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Journey in the Search for the Higgs Boson: The ATLAS and CMS Experiments at the Large Hadron Collider

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The search for the standard model Higgs boson at the Large Hadron Collider (LHC) started more than two decades ago. Much innovation was required and diverse challenges had to be overcome during the conception and construction of the LHC and its experiments. The ATLAS and CMS Collaboration experiments at the LHC have discovered a heavy boson that could complete the standard model of particle physics.

One of the remarkable achievements of 20th-century science is the revelation that a large number of natural phenomena that characterize the world around us can be described in terms of underlying principles of great simplicity and beauty. The standard model (SM) of particle physics is built upon those principles. The SM comprises quarks and leptons as the building blocks of matter, and describes their interactions through the exchange of force carriers: the photon for electromagnetic interactions, the W and Z bosons for weak interactions, and the gluons for strong interactions. Quarks are bound by the strong interaction into protons and neutrons; protons and neutrons bind together into nuclei; electrons bind to nuclei by electromagnetic interaction to form atoms, molecules, and matter. The electromagnetic and weak interactions are unified in the electroweak theory (*1*–*3*). Although integrating gravity into the model remains a fundamental challenge, the SM provides a beautiful explanation, from first principles, of much of Nature that we observe directly.

The SM has been tested by many experiments over the past four decades and has been shown to successfully describe high-energy particle interactions. The simplest and most elegant way to construct the SM would be to assert that all fundamental particles are massless. However, we know this to be untrue, otherwise atoms would not have formed and we would not exist. The question of the origin of mass of fundamental particles is the same as the one that is posed in the unified electroweak theory: Why does the photon remain strictly massless while its close cousins, the W and Z bosons, acquire a mass some 100 times that of the proton? To generate mass of the W and Z bosons, the electroweak gauge symmetry must somehow be broken. For protons or neutrons, which are composite particles, most of the mass arises from the mass equivalent of the internal energy due to the intense binding field of the strong interactions.

Nearly 50 years ago, a mechanism was proposed for spontaneously breaking this symmetry (*4*–*9*) involving a complex scalar quantum field that permeates the entire universe. This new field has the same quantum numbers as the vacuum. The quantum of this field is called the Higgs boson. In addition to imparting mass to the W and Z bosons, this scalar field would also impart masses to the quarks and leptons, all in proportion to their coupling to this field. After the discovery of the W and Z bosons in the early 1980s, the search for the Higgs boson, considered to be an integral part of the SM, became a central theme in particle physics. The discovery of the Higgs boson would establish the existence of this field, leading to a revolutionary step in our understanding of how Nature works at the fundamental level. The elucidation of this mass-generating mechanism became one of the primary scientific goals of the Large Hadron Collider (LHC).

The mass of the Higgs boson (m_H) is not predicted by theory. Below m_H = 600 GeV, previous direct searches at the Large Electron Positron collider (LEP), the Tevatron, and the LHC were unable to exclude mass regions between 114 and 130 GeV (*10*–*14*). Furthermore, in December 2011, the A Toroidal LHC Apparatus (ATLAS) Collaboration and Compact Muon Solenoid (CMS) Collaboration experiments reported an excess of events near a mass of 125 GeV (*13*, *14*). The Tevatron experiments, CDF and D0, recently reported an excess of events in the range 120 to 135 GeV (*15*).

In July 2012, the discovery of a new heavy boson with a mass around 125 GeV was announced at CERN by the ATLAS and CMS experiments (*16*, *17*), and the current data are consistent with the expectation for a Higgs boson. Here, we present an overview of the search for the Higgs boson and highlight some of the exciting implications. Despite its incredible success the SM is still considered incomplete. A number of questions remain: Why would the mass of the Higgs boson be only ~10^2 GeV? What is dark matter? How does the matter-antimatter asymmetry arise? How is gravity to be included? Physics beyond the SM has been much discussed over the past few decades, and such physics might manifest itself via the production of exotic particles such as superparticles from a new symmetry (supersymmetry), heavy Z-like bosons in grand unified theories or theories with extra space-time dimensions.

Design challenges. In the 1980s, it was clear that new accelerators were needed that could reach energies beyond those that had allowed the discovery of many of the subnuclear particles within the SM. Several ideas were vigorously discussed concerning the accelerators and detector concepts most capable of tackling the major open questions in particle physics, often paraphrased as the "known unknowns," and possibly discovering new physics beyond the SM, the "unknown unknowns." Finding the Higgs boson was clearly a priority in the first category and was expected to be challenging. The mass of the Higgs boson (m_H) is not predicted by theory and could be as high as 1000 GeV (1 TeV). This required a search over a broad range of mass, ideally suiting an exploratory machine such as a high-energy proton-proton (pp) collider. The suitability arises from the fact that the energy carried by the protons is distributed among its constituent partons (quarks and gluons), allowing the entire range of masses to be "scanned" at the same time. The main mechanisms predicted to produce the Higgs boson involve the combination of these subnuclear particles and force carriers.

The accelerator favored at CERN to probe the TeV energy scale was a pp collider. The required energy of the collider can be estimated by considering the reaction in which a Higgs boson is produced with a mass, m_H, of 1 TeV. This happens via the WW fusion production mechanism. A quark from each of the protons radiates a W boson with an energy of ~0.5 TeV, implying that the radiating quark should carry an energy of ~1 TeV so as to have a reasonable probability of emitting such a W boson. Hence, the proton should have an energy of ~6 × 1 TeV, as the average energy carried by a quark inside the proton is about one-sixth of the proton energy. The LHC (*18*, *19*) was designed to accelerate protons to 7 TeV, an order of magnitude higher than the most powerful available accelerator, with an instantaneous pp collision rate of 800 million per second.

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It was proposed to build the new accelerator in the existing underground tunnel of LEP. Because the radius of the tunnel is fixed, the value of the magnetic field of the dipole-bending magnets had to be ~8.5 T to hold in orbit the 7-TeV protons. The main challenges for the accelerator were to build ~1200 superconducting dipoles, each 15 m in length, able to reach this magnetic field; the large distributed cryogenic plant to cool the magnets and other accelerator structures; and control systems for the beams. The stored energy in each of the beams at nominal intensity and energy is 350 MJ, equivalent to more than 80 kg of TNT. Hence, if the beam is lost in an uncontrolled way, it can do considerable damage to the machine components, which would result in months of down time [see (*18*, *19*) for further details].

The LHC was approved in 1994 and construction began in 1998. A parallel attempt to build an accelerator that could reach even higher energies was made with the Superconducting SuperCollider (SSC) in Texas in the late 1980s but was canceled in 1993 during the early stages of construction.

