Particle hunters on the trail

The detection of the Higgs boson represented a huge success for the particle accelerator known as the Large Hadron Collider. But other expected or unexpected discoveries, which physicists hoped would explain the appearance of the world we live in, have failed to materialize. Now, **Hermann Nicolai,** Director at the **Max Planck Institute for Gravitational Physics** in Potsdam, and **Siegfried Bethke**, Director at the **Max Planck Institute for Physics** in Munich, are on a quest for new prospects in particle physics.

Inconceivable: this artist's impression from CERN attempts to give an idea of what the Higgs boson is all about. As significant as the particle's discovery was, it is also hard to visualize an elementary particle of this kind.

Photo: Daniel Dominguez/CERN

TEXT **ROLAND WENGENMAYR**

In 2012, the European Organization for Nuclear Research (CERN) announced a sensational discovery: the Higgs boson had been detected at the world's most powerful particle accelerator, the Large Hadron Collider (LHC). This discovery had been a long time coming and served as proof of the mechanism that gives elementary particles their mass, as had already been described in the 1960s by Peter Higgs, François Englert and Robert Brout among other researchers. Without this mechanism, neither we nor the universe we know would exist. Higgs and Englert received the 2013 Nobel Prize in Physics for their theoretical description – Brout had died two years previously. The Higgs boson also provided the final missing building block in what is known as the Standard Model of particle physics.

Since then, however, there have been no more reports from Geneva, at least when it comes to other major discoveries at the LHC. Predictions from the world of theoretical physics had raised high hopes for particle collisions in this accelerator ring, which measures just under 27 kilometers in length. These predictions related to a world of physics beyond the Standard Model and therefore touched upon literally existential relationships.

One such issue is the problem of antimatter, which should actually have been created in the same quantity as matter following the Big Bang – and the two should immediately have annihilated one another. Fortunately that wasn't the case, for a perfectly symmetrical world of that kind would have produced a universe without galaxies, stars and planets, filled only by the light echo left over from this total annihilation.

As astronomers have so far failed to find any antimatter in the universe, it is likely that a tiny, unknown structural flaw in the symmetry between antimatter and matter meant that a – not all that small – quantity of matter was left over, and it is this matter that we have to thank for our own existence. At present, the worlds of nuclear and particle physics, including at the LHC, are engaged in an intensive search for a flaw of this kind in the reflected image of antimatter.

No less mysterious – and just as significant for the universe that we call home – are the concepts of dark matter and dark energy, both of which should be illuminated by the LHC. Dark matter interacts neither with light nor with known matter but makes itself felt by its gravity. It is the only way to explain the high speeds of stars at the edges of galaxies – which indicate that there must be five times as much dark matter as there is visible matter. The gravity of visible matter alone does not generate sufficient accelerating forces. Just as hard to comprehend is the concept of dark energy, which – according to the current understanding – accelerates the expansion of the universe and makes up around three quarters of the energy within it. What this energy might be, however, remains a complete mystery.

The LHC has made almost no progress in the search for explanations for the asymmetry between matter and antimatter the nature of dark matter and dark energy. However, talk of a crisis in particle physics stems primarily from the fact that, so far, the experiments at CERN have failed to help solve another problem in physics. For many decades, clever minds have been attempting to unify the two theoretical pillars of physics, quantum mechanics and the general theory of relativity, into one overarching theory. In the process, physicists also hope to reduce the four fundamental forces that govern physical processes in our world to one common one, such as must have existed during the Big Bang according to their current theories. >

The Standard Model of particle physics and the quantum mechanics on which it is based only describe the microscopic world of elementary particles and the three forces that govern it: the strong and weak nuclear force and the electromagnetic force. Gravity, on the other hand, as the fourth force that falls within the regime of the general theory of relativity, is a huge 40 orders of magnitude weaker; this massive discrepancy is called the hierarchy problem. Gravity only takes effect over large distances and therefore dominates all of the processes taking place in the cosmos but plays no part in the microscopic world.

Both theories are extremely well supported by experimental observations in their own right. Efforts to unify them take various approaches, some of which have predicted discoveries at the LHC that have so far failed to materialize, such as micro black holes, rolled-up extra dimensions and supersymmetries.

DO PHYSICAL THEORIES HAVE TO BE NATURAL?

