CMS: Compact Muon Solenoid

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I. Abstract

The Large Hadron Collider made its debut on September 10, 2008. It is home to multiple different detectors, including the Compact Muon Solenoid that this report will describe. The CMS detector is specialised in high energy particle physics research. The collision debris can be seen through the interaction of the particles with the carefully chosen layers of equipment. There are five main sections in the detector that will be thoroughly described; those being tracker detector, electromagnetic calorimeter, hadron calorimeter, superconducting solenoid magnet, iron return yoke, muon detectors.

II. Introduction

There are currently four fundamental forces knows to scientists, two of those have been realised to be closely related; the weak and the electromagnetic force. These two forces are described by the Standard Model, together with all fundamental particles so far discovered. This suggests that electricity, magnetism, light as well as some types of radioactivity are manifestations of one other force. That is the electroweak force, it is carried by photons as well as the W and Z bosons - this is correctly described by basic equations. However, the Standard Model has shown these particles to manifest without a mass which, while it may be accurate for the photon, is still incorrect for the W and Z bosons which carry an actual mass that is approximately a hundred times larger than that of a proton. A solution to this problem is the Brout-Englert-Higgs mechanism. It gives mass to the W and Z bosons through their interaction with the "Higgs Field", the magnitude of that mass depending on the amount of interaction. The Higgs field has its own associated particle of the name "Higgs boson", which is essentially a visible manifestation of that field. Initially after the Big Bang, the magnitude of the field was zero, but it grew rapidly as the universe cooled and reached a critical value in temperature leading to particles acquiring mass.

In order to confirm the mechanism mentioned above and keep the Standard Model valid, it was crucial to find the Higgs boson. The CMS experiment was to do that side by side with the ATLAS detector through different methods and different equipment in order to make sure the findings are as accurate and reliable as possible.

III. General Design and Requirements

When designing the detector, the priority was to ensure that if the Higgs Boson existed, then it would be found. The theory did not predict the mass of the particle, meaning that a large range of had to be covered. Additionally, a diversity of decay modes was to be used in order to see if any yield the desirable boson. The decay modes were pairs of photons, Z bosons, W bosons, tau leptons and b bosons. The vast variety of situations that CMS was built to investigate would make it great equipment for research on new physics.

Specifically, the detector needed a high performance system[1] to detect and identify muons[16] and their charge over a large range of momenta and angles, as well as a good dimuon mass resolution[11]. A good central tracking system was necessary in order to provide momentum measurements of high accuracy as well as efficiency. Pixel detectors were needed close to the collision region for efficient triggering of tau and b-jets. Since we can only measure particles' qualities by capturing them, the collisions had to have a surrounding that would prevent particles from escaping. An important part of the design was also the centre magnet. The curvature of charged particles' path due to the electromagnetic field would allow for the particle momenta to be measured. The field provided needed to cover an area large enough so that particle momenta could be measured both inside and outside the coil.

Construction of the separate sections would happen on the surface, to then be lowered into the cavern when ready and to installed be into place. This would prevent many safety and access issues of building the detector immediately underground, saving time in the process. In total there had to be 15 separate sections, built and lowered one at a time. Due to the cabling and piping design, each piece of the detector would remain fully accessible, making maintenance easier and faster.

