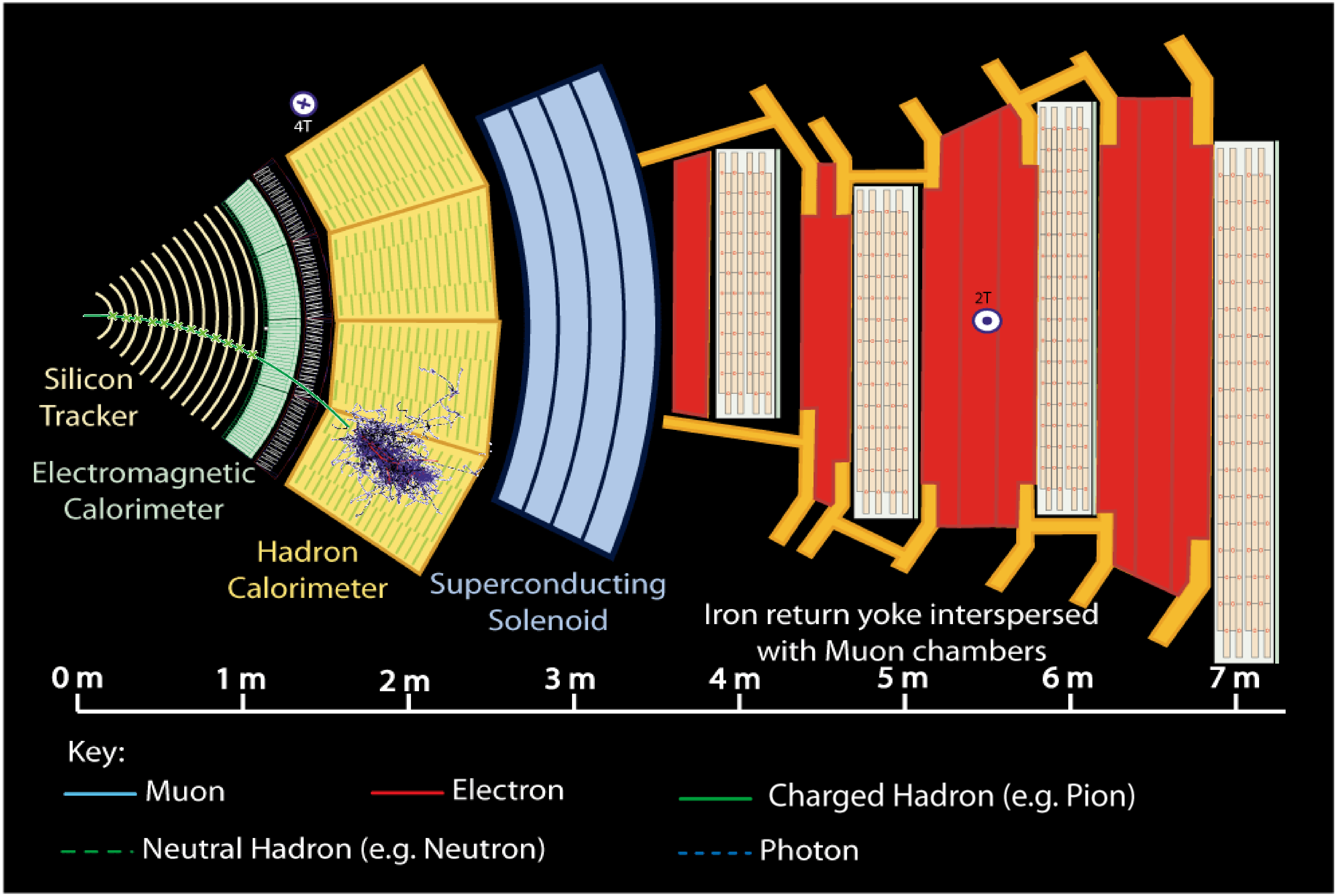
Muons in CMS


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

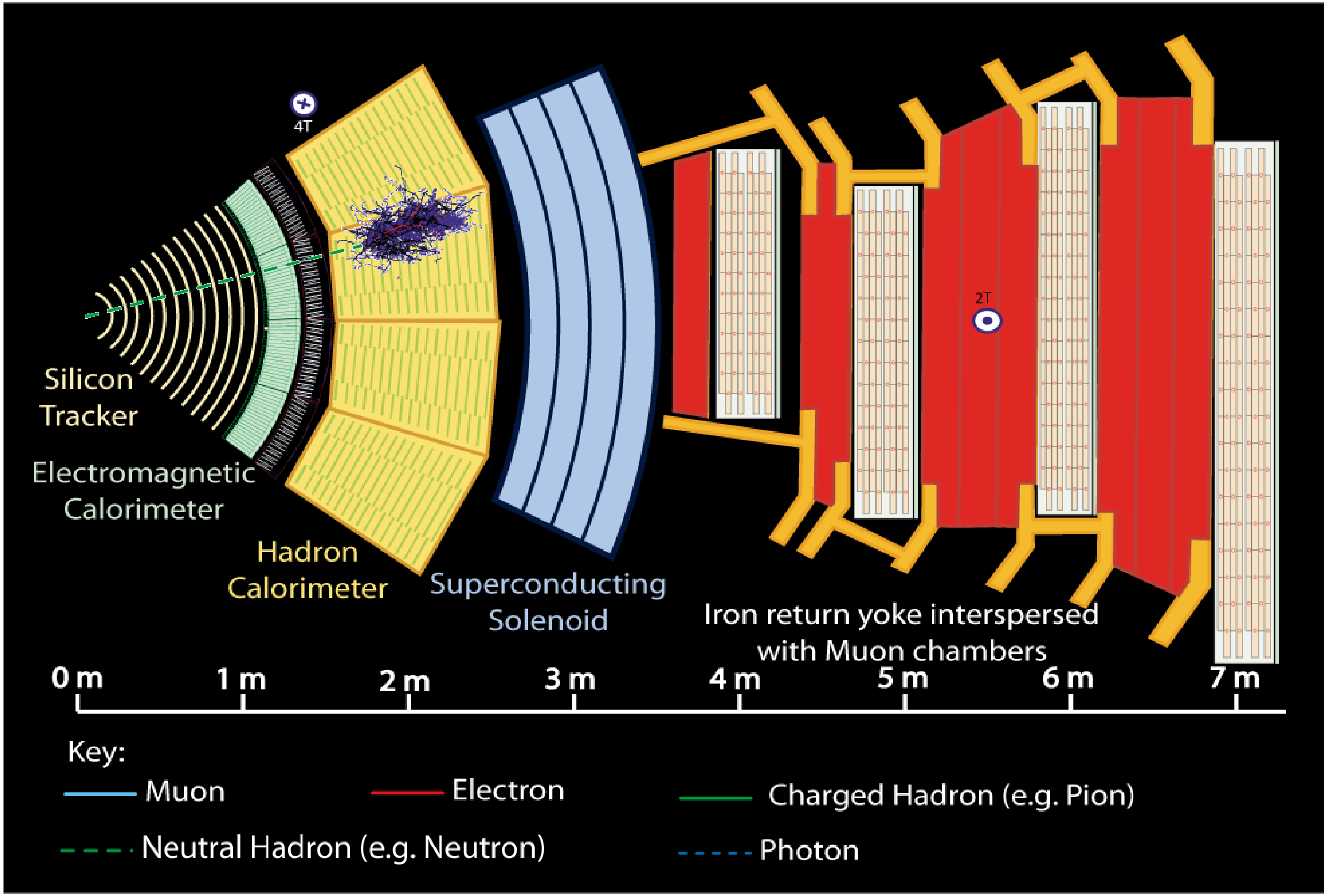
Electrons in CMS



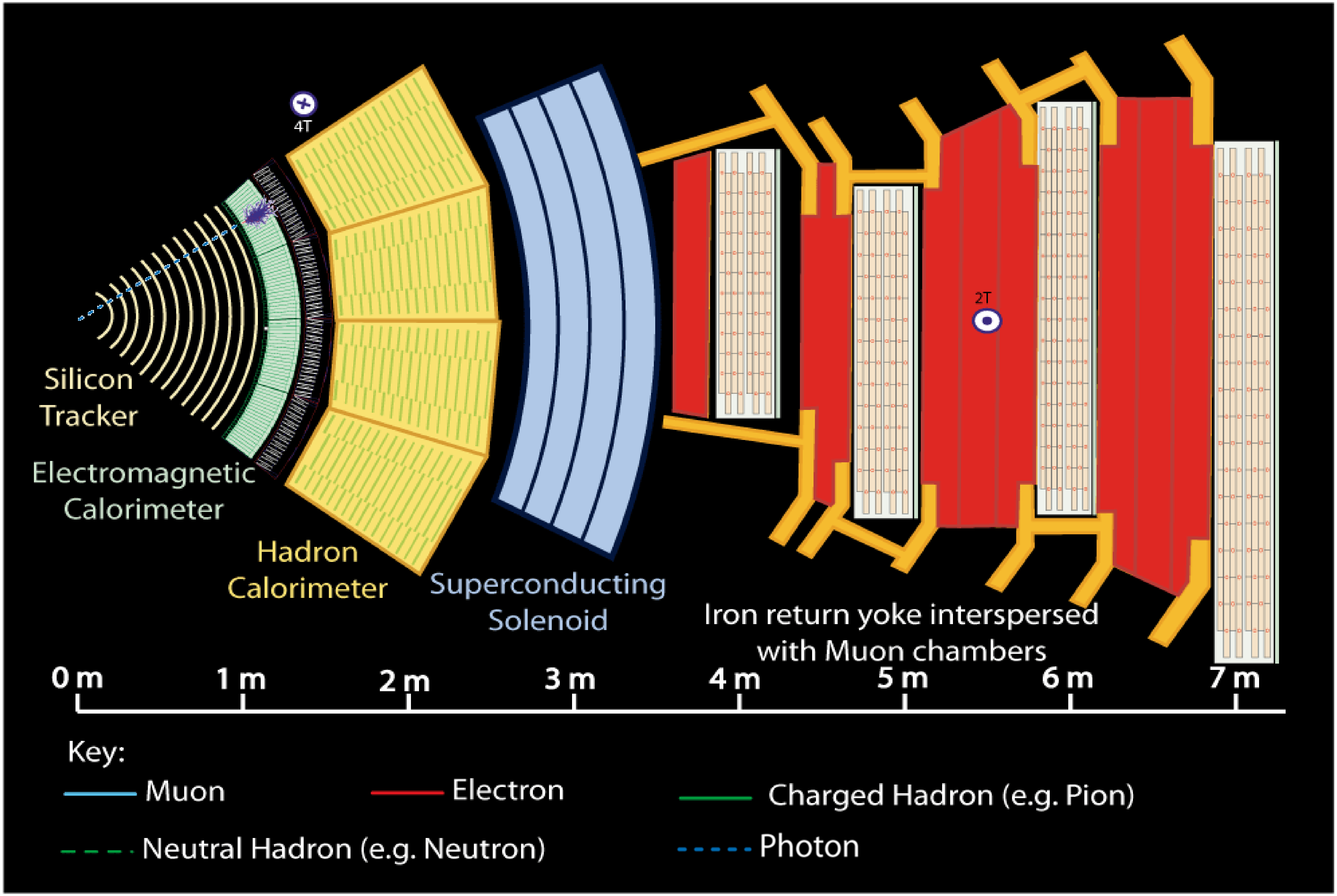
Charged hadrons in CMS



Neutral hadrons in CMS

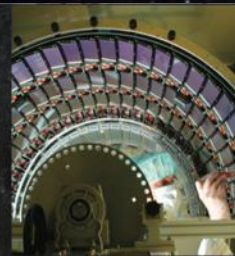


Photons in CMS



The Detector and Detectives

CMS is a large technologically advanced detector comprising many layers, each designed to perform a specific task. Together these layers allow CMS scientists to identify and precisely measure the energies and momenta of all particles produced in collisions at CERN's Large Hadron Collider (LHC).

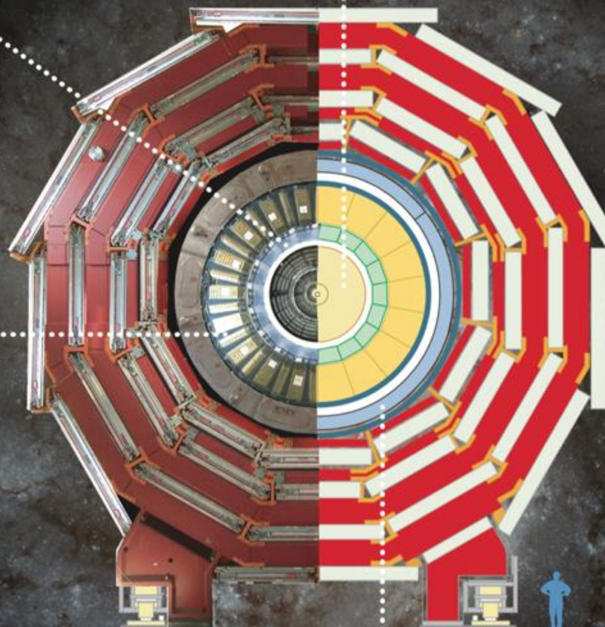


Tracker

Finely segmented silicon sensors (strips and pixels) enable charged particles to be tracked and their momenta to be measured. They also reveal the positions at which long-lived unstable particles decay.

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.



Hadron Calorimeter

Layers of dense material (brass or steel) interleaved with plastic scintillators or quartz fibres allow the determination of the energy of hadrons, that is, particles such as protons, neutrons, pions and kaons.

Muon Detectors

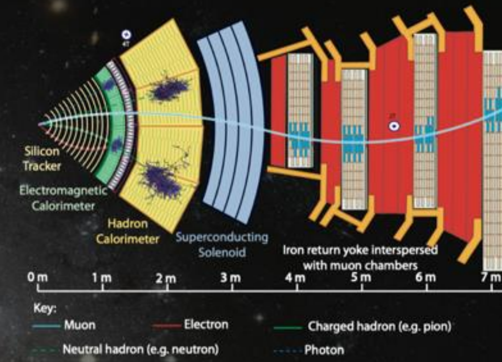
To identify muons (essentially heavy electrons) and measure their momenta, CMS uses three types of detector: drift tubes, cathode strip chambers and resistive plate chambers.

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.

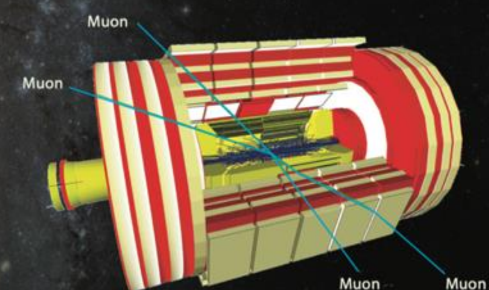
Pattern Recognition

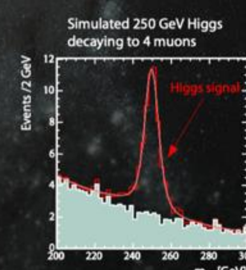
New particles discovered in CMS will be typically unstable and rapidly transform into a cascade of lighter, more stable and better understood particles. Particles travelling through CMS leave behind characteristic patterns, or 'signatures', in the different layers, allowing them to be identified. The presence (or not) of any new particles can then be inferred.



Trigger System

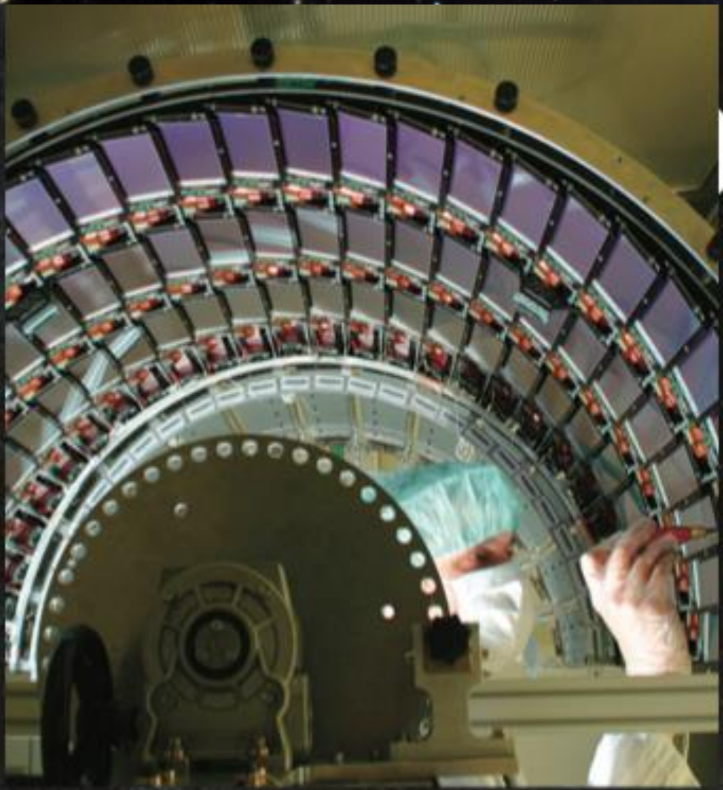
To have a good chance of producing a rare particle, such as a Higgs boson, the particle bunches in the LHC collide up to 40 million times a second. Particle signatures are analysed by fast electronics to save (or 'trigger on') only those events (around 100 per second) most likely to show new physics, such as the Higgs particle decaying to four muons in the figure below. This reduces the data rate to a manageable level. These events are stored for subsequent detailed analysis.





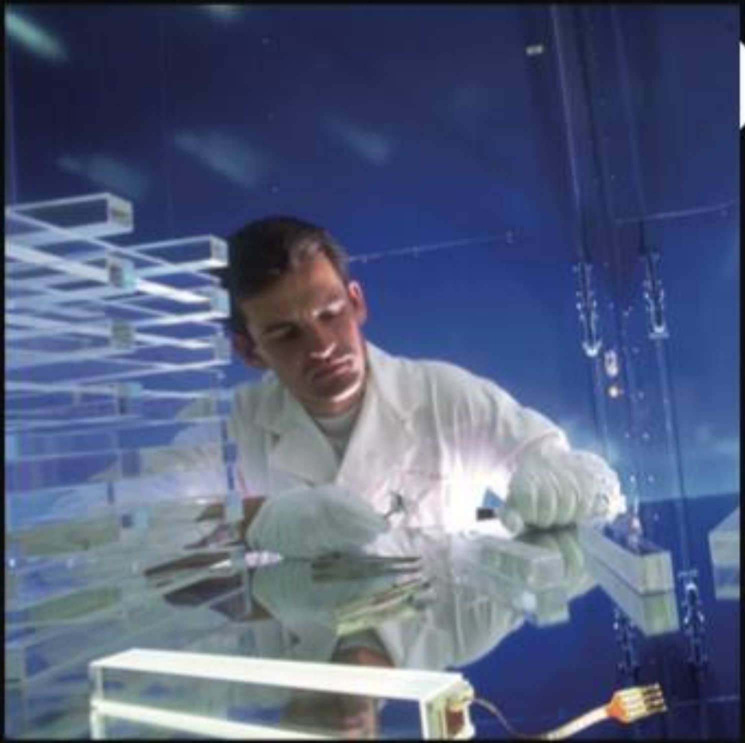
Data Analysis

Physicists from around the world use cutting-edge computing techniques (such as the Grid) to sift through millions of events from CMS to produce plots like the one on the left (a simulation) that could indicate the presence of new particles or phenomena.



Tracker

Finely segmented silicon sensors (strips and pixels) enable charged particles to be tracked and their momenta to be measured. They also reveal the positions at which long-lived unstable particles decay.



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.

Hadron Calorimeter

Layers of dense material (brass or steel) interleaved with plastic scintillators or quartz fibres allow the determination of the energy of hadrons, that is, particles such as protons, neutrons, pions and kaons.

Muon Detectors

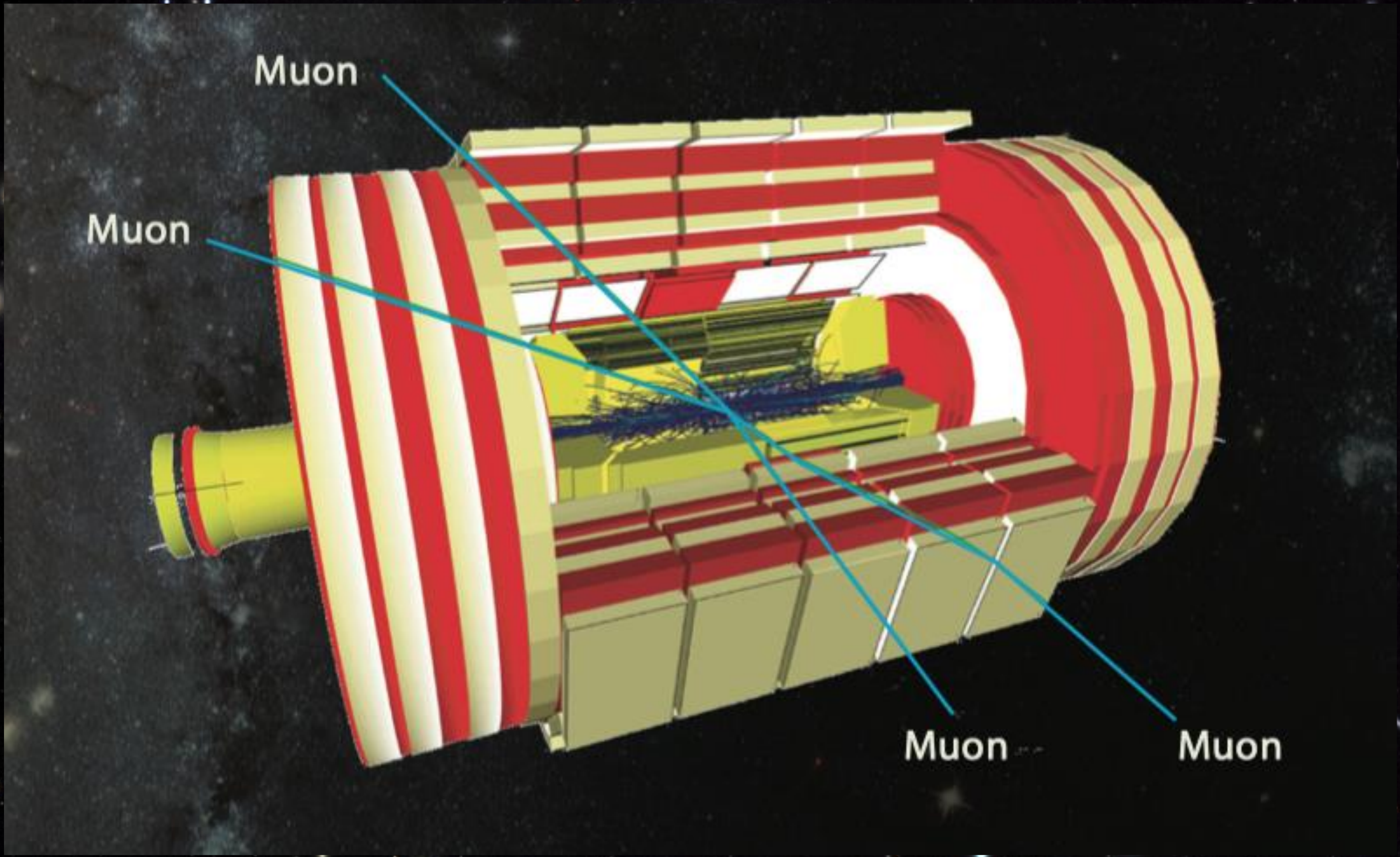
To identify muons (essentially heavy electrons) and measure their momenta, CMS uses three types of detector: drift tubes, cathode strip chambers and resistive plate chambers.

And now a 4th type - GEMs

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.

