

# CMS: a personal journey

Dave Barney, CERN, 5<sup>th</sup> July 2024



### We smash things together and see what happens!



Before the particle accelerator







### After 30 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)
- Proud husband and father! Without the support of my family I could not have done these things!



### Snapshot of my group – not just physicists!

- 115 people (28 women 24%)
  - 39 Physicists
  - 36 Mechanical engineers
  - 16 mechanical/electromechanical technicians
  - 7 Electrical/electronics engineers
  - 5 Computing engineers
  - 4 Administrative assistants
  - 4 Communication professionals
  - 2 Electromechanical engineers
  - 2 Health & Safety engineers

# The Large Hadron Collider...

# Needs Detectors



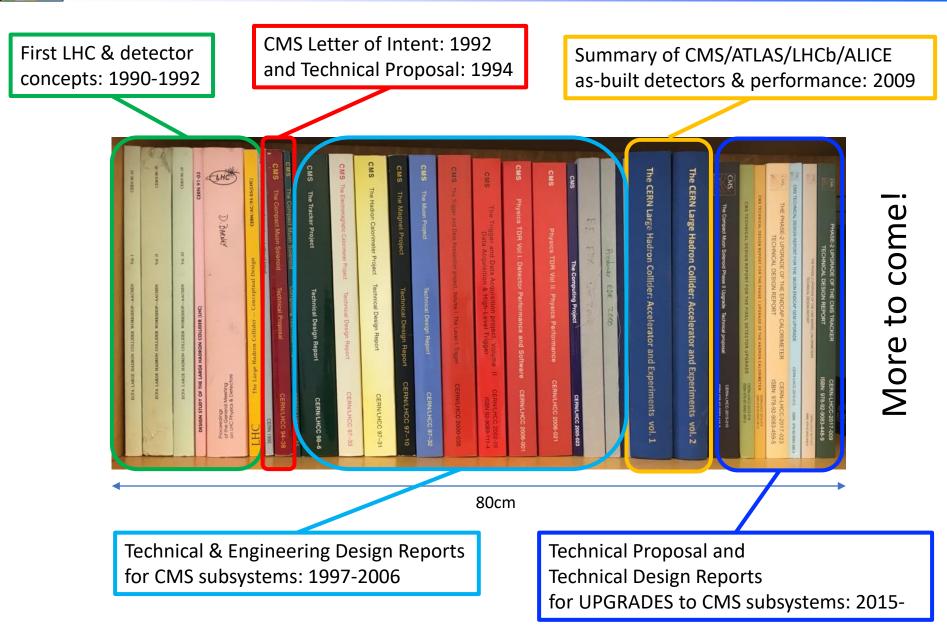
Overall detector design is so simple you can do it with students on a blackboard!



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

# CMS' history goes back to ~1990

CMS



### And my history in CMS goes back to 1994

Technical Proposal: 1994 When I joined the CMS experiment

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CERN/LHCC 97-31	CMS The Hadron Calorimeter Project Technical Design Report CERN
CERN/LHCC 97-10	CMS The Magnet Project Technical Design Report CERN/LH
CERNILHCC 97-32	CMS The Muon Project Technical Design Report CERN
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CERNLHCC 2005-023	CMS The Computing Project CENN
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s vol. 2	The CERN Large Hadron Collider: Accelerator and Experiments vol. 2
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More to come!

80cm

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







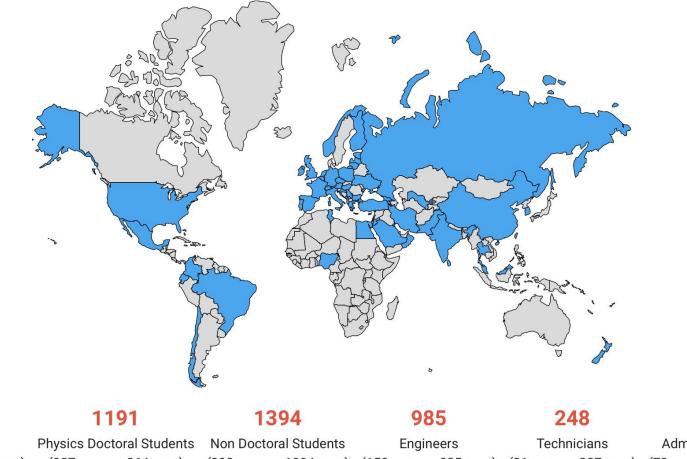
Inc. about 2500 students





### CMS Overview in 2024

The CMS experiment has 6008 active members from 251 institutes coming from 57 countries.



Phd Physicists (400 women 1672 men)

2072

(327 women 864 men)

(390 women 1004 men) (150 women 835 men) (21 women 227 men)

Administratives (73 women 40 men)

113



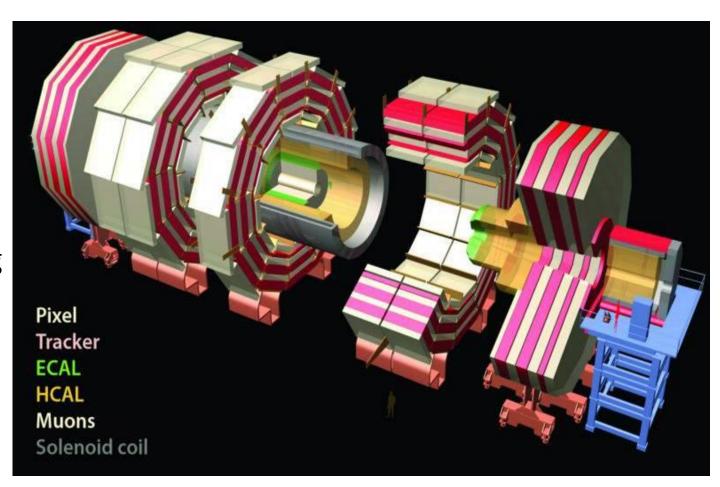
### CMS in a nutshell

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

Is about 15 metres wide and 21.5 metres long

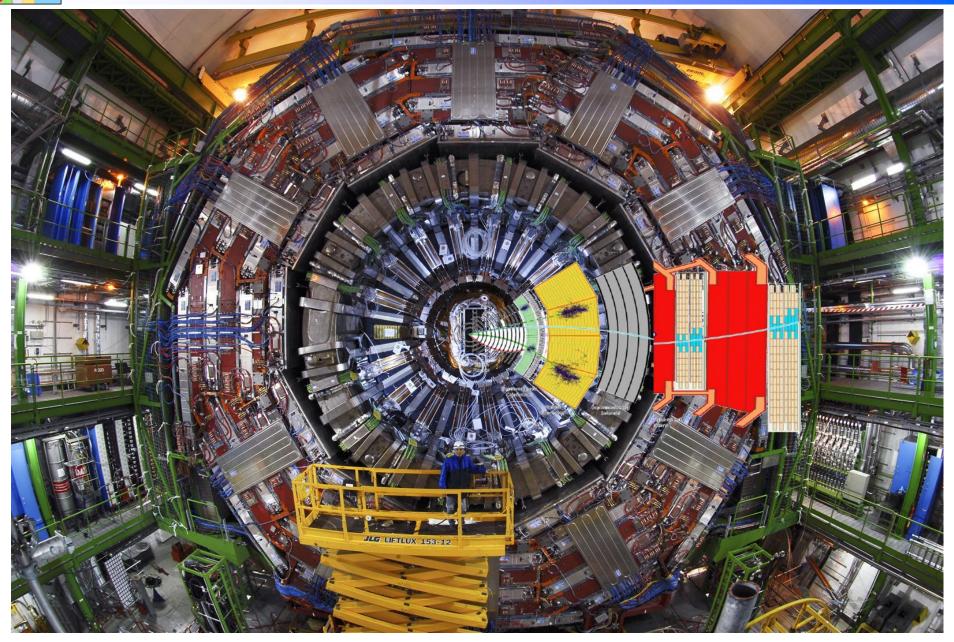
Weighs **twice as much as the Eiffel Tower** – about 14000t

Divided into 5 main detecting layers



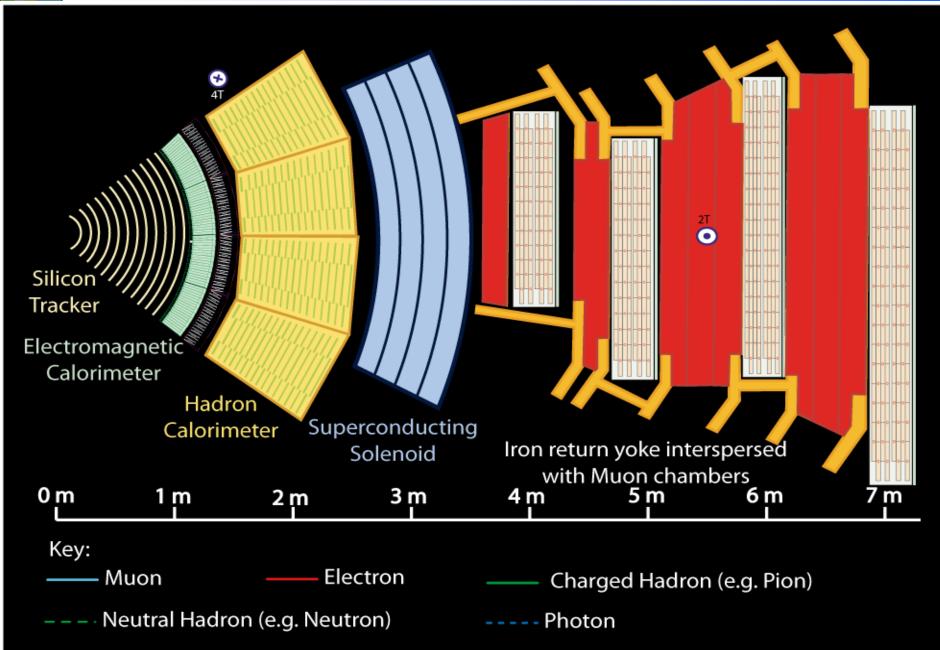
It has been performing excellently during the past 15 years, but we need it to work for another ~20! **Need to upgrade...** 

