



CMS: a personal journey

Dave Barney, CERN, 12th July 2019

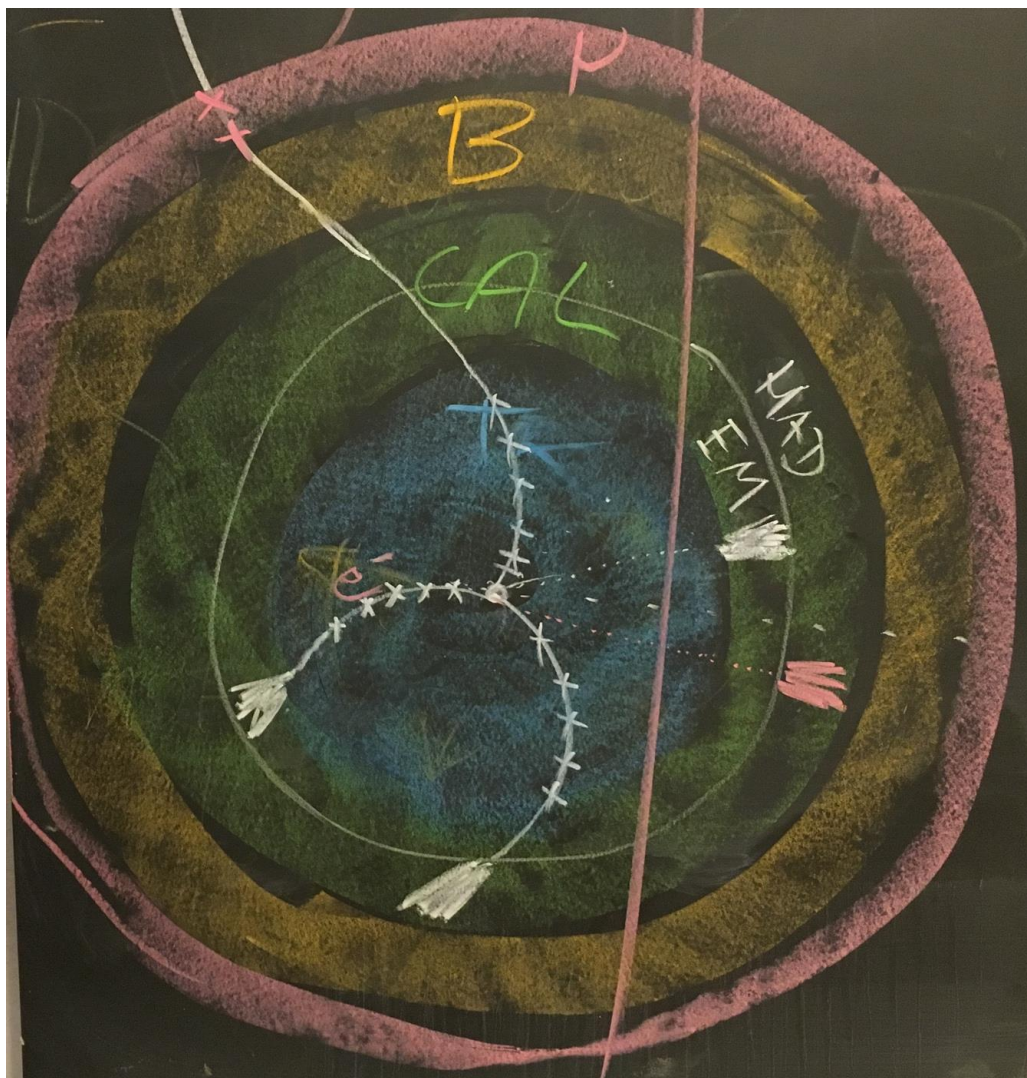
The Large Hadron Collider...



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



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

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

More to come!



And my history in CMS goes back to 1994

Technical Proposal: 1994
When I joined the CMS experiment



More to come!



CMS: a truly global project



CMS Collaboration
~4000 members
~40 countries
~200 Institutes

Inc. about 600 students





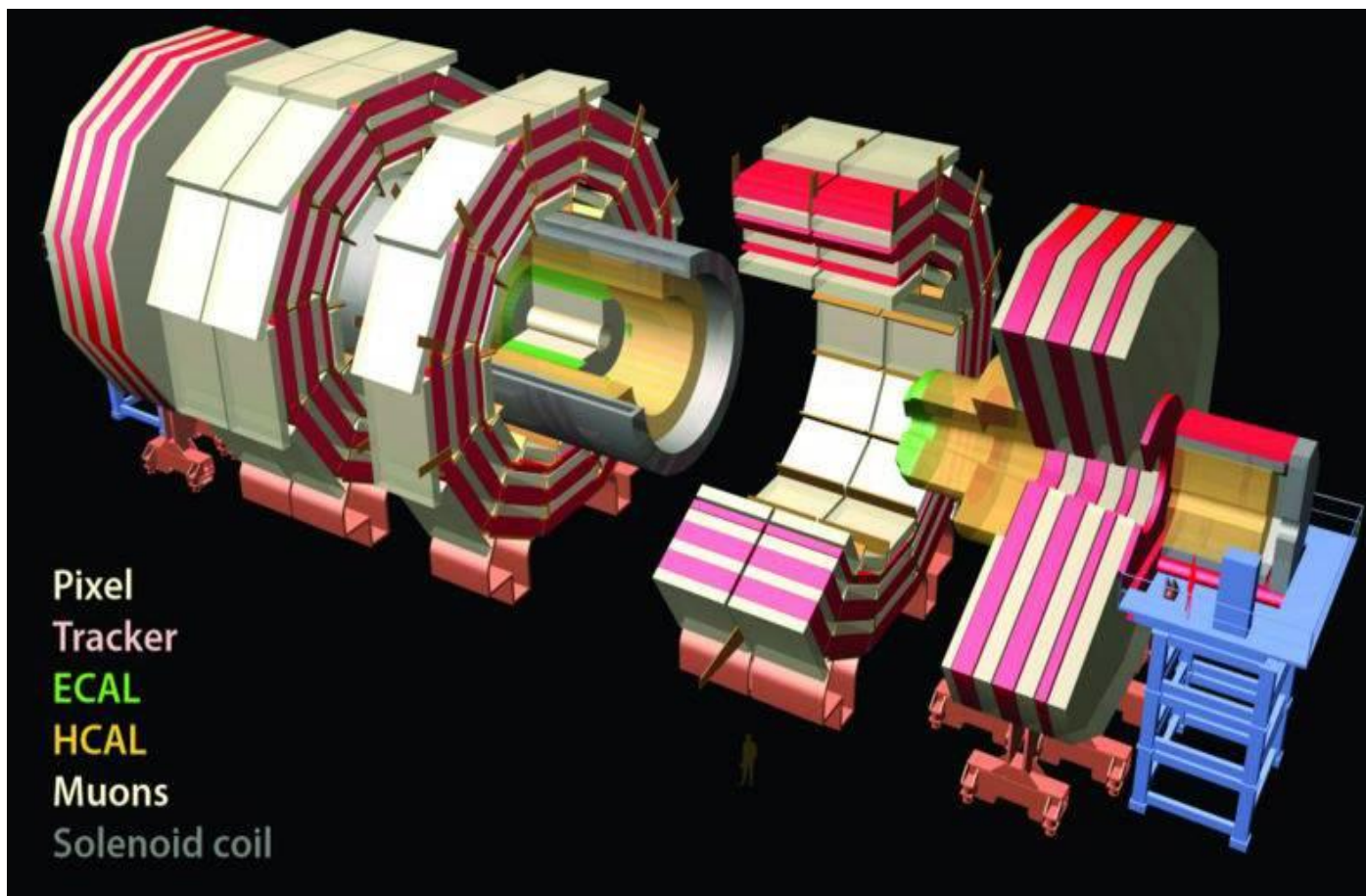
CMS in a nutshell

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

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

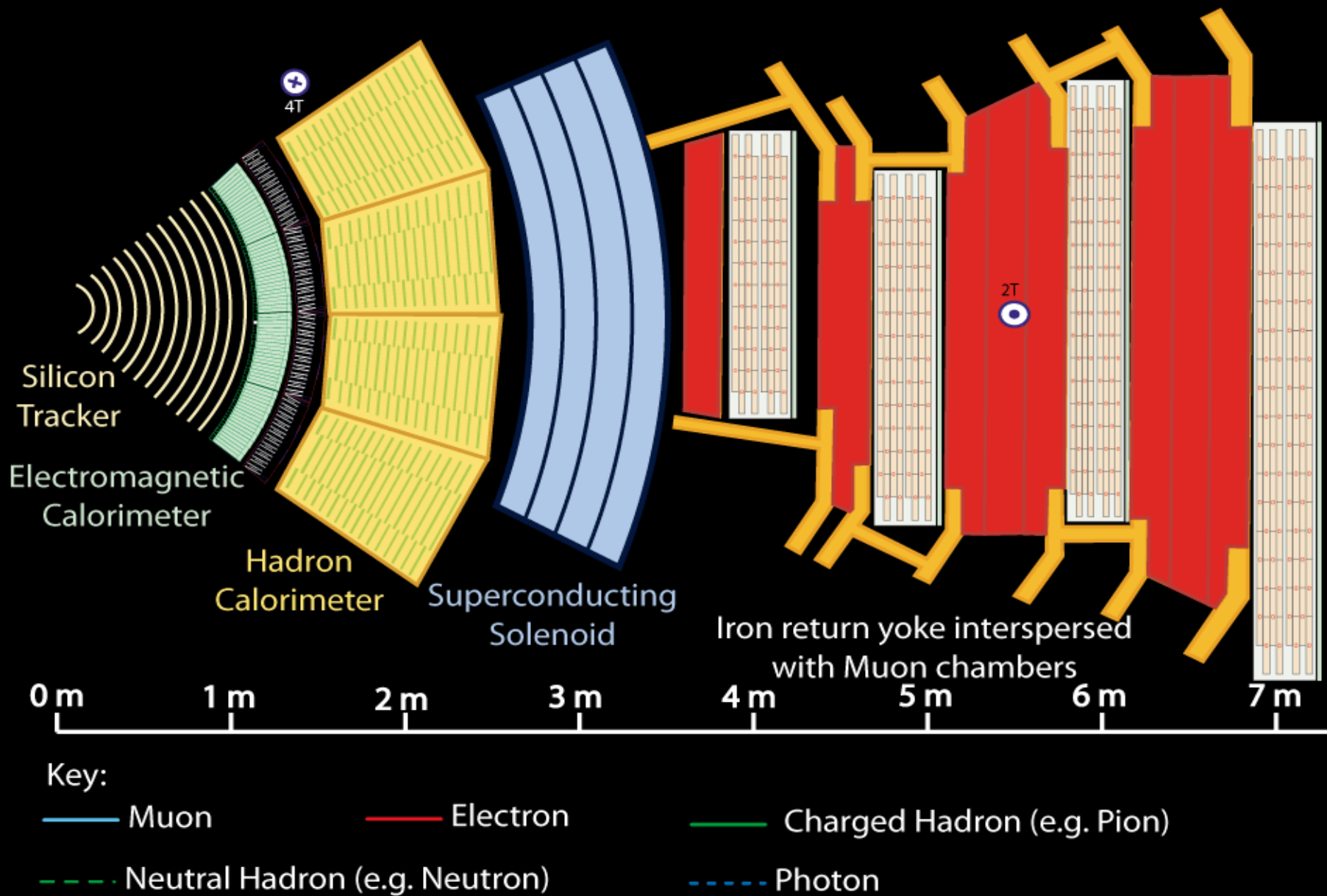
Weighs **twice as much as the Eiffel Tower** – about 14000t

