

CMS: a personal journey

Dave Barney, CERN, 9th August 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



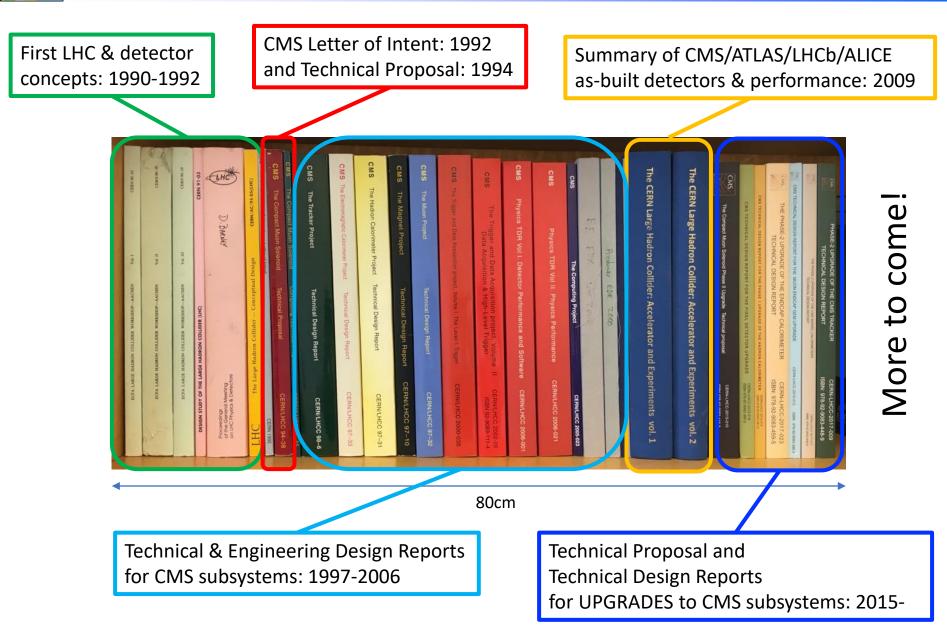
Overall detector design is so simple you can do it with students on a blackboard!



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
CC 2000-038	CMS The Trigger and Data Acquisition project. Volume L The Level-1 Trigger CERWLHCC
HCC 2002-26 92-9083-111-4	CMS The Trigger and Data Acquisition project, Volume II GERNL Data Acquisition & High-Level Trigger ISBN
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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!

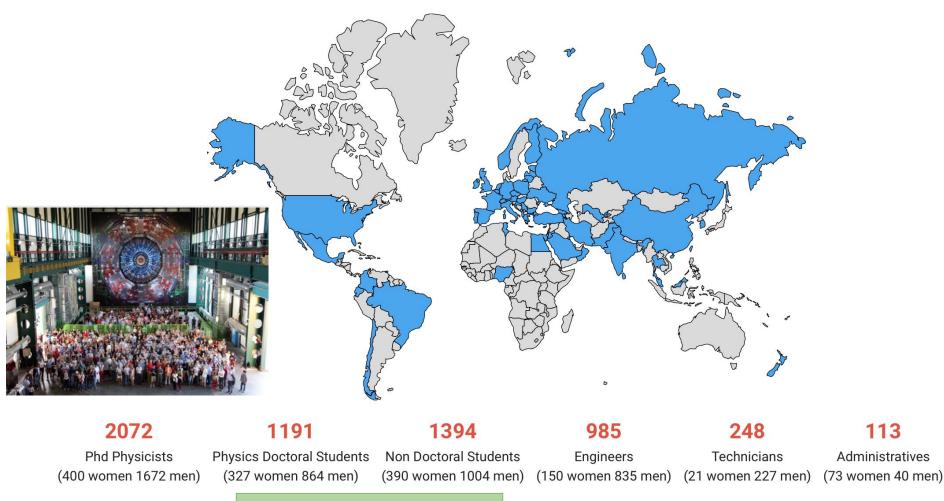
80cm

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



CMS Overview in 2024

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



Inc. about 2500 students



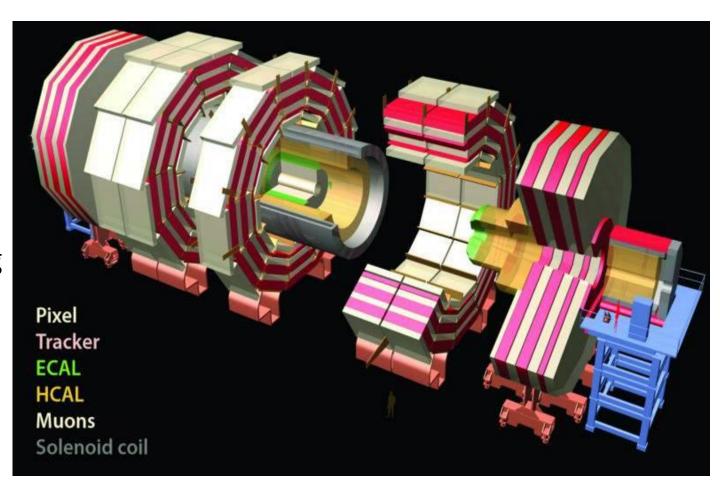
CMS in a nutshell

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

Is about 15 metres wide and 21.5 metres long

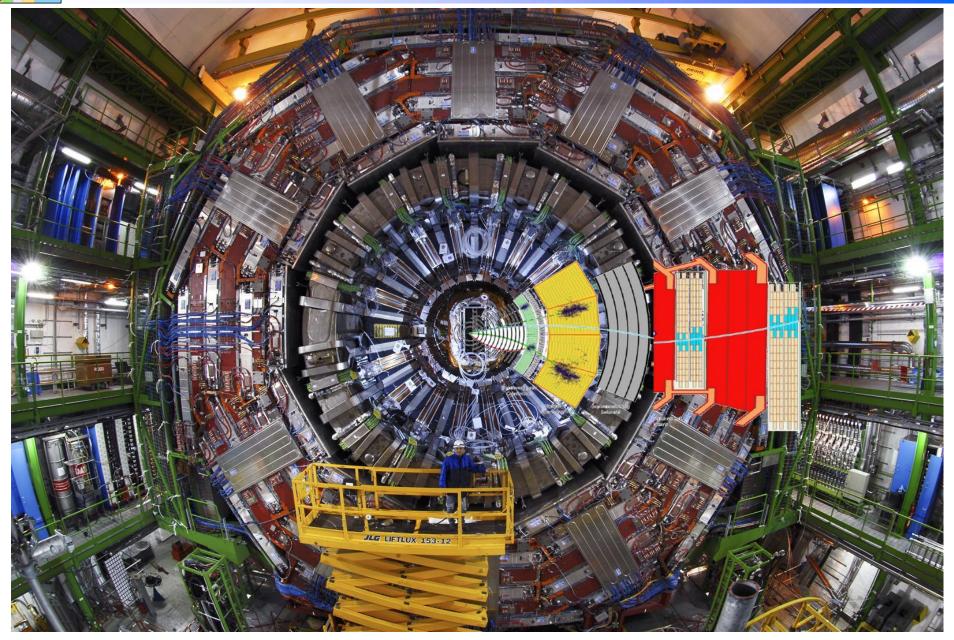
Weighs **twice as much as the Eiffel Tower** – about 14000t

Divided into 5 main detecting layers



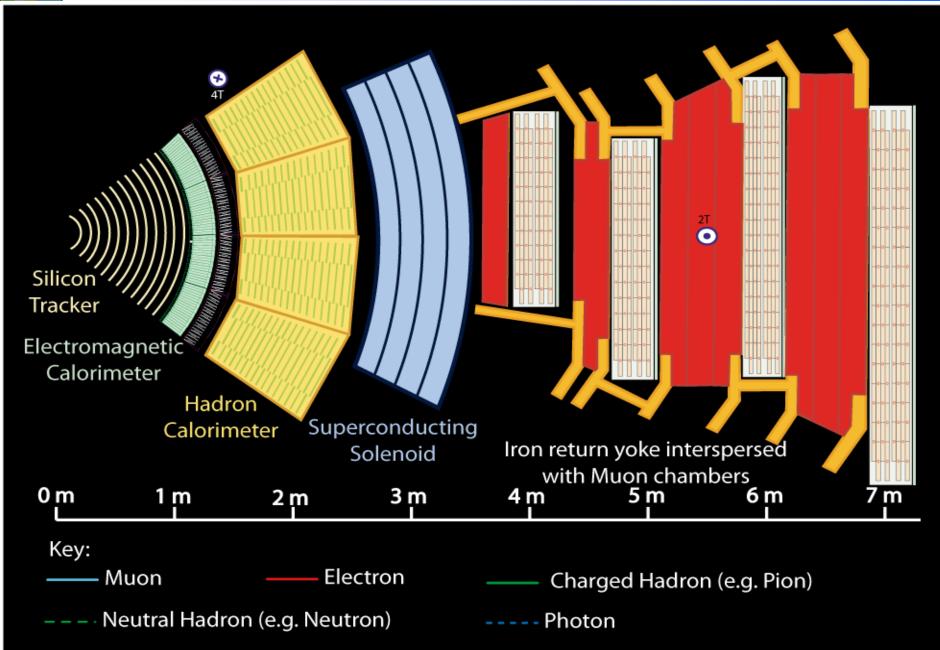
It has been performing excellently during the past 15 years, but we need it to work for another ~20! **Need to upgrade...**