This search for the Higgs boson also provided a stringent benchmark for evaluating the physics performance of various experiment designs under consideration some 20 years ago. The predicted rate of production (= $\mathcal{L}\cdot\sigma$, where $\mathcal{L}$ is the instantaneous luminosity of the colliding beams, measured in units of $cm^{-2}\ s^{-1}$, and σ is the cross section of the production reaction, measured in units of cm^2) and natural width ($\Gamma = \hbar/\tau$, where τ is the lifetime, and $\hbar$ is Planck's constant divided by 2π) of the SM Higgs boson vary widely over the allowed mass range (100 to 1000 GeV). Once produced, the Higgs boson disintegrates immediately in one of several ways (decay modes) into known SM particles, depending on its mass. A search had to be envisaged not only over a large range of masses but also many possible decay modes: in pairs of photons, Z bosons, W bosons, τ leptons, and b quarks. Not only is the putative SM Higgs boson rarely produced in the proton collisions, it also rarely decays into particles that are the best identifiable signatures of its production at the LHC: photons, electrons, and muons. The rarity is illustrated by the fact that Higgs boson production and decay to one such distinguishable signature ($H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$, where [[[$\ell$]]] is a charged lepton, either a muon or an electron) happens roughly only once in 10 trillion pp collisions. This means that a large number of pp collisions per second must be studied; the current operating number is around 600 million per second, corresponding to an instantaneous luminosity of $7 \times 10^{33}\ cm^{-2}\ s^{-1}$. Hence, the ATLAS and CMS detectors operate in the harsh environment created by this huge rate of pp collisions.

A saying prevalent in the late 1980s and early 1990s captured the challenge that lay ahead: "We think we know how to build a high-energy, high-luminosity hadron collider—but we don't have the technology to build a detector for it." The role of the search for the Higgs boson at the LHC in influencing the design of the ATLAS and CMS experiments, and the experimental challenges associated with operating them at very high instantaneous collision rates, are described in (*20*).

Different values of m_H place differing demands on the detectors, none more stringent than in the mass range $m_H < 2 \times m_Z$ (where the mass of the Z boson $m_Z = 90$ GeV). In designing the LHC experiments, considerable emphasis was placed on this region. At masses below ~140 GeV, the SM Higgs boson is produced with a spread (natural width) of mass values of only a few MeV (i.e., a few parts in 10^5) such that the width of any observed mass peak would be entirely dominated by instrumental mass resolution. The Higgs boson decay modes generally accepted to be most promising in this region were those into two photons, occurring a few times in every thousand Higgs boson decays, and those, occurring even less often, into a pair of Z bosons, each of which in turn decays into a pair of two oppositely charged leptons (electrons or muons). However, in a detector with a very good muon momentum resolution and electron/photon energy resolution, the invariant mass of the parent Higgs bosons could be measured precisely enough with the prospect of seeing a narrow peak, over background, in the distribution of the invariant masses of the decay particles (e.g., two photons or four charged leptons). Early detailed studies can be found in (*21*, *22*).

Other signatures are associated with a Higgs boson. Most of these signatures are plagued by larger backgrounds, as the signal characteristics are less distinctive. For example, some of these signatures include narrow sprays of particles, known as "jets," resulting from the fragmentation of quarks. These represent the most likely final states from the decay of a SM Higgs boson, but in a hadron collider they are overwhelmed by the copious production from known SM processes. Among these jets are b quark jets characterized by a short (submillimeter) flight path in the detector before disintegrating. Finally, neutrinos can be produced, which, as neutral weakly interacting leptons, leave the detector without direct trace. Energy balance in the transverse plane of the colliding protons appears to be violated, as the neutrino energy is not measured, leading to the signature of missing transverse energy (E_T^{miss}). For example, when a Higgs boson decays into two Z bosons, one can decay into a charged lepton pair and the other into a pair of neutrinos, leaving as final state an oppositely charged lepton pair and E_T^{miss}.

The conditions in hadron colliders are more ferocious than in electron-positron colliders. For example, at the LHC ~1000 charged particles from ~20 pp interactions emerge from the interaction region in every crossing of the proton bunches. Highly granular detectors (to give low probability of a given cell or channel registering a hit or energy), with fast response and good time resolution, are required. Tens of millions of detector electronic channels are hence required, and these must be synchronized to cleanly separate the different "bursts" of particles emerging from the interaction point every 25 ns. The enormous flux of particles emerging from the interaction region leads to high radiation levels in the detecting elements and the associated front-end electronics. This presented challenges for detectors and electronics not previously encountered in particle physics.

The counterrotating LHC beams are organized in 2808 bunches comprising some 10^{11} protons per bunch separated by 25 ns, leading to a bunch crossing rate of ~40 MHz (the LHC accelerator currently operates at 50-ns bunch spacing with 1380 bunches). The event selection process ("trigger") must reduce this rate to ~0.5 kHz for storage and subsequent detailed offline analysis. New collisions occur in each crossing, and a trigger decision must be made for every crossing. It is not feasible to make a trigger decision in 25 ns; it takes about 3 μs. During this time the data must be stored in pipelines integrated into onboard (front-end) electronics associated with almost every one of 100 million electronic channels in each experiment. This online event selection process proceeds in two steps: The first step reduces the rate from ~40 MHz to a maximum of 100 kHz and comprises hardware processors that use coarse information from the detectors; upon receipt of a positive trigger signal (set by high-momentum muons or high-energy deposits in calorimeters; see below), the data from these events are transferred to a processor farm, which uses event reconstruction algorithms operating in real time to decrease the event rate to ~0.5 kHz before data storage. The tens of petabytes that are generated per year per experiment are distributed to scientists located across the globe and motivated the development of the so-called Worldwide LHC Computing Grid (WLCG) (*23*).

Timeline and general features of the ATLAS and CMS experiments. To accomplish the physics goals, new detector technologies had to be invented and most of the existing technologies had to be pushed to their limits. Several detector concepts were proposed; two complementary ones, ATLAS and CMS, were selected in 1993 after peer review to proceed to detailed design (*24*–*27*). These designs were fully developed, and all elements prototyped and tested, over many years before construction commenced around

1997. Today each experiment comprises more than 3000 scientists and engineers from around 180 universities and laboratories in around 40 countries. Table 1 provides a timeline of these developments.

The typical form of a collider detector is a "cylindrical onion" containing four principal layers. A particle emerging from the collision and traveling outward will first encounter the inner tracking system, immersed in a uniform magnetic field, comprising an array of pixels and microstrip detectors. These measure precisely the trajectory of the spiraling charged particles and the curvature of their paths, revealing their momenta. The stronger the magnetic field, the higher the curvature of the paths, and the more precise the measurement of each particle's momentum. The energies of particles are measured in the next two layers of the detector, the electromagnetic (em) and hadronic calorimeters. Electrons and photons will be stopped by the em calorimeter; jets will be stopped by both the em and hadronic calorimeters. The only known particles that penetrate beyond the hadron calorimeter are muons and neutrinos. Muons, being charged particles, are tracked in dedicated muon chambers. Their momenta are also measured from the curvature of their paths in a magnetic field. Neutrinos escape detection, and their presence gives rise to E_T^{miss}.

ATLAS and CMS have differing but complementary designs (*28*, *29*). The single most important aspect of the overall design is the choice of the magnetic field configuration for measuring the muons. The two basic configurations are solenoidal and toroidal, in which the magnetic field is parallel or azimuthal to the beam axis, respectively. The CMS has a superconducting high-field solenoid with a large ratio of length to inside diameter; ATLAS has a superconducting air-core toroid. These are the two largest magnets of their kind and hold a stored energy of up to 3 GJ. In both magnets a current of ~20 kA flows through the superconductor. The CMS solenoid additionally provides the magnetic field for the inner tracking system, whereas ATLAS has an additional solenoid magnet to carry out the same function.

