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Prospects of elementary particle physics

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Contents

Abstract. **The current situation in high-energy physics is discussed. The review is focused on theoretical ideas underlying new physics beyond the Standard Model (SM) of fundamental interactions: extending the SM symmetry group, adding new particles, increasing the space dimension, and going beyond the limits of local quantum field theory. The priority tasks of contemporary high-energy physics are explored.**

Keywords: particle physics, Standard Model, physics beyond the Standard Model

1. Introduction. Standard Model

Elementary particle physics is perfectly well described today by the Standard Model (SM) of fundamental interactions, which consolidates all recent accomplishments in this area. The SM is a quantum field theory that describes the subatomic world at a level that is currently the most fundamental. The elementary matter fields in the SM are quarks and leptons, which participate in four types of interactions — strong, weak, electromagnetic, and Yukawa — realized via exchanges with quanta of corresponding fields. The SM also contains a zero-spin particle referred to as the Higgs boson, interaction with which generates the masses of all elementary particles. Gravitation, the quantum version of which has not yet been developed, is not included in the SM.

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It is generally believed that the discovery of the Higgs boson has finalized the SM. However, the SM is full of enigmas and, presumably, may need to be modified in the future [1]. Searches for a new physics beyond the SM are inevitably based on a comparison of experimental results with the SM predictions, because the particles observed in the final state are well-known stable particles, and the new physics is usually manifested as an excess of particle yields over a background.

It is helpful to recall the basic concepts underlying the SM and possible ways to advance beyond them. A list of these concepts includes:

- the existence of three gauge symmetry groups: $SU(3) \times SU(2) \times U(1)$;
- the existence of three families of quarks and leptons in representations $(3 \times 2, 3 \times 1, 1 \times 2, 1 \times 1)$;
- spontaneous violation of the electroweak symmetry by the Brout–Englert–Higgs mechanism, accompanied by the emergence of the Higgs boson;
- the mixing of flavors of quarks and leptons by the Cabbibo–Kobayshi–Maskawa (CKM) and Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrices;
- CP violation generated by means of phase factors in flavor-mixing matrices;
- the confinement of quarks and gluons within hadrons;
- the conservation of baryon and lepton numbers;
- CPT invariance, which implies the existence of antiparticles.

The SM concepts allow minor modifications of the minimal scheme. For example, allowed are additional families of matter particles, additional Higgs bosons, and the existence (or absence) of right-handed neutrinos; in addition, neutrinos can also be of the Dirac or Majorana type.

The SM formalism is based on local quantum field theory. The SM is described by a Lagrangian that has been derived based on the requirements of Lorentz invariance, invariance under three local symmetry groups, and renormalizability,

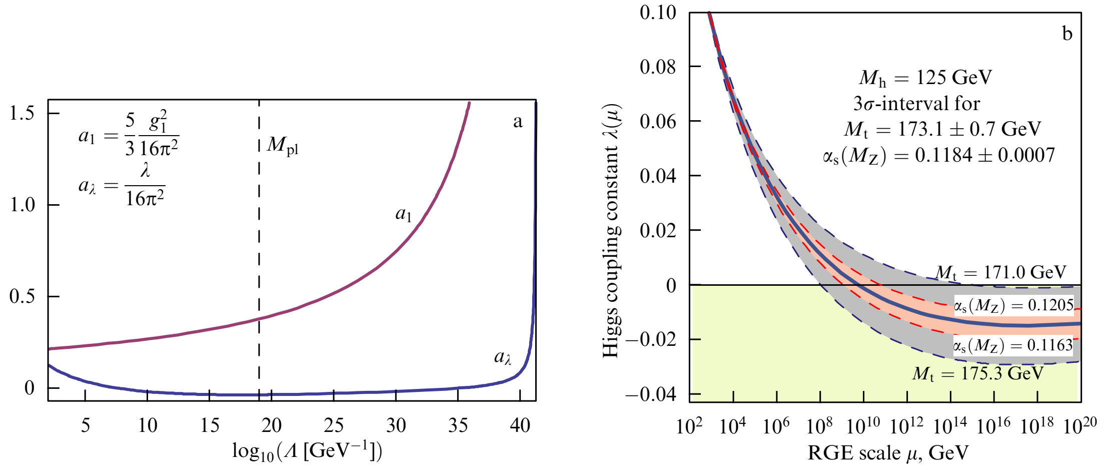

Figure 1. (a) Abelian gauge coupling constant g_1 and the Higgs coupling constant λ as functions of the energy scale Λ. The dashed line shows the Planck scale ($M_{\rm pl}$). (b) Renormalization group evolution (RGE) shown in high resolution in the energy range where the Higgs coupling constant vanishes. $M_{\rm h}$ is the Higgs boson mass, $M_{\rm t}$ is the top-quark mass, M_Z is the Z-boson mass, and $\alpha_{\rm s}$ is the strong coupling constant.

and as a result contains operators of dimensions 2, 3, and 4. This set of requirements is sufficient to fix all interactions between quarks and leptons that occur due to exchange by interaction carriers: gluons, W and Z bosons, photons, and Higgs bosons in the respective cases of strong, weak, electromagnetic, and Yukawa interactions. This scheme only leaves undetermined three gauge interaction constants (strong, weak, and electromagnetic), three (or four) Yukawa matrices, and two parameters of the Higgs potential. They are not predicted within the SM. If right-handed neutrinos exist, a corresponding kinetic term and interaction with the Higgs boson should be added to the Lagrangian. If the neutrino is of the Majorana type, an additional Majorana mass term emerges for the neutrino.

The SM has a number of shortcomings that are only manifested at very high energies, where the SM should presumably be superseded by a new theory. We now list some of them.

1. Running coupling constants become infinitely large at finite energies (Landau pole [2]); this conclusion is valid for both the U(1) coupling constant and the Higgs coupling constant (Fig. 1a). Although this phenomenon occurs at energies that are much higher than the Planck energy, where in our opinion quantum gravity can essentially modify the situation, the theory with a Landau pole is formally inconsistent, because it contains ghost degrees of freedom that eventually cause violation of causality.

2. Radiation corrections result in breaking the stability of the electroweak vacuum. This phenomenon is also related to the behavior of the Higgs coupling constant, which vanishes and then becomes negative at energies close to 10^{11} GeV (Fig. 1b [3]). However, the situation is strongly dependent on the accuracy of measurements and extraction of the top-quark mass and the Higgs boson mass and the order of the perturbation theory. The trend observed in taking higher-order corrections into account is that as the accuracy increases, the instability point shifts to higher energies and might also attain the Planck scale. The situation may change if new heavy particles exist; but this would imply going beyond the SM.

3. The new physics emerging on a high-energy scale can break the electroweak SM scale due to radiation corrections. The reason is that unlike the masses of quarks, leptons, and intermediate vector bosons protected by the weak interaction symmetry, no symmetry protects the Higgs boson mass. Therefore, the electroweak scale can be broken by quantum corrections to the Higgs mass squared that are due to interaction with hypothetical heavy particles and are proportional to the mass of those particles squared. An example of such an interaction in Grand Unified theories is shown in Fig. 2. The existing mass hierarchy $M_{\rm W}/M_{\rm GUT} \sim 10^{-14}$ can then be broken, which is known as the 'hierarchy problem'.

We note that although this is not the problem of the SM per se (quadratic divergences are absorbed into the renormalization of the bare mass, which is not observable), it results in a quadratic dependence of low-energy physics on unknown high-energy physics, a conclusion that cannot be accepted. A resolution of this situation could come from a new physics on the intermediate energy scale.

The SM poses a number of questions, the answers to which are probably beyond its limits. A list of those questions includes the following:

- Why is the SM group symmetry $SU(3)\times SU(2)\times U(1)$?
- Why is the number of matter particle generations equal to three?
- Why is there a quark–lepton symmetry in the SM?
- Why do weak interactions have the V − A structure?
- Why is the SM left–right asymmetric?
- Why are baryon and lepton numbers conserved in the SM?

It is also unclear how some mechanisms operate in the SM. For example, there is no understanding of how

- confinement is realized;

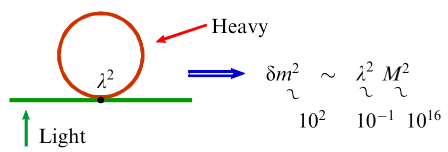

Figure 2. One-loop diagram that contributes to renormalization of the Higgs boson mass due to interaction with hypothetical heavy particles.

• the phase transition from the quark phase to the hadron phase occurs;

• the neutrinos acquire mass;

• *CP* violation occurs in the Universe; and

• the SM can be protected against possible physics effective on a high-energy scale.

There are other questions pertaining to the SM:

• Is the SM a self-consistent theory?

• Does the SM describe all available experimental data?

• Are there any indications of the existence of physics beyond the SM?

• Is there an energy scale in nature other than the electroweak and Planck scales?

• Is the SM compatible with cosmology? (Where does dark matter belong?)