Higgs boson decay to 4 muons

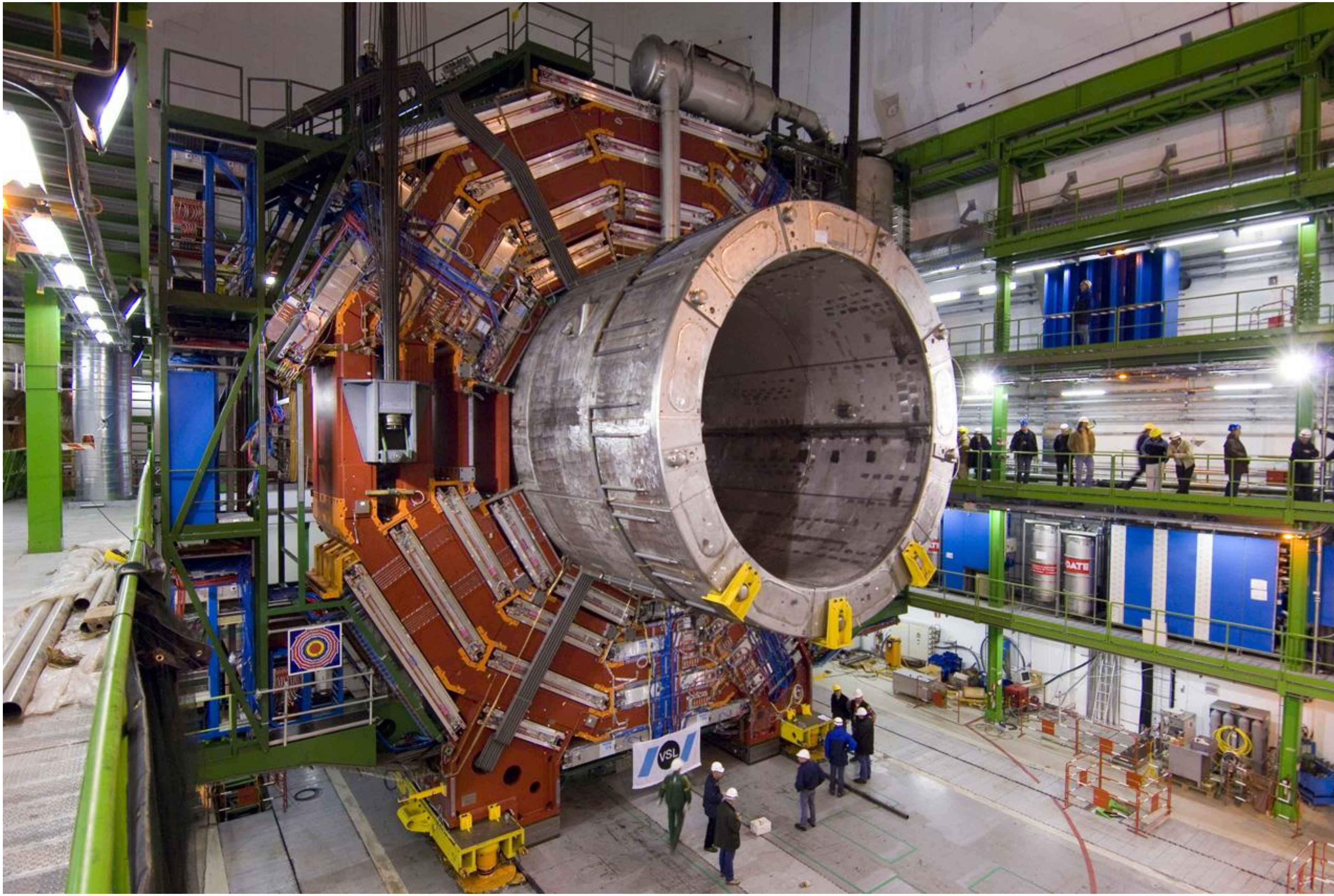


H→4μ Viewed along the beam direction

The origin of the CMS logo

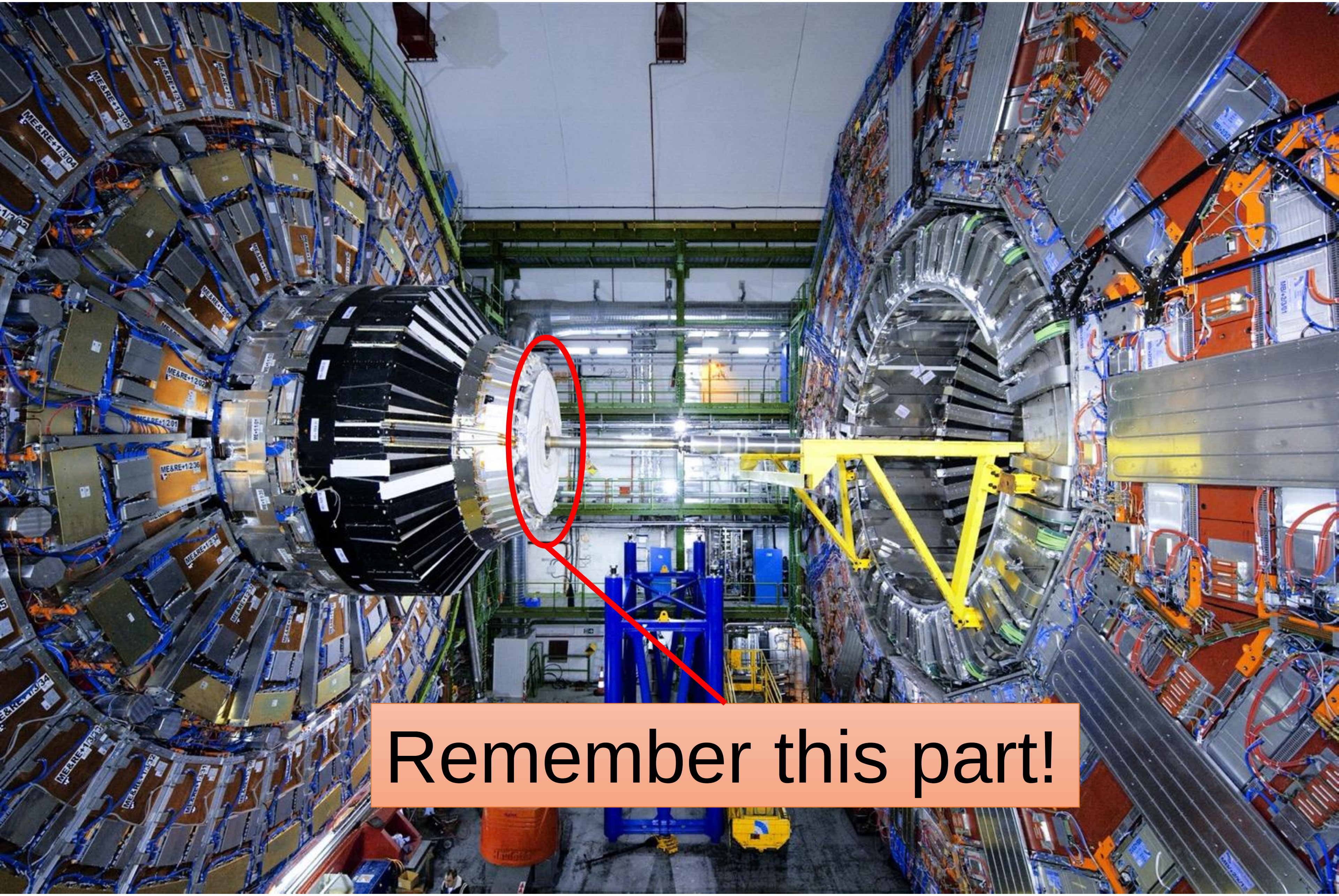
Concept: build on the surface and lower underground

Concept: build on the surface and lower underground



CMS: the most visually amazing detector ever made!

(I may be biased!)



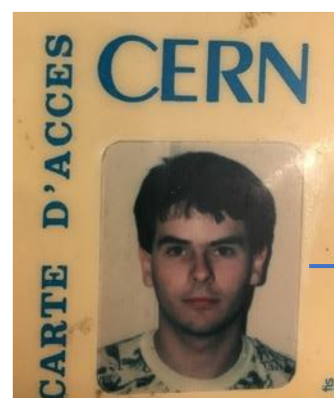
How did I get here?

- Born and bred in the UK. Left school with “OK” A-levels in Physics, Maths, Chemistry and Computer Science

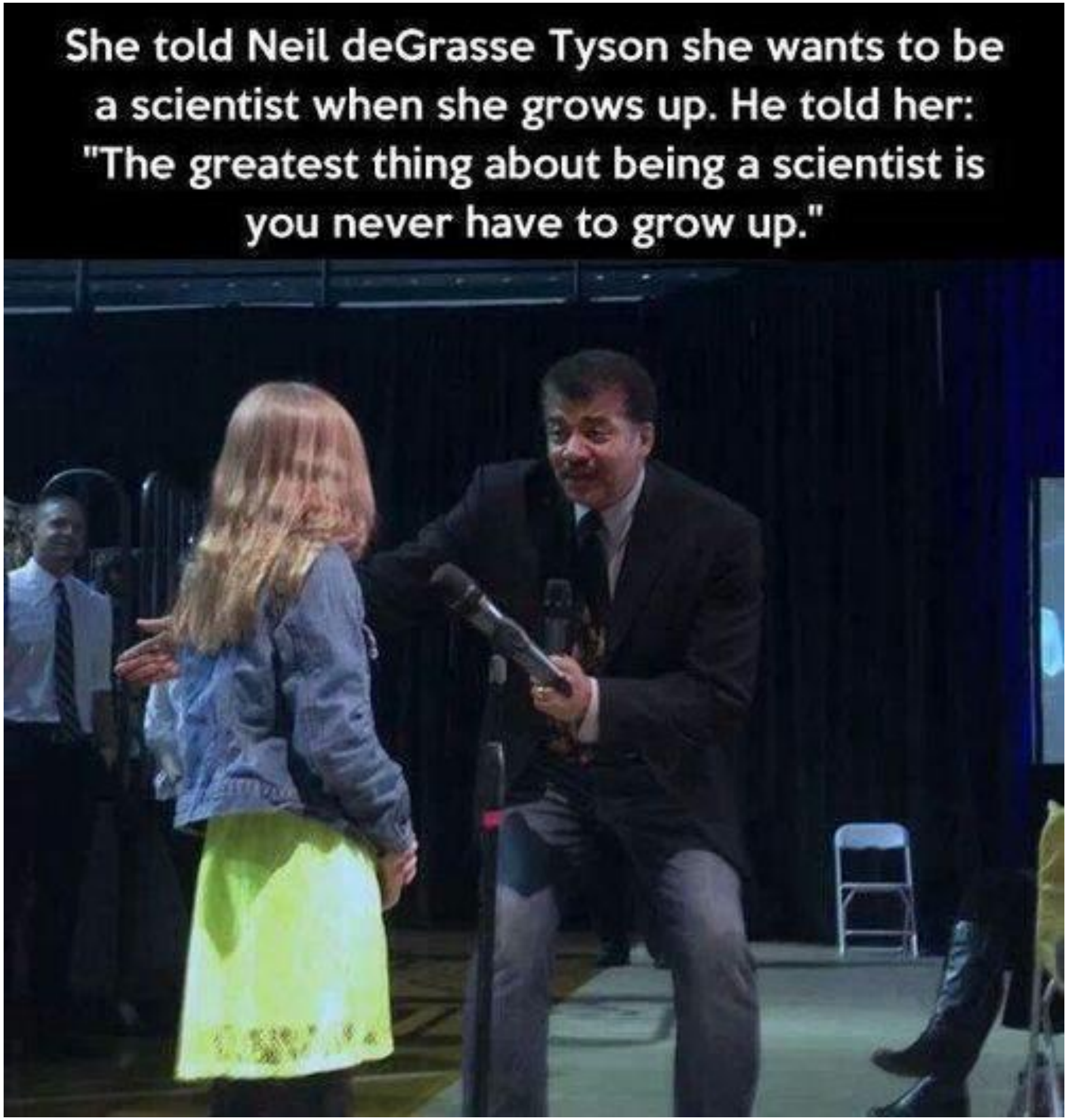
- BSc degree in Physics at Imperial College London (1987-1990)

- PhD in High Energy Physics at Imperial (1990-1993)

- Have been working for CERN for the CMS Experiment for 29 years!



Why did I become a scientist?



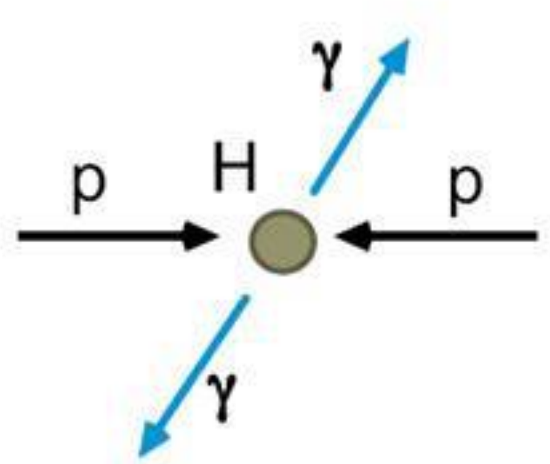
It was also because I had an inspiring physics teacher – Mr. Robert Wilson, of Gaywood Park High School (now King’s Lynn Academy) in King’s Lynn, Norfolk, UK

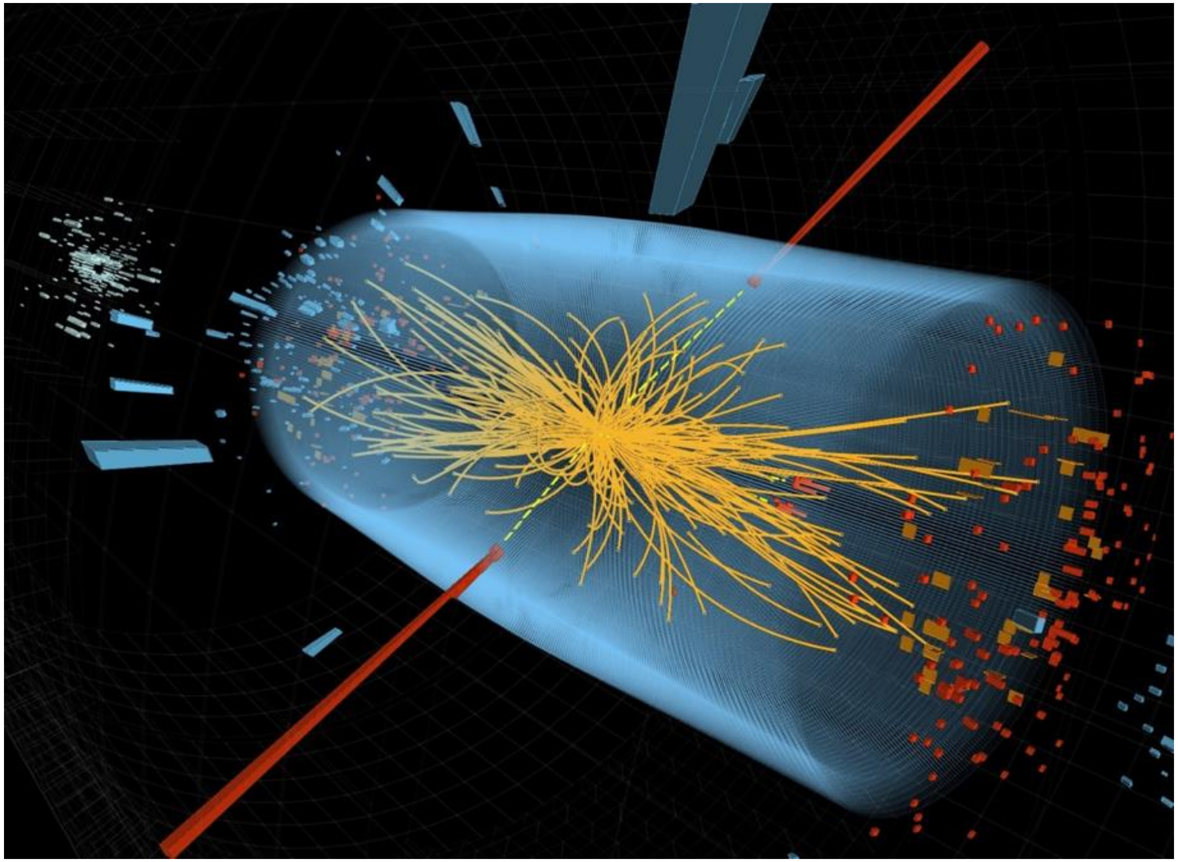
It has been a family affair!

It has been a family affair!

How did CMS find the Higgs boson?

Original CMS design partly based on “seeing” the Higgs boson through its decay to a pair of isolated photons



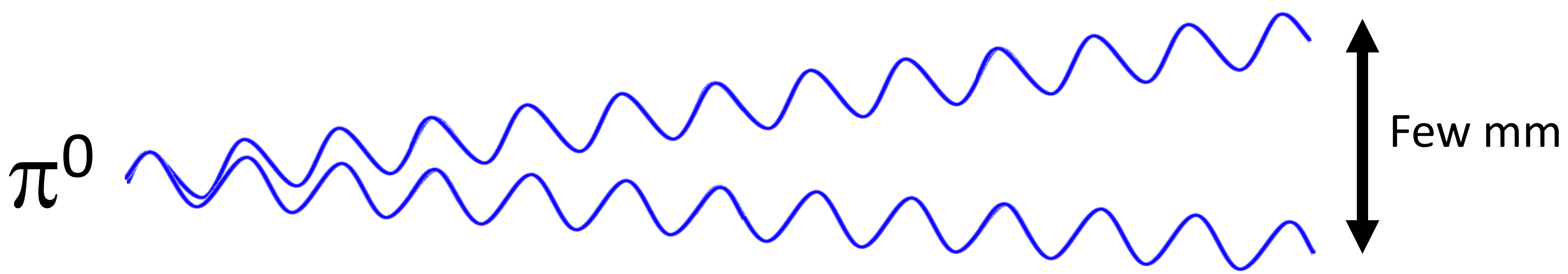


And this is what CMS saw in 2011!

But it wasn't quite that easy!

Photons in CMS don't only come from decays of Higgs bosons

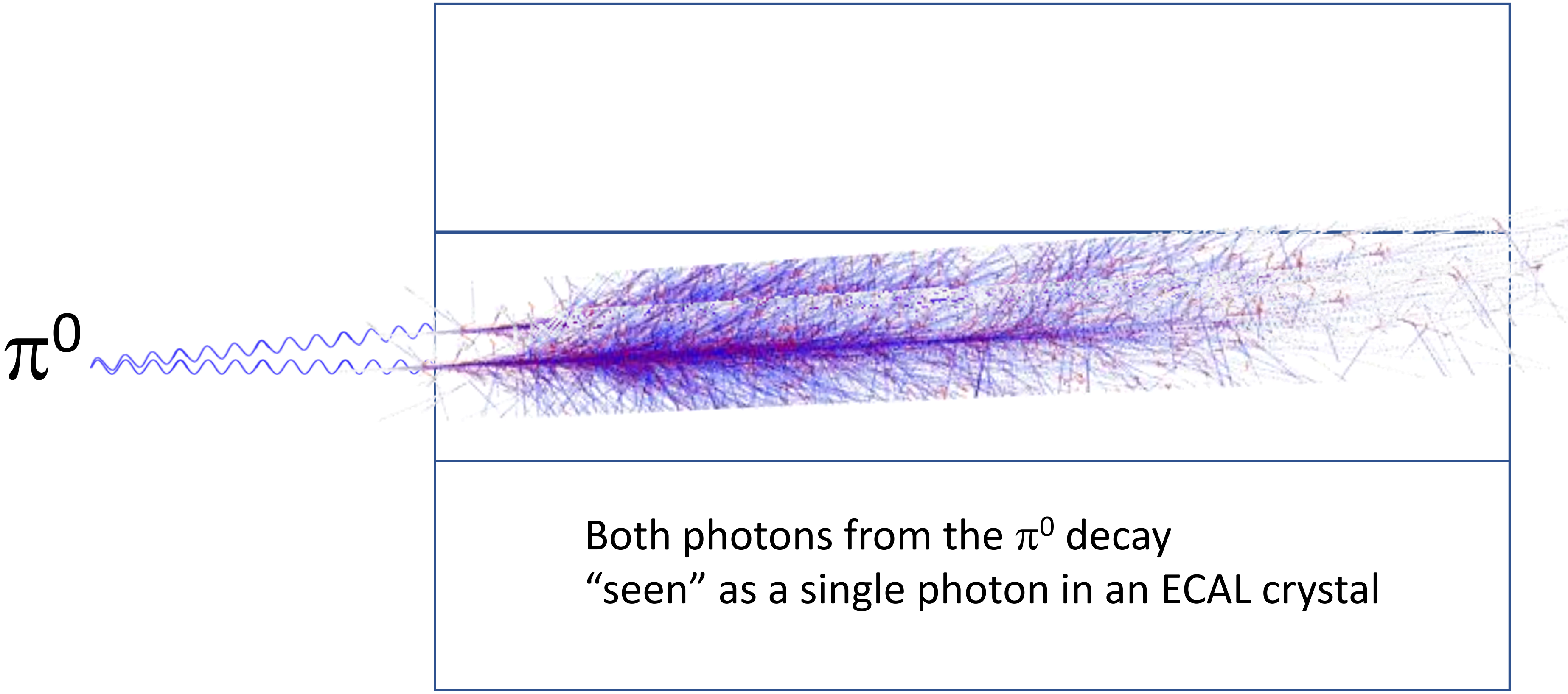
In fact there are other things that "mimic" isolated photons, including decays of neutral pions (π^0), that happen far more frequently than Higgs boson decays!



But it wasn't quite that easy!

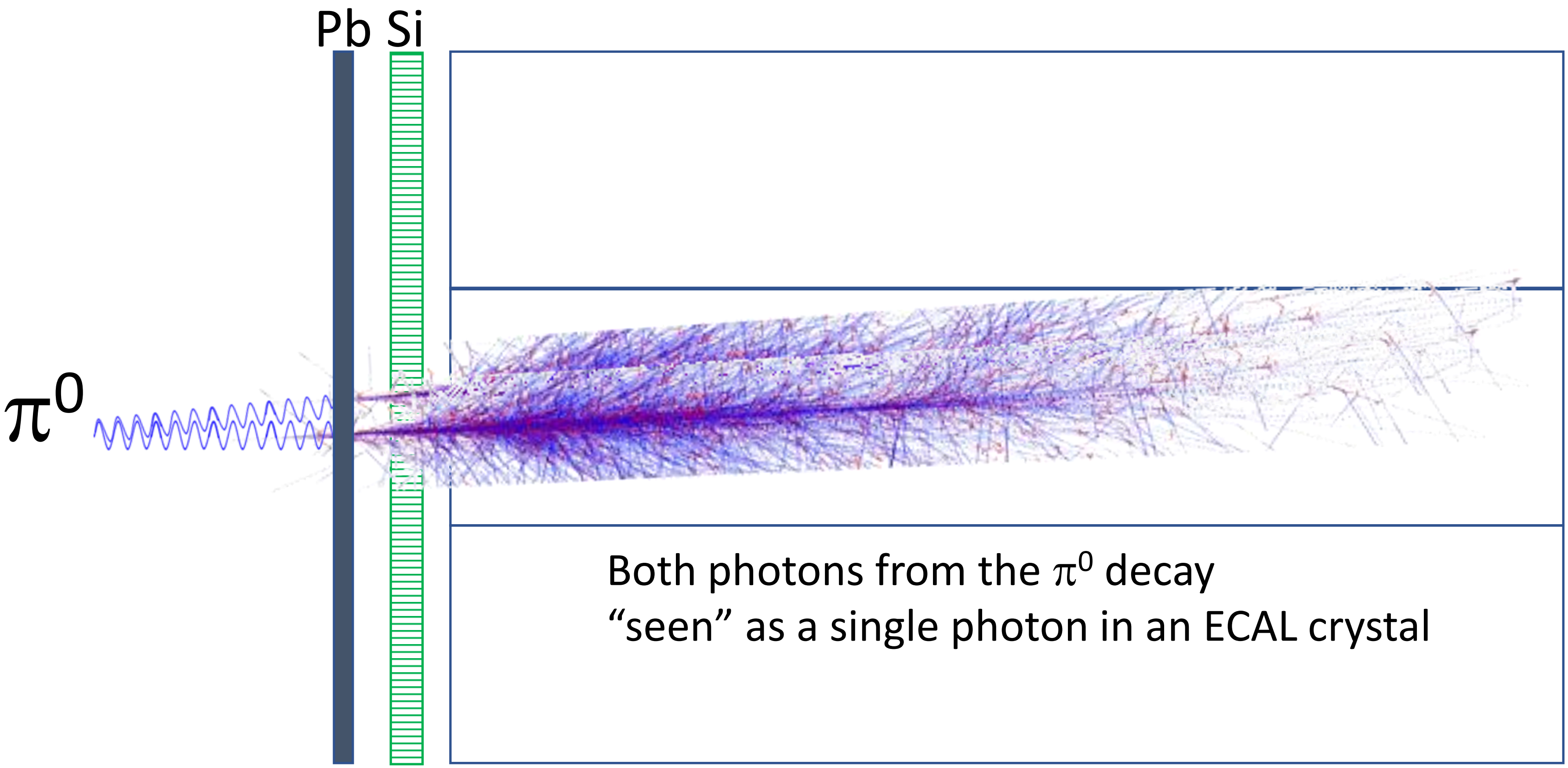
Photons in CMS don't only come from decays of Higgs bosons

In fact there are other things that "mimic" isolated photons, including decays of neutral pions (π^0), that happen far more frequently than Higgs boson decays!



