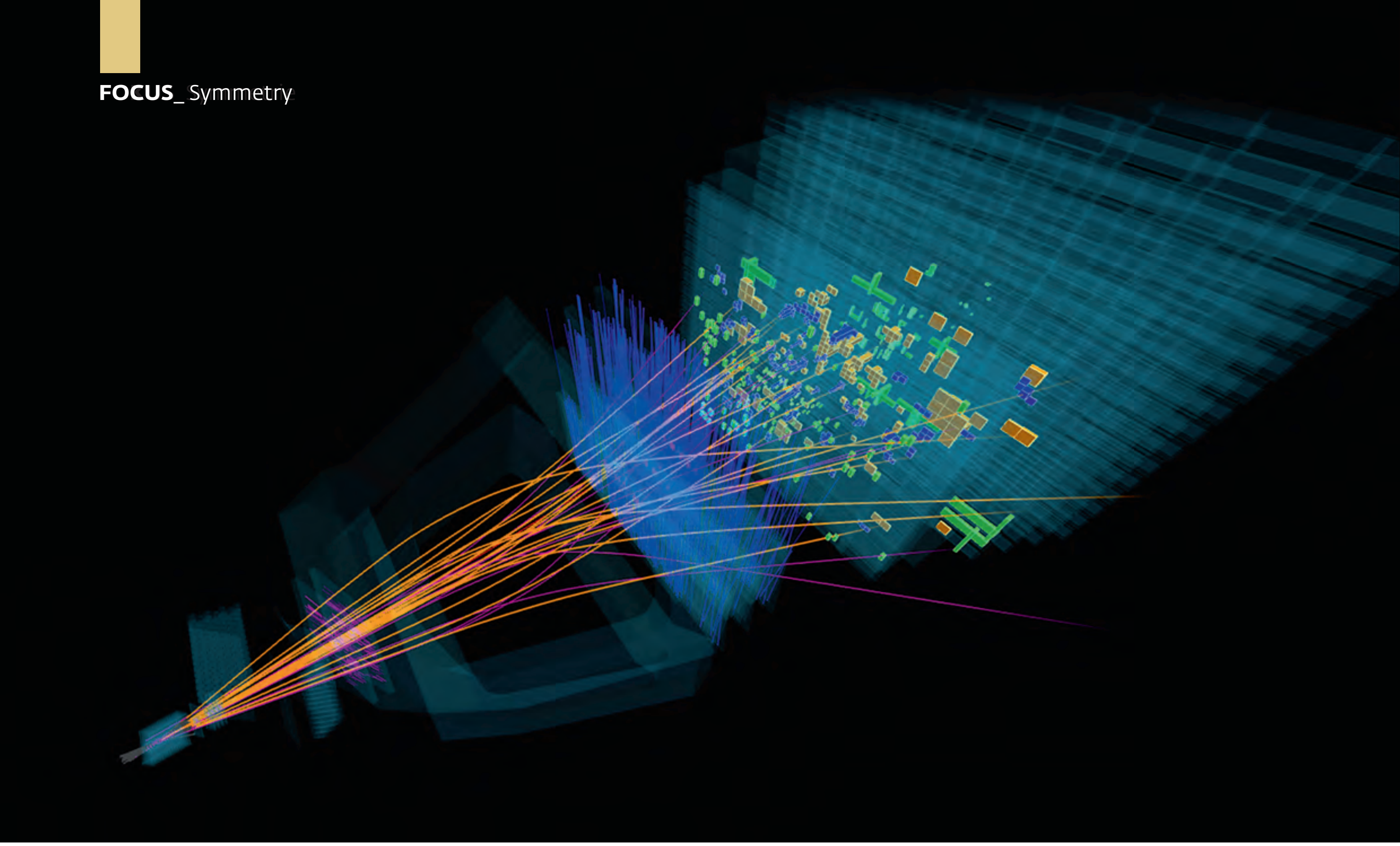
