

CONFERENCES AND SYMPOSIA

PACS number: 01.10.Fv

Physics at the Large Hadron Collider. Higgs boson
(Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 26 February 2014)

DOI: 10.3367/UFNe.0184.201409g.0985

A scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) "Physics at the Large Hadron Collider. Higgs boson" was held in the conference hall of the Lebedev Physical Institute, RAS, on 26 February 2014.

The agenda of the session, announced on the website www.gpad.ac.ru of the Physical Sciences Division, RAS, listed the following reports:

(1) **Boos E E** (Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow) "Standard Model and predictions for the Higgs boson";

(2) **Zaytsev A M** (National Research Center Kurchatov Institute, Moscow) "ATLAS experiment. The Higgs boson and the Standard Model";

(3) **Lanyov A V** (Joint Institute for Nuclear Research, Dubna, Moscow region) "CMS collaboration results: Higgs boson and search for new physics";

(4) **Kazakov D I** (Joint Institute for Nuclear Research, Dubna, Moscow region) "The Higgs boson has been found: what is next?"

Papers written on the basis of oral reports 1, 3, and 4 are published below. An extensive review of the topic in item 2 will be published in an upcoming issue of *Physics–Uspekhi*.

Uspekhi Fizicheskikh Nauk **184** (9) 985 – 1016 (2014)
DOI: 10.3367/UFNr.0184.201409g.0985
Translated by A L Chekhov, A V Lanyov, D I Kazakov; edited by A M Semikhatov

PACS numbers: **12.15.–y**, **12.60.–i**, 14.80.Bn
DOI: 10.3367/UFNr.0184.201409h.0985

Standard Model and predictions for the Higgs boson

E E Boos

1. Introduction

Since school we all know that there are four different types of interaction in nature: gravitational, weak, electromagnetic, and strong. The strong interaction binds protons and neutrons together to form a nucleus and to keep it stable. These are short-range interactions with a characteristic range of the order of the nucleus size, $10^{-12} - 10^{-13}$ cm. Less strong interactions are the well-known electromagnetic ones that ensure the stability of atoms and molecules by attracting the positively charged atomic nucleus and negatively charged electrons to each other. The range of these forces can be very large. We do not feel this directly because, *in toto* atoms and molecules are electrically neutral. The interactions with even smaller forces are the weak ones. They account for the decay of the neutron in a free state and for the instability of many atomic nuclei. In particular, these interactions are responsible for nuclear cycles that result in energy emission from the Sun. The gravitational interactions are the weakest ones, and they bind massive objects together to form planets, the Solar System, galaxies, etc.

All these notions, which we were taught in school, are absolutely true. But the problem lies in the fact that the way interactions manifest themselves depends on the type of interacting objects and on the distance between them. The Standard Model is a quantum theory that describes the mechanisms of Nature on scales 3 to 4 orders of magnitude less than the size of nuclei and protons. The 'microscopes' that allow us to obtain information about phenomena at such extremely small distances are colliders — the ones that do not operate any more: LEP I, LEP II (LEP — Large Electron–Positron collider), SLC (Stanford Linear Collider), HERA (Hadron–Electron Ring Accelerator), Tevatron, etc., as well as the biggest collider in history, the Large Hadron Collider (LHC) — which now operates — and the International Linear Collider (ILC), expected in the future.

To understand what distances can be studied at a specific collider, it is convenient to use the system of natural units, which is standard for high-energy physics. In this system, the units are the Planck constant $\hbar = 6.582 \times 10^{-22}$ MeV s and the speed of light $c = 2.998 \times 10^{10}$ cm s^{-1}. One electron-volt equals the energy that an electron with the charge $q_e = 1.6 \times 10^{-19}$ C obtains after passing through a potential difference of 1 V (1 eV $= q_e$ at 1 V). In the system of natural units, it is assumed that $\hbar = c = 1$, which leads to a simple but very important relation:

$$\frac{1}{\text{GeV}} \approx 2 \times 10^{-14} \text{ cm}$$

(1 GeV $= 10^9$ eV). The Heisenberg uncertainty relation $\Delta x \Delta p \geqslant 1/2$, which holds in the quantum world, tells us that the bigger the possible value of the transferred momentum is, the smaller the distances that can be studied. The transferred momentum 1 TeV $= 10^3$ GeV allows studying phenomena at distances of 10^{-17} cm. Accordingly, at the LHC, where the transferred momentum can be around 1–10 TeV (the range

E E Boos Skobeltsyn Institute of Nuclear Physics,
Lomonosov Moscow State University, Moscow, Russian Federation
E-mail: boos@theory.sinp.msu.ru

Uspekhi Fizicheskikh Nauk **184** (9) 985 – 996 (2014)
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known as the Terascale), the structure of matter can be studied on scales of $10^{-17} - 10^{-18}$ cm.

Earlier, when the collision energy in the center-of-mass frame and, correspondingly, the transferred momentum reached 10–100 GeV, we had the opportunity to 'see' how the world looks on scales that are much smaller than the size of the nucleon, 10^{-13} cm. It turned out that at these scales, the proton and neutron consist of quarks and gluons, which are responsible for the strong interactions. The strength of these interactions weakens as the characteristic distances decrease. The experiments revealed six types of quarks, which are grouped into three generations, two quarks in each. It also turned out that the six discovered leptons form three generations, each consisting of a charged lepton and the corresponding neutrino. At the same time, leptons and quarks do not reveal any inner structure at distances up to $\sim 10^{-17}$ cm. These six quarks and six leptons form the particles of matter. The world around us is built from leptons and quarks of the first generation. Other quarks and leptons appear either in high-energy cosmic rays or under artificial conditions in accelerators and colliders. The six quarks and six leptons grouped into three generations, the corresponding antiparticles, together with vector bosons (photon, $W^{\pm}$, Z, gluons) and the recently discovered scalar boson (Higgs boson) form the set of fundamental particles in the Standard Model (SM).

2. Standard Model

The Standard Model [1–3] is a gauge quantum field theory that is the basis for the description of the microcosm on scales of $10^{-13} - 10^{-17}$ cm. The SM is one of the most significant intellectual achievements over the last 50 years. A large number of theorists and experimentalists took part in the development and comprehensive verification of the SM predictions. More than ten Nobel Prizes were awarded for investigations of different aspects of the SM, including in 2013, received by P Higgs and F Englert. In this article, we mainly discuss the electroweak part of the SM. A detailed discussion of the various aspects of the SM can be found in a series of reviews and lectures (see, e.g., [4–15]).

Our introduction to the SM does not follow the historical principle. To build the SM, we start with a discussion of the main requirements that it should satisfy.

(1) *Reproducibility of the electromagnetic interactions of leptons and quarks that are invariant under the transformation group* $U(1)_{em}$. Charged leptons have the electric charge -1, the neutrino has a zero charge, u-type quarks have the charge $2/3$, and d-quarks have the charge $-1/3$. We recall that the proton has the quark composition uud and the neutron, ddu.

(2) *Reproducibility of the axial vector structure* $(V-A)$ *of the quark and leptonic charged currents*. The structure of charged currents is described by the results of many measurements of the interactions between leptons and quarks involving a change in charge by one unit. The Fermi Lagrangian that describes the muon decay has the form

$$L = \frac{G_F}{\sqrt{2}}\, \bar{\mu}\gamma_\sigma(1-\gamma_5)\,\nu_\mu \bar{e}\gamma_\sigma(1-\gamma_5)\nu_e\,, \qquad (1)$$

where the leptonic current $J_\sigma \sim \bar{l}\gamma_\sigma(1-\gamma_5)\nu_l$ has the $V-A$ structure. This means that only left-handed components Ψ_L of the fermion field take part in the charged current interactions:

$$\Psi = \frac{1-\gamma_5}{2}\,\Psi + \frac{1+\gamma_5}{2}\,\Psi = \Psi_L + \Psi_R\,. \qquad (2)$$

(3) *Independence of the Lagrangian from the field phase or the gauge interaction character*.

This principle can be quickly illustrated as follows. Our theory has to describe leptons and quarks, which are fermions. Fermions are represented as complex fields, which, in addition to the amplitude, have a phase that is defined at each point of space–time. But the Lagrangian cannot depend on such complex phases; therefore, it should contain only bilinear combinations of the field and the conjugate field. However, for the Dirac equation to follow from the Lagrangian, it must contain derivatives (have a kinetic part). But a derivative acts on the field phase and makes an incorrect contribution to the Lagrangian. The way such dependences can be eliminated is by introducing an additional vector field (vector, because the derivative ∂_μ acting on the phase produces a vector). The vector field should be transformed in such way that the additional phase dependence is exactly compensated. The transformation rule for the compensating (gauge) field depends on the specific group, but it is possible in each case and the phase-independence principle itself remains unchanged.

Gauge invariants are constructed by replacing ordinary derivatives by covariant ones: $\partial_\mu \to D_\mu = \partial_\mu - gA_\mu$, and the kinetic terms of the gauge field itself are constructed from the field strength tensor $F_{\mu\nu}$ of the A_μ field.

(4) *Renormalizability and unitarity*. The dimension of the terms (operators) in the SM Lagrangian should not be more than four. By using currents and structures that include covariant derivatives and electromagnetic tensors of the gauge field or fields, we can construct gauge-invariant operators with a dimension greater than four. This means that these operators should be reduced to a unit-free form by introducing specific parameters in the denominator. The presence of such operators would lead to nonunitary behavior of the cross sections at high energies, and the corresponding theories would be nonrenormalizable. The four-fermion Fermi Lagrangian (operator) introduced above has the dimension six, which leads to such a non-renormalizable and nonunitary theory.