2. Possible physics beyond the Standard Model

We take a look at the panorama of high-energy physics from the energy-scale perspective (Fig. 3). Apart from the well-known electroweak scale ($\sim 10^2$ GeV) and Planck scale ($\sim 10^{19}$ GeV), there is also a quantum chromodynamics (QCD) scale $\Lambda_{\rm QCD} \sim 200$ MeV and a range of masses of quarks, leptons, intermediate vector bosons, and the Higgs boson, whose origins are related to the electroweak scale. Hypothetically, there is also a string scale $\sim 10^{18}$ GeV, the Grand Unification scale $\sim 10^{16}$ GeV, a Majorana mass scale $\sim 10^{12}$ GeV, the vacuum stability scale $\sim 10^{11}$ GeV, and, finally, somewhere in the range from 10^3 to 10^{19} GeV, there is a supersymmtery scale.

No definitive indication has been found to date on whether all of these scales and the physics related to them exit, and high-energy physics is currently shrouded in mist that conceals horizons of knowledge from us. Sooner or later, the mist will disperse, and we shall see the paths along which future science will advance. However, we currently live in the era of experiment, where the theory has proposed several paths, and only experiment can show which of them is the right one.

We can go beyond the SM by

(1) extending the SM *symmetry group*: supersymmetry, Grand Unified theories, additional U(1) factors, etc. Arguably, this approach can enable resolving the Landau pole problem, the vacuum stability and hierarchy problems, and the dark matter (DM) problem;

(2) adding *new particles*: new generations of matter particles, new gauge bosons, additional Higgs bosons, additional neutrinos, etc. This approach may provide solutions to the vacuum stability and DM problems;

(3) introducing *extra spatial* dimensions, either compact or flat. This approach opens an entire world of new options, provides solutions to the vacuum stability and hierarchy problems, and offers a new view on gravitation;

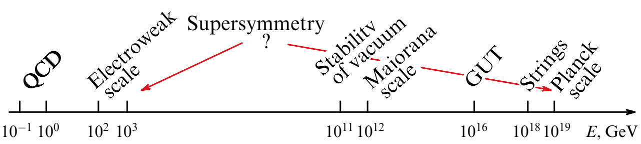

Figure 3. Panorama of high-energy physics from the energy scale perspective.

4) adopting a *new paradigm* beyond local quantum field theory: the theory of strings, branes, and other extended objects. The main task here is to include gravity along with other interactions and develop a quantum gravity theory.

A paradoxical situation has occurred in high-energy physics. A new theory normally emerges as a response to experimental facts that cannot be explained within the old theory; here, however, we are attempting to develop a new theory and are meticulously looking for phenomena beyond the SM, but so far with little success. The observed insignificant deviations from the SM at a level of several sigmas, for example, in forward–backward asymmetry in electron–positron scattering or the anomalous magnetic moment of the muon may be due to the inaccuracy of experiments or processing of experimental results. Neutrino oscillations that signal the neutrino's nonzero mass may require an insignificant modification of the SM but at the same time may prove to be well describable within the unmodified SM. Even DM, which seems to be the single indication of the incompleteness of the SM, may prove to be related to heavy Majorana neutrinos, and nothing beyond this.

There is nevertheless a plethora of theoretical models that go beyond the SM. The question is which of those models will prove to be the correct one and adequately reflect nature. We note that the prevailing paradigm in most attempts to go beyond the SM is the unification concept, which originates from the unification of electricity and magnetism in the Maxwell theory, unification of electromagnetic and weak interactions in the electroweak theory, amalgamation of three forces in the Grand Unification theory, and attempts at unification with gravity and the development of a 'theory of everything' on the basis of string theory. This scenario, although not confirmed by experiment, is still viewed as possible and not having a reasonable alternative.

3. New symmetries

The SM symmetry group can be extended in two directions: extension of the Lorentz group and extension of the internal symmetry group. The first case is about a supersymmetric extension.

3.1 Supersymmetry

Supersymmtery is an extension of the Lorentz group with anticommuting generators [4–6]. In the minimal version, the known Lorentz (Poincaré) group generators, which are the translation generators (four-momentum P_μ) and rotation generators (angular momentum $M_{\mu\nu}$), are extended with a generator Q_α and its complex conjugate counterpart $\bar{Q}_{\dot\alpha}$. These new generators anticommute with each other, $\{Q_\alpha, \bar{Q}_{\dot\alpha}\} = 2\sigma^\mu_{\alpha\dot\alpha} P_\mu$, and commute with other generators. The resulting algebra is referred to as the super-Poincaré algebra. Representations of that algebra contain states with various spins, in contrast to the Poincaré algebra, where spin is a conserved variable. This feature opens the way to unite usual forces with gravity, because gauge interactions are carried by spin-1 particles, while gravity is carried by spin-2 particles, which can belong to the same supermultiplet in the case of supersymmetry. Supersymmetry transformations defined by the generators Q_α change the particle spin by 1/2 [7–12]. Therefore, in the simplest case of one supersymmetric generator — the so-called $N = 1$ supersymmetry — supermultiplets consist of two states whose spins differ by 1/2. If we restrict our consideration to lower spins, we obtain the following supermultiplets:

• a chiral supermultiplet (ϕ, ψ) that contains a scalar state ϕ and a chiral spinor ψ;

• a vector supermultiplet (λ, A_μ) that contains a Majorana spinor λ and a vector field A_μ;

• a gravitational supermultiplet $(\tilde{g}, g)$ that contains the graviton g with spin 2 and gravitino $\tilde{g}$ with spin 3/2.

This is the set of multiplets that are used to build all supersymmetric models with simple supersymmetry.

To develop a supersymmetric SM extension [13–16], all SM particles should be placed into corresponding supermultiplets: quarks, leptons, and Higgs bosons should be placed into a chiral supermultiplet, and the gauge fields into a vector one. Particles belonging to the same multiplet then have identical quantum numbers and differ only by spins. Because the SM does not contain particles with nonequal spins and the same quantum numbers, it is necessary to introduce a corresponding partner for each SM particle, the number of particles doubling in this way (Fig. 4 [17]).[1] In addition, in supersymmetric theories, at least two Higgs doublets must be added, one of which interacts with upper quarks and leptons and the other with lower ones. An interesting feature of the supersymmetric SM is that interactions that violate the baryon and lepton quantum numbers can be forcibly suppressed by imposing a new discrete symmetry, which is referred to as R-parity. Positive R-parity is usually assigned to normal particles, and negative R-parity to their superpartners. This approach has two important consequences: superpartners are always produced pairwise, and the lightest superpartner is stable. The lightest superpartner is an ideal candidate to be the DM particle. It is usually a mixture of superpartners of the photon, the Z boson, and the Higgs boson, the last being a spin-1/2 particle referred to as the neutralino. However, R-parity can also be slightly violated.

There are many versions of how the SM can be extended in a supersymmetric manner. All of them typically contain the same minimal set of fields characteristic of the Minimal Supersymmetric Standard Model (MSSM) (see Fig. 4), but differ by the supersymmetry breaking pattern. The point is that exact supersymmetry results in degeneration between the masses of normal particles and their superpartners, in contradiction to experiment. Therefore, supersymmetry must be broken, preferably spontaneously. However, there is still no supersymmetry breaking mechanism that would be acceptable from the phenomenology perspective, and supersymmetry is commonly broken by adding various soft terms, resulting in enormous arbitrariness.

This arbitrariness, which eventually determines the superpartner mass spectrum, is employed in various models in different ways. There are also models that introduce additional fields, primarily additional Higgs bosons. The simplest extension of this type assumes adding a supersymmetric Higgs singlet. This model, referred to as the Next-to-MSSM (NMSSM) [18], enables obtaining the correct mass of the Higgs boson (125 GeV) already at the tree level without introducing large radiation corrections, as in the MSSM.

The search for supersymmetry in colliders is based on the fact that all types of interactions between superpartners and all coupling constants are known, because they are prescribed by supersymmetry. Only the superparticle masses are not fixed. The superparticles are produced pairwise in collisions of protons and electrons but decay rapidly, and therefore the final state contains only ordinary particles, the missing energy being taken away by the nondetectable neutral lightest superpartner [19, 20]. The search results are usually represented as areas allowed in the space of model parameters. Two approaches have been developed so far.

The first uses universal high-energy parameters m_0 and $m_{1/2}$, i.e., the masses of the particles with spins 0 and 1/2, on a high-energy scale, which determine the entire mass spectrum. This approach is universal but model dependent. The second approach uses the masses of the particles that are searched for in experiment as parameters. This approach, which is specific but not universal, provides information only about the selected particles. Examples of constraints in the parameter space that follow from nonobservation of superpartners in both approaches are shown in Fig. 5 [21, 22].

Supersymmetry has not been confirmed in experiment, and the bounds for superpartner masses have been moved to values in the range from 1 TeV to several TeVs, depending on the particle type.

[1] More accurately, the SM contains one Higgs doublet, resulting in a single Higgs boson, while in the supersymmetric case, it contains two doublets that yield five Higgs bosons and four higgsinos.

