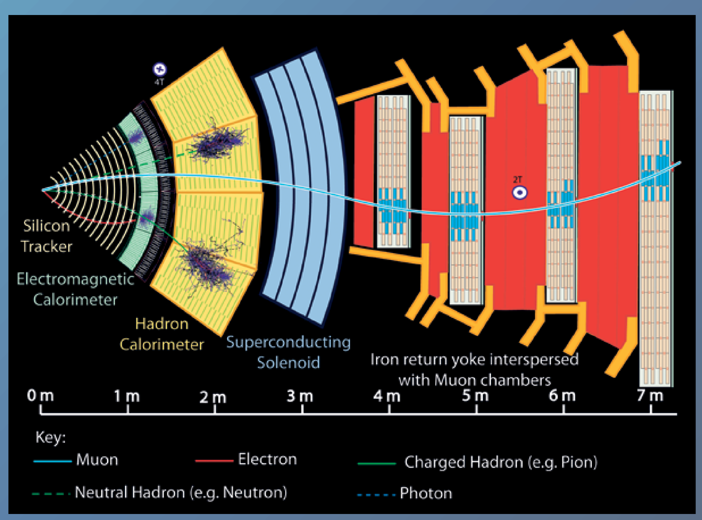
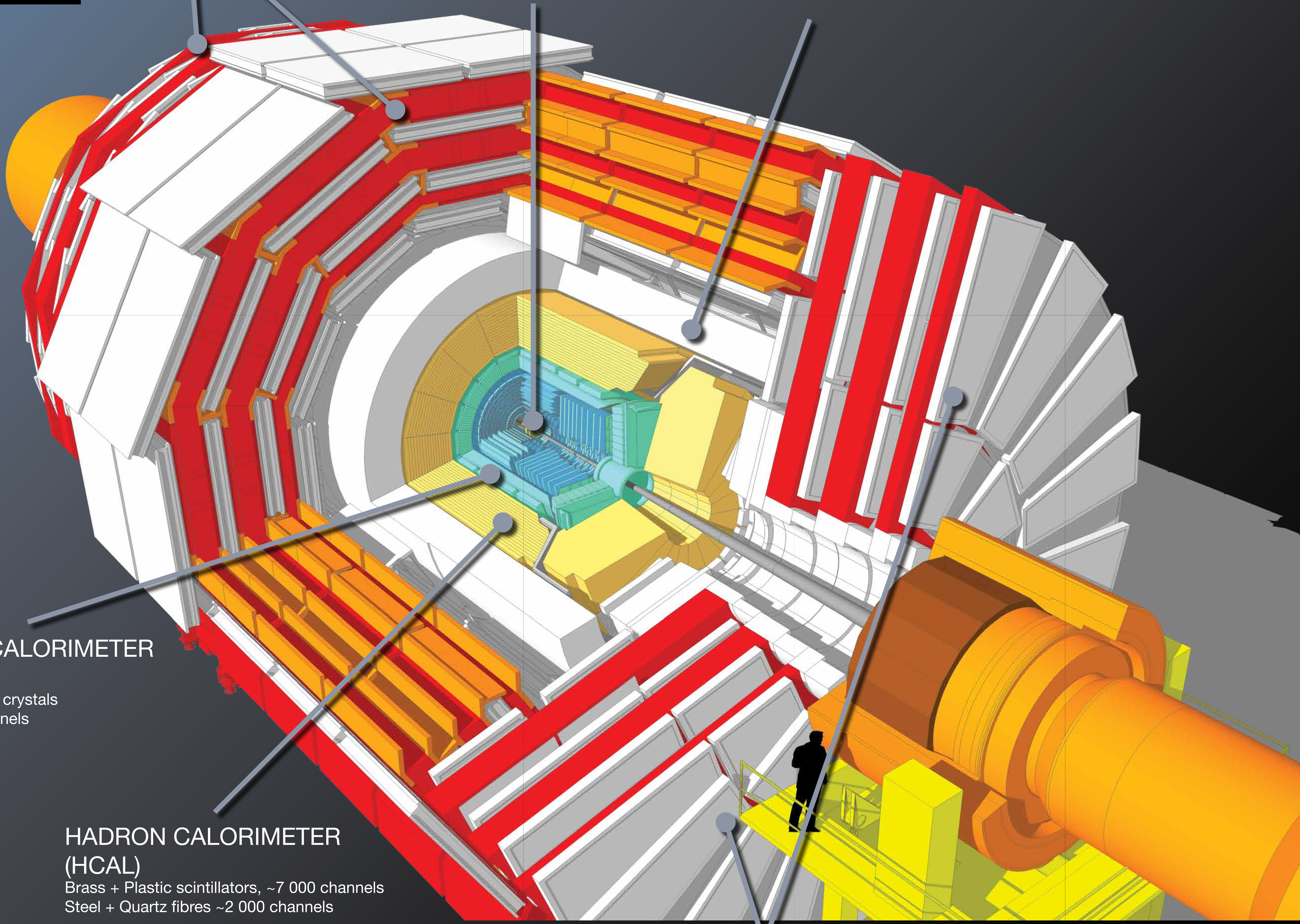
CMS Detector





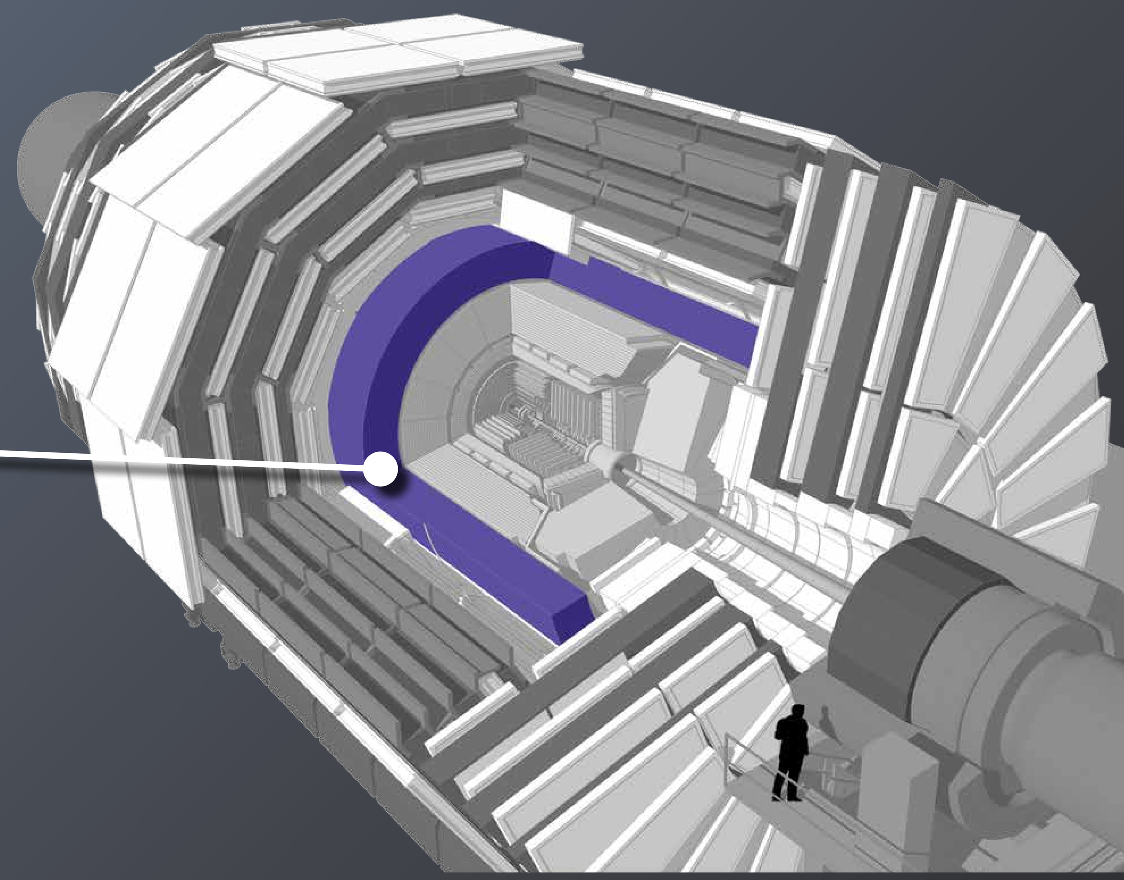
CMS is a gigantic particle detector, located around 100 m below the ground. The apparatus, which can be thought of as a cylindrical onion comprising successive co-axial layers, surrounds one of the four “collision points” of the LHC. Particles produced as a result of proton-proton collisions fly through these layers, leaving their traces in different CMS sub-detectors.

CMS DETECTOR

Total weight: 14 000 tonnes
Diameter: 15 m
Length: 28.7 m
Magnetic field: 3.8 T

CMS Magnet

Superconducting solenoid

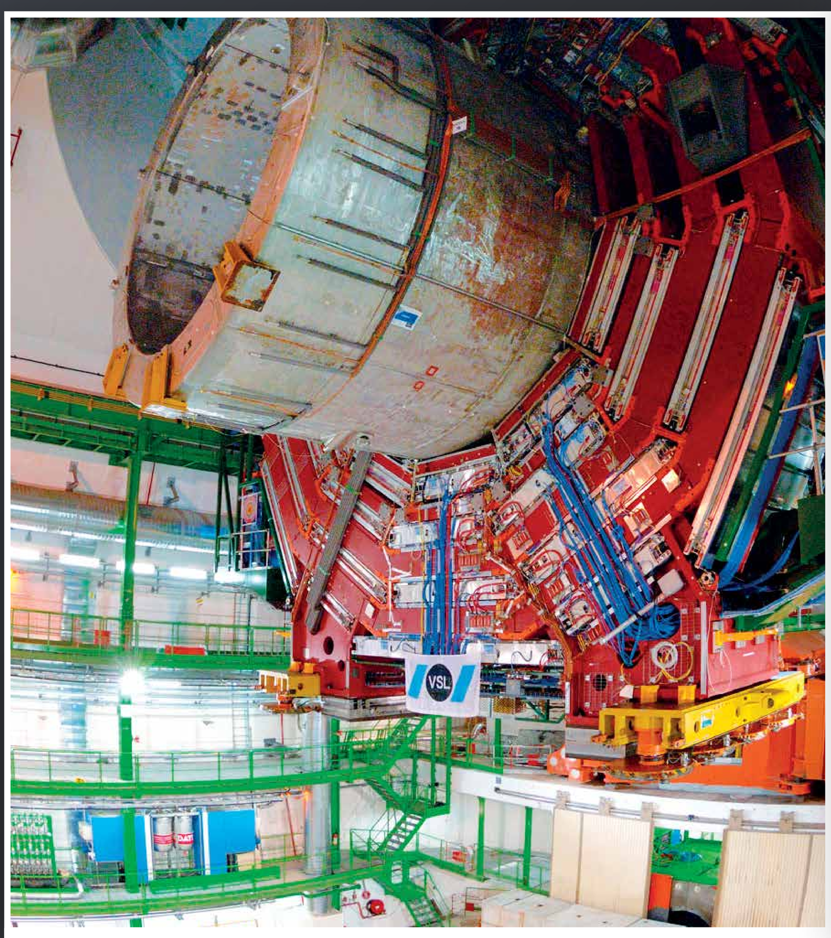


Vertical assembly of the CMS coil modules

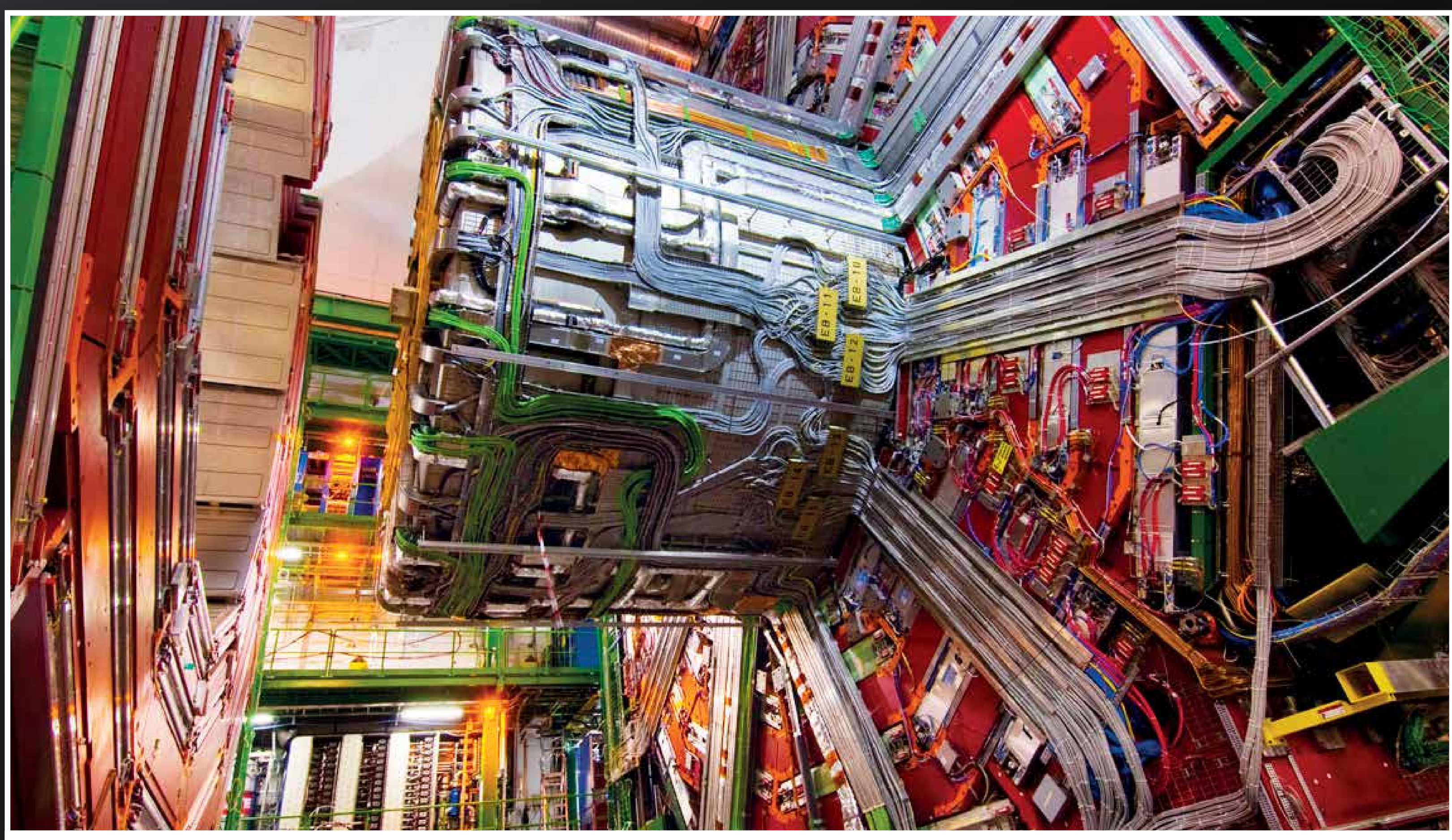
CMS coil being rotated in the construction hall

Coil insertion into the cryostat on the central barrel section “YB0”

CMS magnet ready for testing



Lowering the central barrel section with the coil to the underground collision area: 2000 tonnes lowered to a depth of 100 m in one go

