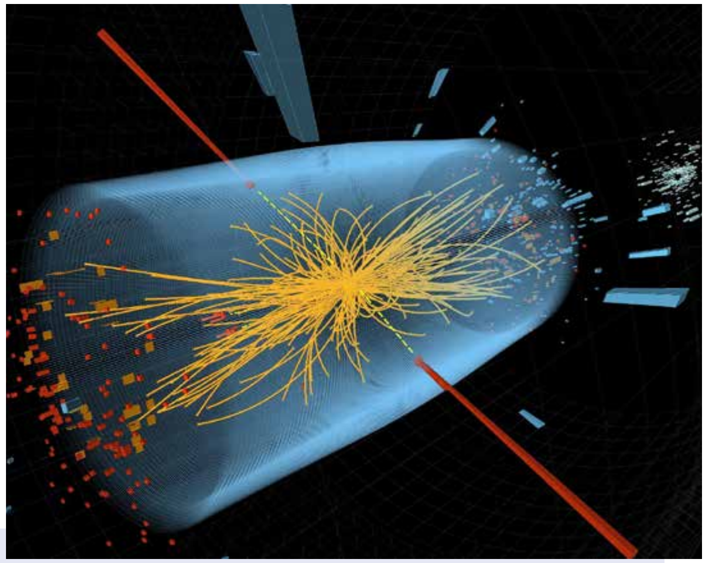
No experiment without theory (and vice versa)

A dusty room with a well-stocked bookcase, a chalkboard, and a coffee maker. The stereotypical working environment of theoretical physicists contrasts sharply with that of their experimental colleagues, who work with huge, billion-dollar machines. Yet one cannot succeed without the other. A look at five major experiments, through a theoretical lens.

Text: Dennis Vaendel



A particle collision in CERN's Large Hadron Collider, as observed in the CMS experiment.
CERN

CERN

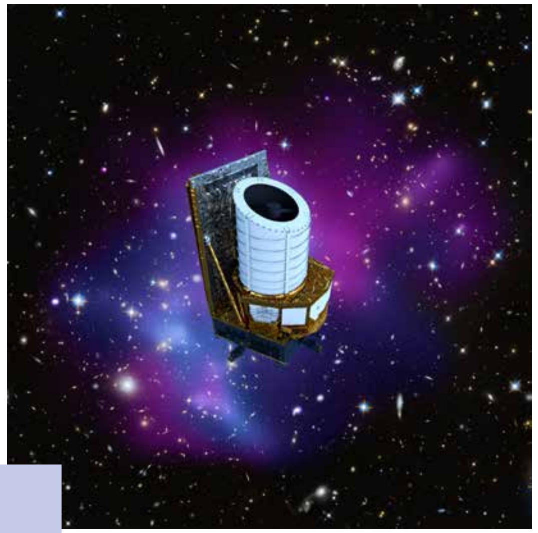
What would particle physics look like today if CERN had never existed? Wouter Waalewijn, a theoretical physicist at the University of Amsterdam, doesn't dare to speculate. 'But I would probably be working in a different field now.'

The institute – a 23-country collaboration based in the French-Swiss border region near Geneva – conducts experiments that also figuratively break borders. 'Both the amount of measurement data provided by CERN and its quality exceed that of other experiments in this field,' says Waalewijn. 'Without this data, we can't test our theories about elementary particles.'

A well-known example is the discovery of the Higgs boson in 2012, with CERN's largest particle accelerator, the Large Hadron Collider. The existence of this elementary particle was crucial to the Standard Model, the theory that describes all known particles, and all known forces except gravity. This theory does not hold up without the Higgs boson.

Now this is not to say that particle physicists can sit back and relax since this discovery. The Standard Model is not complete yet, says Waalewijn. 'In recent years, we have seen increasing indications in measurements that particles don't behave exactly as expected. The puzzle pieces of the Standard Model don't quite fit together yet. But it's unclear where exactly we should be looking for answers.'

That is why theorists are calculating how the current Standard Model should behave in certain situations. 'You can use that information to look for anomalies. If a measurement is different than expected, it tells you where something might be wrong.' In addition, they work out all kinds of different models. Could there be multiple types of Higgs boson or perhaps even completely new families of particles? Do some particles engage in unknown interactions with other particles or with themselves? Their findings can tell CERN researchers where to look for new physics.