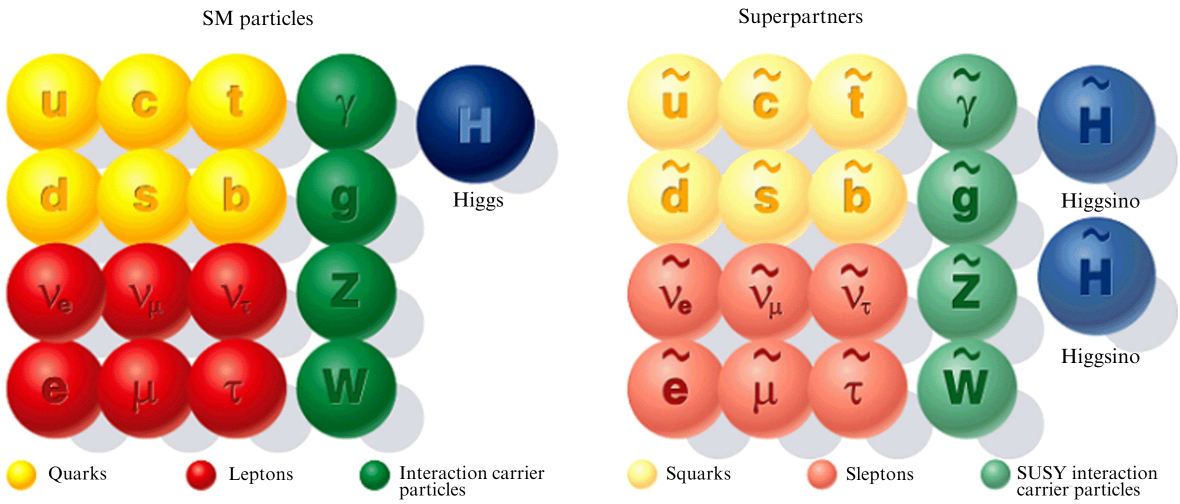

Figure 4. (Color online.) Field content of the minimal supersymmetric (SUSY) extension of the SM.

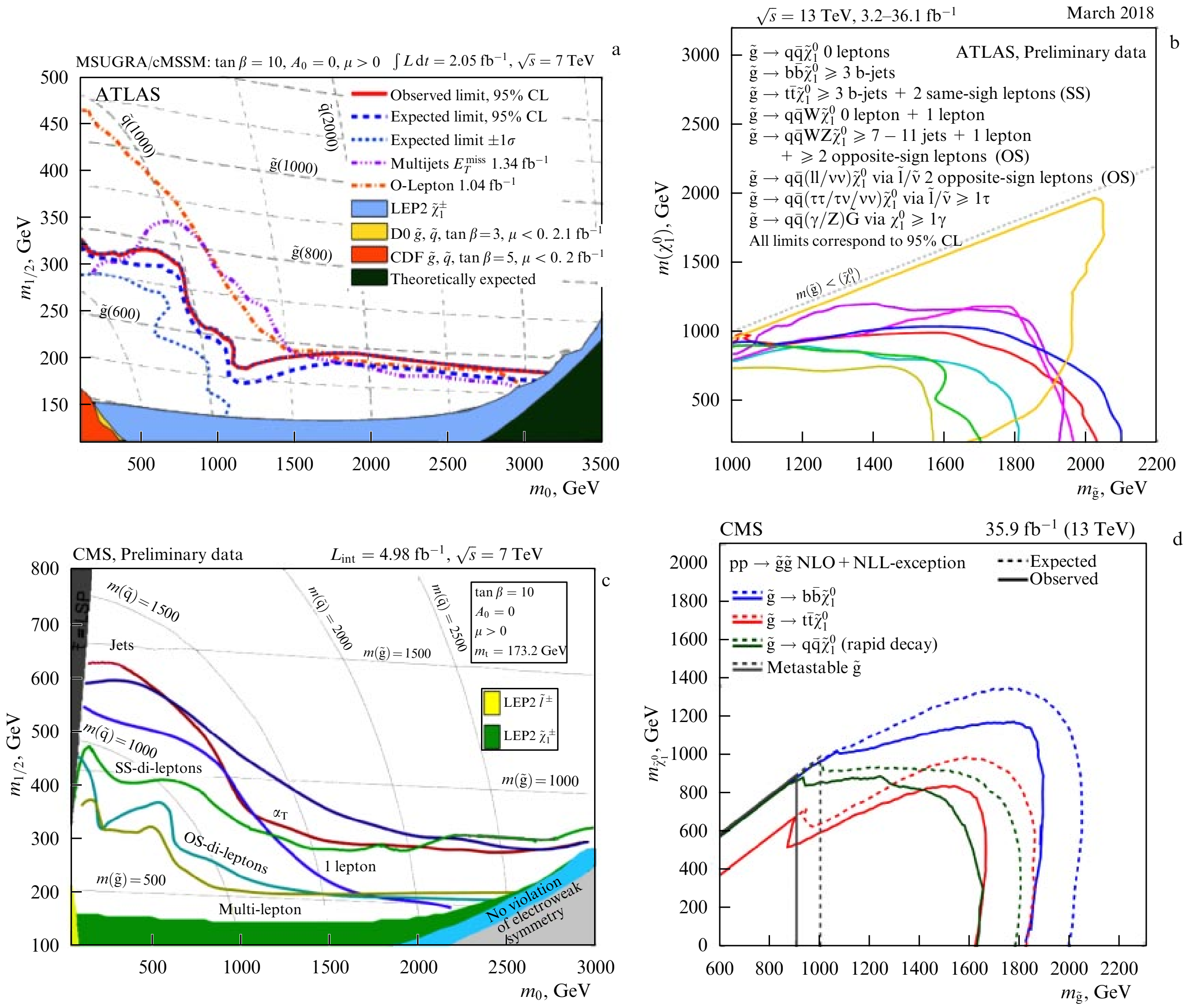

Figure 5. (Color online.) Search for supersymmetry: allowed areas in the parameter space. MSUGRA (Minimal Supergravity model), cMSSM (constrained MSSM), ATLAS (A Toroidal Large Hadron Collider (LHC) ApparatuS), CL (confidence level), CMS (Compact Muon Solenoid), EWSB (Electroweak Symmetry Breaking), NLO (next-to-leading order), NLL (next-to-leading logarithmic order).

3.2 Grand Unified theories

Another example of how the SM symmetry group can be extended is the so-called Grand Unified theories (GUTs), which combine strong, weak, and electromagnetic interactions within a unified theory based on a simple symmetry group [23]. The internal SM symmetry group $SU(3) \times SU(2) \times U(1)$ is embedded into a larger group G_{GUT}. It is assumed that the unification occurs at high energies.

Low energies			$\Rightarrow$	High energies
$SU_c(3) \otimes$	$SU_L(2) \otimes$	$U_Y(1)$	$\Rightarrow$	G_{GUT} (or G^n + discrete symmetry)
gluons,	W, Z	photon	$\Rightarrow$	gauge bosons,
quarks	leptons		$\Rightarrow$	fermions
g_3	g_2	g_1	$\Rightarrow$	g_{GUT}

The reason why the three interactions whose strengths are so different can merge into a unified universal interaction is that the coupling constants in quantum field theory are actually not constants but depend on the distance (momentum transferred), and their values change at high energies. These changes are described by the renormalization group equations, well known in the SM. The low-energy boundary conditions are set by experiment. Regarding the SM, the behavior of the effective couplings of the strong, weak, and electromagnetic interactions is displayed in Fig. 6. It shows that the three constants come close to each other at high energies, presumably due to their common origin: at high energies, there is a single symmetry group and hence a single coupling constant. The symmetry is then spontaneously broken, such that we observe three independent branches of the unified force.

The GUT symmetry group must be large enough to include the SM group and have complex-valued representations to place quarks and leptons in them. Therefore, the rank of that group (the maximum number of linearly independent generators commuting with each other) must be no less than the rank of the SM group, which is 4. We recall the classical rank-l groups $SU_{l+1}, SO_{2l+1}, SO_{2l}, Sp_{2l}$. It follows that the minimal rank-4 group is SU(5). It is used as a basis for the minimal GUT. The next popular candidate is the rank-5 group SO(10). An advantage of that group is that all quarks and leptons belonging to the same generation, including

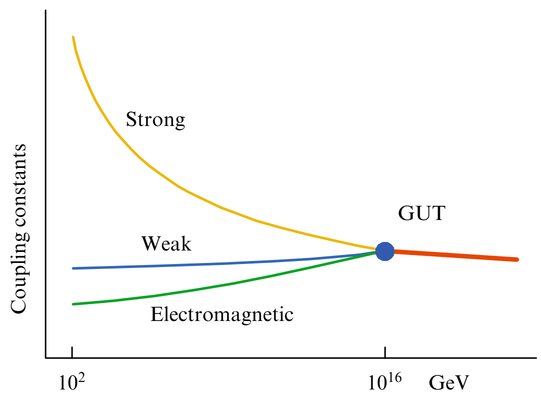

Figure 6. Unification of gauge coupling constants in Grand Unification theory.

right-handed neutrinos, are exactly accommodated into a single representation 16. The number of generators in those groups and hence the number of gauge fields is larger than in the SM. For example, there are 24 gauge fields in the SU(5) group and 48 in the SO (10) group.