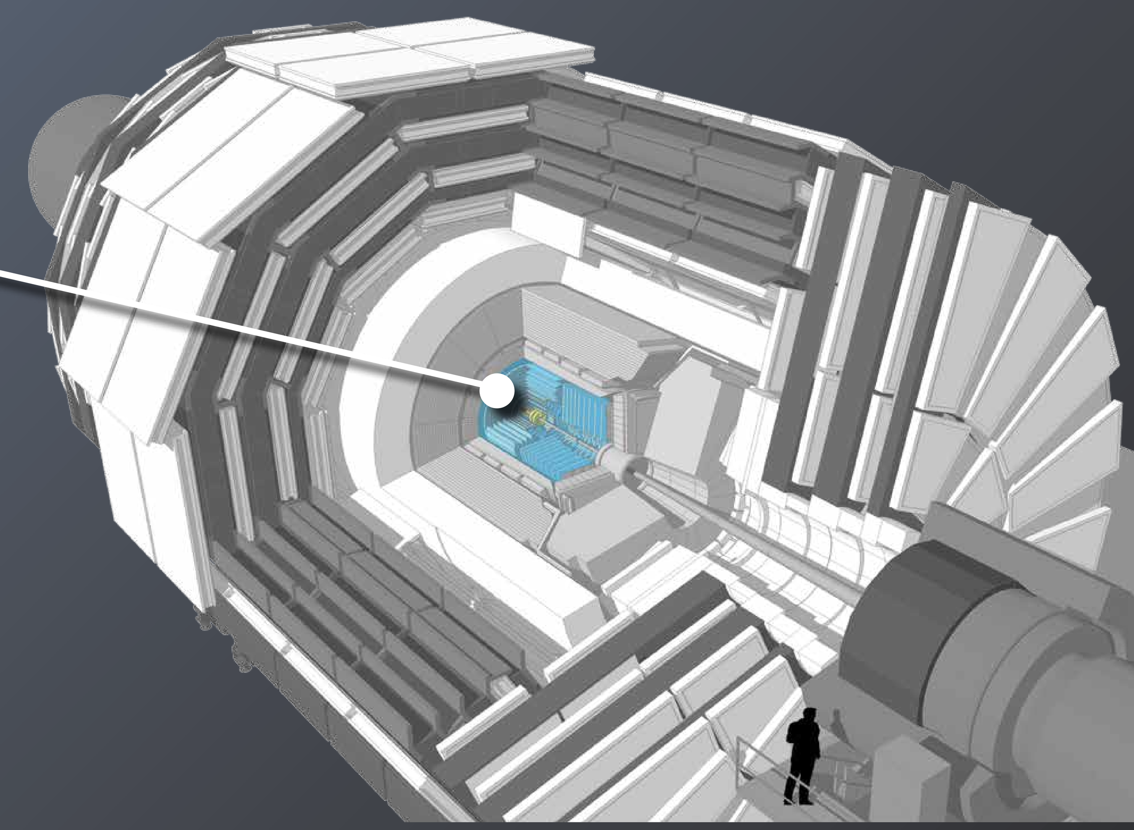


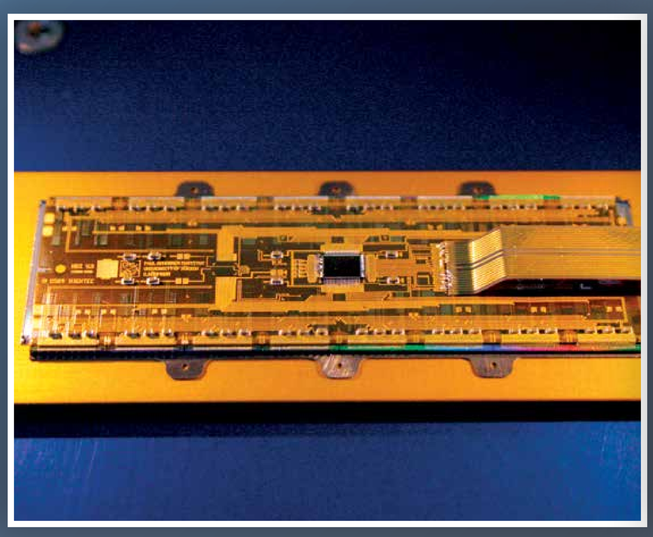
Central barrel and cryostat equipped with detector cables and cooling circuits in its final position in the underground cavern

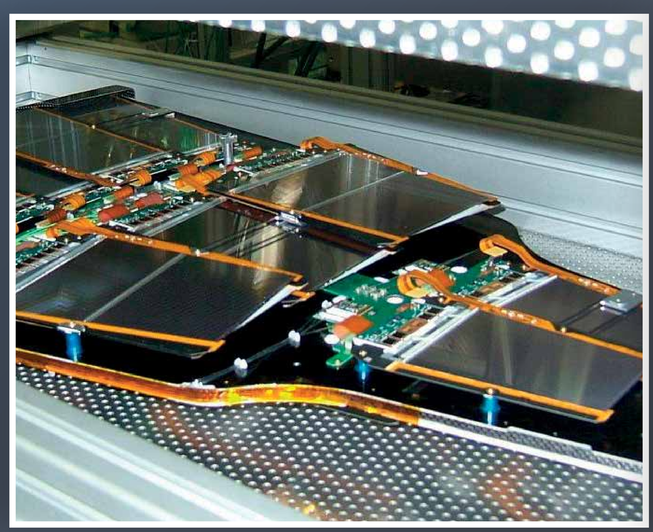
Passing around 18 000 amperes through a 13 m long, 6 m diameter coil of niobium-titanium superconductor, cooled to –270 °C, produces a magnetic field of 3.8 teslas (about 100 000 times stronger than that of the Earth). This field bends the trajectories of charged particles, allowing their separation and measurements of their momenta. The coil has a stored energy of 2.7 gigajoules, (equivalent to the kinetic energy of an Airbus A320 in flight), and together with the return yoke (red wheels) has a weight of 12 500 tonnes (almost twice that of the Eiffel Tower).

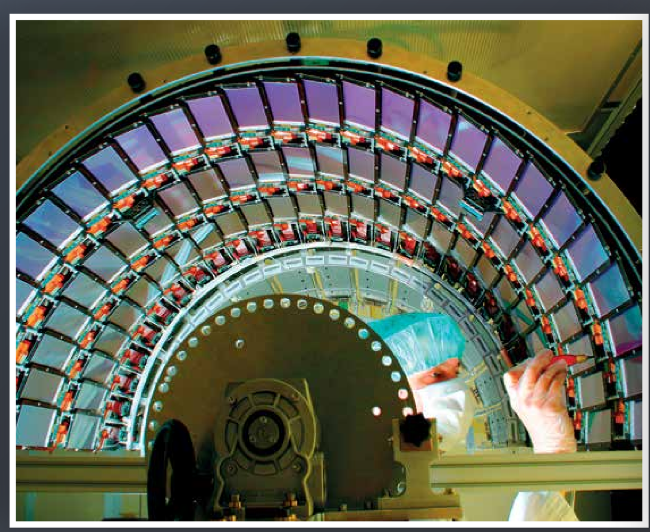
CMS sub-detector

Tracker

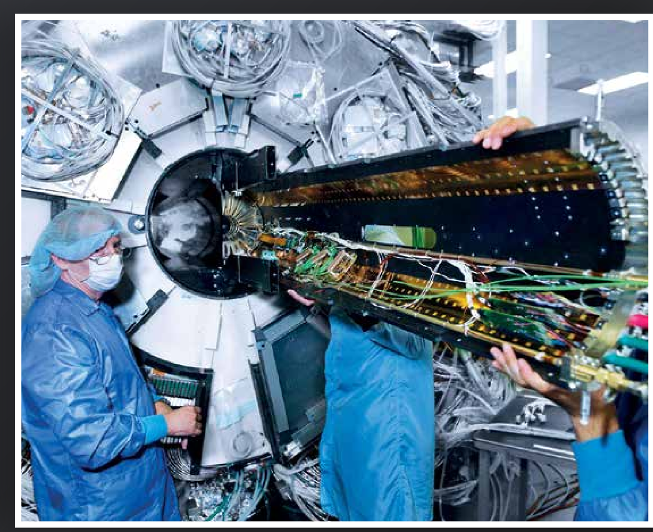



Silicon pixel

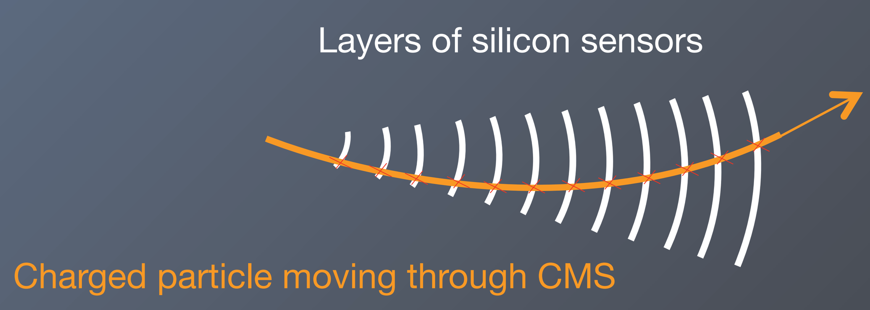

Silicon strip modules


Barrel Tracker


Endcap Tracker

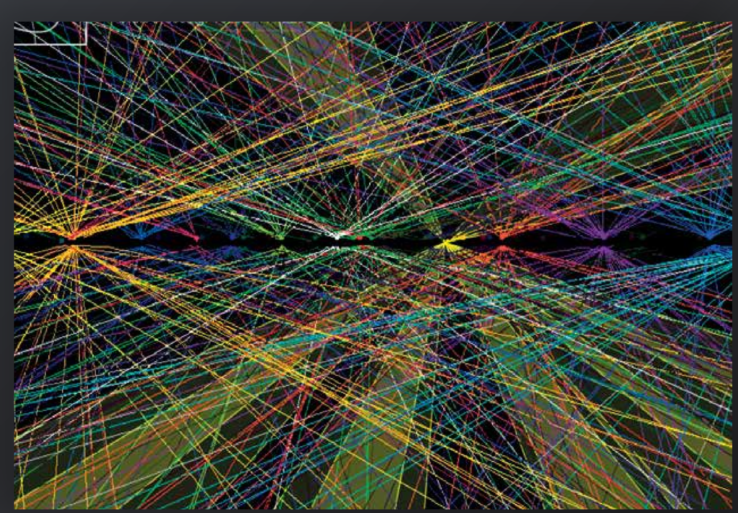

Pixel Tracker

How does the Tracker work?

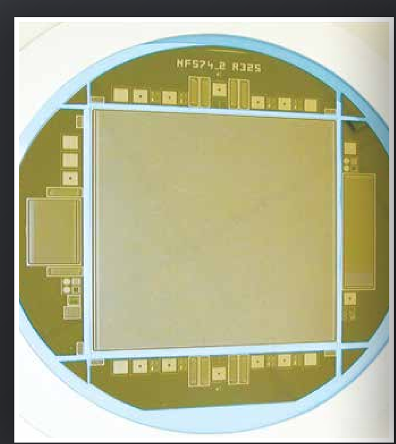


As electrically charged particles, such as electrons, move through CMS, their trajectories are curved by the strong magnetic field. The higher their momentum (~ energy), the less they bend. The particles produce signals as they pass through the layers of silicon sensors comprising the Tracker, which are precisely located (to better than 10 microns). Software then "joins the dots" to reveal the tracks and thus give the particle momenta.

Reconstructed tracks from dozens of collisions taking place inside CMS. These pictures/events occur 40 million times per second and the Tracker, with its high position resolution, is crucial in distinguishing between different primary and secondary vertices (corresponding to the different proton-proton collision points or to decay points of unstable particles).

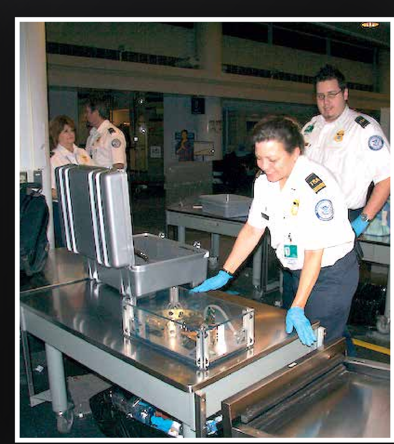


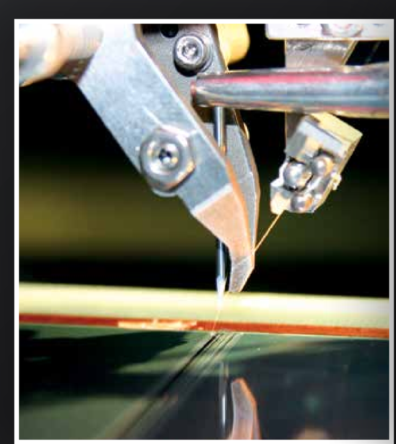
How was the Tracker built?


Sensors are cut from circular wafers of silicon.

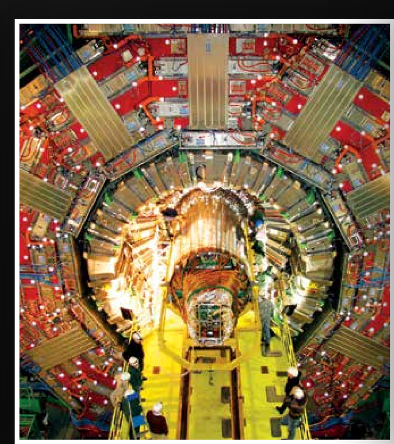

Electronics is added to each sensor to form a "module".

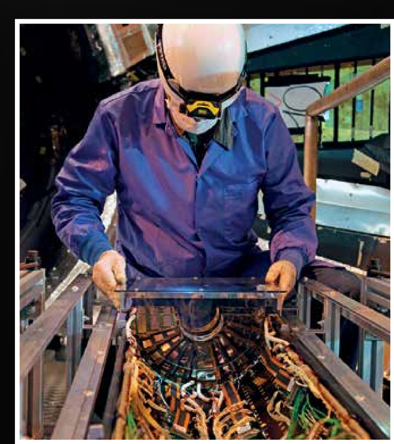

Multiple "rods" of modules form the outer part of the barrel section.


Tracker pixel sensors being transported to CERN from the US


Two sensors are connected with 25µm wires.


Complete modules make an "overlapping" structure – in this case an endcap "petal".