(5) *Absence of chiral anomalies*. Left- and right-handed fields should be included in the theory in different ways. Therefore, it is not obvious a priori whether the theory would have chiral anomalies. The presence of such anomalies would lead to a violation of unitarity and, hence, is not appropriate.

(6) *The possibility of considering three generations of leptons and quarks*. As was mentioned, three generations of leptons and quarks have been discovered, and the SM should consider this fact.

(7) *The possibility of describing massive fermions and gauge bosons without breaking the gauge invariance*. All fermions, with a possible exception of one specific neutrino, have mass. All electroweak gauge bosons, except photons, also have mass. As we see in what follows, the requirement of the possibility of describing massive fields leads to the idea of spontaneous symmetry breaking.

We now proceed with the construction of the SM Lagrangian. Charged currents include only left-handed field components (leptons and neutrinos, u- and d-quarks); hence, left-handed components can be naturally arranged into doublets

$$\begin{pmatrix} \nu_l \\ l \end{pmatrix}_L, \quad \begin{pmatrix} u \\ d \end{pmatrix}_L,$$

which, in analogy with the ordinary isospin, are called weak-isospin doublets. There should be three generations and, because all neutrinos are left-handed, they are grouped in the following way:

generation I		generation II		generation III	
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$.
e_R	u_R, d_R	μ_R	c_R, s_R	τ_R	t_R, b_R

We have introduced left-handed doublets, and we can therefore assume that there should be a corresponding invariance under the group called the weak-isospin group $SU_L(2)$. One could try to add the electromagnetic interaction group $U(1)_{em}$ to that group, but this does not lead to a correct description of all electroweak interactions. Nevertheless, we can assume the invariance under some other group, $U_Y(1)$, and call it the weak-hypercharge group. Moreover, we know from quark spectroscopy that quarks need to have the quantum number 'color', and that there are three different color states. Therefore, it is natural to assume that there is $SU_c(3)$ symmetry to describe the quark color states.

We now take the following step: we require the gauge invariance of the theory under the group

$$SU_c(3) \times SU_L(2) \times U_Y(1) .$$

As soon as we introduce this requirement, we actually have no other option than to write the following Lagrangian, consisting of dimension-four terms:

$$L = -\frac{1}{4} W^i_{\mu\nu}(W^{\mu\nu})^i - \frac{1}{4} B_{\mu\nu}B^{\mu\nu} - \frac{1}{4} G^a_{\mu\nu}(G^{\mu\nu})^a + \sum_{f=1,q} \bar{\Psi}^f_L(iD^L_\mu\gamma^\mu)\Psi^\dagger_L + \sum_{f=1,q} \bar{\Psi}^f_R(iD^R_\mu\gamma^\mu)\Psi^\dagger_R , \quad (3)$$

where

$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g_2\varepsilon^{ijk}W^j_\mu W^k_\nu ,$$
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu , \quad (4)$$
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_s f^{abc}A^b_\mu A^c_\nu ,$$

$$D^L_\mu = \partial_\mu - ig_2 W^i_\mu\tau^i - ig_1 B_\mu\left(\frac{Y^f_L}{2}\right) - ig_s A^a_\mu t^a ,$$
$$D^R_\mu = \partial_\mu - ig_1 B_\mu\left(\frac{Y^f_R}{2}\right) - ig_s A^a_\mu t^a . \quad (5)$$

Here, the indexes i, j, k take values 1, 2, 3, the indexes a, b, c take values $1, \ldots, 8$, and $Y^f_{L,R}$ is the weak hypercharge for left- and right-handed fields of leptons and quarks.

We note an important difference between Abelian and non-Abelian gauge theories. In non-Abelian gauge theories, the gauge charges g_2 and g_s are included both in the covariant derivative, determining interactions with fermions, and in the electromagnetic tensor, determining the interaction between the gauge fields. Therefore, the strength of interaction with fermions cannot be changed without changing the strength of interaction between the gauge bosons themselves. But in Abelian theories, there is no self-interaction of gauge bosons and the gauge invariance principle allows certain freedom — in our case, it is the existence of the $Y_{L,R}$ parameter.

Lagrangian (3) can now be rewritten in terms of charged vector fields $W^\pm_\mu = (W^1_\mu \mp iW^2_\mu)/\sqrt{2}$ and neutral fields W^3_μ and B_μ, which can be a mixture of other fields A_μ and Z_μ with a certain mixing angle θ_W (the Weinberg mixing angle):

$$W^3_\mu = Z_\mu\cos\theta_W + A_\mu\sin\theta_W ,$$
$$B_\mu = -Z_\mu\sin\theta_W + A_\mu\cos\theta_W . \quad (6)$$

The Lagrangian describing the coupling of charged currents (CC) immediately follows from (3) and has the required form (V−A):

$$L^1_{CC} = \frac{g_2}{\sqrt{2}}\,\bar{\nu}_{eL}\gamma_\mu W^+_\mu e_L + \text{h.c.} = \frac{g_2}{2\sqrt{2}}\,\bar{\nu}_e\gamma_\mu(1-\gamma_5)W^+_\mu e + \text{h.c.} , \quad (7)$$

$$L^q_{CC} = \frac{g_2}{2\sqrt{2}}\,\bar{u}\gamma_\mu(1-\gamma_5)W^+_\mu d + \frac{g_2}{2\sqrt{2}}\,\bar{d}\gamma_\mu(1-\gamma_5)W^-_\mu u . \quad (8)$$

For the neutral-current (NC) interaction, according to requirement 1, one of the fields, say, A_μ, must have proper electromagnetic interactions, just as the photon field does. This requirement leads to a series of equations for hypercharges, which have solutions of the form

$$Y^e_R = 2Y^e_L , \quad Y^u_R = -\frac{4}{3}\,Y^e_L , \quad Y^d_R = \frac{2}{3}\,Y^e_L ,$$

where hypercharges are expressed through one independent parameter, for example, the hypercharge of the left-handed lepton doublet Y^e_L (see [16]). One of these equations relates charges to the mixing angle: $g_2\sin\theta_W = -g_1 Y^e_L\cos\theta_W$. This gives the neutral-charge Lagrangian with fields A_μ and Z_μ in the form

$$L_{NC} = e\sum_f Q_f J^{em}_{f\mu}A^\mu + \frac{e}{4\sin\theta_W\cos\theta_W}\sum_f J^Z_{f\mu}Z^\mu , \quad (9)$$

where $J^{em}_{f\mu} = \bar{f}\gamma_\mu f$, $Q_\nu = 0$, $Q_e = -1$, $Q_u = 2/3$, $Q_d = -1/3$, and $J^Z_{f\mu} = \bar{f}\gamma_\mu[v_f - a_f\gamma_5]f$. As a result, Lagrangians (7) and (9), which are derived from Lagrangian (3), have the structure that demonstrates the 'good' properties of the theory:

- proper charged currents (V−A);
- proper electromagnetic interactions;
- the absence of chiral anomalies (the verification of this property is beyond the scope of this article);
- prediction of new neutral currents coupled to the new boson Z_μ. These currents and the boson have been discovered experimentally.

However, the constructed theory cannot properly describe the properties of Nature. Not all the fields in such a theory have masses, while in reality the W and Z bosons, as well as all charged leptons and quarks, have nonzero masses. But, as we introduce mass into the theory, a serious problem appears. The mass terms for bosons $M^2_V V_\mu V^{\mu*}$ and the Dirac mass terms for fermions $m_\psi\bar{\psi}\psi = m_\psi(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$ obviously do not satisfy the gauge invariance requirement: the mass term for the vector field is not invariant under the replacement $V_\mu \to V_\mu + \partial_\mu\alpha$, and in the fermion mass terms, ψ_L and ψ_R are respectively a left-handed doublet and a right-

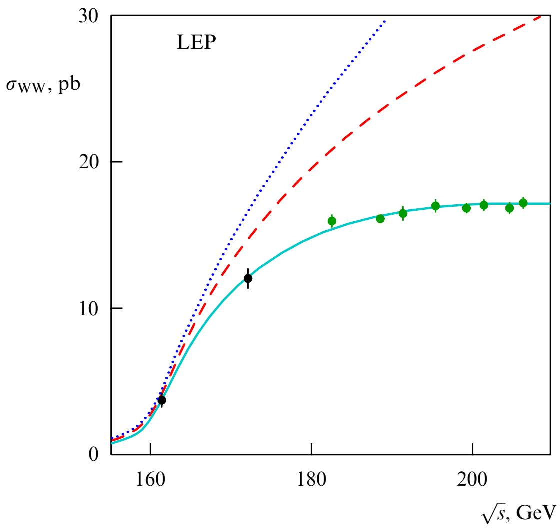


Figure 1. Cross section for WW pair production in comparison with theoretical predictions. Upper curve: contribution of the neutrino-exchange diagram. Middle curve: contribution of diagrams with a photon and neutrino exchange. The contribution of all SM diagrams (lower curve) is in excellent agreement with the experimental results, shown by circles. (See details in [17].)

handed singlet, which means that they transform differently under phase rotations.

The gauge interaction structure that follows from Lagrangian (3) has been reliably proved. The example given in Fig. 1 shows how well the experimental results agree with the structure of the three-boson vertices W^+W^-A and W^+W^-Z that follow from the kinetic part of (3). The situation where the interactions, unlike the states spectrum, are invariant under some certain symmetry, is typical for spontaneous symmetry breaking.

