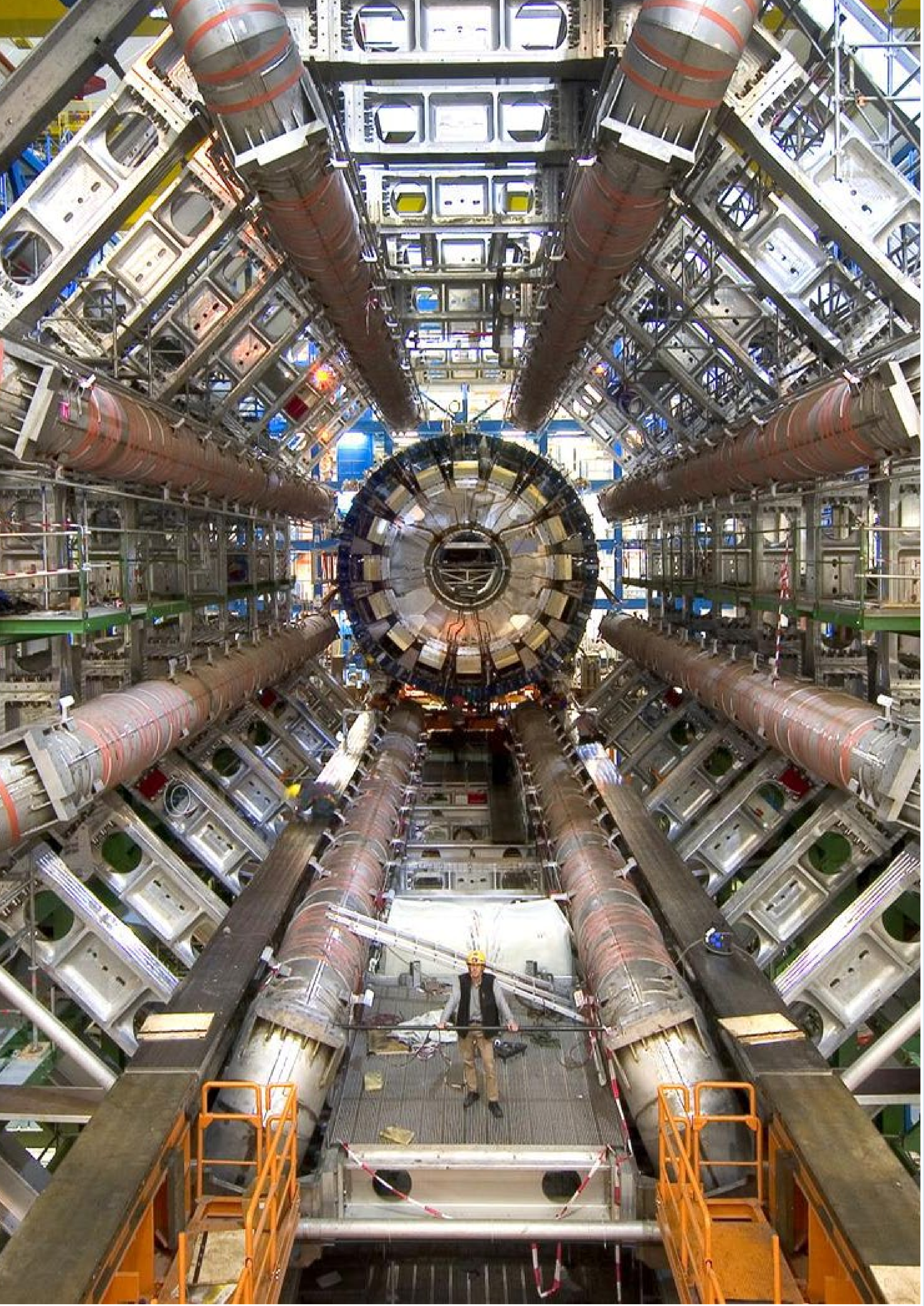

Chapter 5. The Higgs boson

This chapter describes the execution of the research regarding the Higgs boson in two sections. Section 5.1 provides the content of the Higgs boson: what is the Higgs boson, how can you explain what it is to a student, how did scientists research it and where can more information be found about it? This section constitutes the contextual basis for teachers that wish to work with this theme. Section 5.2 describes, on the basis of the seven phases of inquiry-based learning, how this project can be carried out in the classroom. Chapter 1, in which the general guideline of the seven phases is described, forms the basis for this. From there, references are made to the various substantive chapters. We, therefore, recommend the use of chapter 1 as the starting point for the execution of a project in the classroom.

