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## The Higgs boson is found: what is next?

D I Kazakov

### 1. Introduction

The discovery of the Higgs boson in 2012 [1, 2] and the awarding of the Nobel Prize in 2013 have marked an important step in elementary particle physics. The mechanism of fundamental particle mass generation, the Brout–Englert–Higgs mechanism [3, 4], theoretically predicted nearly 50 years ago, is experimentally confirmed. Thus, the Standard Model of fundamental interactions has been logically completed and obtained the status of Standard Theory. By the Standard Model, we understand the description of strong, weak, and electromagnetic interactions between quarks and leptons based on the gauge group  $SU(3)_c \times SU(2)_L \times U(1)_Y$ . Here, quarks are triplets and leptons are singlets with respect to the color group  $SU(3)_c$ , the left components of quarks and leptons are doublets, the right components are singlets with respect to  $SU(2)_L$ , and all of them have a hypercharge with respect to the  $U(1)_Y$  group. The set of matter fields and the carriers of four fundamental forces of the SM are shown in Fig. 1. To the particles already known, all of which were discovered in the 20th century, we should add the Higgs boson, discovered in the 21st century.

In the SM, we have six quarks and six leptons forming three generations and three types of interactions: strong, weak, and electromagnetic, mediated by the quanta of the

**D I Kazakov** Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Moscow region, Russian Federation; Alikhanov Institute for Theoretical and Experimental Physics, Moscow, Russian Federation; Moscow Institute of Physics and Technology, Dolgoprudnyi, Moscow region, Russian Federation  
E-mail: kazakovd@theor.jinr.ru

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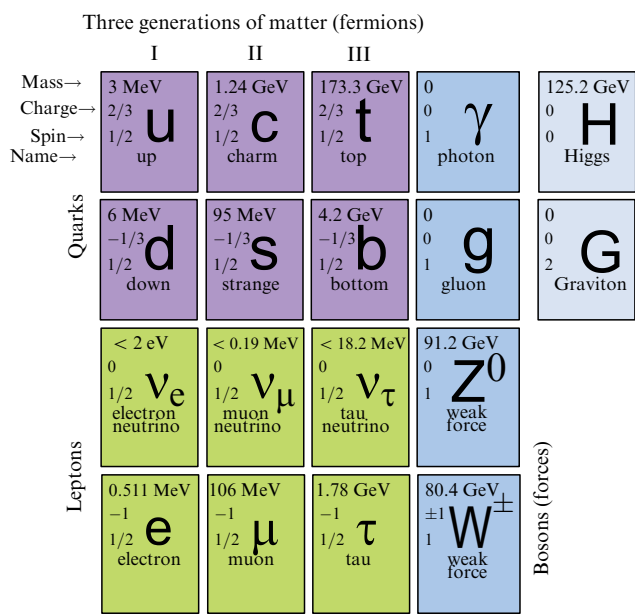


Figure 1. Standard Model of fundamental interactions [5].

corresponding fields: the gluon, the W and Z bosons, and the photon. We should now add the fourth interaction, the Yukawa interaction carried by the Higgs boson. To complete the picture, we should also add the gravitational interaction mediated by the quantum of the gravitation field, the graviton. However, it has not been discovered yet: gravity remains a classical theory. This exhausts all the known fundamental particles and forces in Nature.

The Standard Model of strong, weak, and electromagnetic interactions quantitatively describes practically all experimental data. There is no experiment in particle physics where the deviation from the SM exceeds 2–2.5 standard deviations, and sometimes anomalies that appear disappear with time [6]. It might be that the recently discovered neutrino oscillations will require some minor modification of the SM. However, this is not necessary: the addition of right-handed neutrinos fits well in the SM and allows describing the transformation of one kind of neutrino into another due to mixing, as happens in the quark sector. New precision tests of processes with flavor changing and with CP violation have also passed all checks. Remarkably, all experiments are described with the help of a single Cabibbo–Kobayashi–Maskawa matrix with four parameters. Thus, we are witnessing the triumph of the Standard Model of fundamental interactions as the basis of all phenomena in Nature, except gravity.

The natural question arises: Is this the end of the story or a new stage? The answer given by the scientific community does not leave any doubt: This is the beginning of a new research program for a few decades. Nature still keeps many puzzles!

Discussing various aspects of the SM and some attempts to go beyond it, we follow the schematic diagram shown in Fig. 2 and consider all its elements in detail.

2. The Higgs sector

The Higgs boson has been discovered. At a 96% confidence level, its properties are determined, and they are in good agreement with expectations: this is a particle with spin 0, parity +, and a nonzero vacuum expectation value; it interacts with W and Z bosons as well as with quarks and

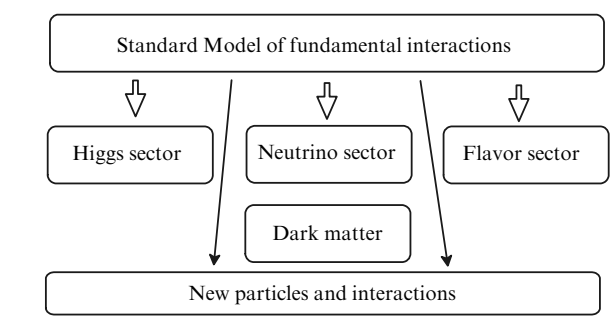


Figure 2. Problematic sectors of the SM and beyond.

leptons (checked for the third generation) with a strength proportional to their masses [7, 8]. Still, the exploration of the Higgs sector of the SM is just beginning. The questions posed require answers:

- Is it the Higgs boson? — Most probably, yes.
- Is it the Higgs boson from the Standard Model? — It looks like it.
- Are there alternatives? — Yes.
- Can it be that we see more than one Higgs boson? — Possibly.
- It is possible to obtain reliable answers to these questions? — Yes.

New experiments at the LHC at twice the energy and at new accelerators (if built) will allow reaching the required accuracy for unambiguous answers to the above questions. We note, however, that it has already been confirmed that particles acquire their masses through the Brout–Englert–Higgs mechanism, no matter what model the Higgs boson corresponds to. We discuss possible alternatives to the minimal Higgs sector. We recall that the minimal SM contains one Higgs doublet, which provides up and down quarks and leptons with the mass simultaneously. In this case, there is only one CP-even Higgs boson (see Fig. 3a). The nearest extension of the SM is the two-Higgs-doublet model [9, 10]. It is also realized in the Minimal Supersymmetric Standard Model (MSSM) [11–14]. There, the up and down quarks and leptons interact with different doublets, each of which has a vacuum expectation value. In this case, there are five Higgs bosons: two CP-even, one CP-odd, and two charged.

The next popular step is the introduction of an additional Higgs field that is a singlet with respect to the gauge group of the SM. In the case of supersymmetry, this model is called the