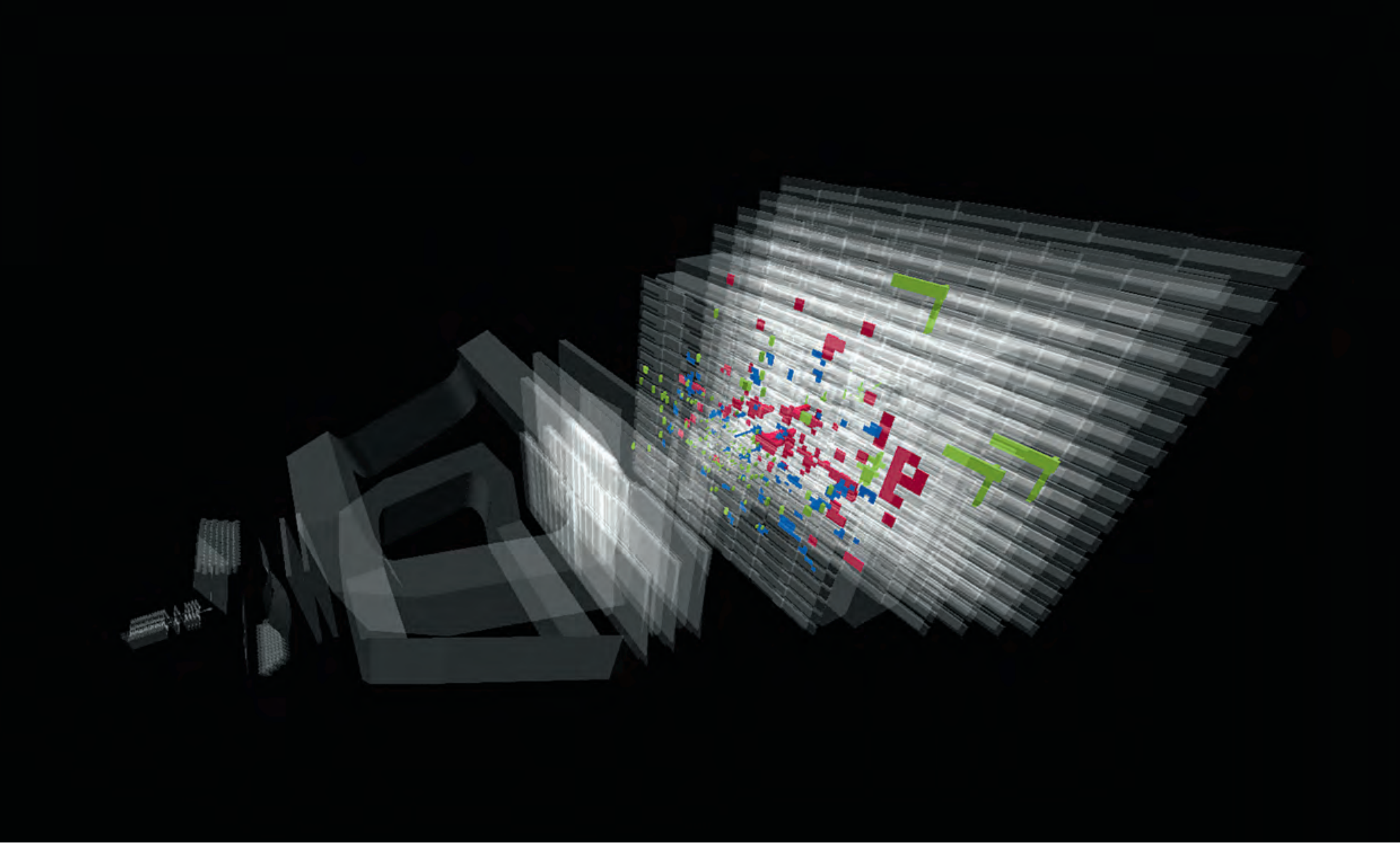