The existence of these phenomena was predicted by several schools of string theory – one of the areas of research seeking to establish a working description of quantum gravity. String theory states that, on the smallest scale, the world is made up of threadlike strings in which other dimensions of space-time are rolled up. According to some predictions, the extra dimensions rolled up in these space-time wraps should have been large enough to reveal themselves at the LHC. Likewise, the experiments should also have seen the emergence of supersymmetric (SUSY) particles, which belong to a supersymmetric mirror-image world and are related to the superstrings version of string theory. As these predictions turned out to be wrong, some specialists believe that the problem lies not in the experiments at the LHC, but in the theories that predicted certain measurement results.

When developing new theories, scientists are guided by criteria such as symmetry, naturalness, and the elegance of mathematical constructions. Among those questioning whether this approach has led researchers

A search engine for new particles: the CMS detector weighs 14,000 tonnes and has 75 million individual measurement channels in order to detect particles. Together with the Atlas detector, it detected the Higgs boson. It is also designed to discover SUSY particles, but none has been detected so far.

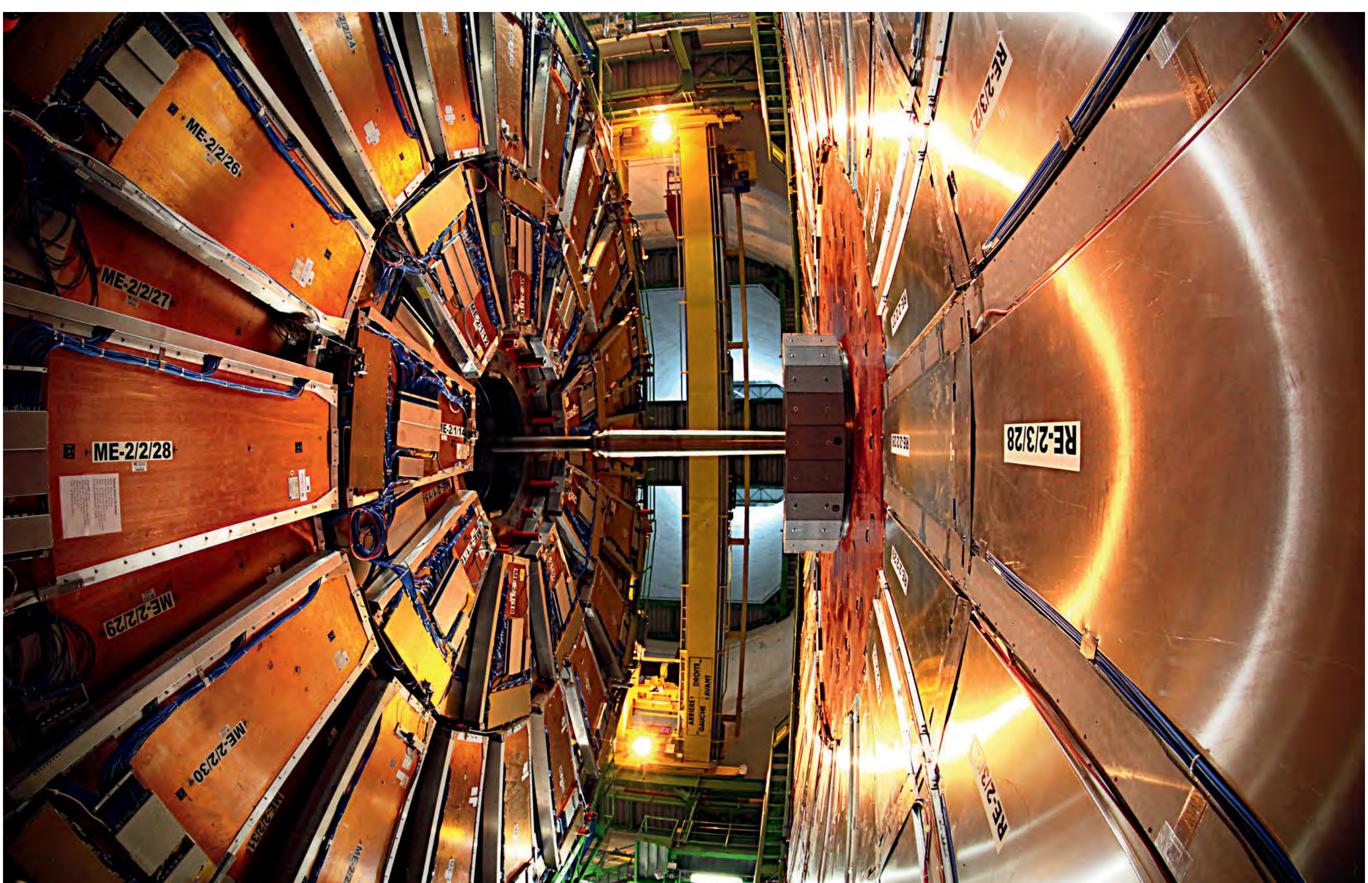


Photo: Michael Hoch/CERN

astray is Sabine Hossenfelder in her book *Das hässliche Universum* ("Lost in Math"). The scientist is currently conducting research into quantum gravity at the Frankfurt Institute for Advanced Studies.

To explain her skepticism around the concept of naturalness, for example, she begins by asking why theorists predicted the appearance of supersymmetric particles or rolled-up extra dimensions at the LHC. "People thought that the Standard Model could not be complete," says Sabine Hossenfelder. "And the reason is that the Standard Model can't be 'natural' in the sense in which the word is used by high-energy physicists."

Since the early 1990s, the idea that theories must satisfy this abstract criterion of naturalness has, in Hossenfelder's analysis, become firmly established without undergoing a proper process of reflection. In very simple terms, the condition stipulates that the masses – as well as other properties of particles – that are relevant to quantum gravity must not differ too much from one another.

A LACK OF EXPERIENCE AT THE MARGINS OF PHYSICS

