ARTICLE

A New Boson with a Mass of 125 GeV Observed with the CMS Experiment at the Large Hadron Collider

The CMS Collaboration*†

The Higgs boson was postulated nearly five decades ago within the framework of the standard model of particle physics and has been the subject of numerous searches at accelerators around the world. Its discovery would verify the existence of a complex scalar field thought to give mass to three of the carriers of the electroweak force—the W^+, W^-, and Z^0 bosons—as well as to the fundamental quarks and leptons. The CMS Collaboration has observed, with a statistical significance of five standard deviations, a new particle produced in proton-proton collisions at the Large Hadron Collider at CERN. The evidence is strongest in the diphoton and four-lepton (electrons and/or muons) final states, which provide the best mass resolution in the CMS detector. The probability of the observed signal being due to a random fluctuation of the background is about 1 in 3×10^6. The new particle is a boson with spin not equal to 1 and has a mass of about 125 giga–electron volts. Although its measured properties are, within the uncertainties of the present data, consistent with those expected of the Higgs boson, more data are needed to elucidate the precise nature of the new particle.

The standard model (SM) of particle physics (*1*–*3*) describes the fundamental particles, quarks and leptons, and the forces that govern their interactions. Within the SM, the photon is massless, whereas the masses of the other carriers of the electroweak force, the $W^\pm$ and Z^0 gauge bosons, are generated through a symmetry-breaking mechanism proposed by three groups of physicists (Englert and Brout; Higgs; and Guralnik, Hagen, and Kibble) (*4*–*9*). This mechanism introduces a complex scalar field, leading to the prediction of a scalar particle: the SM Higgs boson. In contrast, all known elementary bosons are vector particles with spin 1. In the SM, the scalar field also gives mass to the fundamental fermions through a Yukawa interaction (*1*–*3*). The Higgs boson is predicted to decay almost instantly to lighter particles.

The theory does not predict a specific mass for the Higgs boson. Moreover, the properties of the Higgs boson depend strongly on its mass. General arguments indicate that its mass should be less than about 1 TeV (*10*–*13*), although searches for the SM Higgs boson conducted before those at the Large Hadron Collider (LHC) have excluded the mass region below 114.4 GeV (*14*). Searches at the Tevatron have excluded a narrow mass region near 160 GeV (*15*) and recently reported an excess of events in the range from 120 to 135 GeV (*16*–*18*).

The LHC is installed in a circular tunnel 27 km in circumference and 100 m underground, straddling the border between France and Switzerland, near Geneva (*19*). The LHC accelerates clockwise and counterclockwise beams of protons before colliding them head on. These collisions were at a total center-of-mass energy of 7 TeV in 2011 and 8 TeV in 2012, the highest energies reached to date in a particle accelerator. These high-energy collisions enable the production of new, and sometimes very heavy, particles by converting energy into mass in accordance with Einstein's well-known formula $E = mc^2$. The LHC can produce all known particles, including the top quark, which, with a mass of about 173 GeV, is the heaviest known elementary particle. It was predicted that the SM Higgs boson could also be produced at the LHC if it has a mass less than about 1 TeV.

The SM predicts the cross section for the production of Higgs bosons in proton-proton collisions as a function of its mass. The cross section increases with the center-of-mass energy of the collision and decreases with increasing Higgs mass. Despite the high collision energy, the predicted probability of Higgs boson production is extremely small, about 10^{-10} per collision. Thus, to detect a significant number of Higgs bosons a huge number of collisions must be analyzed, which requires very high luminosity. The maximum instantaneous luminosity achieved so far is 7.6×10^{33} cm^{-2} s^{-1}, close to the LHC peak design value that was not expected to be attained until 2015. This was achieved by having 1368 bunches of protons in each beam, spaced 50 ns apart (corresponding to a separation of about 16 m), with each bunch containing about 1.5×10^{11} protons squeezed to a transverse size of about 20 μm at the interaction point. Each bunch crossing yields more than 20 proton-proton collisions on average. The multiple collisions per bunch crossing, known as pileup, are initially registered as a single collision event by the detectors. Resolving the individual collisions within these events is an important challenge for the detectors at the LHC.

The Compact Muon Solenoid (CMS) detector surrounds one of the LHC's interaction points. Heavy particles, such as SM Higgs bosons, created in LHC collisions will typically be unstable and thus rapidly decay into lighter, more stable particles, such as electrons, muons, photons, and hadronic jets (clusters of hadrons travelling in a similar direction). These long-lived particles are what CMS detects and identifies, measuring their energies and momenta with high precision in order to infer the presence of the heavy particles produced in the collisions. Because the CMS detector is nearly hermetic, it also allows for the reconstruction of momentum imbalance in the plane transverse to the beams, which is an important signature for the presence of a neutrino (or a new, electrically neutral, weakly interacting particle) in the collision.

