International Journal of Advance and Applied Research
www.ijaar.co.in
ISSN – 2347-7075 Impact Factor – 7.328
Peer Reviewed Bi-Monthly
Vol.11 No.1 Sept-Oct 2023

Review article for God Particle and LHC Experiment

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DOI- 10.5281/zenodo.10276734

Abstract:

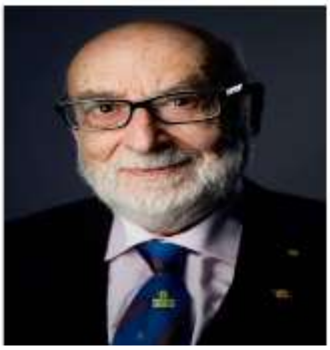
The present study wants to explain the mechanism to how God particles acquire mass through their interactions with the Higgs field. The Higgs boson is a subatomic particle, often referred to as the "God particle," and is a fundamental component of the Standard Model of particle physics. It was first theorized by physicist Peter Higgs in the 1960s. The Higgs boson is associated with the Higgs field, a field of energy that permeates all of space. This field is responsible for giving mass to other particles, such as electrons and quarks. In essence, the Higgs boson helps explain why some particles have mass and others do not. Its discovery in 2012 at the Large Hadron Collider (LHC) was a major scientific breakthrough and confirmed the existence of the Higgs field, contributing to our understanding of the fundamental building blocks of the universe. However after ten years of the discovery of the Higgs boson in 2012, research in the field of particle physics would likely have continued to advance. Scientists would have been studying the Higgs boson's properties and interactions more comprehensively, refining their measurements, and exploring its implications for the Standard Model and beyond. To get the most up-to-date information on the current state of Higgs boson research and any new discoveries or developments that have occurred. We, even get to study its structure and function. We even saw how it played an important role in the discovery of the Higgs boson and studying various topics related to particle physics. Therefore, the present study gives the details study of God particles and its mechanism to form through LHC experiment.

Key words: God particles, LHC experiment.

Introduction:

Have you ever wondered how matter is formed? Is there an omnipotent entity that creates all the matter in the universe? To answer this question, theoretical physicists had developed a hypothetical particle that creates a field where the matter gets mass. Later it was named the Higgs Boson. It is also nicknamed the 'god particle'. The universe is a sophisticated interplay of elementary particles through fundamental forces at the quantum level. During the 1960s, theoretical physicists were in the pursuit of developing a quantum field theory. Here, both force carriers and matter particles are the materialisations of the elementary quantum fields. The standard model has the complete picture of every known fermion and bosons. The Higgs boson is an indispensable entity in particle physics that acts as a fundamental binding factor in the quantum realm. In other wordsthe Higgs boson is the fundamental particle associated with the Higgs field, a field that gives mass to other fundamental particles such as electrons and quarks. A particle's mass determines how much it resists changing its speed or position when it encounters a force. Although not all fundamental particles have mass. The photon, which is the particle of light and carries the electromagnetic force, has no mass at all. The Higgs boson was proposed in 1964 by Peter Higgs, François Englert, and four other theorists to explain why certain particles have mass. Scientists confirmed its existence in 2012 through the ATLAS and CMS experiments at the Large Hadron Collider (LHC) at CERN in Switzerland. This discovery led to the 2013 Nobel Prize in Physics being awarded to Higgs and Englert. Scientists are now studying the characteristic properties of the Higgs boson to determine if it precisely matches the predictions of the Standard Model of particle physics. If the Higgs boson deviates from the model, it may provide clues to thePhysicists explaining the fundamental particles and forces of our universe in terms of the Standard Model – a widely accepted framework based on quantum field theory that predicts almost all known particles and forces aside from gravity with great accuracy. (A separate theory, general relativity, is used for gravity.) In the Standard Model, the particles and forces in nature (aside from gravity) arise from properties of quantum fields known as gauge invariance and symmetries. Forces in the Standard Model are transmitted by particles known as gauge bosons.

SCIENTISTS



FRANCOIS ENGLERT

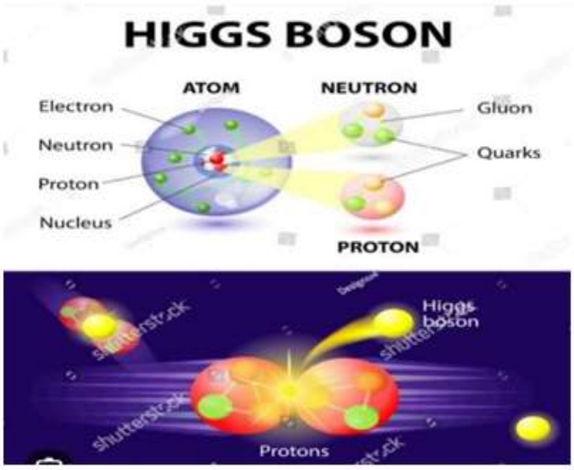
PETER WARE HIGGS

Methods and Materials Used For Theexperiment

Large Hadron Collider:

The **Large Hadron Collider** (**LHC**) is the world's largest and highest-energy particle collider. It was built by the European Organization for Nuclear Research (CERN) between 1998 and 2008 in collaboration with over 10,000 scientists and hundreds of universities and laboratories, as well as more than 100 countries. It lies in a tunnel 27 kilometres (17 mi) in circumference and as deep as 175 metres (57ft) beneath the France–Switzerland border near Geneva. The first collisions were achieved in 2010 at an energy of 3.5 tera electron volt (TeV) per beam, about four times the previous world record. The discovery of the Higgs boson at the LHC was announced in 2012. Between 2013 and 2015, the LHC was shut down and upgraded; after those upgrades it reached 6.5 TeV per beam (13.0 TeV total collision energy). At the end of 2018, it was shut down for three years for further upgrades.

The collider has four crossing points where the accelerated particles collide. Nine detectors, each designed to detect different phenomena, are positioned around the crossing points. The LHC primarily collides proton beams, but it can also accelerate beams of heavy ions: lead–lead collisions and proton–lead collisions are typically performed for one month a year. The LHC's goal is to allow physicists to test the predictions of different theories of particle physics, including measuring the properties of the Higgs boson, searching for the large family of new particles predicted by supersymmetric theories, and other unresolved questions in particle physics.



The LHC consist of 4 detectors which are as follows –

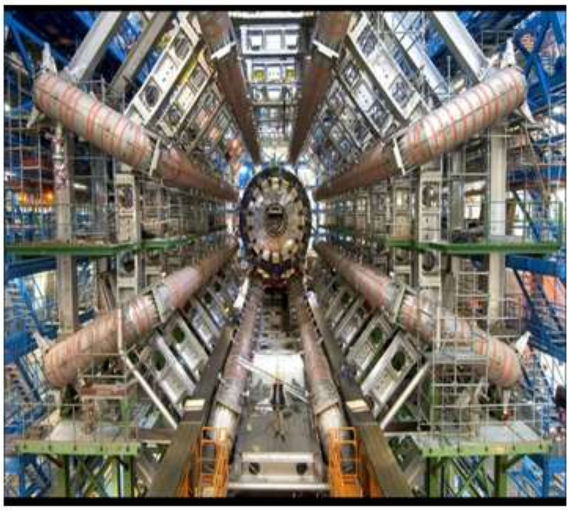
1 ATLAS
2 CMS
3 ALICE
4LHCb

The Traces of Higgs Boson Was Detected By both the Atlas and Compact Muon Solenoid (Cms) Detector

Atlas Detector:

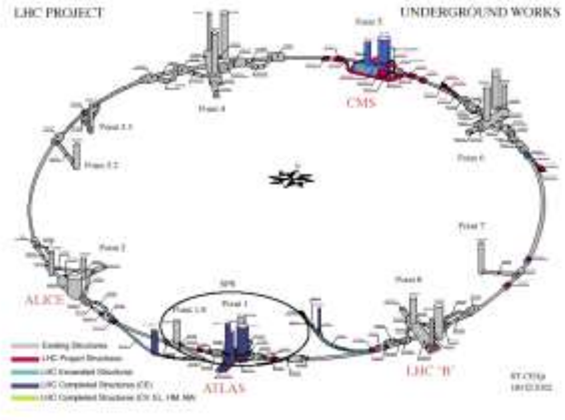
The world’s largest multi-purpose particle detector, ATLAS, is fully installed underground and in operation at CERN. Details of the different sub detectors are presented, together with expected performance aspects. The performance achievements obtained during the two real data-taking periods of ATLAS, cosmic rays and single beam runs of the LHC in fall 2008, are outlined.The ATLAS (A Toroidal Lhc ApparatuS) detector is one of the four experiments which will measure p-p (and Pb ion) collisions at the Large Hadron Collider

(LHC). The LHC is a 26.7 km ring which will provide collisions at a nominal center-of-mass energy of 14 TeV for protons (1150 TeV for Pb ions) with a design luminosity of 1034cm−2s−1. 2808 bunches, each containing O (1011) protons will collide every 25 ns (bunch crossing frequency of 40 MHz), resulting in a pile-up of ∼20 events at peak luminosity. This is an important challenge for the hardware and data acquistion of the four LHC experiments. With this unprecedented energy, the LHC detectors will be used to probe for new physics beyond the Standard Model. ATLAS is a multi-purpose particle physics detector, which means it should be able to measure the signatures of all the possible final stateswe expect to observe from proton-proton (or heavy ion) collisions. They include mainly: tracks from charged particles (hadrons, electrons, muons), energy deposition of electromagnetic and hadronic matter in the calorimeter system (through showering of the particles in many interaction length of material) and tracks from muons escaping the detector. The two main tracking devices, the Inner Detector and the Muon Spectrometer lie inside magnetic fields to allow the measurement of charge and momentum using the tracks. The passage of neutrinos through the detector can be measured using the missing transverse energy in the hermetically closed detector volume. A detailed description of the detector and its performance is presented here.