Divided into **5 main detecting layers**



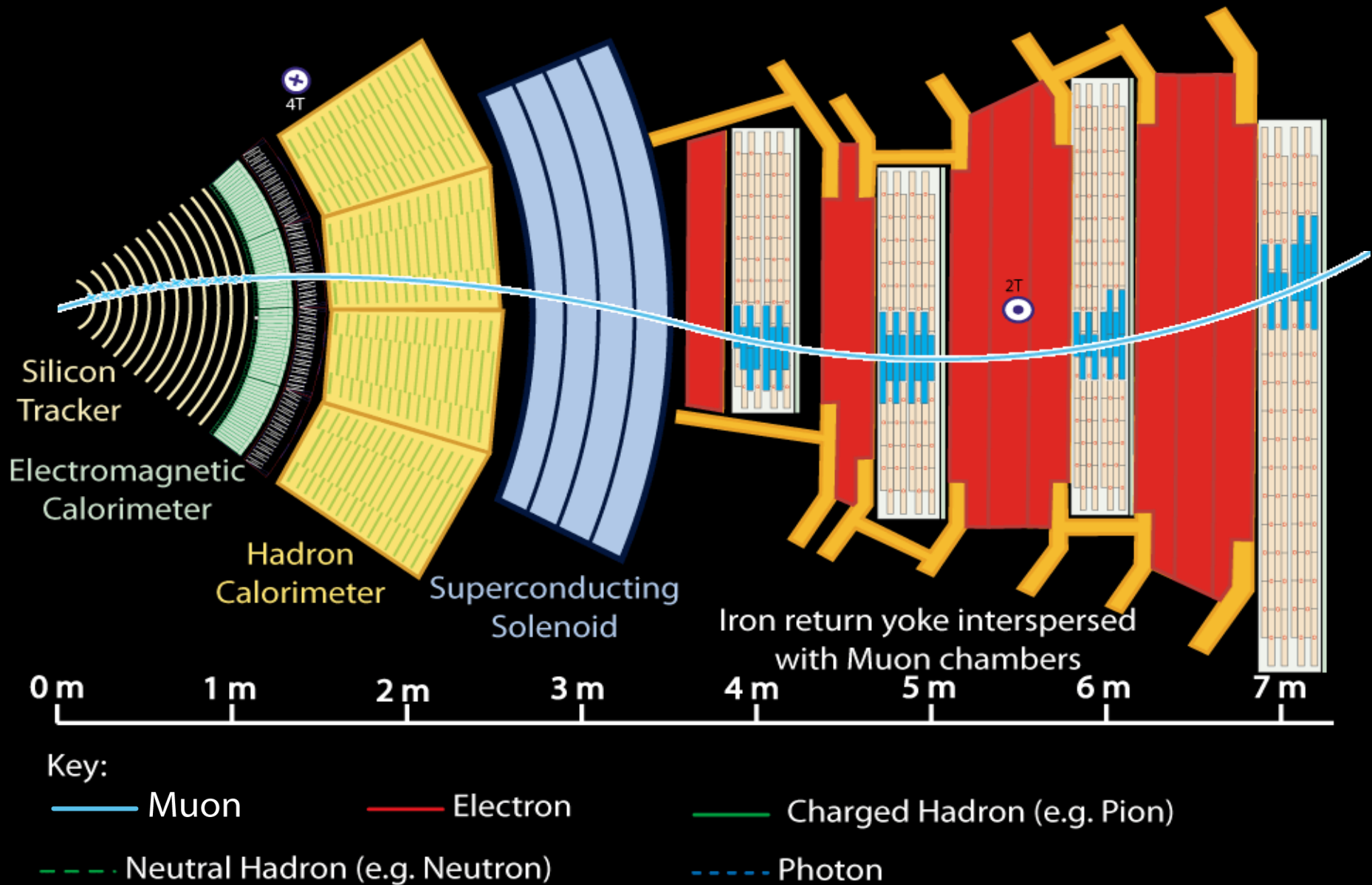


A slice through the CMS Detector



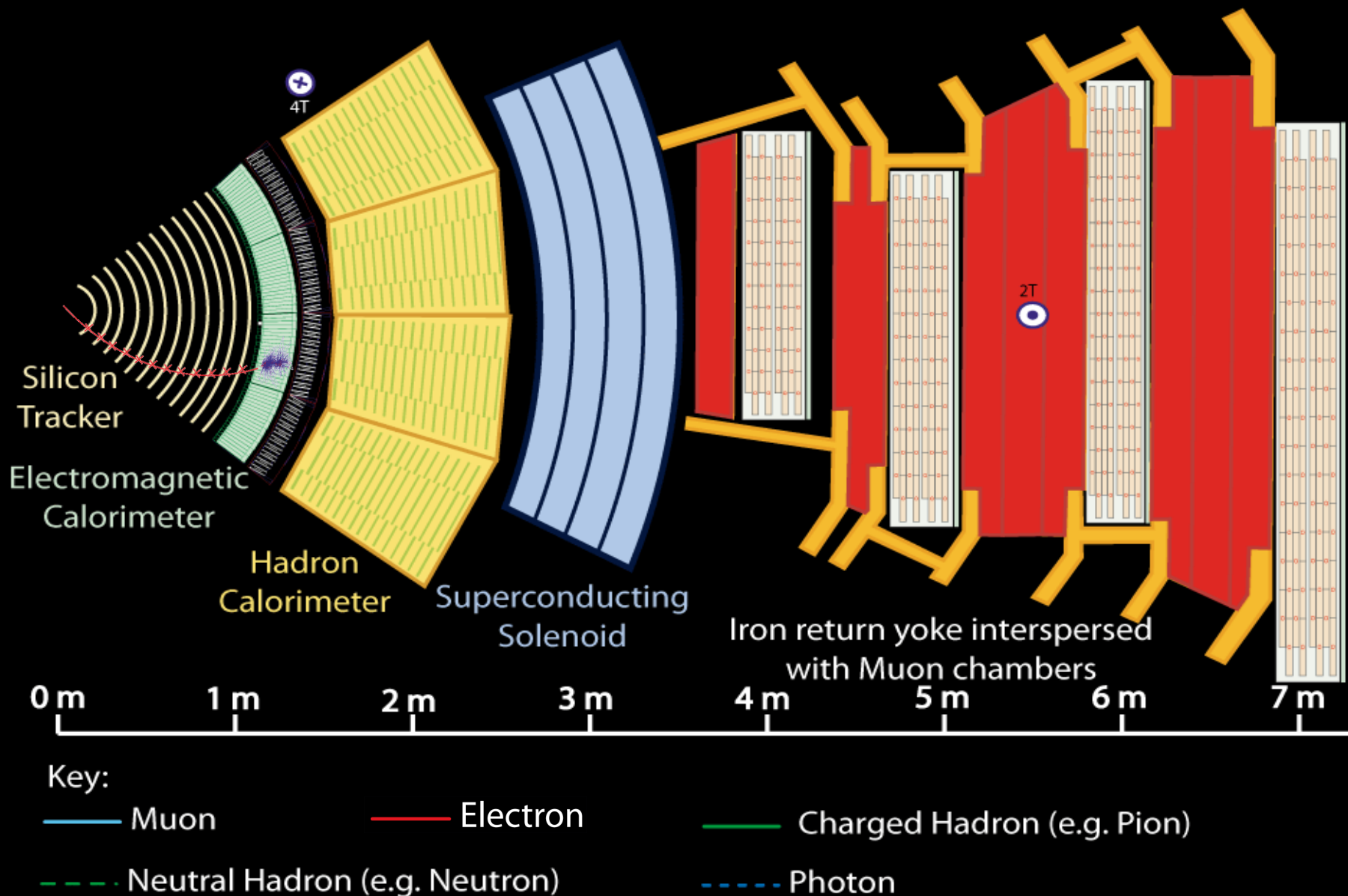


Muons in CMS



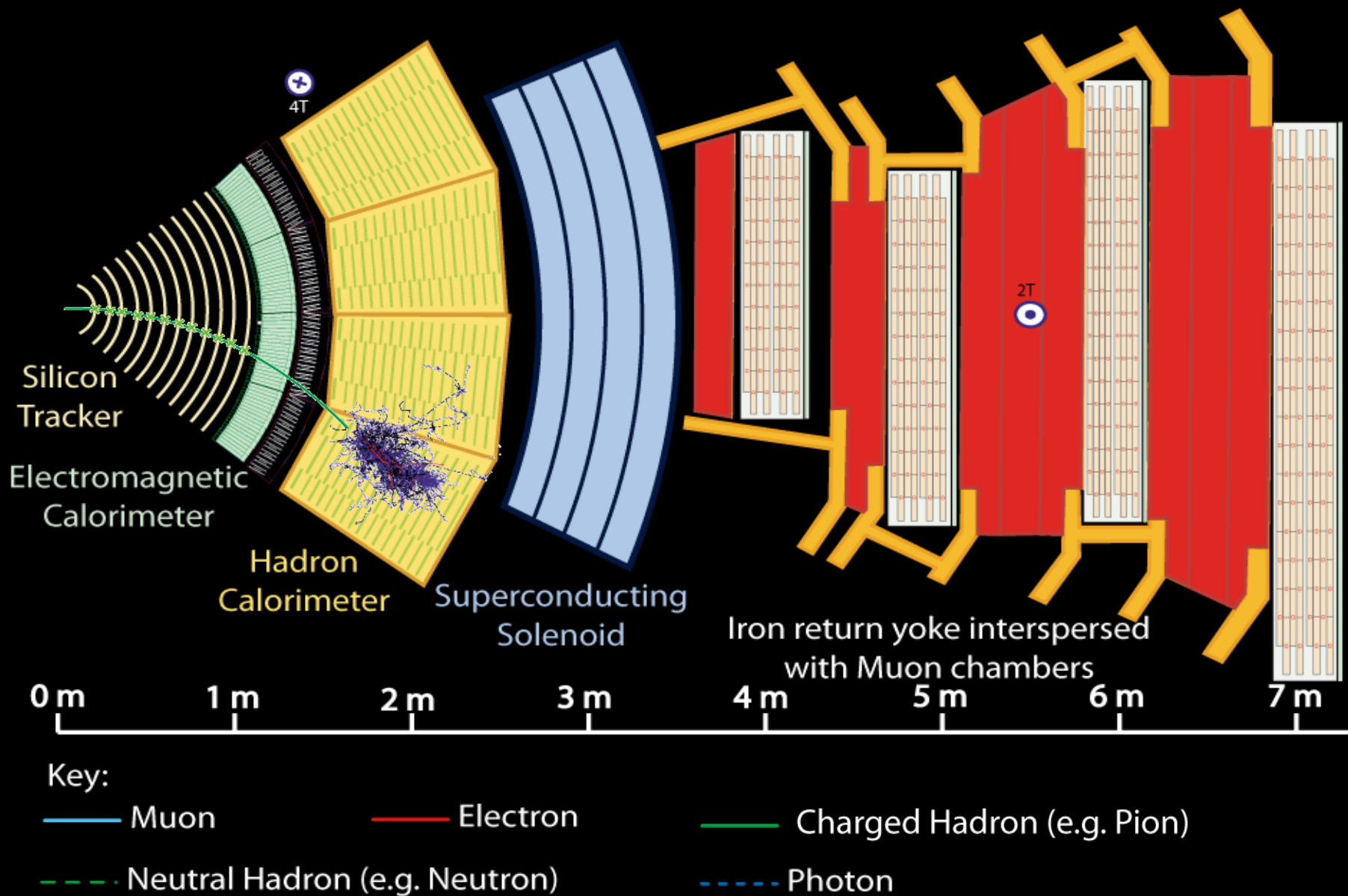


Electrons in CMS

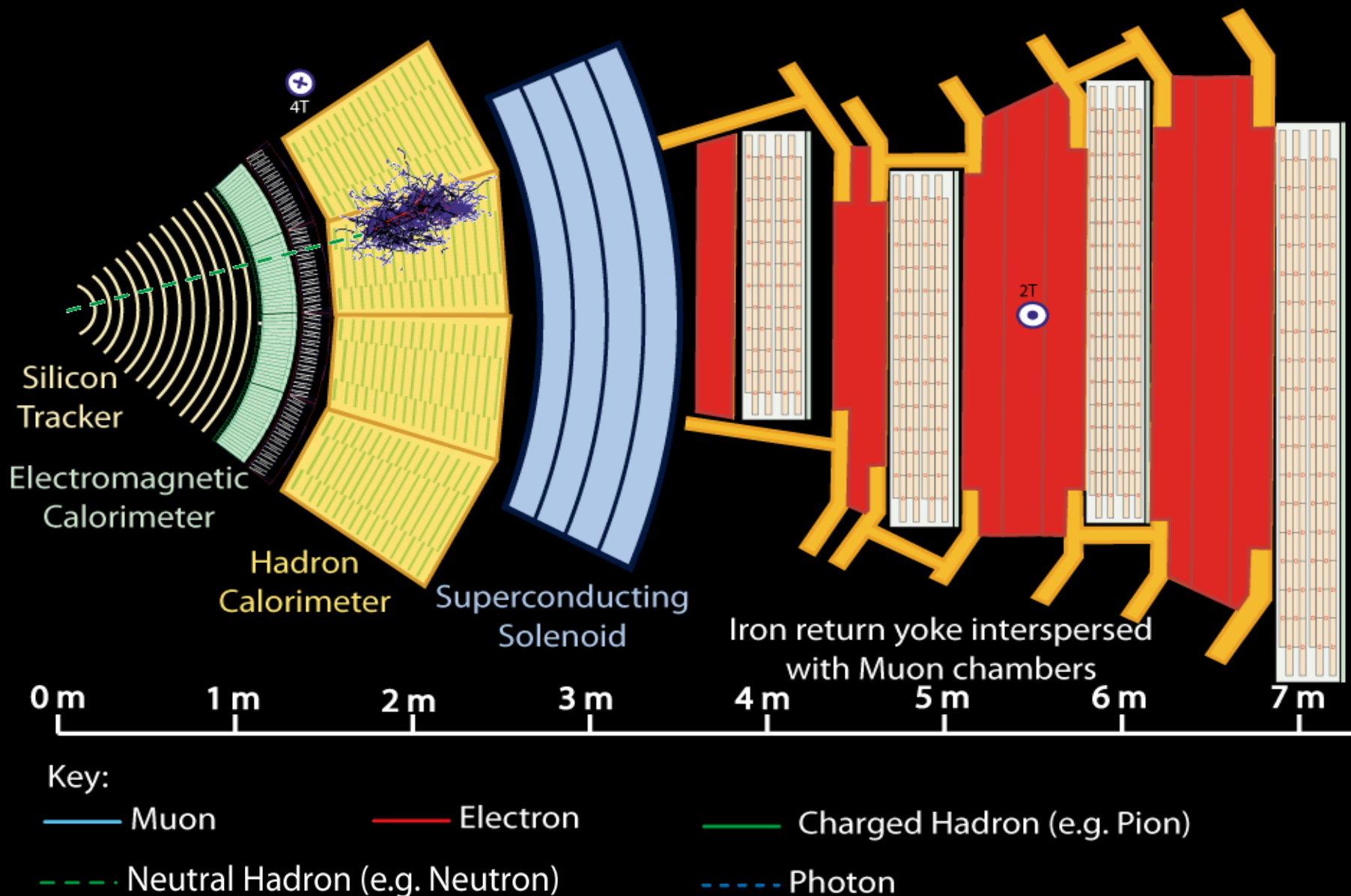




Charged hadrons in CMS

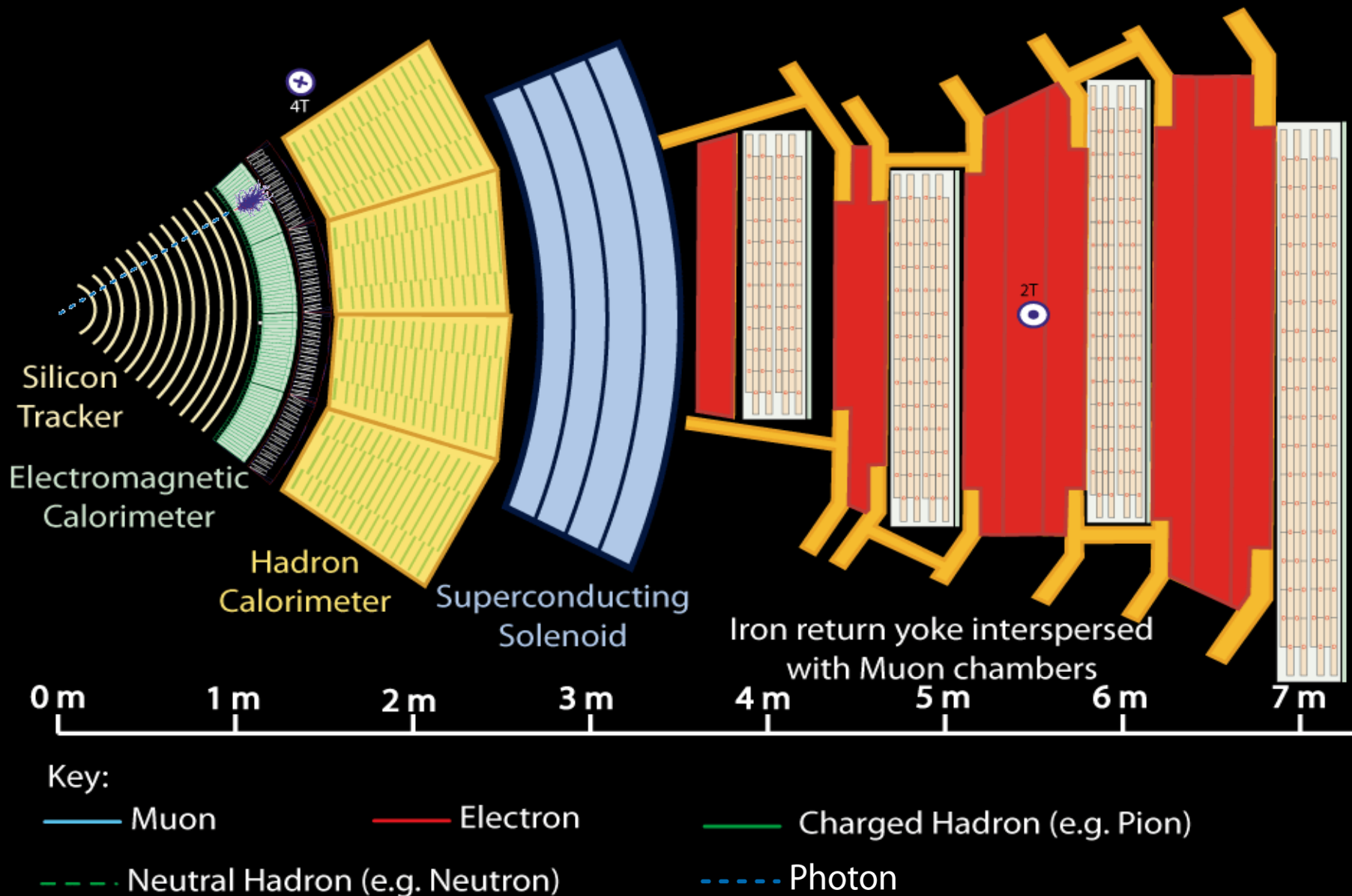


Neutral hadrons in CMS



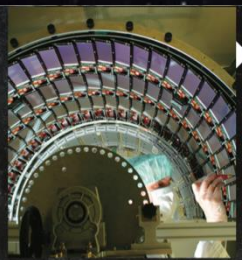


Photons in CMS



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).

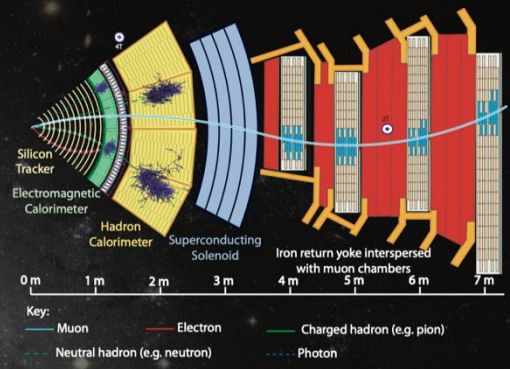


Tracker

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.

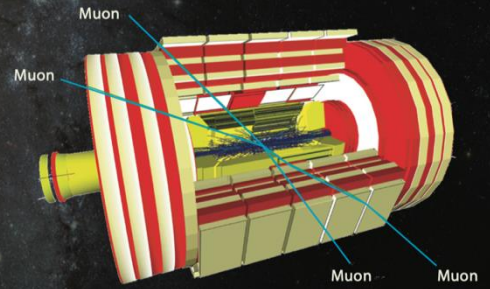
Pattern Recognition

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.



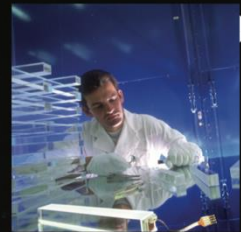
Trigger System

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.



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.



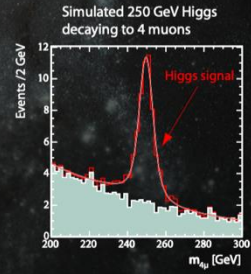
Muon Detectors

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.



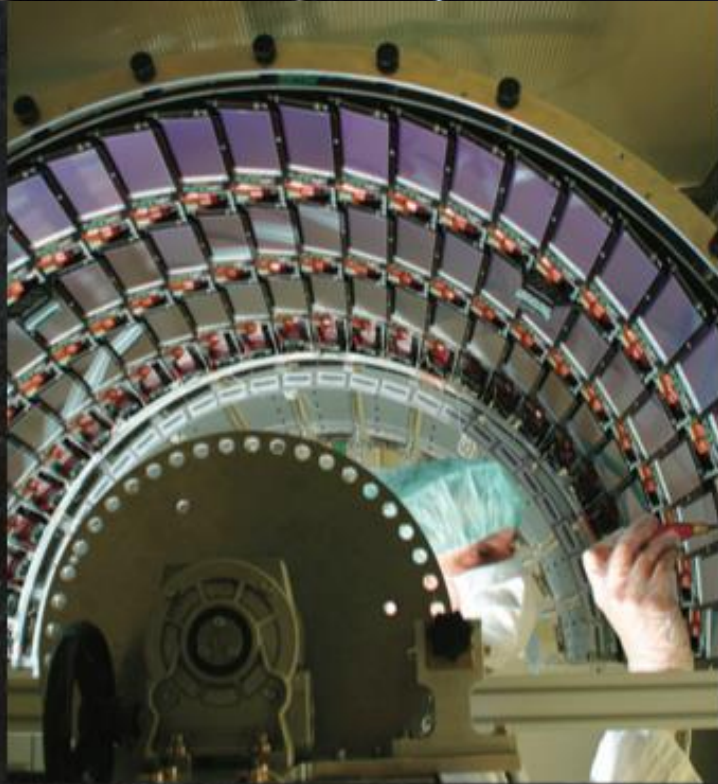
Superconducting Solenoid

Passing 20 000 amperes through a 13 m long, 6 m diameter coil of niobium-titanium superconductor, cooled to $-270^{\circ}C$, 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.



Data Analysis

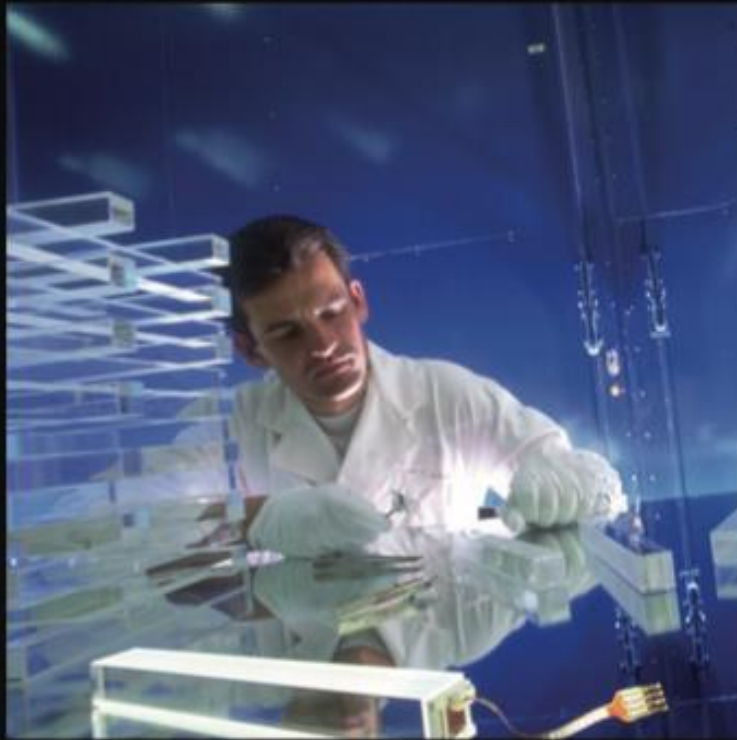
Physicists from around the world use cutting-edge computing techniques (such as the Grid) to sift through millions of events from CMS to produce plots like the one on the left (a simulation) that could indicate the presence of new particles or phenomena.



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.



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Muon Detectors

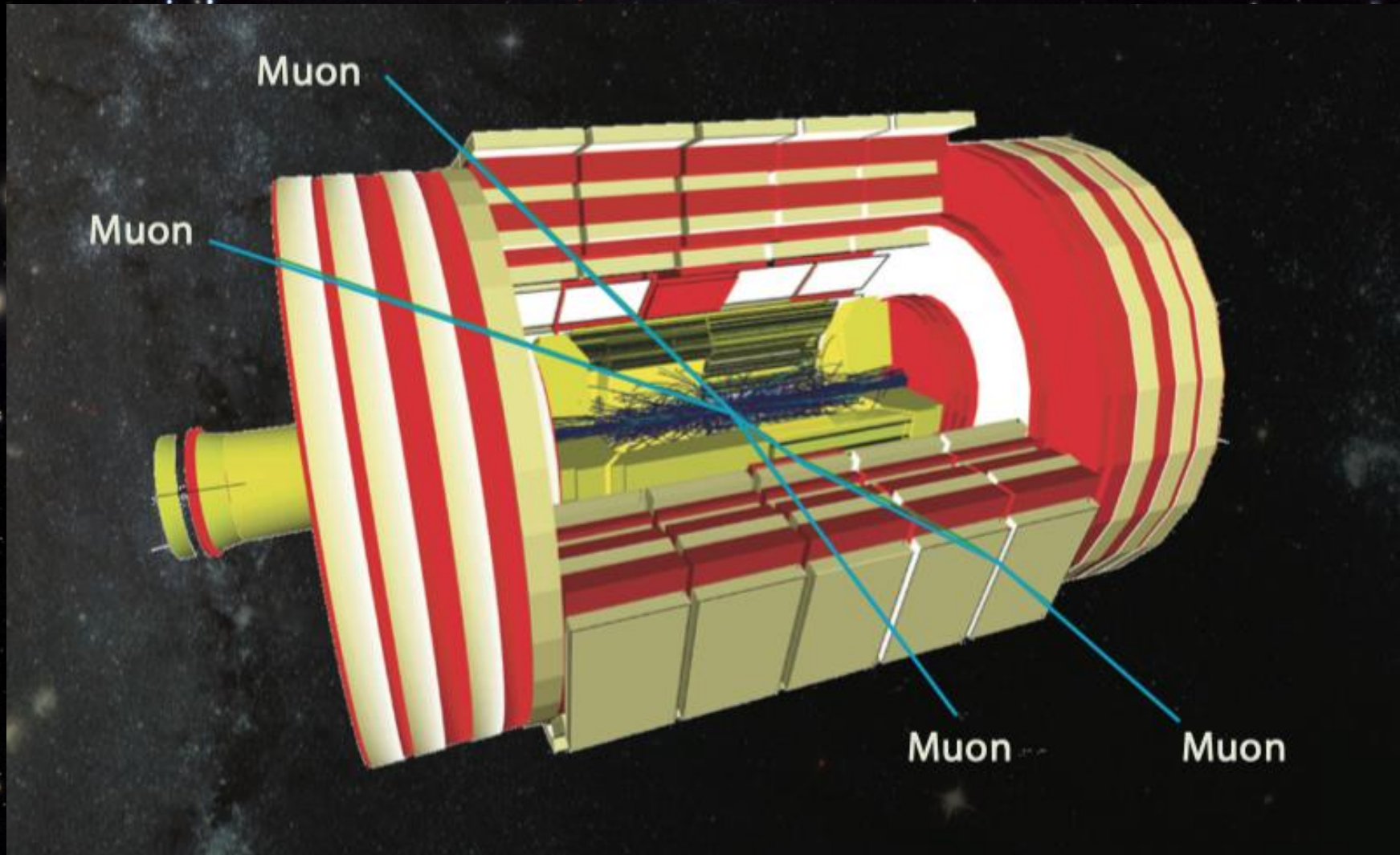
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Higgs boson decay to 4 muons