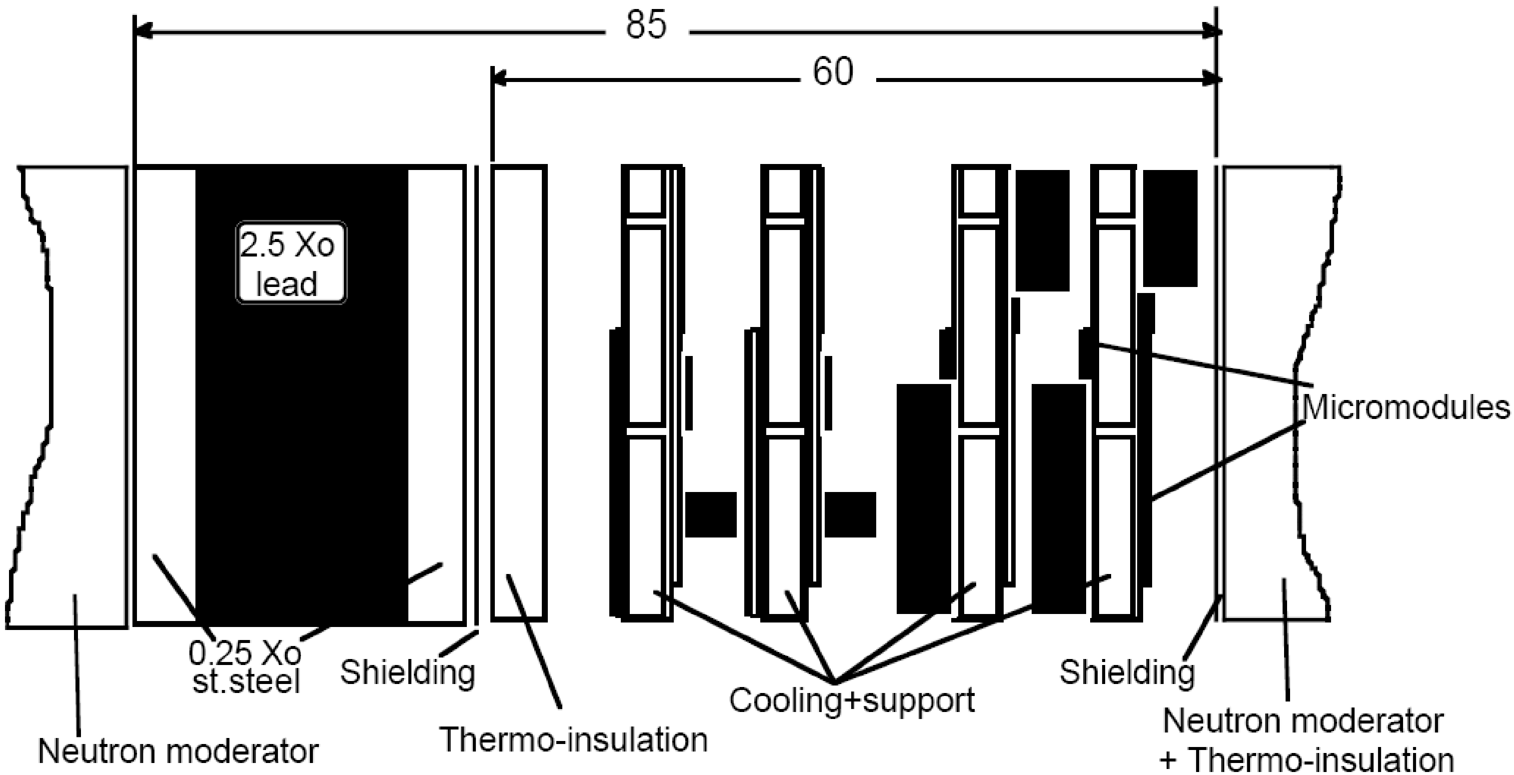
The concept of the Preshower

Put a lead sheet (to initiate electromagnetic showers) and a highly-segmented silicon detector in front of the crystals, to distinguish single photons from closely-space double photons



When I joined CMS in 1994…

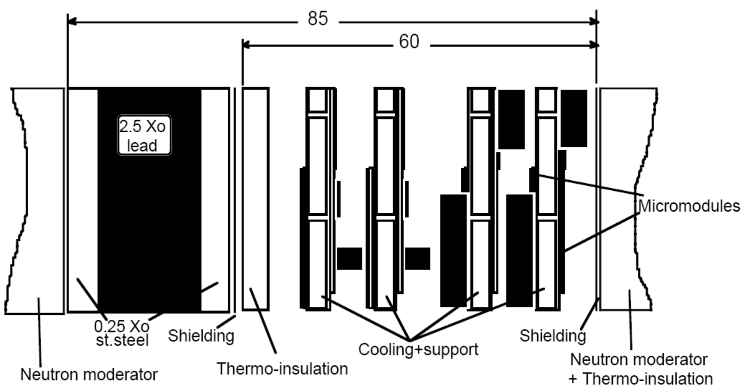
My job was to turn this concept…

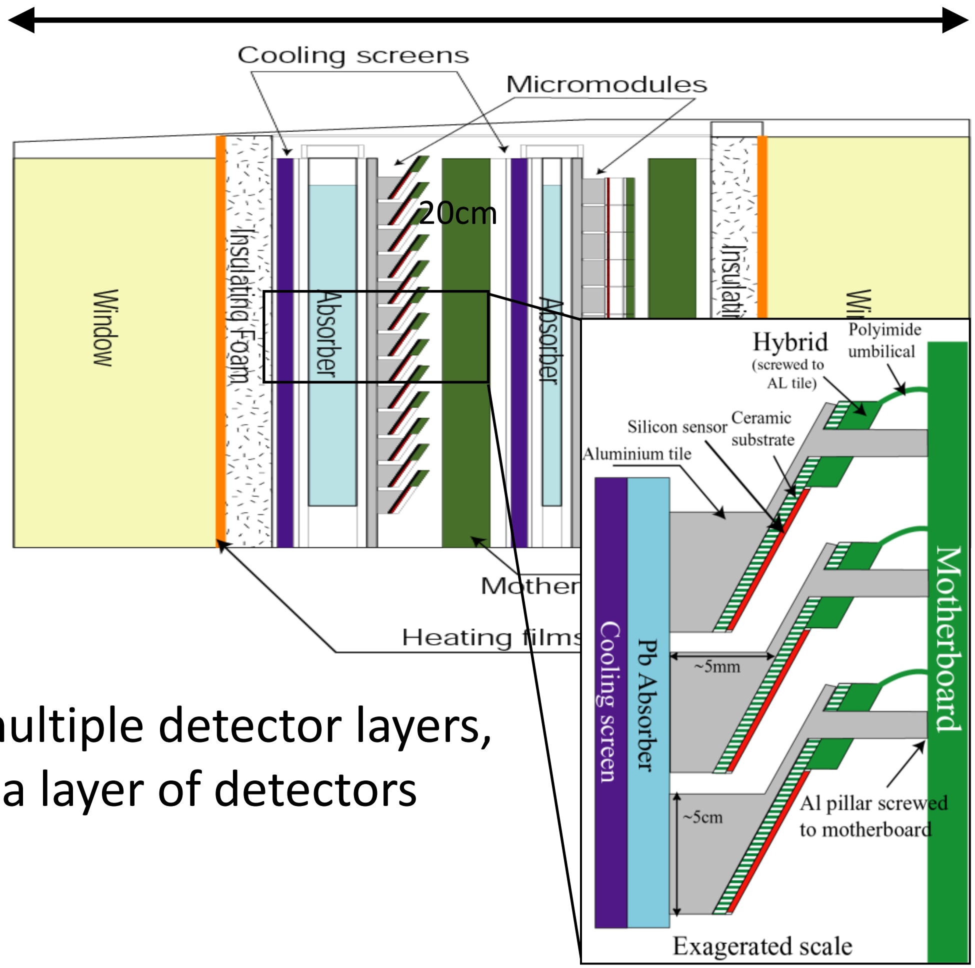


…into some sort of reality

Examples of 3 years of work as an applied physicist!

- Simulation of Preshower detector in CMS:
  - Does it do what it was meant to do? **NO!**
    → overall design was modified/optimized significantly



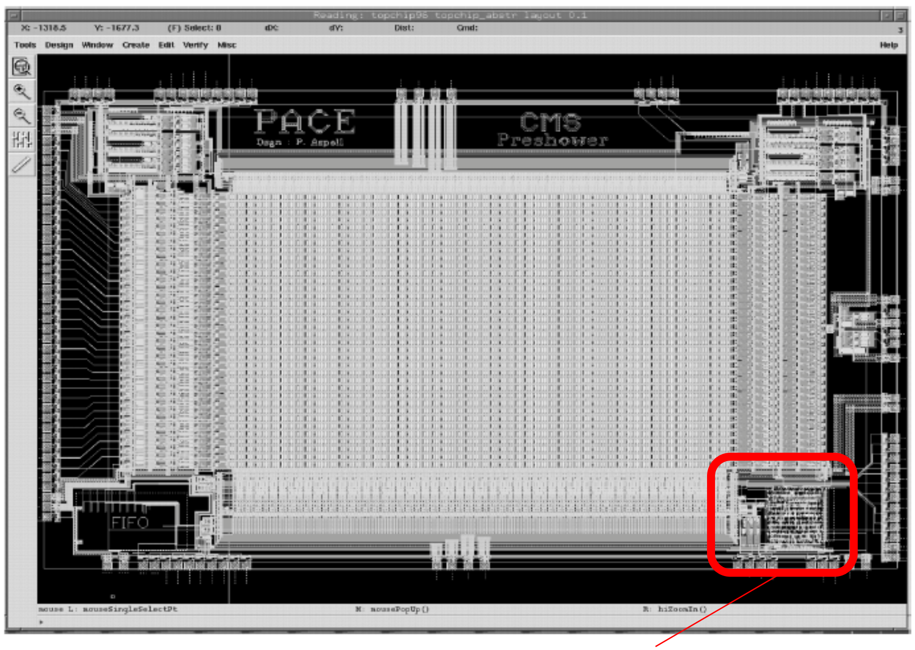


Instead of one absorber followed by multiple detector layers, have two absorbers, each followed by a layer of detectors
➔ essentially the final basic design!

Examples of 3 years of work as an applied physicist!

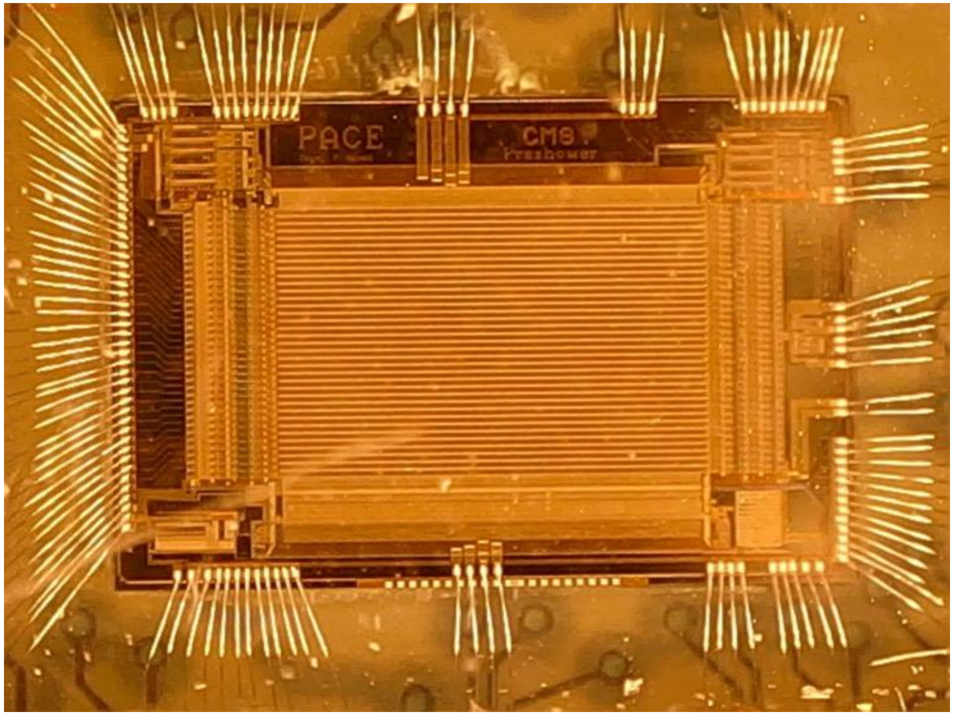
- Designed a part of the prototype front-end microelectronics, called the “sequencer” (determines the order in which to do things etc.)

Below: design of the ”PACE” front-end micro-electronics chip for the Preshower



Dave did this!

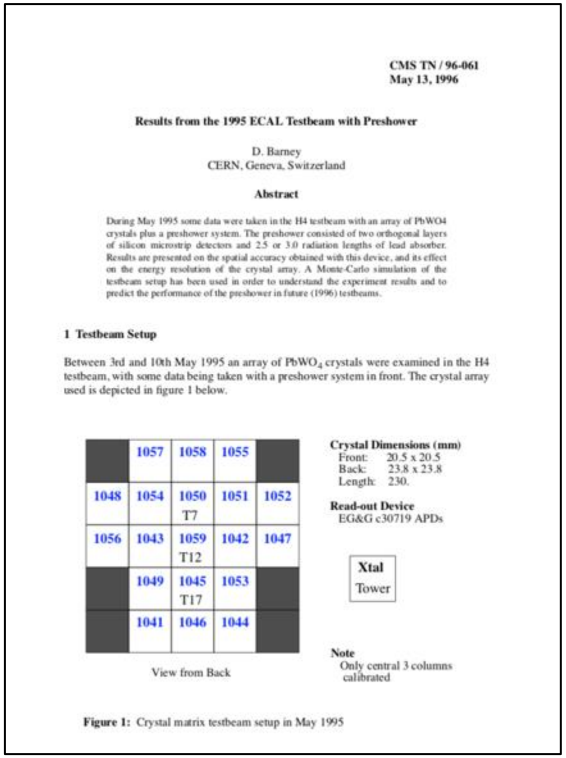
Below: photograph of the ”PACE” front-end micro-electronics chip for the Preshower



~10mm

Examples of 3 years of work as an applied physicist!

- Built and tested prototype silicon detector modules in particle beams at CERN
  → it works!



CMS TN / 96-061
May 13, 1996

Results from the 1995 ECAL Testbeam with Preshower

D. Barney
CERN, Geneva, Switzerland

Abstract

During May 1995 some data were taken in the H4 testbeam with an array of PbWO4 crystals plus a preshower system. The preshower consisted of two orthogonal layers of silicon microstrip detectors and 2.5 or 3.0 radiation lengths of lead absorber. Results are presented on the spatial accuracy obtained with this device, and its effect on the energy resolution of the crystal array. A Monte-Carlo simulation of the testbeam setup has been used in order to understand the experiment results and to predict the performance of the preshower in future (1996) testbeams.

1 Testbeam Setup

Between 3rd and 10th May 1995 an array of $PbWO_4$ crystals were examined in the H4 testbeam, with some data being taken with a preshower system in front. The crystal array used is depicted in figure 1 below.

	1057	1058	1055	
1048	1054	1050 T7	1051	1052
1056	1043	1059 T12	1042	1047
	1049	1045 T17	1053	
	1041	1046	1044	

View from Back

Crystal Dimensions (mm)
Front: 20.5 x 20.5
Back: 23.8 x 23.8
Length: 230.

Read-out Device
EG&G c30719 APDs

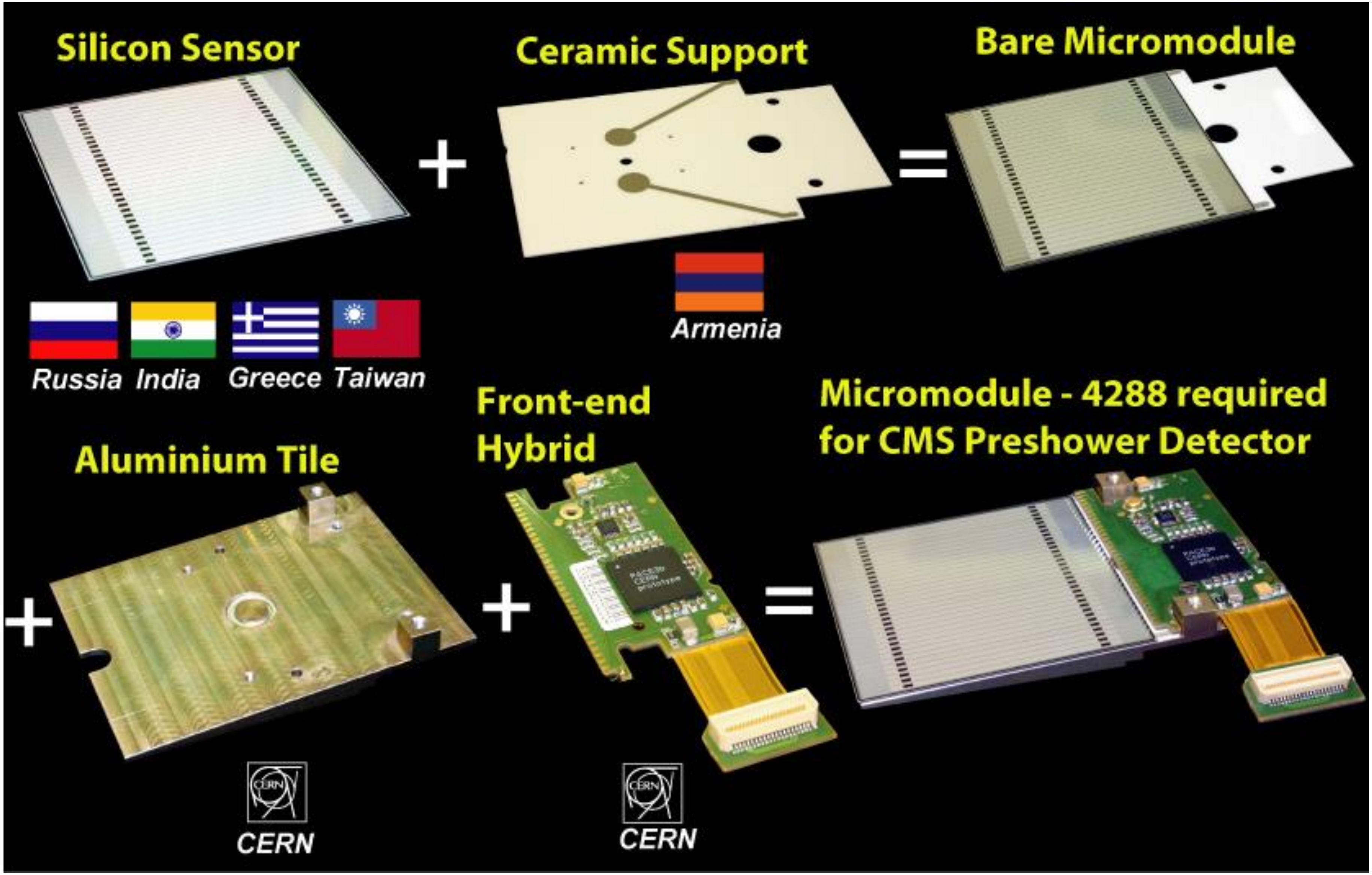
Xtal
Tower

Note
Only central 3 columns calibrated

Figure 1: Crystal matrix testbeam setup in May 1995

Results written-up in official notes

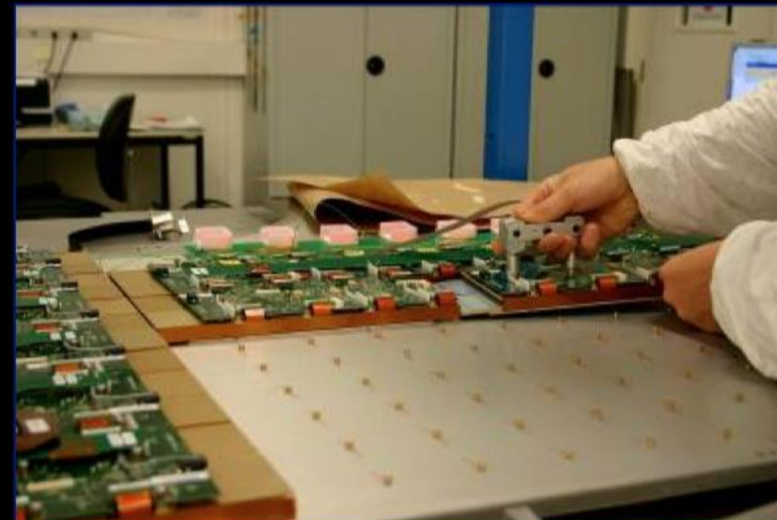
It’s all about teamwork!



