

PHYSICS OF OUR DAYS

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Large Hadron Collider's discovery of a new particle with Higgs boson properties

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Abstract. **We outline the results of the ATLAS and CMS collaborations, which announced a new particle with properties consistent with those expected from the Standard Model Higgs boson. At a qualitative level, we describe the roles played by the Englert–Brout–Higgs field and the Higgs boson in the theory of fundamental particles and their interactions. We also discuss prospects for theoretical and experimental studies in the new area of elementary particle physics.**

1. Introduction

On 4 July 2012, an event took place that was of salient importance for modern physics: at a CERN seminar, the discovery was announced of a new particle with properties, as cautiously declared by the authors, consistent with the expected properties of the theoretically predicted elementary boson of the Standard Model of particle physics. Following conventional terminology, this boson is called the Higgs boson, although this name is not quite appropriate (we comment on this in Section 3.3). In any case, the issue concerns the discovery of one of the central objects in fundamental physics, which has no analogues among the known elementary particles and occupies a unique place in the physical picture of the world. The special role of the new particle and, more broadly, of the new scalar sector of elementary particle physics was formulated by L B Okun at the International lepton–photon symposium in Bonn in his concluding report: "Prospects of particle physics: August 1981," the translation of which into Russian is published for the first time in this issue of *Physics–Uspekhi* [1]. In the same report, the search for the Higgs boson was called the problem number one for modern physics, which should unite the efforts of not only theoreticians but also experimentalists and accelerator specialists.

The first indications of the existence of a new boson were already obtained in December 2011 in the ATLAS and CMS experiments at the Large Hadron Collider of CERN. Moreover, not long before 4 July, data obtained at the Tevatron proton–antiproton collider (Fermilab, USA) were also reported to point to the existence of a new boson. All the above was insufficient to claim a discovery, but the amount of data collected at the Large Hadron Collider has doubled since December and, moreover, the methods of data analysis have improved. The result turned out to be impressive: in the ATLAS and CMS experiments separately, the statistical significance achieved was at a level that in elementary particle physics is considered the level of a discovery (5 standard deviations).

The atmosphere at the 4 July seminar was quite festive. Besides scientists working at CERN and students participating in CERN summer programs, the participants in a major conference on high-energy physics, which opened exactly on 4 July in Melbourne, took part in the seminar. The seminar was broadcast via Internet to scientific centers and universities all over the world, including Russia, naturally. After the impressive talks by the spokespersons of the collaborations CMS, Joseph Incandela, and ATLAS, Fabiola Gianotti, Director General of CERN Rolf Heuer concluded: "I think we have it!"

So what do 'we have', and why was it invented by theoreticians?

2. What is known of the new particle?

First of all, we recall that the minimal theory of the microworld is called the Standard Model. This theory describes all known elementary particles and all interactions among

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them.[1] The theory is minimal because, besides the already known particles, it involves only one more, the Higgs boson, which is an elementary (not composite) particle (below, we also discuss other possibilities). The Higgs boson was the only particle of the Standard Model hitherto not discovered.

Most aspects of the Standard Model, with the exception of the new sector to which the Higgs boson belongs, have been tested in numerous experiments, and therefore the main task of the Large Hadron Collider consists in clarifying whether the minimal version of the theory is actually realized in Nature and how fully this theory describes the microworld.[2]

Quite naturally, the program involving searches for the Higgs boson was from the very beginning one of the principal, if not the principal, programs at the CERN Large Hadron Collider.[3] Implementation of this program resulted in the discovery of the new particle. It is quite heavy by the standards of the physics of the microworld. In this domain of physics, mass is measured in units of energy, in accordance with the relation $E_0 = mc^2$ between the mass and rest energy. The unit of energy used is the electronvolt (eV), and its derivatives are MeV, GeV, TeV (10^6, 10^9, and 10^{12} eV, respectively). The electron mass in these units is 0.5 MeV, the proton mass is approximately 1 GeV, and the mass of the heaviest known elementary particle, the t-quark, is 173 GeV. The mass of the new boson amounts to 125–126 GeV (to be more precise, $125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$ GeV from the CMS data [2] and $126.0 \pm 0.4(\text{stat.}) \pm 0.4(\text{syst.})$ GeV from the ATLAS data [3], where the statistical and systematic uncertainties are indicated).

This new particle (conventionally denoted by H) has no electric charge. It is unstable and can decay in different ways. It was discovered at the Large Hadron Collider [2, 3] in studies of decays into two photons, $H \to \gamma\gamma$, and into two electron–positron and/or muon–antimuon pairs, $H \to e^+e^-e^+e^-$, $H \to e^+e^-\mu^+\mu^-$, and $H \to \mu^+\mu^-\mu^+\mu^-$. Processes of the second kind proceed in two stages: first, the new particle decays into two known heavy neutral particles, namely, two Z-bosons, one of which is virtual, and then each of the Z-bosons decays into an e^+e^- or $\mu^+\mu^-$ pair. This is written as $H \to ZZ^* \to 4l$, where the asterisk indicates the virtual particle and l is one of the leptons, $e^\pm$ or $\mu^\pm$. Both the CMS and ATLAS collaborations also report a certain excess of events, which can be due to the decays $H \to WW^* \to l\nu l\nu$, where the W-boson is another known heavy, electrically charged particle (therefore, a W^+W^- pair is produced first), and ν is the electron or muon neutrino. This excess, however, presently does not have high statistical significance.