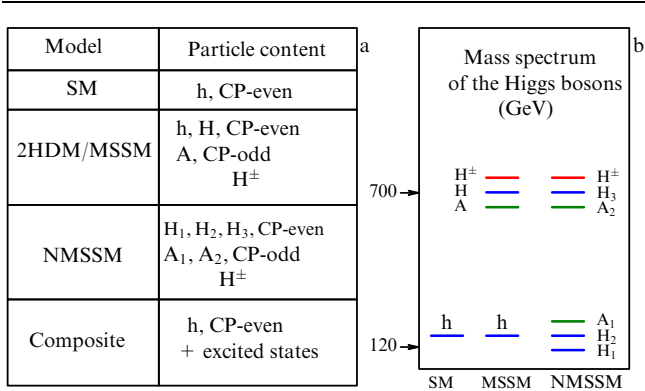
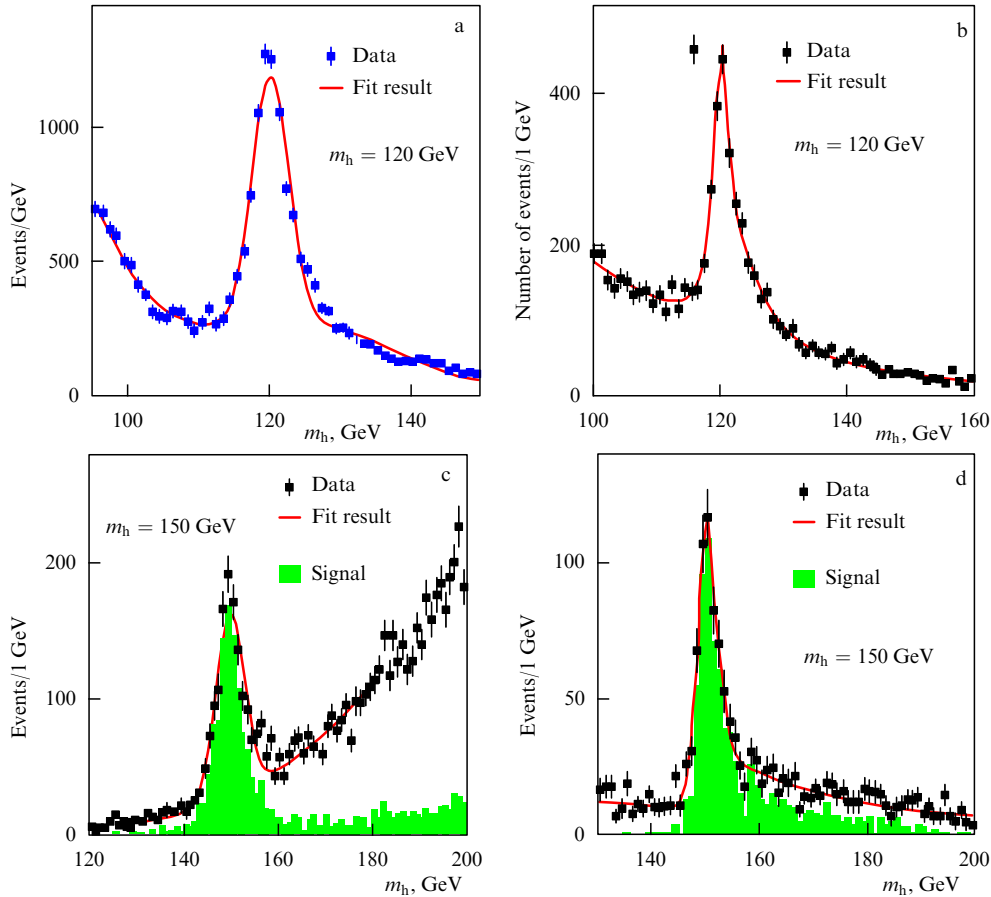


Figure 3. (a) Field content and (b) spectrum in various models of the Higgs sector.



**Figure 4.** Measurement of the mass and the width of the Higgs boson in various channels at the ILC: (a)  $e^+e^- \rightarrow HZ \rightarrow b\bar{b}q\bar{q}$ , (b)  $q\bar{q}l^+l^-$ , (c)  $W^+W^-q\bar{q}$ , (d)  $W^+W^-l^+l^-$ .

NMSSM, next-to minimal [15]. Here, we already have seven Higgs bosons. The sample spectrum of particles for various models is shown in Fig. 3b. In the NMSSM, there are two light CP-even Higgs bosons, and the discovered particle might correspond to both  $H_1$  and  $H_2$ . The reason why we do not see the lightest Higgs boson  $H_1$  in the second case is that it has a large admixture of the singlet state, and hence very weakly interacts with the SM particles.

Finally, it is possible that the Higgs boson is a composite state like the  $\pi$ -meson [16]. Then, besides the ground state, there should be excited heavier states.

In all these cases, one of the Higgs bosons is very close in its properties to the SM Higgs boson, and it is quite possible that we see just one of these states. Hence, the Higgs sector needs to be explored. We must be convinced in the presence or absence of heavy and charged Higgs bosons.

The task for the near future is the precision analysis of the discovered Higgs boson. It is necessary to measure its characteristics like mass, width, and all decay constants with an accuracy ten times higher than the one reached. Quite possibly, this task requires the construction of an electron–positron collider, for instance, the linear collider ILC. Figure 4 shows the expected results for the Higgs boson mass measurement at the ILC in various channels [17]. It is planned that the accuracy of the Higgs mass measurement will reach  $\sim 50$  MeV, that is, 5–7 times higher than the existing one.

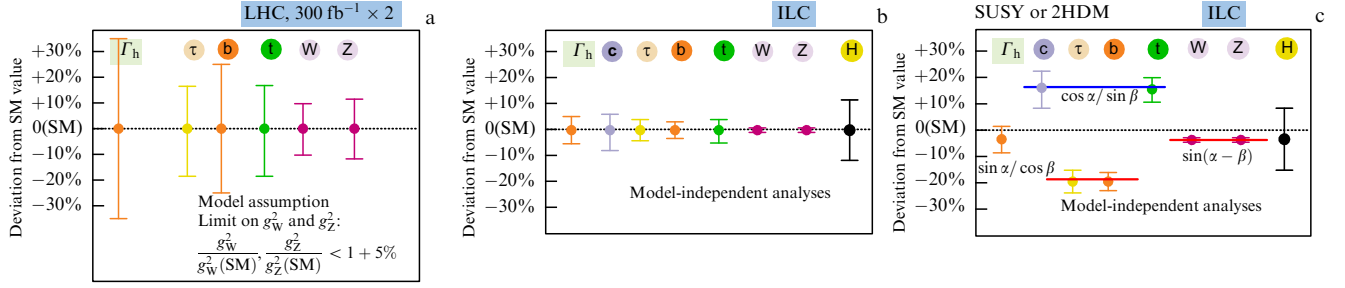
Another task is the accurate determination of the constants of all decays, which will possibly allow distin-

guishing between the one-doublet and two-doublet models. Figure 5 shows the planned accuracies of the measurement of the couplings of the Higgs boson to SM particles at the LHC for the integrated luminosity  $300 \text{ fb}^{-1}$  (Fig. 5a), which is ten times higher than today. For comparison, we also show the same data for the ILC (Fig. 5b). The accuracy of measurements of the couplings at the ILC will allow not only distinguishing different models, but also checking the predictions of supersymmetric theories (Fig. 5c).

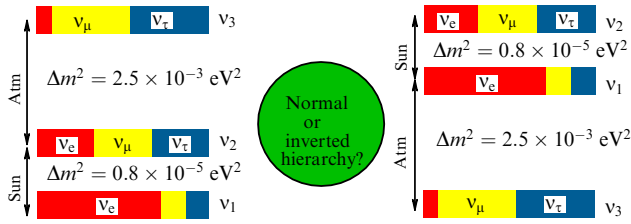
### 3. Neutrino sector

With the discovery of neutrino oscillations, neutrino physics has entered a new phase: the mass differences of different neutrino types and the mixing angles have been measured. At last, the answer to the question of neutrino mass was obtained. We now know that neutrinos are massive. In this way, the lepton sector of the SM took a form identical to that of the quark sector, and it was confirmed that the SM has the quark–lepton symmetry. Nevertheless, the reason for such symmetry remains unclear; it might well be that it is a consequence of the grand unification of interactions. However, the answer to this question lies beyond the SM.

At the same time, the neutrino sector of the SM is still not fully understood. First of all, this concerns the mass spectrum. Neutrino oscillations allow determining only the squares of the mass difference for various neutrinos. The obtained picture is shown in Fig. 6 [19]. The color pattern shows the fraction of various types of neutrinos in mass eigenstates.



**Figure 5.** Measurement of Higgs boson couplings at the LHC and ILC [18].



**Figure 6.** (Color online.) Normal and inverse hierarchy of neutrino masses.

Besides the hierarchy problem (normal or inverted), there is also an unclear question of the absolute scale of neutrino masses. We may hope to answer this question in two ways. The first one is the direct measurement of the electron neutrino mass in the  $\beta$ -decay experiment. According to the Troitsk–Mainz experiment, the upper bound on the neutrino mass today is  $m_{\nu_e} < 2$  eV [20, 21]. The KATRIN preparatory experiment [22] will be able to move this bound to  $< 0.2$  eV. However, this might not be enough, if we trust the astrophysical data. The determination of the sum of neutrino masses from the spectrum of the cosmic microwave background is an indirect but rather accurate way to find the absolute mass scale. At the early stage of the Universe, during the fast cooling process, particles fell out of thermodynamic equilibrium at a temperature proportional to their masses and their abundance ‘froze down’, influencing the spectrum. Hence, fitting the spectrum of CMB fluctuations allows determining the number of light neutrino species and the sum of their masses [23, 24]. The result of the latest PLANCK space mission [25] looks like  $\sum m_\nu < 0.23$  eV. This number is still much bigger than the neutrino mass difference shown in Fig. 6. Thus, the absolute scale of neutrino masses is still an open question.

