Standard Model and the Four Fundamental Forces

All matter - humans, animals, plants and planets - are made of atoms. In the nucleus of the atoms are the positively charged protons and neutral neutrons and in the atomic shell the negatively charged electrons. We have already dealt with the structure of atoms and the periodic table of the elements elsewhere. But atoms are also composed of even smaller particles. Physicists have summarized their knowledge of the smallest particles in the so-called standard model of particle physics. In the interplay between many experimental results and various theoretical models, the "Standard Model of Particle Physics" was created in several steps between 1961 and 1973. Although it has retained this modest name, today, more than 40 years later, it is considered to be the most profound insight yet produced by natural science into the origin, structure and behavior of matter in our universe. All subatomic processes observed so far perfectly match the predictions of the Standard Model.

So, in this paper, we will learn about the Standard Model of particle physics.

What is the Standard Model?

Elementary particles are all components of the universe, which are assumed to be not divisible further. This includes the matter and antimatter particles as well as the exchange particles.

Elementary particles do not possess any spatial extension - at least none, which could be measured with today's measuring instruments. All elementary particles of the same kind have the same mass and the same charges.

Elementary particles follow the laws of quantum mechanics. For example, their location and momentum cannot be measured or predicted exactly at the same time, but only in terms of probabilities.

Elementary particles are not perceptible to our senses, but they leave traces that can be made visible with special measuring instruments. Such traces were first observed in cloud chambers at the end of the 19th century. In them, electrically charged particles ionize the molecules they fly past; liquid droplets attach to the ions and become visible as fog trails. Modern detectors, such as those at the international research center CERN in Geneva, are also based in part on ionization, but they also make use of other effects.

Particle accelerators are needed to specifically create and study massive, unstable particles. In particle collisions, part of the particles' kinetic energy is converted into mass (according to the mass-energy equivalence E = mc 2). The technology to accelerate particles to ever higher energies has been progressively developed since the 1950s, allowing the creation of ever more massive particles.

The Standard Model describes all the phenomena of the microcosm known to us and includes the following types of particles (Fig. 1): the particles of which matter is composed (matter particles), and the interactions between them, which also take place via small particles (exchange particles). Another component of the Standard Model is the Higgs particle, which is neither a matter particle nor an exchange particle.