We recall that elementary particles are characterized by spin, i.e., the internal angular momentum, which can be half-integer (fermions) or integer (bosons) in units of the Planck constant $\hbar$. All the elementary particles known until recently have a nonzero spin equal to 1/2 in the case of charged leptons (the electron, the muon, anf the τ-lepton), neutrinos, and quarks, and 1 in the case of the photon and other particles[4] (we list them below). From the existence of the decays discussed, it follows that the new particle has an integer spin, i.e., it is a boson. Furthermore, its spin cannot be equal to unity (a particle of spin 1 cannot decay into two photons). There remain spins 0, 2, or higher. Although no direct experimental measurement of the new particle spin exists, it is extremely improbable that we are dealing with a particle of spin 2 or higher. The H spin is most probably equal to zero. The Higgs boson should be precisely such a particle.

Everything that is presently known about the new particle is consistent with it being interpreted as the Standard Model Higgs boson (a discussion of the Standard Model can be found, e.g., in Ref. [5]; details are presented in Ref. [6]). In the framework of the Standard Model, it is possible to calculate both the Higgs boson production probability in proton–proton collisions at the Large Hadron Collider and the probabilities of its $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ decays, thus predicting the number of expected events. Precisely these predictions are confirmed by experiments, naturally, to within experimental uncertainties (Figs 1, 2) (we note that CMS and ATLAS use somewhat different quantities for characterizing the signal).

These uncertainties are still large and moreover, as we have seen, the measured quantities are few. Nevertheless, it is difficult to doubt that precisely the Standard Model Higgs

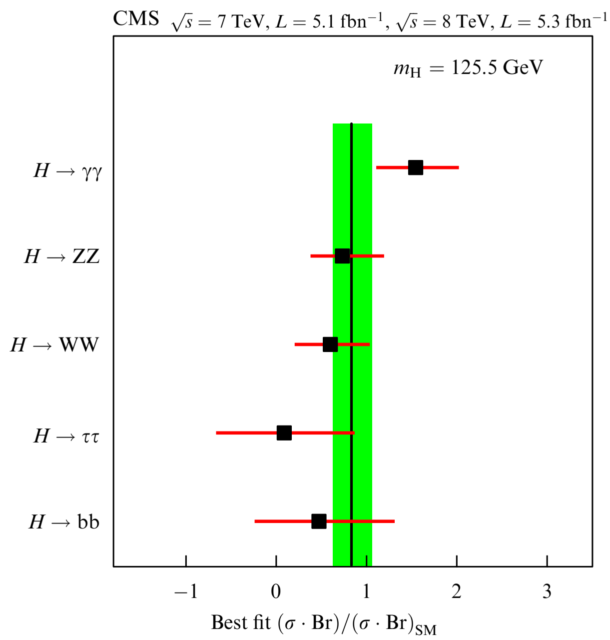

Figure 1. Ratios of the signals and the Standard Model predictions obtained in the CMS experiment [2]. Given are the ratios $(\sigma \cdot \text{Br})/(\sigma \cdot \text{Br})_{SM}$, where the numerator is the measured product of the new particle production cross section and its branching ratio for the channel indicated, and the denominator is the value of the same product calculated for the Standard Model Higgs boson. The notation $H \to ZZ$ and $H \to WW$ indicates the decays $H \to ZZ^* \to 4l$ and $H \to WW^* \to l\nu l\nu$, discussed in the text. Shown also are the results for the decay $H \to \tau^+\tau^-$ and the process $pp \to VH \to Vb\bar{b}$, where V stands for the W^- or Z-boson (see the end of Section 2). The vertical band shows the averaged value 0.87 ± 0.23. Here, unity corresponds to the Standard Model, while zero corresponds to the absence of a new particle. Both general agreement with the Standard Model and large uncertainties are seen. At the top, the total collision energies of the protons, $\sqrt{s}$ = 7 TeV and 8 TeV, are shown together with the integrated luminosities L.

[1] The gravitational interaction stands apart: independently of what kinds of particles exist, it is described by the general relativity theory.

[2] The Standard Model is actually incomplete, as is evidenced by cosmological data [4, 5]. Whether the incompleteness of the Standard Model will be manifested at Large Hadron Collider energies remains an open and intriguing issue.

[3] The Large Hadron Collider is an accelerator producing colliding proton beams. In 2011, the energy of protons in each of the beams amounted to 3.5 TeV, and hence the total collision energy was 7 TeV. In 2012, the total energy achieved in the collider was 8 TeV. The planned total collision energy is 14 TeV.

[4] The graviton spin must be equal to 2.

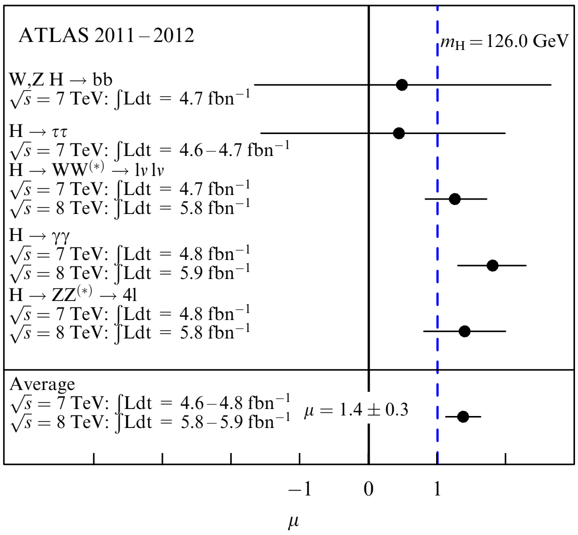

Figure 2. Ratios of the signals and the Standard Model predictions obtained in the ATLAS experiment [3]. Shown is the quantity μ equal to the ratio of the new particle production cross section and the Standard Model prediction. The branching ratios of the H decays are considered to be the same as in the Standard Model. The value $\mu = 1$ corresponds to the Standard Model, and the zero value corresponds to the absence of any new particle. The results are presented for the same processes as in Fig. 1. At the bottom, the averaged value $\mu = 1.4 \pm 0.3$ is shown. For each process, the collision energies and integrated luminosities at which the data used in the analysis were obtained are indicated.

boson or something very similar to it has been discovered, especially if we take into account that the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ decays should be very rare:[5] in the Standard Model, only 2 out of 1000 Higgs bosons decay into two photons and 1 out of 10^4 [7] decay into two e^+e^- and/or $\mu^+\mu^-$ pairs (to be more precise, the Standard Model predicts that the branching ratios of the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ decays are respectively equal to 2.3×10^{-3} and 1.3×10^{-4}; here and below, the numerical values presented correspond to $m_H = 125$ GeV).