For example, the physicist says, we would "consider a sunflower with a height of a million kilometers to be unnatural." However, a sunflower with a height in the order of about one meter is natural; we know this from our own experience. "In the Standard Model, all numbers are 'natural' in this sense," explains Hossenfelder, "except the mass of the Higgs boson." In the mathematical representation used by theoretical physics, it is 15 powers of ten too small and therefore unnatural for many theorists.

According to Sabine Hossenfelder, the problem with this concept of naturalness is the lack of experience when breaking new ground in physics. When we look at a field of sunflowers for the first time, experience tells us that extremely large flowers cannot exist. But at the margins of modern physics, we lack this kind of experience. According to Hossenfelder and a number of other theorists, naturalness therefore fails as an aesthetic criterion – especially as mathematics, the primary tool of theory, offers no logical justification for an aesthetic criterion of this kind.

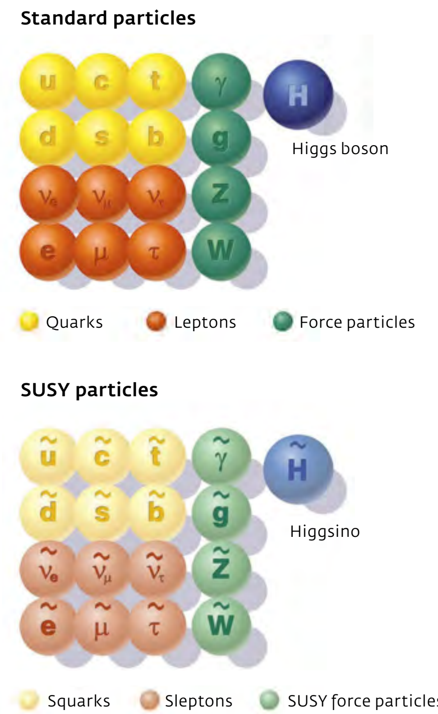
Another guiding star for researchers working on new theories is the principle of symmetry, and this approach has so far proved highly successful. In the world that is perceptible to humans, symmetries occur time and time and again, as do small deviations. For proof of this, we need look no further than the two halves of our own faces. While symmetries are thus occasionally of use also in everyday life, they play an essential role in the laws of fundamental physics. For example, symmetry considerations led the British theorist Paul Dirac to predict the existence of antimatter.

Symmetry is another criterion where Sabine Hossenfelder believes there is a risk that a concept of beauty that has become established based on positive experiences could also be misleading in fundamental physics. "Perhaps the universe is not as beautiful as particle physicists would like it to be," she says.

Hossenfelder's criticism receives mixed responses from the world of particle physics. Some find it destructive, while others react positively. Speculation about a crisis in particle physics is similarly controversial.

"In my view, there's no crisis at all – that assessment relates only to very specific theoretical approaches," says Hermann Nicolai, Director at the Max Planck Institute for Gravitational Physics in Potsdam. "On the one hand, the CERN experiment is a complete success because it once again offers excellent proof of the Standard Model. On the other, the precise point of these experiments is to eliminate incorrect models from the proliferation of theoretical ideas, and that is something that the LHC has also achieved."