The Grand Unified theories provide solutions to a number of SM problems (for example, the Landau pole problem), reduce the number of arbitrary parameters, combine quarks and leptons into a single family, and open a way to the violation of the baryon and lepton numbers. At the same time, they involve a number of new problems, first and foremost, the hierarchy problem. Indeed, the unification of the coupling constants occurs on the GUT scale of the order of 10^{15}–10^{16} GeV, where the GUT group is spontaneously broken. New heavy particles then acquire a mass of the order of the GUT scale. In interacting with the SM Higgs boson, they generate radiation corrections to its mass that are of the order of their own mass squared, violating the mass hierarchy in this way (see Fig. 2). A solution to this problem may be found, for example, in a supersymmetric GUT, where such undesirable corrections are canceled by contributions from superpartners in all orders of the perturbation theory. Thus, supersymmetry stabilizes the GUT, eliminating the effects of unknown heavy physics and preserving the hierarchy.

Because quarks and leptons belong to the same representation in the GUT, transitions between quarks and leptons occur as a result of interaction with new heavy gauge fields. This implies that the baryon and lepton numbers are violated, a phenomenon that does not exist in the SM. A key GUT prediction is baryon decay according to the scheme shown in Fig. 7a, where the π^0 meson and positron are produced. The proton lifetime is then proportional to the heavy X-boson mass, $\tau_p \sim M_X^4$, yielding a τ_p value over 10^{33} years. Current experimental data set only a lower bound on the proton lifetime, $\sim 10^{34}$ years. At the same time, other proton decay modes emerge in the supersymmetric case, in which the K^+ meson and antineutrino are produced (Fig. 7b). The proton decay is additionally suppressed in this case owing to the superpartner loop. The experimental constraint is somewhat weaker, being of the order of 10^{33} years. Searches for proton decay are now in progress. If this decay is found, it would be a confirmation of the Grand Unification hypothesis.

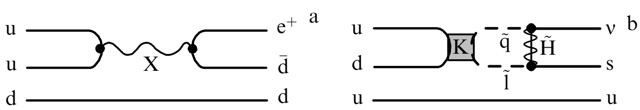

Figure 7. Diagrams contributing to proton decay in (a) standard GUT and (b) its supersymmetric version.

3.3 Extra symmetry factors

A less radical change in the SM symmetry group is the introduction of extra $U(1)'$ or $SU(2)'$ symmetry factors, etc. Such additional factors characteristic of string models could, generally speaking, extend the SM symmetry pattern. Such factors result in the emergence of additional gauge bosons A', Z', W', etc. These last could manifest themselves in the collider as characteristic single- or two-jet events with a high energy (Fig. 8 [24]). Processes with the possible production of the Z' boson (di-muon events) or W' boson (single-muon events), resonance two-boson processes, and monojets with missing energy are explored in experiments. No positive results have been obtained so far, and the masses of these hypothetical particles are now constrained at the level of several TeVs.

Another popular example of new symmetries is the inclusion of an extra $U(1)'$ factor with which the so-called dark photon is associated. Mixing due to the nondiagonal term $\mathcal{L} \sim F_{\mu\nu} F'_{\mu\nu}$ allows the ordinary photon to be converted into the dark one, an event that can be observed experimentally. The dark photon is presumably a DM particle.

4. New particles

The SM can be extended by adding new particles, as was shown above using an example of supersymmetry or extra symmetry factors. But there are many other ways to add new particles that do not involve extension of the symmetry group.

4.1 Extended Higgs sector

A possible extension of the SM Higgs sector is an important problem, whose resolution may be found shortly. Is the discovered Higgs boson a single boson of that kind? What alternatives are there to the minimal one-doublet model? As a minimum, additional scalar particles that are singlets, doublets, or triplets under the SU(2) group can be added to the SM. How can this option be checked experimentally? There are two ways to do so. The first is to measure the coupling constants of the 125 GeV Higgs boson with quarks,

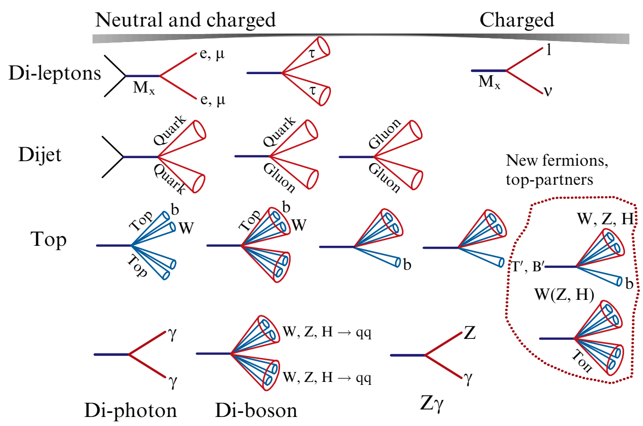

Figure 8. One- and two-jet high-energy events in models with extra symmetry factors.

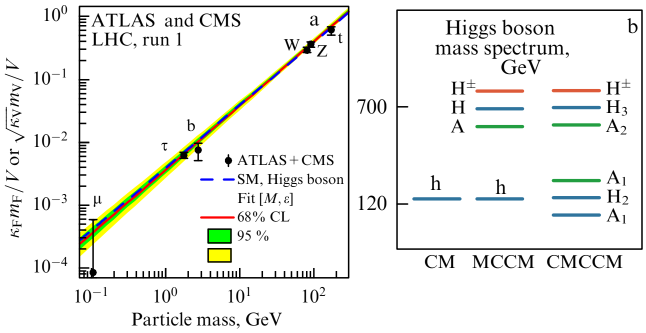

Figure 9. (Color online.) (a) Yukawa coupling constants as functions of particle masses and (b) the Higgs boson mass spectrum in models with an extended Higgs sector.

leptons, and intermediate vector bosons and check whether they deviate from the SM predictions. Those predictions correspond in the last case to the straight line in Fig. 9a, where they are shown as a function of particle masses [25]. Of importance here is the accuracy of measurements, which can be attained at a sufficiently high luminosity.

The second way is to directly observe additional Higgs bosons. The situation can be different depending on the model. For comparison, Fig. 9b shows a set of Higgs fields and the allowed spectrum of their masses for the two-doublet supersymmetric model (MSSM) and with an additional singlet introduced (NMSSM). We can see that in some cases the number of light Higgs bosons is more than one and, possibly, only one of them has been discovered so far.

To accurately measure the coupling constants of Higgs bosons, it is necessary to increase luminosity or, possibly, to build a new linear e^+e^- collider. This would make it possible not only to observe deviations from the SM but also, for example, to discriminate the standard two-doublet model from the supersymmetric one (Fig. 10 [26]). For this, the Higgs boson mass must be measured with an accuracy of several tens of MeV.

Searches for additional Higgs bosons, both neutral and charged, are now in progress in various channels at the Large Hadron Collider. So far, only constraints on the masses and interaction parameters have been obtained. Unfortunately, there are no clear-cut theoretical predictions for these parameters, in contrast to the case of the 125 GeV Higgs boson. Results of experimental analysis are presented in Fig. 11 [27]. Searches for additional Higgs bosons in the mass range $200 < m_H < 1000$ GeV have not yet yielded any results.

4.2 Axions and similar particles

Particles of a totally different type are represented by axions and similar particles related to *CP* violation in strong interactions. *CP* violation is known to occur in the SM owing to the presence of phase factors in flavor-mixing matrices. This phase is very small in the quark sector, $\delta_{13} = 1.2 \pm 0.1$ rad. However, owing to the axial anomaly, strong interactions generate a new effective interaction $(\alpha_s/8\pi)\, G\tilde{G}\theta_{QCD}$, which has a topological nature and modifies the *CP*-violating phase: $\theta = \theta_{QCD} + N_f\delta$. Due to the presence of this phase, the neutron acquires an anomalous dipole moment $d_n = -4 \times 10^{-3} \times \theta$ $[e \times \mathrm{fm}]$. At the same time, the experimental constraint on the anomalous dipole moment of the neutron is very stringent: $|d_n| < 3 \times 10^{-13}$ $[e \times \mathrm{fm}]$, yielding $\theta < 10^{-10}$. A value this small needs to be explained.

The required explanation was found by transforming the parameter θ into a dynamic field whose vacuum expectation value determines the *CP*-violation parameter. This value, which is zero in the potential minimum, acquires a small magnitude generated by nonperturbative dynamics. The axial symmetry related to that field is spontaneously broken, as a result of which a Goldstone boson emerges, which then acquires a small mass. This particle is referred to as the axion, and the mechanism by which the parameter θ is dynamically suppressed is referred to as the Peccei–Quinn mechanism [28, 29]. The axion is characterized by two parameters: the mass m_a and the constant of its coupling to gluons $1/f_a$. Searches for the axion have so far failed to yield any results; the allowed areas are shown in Fig. 12 [30]. We can see that only very small masses or very large f_a values are possible.

It turns out that coherent oscillations of the axion field (we recall that the axion is a boson) can create a condensate that is a form of DM. Despite the small axion mass, the DM may be cold, because it is not in the thermal equilibrium state. Thus, if the axion exists, some part of the DM is inevitably of an axion type.

4.3 Neutrino

Although our knowledge about neutrinos is quite vast, this particle remains an enigma. One of the questions pertaining to this particle is the number of neutrino types and, more generally, the number of matter particle generations. The answer to these questions is given by experiments where the Z-boson decay width (Fig. 13a [31]) and temperature fluctuations of the microwave background (Fig. 13b [32]) are measured.