Another unsolved problem of the neutrino sector is the nature of the neutrino: is it a Majorana particle or a Dirac one, is it an antiparticle of itself or not? We must bear in mind that particles with spin 1/2 are described by the Dirac equation, the solutions being bispinors. They can be divided into two parts, corresponding to the left or right polarization,

$$\nu_D = \begin{pmatrix} \nu_L \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ \nu_R \end{pmatrix}, \quad \nu_L \neq \nu_R^*, \quad m_L = m_R. \quad (1)$$

Both parts have the same mass, since this is just one particle with two polarization states. At the same time, in the case of a neutral particle, the Dirac bispinor can be split into two real

parts,

$$\nu_D = \begin{pmatrix} \xi_1 \\ \xi_1^* \end{pmatrix} + \begin{pmatrix} \xi_2 \\ \xi_2^* \end{pmatrix}, \quad m_{\xi_1} \neq m_{\xi_2}. \quad (2)$$

Each of these parts is a Majorana spinor obeying the condition  $\nu_M = \nu_M^*$ , i.e., if the neutrino is a Majorana spinor, then it is an antiparticle of itself. These two Majorana spinors can have different masses. Hence, if this possibility is realized in Nature, we have just discovered the light neutrino, and the heavy ones can have much bigger masses.

An argument in favor of the Majorana neutrino is the smallness of their masses. If they follow from the usual Brout–Englert–Higgs mechanism, the corresponding Yukawa couplings are extremely small, of the order  $10^{-12}$ . In the case of the Majorana neutrino, this can be avoided by using the see-saw mechanism [26, 27]: the small masses of light neutrinos appear due to the large Majorana mass

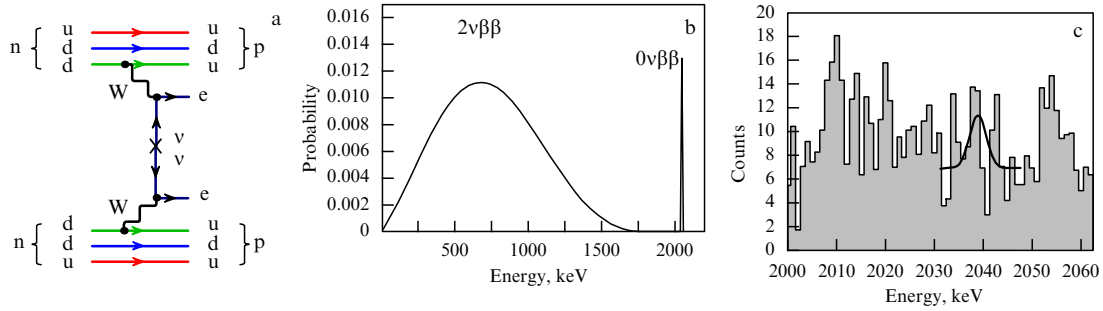
$$M_\nu = \begin{pmatrix} L & R \\ L & R \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}, \quad m_1 = \frac{m_D^2}{M}, \quad m_2 = M. \quad (3)$$

Thus, the neutrino Yukawa coupling may have the usual lepton value and the Majorana mass  $M$  might be of the order of the grand unification scale. In this case, we also have the maximal mixing in the neutrino sector.

The nature of the neutrino can be elucidated by studying the double  $\beta$ -decay. If the neutrinoless double  $\beta$ -decay is possible, then the neutrino is a Majorana particle, since that decay is forbidden for the Dirac neutrino. The corresponding Feynman diagram is shown in Fig. 7. It also shows the energy spectrum of electrons for the usual and neutrinoless  $\beta$ -decay [28]. As we can see, two types of spectra are easily distinguishable. However, their practical observation is rather cumbersome. The histogram shown in Fig. 7c is the experimentally measured electron spectrum of double  $\beta$ -decay. The solid bold line shows the expected position of the maximum in the spectrum of two electrons corresponding to double neutrinoless  $\beta$ -decay.

As a result, today there are no clear indications of the existence of double neutrinoless  $\beta$ -decay. Experiments are carried out on the isotopes  $^{48}\text{Ca}$ ,  $^{76}\text{Ge}$ ,  $^{82}\text{Se}$ ,  $^{130}\text{Te}$ ,  $^{136}\text{Xe}$ , and  $^{150}\text{Nd}$ . Modern estimates of the lifetime are [29–31]

$$\begin{aligned} T_{1/2} 2\nu\beta\beta(^{136}\text{Xe}) \times 10^{21} \text{ yr} \\ = 2.23 \pm 0.017 (\text{stat.}) \pm 0.22 (\text{syst.}), \\ T_{1/2} 0\nu\beta\beta(^{136}\text{Xe}) \times 10^{25} \text{ yr} > 1.6 \text{ (90 \% CL)}. \end{aligned}$$



**Figure 7.** (a) Neutrinoless double  $\beta$ -decay. (b) The energy spectrum of electrons in the usual and neutrinoless decay of the isotope  $^{76}\text{Ge}$ . (c) The experimentally measured spectrum of electrons [28].

Thus, the nature of the neutrino remains an unresolved issue of the SM.

#### 4. The flavor sector

Three generations of matter particles are presented in Fig. 1. At the moment, there is no theoretical answer to the question of how many generations exist in Nature. We have only the experimental facts that can be interpreted as an indication of the existence of three generations. They assume the presence of quark–lepton symmetry, since they refer to the number of light neutrinos and, due to this symmetry, to the number of generations.

The first fact is the measurement at the electron–positron collider LEP of the profile and the width of the Z boson. The Z boson can decay into quarks, leptons, and neutrinos with a total mass less than its own mass, and, measuring the width of the Z boson, we can find the number of light neutrinos. This is not true for neutrinos with a mass bigger than 45 GeV. The fit to the data corresponds to the number of neutrinos equal to  $N_\nu = 2.984 \pm 0.008$ , i.e., 3 (Fig. 8a) [32].

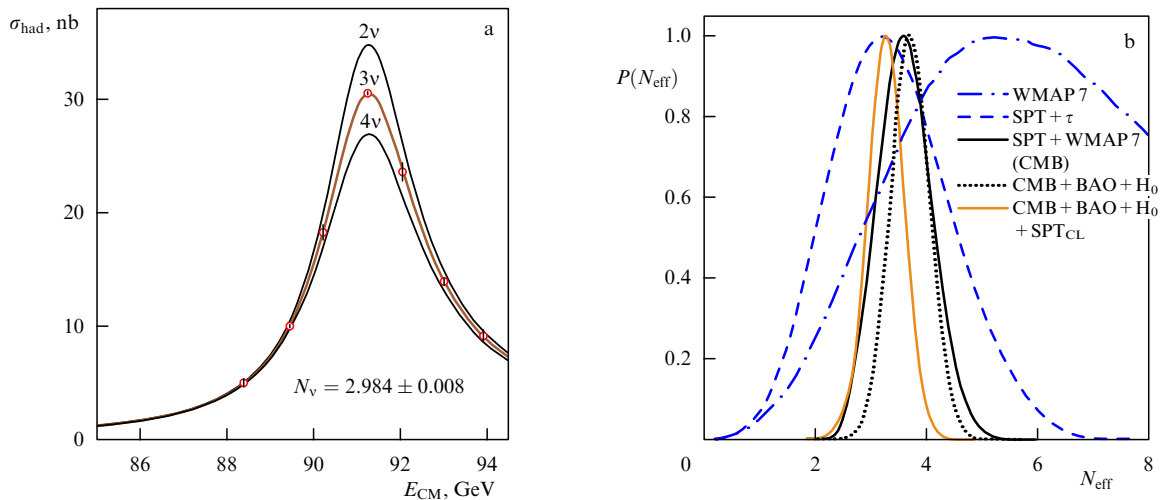
The same conclusion follows from the fit of the spectrum of thermal fluctuations of the CMB. The number of light neutrinos, as well as their mass spectra, is reliably determined from the CMB shape (see Fig. 8b). The obtained

number is  $N_\nu \leq 3.30 \pm 0.27$  [33], i.e., it is also consistent with 3 but still leaves some space for an additional sterile neutrino.