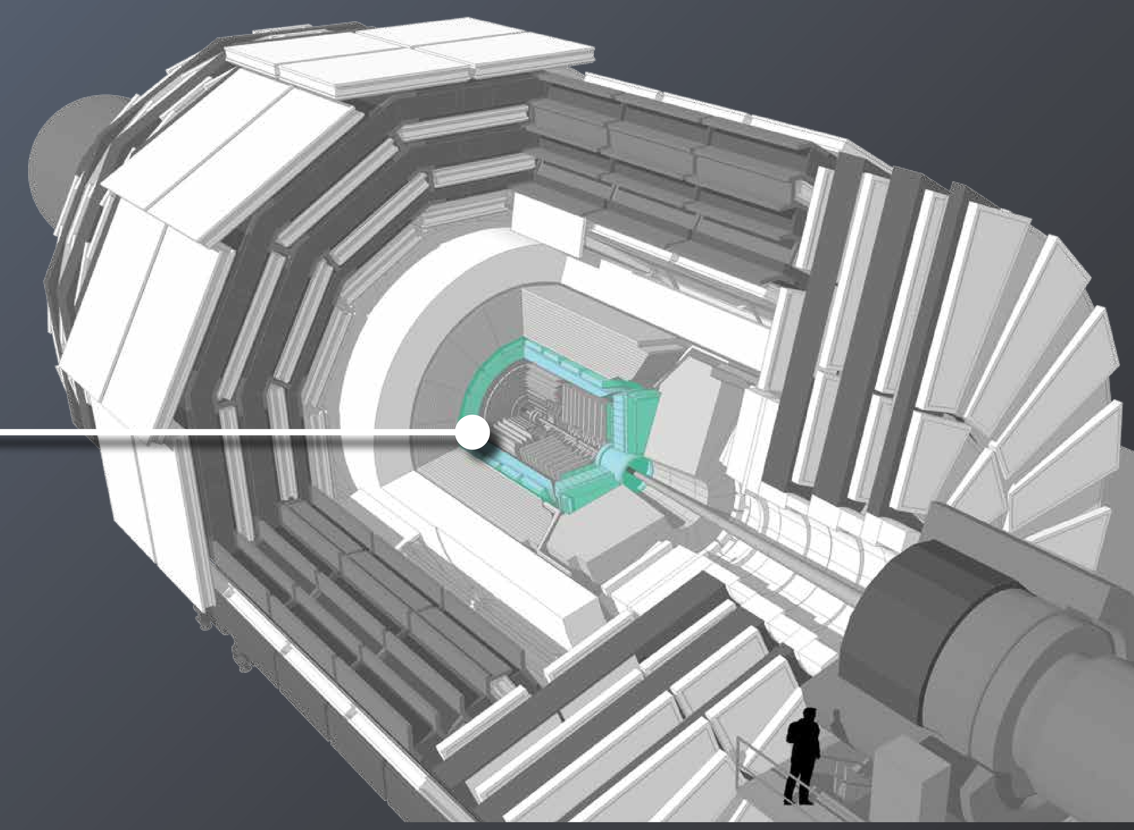

Installing the strip Tracker


Pixel detector being installed around the beam pipe in CMS

Nearly 17 000 finely segmented silicon sensors (strips and pixels) enable traking of charged particles and measurement of their momenta. They also reveal the positions at which relatively long-lived unstable particles decay. The silicon-strip sensors are very thin (about 300 microns deep) and the individual strips are narrower than a human hair (down to 20 microns across). The total surface area of the detector is about the same as a tennis court, and contains ~10 million individual strips. The 66 million pixels, at the heart of CMS, are each just 150 microns x 100 microns in area, allowing separation of closely spaced particle trajectories.

CMS sub-detector

Electromagnetic Calorimeter (ECAL)

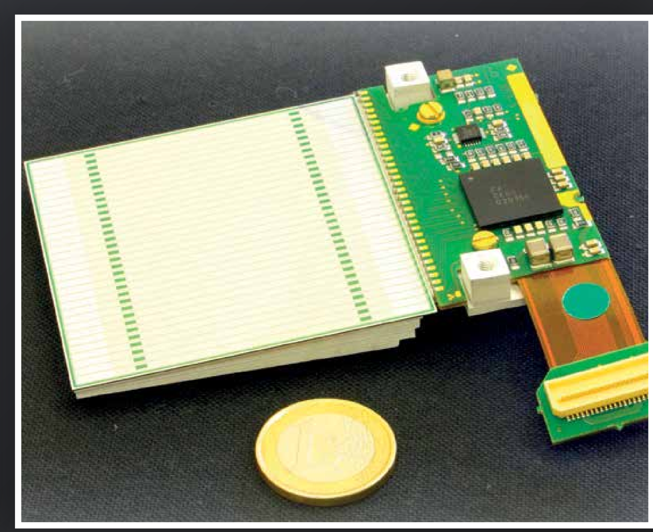



Barrel ECAL


Endcap Preshower


Endcap ECAL


Lead tungstate, before and after cutting and polishing

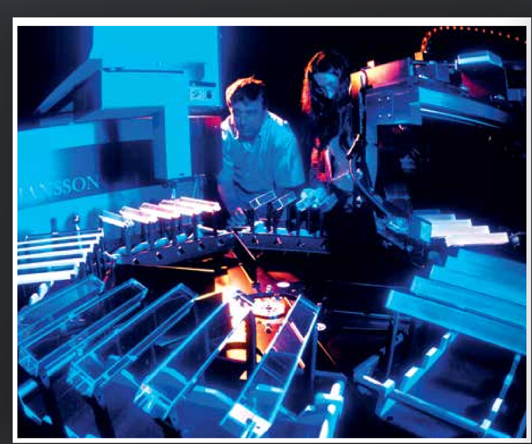

Preshower silicon sensor

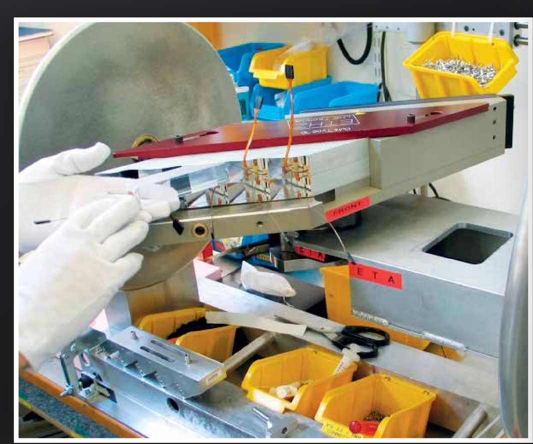
How does the ECAL work?

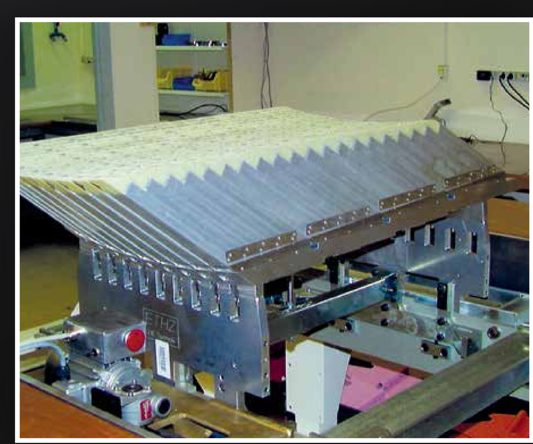
Incoming electrons and photons release all of their energy by producing a shower of particles as they penetrate the material of the lead tungstate crystals. The light produced in the shower is measured by a photodetector glued to the back face of each crystal. Two different types of photodetectors are used: avalanche photodiodes (APDs) in the barrel section, and vacuum phototriodes (VPTs) in the endcap sections. The amount of light detected is directly proportional to the initial energy of the electron/photon.

How was the ECAL built?


Growing a single lead tungstate crystal takes about two days.

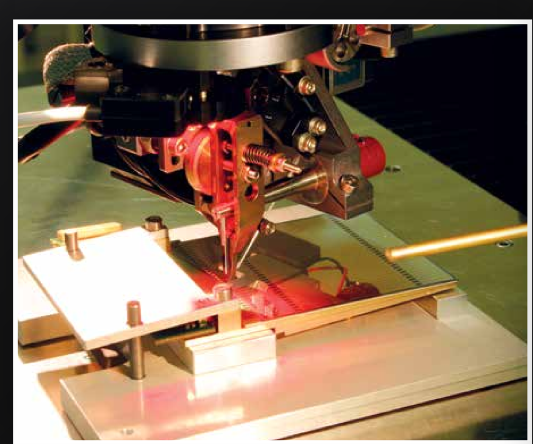

After cutting and polishing, all crystals are characterized.

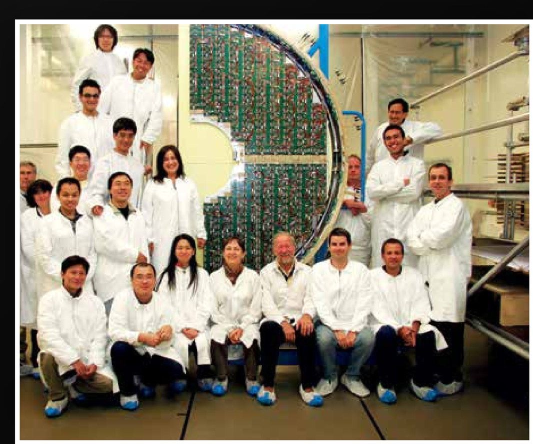

Photodetectors are glued to the crystals which are then inserted into support structures.


Up to 1700 crystals are grouped together.


Electronics, monitoring, safety and cooling systems are added .


5x5 groups of crystals being mounted on an endcap.

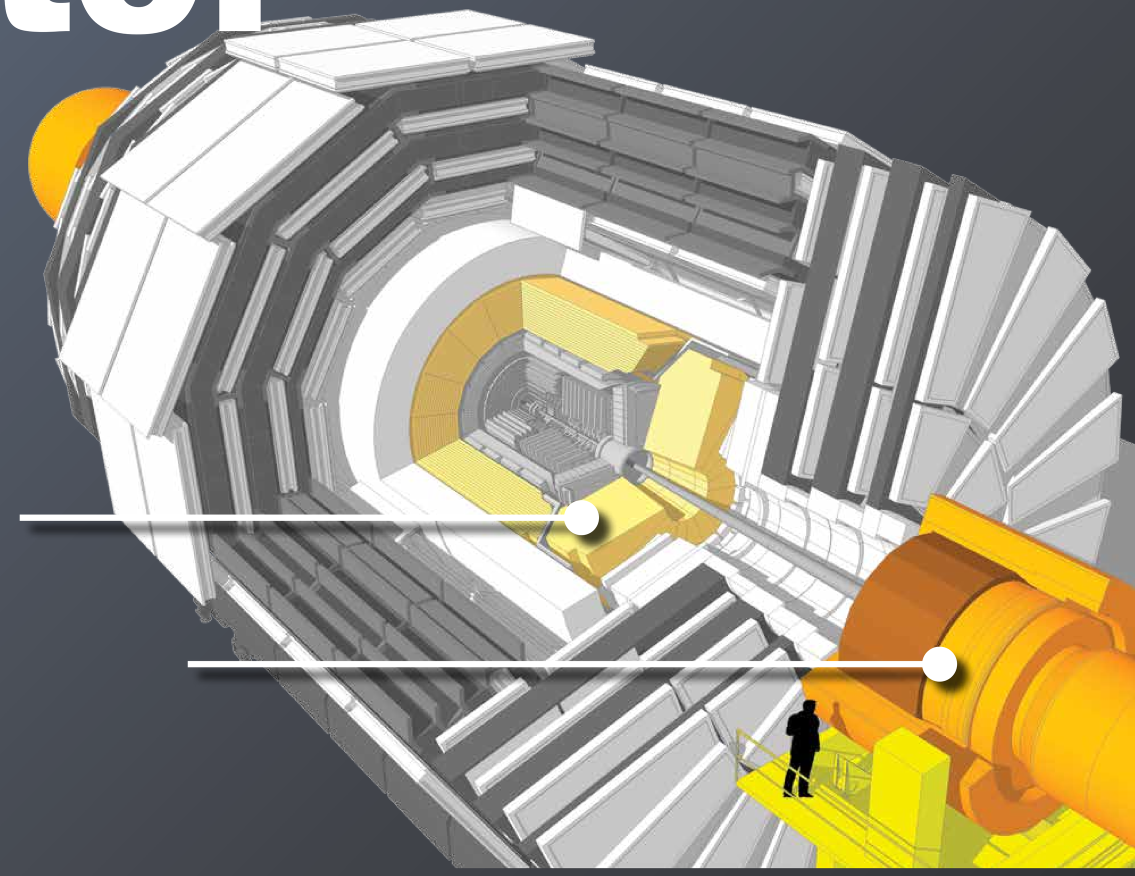

Silicon sensors for the Preshower detector being wire-bonded to readout electronics.


A half-disc of the Preshower detector, ready for installation.

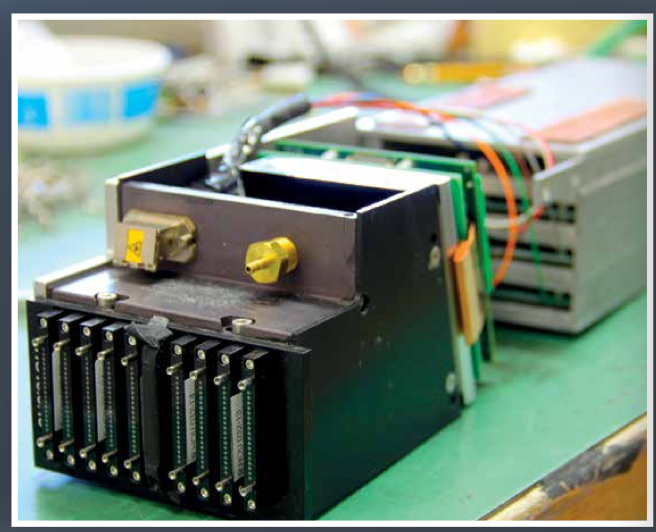
The Electromagnetic Calorimeter (ECAL) comprises three sections: a barrel and two endcaps, and contains 75 848 crystals of lead tungstate ($PbWO_4$), a material which is 86% metal by weight yet completely transparent. The crystals have dimensions 2.2 x 2.2 x 23 cm^3 and 2.9 x 2.9 x 22 cm^3 in the barrel and endcap sections respectively. They provide high-precision measurements of the energies of electrons and photons produced in LHC collisions within CMS. A Preshower detector, comprising 4288 silicon sensors, each measuring 6.1 x 6.1 x 0.03 cm^3, enhances particle identification in the endcaps.