IV. Detector

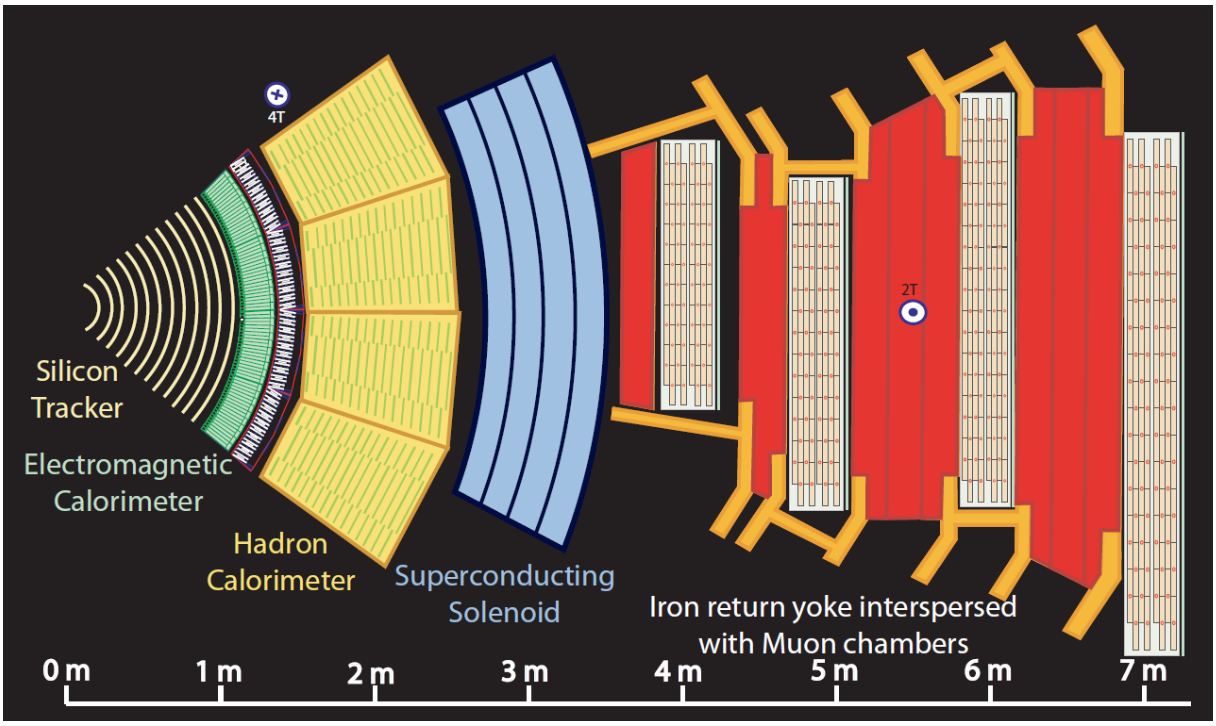

Figure 1[2]: Diagram showing the cross-section of the CMS detector, with different parts labelled.

The first section of the detector that will be discussed is the tracker detector[3]. Its position right at the centre of the detector, surrounding the collision area can be seen in Figure 1, labelled as Silicon Tracker. The momentum of particles is calculated based on their curvature caused by the electromagnetic field. The tracker detector records the path by finding particle positions at different key points, which are then used to find the exact curvature. This part of the detector system is made entirely out of silicon, which is why it is also referred to as the silicon tracker. In the position closest to the interaction area are the pixel detectors. The size of a single pixel is 100 × 150 µm2. The pixels are arranged on three 53cm long barrel layers, which are located at radii of 4.4 cm, 7.3 cm and 10.2 cm, and on endcap disks, 2 of which are located on either end of the barrels. The end disks extend from 6 cm to 15cm in radius. These pixels work on the premise of ejecting an electron when a charged particle passes through, leaving behind electron-hole pairs. An electric current is used to collect the charges and their signal is later amplified and recorded. Further out, there is no longer a need for the accuracy of the silicon pixels, and silicon microstrip[4] detectors are used instead. The strip trackers are separated into two different sections, the first one (the one closer to the pixel detectors) is called the Tracker Inner Barrel and consists of 4 layers. The silicon sensors here are 320 µm thick and have a minimum size of 10 cm ×80 µm. The second section is called Tracker Outer Barrel and consists of 6 layers – 2 double sided layers, and further out another 4 single sided layers. Here they are 500 µm thick, and their maximum size is 25 cm × 180 µm. The silicon microstrip detectors work the same way as the previously mentioned pixels, using the electron-hole pairs. In order to minimise the damage to the silicon caused by high energy radiation, this area of the detector is kept at -20^{o}C[4] to prevent the damage from spreading.

As it can be seen in Figure 1, the next part of the detector is the Electromagnetic Calorimeter[13]. It consists of 61200 lead tungstate ($PbWO_4$)[20] crystals covering the central barrel part, as well as another 7324 crystals covering the two end caps at each end of the barrel. Lead tungstate has multiple different properties that made it a great material for the purpose of the CMS experiment. First of all, it exhibits the property of scintillation. A scintillator material will exhibit luminescence when it is hit by ionising radiation. It will absorb the energy of the incoming particle and then re-emit that energy in the form of electromagnetic waves in the visible spectrum. $PbWO_4$ also has a high density, a short radiation length, fast scintillation decay time as well as a small Molière radius. This results in a radiation resistant calorimeter with fine granularity that is also fast. The main problem that has to be worked around is the low light output that it provides. It requires the use of radiation tolerant photodetectors[21] that can operate in a magnetic field in order to amplify the light yield. In the Barrel, the avalanche photodiodes are used. These were specifically developed for the CMS ECAL and have an active area of 5 x 5 mm^2. Then in the Endcaps, the vacuum phototriodes[22] are used. Same as previously, these were also specifically developed for this experiment. They are photomultipliers with a single gain stage, with a diameter of 25 mm and an active area of 280 mm^2.