As follows from these absolutely dissimilar experiments, the number of light neutrinos and, given the quark–lepton

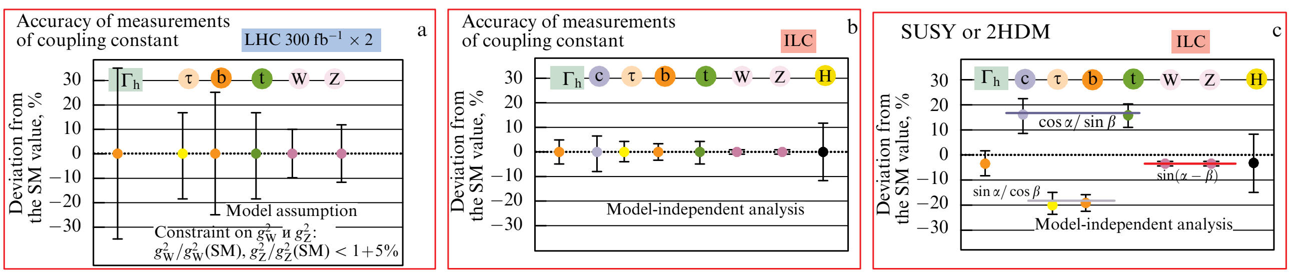

Figure 10. (Color online.) High-precision measurements of coupling constants of the Higgs boson at the Large Hadron Collider (LHC) and the International Linear Collider (ILC). 2HDM means the two-Higgs doublet model.

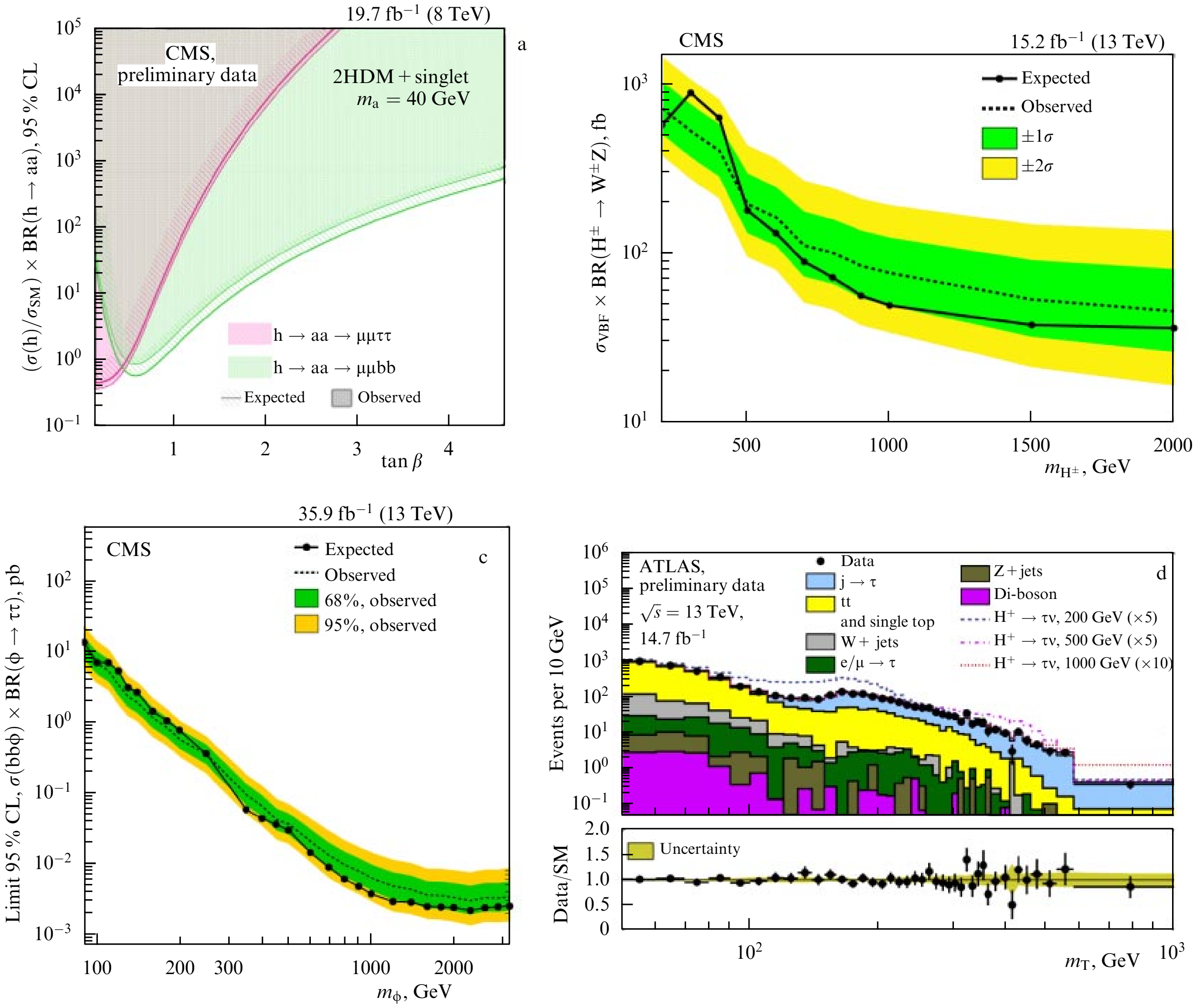

Figure 11. (Color online.) Search for heavy Higgs bosons: allowed areas of parameters.

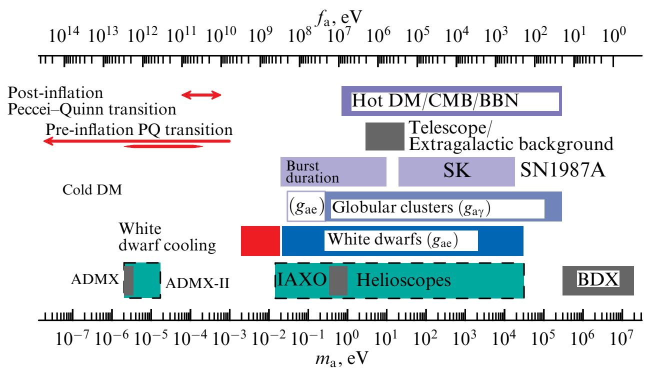

Figure 12. Allowed areas of the axion mass and coupling constant. CMB (Cosmic Microwave Background), BBN (Big Bang Nucleosynthesis), SK (Super-Kamiokande laboratory), ADMX (Axion Dark Matter experiment), IAXO (International AXion Observatory), and BDX (Beam Dump eXperiment).

symmetry, the number of matter particle generations in the SM is three, and all of them have been discovered. This conclusion is confirmed by high-precision experiments in which rare decays are observed: they also preclude the existence of a fourth generation of heavy quarks. But have we actually observed all of the neutrinos? If the neutrino is a Majorana particle, then there are also heavy neutrinos that have not been observed yet. Moreover, it is sometimes hypothesized that there are sterile neutrinos, whose existence may eliminate the disagreement between some neutrino experiments (Liquid Scintillator Neutrino Detector (LSND), MiniBoone, and reactor anomaly).

There is also the neutrino mass problem. The oscillation experiments quoted above only yield the difference between the masses squared and, worse, in two opposite variants (direct and inverse hierarchy), but fail to set the absolute mass scale (Fig. 14 [33]). That scale can be fixed by measuring the β-decay spectrum or, again, microwave background temperature fluctuations. A bound on the electron neutrino mass has been obtained in the first approach: $m_{\nu_e} < 2$ eV [34, 35]; this constraint will be lowered in the nearest future to 0.2 eV. At the same time, there is a rather accurate cosmological bound: $\sum m_\nu < 0.23$ eV [36, 37].

Another neutrino-related problem pertains to its nature. Is the neutrino a Dirac or a Majorana particle? We recall that the solution of the Dirac equation for a massive spin-1/2 particle is a four-component spinor that can be split into two two-component spinors in two different ways: either into two complex-valued, left- and right-handed parts, which correspond to two polarizations, or into real- and imaginary-valued parts, each of which represents an independent

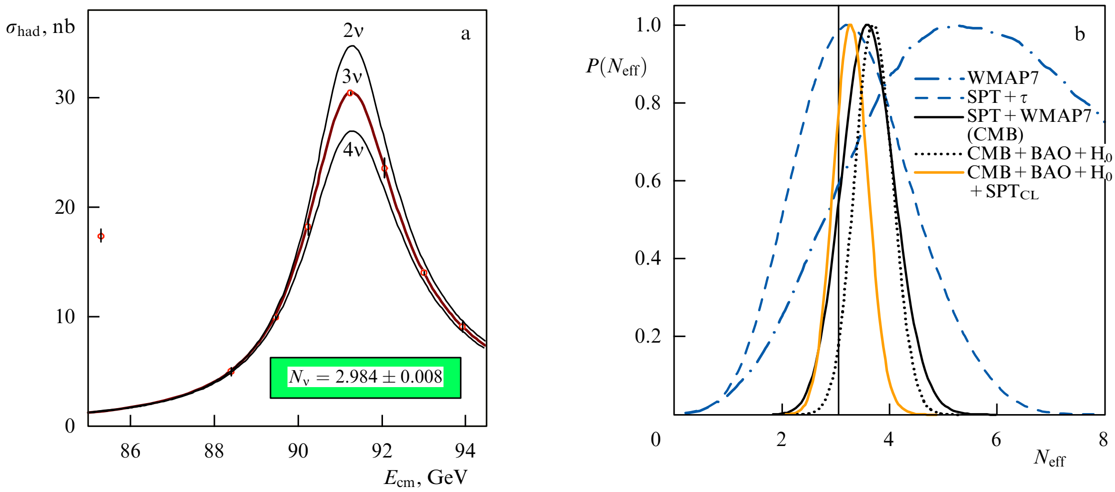

Figure 13. Constraints on the number of SM particle generations that follow from (a) the Z-boson width measured by the ALEPH, DELPHI, L3, and OPAL collaborations [32] and (b) measurements of temperature fluctuations of the cosmic microwave background. Circles in Fig. a show averaged measurement results, and error bars are increased tenfold for better visibility. E_{cm} is the center-of-mass energy, WMAP7 is the Wilkinson Microwave Anisotropy Probe, 7 years of operations, SPT is South Pole Telescope, and BAO is Baryon Acoustic Oscillation.