CMS sub-detector

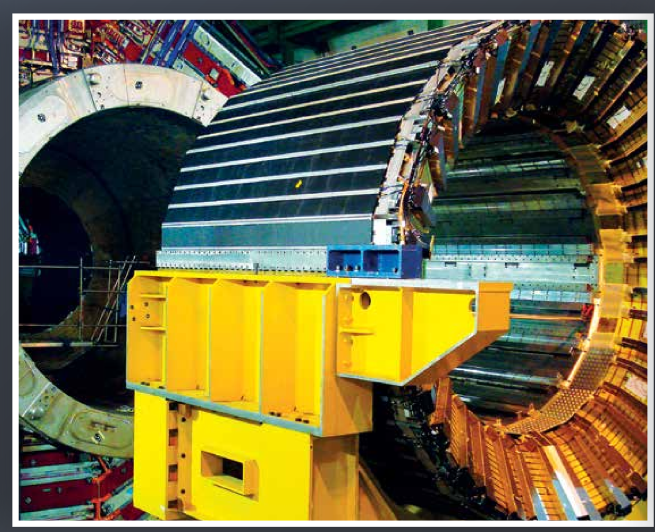
Hadron Calorimeter (HCAL)



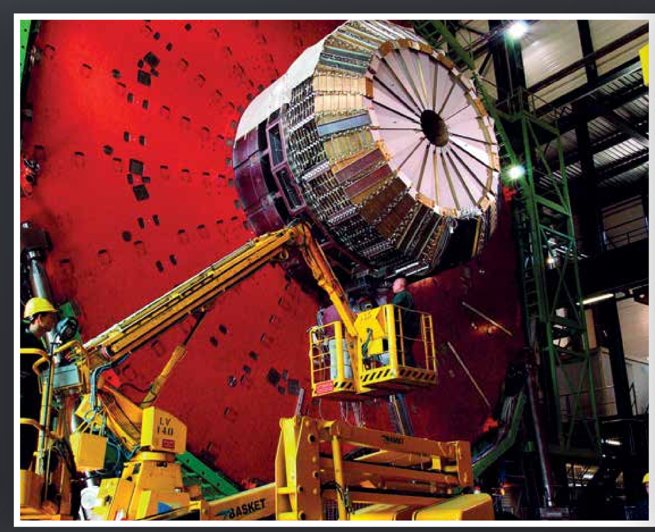
Optical fibres carry the signals of particles detected by HCAL



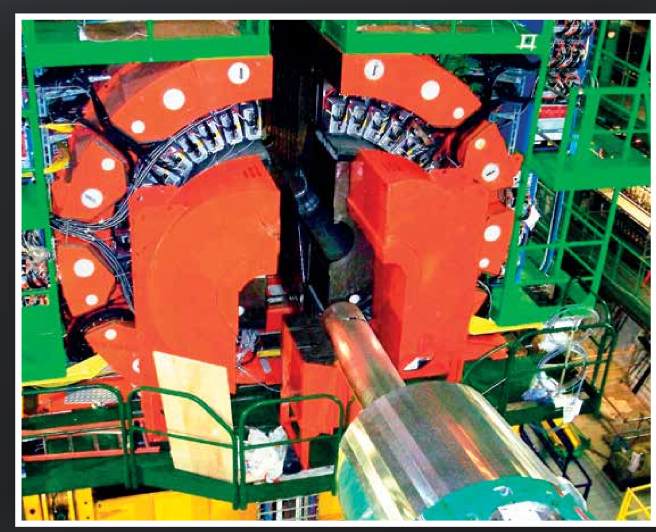
Silicon Photomultiplier (SiPM) readout modules amplify the signal



HCAL Barrel

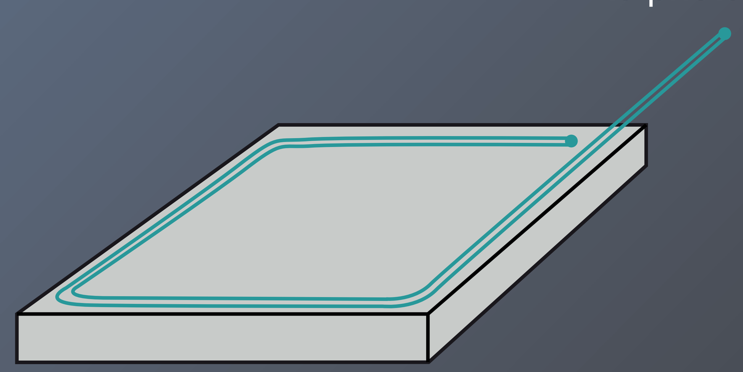


HCAL Endcap



HCAL Forward Calorimeter

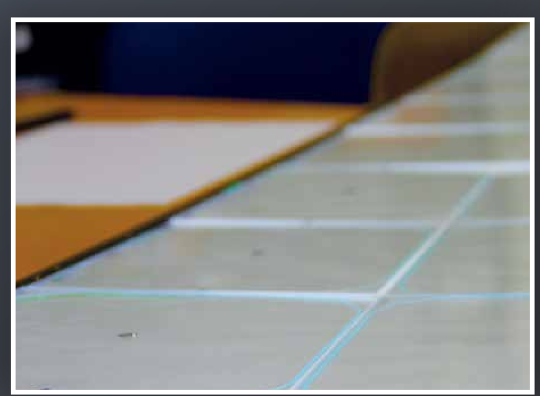
How does the HCAL work?



Layers of dense absorbers (brass or steel) interleaved with plastic scintillators or quartz fibres are used to determine the energies of hadrons produced in LHC collisions within CMS. Incoming hadrons release all of their energy by producing a shower of particles as they penetrate the absorber plates.

When this shower passes through layers of plastic scintillators, a pulse of blue-violet light is emitted. This light is absorbed by optical fibres, with a diameter of less than 1 mm, that are inserted into each scintillator tile. The fibres shift the blue-violet light into the green region of the spectrum, which is carried by clear fibers to photo-detectors. The amount of light detected is directly proportional to the initial energy of the hadron.

How was the HCAL built?



Scintillators with optical fibres form “megatiles” used in the HCAL Barrel.

HCAL Barrel is made up of 36 wedges, each of which weighs as much as 6 elephants.

Over one million World War II brass shell cases from the Russian Navy were recycled into components for the HCAL Endcap.

One HCAL Endcap disc during construction.

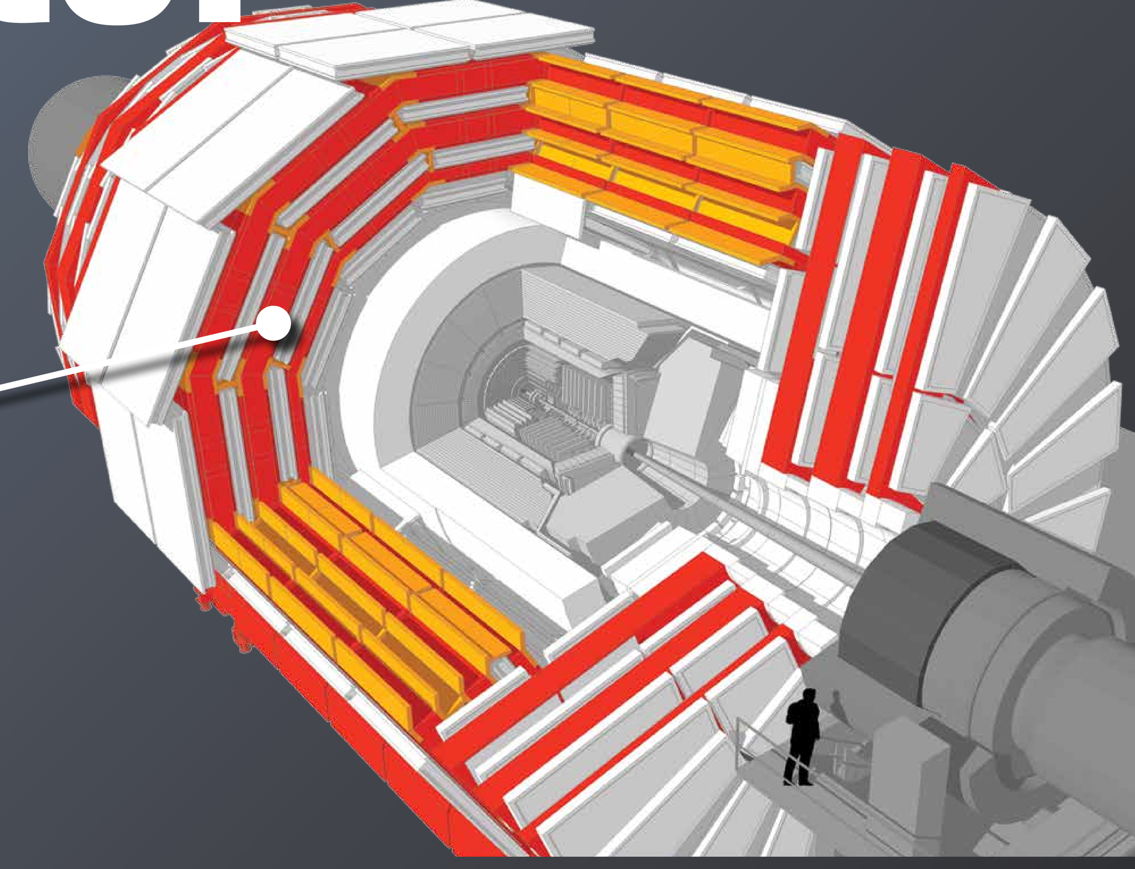
Quartz fibres make up modules of the Forward Hadron Calorimeter.

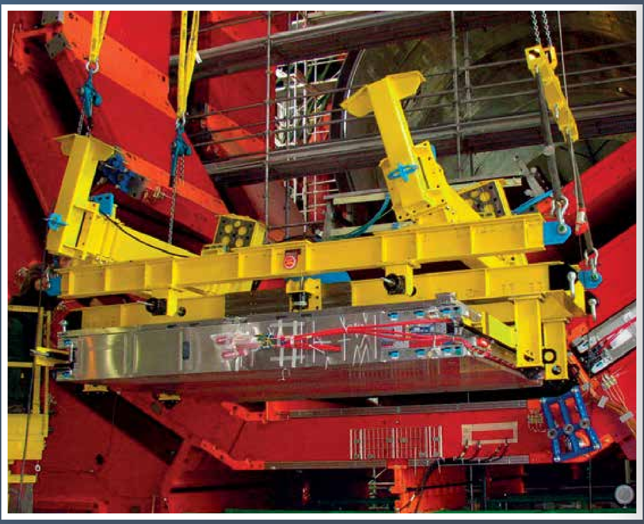
Hadron Forward Calorimeter was the first CMS section to be lowered to the cavern.

The Hadron Calorimeter (HCAL) measures the energy of particles called “hadrons”, such as protons, neutrons, kaons and pions, which are composed of quarks and gluons. In addition, it helps determine indirectly the presence of non-interacting, neutral particles such as neutrinos. With the exception of muons and neutrinos, the HCAL is designed to stop all other known particles produced in collisions inside CMS. The HCAL consists of 70 000 tiles grouped into scintillator trays sandwiched between layers of brass, and 450 000 quartz fibres embedded in a steel matrix.

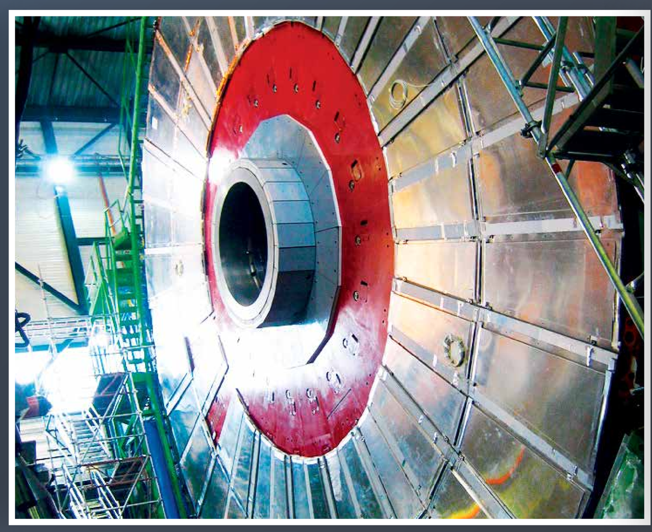
CMS sub-detector

Muon System



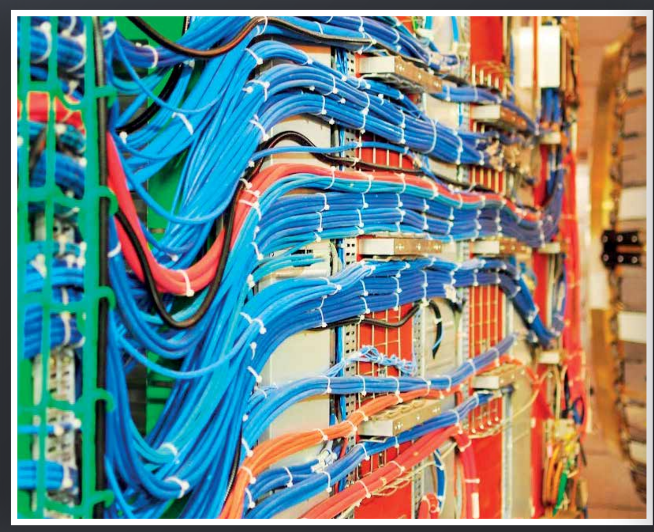


Drift Tube chambers (DT) and Resistive Plate Chambers (RPC) being inserted the barrel section (central region)



Resistive Plate Chambers (RPC) in the CMS endcaps

Cabling of the CMS Muon System



Cabling of the CMS Muon System

Cathode Strip Chambers (CSC) in the CMS endcaps

What are the CMS muon detectors?

250 Drift Tube chambers (DT): Measure points along muon trajectories in the barrel section of the muon system.

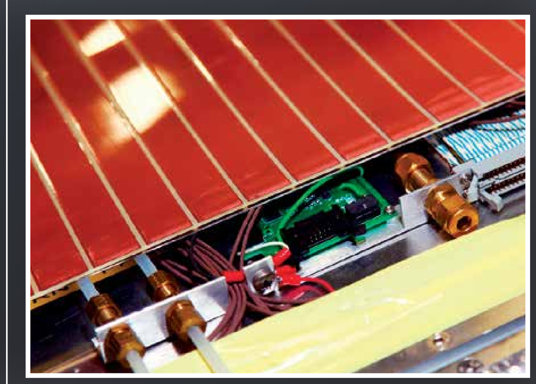
Muons passing through the gas of the chambers knock off electrons that are drawn to positively charged wires.

Measuring the time taken by the electrons to reach the wire indicates the distance from the wire, and thus the point where the muon passed through the chamber.

540 Cathode Strip Chambers (CSC): Measure muon trajectories in the endcaps.

The chambers contain an array of positively charged wires, strung like a harp, over strips that run perpendicular to them.

The movement of electrons to wires and the induced charge on the strips give two orthogonal position co-ordinates.

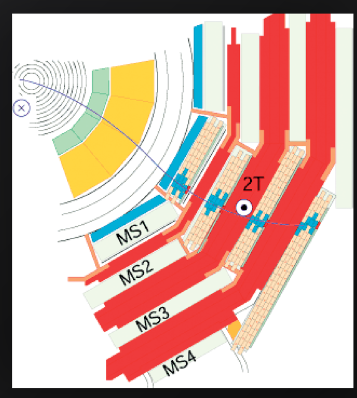


1056 Resistive Plate Chambers (RPC): Present in both the barrel section and the endcaps.

Two gas chambers each made of two oppositely-charged Bakelite electrodes, with a copper strip between the chambers.

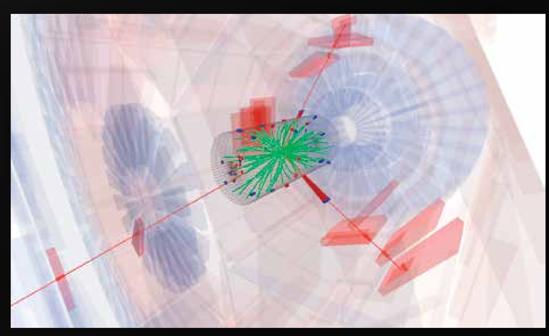
Excellent time-resolution helps identify the collision that produced the observed muons.

How does CMS measure muons?



The muon system of CMS consists of a barrel section and two endcaps, and contains a total of 1846 chambers, interleaved with the steel plates of the magnetic-field-return yoke. When a muon passes through the gas contained within the chambers, it knocks out electrons that are drawn to positively charged wires producing electrical signals. The detectors register these signals to determine successive points on the trajectory of the traversing muon. By tracking these points through the multiple layers of each chamber, the full trajectory of the muon from the inner Tracker all the way through the muon detectors is established.

Importance of measuring muons



The decay of a heavy particle often results in the emission of one or more muons. Thus the detection of a high-momentum muon in CMS gives a strong indication that an interesting interaction has occurred.
Because muons are the only charged particles that are able to penetrate the calorimeter and the iron yoke to traverse the muon detectors, processes containing muons are cleaner and easier to analyse than others.
As an example, the “golden channel” for the observation of Higgs decays consists of events with four muons (see image) in which the Higgs boson decays into two Z bosons, each of which further decays to two muons.