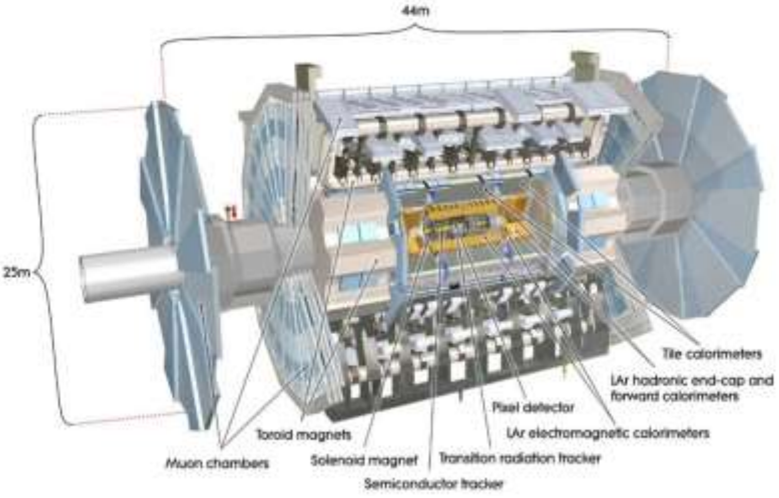
Layered design:

The interaction point where the particle beams collide, the detector is designed in layers made up of detectors of different types, each of which is designed to observe specific types of particles. The different traces that particles leave in each layer of the detector allow for effective particle identification and accurate measurements of energy and momentum. (The role of each layer in the detector is discussed below.) As the energy of the particles produced by the accelerator increases, the detectors attached to it must grow to effectively measure and stop higher-energy particles. As of 2022, the ATLAS detector is the largest ever built at a particle collider



Detector system:

The ATLAS detector consists of a series of ever-larger concentric cylinders around the interaction point where the proton beams from the LHC collide. Maintaining detector performance in the high radiation areas immediately surrounding the proton beams is a significant engineering challenge.



The detector can be divided into four major systems:

1) Inner Detector;
2) Calorimeters;
3) Muon Spectrometer;
4) Magnet system.

Each of these is in turn made of multiple layers. The detectors are complementary: the Inner Detector tracks particles precisely, the calorimeters measure the energy of easily stopped particles, and the muon system makes additional measurements of highly penetrating muons. The two magnet systems bend charged particles in the Inner Detector and the Muon Spectrometer, allowing their electric charges and momenta to be measured. The only established stable particles that cannot be detected directly are neutrinos; their presence is inferred by measuring a momentum imbalance among detected particles. For this to work, the detector must be "hermetic", meaning it must detect all non-neutrinos produced, with no blind spots. The installation of all the above detector systems was finished in August 2008. The detectors collected millions of cosmic rays during the magnet repairs which took place between fall 2008 and fall 2009, prior to the first proton collisions. The detector operated with close to 100% efficiency and provided performance characteristics very close to its design values.

Inner Detector:

The Inner Detector begins a few centimetres from the proton beam axis, extends to a radius of 1.2 metres, and is 6.2 metres in length along the beam pipe. Its basic function is to track charged particles by detecting their interaction with material at discrete points, revealing detailed information about the types of particles and their momentum. The Inner Detector has three parts, which are explained below. The magnetic field surrounding the entire inner detector causes charged particles to curve; the direction of the curve reveals a particle's charge and the degree of curvature reveals its momentum. The starting points of the tracks yield useful information for identifying particles; for example, if a group of tracks seem to originate from a point other than the original proton–proton collision, this may be a sign that the particles came from the decay of a hadron with a bottom quark

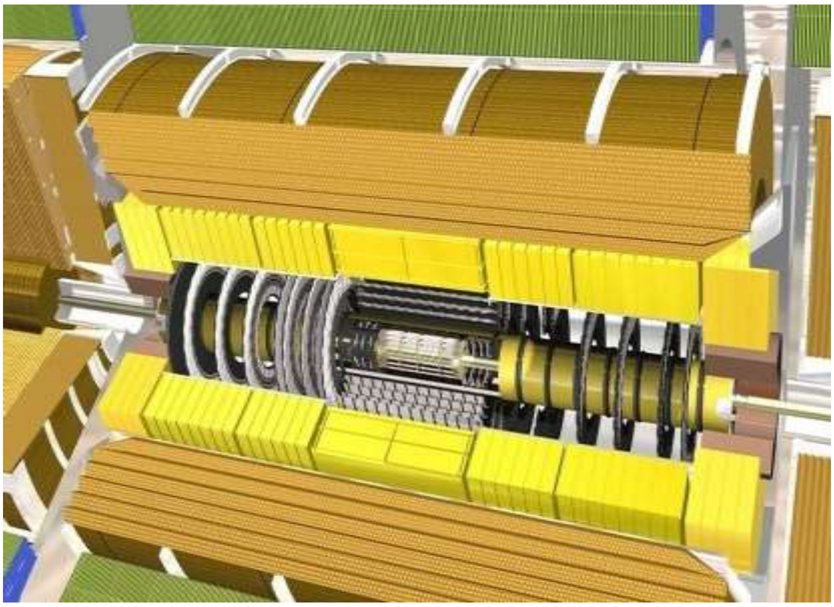
Pixel Detector:

The Pixel Detector, the innermost part of the detector, contains four concentric layers and three disks on each end-cap, with a total of 1,744 *modules*, each measuring 2 centimetres by 6 centimetres. The detecting material is 250 µm thick silicon. Each module contains 16 readout chips and other electronic components. The smallest unit that can be read out is a pixel (50 by 400 micrometres); there are roughly 47,000 pixels per module.

The minute pixel size is designed for extremely precise tracking very close to the interaction point. In total, the Pixel Detector has over 92 million readout channels, which is about 50% of the total readout channels of the whole detector. Having such a large count created a considerable design and engineering challenge. Another challenge was the radiation to which the Pixel Detector is exposed because of its proximity to the interaction point, requiring that all components be radiation hardened in order to continue operating after significant exposures.

Semi-Conductor Tracker*:*

The Semi-Conductor Tracker (SCT) is the middle component of the inner detector. It is similar in concept and function to the Pixel Detector but with long, narrow strips rather than small pixels, making coverage of a larger area practical. Each strip measures 80 micrometres by 12 centimetres. The SCT is the most critical part of the inner detector for basic tracking in the plane perpendicular to the beam, since it measures particles over a much larger area than the Pixel Detector, with more sampled points and roughly equal (albeit one-dimensional) accuracy. It is composed of four double layers of silicon strips, and has 6.3 million readout channels and a total area of 61 square meters.



Transition Radiation Tracker:

The Transition Radiation Tracker (TRT), the outermost component of the inner detector, is a combination of a straw tracker and a transition radiation detector. The detecting elements are drift tubes (straws), each four millimetres in diameter and up to 144 centimetres long. The uncertainty of track position measurements (position resolution) is about 200 micrometres. This is not as precise as those for the other two detectors, but it was necessary to reduce the cost of covering a larger volume and to have transition radiation detection capability. Each straw is filled with gas that becomes ionized when a charged particle passes through.

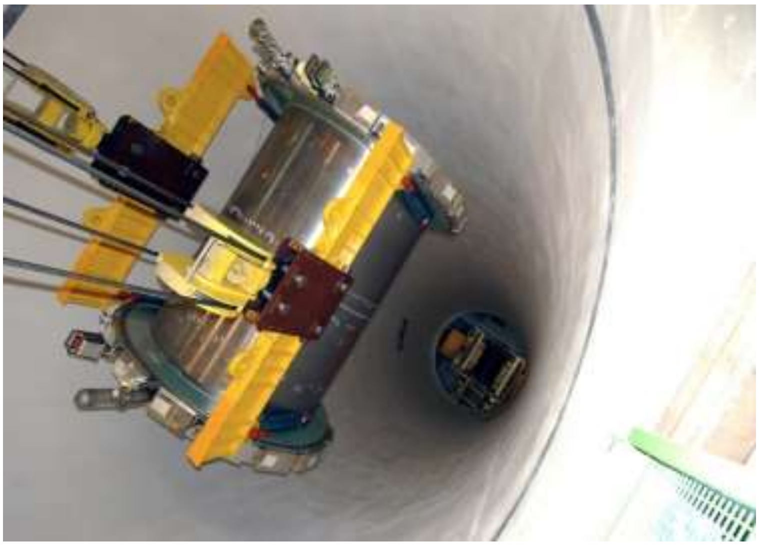
The straws are held at about −1,500 V, driving the negative ions to a fine wire down the centre of each straw, producing a current pulse (signal) in the wire. The wires with signals create a pattern of 'hit' straws that allow the path of the particle to be determined. Between the straws, materials with widely varying indices of refraction cause ultra-relativistic charged particles to produce transition radiation and leave much stronger signals in some straws. Xenon and argon gas is used to increase the number of straws with strong signals. Since the amount of transition radiation is greatest for highly relativistic particles (those with a speed very near the speed of light), and because particles of a particular energy have a higher speed the lighter they are, particle paths with many very strong signals can be identified as belonging to the lightest charged particles: electrons and their antiparticles, positrons. The TRT has about 298,000 straws in total.