At the nominal pp collision rate, the particle flux varies from 10^8 cm^{-2} s^{-1} (at a radius of r = 4 cm) to 2×10^6 cm^{-2} s^{-1} (at r = 50 cm), requiring small detection cells (channels) of typical size varying from 100 μm × 100 μm (pixels) to 10 cm × 100 μm (microstrips). The more channels there are, the easier it is to recognize the trajectories of all the charged particles produced. In practice, the number of channels is limited by the cost of the associated electronics, by the power they dissipate (which in turn requires cooling fluids), and by the need to minimize the amount of material in front of the em calorimeter. The inner tracker detectors, comprising silicon sensors and gaseous "straw" chambers, were challenging to develop because of the need to operate in a harsh radiation environment, especially when close to the beam pipe. Radiation-hard electronics associated with each cell, with a high degree of functionality, needed to be packed into as small a space as possible, using as little material as possible.

In the early 1990s there were only two complementary possibilities for the em calorimeters that could perform in a high-radiation environment and had good enough electron and photon energy resolution to cleanly detect the two-photon decay of the SM Higgs boson at low mass: a lead–liquid argon sampling calorimeter, chosen by ATLAS, and fully sensitive dense lead tungstate scintillating crystals, chosen by CMS. Both are novel techniques, and each was tested and developed over many years before mass production could commence. The electrons and positrons in the electromagnetic showers excite atoms of lead tungstate or ionize atoms of liquid argon, respectively. The amount of light emitted, or charge collected, is proportional to the energy of the incoming electrons or photons.

The hadron calorimeters in each detector are similar and are based on known technologies: alternating layers of iron or brass absorber in which the particles interact, producing showers of secondary particles, and plastic scintillator plates that sample the energy of these showers. The total amount of scintillation light detected by the photodetectors is proportional to the incident energy.

The muon detectors used complementary technologies based on gaseous chambers: drift chambers and cathode strip chambers that provide precise position measurement (and also provide a trigger signal in the case of CMS), and thin-gap chambers and/or resistive plate chambers that provide precise timing information as well as a fast trigger signal.

The electronics on the detectors, much of which was manufactured in radiation-hard technology, represented a substantial part of the materials cost of the LHC experiments. The requirement of radiation hardness was previously found only in military and space applications.

The construction of the various components of the detectors took place over about 10 years in universities, national laboratories, and industries, from which they were sent to CERN in Geneva. This paper can do only partial justice to the technological challenges that had to be overcome in developing, constructing, and installing all the components in the large underground caverns. All the detector elements were connected to the off-detector electronics, and data were fed to computers housed in a neighboring service cavern. Each experiment has more than 50,000 cables with a total length exceeding 3000 km, and more than 10,000 pipes and tubes for services (cooling, ventilation, power, signal transmission, etc.). Access to repair any substantial fault, or faulty connection, buried inside the experiment would require months just to open the experiments. Hence, a high degree of long-term operational reliability, which is usually associated with space-bound systems, had to be attained.

The design of the ATLAS experiment. The design of the ATLAS detector (*28*) was based on a superconducting air-core toroid magnet system containing ~80 km of superconductor cable in eight separate barrel coils (each 25 m × 5 m in a "racetrack" shape) and two matching end-cap

Table 1. The timeline of the LHC project.

1984	Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne.
1987	Workshop on Physics at Future Accelerators, La Thuile, Italy; the Rubbia "Long-Range Planning Committee" recommends the LHC as the right choice for CERN's future
1990	European Committee for Future Accelerators (ECFA) LHC Workshop, Aachen, Germany (discussion of physics, technologies, and designs for LHC experiments)
1992	General Meeting on LHC Physics and Detectors, Évian-les-Bains, France (four general-purpose experiment designs presented along with their physics performance)
1993	Three letters of intent evaluated by the CERN peer review committee LHCC; ATLAS and CMS selected to proceed to a detailed technical proposal
1995	The LHC accelerator approved for construction
1996	ATLAS and CMS technical proposals approved
1997	Formal approval for ATLAS and CMS to move to construction (materials cost ceiling of 475 million Swiss francs)
1997	Construction commences [after approval of detailed engineering design of subdetectors (magnets, inner tracker, calorimeters, muon system, trigger, and data acquisition)]
2000	Assembly of experiments commences; LEP accelerator is closed down to make way for the LHC
2008	LHC experiments ready for pp collisions; LHC starts operation; an incident stops LHC operation
2009	LHC restarts operation; pp collisions recorded by LHC detectors
2010	LHC collides protons at high energy (center-of-mass energy of 7 TeV)
2012	LHC operates at 8 TeV; discovery of a Higgs-like boson

toroid systems. A field of ~0.5 T is generated over a large volume. The toroids are complemented with a smaller solenoid (diameter 2.5 m, length 6 m) at the center, which provides a magnetic field of 2 T.

The detector includes an em calorimeter complemented by a full-coverage hadronic calorimeter for jet and E_T^{miss} measurements. The em calorimeter is a cryogenic lead–liquid argon sampling calorimeter in a novel "accordion" geometry allowing fine granularity, both laterally and in depth, and full coverage without any uninstrumented regions. A plastic scintillator–iron sampling hadronic calorimeter, also with a novel geometry, is used in the barrel part of the experiment. Liquid argon hadronic calorimeters are used in the end-cap regions near the beam axis. The em and hadronic calorimeters have 200,000 and 10,000 cells, respectively, and are in an almost field-free region between the toroids and the solenoid. They provide fine lateral and longitudinal segmentation.

The momentum of the muons can be precisely measured as they travel unperturbed by material for more than ~5 m in the air-core toroid field. About 1200 large muon chambers of various shapes, with a total area of 5000 m^2, measure the impact position with an accuracy better than 0.1 mm. Another set of about 4200 fast chambers are used to provide the "trigger." The chambers were built in about 20 collaborating institutes on three continents. (This was also the case for other components of the experiment.)

The reconstruction of all charged particles, including that of displaced vertices, is achieved in the inner detector, which combines highly granular pixel (50 μm × 400 μm elements leading to 80 million channels) and microstrip (13 cm × 80 μm elements leading to 6 million channels) silicon semiconductor sensors placed close to the beam axis, and a "straw tube" gaseous detector (350,000 channels), which provides about 30 to 40 signal hits per track. The latter also helps in the identification of electrons using information from the effects of transition radiation.

The air-core magnet system allows a relatively lightweight overall structure leading to a detector weighing 7000 tonnes. The muon spectrometer defines the overall dimensions of the ATLAS detector: a diameter of 22 m and a length of 46 m. Given its size and structure, the ATLAS detector had to be assembled directly in the underground cavern. Figure 1 shows one end of the cylindrical barrel detector after about 4 years of installation work, 1.5 years before completion. The ends of four of the barrel toroid coils are visible, illustrating the eightfold symmetry of the structure.