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



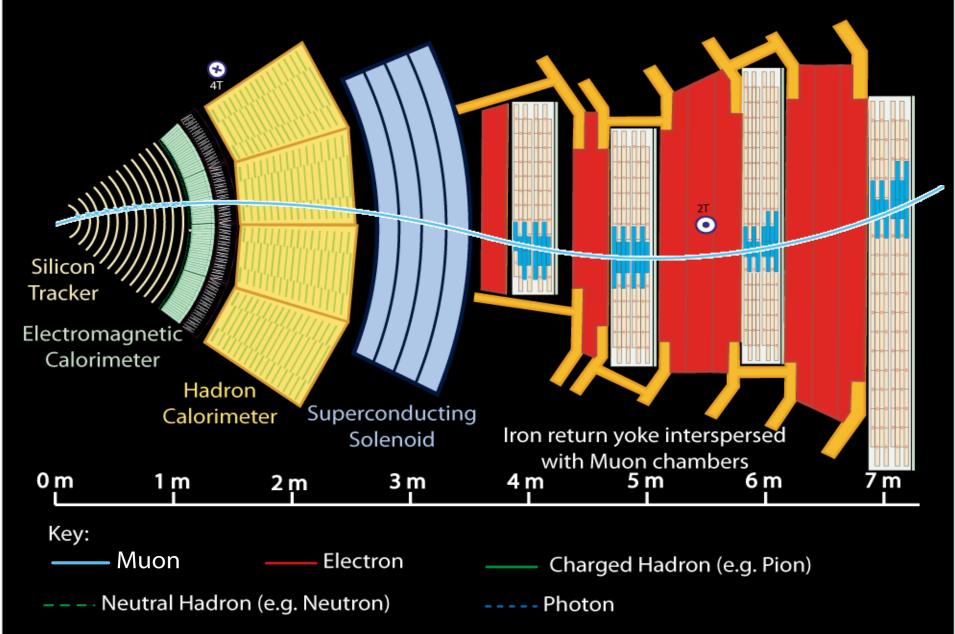
A slice through the CMS Detector

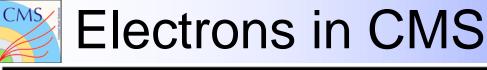
CMS

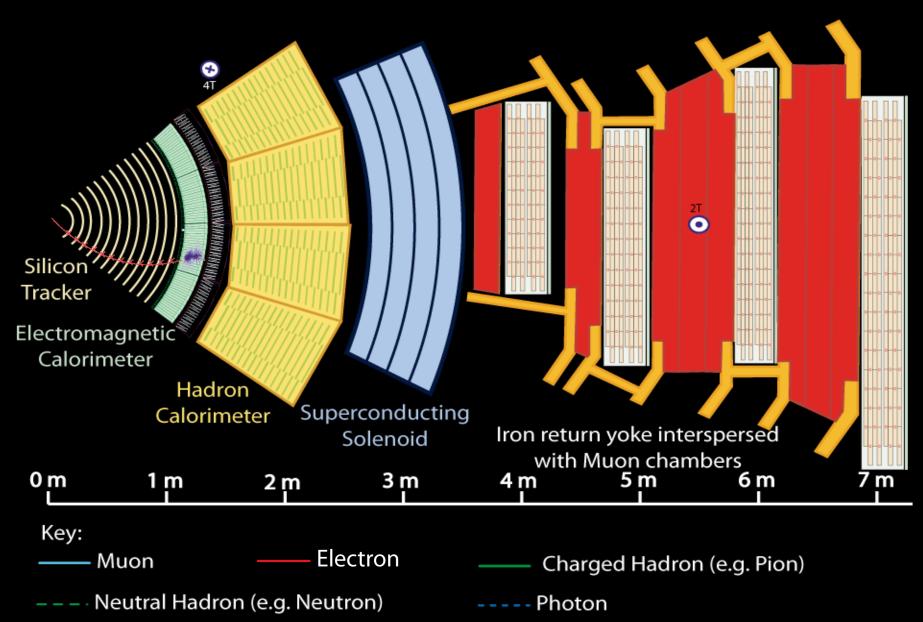




Muons in CMS

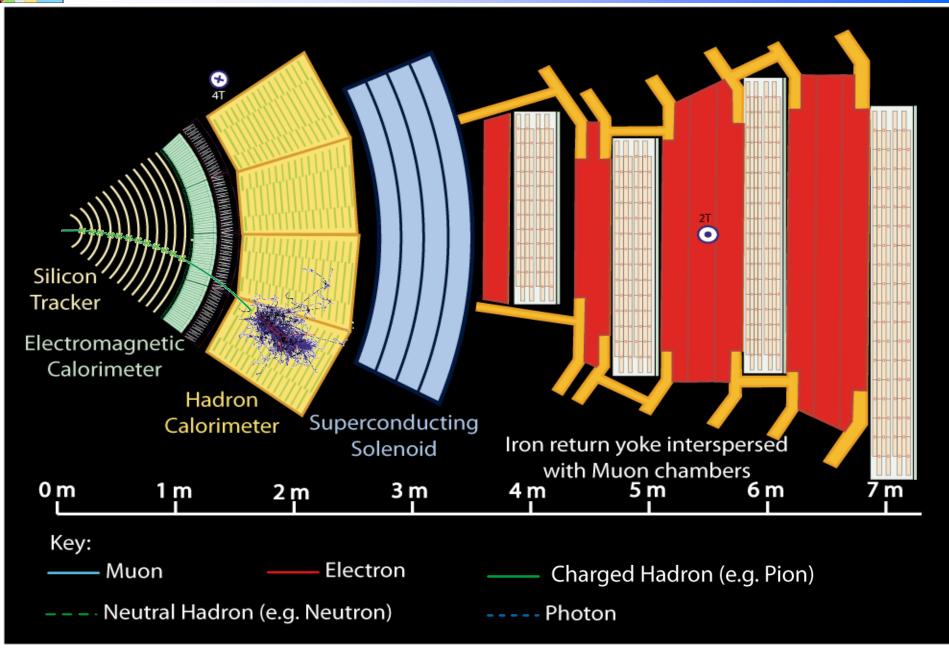




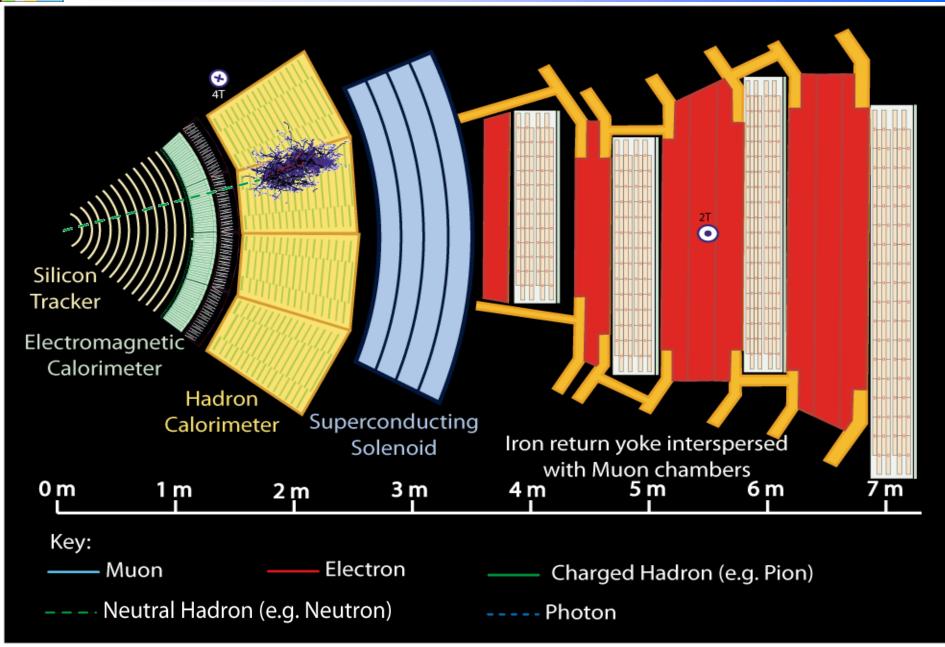


Charged hadrons in CMS

CMS

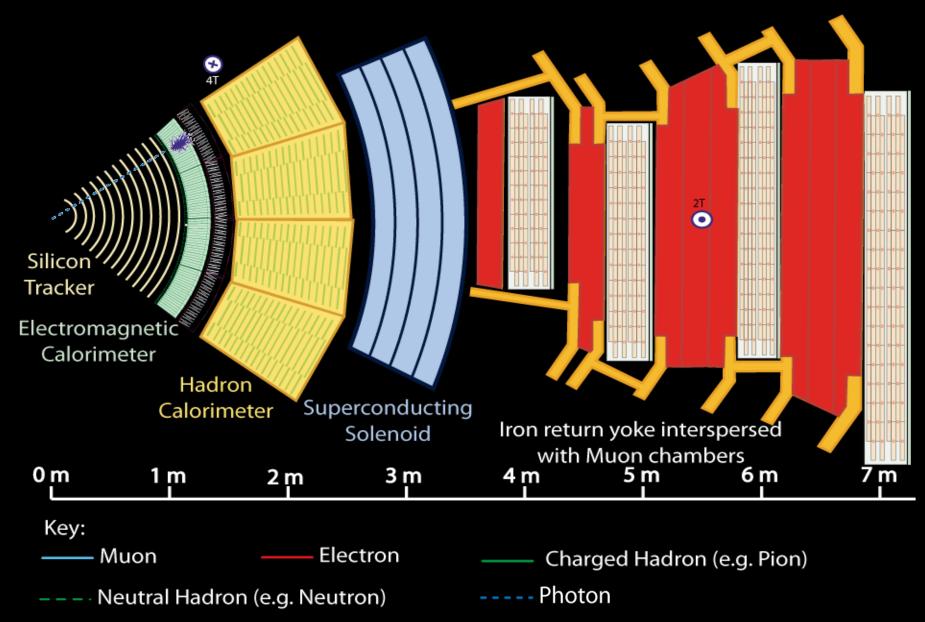


Neutral hadrons in CMS





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).

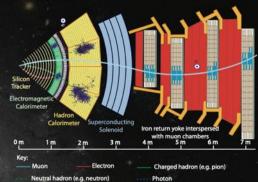


Tracker

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.

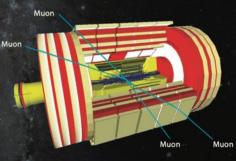
Pattern Recognition

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 Data Analysis

m [GeV]

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 (PbWO₄) are used to measure precisely the energies of electrons and photons. A 'preshower' detector, based on silicon sensors, helps particle identification in the endcaps.