Calorimeters:

The calorimeters are situated outside the solenoidal magnet that surrounds the Inner Detector. Their purpose is to measure the energy from particles by absorbing it. There are two basic calorimeter systems: an inner electromagnetic calorimeter and an outer hadronic calorimeter. Both are sampling calorimeters; that is, they absorb energy in high-density metal and periodically sample the shape of the resulting particle shower, inferring the energy of the original particle from this measurement.

Electromagnetic calorimeter:

The electromagnetic (EM) calorimeter absorbs energy from particles that interact electromagnetically, which include charged particles and photons. It has high precision, both in the amount of energy absorbed and in the precise location of the energy deposited. The angle between the particle's trajectory and the detector's beam axis (or more precisely the pseudorapidity) and its angle within the perpendicular plane are both measured to within roughly 0.025 radians. The barrel EM calorimeter has accordion shaped electrodes and the energy-absorbing materials are lead and stainless steel, with liquid argon as the sampling material, and a cryostat is required around the EM calorimeter to keep it sufficiently cool.

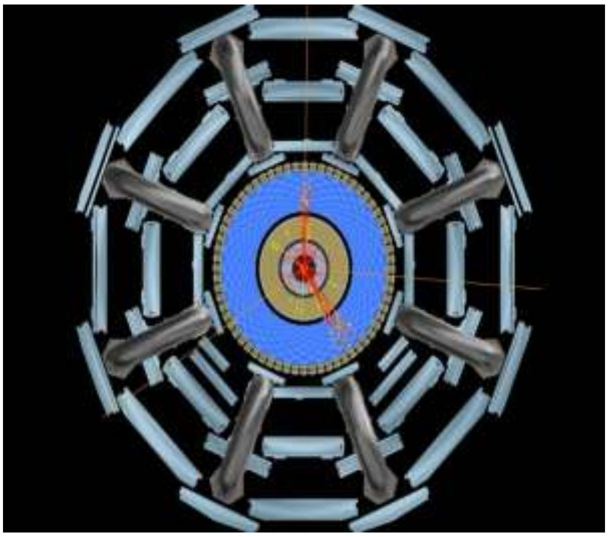


Hadron calorimeter:

The hadron calorimeter absorbs energy from particles that pass through the EM calorimeter, but do interact via the strong force; these particles are primarily hadrons. It is less precise, both in energy magnitude and in the localization (within about 0.1 radians only). The energy-absorbing material is steel, with scintillating tiles that sample the energy deposited. Many of the features of the calorimeter are chosen for their cost-effectiveness; the instrument is large and comprises a huge amount of construction material: the main part of the calorimeter – the tile calorimeter – is 8 metres in diameter and covers 12 metres along the beam axis. The far-forward sections of the hadronic calorimeter are contained within the forward EM calorimeter's cryostat, and use liquid argon as well, while copper and tungsten are used as absorbers.

Muon Spectrometer:

The Muon Spectrometer is an extremely large tracking system, consisting of three parts:

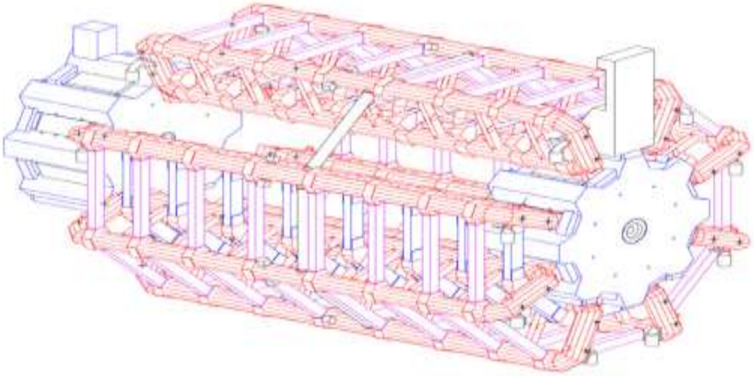


- A magnetic field provided by three toroidal magnets;
- A set of 1200 chambers measuring with high spatial precision the tracks of the outgoing muons;
- A set of triggering chambers with accurate time-resolution.

The extent of this sub-detector starts at a radius of 4.25 m close to the calorimeters out to the full radius of the detector (11 m). Its tremendous size is required to accurately measure the momentum of muons, which first go through all the other elements of the detector before reaching the muon spectrometer. It was designed to measure, standalone, and the momentum of 100 GeV muons with 3% accuracy and of 1 TeV muons with 10% accuracy. It was vital to go to the lengths of putting together such a large piece of equipment because a number of interesting physical processes can only be observed if one or more muons are detected, and because the total energy of particles in an event could not be measured if the muons were ignored. It functions similarly to the Inner Detector, with muons curving so that their momentum can be measured, albeit with a different magnetic field configuration, lower spatial precision, and a much larger volume. It also serves the function of simply identifying muons – very few particles of other types are expected to pass through the calorimeters and subsequently leave signals in the Muon Spectrometer. It has roughly one million readout channels, and its layers of detectors have a total area of 12,000 square meters.

Magnet System:

Two large superconducting magnet systems to bend the trajectory of charged particles, so that their momenta can be measured. This bending is due to the Lorentz force, whose modulus is proportional to the electric charge



Solenoid Magnet:

The inner solenoid produces a two tesla magnetic field surrounding the Inner Detector. This high magnetic field allows even very energetic particles to curve enough for their momentum to be determined, and its nearly uniform direction and strength allow measurements to be made very precisely. Particles with momenta below roughly 400 MeV will be curved so strongly that they will loop repeatedly in the field and most likely not be measured; however, this energy is very small compared to the several TeV of energy released in each proton collision.

Toroid Magnets:

The outer toroidal magnetic field is produced by eight very large air-core superconducting barrel loops and two smaller end-caps air toroidal magnets, for a total of 24 barrel loops all situated outside the calorimeters and within the muon system. This magnetic field extends in an area 26 metres long and 20 metres in diameter, and it stores 1.6 gigajoules of energy. Its magnetic field is not uniform, because a solenoid magnet of sufficient size would be prohibitively expensive to build. It varies between 2 and 8 Teslameters Forward detectors

Further information: ATLAS Forward Proton Project

The ATLAS detector is complemented by a set of four sub-detectors in the forward region to measure particles at very small angles.

LUCID (Luminosity Cherenkov Integrating Detector)

Is the first of these detectors designed to measure luminosity, and located in the ATLAS cavern at 17 m from the interaction point between the two muon endcaps;

ZDC (Zero Degree Calorimeter)

Is designed to measure neutral particles on-axis to the beam, and located at 140 m from the IP in the LHC tunnel where the two beams are split back into separate beam pipes;

AFP (Atlas Forward Proton)

Is designed to tag diffractive events, and located at 204 m and 217 m;

ALFA (Absolute Luminosity For ATLAS)

Is designed to measure elastic proton scattering located at 240 m just before the bending magnets of the LHC arc.

Data systems

Data generation:

Earlier particle detector read-out and event detection systems were based on parallel shared buses such as VMEbus or FASTBUS. Since such a bus architecture cannot keep up with the data requirements of the LHC detectors, all the ATLAS data acquisition systems rely on high-speed point-to-point links and switching networks. Even with advanced electronics for data reading and storage, the ATLAS detector generates too much raw data to read out or store everything: about 25 MB per raw event, multiplied by 40 million beam crossings per second (40 MHz) in the center of the detector. This produces a total of 1 petabyte of raw data per second. By avoiding to write empty segments of each event (zero suppression), which do not contain physical information, the average size of an event is reduced to 1.6 MB, for a total of 64 terabyte of data per second.

Trigger system:

The trigger system uses fast event reconstruction to identify, in real time, the most interesting events to retain for detailed analysis. In the second data-taking period of the LHC, Run-2, there were two distinct trigger levels:

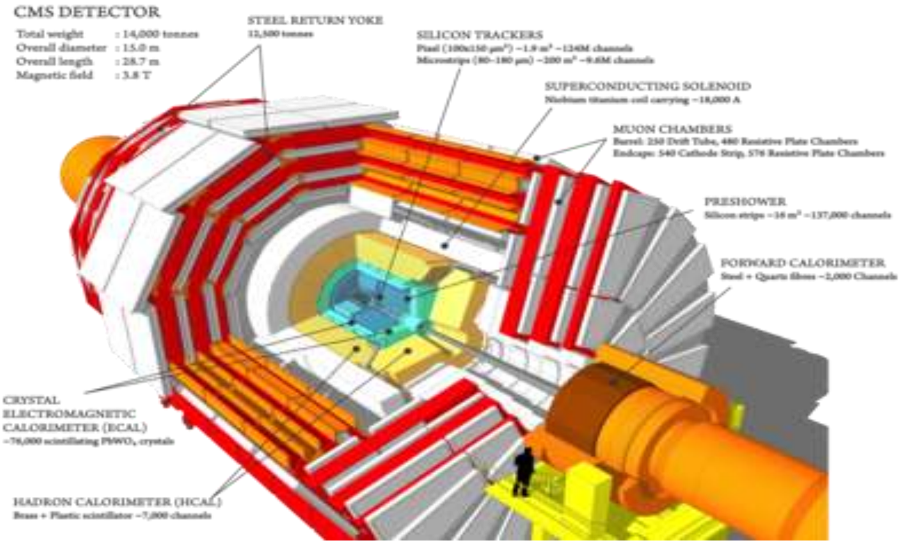
The Level 1 trigger (L1), implemented in custom hardware at the detector site. The decision to save or reject an event data is made in less than 2.5 μs. It uses reduced granularity information from the calorimeters and the muon spectrometer, and reduces the rate of events in the read-out from 40 MHz to 100 kHz. The L1 rejection factor in therefore equal to 400. The High Level Trigger trigger (HLT), implemented in software, uses a computer battery consisting of approximately 40,000 CPUs. In order to decide which of the 100,000 events per second coming from L1 to save, specific analyses of each collision are carried out in 200 μs. The HLT uses limited regions of the detector, so-called Regions of Interest (RoI), to be reconstructed with the full detector granularity, including tracking, and allows matching of energydeposits to tracks. The HLT rejection factor is 100: after this step, the rate of events is reduced from 100 to 1 kHz. The remaining data, corresponding to about 1,000 events per second, are stored for further analyses.