In more than half of the cases, the Higgs boson should decay into a b-quark–b-antiquark pair, $H \to b\bar{b}$. The production of $b\bar{b}$ pairs in proton–proton (and proton–antiproton) collisions is a very frequent phenomenon, even without any Higgs boson, and it is difficult to identify the Higgs boson signal against this background. Therefore, the process studied is a collision of protons in which a Higgs boson is produced together with a W-boson, after which H decays into a $b\bar{b}$ pair and W decays into an $l\nu$ pair, where l is once again either $e^{\pm}$ or $\mu^{\pm}$. The W decay results in the production of a high-energy lepton and an energy imbalance (the neutrino is not observed). This feature allows a strong suppression of the background. A similar process, $pp \to ZH$, is used involving subsequent $H \to b\bar{b}$ and $Z \to 2l$ or $Z \to 2\nu$ decays. Identification of these processes against the background has not yet been successful in experiments at the Large Hadron Collider (see Figs 1, 2). This has been partly achieved in the CDF experiment at the Tevatron collider [8], although the statistical significance amounted to 2.7 standard deviations, which is noticeably lower than at CERN for the processes $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$. The CDF data are also consistent with the Standard Model predictions.

To conclude the description of the known properties of the new particle, we note that its lifetime is quite long by the standards of the physics of the microworld. The available experimental data permit estimating the lower limit of its lifetime as $\tau_H \gtrsim 10^{-24}$ s, which does not contradict the Standard Model prediction $\tau_H = 1.6 \times 10^{-22}$ s [7]. For comparison, the t-quark lifetime is $\tau_t = 3 \times 10^{-25}$ s [9]. We note that direct measurement of the new particle lifetime is not likely to be possible at the Large Hadron Collider.

3. Why is the Higgs boson needed?

The theory predicting the Higgs boson has been thoroughly developed and described in detail (see, e.g., Refs [6, 10]). Here, we try to present some explanations at a very qualitative and intuitive level. We hope they can be comprehensible to nonspecialists. Notes of a somewhat more technical character are given in footnotes; they can be skipped in the first reading.

We start by recalling that each elementary particle in quantum theory is a quantum of a certain field and, vice versa, each field has its own particle — quantum — corresponding to it; the best known example is the electromagnetic field and its quantum, the photon. Therefore, the question raised in the title of this section can be reformulated as follows:

Why is a new field necessary and what properties is it expected to have?

The short answer is that symmetries of the theory of the microworld — the Standard Model or some other more complicated theory — forbid elementary particles to have masses, while the new field breaks these symmetries and allows the existence of particle masses. In the Standard Model (and only in it!), which is the simplest version of the theory, all the properties of the new field and, correspondingly, of the new boson, with the exception of its mass, are again predicted unambiguously on the basis of symmetry arguments. Deciphering this short paragraph, naturally, requires a discussion, even if only in general terms, of the role of symmetries in the physics of the microworld.

3.1 Symmetries, conservation laws, and bans

Each symmetry has its own conservation law corresponding to it. For example, symmetry with respect to time shifts (the fact that physical laws are the same at each moment of time) has the energy conservation law corresponding to it; symmetry with respect to displacements in space has the momentum conservation law corresponding to it; and the angular momentum conservation corresponds to the symmetry with respect to rotations in space. Conservation laws can also be interpreted as bans: the symmetries mentioned forbid a closed system to experience changes in energy, momentum, or angular momentum in the course of its evolution.

Likewise, each conservation law has its own symmetry corresponding to it; this statement is precise in quantum theory. A question arises: what symmetry corresponds to the conservation of electric charge? The symmetries of space and time, just mentioned, clearly have nothing to do with it. Nevertheless, such a symmetry exists: besides evident, space–time, symmetries, there exist 'internal' symmetries that are not evident. Precisely one of them ensures the

[5] The difficulties that had to be overcome in discovering the new particle are illustrated by the fact that the CMS experiment registered only about 5 events of the decay $H \to ZZ^* \to 4l$. The situation with the ATLAS experiment was similar.

conservation of electric charge.[6] For us, it is important that the same internal symmetry, only understood in a broader sense as a gauge (gradient) invariance,[7] also explains the fact that light can exhibit only two types of polarization: left-handed and right-handed.

To demonstrate how nontrivial the existence of only two types of light polarization is, we digress from the discussion of symmetries and consider known particles of spin 1. Besides photons, gluons, which are insignificant for our further consideration, also have spin 1.[8] Moreover, there are three more spin-1 particles: the aforementioned electrically charged W^+-, W^--bosons and the neutral Z-boson. Precisely these particles are considered in what follows.