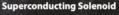
Hadron Calorimeter

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.

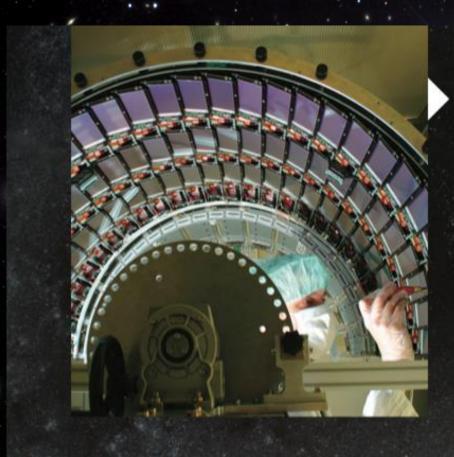


Muon Detectors

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.



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.



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Hadron Calorimeter

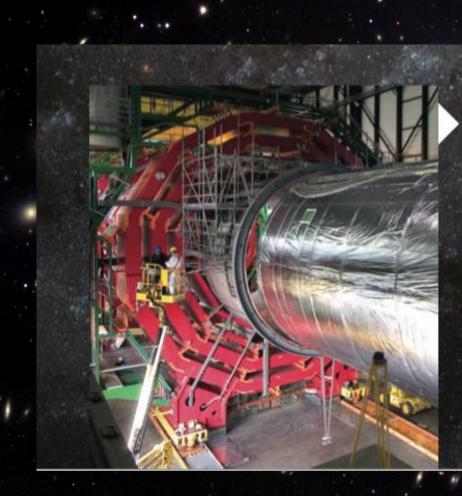
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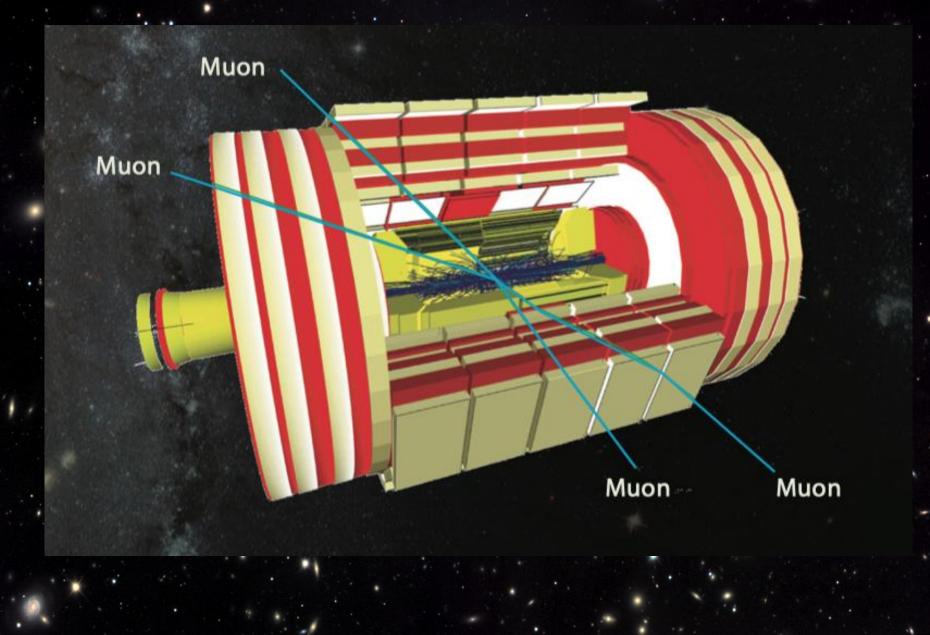
And now a 4th type - GEMs



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



\gg H \rightarrow 4 μ Viewed along the beam direction







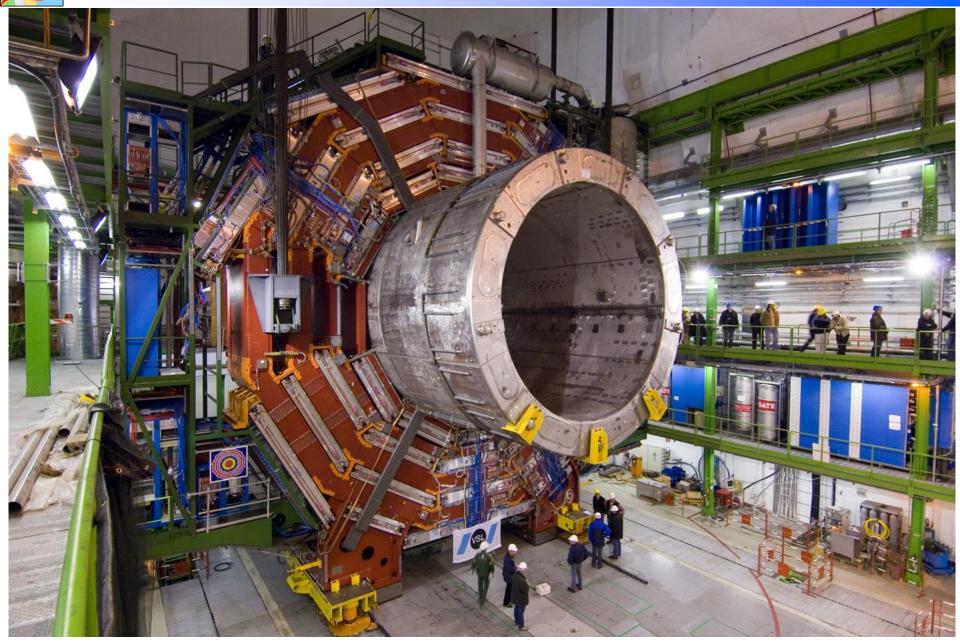


Concept: build on the surface and lower underground



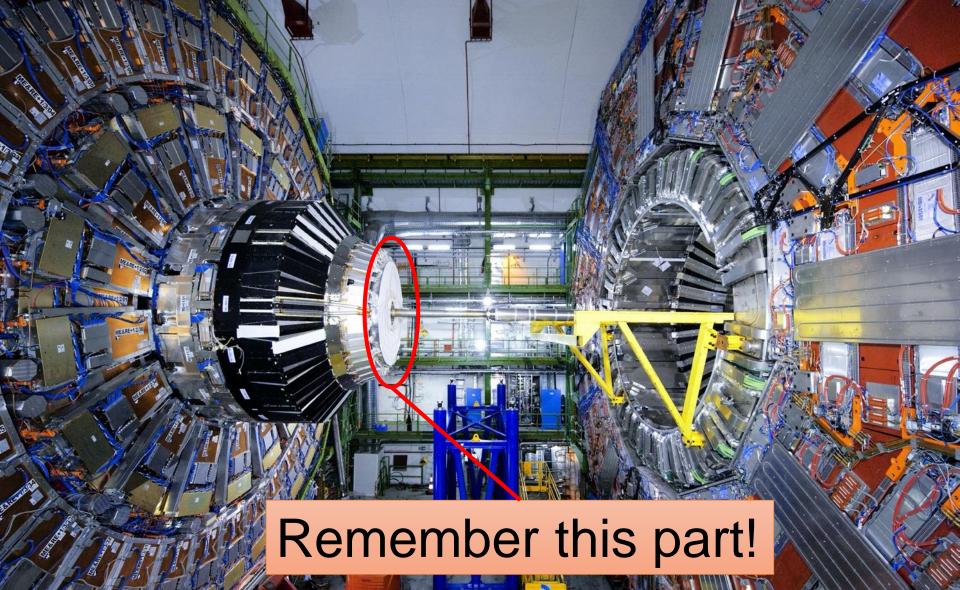
Concept: build on the surface and lower underground