A few years later…

2008: Final assembly and testing

3 types of “ladder” filled with Si sensors

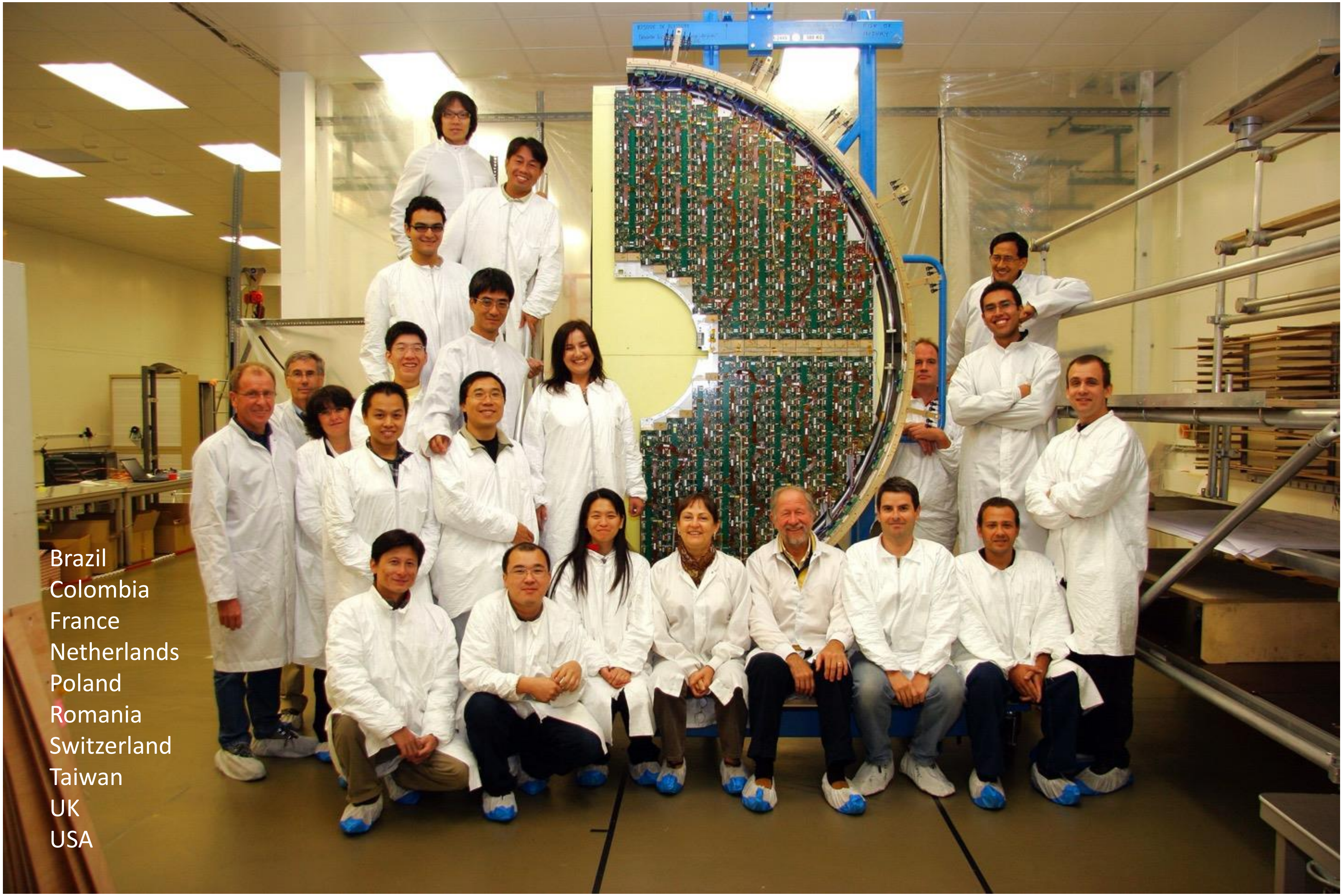


Installing ladders on the absorbers

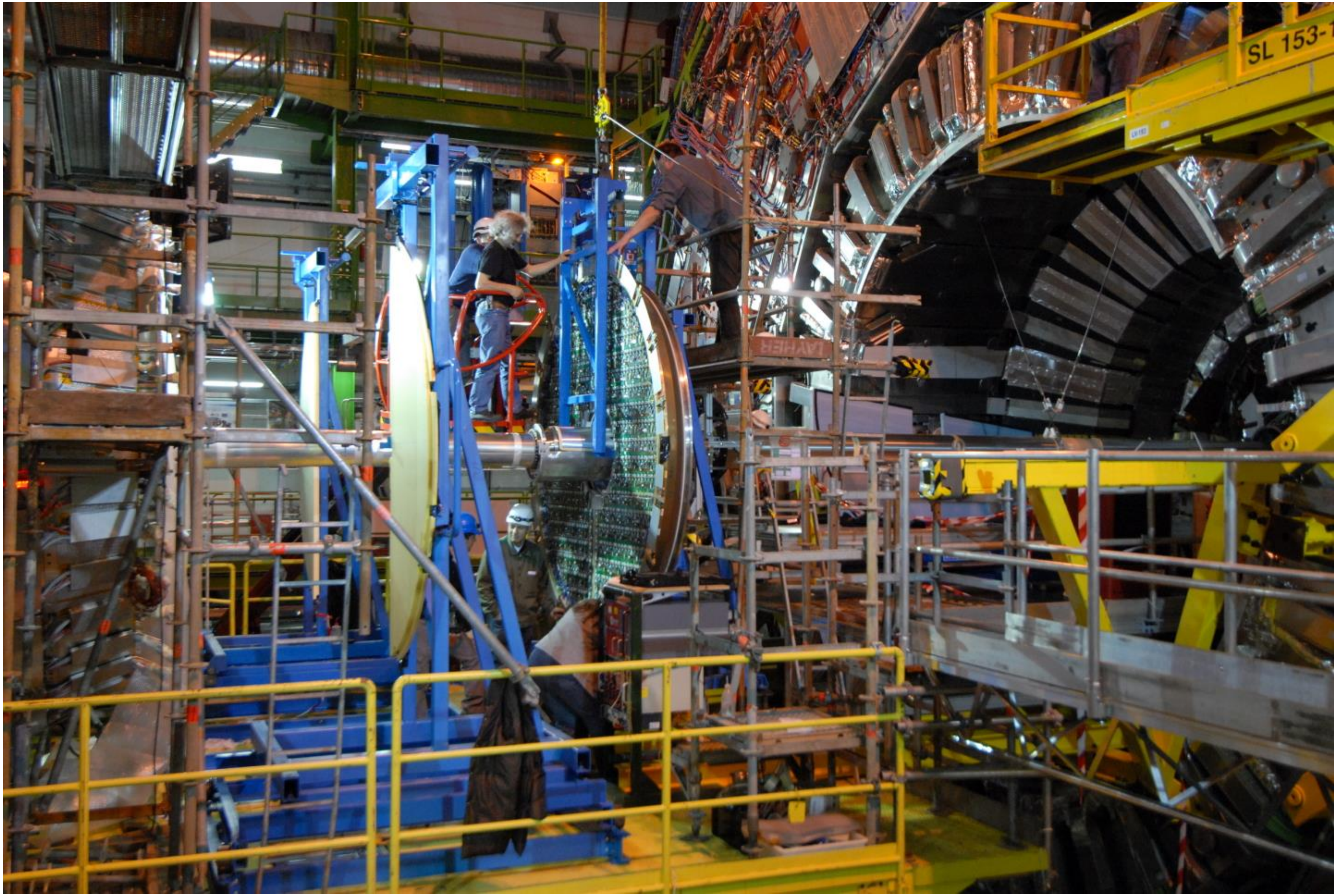
Testing a column of ladders

Fully assembled “Dee” plane

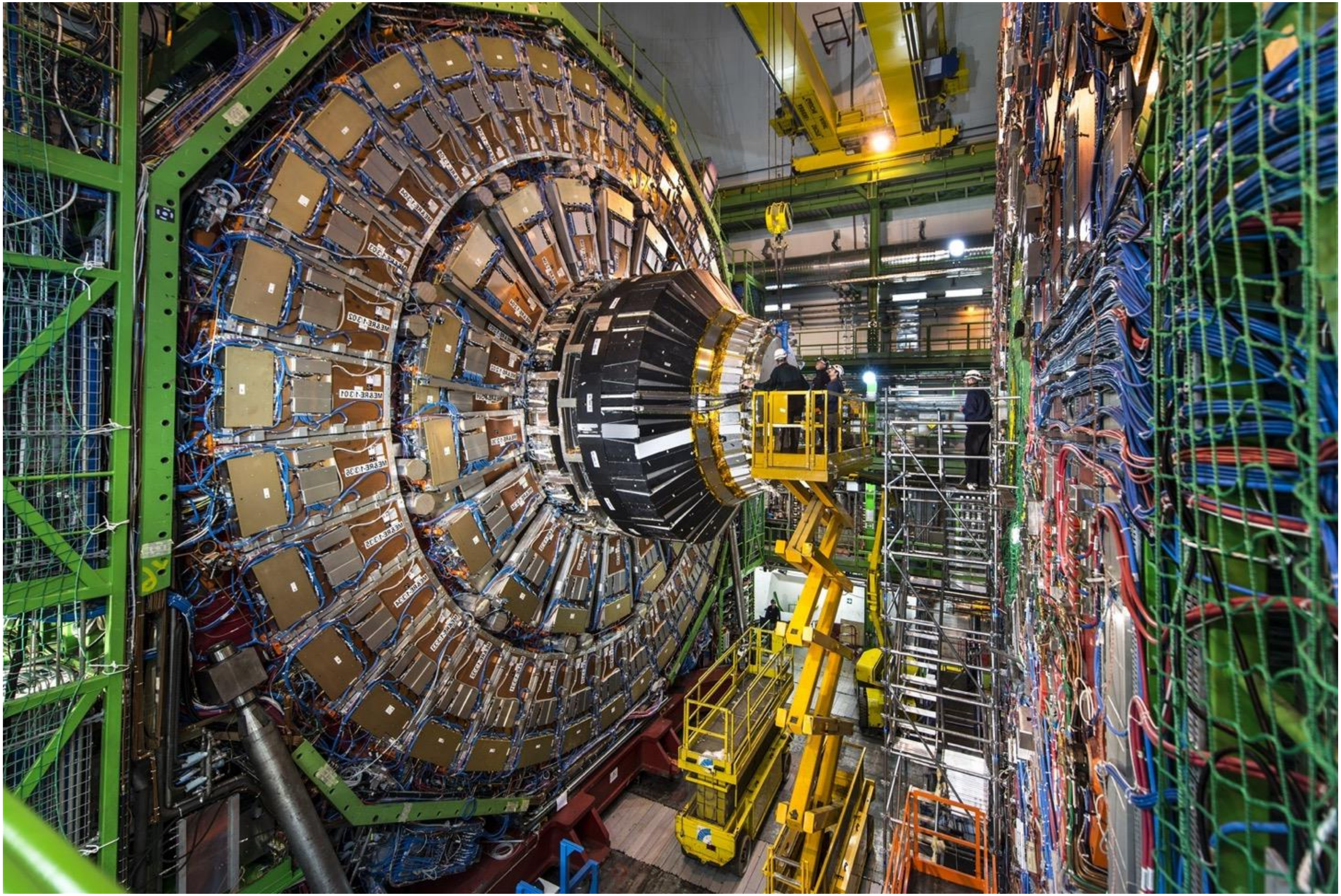
A few years later…



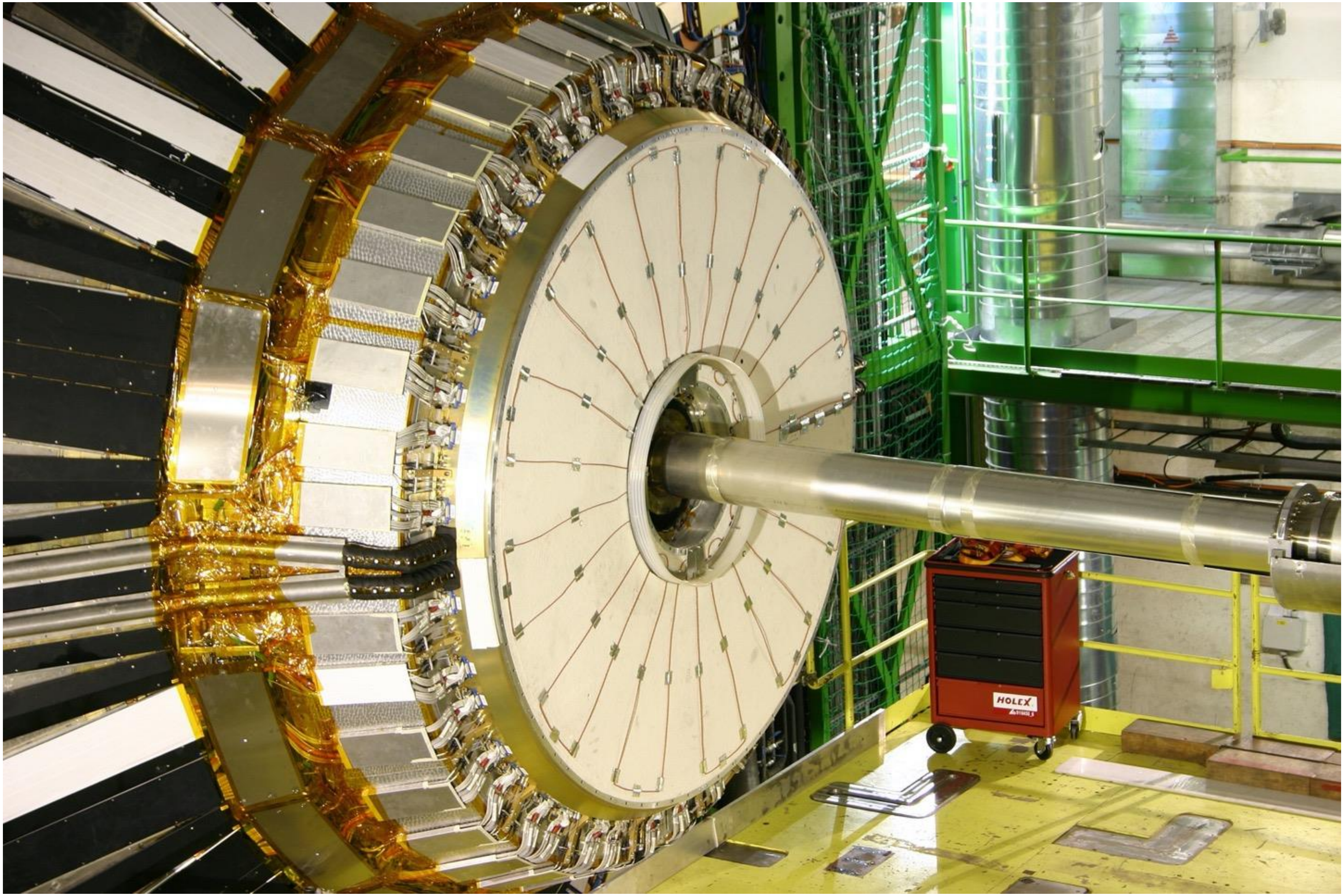
Installation of Preshower in CMS



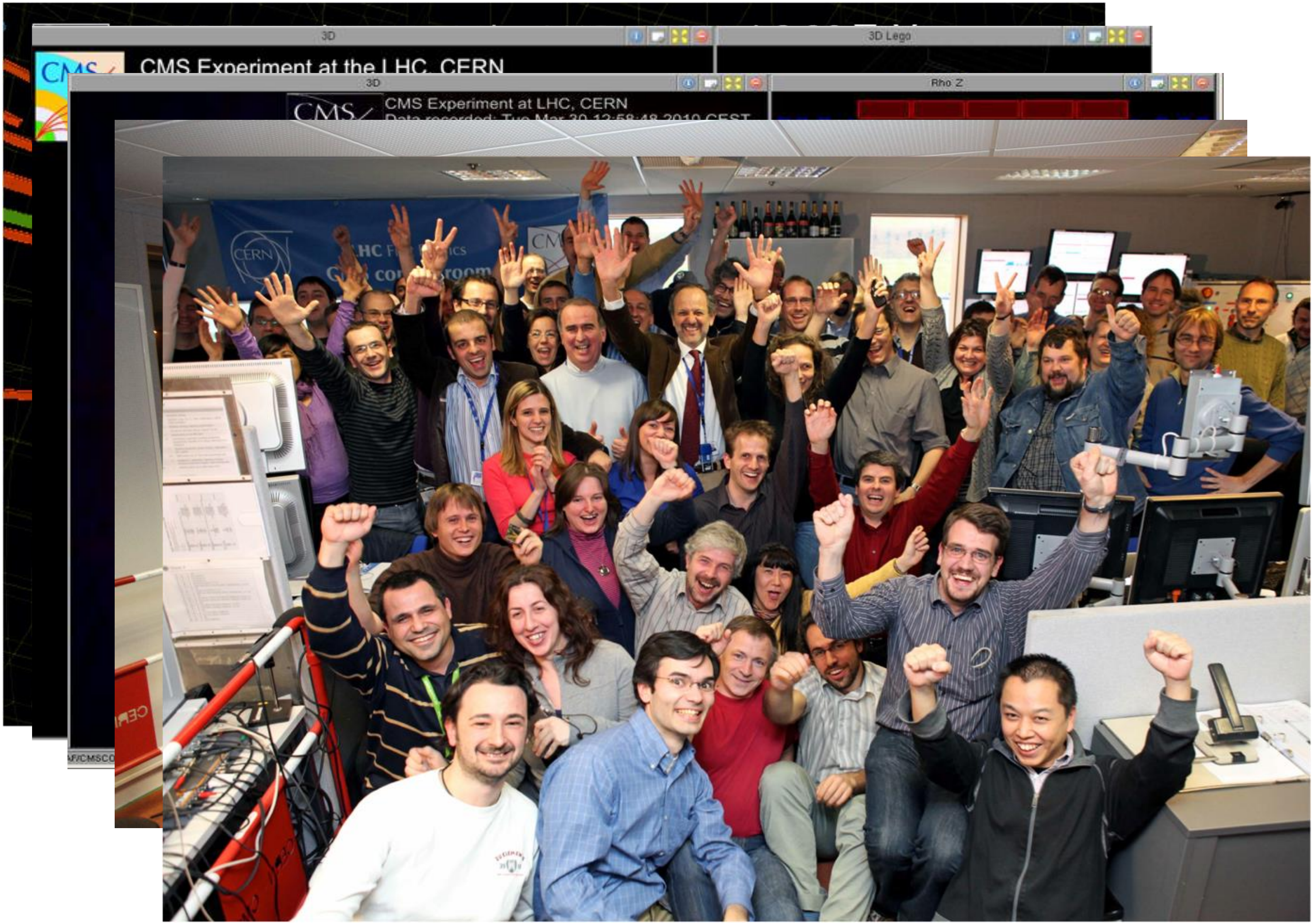
Preshower installed in CMS!



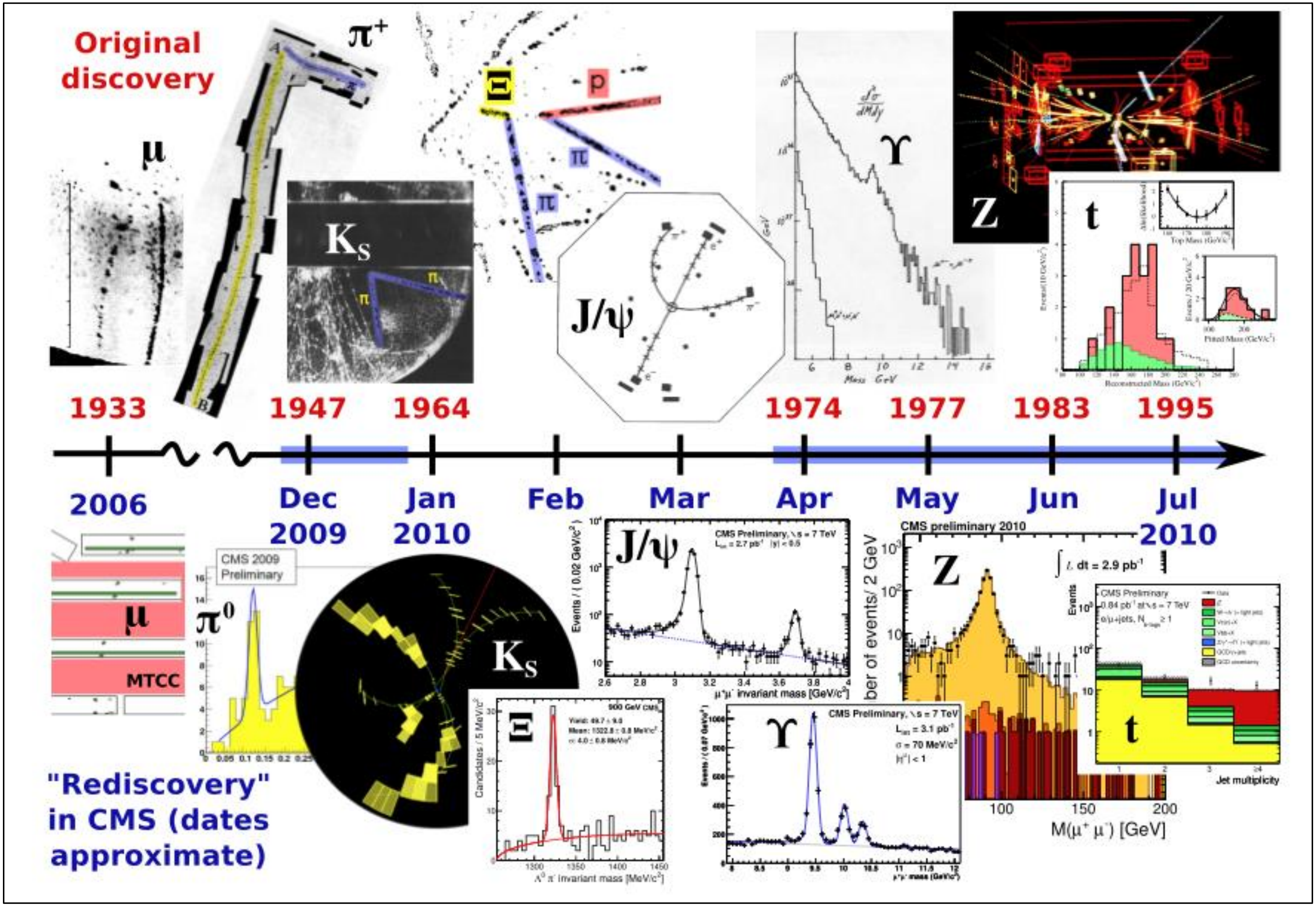
Preshower installed in CMS!



First collisions in 2009



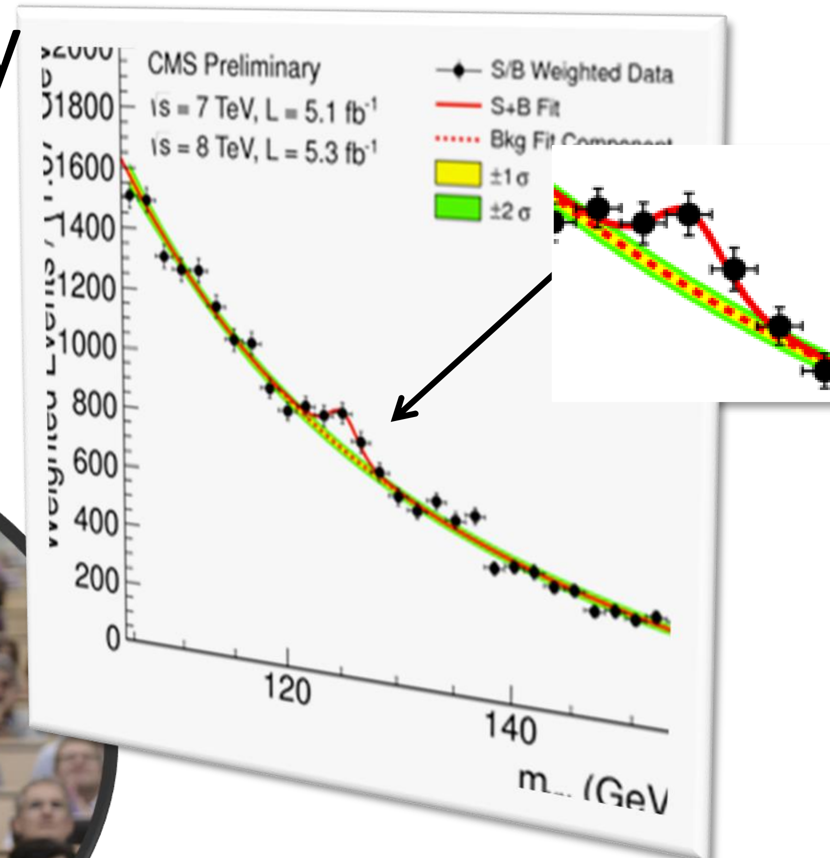
Re-discovery in CMS



And just a couple of years later…

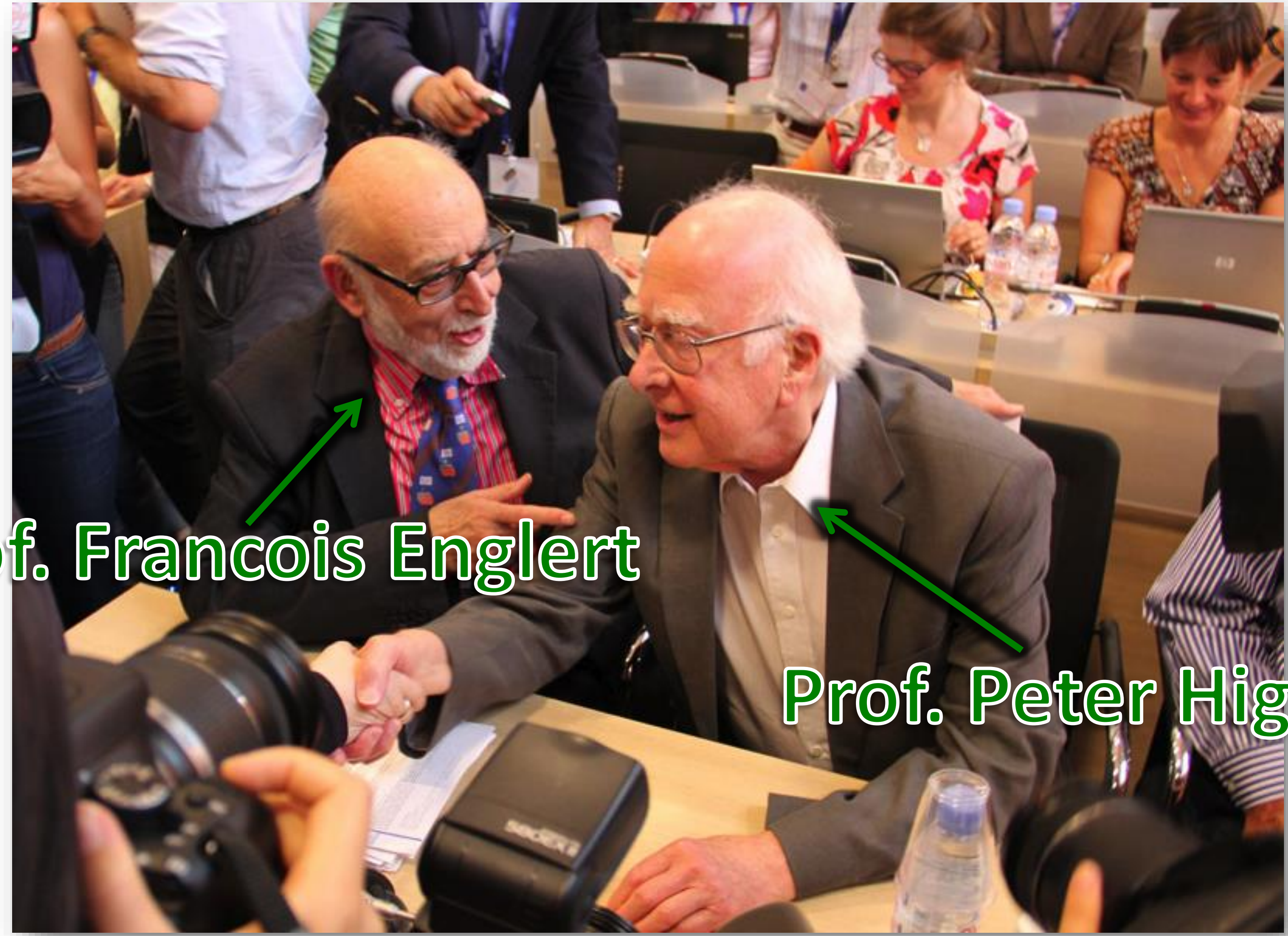
We announced a discovery
on 4th July 2012

Joe Incandela
CMS Spokesperson 2012-2013



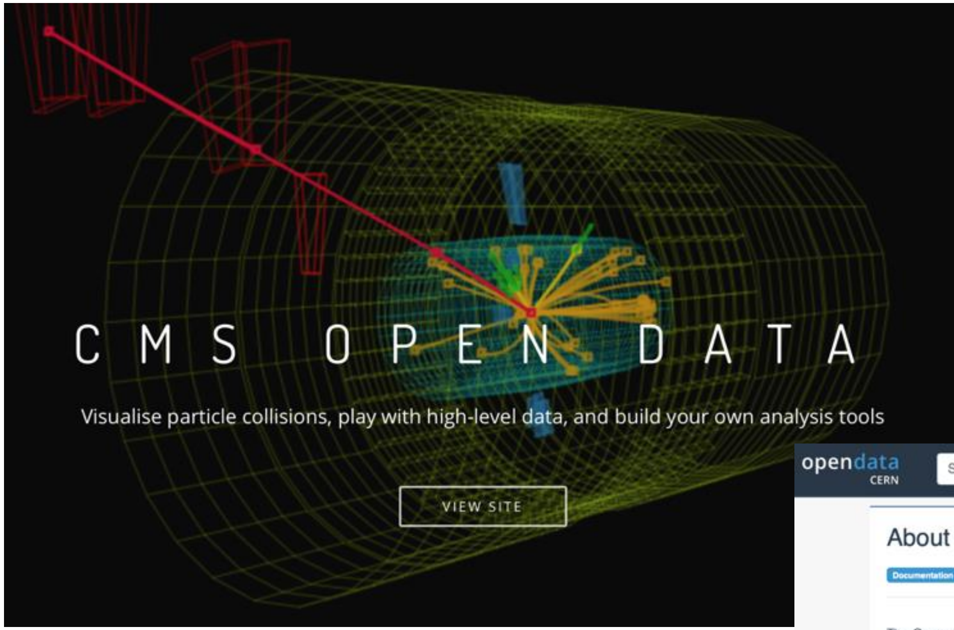
That made a lot of physicists very happy!

Including these two guys



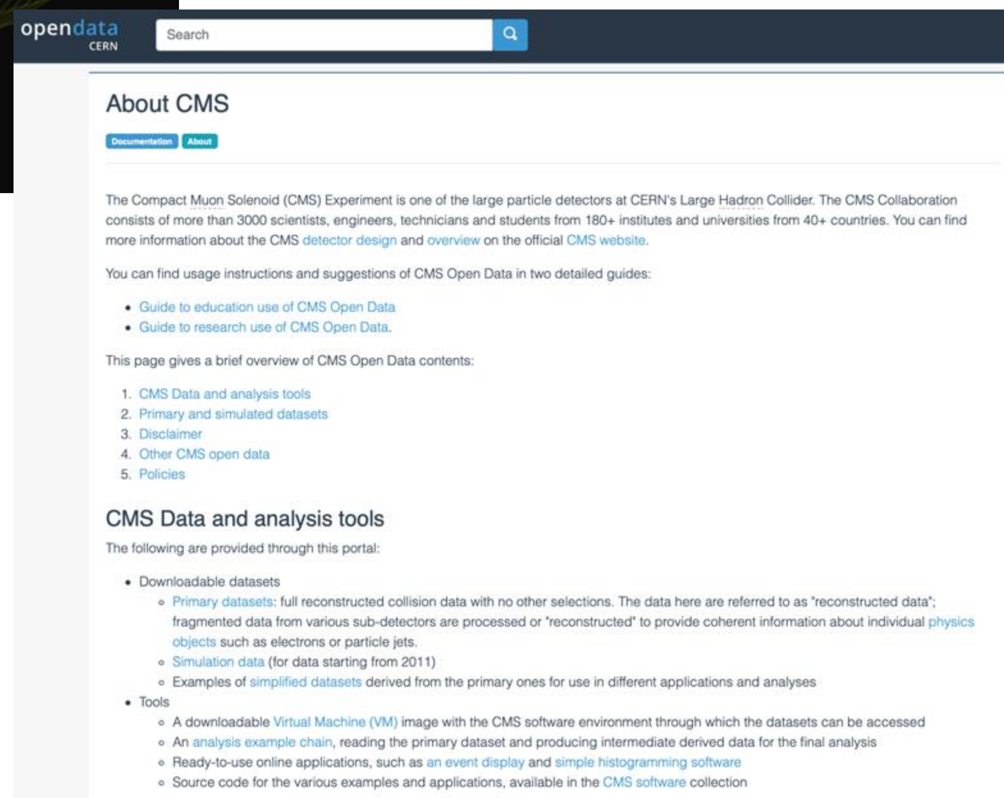
And the world's media also got excited!