### 200 Mpix 3-D camera taking 40 million photos/second!



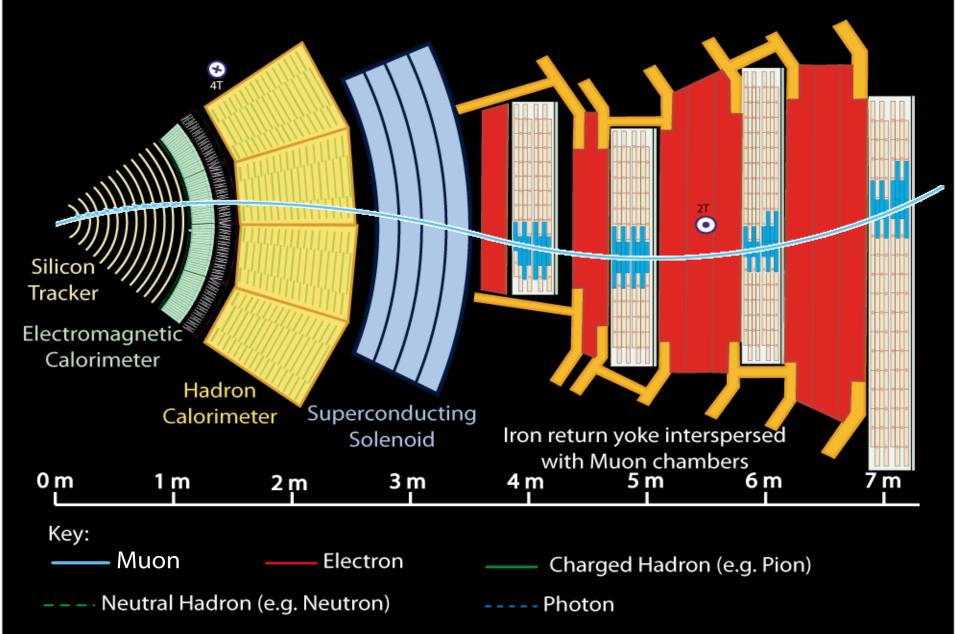
# A slice through the CMS Detector

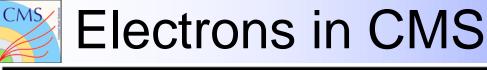
CMS

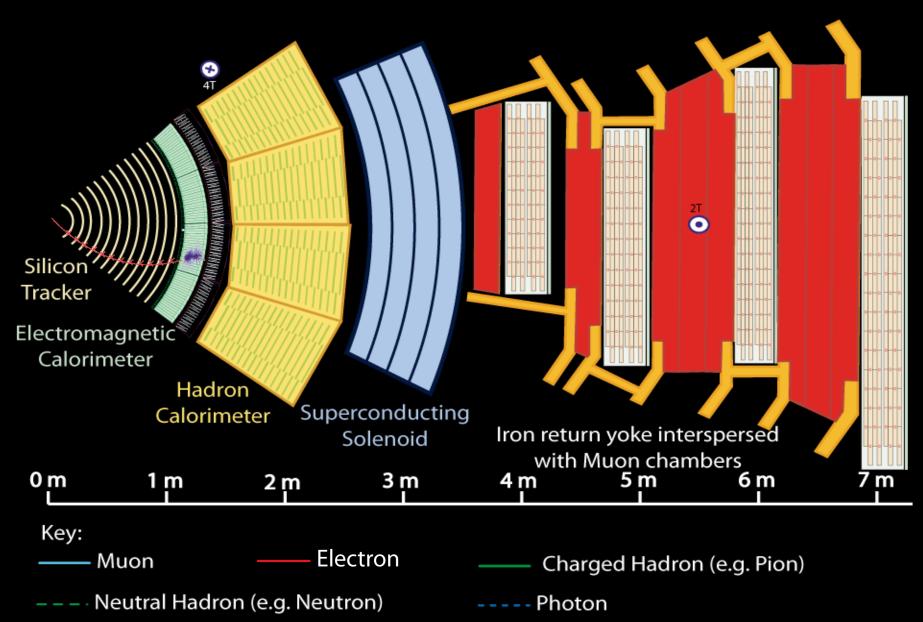




## Muons in CMS

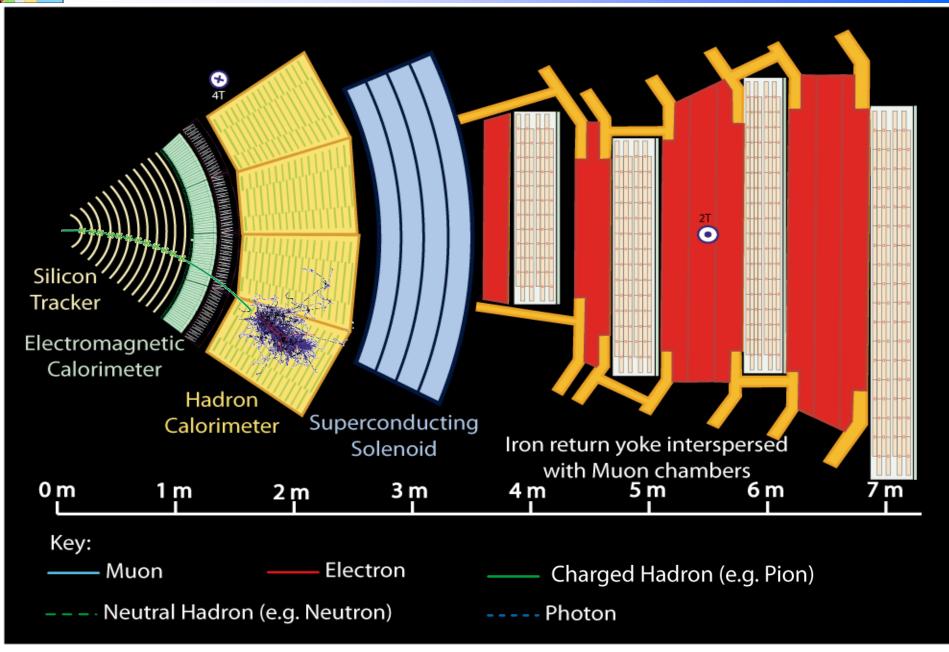




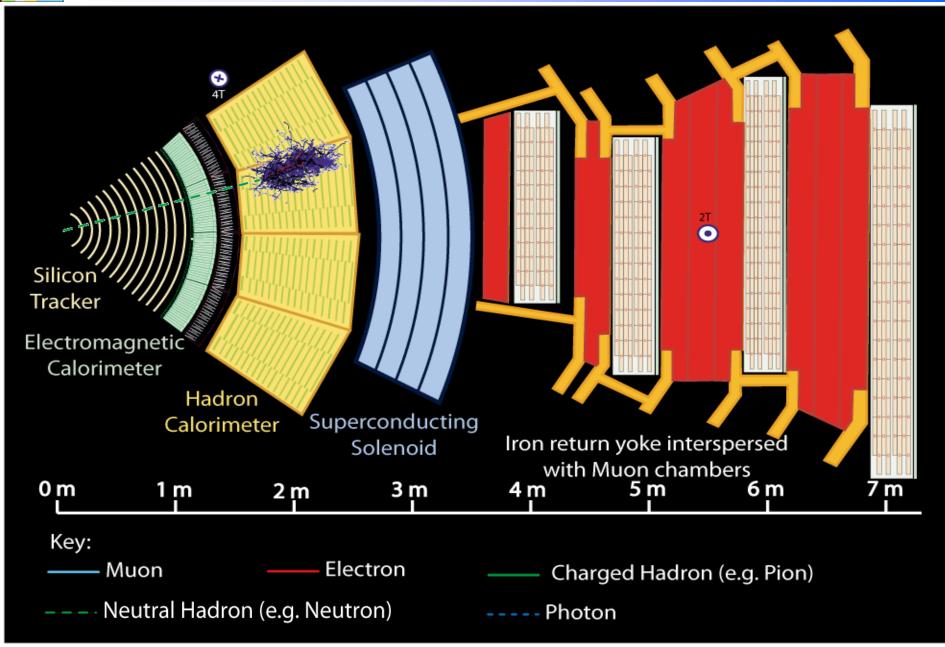


## Charged hadrons in CMS

CMS

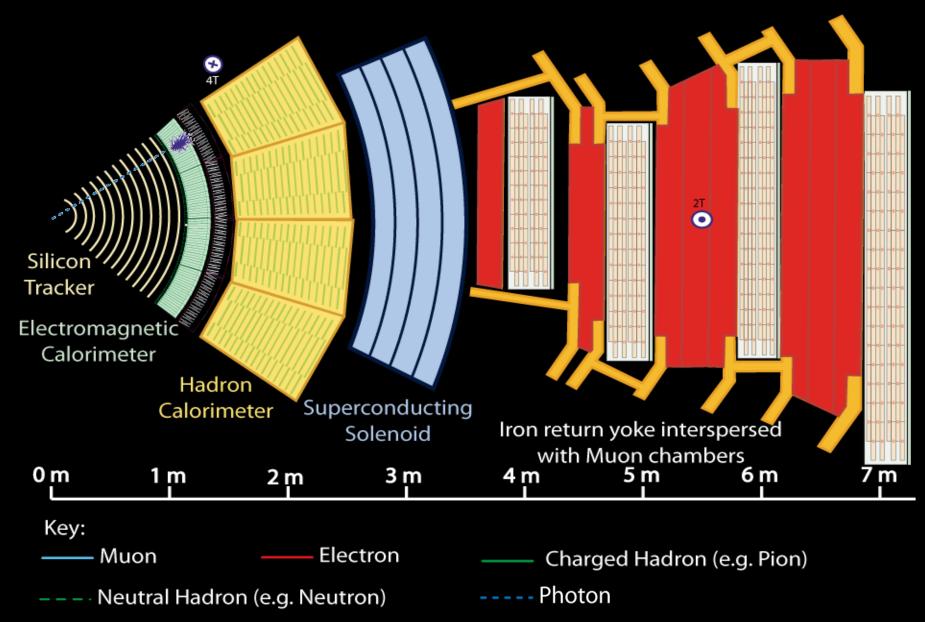


# Neutral hadrons in CMS





## 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).

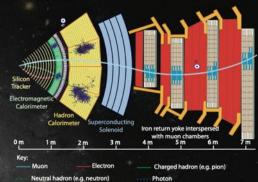


#### Tracker

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 longlived unstable particles decay.

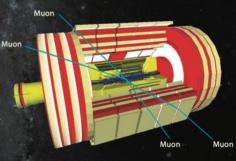
#### **Pattern Recognition**

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.



#### Simulated 250 GeV Higgs decaying to 4 muons

m [GeV]

**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.



#### Electromagnetic Calorimeter

Nearly 80 000 crystals of lead tungstate (PbWO<sub>4</sub>) are used to measure precisely the energies of electrons and photons. A 'preshower' detector, based on silicon sensors, helps particle identification in the endcaps.



#### 

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



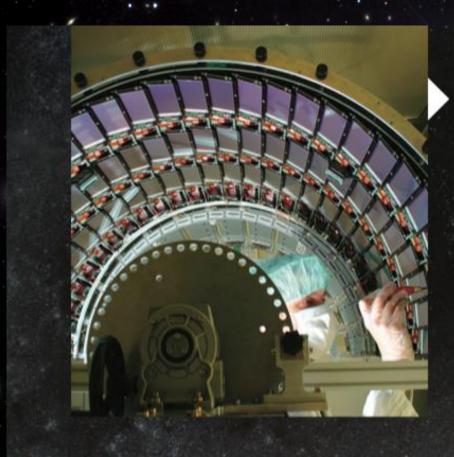
#### **Muon Detectors**

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.



### Tracker

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### Hadron Calorimeter .....