We recall that in the Ginzburg–Landau superconductivity theory [18] (see also [15]), the free energy that is invariant under spatial rotations and is a function of the temperature T and squared magnetization $\mathbf{M}$ can be expanded in a power series in magnetization:

$$F(T, |\mathbf{M}|^2) = f_0(T) + \frac{1}{2}\,\mu^2(T)|\mathbf{M}|^2 + \frac{1}{4}\,\lambda(T)|\mathbf{M}|^4 + \ldots\,.$$

From the requirement of an energy minimum, we obtain

$$\frac{\partial F}{\partial \mathbf{M}} = 0 \Rightarrow \left(\mu^2(T) + \lambda(T)|\mathbf{M}|^2\right)\mathbf{M} = 0\,. \qquad (10)$$

If at some critical temperature $\mu^2(T_{\text{crit}}) = 0$, then the situation is possible where $\mu^2(T) > 0$ for $T > T_{\text{crit}}$ and $\mu^2(T) < 0$ for $T < T_{\text{crit}}$. If $\mu^2(T) < 0$, then the solution $|\mathbf{M}_0|^2 = -\mu^2/\lambda$ realizes the energy minimum. Any specific direction of the magnetization vector $\mathbf{M}_0$ that the system chooses spontaneously breaks the original rotational symmetry.

3. Spontaneous symmetry breaking in the Standard Model. The Brout–Englert–Higgs mechanism

In analogy with the ideas of the Ginzburg–Landau theory, to the SM Lagrangian (3), we add a complex scalar-field Lagrangian that is invariant under the same group $SU_L(2) \times U_Y(1)$:

$$L_\Phi = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda^4 (\Phi^\dagger \Phi)\,, \qquad (11)$$

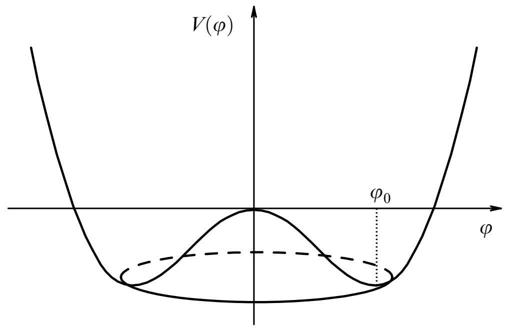


Figure 2. Higgs field potential.

where Φ is a complex doublet and the covariant derivative has the form

$$D_\mu = \partial_\mu - \mathrm{i} g_2 W_\mu^i \tau^i - \mathrm{i} g_1 \frac{Y_{\text{h}}}{2} B_\mu\,. \qquad (12)$$

Here, Y_{h} is the hypercharge of a scalar field, known as the Higgs field. This field potential, shown in Fig. 2, has a minimum

$$|\varphi_0| = \sqrt{\frac{|\mu^2|}{2\lambda}} = \frac{v}{\sqrt{2}} > 0$$

for negative μ^2, analogous to the potential in the Ginzburg–Landau theory. Any specific vacuum solution breaks the phase-shift (gauge) symmetry.

Any random complex scalar field, an $SU_L(2)$ doublet, can be parameterized by four real fields:

$$\Phi(x) = \exp\left(-\mathrm{i}\,\frac{\xi^i(x)\,t^i}{v}\right)\begin{pmatrix} 0 \\ \dfrac{v + h(x)}{\sqrt{2}} \end{pmatrix}. \qquad (13)$$

Because Lagrangian (11) is invariant under gauge transformations

$$\Phi(x) \to \Phi'(x) = \exp\left(\mathrm{i} g_2 \alpha^i t^i\right) \Phi(x)\,, \qquad (14)$$

we can fix the gauge $g_2\alpha^i(x) = \xi^i(x)/v$ such that all the fields $\xi^i(x)$ disappear from the Lagrangian under the corresponding gauge field transformation, leaving only physical degrees of freedom. In this gauge, called unitary, after expressing the fields W_μ^1, W_μ^2, W_μ^3, and B_μ in terms of $W_\mu^\pm$, A_μ, Z_μ, and

$$\Phi(x) = \begin{pmatrix} 0 \\ \dfrac{v + h(x)}{\sqrt{2}} \end{pmatrix},$$

the Lagrangian L_Φ takes the form

$$L = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}(2\lambda v^2)h^2 - \lambda v h^3 - \frac{\lambda}{4}\,h^4 + M_{\text{W}}^2 W_\mu^+ W^{\mu-}\left(1 + \frac{h}{v}\right)^2 + \frac{1}{2}\,M_Z^2 Z_\mu Z^\mu \left(1 + \frac{h}{v}\right)^2, \qquad (15)$$

where we can see the new scalar boson (Higgs) field $h(x)$ with the mass $M_{\text{h}}^2 = 2\lambda v^2$, the mass terms $M_{\text{W}} = (1/2)\,g_2 v$ for the fields $W_\mu^\pm$ and $M_Z = (1/2)(g_2 \cos\theta_{\text{W}} + g_1 Y_{\text{h}} \sin\theta_{\text{W}})v$ for the field Z_μ, as well as the term for the interaction of the fields W

and Z with the Higgs boson and the Higgs boson self-coupling terms h^3 and h^4.

The requirement that the mass of the field A_μ vanishes has the form

$$g_2 \sin\theta_{\rm W} - g_1 Y_{\rm h} \cos\theta_{\rm W} = 0\,.$$

After comparing this requirement with the one that followed from the requirement of proper electromagnetic interactions for the A_μ field,

$$g_2 \sin\theta_{\rm W} + g_1 Y_{\rm L}^{\rm e} \cos\theta_{\rm W} = 0\,,$$

we can conclude that the field A_μ corresponds to the photon field, which is massless and describes proper electromagnetic interactions with fermions, only when the Higgs boson and the lepton doublet hypercharges have the same absolute values but different signs:

$$Y_{\rm h} = -Y_{\rm L}^{\rm e}\,.$$

The vacuum

$$\Phi(x) = \begin{pmatrix} 0 \\ \dfrac{v + h(x)}{\sqrt{2}} \end{pmatrix}$$

breaks both symmetries, $\mathrm{SU_L}(2)$ and $\mathrm{U_Y}(1)$. However, there is a combination of the generators that leaves the vacuum unchanged:

$$\exp\,(\mathrm{i}\hat{T}_i\theta_i)\,\Phi_{\rm vac} = \Phi_{\rm vac} \Rightarrow \hat{T}_i \Phi_{\rm vac} = 0\,.$$

Such a combination fixes the value of $Y_{\rm h}$ to be $Y_{\rm h} = 1$:

$$\hat{T}_3 + \frac{1}{2}\,Y_{\rm h} = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + \frac{1}{2}\,Y_{\rm h}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}.$$

This condition means that the vacuum is electrically neutral and the $\mathrm{SU_L}(2) \times \mathrm{U_Y}(1)$ symmetry is broken down to $U_{\rm em}(1)$. The value of the Higgs field hypercharge $Y_{\rm h} = 1$ fixes the hypercharge $Y_{\rm L}^{\rm e}$. The expressions for the masses of the $\mathrm{W}^\pm$ bosons then satisfy the famous relation

$$M_{\rm W} = M_{\rm Z} \cos\theta_{\rm W}\,.$$

We note that the fields $\xi^i(x)$ in Eqn (13) have disappeared from the Lagrangian in the unitary gauge. However, following the Goldstone theorem, we would expect the existence of $4 - 1 = 3$ massless bosons corresponding to the number of generators that break the symmetry. These three bosons in gauge theory become (are 'eaten' by) longitudinal components of the vector fields $W^\pm$ and Z, which transform from components with no mass and two degrees of freedom into ones with mass and three degrees of freedom. This mechanism of mass generation is called the Brout–Englert–Higgs (BEH) mechanism [19-21].

4. Brout–Englert–Higgs mechanism for fermions

The BEH mechanism of spontaneous symmetry breaking allows producing mass not only for gauge bosons but also for fermions.

We can construct only two gauge-invariant Yukawa-type operators that, under spontaneous symmetry breaking, lead to the Dirac mass terms for fermions: $\bar{Q}_{\rm L}\Phi d_{\rm R} + \mathrm{h.c.}$ and $\bar{Q}_{\rm L}\Phi^{\rm C} u_{\rm R} + \mathrm{h.c.}$, where

$$Q_{\rm L} = \begin{pmatrix} u_{\rm L} \\ d_{\rm L} \end{pmatrix}, \quad \Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h \end{pmatrix},$$

$$\Phi^{\rm C} = \mathrm{i}\sigma^2 \Phi^\dagger = \frac{1}{\sqrt{2}}\begin{pmatrix} v + h \\ 0 \end{pmatrix},$$

σ^2 is the second Pauli matrix, and h.c. stands for Hermitian conjugate terms.

These two operators produce masses for the respective up and down fermions:

$$(\bar{u}_{\rm L}\ \bar{d}_{\rm L})\begin{pmatrix} 0 \\ v \end{pmatrix} d_{\rm R} + \bar{d}_{\rm R}(0\ v)\begin{pmatrix} u_{\rm L} \\ d_{\rm L} \end{pmatrix} = v(\bar{d}_{\rm L} d_{\rm R} + \bar{d}_{\rm R} d_{\rm L}) = v\bar{d}d\,.$$

However, the gauge invariance principle allows constructing more general operators, where possible mixing in quark and lepton sectors is taken into account:

$$L_{\rm Yukawa} = -\Gamma_{\rm d}^{ij}\bar{Q}_{\rm L}^{\prime i}\Phi\, d_{\rm R}^{\prime j} + \mathrm{h.c.} - \Gamma_{\rm u}^{ij}\bar{Q}_{\rm L}^{\prime i}\Phi^{\rm C}\, u_{\rm R}^{\prime j} + \mathrm{h.c.}$$
$$- \Gamma_{\rm e}^{ij}\bar{L}_{\rm L}^{\prime i}\Phi e_{\rm R}^{\prime j} + \mathrm{h.c.} \qquad (16)$$

Substituting fields Φ and $\Phi^{\rm C}$ in the unitary gauge leads to the Lagrangian of the form

$$L_{\rm Yukawa} = -\Big(M_{\rm d}^{ij}\bar{d}_{\rm L}^{\prime i} d_{\rm R}^{\prime j} + M_{\rm u}^{ij}\bar{u}_{\rm L}^{\prime i} u_{\rm R}^{\prime j} + M_{\rm e}^{ij}\bar{e}_{\rm L}^{\prime i} e_{\rm R}^{\prime j} + \mathrm{h.c.}\Big) \times \left(1 + \frac{h}{v}\right),$$

where $M^{ij} = \Gamma^{ij} v/\sqrt{2}$.