We report the observation of a new particle that has properties consistent with those of the SM Higgs boson. This paper provides an overview of the experiment and results that are described in greater detail in (*20*). The study examines five SM Higgs boson decay modes. Three modes result in pairs of bosons (γγ, ZZ, or W^+W^-), and two modes yield pairs of fermions ($b\bar{b}$ or $\tau^+\tau^-$), where γ denotes a photon, Z and W denote the force carriers of the weak interaction, b denotes a bottom quark (and $\bar{b}$ its antiquark), and τ denotes a tau lepton. In the following, we omit the particle charges and use b to refer to both the quark and antiquark. The unstable W, Z, b, and τ particles decay to final states containing electrons, muons, neutrinos, and hadronic jets, all of which can be detected (directly or, in the case of neutrinos, indirectly) and measured with the CMS detector. An independent observation was made by the ATLAS collaboration (*21*, *22*), which further strengthens our interpretation.

Overview of the CMS detector. The CMS detector measures particles produced in high-energy proton-proton and heavy-ion collisions (*23*). The central feature of the detector is a superconducting solenoid 13 m long, with an internal diameter of 6 m. Within its volume it generates a uniform 3.8-T magnetic field along the axis of the LHC beams. Within the field volume are a silicon pixel and strip tracker, a lead tungstate ($PbWO_4$) scintillating crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter (HCAL). Muons are identified and measured in gas-ionization detectors embedded in the outer steel magnetic-flux-return yoke. The detector is subdivided into a cylindrical barrel part and endcap disks on each side of the

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This probability corresponds to a local significance of 5σ. The probability of observing this large a fluctuation anywhere in the mass range of 114 to 130 GeV, where the Higgs boson had not been excluded by previous data, is small and results in a global significance of 4.6σ. The global significance is smaller than the local value because of the look-elsewhere effect. Both measures convincingly show that this is not a background fluctuation, but rather the observation of a new particle. The expected sensitivity with the present data for a 125 GeV SM Higgs boson amounts to a local significance of $5.8 \pm 1.0\sigma$, consistent with the signal observed at 5σ.

In addition to being able to say with high confidence that a new particle has been observed, and that it is a boson with spin not equal to one, we were also able to derive some of its properties, such as its mass. And, as mentioned above, once the mass is known the SM allows us to calculate many other properties, such as the fractions of Higgs bosons decaying in different ways, and compare these expectations with our measurements. This is expressed as the signal strength, that is, the measured production rate of the signal, which can be determined for each decay mode individually and for the overall combination of all channels, normalized to the predicted Higgs boson production rate. The signal strength was defined to be equal to one for the SM Higgs boson. The measured signal strength was highest in the diphoton channel, namely 1.6 ± 0.4, whereas that in the ZZ channel was $0.7^{+0.4}_{-0.3}$. By using the high-resolution diphoton and ZZ channels discussed above, which show a resonance peak, we obtained the 68% confidence level (CL) contours for the signal strength versus the boson mass (Fig. 7 left). We also show the combination of the diphoton and ZZ decay modes, where the relative signal strengths of these two modes are constrained by the expectations for the SM Higgs boson. To extract the value of the mass in a model-independent way, we allowed the signal yields of the combined channels to vary independently. The combined best-fit mass is 125.3 ± 0.4 (statistical) $\pm$ 0.5 (systematic) GeV.

The signal strengths for all five channels are depicted in Fig. 7 (right). The overall combined signal strength, including all channels, is 0.87 ± 0.23. Hence, these results are consistent, within relatively large statistical and systematic uncertainties, with the expectations for the SM Higgs boson.

The CMS data also rule out the existence of the SM Higgs boson in the ranges of 114.4 to 121.5 GeV and 128 to 600 GeV at 95% CL (*20*). Lower masses were already excluded by CERN's Large Electron Positron collider at the same CL (*14*).

More data are needed to establish whether this new particle has all the properties of the SM Higgs boson or whether some do not match. The latter may imply new physics beyond the SM. This particle has the potential to be a portal to a new landscape of physical phenomena that is still hidden from us. The CMS experiment is in an excellent position to undertake this research in the years to come.

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Supplementary Materials

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