Nicolai has never believed in SUSY particles himself, although he is very familiar with the history of supersymmetry's development. He obtained his doctorate under Julius Wess, one of the pioneers in this field of research.



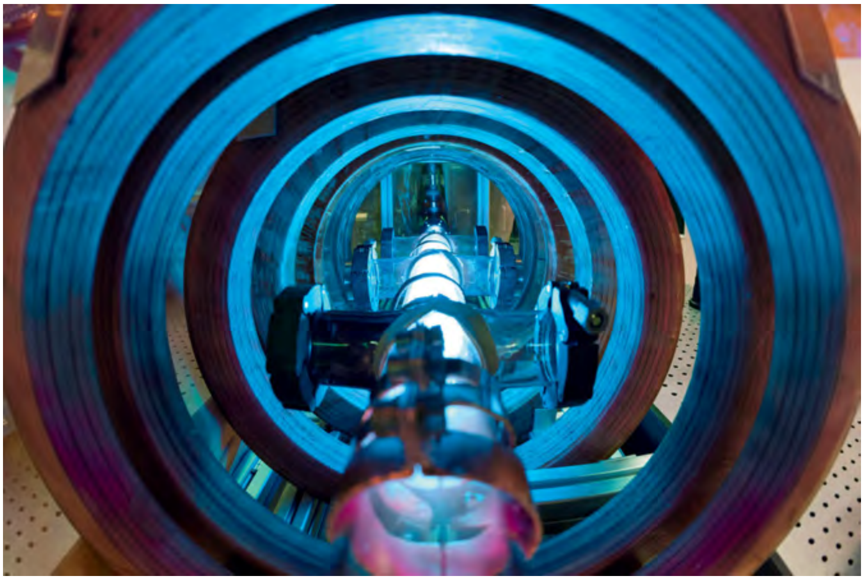
Illusory symmetry: according to some theories, SUSY particles were expected to join the collection of standard elementary particles. As they have not yet been detected in experiments, an increasing number of physicists believe they are an illusion.

Hermann Nicolai explains that the main motivation for supersymmetry was originally that it would combine internal symmetries of particle physics with symmetries of space-time. This was seen as a step towards unifying the general theory of relativity with quantum mechanics in order to derive a description of quantum gravity.

"However, these newer supersymmetric models that predicted the discovery of SUSY particles at the LHC do not realize the original goal of merging space-time and internal symmetries," says Nicolai. It quickly became clear, he explains, that a naive application of supersymmetry would conflict with observations.

"It was not until the start of the 1980s that people came up with the idea that supersymmetry could solve the hierarchy problem," says Nicolai. In other words, this theoretical construct was expected to close the explanatory gap arising from, among other things, the huge difference between the strengths of gravity and the other three fundamental forces. "But the price was high,"

Graphic: DESY



Scenario for future collision experiments: accelerators in which particles ride on a plasma wave, as seen here at CERN, could achieve far higher energies than conventional devices of the same size. This will likely pave the way for new insights into physics.

he says, because this most simple version of supersymmetry requires every elementary particle in the Standard Model to have a supersymmetric partner with almost identical properties.

"If this idea had been correct, then signs of it should already have been visible at the LEP accelerator," says the Max Planck researcher. The Large Electron-Positron Collider (LEP) was the forerunner to the LHC in the ring-shaped tunnel in Geneva. "The plain and simple truth is probably that there isn't much more to it than the Standard Model."

However, Nicolai emphasizes that supersymmetry and the approaches that go beyond it are by no means at an end, even if there may not be any SUSY particles. In general, Hermann Nicolai remains convinced that the principles of symmetry will be a key factor when it comes to developing a theory of quantum gravity and unifying it with the Standard Model, but that the current situation goes to show that "nature is far more subtle than many prominent colleagues imagined." And the researcher emphasizes: "I therefore see the LHC results above all as a great challenge for the world of theory: namely, to derive the Standard Model – just as it is – from a more fundamental approach."

Whether or not the theory of particle physics is in crisis is clearly a question of perspective. Some schools of thought have indeed seen decades of work reduced to rubble, while others are unaffected. But what do experimental physicists, who are responsible for testing the predictions derived from theory, make of the situation? One such experimenter is Siegfried Bethke, Director at the Max Planck Institute for Physics in Munich.