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### **Muon Detectors**

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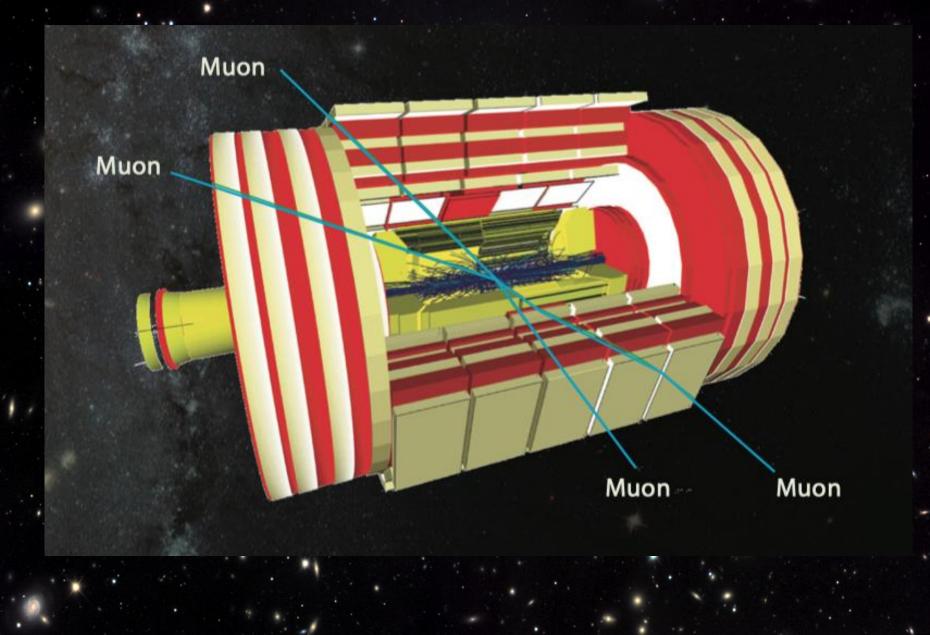
And now a 4<sup>th</sup> type - GEMs



### **Superconducting Solenoid**

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### Higgs boson decay to 4 muons



# $\gg$ H $\rightarrow$ 4 $\mu$ Viewed along the beam direction







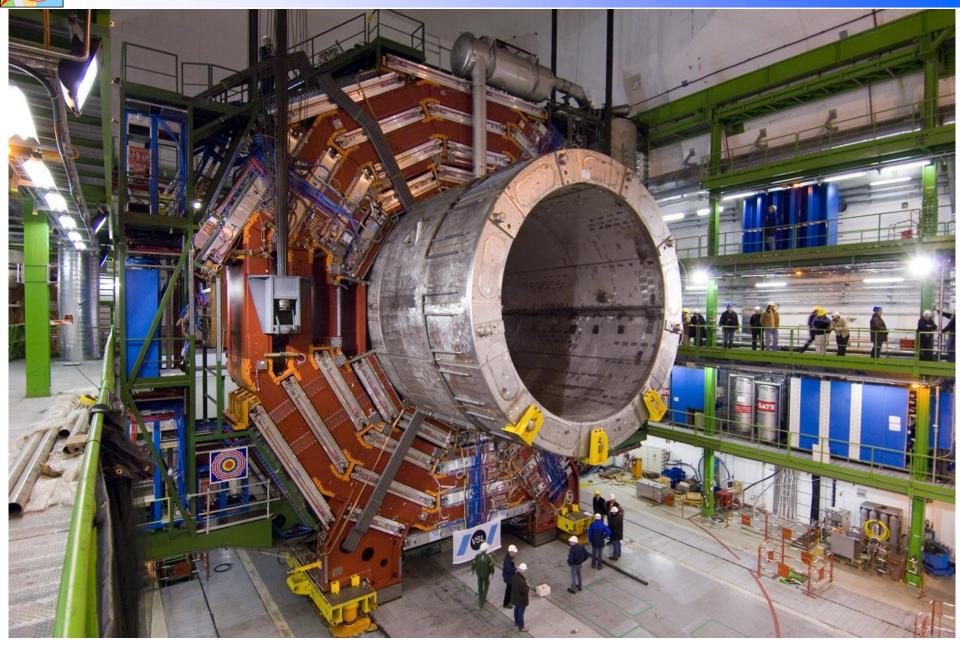


### Concept: build on the surface and lower underground



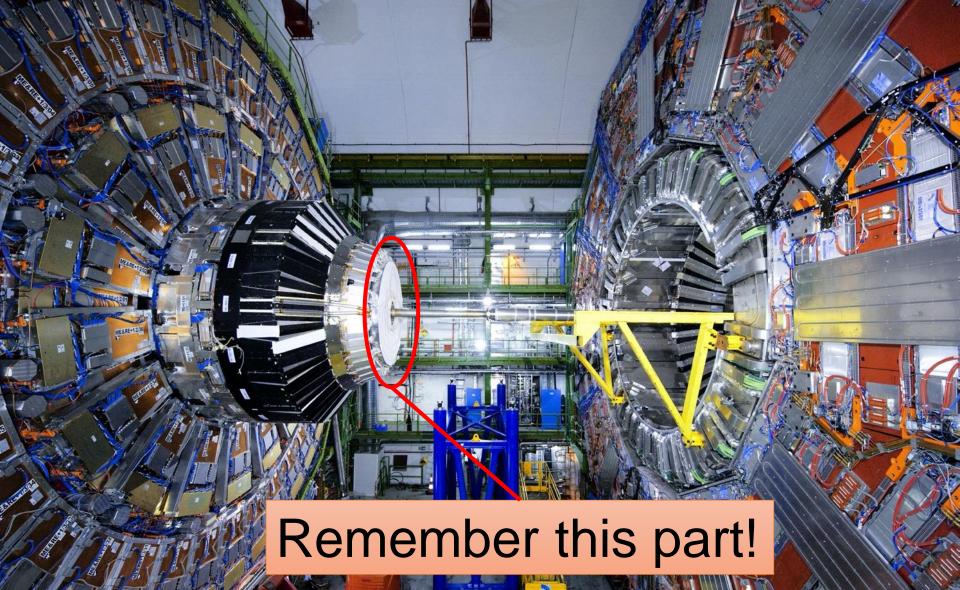
### Concept: build on the surface and lower underground

CMS





# CMS: the most visually amazing detector ever made!





- 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)
  - CERN Summer Student in 1990
- PhD in High Energy Physics at Imperial (1990-1993)
  - Based in UK with visits to CERN
- Have been working for CERN for the CMS Experiment for 30 years!







# 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."





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!

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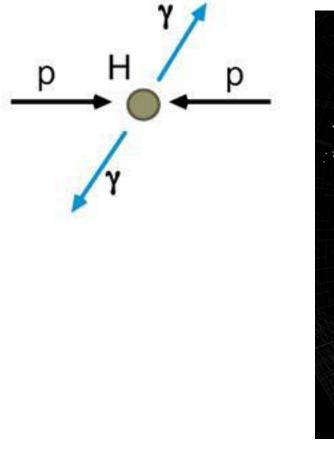
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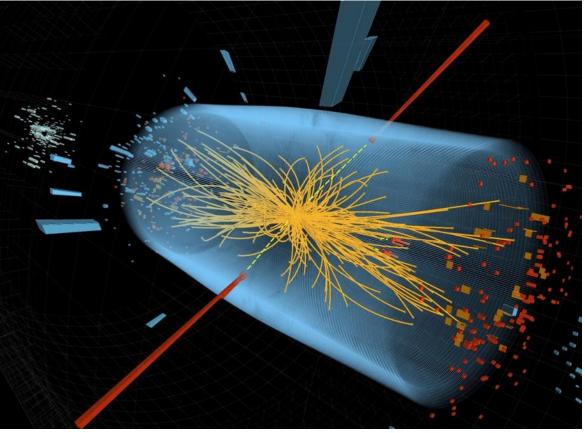
# It has been a family affair!



# 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



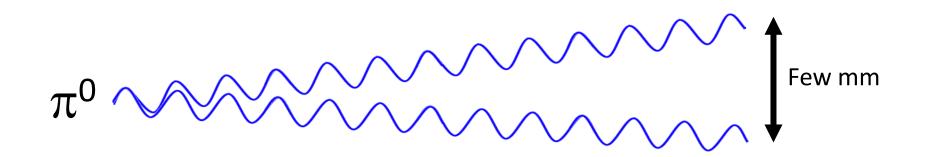


And this is what CMS saw in 2011!

# But it wasn't quite that easy!

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

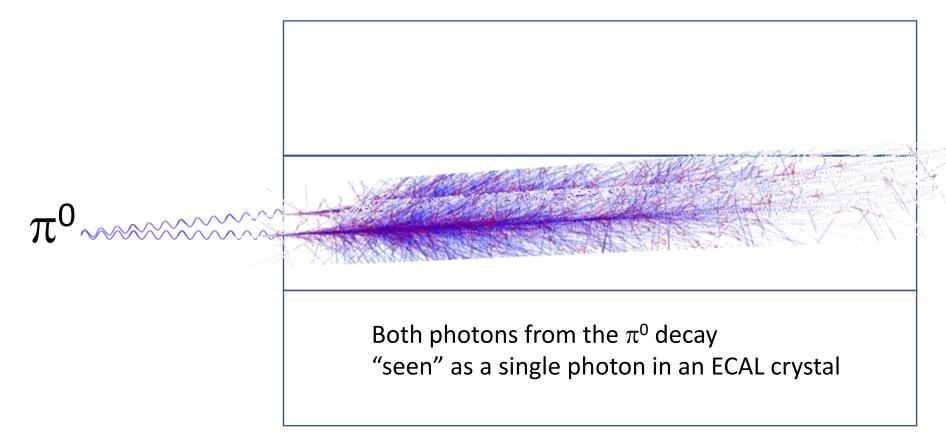
In fact there are other things that "mimic" isolated photons, including decays of neutral pions ( $\pi^0$ ), that happen far more frequently than Higgs boson decays!



# But it wasn't quite that easy!

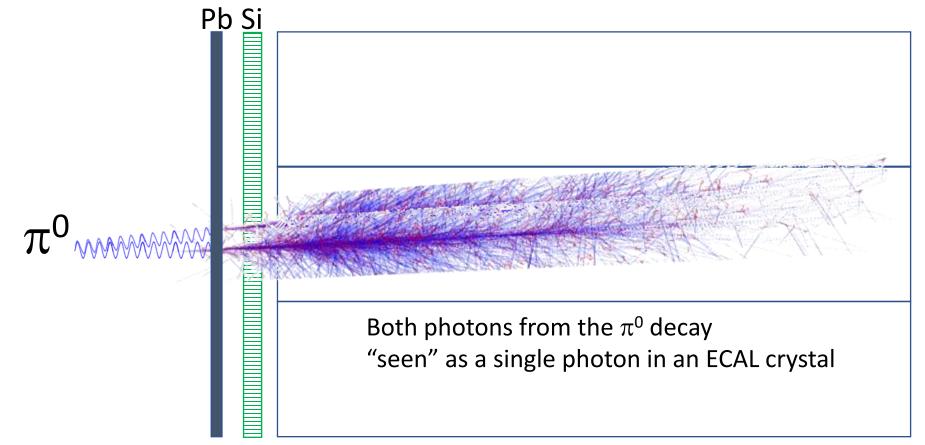
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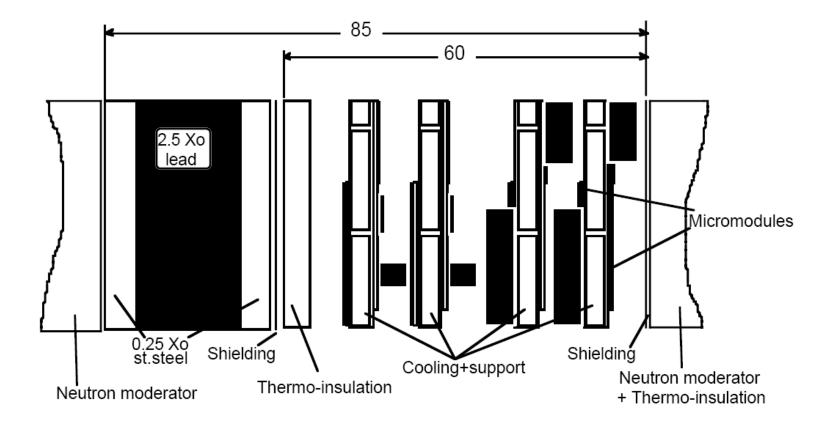
# The concept of the Preshower

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...