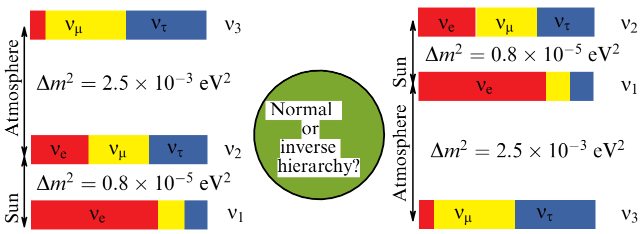

Figure 14. (Color online.) Neutrino mass spectrum obtained by fitting the model to experimental data on neutrino oscillations.

particle,

$$\nu_D = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}, \quad \nu_{M_1} = \begin{pmatrix} \xi_1 \\ \xi_1^* \end{pmatrix}, \quad \nu_{M_2} = \begin{pmatrix} \xi_2 \\ \xi_2^* \end{pmatrix}.$$

The Dirac-particle masses are identical, $m_{\nu_L} = m_{\nu_R}$, and the particle is different from its antiparticle, $\nu_D \neq \nu_D^*$, while the Majorana-particle masses are different, $m_{M_1} \neq m_{M_2}$, but the Majorana neutrinos are identical to their own antiparticles, $\nu_{M_i} = \nu_{M_i}^*$.

These two options concerning the nature of the neutrino can be discriminated in an experiment on double neutrinoless β-decay, which is schematically depicted in Fig. 15a. This decay, which is only possible if the neutrino is a Majorana particle, can be detected by measuring the electron energy: a sharp peak is supposed to emerge in the case of neutrinoless β-decay (Fig. 15b [38]). However, a dense comb is observed in actual experiments (Fig. 15c [39]), in which the sought peak can hardly be distinguished. There is to date no reliable evidence of the double neutrinoless β-decay. Only a constraint on the decay time is available: $T_{1/2}0\nu\beta\beta(^{136}\mathrm{Xe}) \times 10^{25}$ years $> 1.6(90\,\%$ CL) [40]. We note that the resolution of this dilemma depends on whether the neutrino mass hierarchy is direct or inverse. In the case of the inverse hierarchy, there is a lower bound on the effective mass of the neutrino in the double β-decay that can be attained in experiment. However, there is no such limit in the case of the normal hierarchy, and the β-decay probability can become arbitrarily small (Fig. 16 [41]).

Various experimental attempts have been made to find the fourth, sterile neutrino. As was noted above, if that neutrino exists, it would help resolve some disagreements in neutrino oscillation experiments. However, only bounds on the mass differences and mixing angles have been determined so far.

4.4 Dark matter

Modern cosmological data on supernova bursts and microwave background temperature fluctuations show that the observed matter makes up only 4% of the total energy of the Universe, another 26% is dark (nonradiant) matter, and the

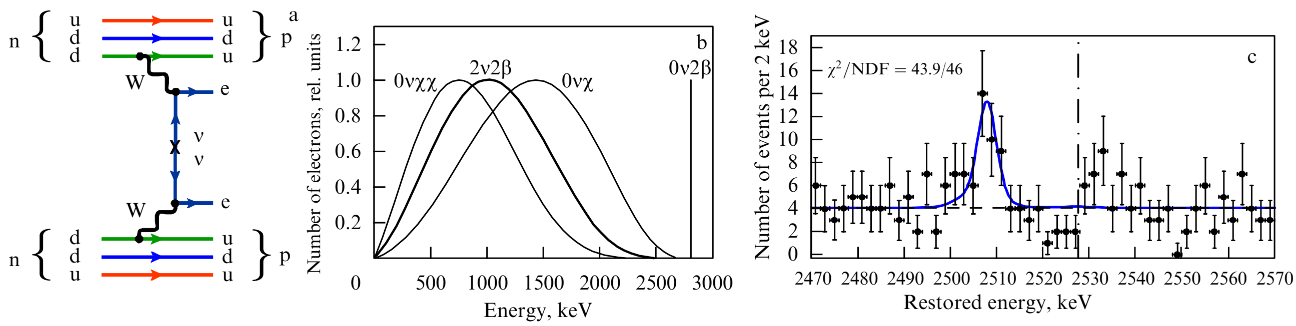

Figure 15. (a) Neutrinoless double β-decay and (b) electron energy spectrum in an ideal situation and (c) nuclear processes. NDF means the number of degrees of freedom.

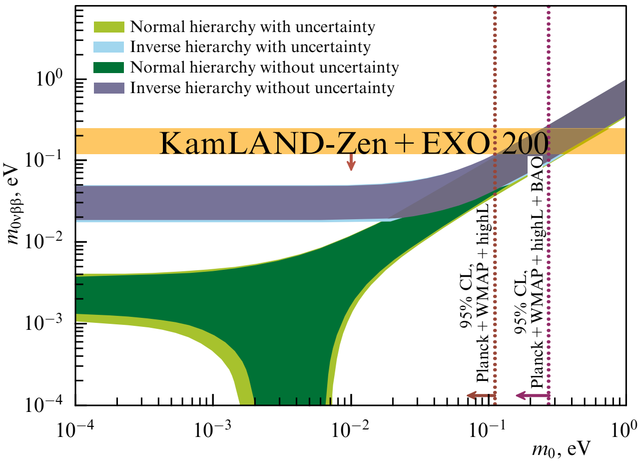

Figure 16. (Color online.) Experimentally allowed values of the neutrino effective mass in double neutrinoless β-decay for direct and inverse mass hierarchies. EXO is Enriched Xenon Laboratory.

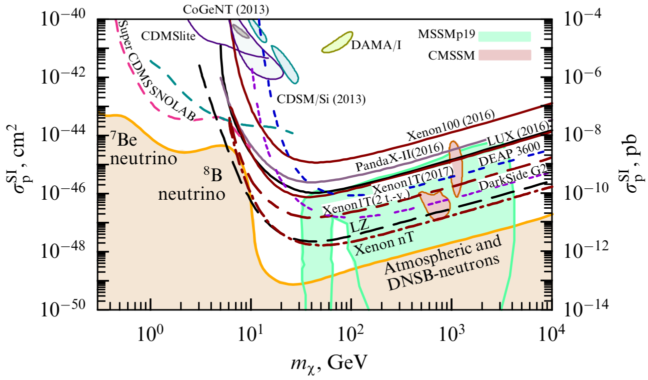

Figure 17. (Color online.) Result of direct searches for DM: allowed areas in the (cross section σ_p^{SI}, mass m_χ) space (the superscript SI means 'spin independent'). The neutrino threshold is shown with the orange line. CoGeNT (Coherent Germanium Neutrino Technology), CDMS (Cryogenic Dark Matter Search), CDMSlite (CDMS low ionization threshold experiment), SNOLAB (Sudbury Neutrino Observatory Laboratory), PandaX-II (Particle and Astrophysical Xenon Detector II), LUX (Large Underground Xenon experiment), DEAP (Dark matter Experiment using Argon Pulseshape discrimination), LZ–LUX-ZEPLIN (ZonEnd Proportional scintillation on LIquid Noble gases), and DNSB (Double Neutron Star Binary).

remaining 70% is due to the vacuum energy [42]. Dark matter presumably consists of neutral stable particles that have survived since the Big Bang and participate in gravitational and, presumably, weak interactions. It cannot be ruled out that DM consists of more than one component, of which some may participate in new, superweak, interactions. It is believed that dark matter is localized on a galactic scale, its density decreasing with the distance from the Galaxy center and extending far beyond its visible part. The presence of DM is responsible for the rotation curves of stars featuring a characteristic flat shape in spiral galaxies.

Only one of the SM particles can, owing to its properties, be a candidate for the DM particle, and this is the Majorana neutrino [43]. Normal light neutrinos fail to provide the required mass. However, the problem of whether a heavy Majorana neutrino exists is still unresolved.