Matter Undergoes **the Vampire Test**

It was nothing more than a tiny asymmetry between matter and its mirror image, antimatter, that led to an excess of matter in the universe. We owe our existence to this asymmetry. Research groups at **Max Planck Institutes** in **Heidelberg, Munich** and **Garching** are pursuing different routes to find out why matter, like vampires, has lost its mirror image.

TEXT **THOMAS BÜHRKE**

Graphic: CERN



Searching for the asymmetry between matter and antimatter: Physicists at the LHC analyze the decay products of particles, which leave signals behind in the different detector layers; these signals are shown here as colored rectangular blocks.

Graphic: CERN

Down the centuries, philosophers have been haunted by the conundrum of why matter exists in the universe. Gottfried Wilhelm Leibniz put it in a nutshell: "Why is there something rather than nothing?" The problem is not only a philosophical one, but also a physical one, which is why physicists have spent decades searching for a solution to this mystery. As in many areas of physics, symmetries play a crucial role.

It's been 100 years since mathematician Emmy Noether noticed the fundamental connections that exist between geometrical symmetries in space and time, and the laws of conservation in physics. The law of energy conservation, for example, follows from these symmetries: in a closed system, energy can neither be created nor destroyed. A perpetual motion machine is therefore impossible. The conservation of the total momentum, for example when two spheres collide, can be explained similarly on the basis of symmetry.

Over the last few decades, however, physicists have realized that it is not only symmetries that are important: "We know these already – the big mystery is the asymmetries," says Michael Schmelling, from the Max Planck Institute for Nuclear Physics, who is involved in one of the major experiments at the LHC particle accelerator at CERN in Geneva. In fact, if the construction kit of elementary particles had a completely symmetric structure, there would be no matter in the universe, and therefore neither Earth nor us humans.

ONE ANTIPARTICLE FOR EACH ELEMENTARY PARTICLE

The reason why perfect symmetry would have made the existence of matter impossible lies in the events during the Big Bang: according to our current thinking, the universe was filled with radiation and matter of inconceivably high temperature and density during the first billionth of a second. It was a seething mixture of particles that converted into radiation and back into matter.

Physicists know, however, that antiparticles are created in the same amount as particles in such an environment. This piece of knowledge, too, is already several decades old: for each type of elementary particle, there is a corresponding antiparticle that differs only in the sign of the electric charge, but has precisely identical properties otherwise. The antiproton, for example, looks like an ordinary proton, but has an opposite (negative) charge.

Although there is no doubt that antiparticles were created in the beginning, they are practically non-existent in the universe. This is because the two unequal partners have the fatal characteristic that they annihilate each other in a flash of radiation when they meet. For the Big Bang, this means that if perfect symmetry had existed at the time, there would have been just as many particles as antiparticles created in the sea of radiation – and they would all have mutually annihilated each other. The universe would then consist solely of radiation. So where does matter come from? >

Collisions under surveillance: Dmitry Popov (front), Michael Schmelling and Burkhard Schmidt (from left) watch the raw data being processed in the control room of the LHCb experiment.

In order for any matter to survive after the Big Bang, there must have been a tiny imbalance: only a very small number of particles remained each time when approximately one billion matter-antimatter pairs were annihilated. This difference appears to be very minute, but we owe our existence to it. The physicists have only a vague idea of how this asymmetry came about: "It can possibly be thought of as a phase transition, like water turning into ice upon freezing," explains Schmelling. "The asymmetry was frozen in, so to speak, firmly cementing the dominance of matter in the universe."

This theory goes back to Russian physicist and Nobel Peace Prize laureate Andrei Sakharov. When he published it in 1967, he based the theory on an experiment that had shaken physicists' belief in nature's symmetries to the very core three years earlier. James Cronin and Val Fitch had investigated the decay of so-called K mesons in an accelerator at Brookhaven National Laboratory. These particles consist of two quarks, which are elementary particles, and they are unstable. Fractions of a second after being created they decay into other particles.

THE STANDARD MODEL IS FLEXIBLE TO A CERTAIN EXTENT

Cronin and Fitch investigated the decays of K mesons and compared them with those of anti-K mesons. When they found a tiny difference between the two decay modes on the order of one tenth of a percent, it was an absolute shock for the physics community. In this case, the perfect symmetry between matter and antimatter was violated, as physicists say.

But they were unable to explain the excess of matter in the Big Bang in this way; the asymmetry measured was much too small – it would have to be a billion times bigger. Theoreticians Toshihide Masukawa and Makoto Kobayashi incorporated this asymmetry into the Standard Model of particle physics and were awarded the Nobel Prize in Physics for their work in 2008. Cronin and Fitch had already been honored with this distinction in 1980.