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



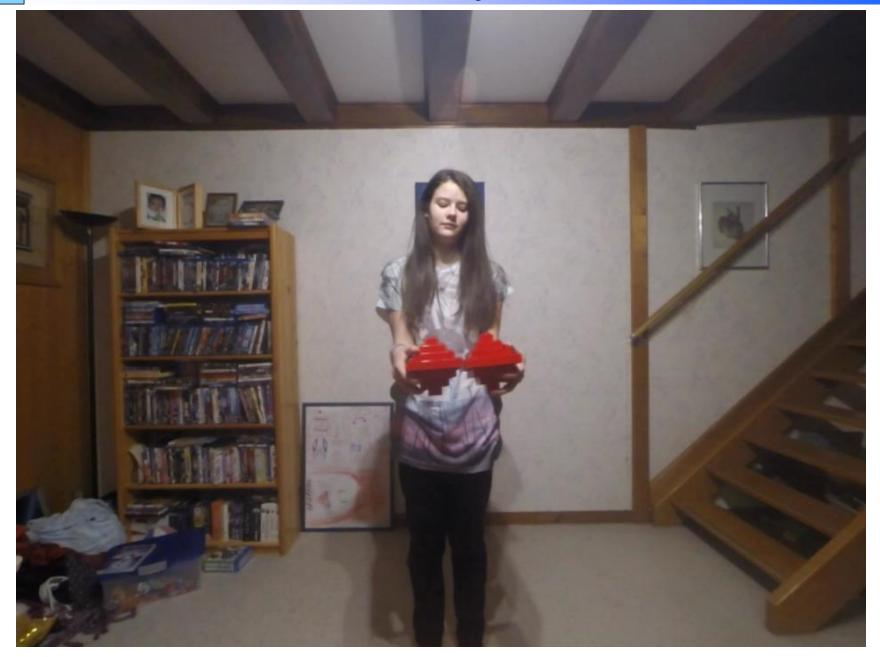


It has been a family affair!

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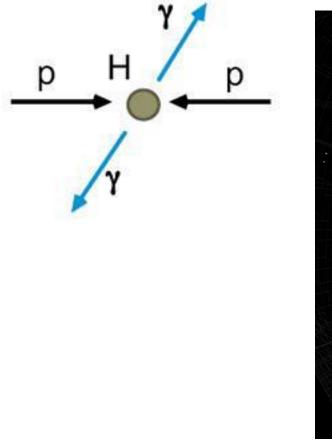
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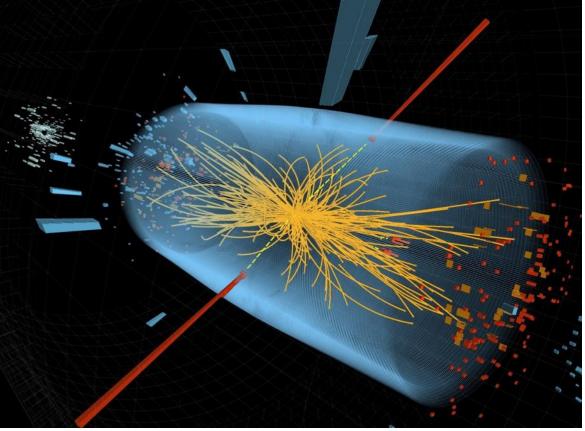
It has been a family affair!



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



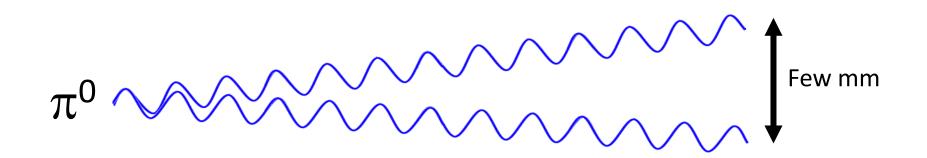


And this is what CMS saw in 2011!

But it wasn't quite that easy!

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

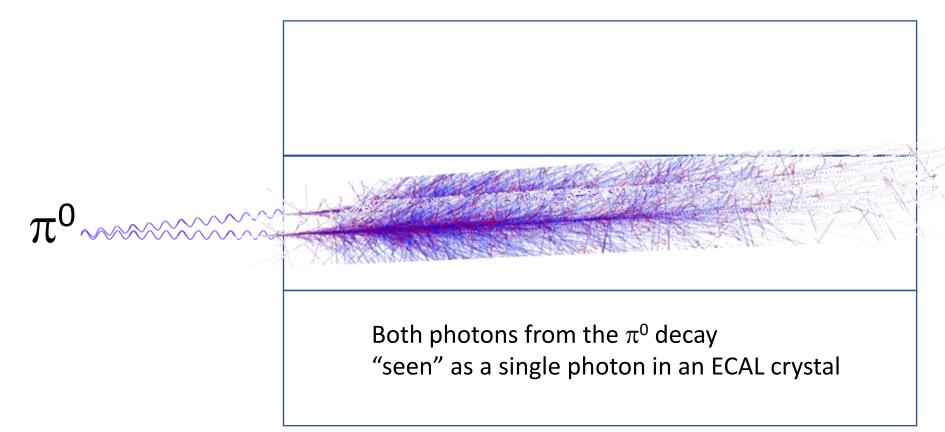
In fact there are other things that "mimic" isolated photons, including decays of neutral pions (π^0), that happen far more frequently than Higgs boson decays!



But it wasn't quite that easy!

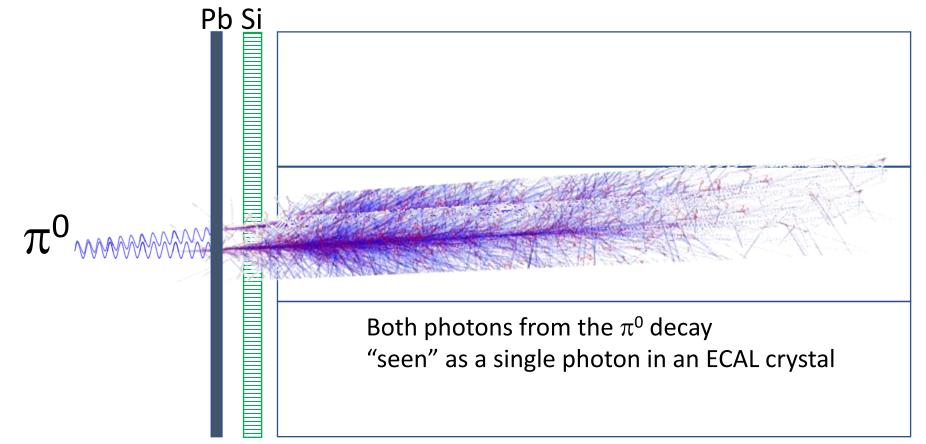
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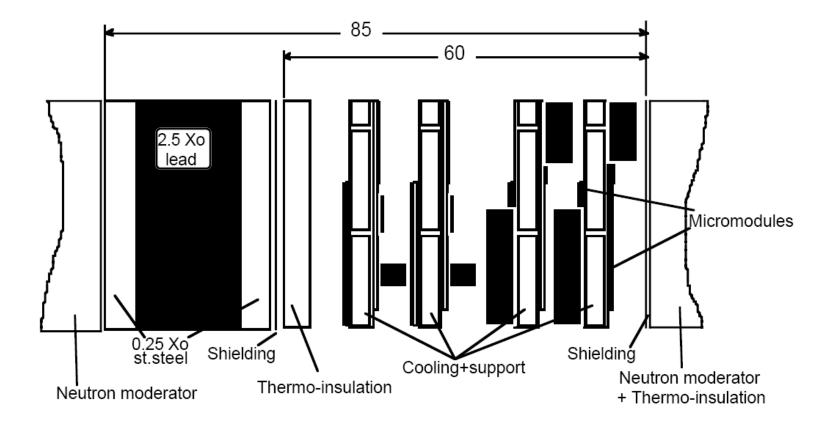
The concept of the Preshower

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...