Original publication in Dutch:
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The Higgs boson

5.1 The Higgs boson or the reason why objects have mass

Nicolo de Groot (Professor High Energy Physics), Frank Filthaut (Associate Professor High Energy Physics), Melissa van Beekveld (Master's Student) and Remco Castelijn (Master's Student). All work or study at the Department of Experimental High Energy Physics at the Radboud University in Nijmegen.

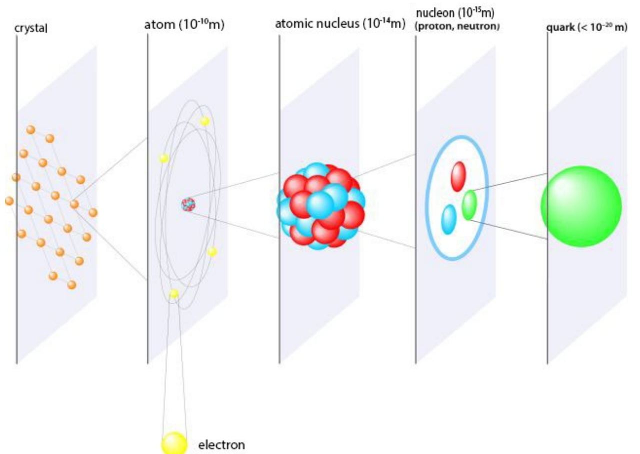
Introduction

The discovery of the Higgs boson not only represented a scientific breakthrough, it also marked the fulfilment of a fifty year old prediction of its discovery. Peter Higgs, from whom the particle's name is derived, predicted the existence of such a particle using mathematical calculations. He believed that without the existence of such a particle, understanding how the material world is put together would be an impossible feat, as there would be no way to explain why objects have mass. One of the main reasons the discovery of the Higgs boson has taken so long, is because it is very difficult to perceive. An instrument the size of the city of Utrecht, was ultimately necessary to confirm its existence: the Large Hadron Collider (LHC) of the research institute CERN located in Geneva, Switzerland. This chapter is focused on the Higgs boson.

However, before we further describe the Higgs boson, we will first provide an introduction into the world of elementary particles, which encompasses the smallest units of all matter in the universe. The Higgs boson itself is such an elementary particle

Particles: the basis of all matter

Since the time of the Greeks, man has wondered what the smallest units of matter are. The smallest measurement that is still perceivable with the naked eye is approximately a tenth of a millimetre. This equates to roughly the thickness of a banknote or the size of a human oocyte. Other cells can be up to a hundred times smaller: a micrometre. If we then zoomed in another thousand times, we would be able to perceive objects the size of a nanometre, a millionth of a millimetre and the typical size of molecules. Atoms are still ten times smaller. Atoms are composed of a core that carries a positive electrical charge surrounded by a cloud of negatively charged electrons. The core of an atom is in cross-section ten thousand times smaller than the atom itself. Atoms, therefore, contain a vastness of empty space. A core is, in turn, composed of two types of particles: positively charged protons and uncharged (neutral) neutrons. These are, in turn, composed of quarks. All matter on Earth can essentially be broken down into quarks and neutrons.



Different levels of which matter is made up of.

Under cosmic rays or in special laboratories, there appear to be numerous forms in which matter can exist, different from earthly matter. In such variations of matter, different types of quarks exist, the electron is endowed with two heavier siblings and there are three neutral and very light particles that are released from radioactive decay, namely neutrinos. How small these particles are cannot be measured precisely. However, what we do know is that these particles are smaller than a billionth of a billionth of a meter: an attometre.

All of these particles push and pull on each other in different ways. We call these interactions forces. There are four importance forces to distinguish: gravity (the reason why things falls to the ground), electromagnetic force (for example a magnet works with an electromagnetic force), strong nuclear forces (which hold quarks in protons and neutrons) and finally, weak nuclear forces, which are responsible for radioactive decay and the burning of the Sun. For each force, another particle comes into play: the force particles. For electromagnetic force, this is photon. Light is made up of photons, just like radio waves and thermal radiation. The photon is weightless, it carries no mass. The strong nuclear force has gluons, which are also weightless; the weak nuclear force has W and Z particles, which are hundred times heavier than protons or neutrons.