'If it were easy to discover the nature of dark matter, my job would be boring'

The Euclid space telescope should shine more light on dark matter and ditto energy.
ESA/ATG MEDIALAB (SPACE TELESCOPE); NASA/ESA/CXC/C. MA, H. EBELING, E. BARRETT (UNIVERSITY OF HAWAII/IFA) E.A./STSCI (BACKGROUND)

Euclid

Whereas particle physicists are busy solving their puzzle, cosmologists first have to figure out exactly what their puzzle pieces look like. Only a few percent of the universe appear to be composed of 'normal' matter, made of particles from the Standard Model. Theoretical models and indirect observations show that the rest consists of dark matter and dark energy. But what these mysterious goodies are made of is still shrouded in mystery.

The Euclid space telescope, scheduled for launch in 2023, will help physicists shine more light on the matter. How? By imaging more than a billion distant galaxies extremely accurately. 'This is because the images of these galaxies can be distorted by dark matter, which acts as a so-called gravitational lens,' says Elisa Chisari of Utrecht University.

By combining the measured distortions of a gigantic number of galaxies, astronomers aim to create a detailed map of the distribution of dark matter in the universe. 'We then compare these with what you would expect to see for the different interpretations of dark matter, to test whether they could be correct,' says Chisari. 'This requires accurate theoretical models. Because the better the measurements, the more precise your model must be.'

Theories that explain dark energy can also be put to the test using Euclid. For example, the telescope can measure how the 'dark matter map' of the universe has changed from the Big Bang to the present, which tells us something about the expansion of the universe, a process that may be accelerated by dark energy. 'This will allow us to test, among other things, the most popular description of the cosmos, the so-called Lambda-CDM model,' says Chisari. 'Recent measurements are already hinting at cracks in this model. So, I look forward to what observatories like Euclid will tell us about this.'

Detectors like ANTARES can detect neutrinos that are an indication of dark matter.
F. MONTANET/CNRS FOR ANTARES

ANTARES

Gazing at galaxies is not the only way physicists are trying to figure out the true nature of dark matter. Particle physicists are making an attempt as well, using large, undersea neutrino detectors such as ANTARES in the Mediterranean.

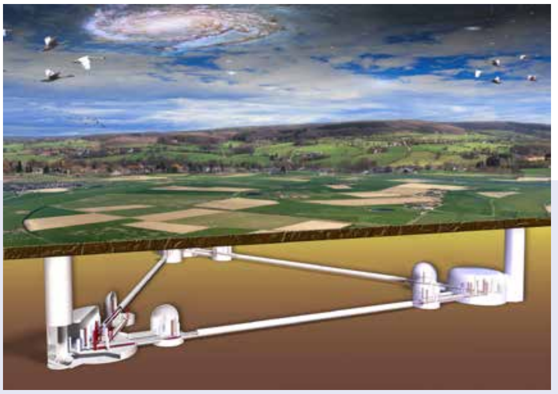
According to theoretical models, some dark matter candidates, including the WIMP (weakly interacting massive particle), popular among physicists, can annihilate each other or decay, releasing highly energetic neutrinos. Detectors like ANTARES can observe these neutrinos. If they turn out to come from the direction of the sun or the centre of the Milky Way, that's a smoking gun for the existence of particles like WIMPs, says Christoph Weniger, a theorist at the University of Amsterdam. 'These are places where there may be a lot of WIMPs.'

In practice, however, the universe remains eerily silent. Although ANTARES has been active since 2008, this detector has not yet detected such neutrinos. Future, more sensitive detectors – such as KM3NeT, which is also emerging on the bottom of the Mediterranean – may be more successful.

Now, the lack of measurements does not mean that the research area is at a standstill. On the contrary. 'Theorists have actually made an awful lot of progress in recent years,' says Weniger. 'Some candidate particles have been dropped, for example, because calculations have shown that they cannot exist. Models have also been developed for completely new particles, including ways to catch them in the act. This, in turn, provides new directions in which observational researchers can search.'

In the meantime, we wait patiently and hope for an actual detection, sighs Weniger. 'But if it were easy to discover the nature of dark matter, my job would be boring.'