Analysis process:

ATLAS permanently records more than 10 petabytes of data per year.Offline event reconstruction is performed on all permanently stored events, turning the pattern of signals from the detector into physics objects, such as jets, photons, and leptons. Grid computing is being used extensively for event reconstruction, allowing the parallel use of university and laboratory computer networks throughout the world for the CPU-intensive task of reducing large quantities of raw data into a form suitable for physics analysis. The software for these tasks has been under development for many years, and refinements are ongoing, even after data collection has begun. Individuals and groups within the collaboration are continuously writing their own code to perform further analyses of these objects, searching the patterns of detected particles for particular physical models or hypothetical particles. This activity requires processing 25 petabyte of data per week

Compact Muon Solenoid:

The Compact Muon Solenoid (CMS) experiment is one of two large general-purposeparticle physicsdetectors built on the Large Hadron Collider (LHC) at CERN in Switzerland and France. The goal of the CMS experiment is to investigate a wide range of physics, including the search for the Higgs boson, extra dimensions, and particles that could make up dark matter.



CMS is 21 metres long, 15 m in diameter and weighs about 14,000 tonnes Over 4,000 people, representing 206 scientific institutes and 47 countries, form the CMS collaboration who built and now operate the detector. It is located in a cavern at Cessy in France, just across the border from Geneva. In July 2012, along with ATLAS, CMS tentatively discovered the Higgs boson.By March 2013 its existence was confirmed.

Background:

Recent collider experiments such as the now-dismantled Large Electron-Positron Collider and the newly renovated Large Hadron Collider (LHC) at CERN, as well as the (as of October 2011) recently closed Tevatron at Fermilab have provided remarkable insights into, and precision tests of, the Standard Model of Particle Physics. A principal achievement of these experiments (specifically of the LHC) is the discovery of a particle consistent with the Standard Model Higgs boson, the particle resulting from the Higgs mechanism, which provides an explanation for the masses of elementary particles. However, there are still many questions that future collider experiments hope to answer. These include uncertainties in the mathematical behaviour of the Standard Model at high energies, tests of proposed theories of dark matter (including supersymmetry), and the reasons for the imbalance of matter and antimatter observed in the Universe.

Physics goals:

Panorama of CMS detector, 100m below the ground.

The main goals of the experiment are:

- to explore physics at the TeV scale
- to further study the properties of the Higgs boson, already discovered by CMS and ATLAS
- to look for evidence of physics beyond the standard model, such as supersymmetry, or extra dimensions
- to study aspects of heavy ion collisions.

The ATLAS experiment, at the other side of the LHC ring is designed with similar goals in mind, and the two experiments are designed to complement each other both to extend reach and to provide corroboration of findings. CMS and ATLAS use different technical solutions and design of its detector magnet system to achieve the goals.

CMS Layers:

The interaction point:

This is the point in the centre of the detector at which proton-proton collisions occur between the two counter-rotating beams of the LHC. At each end of the detector magnets focus the beams into the interaction point. At collision each beam has a radius of 17 μm and the crossing angle between the beams is 285 μrad.

At full design luminosity each of the two LHC beams will contain 2,808 bunches of 1.15×10^{11} protons. The interval between crossings is 25 ns, although the number of collisions per second is only 31.6 million due to gaps in the beam as injector magnets are activated and deactivated.

At full luminosity each collision will produce an average of 20 proton-proton interactions. The collisions occur at a centre of mass energy of 8 TeV. But, it is worth noting that for studies of physics at the electroweak scale, the scattering events are initiated by a single quark or gluon from each proton, and so the actual energy involved in each collision will be lower as the total centre of mass energy is shared by these quarks and gluons (determined by the parton distribution functions). The first test which ran in September 2008 was expected to operate at a lower collision energy of 10 TeV but this was prevented by the 19 September 2008 shutdown. When at this target level, the LHC will have a significantly reduced luminosity, due to both fewer proton bunches in each beam and fewer protons per bunch. The reduced bunch frequency does allow the crossing angle to be reduced to zero however, as bunches are far enough spaced to prevent secondary collisions in the experimental beampipe.

Layer 1 – The tracker:

Momentum of particles is crucial in helping us to build up a picture of events at the heart of the collision. One method to calculate the momentum of a particle is to track its path through a magnetic field; the more curved the path, the less momentum the particle had. The CMS tracker records the paths taken by charged particles by finding their positions at a number of key points.

The tracker can reconstruct the paths of high-energy muons, electrons and hadrons (particles made up of quarks) as well as see tracks coming from the decay of very short-lived particles such as beauty or “b quarks” that will be used to study the differences between matter and antimatter. The tracker needs to record particle paths accurately yet be lightweight so as to disturb the particle as little as possible. It does this by taking position measurements so accurate that tracks can be reliably reconstructed using just a few measurement points. Each measurement is accurate to 10 µm, a fraction of the width of a human hair. It is also the inner most layer of the detector and so receives the highest volume of particles: the construction materials were therefore carefully chosen to resist radiation. The CMS tracker is made entirely of silicon: the pixels, at the very core of the detector and dealing with the highest intensity of particles, and the silicon microstrip detectors that surround it. As particles travel through the tracker the pixels and microstrips produce tiny electric signals that are amplified and detected. The tracker employs sensors covering an area the size of a tennis court, with 75 million separate electronic read-out channels: in the pixel detector there are some 6,000 connections per square centimetre.

The CMS silicon tracker consists of 14 layers in the central region and 15 layers in the endcaps. The innermost four layers (up to 16 cm radius) consist of 100 × 150 μm pixels, 124 million in total. The pixel detector was upgraded as a part of the CMS phase-1 upgrade in 2017, which added an additional layer to both the barrel and endcap, and shifted the innermost layer 1.5 cm closer to the beamline. The next four layers (up to 55 cm radius) consist of 10 cm × 180 μm silicon strips, followed by the remaining six layers of 25 cm × 180 μm strips, out to a radius of 1.1 m. There are 9.6 million strip channels in total. During full luminosity collisions the occupancy of the pixel layers per event is expected to be 0.1%, and 1–2% in the strip layers. The expected HL-LHC upgrade will increase the number of interactions to the point where over-occupancy would significantly reduce track-finding effectiveness. An upgrade is planned to increase the performance and the radiation tolerance of the tracker. This part of the detector is the world's largest silicon detector. It has 205 m^2 of silicon sensors (approximately the area of a tennis court) in 9.3 million microstrip sensors comprising 76 million channels.

Layer 2 – The Electromagnetic Calorimeter:

The Electromagnetic Calorimeter (ECAL) is designed to measure with high accuracy the energies of electrons and photons. The ECAL is constructed from crystals of lead tungstate, $PbWO_4$. This is an extremely dense but optically clear material, ideal for stopping high energy particles. Lead tungstate crystal is made primarily of metal and is heavier than stainless steel, but with a touch of oxygen in this crystalline form it is highly transparent and scintillates when electrons and photons pass through it. This means it produces light in proportion to the particle's energy. These high-density crystals produce light in fast, short, well-defined photon bursts that allow for a precise, fast and fairly compact detector. It has a radiation length of $\chi_0 = 0.89$ cm, and has a rapid light yield, with 80% of light yield within one crossing time (25 ns). This is balanced however by a relatively low light yield of 30 photons per MeV of incident energy. The crystals used have a front size of 22 mm × 22 mm and a depth of 230 mm. They are set in a matrix of carbon fibre to keep them optically isolated, and backed by silicon avalanche photodiodes for readout.

The ECAL, made up of a barrel section and two "endcaps", forms a layer between the tracker and the HCAL. The cylindrical "barrel" consists of 61,200 crystals formed into 36 "supermodules", each weighing around three tonnes and containing 1,700 crystals. The flat ECAL endcaps seal off the barrel at either end and are made up of almost 15,000 further crystals. For extra spatial precision, the ECAL also contains pre-shower detectors that sit in front of the endcaps. These allow CMS to distinguish between single high-energy photons (often signs of exciting physics) and the less interesting close pairs of low-energy photons. At the endcaps the ECAL inner surface is covered by the pre-shower subdetector, consisting of two layers of lead interleaved with two layers of silicon strip detectors. Its purpose is to aid in pion-photon discrimination.

Layer 3 – The Hadronic Calorimeter:

The Hadron Calorimeter (HCAL) measures the energy of hadrons, particles made of quarks and gluons (for example protons, neutrons, pions and kaons). Additionally it provides indirect measurement of the presence of non-interacting, uncharged particles such as neutrinos. The HCAL consists of layers of dense material (brass or steel) interleaved with tiles of plastic scintillators, read out via wavelength-shifting fibres by hybrid photodiodes. This combination was determined to allow the maximum amount of absorbing material inside of the magnet coil. The high pseudorapidity region (3.0\;<\;|\eta |\;<\;5.0) is instrumented by the Hadronic Forward (HF) detector. Located 11 m either side of the interaction point, this uses a slightly different technology of steel absorbers and quartz fibres for readout, designed to allow better separation of particles in the congested forward region. The HF is also used to measure the relative online luminosity system in CMS. About half of the brass used in the endcaps of the HCAL used to be Russian artillery shells.