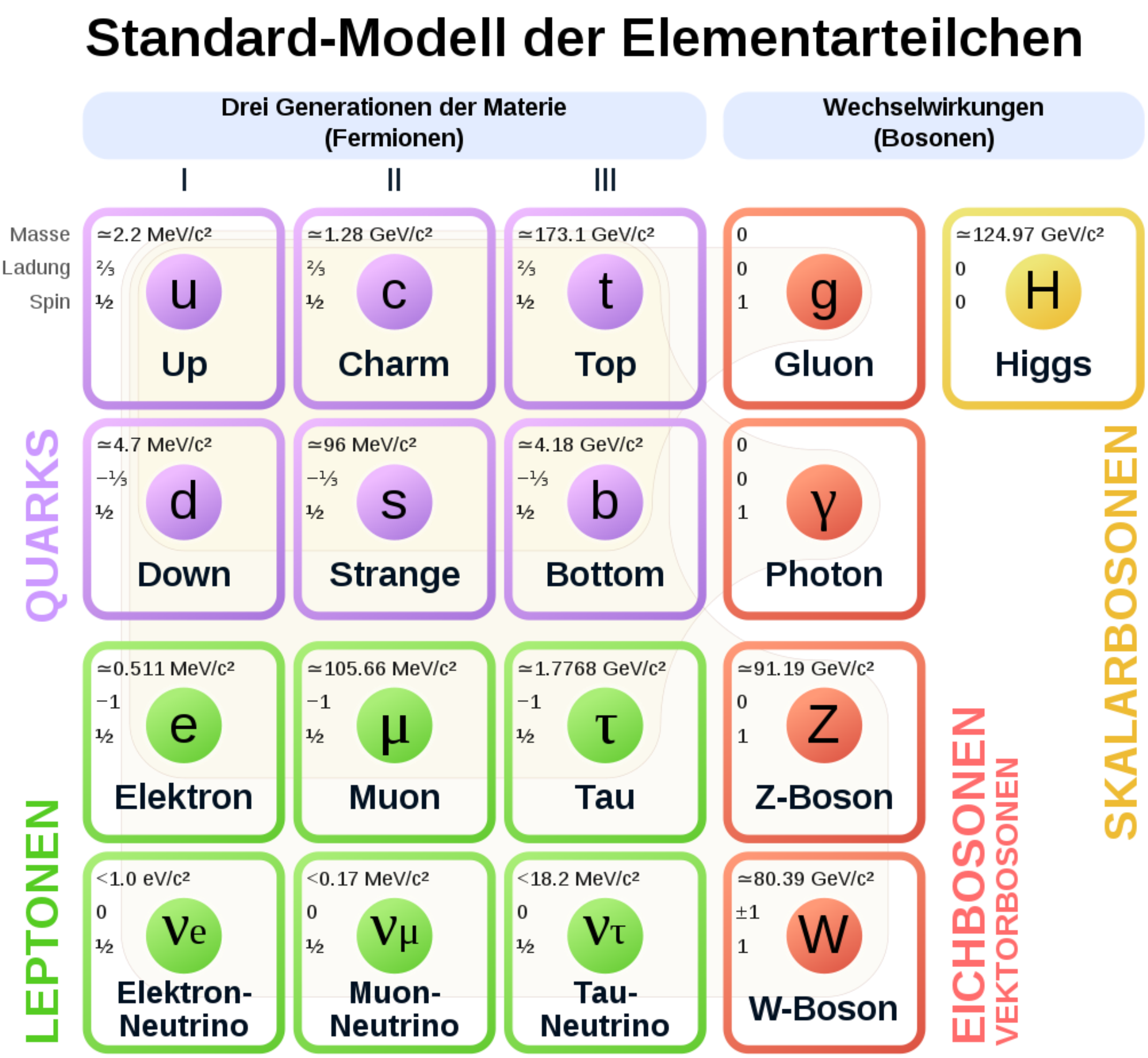


Fig. 1: Standard model of particle physics

The Standard Model also describes the important forces between them: the strong force, the weak force and the electromagnetic force. Only (the comparatively very weak) gravitation as the fourth basic force is not considered (fig. 2).

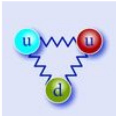
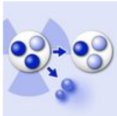
Wechselwirkung	 Starke Wechselwirkung	 Schwache Wechselwirkung	 Elektromagnetische Wechselwirkung	 Gravitation
Beispiele für Wirkung	Zusammenhalt des Protons	Betazerfall: Ein Proton wandelt sich in ein Neutron um (oder umgekehrt). Kernfusion: In der Sonne verschmelzen vier Protonen zu einem Heliumkern.	Magnetismus, Licht, ...; Chemische Bindungen; Photoeffekt	Anziehung zwischen Massen: Schwerkraft, Umlauf der Planeten um die Sonne
Ladung	Starke Ladung ("Farbladung")	Schwache Ladung	Elektrische Ladung	
Botenteilchen	Gluonen	W^+, W^-, Z	Photon	
Reichweite	$2 \cdot 10^{-15}$ m (Protonendurchmesser)	$2 \cdot 10^{-18}$ m ($\frac{1}{1000}$ Protonendurchmesser)	unbegrenzt	unbegrenzt
Kopplungsparameter	$\alpha_S \approx \frac{1}{2},..,\frac{1}{10}$	$\alpha_W \approx \frac{1}{30}$	$\alpha_{em} \approx \frac{1}{137}$	$\alpha_{grav} \approx \frac{1}{10^{45}},..,\frac{1}{10^{38}}$

Fig. 2: the Four Fundamental Forces

Antimaterie

For every elementary particle there is a so-called antiparticle (Fig. 3). It has exactly the same properties as the corresponding elementary particle, for example exactly the same mass. However, its charges are opposite. Thus, the antiparticle of the negatively charged electron is the positively charged positron. When particle and antiparticle collide, they annihilate each other.