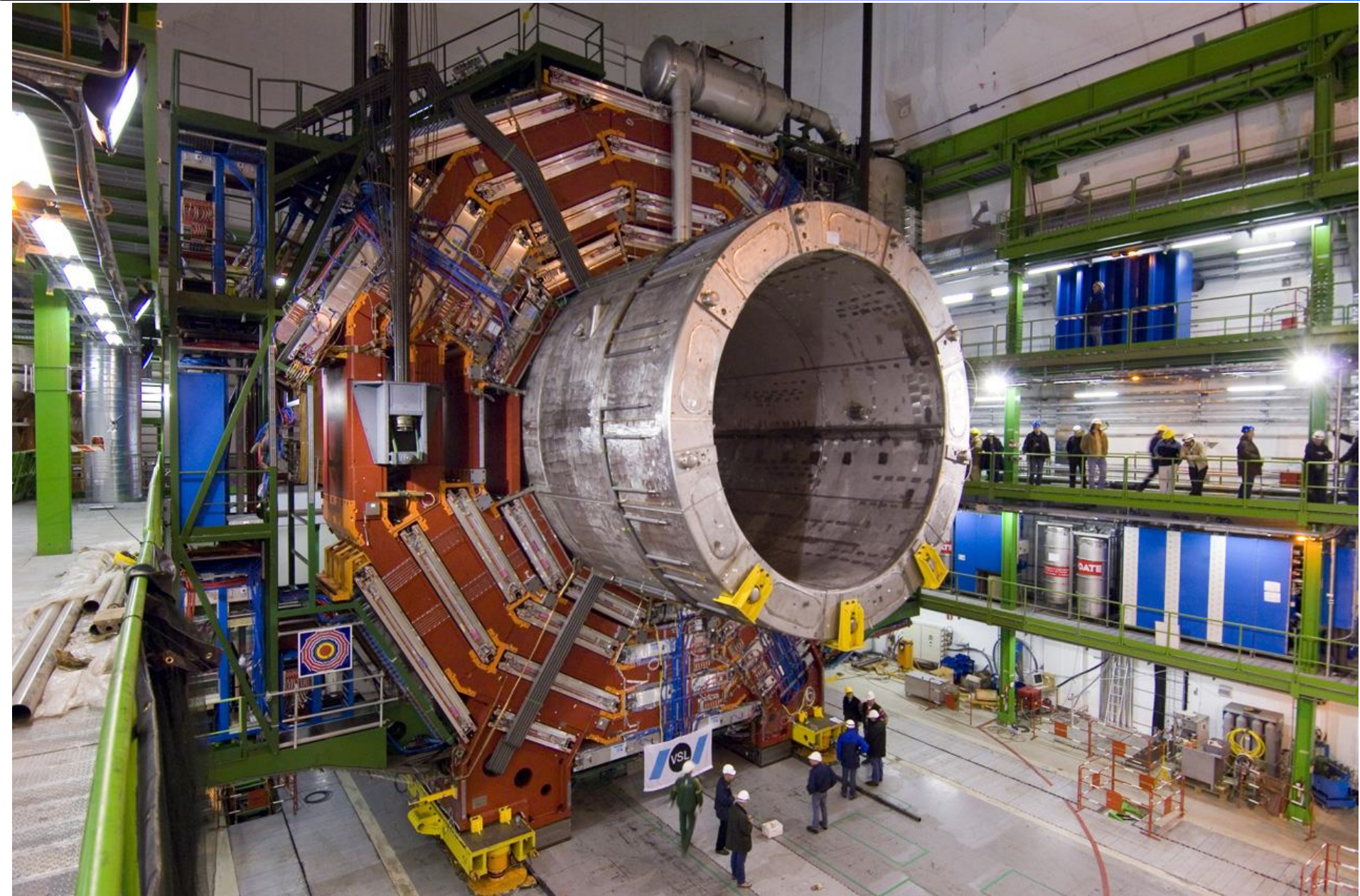


The origin of the CMS logo

Concept: build on the surface and lower underground



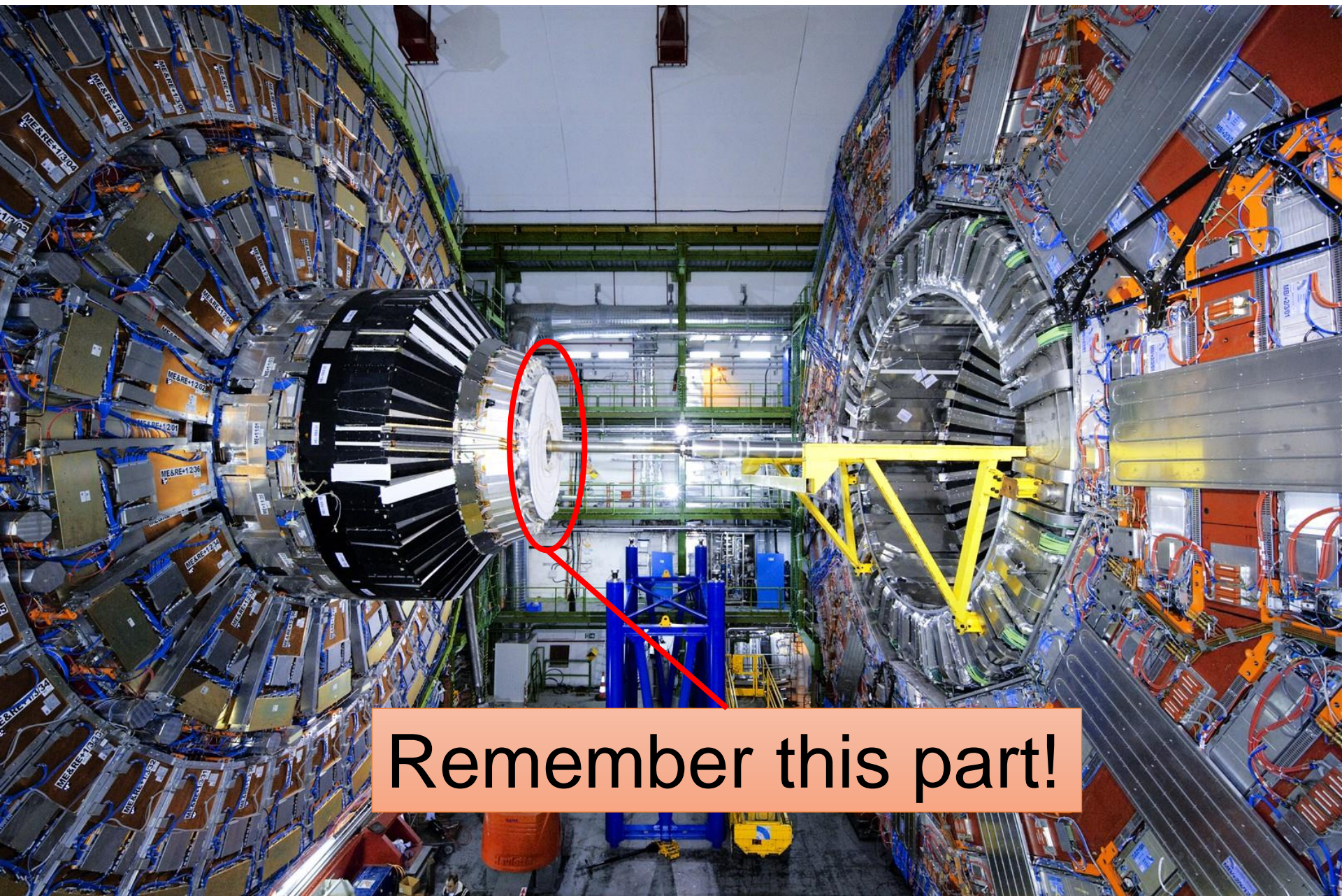
Concept: build on the surface and lower underground





CMS: the most visually amazing detector ever made!

(I may be biased!)



Remember this part!

Why did I become a scientist?

She told Neil deGrasse Tyson she wants to be a scientist when she grows up. He told her: "The greatest thing about being a scientist is you never have to grow up."





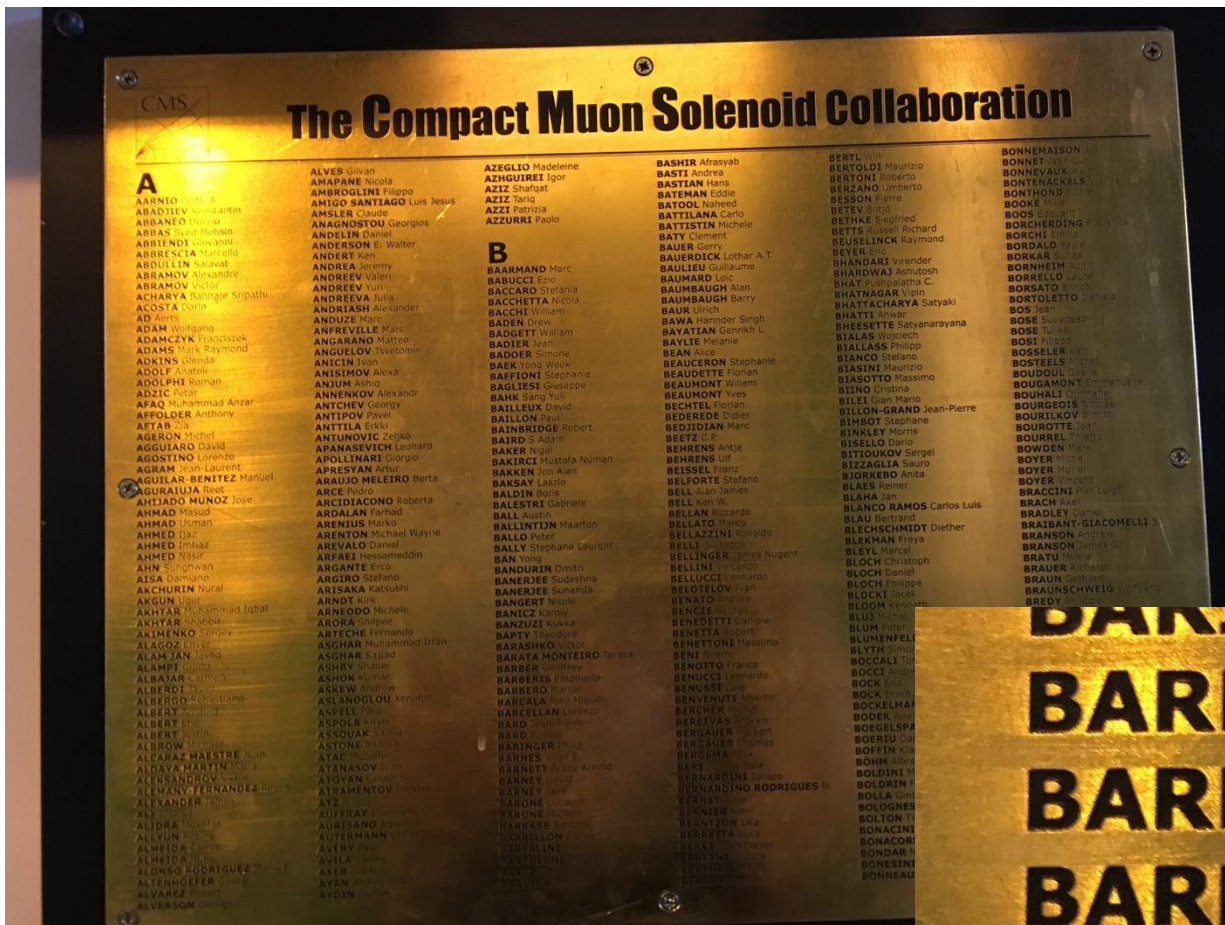
How did I get here?

- 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 25 years!



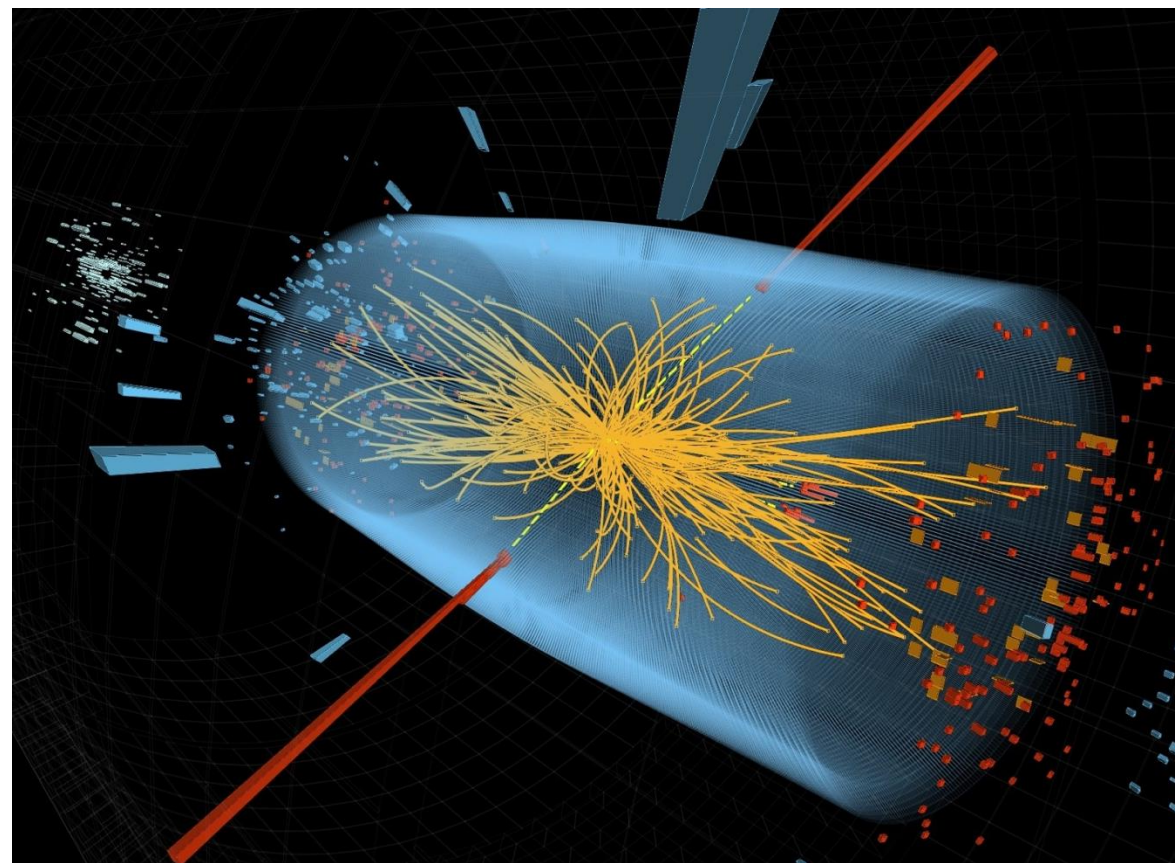
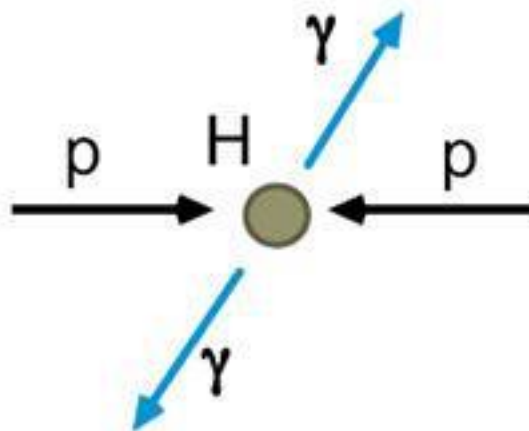


It has been a family affair!



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

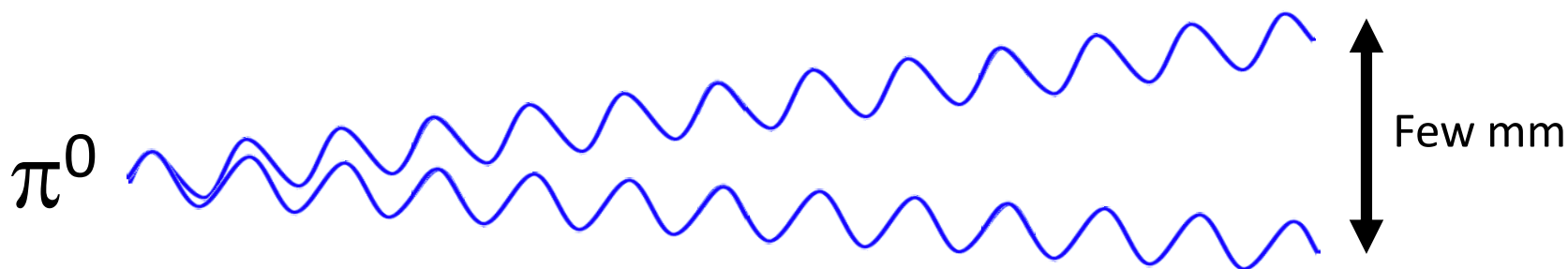


And this is what CMS saw in 2011!

But it wasn't quite that easy!

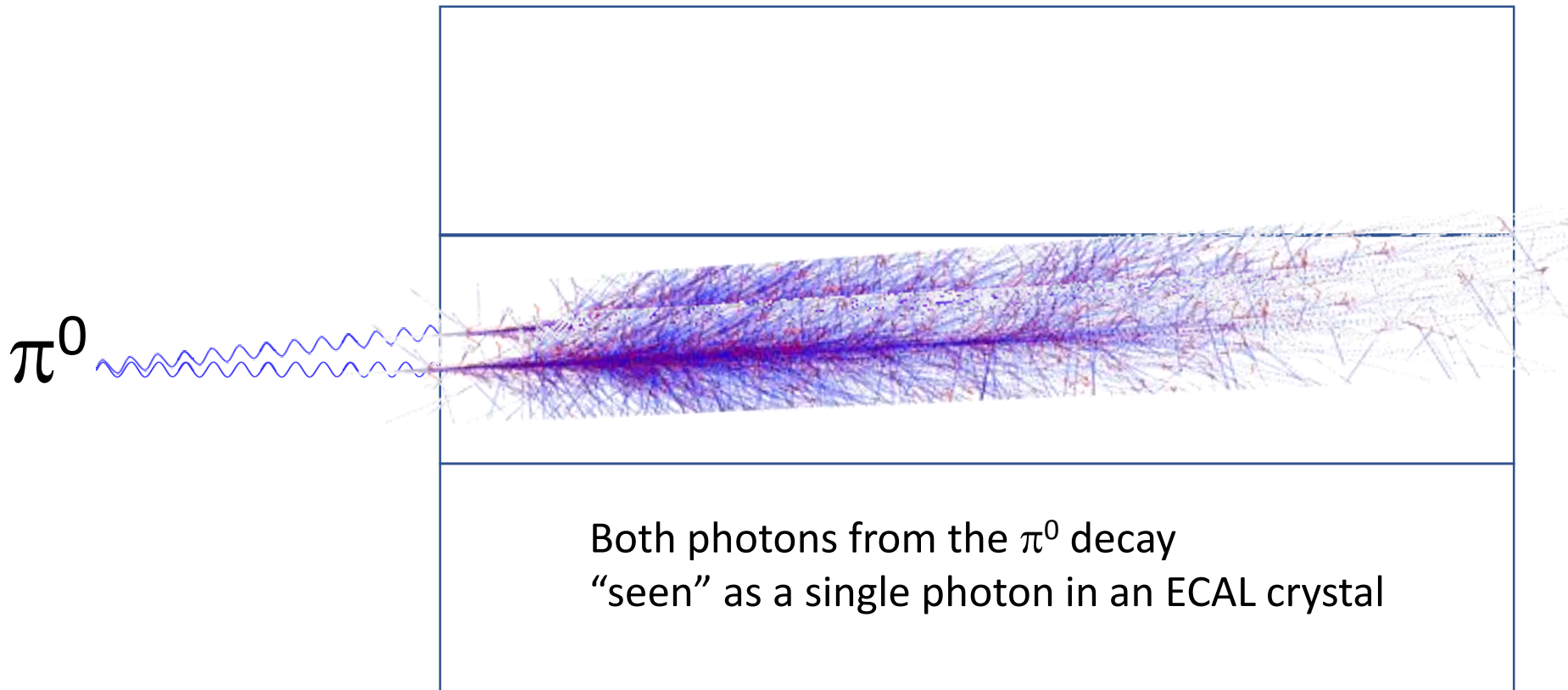
Photons in CMS don't only come from decays of Higgs bosons

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!