We now consider the fact that physical states are those with a certain mass. Mass matrices can be diagonalized by unitary transformations

$$d'_{{\rm L}i} = (U_{\rm L}^{\rm d})_{ij}\, d_{{\rm L}j}\,, \quad d'_{{\rm R}i} = (U_{\rm R}^{\rm d})_{ij}\, d_{{\rm R}j}\,,$$
$$u'_{{\rm L}i} = (U_{\rm L}^{\rm u})_{ij}\, u_{{\rm L}j}\,, \quad u'_{{\rm R}i} = (U_{\rm R}^{\rm u})_{ij}\, u_{{\rm R}j}\,,$$
$$l'_{\rm L} = (U_{\rm L}^{\rm l})\, l_{\rm L}\,, \quad l'_{\rm R} = (U_{\rm R}^{\rm l})\, l_{\rm R}\,,$$
$$U_{\rm L} U_{\rm L}^\dagger = 1\,, \quad U_{\rm R} U_{\rm R}^\dagger = 1\,, \quad U_{\rm L}^\dagger U_{\rm L} = 1\,.$$

After the diagonalization, the mass matrices have the form

$$(U_{\rm L}^{\rm u})^\dagger M_{\rm u} U_{\rm R}^{\rm u} = \begin{pmatrix} m_{\rm u} & 0 & 0 \\ 0 & m_{\rm c} & 0 \\ 0 & 0 & m_{\rm t} \end{pmatrix},$$

$$(U_{\rm L}^{\rm d})^\dagger M_{\rm d} U_{\rm R}^{\rm d} = \begin{pmatrix} m_{\rm d} & 0 & 0 \\ 0 & m_{\rm s} & 0 \\ 0 & 0 & m_{\rm b} \end{pmatrix},$$

$$(U_{\rm L}^{\rm l})^\dagger M_{\rm l} U_{\rm R}^{\rm l} = \begin{pmatrix} m_{\rm e} & 0 & 0 \\ 0 & m_{\mu} & 0 \\ 0 & 0 & m_{\tau} \end{pmatrix}.$$

The Yukawa Lagrangian has the following structure (in the simplest case where we assume neutrinos to be left-handed and massless):

$$L_{\rm Yukawa} = -\Big(m_{\rm d}^i \bar{d}_{\rm L}^i d_{\rm R}^i + m_{\rm d}^{*i}\bar{d}_{\rm R}^i d_{\rm L}^i + m_{\rm u}^i \bar{u}_{\rm L}^i u_{\rm R}^i + m_{\rm u}^{*i}\bar{u}_{\rm R}^i u_{\rm L}^i + m_{\rm l}^i \bar{l}_{\rm L}^i l_{\rm R}^i + m_{\rm l}^{*i}\bar{l}_{\rm R}^i l_{\rm L}^i\Big)\left(1 + \frac{h}{v}\right),$$

which contains Dirac mass terms for all fermions and the Higgs boson interaction $h(x)$, which is proportional to the fermion masses.

We note that neutral currents, containing either only up or only down fermions, also become diagonal after unitary rotations that diagonalize mass matrices. As a result, the SM predicts the nonexistence of the generation or flavor-changing neutral currents (FCNCs).

The charged currents include up and down quarks that are rotated under the diagonalization by different unitary matrices:

$$u' \to (U_{\rm L}^{\rm u})u\,, \quad d' \to (U_{\rm L}^{\rm d})d\,,$$
$$J_{\rm C} \sim (U_{\rm L}^{\rm u})^{\dagger} U_{\rm L}^{\rm d}\,\bar{u}_{\rm L}\hat{Q}\,d_{\rm L}\,.$$

The matrix $V_{\rm CKM} = (U_{\rm L}^{\rm u})^{\dagger} U_{\rm L}^{\rm d}$ is also unitary and mixes the charged currents in the SM. This matrix is called the Cabibbo–Kobayashi–Maskawa (CKM) mixing matrix. In general, a unitary 3×3 matrix is parameterized by three real angles and one complex phase. The presence of this phase leads to processes with CP-invariance violation.

In this short article, we do not discuss the full variety of phenomena that are related to the mixing matrix. We only note that the main principle — gauge invariance — allows including a CP violation in theory. However, it does not predict the scale of this violation, which is to be derived from experiment together with fermion masses and CKM-matrix angles.

In this way, the BEH mechanism produces masses for bosons and fermions, without violating the interaction gauge invariance. Moreover, the SM, being a theory with massive fields described by the BEH mechanism, is also unitary and renormalizable. The unitarity was already demonstrated: all nonphysical degrees of freedom have disappeared from the theory in the unitary gauge. The renormalizability of the theory follows from its gauge invariance (see a detailed discussion in book [22]). Indeed, in the unitary gauge, the massive vector field propagator has the form

$$D_{\mu\nu}(p) = -\frac{\rm i}{p^2 - M_V^2}\left(g_{\mu\nu} - \frac{p_\mu p_\nu}{M_V^2}\right). \tag{17}$$

The last term in parentheses in the right-hand side of (17) is proportional to $1/M_V^2$ and can lead to an incorrect behavior of the theory for energies $\gg M_V$. A priori, it is not clear that all the contributions corresponding to these longitudinal terms in the massive vector field propagators are reduced after the calculation of physical quantities such as the cross sections or kinematic distributions. But, due to the gauge invariance, the theory can be quantized in other gauges, where nontrivial contributions of nonphysical degrees of freedom would remain (Goldstone bosons, ghost fields). However, in this gauge, the massive vector field and nonphysical bosons propagators have the form

$$D_{\mu\nu}^{\xi} = -\frac{\rm i}{k^2 - M_V^2}\left[g_{\mu\nu} - (1-\xi)\,\frac{k_\mu k_\nu}{k^2 - \xi M_V^2}\right], \tag{18}$$
$$D^{\rm c} = \frac{\rm i}{p^2 - \xi M_V^2}$$

with 'good' behavior at large energies, where $D^{\rm c}$ is the causal Feynman propagator.

In this way, the SM, whose construction is based on the gauge invariance principle, is both unitary and renormalizable. We recall that the dimension of all terms in the SM Lagrangian is not more than four and, as a result, the interaction constants g_1 and g_2 are dimensionless.

As was mentioned above, Englert and Higgs received the 2013 Nobel Prize for the development of the BEH mechanism. The work of 't Hooft and Veltman was recognized by the Nobel Committee in 1999 "for elucidating the quantum structure of electroweak interactions in physics." We emphasize the fundamental role of the work of Faddeev, Popov, and Slavnov (see [22] and the references therein), where methods of non-Abelian gauge-theory quantization were developed, in particular for theories with spontaneous symmetry breaking.

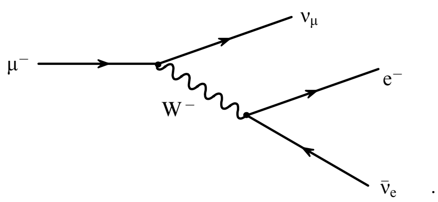
5. Predictions for the SM Higgs boson

What did we know about the SM Higgs boson before its direct observation?

We consider the Lagrangian of the SM Higgs sector, which unites the corresponding boson and fermion parts, mentioned above in Sections 2–4:

$$L_{\rm h} = \frac{1}{2}(\partial^\mu h)(\partial_\mu h) + \frac{M_{\rm h}^2}{2}\,h^2 - \frac{M_{\rm h}^2}{2v}\,h^3 - \frac{M_{\rm h}^2}{8v^2}\,h^4$$
$$+ \left(M_{\rm W}^2 W_\mu^+ W^{-\mu} + \frac{1}{2}\,M_{\rm Z}^2 Z_\mu Z^\mu\right)\left(1 + \frac{h}{v}\right)^2$$
$$- \sum_f m_f \bar{f} f\left(1 + \frac{h}{v}\right). \tag{19}$$

All the coupling constants in Lagrangian (19) are expressed through the Higgs boson mass $M_{\rm h}$. Masses of the $\rm W^{\pm}$ and Z bosons, as well as the lepton and quark masses, are known from experimental observations. The vacuum expectation value parameter for the Higgs field v is also well defined from the measurement of the four-fermion interaction constant $G_{\rm F}$. As an example, we consider the μ^- decay, which is described by the diagram



Because $m_\mu \ll M_{\rm W}$, the momentum in the W-boson propagator can be neglected, and after comparing the structure of the Fermi four-fermion interaction with the charged-current Lagrangian (7), we can obtain the relation

$$\frac{g_2^2}{8M_{\rm W}^2} = \frac{G_{\rm F}}{\sqrt{2}}\,. \tag{20}$$

But in the SM, the W-boson mass appears due to the BEH mechanism and, as was shown above,

$$M_{\rm W}^2 = \frac{1}{4}\,g_2^2 v^2\,. \tag{21}$$

It follows from relations (20) and (21) that

$$v = \frac{1}{(\sqrt{2}\,G_{\rm F})^{1/2}} = 246.22~{\rm GeV}\,, \tag{22}$$

using the high-accuracy G_F measurement

$$G_F = 1.1663787(6) \times 10^{-5}\ \mathrm{GeV}^{-2}\,.$$

Once again, we note the significance of the gauge invariance principle: relations (20) and (21) include the constant g_2 of the same gauge group $SU_L(2)$. The vacuum expectation value of the Higgs field v is fixed by the parameter G_F, which was introduced and measured long before the BEH mechanism was described.