A massive particle of spin s has $2s+1$ states with different spin projections onto a given axis. For example, the spin of an electron ($s=1/2$) can be directed in its rest frame either upward ($s_z=+1/2$) or downward ($s_z=-1/2$). The Z-boson has a nonzero mass and spin $s=1$; therefore, it has three states with different spin projections: $s_z=+1$, 0, or -1. The situation with massless particles is totally different. Because they always travel with the speed of light, it is impossible to pass to a reference frame where such a particle is at rest. We can nevertheless deal with its helicity, the spin projection onto the direction of motion. Although the photon spin is equal to unity, there can only be two such projections: along and against the direction of motion. This is precisely how the right-handed and left-handed polarizations of a photon (light) are determined. The third state with zero spin projection, which should have existed if the photon had mass, is forbidden by the internal symmetry of electrodynamics. Thus, this internal symmetry also forbids the photon to have mass![9]

3.2 Peculiarities of weak interactions

Unlike the photon, responsible for electromagnetic interactions, the carriers of weak interactions, the $W^\pm$- and Z-bosons, are massive. These particles, discovered in 1983 at the Sp$\bar{\text{p}}$S proton–antiproton collider of CERN and predicted long before by theoreticians, have spin 1, while their masses are quite large: the $W^\pm$-bosons have the mass equal to 80 GeV, and the Z-boson mass is 91 GeV. The properties of $W^\pm$- and Z-bosons are now well known, mainly owing to experiments performed at the LEP (CERN) and SLC (SLAC, USA) electron–positron colliders and the Tevatron (Fermilab, USA) proton–antiproton collider: the measurement precision of a number of quantities relevant to $W^\pm$- and Z-bosons exceeds 0.1%. These properties, like those of other particles, are perfectly described by the Standard Model [1].

As has already been mentioned, each of the $W^\pm$- and Z-bosons can be in three spin states, instead of two, like the photon. Nevertheless, their interactions with fermions and each other are essentially arranged in the same way as the interaction of a photon. For example, a photon interacts with the electric charge of an electron and with the electric current caused by a moving electron. Precisely in the same manner, a Z-boson interacts with a certain charge of an electron and with the current due to the motion of an electron, although these charges and currents do not coincide with electric ones. Up to an important peculiarity to be discussed shortly, the analogy is complete, if, besides the electric charge, a certain Z-charge is also assigned to the electron. Quarks and neutrinos also have their own Z-charges.

The analogy to electrodynamics extends even further. As in the theory of the photon, the theory of $W^\pm$- and Z-bosons has an internal symmetry similar to the gauge invariance of quantum electrodynamics.[10] In accordance with the complete analogy to the photon, this internal symmetry forbids $W^\pm$- and Z-bosons to have a third polarization and, consequently, mass. We see that the symmetry ban on mass for a spin-1 particle actually works in the case of the photon but not in the case of $W^\pm$- and Z-bosons!

More is to follow. Weak interactions — the interactions of electrons, neutrinos, quarks, and other particles with $W^\pm$- and Z-bosons — are arranged in such a manner as if fermions had no mass. To clarify this statement, we imagine a world in which the electron mass is equal to zero. In such a world, the electron would travel with the speed of light and could have a spin directed along or against the direction of its motion. As in the case of the photon, in the first case we would speak of an electron with right-handed polarization or, briefly, of a right-handed electron, and in the second case, of a left-handed electron. Remarkably, the right-handed and left-handed electrons would be totally different particles: the right-handed electron would never transform into a left-handed one, and vice versa. Indeed, the transformation of a right-handed electron into a left-handed one in flight would be forbidden by the conservation of angular momentum (in our case, spin), while interactions of the electron with a photon or Z-boson would not alter its polarization. There still remains the interaction of the electron with the W-boson, which transforms the electron into a neutrino, but the right-handed electron would take no part at all in this interaction. Thus are weak interactions arranged.

An important peculiarity in this picture, alluded to above, is that the Z-charges of the left-handed and right-handed electrons are different: the left-handed electron interacts with the Z-boson more strongly than the right-handed one. This is an experimental fact. A similar property is exhibited by muons, tau-leptons, and quarks. In a world with massless fermions, this property would not lead to any contradiction: the left-handed and right-handed electrons would simply be different particles. We are not surprised that different particles, for example, electrons and neutrinos, have different electric charges (in that case, -1 and 0). But in the real world, where the electron has mass, the difference between the left-handed and right-handed electrons is effaced. Indeed, we would be tempted to say that an electron with its spin directed

[6] This is the symmetry under the transformations $\psi \to \exp(\mathrm{i}\alpha)\,\psi$, where ψ is the electron field and α is a parameter of the transformation.

[7] Here, we mean the invariance under the gauge transformations $\psi(x) \to \exp(\mathrm{i}\alpha(x))\,\psi(x)$, $A_\mu(x) \to A_\mu(x)+(1/e)\,\partial_\mu\alpha(x)$, where A_μ is the electromagnetic vector potential, e is the electron charge, $\alpha(x)$ is an arbitrary function of four-dimensional coordinates, and $\partial_\mu = \partial/\partial x^\mu$.

[8] Gluons are responsible for strong interactions between quarks, and they bind quarks to protons, neutrons, and other composite particles, hadrons.

[9] The equation for a free vector field of mass m has the form $\partial_\mu F^{\mu\nu} + m^2 A^\nu = 0$, where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$. If $m \neq 0$, it is not invariant under gauge transformations $A_\mu(x) \to A_\mu(x) + (1/e)\,\partial_\mu\alpha(x)$, but if $m=0$, it is invariant (in the latter case, it is simply the set of Maxwell equations in the vacuum). Therefore, the requirement of the invariance under gauge transformations fixes $m=0$.

[10] Here, we are somewhat simplifying the situation, without violating the essential truth of the issue. Actually, photons and $W^\pm$- and Z-bosons are all described together by a single theory with a common, quite broad, internal symmetry corresponding to the $\mathrm{SU}(2)\times\mathrm{U}(1)$ gauge group.

along the direction of its motion is a right-handed electron. But because the speed of a massive electron is less than the speed of light, we can always pass to a reference frame moving faster than the electron itself. In the new reference frame, the electron moves in the direction opposite to the previous one, while the spin points in the same direction as before. The spin projection onto the direction of motion is then negative, and therefore such an electron must be considered left-handed, instead of right-handed. Hence, there is no way, independent of the reference frame, to determine the sign of polarization of an electron.