Mass and weight

Mass and weight are often used interchangeably in everyday speech, but within the field of physics, these terms are not loosely interchanged. Weight is relative and depends on gravity: the force of attraction of the earth on an object. An object on the moon will have a different weight than on Earth and in space objects are even weightless. Just look at films filmed on the international space station (ISS). Weight, therefore, varies depending on where you are. However, mass remains constant. The mass of an astronaut that weighs 75 kg on Earth will still have a mass of 75 kg in space. To simplify things, the term weight will be primarily used, but in essence we are referring to mass. This is because the Higgs boson is omnipresent and not just in gravity. To reiterate that idea that we are actually dealing with mass, we will occasionally add the word mass in brackets following the word weight.

The Standard Model and the missing particle

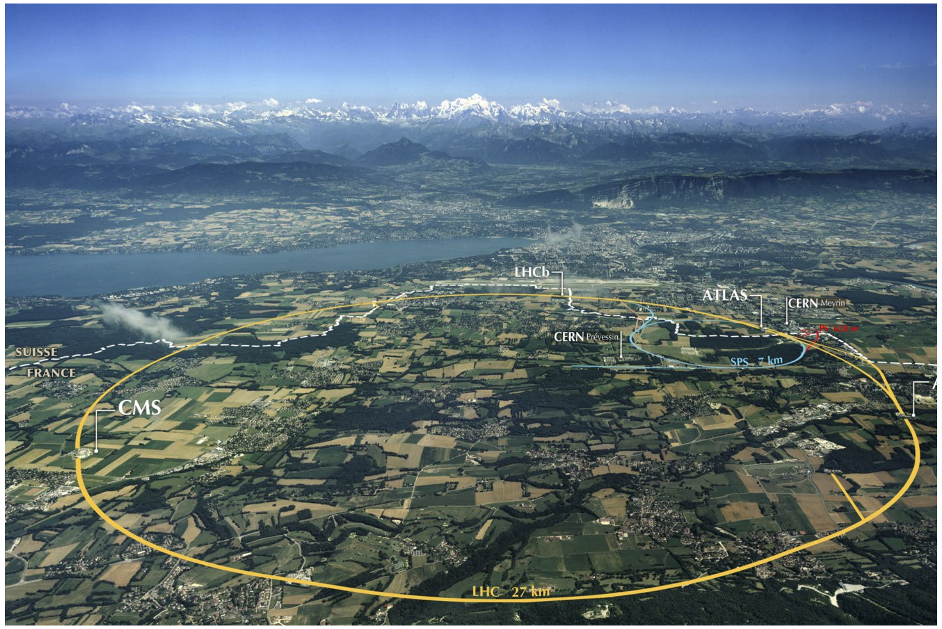
Matter and the electromagnetic, strong and weak forces are described by the Standard Model of elementary particles. This model allows us to calculate what happens during collisions between protons and electrons, sometimes with an accuracy of up to ten decimal places. A problem regarding this model is that it only really works if all particles have no weight (mass), but this is absolutely not the case. This is where the Higgs boson comes into play. Not only do particles have weight, there are vast discrepancies in weight between particles. The Higgs boson offers a solution to this problem.

In 1964, three scientists by the names of Robert Brout, François Englert and Peter Higgs devised a means to explain why particles have weight (mass), which as a result endows all matter with weight (mass). They reasoned that the 'empty space' between particles is not as empty as believed, but that this space was filled by a field (imagine a field as a magnetic field). The interaction of particles with this field endows the particles with weight. This field would later come to be known as the Higgs field. In line with the theory of the Standard Model, particles would move at the speed of light if it were not for the Higgs field. But some particles are affected by the presence of the Higgs field, interact with it and are slowed down by it. A part of their kinetic energy is translated into weight. The stronger the interaction of a particle with the Higgs field, the greater the weight.