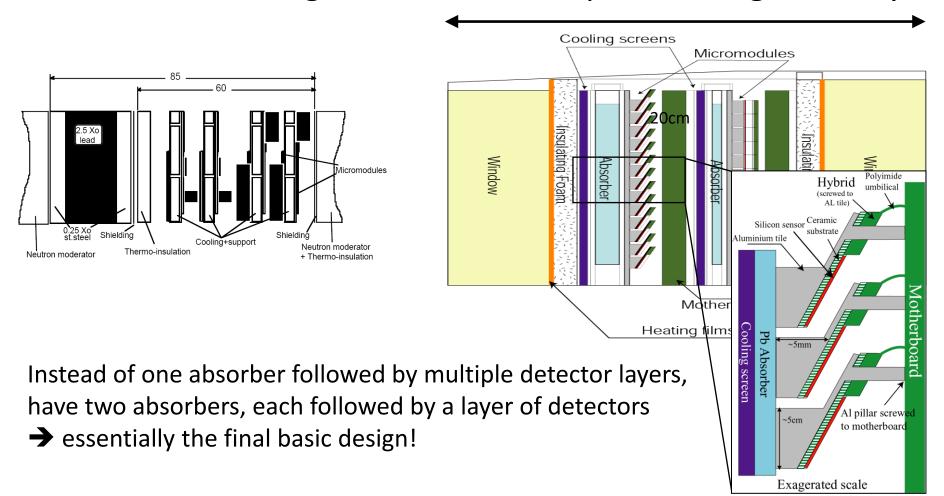


## ... into some sort of reality



## 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

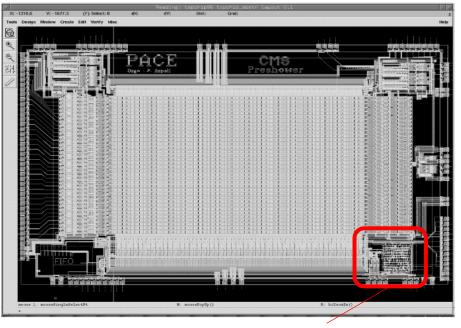




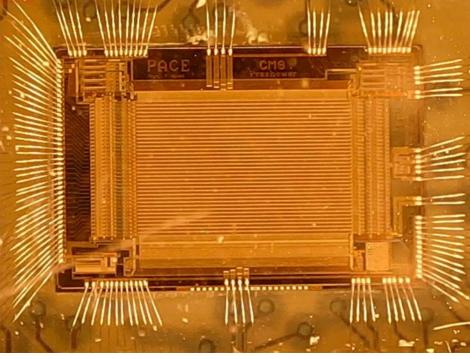
### Examples of 3 years of work as an applied physicist!

• 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



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



#### Dave did this!



### Examples of 3 years of work as an applied physicist!

 Built and tested prototype silicon detector modules in particle beams at CERN  $\rightarrow$  it works! CMS TN / 96-061 May 13, 1996

Results from the 1995 ECAL Testheam with Preshower

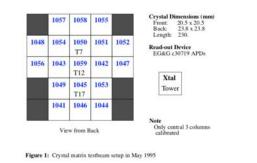
D. Barney CERN, Geneva, Switzerland

#### 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 stbeam setup has been used in order to understand the experiment results and to predict the performance of the preshower in future (1996) test

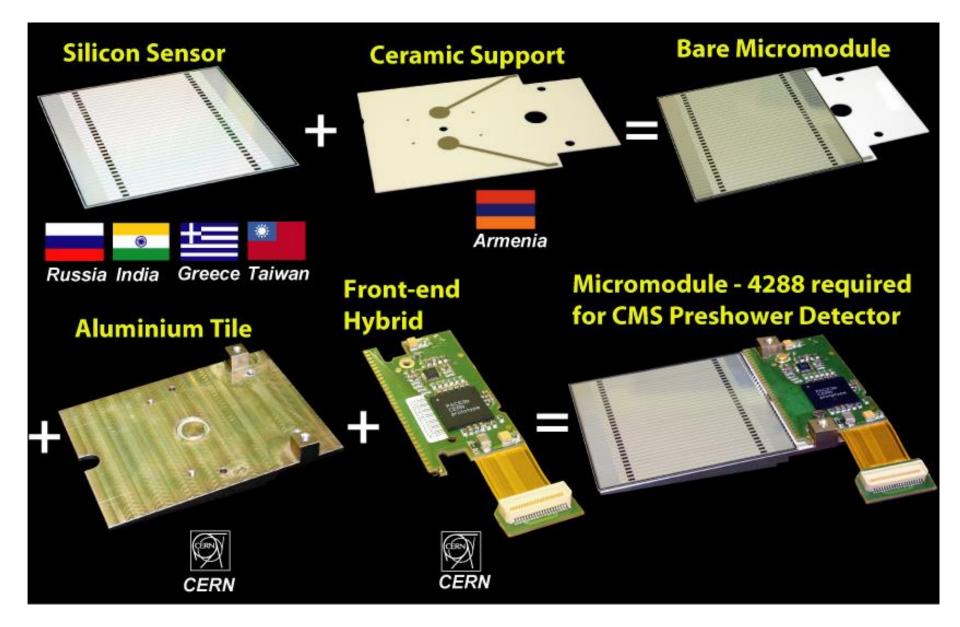
#### 1 Testbeam Setup

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.



#### **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



Testing a column of ladders

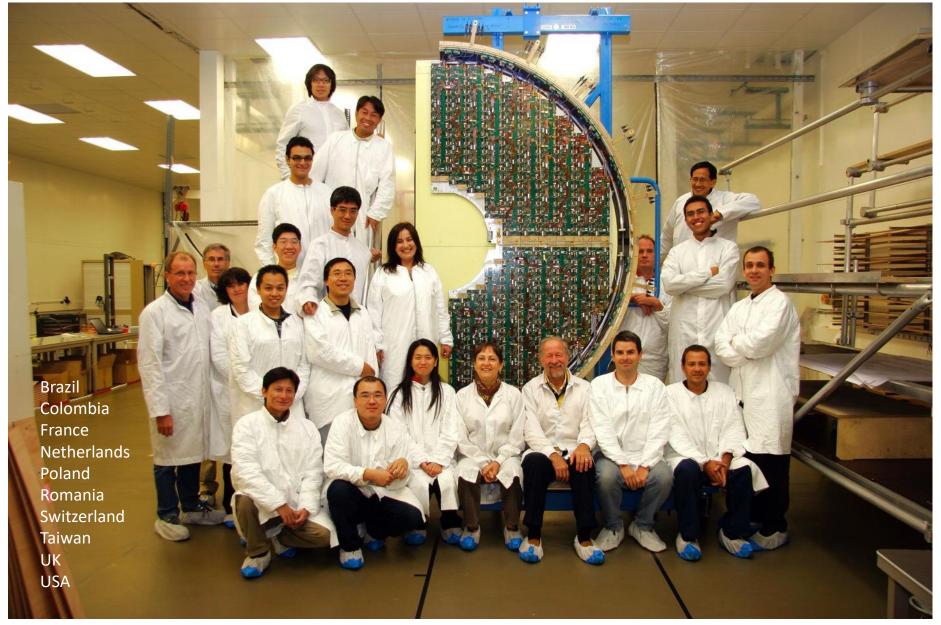


#### Installing ladders on the absorbers

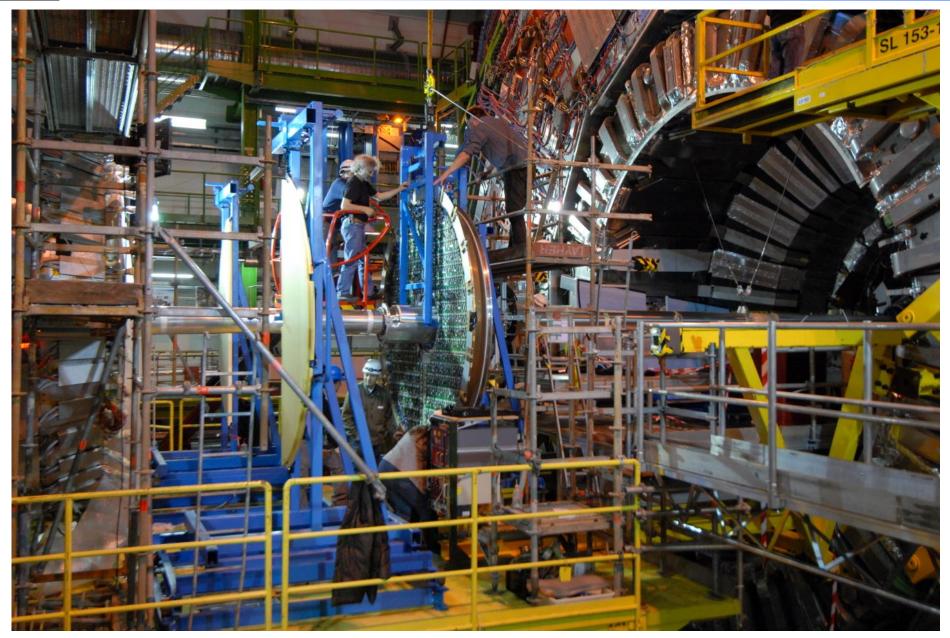




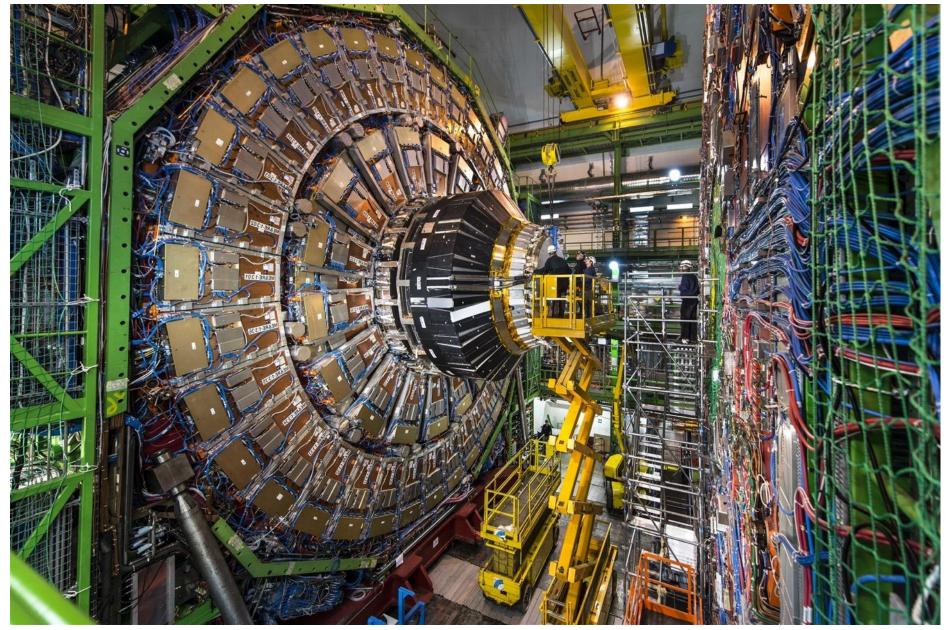
# A few years later...