The design of the CMS experiment. The design of the CMS detector (*29*) was based on a superconducting high-field solenoid, which first reached the design field of 4 T in 2006. The CMS design was first optimized to detect muons from the H → ZZ → 4μ decay. To identify these muons and measure their momenta, the interaction region of the CMS detector is surrounded with enough absorber material, equivalent to about 2 m of iron, to stop all the particles produced except muons and neutrinos. The muons have spiral trajectories in the magnetic field, which are reconstructed in the surrounding drift chambers. The CMS solenoid was designed to have the maximum magnetic field considered feasible at the time, 4 T. This is produced by a current of 20 kA flowing through a reinforced Nb-Ti superconducting coil built in four layers. Economic and transportation

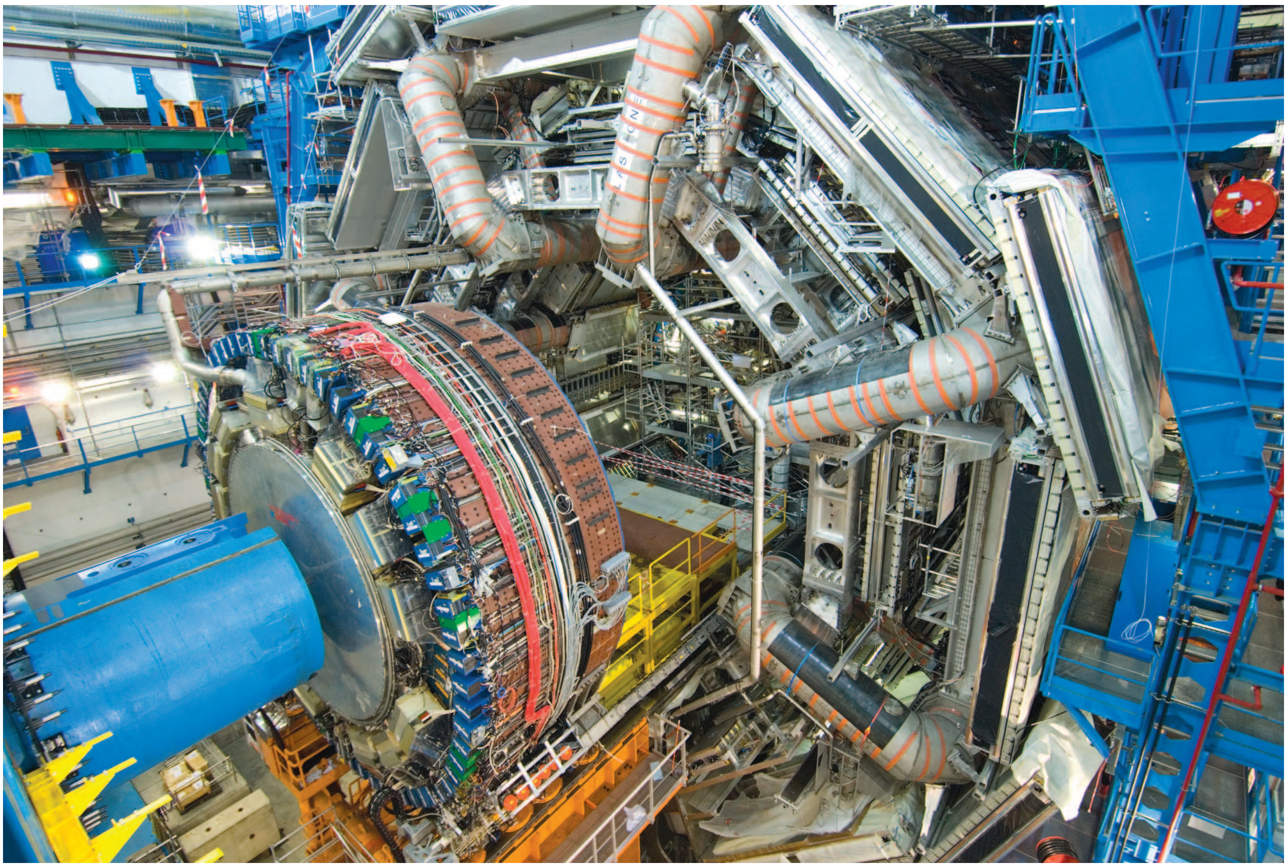

Fig. 1. Photograph of one end of the ATLAS detector barrel with the calorimeter end cap still retracted before its insertion into the barrel toroid magnet structure (February 2007 during the installation phase).

constraints limited the outer radius of the coil to 3 m and its length to 13 m. The field is returned through an iron yoke, 1.5 m thick, which houses four muon stations to ensure robustness of measurement and full geometric coverage. The iron yoke is sectioned into five barrel wheels and three end-cap disks at each end, for a total weight of 12,500 tonnes. The sectioning enabled the detector to be assembled and tested in a large surface hall while the underground cavern was being prepared. The sections, weighing 350 to 2000 tonnes, were then lowered sequentially between October 2006 and January 2008, using a dedicated gantry system equipped with strand jacks; this represented the first use of this technology to simplify the underground assembly of large experiments.

The next design priority was driven by the search for the decay of the SM Higgs boson into two photons. This called for an em calorimeter with the best possible energy resolution. A new type of crystal was selected: lead tungstate ($PbWO_4$) scintillating crystal. Five years of research and development (1993–1998) were necessary to improve the transparency and the radiation hardness of these crystals, and it took more than 10 years (1998–2008) of round-the-clock production to manufacture the 75,848 crystals—more crystals than were used in all previous particle physics experiments put together. The last of the crystals was delivered in March 2008.

The solution to charged particle tracking was to opt for a small number of precise position measurements of each charged track (~13 each with a position resolution of ~15 μm per measurement), leading to a large number of cells distributed inside a cylindrical volume 5.8 m in length and 2.5 m in diameter: 66 million silicon pixels, each 100 μm × 150 μm, and 9.3 million silicon microstrips ranging from ~10 cm × 80 μm to ~20 cm × 180 μm. With 198 m^2 of active silicon area, the CMS tracker is by far the largest silicon tracker ever built.

Finally, the hadron calorimeter, comprising ~3000 small solid angle projective towers covering almost the full solid angle, is built from alternate plates of ~5 cm brass absorber and ~4-mm-thick scintillator plates that sample the energy. The scintillation light is detected by photodetectors (hybrid photodiodes) that can operate in the strong magnetic field. Figure 2 shows the transverse view of the barrel part of CMS in late 2007 during the installation phase in the underground cavern.

Preparation of the experiments. All detector components were tested at their production sites, after delivery to CERN, and again after their installation in the underground caverns. The experiments made use of the constant flow of cosmic rays impinging on Earth. Even at depths of 100 m, there is still a small flux of muons—a few hundred per second traversing each of the experiments. The muons were used to check the whole chain from the hardware to the analysis programs of the experiments, and also to align the detector elements and calibrate their response prior to pp collisions (*30*, *31*).