Therefore, symmetries of the Standard Model (which we choose for definiteness, although everything to be said is also relevant to any other version of the theory) should have forbidden the existence of mass not only for $W^{\pm}$- and Z-bosons but also for fermions: only in the case of zero mass can one speak of left-handed and right-handed electrons, having different Z-charges. In a world where all symmetries of the Standard Model would be realized like in electrodynamics, all elementary particles would have zero masses. In the real world, these masses exist, and therefore something must be happening to the symmetries of the Standard Model.

3.3 Symmetry breaking

In discussing the relation between symmetries and conservation laws and bans, we neglected a certain circumstance. It consists in the fact that conservation laws and symmetry bans are fulfilled only when the symmetry is present explicitly. But broken symmetries can also exist. For example, in a homogeneous sample of iron at room temperature, there is always a magnetic field pointing in some direction; the sample is actually a magnet. If there were live creatures inside this magnet, they would discover that not all directions in the space surrounding them are equivalent: an electron moving across the magnetic field is subjected to a Lorentz force, unlike an electron moving along the magnetic field. Thus, the magnetic field inside the sample breaks the symmetry with respect to rotations in space. The angular momentum conservation is therefore not fulfilled inside a magnet. Here, we are dealing with spontaneous symmetry breaking. In the absence of external influences (for example, Earth's magnetic field), magnetic fields in different samples of iron can point in different directions, and none of these directions can be considered preferable. The original symmetry with respect to rotations still exists, but it manifests itself in that the magnetic field inside the sample can point in any direction. But because the magnetic field did arise, a certain direction was also singled out and the symmetry inside the magnet happened to be broken. At a more formal level, the equations (the Hamiltonian, the Lagrangian) controlling the interaction of iron atoms with each other and with the magnetic field are symmetric with respect to rotations in space, but the state of the system comprising these atoms, i.e., the iron sample, is not symmetric. This is precisely the essence of the phenomenon of spontaneous symmetry breaking. We are here dealing with the ground state, having the least energy. A sample of iron eventually occurs in that state, even if initially it was not magnetized.

We see that spontaneous breaking of a certain symmetry occurs when the equations of the theory are symmetric, while the ground state is not. The term 'spontaneous' is used in this case because the system itself, without our participation, chooses a nonsymmetric state, because it is the most advantageous state from the standpoint of energy. From the above example it is clear that if a symmetry is spontaneously broken, the conservation laws and bans based on it are not fulfilled; our example concerns the angular momentum conservation. We stress that the complete symmetry of a theory can be violated only partly: in our example, of the complete symmetry with respect to all rotations in space, only symmetry with respect to rotations around the magnetic field direction remains manifest and unbroken.

The creatures living inside the magnet could have asked themselves the following question: "In our world, not all directions are equivalent, but is space itself fundamentally nonsymmetric with respect to rotations?" Having studied the motion of electrons and constructed an appropriate theory (in this case, electrodynamics), they would have understood that the answer to this question is negative: the equations of this theory are symmetric, but this symmetry is spontaneously broken owing to the magnetic field 'spilled out' around them. If they had developed this theory further, they would have predicted that a field responsible for spontaneous symmetry breaking should have its own quanta, photons. And they would have verified that these quanta actually existed, being produced in collisions of electrons.

In general terms, the situation in elementary particle physics is similar to the one just described. But there are also important differences. First, naturally, no medium similar to the crystal lattice of iron atoms exists. The state of least energy in Nature is the vacuum (by definition!). This does not mean that there cannot be any fields homogeneously 'spilled out' in the vacuum. On the contrary, the discrepancies discussed in Section 3.2, testify that the symmetries of the Standard Model (more precisely, part of them) must be spontaneously broken, and this implies that a field exists in the vacuum that is responsible for this symmetry breaking. Second, the issue concerns not space–time symmetries but internal symmetries. The presence of a field in the vacuum should not lead to violation of space–time symmetries. Hence follows the conclusion that, unlike the magnetic field, this field must not single out any direction in space (more precisely, in space–time, because we are dealing with relativistic physics). Fields with such a property are called scalar fields; their corresponding particles have spin 0. Therefore, a field spilled out in the vacuum and leading to symmetry breaking must be new: the fields that we explicitly or implicitly mentioned above (the electromagnetic field, the fields of $W^{\pm}$- and Z-bosons, and the gluon field) have the corresponding particles of spin 1; such fields single out directions in space–time and are called vector fields, but we need a scalar field. Fields corresponding to fermions (spin 1/2) are not suitable, either. Third, the new field must not fully break the symmetries of the Standard Model: the internal symmetry of electrodynamics must remain unbroken. Finally, and most importantly, the interaction of the new field spilled out in the vacuum with $W^{\pm}$- and Z-bosons, electrons, and other femions, must result in these particles acquiring mass.

The mechanism for generating the masses of particles of spin 1 (in Nature, these are $W^{\pm}$- and Z-bosons) by spontaneous symmetry breaking was proposed in the context of elementary particle physics [11] by theoreticians from Brussels, Francois Englert and Robert Brout [12] and somewhat later

[11] Some reservations here and below originate from the fact that quite similar mechanisms had previously been known in condensed matter physics owing to the works of London, Ginzburg–Landau, Bogoliubov, Bardeen–Cooper–Schrieffer, Anderson, and others.

by a physicist from Edinburgh, Peter Higgs [13, 14]. This occurred in 1964. They were inspired by the idea of spontaneous symmetry breaking (but in theories without vector fields, i.e., without spin-1 particles) introduced in elementary particle physics in 1960–1961 in the works of Nambu [15], Nambu and Jona-Lasinio [16, 17], Vaks and Larkin [18], and Goldstone [19, 20]. Unlike the previous authors, Englert, Brout, and Higgs considered a theory (conceptual at the time) that involved both a scalar (spin-0) field and a vector (spin-1) field. In this theory, an internal symmetry exists, quite similar to the gauge invariance of electrodynamics, but, unlike in electrodynamics, the internal symmetry is spontaneously broken by a homogeneous scalar field present in the vacuum. A remarkable result obtained by Englert, Brout, and Higgs was the demonstration of the fact that this symmetry breaking automatically implies that a spin-1 particle — the vector field quantum — becomes massive.