The Standard Model is like a construction kit that contains all known elementary particles and the forces acting between them. This model works wonderfully, but is flexible to a certain extent. Although it specifies the number and type of the particles, it can't predict certain physical quantities, which must be taken from measurements. These include the masses, for example, which then have to be incorporated into the model.

An asymmetry like that observed in the neutral K-meson system can still be accommodated without the building collapsing. However, there are expected to be limits, and these have to be explored experimentally and theoretically. It only becomes really exciting when researchers discover asymmetries that break the bounds of the Standard Model: such discrepancies may explain the existence of matter, but they would force the physics community to abandon the old model and extend existing theory to encompass new physics, so to speak.

The researchers are therefore continuing their search for these deviations from perfect symmetry. More recently, this search has concentrated on a different species of meson: the B mesons, which exist in different variants. Today, the ideal instrument for studying these is the CERN Large Hadron Collider (LHC), in which protons circle in opposite directions and collide with extremely high energy. Many different particles form in the ensuing fireballs, including B mesons and their anti-partners, whose decay particles are analyzed with the LHCb detector.

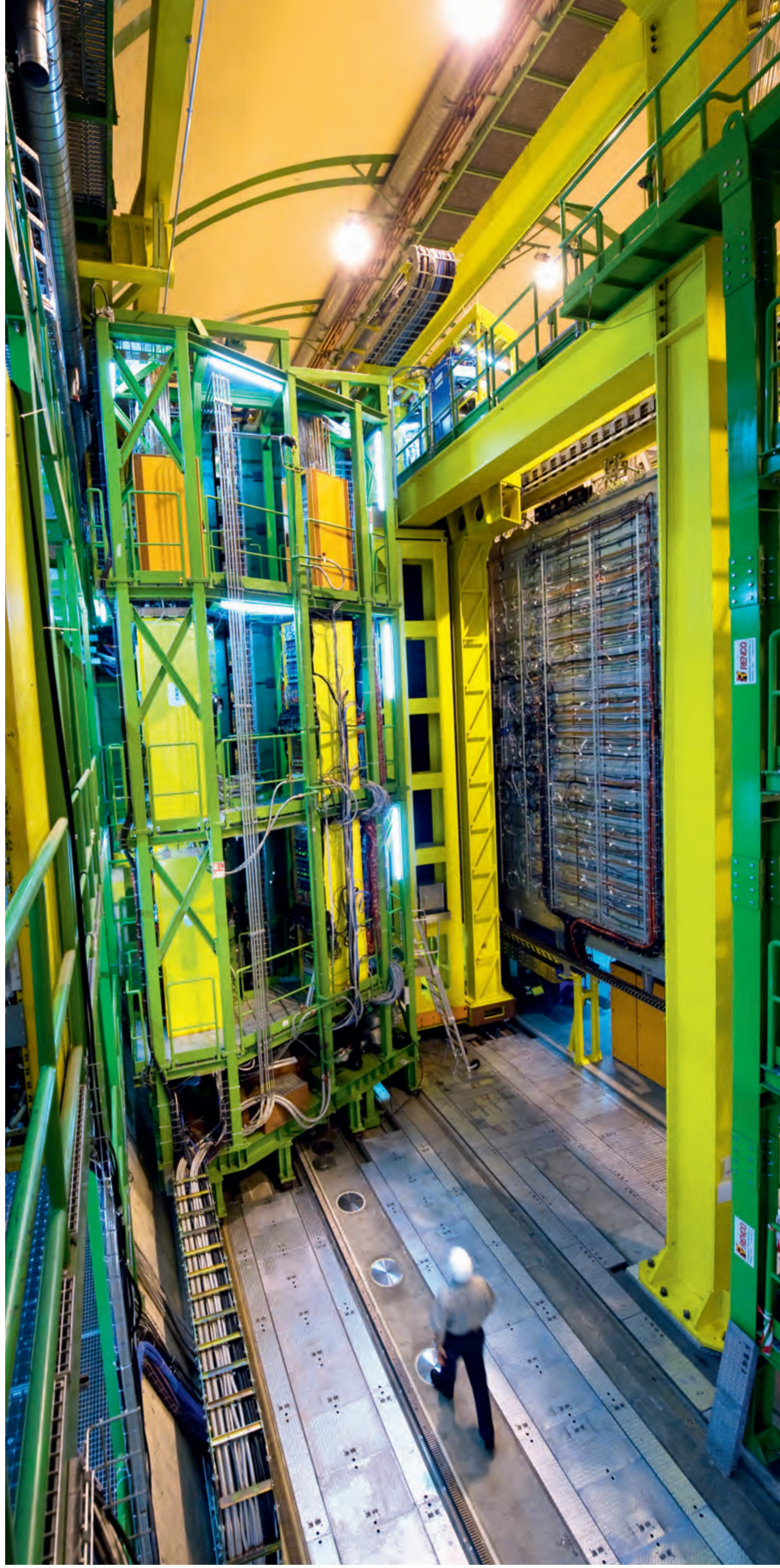
Schmelling's group made crucial contributions to the development and construction of the silicon detector for this device, which is the size of a three-story house. The silicon detector alone covers an area of around 11 square meters and can detect the passage of a charged particle with an accuracy of 0.05 millimeters – approximately the thickness of a human hair.