The ATLAS and CMS experiments would generate huge amounts of data (tens of petabytes of data per year; 1 PB = 10^6 GB), requiring a fully distributed computing model. The LHC Computing Grid allows any user anywhere access to any data recorded or calculated during the lifetime of the experiments. The computing system consists of a hierarchical architecture of tiered centers, with one large Tier-0 center at CERN, about 10 large Tier-1 centers at national

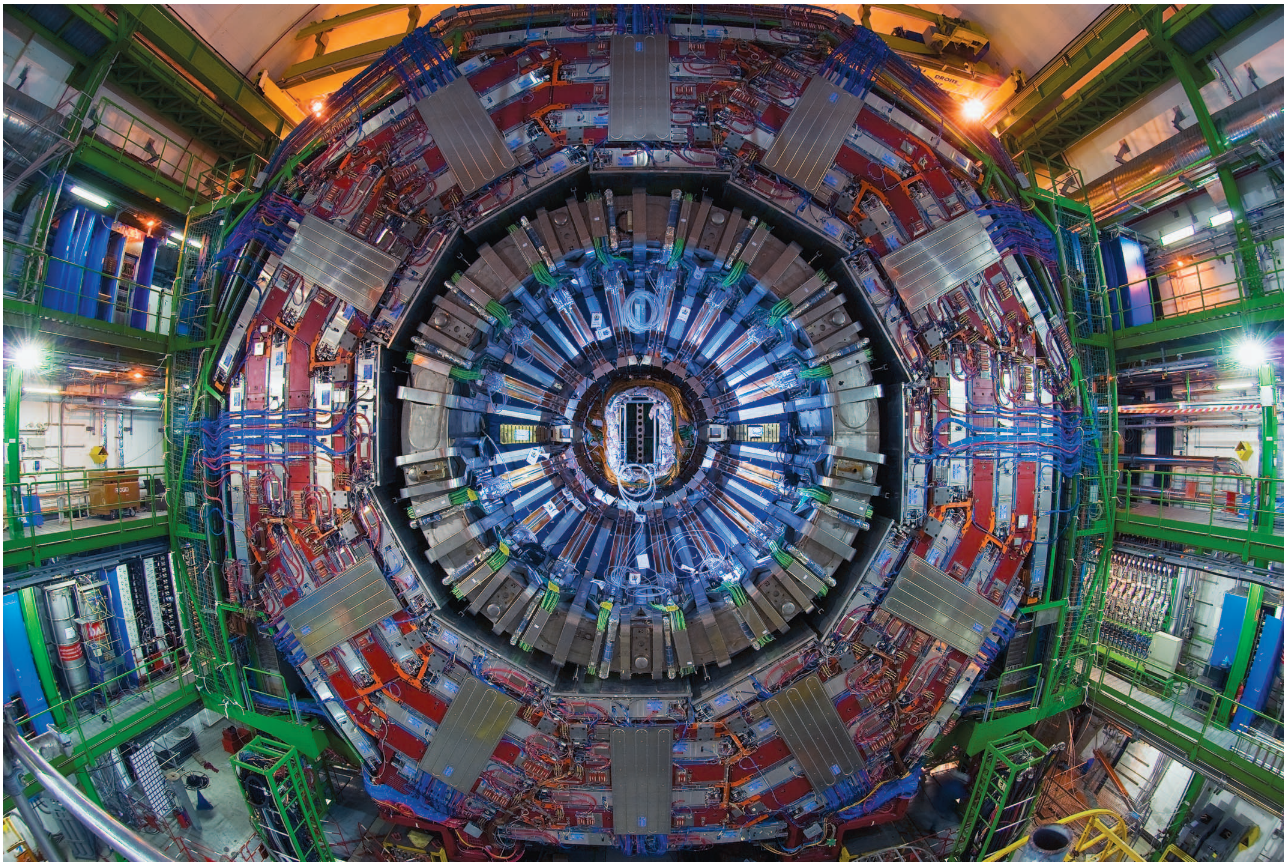

Fig. 2. Transverse section of the barrel part of CMS illustrating the successive layers of detection starting from the center where the collisions occur: the inner tracker, the crystal calorimeter, the hadron calorimeter, the superconducting coil, and the iron yoke instrumented with the four muon stations. The last muon station is at a radius of 7.4 m.

computing facilities, and about 100 Tier-2 centers at various institutes. The center at CERN receives the raw data, carries out prompt reconstruction almost in real time, and exports the raw and reconstructed data to the Tier-1 centers and also to Tier-2 centers for physics analysis. The Tier-0 centers must keep pace with the event rate of 0.5 kHz (~1 MB of raw data per event) from each experiment. The large Tier-1 centers provide long-term storage of raw data and reconstructed data outside of CERN (a second copy). They carry out second-pass reconstruction, when better calibration constants are available. The large number of events simulated by Monte Carlo methods and necessary for quantifying the expectations are produced mainly in Tier-2 centers.

The operation of the LHC accelerator and the experiments. The LHC accelerator began to operate on 10 September 2008. On 19 September 2008, during the final powering tests of the main dipole circuit in the last sector (3-4) to be powered up, an electrical fault in one of the tens of thousands of connections generated a powerful spark that punctured the vessel of a magnet, resulting in a large release of helium from the magnet cold mass and leading to mechanical damage to ~50 magnets. These were repaired in 2009, and it was decided to run the accelerator at an energy of 3.5 TeV per beam (i.e., at half the nominal energy).

The first pp collisions (at an energy of 450 GeV per beam) occurred on 23 November 2009; the first high-energy collisions (at 3.5 TeV per beam) were recorded on 30 March 2010, and since then the collider has operated smoothly, providing the two general-purpose experiments, ATLAS and CMS, with data samples corresponding to an integrated luminosity of close to 5 fb^{-1} (fb, femtobarn) during 2011, and another 5 fb^{-1}, at the slightly higher energy of 4 TeV per beam, up to June 2012. In total, these data (~10 fb^{-1}) correspond to the examination of some 10^{15} pp collisions. Typically, there are 20 overlapping pp interactions ("pile-up") in the same crossing of proton bunches as the interaction of interest. ATLAS and CMS have recorded ~95% of the collision data delivered with the LHC operating in stable conditions. In all, 98% of the roughly 100 million electronic readout channels in each experiment have been performing at design specification. This outstanding achievement is the result of a constant and dedicated effort by the teams of physicists, engineers, and technicians responsible for the hardware, software, and maintenance of the detectors. This efficient operation of the accelerator and the experiments has led to the discovery of the Higgs-like boson soon after the first pp collisions at high energy.

The ATLAS and CMS experiments started recording high-energy pp collisions in March 2010 after a preliminary low-energy run in the autumn of 2009. Many SM processes, including inclusive production of quarks (seen as hadronic jets), bottom quarks, top quarks, and W and Z bosons, have been measured with high precision. These measurements, in a previously unexplored energy region, confirm the predictions of the SM. It is essential to establish this agreement before any claims for new physics can be made, as SM processes constitute large backgrounds to new physics.

Extensive searches for new physics beyond the SM have also been performed. New limits have been set on quark substructure, supersymmetric particles (e.g., disfavoring at 95% CL gluino masses below 1 TeV in simple models of supersymmetry), potential new bosons (e.g., disfavoring at 95% CL new heavy W-like W′ and Z-like Z′ bosons with masses below 2 TeV for couplings similar to the ones for the known W and Z bosons), and even signs of TeV-scale gravity (e.g., disfavoring at 95% CL black holes with masses below 4 TeV).