Layer 4 – The magnet:

The CMS magnet is the central device around which the experiment is built, with a 4 Tesla magnetic field that is 100,000 times stronger than the Earth’s. CMS has a large solenoid magnet. This allows the charge/mass ratio of particles to be determined from the curved track that they follow in the magnetic field. It is 13 m long and 6 m in diameter, and its refrigerated superconducting niobium-titanium coils were originally intended to produce a 4 T magnetic field. The operating field was scaled down to 3.8 T instead of the full design strength in order to maximize longevity. The Inductance of the magnet is 14 H and the nominal current for 4 T is 19,500 A, giving a total stored energy of 2.66 GJ, equivalent to about half-a-tonne of TNT. There are dump circuits to safely dissipate this energy should the magnet quench. The circuit resistance (essentially just the cables from the power converter to the cryostat) has a value of 0.1 mΩ which leads to a circuit time constant of nearly 39 hours. This is the longest time constant of any circuit at CERN. The operating current for 3.8 T is 18,160 A, giving a stored energy of 2.3 GJ. The job of the big magnet Is to bend the paths of particles emerging from high-energy collisions in the LHC. The more momentum a particle has the less its path is curved by the magnetic field, so tracing its path gives a measure of momentum.

CMS began with the aim of having the strongest magnet possible because a higher strength field bends paths more and, combined with high-precision position measurements in the tracker and muon detectors, this allows accurate measurement of the momentum of even high-energy particles. The tracker and calorimeter detectors (ECAL and HCAL) fit snugly inside the magnet coil whilst the muon detectors are interleaved with a 12-sided iron structure that surrounds the magnet coils and contains and guides the field. Made up of three layers this “return yoke” reaches out 14 metres in diameter and also acts as a filter, allowing through only muons and weakly interacting particles such as neutrinos. The enormous magnet also provides most of the experiment’s structural support, and must be very strong itself to withstand the forces of its own magnetic field.

Layer 5 – The muon detectors and return yoke:

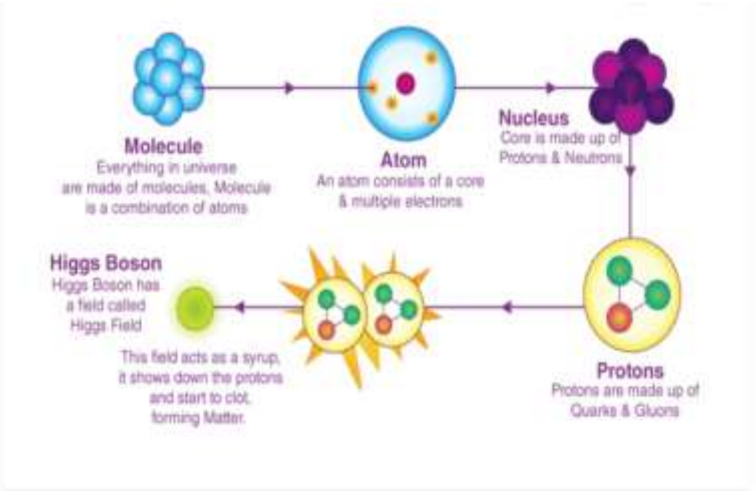
As the name “Compact Muon Solenoid” suggests, detecting muons is one of CMS's most important tasks. Muons are charged particles that are just like electrons and positrons, but are 200 times more massive. We expect them to be produced in the decay of a number of potential new particles; for instance, one of the clearest "signatures" of the Higgs Boson is its decay into four muons. Because muons can penetrate several metres of iron without interacting, unlike most particles they are not stopped by any of CMS's calorimeters. Therefore, chambers to detect muons are placed at the very edge of the experiment where they are the only particles likely to register a signal. To identify muons and measure their momenta, CMS uses three types of detector: drift tubes (DT), cathode strip chambers (CSC), resistive plate chambers (RPC), and Gas electron multiplier (GEM). The DTs are used for precise trajectory measurements in the central barrel region, while the CSCs are used in the end caps. The RPCs provide a fast signal when a muon passes through the muon detector, and are installed in both the barrel and the end caps. The drift tube (DT) system measures muon positions in the barrel part of the detector. Each 4-cm-wide tube contains a stretched wire within a gas volume. When a muon or any charged particle passes through the volume it knocks electrons off the atoms of the gas. These follow the electric field ending up at the positively charged wire. By registering where along the wire electrons hit (in the diagram, the wires are going into the page) as well as by calculating the muon's original distance away from the wire (shown here as horizontal distance and calculated by multiplying the speed of an electron in the tube by the time taken) DTs give two coordinates for the muon's position. Each DT chamber, on average 2 m x 2.5 m in size, consists of 12 aluminium layers, arranged in three groups of four, each with up to 60 tubes: the middle group measures the coordinate along the direction parallel to the beam and the two outside groups measure the perpendicular coordinate.

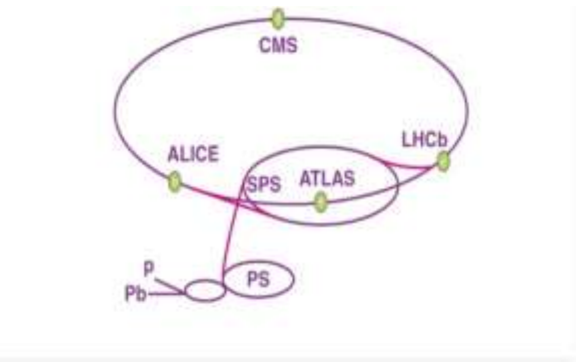
Cathode strip chambers (CSC) are used in the endcap disks where the magnetic field is uneven and particle rates are high. CSCs consist of arrays of positively charged “anode” wires crossed with negatively charged copper “cathode” strips within a gas volume. When muons pass through, they knock electrons off the gas atoms, which flock to the anode wires creating an avalanche of electrons. Positive ions move away from the wire and towards the copper cathode, also inducing a charge pulse in the strips, at right angles to the wire direction. Because the strips and the wires are perpendicular, we get two position coordinates for each passing particle. In addition to providing precise space and time information, the closely spaced wires make the CSCs fast detectors suitable for triggering. Each CSC module contains six layers making it able to accurately identify muons and match their tracks to those in the tracker. Resistive plate chambers (RPC) are fast gaseous detectors that provide a muon trigger system parallel with those of the DTs and CSCs. RPCs consist of two parallel plates, a positively charged anode and a negatively charged cathode, both made of a very high resistivity plastic material and separated by a gas volume. When a muon passes through the chamber, electrons are knocked out of gas atoms. These electrons in turn hit other atoms causing an avalanche of electrons.

The electrodes are transparent to the signal (the electrons), which are instead picked up by external metallic strips after a small but precise time delay. The pattern of hit strips gives a quick measure of the muon momentum, which is then used by the trigger to make immediate decisions about whether the data are worth keeping. RPCs combine a good spatial resolution with a time resolution of just one nanosecond (one billionth of a second). Gas electron multiplier (GEM) detectors represent a new muon system in CMS, in order to complement the existing systems in the endcaps. The forward region is the part of CMS most affected by large radiation doses and high event rates. The GEM chambers will provide additional redundancy and measurement points, allowing a better muon track identification and also wider coverage in the very forward region. The CMS GEM detectors are made of three layers, each of which is a 50 μm thick copper-cladded polyimide foil. These chambers are filled with an Ar/CO_2 gas mixture; where the primary ionisation due to incident muons will occur which subsequently result in an electron avalanche, providing an amplified signal

Discovery of Higgs Boson:

Since the 1960s, physicists have searched for the elusive ‘god particle’. The Higgs boson is extremely unstable and decays instantaneously. Therefore, it wasn’t easy to detect or observe it.





Particle accelerators in CERN have been conducting continuous experiments to find the particle. After 40 years of search, on 4 July 2012, an elementary particle with the exact characteristics (Higgs boson) was discovered by CMS and ATLAS experiments at LHC (Large Hadron Collider).Scientists have observed the new particle in the region in the vicinity of 125 GeV. The detected particle was consistent with the properties of the theoretical Higgs boson. However, further extensive studies have to be done to determine whether the particle is exactly the Higgs particle forecasted by the Standard Model. In 2013, Peter Higgs and François Englert were jointly awarded the Nobel Prize for the theoretical discovery of an identical mechanism related to the Higgs field. They developed a theoretical framework of ‘how particles get their mass?’. Observational results of the LHC confirmed their prediction.

What is a Higgs Boson?

The Higgs boson is the elementary particle linked with the Higgs field. It is a field that imparts mass to other subatomic particles, such as quarks and electrons. In other words, it is the boson or carrier particle of the Higgs field which fills the space and equips all the elementary particles with mass through its interplay with them. The Higgs particle is a scalar boson with positive parity, no electric charge, no colour charge and zero spins. It is very unstable, and perhaps it decays into other elementary particles instantly.The Higgs boson and Higgs field are named after the theoretical physicist

Peter Higgs. He is one of the physicists who introduced the basic concept of the Higgs field. Interestingly, science enthusiasts call it the God particle.