And **you** can make measurements with CMS data!



https://cms.cern/interact-with-cms

http://opendata.cern.ch/docs/about-cms


opendata CERN

Search

About CMS

Documentation About

The Compact Muon Solenoid (CMS) Experiment is one of the large particle detectors at CERN's Large Hadron Collider. The CMS Collaboration consists of more than 3000 scientists, engineers, technicians and students from 180+ institutes and universities from 40+ countries. You can find more information about the CMS detector design and overview on the official CMS website.

You can find usage instructions and suggestions of CMS Open Data in two detailed guides:

- Guide to education use of CMS Open Data
- Guide to research use of CMS Open Data.

This page gives a brief overview of CMS Open Data contents:

1. CMS Data and analysis tools
2. Primary and simulated datasets
3. Disclaimer
4. Other CMS open data
5. Policies

CMS Data and analysis tools

The following are provided through this portal:

- Downloadable datasets
  - Primary datasets: full reconstructed collision data with no other selections. The data here are referred to as "reconstructed data"; fragmented data from various sub-detectors are processed or "reconstructed" to provide coherent information about individual physics objects such as electrons or particle jets.
  - Simulation data (for data starting from 2011)
  - Examples of simplified datasets derived from the primary ones for use in different applications and analyses
- Tools
  - A downloadable Virtual Machine (VM) image with the CMS software environment through which the datasets can be accessed
  - An analysis example chain, reading the primary dataset and producing intermediate derived data for the final analysis
  - Ready-to-use online applications, such as an event display and simple histogramming software
  - Source code for the various examples and applications, available in the CMS software collection

Including "Masterclasses" – fully web-based

CMS e-Lab

e-Labs Home | Teacher Home | Student Home

High school students use cutting-edge tools to do scientific investigations.

Real Event Superimposed on Detector

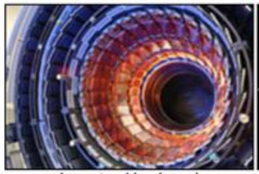
At CERN near Geneva, Switzerland, the Large Hadron Collider (LHC) collides protons at the highest energies ever achieved in the laboratory to reveal new knowledge about matter and energy. Giant detectors make careful measurements from the collisions. One of these detectors is CMS, the Compact Muon Solenoid.

Physicists working on CMS and its sister detector, ATLAS, first calibrated their experiments by rediscovering the particles of the Standard Model. They added to that picture in 2012 with the discovery of the Higgs boson, the long-sought key to understanding the masses of fundamental particles. Yet physicists know that the Standard Model does not explain everything. The search for new physics continues beyond the Standard Model.

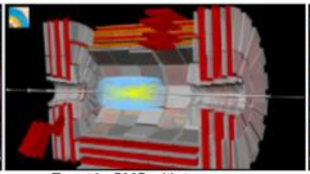
CMS e-Lab Student Home provides a guide with resources to create a research project, access to authentic CMS data and analysis tools for conducting that research, and ways to collaborate. The Teacher Home has learner objectives, assessment rubrics, standards, management tools, and more.

Join our learning community built around the CMS e-Lab and the QuarkNet CMS data thread as we probe the physics uncovered by CMS. What are the elementary constituents of matter? What are the fundamental forces that control their behavior at the most basic level?

[Information common for all e-Labs](#)
[Check out our online resources](#)

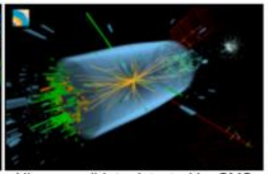


Inner tracking barrel



Event in CMS with two muons

Detector before closure 2008



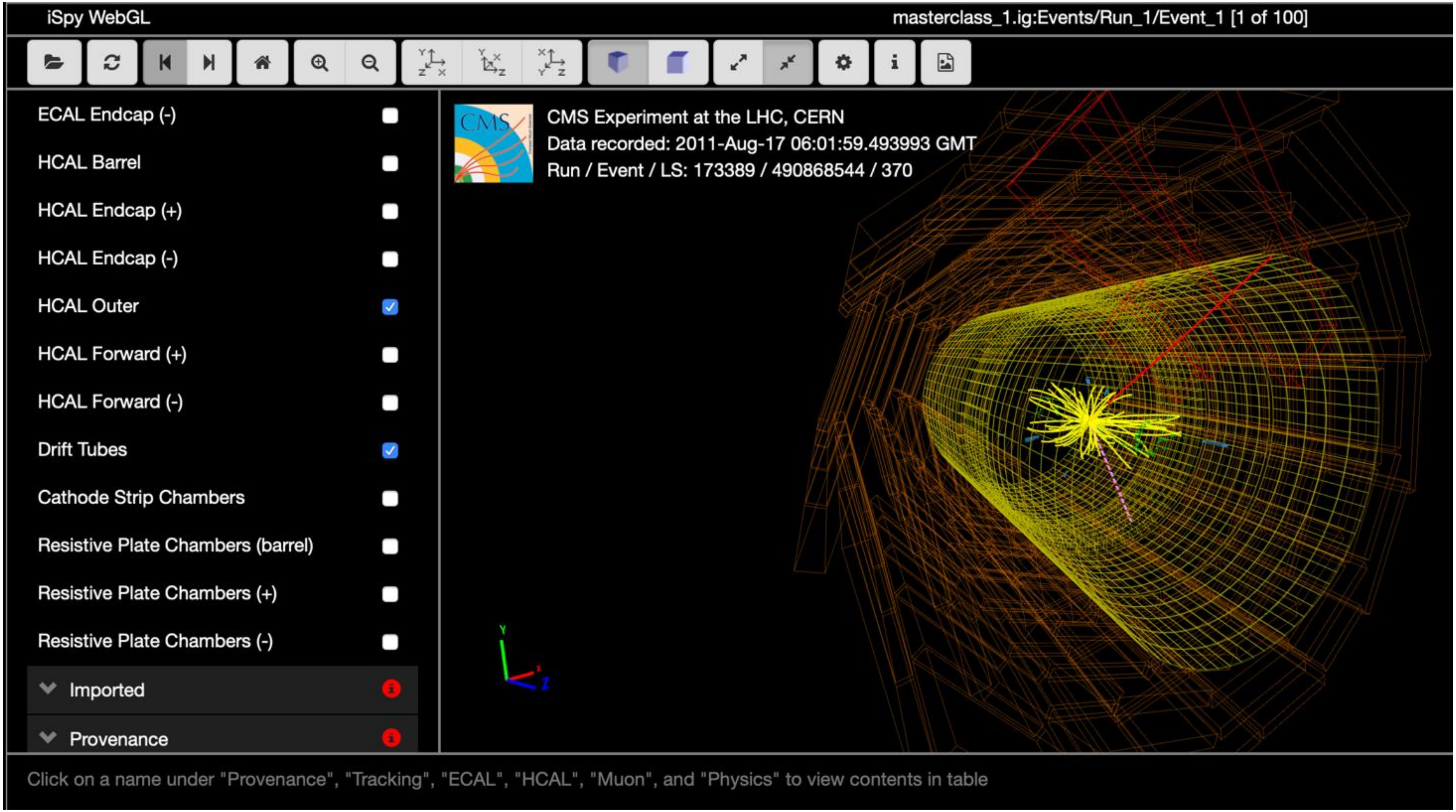
Higgs candidate detected by CMS

This project is supported in part by the National Science Foundation and the Office of High Energy Physics in the Office of Science , U.S. Department of Energy. Opinions expressed are those of the authors and not necessarily those of the Foundation or Department.

http://www.i2u2.org/elab/cms/home/project.jsp

Including “Masterclasses” – fully web-based

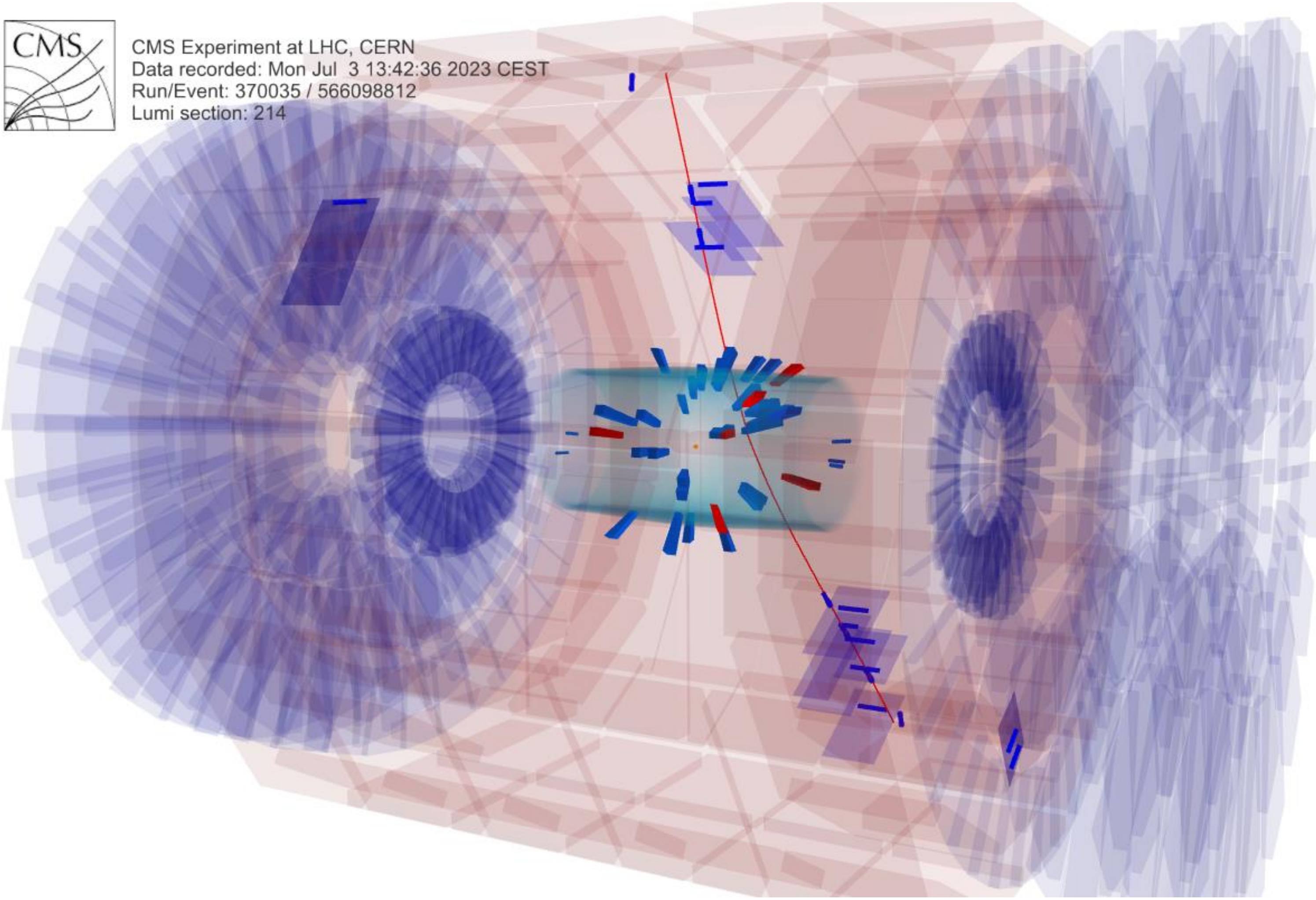
Understanding the structure of the proton (spoiler: it is NOT uud!) just by looking at images!



http://www.i2u2.org/elab/cms/ispy-webgl/

Or you may just want to see the latest images from CMS…

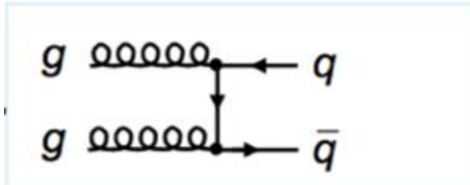
https://cmsonline.cern.ch/evtdisp/3DTower.png

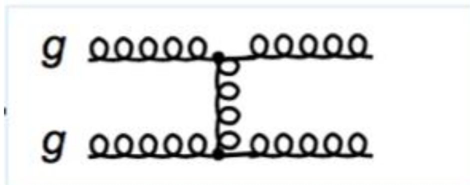


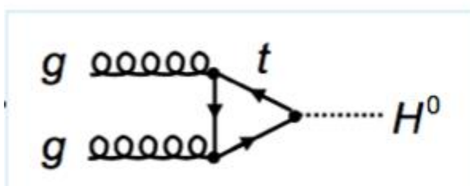
CMS is a LONG way from its final destination!

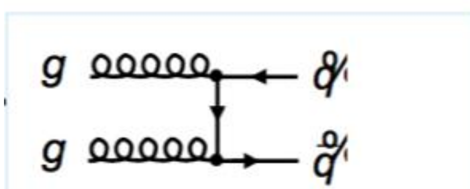
The LHC is not just a "gluon collider"

On Wednesday André showed you:

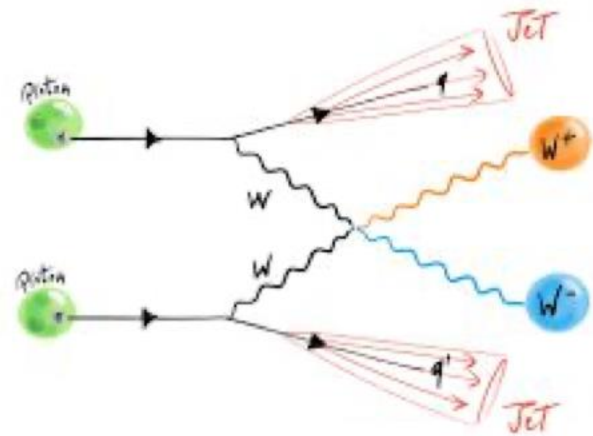




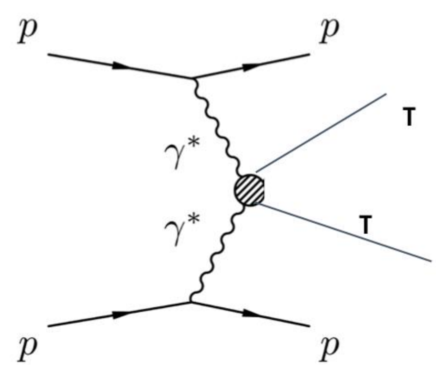




But the LHC also collides vector bosons (W, Z)



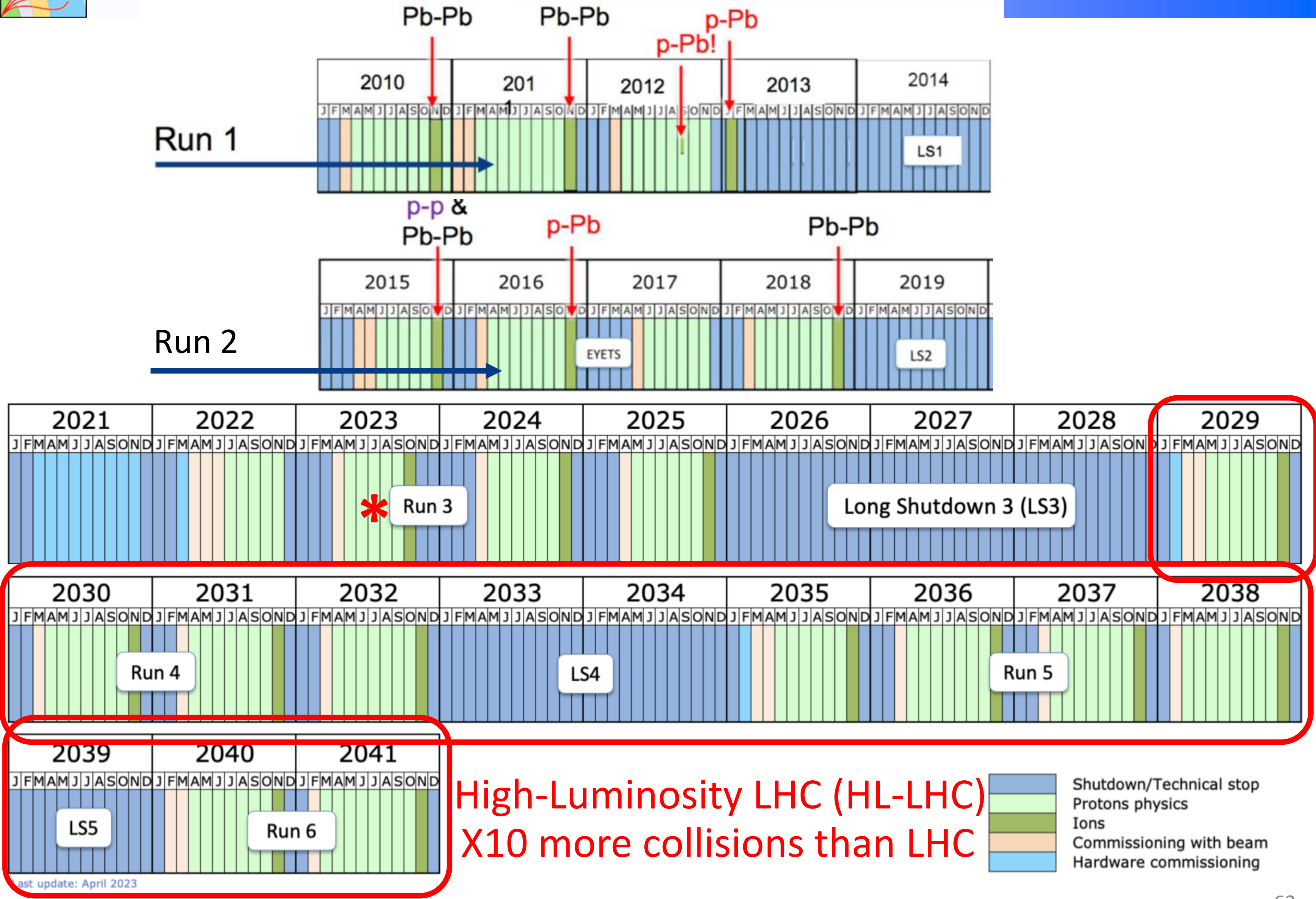
And it also collides photons!



These are **much rarer**, but provide **more insight** into the Standard Model as well as being sensitive to **new physics**…

We need more collisions! A **lot** more!

CMS has taken ~3% of the planned amount of data!



So what next?

Nima Arkani-Hamed

CERNCOURIER | International journal of high-energy physics

Home | About | News | Features | Community | Viewpoint | Reviews | Arc

FEATURE

Interview: In it for the long haul

8 March 2019

“The discovery of the **Higgs particle** – especially with nothing else accompanying it so far – is unlike anything we have seen in any state of nature, and is profoundly “new physics” in this sense. ...theoretical attempts to compute the vacuum energy and the scale of the Higgs mass pose gigantic, and perhaps interrelated, theoretical challenges. While we continue to scratch our heads as theorists, the most important **path forward for experimentalists is completely clear**:

measure the hell out of these crazy phenomena!

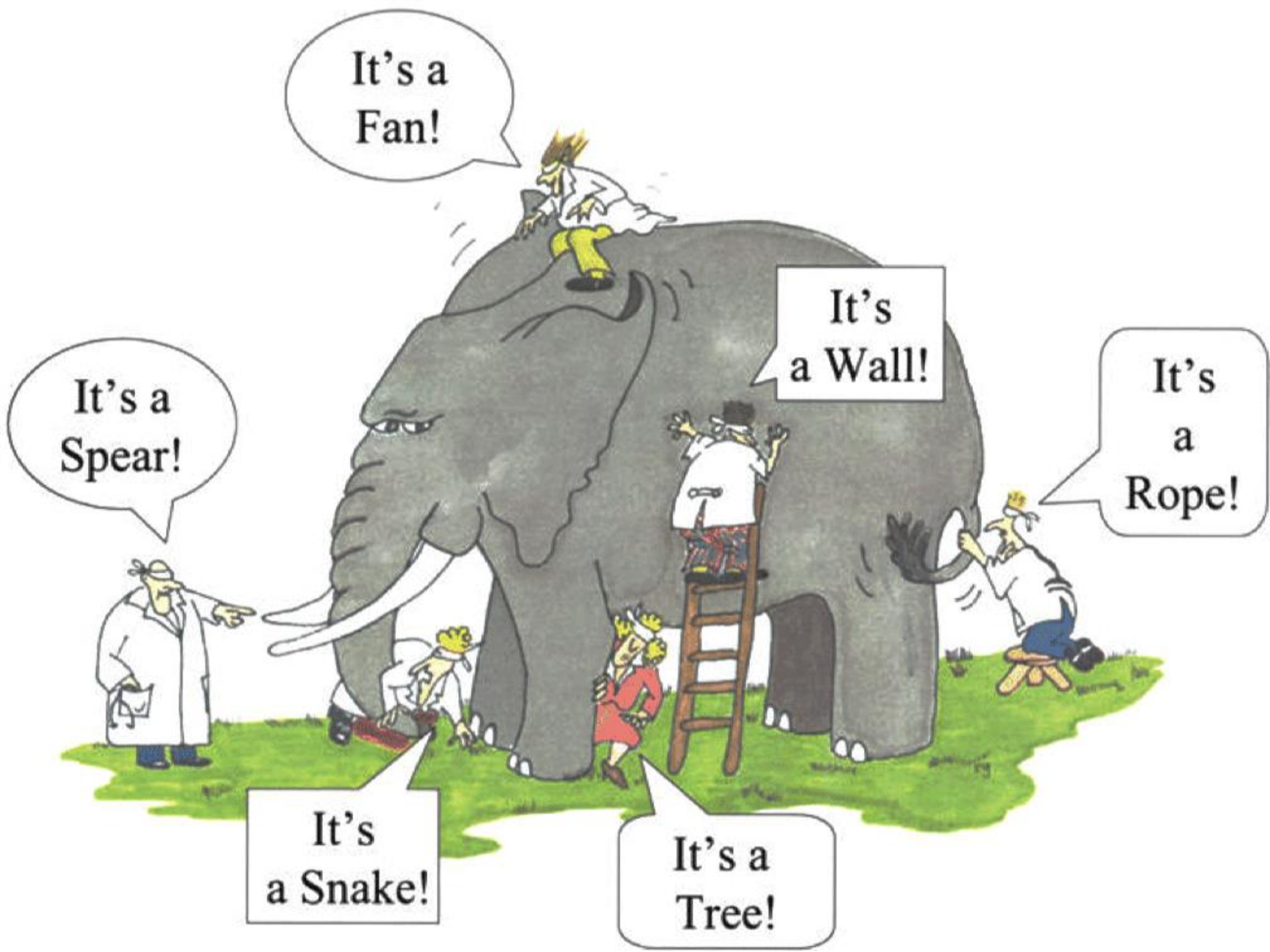
“**It is the first example we’ve seen of the simplest possible type of elementary particle. It has no spin, no charge, only mass, and this extreme simplicity makes it theoretically perplexing.** ...”

https://cerncourier.com/in-it-for-the-long-haul/


It’s
a
Rope!