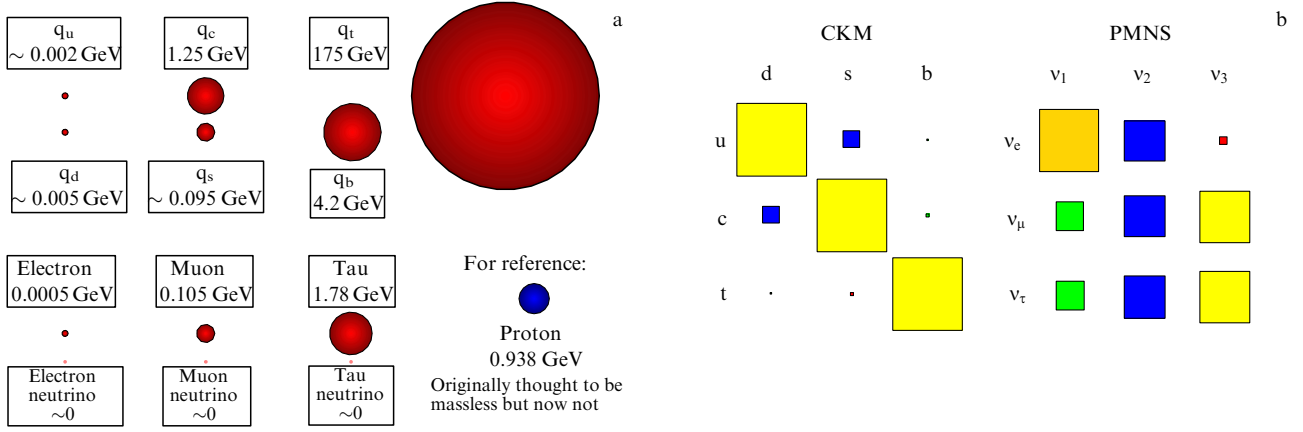
Finally, there are complementary data on precision measurements of the probabilities of rare decays, where hypothetical additional heavy-quark generations might contribute. According to these data, the fourth generation is excluded at a 90% confidence level [34–36].

A natural question arises: why does Nature need three copies of quarks and leptons? All that we see around us is made of protons, neutrons, and electrons, i.e., of u and d quarks and electrons — particles of the first generation. The particles made of the quarks of the next two generations and heavy leptons, copies of the electron, quickly decay and are observed only in cosmic rays or accelerators. Why do we need them?

Possibly, the answer to this question is concealed not in the SM but in the properties of the Universe: the existence of baryon asymmetry of the Universe, which is a necessary condition for the existence of stable matter, requires CP violation [37, 38]. This requirement, in turn, is achieved in the SM due to a nonzero phase in the mixing matrices of quarks and leptons. The nonzero phase appears only for the number of generations  $N_g \geq 3$ . The usual parameterization of the mixing matrix in the case of three generations has the



**Figure 8.** (a) Experimentally measured profile of the Z boson and the number of light neutrinos, measured by the ALEPH, DELPHI, L3, and OPAL collaborations [32].  $E_{\text{CM}}$  is the energy in the center-of-mass system. Dots show the averaged measurement results. The vertical bars representing experimental errors are scaled by a factor of 10 for clarity. (b) The fit of the number of light neutrinos from the temperature fluctuations of CMB. (WMAP 7 — Wilkinson Microwave Anisotropy Probe, 7 years of work, SPT — South Pole Telescope, BAO — Baryon Acoustic Oscillations.)



**Figure 9.** (a) Mass spectrum of quarks and leptons and (b) the CKM and the PMNS mixing matrices. The area of the circles and squares is proportional to the numerical values of parameters.

form [39]

$$K = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\exp(-i\delta) \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}\exp(i\delta) & c_{12}c_{23} - s_{12}s_{23}s_{13}\exp(i\delta) & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}\exp(i\delta) & -c_{12}s_{23} - s_{12}c_{23}s_{13}\exp(i\delta) & c_{23}c_{13} \end{pmatrix}. \quad (4)$$

It is this phase  $\delta$  in the quark, as well as the lepton mixing matrix, that is the source of CP violation in the SM.

The next puzzle of the SM is the mass spectrum of quarks and leptons. Because the masses of all fundamental particles in the SM arise from the vacuum expectation value of a single Higgs field,

$$\begin{aligned} m_{\text{quark}} &= y_{\text{quark}} v, \\ m_{\text{lepton}} &= y_{\text{lepton}} v, \\ m_W &= \frac{g}{\sqrt{2}} v, \\ m_Z &= \frac{\sqrt{g^2 + g'^2}}{\sqrt{2}} v, \\ m_h &= \sqrt{\lambda} v, \\ m_\gamma &= 0, \\ m_{\text{gluon}} &= 0, \end{aligned} \quad (5)$$

the spectrum of masses is the spectrum of Yukawa couplings, and it is absolutely arbitrary and unclear. Indeed, if we look at numerical values (Fig. 9a) [40], we see a significant disproportion. The difference in the masses of the first and third generations reaches three orders of magnitude. The understanding of the mass spectrum remains one of the vital problems of the SM.

The mixing matrices of quarks (the Cabibbo–Kobayashi–Maskawa matrix) and leptons (the Pontecorvo–Maki–Nakagawa–Sakato matrix) are equally unclear. If the CKM matrix is almost diagonal, the PMNS matrix is almost uniform (see Fig. 9b) [41]. What explains the big difference? The phases in both matrices, which play the key role in CP violation, are also arbitrary. Here possibly lies the answer to the question of the source of CP violation: the quark or the lepton sector? The point is that the nonzero phase is usually multiplied by  $\sin \theta_{13}$ ,

which is very small in the quark sector but is noticeable in the lepton one. This may mean that *baryogenesis* in fact goes through *leptogenesis* [42–44]. This important question still awaits an answer.

## 5. Can the SM be valid up to the Planck scale?

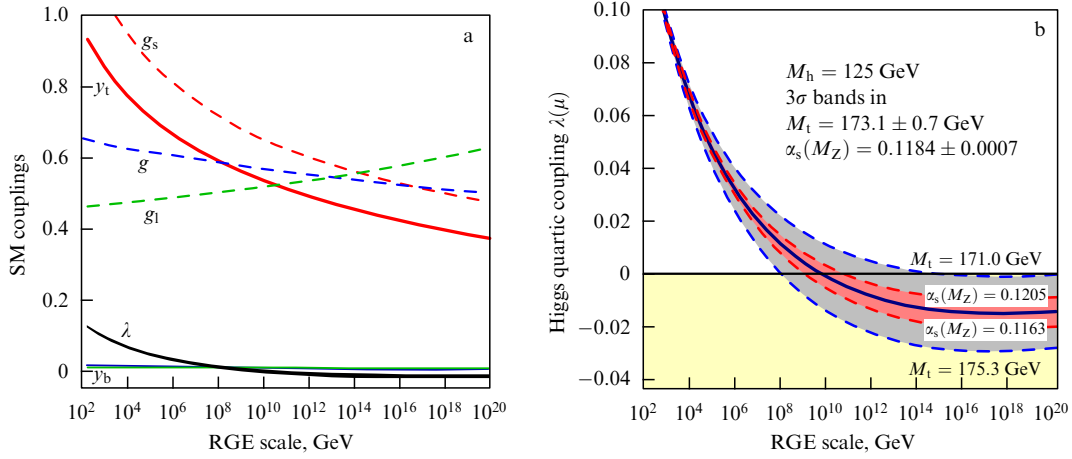
The measured mass of the Higgs boson fixes the last unknown parameter of the SM (except, probably, the masses of Majorana neutrinos), and we can wonder whether the SM is valid up to the Planck scale. This means that the parameters of the SM being continued to energies of the order of the Planck scale stay finite and do not change sign, and hence the theory remains meaningful and has a stable vacuum. To answer this question, we consider the evolution of the SM coupling constants with energy from the electroweak scale to the Planck scale. The evolution plots for the gauge, Yukawa, and Higgs couplings are shown in Fig. 10a [45]. The zoomed picture of the evolution of the Higgs coupling is shown in Fig. 10b. We can see that the Higgs coupling crosses zero near the grand unification scale and the crossing point strongly depends on the values of  $M_t$  and  $\alpha_s$ . With the two-loop corrections taken into account, the vacuum stability condition determines the lower bound on the Higgs mass if the SM is valid up to the Planck scale [45]:

$$M_h[\text{GeV}] > 129.4 + 1.4 \left( \frac{M_t[\text{GeV}] - 173.1}{0.7} \right) - 0.5 \left( \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0_{\text{th}}, \quad (6)$$

