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

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

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 (i.e., 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 "pellet".

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 tracking 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.
The Electromagnetic Calorimeter (ECAL) comprises three sections: a barrel and two endcaps, and contains 75,848 crystals of lead tungstate (PbWO₄), a material which is 86% metal by weight yet completely transparent. The crystals have dimensions 2.2 x 2.2 x 23 cm³ and 2.9 x 2.9 x 22 cm³ 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 cm³, enhances particle identification in the endcaps.
**CMS sub-detector**

**Hadron Calorimeter (HCAL)**

**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?**

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

What are the CMS muon detectors?

- Drift Tube chambers (DT) and Resistive Plate Chambers (RPC) being inserted in the barrel section (partial 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

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 magnet-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 clearer and easier to analyze than others. As an example, the "golden channel" for the observation of Higgs decays consists of events with four muons (two in each of 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.
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%).
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.

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.
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.
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.
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.
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 m³ 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.
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, \( \frac{1}{2} \) in the appropriate units. More generally, particles with half-integer values of angular momentum (\( \frac{1}{2}, \frac{3}{2}, \text{etc} \)) are referred to as "fermions".

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 \( \frac{1}{2} \) 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".

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".

MATTER
0.1 m

ATOM
\~10^{-16} m

NUCLEUS
\~10^{-14} m

QUARK
\~10^{-18} m

PROTON
\~10^{-18} m
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.

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 at yet unseen signatures.

Dark matter and Supersymmetry

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.

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 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.

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.