Returning to Lagrangian (19), we note that all the parameters in it have been measured experimentally except the Higgs boson mass. This allowed performing various calculations for different Higgs-boson mass ranges and obtaining a set of quantitative predictions and experimental constraints:

• predictions for the decay widths and production cross sections via different channels;

• constraints that follow from the SM unitarity requirements;

• constraints that follow from the SM self-consistency;

• constraints that follow from direct observations in colliders;

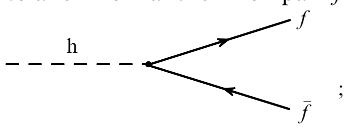
• constraints that follow from the comparison of loop corrections for mass with precision measurements.

We now discuss these predictions.

(1) Directly from Lagrangian (19), we can derive Feynman rules for the Higgs boson interaction with fermions, $W^{\pm}$ and Z bosons, as well as for self-interaction vertices h^3 and h^4 of the Higgs boson itself. Using Feynman rules, we can calculate the partial Higgs boson decay widths and production cross sections, taking the leading strong (and in several cases, electroweak) corrections into account (see [23]).

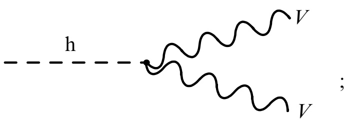
The Feynman diagrams for the main decay channels are as follows:

— decay into a fermion–antifermion pair $f = \bar{b}, \bar{c}, \tau, \mu$:



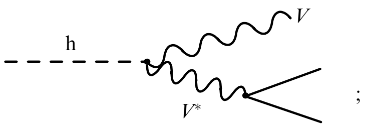
;

— decay into real vector bosons $V = W, Z$ ($M_h > 2M_V$):



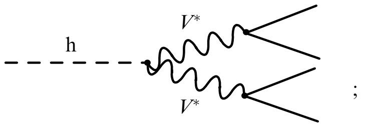
;

— decay into real and virtual bosons ($M_V < M_h < 2M_V$):



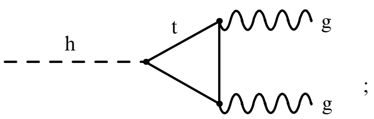
;

— decay into two virtual bosons $V = W, Z$ ($M_h < M_V$):



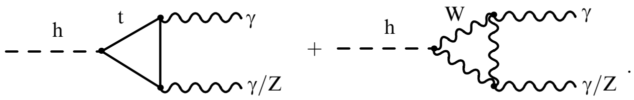
;

— decay into two gluons:



;

— decay into two photons, a photon and a Z boson:



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The characteristic behavior of the total Higgs boson decay width and of the branching ratios of the decays through different channels is shown as a function of the Higgs boson mass in Figs 3 and 4 [23].

It is important to note that for small Higgs boson masses ($M_h \leqslant 130$ GeV), the leading contribution to the width is made by the decay into a pair of quarks $b\bar{b}$, and the total decay width is small compared with the mass. For example, for $M_h = 125$ GeV, the total decay width Γ_h is approximately 4 MeV. For bigger masses, the decay into a pair of W bosons becomes dominant and the decay width rapidly increases as M_h^3 and for the mass ~ 1 TeV reaches a value near 0.5 TeV, which shows that for such large masses, the SM Higgs boson itself is no longer a particle, and the SM becomes a meaningless theory. We note that the branching ratio of decay into two photons is extremely low, of the order 10^{-3}. However, this channel has huge significance for the Higgs-boson search at the LHC due to the good signal-to-noise ratio.

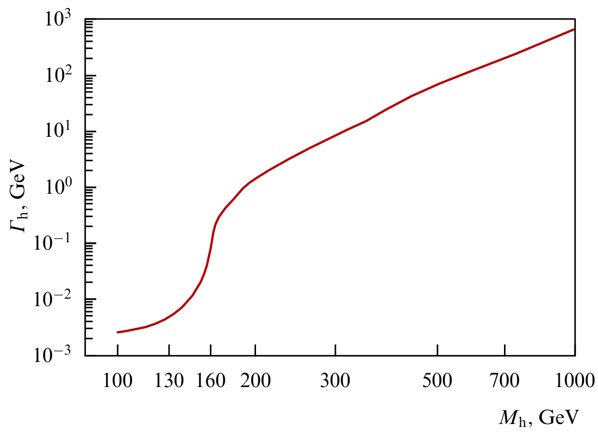


Figure 3. Total width of Higgs boson decay Γ_h versus its mass M_h. (See [23].)

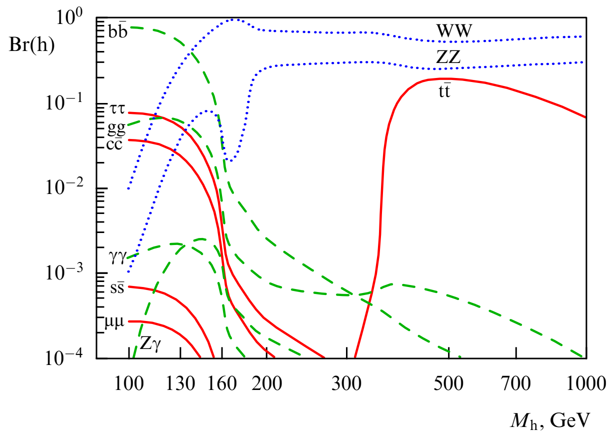
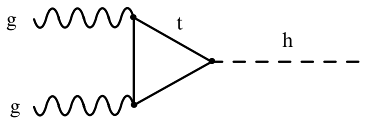


Figure 4. Branching ratio of Higgs boson decay through different channels versus its mass. (See [23].)

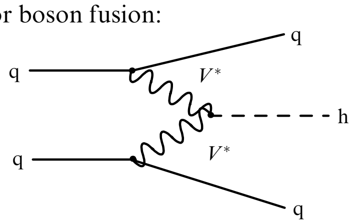
The main channels for the Higgs boson creation at the LHC are:

— gluon–gluon fusion:



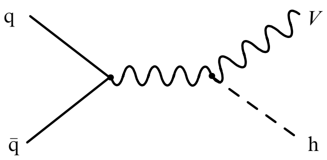
;

— vector boson fusion:



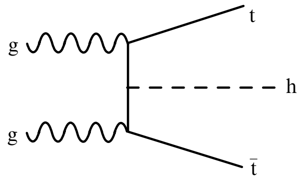
;

— associated production of W/Z and h:



;

— associated production of a top–antitop quark pair and h:



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The results of calculations of the Higgs boson production cross sections at the LHC with the consideration of higher orders and for the collision energies 7, 8, and 14 TeV are shown in Fig. 5 [24].

The leading contribution to the production cross section is made by gluon–gluon fusion. We note that for the Tevatron energies, only two production channels are possible: gluon–gluon and the associated production of W/h and h. We emphasize that at the LHC, an interesting processes for small Higgs-boson masses would be its associated production with the b-quark pair $gg \to b\bar{b}h$ [25] and the associated production of h with a single top quark [26]. The cross sections of these processes are shown in Figs 6 and 7.

(2) In quantum theory, the optical theorem can be derived from the unitarity requirement, relating the total cross section of the process to the forward scattering amplitude:

$$\sigma = \frac{1}{s}\,\mathrm{Im}\,A(\theta = 0) = \frac{16\pi}{s}\sum_{l=0}^{\infty}(2l+1)|a_l|^2\,, \qquad (23)$$

where a_l is the partial-wave amplitude. Hence, $\mathrm{Im}\,a_l = |a_l|^2$, or

$$\left|\mathrm{Re}\,a_l\right|^2 + \left(\mathrm{Im}\,a_l - \frac{1}{2}\right)^2 = \frac{1}{4}\,,$$

which means that $|\mathrm{Re}\,a_l| < 1/2$.

In the SM, the most 'dangerous' in the sense of energetic growth are amplitudes that involve the W- and Z-boson longitudinal components. These longitudinal components originate in the SM, according to the BEH mechanism, from the corresponding Goldstone bosons. Therefore, the scattering amplitudes of the two longitudinal W can be easily found

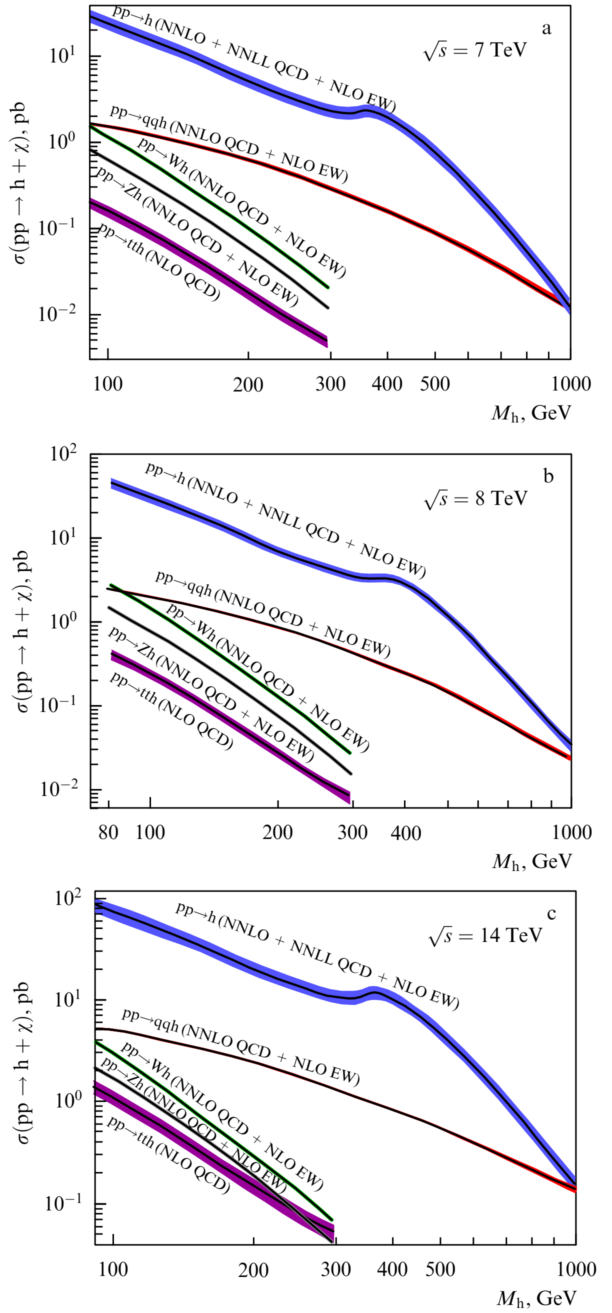
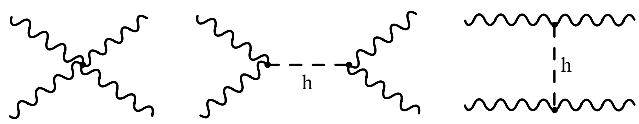