After physicists in the US and Japan had already discovered an asymmetry of 8 percent for B0 mesons, the LHCb collaboration concentrated on the B0s, the brother meson, which can be produced in large numbers in the LHC. The surprise came three years ago: the researchers had found an asymmetry of unprecedented magnitude – 27 percent – when comparing the decays of B0s mesons and their anti-mesons. Were they finally hot on the trail of something that would lead them to the cause of the mysterious preference for matter during the Big Bang?

Unfortunately not – even this very strong asymmetry can probably still be explained as part of the Standard Model, as the theoreticians quickly announced. Only a value that does not fit in there could be an indication of a physics beyond the Standard Model, one that could make the excess of matter understandable. Scientists at the LHC are currently searching diligently for it, but so far without success.

The stream of data from the LHC is still a long way from being completely evaluated, however, and the search for a symmetry violation continues in the decays of other species of mesons. But Michael Schmelling wants to look for another effect that would shake the foundations of today's physics: the fact that the characteristics of a meson decay, such as the life of the particles, depend on spatial orientation – in other words, on the orientation of the experimental arrangement with respect to the fixed stars.

An abundance of experiments have confirmed to this day that space is isotropic – that is, it has no direction that



An experiment as high as a house:
The physicists were able to walk through the 21-meter-long, 10-meter-high and 5,600-ton LHCb detector while it was being set up.

Photo: CERN

Christian Kiesling (right) and his colleagues assess the progress as the Belle-II detector at SuperKekB is being set up. Kiesling points to an opening that will house the vertex detector, whose task is to determine the exact position of the decay. The heart of this instrument is the dual-layer pixel detector (top left), inside which the decays take place. It is composed of modules whose image sensors each comprise 200,000 pixels (bottom left).

is somehow preferred. Physically, the direction in which a light beam is sent in free space is irrelevant; it will always propagate in the same way and with the same speed. The most precise experiments confirm this to an accuracy of 15 decimal places. But what about the decay properties of particles and antiparticles?

In order to approach this question, one has to consider the interparticle forces contained in the Standard Model construction kit. In the case of light, only the electromagnetic force is of any consequence. When particles decay, the so-called weak force, which acts only within the atomic nucleus, comes into play. It is theoretically conceivable that this weak force interacts with an unknown, hypothetical energy field that permeates space. This idea is not without reason. In 1998, cosmologists discovered that such an energy field does indeed exist in the universe: dark energy. It acts like pressure in a boiler, driving the universe apart and accelerating the expansion.

Analogously, one can therefore also imagine a direction-dependent background field that affects the weak force, but not the electromagnetic one. It would then be possible for the characteristics of a particle decay to depend on the direction in which one was moving relative to this background field – just like the speed of a ship depends on whether it is moving with or against the current. This is all hypothetical, says Schmelling, “but we want to check it out.”