The Muon System of CMS is designed, as the name suggests, to detect muons, which are heavier cousins of the electron and particles crucial to many studies at the LHC. Muons can penetrate several metres of ordinary matter and are not stopped by any of CMS’s calorimeters. Therefore, muon chambers are placed on the external layers of the detector where only muons are likely to register a signal. A muon must pass tens of detection units, which provide the necessary redundancy for an accurate measurement of its momentum and trajectory.

Data

Trigger and Data Acquisition

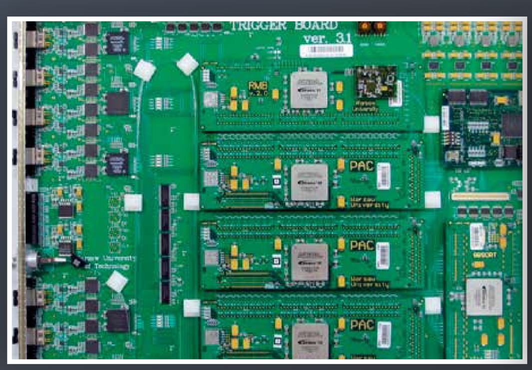
A table containing the status of the various components of the experiment.

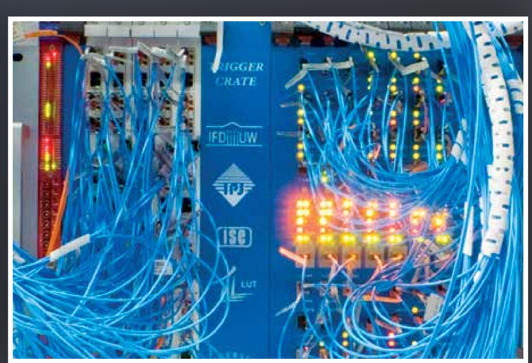
A graphical display symbolizing the different stages in the data-taking system: Experts can read off the instantaneous and time-averaged fractions of the online computing resources that are in use, and whether there are any problems in the ongoing run.

Important status information for the ongoing data-taking exercise

A graphical display of a collision that has just occurred in the detector

A display where experts can read the history of the data taking: For example, a new "run" with collisions starts where the top horizontal bars all turn green. The green line in the graph shows the rate at which collision data are selected by the electronics for further analysis. The white triangle is a measure of the number of collision events recorded in the specific run.





Examples of custom hardware designed to perform the selection tasks

Commercial network equipment used to collect the data produced by the detector and move them to an online computing facility running the HLT algorithm (HLT farm)

Some of the ~2000 servers in the HLT farm located close to CMS

How does the Trigger work?

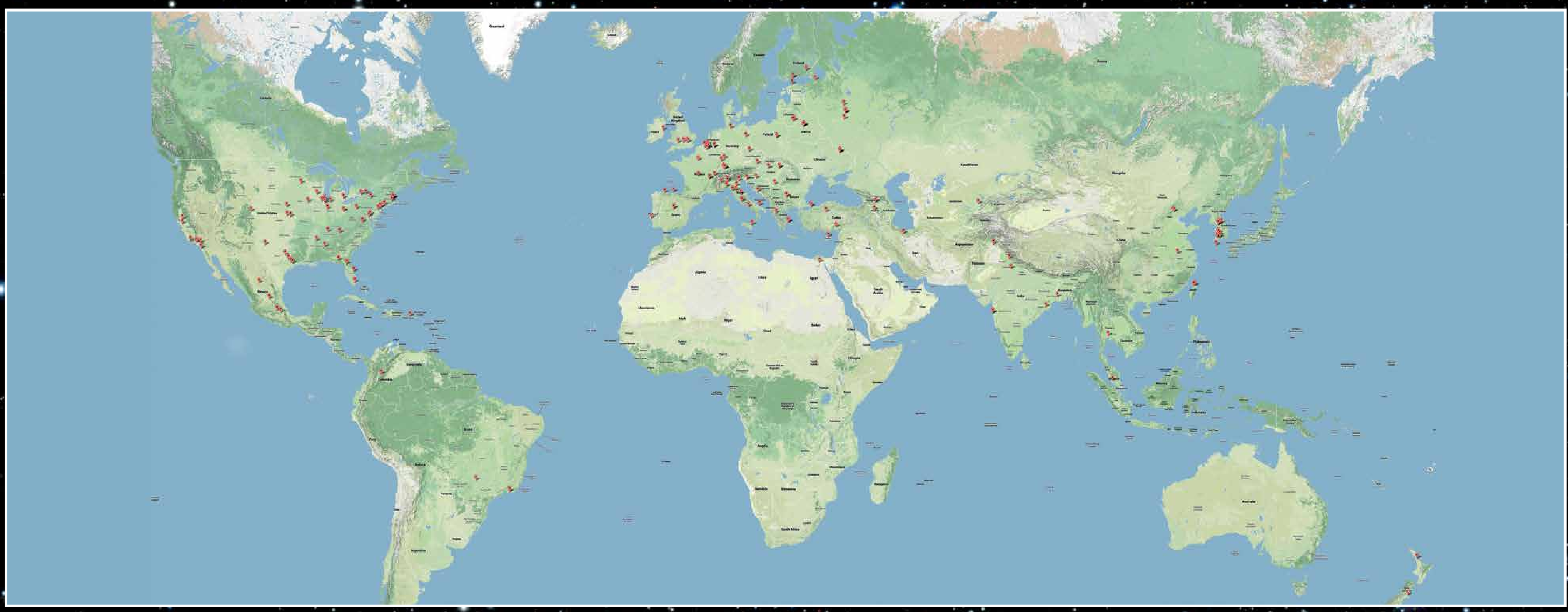
The Level-1 Trigger looks in real time at the hundreds of millions of proton-proton collisions that occur every second of LHC operation and selects no more than 100 000 for further analysis.

For each collision that has been classified as interesting by the L1 Trigger, the Data Acquisition (DAQ) system collects data fragments from several hundred detector components and assembles these "fragments" into a data structure called an "event". An event contains all the detector information from a single crossing of the proton beams, and approximately 100 Gigabytes of data traverse the system per second.

The assembled events are then distributed to the High-Level Trigger (HLT) computer farm for further analysis, and only around a thousand of them are retained each second.

The LHC delivers proton collisions 40 000 000 times per second; if CMS were to retain all the data, each second's worth of collisions would require as much storage as 10 000 volumes of the Encyclopaedia Britannica. To cope with the amount of data produced, the Trigger and Data Acquisition System (TriDAS) does a pre-selection of the most "interesting" collisions while discarding all the rest (~99.99999%).

CMS: A Worldwide Adventure



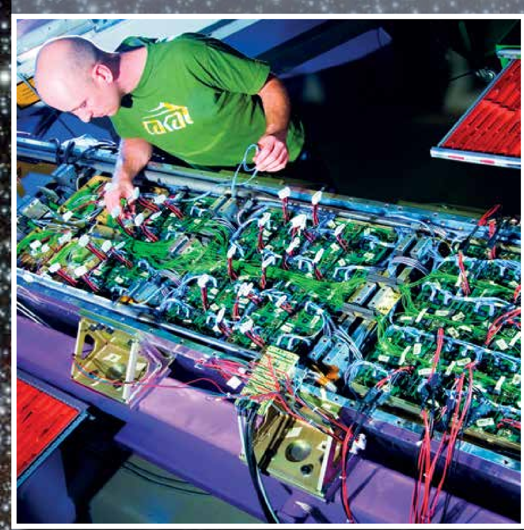
The CMS experiment is one of the largest international scientific collaborations in history, involving more than 3000 scientists, engineers, and students from 182 institutes in 42 countries.

A small fraction of the CMS Collaboration celebrating the discovery of the Higgs boson in 2012, assembled 100 m above their "microscope", the CMS detector itself.

Physicists celebrating the first 7 TeV proton-proton collisions in CMS on 30th March 2010

At work in the CMS Control Room at Point 5, near Cessy, in France

Some of the CMS Tracker team finishing the installation of the Pixel detector



A researcher puts the finishing touches to a Supermodule of the Electromagnetic Calorimeter

Some of the CMS team responsible for the laying of the detector services (cables, optical fibers and cooling pipes)

Solving the mysteries of the Universe requires the involvement and collaboration of scientists, engineers and students from a multitude of disciplines.

Components of CMS have been designed and constructed in academic institutes around the world, as well as in industry, before being brought to CERN for final assembly.

CMS Institutes

As of September 2014

Armenia
Yerevan Physics Institute
Austria
Institut für Hochenergiephysik der OeAW
Belarus
Research Institute for Nuclear Problems
National Centre for Particle and High Energy Physics
Research Institute of Applied Physical Problems
Byelorussian State University
Belgium
Universiteit Antwerpen
Vrije Universiteit Brussel
Université Libre de Bruxelles
Ghent University
Université Catholique de Louvain
Université de Mons
Brazil
Centro Brasileiro de Pesquisas Fisicas
Universidade do Estado do Rio de Janeiro
Universidade Estadual Paulista (a), Universidade Federal do ABC (b)
Bulgaria
Institute for Nuclear Research and Nuclear Energy
University of Sofia
China
Institute of High Energy Physics
University for Science and Technology of China
State Key Laboratory of Nuclear Physics and Technology, Peking University
Colombia
Universidad de Los Andes
Croatia
Technical University of Split
University of Split
Institute Rudjer Boskovic
Cyprus
University of Cyprus
Czech Republic
Charles University
Egypt
Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics
Estonia
National Institute of Chemical Physics and Biophysics
Finland
Helsinki Institute of Physics
Department of Physics, University of Helsinki
Lappeenranta University of Technology
France
Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon
Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3
Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS
DSM/IRFU, CEA/Saclay
Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3
Georgia
Institute of High Energy Physics and Informatization, Tbilisi State University
E. Andronikashvili Institute of Physics, Academy of Science
Germany
RWTH Aachen University, I. Physikalisches Institut
RWTH Aachen University, III. Physikalisches Institut A
RWTH Aachen University, III. Physikalisches Institut B
Deutsches Elektronen-Synchrotron
University of Hamburg
Institut für Experimentelle Kernphysik
Greece
University of Athens
Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos
University of Ioánnina
Hungary
Institute of Nuclear Research ATOMKI
KFKI Research Institute for Particle and Nuclear Physics
University of Debrecen
India
Panjab University
University of Delhi
Saha Institute of Nuclear Physics
Bhabha Atomic Research Centre
National Institute of Science Education and Research
Tata Institute of Fundamental Research - EHEP
Tata Institute of Fundamental Research - HECR
Iran
Institute for Research in Fundamental Sciences (IPM)
Ireland
University College Dublin
Italy
INFN Sezione di Bari (a); Università di Bari (b); Politecnico di Bari (c)
INFN Sezione di Bologna (a); Università di Bologna (b)
INFN Sezione di Catania (a); Università di Catania (b)
INFN Sezione di Firenze (a); Università di Firenze (b)
INFN Laboratori Nazionali di Frascati
INFN Sezione di Genova (a); Università di Genova (b)
INFN Sezione di Milano-Bicocca (a); Università di Milano-Bicocca (b)
INFN Sezione di Napoli (a); Università di Napoli 'Federico II' (b); Università della Basilicata (Potenza) (c); Università G. Marconi (Roma) (d)
INFN Sezione di Padova (a); Università di Padova (b); Università di Trento (Trento) (c)
INFN Sezione di Pavia (a); Università di Pavia (b)
INFN Sezione di Perugia (a); Università di Perugia (b)
INFN Sezione di Pisa (a); Università di Pisa (b); Scuola Normale Superiore di Pisa (c)
INFN Sezione di Roma (a); Università di Roma (b)
INFN Sezione di Torino (a); Università di Torino (b); Università del Piemonte Orientale (Novara) (c)
INFN Sezione di Trieste (a); Università di Trieste (b)
Korea
Cheju National University
Chonbuk National University
Chonnam National University, Institute for Universe and Elementary Particles
Dongshin University
Kangwon National University
Konkuk University
Korea University
Kyungpook National University
Seonam University
Seoul National University of Education
Seoul National University
University of Seoul
Sungkyunkwan University
Wonkwang University
Lithuania
Lithuanian Academy of Sciences
Vilnius University
Malaysia
University of Malaya Jabatan Fizik
Mexico
Centro de Investigacion y de Estudios Avanzados del IPN
Universidad Iberoamericana
Benemerita Universidad Autonoma de Puebla
Universidad Autónoma de San Luis Potosí
New Zealand
University of Auckland
University of Canterbury
Pakistan
National Centre for Physics, Quaid-I-Azam University
Poland
Institute of Experimental Physics, Faculty of Physics, University of Warsaw
National Centre for Nuclear Research
Portugal
Laboratório de Instrumentação e Física Experimental de Partículas
Russia
Joint Institute for Nuclear Research
Institute for Nuclear Research
Institute for Theoretical and Experimental Physics
P.N. Lebedev Physical Institute
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University
State Research Center of Russian Federation, Institute for High Energy Physics
Petersburg Nuclear Physics Institute
Serbia
University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences
Spain
Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT)
Universidad Autónoma de Madrid
Universidad de Oviedo
Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria
Switzerland
CERN, European Organization for Nuclear Research
Paul Scherrer Institut
Institute for Particle Physics, ETH Zurich
Universität Zürich
Taiwan
National Central University
National Taiwan University (NTU)
Thailand
Chulalongkorn University
Turkey
Cukurova University
Middle East Technical University, Physics Department
Bogazici University
Istanbul Technical University
Ukraine
Institute of Single Crystals of National Academy of Science
National Scientific Center, Kharkov Institute of Physics and Technology
Kharkov State University
United Kingdom
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USA
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Baylor University
Boston University
Brown University
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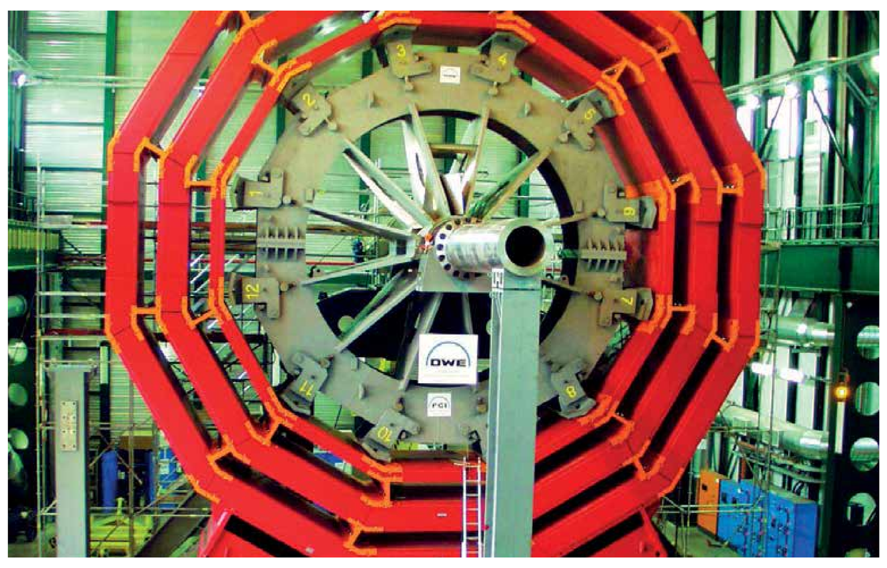
Carnegie Mellon University
University of Illinois at Chicago (UIC)
University of Colorado at Boulder
Cornell University
Fairfield University
Fermi National Accelerator Laboratory
Florida International University
Florida State University
Florida Institute of Technology
University of Florida
The University of Iowa
Johns Hopkins University
Kansas State University
The University of Kansas
Lawrence Livermore National Laboratory
University of Maryland
University of Minnesota
University of Mississippi
Massachusetts Institute of Technology
University of Nebraska-Lincoln
Northeastern University
Northwestern University
University of Notre Dame
The Ohio State University
Princeton University
University of Puerto Rico
Purdue University
Purdue University Calumet
Rice University
University of Rochester
The Rockefeller University
Rutgers, The State University of New Jersey
State University of New York at Buffalo
University of Tennessee
Texas A&M University
Texas Tech University
University of California, Davis
University of California
University of California, Riverside
University of California, Santa Barbara
University of California, San Diego
Vanderbilt University
University of Virginia
Wayne State University
University of Wisconsin
Uzbekistan
Institute of Nuclear Physics of the Uzbekistan Academy of Sciences