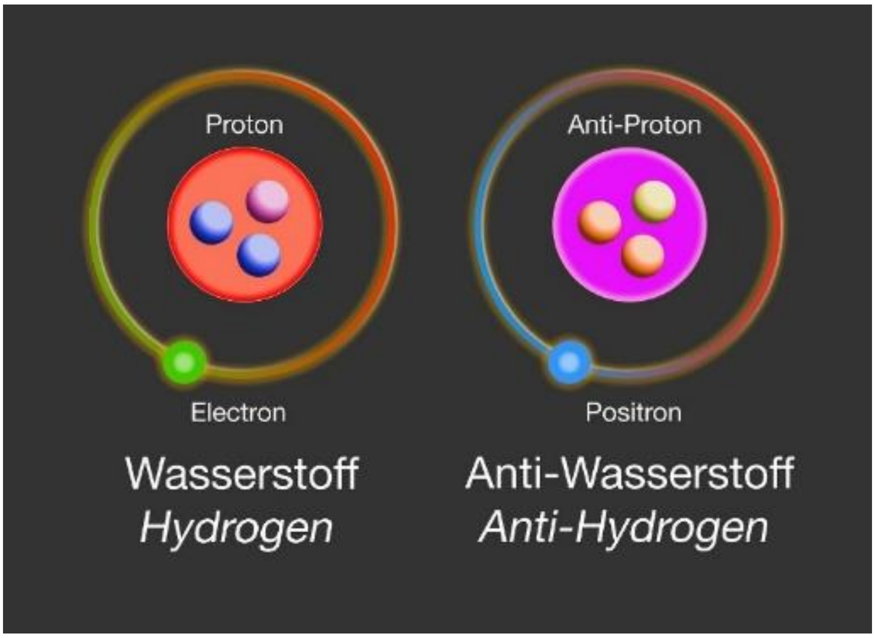


Fig. 3: Mater and Antimatter

In the early formation phase of our universe, the creation and annihilation of particles were in equilibrium. After a few seconds, however, the universe had cooled down to the point where only particle-antiparticle pairs were annihilating, but no new ones were being created. Traces of this annihilation process we still see today: the photons of the cosmic background radiation.

According to this conception, however, all created matter and antimatter should have annihilated. Now, however, the sun, the planets and everything else in the universe consist of matter. Therefore one assumes that in the early phase of the universe there were decays of particles which produced a little bit more matter than antimatter. The tiny surplus left over after the annihilation forms all the visible matter in our universe today.

What are matter particles?

Matter consists of matter particles (also called fermions). There are twelve matter particles in total, divided into six quarks and six leptons. Both groups consist of particles of three generations (Fig. 1).

The particles of different generations are similar in their properties, but they differ from each other in their mass: the matter particles of the second and third generations are heavier than those of the first family. Moreover, the matter particles of the second and third generation are unstable, that is, they decay into particles of the first family. The matter particles of the second and third generation, which existed in large quantities in the early phase of our universe, have decayed into their lighter siblings in the course of the expansion of the universe. Today, the visible matter surrounding us consists exclusively of first-generation particles.

The first generation quarks include the up quarks and down quarks. They form the neutrons and protons. Charm and strange quarks are the second generation quarks, and finally top and beauty quarks (also called bottom quarks) make up the third generation members.

Quarks have a half-integer spin. A spin describes the intrinsic angular momentum of a particle. Quarks have an electric elementary charge. This is +2/3 e for the up, charm and top quarks and - 1/3 e for the down, strange and bottom quarks. Each quark of a higher generation has a larger mass than the corresponding quark of the lower generation. However, the masses also differ strongly within the generations. Moreover, in addition to its electric charge, each quark also carries a second type of charge called color charge or color. Quarks can carry the color charges red (r), blue (b), and green (g).

The second group of fermionic elementary particles, also with half-integer spin, are the leptons, of which there are also six. They are also divided into three generations. Per generation we have here in each case a massive charged particle and its associated neutrino, which is electrically neutral and very light in the ratio.

Leptons of the first generation are the electron and the electron neutrino. The second generation is formed by the muon and the muon neutrino, and the third generation leptons represent the tau and the tau neutrino.

Second and third generation particles can be artificially created in particle accelerators such as the LHC for very short periods of time before decaying back into their lighter family members. In addition, they are often created in cosmic rays falling to Earth.

Exchange particles and fundamental forces

Interactions or forces exist between matter particles that hold matter together (Fig. 2). The interactions that prevail between matter particles are the electromagnetic force, the weak force, and the strong force. They arise because matter particles exchange tiny exchange particles called bosons. The fourth known fundamental force, gravity, plays no role in the microcosm. Therefore, scientists have some theoretical conjecture, but so far no experimental evidence of what a corresponding theory of gravity with gravitons as exchange particles might look like.

Physicists have found that all interactions are caused by the exchange of exchange particles. They have even found the reason for the existence of the interactions: the symmetries (fig. 4).