Higgs Field

The Higgs field is an energy field that is believed to be present in every area of the known universe. The field co-occurs with an elementary particle called the Higgs boson. The field constantly interacts with other fundamental particles like electrons, quarks, etc. In simple words, when indivisible particles interact with this field, they gain mass. The Higgs field does not create mass. If that is the case, it violates the laws of conservation (matter or energy cannot be created or destroyed). In reality, mass is gained by the particles through the interaction of the Higgs field with the Higgs boson. The Higgs boson has a relative mass in the form of energy. When a massless particle interacts with the field, the particle will slow down as the particle's mass will increase exponentially. If there is no Higgs field, particles will not have any mass and will float effortlessly at light speed. The Higgs field is a scalar quantity, with two electrically charged and two neutral components that make a sophisticated doublet of weak isospin symmetry. Its potential has nonzero reading everywhere, which shatters the weak isospin symmetry of the electro-weak interaction, and through the Higgs field, some particles gain mass. In technical terms, the Higgs mechanism uses bosons to acquire rest mass without directly disrupting gauge invariance.Higgs field was zero immediately after the big bang. As the universe's temperature dropped below a threshold value, the Higgs field grew instantaneously. Elementary particles started to gain mass by interacting with this field. The more a fundamental particle reacts with the field, the heavier it will become.

Why is the Higgs boson important?

In 1964, researchers had begun to use quantum field theory to study the weak nuclear force — which determines the atomic decay of elements by transforming protons to neutrons — and its force carriers the W and Z bosons. The weak force carriers should be massless, and if they weren't this risked breaking a principle of nature called symmetry which — just like the symmetry of a shape ensures it looks the same if it is turned or flipped — ensures the laws of nature are the same however they are viewed. Putting mass arbitrarily onto particles also caused certain predictions to trend towards infinity. Yet, researchers knew that because the weak force is so strong over short distance interactions — much more powerful than gravity — but very weak over longer interactions, its bosons must have mass.

The solution proposed by Peter Higgs François Englert, and Robert Brout, in 1964 was a new field and a way to "trick" nature into breaking symmetry spontaneously. An article from CERN compares this to a pencil standing on its tip — a symmetrical system — suddenly tipping to point in a preferred direction destroying its symmetry. Higgs and his fellow physicist proposed that when the universe was born it was filled with the Higgs field in a symmetrical, but unstable state — like the precariously balanced pencil The field quickly, in just fractions of a second, finds a stable configuration, but this in the process breaks its symmetry. This gives rise to the Brout-Englert-Higgs mechanism which grants mass to the W and Z bosons. What was later discovered about the Higgs field was that it would not only give mass to the W and Z bosons but that it would grant mass to many other fundamental particles. Without the Higgs field and the Brout-Englert-Higgs mechanism, all fundamental particles would race around the universe at the speed of light. This theory doesn't just explain why particles have mass but also, why they have different masses. Particles that interact — or "couple" — with the Higgs field more strongly are granted greater masses. Even the Higgs boson itself gets its mass from its own interaction with the Higgs field. This has been confirmed by watching how Higgs boson particles decay.

One particle not granted mass by the Higgs field is the basic particle of light — the photon. This is because spontaneous symmetry breaking doesn't happen for photons as it does for its fellow force-carrying particles the W and Z bosons. This mass-granting phenomenon also only applies to fundamental particles like electrons and quarks. Particles like protons —made up of quarks — get most of their mass from the binding energy that holds their constituents together. While all this conforms well to theory, the next step was to discover evidence of the Higgs field by detecting its force-carrying particle. Doing this would be no simple task, in fact, it would require the largest experiment and most sophisticated machine in human history. In this way, the search for the Higgs boson itself has pushed both particle accelerator and detector technology to its limits — with the ultimate expression of this being the Large Hadron Collider (LHC). How it started Large hadron collider [lhc] makes history Proton Beams Complete Circuit. The dots in this image represent the proton beam making its first trip around the Large Hadron Collider. The lower left dot is the injected beam beginning its 27 kilometer trip. The upper right dot is the same beam as it returns to the injection point. The fact that both dots appear in the same image is confirmation that the protons made it all the way around.

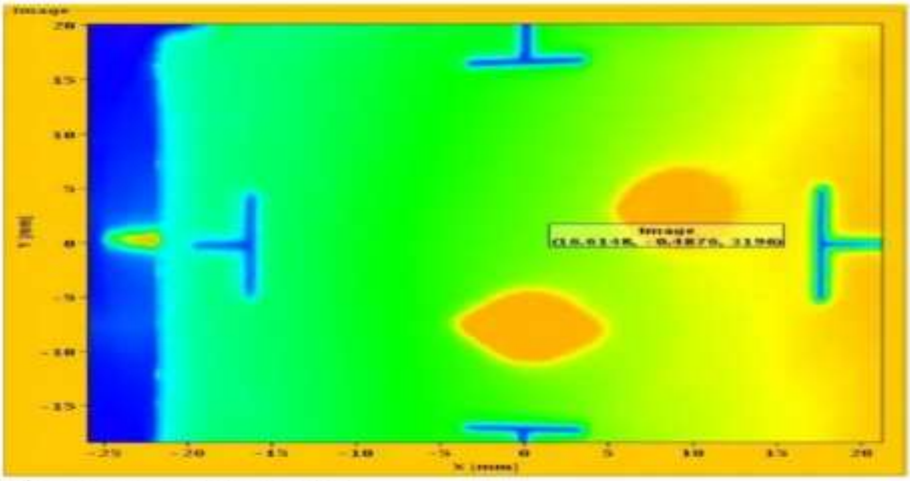


Photo courtesy CERN

A Particle is born: Making the Higgs Famous [Michael Schirber, July 2022]:

The Higgs discovery, announced on July 4, 2012, was a major happening in science but also in science communication. Rarely has so much effort been made to engage the public over a fundamental physics topic. Front-page headlines, best-selling books, public lectures, TV interviews, and feature-length films all tried to explain the Higgs boson—a particle whose claim to fame is its association with the generation of mass. Ten years later, the Higgs may not be a household name, but the intense limelight on this fundamental entity did offer communicators an opportunity to tell a larger story about the scientific enterprise. “The Higgs boson is the capstone of the standard model of particle physics,” says physicist Sean Carroll from the California Institute of Technology, who wrote about the Higgs in his 2012 book *The Particle at the End of the Universe*. He’s also helped to popularize the Higgs by giving public lectures, writing blogs, and making TV appearances. He believes the discovery was a “watershed moment,” as it showed that physicists were clearly on the right track with their understanding of the fundamental workings of the Universe. “That kind of accomplishment should not go unrecognized,” Carroll says.

CERN

So how have science communicators tried to make the Higgs boson famous? One of the earliest attempts was by the Nobel prize winner Leon Lederman, who wrote the 1993 popular science book *The God Particle*. In it, Lederman described the Higgs as the crucial but elusive piece to our understanding of the structure of matter. “[The book] was spectacularly successful in that you literally cannot have a conversation with a person on the street about the Higgs without someone talking about the God particle,” Carroll says. But many physicists regret the connection that was made between the Higgs and religion. “There’s a lot of work to be done in undoing the damage,” Carroll says. Another early attempt at capturing the public’s imagination came with the **cocktail party analogy**, which earned David Miller of the University College London a bottle of champagne from the UK science minister in 1993. Miller likened the Higgs field—a space-filling energy out of which the Higgs boson arises—to a bustling crowd of partygoers. When a celebrity tries to walk through the room, the crowd presses toward them, slowing their progress. In a similar way, the Higgs field can be drawn toward a particle, slowing its progress and giving it mass.

The Higgs is more drawn, for example, to the top quark than to the up quark, hence the top is more massive than the up. These types of metaphors offer a basic appreciation of the physics behind the Higgs boson and its field. But getting people to take the time to learn about the Higgs requires a more human approach, says Mark Levinson—director of the 2013 film *Particle Fever*. “If you really want to get the message out, if you want to engage a bigger audience, it needs to be personalized,” he says. His award-winning film—which ran in theaters across the globe and was distributed on Netflix—recounts the efforts at CERN in Switzerland leading up to the Higgs discovery, with Levinson’s cameras following a handful of theorists and experimentalists during their day-to-day activities. “It is interesting to show why people pursue these incredibly abstract ideas,” he says. When Levinson started shooting in 2008, he was not focused on the Higgs boson, as physicists had warned him that a discovery might take too long to materialize. But once promising signs showed up at CERN’s Large Hadron Collider (LHC), Levinson and his editor Walter Murch retooled their film’s narrative to give a leading role to the Higgs. They even created a graphic with the Higgs in the center—a representation that the physics community has come to embrace, Levinson says (Fig. **1**). The movie’s big climactic scene is when LHC scientists revealed their data to a packed auditorium that included a visibly moved Peter Higgs, who began working in the 1960s—along with other theorists—on his namesake particle. Seeing an 80-year-old physicist tear up over a vindication of his life’s work, “that’s a great story,” Levinson says. The 2012 announcement was a media hit as well, with over 12,000 news reports on the Higgs boson, according to James Gillies, who was head of CERN’s communication group when the discovery was announced (Fig. **2**). Like Levinson, Gillies believes the Higgs was an easy sell to the public because the human effort surrounding the discovery was so immense. “We cast fundamental science as the latest step in humankind’s journey of exploration,” he says. Gillies admits that it can be difficult to assess whether the Higgs excitement had a lasting impact on the public’s appreciation of fundamental science. Very little data has been collected on changes in scientific understanding following a big discovery. “But there’s no doubt in my mind that CERN, LHC, and Higgs are quite common currency these days,” Gillies says. “My experience has taught me that people are more curious about basic research than we tend to think.” Levinson agrees. “Many people have said, I really didn’t understand it, but I loved the film.” The science, he says, is rather complicated, but the story about scientists and their passion is something that audiences can identify with.