Undoubtedly, the most striking result to emerge from the ATLAS and CMS experiments is the discovery of a new heavy boson with a mass of ~125 GeV. The analysis was carried out in the context of the search for the SM Higgs boson.

For m_H around 125 GeV, and from the number of collisions examined, some 200,000 Higgs bosons would have been produced in each experiment. Folding in the branching fraction, each experiment expected to identify a comparatively tiny number of signal events (e.g., a few hundred two-photon events or tens of four-lepton events) from a hypothetical Higgs boson, before including factors of efficiency. The four–charged-lepton mode ($H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$) offers the promise of the purest signal ($S/B \sim 1$, where S is the number of expected signal events and B is the number of expected background events) and has therefore been called the "golden channel."

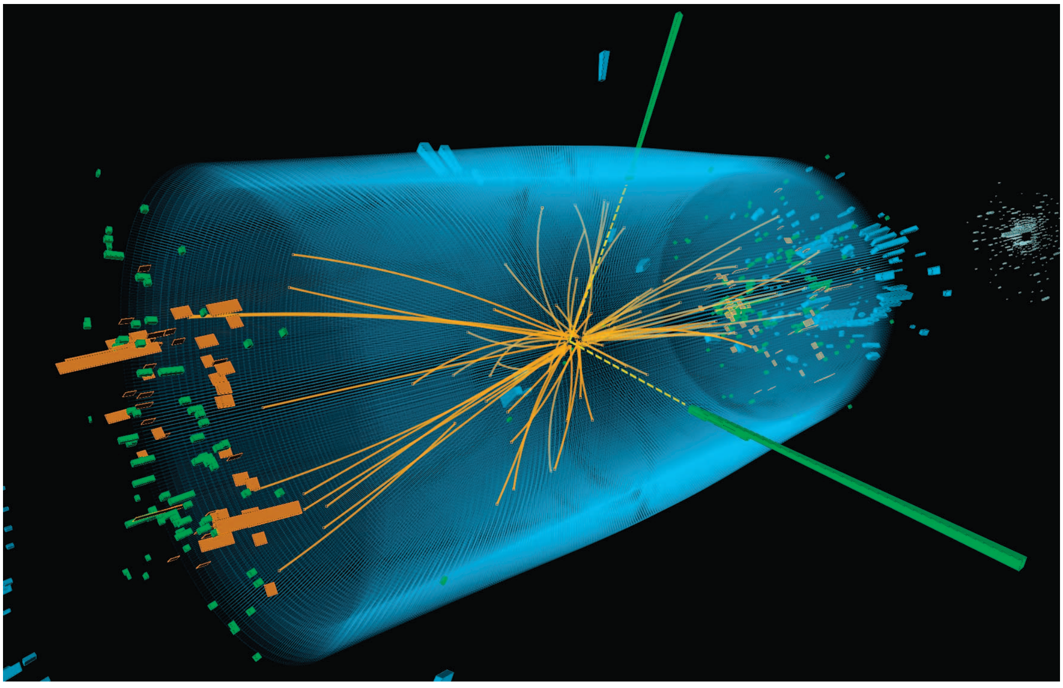

Fig. 3. Event recorded with the CMS detector on 13 May 2012 at a proton-proton center-of-mass energy of 8 TeV. The event shows characteristics expected from the decay of the SM Higgs boson to a pair of photons (dashed yellow lines and green towers). Solid yellow lines represent the reconstructed trajectories of the charged particles produced in addition to the two photons in the same collision. The event could also be due to known SM background processes.

The search for the Higgs boson is carried out in a variety of modes. Below, we give some details of the two modes that have the best invariant mass resolution and had played a particularly important role in the design of the ATLAS and CMS experiments.

H → γγ. In our detectors, the signature of the H → γγ decay mode is a pair of isolated photons each with a high transverse momentum of ~30 GeV or higher. Transverse momentum is the component of the momentum vector projected onto the plane perpendicular to the beams. Figure 3 shows such an event recorded with the CMS detector.

Events containing two isolated photon candidates were selected with the goal of identifying a narrow peak in the diphoton invariant mass distribution superimposed on a large background. This background arises from two sources: the dominant and irreducible one from a variety of SM processes, and a reducible background where one or both of the reconstructed photon candidates originate from misidentification of jet fragments.

The criteria to distinguish real photons from those coming from jet fragmentation (labeled "fake photons") depend on the detector technologies of the two experiments. Both experiments are able to reject fake photons such that their contribution to the background is only 25% of the total. The size of this contribution was the subject of much debate in the 1990s, and the low value has been attained through the design of the em calorimeters and the rejection power of the associated analyses.

To enhance the sensitivity of the analysis, candidate two-photon events were separated into many mutually exclusive categories of different expected *S/B* ratios. These categories are defined on the basis of the expected properties

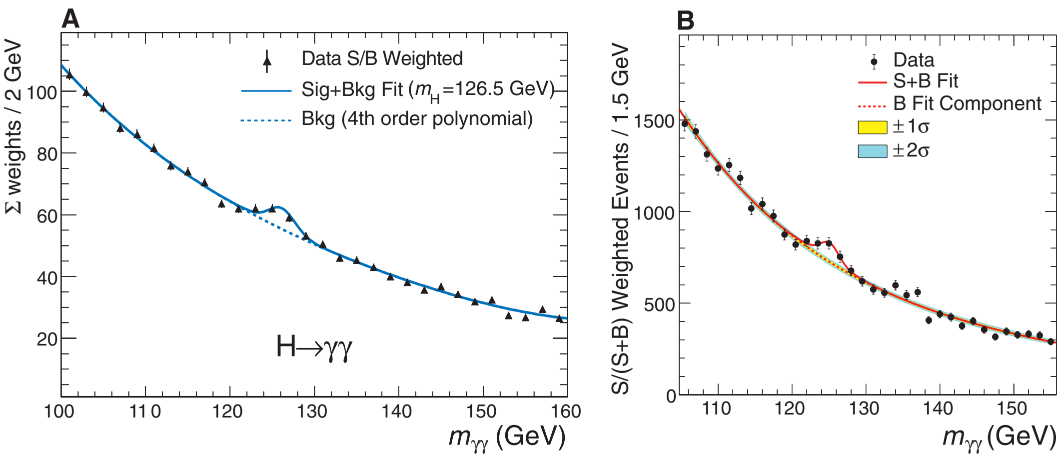

Fig. 4. (**A**) The two-photon invariant mass distribution in ATLAS of selected candidate events weighted by the *S/B* value of the category in which it falls. The 7-TeV and 8-TeV data are combined and correspond to a total integrated luminosity of 10.7 fb^{-1}. (**B**) The two-photon invariant mass distribution in CMS of selected candidate events weighted by the *S/*(*S* + *B*) value of the category in which it falls. The 7-TeV and 8-TeV data are combined and correspond to a total integrated luminosity of 10.4 fb^{-1}.