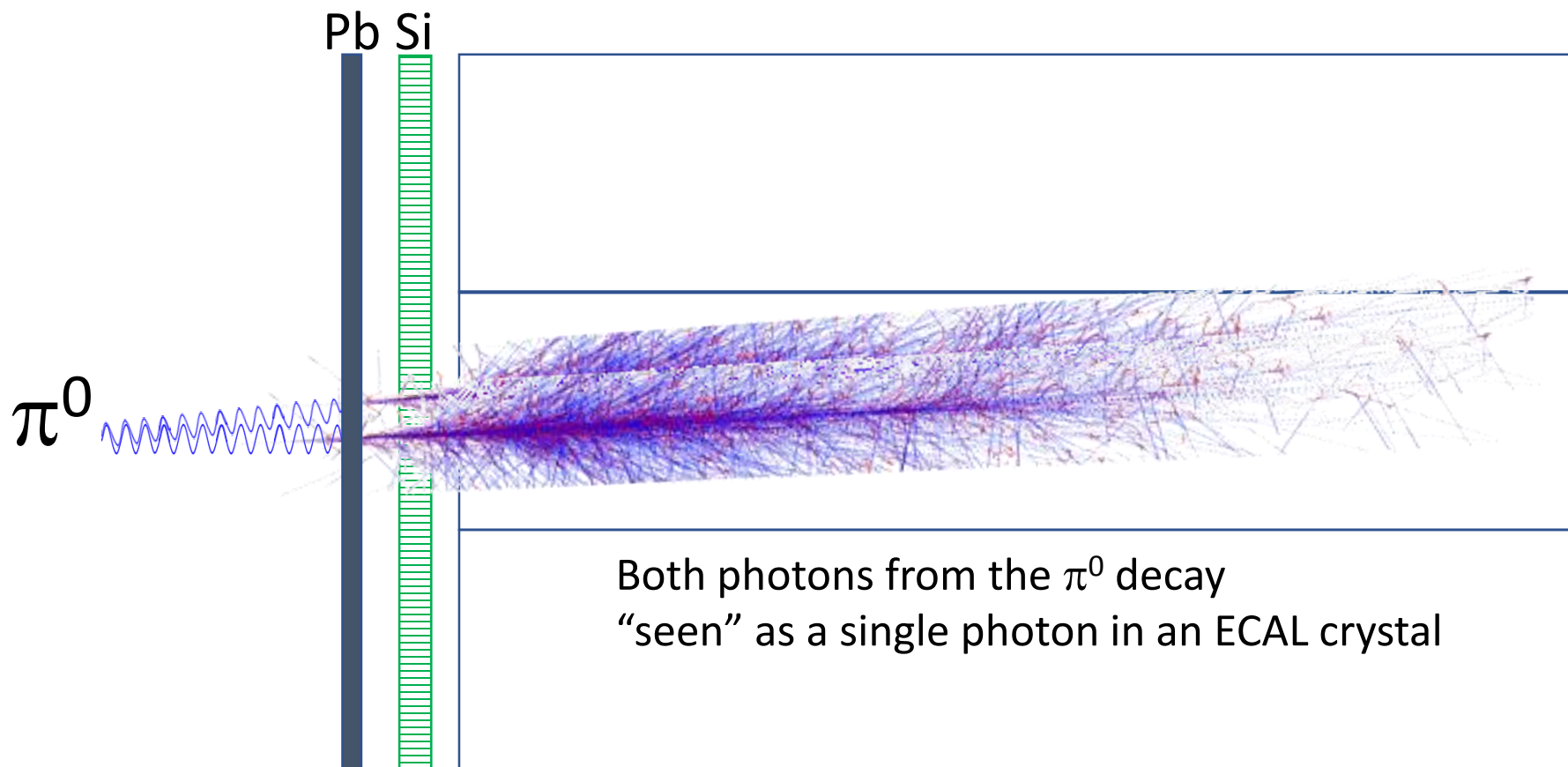
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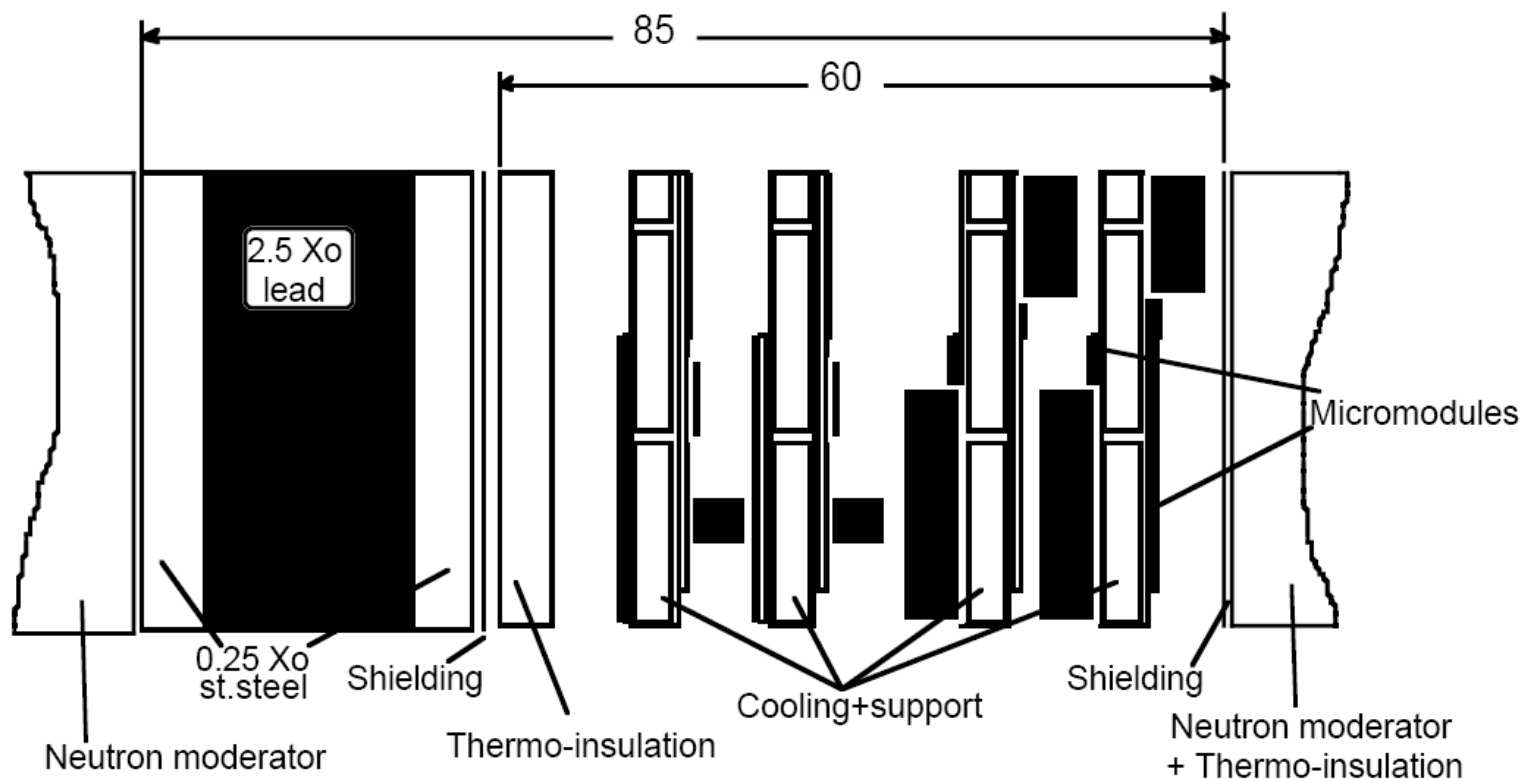
The concept of the Preshower

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...

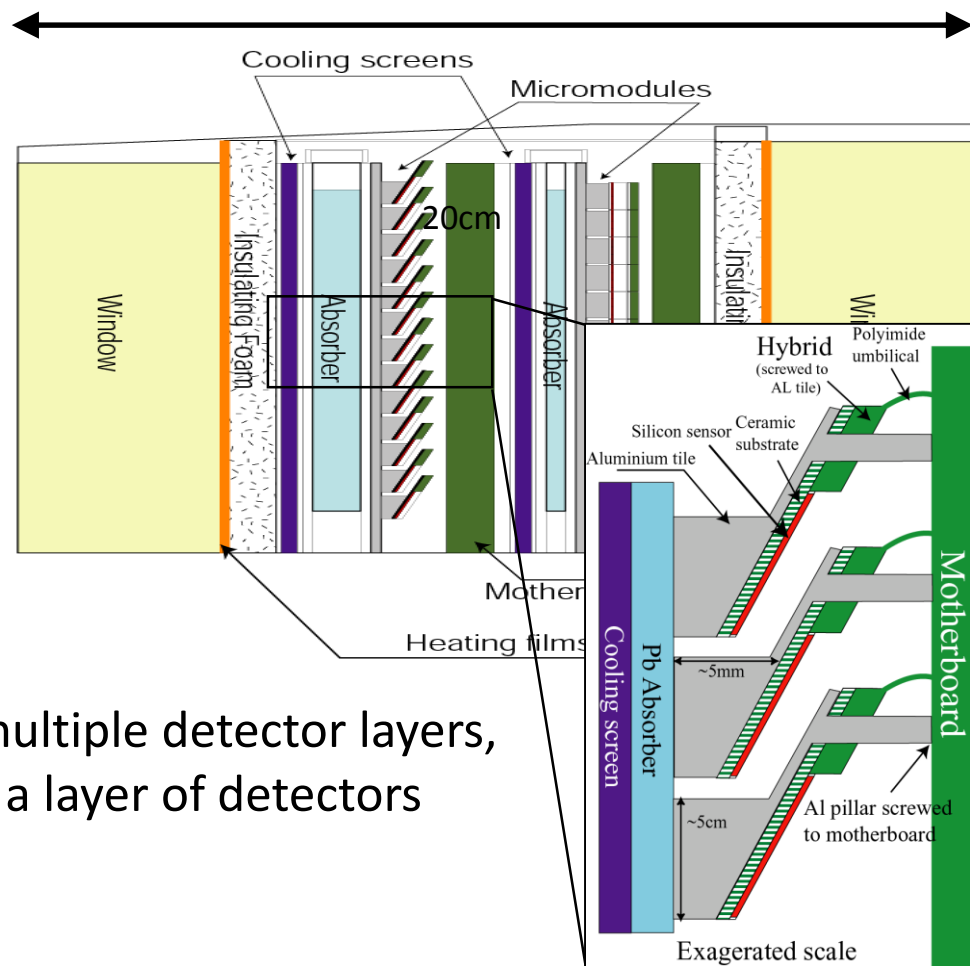
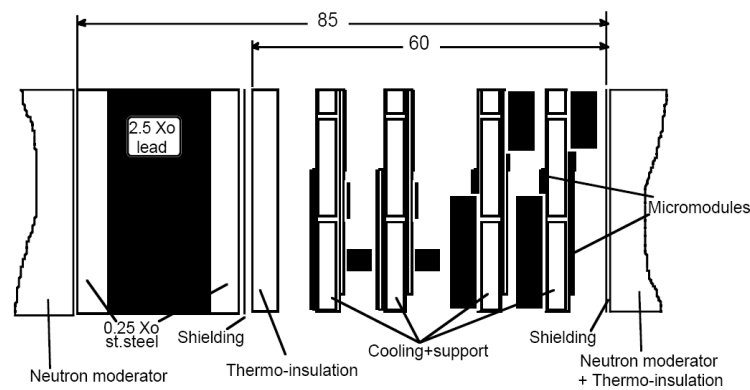
My job was to turn this concept...



...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

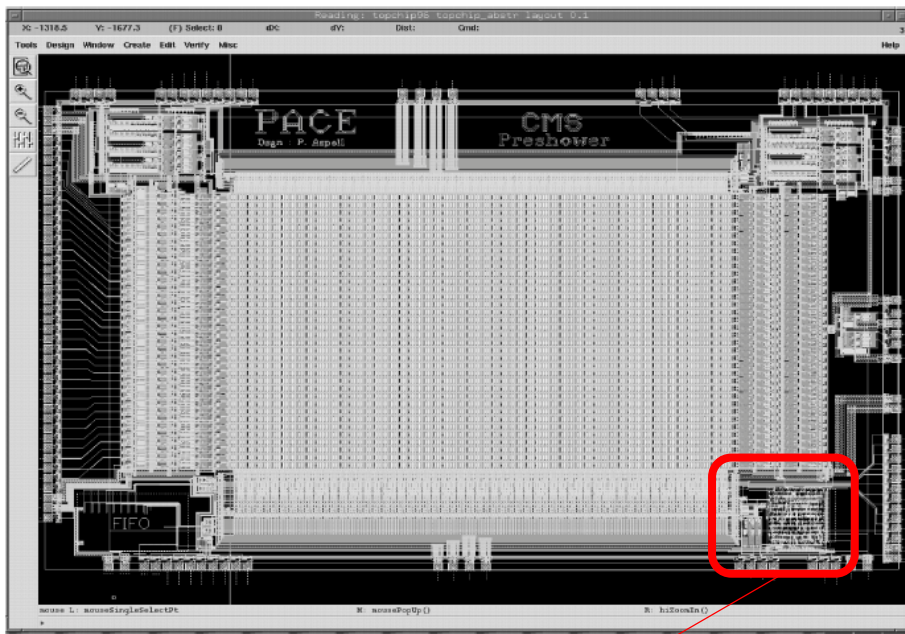


Instead of one absorber followed by multiple detector layers, have two absorbers, each followed by a layer of detectors
 → essentially the final basic design!

Examples of 3 years of work as an applied physicist!

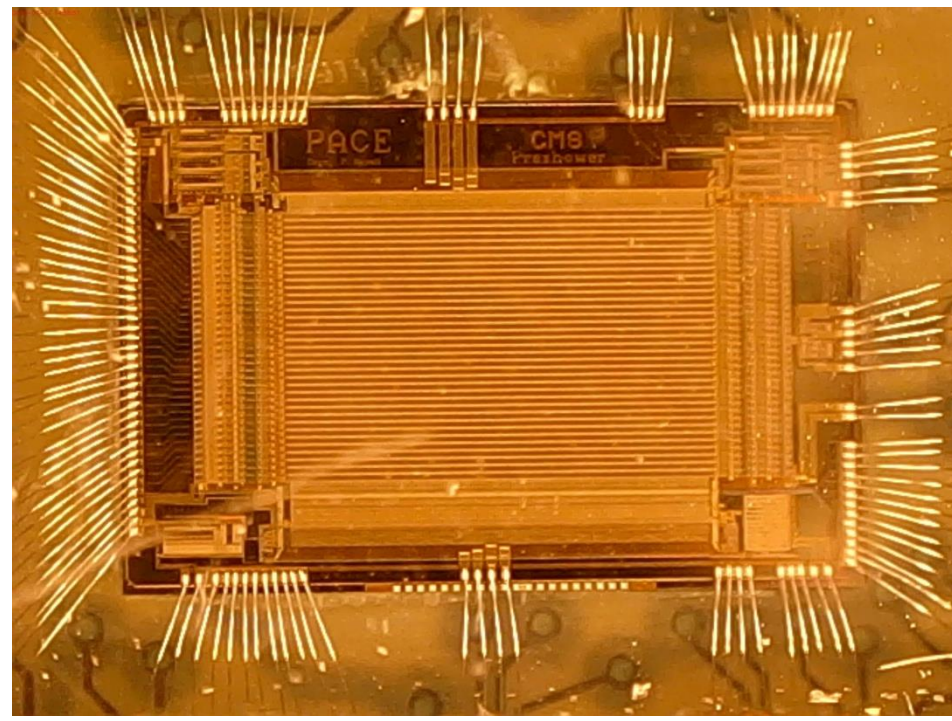
- Designed a part of the prototype front-end microelectronics, called the “sequencer” (determines the order in which to do things etc.)

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 PbWO₄ 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	1051	1052
		T7		
1056	1043	1059	1042	1047
		T12		
	1049	1045	1053	
		T17		
	1041	1046	1044	

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

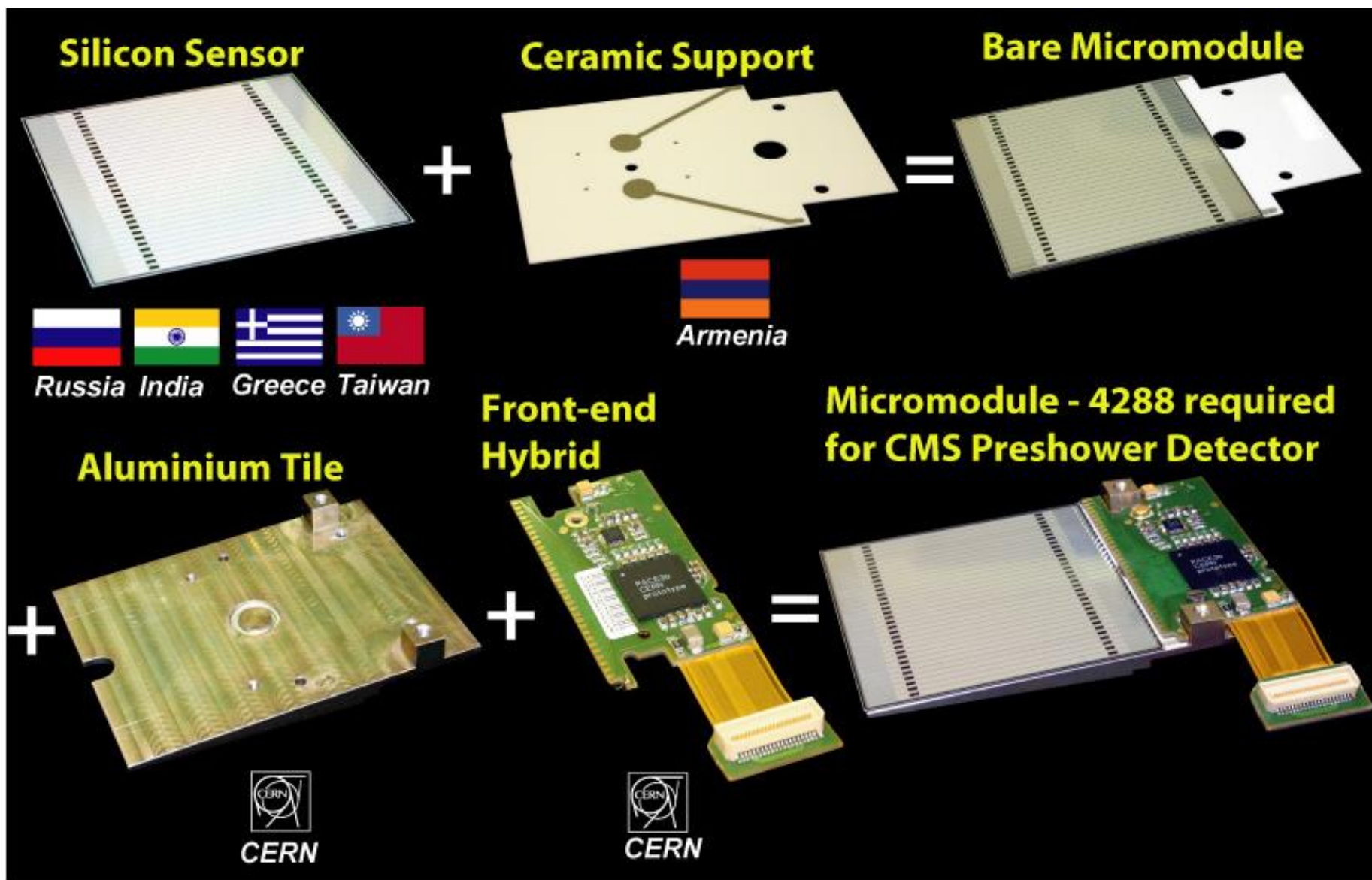
Note
 Only central 3 columns calibrated

View from Back

Figure 1: Crystal matrix testbeam setup in May 1995

Results written-up
in official notes

It's all about teamwork!

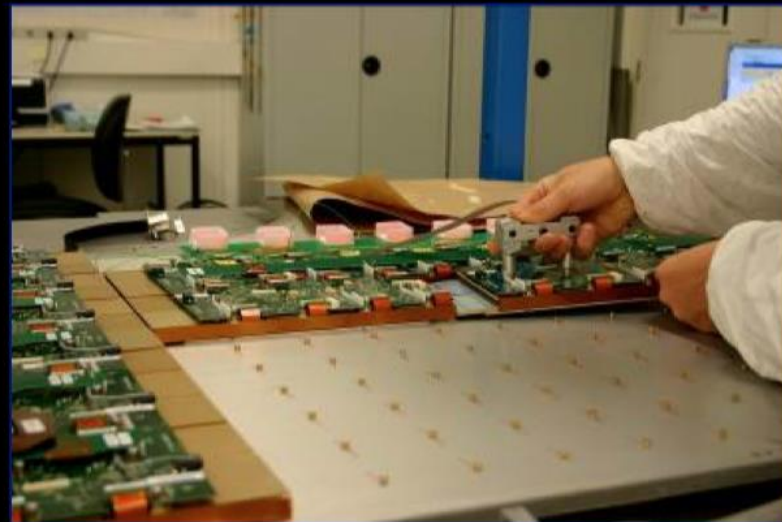


A few years later...