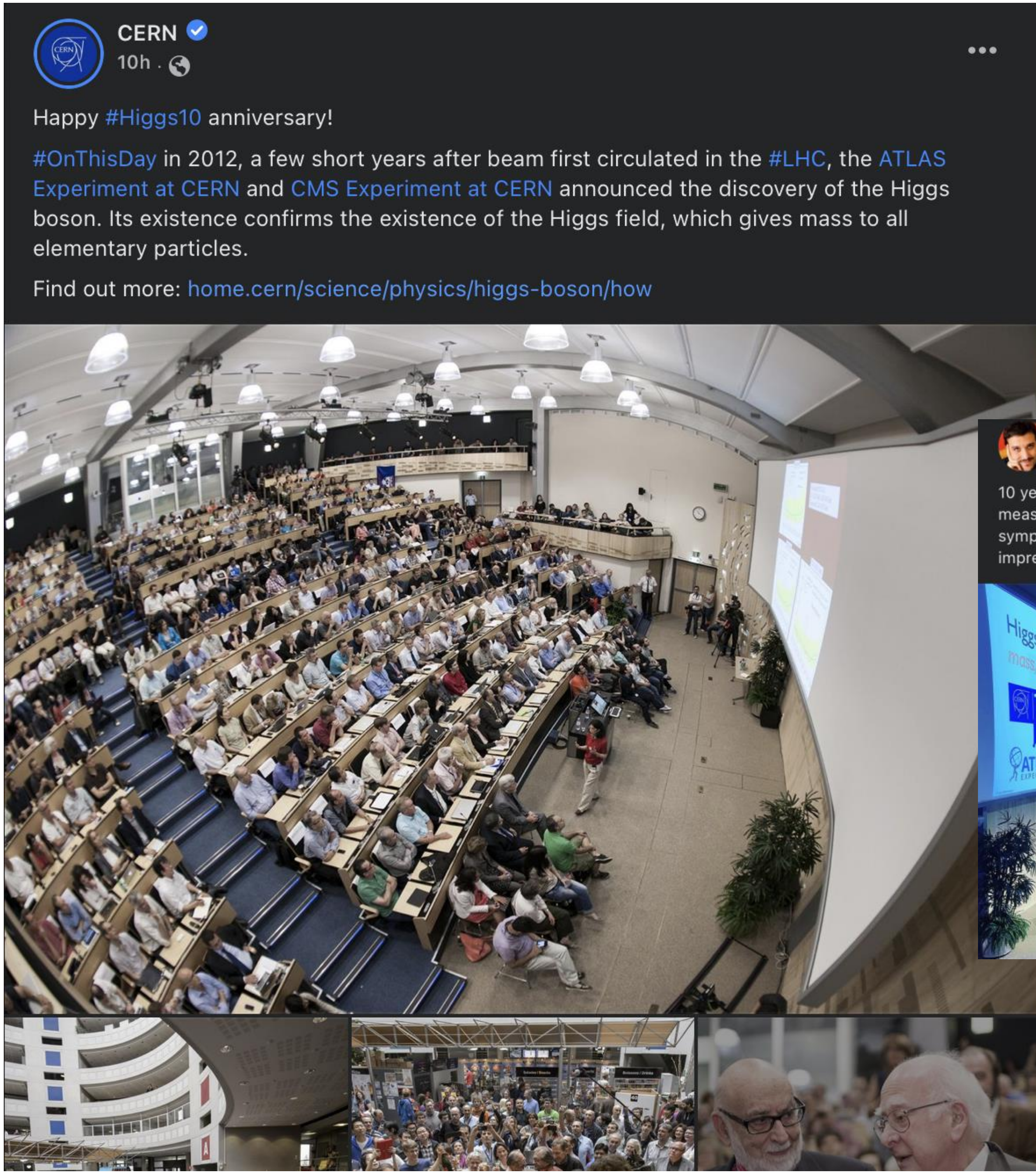

It’s a Spear!

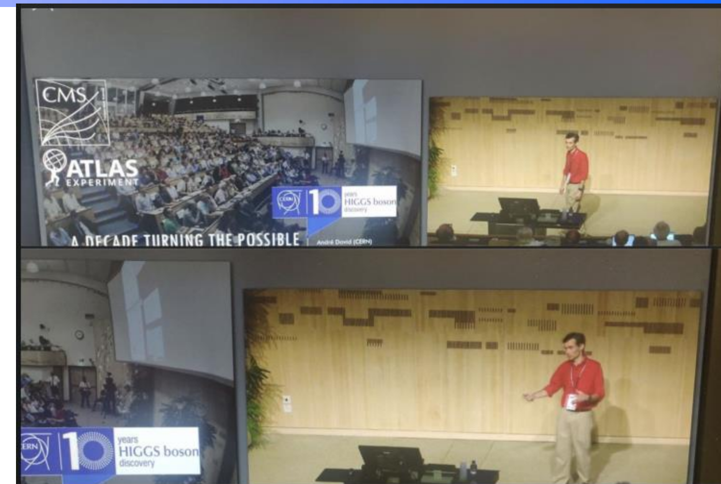

It's a Wall!

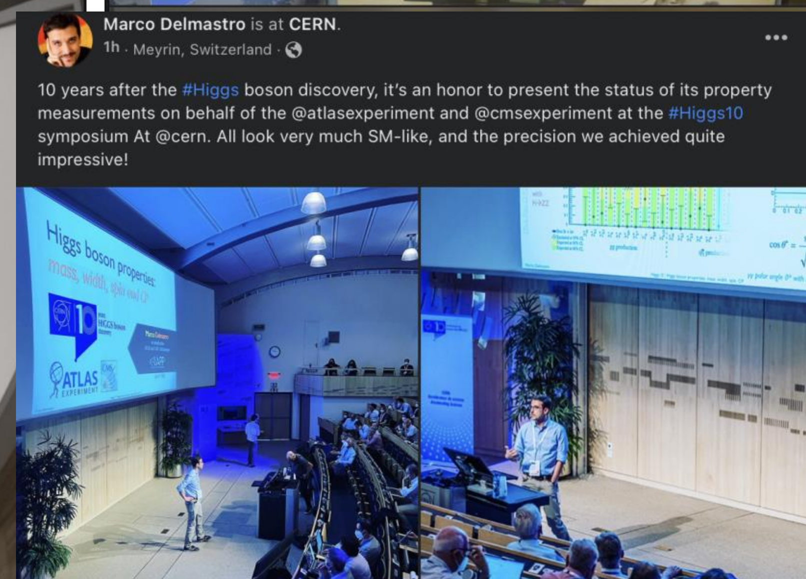


It's a Fan!
It's a Wall!
It's a Spear!
It's a Rope!
It's a Snake!
It's a Tree!

2012 **started a new era of physics**: Higgs physics!





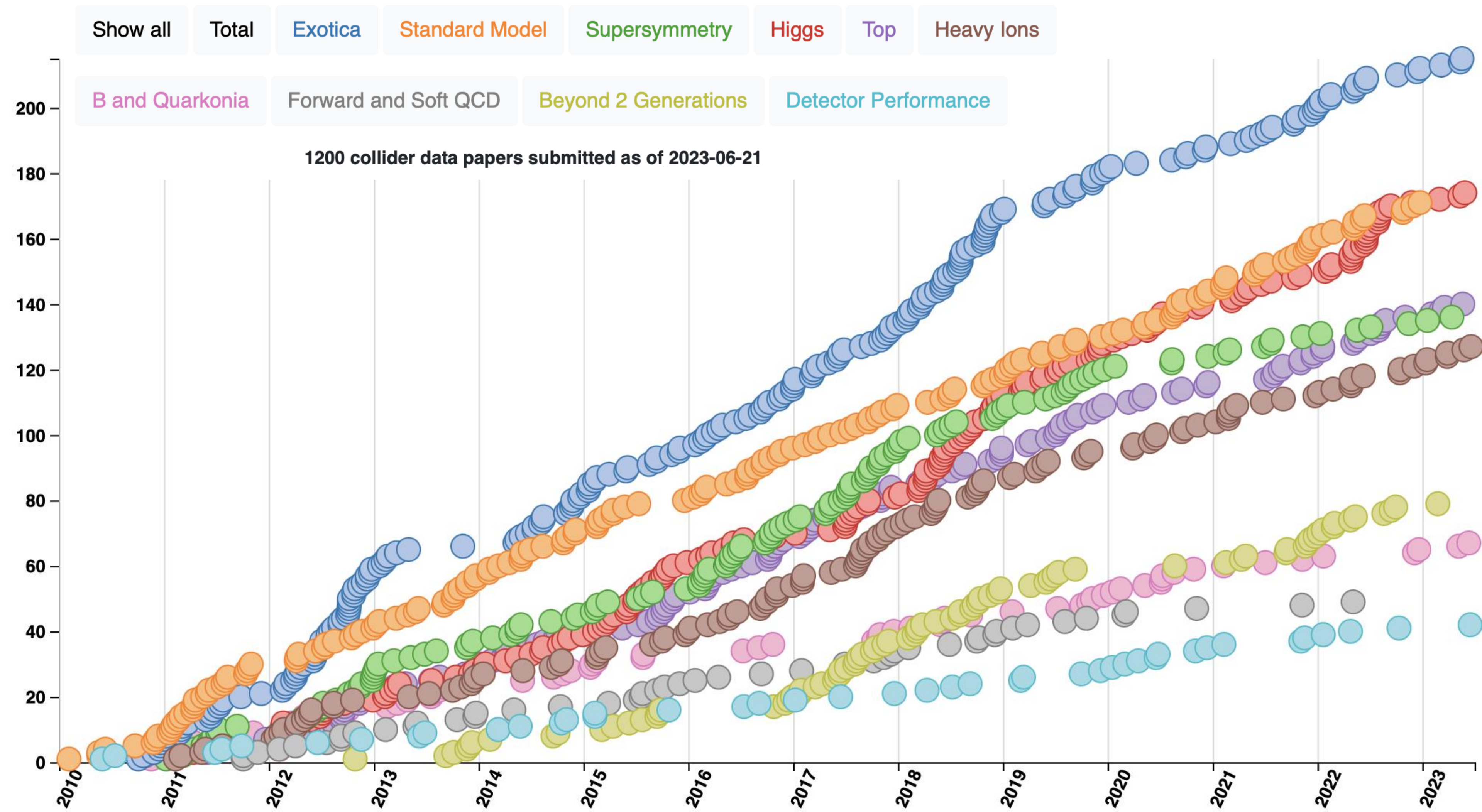


July 4th 2022!

10th anniversary

1145 papers published on data taken with CMS!

Including >170 papers on studies of the properties of the Higgs boson!



And where was I on July 4th?

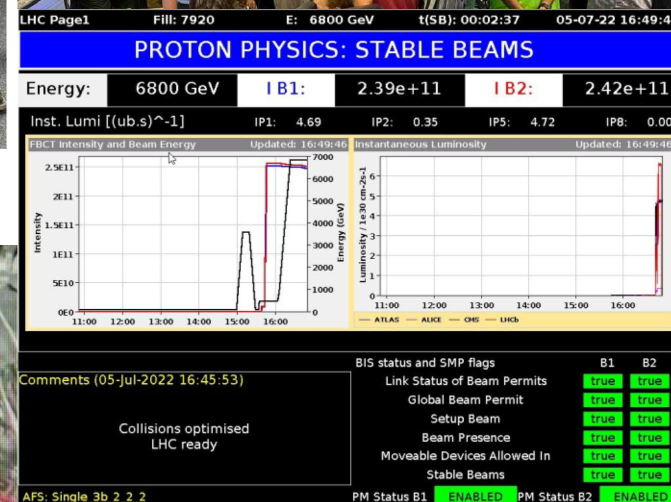
2012: part of the crowd at ICHEP in Melbourne, responsible for CMS Education & Outreach

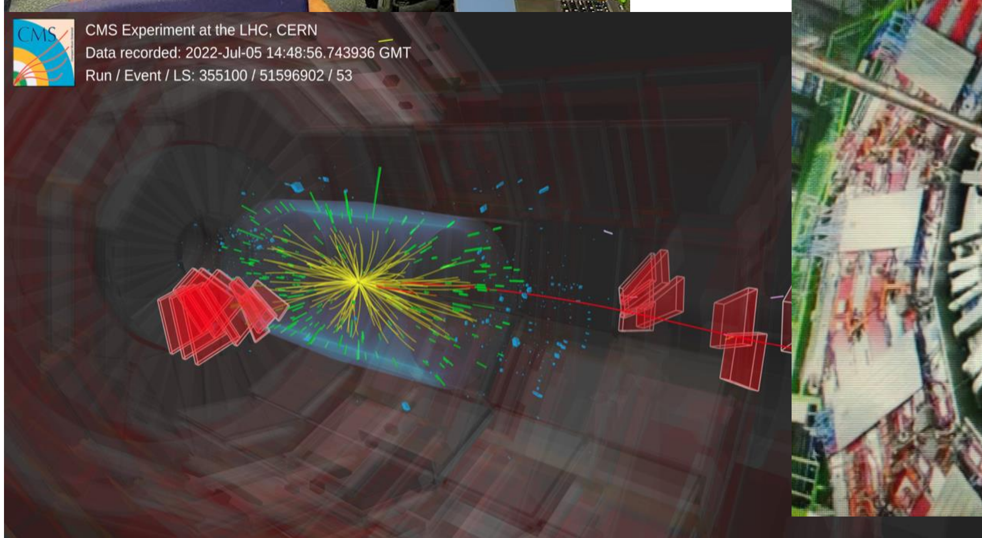
2012: and out celebrating in the evening with ATLAS E&O coordinator Steve Goldfarb and others!

2022: 100m underground fixing a power supply!

4th July is also my daughter's birthday (2001)

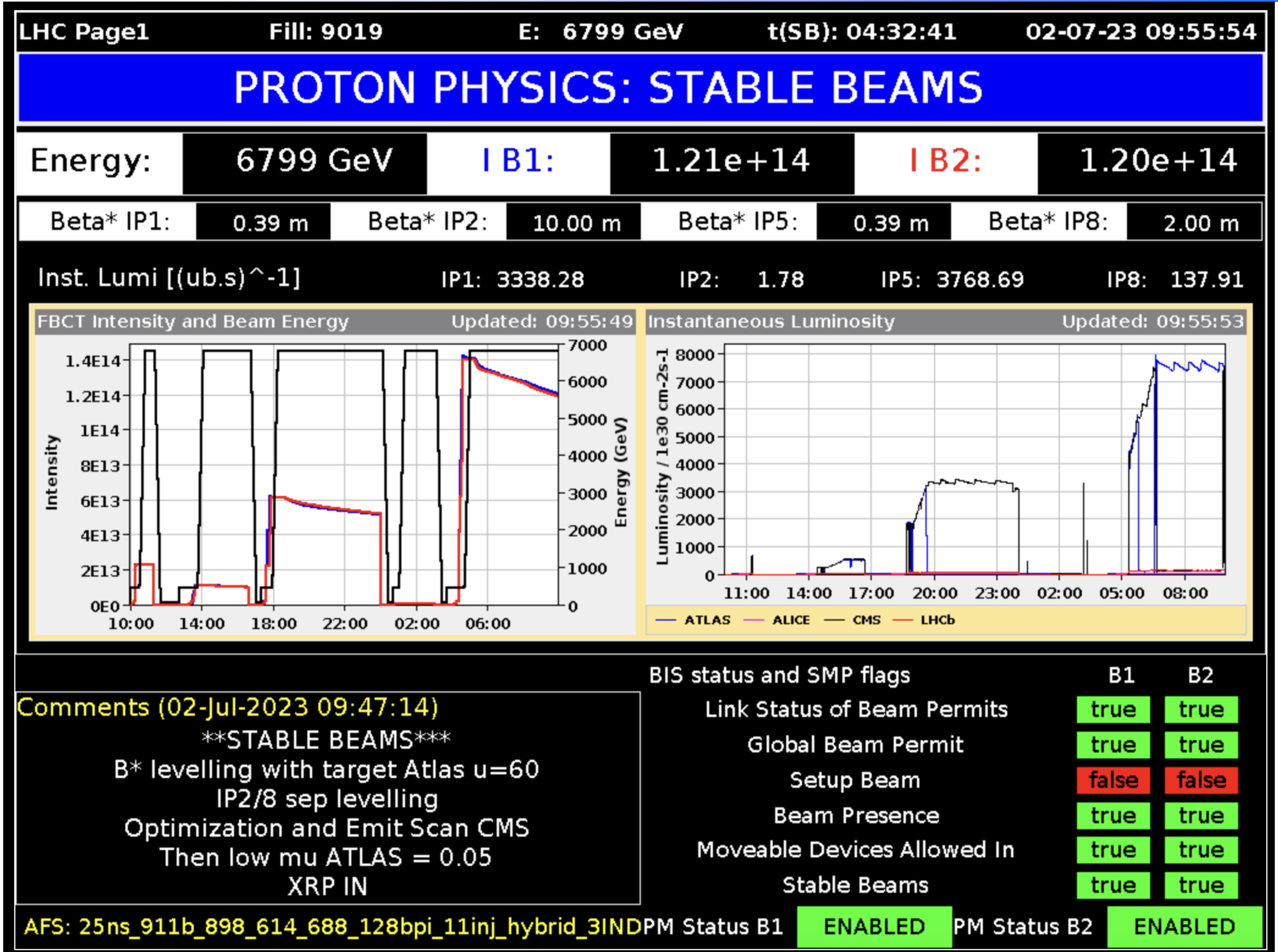
July 5th 2022 – restart of LHC @ 13.6 TeV



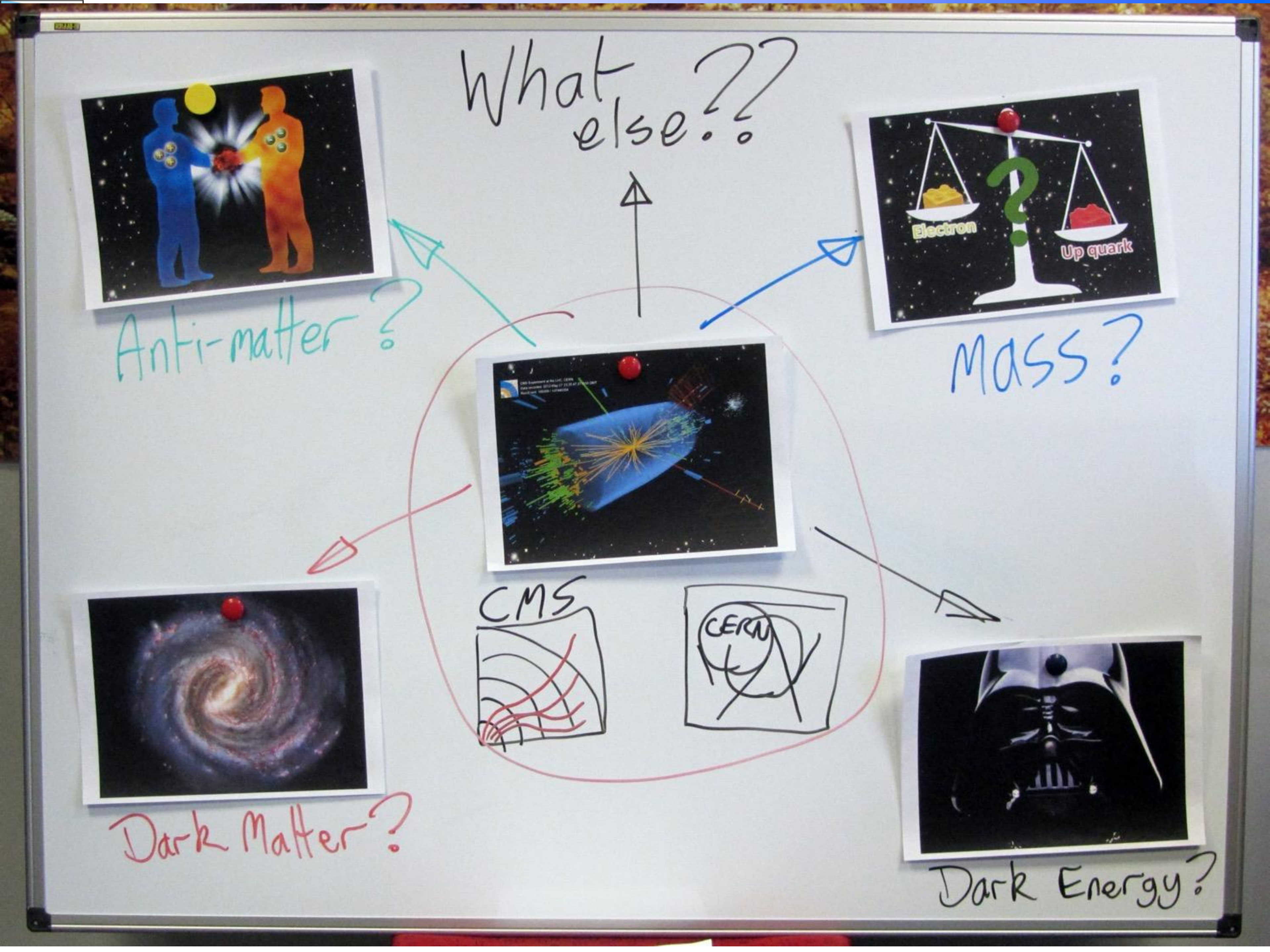


Another 3 years of data taking started last year!

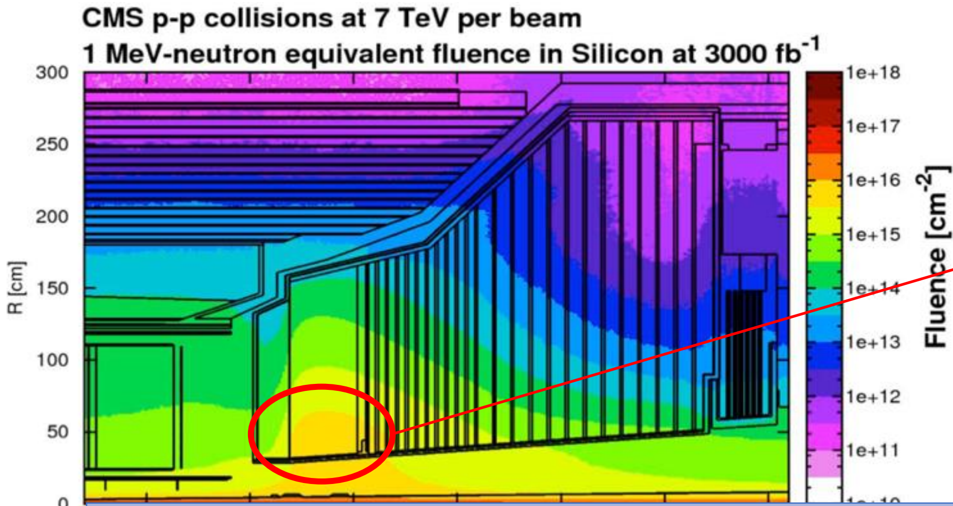
Status of the LHC right now (almost)



https://op-webtools.web.cern.ch/vistar/vistars.php


What else??
Anti-matter?
Electron
Up quark
Mass?
CMS
CERN
Dark Matter?
Dark Energy?

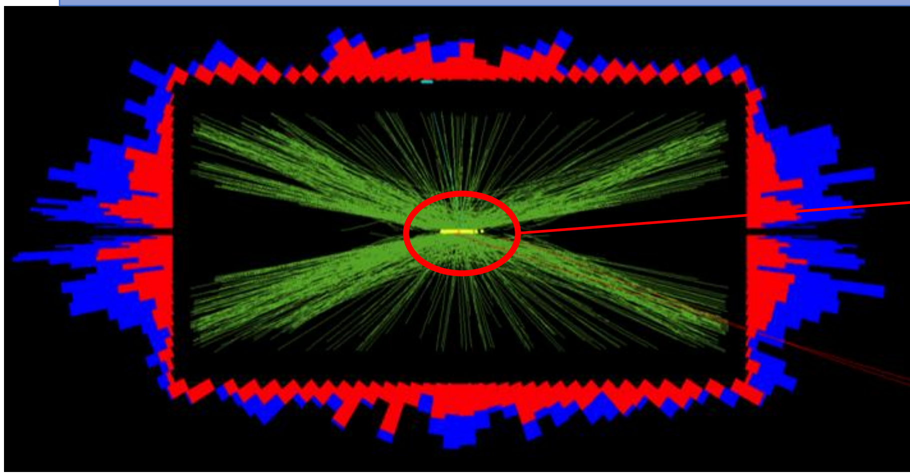
But it's not that simple for the CMS detector: radiation and pileup (CMS designed for PU=20) are a major problem

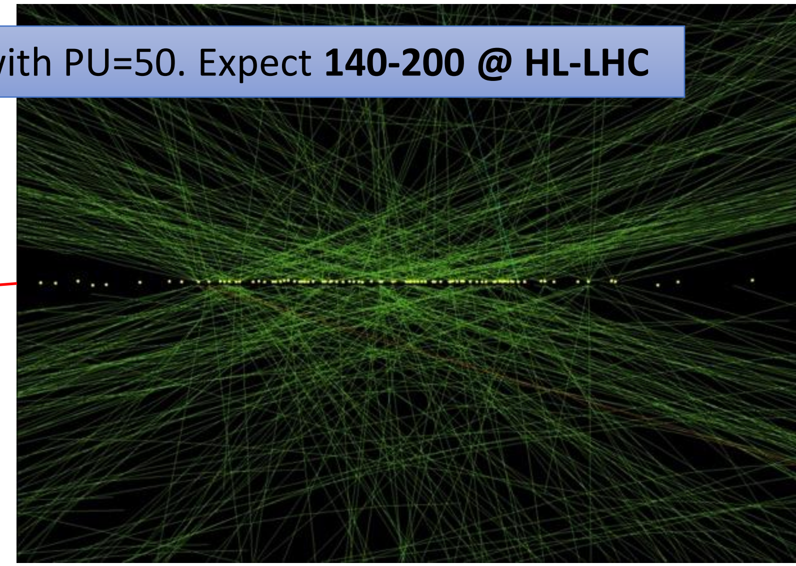


CMS @ HL-LHC:

~**10^{16}** 1 MeV n_{eq} cm^{-2} @ 3ab^{-1}
in forward calorimeters,
with **pileup ~200**
And up to **2 MGy** absorbed dose

78 pileup events in 2012. Presently running routinely with PU=50. Expect **140-200 @ HL-LHC**