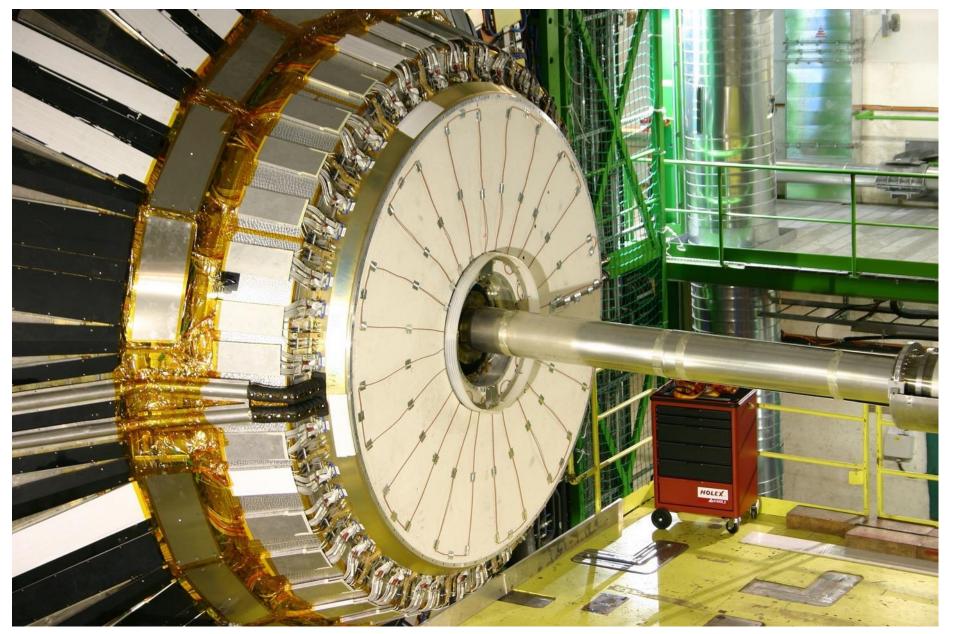
# Installation of Preshower in CMS



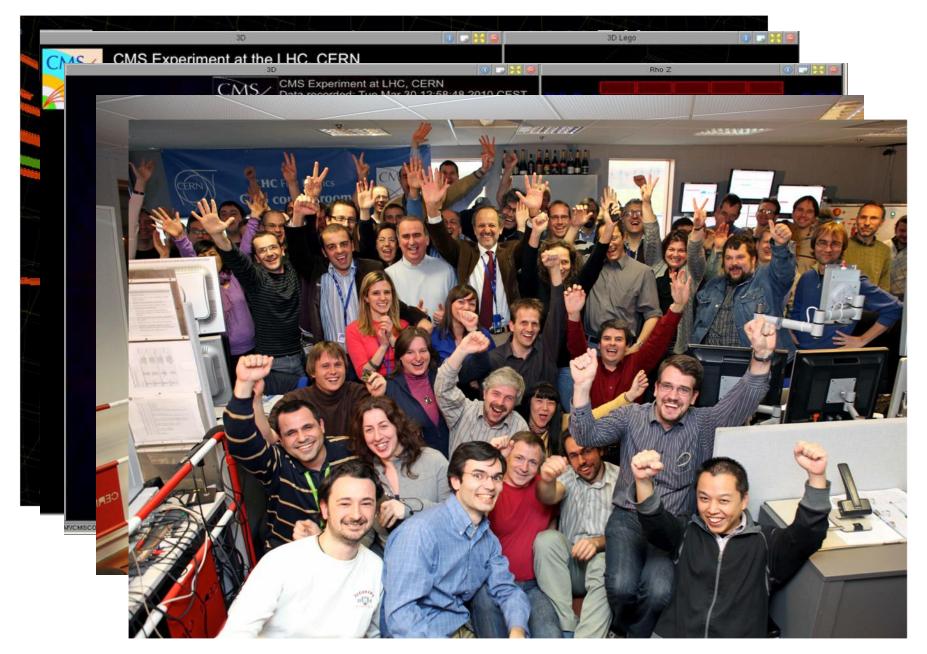
# Preshower installed in CMS!



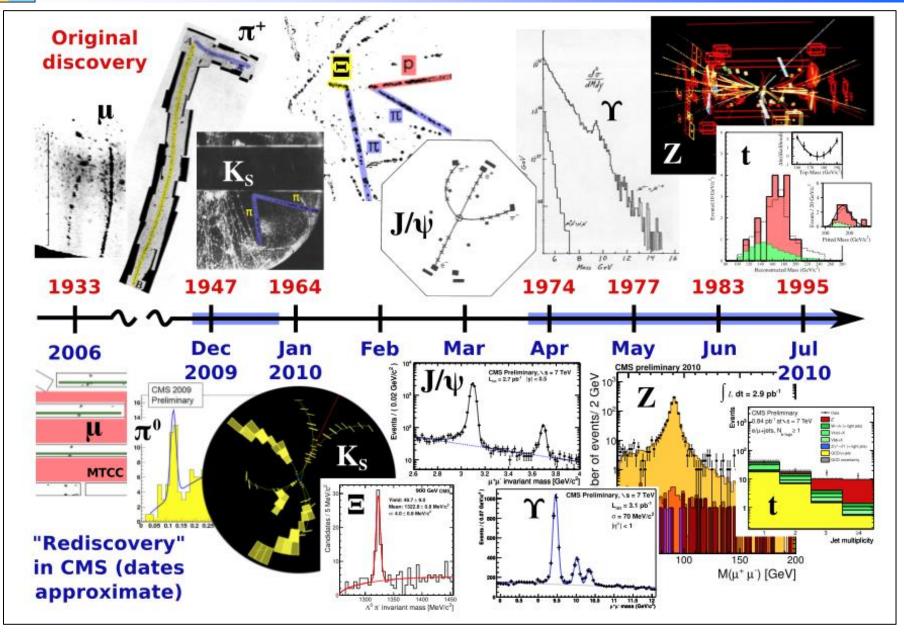
# Preshower installed in CMS!



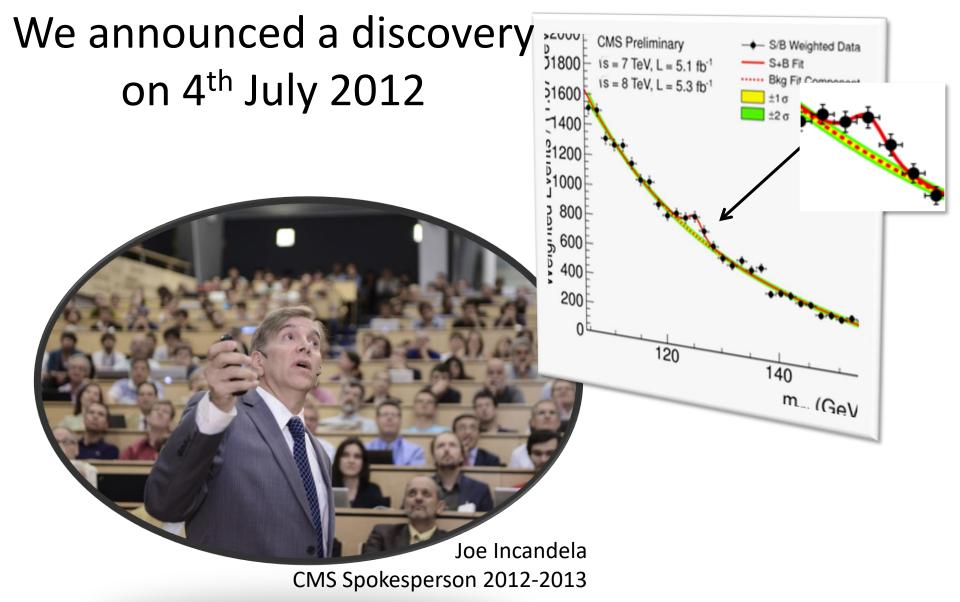




# Re-discovery in CMS



# And just a couple of years later...





## 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





Fer

## **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

or CERN researcher Albert de Roeck explains the Higgs



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《科學人》粉絲腸 喜爱科基斯知的位 CO NAN

自众子那一刻 111. 中型大量子對機構 (LAC) 的第一編科学家展展见数了「金子」把的考虑 产活胺:集合原人之力的「大科學」LBC展開打了部员的一位

/35/68

F家道尋着格斯粒子長達數十年, 如今餐於在LHC的實驗結果中, 群员;

1成某解功的数千人的课程、课程或目现获获学习合作的副係, 差推面利 就实相符分析品質的重要編載,

·新發現的粒子是当符合標準構築氛囲的希格累粒子、潮有額LBC對它的特許 教史多分析,近但是未来幾年內LHC的重要工作。 20

- -



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



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

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

CCMS Consists of more than 3000 scientists, engineers, technicians and students from 180+ institutes and universities from 40+ countries. You 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: CMS Data and analysis tools Primary and simulated datasets Guide to CMS open data Guide to CMS open data Guide to education use of the contents: CMS Data and analysis tools CMS Data and CMS Da		About CMS
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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 <b>CMS Data and analysis tools</b> 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	<u></u>	You can find usage instructions and suggestions of CMS Open Data in two detailed guides:
<ol> <li>CMS Data and analysis tools</li> <li>Primary and simulated datasets</li> <li>Disclaimer</li> <li>Other CMS open data</li> <li>Policies</li> </ol> <b>CMS Data and analysis tools</b> The following are provided through this portal: <ul> <li>Downloadable datasets</li> <li>Primary datasets: full reconstructed collision data with no other selections. The data here are referred to as 'reconstructed dat fragmented data from various sub-detectors are processed or 'reconstructed' to provide coherent information about individual</li></ul>		
<ul> <li>2. Primary and simulated datasets</li> <li>3. Disclaimer</li> <li>4. Other CMS open data</li> <li>5. Policies</li> </ul> <b>CMS Data and analysis tools</b> The following are provided through this portal: <ul> <li>Downloadable datasets</li> <li>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</li></ul>		This page gives a brief overview of CMS Open Data contents:
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 individua		<ol> <li>Primary and simulated datasets</li> <li>Disclaimer</li> <li>Other CMS open data</li> </ol>
Downloadable datasets     Primary datasets:     Tragmented data from various sub-detectors are processed or "reconstructed" to provide coherent information about individuate		CMS Data and analysis tools
<ul> <li>Primary datasets: full reconstructed collision data with no other selections. The data here are referred to as "reconstructed dat fragmented data from various sub-detectors are processed or "reconstructed" to provide coherent information about individua</li> </ul>		The following are provided through this portal:
Simulation data (for data starting from 2011)     Examples of simplified datasets derived from the primary ones for use in different applications and analyses     Tools		<ul> <li>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.</li> <li>Simulation data (for data starting from 2011)</li> <li>Examples of simplified datasets derived from the primary ones for use in different applications and analyses</li> </ul>

- 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



Teacher Home e-Labs Home

Student Home

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



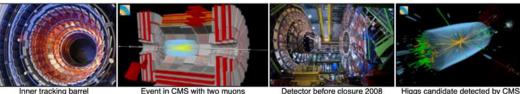
At CERN near Geneva, Switzerland, the Large Hadron Collider (LHC) collides protons at the highest energies ever achieved in the laboratory to reveal new knowledge about matter and energy. Giant detectors make careful measurements from the collisions. One of these detectors is CMS, the Compact Muon Solenoid.

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



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.

Detector before closure 2008

Higgs candidate detected by CMS



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!