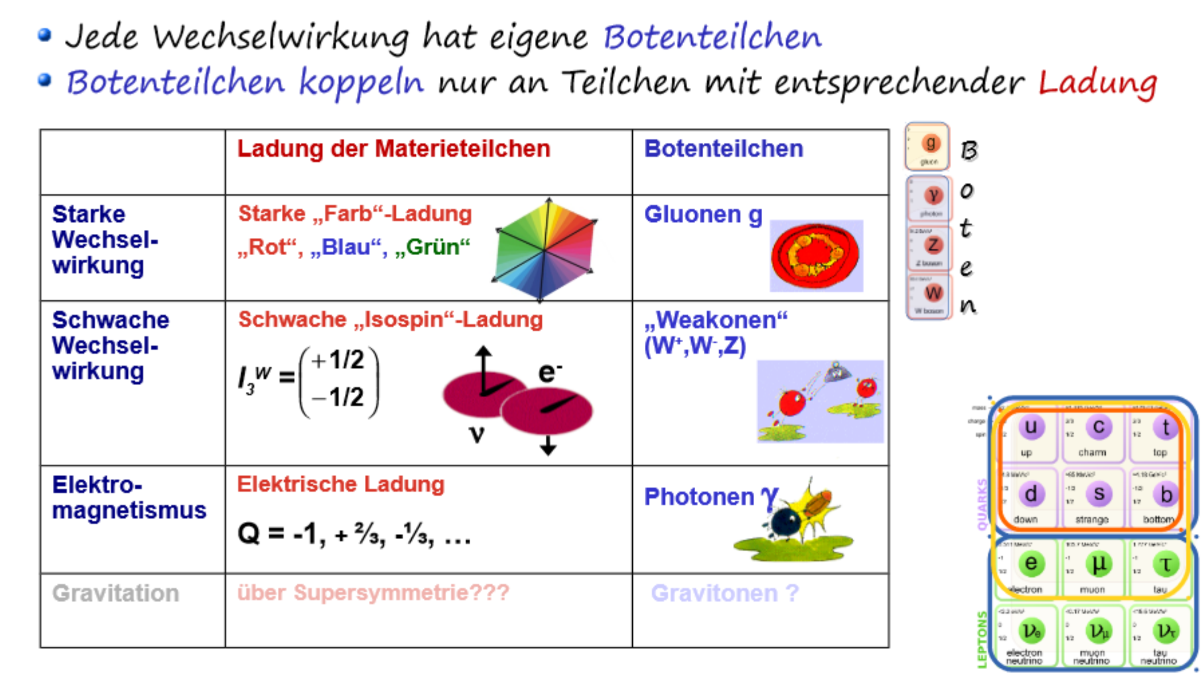


Fig. 4: Symmetries

Symmetry always prevails where one changes something, but nevertheless the appearance remains the same. The standard model is based on three symmetries, which, however, have nothing to do with the spatial form of the elementary particles, but rather with their charge properties. To each of the three symmetries belongs exactly one kind of charge: The electric charge familiar to us, a "strong color charge" of the quarks, and a "weak charge". The charge symmetries can be thought of as changes of scales. In order to achieve that with change of the scales connected with the charges nothing changes in the appearance, permanent adjustments to the new scales are necessary. This work is done by exchange particles belonging to each symmetry, which run back and forth between the matter particles and cause thereby an interaction.

The electromagnetic force originates from the exchange of photons, of which also the light consists. An electrically charged elementary particle can generate and annihilate a photon. If it interacts with another electrically charged elementary particle, it produces a photon which is exchanged with and annihilated by the other elementary particle. Thus, the photon transmits the interaction. Since the photon is massless, the electromagnetic force acts over very long ranges between charged particles.

The strong force holds the quarks inside protons and neutrons together. Here, the matter particles exchange so-called gluons, of which there are eight different ones.

The strong charge (often called the color charge) determines whether a particle is subject to the strong interaction. Quarks and antiquarks carry a color charge, as do the exchange particles of the strong interaction, the gluons.

While each particle type can only assume a certain electric charge (in the case of electrons: -1), there are quarks with three different color charges. They are called red, blue and green, and in the case of antimatter anti-red, anti-blue and anti-green (fig. 5).

Fig. 5: Quarks do not occur individually, but only in color-neutral or "white" combinations. Either a quark briefly joins together with an antiquark (left), or three quarks or three antiquarks can join together (right).

In nature, quarks do not occur individually, but only in color-neutral or "white" combinations (Fig. 5). This can happen in two ways: Either three quarks join together (red + green + blue = white) as happens, for example, with protons and neutrons. These particles are summarized under the generic term "baryons". The most important baryons are probably the proton (uud) and the neutron (udd), from which the atomic nuclei are formed and which are accordingly called nucleons. A proton consists of two up and one down quark, a neutron of one up and two down quarks.