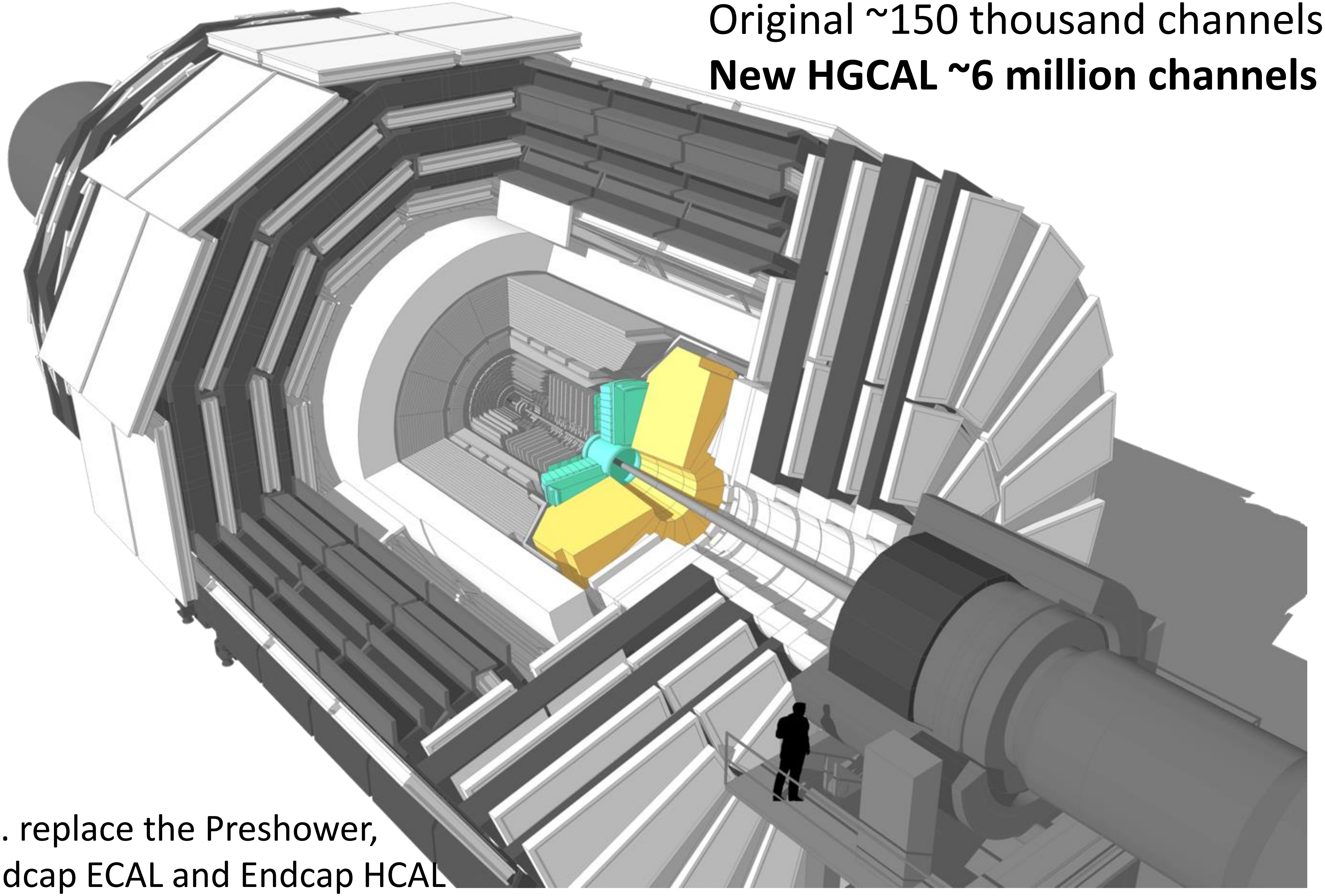


All on-detector electronics will also be obsolete by LS3,
due to necessary upgrades to the trigger and DAQ systems

e.g. CMS will replace all endcap calorimeters with the "High Granularity Calorimeter"

Original ~150 thousand channels

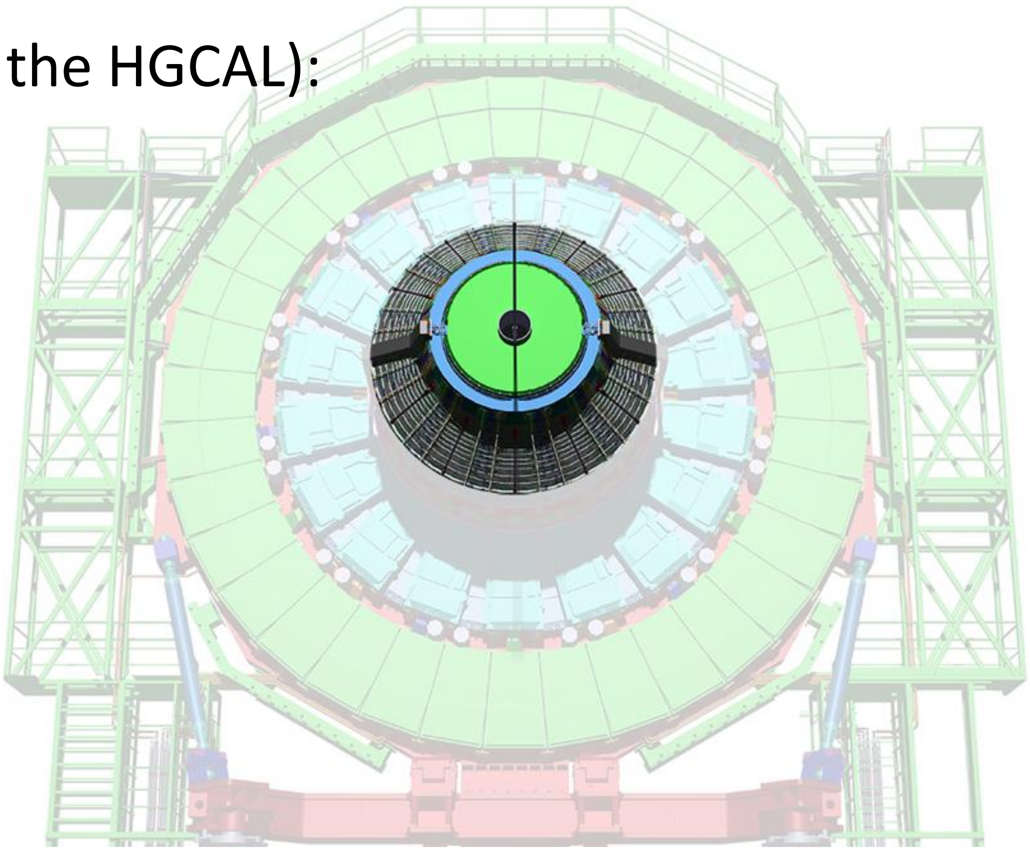
New HGCAL ~6 million channels



i.e. replace the Preshower, Endcap ECAL and Endcap HCAL

A wise person once said (about the HGCAL):

"there are no show-stoppers; it is all just engineering"



Another person responded:

"HGCAL is perhaps the most challenging engineering project ever undertaken in particle physics"

And this is what I have been working on for the past 8 years

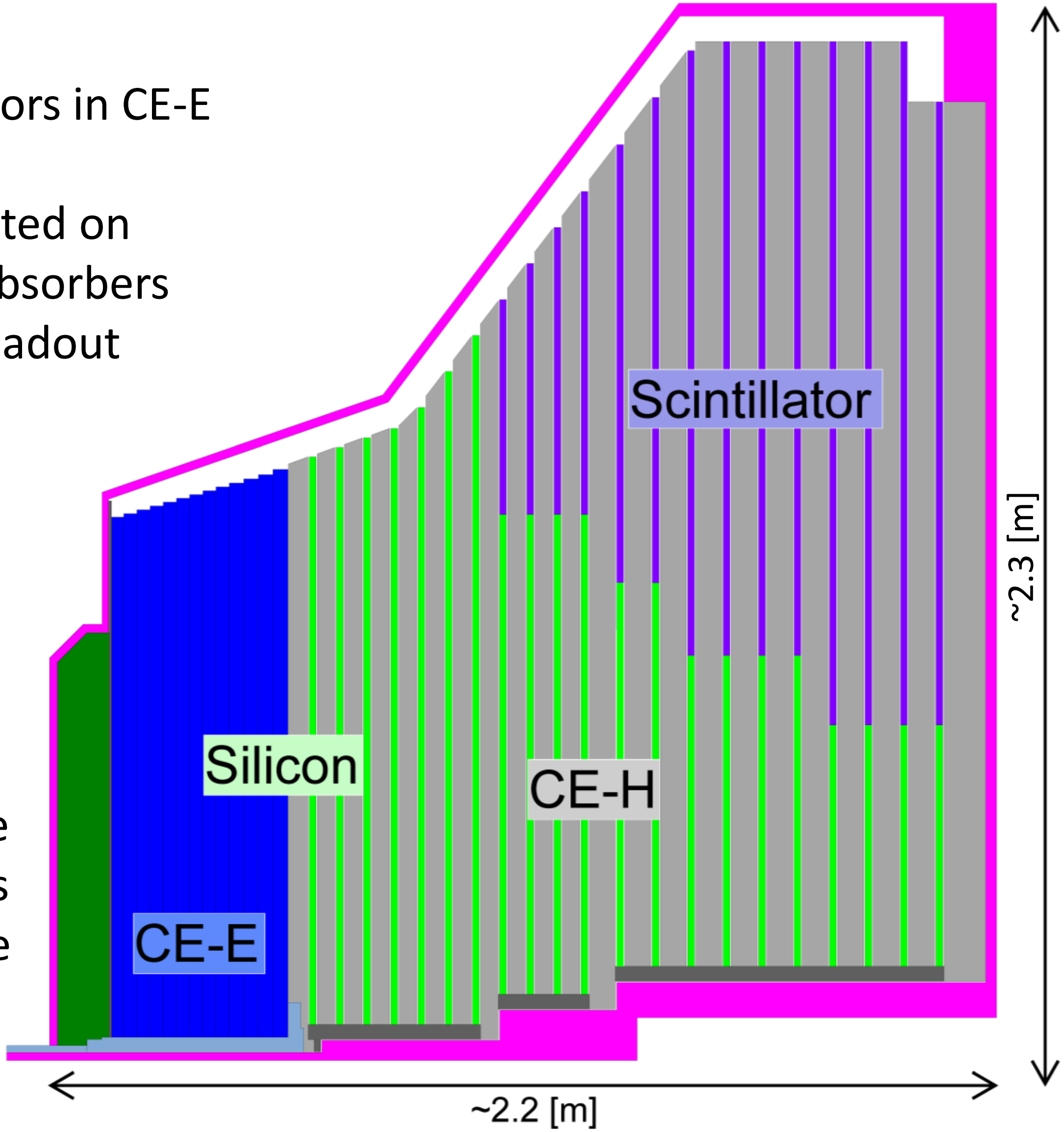
CMS HGCAL ("CE"): a sampling calorimeter with unprecedented number of readout channels

Active Elements:

- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of CE-H

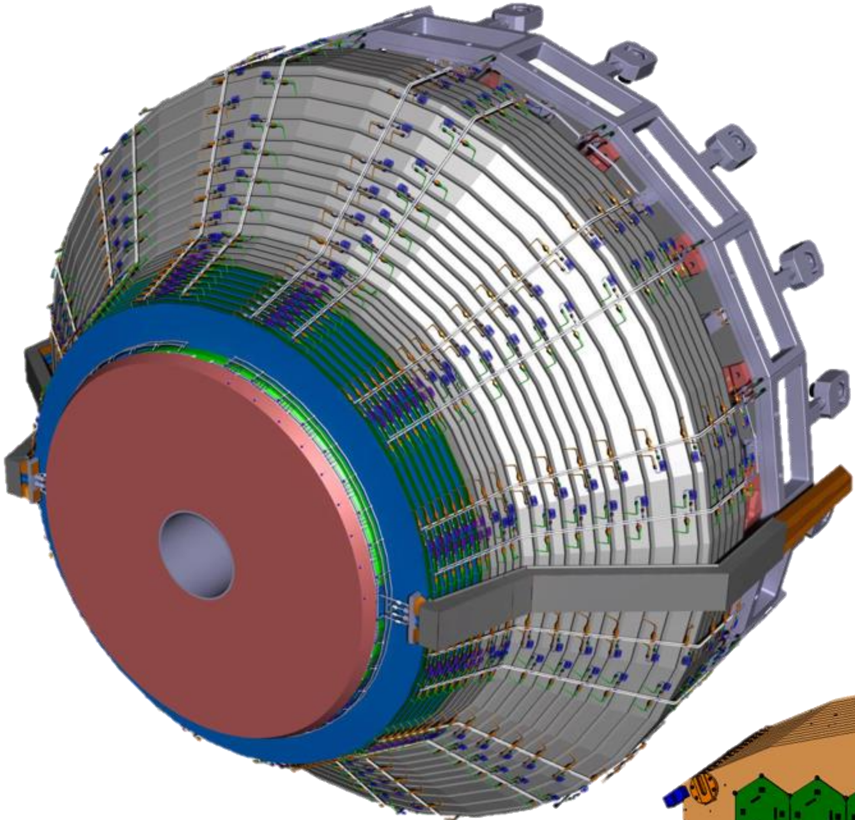
Key Parameters:

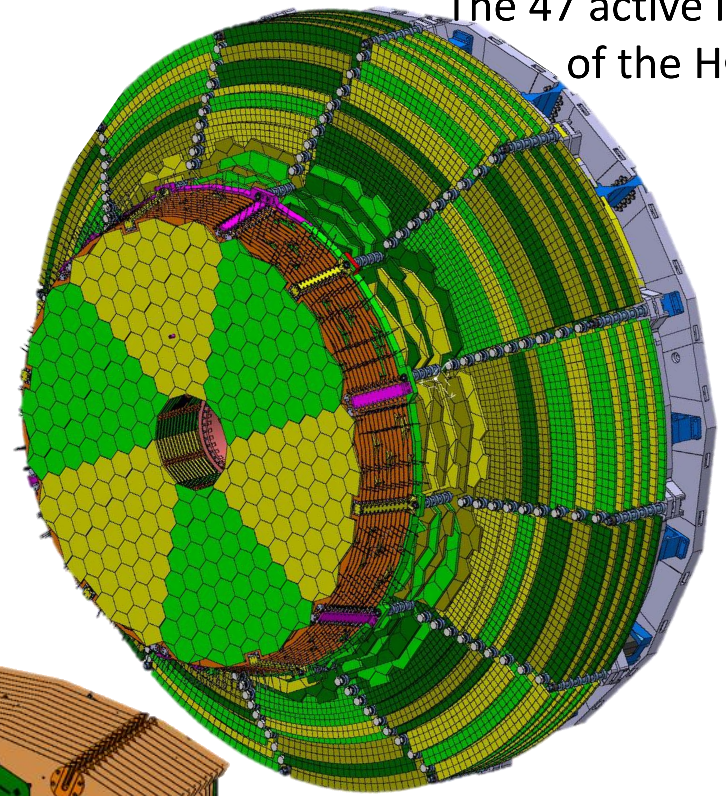
Coverage: $1.5 < |\eta| < 3.0$
~215 tonnes per endcap
Full system maintained at -30°C
~620m² Si sensors in ~26000 modules
~6M Si channels, 0.6 or 1.2cm² cell size
~370m² of scintillators in ~3700 boards
~240k scint. channels, 4-30cm² cell size
Power at end of HL-LHC:
~125 kW per endcap



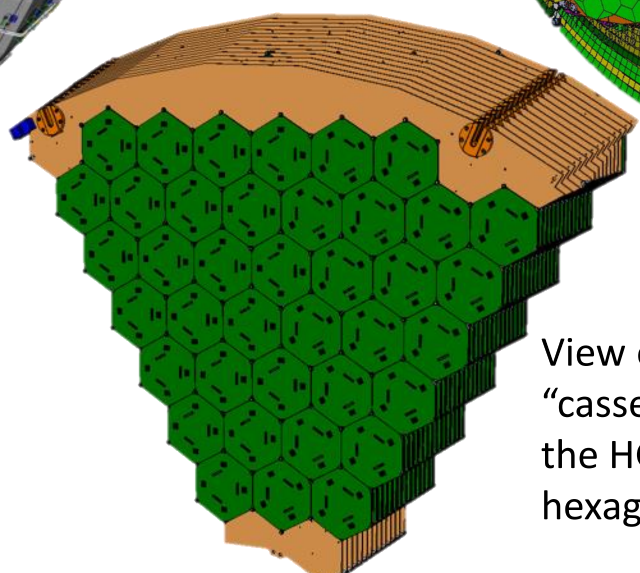
Electromagnetic calorimeter (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 26 layers, 25 X_0 & ~1.3λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 21 layers, ~8.5λ

Unboxing the HGCAL





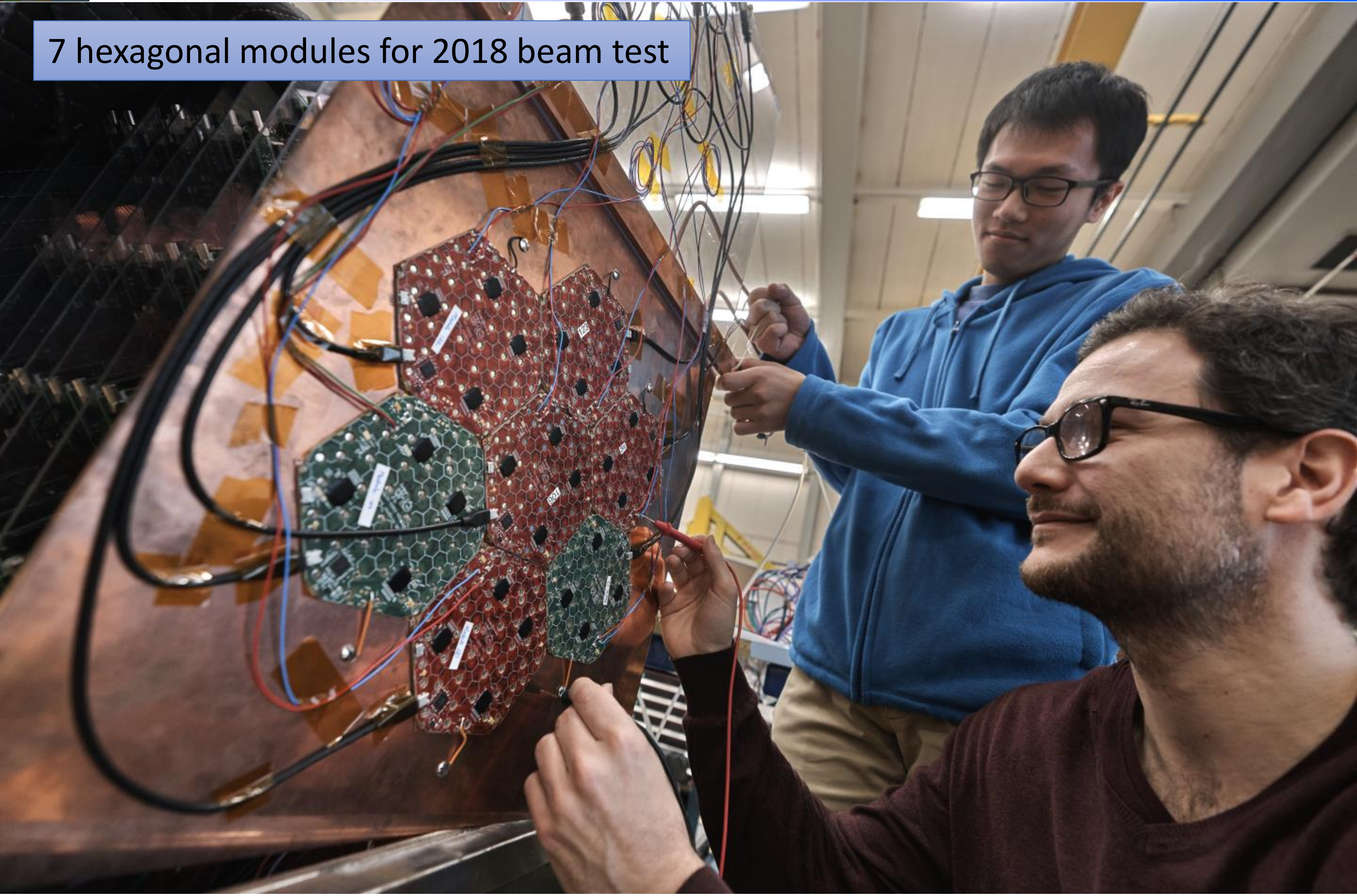
The 47 active layers of the HGCAL



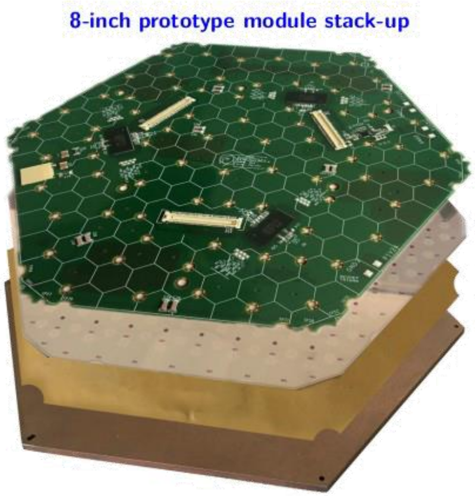
View of some of the "cassettes" forming the HGCAL, including hexagonal silicon modules

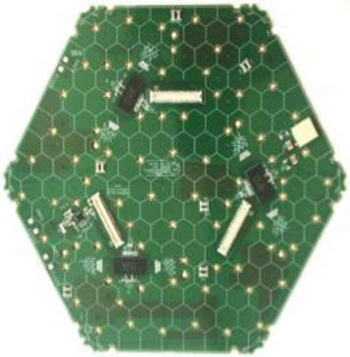
Silicon modules are arranged in hexagonal matrices to cover fiducial area of HGCAL

7 hexagonal modules for 2018 beam test

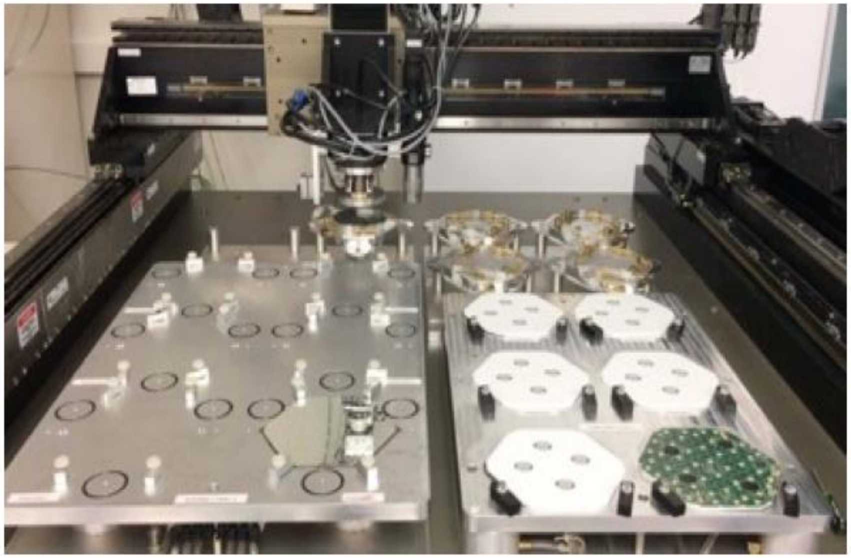


HGCAL will include 26000 modules based on hexagonal silicon sensors with 0.5-1cm^2 cells



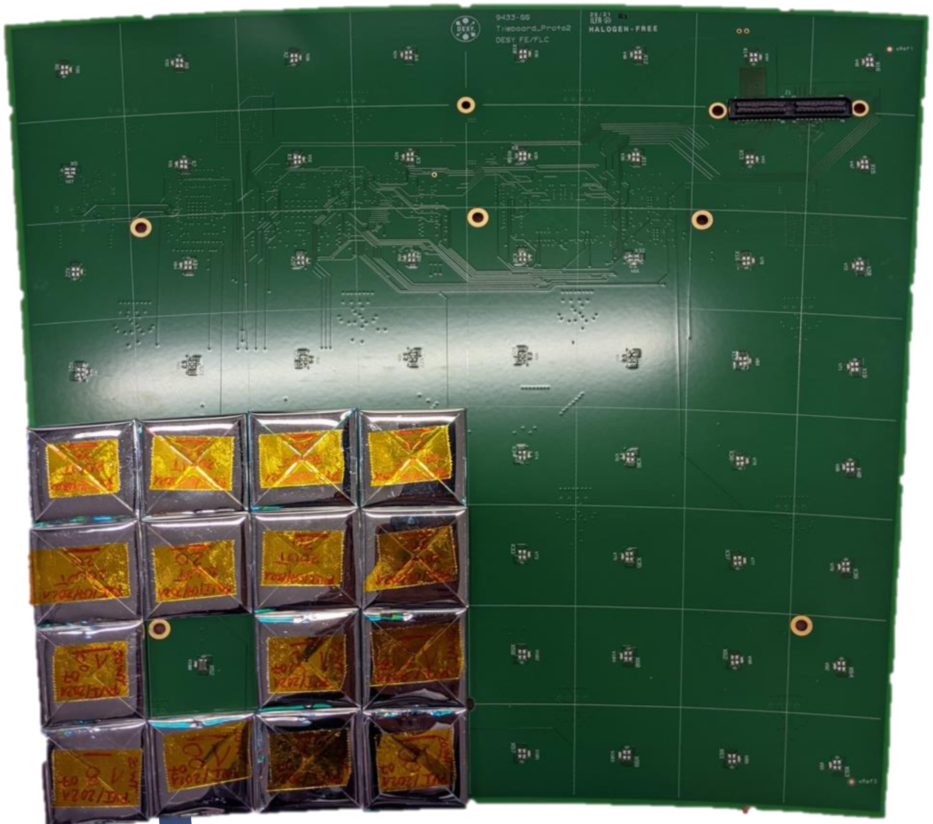


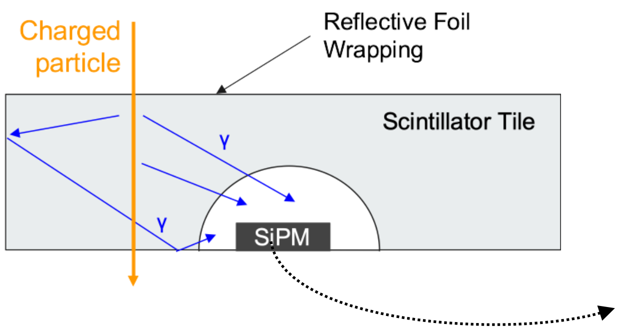
- Robust module constructed from a baseplate, insulating layer, silicon sensor, and readout PCB
- Automated assembly process using gantry and robotic wirebonder developed at UCSB
  - Highly-repeatable, being replicated to five additional module assembly centers worldwide