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

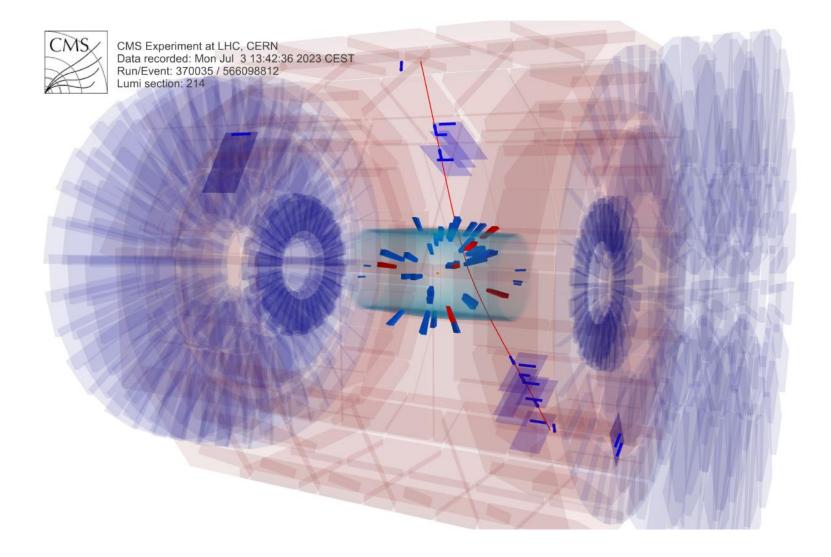
CMS

#### 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



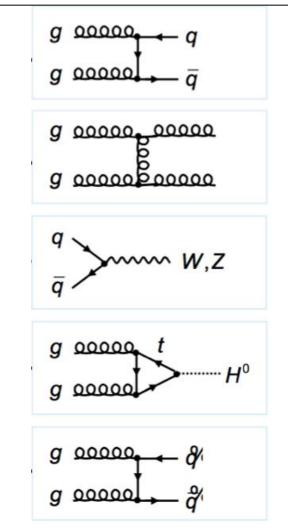


# CMS is a LONG way from its final destination!

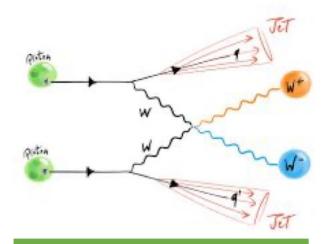
# The LHC is not just a "gluon collider"

When protons "collide", what really happens is that the constituents collide – mostly the gluons!

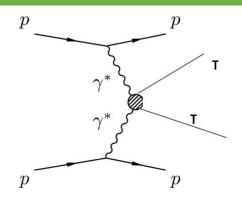
CMS



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



And it also collides photons!



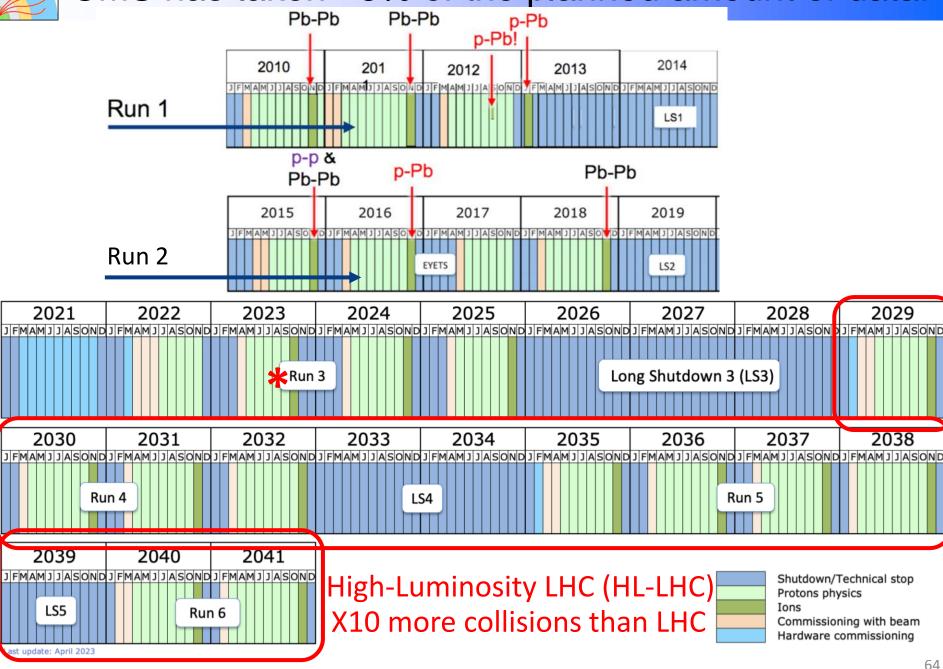
These are **much rarer**, but provide **more insight** into the Standard Model as well as being sensitive to **new physics**...



# We need more collisions! A lot more!

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

CMS





## So what next?



#### Nima Arkani-Hamed

"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**:

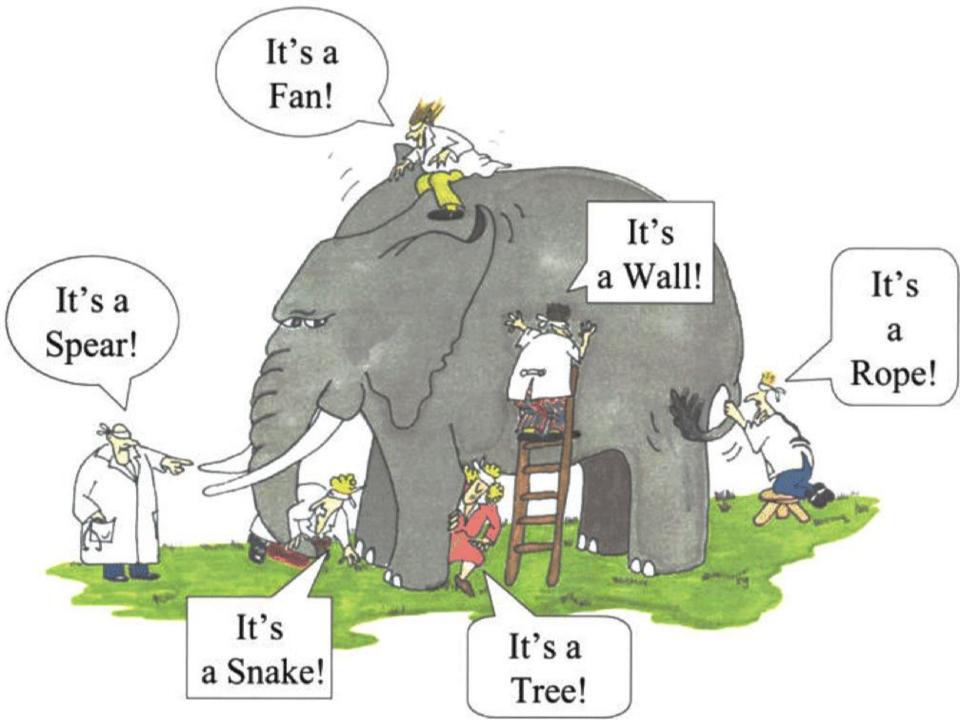
#### measure the hell out of these crazy

"Iphenformane 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. ..."











 <u>https://www.instagram.co</u> m/p/C9ANjURtEb5/



- 4 facts about the Higgs boson that perhaps you didn't know, including:
  - The Higgs boson (and field) interacts with ALL massive particles, including ones we have not yet discovered
     → studying the Higgs boson can tell us about the unexplored Universe!



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



•••

#### Happy #Higgs10 anniversary!

**#OnThisDay** in 2012, a few short years after beam first circulated in the **#LHC**, the **ATLAS Experiment at CERN** and **CMS Experiment at CERN** announced the discovery of the Higgs boson. Its existence confirms the existence of the Higgs field, which gives mass to all elementary particles.

Find out more: home.cern/science/physics/higgs-boson/how



Marco Delmastro is at CERN. 1h - Meyrin, Switzerland · 🔇

...

10 years after the #Higgs boson discovery, it's an honor to present the status of its property measurements on behalf of the @atlasexperiment and @cmsexperiment at the #Higgs10 symposium At @cern. All look very much SM-like, and the precision we achieved quite impressive!

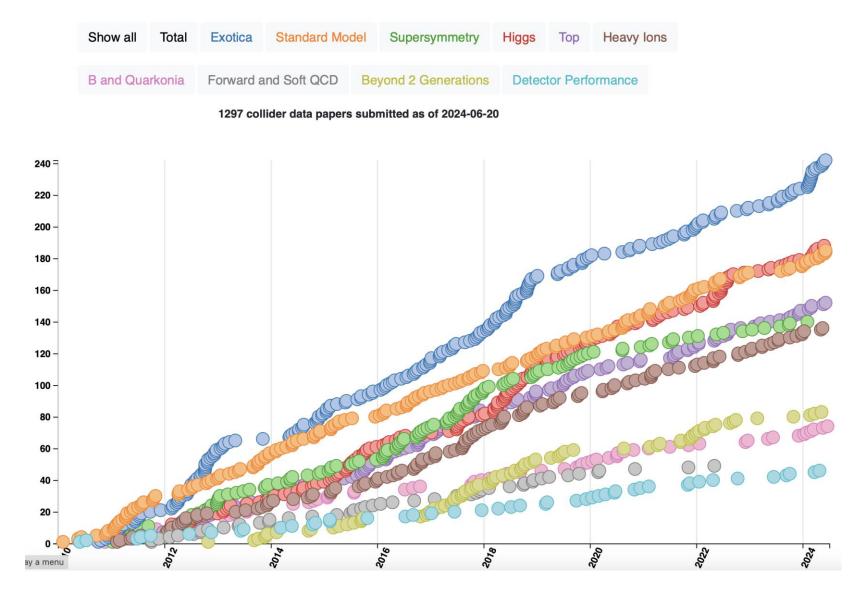


## July 4<sup>th</sup> 2022! 10<sup>th</sup> anniversary

#### 1145 papers published on data taken with CMS!

CMS

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



## And where was I on July 4<sup>th</sup>?

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!

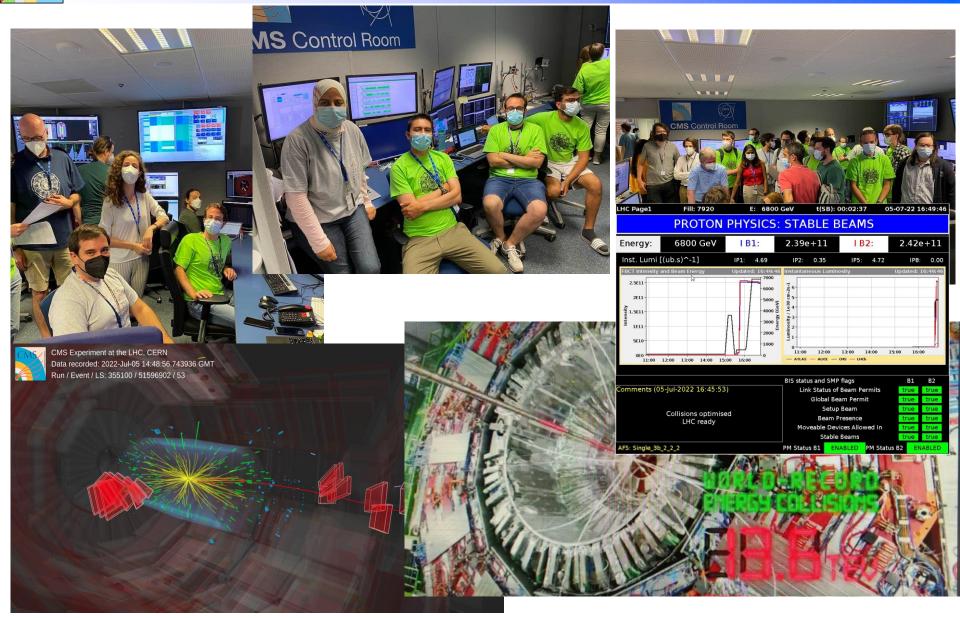




### 4<sup>th</sup> July is also my daughter's birthday (2001)



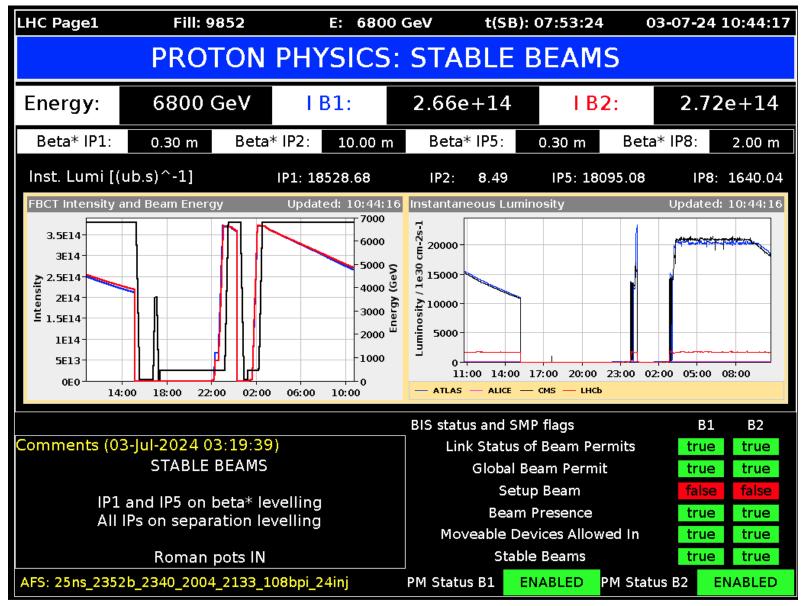
### July 5th 2022 – restart of LHC @ 13.6 TeV