HOPING FOR A POINTER IN THE DIRECTION OF DARK MATTER

From the Max Planck side, Bethke and his group substantially contributed to design and build the Atlas detector, one of the two major experiments that detected the Higgs boson at the LHC. As the German scientific delegate on the CERN Council, he currently participates in the Update of the European Strategy for Particle Physics.

"Particle physics is not in crisis – although it's not easy to plan for the future right now," Siegfried Bethke says, adding that despite the lack of projects coming from the world of theory, there is still plenty for experimental physicists to do. Above all, many properties of the Higgs boson are still unknown – and as it is a key particle in the Standard Model, particle physicists want to take precise measurements of it. Moreover, they hope that the analysis of the Higgs boson will point them in the right direction in terms of where and how to continue their search for dark matter. After all, dark matter currently only makes itself felt by its gravity, which is connected with the Higgs boson.

However, the LHC is not all that well suited to precise analyses of the Higgs boson, for it generates it too rarely. The LHC was merely the search engine, so to speak, for finding the particle in the first place. The world of particle physics is therefore discussing smaller, more-specialized accelerators that produce the Higgs boson at higher rates so that it can be analyzed efficiently. The International Linear Collider (ILC), which has been planned in Japan for a number of years, is intended to be one such "Higgs factory," but it remains to be seen whether the project will actually be put into practice.

The ILC would also be a conventional accelerator from a technical perspective. Siegfried Bethke is advocating an unconventional alternative, known as CLIC (Compact LInear Collider), that is currently being developed at CERN. Although CLIC would require the construction of a new, straight tunnel in Geneva, it could achieve a higher energy than the ILC and would therefore also allow researchers to study the top quark. This was discovered in 1995, based on the latest successful prediction of a new particle originally made in 1977. The top quark is as heavy as an atom of gold, existed only briefly after the Big Bang, and can now be created in a particle accelerator.

Apparently, CLIC would therefore offer profound insights into the physics of the hot and compact baby universe. And, in the more distant future, it may be possible for the CLIC tunnel to incorporate revolutionary accelerator technology, known as AWAKE, that is currently being researched at CERN. This could achieve significantly higher energies and therefore cast light on even smaller structures in the world of elementary particles.

Whether or not these accelerators will open the door to a new world of physics is impossible to predict – as is so often the case in basic research. But it is rarely possible to plan major discoveries in physics. It's a bit like Christopher Columbus, who went looking for a sea passage to India, was almost defeated by a mutiny on the way, and ultimately discovered America. ◄

Photo: Julien Marius Ordan/CERN

SUMMARY

- **The experiments at the Large Hadron Collider led to the detection of the Higgs boson, but other predicted discoveries, such as supersymmetric particles, have failed to materialize.**
- **As some of the predictions of theoretical particle physics were not borne out, a number of theorists are calling on researchers to abandon their insistence on the existing guidelines for developing theories. They cast doubt on criteria such as naturalness, the elegance of mathematical constructions, and symmetry.**
- **However, many theorists – including the Max Planck researcher Hermann Nicolai – see symmetry in particular as being an important guideline for the development of new theories. Above all, this includes the search for a theory that merges the general theory of relativity and quantum mechanics to produce a description of quantum gravity.**
- **Despite this theoretical reorientation, experimental particle physicists see an opportunity to answer numerous research questions with the help of particle accelerators. For example, they want to take precise measurements of the properties of the Higgs boson, which they hope will provide clues about dark matter.**

GLOSSARY

Hierarchy problem is the term used by physicists for the extremely large difference in the strength of the strong and weak nuclear force and the electromagnetic force, on the one hand, and gravity, which is much weaker, on the other. This also applies to the step down from the elementary particles to the extremely small "Planck scale," which constitutes a fundamental frame of reference in physics. On this scale, it may be possible to unify the four fundamental forces.

Naturalness has, until now, served as a guideline for theoretical particle physics during the development of new theories. Critics consider this to be a flawed approach.

Standard Model of particle physics: This describes processes in the microscopic world and includes the elementary particles that make up matter and the forces acting between those particles, as well as the Higgs mechanism and the corresponding Higgs boson. This Standard Model follows the laws of quantum mechanics.

Symmetry plays a considerable role in physics. One example are the properties of antimatter, which are a mirror image of those of normal matter. This is how the British theorist Paul Dirac predicted their existence. Theoretical physics, however, also uses a multitude of abstract, mathematical symmetries.