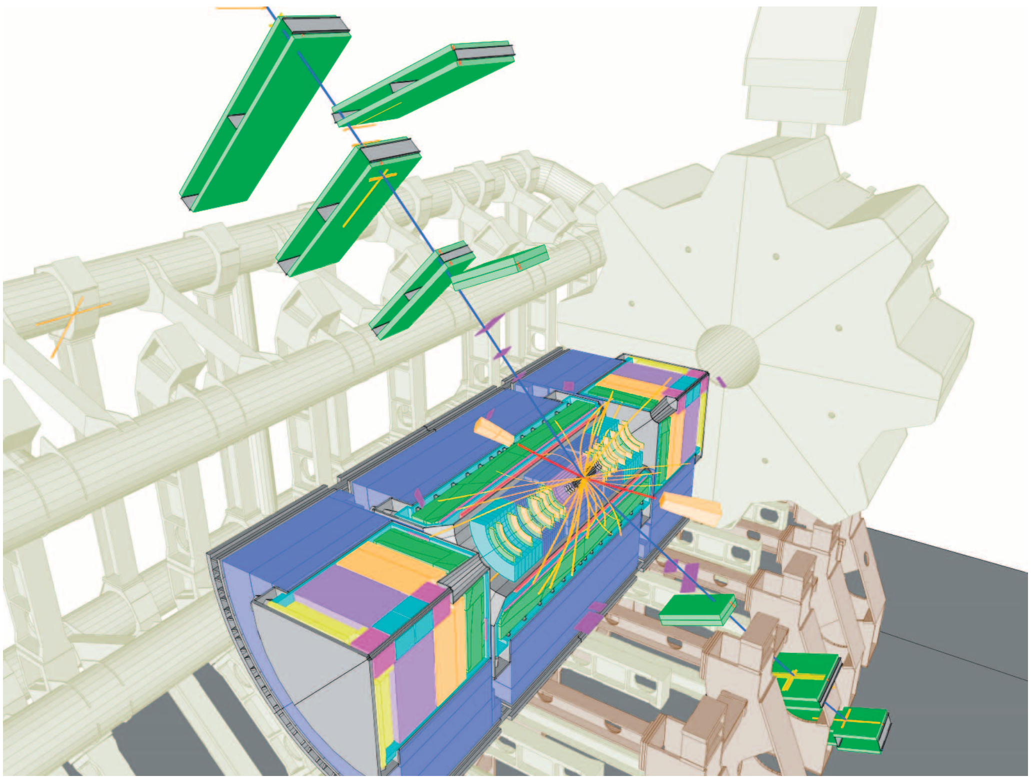

Fig. 5. Event recorded with the ATLAS detector on 30 May 2011 at a proton-proton center-of-mass energy of 7 TeV. The event shows characteristics expected from the decay of the SM Higgs boson to a pair of Z bosons, which in turn decay to a pair of electrons (red tracks and yellow towers) and a pair of muons (blue tracks and muon chamber hits in green). The invariant mass of the 2e2μ system is 124.3 GeV. The event could also be due to known SM background processes.

of the reconstructed photons and on the presence of two jets expected to accompany a Higgs boson produced through the vector-boson fusion process, a particularly sensitive category. The analysis of events in each category represented a separate measurement, with a specific mass resolution and background, and the results from each category were statistically combined through a procedure that used likelihood analysis.

The distributions of the two-photon invariant masses, weighted by category, are shown in Fig. 4 for ATLAS and CMS, respectively, along with the best fit of a signal peak on top of a continuum background. The weight chosen was proportional to the expected *S/B* in the respective category.

An excess of events, over the background, was observed at a mass of ~125 GeV by both experiments, corresponding to a local significance of 4.5 standard deviations (σ) for ATLAS and 4.1σ for CMS.

H → ZZ → ℓℓℓℓ. The signature of the H → ZZ → ℓℓℓℓ decay mode is two pairs of oppositely charged isolated leptons (electrons or muons). The main background arises from a small continuum of known and nonresonant production of Z boson pairs. Figure 5 shows an event recorded with the ATLAS detector with the characteristics expected from the decay of the SM Higgs boson to a pair of Z bosons, one of which subsequently decays into a pair of electrons and the other into a pair of muons.

For a Higgs boson with a mass below twice the mass of the Z boson, one of the lepton pairs will typically have an invariant mass compatible with the Z boson mass (~91 GeV), whereas the other one will have a considerably lower mass, called "off-mass shell." Because there are differences in the instrumental backgrounds and in the mass resolutions for the three possible combinations of electron and muon pairs (4e, 4μ, and 2e2μ), the searches were made in these independent subchannels and then combined statistically with a likelihood procedure. In the case of CMS, the angular distribution of the four leptons is included in the likelihood.

Figure 6 shows the four-lepton invariant mass distribution for the ATLAS and CMS experiments, in each case for the combination of all the channels (4e, 4μ, and 2e2μ). The peak near 90 GeV corresponds to the expected but rare decay of Z bosons to four leptons (Z → ℓℓℓℓ). The rate is higher in the CMS experiment than in ATLAS because of differing kinematic criteria applied to the four leptons. Both experiments observe a small but significant excess of events around an invariant mass of about 125 GeV above the expected continuum background, with a spread as expected from the mass resolution and statistical fluctuations corresponding to a local significance of 3.4σ and 3.2σ in ATLAS and CMS, respectively.

Combined results. The ATLAS and CMS experiments have both studied more Higgs boson decay modes than described in this paper, as discussed in the associated papers in this issue and (*16*, *17*). Figure 7 shows the combined statistical significance observed for the different Higgs mass hypotheses by the ATLAS and CMS experiments, respectively. The largest

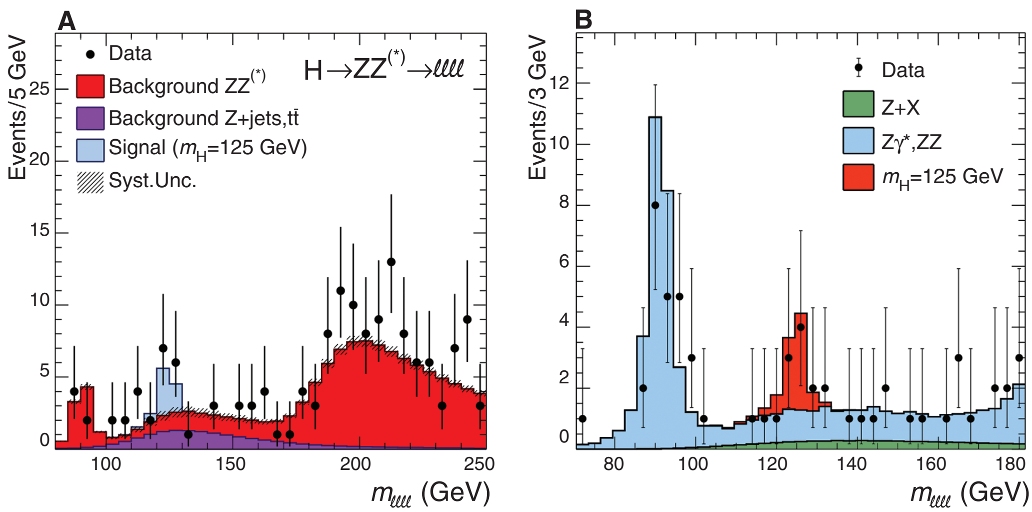

Fig. 6. (**A** and **B**) The distribution of the four-lepton invariant mass, $m_{\ell\ell\ell\ell}$, in ATLAS (A) and CMS (B) for the selected candidates relative to the background expectation. The signal expectation for a SM Higgs boson with m_H = 125 GeV is also shown. The 7-TeV and 8-TeV data are combined and correspond to a total integrated luminosity of 10.7 fb^{-1} for ATLAS and 10.4 fb^{-1} for CMS.