2008: Final assembly and testing



3 types of "ladder" filled with Si sensors



Installing ladders on the absorbers

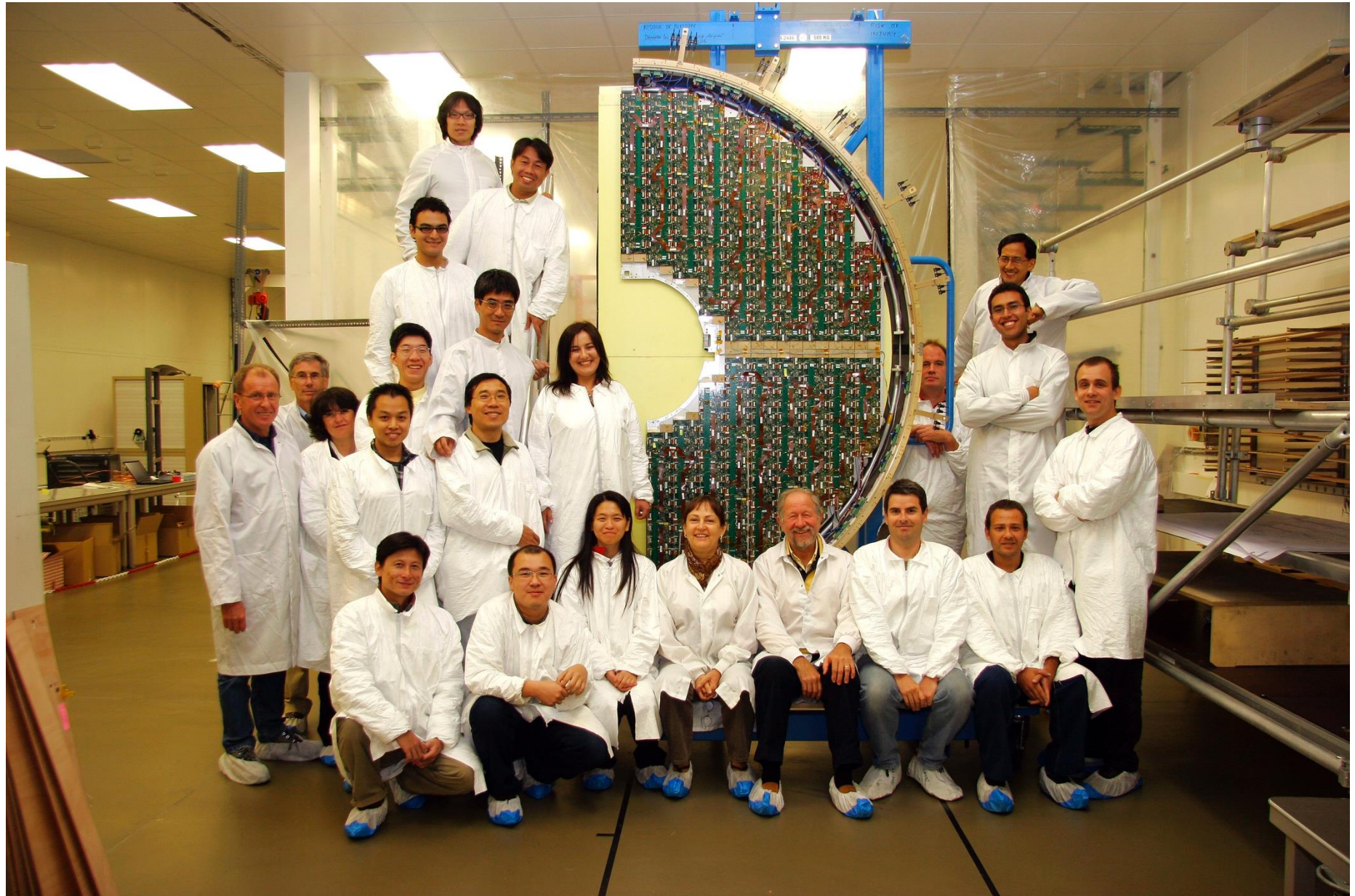


Testing a column of ladders

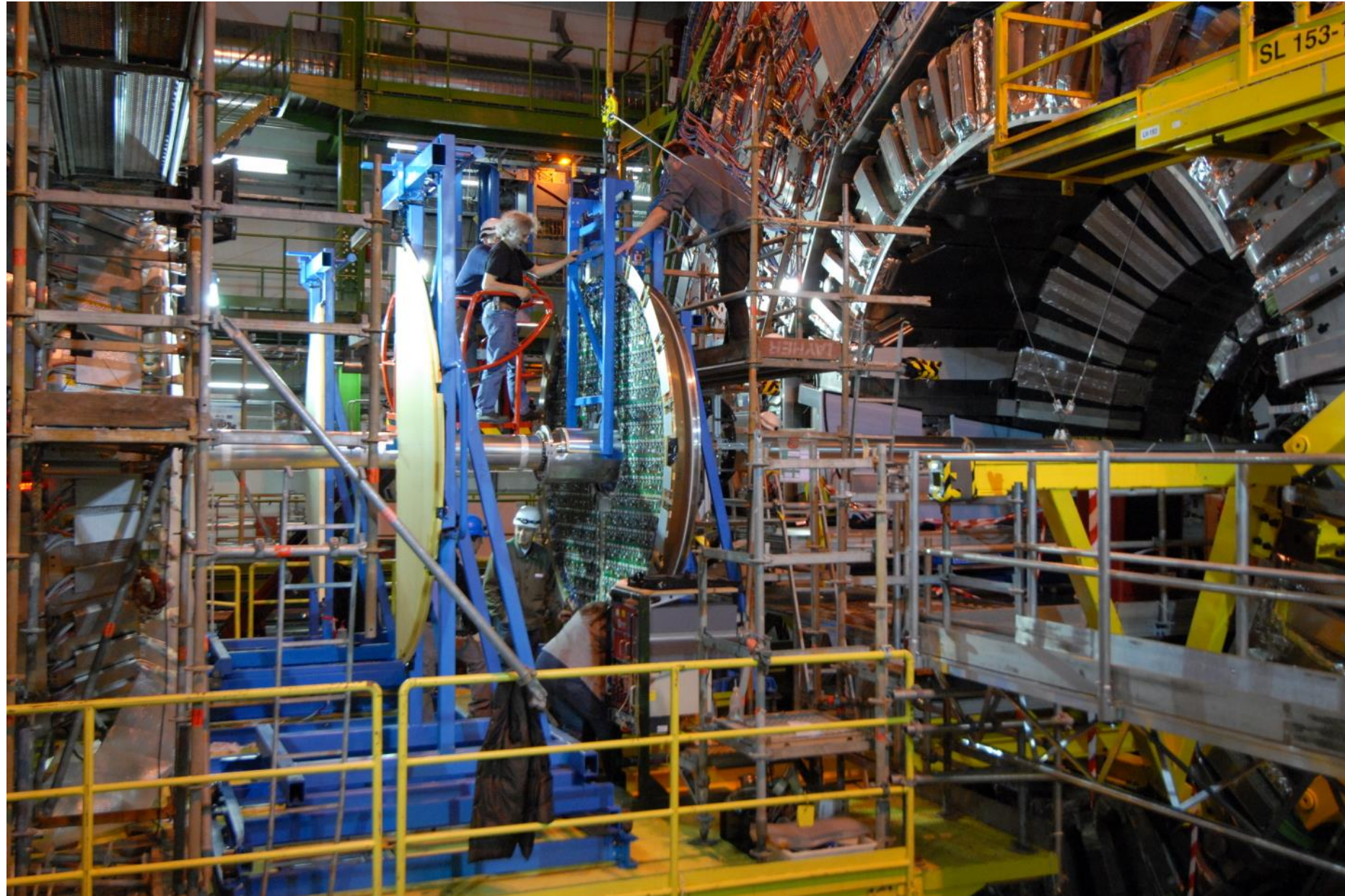


Fully assembled "Dee" plane

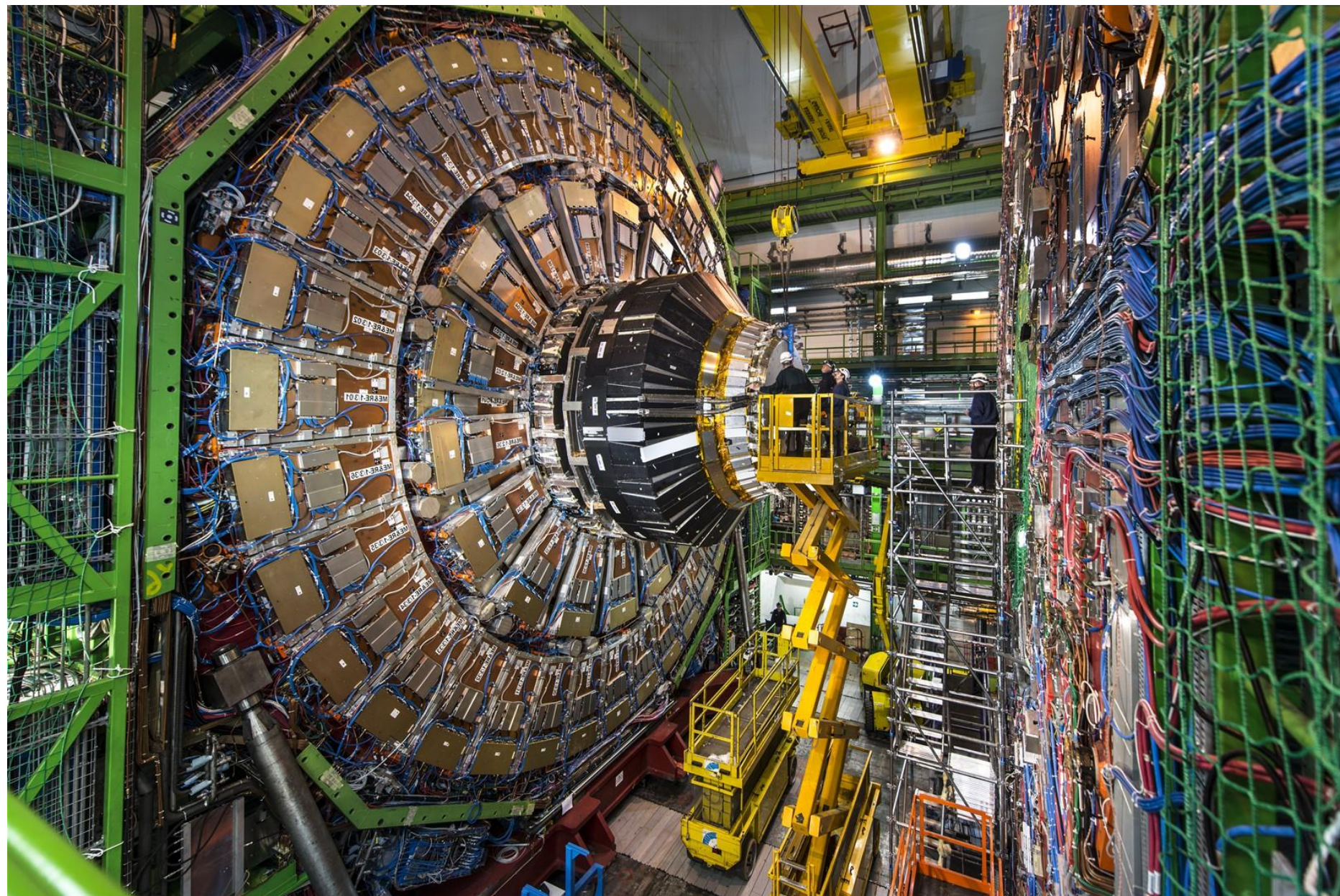
A few years later...



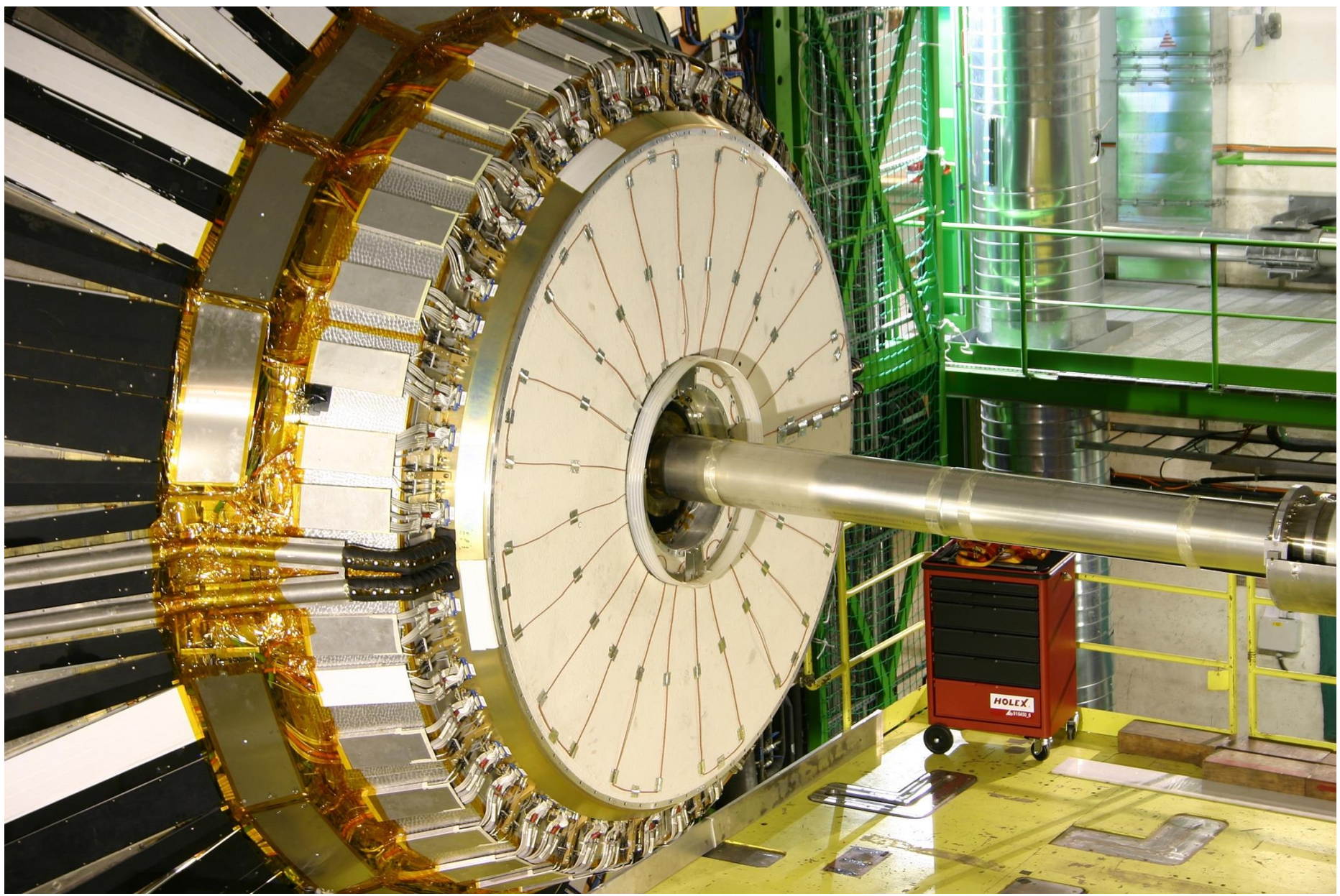
Installation of Preshower in CMS



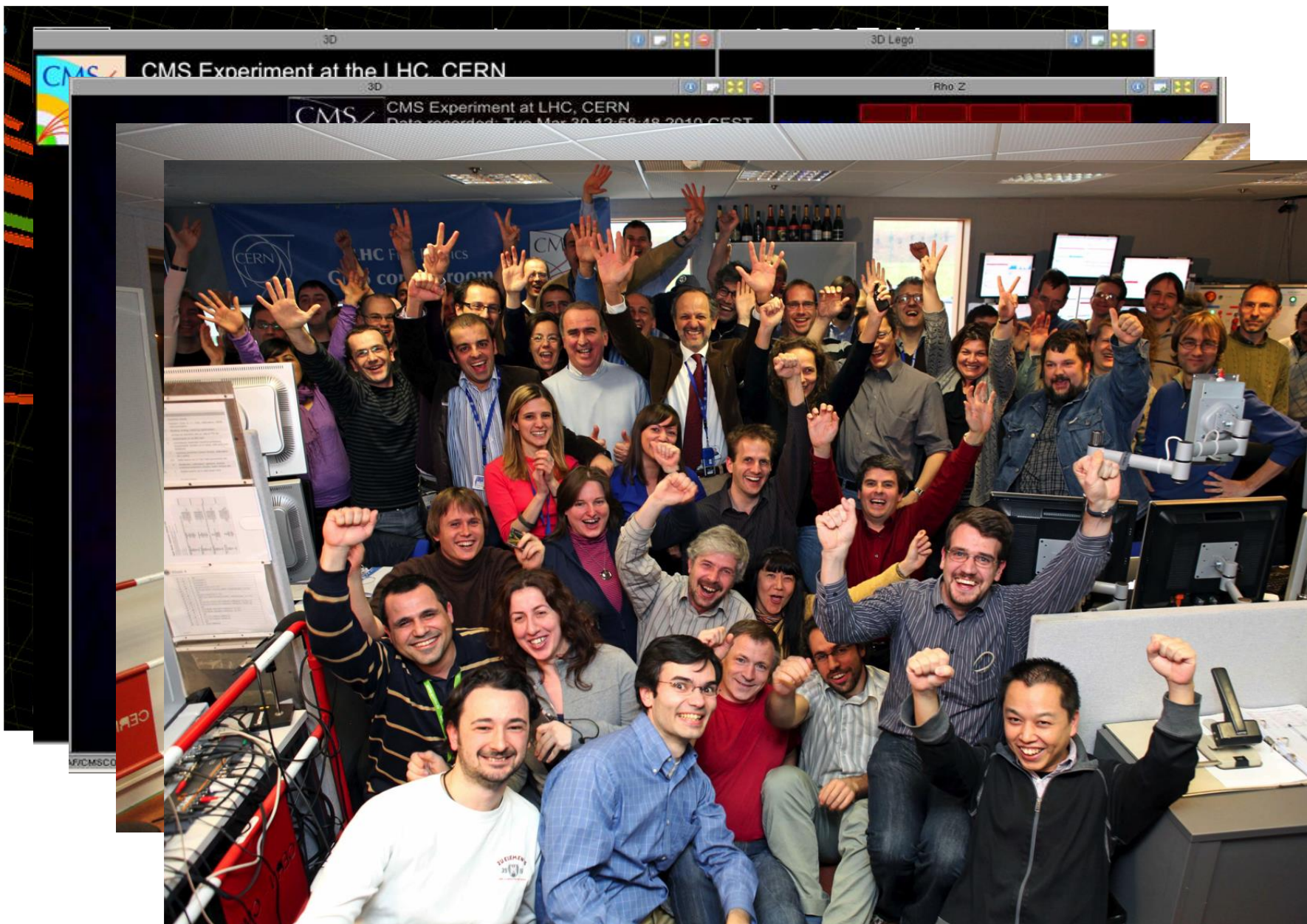
Preshower installed in CMS!



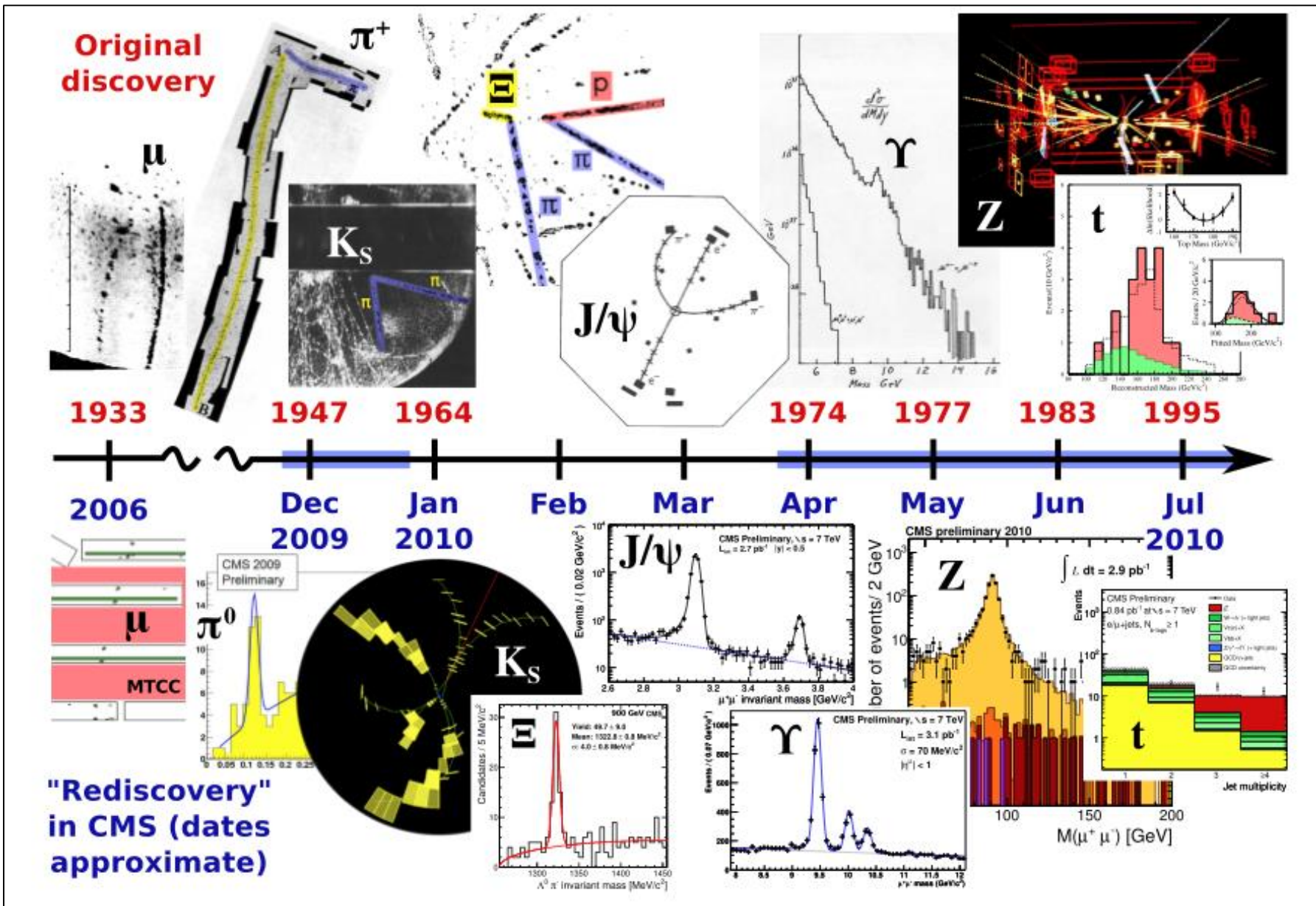
Preshower installed in CMS!