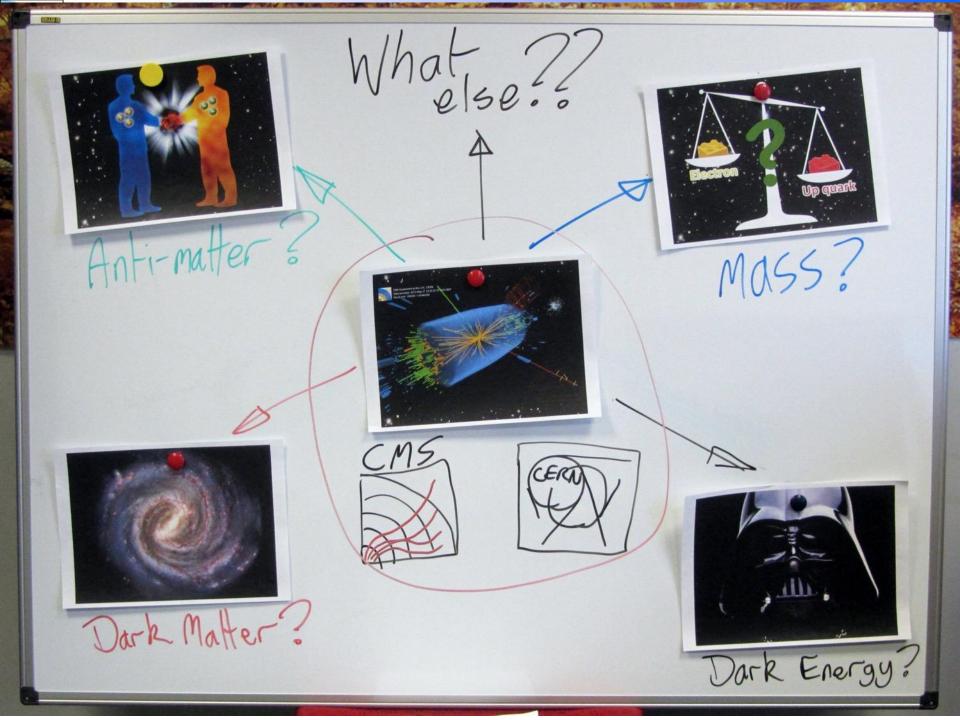
Another 3 years of data taking started two years ago!



## Status of the LHC right now (almost)

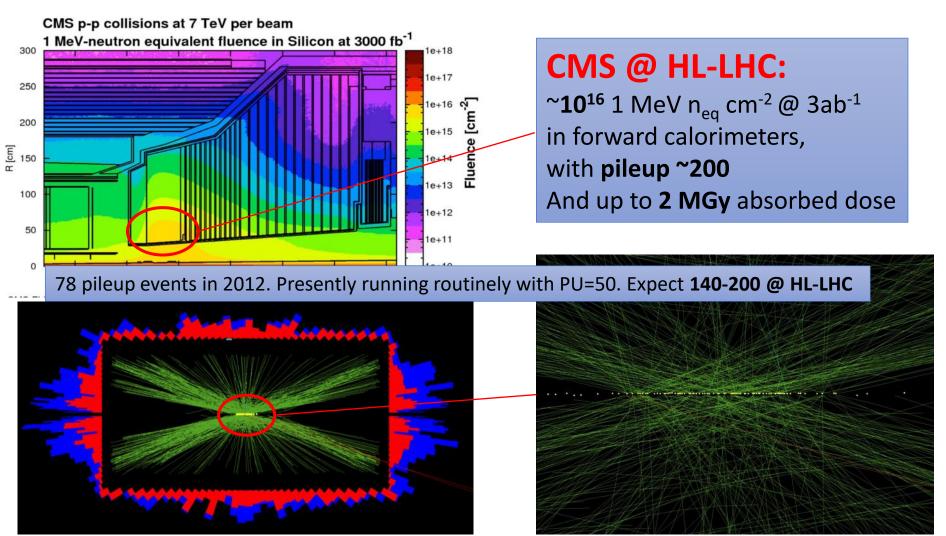


https://op-webtools.web.cern.ch/vistar/vistars.php





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



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 9 years



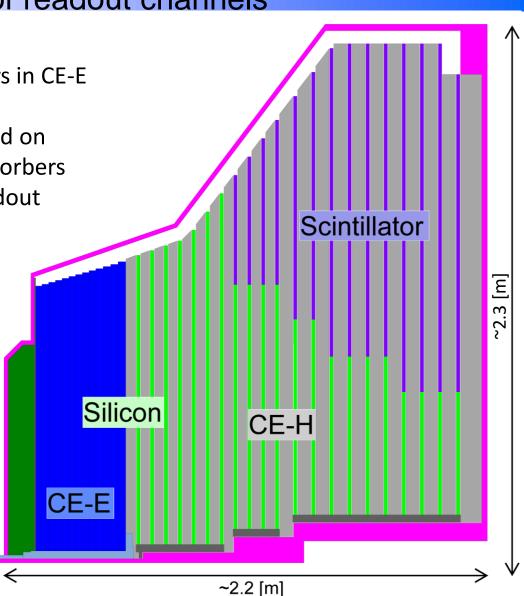
CMS HGCAL ("CE"): a sampling calorimeter with unprecedented number of readout channels

#### **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 < |η| < 3.0 ~215 tonnes per endcap Full system maintained at -30°C ~620m<sup>2</sup> Si sensors in ~26000 modules ~6M Si channels, 0.6 or 1.2cm<sup>2</sup> cell size ~370m<sup>2</sup> of scintillators in ~3700 boards ~240k scint. channels, 4-30cm<sup>2</sup> 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<sub>0</sub> & ~1.3 $\lambda$ Hadronic calorimeter (CE-H): Si & scintillator, steel absorbers, 21 layers, ~8.5 $\lambda$  <sub>8</sub>

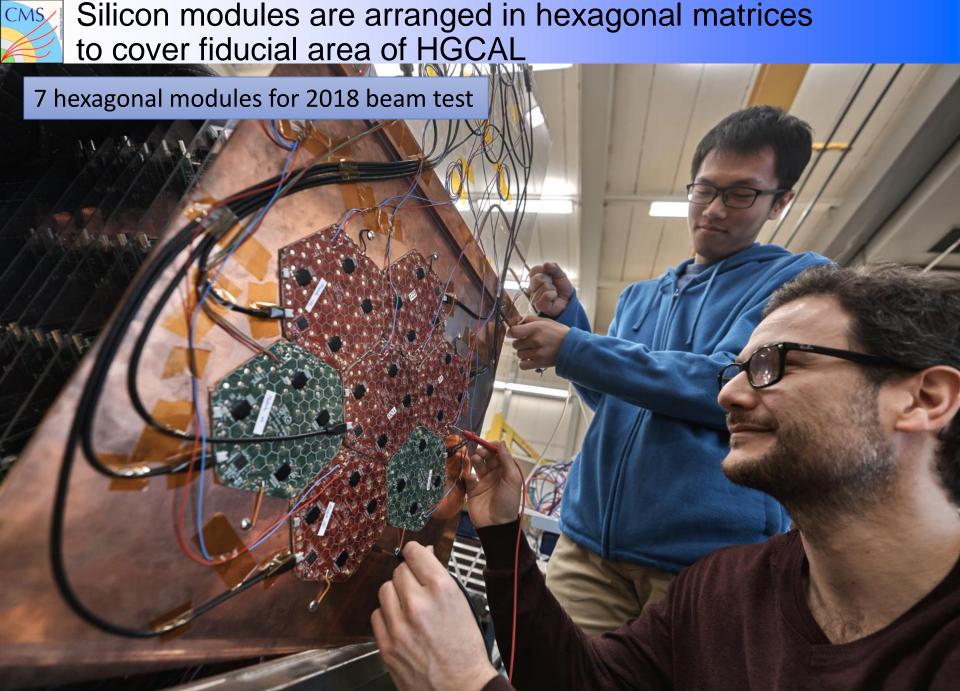


### Unboxing the HGCAL

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

The 47 active layers

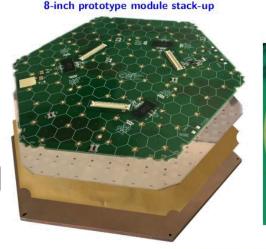
of the HGCAL



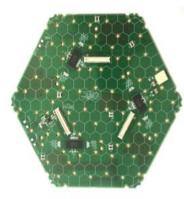


## HGCAL will include 26000 modules based on hexagonal silicon sensors with 0.5-1cm<sup>2</sup> cells

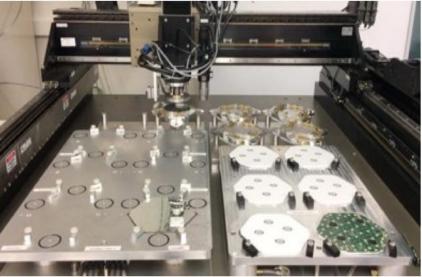
 Robust module constructed from a baseplate, insulating layer, silicon sensor, and readout PCB







- Automated assembly process using gantry and robotic wirebonder developed at UCSB
  - Highly-repeatable, being replicated to five additional module assembly centers worldwide