Other particles, such as the photon, are not affected by the Higgs field and remain weightless. Unfortunately, we cannot perceive this field, which is a problem if we wish to proof its existence. That is why it is so significant that Peter Higgs predicted that a missing particle was at work here. That particle (and along with it, the field), therefore, received his name: the Higgs boson. While the field cannot be perceived, the particle itself can be. Ultimately, detecting the Higgs particle was no easy feat. Physicists across the globe have devoted 50 years to detecting it, following the prediction of Peter Higgs. Even with the most powerful microscope (electron microscope), elementary particles cannot be perceived. To do this, an enormous installation was required: a particle accelerator.

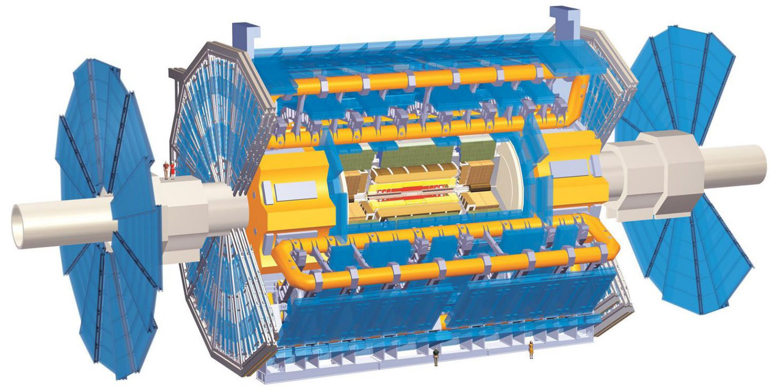
The Large Hadron Collider, the world's largest particle accelerator

On the border of Switzerland and France, near Geneva, lies the CERN laboratory. At a depth of 100 meter, the world's largest particle accelerator, known as the Large Hadron Collider (LHC), was constructed between 1998 and 2008. In this circular accelerator with a circumference of 27 km, proton packets (100 billion protons) are fired at equivalent proton packets to orchestrate proton-proton collisions, a process which is performed 20 million times per second. The energy per collision amounts to 8 Terra electron volt, 8,000 times the energy contained in the weight of a proton. Altogether, the protons weigh only half a nanogram (a billionth of a gram), but the energy of the packets is roughly equivalent to that of a 200 meter long express train racing at 200 km per hour.



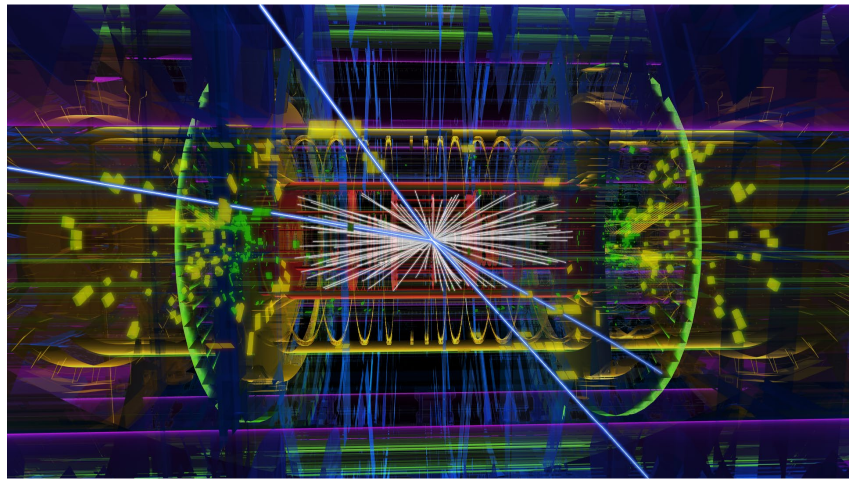
The outline of the Large Hadron Collider.

Upon a proton-proton collision, many new particles are produced. Surrounding the point of collision, enormous measuring devices, also called detectors, measure the position and energy of the outgoing particles and translate these into electronic signals. One of these detectors is the ATLAS detector; a detector that scientists from the Radboud University are in collaboration with. In collaboration with researchers from other universities, experiments, such as those involved in detecting the Higgs boson, are conducted using this detector. The ATLAS detector (see image) is 40 metres long, 25 metres high and 25 metres wide.



The ATLAS detector.

However, even with an enormous particle accelerator, such as the LHC, detecting a Higgs boson is no easy task. The Higgs boson exists momentarily before disintegrating into other particles within the detector.



An image illustrating a collision with a Higgs boson inside the ATLAS detector. The Higgs boson disintegrates into four other particles. These particles are represented as long blue traces.