First collisions in 2009



Re-discovery in CMS

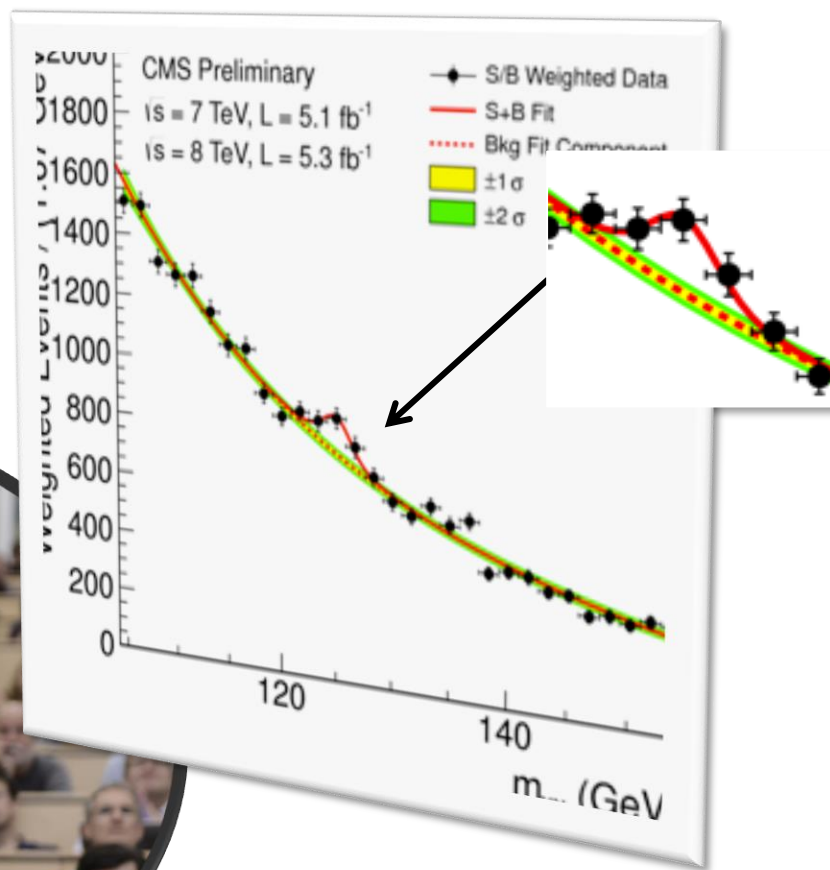


And just a couple of years later...

4th July 2012



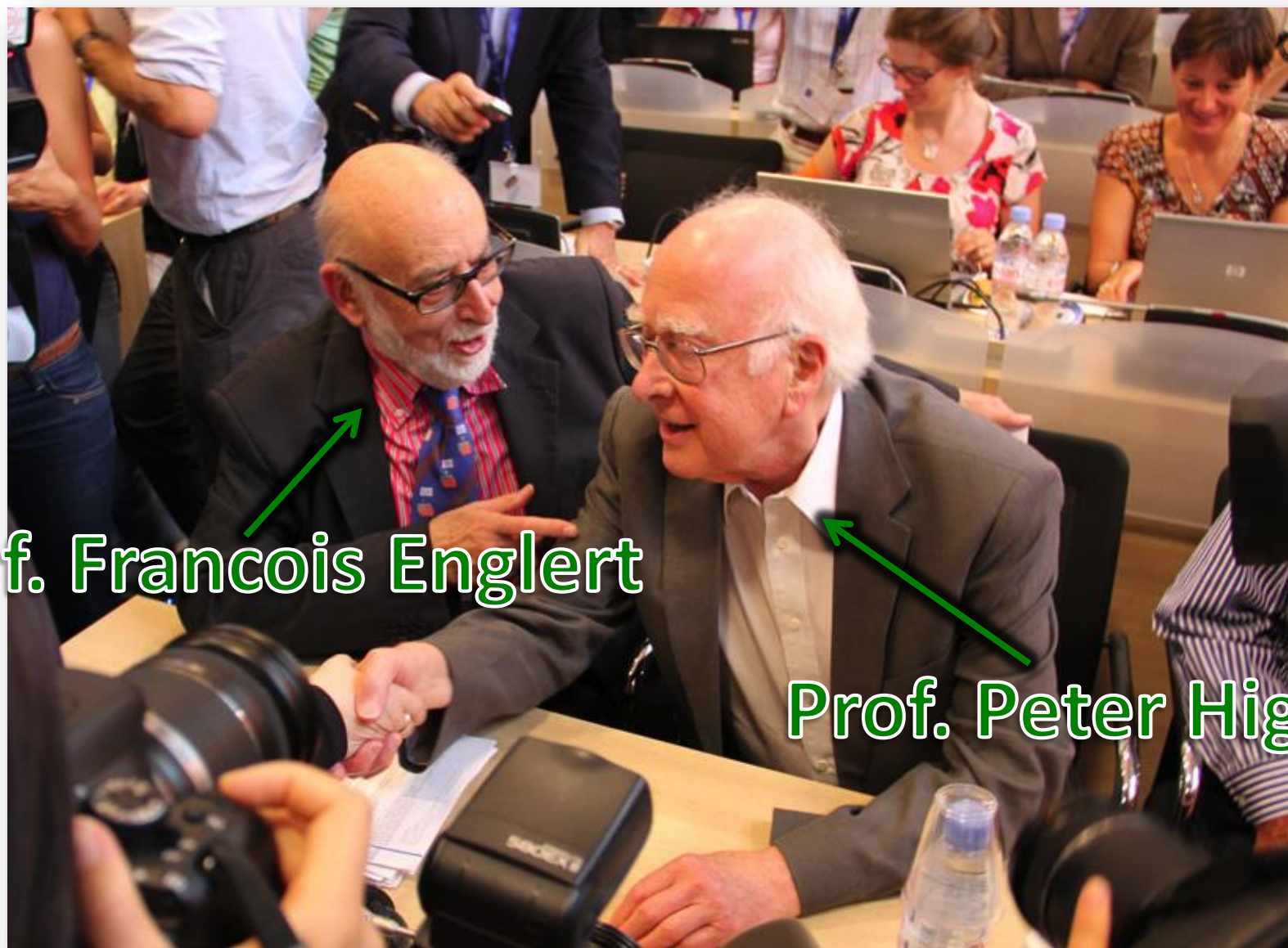
Joe Incandela
CMS Spokesperson 2012-2013



That made a lot of physicists very happy!



Including these two guys



Prof. Francois Englert

Prof. Peter Higgs



And the world's media also got excited!



The Nobel Prize in Physics 2013
François Englert, Peter Higgs

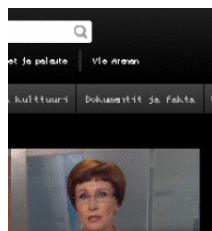
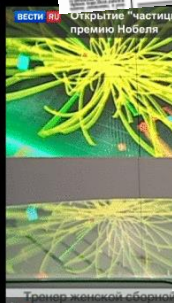
The Nobel Prize in Physics 2013



Photo: A. Mahmoud
François Englert
Prize share: 1/2



Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

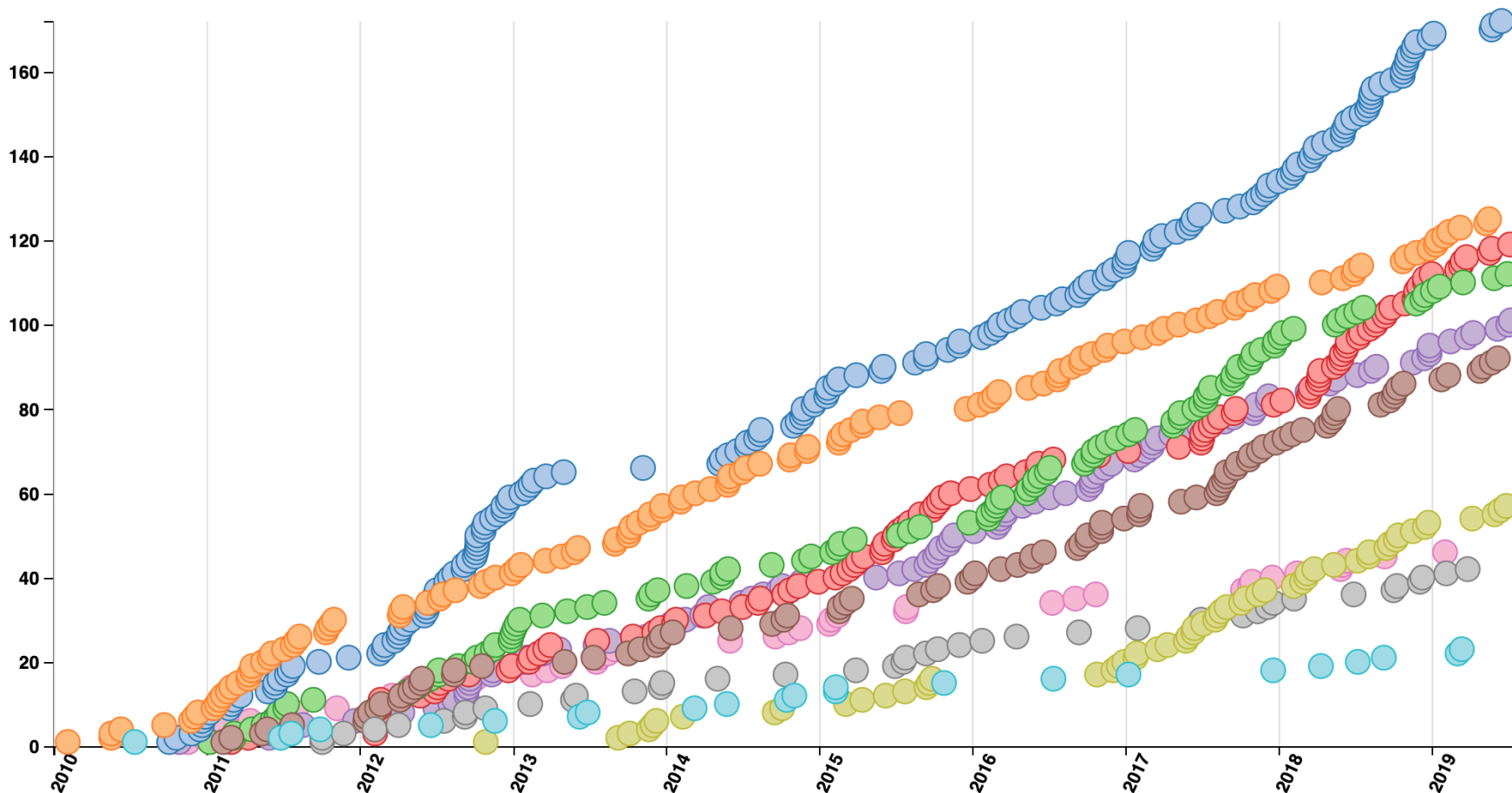




891 papers published on data taken with CMS!

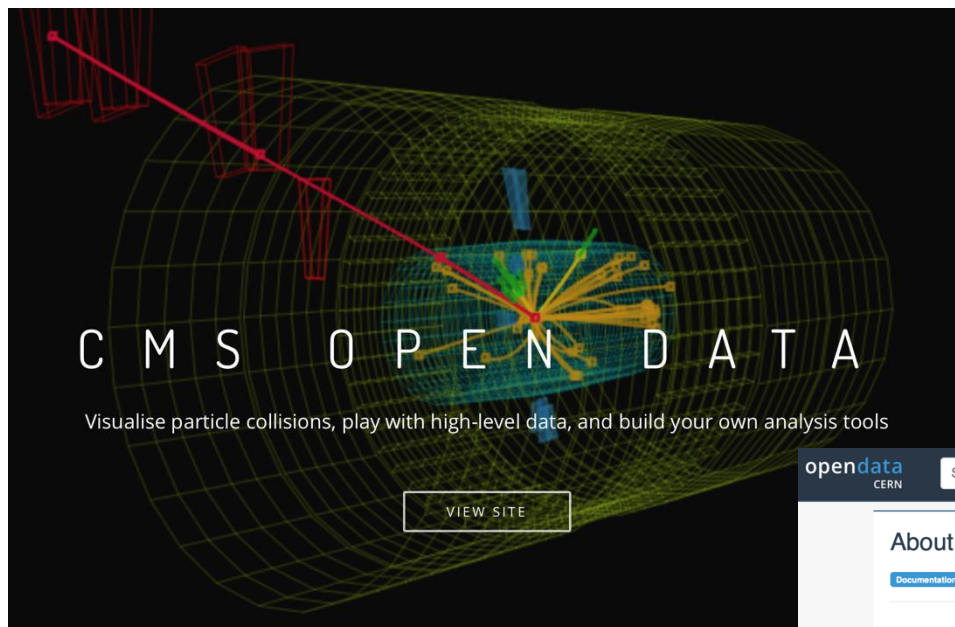
- Show all
- Total
- Exotica
- Standard Model
- Supersymmetry
- Higgs
- Top
- Heavy Ions
- B and Quarkonia
- Forward and Soft QCD
- Beyond 2 Generations
- Detector Performance

891 collider data papers submitted as of 2019-07-09





And you and your students 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.

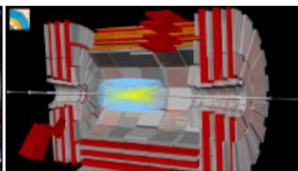
CMS e-Lab Student Home provides a guide with resources to create a research project, access to authentic CMS data and analysis tools for conducting that research, and ways to collaborate. The Teacher Home has learner objectives, assessment rubrics, standards, management tools, and more.

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](#)



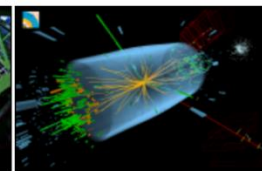
Inner tracking barrel



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!

iSpy WebGL masterclass_1.ig:Events/Run_1/Event_1 [1 of 100]

ECAL Endcap (-)	<input type="checkbox"/>
HCAL Barrel	<input type="checkbox"/>
HCAL Endcap (+)	<input type="checkbox"/>
HCAL Endcap (-)	<input type="checkbox"/>
HCAL Outer	<input checked="" type="checkbox"/>
HCAL Forward (+)	<input type="checkbox"/>
HCAL Forward (-)	<input type="checkbox"/>
Drift Tubes	<input checked="" type="checkbox"/>
Cathode Strip Chambers	<input type="checkbox"/>
Resistive Plate Chambers (barrel)	<input type="checkbox"/>
Resistive Plate Chambers (+)	<input type="checkbox"/>
Resistive Plate Chambers (-)	<input type="checkbox"/>
▼ Imported	<input checked="" type="checkbox"/>
▼ Provenance	<input checked="" type="checkbox"/>

CMS Experiment at the LHC, CERN
Data recorded: 2011-Aug-17 06:01:59.493993 GMT
Run / Event / LS: 173389 / 490868544 / 370

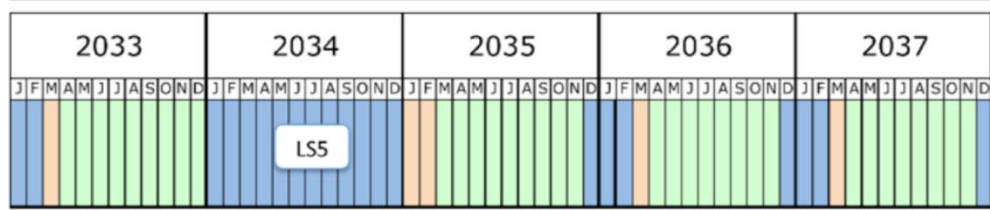
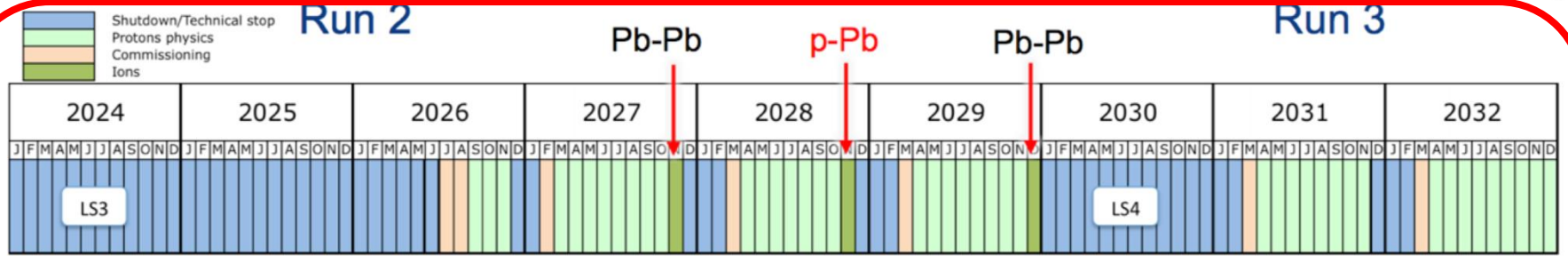
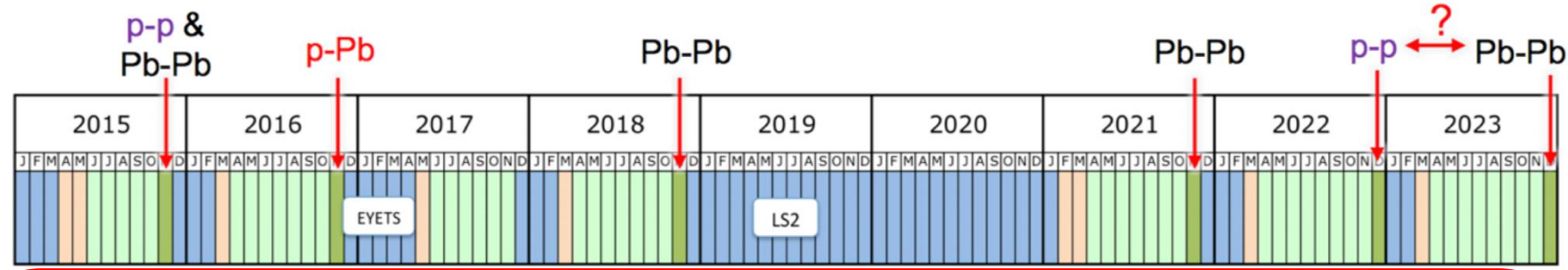
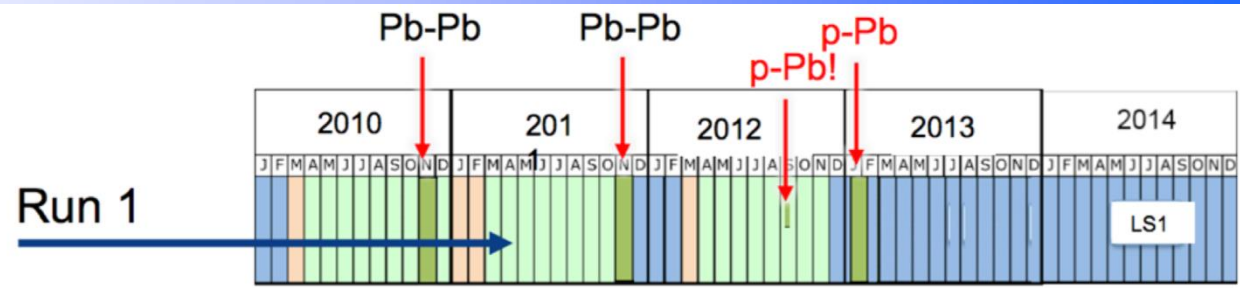
Click on a name under "Provenance", "Tracking", "ECAL", "HCAL", "Muon", and "Physics" to view contents in table

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

**CMS is a LONG way
from its final
destination!**



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



Run 6

High-Luminosity LHC (HL-LHC)

X10 more data than LHC

So what next?



Nima Arkani-Hamed

CERN COURIER | International journal of high-energy physics

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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/>

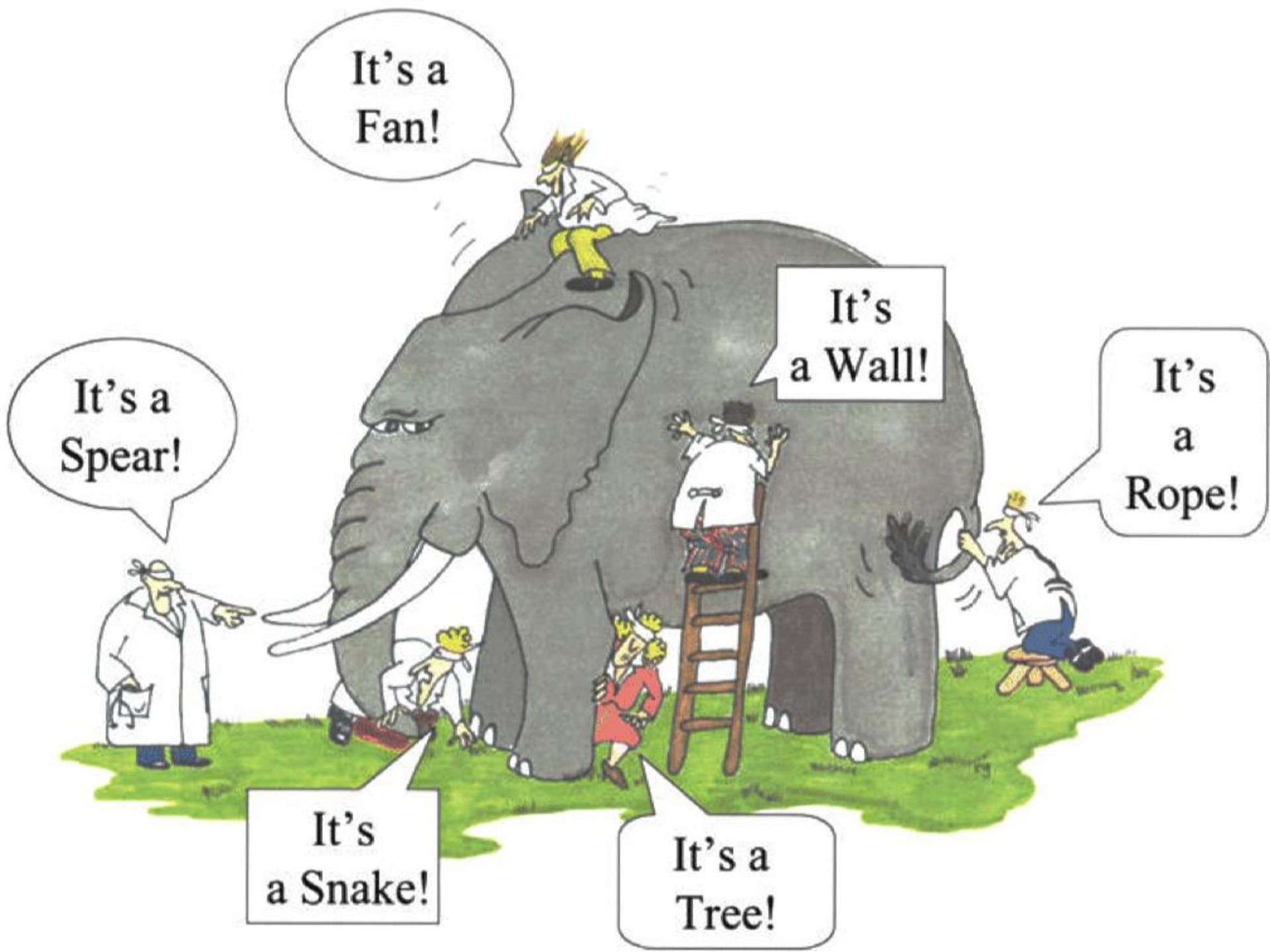


It's a
Spear!