“The Higgs is fundamental to the physics theory, but it’s bigger than that,” Levinson says. “It’s more about our quest to understand the way the Universe works.” “There’s no shortage of enthusiasm among the public to learn about the Higgs boson,” Carroll says. He thinks science communicators can always do better, “but I think the Higgs boson is something where we did take advantage of the excitement to teach people a little bit of physics.” For his part, Carroll used the discovery to explain some of the quantum field theory that lies at the basis of the Higgs boson prediction. “We might as well leverage our big, happy discoveries to better acquaint the public with how science works and what scientists are finding.” Direct tests of the couplings of the Higgs boson to fermions confirmed the mechanism that gives mass to the W and Z bosons, thus making the electroweak interaction short range. A recent highlight is the direct observation of the Higgs boson coupling to muons. The observed properties of the Higgs boson put the standard model vacuum intriguingly close to the border between stable and metastable. Further connections to the open questions pertaining to baryogenesis, the nature of dark matter and dark energy and cosmic inflation mean that the Higgs boson is central to our understanding of the Universe. Precision measurements of the Higgs boson to further probe its interactions and possible deeper origin and structure are an essential part of the High-Luminosity Large Hadron Collider programme and were recently identified by the European Strategy for Particle Physics to be the highest priority for the next high-energy collider facility.

Higgs Boson after 10 Year or As of Now.

The discovery of the Higgs boson, ten years ago, was a milestone that opened the door to the study of a new sector of fundamental physical interactions. We review the role of the Higgs field in the Standard Model of particle physics and explain its impact on the world around us. We summarize the insights into Higgs physics revealed so far by ten years of work, discuss what remains to be determined and outline potential connections of the Higgs sector with unsolved mysteries of particle physics. Ten years ago, on 4 July 2012, scientists and journalists gathered at CERN, and remotely around the world, for the announcement of the discovery of a new fundamental particle, the Higgs boson. The discovery, by the ATLAS1 and CMS2 collaborations at the Large Hadron Collider (LHC), came almost 50 years after theorists had postulated the existence of such a particle. The significance of the discovery was not only that a new, long-awaited particle had been found, but that the existence of this particle provides first direct evidence that surrounding us there is a new kind of fundamental 'field', known as the Higgs field. Fields in physics are familiar in everyday life, for example in the form of the earth's magnetic field, and its impact on the needle of a compass. The most important difference between the Higgs field and a magnetic field is that if one removes the magnetic source, the magnetic field disappears. By contrast, the Higgs field is non-zero everywhere, all the time, independently of whether anything else is present in the Universe. In a way, it is reminiscent of the ancient Greek concept of Aether with the crucial difference that it is consistent with Einstein's theory of special relativity. Physicists' current theory of fundamental particles and forces is known as the Standard Model, a theoretical framework that provides a description of elementary particles and the forces that make them interact with one another, with the exception of gravity. Within the Standard Model, the Higgs field is essential to describe the world as we know it. As we shall see below, the strength of the interaction between any particle and the Higgs field directly affects a fundamental property of that particle: its mass. As such3, it ultimately determines the size of atoms, makes the proton stable and sets the timescale of radioactive (β) decays, which for example impact the lifetime of stars (Table 1). Yet, in everyday life, we do not notice that the Higgs field is all around us. The only way we have of revealing the Higgs field is to perturb it, a little like throwing a stone into water and seeing the ripples. The particle known as the Higgs boson is the manifestation of such a perturbation. The significance of its discovery in 2012 was such that the Nobel prize was awarded one year later to François Englert and Peter Higgs who, with the late Robert Brout, were the first to discuss the potential importance of such a field for fundamental physics4–6. Since then, the Higgs boson has become a powerful tool to study the ways in which the underlying Higgs field affects the fundamental particles of the Standard Model. Furthermore, the ubiquity of the Higgs field means that the Higgs boson is, today, widely used in the search for signatures of particles or effects that are hitherto unknown and lie outside the Standard Model.

The Higgs boson in the Standard Model In the Standard Model, aside from the Higgs boson, there are two kinds of particles. There are fermions, such as the up and down quarks and the electron, which make up ordinary matter. These specific particles (together with one of the three neutrinos) are called first-generation fermions. Two further sets of fermions (second and third generations) involve heavier particles, not normally present in the world around us. Additionally, there are the force carriers: the photon, the W and Z bosons and the gluon, collectively called vector bosons. When these are exchanged between two fermions, they create an attractive or repulsive force between those fermions: photons carry the electromagnetic force, W and Z bosons the weak force and gluons the strong force. In the 1960s, as physicists were taking the first steps towards assembling this picture, it remained unclear whether a self-consistent theory that included massive force carriers could be constructed. This question was being posed in the context of nuclear physics and also superconductivity in condensed matter physics. Researchers found that such a theory was ultimately possible if one introduced an interaction of the force carriers with a 'Higgs' field, and if one could also engineer a non-zero value for that field4–9. As the electroweak part of the Standard Model was being developed10–12, interactions of particles with a Higgs field were to become a central part of its formulation, especially in order to generate masses for the W and Z bosons, as required for consistency with experimental observations, while photons and gluons remain massless. Remarkably, interactions with the Higgs field also provided a consistent theoretical mechanism for producing fermion masses: each fermion interacts with the Higgs field with a different strength (or 'coupling'), and the stronger the interaction, the larger the resulting mass for the particle. Within the Standard Model the interaction is known as a 'Yukawa' interaction13. Thus any question about the origin of the masses of fermions reduces to a question about the origin of the interactions of fermions with the Higgs field. Why is the Higgs field non-zero in the first place? According to the Standard Model there is a potential energy density associated with the value of the

Higgs field and the lowest potential energy corresponds to a non-zero value of the Higgs field. The Standard Model potential has a form dictated by internal consistency conditions. With some simplifications, labelling the magnitude of the Higgs field as ϕ, the potential has the form