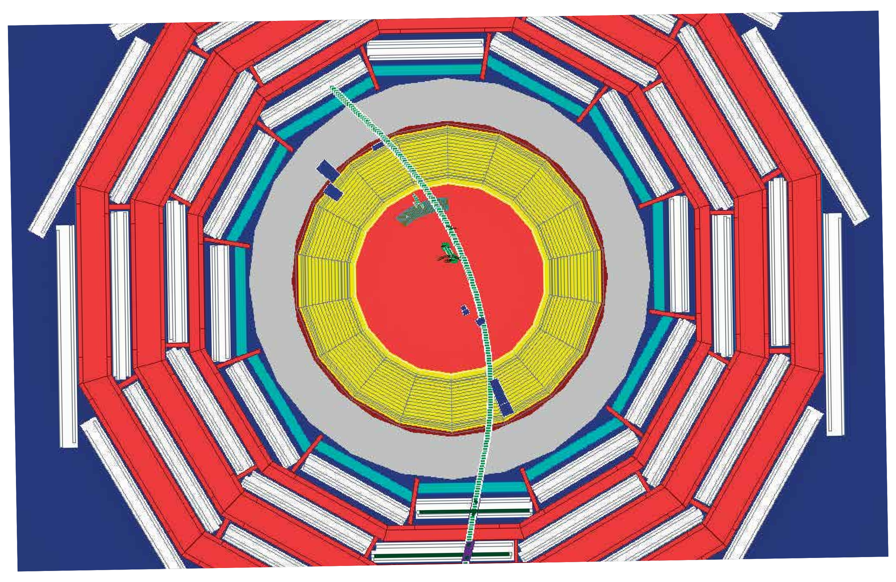
CMS Construction



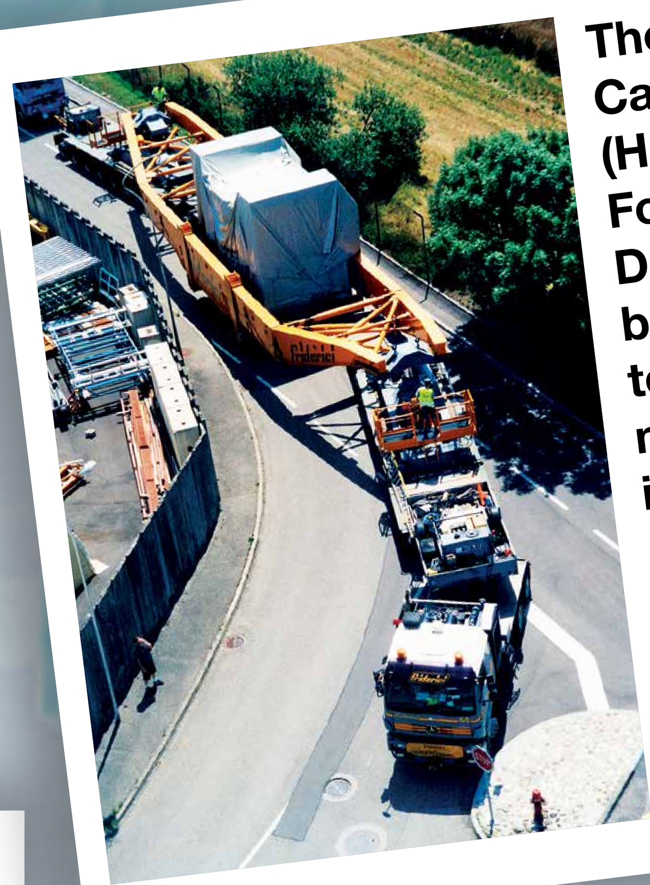
One of the five “wheels” in the barrel section of the magnetic-field-return yoke being put together with the aid of a “spider”, the holding structure in grey

The completed magnetic-field-return yoke

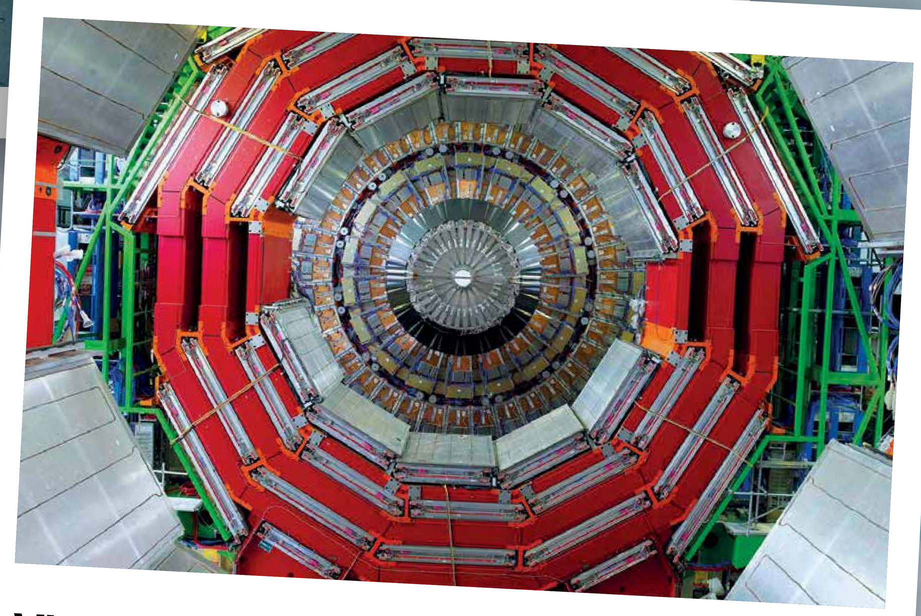
The assembly of the solenoid



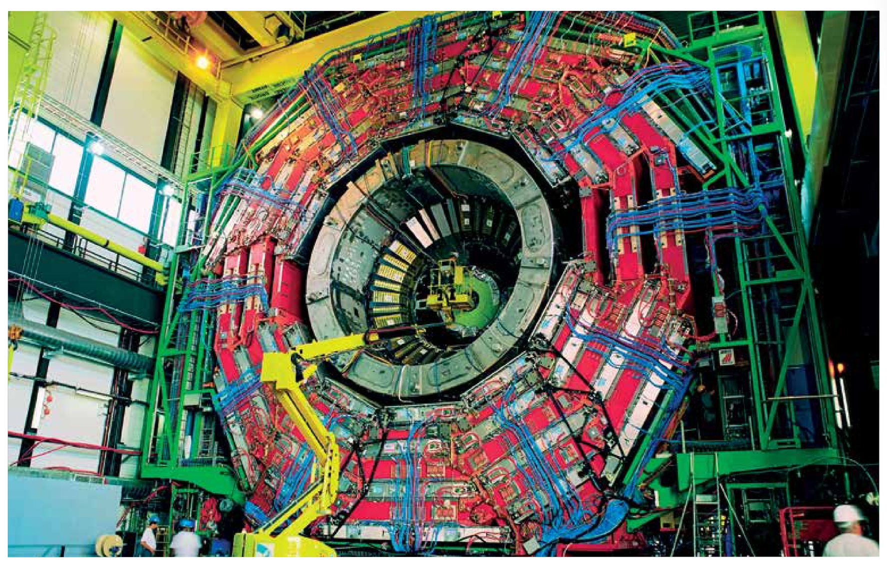
A cosmic ray detected during the test of the solenoid before lowering to the cavern



The Hadron Calorimeter (HCAL Forward Detector being taken to Point 5, near Cessy in France



View of the Muon Detectors inserted in the magnetic-field-return yoke



The solenoid and parts of the detector, prior to the test in autumn 2006

The first endcap disk of the magnetic-field-return yoke ready for lowering

Components of CMS were fabricated in academic institutes and factories all over the world, with the final assembly taking place at Point 5. The CMS Detector was pre-assembled into 15 large slices and many smaller sections, in the surface assembly hall directly above the underground cavern. The various detector elements are arranged in co-axial layers around the central beam pipe, giving a cross-sectional view like a slice of an onion.

The endcap sections being reordered on the surface prior to lowering into the experimental cavern

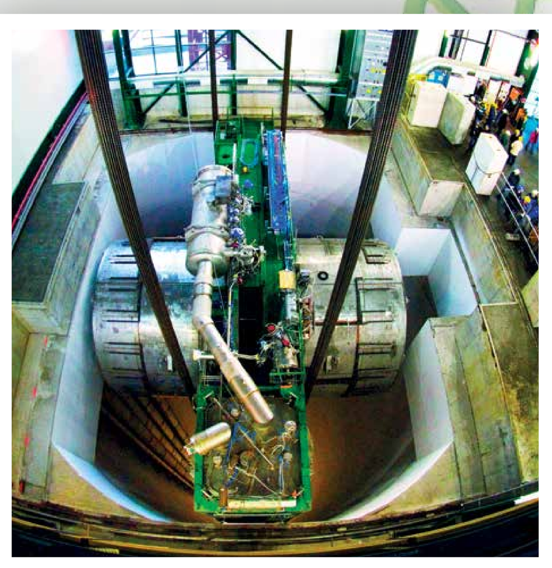
Lowering and Underground Installation

Lowering of one of the two Hadron Forward Calorimeters

Lowering

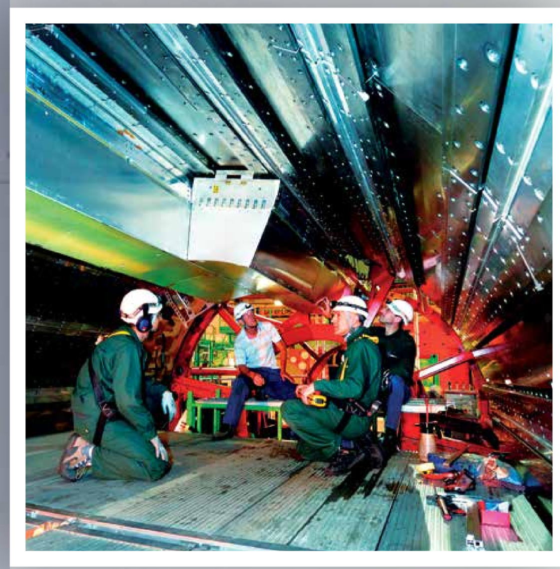
One of the disks resting on the cavern floor after its descent, with a second disk being lowered behind it

One of the CMS sections (an endcap disk in this case) being lowered into the underground cavern

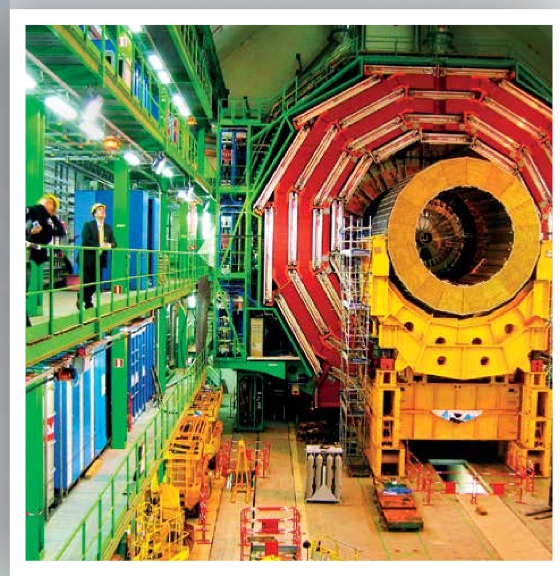


The heaviest piece, containing the solenoid, took 12 hours of careful operation to be lowered, with a clearance on each side of just 10 centimetres

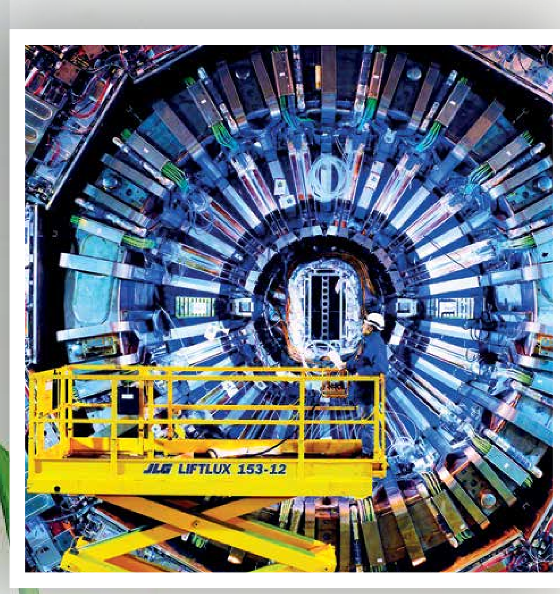
Underground installation



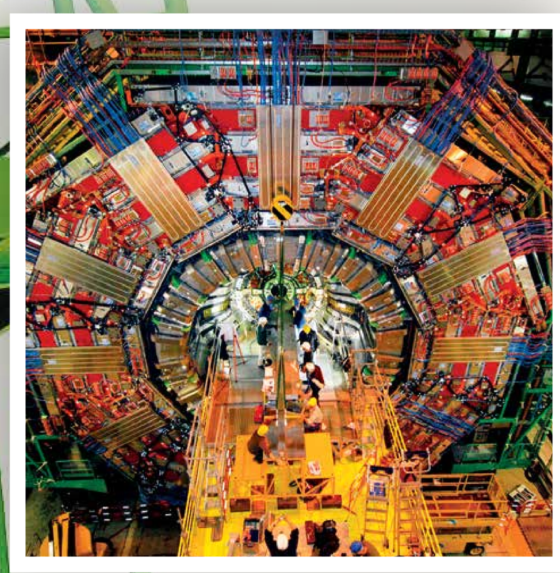
Installation of the Barrel Electromagnetic Calorimeter



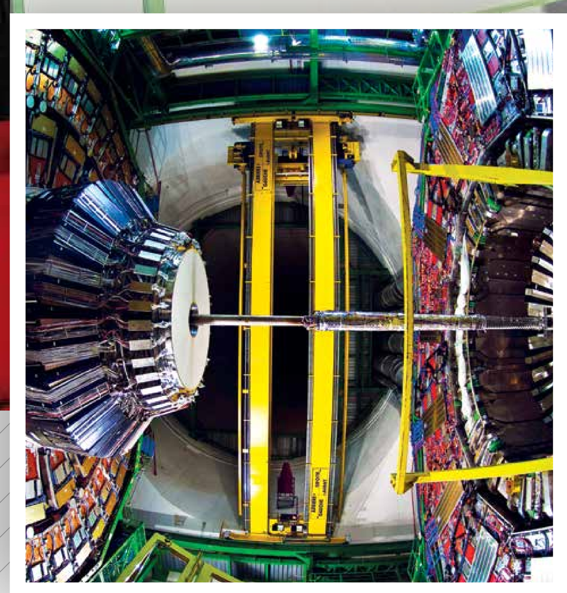
Installation of the Barrel Hadron Calorimeter