SEARCHING FOR VARIATIONS OVER ONE DAY

The task now is to compare the decays and other properties of particles and antiparticles relative to the hypothetical energy field, so depending on the orientation of the experimental setup with respect to the fixed stars. “If a dependence on orientation exists, we ought to see variations with a period of one day, because our orientation toward the fixed stars is different at night than during the day,” says Schmelling. The data has already been collected, and the LHC will provide more in the future.

The experiment at the LHC, which is tracking down the asymmetry between matter and antimatter, is to be additionally supplemented by a further accelerator experiment. If everything goes according to plan, it will start in two years: after an eight-year upgrade phase, the SuperKekB accelerator at the Tsukuba research center in Japan is to run at full speed. In two separate rings each measuring three kilometers in circumference, electrons and antielectrons (positrons) circle in opposite directions and collide at a single location.

Although SuperKekB is smaller than the LHC and doesn’t accelerate the particles to anywhere near the energies achieved there, it is set up such that many more pairs of B mesons and their antiparticles are created during collisions than is the case at the LHC – and immediately decay again. Physicists therefore like to call it the B factory. In this installation, the background from other particles is significantly weaker, making data analysis easier than at the LHC. In addition, this installation allows researchers to study the B meson decay modes, which remain fundamentally hidden to the LHC.

Starting at the end of 2018, the super-factory is expected to produce up to 40 times as many B mesons per unit of time as its predecessor – which already held the world record until it was taken out of service in 2010. In order to be able to precisely analyze the decay products of the particles, the previous detector, called Belle, which detects the particles produced in the meson decay, had to undergo significant technical improvements.

Photos: MPI for Physics (top and right), L. Andricek/HLL@MPG (bottom left)

The central element of Belle II is a vertex detector that can determine the direction of flight and the place of origin – the vertex – of a particle to within one-hundredth of a millimeter. The heart of this instrument is a pixel vertex detector that in turn consists of 40 image sensors. One of these sensors comprises 200,000 individual pixels.

If a particle impinges on such a pixel, a tiny signal is generated and amplified in the pixel itself. "Measuring a mere 50 by 60 micrometers, the pixels are small marvels in themselves," says Christian Kiesling, the spokesperson of the international detector collaboration and a researcher at the Max Planck Institute for Physics in Munich. The pixel vertex detector was designed and built here and at the Munich-based semiconductor laboratory of the Max Planck Society. "Developing this detector, which is the only one of its kind in the world, cost us a lot of blood, sweat and tears," says the scientist.

At the SuperKekB, the researchers want to use Belle II primarily to study also those decay modes of B mesons that are extremely rare, because theoreticians provide very accurate predictions for these particles In other words, the Standard Model is not as flexible here, and can best be checked experimentally. A further part of the program is to investigate other unstable particles as well – always in the hope of finding an asymmetry between particle and corresponding antiparticle somewhere that can explain the excess of matter in the world.

Whether at the LHC or SuperKekB, the decay experiments take place at incredibly high energies. However, the search for the asymmetry between matter and antimatter can take other paths, too. The alternative consists simply in comparing the properties of elementary particles and their antiparticles as accurately as possible. They should be identical, apart from the sign. Any difference, however small, would contradict today's physics. Even the flexible Standard Model doesn't leave any room for maneuver here.