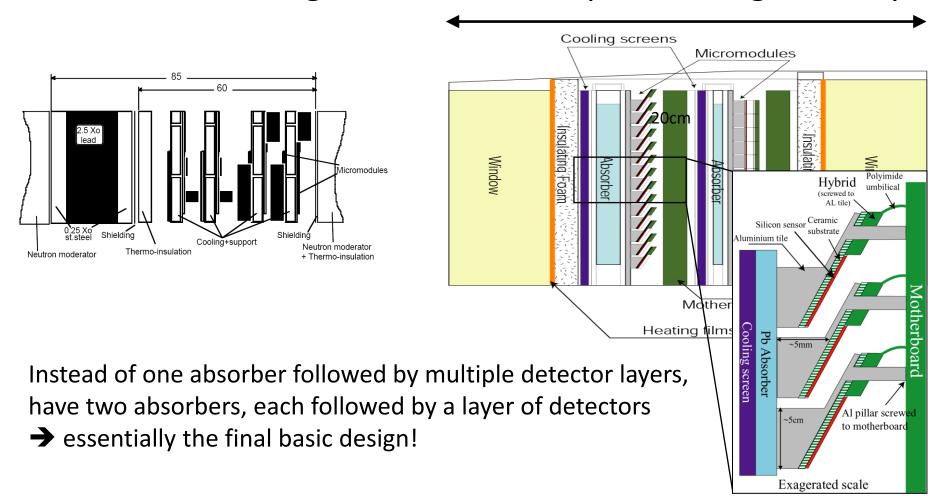


... into some sort of reality



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

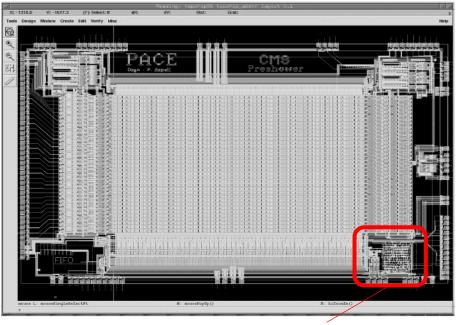




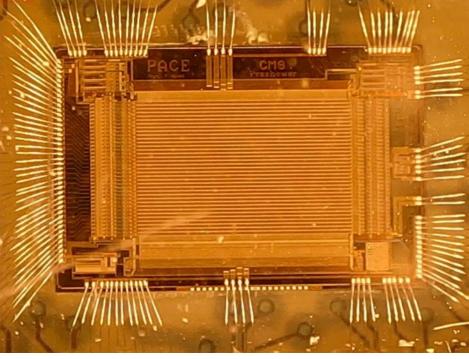
Examples of 3 years of work as an applied physicist!

 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
 → it works!

CMS TN / 96-061 May 13, 1996

Results from the 1995 ECAL Testbeam with Preshower

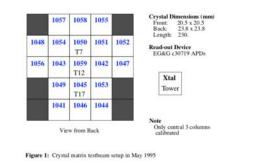
D. Barney CERN, Geneva, Switzerland

Abstract

During May 1995 some data were taken in the H4 starbeam within a mray of PMWO1 cyrlafs plus a prepriodent system. The producest 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 repuisal accuracy obtained with this device, and as effect on the energy resultation of the crystal array. A Moute Carlo simulation of the testbeam setup has been used in order to understand the experiment results and to predict the performance of the predocurin fairure (1999) insthemans.

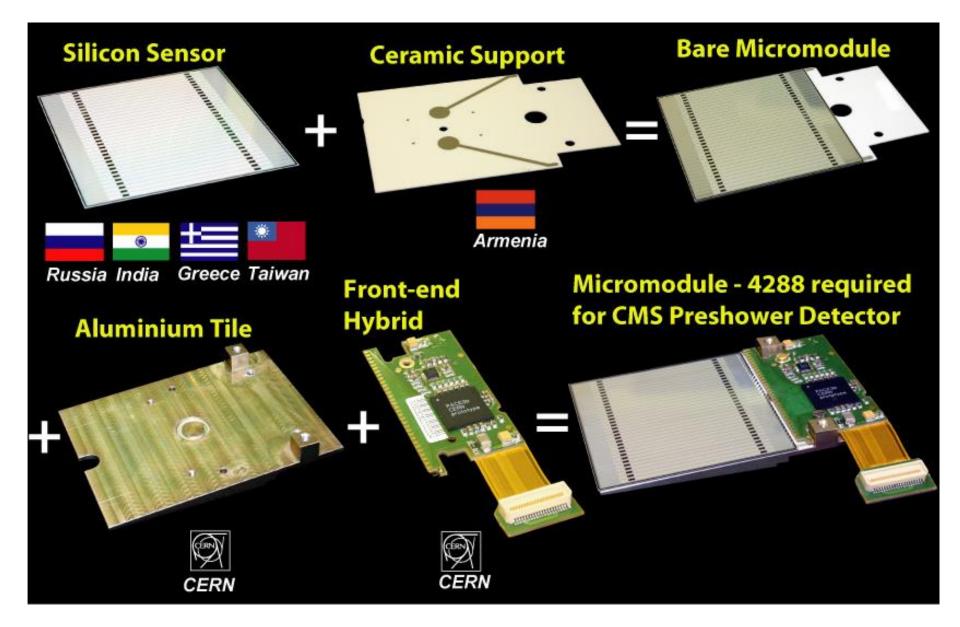
1 Testbeam Setup

Between 3rd and 10h May 1995 an array of $PbWQ_4$ 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.



Results written-up in official notes

It's all about teamwork!



A few years later...