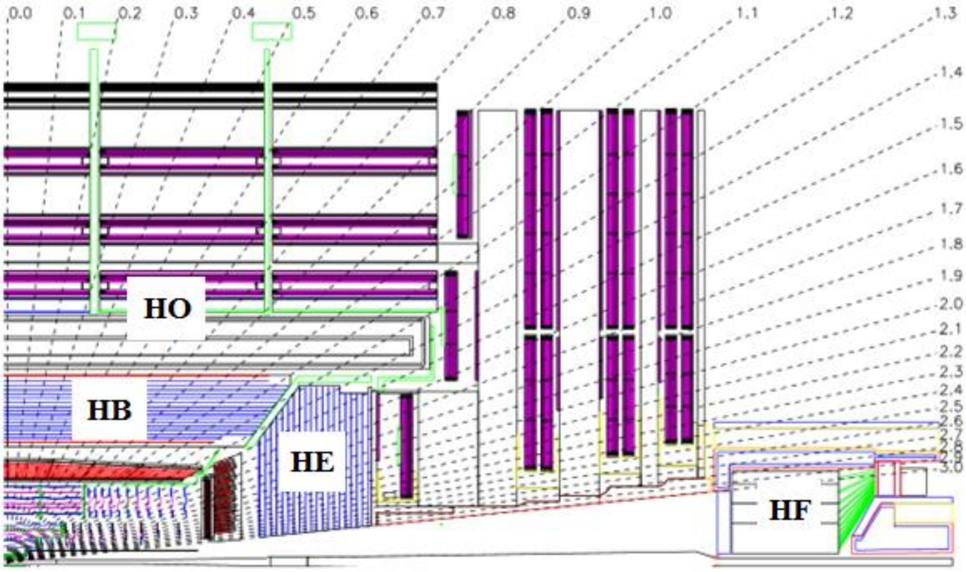

Figure 2[23]: Diagram showing the CMS detector with the hadron barrel (HB), endcap (HE), outer (HO) and forward (HF) calorimeters labelled.

Hadron Calorimeter[5] (HCAL) measures the energy of hadrons. A Hadron is a particle made up of quarks and gluons. Knowing their energy and momentum values allows us to calculate the same for non-interacting particles with neutral charge, e.g. neutrino. These "invisible" particles allow us to find out what new particles (if any) have been formed in the collisions. This includes particles such as the Higgs Boson, or supersymmetric particles. We can find out what particles were present as we know what daughters (a daughter is a particle that a mother particle decayed into) they are likely to decay into. If we find the particles that we expect the Higgs Boson to decay into, then we know that it was there. Energy and Momentum conservation laws are what allows us to find the non-interacting particles. Essentially, if we see an imbalance in the form of a jet in one direction and nothing in the other, we know that there was something there that we can't see. To reliably find these invisible particles, the HCAL must be hermetic - it has to be able to record every interacting particle so that no energy or momentum imbalance goes unnoticed. The measurement of jets and missing transverse energy is done in conjunction with the ECAL sub detectors. The HCAL[13] surrounds the ECAL sub detector system completely. It has four distinctive sections, the hadron barrel[13] (HB), endcap[13] (HE), outer[13] (HO) and forward[13] (HF) calorimeters - the placement of these can be seen in Figure 2. Its barrel and endocarps consist of brass and scintillator plates. There are 70 000 tiles of the active medium used in the Hadron Calorimeter. These are grouped into scintillator tray units to avoid handling single pieces. It also allows for easy replacement if the need for that arises. The Hadron Barrel (HB) is split into two sections. Those two half-barrel[14] sections are each inserted and hang from the rails from either side of the superconducting solenoid.