The Tracker and barrel calorimeters installed within the magnet volume



Installation of the beam pipe

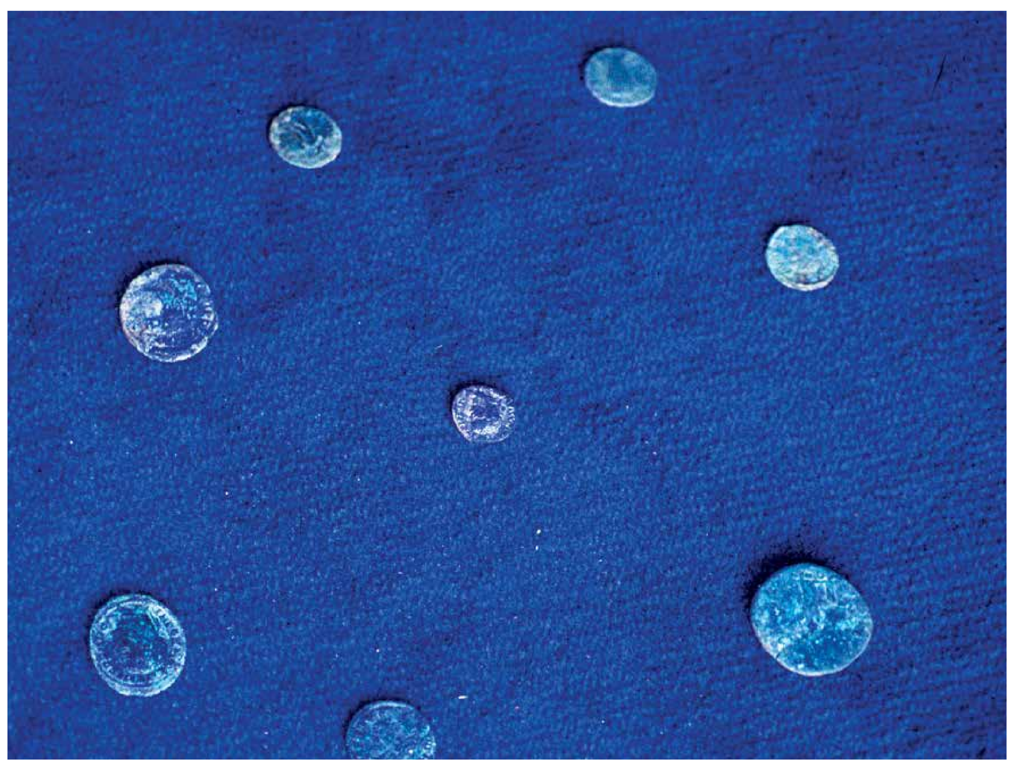


The fully assembled barrel and one endcap just prior to closing the CMS Detector, with the beam pipe visible in the centre

CMS Detector closed (September 2008) and ready for the LHC beam

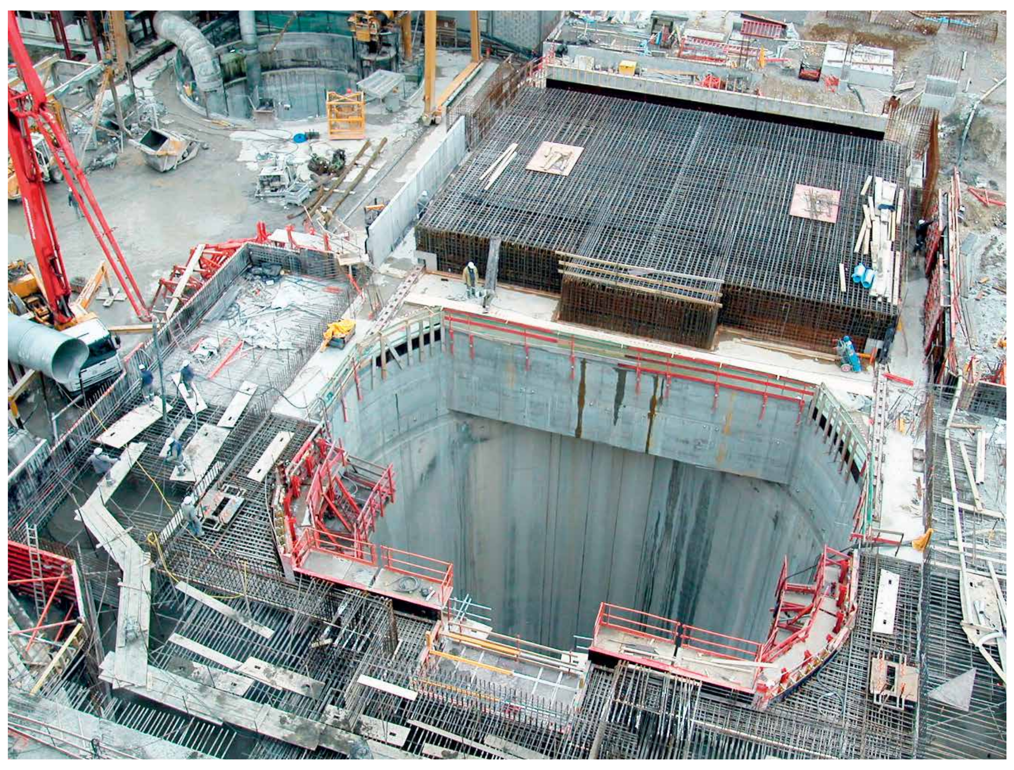
Once the CMS Underground Experimental Cavern was ready for the detector, the individual sections, each weighing between **200 and 2000** tonnes, were lowered 100 metres underground to be installed in position. This process began in November 2006 and took several months of painstaking and careful assembly. The task was completed on schedule and CMS was ready for LHC beam in September 2008.

Site Geography and Civil Engineering








The CMS experimental site is located in the foothills of the Jura Mountains in the commune of Cessy in the Pays de Gex region of France.

The location has been inhabited since Roman times. Whilst excavating around the site, CMS engineers unearthed a Roman villa, complete with pots, tiles and coins. The roman coins found were minted in Ostia, London and Lyon between 309 and 315 AD.

After archaeological survey, the villa site was covered in a layer of sand to allow for possible future investigation or display.

Site Geography and Civil Engineering

















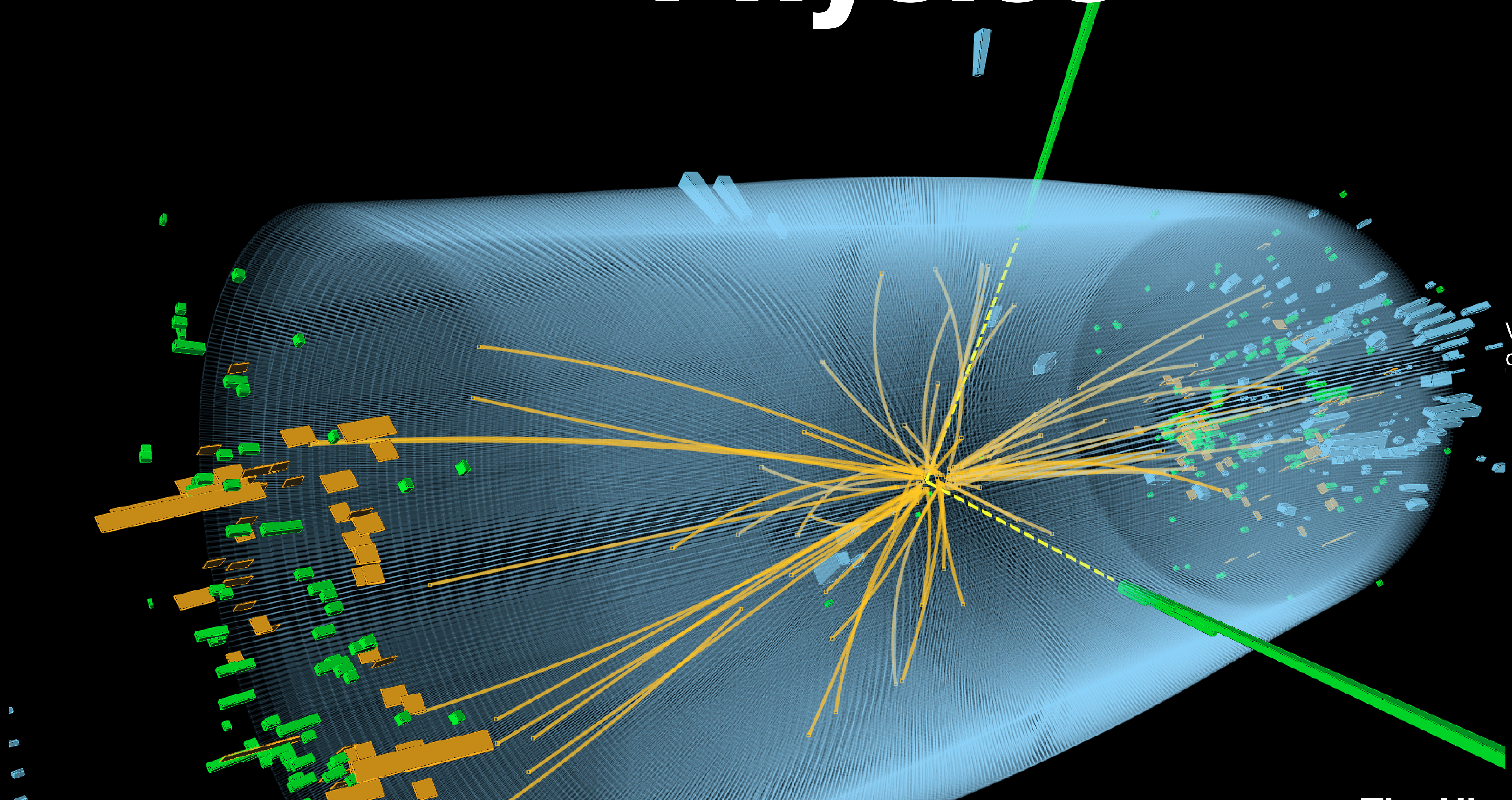



Preparing the underground experimental area proved to be challenging. Fast-flowing underground water impeded excavation of the 100 m deep vertical shaft giving access to the subterranean cavern. Liquid nitrogen (at -200 °C), supplied via a ring of pipes, was used to create a circular barrier of ice (3m wide and 50m deep) within which the shaft was excavated and then lined with concrete.

The 200 000 m^3 of Molasse rock removed during excavation of the shaft and underground caverns, was used to landscape the area around the site.

The assembly hall on the surface was finished in 2000, while the shaft and the underground experimental areas were ready to accommodate the CMS detector in 2005.

Physics



Visualization of a Higgs boson candidate in CMS

What are we made of?

The matter around us is formed from three stable particles: electrons, up quarks and down quarks; the up and down quarks combine to form protons and neutrons which in turn combine with electrons to form atoms and molecules.

In addition there are unstable particles of matter: the charm, strange, top and bottom quarks; two heavier cousins of the electron called the muon and the tau; and the electron neutrino, the muon neutrino and the tau neutrino. Matter particles behave as if they were tiny spinning tops, with one common characteristic: they all have the same angular momentum, equal. "½" in the appropriate units. More generally, particles with half-integer values of angular momentum (½, 1½, etc) are referred to as "fermions".

The Standard Model

These fermions are governed by four known forces: gravity, electromagnetism, the strong force and the weak force. The strong force binds quarks together to form composite particles, such as protons and neutrons. The weak force is involved in particle transformations, including radioactive decays, and plays a key role in the release of energy in the Sun.

The Standard Model of particle physics is a mathematical model based on quantum mechanics and relativity that describes all known fermions and all forces except gravity. It also includes particles that transmit these forces. Force particles also behave as if they were tiny spinning tops, except in this case their angular momentum is "1" in the same units as matter particles. More generally, particles with integer values of angular momentum (0, 1, 2, etc) are referred to as "bosons".

The Higgs boson

Physicists discovered that electromagnetism and the weak force could be unified into the so-called "electroweak" force. But the fundamental symmetries responsible for this unification require all particles to be massless, which, is not the case!

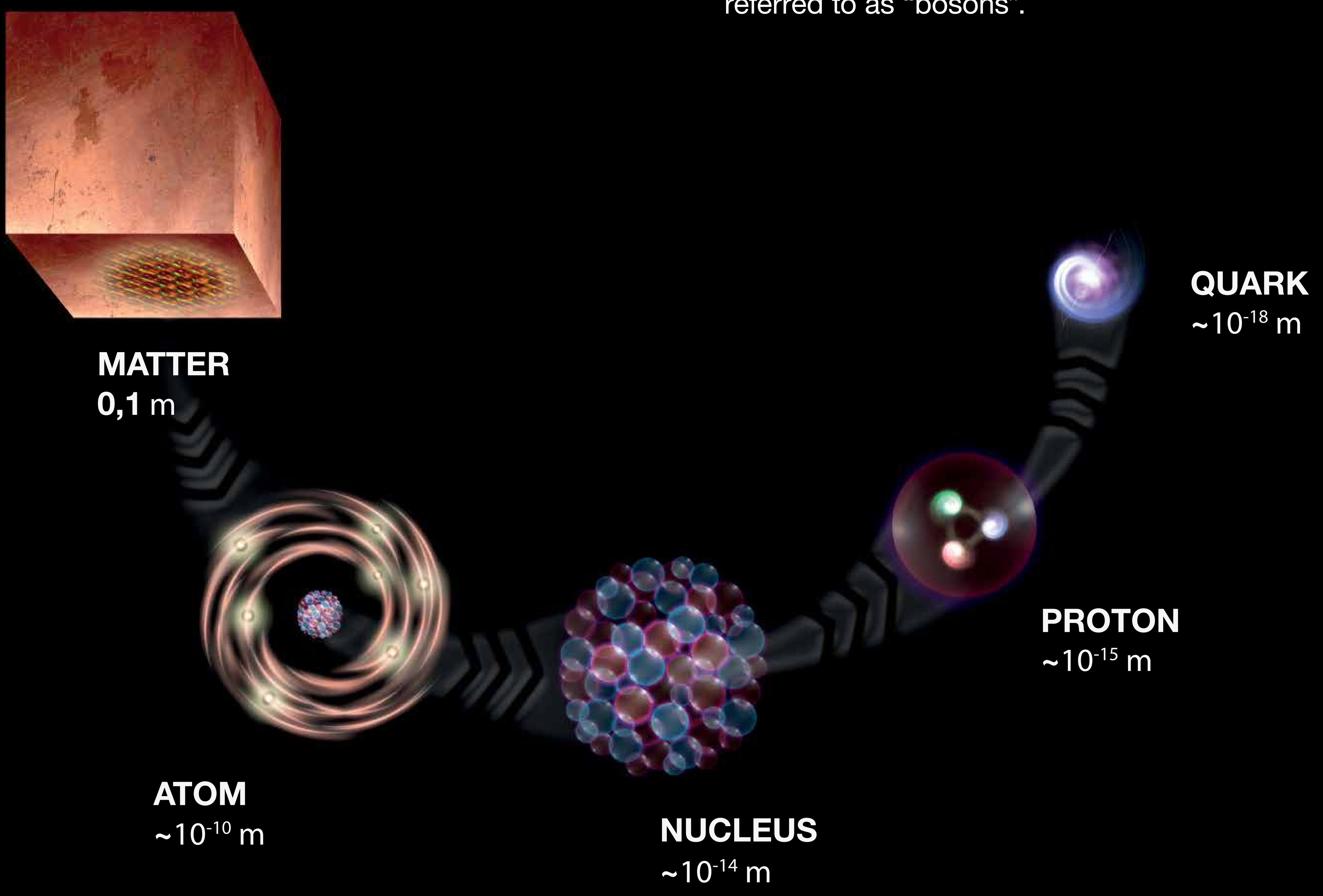
In 1964, Robert Brout, François Englert and Peter Higgs proposed a mechanism to explain how particles acquired mass by spontaneously breaking the underlying symmetries. They predicted that a force field pervading the entire Universe is responsible for this electroweak symmetry-breaking and is transmitted by its own particle, now referred to as the Higgs boson.