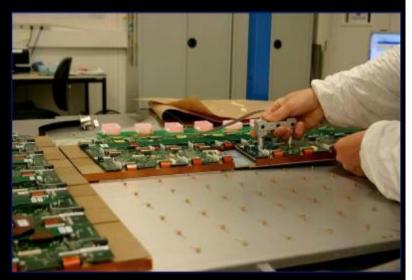
2008: Final assembly and testing



3 types of "ladder" filled with Si sensors



Testing a column of ladders

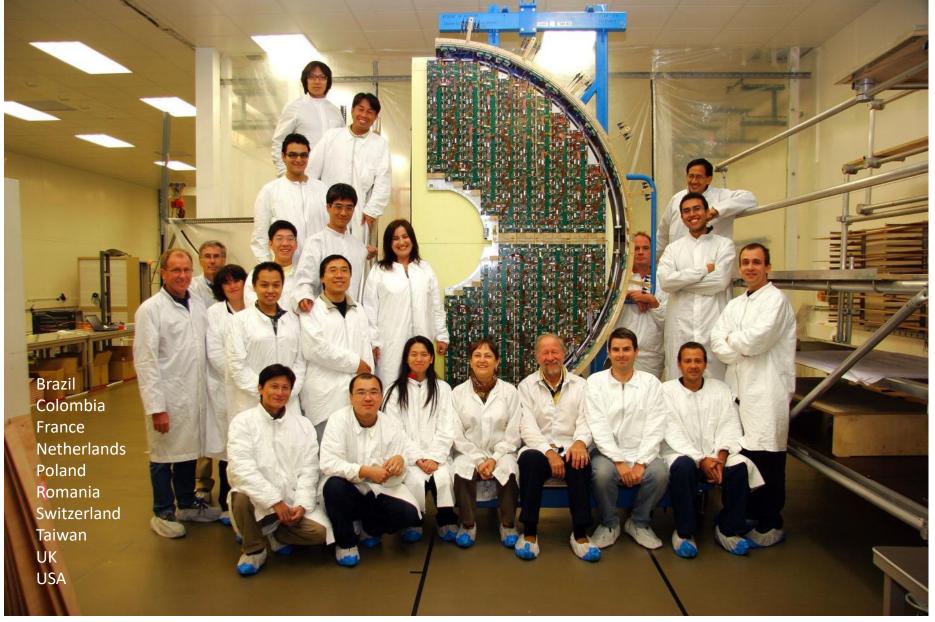


Installing ladders on the absorbers

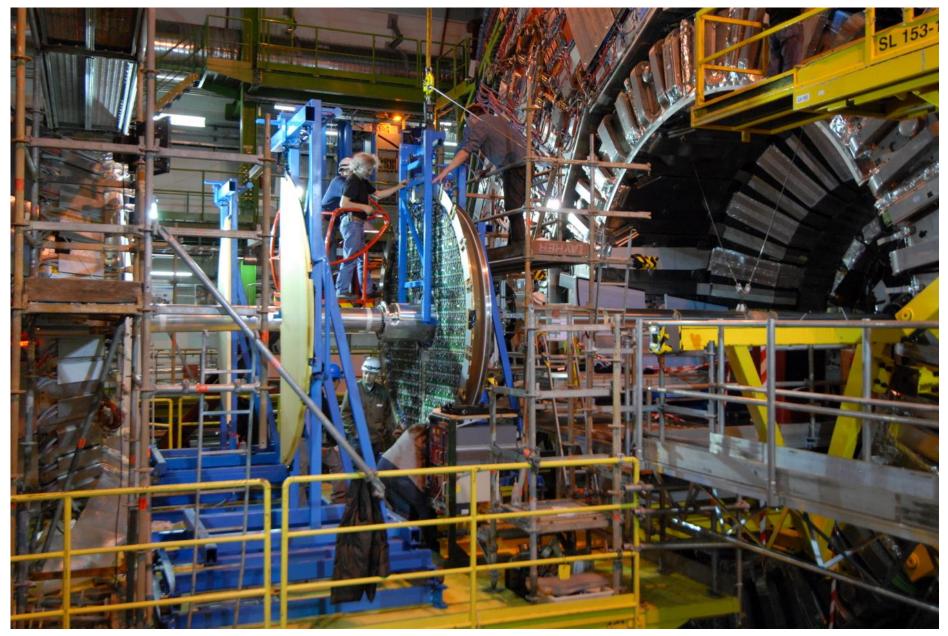




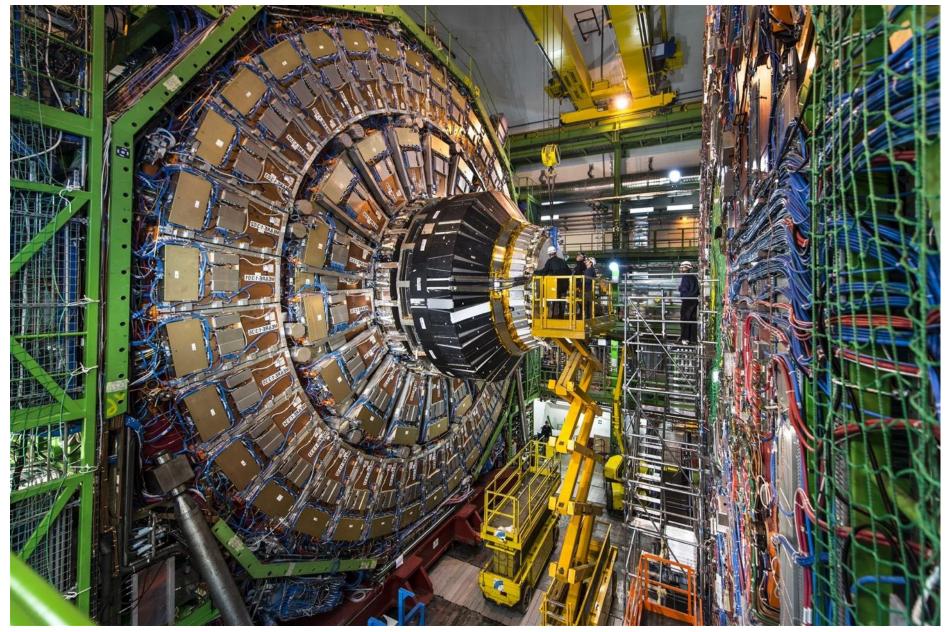
A few years later...



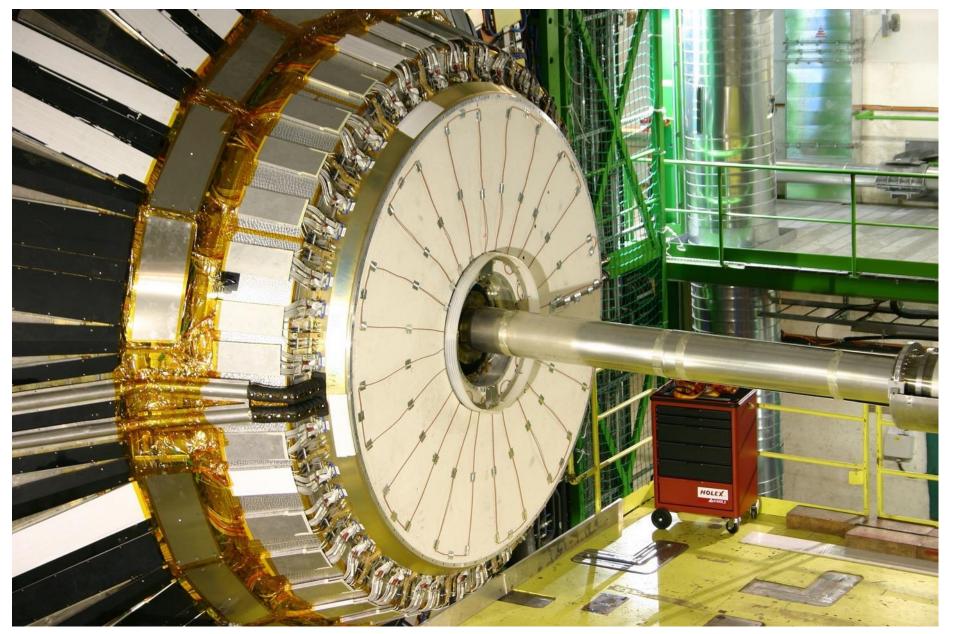
Installation of Preshower in CMS



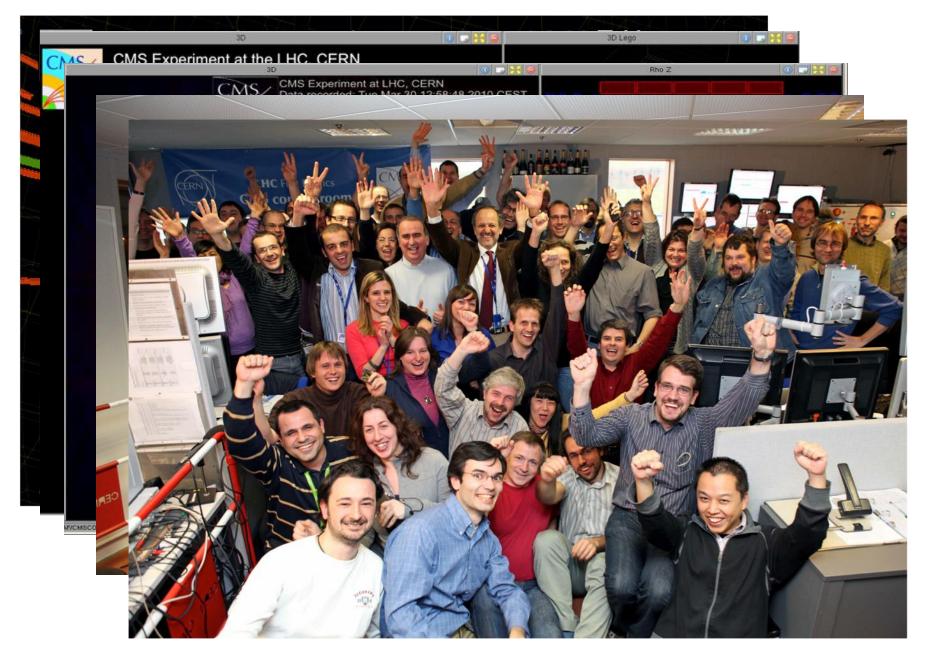
Preshower installed in CMS!



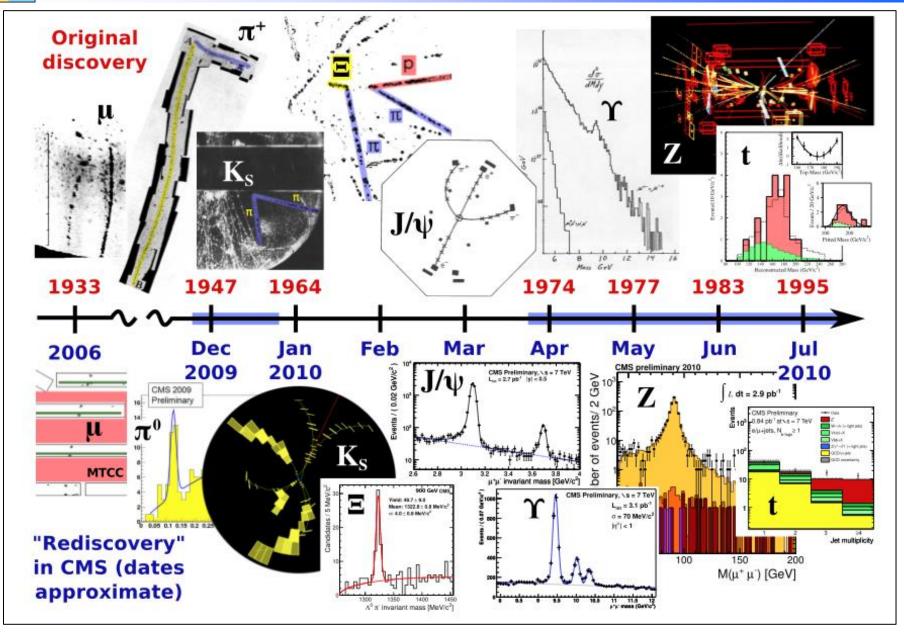
Preshower installed in CMS!