The superconducting magnet[6] was designed for CMS to reach appropriate magnitude in the right quantities. At full current it has a stored energy of 2.6 G. It reaches a 3.8 T[15] field in a free bore of 6 m diameter, as well as 12.5 m length[12]. New features are present at the superconducting solenoid used here that have not been seen before. Firstly, the winding is composed of 4 layers rather than the usual 1 or 2. Secondly, the conductor made from a Rutherford-type cable which is co-extruded with pure aluminium is now also mechanically reinforced with an aluminium alloy. And the last is feature is not a new design or technology, but purely its size. It has the following dimensions: 6.3 m cold bore, 12.5 m length, 220 t mass. The coil itself is however kept small, making the CMS coil a "this coil" as a result. The electromagnetic field created by the magnet covers the area ranging from the innermost part of the detector; the pixel detectors, all the way out to the hadron calorimeter (HCAL). An important feature of the magnet is that the material used is a superconductor. Superconductors conduct electricity with no resistance when at a low enough temperature. For that purpose, the solenoid is cooled down to -268.5ºC. Cooling down of the solenoid to the desired temperature took a total of 24 days[19]. Due to the coil shrinkage caused by the decrease in temperature, extra measures had to be later taken in order to compensate for the change in size.

The flux from the solenoid magnet is returned through the 10 000 t yoke. The main purpose of the yoke is to prevent any remaining particles from going through, expect muons and neutrinos. The iron return yoke is composed of 11 large elements[18], 6 endcap disks and 5 barrel wheels. The outer diameter[17] of the iron flats is 14m, and the length of the barrel is 13 m. Each endcap had a mass of 2000 t. Despite the mass, these elements can be moved relatively easily which allows access and assembly of the subdetectors.

The Muon Chambers[7] are the last part of the detector that can be seen in Figure 1, there they are interleaved with iron return yoke plates. Muons are charged particles; they are likely to be produced through decay. The Higgs Boson is one of the most important particles that is can decay from, which is why it's crucial to capture all information we can get on muons. The Muon Detector is the outermost layer for a reason. The previously mentioned calorimeters are incapable of capturing muons, so the equipment meant to detect them has been placed far enough out that no other particles should be reaching this part. This way there will be no interference signal from all the other collision debris. Yet again the position of the particles is tracked as it goes through the layers of equipment, which then allows momentum to be measured based on the path curvature. There is a total of 1400 muon chambers, as well as 250 drift tubes and 540 cathode strip chambers to track the particles' positions. There are also 610 resistive plate chambers which forms a trigger system - this decides whether or not to keep the acquired muon data.

In the barrel part of the muon detector you can find the Muon Drift Tube[8] system. Each tube is 4 cm wide. The tubes contain a stretched wire held within a gas. Charged particles passing through the gas will ionise any atoms they come in contact with. The delocalised electrons will then follow an electric field leading up to the positively charged wire. The path of a particle can be tracked my recording where along the wire the electrons were collected. An entire drift chamber is 2 m x 2.5 m in size. Inside there are 12 layers divided into three groups of four layers each. Each group holds up to 60 tubes.

In the endcap disks of the Muon Detector, the Cathode Strip Chambers[9] are used. In these areas the magnetic field is uneven, and the particle rates are high. Similarly, to the DT system, there are positively charged wires within a gas. This time however, in addition to that there are also copper cathode strops within the gas volume. When ionising particles pass through, the delocalised electrons yes again will move towards the anode wires, which leads to an avalanche of electrons. The positive gas ions on the other note move towards the cathode strops, away from the wire. There they induce a charge pulse in the strips. This results in two position coordinates for each passing particle thanks to the perpendicular position of the wires to the strips.

The last part of the Muon detector is the Resistive Plate Chambers[10]. This consists of two parallel plates. One is a positively charged anode and the other is a negatively charged cathode. They are made of a plastic material with a property of very high resistivity. The space between them is filled with a gas. Yet again, any passing Muon or other charged particle will ionise the gas. This time the electrons cause an event chain where each one hits another atom, causing an avalanche of electrons which are then detected by an external detecting strip. This happens at a delay which is taken into account when carrying out calculations. The strips that give off a signal are then used to calculate the Muon momentum, and this information can be either accepted or rejected by the trigger system.

V. Conclusion

The major discovery of the CMS detector system that it was designed for has already been achieved, with the observation of the Higgs Boson in partnership with the ATLAS experiment we are now able to further our understanding of the universe based on the knowledge we have of the Standard Model. Further research so far goes into physics beyond the Standard Model, including Supersymmetry. Extra dimensions are another thing that the CMS can be used to look into in the future, as well as heavy ion collisions. Due to the wide range of particles that the detector is capable of recording, we can use the CMS detector for further research in areas not necessarily related to what has been done so far; there is still potential for many different discoveries.

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