Particles interacting with this force field acquire mass in proportion to the strength of the interaction; those that are unaffected by the field – such as photons, the particles of light – remain massless.

In 2012, CMS and ATLAS discovered a new particle whose properties are consistent with those expected for the Standard Model Higgs boson.

The above collision shows a candidate event for the production of a Higgs boson measured in CMS. The Higgs boson subsequently decays into two photons (illustrated by the dashed lines).

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

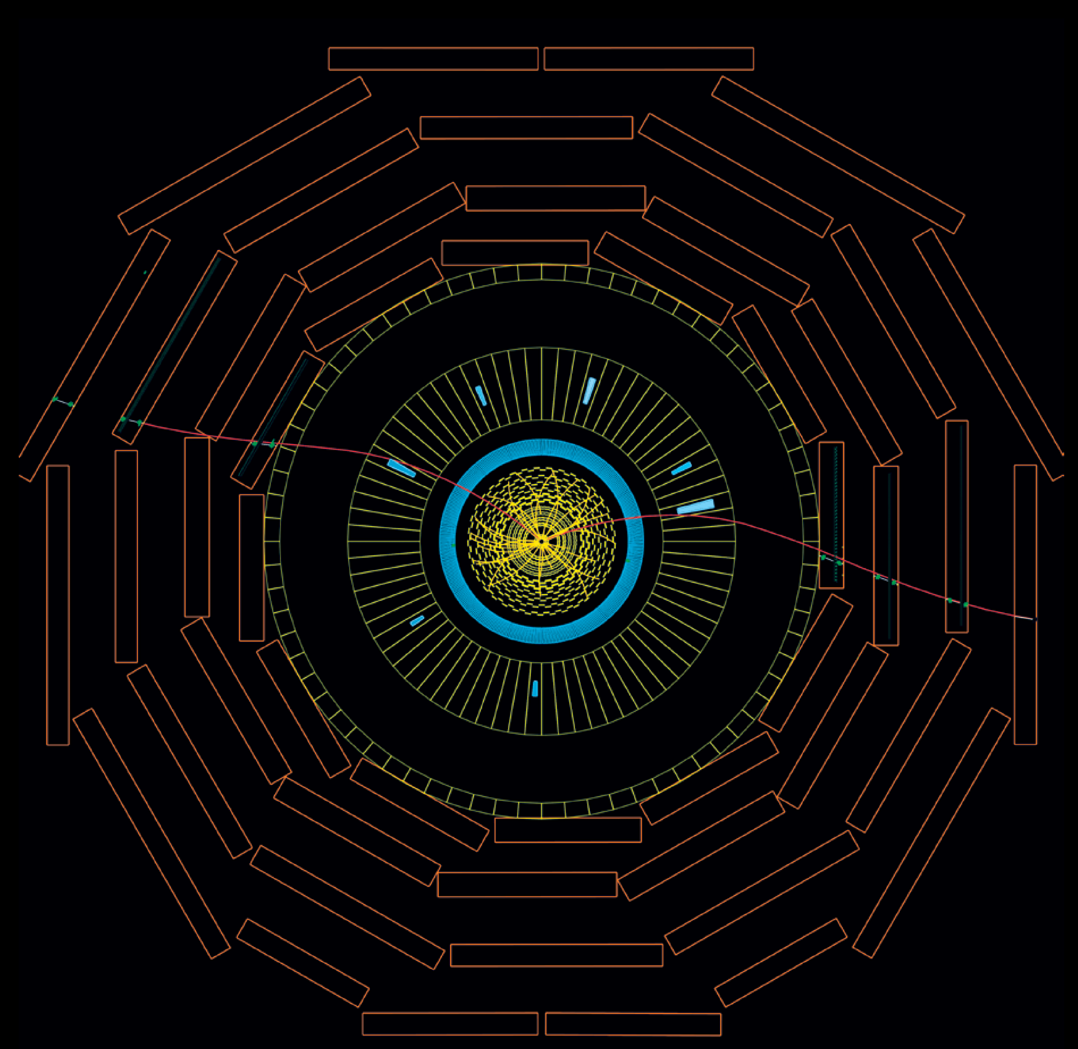


Physics

The missing antimatter

Each elementary particle of matter has an associated particle of antimatter. When a particle meets its antiparticle, they annihilate each other with the release of energy. The first observed antiparticle was the positron or anti-electron.

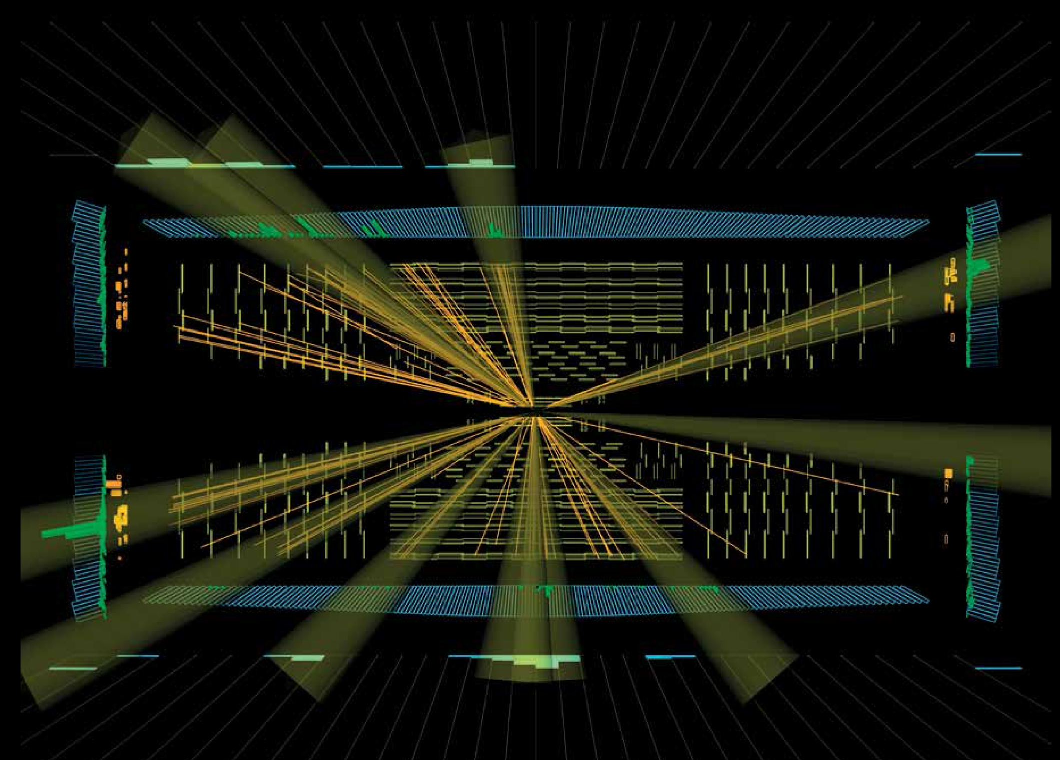
We believe that when our Universe formed, matter and antimatter were produced in equal amounts. Clearly, something must have happened subsequently to cause an imbalance between matter and antimatter, resulting in the matter-dominated Universe we observe today. What physics processes are responsible for this imbalance? CMS is studying many rare physics processes in order to understand if this result of a phenomenon known as CP violation, or if there are additional effects that are as yet unknown.



A Upsilon particle produced within CMS decays symmetrically into a muon and an anti-muon. The magnetic field inside CMS bends the muon and anti-muon in opposite directions.

Extra spatial dimensions

Albert Einstein demonstrated that the three dimensions of space can be merged with time to give us four-dimensional “spacetime”. Theories such as string theory, however, predict that our Universe is made of several more spatial dimensions – up to a total of 10! The existence of these extra dimensions might explain why gravity is so weak compared to the other three forces. Certain characteristics of proton collisions could only be produced in the presence of extra dimensions. CMS is therefore conducting many searches devoted to observing these as yet unseen signatures.



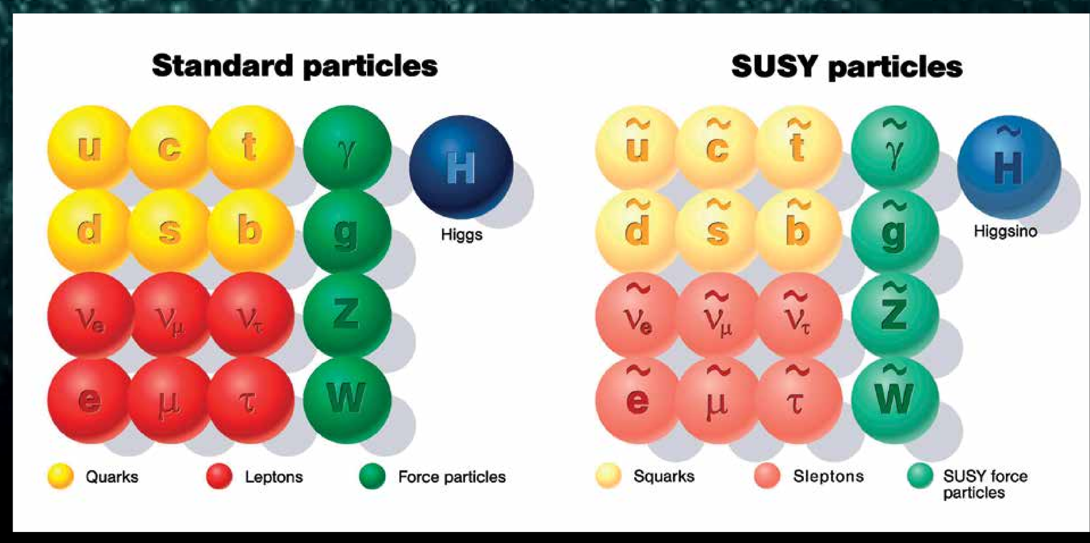
An abundance of ‘particle jets’ as seen in this CMS collision event could point to the presence of extra dimensions in our Universe.

The primordial soup

Particles known as gluons hold quarks together to form particles such as protons and neutrons. It is thought that under the extremely high temperature conditions of the very early Universe, quarks and gluons existed freely, in a soup-like state referred to as a the “quark-gluon plasma”.

By smashing together lead nuclei, as seen in the event display on the right, CMS can recreate conditions that existed mere fractions of a second after the Big Bang, and study the quark-gluon plasma.

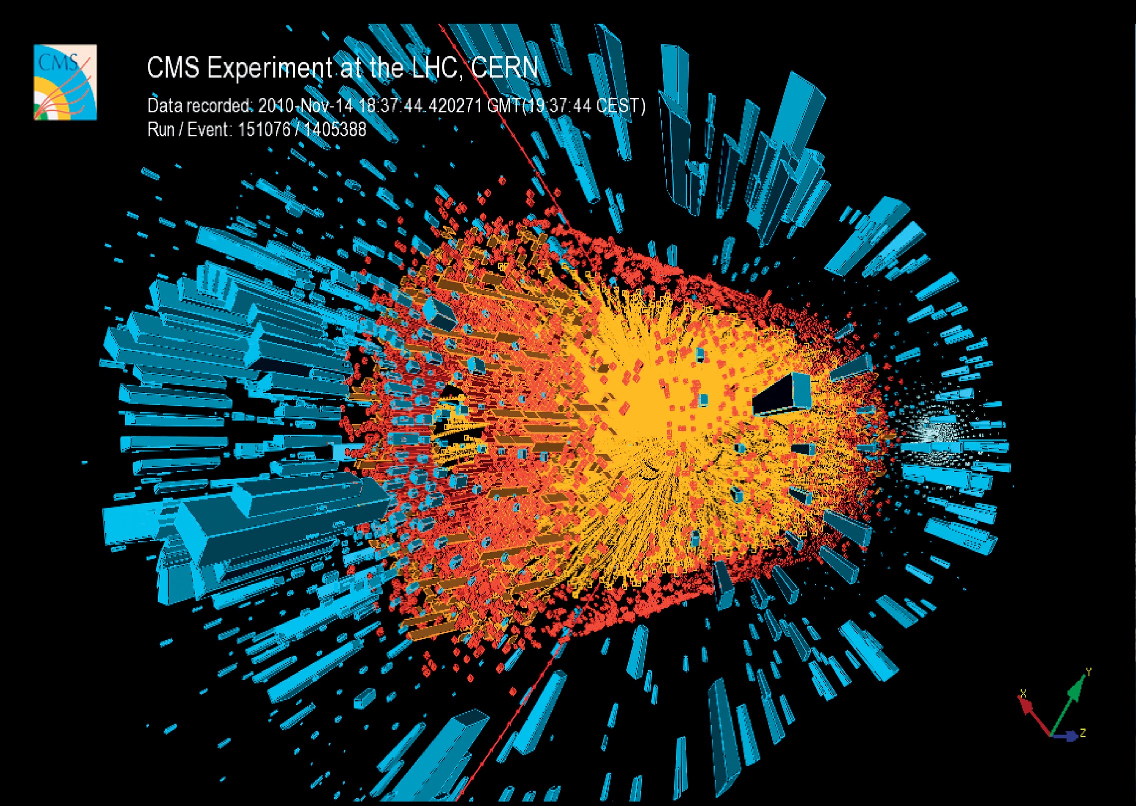
Dark matter and Supersymmetry



Supersymmetry predicts superpartners for all the known and observed particles in our Universe.

Astrophysical observations tell us that 95% of the Universe is of unknown nature. A quarter of the material in the Universe is thought to be made of so-called dark matter, which cannot be observed with telescopes. Supersymmetry or SUSY, is a popular extension of the Standard Model that suggests that every particle of the Standard Model has a SUSY partner: each fermion has a bosonic partner, and each boson has a fermionic partner. In some SUSY models, the lightest of these new particles is stable, providing a dark-matter candidate that might explain all the missing matter in our Universe. The main motivation for SUSY, however, is that it provides a good solution to the ‘hierarchy problem’, namely the big question of why the Higgs boson has such a relatively low mass when in theory, it should naturally have a huge value.

If supersymmetric particles exist within the reach of LHC energies, proton collisions within CMS will reveal their presence.



Asking questions and trying to understand the world around us is one feature separating humans from all other creatures. At CMS, scientists are looking into the unknown and trying to answer the most fundamental questions about our Universe.

Approximately 13 800 000 000 years ago, a huge explosion gave rise to our Universe and everything within it. This explosion, which we call the Big Bang, left the Universe in a very hot and dense state. Within a few moments it started to cool down, giving conditions that were just right to produce the building blocks of all the matter you observe around you.

To study these building blocks as well as other particles that haven’t been around since the earliest moments of our Universe, the LHC smashes protons together at energies never achieved before in controlled conditions.

The LHC also smashes lead nuclei for short periods of time to recreate the hot and dense conditions of the early Universe and study the behaviour of matter under those conditions.