Alternatively, a quark can pair up with an antiquark for a short time (color + matching anticolor = white). These pairs are called "mesons." An example of this are the pions, which are created, among other things, when cosmic rays hit the Earth's atmosphere. Gluons can carry eight combinations of color charges.

Six gluons have two color charges each. A quark can change its color charge by emitting a corresponding gluon. Furthermore, there are two gluons with multiple color charges. These mediate interactions between quarks in which their color charge does not change (Fig. 6).

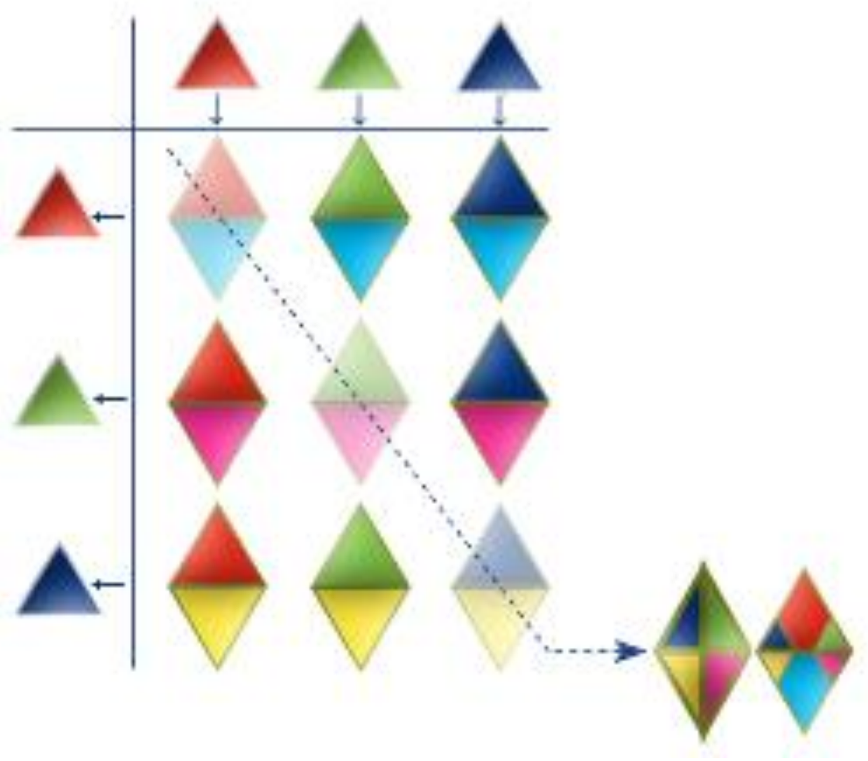


Fig. 6: Gluons carry combinations of two or more color charges. A quark with one color in the top row can transform into a quark in the left column by emitting the corresponding two-color gluon. There are only eight gluons instead of nine, because interactions without color change are mediated by two gluons carrying combinations of several color charges.

The strong interaction is the "strongest" of the interactions, as its name implies, but its effective range is limited to the nucleus of the atom.

The weak force acts on all elementary particles, including electrically uncharged ones. It is responsible for radioactive decays, for example. It takes place via the exchange of so-called Z-bosons and W-bosons. The range of the weak force is very small, because the exchange particles mediating it have very large mass. The W and Z bosons weigh almost 100 times as much as a proton.

The matter particles and the exchange particles differ from each other in one important respect: the spin or intrinsic angular momentum. Matter particles are assigned a half-integer spin, such as ½. The exchange particles have an integer spin, for example 1.

Higgs-Boson

But where the elementary particles get their mass from, could not be answered within the framework of this model for a long time.

In 1964, three independent papers appeared in the journal Physical Review Letters on a mechanism that could explain the mass of elementary particles. All three papers took different perspectives and each contributed to the overall idea. The authors were François Englert and Robert Brout, Peter Higgs, and Gerald Guralnik, Carl Hagen, and Tom Kibble.

One of them, the British physicist Peter Higgs, developed a formal mechanism by which initially massless particles become massive by interacting with a background field (the Higgs field). Originally developed in the context of solid-state physics, the same principle was applied to elementary particle physics. It is interesting to note that a property of the particles which was originally considered to be fundamental (i.e. the mass) now appears as a "side effect" of an interaction.