Figure 5. Cross sections of the main Higgs-boson production processes at the LHC at energies 7, 8, and 14 TeV. The calculation was performed considering perturbations of various orders that follow the leading order (LO): NLO (Next-to-LO), NNLO (Next-to-NLO), NNLL (Next-to-Next-to Leading Logarithmic); EW — electroweak, QCD — Quantum Chromodynamics. (See [24].)

from the Goldstone-boson scattering diagrams:



,

$$A(W^+W^- \to W^+W^-)$$
$$= -\left[2\,\frac{M_h^2}{v^2} + \left(\frac{M_h^2}{v}\right)^2 \frac{1}{s - M_h^2} + \left(\frac{M_h^2}{v}\right)^2 \frac{1}{t - M_h^2}\right]. \qquad (24)$$

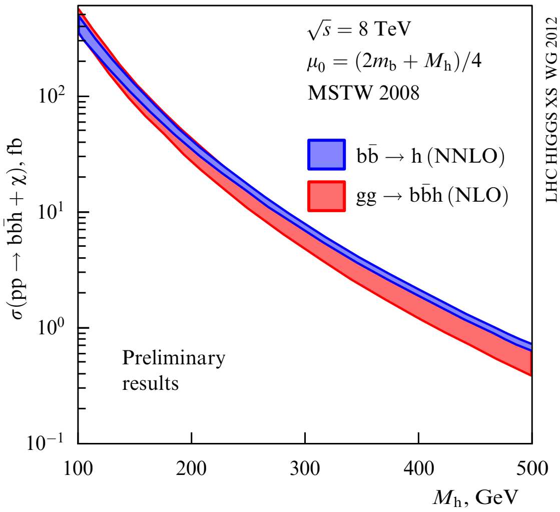


Figure 6. Cross section of the Higgs-boson and $b\bar{b}$-quark pair associated production. The calculations were performed using the distribution function (Martin–Stirling–Thorne–Watt parton distribution function) and taking into account the errors in the five-flavor scheme (upper darkened area) and in the four-flavor scheme (lower shaded area). (See [25].)

For the $l = 0$ partial-wave amplitude, we obtain

$$a_0 = \frac{1}{16\pi s}\int_s^0 dt\,|A| = -\frac{M_h^2}{16\pi v^2}\left[2 + \frac{M_h^2}{s - M_h^2} - \frac{M_h^2}{s}\log\left(1 + \frac{s}{M_h^2}\right)\right]. \quad (25)$$

The condition $|\mathrm{Re}\,a_l| < 1/2$ then leads to two possible results:

$$a_0 \xrightarrow{s \gg M_h^2} -\frac{M_h^2}{8\pi v^2}, \quad M_h \leqslant 870\ \text{GeV},$$

$$a_0 \xrightarrow{s \ll M_h^2} -\frac{s}{32\pi v^2}, \quad \sqrt{s} \leqslant 1.7\ \text{GeV}.$$

Consequently, to satisfy the unitarity requirement, either the theory must contain the Higgs boson with a mass not less than 870 GeV (710 GeV with all $V_L V_L$-scattering channels considered), or the SM stops working for $\sqrt{s} \leqslant 1.7$ TeV (1.2 TeV), and something beyond the SM has to surface in order to sustain the unitarity.

(3) The bounds follow from the renormalization group equation for the Higgs-boson self-coupling evolution:

$$\frac{d\lambda}{d\ln Q^2} \simeq \frac{1}{16\pi^2}\left\{12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4 - \frac{3}{2}\lambda(3g_2^2 + g_1^2) + \frac{3}{16}\left[2g_2^4 + (g_2^2 + g_1^2)^2\right]\right\}, \quad (26)$$

where $\lambda_t = m_t/v$ is the Yukawa coupling constant for the top quark.

For large λ, terms of the order of λ^2 are dominant, and Eqn (26) becomes

$$\frac{d\lambda}{d\ln Q^2} = \frac{3}{4\pi^2}\lambda^2(Q^2),$$

which has the solution

$$\lambda(Q^2) = \lambda(v^2)\left[1 - \frac{3}{4\pi^2}\lambda(v^2)\ln\frac{Q^2}{v^2}\right]^{-1}.$$

The 'triviality' bound means that the Landau 'zero point' must not be reached, which relates the permissible limit for the Λ_C scale and the Higgs-boson mass.

For small λ, Eqn (26) contains two dominant terms, which do not depend on λ. This leads to the solution

$$\lambda(Q^2) = \lambda(v^2) + \frac{1}{16\pi^2}\left\{-12\frac{m_t^4}{v^4} + \frac{3}{16}\left[2g_2^4 + (g_2^2 + g_1^2)^2\right]\right\}\ln\frac{Q^2}{v^2}. \quad (27)$$

Because λ and the mass M_h satisfy the relation $M_h^2 = 2\lambda v^2$, the 'stability' requirement, which is the positive sign of the coupling constant λ (the Higgs-field potential must not bend down), provides the relation

$$M_h^2 > \frac{v^2}{8\pi^2}\left\{-12\frac{m_t^4}{v^4} + \frac{3}{16}\left[2g_2^4 + (g_2^2 + g_1^2)^2\right]\right\}\ln\frac{Q^2}{v^2}. \quad (28)$$

Figure 8 shows the allowed area for the Higgs boson mass M_h versus the scale Λ (between two limiting curves). We can see

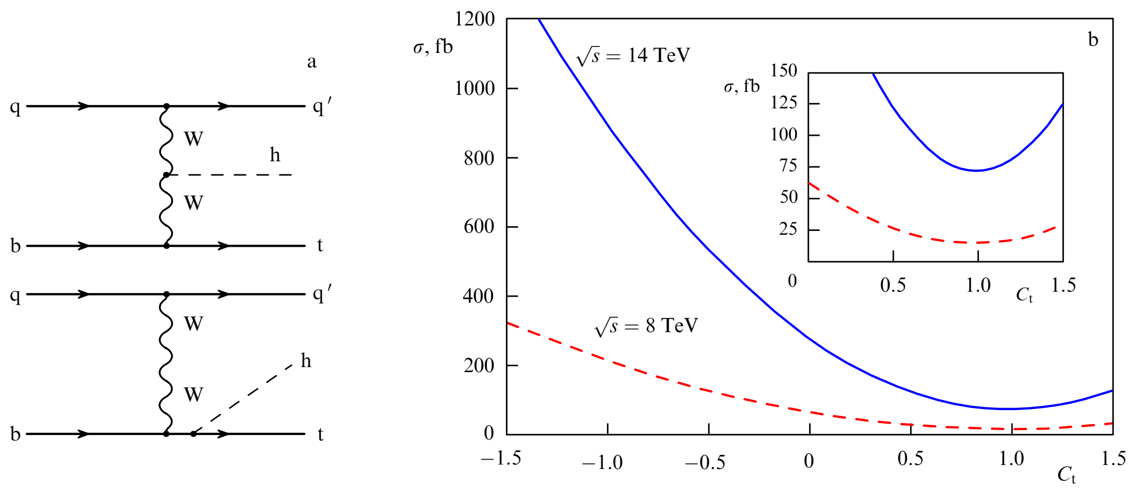


Figure 7. (a) Feynman diagrams for the associated production of the Higgs boson and a single top quark. In the lower diagram, the Higgs boson radiates from the top quark, and in the upper one, it radiates from the W boson. (b) Cross section of the Higgs boson associated production with a single top quark versus the normalization value of the coupling constant for the top quark and the Higgs boson. (See [26].)

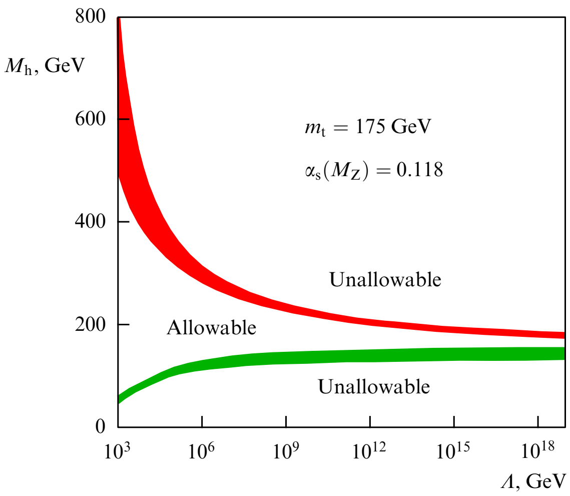
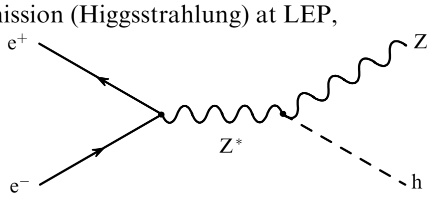


Figure 8. Allowed mass region for the Higgs boson versus the scale. The results were obtained from the SM consistency: the Landau pole should not be reached, which yields the 'triviality' requirement (upper curve); the Higgs-potential stability yields the lower curve.

that the theory with the Higgs boson mass of approximately 130 GeV can be self-consistent at very large scales, up to the range where the SM applies.