$$V(\phi) \propto -\phi^2 + \frac{1}{2}\phi^4 .$$

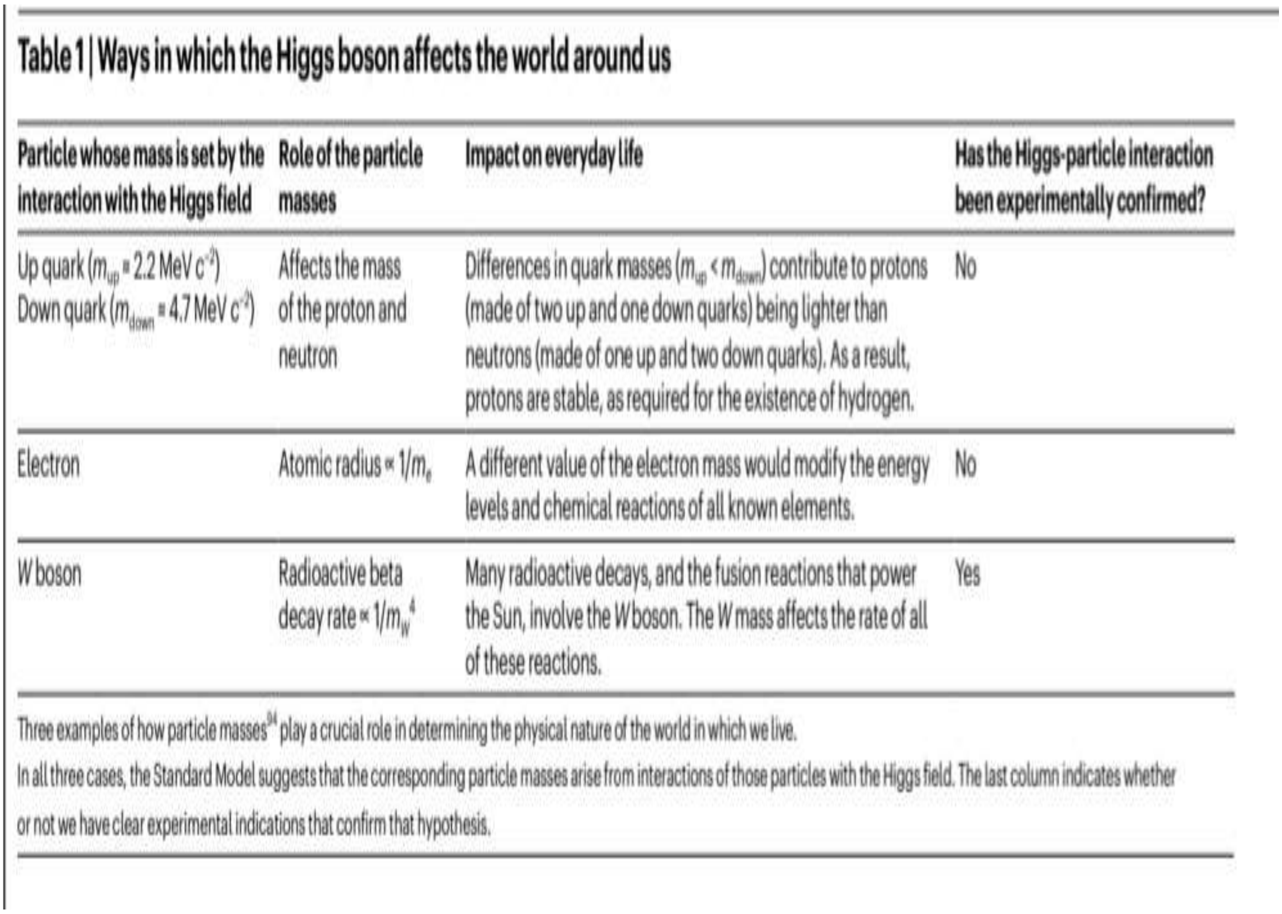


Table 1 | Ways in which the Higgs boson affects the world around us

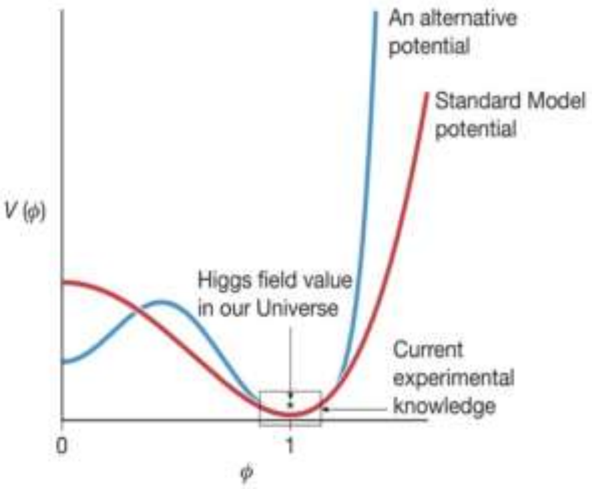
Particle whose mass is set by the interaction with the Higgs field	Role of the particle masses	Impact on everyday life	Has the Higgs-particle interaction been experimentally confirmed?
Up quark (m_{up} = 2.2 MeV c^{-2}) Down quark (m_{down} = 4.7 MeV c^{-2})	Affects the mass of the proton and neutron	Differences in quark masses ($m_{up} < m_{down}$) contribute to protons (made of two up and one down quarks) being lighter than neutrons (made of one up and two down quarks). As a result, protons are stable, as required for the existence of hydrogen.	No
Electron	Atomic radius ∝ $1/m_e$	A different value of the electron mass would modify the energy levels and chemical reactions of all known elements.	No
W boson	Radioactive beta decay rate ∝ $1/m_W^4$	Many radioactive decays, and the fusion reactions that power the Sun, involve the *W* boson. The *W* mass affects the rate of all of these reactions.	Yes

Three examples of how particle masses[94] play a crucial role in determining the physical nature of the world in which we live.

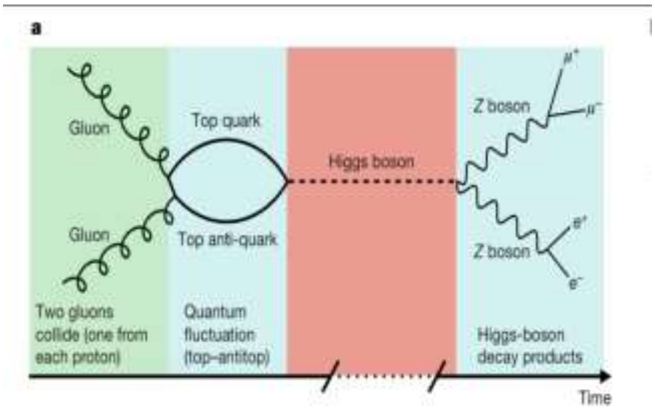
In all three cases, the Standard Model suggests that the corresponding particle masses arise from interactions of those particles with the Higgs field. The last column indicates whether or not we have clear experimental indications that confirm that hypothesis.

This is illustrated by the red line in Fig. 1. The minimum of the potential, that is, the energetically most favourable choice for ϕ, lies at a value of ϕ that is non-zero, $\phi = 1$. An important implication of the non-zero constant value of the Higgs field is the impossibility to carry angular momentum, or more technically having ‘spin 0’. A non-zero value for the spin would break at least one of the well-tested space–time symmetries. Hence, the excitation of the Higgs field, the Higgs boson, must be a spin-0 particle and it is in fact the only known fundamental particle with this property. One of the reasons for the central importance of the discovery of the Higgs boson was that it finally made it possible to start testing the remarkable theoretical picture outlined above. It is not possible to probe the interactions of a given particle with the Higgs field. However, one can instead measure a particle’s interaction with the excitations of the Higgs field, that is, with a Higgs boson. If the Standard Model provides the correct picture for the generation of mass, the strength of any particle’s interaction with the Higgs boson has to be directly related to that particle’s mass. Aside from providing a powerful way of testing the Higgs mechanism, the interaction of the Higgs boson with other particles is intriguing because it implies the existence of a ‘fifth force’, mediated by the exchange of Higgs bosons. The fact that such a force is stronger for heavier particles makes it qualitatively different from all other interactions in the Standard Model, whose interaction strengths come in multiples of some basic unit of charge, like the electron charge for the electric force. The pattern is, if anything, more reminiscent of gravity, but with

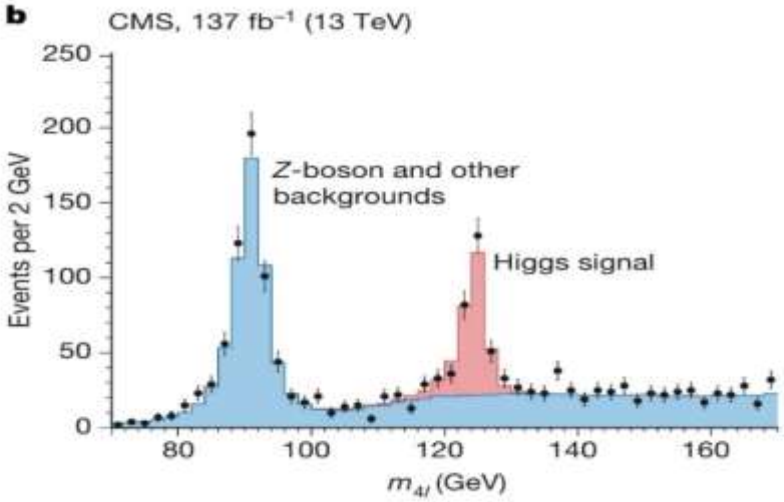
Fig. Higgs potential.



The potential energy density Vϕ () associated with the Higgs field ϕ, as a function of the value of ϕ. The red curve shows the potential within the Standard Model. The Higgs field has a value corresponding to a minimum of the potential and the region highlighted in black represents our current experimental knowledge of the potential. Alternative potentials that differ substantially from the Standard Model away from that minimum (for example, the blue curve) would be equally consistent with current data important differences. One is that the force mediated by the Higgs boson is active only at very short distances, whereas Einstein's gravity acts over all distance scales. Another is that the Higgs boson couples directly only to elementary Standard Model particles. By contrast, gravity couples to the total mass.



In ordinary matter, that total mass is much larger than the sum of the elementary particle masses, because the strong force contributes substantially to the proton and neutron masses14. What we know so far and how the Higgs mechanism provides the simplest model to explain particle masses in a way that is consistent with the electroweak interactions. As physicists we should seek to establish whether it is the model chosen by nature. Experimental studies of the Higgs boson take place at particle colliders. The likelihood of producing a Higgs boson in a collision becomes larger when the particles that collide interact strongly with the Higgs field, that is, when they are heavy. At the high centre-of-mass energies that are required, particle physicists know how to collide just two things: protons and electrons, as well as their antiparticles. That poses an issue, because electrons and the particles that make up protons are light, that is, they interact only very weakly with the Higgs boson. The approach of particle physicists is to exploit the occasional production of heavy particles in the high-energy collision of light particles, and to then have those heavy particles produce a Higgs boson. CERN's LHC collides protons, which are mostly made of up and down quarks and gluons. The most frequent way of producing a Higgs boson is for a pair of gluons, one from each proton, to collide and create a top quark and a top anti-quark as a very short-lived quantum fluctuation. The top quark is the heaviest known particle (about 184 times the proton mass) and so the top and anti-top quarks interact strongly with the Higgs field, thereby occasionally producing a Higgs boson. A short while later (about 10−22 s), the Higgs boson decays. About 2.6% of decays are to a pair of Z bosons, which themselves also decay almost immediately, for example each to an electron–positron or muon–anti-muon pair (so-called charged leptons), which gives a distinctive experimental signature. This sequence is illustrated in Fig. 2a. The ATLAS and CMS experiments at the LHC select events with four such leptons and record the total of the energy of the leptons (in their centre-of-mass frame). There are a variety of ways in which four leptons can be produced, but for those events in which they come from a Higgs-boson decay, the total energy is expected to cluster around the Higgs mass—the red peak in Fig. 2b. That red peak provides considerable information: (1) the existence of the peak near 125 GeV tells us that there is a new particle, the Higgs boson; (2) the position of the peak indicates the mass of the Higgs boson; (3) other features of the events in the peak, for example the relative angular distributions of



Conclusion:

The present study wants to explain the mechanism to how God particles acquire mass through their interactions with the Higgs field. The Higgs boson is a subatomic particle, often referred to as the "God particle," and is a fundamental component of the Standard Model of particle physics. If the Standard Model provides the correct picture for the generation of mass, the strength of any particle’s interaction with the Higgs boson has to be directly related to that particle’s mass. Aside from providing a powerful way of testing the Higgs mechanism, the interaction of the Higgs boson with other particles is intriguing because it implies the existence of a ‘fifth force’, mediated by the exchange of Higgs bosons. The fact that such a force is stronger for heavier particles makes it qualitatively different from all other interactions in the Standard Model, whose interaction strengths come in multiples of some basic unit of charge, like the electron charge for the electric force.

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