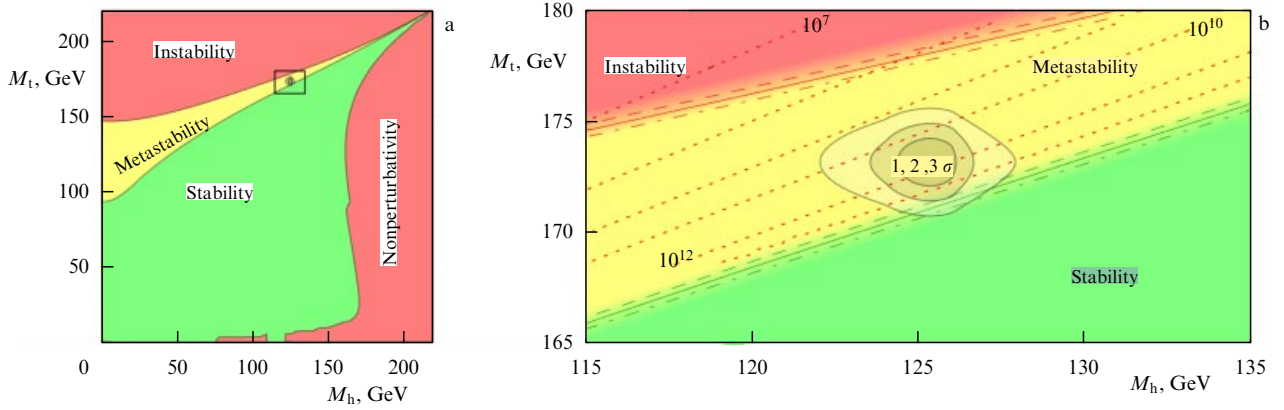
which gives  $M_h > 129.4 \pm 1.8$  GeV. Thus, the value of 125–126 GeV happens to be slightly lower and the stability condition for the Higgs vacuum is violated at the scale of  $10^{10} - 10^{14}$  GeV.

The effective potential of the Higgs field happens to be very sensitive to the values of the Higgs boson and top quark masses. In Fig. 11 [45], it is shown that the measured values of these masses correspond to a point sitting just on the border line between a stable and an unstable phase. Thus, surprisingly, we are in the metastable region on the border of two phases. It should be noted that the presence of a metastable vacuum is not a problem of the SM, because the lifetime is rather big. However, the addition of any new particles or new physics at the intermediate scale might essentially change the whole picture. It is interesting that all this happens near the





**Figure 10.** (a) Evolution of the gauge couplings  $g_1 = \sqrt{5/3} g'$ ,  $g_2 = g$ , and  $g_3 = g_s$ , Yukawa couplings of the third generation  $y_b$  and  $y_t$ , and the Higgs coupling  $\lambda$  and (b) RG evolution of  $\lambda$  for the variation of  $M_t$  and  $\alpha_s$  within  $\pm 3\sigma$  [45].



**Figure 11.** (a) SM vacuum stability, metastability, and instability regions in the plane  $M_t - M_h$ . (b) The region corresponding to the measured values is zoomed to the right. The dashed lines show the instability scale in GeV.

grand unification scale, which may be accidental, but may as well indicate that some essential changes in the description of Nature occur at this scale.

## 6. Dark matter

The existence of dark matter has been known since the 1930s. However, the situation changed when the energy balance of the Universe was obtained and it became clear that there is six times more dark matter than ordinary matter (Fig. 12a) [46, 47]. The existence of dark matter, which is known so far due to its gravitational influence, is supported by the rotational curves of stars, galaxies, and clusters of galaxies (Fig. 12b), gravitational lenses, and the large-scale structure of the Universe [48, 49]. Therefore, the question appears: What is dark matter made of; can it be some nonshining macro object like extinct stars, or molecular clouds, or are these micro particles? In the last case, dark matter becomes a subject of particle physics.

According to the latest astronomical data, at least in our galaxy, there is no evidence of the existence of macro objects, so-called MACHOs. At the same time, dark matter is required for a correct description of star rotation. The hypothesis of the microscopic nature of dark matter is therefore dominant. In order to form the large-scale structure of the Universe, dark matter has to be cold, i.e., nonrelativistic; hence, DM particles have to be heavy.

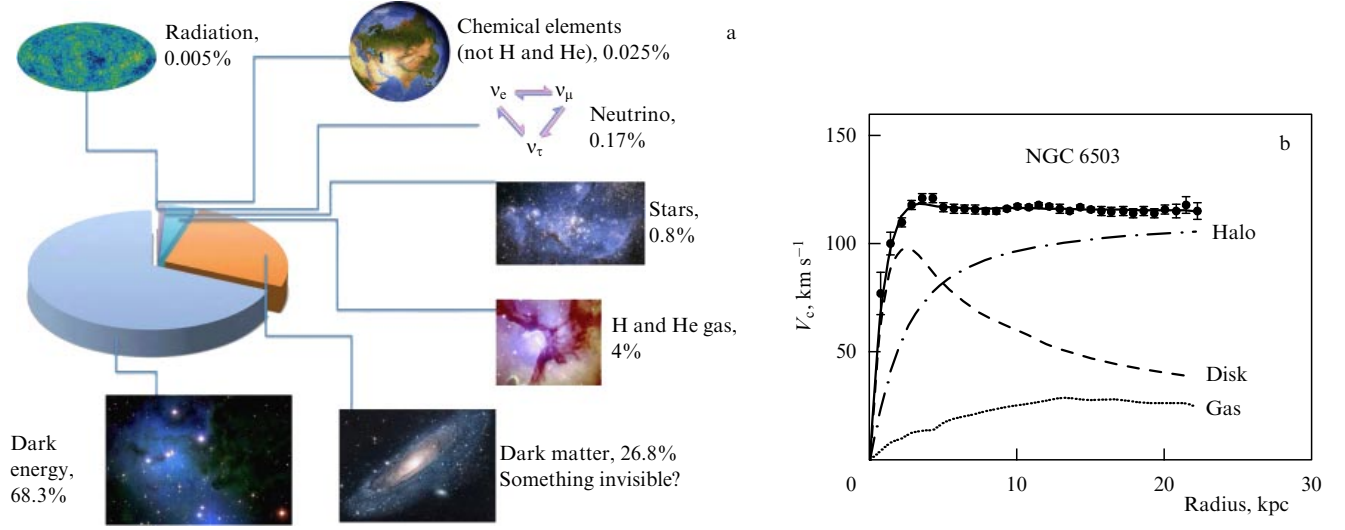
According to estimates, their mass has to be above a few tens of keV [52]. In addition, DM particles have to be stable or long-lived to have survived since the Big Bang. Thus, we need a neutral, stable, and relatively heavy particle.

In the SM, the only stable neutral particle is the neutrino. However, if the neutrino is a Dirac particle, its mass is too small to form dark matter. Therefore, the only possibility of describing dark matter within the SM is the existence of heavy Majorana neutrinos. Otherwise, we have to assume some new physics beyond the SM. The possible candidates are neutralinos, sneutrinos, and gravitinos in the case of a supersymmetric extension of the SM [53], and also a new heavy neutrino [54], a heavy photon, a sterile Higgs boson, etc. [55]. An alternative way to form dark matter is the axion field, a hypothetical, light, strongly interacting particle [56]. In this case, dark matter differs by its properties.