Einstein Telescope



The Einstein Telescope, a huge gravitational wave detector, might be built in the south of Limburg.
MARCO KRAAN/NIKHEF

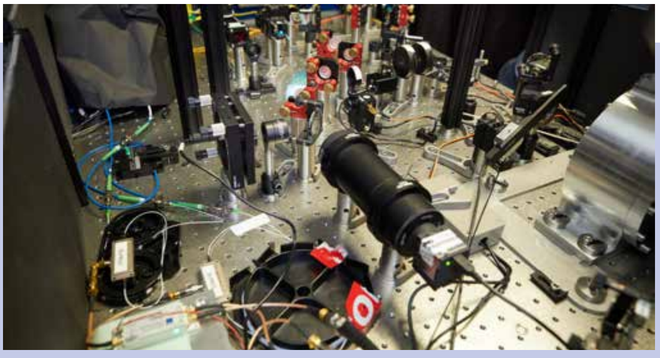
Physicists working on gravitational waves know that patience is a virtue. Using his general theory of relativity, Albert Einstein predicted the existence of these ripples in spacetime as early as 1916. It took another century for physicists to observe them directly.

This was an experimental feat, in which theorists also played an important role. 'The signals from gravitational waves are very weak,' explains Tanja Hinderer, a theoretical physicist at Utrecht University. 'Recognising waves among all the measurement noise and then determining how and where they originated depends entirely on theoretical models.'

Now that it is possible to measure gravitational waves, an entirely new window on the universe has opened. For example, observatories such as LIGO in the United States and Virgo in Italy have already revealed dozens of black hole collisions.

But this is only the beginning. A new generation of detectors is on the way, including the Einstein Telescope. This underground detector, which may be built in the south of Limburg, will look much deeper into the universe, and make measurements ten times more precise than LIGO and Virgo. In doing so, it takes research to an even higher level, says Hinderer. 'There will be many more observations that reveal in detail the properties of merging black holes. This will allow us to test very accurately whether these cosmic collisions behave as the general theory of relativity dictates. Possible anomalies could lead to completely new physics.'

In addition, the detector can uncover completely unknown territory. For example, it is possible to study recently merged neutron stars, in which matter reaches unprecedented densities. 'There is also a whole zoo of exotic, compact objects that theorists suspect may exist,' says Hinderer. 'For example, boson stars, or stars composed entirely of dark matter or energy. The Einstein Telescope is so sensitive that it can measure collisions between these kinds of strange, hypothetical objects. Using their models, theorists will then have to explain exactly what was observed. This can shed light on very interesting physics, from the nature of dark matter to quantum gravity.'



At the QuTech lab, founded by TU Delft and TNO, work is being done toward the quantum computer and the quantum internet.
QUTECH

Quantum computer

Shooting holes in existing theories or discovering completely new physics: those are not every theorist's main goals. Some branches of physics may just be 'complete', says Carlo Beenakker, a theoretical physicist at Leiden University. As an example, he mentions his own field, quantum mechanics, which describes the behaviour of particles and energy at the very smallest scale. 'I'm still working with physics that was developed a century ago.'

So, what do theoretical physicists do? Apply theory to new contexts, to advance technological developments. 'Quantum mechanics is proving to have applications that physicists would have been flabbergasted by a century ago,' says Beenakker. For example, the quantum computer, which can perform certain calculations much faster than ordinary computers. The principle behind this was fully developed by quantum physicists as early as the 1980s and 1990s. First, tentative versions of this computational beast have recently been built by more and more laboratories and companies. The winning design just isn't known yet, Beenakker says. 'Physicists are working on different types of qubits. These are the quantum versions of bits, the information carriers used by computers. To figure out which type of qubit works best, theorists suddenly have to start programming, which works in a completely different way than for a normal computer because you have to take into account the laws of the quantum world.'

You want to make sure that no errors creep into the calculations. Normally, you would do this by checking the value of bits. However, the power of a qubit is that it can have two values at the same time. At least, as long as you don't determine that bit's value. But if that's not allowed, how do you check a qubit? 'Theorists have to find ways to work around this, to prevent the quantum computer from crashing all the time,' says Beenakker.

Whether the quantum computer can ultimately live up to its sky-high expectations? Beenakker is optimistic. 'Although it remains to be seen what the final, major applications will be. Within physics, however, the current generation of quantum computers has already proven its worth. In many fields, their calculations are leading to wonderful theoretical results.' ■