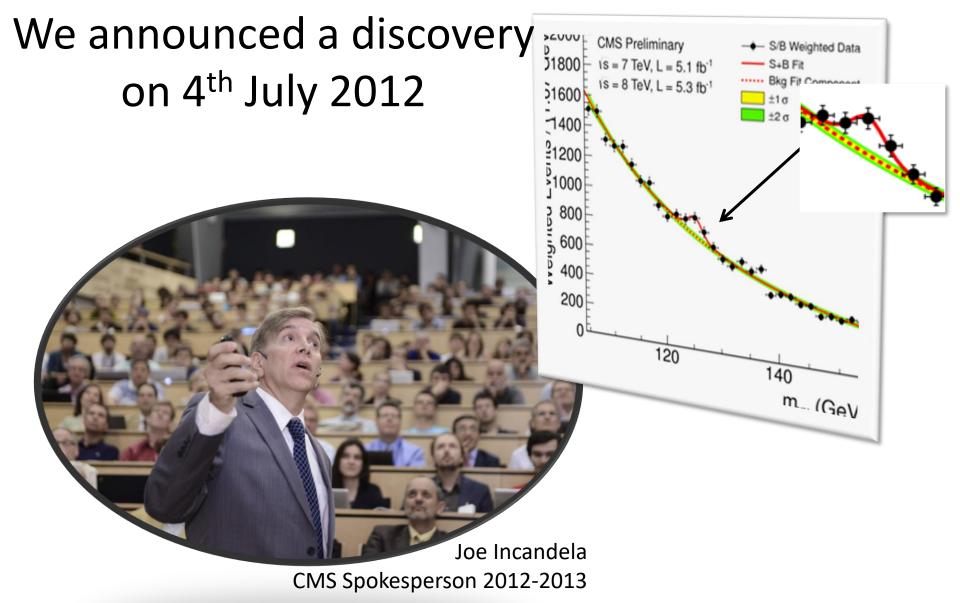




Re-discovery in CMS



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



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Vie Arener ulttuuri Dokumentit is fakta



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展開打了部亮的一位

/35/68

F家道导着特斯校子是谨慎十年, 如今新於否LHC的算服相乐中, 假证

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。 00

- -



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 4th 2022! 10th anniversary Higgs-boson 12th anniversary a month ago!

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

CMS



- 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 \rightarrow studying the Higgs boson's properties in detail can tell us about the unexplored Universe!

And where was I on July 4th?

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





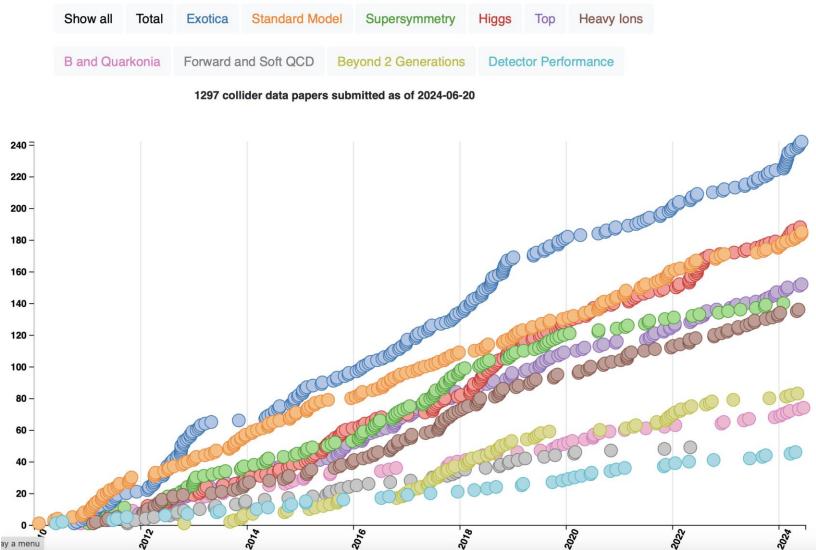
2012: and out celebrating in the evening with ATLAS E&O coordinator Steve Goldfarb and others!

2022: 100m underground fixing a power supply!





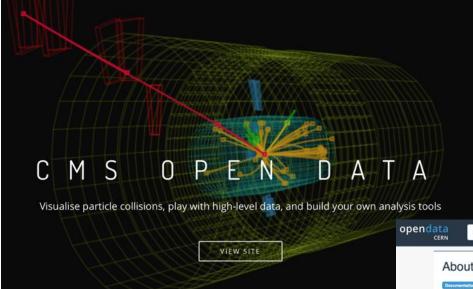
1300 papers published on data taken with CMS!



Including >180 papers on studies of the properties of the Higgs boson!



And you can make measurements with CMS data!



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

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

	CERN
	About CMS
	Discurrentiation About
	The Compact Muon Solenoid (CMS) Experiment is one of the large particle detectors at CERN's Large Hadron Collider. The CMS Collaboration
cms	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
	 Examples or simplified datasets derived nom the primary ones for use in dimerent applications and analyses Tools
	A downloadable Virtual Machine (VM) image with the CMS software environment through which the datasets can be accessed

- 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 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.

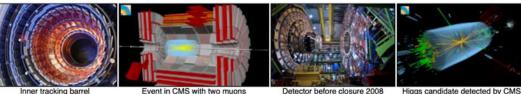
e-Labs Home

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

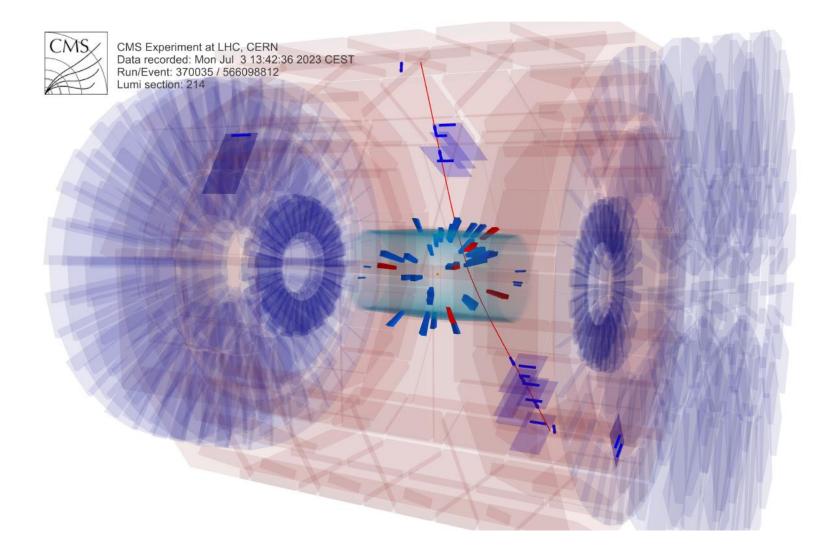
CMS

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



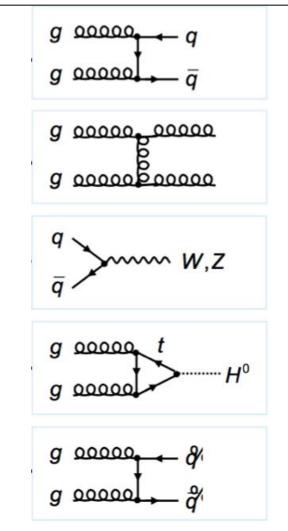


CMS is a LONG way from its final destination!

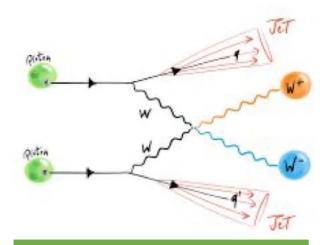
The LHC is not just a "gluon collider"

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

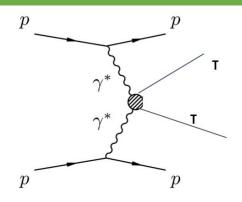
CMS



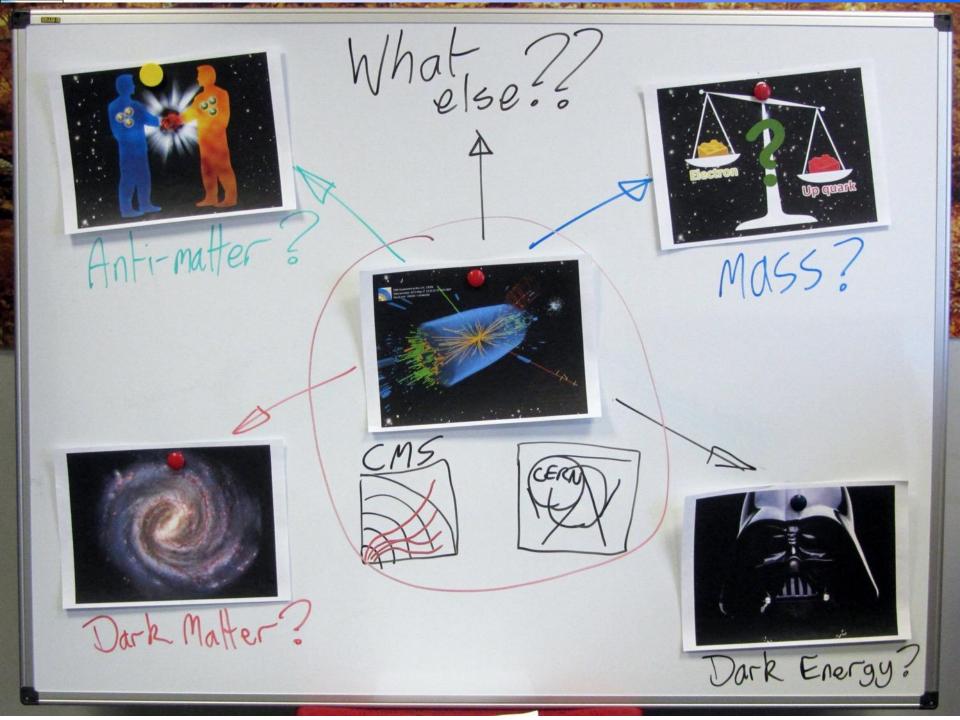
But the LHC also collides vector bosons (W, Z)



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**...