A straightforward generalization of the Englert–Brout–Higgs mechanism, with fermions and their coupling to the symmetry-breaking scalar field included into the theory, also results in the generation of fermion masses. Everything starts shaping up! The Standard Model is obtained by a further generalization involving the inclusion of several vector fields instead of one (photons and $W^{\pm}$- and Z-bosons; gluons are a separate story: they have nothing to do with the Englert–Brout–Higgs mechanism), and different types of fermions. This generalization is actually quite nontrivial; it was initiated by Glashow [21] and completed by Weinberg [22] and Salam [23].

We now return to 1964. To investigate the properties of their theory, Englert and Brout used quite a baroque, from the modern standpoint, approach. Most likely for this reason they did not notice that together with a massive particle of spin 1, this theory predicted the existence of one more particle, a boson of spin 0. Higgs noticed that [14], and now this new spinless particle is often called the Higgs boson. As we noted at the beginning of this article, such a terminology does not seem to be quite correct: the key proposal to use a scalar field for spontaneous symmetry breaking and for generating the masses of spin-1 particles was actually first made by Englert and Brout. Without going into terminological details, we stress that the new boson with zero spin is the quantum of the symmetry-breaking scalar field. Precisely this makes it unique [1].

Here, a comment is in order. We repeat that if there were no spontaneous symmetry breaking, $W^{\pm}$- and Z-bosons would be massless. Each of them would have two spin states, two types of quanta, like the photon. Hence, we would have a total of $2 \times 3 = 6$ spin states of $W^{\pm}$- and Z-bosons. In the Standard Model, the $W^{\pm}$- and Z-bosons are massive: each of them has three spin states resulting in $3 \times 3 = 9$ types of quanta in total. The question arises as to where the three 'excess' types of quanta come from. The point is that in the Standard Model, it is necessary to introduce not one but four scalar Englert–Brout–Higgs fields. The quantum of one of them is the Higgs boson discovered at CERN. Owing to spontaneous symmetry breaking, the quanta of the other three fields precisely transform into the three 'excess' quanta of the massive $W^{\pm}$- and Z-bosons. It is useless to search for them: they were found long ago, because $W^{\pm}$- and Z-bosons are known to have mass.

By the way, this arithmetic is consistent with all four Englert–Brout–Higgs fields being scalar: their quanta have spin 0. Massless $W^{\pm}$- and Z-bosons would have spin projections onto the direction of motion equal to -1 and $+1$. In the case of massive $W^{\pm}$- and Z-bosons, these projections take the values -1, 0, and $+1$, i.e., the 'excess' quanta have zero projections. The three Englert–Brout–Higgs fields giving rise to these excess quanta also have zero spin projections onto the direction of motion, simply because their spins are zero. Everything matches.

Thus, the Higgs boson is the quantum of one of the four Englert–Brout–Higgs scalar fields present in the Standard Model. The other three are absorbed by the $W^{\pm}$- and Z-bosons and become their third, missing spin states.

3.4 Is the Higgs boson really necessary?

The most astonishing thing in this story is that we now understand the following: the Englert–Brout–Higgs mechanism is by no means the only possible one for symmetry breaking in the physics of the microworld and for generating the masses of elementary particles, and the Higgs boson might have not existed. We learn this, for instance, from condensed matter physics. It gives numerous examples of spontaneous symmetry breaking and of the diversity of mechanisms of such symmetry breaking. In most cases, nothing similar to the Higgs boson exists in these examples.

The closest solid-state analog of the Standard Model spontaneous symmetry breaking in the vacuum is spontaneous breaking of the internal symmetry of electrodynamics inside the body of a superconductor. It leads to a photon inside a superconductor having mass in a certain sense (similarly to $W^{\pm}$- and Z-bosons in the vacuum). This is manifested in the Meissner effect — the expulsion of the magnetic field from a superconductor.

The effective Ginzburg–Landau theory of superconductivity is quite similar to the Englert–Brout–Higgs theory (to be more precise, vice versa: the Ginzburg–Landau theory is 14 years older). The Ginzburg–Landau theory also involves a scalar field, which is homogeneously spilled out over the superconductor, which leads to spontaneous symmetry breaking. However, the Ginzburg–Landau theory is not without reason called effective: it describes many properties of superconductors correctly, but is unsuitable for understanding the origin of superconductivity. No scalar field actually exists in a superconductor; there are electrons and the crystal lattice, while superconductivity is due to the special properties of the ground state of the system of electrons, the interaction among which gives rise to these properties.

Can such a picture also occur in the microworld? Could it be that no fundamental scalar field spilled out in the vacuum exists, while spontaneous symmetry breaking is due to totally different reasons? The theoretical answer to this question is positive. An example is the so-called technicolor model, proposed in 1979 by the aforementioned Weinberg [24] and Susskind [25] (see also Ref. [1]). This model involves no fundamental scalar fields and no Higgs boson. Instead, there are many new elementary particles with properties similar to those of the known quarks. Precisely the interaction between these new particles leads to spontaneous symmetry breaking and to the generation of the masses of $W^{\pm}$- and Z-bosons. Concerning the masses of fermions, the situation is worse, but this problem can also be resolved by complicating the theory.