It's
a Wall!



It's a Fan!

It's a Spear!

It's a Wall!

It's a Rope!

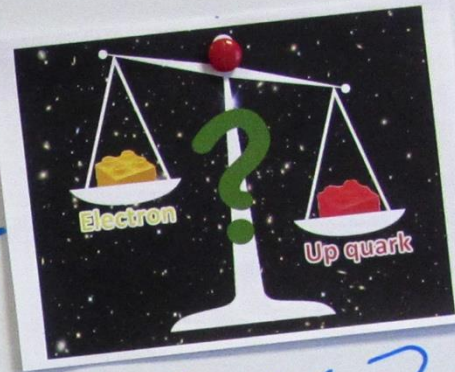
It's a Snake!

It's a Tree!

What else??



Anti-matter?



Mass?



Dark Matter?

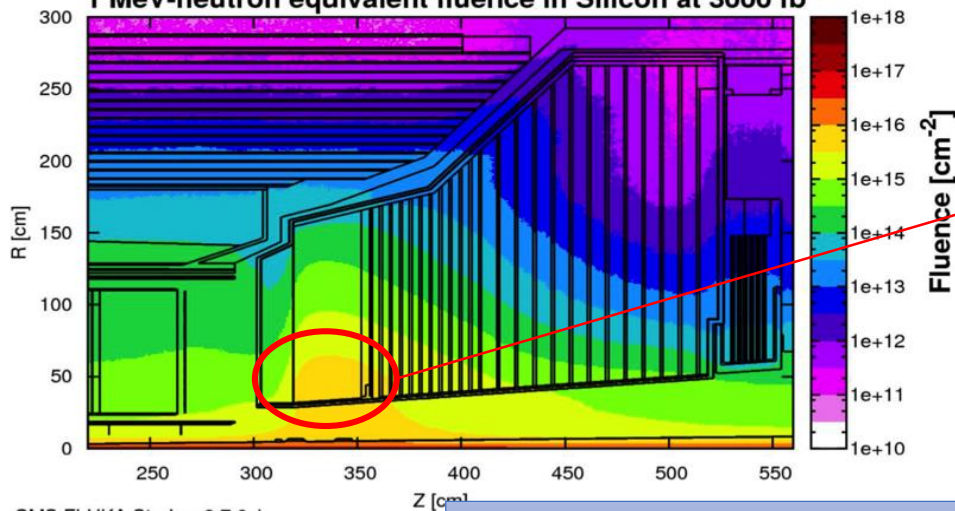


Dark Energy?



But it's not that simple for the CMS detector: radiation and pileup are a major problem

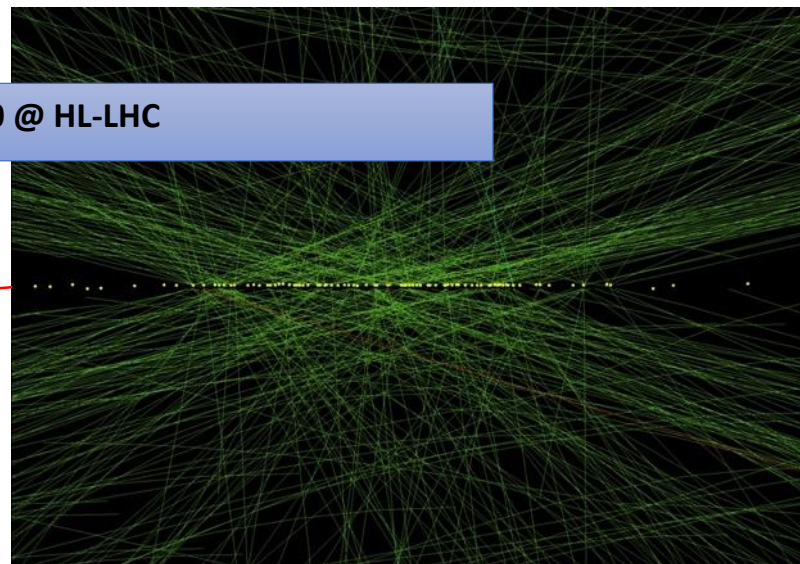
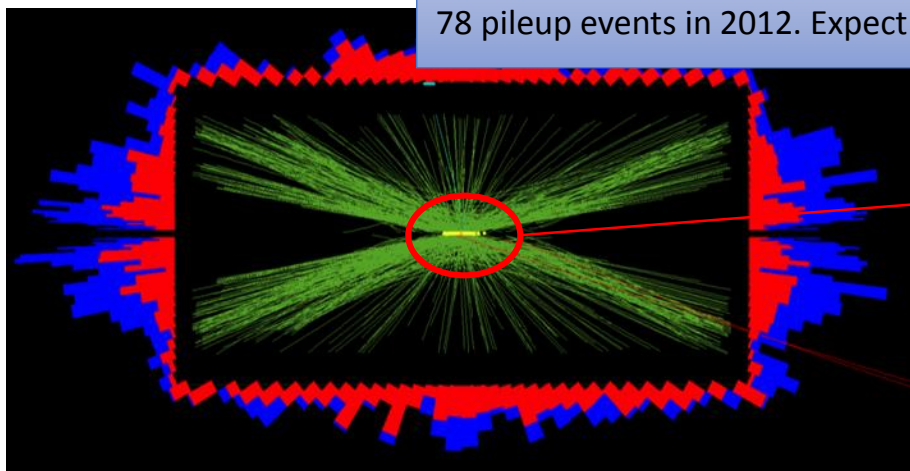
CMS p-p collisions at 7 TeV per beam
1 MeV-neutron equivalent fluence in Silicon at 3000 fb⁻¹



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

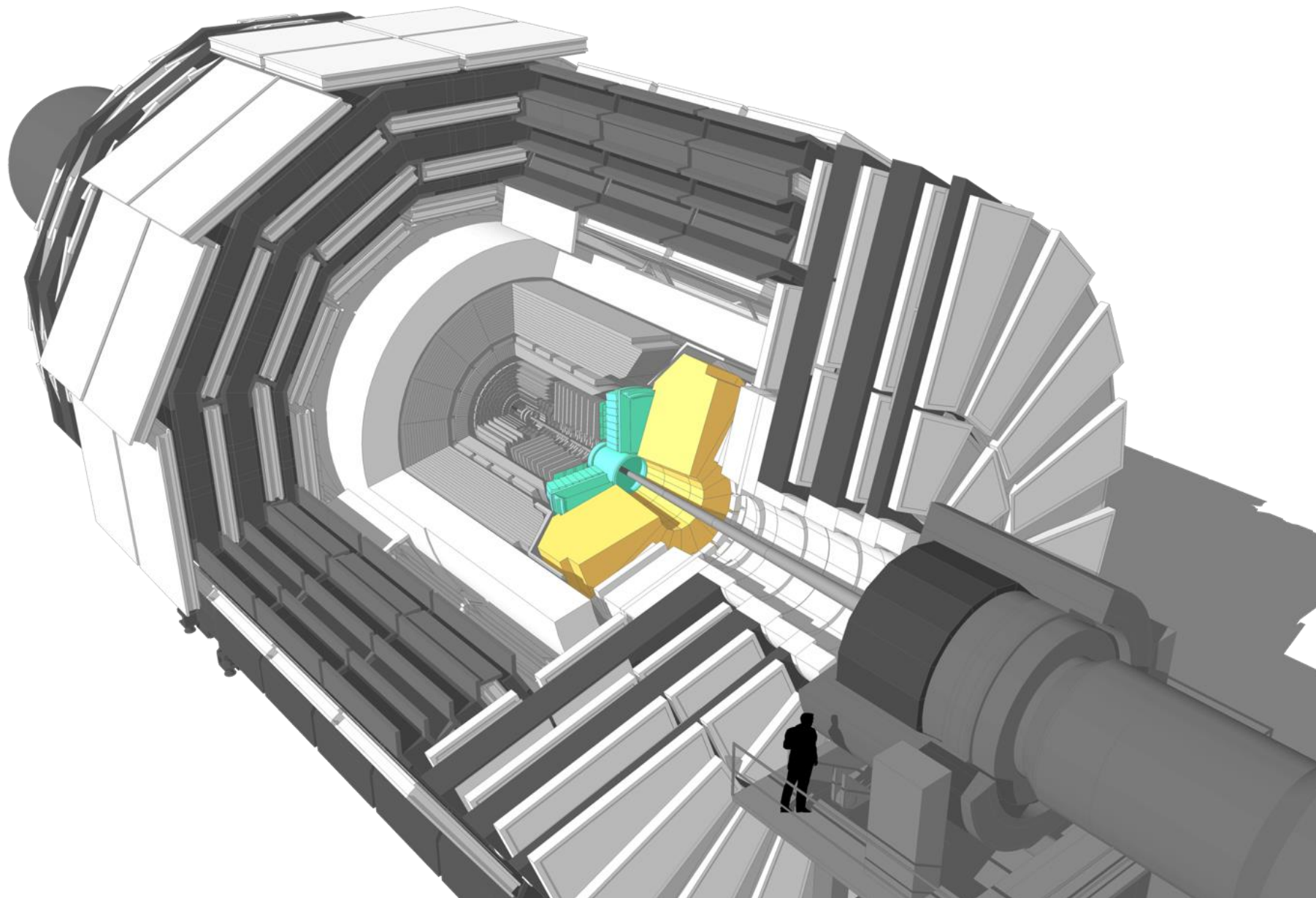
78 pileup events in 2012. Expect 140-200 @ HL-LHC



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”



A wise person once said (about the HGICAL):

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

Another person responded:

**“HGICAL is perhaps the most challenging
engineering project ever undertaken in particle physics”**



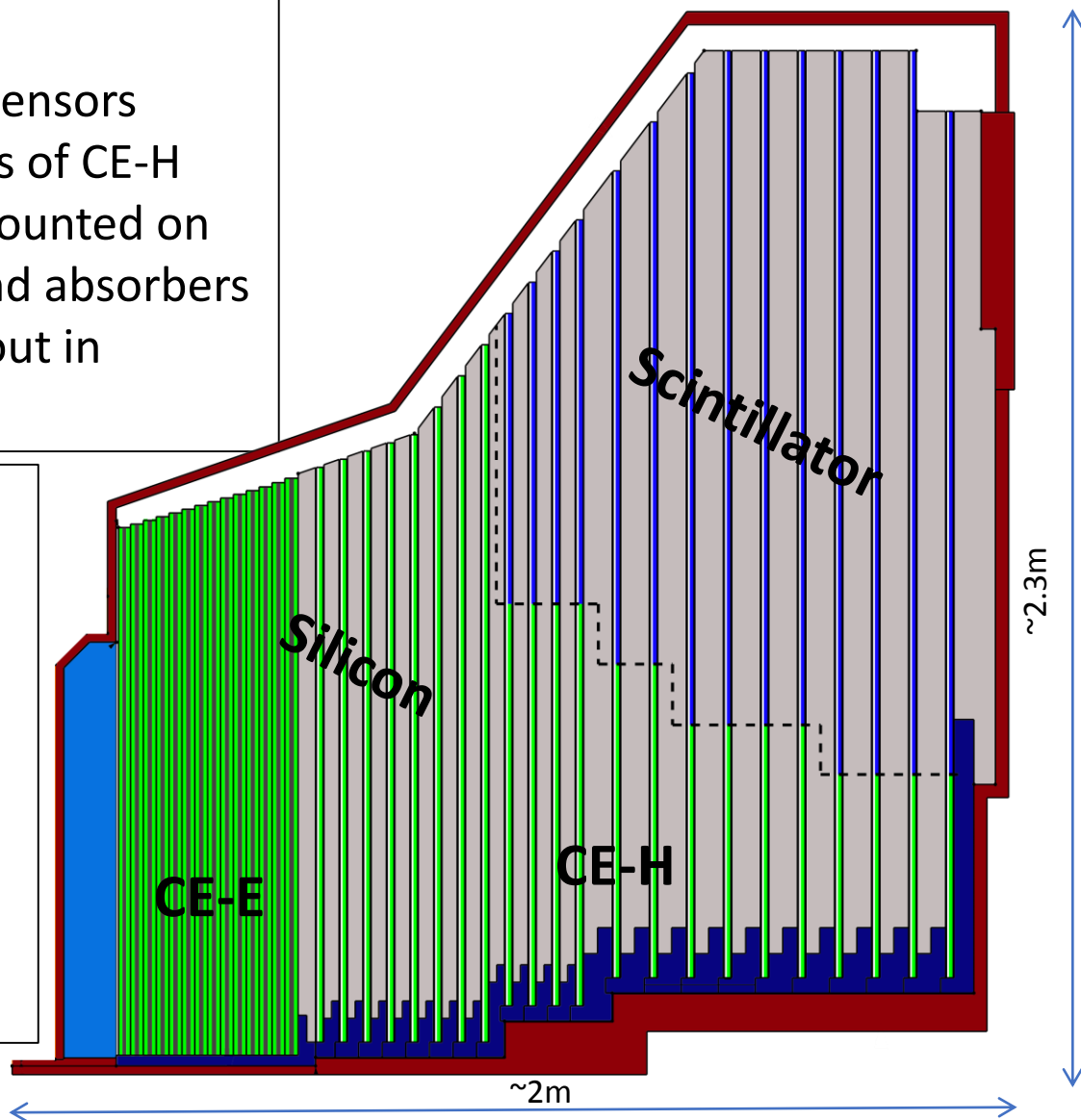
CMS HGCAL (“CE”): a sampling calorimeter with unprecedented number of readout channels

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 SiPM readout in low-radiation regions of CE-H

Key Parameters:

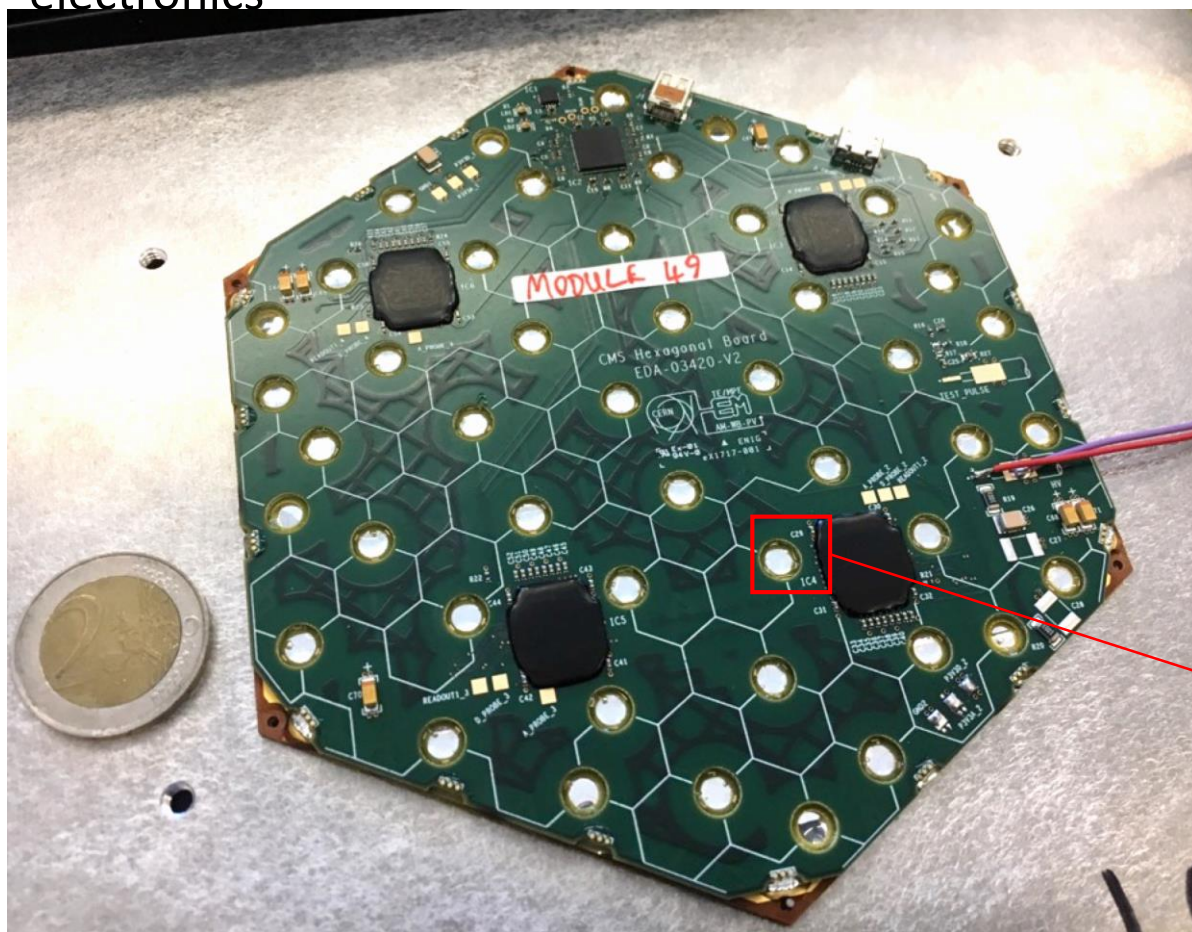
Coverage: $1.5 < |\eta| < 3.0$
 ~215 tonnes per endcap
 Full system maintained at -30°C
 ~620m² Si sensors in ~30000 modules
 ~6M Si channels, 0.5 or 1cm² cell size
 ~400m² of scintillators in ~4000 boards
 ~400k scint. channels, 4-30cm² cell size
 Power at end of HL-LHC:
 ~125 kW per endcap



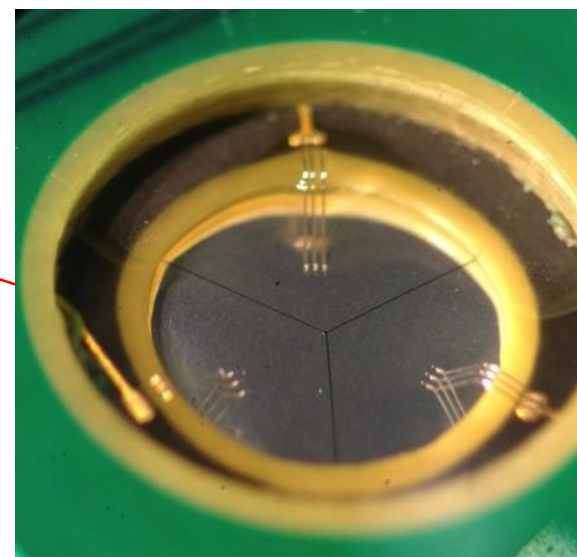
Electromagnetic calorimeter (CE-E): **Si**, Cu & CuW & Pb absorbers, 28 layers, $25 X_0$ & $\sim 1.3\lambda$
 Hadronic calorimeter (CE-H): **Si** & **scintillator**, steel absorbers, 22 layers, $\sim 8.5\lambda$

HGCAL will include 30000 modules based on hexagonal silicon sensors with 0.5-1cm² cells