All other candidates for the role of DM particles are not part of the SM. The list of those candidates includes supersymmetric neutralinos, sneutrinos and gravitinos [44], axions and their superpartners, axinos [45], heavy photons, light sterile Higgs bosons, and heavy pseudo-Goldstone particles emerging as a result of violation of new symmetries [46]. A special group consists of particles that participate in the standard weak interactions, so-called weakly interacting massive particles (WIMPs). The main argument in favor of WIMPs as DM particles is that their annihilation cross section, which is needed to produce the required amount of relic DM, is approximately 1 pb, i.e., close to a typical weak cross section. If DM actually consists of WIMPs, they can be detected in three different ways: finding the annihilation signal in cosmic rays, observing scattering on a deep underground target, or triggering production of those particles at an accelerator, where the missing energy and momentum could signal their existence. All of these processes are closely related; however, searches for a signal from DM have not yet yielded any results.

Figure 17 [47] shows the results of direct detection of DM. Everything located above the corresponding curves is excluded. We can see that experiment is rapidly advancing to increasingly smaller cross sections to eventually come close to the so-called neutrino floor, displayed in orange. The background of neutrino scattering cannot be eliminated in that region. However, to attain that floor, the measured cross sections should be diminished by two orders of magnitude.

If DM consists of particles that participate in very weak or only gravitational interactions, detecting those particles may become problematic.

5. Extra space dimensions

The apparently paradoxical idea of extra space dimensions has gained considerable popularity, although no experimental confirmation whatsoever of that idea is available. This situation is explained by the wealth of opportunities that the new dimensions open, on the one hand, and the fact that a a consistent formulation of string theory is only possible for a critical dimensionality equal to 26 for the bosonic string and 10 for the fermionic one [48], on the other hand. String theory has thus stimulated studies of multidimensional theories. A natural question arises: why do we not we see any extra space dimensions? There are two options: compact small-radius extra dimensions and localization of observables on a 4D hyper-surface (brane) (Fig. 18).

5.1 Compact extra dimensions

The idea of compact extra dimensions dates back to the Kaluza–Klein theory [49–51], in which the fact that extra dimensions are unobservable is explained by their compactness. If a field function that depends on usual space–time coordinates x and extra-dimensional coordinates y is expanded in eigenfunctions of a compact manifold, $\phi(x, y) = \sum_0^\infty \phi_n(x)\, Y_n(y)$, we obtain an infinite tower of so-called KK excitation modes with an increasing mass spectrum that is controlled by the compact-manifold topology. Mass splitting is inversely proportional to the radius of the compact dimensions. From the 4D-world perspective, we thus obtain a theory with an infinite number of heavy particles, and with zero modes corresponding to usual SM particles.

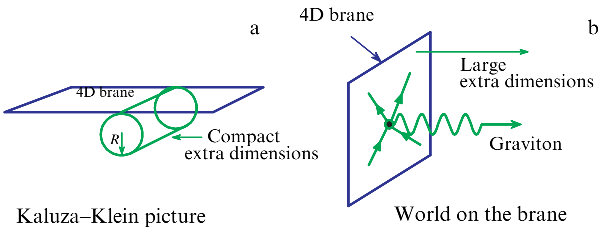

Figure 18. (a) Compact and (b) flat extra spatial dimensions.

It is generally assumed that the extra dimensions are primarily permeated by gravity. The impact of that is twofold: first, KK gravitons emerge and, second, the form of Newton's law and the gravitational constant it contains are modified. Indeed, the 4D Newton constant is related to the $(4+d)$-dimensional one as $G_{\mathrm{N}(4)} = (1/V_d)\, G_{\mathrm{N}(4+d)}$, and therefore the smallness of the gravitational interaction in the 4D space can be explained by the compact manifold volume, even if the $(4+d)$-dimensional constant is relatively strong. The scale hierarchy problem is translated in this way into a hierarchy of sizes of the d-dimensional compact space, and the Newton law is modified to the form

$$V \approx \begin{cases} G_{\mathrm{N}(4)} \dfrac{m_1 m_2}{r}\,, & r \gg R\,, \\[2ex] G_{\mathrm{N}(4)} \dfrac{m_1 m_2}{r}\, S_{d-1} \left(\dfrac{R}{r}\right)^d \Gamma(d) = G_{\mathrm{N}(4+d)} \dfrac{m_1 m_2}{r^{d+1}}\, S_{d-1} \Gamma(d)\,, & r \ll R\,. \end{cases}$$

Attempts to find modifications to Newton's law have failed, but the accuracy of tests has been enhanced by two orders of magnitude [52].

The phenomenological consequences of models with extra dimensions are primarily related to the effect of massive KK gravitons. There are two types of processes in which the KK mode effect can be detected in accelerator experiments: emission of gravitons and exchange by virtual gravitons.

If emitted, gravitons can no longer be detected and manifest themselves as missing energy. Although each individual emission event is suppressed by the Planck mass, the total production cross section increases as the energy increases owing to the multitude of KK states (Fig. 19a [53]). The main process at $\mathrm{e^+e^-}$ colliders is $\mathrm{e^+e^-} \to \gamma \mathrm{h^n}$, to which the process $\mathrm{e^+e^-} \to \gamma\nu\bar{\nu}$ is a background. A characteristic process at the Larger Hadron Collider is the production of jets where energy is missing: $\mathrm{pp} \to$ jets + missing energy. The main subprocess that yields the maximum contribution is the merging of quarks and gluons $\mathrm{qg} \to \mathrm{qh^{(n)}}$. Examples of other subprocesses are $\mathrm{q\bar{q}} \to \mathrm{gh^{(n)}}$ and $\mathrm{gg} \to \mathrm{gh^{(n)}}$.

Virtual KK-mode exchange is another process in which extra dimensions can be discovered. Typical processes where the exchange by virtual gravitons can be observed are a) $\mathrm{e^+e^-} \to \gamma\gamma$; b) $\mathrm{e^+e^-} \to \mathrm{f\bar{f}}$, for example, the Bhabha scattering $\mathrm{e^+e^-} \to \mathrm{e^+e^-}$ or Müller scattering $\mathrm{e^-e^-} \to \mathrm{e^-e^-}$; and c) contribution of gravitons to the Drell–Yan process. A signal indicating an exchange by the KK modes is a deviation in the number of events and the left–right polarization asymmetry from the SM predictions (Fig. 19b [54]).

Moreover, gravitons can participate in processes that do not exist in the SM at the tree level, such as $\mathrm{e^+e^-} \to \mathrm{HH}$ or $\mathrm{e^+e^-} \to \mathrm{gg}$. If such events are discovered with large cross sections, it would indicate that extra dimensions do exist.

5.2 Large extra dimensions

An alternative to compact extra dimensions are arbitrarily large dimensions, which we do not observe due to localization of observables on a 4D hypersurface, usually referred to as a brane [55, 56]. Particles can be confined to the brane by attraction forces, and to leave it, they need to gain a large energy. It is also hypothesized that SM fields are localized on the brane while gravity extends to extra measurements. The graviton KK modes emerge in this case as well. A popular model with large extra dimensions, the so-called Randall–Sundrum model [57, 58], contains two branes in a twisted 5D space, $\mathrm{E}_5 = \mathrm{M}_4 \otimes \mathrm{S}^1/\mathrm{Z}_2$. A specific feature of that model is that it contains a metrics deformation factor, as a result of which gravity on one brane, which is called the Planck brane, is characterized by the normal Planck mass, while on the other brane, which is called the TeV brane, the gravitational scale is exponentially suppressed by the deformation factor, and therefore a huge hierarchy of scales does not emerge. This also pertains to the spectrum of KK gravitons, which are separated by a large gap on one brane and located close to each other on the other brane.

Of phenomenological interest is the TeV brane on which interactions between KK gravitons are not suppressed by the Planck mass, and the first excitations can have a mass of the order of 1 TeV, to be experimentally observable with accelerators. The lowest KK excitations should manifest themselves as resonances in the production of ordinary particles (Fig. 20a [58]). Whether the resonance production of massive gravitons is detectable in proton collisions

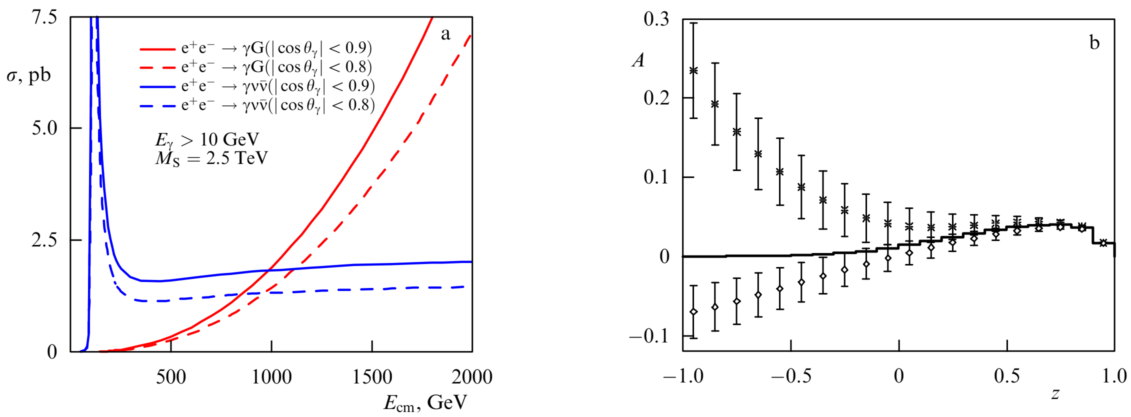

Figure 19. (a) Increase in the total cross section of graviton production as the energy increases. (b) Cross section of particle production with the graviton in the intermediate state as a function of the azimuthal angle.