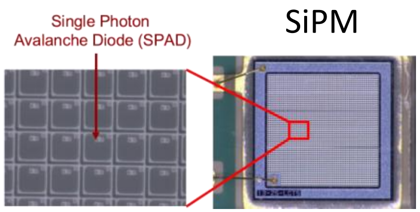


HGCAL will also include 370m^2 of scintillator tiles with on-tile SiPM readout

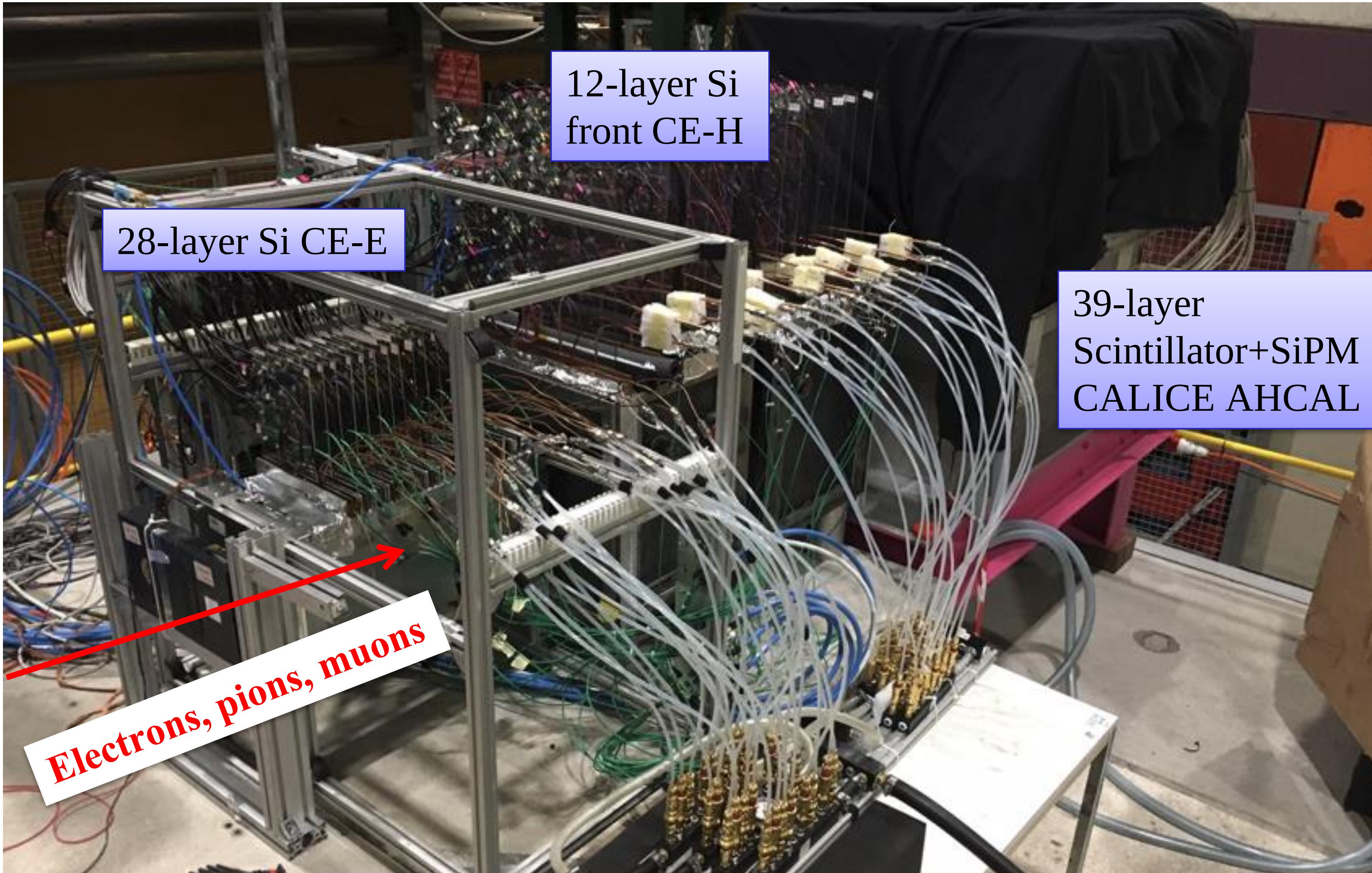
- **“Tile board” PCB**
  - Connects Silicon photo multipliers (SiPM) to HGCROC ASIC.
  - Connects to motherboard for control and data transfer.
- **Wrapped scintillating tiles**
  - Reflective foil wrapping.
  - Light collected by SiPM.
  - Light injection LED.







Large-scale beam-tests of prototypes in 2018



A brief aside on Calorimeter σ_E/E

From André's presentation on Wednesday:

Energy resolution

- Usual parameterization for calorimeters:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{b}{E}\right)^2 + c^2 \quad \text{or, more simply} \quad \frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- **a: Stochastic (or "sampling") term**
  - Accounts for statistical fluctuation of the number of primary signal generating happenings.
- **b: Noise term**
  - Electronics noise (i.e., its energy equivalent).
  - Pileup (other energy entering the measurement area).
- **c: Constant term**
  - Non-uniformity of signal generation or collection.
  - Intercalibration errors.
  - Other fluctuations directly proportional to energy; fluctuation in the EM component in hadronic showers.

IHSTP - 2023 physics.is.great@cern.ch

CMS ECAL Energy Res. today

$$\sigma_E/E = \frac{.028}{\sqrt{E}} \oplus 0.003$$

ATLAS ECAL Energy Res. today

$$\sigma_E/E = \frac{.10}{\sqrt{E}} \oplus 0.0017$$

CMS HGCAL Energy Resolution (expected)

$$\sigma_E/E = \frac{0.24}{\sqrt{E}} \oplus 0.001$$

Which looks terrible!

But

In the endcaps of CMS a typical γ from $H \rightarrow \gamma\gamma$ has E_T~60 GeV, so an **Energy of ~150 GeV or more**

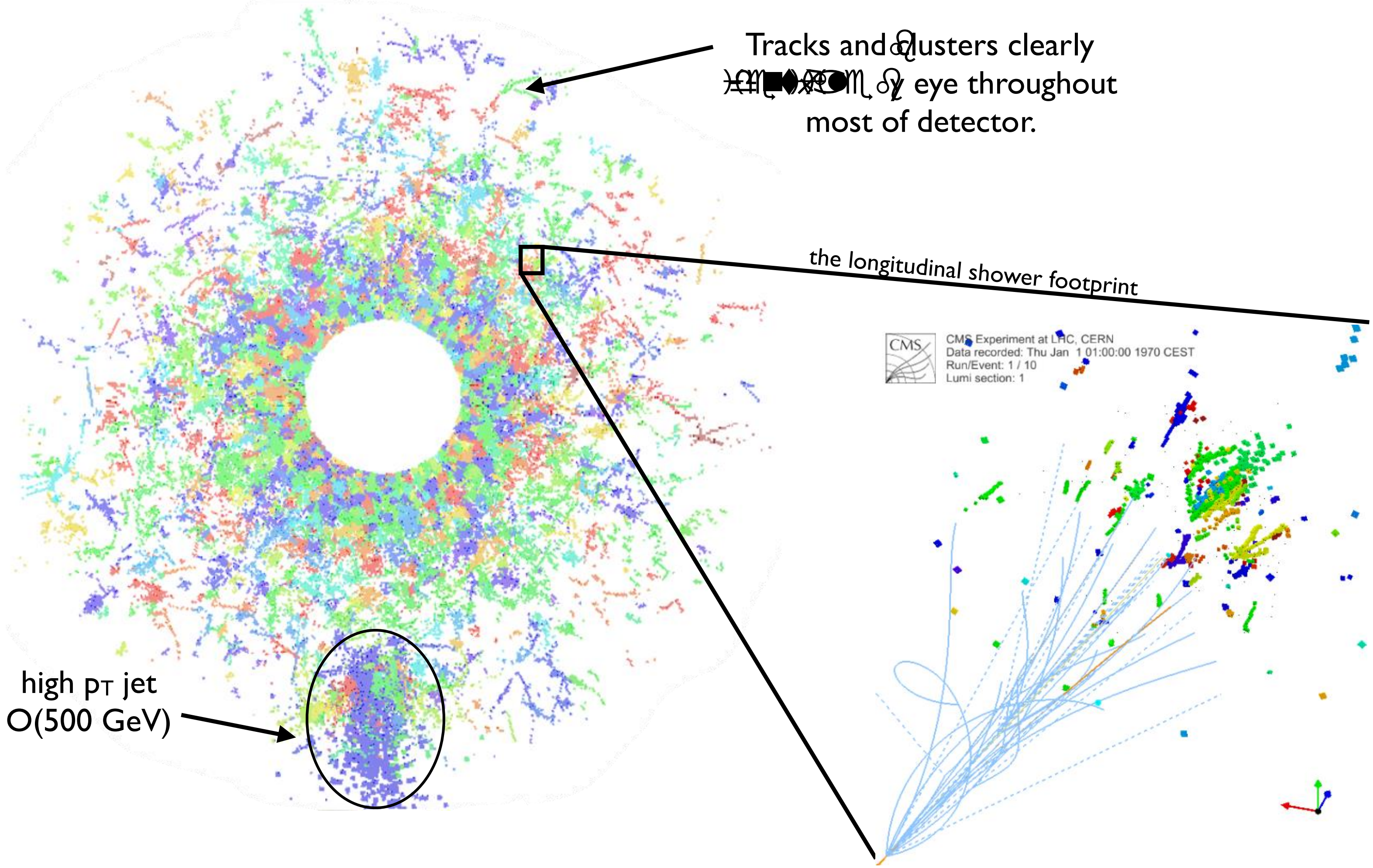
So:

- in CMS today: σ_E/E(150 GeV) = ~0.6 GeV
- in ATLAS today: σ_E/E(150 GeV) = ~1.2 GeV
- in HGCAL: σ_E/E(150 GeV) = ~3 GeV

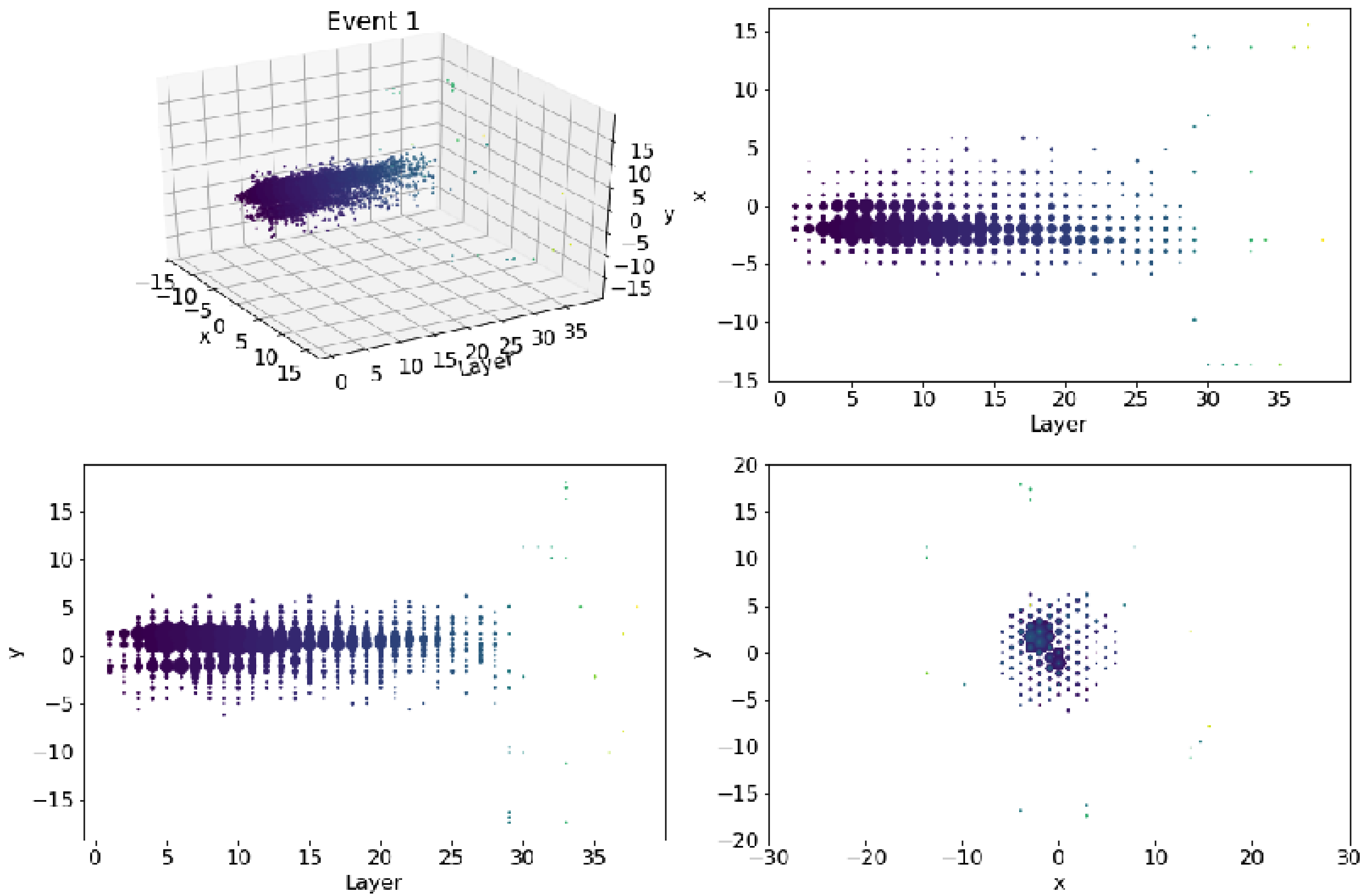
So the difference is not huge, but σ_E is not the only important feature of HGCAL…

HGCAL has the potential to visualize individual components of showers – 5D calorimeter

Simulation of 140 pileup events in CMS



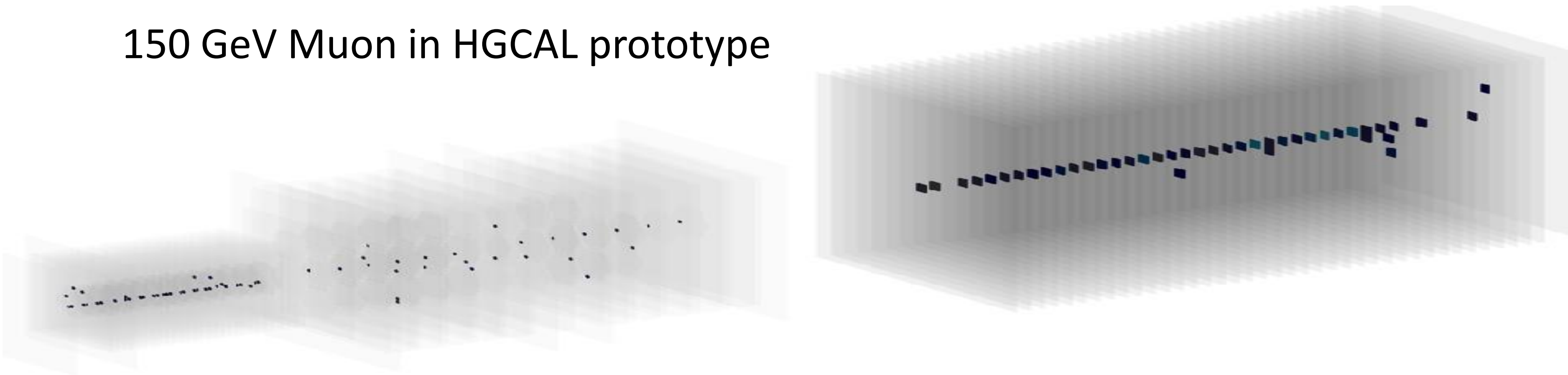
300 GeV electron shower: event display



2 energy clusters seen due to **electron bremsstrahlung** upstream of HGCAL

And other types of particle…

150 GeV Muon in HGCAL prototype

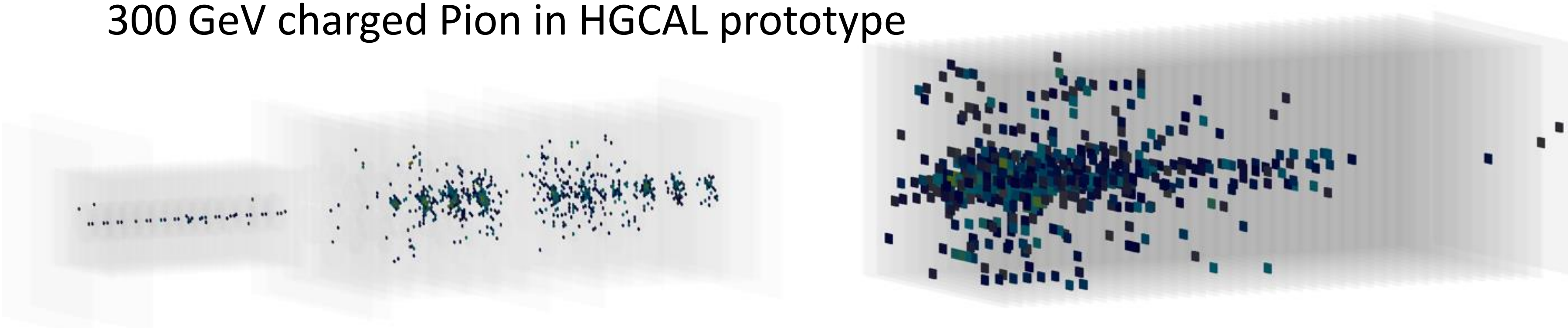


28-layer Si CE-E

12-layer Si front CE-H

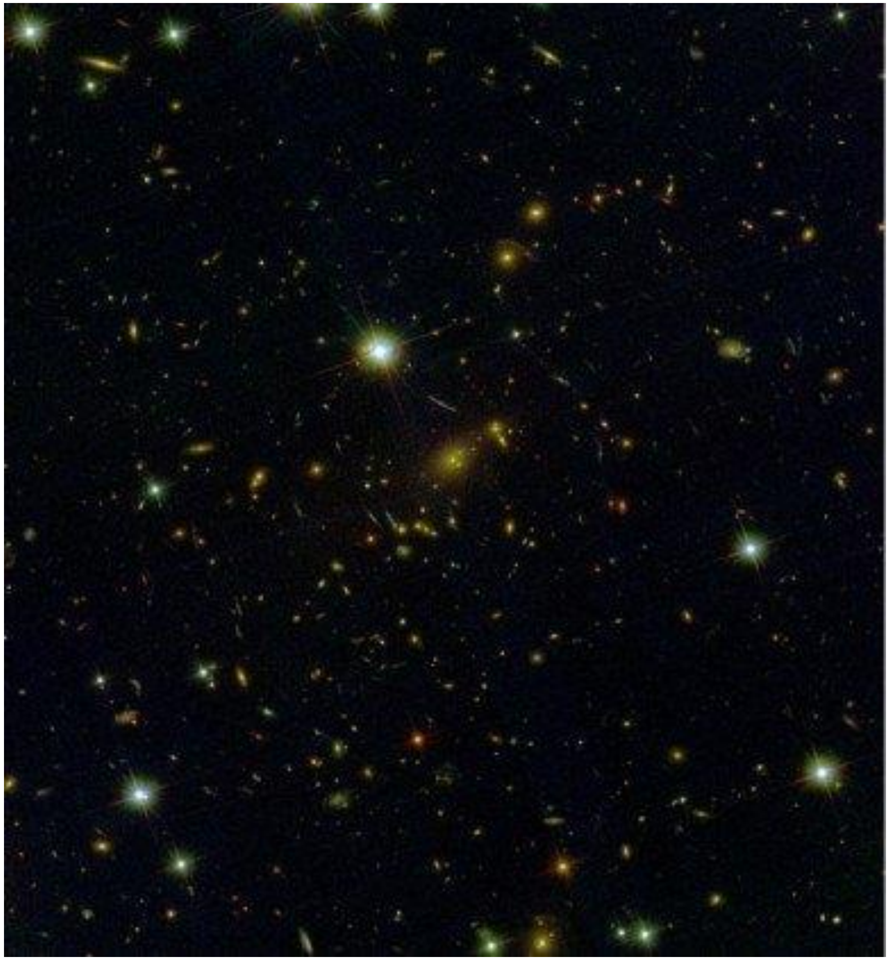
39-layer Scintillator+SiPM CALICE AHCAL

300 GeV charged Pion in HGCAL prototype



HGCAL vs existing endcap calorimeters

CMS Endcap Calorimeters **before** LS3



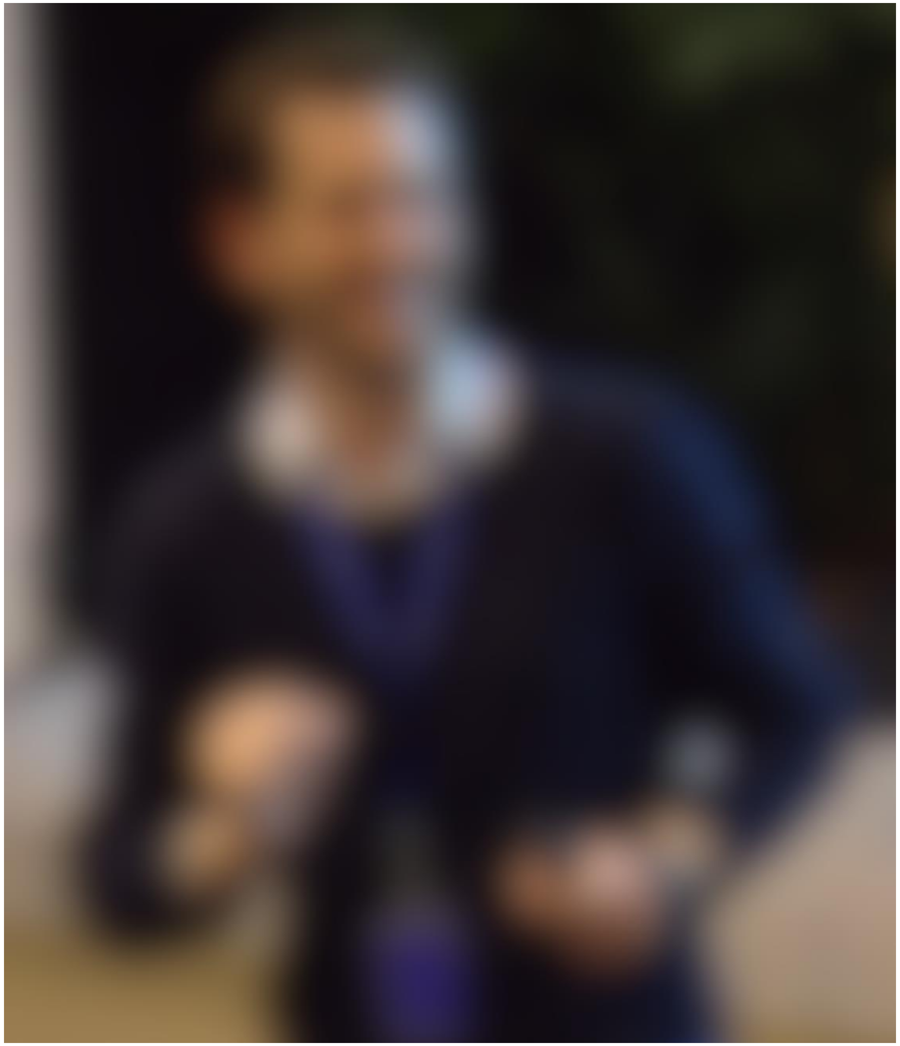
Courtesy: Hubble Space Telescope

CMS Endcap Calorimeters **after** LS3

Courtesy: James Webb Space Telescope

Or, if you prefer…

CMS Endcaps now…



CMS Endcaps for HL-LHC!

Starting to train the next generations

Starting to train the next generations

UK and Swiss High-school students in 2019

We are in the final R&D phase, soon moving to production, assembly and commissioning

- **Finalization of design, prototyping towards final systems (2 years)**
- **Engineering Design Report (February 2023) and Electronic System Review (ESR later this year)**
  - This is a **much** faster timescale than the original CMS construction phase
- **Market Surveys, orders, preproduction, qualification of final components**
- **Production starts in <1 year !**
- **Installation of HGCAL in ~2027/2028**
- **Ready for HL-LHC operation to start in 2029**
- **And operate for >10 years with essentially zero maintenance**

After 29 years on one experiment there is still much to learn and do! And being a “physicist” rarely involves wearing a white coat!

Some career highlights:

- Helped design the CMS Preshower detector (inc. electronics)
- **Led the Preshower project** through the production, assembly, installation & operation phases (and am still responsible for it!)
- **Led the CMS ECAL project** (100 MCHF detector, around 330 people) between 2012-2015 (having been deputy for 4 years previously)
- CMS HGCAL beam/system-test coordinator for 4 years
- Leading design/procurement of some HGCAL components
- **Chair of HGCAL Editorial Board and Conference Committee** for 3 years
- **Group Leader of CERN EP-CMX group** since 2016: CMS Experimental Systems (~120 people) involved in CMS operations, upgrades and Technical Coordination
- **Scientific Secretary of CMS Collaboration Board** (2021-2023)
- Member of CERN Senior-Staff advisory group “**The Nine**” to the Director General (2021-2024)
- CERN representative on **EIROforum** Instrumentation Working Group
- CMS **Education & Outreach coordinator** 2000-2013
- Co-chair of International Particle Physics Outreach Group (**IPPOG**) for a few years
- Interim CMS Head of Communications (2023)