This seems to contradict the argument in Section 3.3, asserting that symmetry must be broken precisely by a scalar field. The loophole here lies in the fact that the scalar field may be composite, meaning that the quanta corresponding to it may not be elementary, but composed of other, elementary, particles.

In this connection, we recall the Heisenberg quantum mechanical uncertainty relation $\Delta x\,\Delta p \geqslant \hbar$, where Δx and Δp are the uncertainties in position and momentum. One of its manifestations is that the structure of composite objects with a characteristic size Δx is only revealed in processes involving the participation of particles with sufficiently large momenta $p \geqslant \hbar/\Delta x$, and, consequently, with sufficiently high energies. At low energies, a composite particle is similar to an elementary particle. For an effective description of such particles at low energies, it is quite reasonable to regard them as quanta of some field. If the spin of a composite particle is zero, this field is a scalar.

A similar situation is realized, for example, in the physics of π-mesons, particles of spin 0. Until the mid-1960's, π-mesons were not known to consist of quarks and antiquarks. At the time, π-mesons were described by elementary scalar fields.[12] We now know that π-mesons are composite particles, but the 'old' field theory of π-mesons remains valid while applied to processes at low energies. The quark structure of π-mesons starts to become apparent only at energies of the order of 1 GeV and higher, and then this theory no longer works. The energy scale of 1 GeV has appeared here for a reason: it is the scale of strong interactions that bind quarks into π-mesons, protons, neutrons, and other hadrons; it is the mass scale of strongly interacting particles, for example, of protons. We note that π-mesons themselves stand apart: for a reason that we do not discuss here, they have significantly smaller masses: $m_{\pi^\pm} = 140$ MeV and $m_{\pi^0} = 135$ MeV.

Therefore, the scalar fields responsible for spontaneous symmetry breaking can, in principle, be composite. Precisely such a situation is assumed in the technicolor model. In this case, the three spinless quanta that are absorbed by the $W^\pm$- and Z-bosons and become their missing spin states are closely analogous to π^+-, π^--, and π^0-mesons, except that the corresponding energy scale is not 1 GeV but several TeV. Within such a picture, the existence is expected of numerous composite particles — analogs of the proton, neutron, ρ-meson, etc. — with masses in the range of several TeV. The relatively light Higgs boson, on the contrary, is absent in this picture. One more feature of the model is that $W^\pm$- and Z-bosons here are partly composite particles, because, as we have already said, some of their components are similar to π-mesons.[13] This should have been manifested in the interactions of $W^\pm$- and Z-bosons.

Just this last circumstance led to the technicolor model being rejected (at least in its initial formulation) long before the recent experimental finding of the new boson: precise measurements of the properties of $W^\pm$- and Z-bosons at LEP and SLC are not consistent with the model predictions. The discovery of the new boson led to the model finally being given up for good. The technicolor model, however, is by far not the only one involving composite scalar fields, and the idea of compositeness seems no less attractive than the Englert–Brout–Higgs theory that involves elementary scalar fields (a general analysis of the predictions by composite models is presented in Ref. [26]). Naturally, after the discovery of the new boson at CERN, the idea of compositeness ended up in a more difficult situation than before: if this particle were composite, it should be sufficiently successful in mimicking an elementary Higgs boson. Nevertheless, the issue is not closed: new data from the Large Hadron Collider are required, in particular, more accurate measurements of the properties of the new boson.

4. The discovery has been made. What's next?

As the working hypothesis, we now return to the minimal version of the theory — the Standard Model with a single elementary Higgs boson. In this theory, just the Englert–Brout–Higgs field (more precisely, fields) provide masses for all elementary particles, and therefore the interaction of each of these particles with the Higgs boson is strictly fixed. The larger the mass of a particle is, the stronger its interaction; the stronger the interaction, the higher the probability of the Higgs boson decay into a pair of particles of the given sort. Decays of the Higgs boson into pairs of quite heavy particles $t\bar{t}$, ZZ, and W^+W^- are forbidden by energy conservation. The next in mass is the b-quark with the mass $m_b = 4$ GeV, and precisely for this reason, as we have already said, the Higgs boson most readily decays into a $b\bar{b}$ pair. Also of interest is the decay of the Higgs boson into a pair of quite heavy τ-leptons $H \to \tau^+\tau^-$ ($m_\tau = 1.8$ GeV); this should occur with a probability of 6% [7]. Besides the decays $H \to \gamma\gamma$, $H \to ZZ^* \to 4l$, and $H \to WW^* \to l\nu l\nu$ discussed above, we also note the decay $H \to Z\gamma$, whose probability should amount to 0.15%. It will be possible to measure these probabilities at the Large Hadron Collider, and any deviation from the predictions indicated will signify that the Standard Model is not correct (estimates of these deviations for certain classes of theories extending the Standard Model can be found in Ref. [27]). And, conversely, agreement with predictions of the Standard Model will more and more convince us of its validity.

The same can be said about Higgs boson production in collisions of protons at the Large Hadron Collider. The Higgs boson can be produced alone (by the fusion of gluons, Fig. 3a) or together with a pair of high-energy light quarks (the fusion of vector bosons, Fig. 3 b), or together with a single W- or Z-boson (Fig. 3c) or, finally, together with a $t\bar{t}$ pair (Fig. 3d). It is possible to identify the particles produced together with the Higgs boson, and therefore the various production

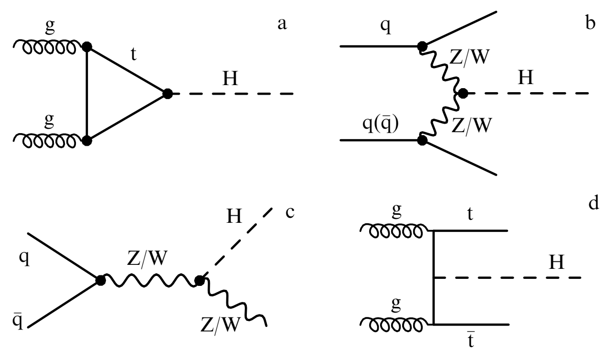

Figure 3. Examples of Feynman diagrams describing production of the Higgs boson in pp collisions; g, q, and q̄ stand for a gluon, a light quark (u or d), and a light antiquark inside a proton.