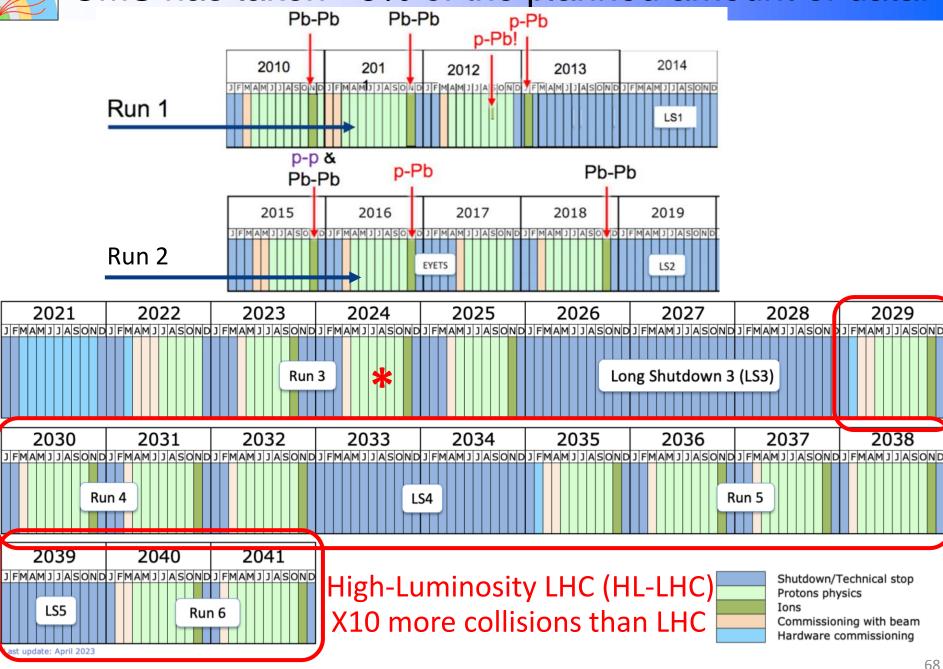




We need more collisions! A lot more!

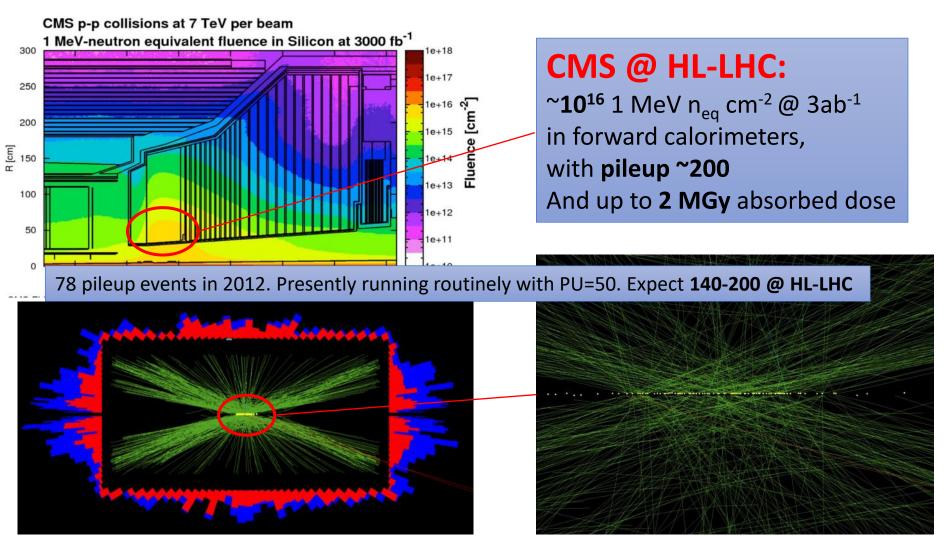
CMS has taken ~5% of the planned amount of data!

CMS





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



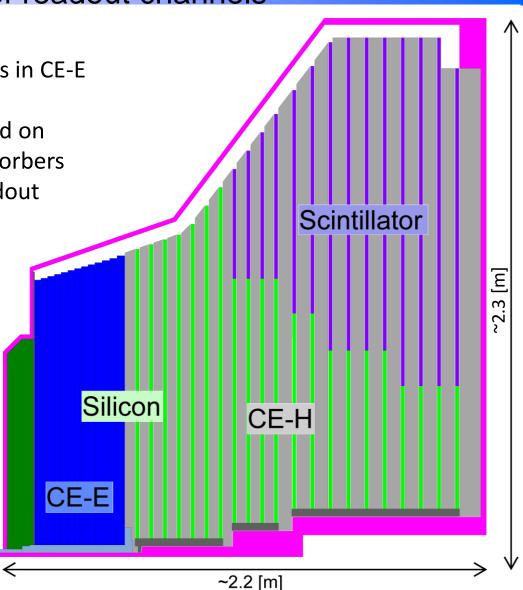
CMS HGCAL ("CE"): a sampling calorimeter with unprecedented number of readout channels

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 ~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 X₀ & ~1.3 λ Hadronic calorimeter (CE-H): Si & scintillator, steel absorbers, 21 layers, ~8.5 λ 7

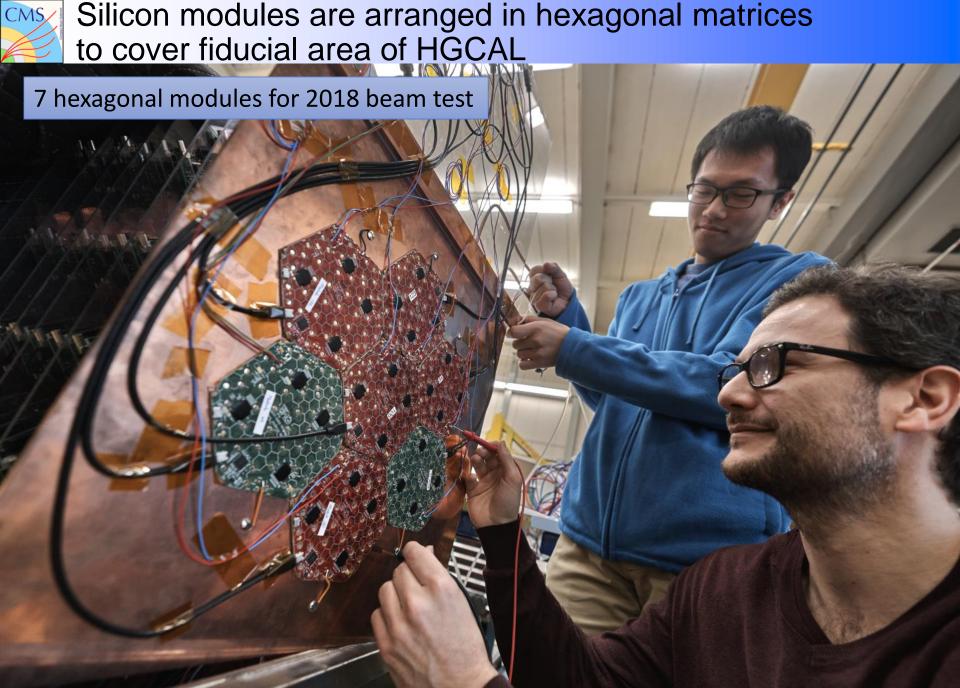


Unboxing the HGCAL

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

The 47 active layers

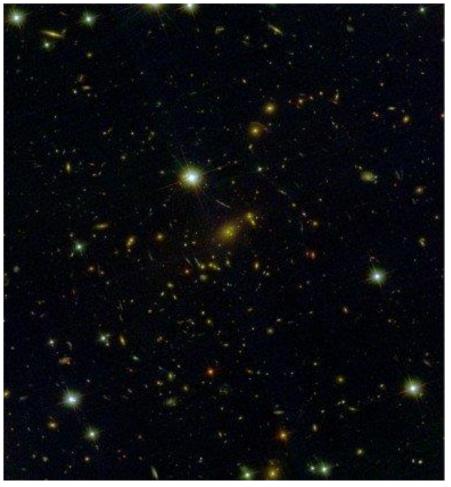
of the HGCAL



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!



"The more I learn, the more I realize how much I don't know"

What is stuff made from? We only understand about 5% of it! Why are things the way they are? We really don't know! e.g. why do spiral galaxies move like they do? What's going to happen? The Universe is expanding at an increasing rate - but we don't understand why!

Dark Matter Dark Energy

A. Einstein

Composition of the Universe



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>



And finally...

Thanks to the fifteen people who have already filled the survey about sources of information about CERN – really appreciated! Anyone else?

Please encourage your students to fill this form too!

https://cern.ch/who7v