A POSSIBLE ASYMMETRY IN THE MAGNETIC MOMENT

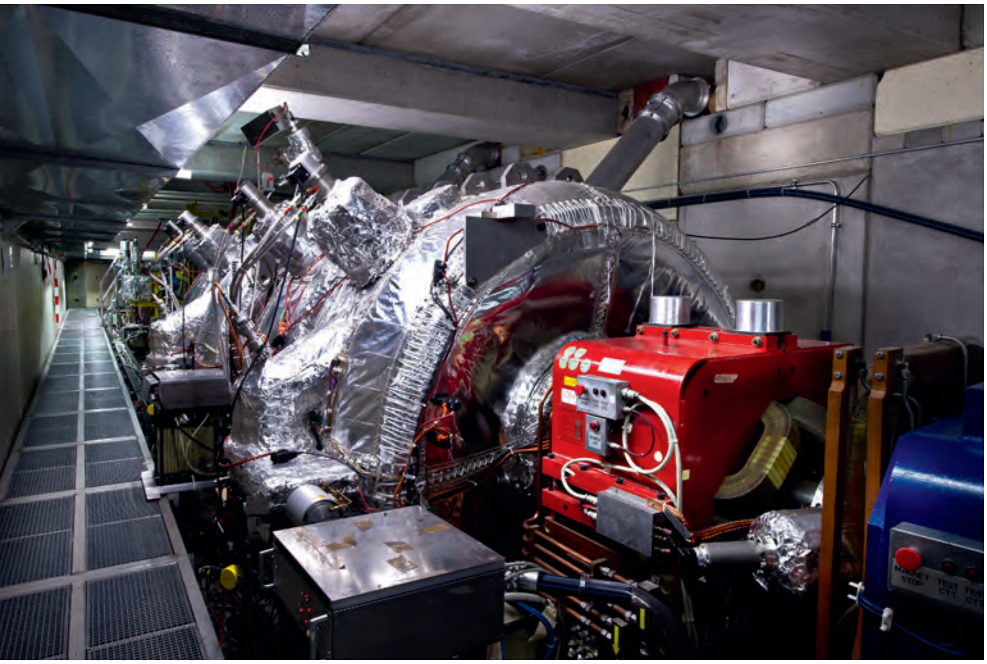
One group working with Klaus Blaum, Director at the Max Planck Institute for Nuclear Physics, is investigating the properties of protons, the nuclei of hydrogen atoms, and antiprotons. Thus far, the researchers have achieved the most accurate results for the comparison of the charge-to-mass ratio of the two particles. This combination is experimentally easier to measure than the individual quantities.

The procedure begins by transferring one proton or antiproton into a vacuum vessel where an electric field and a magnetic field trap and store it. The particle then executes a circular motion around the axis of the magnetic field; this orbiting can be measured very accurately and provides the sought-after quantity (MaxPlanckResearch 4/2010, page 46 ff.). "This experiment is very delicate and requires a great deal of experience, because we are working with only a single proton or antiproton," says Klaus Blaum. In mid-2015, the BASE collaboration, headed by Blaum's former colleague Stefan Ulmer, published the world's most accurate result to date in the journal Nature. The result shows that the charge-to-mass ratios of the two particles agree to within less than one part in a billion.

The researchers are now using this experimental experience to compare a further characteristic property of protons and antiprotons: the magnetic moment. This can be roughly thought of as the strength of the magnetic field generated by a single proton. The value is extremely small and more difficult to measure than the charge-to-mass ratio. According to theoretical predictions, however, it could be a prime contender for an asymmetry between matter and antimatter. The year before last, an international collaboration involving the group from Heidelberg, as well as the University of Mainz, GSI in Darmstadt and the RIKEN research institution in Japan, among others, successfully determined the magnetic moment of the proton to within three parts per billion – a world record! >

Researchers in Klaus Blaum's group use a Penning trap to capture charged particles, such as protons and antiprotons. Ring-shaped electrodes generate the electric fields to trap the ions.

Graphic: BASE, CERN



A storage device for antimatter: A decelerator at CERN slows down antiprotons, which are subsequently used in further experiments.

Photo: CERN

The researchers next plan to carry out the corresponding measurement on the antiproton. To do this, the physicists will have to take their apparatus to CERN, where a small accelerator, the Antiproton Decelerator, supplies the cold antiprotons. “We want to measure the magnetic moment of a single antiproton there and improve the accuracy ten- to a hundred-fold by the end of 2018,” explains Blaum. This is a race against time because, in September 2018, the LHC will be switched off for a protracted maintenance break, at which time antiproton production will come to a standstill as well.

Experimenting with antihydrogen – atoms that consist of one antiproton and one antielectron (positron) – is even more demanding. CERN is currently the only place in the world where these experiments are possible. The first tricky problem consists in bringing antiprotons and positrons together and cooling them to such an extent that they combine to form anti-atoms. The second problem occurs at precisely that moment: in contrast to their two components, the anti-atoms are electrically neutral and not so easy to trap and store.