The Higgs mechanism describes how the fundamental property "mass" comes about at the level of elementary particles. As a central component of the standard model of elementary particle physics, the mechanism explains why certain exchange particles (the "gauge bosons" of the weak interaction) do not have zero mass. According to it, they gain their mass by interacting with the so-called Higgs field, which is ubiquitous throughout the universe. Also the masses of all other (massive) elementary particles like electrons and quarks are explained as a consequence of the interaction with the Higgs field. With this approach, it became possible to interpret the weak and electromagnetic interactions as two differently strong aspects of a single fundamental electroweak interaction, which is one of the most important steps towards the establishment of the Standard Model (Fig. 13).

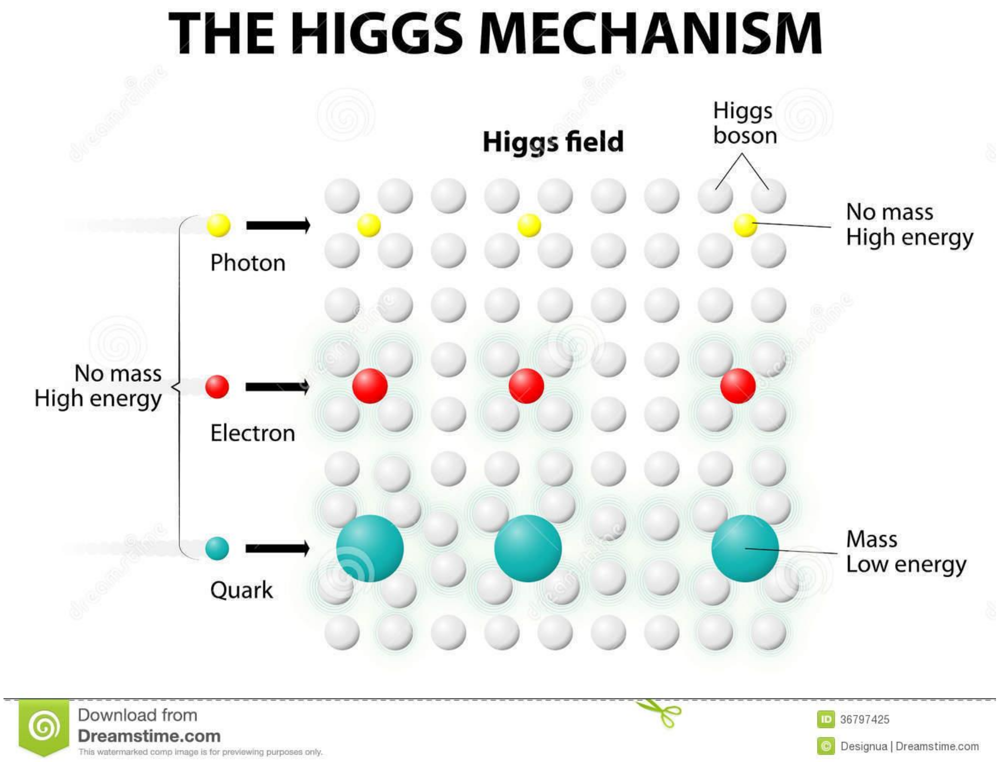


Fig. 7: Higgs-Mechanism

In the process, the theory predicted the existence of a new elementary particle. While the Higgs field is not directly measurable, its existence requires the appearance of another elementary particle, the "Higgs boson."

But whether this hypothetical particle actually existed was unclear for a long time. In July 2012, the breakthrough finally came: using the Large Hadron Collider at the CERN research center, scientists discovered an elementary particle that exhibited many of the properties of the postulated Higgs boson. After further analysis, it turned out that it was indeed the long-sought Higgs particle.

The Higgs particle has no electric charge and spin 0, so it is a boson. With the discovery of the Higgs boson, it became apparent that their purely theoretical considerations could be confirmed experimentally.

The Standard Model was essentially developed in the years 1961-1973. It has been extensively tested and researched and provides an excellent description of the building blocks of the world and their interactions. However, there are also a number of open questions that it cannot answer.

For example, it does not take gravity into account. This plays a large role on earth for us humans, but is so weak in the world of the smallest particles that it can be neglected. Up to now the interaction particle for the gravitation has not been proved yet.

Furthermore, about a quarter of the universe consists of dark matter. This matter cannot be explained by the particles of the Standard Model. Suitable candidates for particles that make up dark matter are supersymmetric particles.

Physicists all over the world continue to develop the Standard Model and extend it with suitable approaches that, for example, take gravity or supersymmetry into account, but at the same time do not fundamentally overthrow the Standard Model.

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