(4) Direct bounds on the Higgs-boson mass M_h were obtained at the LEP and Tevatron colliders before the LHC started working. The study of the process with the Higgs-boson emission (Higgsstrahlung) at LEP,



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led to the lower bound

$$M_h > 114.4 \text{ GeV}$$

with a 95% confidence level.

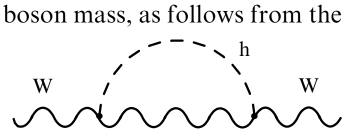
The Higgs boson mass was excluded from the interval $M_h \sim 160-170$ GeV at the Tevatron after a study of the gluon fusion process with a decay into two W-bosons.

(5) Very important constraints follow from the LEP and Tevatron precision measurements of the W-boson and top-quark masses, which are

$$M_W = 80385 \pm 15 \text{ MeV},$$

$$M_t = 173.18 \pm 0.56\,(\text{stat.}) \pm 0.75\,(\text{syst.}) \text{ GeV}.$$

In the SM, as in a quantum field theory, the W-boson mass acquires loop corrections, which depend logarithmically on the Higgs boson mass, as follows from the diagram



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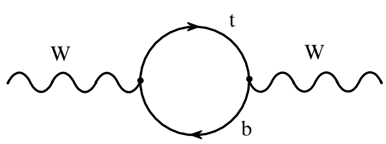
and quadratically on the top-quark mass, as follows from the diagram



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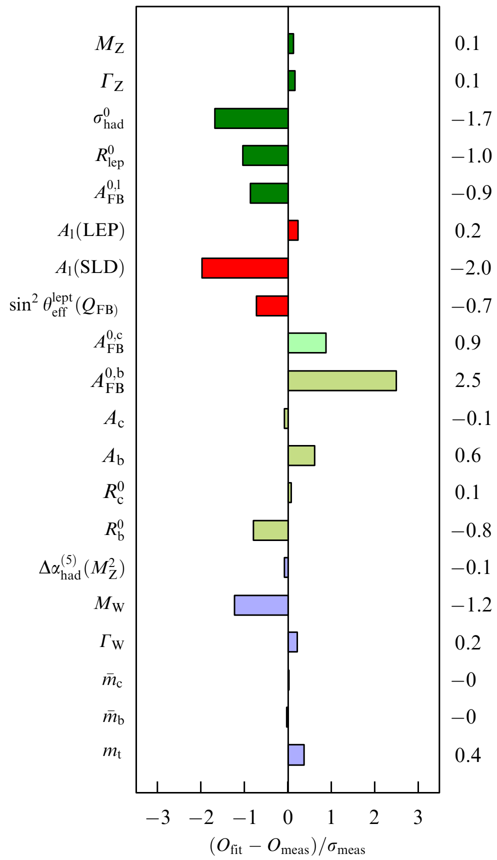


Figure 9. Global fit of precision experimental data on a series of quantities, indicated in the left column, with the calculation results for these quantities in the SM, considering the loop-corrections contribution (see details in [27]).

Comparing these mass shifts and the measurement accuracy, we can obtain the upper bound

$$M_h < 155 \text{ GeV}, \ 95\% \text{ CL}.$$

We note that a comparison of the precision measurement results at the LEP, SLC, and Tevatron colliders with the calculation results in the framework of the SM, where quantum corrections to the leading approximation were considered, showed how well the description works. The results of this comparison are shown in Fig. 9. We note that the Gfitter collaboration for all data fitting, including constraints from direct searches and from a comparison with loop corrections, has presented the result shown in Fig. 10 [27]. The best value for the Higgs boson mass turned out to be

$$M_h = 125 \pm 10 \text{ GeV},$$

which is in good agreement with the mass of the Higgs boson discovered later at the LHC. An interesting fact is that earlier, after the W-boson and top-quark mass fitting, the top-quark mass of 178 GeV was estimated with a 20% accuracy, followed by the direct observation of the top quark at the Tevatron.

6. Conclusion

Finally, we can make the following conclusions.

(1) The Standard Model is a renormalizable quantum field theory free of chiral anomalies, with spontaneous

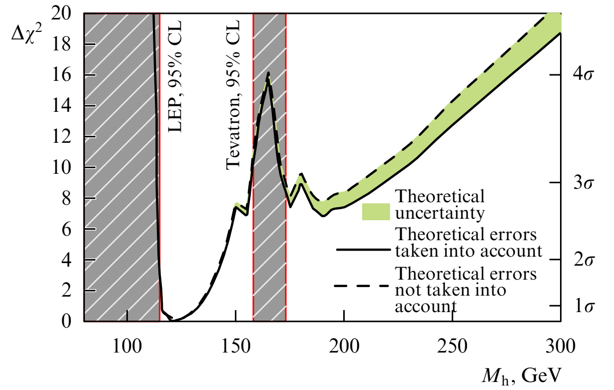


Figure 10. Best fit of experimental data on the precision measurement of electroweak parameters with the results of theoretical calculations in the SM framework versus the Higgs boson mass. The plot illustrates the results with theoretical errors both taken and not taken into account, as well as constraints obtained from direct searches at the LEP and Tevatron. These constraints are shown by shaded rectangles (see the details in [27]).

electroweak symmetry breaking. The SM predictions for various observables, including the widths and branching ratios of the decays, various asymmetries, process cross sections, and kinematic distributions are in impressive agreement with the experimental results.

(2) The SM with massless neutrinos has 18 free parameters:

• four parameters in the electroweak and Higgs sector: g_1, g_2, μ^2, λ, which can be expressed through the parameters that are measured with the highest accuracy:

$$\alpha_{\text{em}} = \frac{e^2}{4\pi}\,, \ \sin\theta_{\text{W}}\,, \ M_{\text{Z}}\,, \ M_{\text{h}};$$

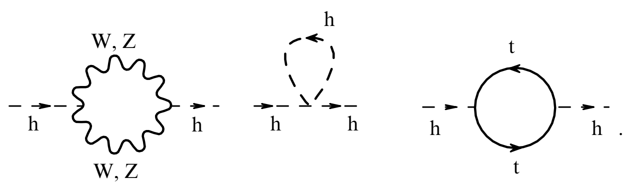
• six quark masses and three charged-lepton masses;

• three angles and one phase in the Cabibbo–Kobayashi–Maskawa mixing matrix;

• $\alpha_{\text{QCD}} = g_s^2/(4\pi)$, the coupling constant for strong interactions.[1]

(3) The SM allows calculating the characteristics of many processes, understanding and describing many phenomena, but at the same time does not predict the parameter values.

(4) The simplest SM Higgs mechanism has one significant problem: it is not stable under quantum loop corrections to the Higgs boson mass itself (the problem of hierarchy or the 'naturalness' of the SM). The diagrams that make a contribution to the Higgs-boson mass correction are



The correction that corresponds to these diagrams,

$$\delta M_{\text{h}}^2 = \frac{3G_{\text{F}}}{4\sqrt{2}\,\pi^2}\,(2M_{\text{W}}^2 + M_{\text{Z}}^2 + M_{\text{h}}^2 - 4M_{\text{t}}^2)\Lambda^2 \approx -(0.2\Lambda)^2\,,$$

depends quadratically on the scale Λ that is connected with any 'new physics' or any new object that can make a contribution to the Higgs-boson mass parameter. The corrections to the masses of all other SM particles, except the scalar Higgs boson, depend on Λ logarithmically, or weakly, which is guaranteed by the symmetries of the theory, which is chiral for fermions and gauge for bosons. The symmetry that would forbid such a strong mass dependence on the scale is absent for the scalar Higgs boson. If we required the corrections to the Higgs boson mass to be less than the mass itself, $\delta M_{\text{h}} < M_{\text{h}}$, the upper limit for Λ would be a value less than 1 TeV, which almost contradicts the data, because no 'new physics' has been discovered on this scale. This difficulty, possibly a technical one, is known as the 'little hierarchy problem'. In order to solve this problem, one should, presumably, introduce something in addition to the SM.

In this short article, we have mainly discussed the electroweak sector of the SM with the BEH mechanism, together with the Higgs boson production, properties, and bounds. We did not discuss the strong sector of the SM, quantum chromodynamics, CKM matrix physics, neutrino-sector physics, and many other aspects. The search for and discovery of the Higgs boson in the LHC in the CMS (Compact Muon Solenoid) and ATLAS (A Toroidal LHC ApparatuS), the consequences of this discovery, SM difficulties, theoretical ideas of going beyond the framework of the SM, and the search for 'new physics effects' are discussed in other reports, which were presented at the scientific session of the Physical Sciences Division of the Russian Academy of Sciences, "Physics at the Large Hadron Collider. Higgs boson," 26 February 2014.

The author is grateful to V A Rubakov for the opportunity to prepare this report. The work was done with a partial financial support from the RFBR (grant 12-02-93108) and the Program for Support of Leading Scientific Schools (grant 3042.2014.2).