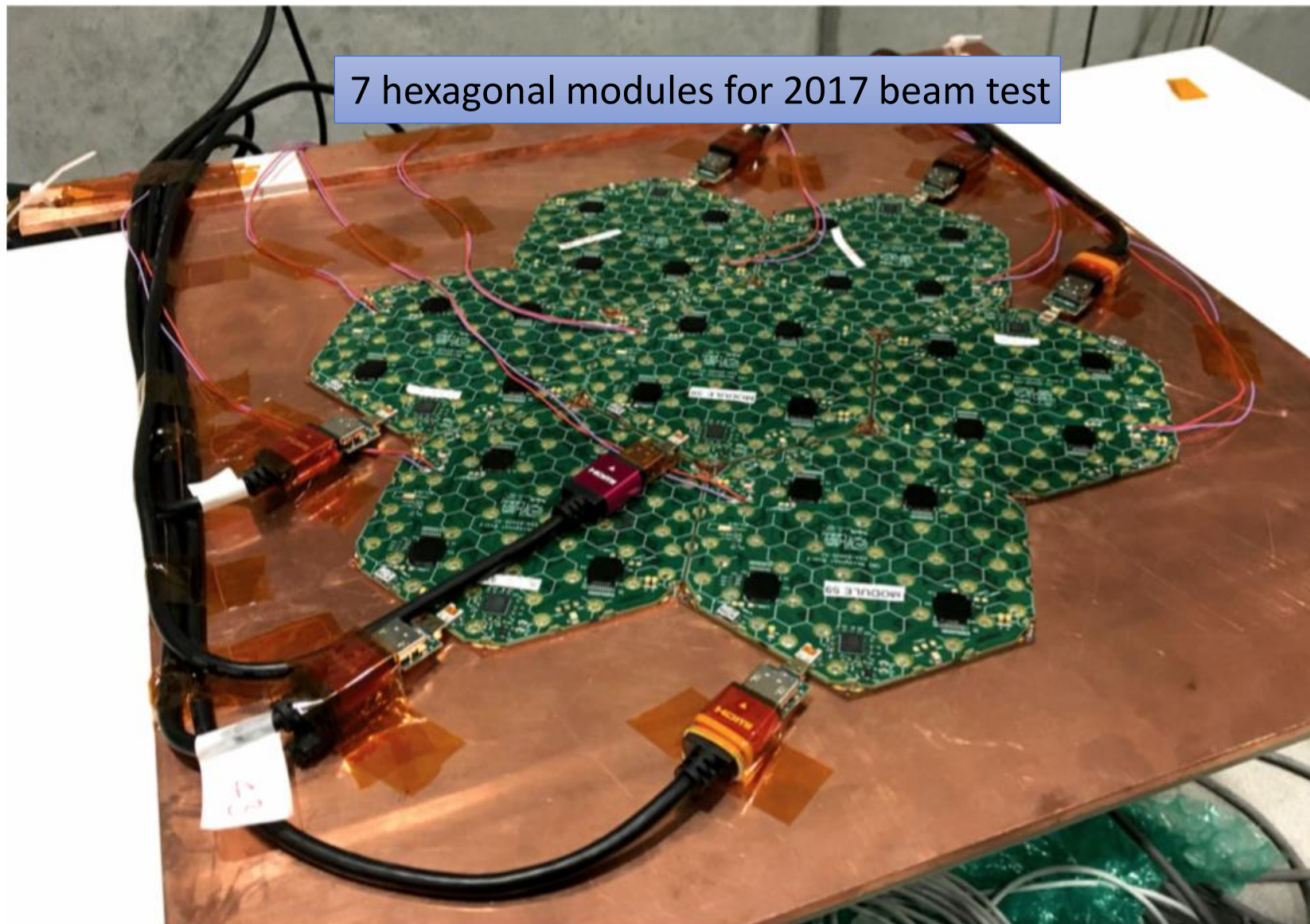
Silicon sensor glued to baseplate and PCB containing front-end electronics



Wire bonding from PCB to silicon through stepped holes

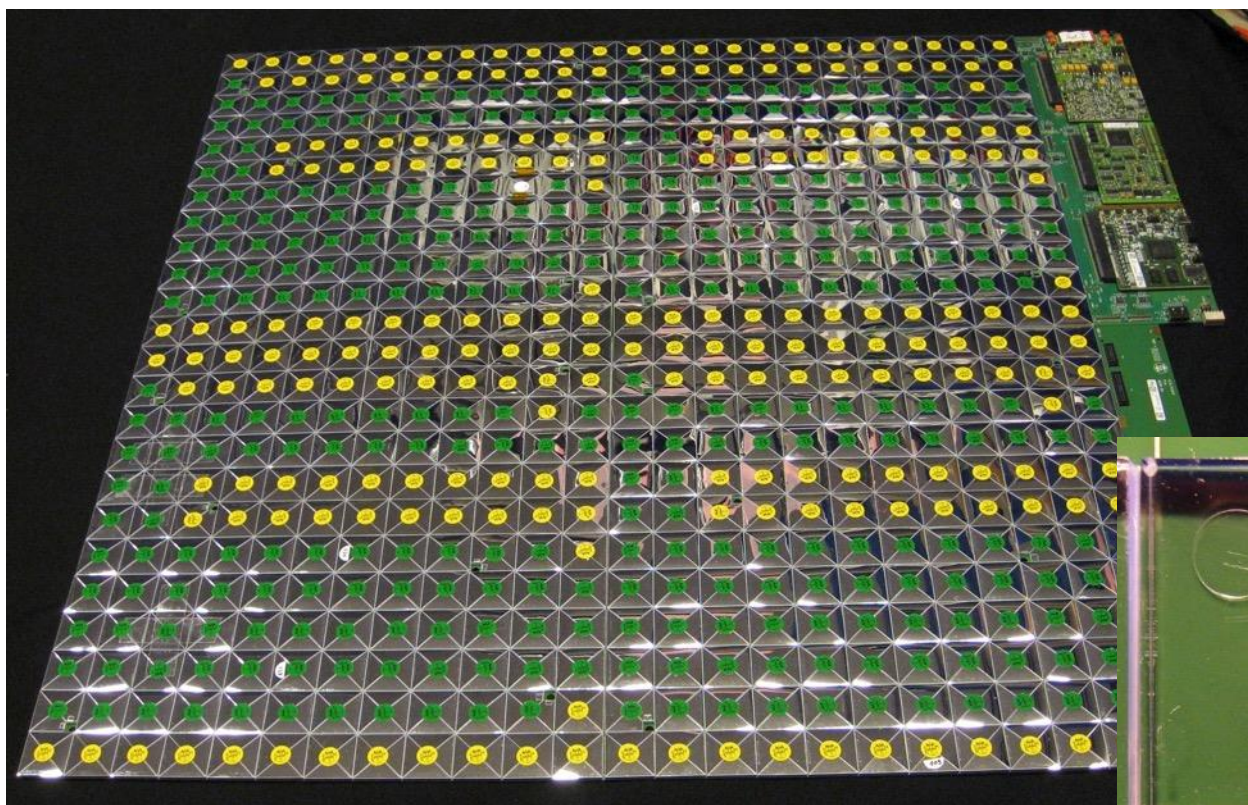


Silicon modules are arranged in hexagonal matrices to cover fiducial area of HGCAL





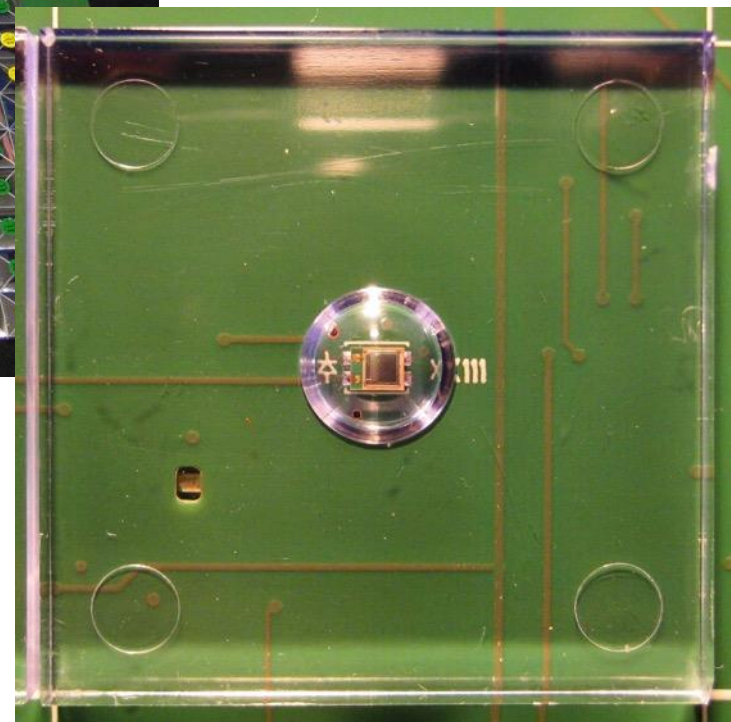
HGCAL will also include 500m² of scintillator tiles with on-tile SiPM readout



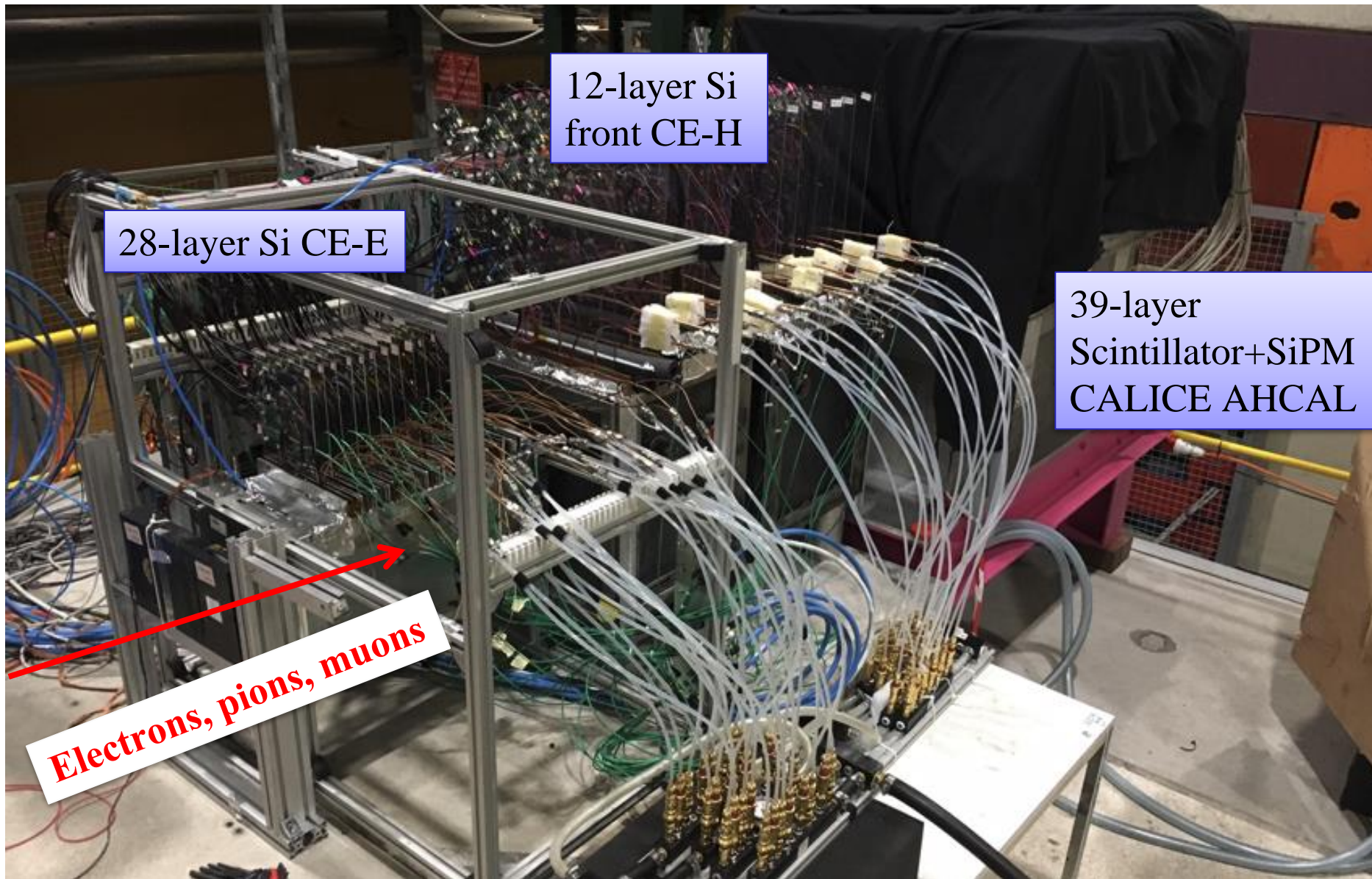
SiPMs already used successfully in e.g. CMS HCAL Phase 1 upgrade

Tile boards or “megatiles” limited in size by CTE of different components

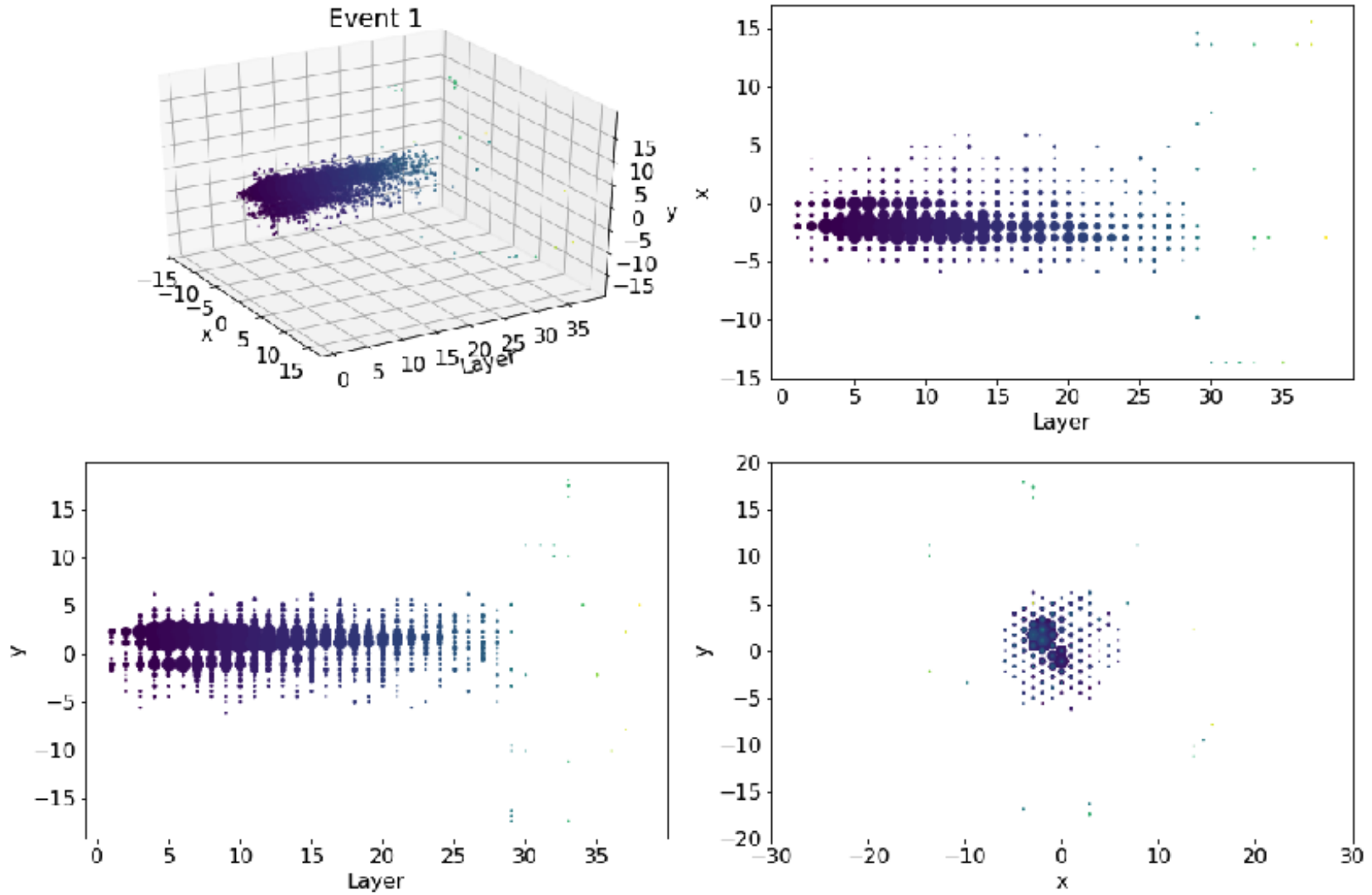
For first beam tests, modified CALICE AHCAL used for rear hadron calorimeter:
3x3cm² scintillator tiles + direct SiPM readout



Large-scale beam-tests of prototypes in 2018



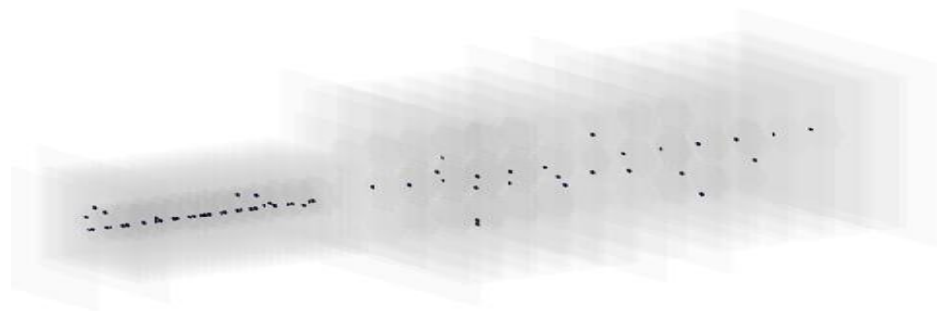
300 GeV electron shower: event display



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

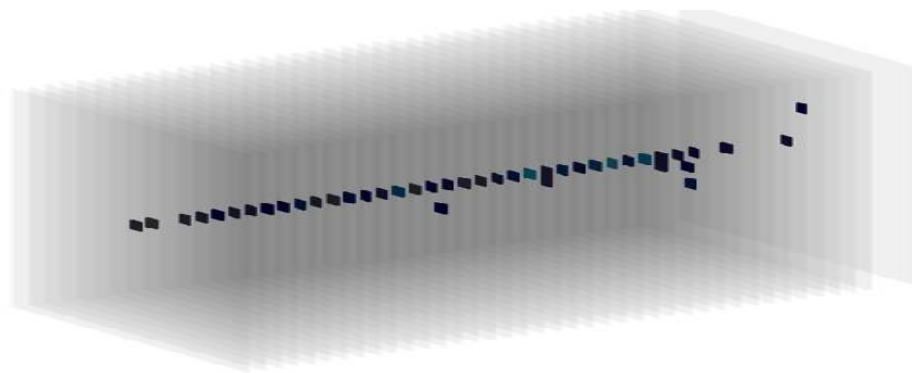
And other types of particle...

150 GeV Muon in HGCAL prototype



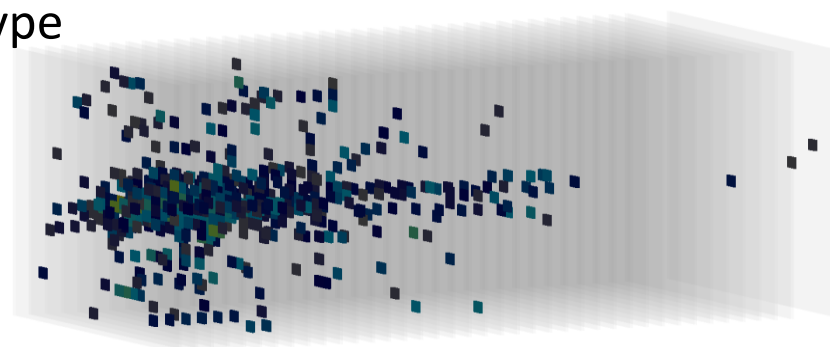
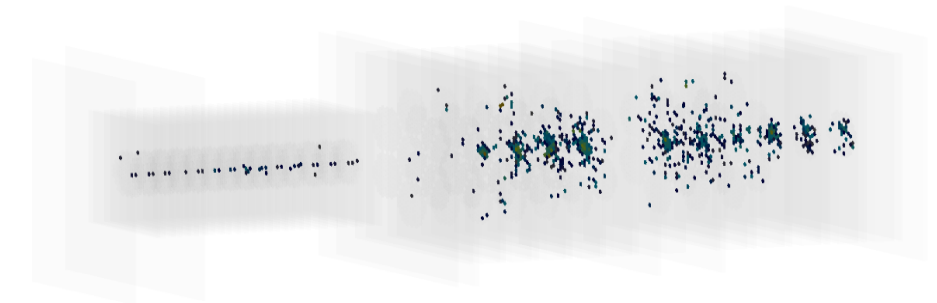
28-layer Si CE-E

12-layer Si front CE-H



39-layer Scintillator+SiPM CALICE AHCAL

300 GeV charged Pion in HGCAL prototype



Starting to train the next generations



Starting to train the next generations





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 Review (March 2021) and ESRs**
 - This is a **much** faster timescale than the original CMS construction phase
- **Market Surveys, orders, preproduction, qualification of final components**
- **Production starts in <3 years !**
- **Installation of 1st endcap ~March 2025 and 2nd endcap 2 months later**
- **Ready for HL-LHC operation in 2026**
- **And operate for >10 years**

After 25 years on one
experiment there is still much to
learn and do!

Your students could be
our next wave of
physicists/engineers/technicians