So in actuality, we cannot see the Higgs boson, even with these large detectors. What we do see is the outcome, namely the particles that were derived from the disintegration of the Higgs boson. There are various outcomes possible after a Higgs boson has disintegrated. If we know how heavy a particle is and how heavy a Higgs boson is, then knowing the outcome we can calculate whether a Higgs boson formed upon collision. Different processes can amount to the same outcome like the disintegration of a Higgs boson. Therefore, a great number of collisions must be measured before we can truly claim to have detected the Higgs boson.

The discovery of the Higgs boson

In 2012 we discovered a new particle presumed to be the Higgs boson using the ATLAS detector. Another detector part of the LHC substantiated this discovery. It was announced that evidence for a new particle was found and that the particle in question may as well be the Higgs boson. Follow-up research ultimately verified this claim. In honour of their discovery, François Englert and Peter Higgs were awarded the Noble Prize in Physics in 2013, nearly 50 years after theorising the existence of the Higgs field and Higgs boson. Unfortunately, Robert Brout, who co-predicted its existence, passed away in 2011. And since Noble Prizes are not awarded to the deceased, he could not share in the honour. With that said, his contribution has not been forgotten.

With the discovery of the Higgs boson, the Standard Model was completed. This implies that physicists now understand how most forces operate, what the building blocks of matter are and why matter possess the attribute of weight.

Technology (or the creativity of the human mind), however, is not advanced enough to understand the practical applications of this discovery. As of right now, the primary advantage is a better understanding of how our world is put together. But scientific knowledge often gets quickly translated into practical applications despite not always being conceived or pursued for that reason. To give an example: the discoverer of radio waves could not foresee the amount of applications it would later be used for. As a result of its discovery, we are now capable of communicating wirelessly, listening to the radio and using mobile phones. Scientists are not always occupied with the technological or social utility of the things they discover. An importing driving force for some scientists could simply be to better understand how the world works and for some scientists, this is their sole motivation.

- Nicolo de Groot gave a lecture during the WKRU Winter School about the Higgs boson in 2014. This lecture is available on the website www.wetenschapdeklasin.nl [only available in Dutch].

The Higgs boson

Prof. dr. Nicolo de Groot

Nicolo de Groot (1964) was primarily interested in fossils, extinct animals such as dinosaurs, and stars and planets during primary school. Once in secondary school, physics became his favourite subject and he found himself particularly interested in forces and particles. This lead to his decision to study physics at the University of Twente and at the University of Amsterdam. In 1993, he earned his doctorates at the University of Amsterdam with his research on the properties of the Z particle. More precisely, his research focused on the decay of Z particles into b and c quarks. His research was conducted at CERN in Geneva using a different accelerator: the LEP accelerator, which was constructed in the same tunnel as the Large Hadron Collider. Following his research in Geneva and California with different accelerators, Nicolo obtained a position as an associate professor at the University of Bristol in England (1999-2001) and was shortly after assigned as chief researcher at the Rutherford Appleton Laboratory (2001-2004). As of 2004, he has occupied the role of professor of experimental particle physics at the Radboud University Nijmegen and at Nikhef, an institute where research is conducted on particles and where researchers from various Dutch universities work together. Nicolo is one of the programme leaders of the ATLAS experiment (whereby the ATLAS detector at CERN is involved) in the Netherlands and devotes a lot of research to the Higgs boson.

dr. Frank Filthaut

Frank Filthaut's (1967) interest for physics was sparked during secondary school when it dawned upon him that the language of mathematics could be used to understand nature. Frank studied physics at the Radboud Unversity in Nijmegen from 1985 to 1989. He earned his doctorates at the same university in 1993 for his measurements on the decay of the Z particle into quarks. These measurements provided the first precise information about the Z particle, in particular its mass and its decay rate. After earning his doctorates, he remained active in researching W and Z particles. First employed at an American university at CERN and later as Fellow of CERN, he studied electron positron collisions in the LEP accelerator. In 2000, he returned to Radboud University to work on an experiment involving a different accelerator positioned in the US. This accelerator was a predecessor (and recently a competitor!) of the LHC. In Nijmegen, he has dedicated his time in the search for the Higgs boson. Since 2008 he started working with the Large Hadron Collider and until October 2012 he was the leader of the Dutch group within the Nikhef partnership that engaged in the search for the Higgs boson. This group, despite its relatively small size, has made some major contributions to the discovery of the Higgs boson in 2012. Since its discovery, Frank has been closely involved in further detailed studies regarding the Higgs boson. Through experiments, scientists are studying whether the properties of the Higgs boson are in line with those predicted by the Standard Model of particle physics or whether the properties provide indications that call for an adjustment of the model. If it appears that the Standard Model must be adjusted, it will have repercussions for our understanding of nature at the fundamental level.