[12] To be more precise, pseudoscalar fields, but this subtlety is not essential for us.

[13] Such a possibility is consistent with the $W^\pm$- and Z-bosons having masses that are small compared with the new energy scale of the order of several TeV: as we have noted, π-mesons also have small masses compared to the hadron scale of 1 GeV.

mechanisms can be studied separately at the Large Hadron Collider. This allows extracting information on the interaction of the Higgs boson with $W^{\pm}$- and Z-bosons and the t-quark.

Finally, an important property of the Higgs boson is its self-coupling. This should be manifested in the process $H^* \to HH$, where H^* is a virtual particle. The properties of this interaction are also unambiguously predicted in the Standard Model. In any case, its investigation is an issue for the distant future.

We see that an extensive program exists for studying interactions of the new boson at the Large Hadron Collider. Its implementation will result in clarifying whether Nature is described by the Standard Model or we have to deal with another, more complicated (or, maybe, more simple) theory. However, estimates presented, e.g., in Ref. [27] show that the accuracy with which the coupling constants of the new boson with other particles will be determined in experiments at the Large Hadron Collider will quite probably be insufficient for resolving this issue. Further progress, related to significant improvement of the measurement precision [28], will require the construction of a new accelerator: an e^+e^- collider with a record energy for such types of machines. In this journey, numerous surprises may lie in wait for us.

5. Instead of a conclusion: in search of 'new physics'

From a 'technical' standpoint, the Standard Model is inherently consistent. This means that in its framework — at least in principle, and quite frequently also in practice — it is possible to calculate any physical quantity (of course, we mean those phenomena that the Standard Model is supposed to describe; see footnote 2), and the result contains no uncertainties. Nevertheless, many, although not all, theoreticians consider the situation in the Standard Model to be not quite satisfactory. This is primarily related to the problem of its energy scale [1].

It is clear from the foregoing that the energy scale of the Standard Model is of the order of $M_{\rm SM} = 100$ GeV.[14] This is the mass scale of $W^{\pm}$- and Z-bosons and of the Higgs boson. Is that a lot or a little?

In physics, one more energy scale exists. It is related to gravity and equals the Planck mass $M_{\rm Pl} = 10^{19}$ GeV. At low energies, gravitational interactions between particles are negligibly weak, but they become stronger as the energy increases, and at energies of the order of $M_{\rm Pl}$ gravity becomes strong. The range of energies above $M_{\rm Pl}$ is the region of quantum gravity, whatever it may represent. For us, it is important that gravity is probably the most fundamental interaction and that the gravitational scale $M_{\rm Pl}$ is the most fundamental energy scale. Why then is the scale of the Standard Model, $M_{\rm SM} = 100$ GeV, so far from $M_{\rm Pl} = 10^{19}$ GeV?

This problem has another, somewhat subtler, aspect. It is related to the fact that all parameters initially involved in the theory acquire radiative corrections due to interaction with virtual particles. In quantum electrodynamics, these corrections (for instance, the anomalous magnetic moment of the electron) are small, but in the Englert–Brout–Higgs sector they are enormous. This is a peculiarity of the elementary scalar fields in this sector; other fields exhibit no such property. The main effect here consists in the radiative corrections striving to 'pull up' the energy scale of the Standard Model, $M_{\rm SM}$, to the gravitational scale $M_{\rm Pl}$. Staying within the Standard Model, the only way out is to choose the initial parameters of the theory such that, with the radiative corrections taken into account, they lead to the correct value of $M_{\rm SM}$. Here, the fine tuning should amount to a value close to $M_{\rm SM}^2/M_{\rm Pl}^2 = 10^{-34}$! This is precisely the second aspect of the Standard Model energy scale: it does not seem likely that such a fine tuning exists in Nature.

Many (although not all, we repeat) theoreticians believe that this problem clearly demonstrates the necessity of going beyond the Standard Model. If the Standard Model stops working or is significantly extended at the energy scale $M_{\rm NP}$, the argument concerning the radiative corrections is modified. Roughly speaking, the required fine tuning of the parameters then amounts to $M_{\rm SM}^2/M_{\rm NP}^2$, while in reality two orders of magnitude weaker. This means that no fine tuning of the parameters is required if the scale of the 'new physics' lies in the range of 1–2 TeV, i.e., exactly in the region available at the Large Hadron Collider.

What sort of physics could the 'new physics' be? Theoreticians are not unanimous concerning this issue. One of the versions involves the composite nature of scalar fields providing spontaneous symmetry breaking. We discussed it in Section 3.4. Another, even more popular (for the time being?) possibility invokes supersymmetry, which predicts a whole 'zoo' of new particles with masses in the range from hundreds of GeV up to several TeV [1, 29, 30]. Quite exotic versions, such as extra dimensions of space, are also discussed [31–33].

In spite of all the efforts, no experimental evidence of any new physics has yet been obtained. Generally speaking, this may sound alarming: do we really understand everything correctly? It may quite be, however, that we have not reached the new physics in energy and in the collected statistic, and that new revolutionary discoveries are around the corner. Once again, the main hopes here are pinned on the Large Hadron Collider, which will start operating in a year and half at its designed energy of 13–14 TeV and rapidly collect data. Let us follow the news!

[14] Here, we are not speaking of strong interactions, whose scale is 1 GeV; with this scale, everything is much simpler.

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