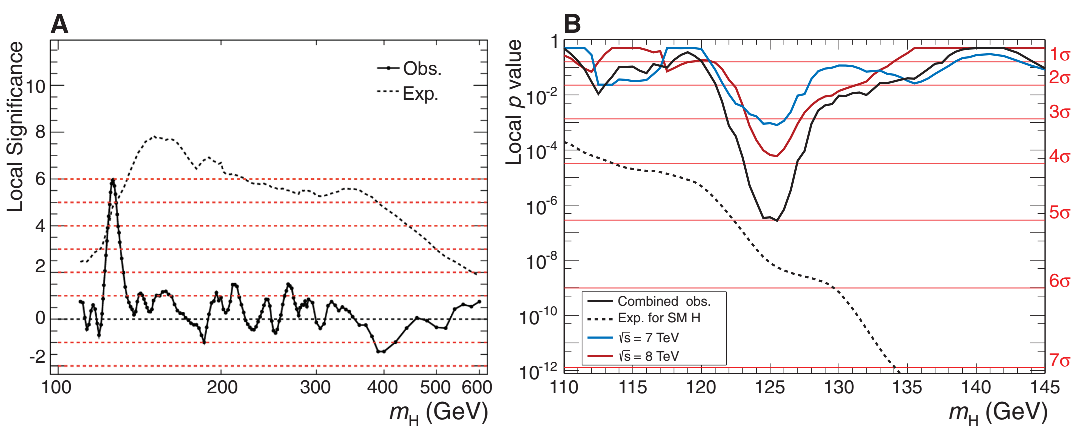

Fig. 7. (**A** and **B**) Combined search results in ATLAS (A) and CMS (B) detectors as a function of m_H for the observed and expected local significance based on the estimated background from SM processes. The 7-TeV and 8-TeV data are combined and correspond to a total integrated luminosity of 10.4 to 10.7 fb^{-1} for ATLAS and 10.4 fb^{-1} for CMS.

local significance is observed for a SM Higgs boson mass of m_H = 126.5 and 125.5 GeV, where it reaches 6.0σ and 5.0σ, corresponding to a background fluctuation probability of 2 × 10^{-9} and 5 × 10^{-7} for the ATLAS and CMS experiments, respectively. The expected local significance in the presence of a SM Higgs boson signal at these masses is found to be 4.9σ for the ATLAS experiment and 5.8σ for the CMS experiment. The evidence for a new particle is strengthened by the observation in two different experiments, comprising complementary detectors, operating independently.

In both experiments the excess was most significant in the two decay modes γγ and ZZ. These two decay modes indicate that the new particle is a boson; the two-photon decay implies that its spin (J) is different from 1 (*32*, *33*). Because the Higgs field is scalar, the spin of the SM Higgs boson is predicted to be zero.

Furthermore, the number of observed events is roughly equal to the number of events expected from the production of a SM Higgs boson for all the decay modes analyzed, within the errors, in both experiments. The measured value of the observed/expected ratio, for the combined data from all the decay modes, was found to be 1.4 ± 0.3 and 0.87 ± 0.23 for the ATLAS and CMS experiments, respectively. The best estimates of the masses measured by the ATLAS and CMS experiments are also consistent: 126.0 ± 0.6 GeV and 125.3 ± 0.6 GeV, respectively.

Outlook. The results from the two experiments are consistent, within uncertainties, with the expectations for the SM Higgs boson, a fundamental spin-0 (scalar) boson. Much more data need to be collected to enable rigorous testing of the compatibility of the new boson with the SM and to establish whether the properties of the new particle imply the existence of physics beyond the SM. For this boson, at a mass of ~125 GeV, almost all the decay modes are detectable, and hence comprehensive tests can be made. Among the remaining questions are whether the bosons have spin J = 0 or J = 2, whether their parity is positive or negative, whether they are elementary or composite, and whether they couple to particles in the exact proportion predicted by the SM [i.e., for fermions (f) proportional to m_f^2 and for bosons (V) proportional to m_V^4]. These properties are studied via the new boson's rate of decay into different final states, the angular distributions of the decay particles, and its rate of production in association with other particles such as W and Z bosons. The SM Higgs boson is predicted to be an elementary particle with $J^P = 0^+$. Much progress is expected, as by the end of 2012 the ATLAS and CMS detectors should be able to triple the amount of data used for the results presented here. The LHC will then be shut down in 2013 and 2014 to refurbish parts of the accelerator so that it will be able to reach its full design energy (14 TeV) and enable precise measurements of the properties of the new bosons and the full exploration of the physics of the TeV energy scale, especially the search for physics beyond the SM.

It is known that quantum corrections make the mass of a fundamental scalar particle float up to the next highest physical mass scale currently known, which, in the absence of extensions to the SM, is as high as 10^{15} GeV. A favored conjecture states that this is avoided by a set of heavy particles not yet discovered. For each known SM particle there would be a partner with spin differing by half a unit; fermions would have boson partners and vice versa, in a symmetry called supersymmetry. This happens because in quantum mechanics, corrections involving fermions and bosons have opposite signs for their amplitudes and hence cancel each other. In the minimal supersymmetry model, five types of Higgs bosons are predicted to exist. Furthermore, the lightest stable neutral particle of this new family of supersymmetric particles could be the particle constituting dark matter. If, as conjectured, such particles are light enough, they ought to reveal themselves at the LHC.

The discovery of the new boson suggests that we could well have discovered a fundamental scalar field that pervades our universe. Astronomical and astrophysical measurements point to the following composition of energy-matter in the universe: ~4% normal matter that "shines," ~23% dark matter, and the rest forming "dark energy." Dark matter is weakly and gravitationally interacting matter with no electromagnetic or strong interactions. These are the properties carried by the lightest supersymmetic particle. Hence the question: Is dark matter supersymmetric in nature? Fundamental scalar fields could well have played a critical role in the conjectured inflation of our universe immediately after the Big Bang and in the recently observed accelerating expansion of the universe that, among other measurements, signals the presence of dark energy in our universe.

The discovery of the new boson is widely expected to be a portal to physics beyond the SM. Physicists at the LHC are eagerly looking forward to establishing the true nature of the new boson and to the higher-energy running of the LHC, to find clues or answers to some of the other fundamental open questions in particle physics and cosmology. Such a program of work at the LHC is likely to take several decades.

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Acknowledgments: The construction, and now the operation and exploitation, of the large and complex ATLAS and CMS experiments have required the talents, the resources, and the dedication of thousands of scientists, engineers, and technicians worldwide. Many have already spent a substantial fraction of their working lives on these experiments. This paper is dedicated to all our colleagues who have worked on these experiments. None of these results could have been obtained without the wise planning, superb construction, and efficient operation of the LHC accelerator and the WLCG computing.

10.1126/science.1230827

Science | AAAS

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Science **338**, 1560 (2012);
DOI: 10.1126/science.1230827