But why go to all this trouble with atoms when investigations on elementary particles such as protons and their counterparts from the anti-world are easier? One reason is, again, the accuracy that is possible with measurements on atoms. Hardly any quantum-physical value has been measured so accurately as one particular transition of the electron in the hydrogen atom. Physicists use the term transition to describe the lifting of an electron into a higher energy state or its falling back into a lower energy state.

DOES THE ANTI-APPLE FALL UP?

The fact that the energy exchanged during the transition can be measured so accurately owes to Theodor W. Hänsch, Director at the Max Planck Institute of Quantum Optics in Garching, who developed the so-called frequency comb, for which he was awarded the Nobel Prize in Physics in 2005. This technology enables the frequency of the hydrogen transition to be measured with a spectrometer to an accuracy of 14 decimal places, so if one aims to find minimal differences between matter and antimatter, this technique is the most accurate. Masaki Hori’s group at the Max Planck Institute in Garching has been working on this feat since 2008 as part of the international ATRAP collaboration.

But it is also possible to measure a second property on the antihydrogen, one that could disclose a difference between matter and antimatter: free fall under the effect of gravity alone, which can be demonstrated only on electrically neutral particles. Alban Kellerbauer and his colleagues are working on such experiments at the Max Planck Institute for Nuclear Physics.

Their work is based on the somewhat exaggerated question: Does the anti-apple fall up? It doesn’t have to be quite that blatant – even the tiniest difference between matter and antimatter in free fall would be an assault on the very foundations of physics, especially on Einstein’s general theory of relativity. This assumes that all bodies fall with equal speed in the gravitational field regardless of their composition, shape or mass.

Since 2010, Kellerbauer’s team, together with colleagues from the international AEGIS collaboration, has been developing an apparatus at CERN to investigate the free fall of antihydrogen. Like their colleagues in the ATRAP collaboration, they must first produce its atoms from one antiproton and one positron, each of which is produced separately. The whole atoms now fly through a horizontal tube about one meter in length before they impinge on the detector.

If the anti-atoms behave like normal atoms, gravity will cause them to sink around ten micrometers (one millionth of a meter) over a distance of one meter. In order to check this, the physicists need a detector with very high spatial resolution. “It may sound antiquated, but our best experience has been with a photo emulsion,” says Alban Kellerbauer: “This enables us to determine the impact location to within 60 nanometers.”

Experimenting with antiparticles is very difficult because they prefer to unite with their matter partners in a flash of light, and these partners are found all around them in this world. The AEGIS group wants to prevent this self-destructive partner selection, of course. Although this is not easy experimentally, the researchers are doing all they can to complete their first measurements before the LHC is switched off in fall 2018. “By then, we hope to have achieved an accuracy of 30 percent,” says Kellerbauer.

In principle, this will initially provide an answer only to the question of whether antimatter falls up or not. It would be incredible if it really were to take the opposite route of matter in the gravitational field. That would turn physics on its head and manifest a fundamental inequality between matter and antimatter in which only the most daring researchers would currently like to believe. It’s more likely that the difference between matter and antimatter is significantly more subtle. And it looks like the researchers will need to exercise patience for a while longer, regardless of which path they are pursuing in their search for this difference. ◂

TO THE POINT

- **Matter and antimatter formed in the Big Bang. An asymmetry between them meant that a small quantity of matter remained, but no antimatter. The excess cannot be explained as part of the Standard Model of particle physics.**
- **Physicists are searching for the asymmetry in different ways. At the LHC and SuperKekB particle accelerators, for example, they are analyzing the decays of short-lived B mesons, which consist of one quark and one antiquark. They are also comparing the physical properties of particles and antiparticles, such as their behavior in the gravitational field.**
- **The previously observed asymmetries during the decays of mesons can still be reconciled with the Standard Model and therefore can’t explain the excess of matter.**

GLOSSARY

Mesons themselves are not elementary particles, as they consist of one quark and one antiquark. More than 100 types of mesons are currently known; they differ in the quarks that are paired in them.

Standard Model of particle physics: This theory describes all elementary particles and the interaction between them with the exception of gravity. The excess of matter in the universe cannot be explained with the Standard Model, as this excess is based on an asymmetry between matter and antimatter that is incompatible with the Standard Model.