The dominant hypothesis is that dark matter is made of weakly interacting massive particles, WIMPs. This hypothesis is supported by the following fact: the concentration of dark matter after a particle falls from thermal equilibrium is determined by the Boltzmann equation [53]

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle(n_\chi^2 - n_{\chi,\text{eq}}^2), \quad (7)$$

where  $H = \dot{R}/R$  is the Hubble constant,  $n_{\chi,\text{eq}}$  is the concentration in the equilibrium, and  $\sigma$  is the dark matter annihila-



**Figure 12.** (a) Energy balance of the Universe [50] and (b) rotation curves of stars in the spiral galaxy [51].

tion cross section. The relic density is expressed through the concentration  $n_\chi$  as

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \approx \frac{2 \times 10^{27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle}. \quad (8)$$

Keeping in mind that  $\Omega_\chi h^2 \approx 0.113 \pm 0.009$  and  $v \sim 300 \text{ km s}^{-1}$ , we obtain the cross section

$$\sigma \approx 10^{-34} \text{ cm}^2 = 100 \text{ pb}, \quad (9)$$

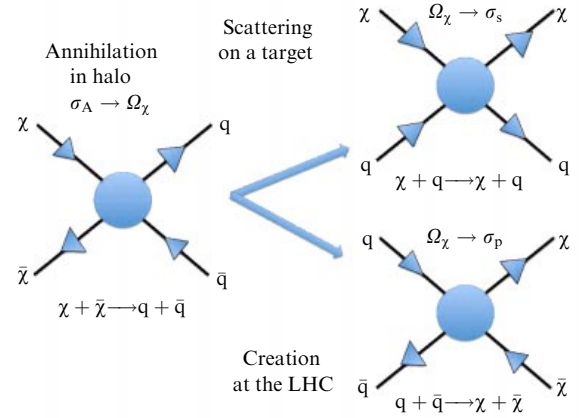
which is a typical cross section for a weakly interacting particle with a mass of the order of the Z-boson mass.

These particles presumably form an almost spherical galactic halo with a radius a few times bigger than the size of shining matter. Being gravitationally bounded, the DM particles cannot leave the halo and cannot stop, because they cannot drop the energy by emitting photons, as charged particles do. In the Milky Way, in the region of the Sun, the dark matter density should be  $\sim 0.3 \text{ GeV cm}^{-3}$  in order to obtain the observed rotation velocity of the Sun around the center of the galaxy,  $\sim 220 \text{ km s}^{-1}$ .

The search for dark matter particles is based on three reactions, whose cross sections are related by the crossing symmetry (Fig. 13) [57]. First, there is the annihilation of dark matter in the galactic halo, which leads to the creation of ordinary particles and should appear as a kink in the spectrum of cosmic rays for diffused gamma rays, antiprotons, and positrons. Second, we have the scattering of DM on a target, which should lead to a recoil of the nucleus of the target when hit by a particle with a mass of the order of the Z-boson mass. And third is the direct creation of DM particles at the LHC, which, due to their neutrality, should manifest themselves in the form of missing energy and transverse momentum.

In all these areas, there is an intensive search for the signal of DM. The results of this search for all three cases are shown in Figs 14 and 15.

As we can see from the cosmic ray data (see Fig. 14), there is no statistically significant excess above the background in the antiproton sector [58]. In the positron data, there is some confirmed increase; however, its origin is usually connected not with DM annihilation but with a



**Figure 13.** The search for dark matter.

new astronomical source [59]. The spectrum of diffused gamma rays, like that of antiprotons, is consistent with the background within the uncertainties.

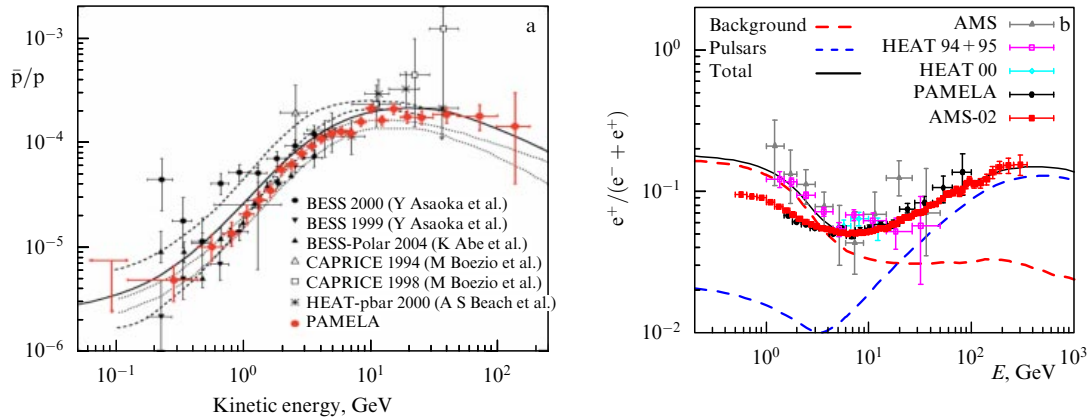
As regards the direct detection of DM, there is no positive signal so far. The results of the search can be presented in the plane mass–cross-section. We can see from Fig. 15a [60] that currently cross sections up to  $10^{-45} \text{ cm}^2$  are reached for masses near 100 GeV. In the near future, it is planned to advance by two orders of magnitude.

The results of the DM search at the LHC are also shown in the plane mass–cross-section [61, 62]. Here, the signal of DM creation is also absent. As follows from Fig. 15b, the achieved bound of possible cross sections at the LHC is worse than in underground experiments for all mass regions except small masses  $< 10 \text{ GeV}$ , where the accelerator is more efficient. We note, however, that the interpretation of the LHC data as the registration of DM particles is ambiguous, and definite conclusions can be made only together with the data from cosmic rays and the direct detection of the scattering of DM.

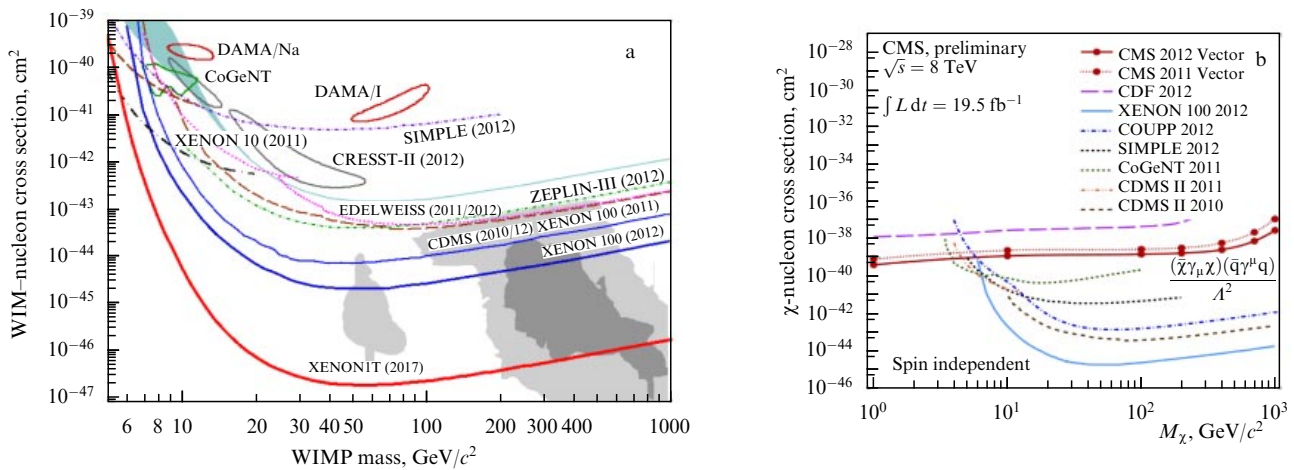
## 7. New particles and interactions

With the TeV energy achieved, which is one order of magnitude above the electroweak scale, we enter into a new





**Figure 14.** The search for a dark matter signal in the spectrum of (a) antiprotons and (b) positrons in the experiments BESS (Balloon-borne Experiment with Superconducting Spectrometer), CAPRICE (Cosmic AntiParticle Ring Imaging Cherenkov Experiment), HEAT (High Energy Antimatter Telescope), and PAMELA (Payload for Antimatter Matter Exploration and Light nuclei Astrophysics).



**Figure 15.** (Color online.) (a) The WIMP–nucleon scattering cross section as a function of the WIMP mass; the results of direct search for DM in the experiments DAMA/Na (/I) (DAMA stands for Dark Matter), XENON 10 (100, 1T), CoGeNT (Coherent Germanium Neutrino Technology), SIMPLE (Superheated Instrument for Massive Particle Experiment), CRESST-II (Cryogenic Rare Event Search with Superconducting Thermometers), COUPP (Chicago Land Observatory for Underground Particle Physics), EDELWEISS (Expérience pour Détecter Les Wimps En Site Souterrain), ZEPLIN-III (ZonEd Proportional scintillation LIquid Noble gases), CDMS (Cryogenic Dark Matter Search). (b) Bounds on the production of DM  $\chi$  particles. Shown are preliminary results of the CMS (Compact Muon Solenoid) experiment at the LHC. For comparison, results of the CDF (Collider Detector at Fermilab) experiment and underground experiments are shown.

energy region where we can expect the appearance of new particles and new interactions. However, there is no guarantee that they exist, which makes it all the more intriguing to unveil the mystery.