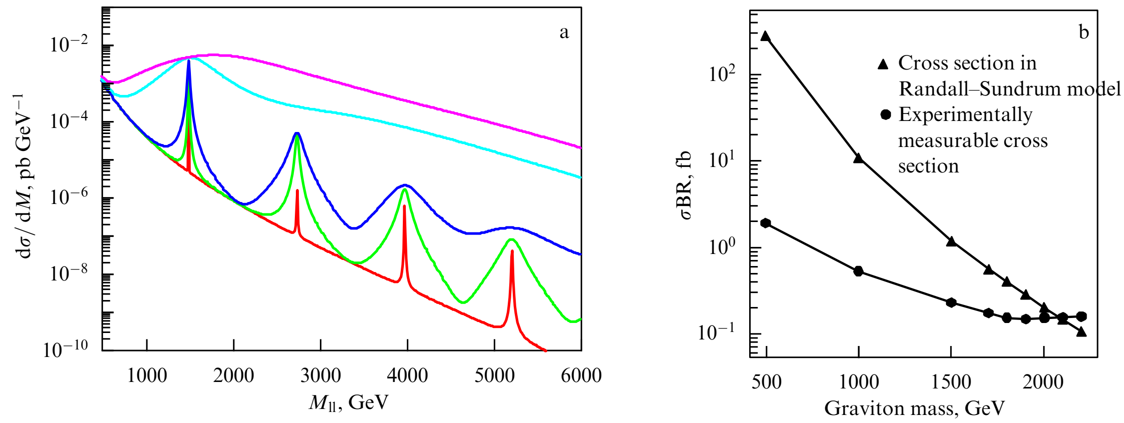

Figure 20. (a) Production of KK gravitons in the Drell–Yan process at $M_1 = 1500$ GeV at the LHC and (b) the background production cross section as a function of graviton masses.

$pp \to h^{(1)} \to e^+e^-$ at the LHC depends on the process cross section. The main background comes from the process $pp \to Z/\gamma^* \to e^+e^-$. The estimated cross section of the process $h^{(1)} \to e^+e^-$ as a function of the graviton mass in the Randall–Sundrum model is shown in Fig. 20b [59]. We can see that the detection is possible if $M_1 \leqslant 2080$ GeV.

No signals from extra dimensions have been observed to date, and only constraints on the allowed masses are available. Data on the emission of gravitons with the missing energy into an extra dimension set a mass bound $M_* \geqslant 3-5$ TeV, data on excited states of quarks and gluons with higher spins give $M_* > 5$ TeV, and data on the KK modes of gauge bosons give $M_* > 1-4$ TeV, etc.

The Planck mass being effectively diminished in higher dimensions results in strong gravity, which can cause the production of microscopic black holes at the LHC. Although such black holes are supposed to evaporate almost instantaneously, the phenomenon can be tested experimentally. So far, only a mass bound of the order of 5 TeV has been obtained.

6. String and brane theory

The most ambitious attempt to go beyond the SM is to change the paradigm of local quantum field theory and move to nonlocal theories. The pioneer in this approach is string theory, a theory of one-dimensional extended objects [48]. As a natural development of these ideas, objects of any dimension, branes (from the word ''membrane,'' which refers to a 2D surface) have been introduced. The theory of such objects is currently under development, but some of its qualitative implications have been widely discussed since long ago.

6.1 String theory

String theory describes one-dimensional extended objects that in the process of propagating sweep a 2D worldsheet. The action for such objects is defined by a direct generalization of the action for a point-like particle:

$$S = -m \int d\tau \sqrt{-\frac{dX^\mu}{d\tau}\frac{dX^\nu}{d\tau}\,\eta_{\mu\nu}}$$

$$\Rightarrow S = -\frac{1}{2\pi l_S^2}\int d^2\sigma \sqrt{-\det\left(\frac{dX^\mu}{d\sigma^\alpha}\frac{dX^\nu}{d\sigma^\beta}\,\eta_{\mu\nu}\right)}\,.$$

Strings can be open and closed. The string excitation spectrum, which is associated with particles, contains spin-1 fields for open strings and spin-2 fields for closed ones, which correspond to gauge fields and gravitons, respectively. In addition to oscillation modes, a string also has modes that are related to winding the world line on the string. These modes taken together determine the complete string spectrum. The string is characterized by a minimal size, which is referred to as the string length. It is assumed that this size is close to the Planck scale.

Quantum string theory is formulated in a space of critical dimension where the theory is free of the conformal anomaly. The critical dimension is 26 for the bosonic string and 10 for the fermionic string. Apart from this, tachyons can emerge in the string spectrum. To remove them, a supersymmetric tachyon-free string is considered whose spectrum begins with massless modes that are usually associated with point-like particles of a quantum field model.

To derive an effective 4D low-energy theory containing massless modes from string theory, compactification of the 'unnecessary' dimensions is needed. Properties of the compact 6(7)-dimensional manifold determine specific properties of the resulting theory. For example, degeneration of the compact space in shape and dimensions, which is expressed in the form of scalar fields referred to as moduli, determines coupling constants, while various topologies of the compact manifold determine the symmetry group and fields in the 4D theory. The variety of the currently available options does not allow selecting a preferable scheme and making specific predictions.

The most preferable model from the phenomenological perspective is the so-called heterotic string. In particular, it unifies gauge fields and the Higgs field, which allows predicting the coupling constants and obtaining the top-quark mass in the range of 170 GeV. It also supports cancelation of anomalies and predicts the GUT symmetry group SO(32) or $E_8 \times E_8$. The right-handed neutrino and Majorana mass term, as well as proton decay, emerge in the theory. The effective low-energy theory provides the desired unification with gravity and contains a mechanism that breaks supersymmetry due to supergravity effects.

String theory incorporates not only strings but also extended objects of any dimension. A picture emerges where the world is built of branes on which open strings begin and end, while closed strings propagate in a multidimensional world.

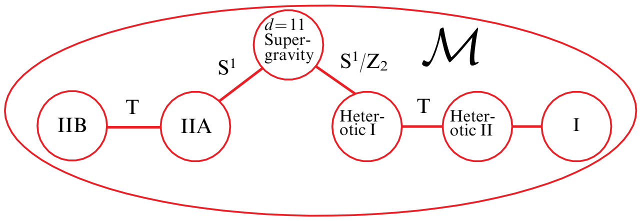

Figure 21. String landscape and $\mathcal{M}$-theory.

6.2 $\mathcal{M}$-theory and the theory of everything

There are five types of consistent string theories that are free of conformal anomalies and tachyons. These are the so-called strings of types I, IIA, and IIB and two heterotic strings [60, 61]. All of them exist in 10 dimensions and have supersymmetry on the 2D worldsheet of the string and, as a consequence, space–time supersymmetry in 10D space–time. All these string theory models are believed to be different vacua of a unified theory referred to as the $\mathcal{M}$-theory; however, no suitable formulation of it has been proposed. Another $\mathcal{M}$-theory vacuum is the 11D supergravity theory (Fig. 21 [62]).

It is hypothesized that such an all-encompassing theory will be the 'theory of everything', i.e., will describe all the main laws of nature on a fundamental level. However, the structure of that theory remains vague. It is not clear what degrees of freedom are fundamental. Moreover, it cannot be ruled out that mutually dual descriptions of the same reality are possible. An example of such duality is the so-called AdS/CFT correspondence,[2] according to which some characteristics of the theory can be described in terms of both 4D conformal field theory and classical gravity in the 5D de Sitter space [63, 64]. We are still very far in this area from making specific predictions that would be verifiable in experiments.

7. Conclusion. Priority tasks of high-energy physics

The success of the Standard Model and immense efforts aimed at both testing it and searching for new physics in accelerator and nonaccelerator experiments will drive the development of high-energy physics in the nearest future. Experiments conducted at the Large Hadron Collider are at the frontier of knowledge. It is on those experiments that the success of all of high-energy physics depends. However, the current situation is such that there is no area where a discovery could be guaranteed. We are only making the first steps into the unexplored territory, and it is of immense interest to discover the secrets it contains. Diligence and patience are needed on that path. There are many physical models that suggest the presence of physics on various energy scales. It is only future experiments that will be able to show which of them are correct and do describe nature. Today, we can only speak about priority tasks, a list of which includes:

- exploration of the Higgs sector;
- search for DM particles;
- search for new physics (supersymmetry);
- additional search for DM and studies of neutrino properties in nonaccelerator experiments;
- resumption of studies on confinement, exotic hadrons, and dense hadron matter, which have been temporarily suspended but are now coming to the forefront.

Further progress in high-energy physics essentially depends on the results of these explorations.

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[2] Anti-de Sitter/Conformal Field Theory correspondence.

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