References

1. Glashow S L *Nucl. Phys.* **22** 579 (1961)
2. Weinberg S *Phys. Rev. Lett.* **19** 1264 (1967)
3. Salam A *Conf. Proc.* **C680519** 367 (1968)
4. Buchmüller W, Lüdeling C, in *European School of High-Energy Physics, Kitzbühel, Austria, 2005* (CERN-2006-014, Ed. R Fleischer) (Geneva: CERN, 2006) p. 1; hep-ph/0609174
5. Pich A, in *European School of High-Energy Physics, Aronsborg, Sweden, 2006* (CERN-2007-005, Ed. R Fleischer) (Geneva: CERN, 2007) p. 1; arXiv:0705.4264
6. Vysotsky M I et al., in *Trudy Letnei Shkoly Fonda 'Dinastiya', 2006* (Works of the 'Dynasty' Foundation Summer-School) (Moscow: Art-Biznes-Tsentr, 2008) p. 299
7. Altarelli G, in *The Landolt–Börnstein Database, Group I, 21A, 5* (Springer Materials, Ed. H Schopper) (Berlin: Springer-Verlag, 2008); http://www.springermaterials.com/docs/bookshelf.html
8. Rubakov V, in *European School of High-Energy Physics, Herbeumont-sur-Semois, Belgium, 2008* (CERN-2009-002, Eds N Ellis, R Fleischer) (Geneva: CERN, 2009) p. 1
9. Hollik W, in *European School of High-Energy Physics, Bautzen, Germany, 2009* (CERN-2010-002, Eds C Grojean, M Spiropulu) (Geneva: CERN, 2010) p. 1; arXiv:1012.3883
10. Leonidov A V, in *Fizika Elementarnykh Chastits v Preddverii Bol'shogo Adronnogo Kollaidera. Letnyaya Shkola Fonda Dmitriya Zimina 'Dinastiya'* (Elementary Particles Physics in Anticipation of the Large Hadron Collider. Dmitry Zimin 'Dynasty' Foundation Summer-School) (Moscow: LENAND, 2011) p. 7
11. Boos E E, in *Fizika Elementarnykh Chastits v Preddverii Bol'shogo Adronnogo Kollaidera. Letnyaya Shkola Fonda Dmitriya Zimina 'Dinastiya'* (Elementary Particles Physics in Anticipation of the

[1] Nonzero masses and mixing of the neutrinos give additional parameters. Here, we do not take these aspects into account, because the corresponding phenomena involving neutrinos are not yet accessible for study at colliders.

Large Hadron Collider. Dmitry Zimin 'Dynasty' Foundation Summer-School) (Moscow: LENAND, 2011) p. 156
12. Rubakov V A *Phys. Usp.* **55** 949 (2012); *Usp. Fiz. Nauk* **182** 1017 (2012); *Phys. Usp.* **54** 633 (2011); *Usp. Fiz. Nauk* **181** 655 (2011)
13. Okun L B *Phys. Usp.* **55** 958 (2012); *Usp. Fiz. Nauk* **182** 1026 (2012)
14. Okun L B *Phys. Usp.* **55** 963 (2012); *Usp. Fiz. Nauk* **182** 1031 (2012)
15. Altarelli G "Collider physics within the Standard Model: a primer", CERN-PH-TH-2013-020; arXiv:1303.2842
16. Boos E "Field theory and the electro-weak Standard Model", in *The 2013 European School of High-Energy Physics, Hungary, 5–18 June 2013*
17. The ALEPH Collab., The DELPHI Collab., The L3 Collab., The OPAL Collab., The LEP Electroweak Working Group *Phys. Rep.* **532** 119 (2013); CERN-PH-EP/2013-022; arXiv:1302.3415
18. Ginzburg V L, Landau L D *Zh. Eksp. Teor. Fiz.* **20** 1064 (1950); Ginzburg V L *On Superconductivity and Superfluidity* (Berlin: Springer, 2009) p. 113
19. Englert F, Brout R *Phys. Rev. Lett.* **13** 321 (1964)
20. Higgs P W *Phys. Lett.* **12** 132 (1964)
21. Higgs P W *Phys. Rev. Lett.* **13** 508 (1964)
22. Faddeev L D, Slavnov A A *Gauge Fields, Introduction to Quantum Theory* 2nd ed. (Reading, Mass.: Addison-Wesley Publ., 1991); Translated from Russian: *Vvedenie v Kvantovuyu Teoriyu Kalibrovochnykh Polei* 2nd ed. (Moscow: Nauka, 1988)
23. Djouadi A *Phys. Rep.* **457** 1 (2008)
24. Dittmaier S et al. (LHC Higgs Cross Section Working Group) *Handbook of LHC Higgs Cross Sections*: 1. *Inclusive Observables* (Geneva: CERN, 2011) DOI:10.5170/CERN-2011-002; arXiv:1101.0593
25. Campbell J M et al. "Higgs boson production in association with bottom quarks", in *Physics at TeV Colliders. Proc. of the Workshop, Les Houches, France, May 26–June 3, 2003*; hep-ph/0405302
26. Biswas S, Gabrielli E, Mele B *JHEP* **2013** (01) 088 (2013)
27. Baak M et al. *Eur. Phys. J. C* **72** 2003 (2012)

PACS numbers: **11.30.–j, 12.15.–y, 12.60.–i, 14.70.–e**, 14.80.Bn, **95.35.+d**
DOI: 10.3367/UFNe.0184.201409i.0996

CMS collaboration results: Higgs boson and search for new physics

A V Lanyov[1]

1. Introduction

Predictions of the Standard Model (SM) describe well the observed elementary particle physics phenomena. An important part of the SM is the Brout–Englert–Higgs mechanism, which introduces the scalar Higgs field with a nonzero vacuum expectation as a result of spontaneous symmetry breaking. Due to interaction with this field, particles acquire nonzero masses and, because of the quantum excitations of the Higgs field, a new elementary particle appears: the Higgs boson. But until recently there was no experimental evidence for the existence of the Higgs boson. One of the main physics goals of constructing the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN, Switzerland) was to determine whether the Higgs boson exists, what its mass is, and whether its characteristics agree with those expected in the SM. Certain discoveries were expected to happen at the full design center-of-mass energy of colliding protons $\sqrt{s} = 14$ TeV and the originally planned integrated luminosity $\mathcal{L}\,\mathrm{d}t = 300\ \mathrm{fb}^{-1}$: either the Higgs boson or other new strong effects, because otherwise, at the energy above 1 TeV, a perturbative unitarity violation in the scattering of the intermediate vector bosons would occur [1]. Other major physics goals of the LHC construction were the search for physics Beyond the SM (BSM), implementing various ideas, such as electroweak symmetry breaking, the hierarchy problem, incorporation of gravity into quantum theory, grand unification, supersymmetry, the existence of dark matter particles, etc. [2, 3].

This summary report provides an overview of the most interesting recent results of the CMS Collaboration, including the discovery of the Higgs boson [4, 5] and the rare decay $B_s \to \mu^+\mu^-$ [6], and the search for BSM physics using a full dataset of the first run held in 2011–2012 at the LHC at energies $\sqrt{s} = 7$ and 8 TeV.

[1] On behalf of the CMS collaboration.

A V Lanyov Joint Institute for Nuclear Research, Dubna, Moscow region, Russian Federation
E-mail: Alexander.Lanyov@cern.ch

Uspekhi Fizicheskikh Nauk **184** (9) 996–1004 (2014)
DOI: 10.3367/UFNr.0184.201409i.0996
Translated by A V Lanyov; edited by A M Semikhatov

2. CMS detector

The Compact Muon Solenoid (CMS) is one of the two general-purpose detectors located at the LHC (Fig. 1). Its name originates from the world's largest superconducting solenoid with an inner diameter of 6 m, length of 12.5 m, and magnetic field of 3.8 T, cooled by liquid helium to −269 °C. In the center, around the interaction point of proton beams with an energy of 4 TeV, there is a silicon tracker that reconstructs interaction vertices and momenta of charged particles by the curvature of the tracks in the magnetic field up to the pseudorapidity $|\eta| < 2.5$ (i.e., for a polar angle up to $\theta > 9.4°$ in accordance with the definition of the pseudorapidity $\eta = -\ln[\tan(\theta/2)]$). Ionization calorimeters are located around the tracker: 1) an electromagnetic calorimeter based on lead–tungstate ($PbWO_4$) crystals reconstructing the position and energy of electromagnetic showers and in this way determining the position and energy of photons, electrons, and positrons up to the pseudorapidity $|\eta| < 3$; 2) a hadron calorimeter based on layers of brass and a scintillator determining the parameters of hadronic showers and hadronic jets. The tracker and calorimeters are located inside the superconducting solenoid surrounded by a steel magnetic return yoke and a muon system in the range $|\eta| < 2.4$ and consist of a barrel part based on drift tubes and an endcap part based on cathode strip chambers, as well as resistive planar chambers for making a fast muon trigger in the range $|\eta| < 1.6$. The system ensures reconstruction of muon tracks with a precision $\sigma(p_T)/p_T < 0.05$ for the transverse momenta up to $p_T < 1$ TeV in the barrel part. A detailed description of the detectors and the characteristics is given in [7,8]. The full spectrum of the invariant mass of the muon pairs in Fig. 2 displays the known resonances in the range from 1 to 100 GeV; due to a good momentum resolution, there is a distinct separation of the individual peaks from the ground state of the Upsilon meson $\Upsilon(1S)$ and the radial excitations $\Upsilon(2S)$ and $\Upsilon(3S)$. The first physics run was completed in 2012, with the respective integrated luminosities ~ 5 and 20 fb^{-1} obtained at $\sqrt{s} = 7$ and 8 TeV. The luminosity reached $\mathcal{L} = 7 \times 10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and the average number of interactions per proton–proton collision reached 21. The CMS detector effectively operated with these occupancies and recorded over 90% high-quality data, which made it possible to discover the Higgs boson and other interesting physics.