There are various suggestions concerning the new physics that may exist at the TeV scale and beyond. They include: low-energy supersymmetry, extra space–time dimensions, additional gauge symmetries, excited states of quarks, leptons, and gauge bosons, leptoquarks, exotic hadrons, new heavy generations, long-lived particles, and mini black holes. They have different theoretical statuses and the search for the new physics is being performed in a wide range. In Fig. 16, we show modern limits reached in various channels at the LHC [63]. So far, there have been no signals of the new physics, but we should remember that we are on the border of the known reality, on the border of mystery. Already, the very possibility of looking beyond the horizon and seeing what is there is incentive!

The most discussed and most expected new physics is low-energy supersymmetry [11–14]. There are several

reasons why supersymmetry is attracting the attention of theorists and experimentalists. However, the main reason, from our point of view, is that supersymmetry is a dream of a unified theory of all the known interactions, including gravity. The specific feature of supersymmetric theories is the doubling of particles: each particle of the SM has its own partner, called superpartner, with the same quantum numbers but with spin that differs by 1/2 (Fig. 17). The MSSM also contains two Higgs doublets and the corresponding higgsinos.

We recall what is remarkable in TeV scale supersymmetry and what is remarkable in supersymmetry in general.

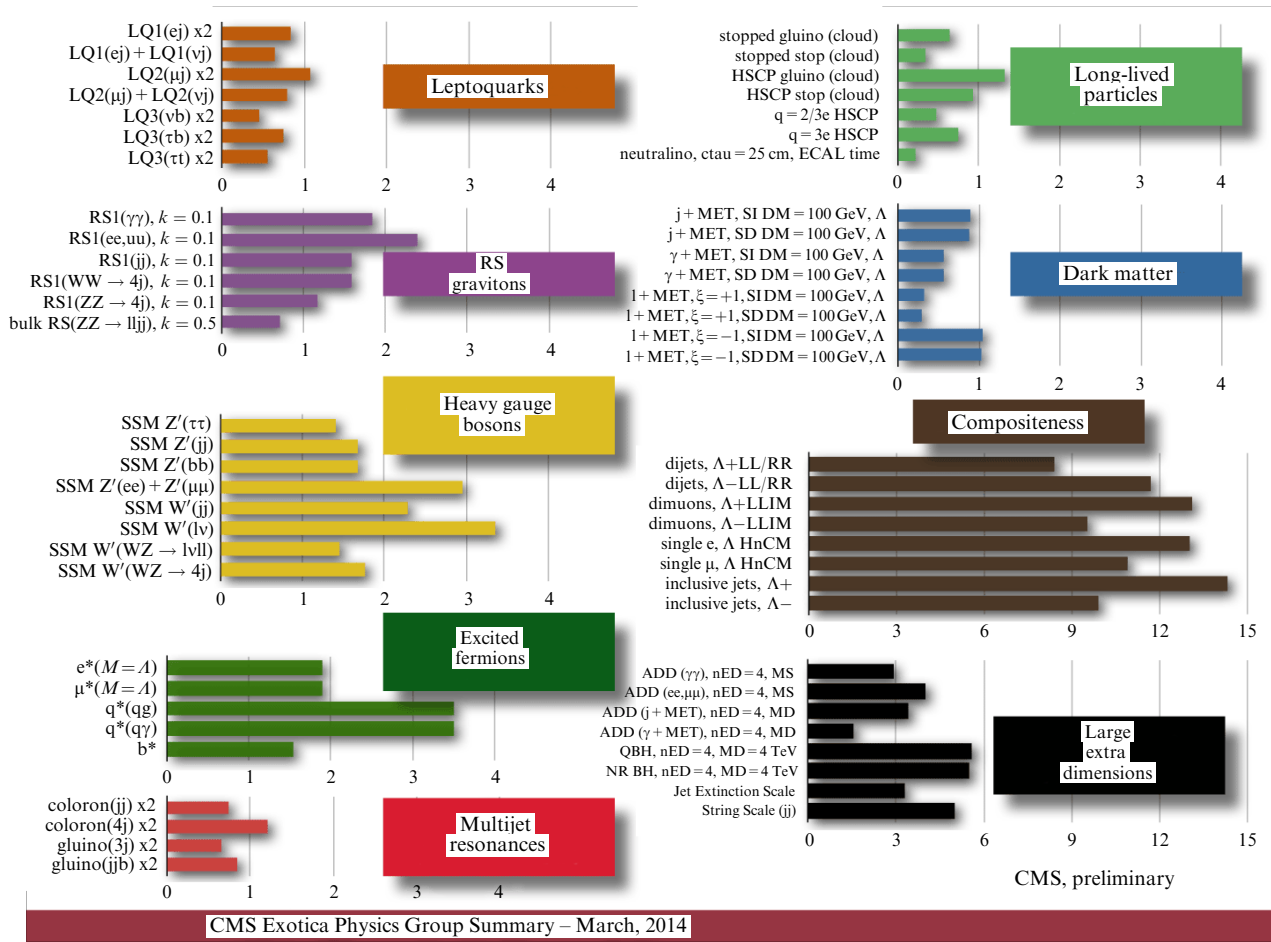
Supersymmetry at the TeV scale:

- leads to unification of the gauge coupling constants (GUT);

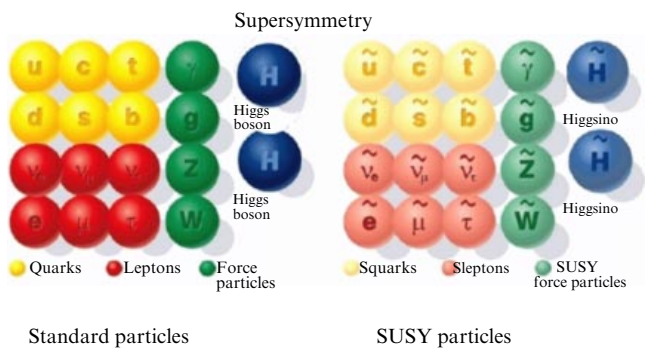
- solves the hierarchy problem in the Higgs sector;
- ensures electroweak symmetry breaking.

Supersymmetry in particle physics:

- enables inclusion of gravity in the unified theory;
- allows the existence of dark matter;



**Figure 16.** Search for the manifestation of the new physics at the LHC. The constraints in different channels are shown. The numbers are given in TeV.

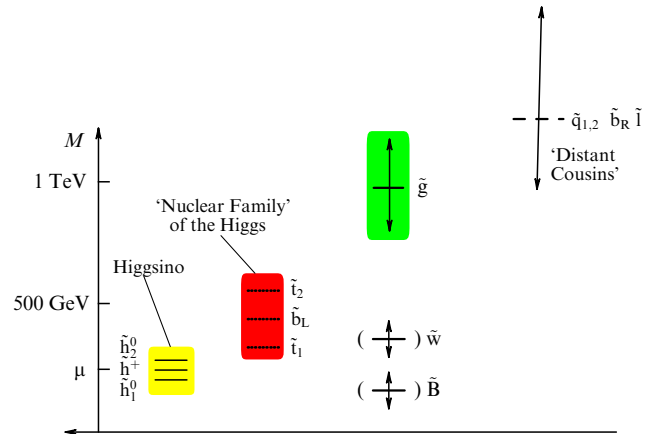


**Figure 17.** (Color online.) Particle content of the minimal supersymmetric model [64].

- stabilizes the string theory underlying the unified scheme.

Predictions of the superpartner mass spectrum are typically based on so-called naturalness, assuming the natural hierarchy of masses of strongly and weakly interacting particles (Fig. 18). We note, however, that all predictions are largely model dependent (which is of course also true for the analysis of experimental data).