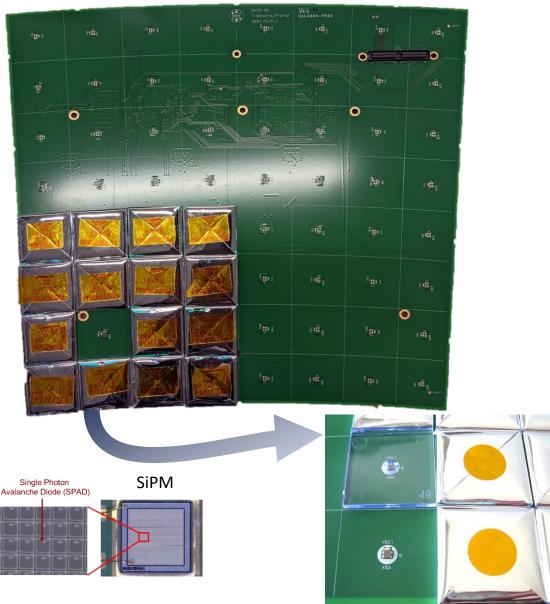


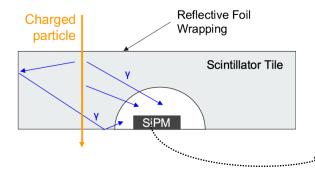


## HGCAL will also include 370m<sup>2</sup> of scintillator tiles with on-tile SiPM readout

#### • "Tile board" PCB

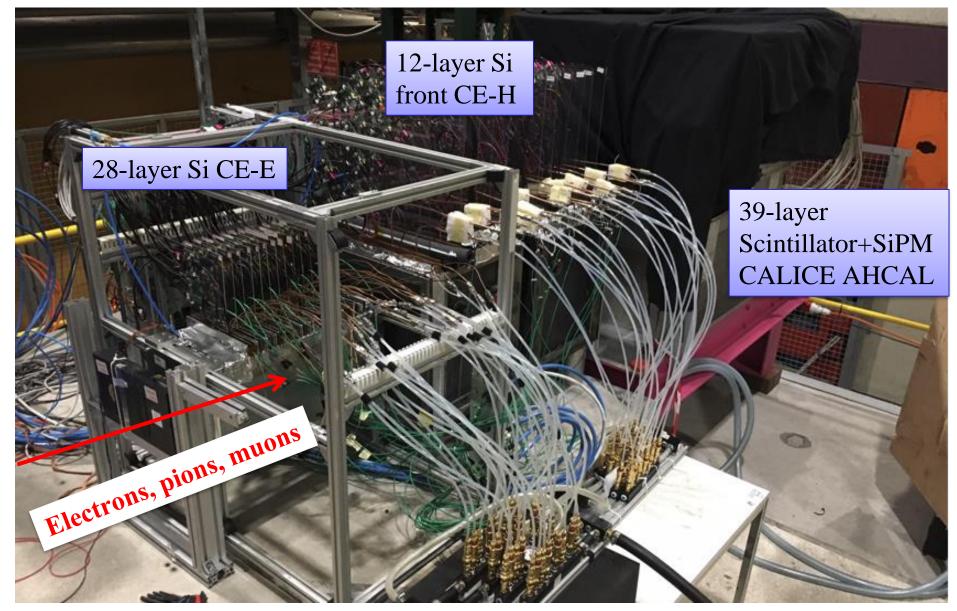
- Connects Silicon photo multipliers (SiPM) to HGCROC ASIC.
- Connects to motherboard for control and data transfer.
- Wrapped scintillating tiles
  - Reflective foil wrapping.
  - Light collected by SiPM.
  - Light injection LED.







### Large-scale beam-tests of prototypes in 2018



## A brief aside on Calorimeter $\sigma_{E}/E$

### **Energy resolution**

Usual parameterization for calorimeters:

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

- 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

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

### ATLAS ECAL Energy Res. today

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

### CMS HGCAL Energy Resolution (expected)

$$\sigma_{\rm E}/{\rm E} = rac{0.24}{\sqrt{E}} \oplus 0.001$$

#### Which looks terrible!

But

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

#### So:

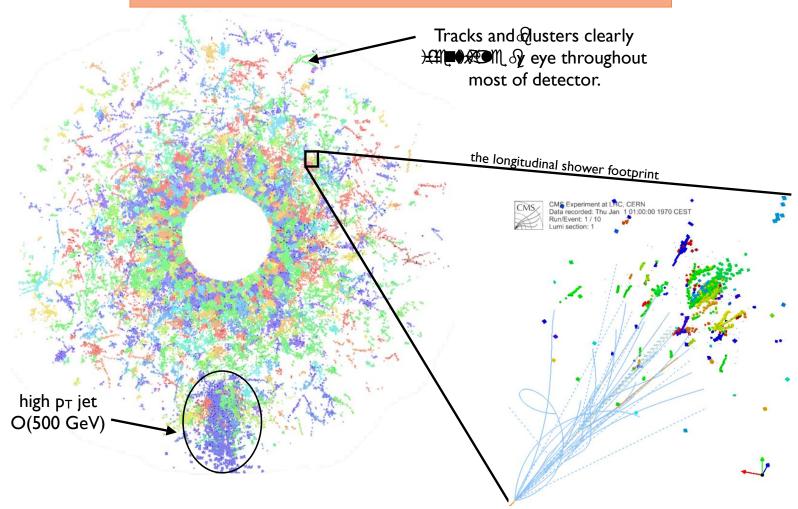
- in CMS today:  $\sigma_{\rm E}/{\rm E}(150~{\rm GeV})$  = ~0.6 GeV
- in ATLAS today:  $\sigma_{e}$  /E(150 GeV) = ~1.2 GeV
- in HGCAL:  $\sigma_{\rm E}$  /E(150 GeV) = ~3 GeV

So the difference is not huge, but  $\sigma_{\rm E}$  is not the only important feature of HGCAL...

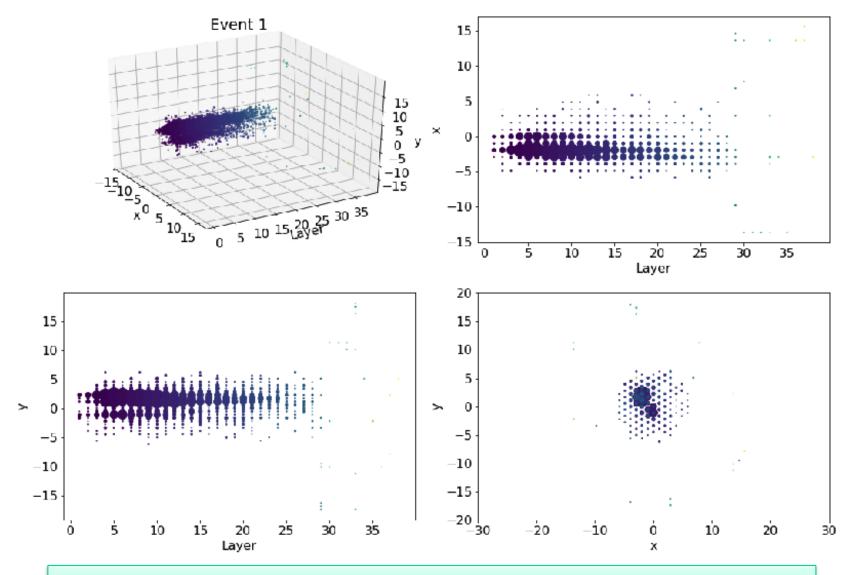


HGCAL has the potential to visualize individual components of showers – 5D calorimeter

### Simulation of 140 pileup events in CMS

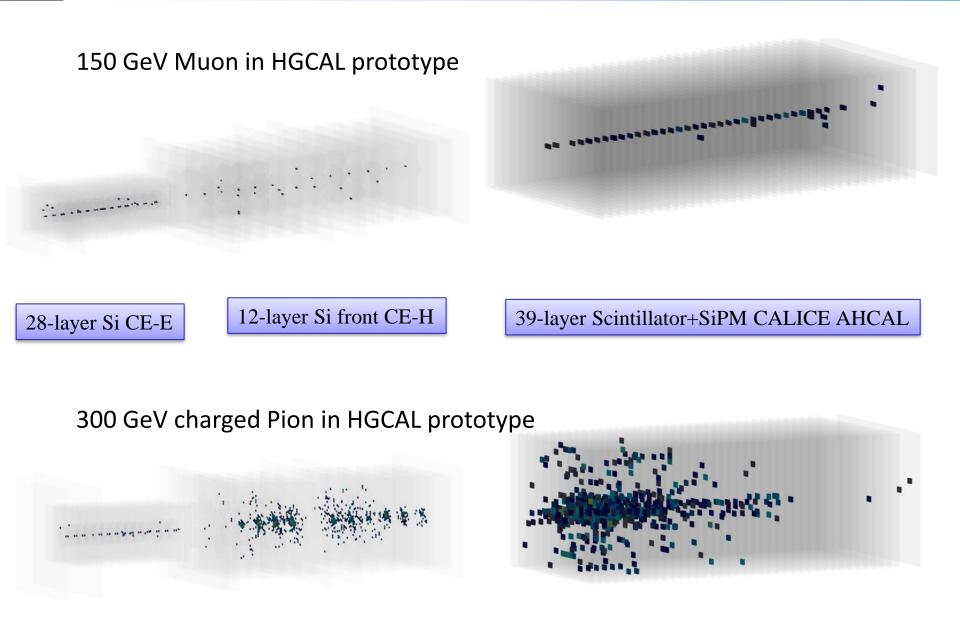


### 300 GeV electron shower: event display



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

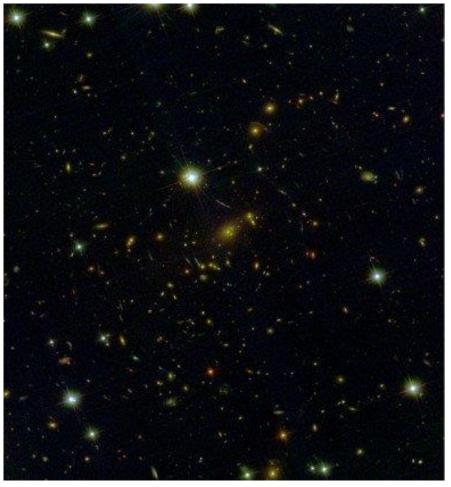
### And other types of particle...



## HGCAL vs existing endcap calorimeters

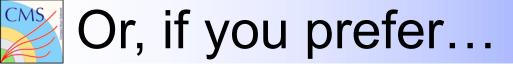
#### CMS Endcap Calorimeters **before** LS3

CMS Endcap Calorimeters after LS3



Courtesy: Hubble Space Telescope

Courtesy: James Webb Space Telescope



### 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





- ~600 tonnes of mechanics, detectors, electronics and services to be produced and tested extensively in the next 3 years
- 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 30 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)
- Proud husband and father! Without the support of my family I could not have done these things!



### Snapshot of my group – not just physicists!

- 115 people (28 women 24%)
  - 39 Physicists
  - 36 Mechanical engineers
  - 16 mechanical/electromechanical technicians
  - 7 Electrical/electronics engineers
  - 5 Computing engineers
  - 4 Administrative assistants
  - 4 Communication professionals
  - 2 Electromechanical engineers
  - 2 Health & Safety engineers

## How can your students come here?

- Under 18
  - Private or school visit
    - School visits can contact people like me to have a Q&A session with the kids
  - "stage d'observation": unpaid 1-week job shadowing of a scientist/engineer Not so easy to get, but can be a fun opportunity! <u>https://internship-portal.web.cern.ch/job-shadowing</u>
- During a bachelor's or master's degree
  - CERN "Technical Student" and "Admin Student" programs for applied physics, engineering, communications etc. Up to 14 months working in a research group on a technical topic <u>https://careers.smartrecruiters.com/CERN/tech</u>
  - CERN Summer Student program after at least 3 years of a degree) 2-2.5 months of lectures plus research
     https://home.web.cern.ch/summer-student-programme

https://home.web.cern.ch/summer-student-programme

- After the bachelor's/master's degree
  - CERN Doctoral Student program for applied physics, engineering etc. Up to 3 years working in a research group on a technical topic and associated to a university <u>https://jobs.smartrecruiters.com/CERN/743999986658044-doctoral-student-programme</u>
  - CERN "Origin" program for graduates: up to 3 years working in a research group on physics, engineering, communications, administration etc. <u>https://careers.cern/origin-university-graduates</u>
  - Or "Quest" program for people with a Master's plus at least two years of experience <u>https://careers.smartrecruiters.com/CERN/experienced-graduates</u>