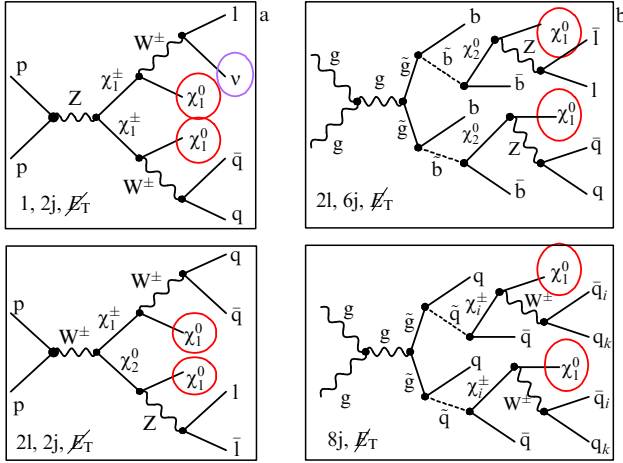
The weakest point of modern supersymmetric extensions of the SM is the problem of supersymmetry breaking. The scheme accepted today, based on a hidden sector, contains large arbitrariness and strongly depends on a particular



**Figure 18.** Typical 'natural' mass spectrum of superpartners [65].

mechanism. The most natural and developed method of SUSY breaking is the mechanism of spontaneous breaking in the gravity sector with a subsequent transfer of breaking into the visible sector due to gravitational interaction. In this case, the 'natural' scenario is realized.

Under the assumption that supersymmetry exists at the TeV scale, the superpartners of ordinary particles have to be produced at the LHC. Typical processes of creation of superpartners in strong and weak interactions are shown in Fig. 19 [66]. The typical signature of supersymmetry is the

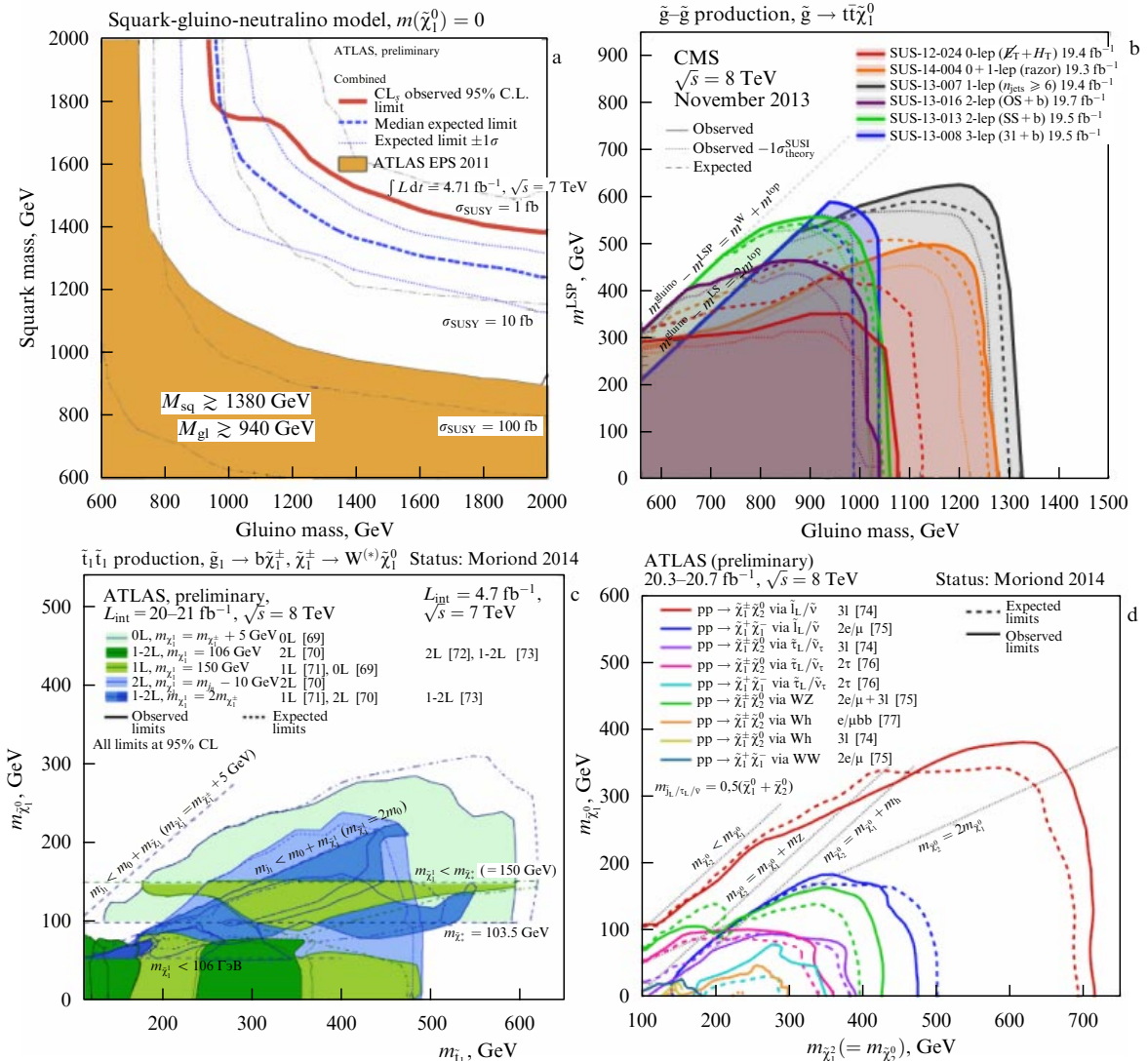


**Figure 19.** Creation of superpartners in weak (a) and strong (b) interactions. The expected final states are also shown.

presence of missing energy and missing transverse momentum carried away by the lightest supersymmetric particle  $\chi_1^0$ , which is neutral and stable.

The search for supersymmetry is being conducted in direct experiments with the creation of superpartners at colliders, as well as in precision measurements of low-energy processes where supersymmetry might indirectly be manifested, and also in astrophysical and underground experiments.

To date, the creation of superpartners at the LHC has not been detected; there are only bounds on the masses of the hypothetical new particles. As we can see from Fig. 20, the progress achieved during one year of the LHC run is rather remarkable. The boundary of possible values of masses of scalar quarks and gluinos has reached approximately 1500 and 1000 GeV, respectively. For stop quarks, it is almost half as much. This is because the created squark always decays into the corresponding quark and, in the case of the top quark, due to its heaviness, the phase space shrinks and the resulting branching ratio decreases. For the lightest neutralino, the mass bound varies between 100 and 400 GeV, depending on the values of other masses. The constraints on the masses of charged weakly interacting particles are almost two times higher than those for the neutral ones but depend on the decay mode. We stress once more that the obtained mass bounds depend on the assumed decay modes, which, in turn, depend on the mass spectrum



**Figure 20.** Search for supersymmetry at the LHC. Shown are the mass bounds for (a, b) strongly interacting and (c, d) weakly interacting particles [67, 68].

of superpartners, which is unknown. The presented constraints refer to the natural scenario.

Still, the enormous progress reached by the LHC is slightly disappointing. The natural question arises: Are we looking in the right direction? Or maybe we have not yet reached the needed mass interval? The answers to these questions can be obtained in the next runs of the collider. For the doubled energy, the cross sections of particle production with masses around 1 TeV increase by almost an order of magnitude, and we might expect much higher statistics.

The conclusions that can be made today are [78]:

- We have not seen supersymmetry so far,
- The obtained constraints are model dependent,
- The model contains many parameters, and there is still plenty of space for supersymmetry,
- It is possible that another scheme of SUSY breaking is being realized,
- The run of the accelerator at a maximal energy of 14 TeV in 2015–2017 will be crucial for the discovery of low-energy supersymmetry.

## 8. Conclusion. Forward into the future

The Standard Model of fundamental interactions, created, worked out, and experimentally tested over the last 50 years and triumphantly completed with the discovery of the Higgs boson, is still hiding many mysteries and unresolved problems. Their solution requires great efforts over many years, and possibly during their exploration many new particles and new interactions will be discovered, leading to an extension of the SM.

Upcoming tasks (at the LHC) are [79]:

- The study of the properties of the new scalar particle with maximal possible precision,
- The search for any possible deviations from the SM indicating the existence of new physics,
- The direct search for the new physics at the TeV scale.

The fulfillment of this program might require the construction of a new electron–positron collider, in addition to the existing hadron collider.

We should not forget the problem of flavor. The flavor sector of the SM is empirical and has no proper theoretical understanding so far.

This program also has to include nonaccelerator experiments investigating neutrino physics and the search for dark matter, astrophysical experiments unraveling the properties of the Universe, and a program for studying the structure of hadron matter in collisions of heavy ions.

We live in an exciting time and have the chance to unveil a mystery!

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