How Radboud physicists contributed to discovering the Higgs boson

Date: unknown

Physicists from the Radboud University played an important role in the experiments that ultimately revealed the Higgs boson. On July 4, 2012, CERN announced the discovery of the Higgs boson, which involved the collective effort of hundreds of researchers that ran experiments for years using the particle accelerator in Geneva. Nijmegen scientists from the groups under Professor Nicolo de Groot and Professor Sijbrand de Jong played an important role in this effort.

De Groot: ‘There are around hundred people occupied with the Higgs research at CERN, the rest of the staff is responsible for the equipment and such. Of those that were truly part of the research, many are related to our institute, IMAPP, in Nijmegen.’

Searching more efficiently

The Higgs boson’s lifespan is so short that it cannot be detected directly. The presence of a Higgs boson is deduced from the way it disintegrates into W and Z particles, which in turn become muons and electrons. The particle accelerator is equipped with multiple detectors to measure the decay. The scientists from Nijmegen work with the ATLAS detector, which is roughly half the size of Notre Dame. The ATLAS detector measures the particles in different ‘channels’. A PhD student working under De Groot greatly improved the efficiency of the ZZ channel, which allowed for finding more candidates for the Higgs boson. Nijmegen was also busy with the WW channel, which was very important in dismissing a heavier version of the Higgs boson. The researchers had a major role in the central data production of this particular channel and succeeded in resolving several pesky backgrounds (a type of white noise). De Groot: ‘All of them were frequently the first to present new results with the last data from the experiment.’

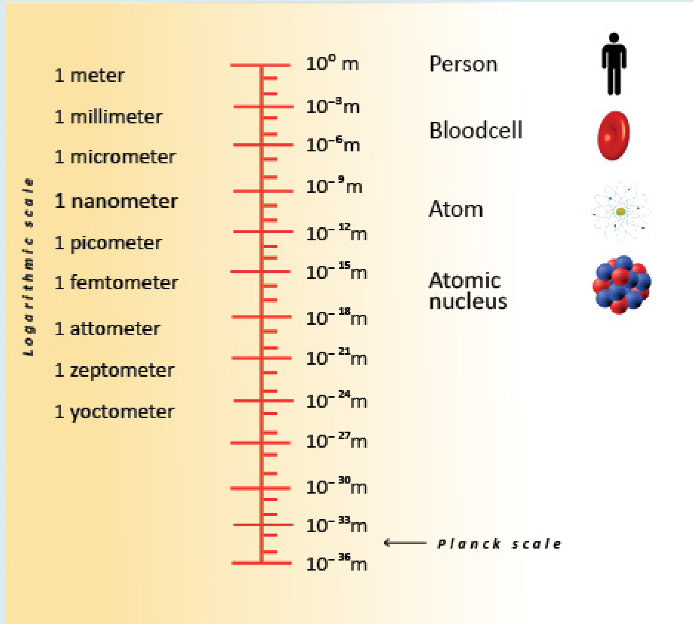
Particle software

That there are now sufficient measurements of the Higgs boson to claim with reasonable confidence (5 sigma or higher in scientific jargon) that the particle exists is partly accredited to the sharp calculations performed by the scientists from Nijmegen. Additionally, Nijmegen also contributed to construction of the particle accelerator in Geneva. ‘We made a major contribution to the electronics of the muon system and the software that allows for the visualisation of the collisions. Let us also not forget to mention that Jos Engelen, who was the scientific director of CERN for many years, is an alumnus of Nijmegen. He worked hard to get the Large Hadron Collider completed and operational.

Source: http://www.ru.nl/onderzoek/over/onderzoeksthema/natuurkunde/vm/hielpen-vinden-higgs

How do you explain the Higgs boson to students?

Below are the most important concepts explained more simply. The teacher can use the texts in the boxes to better explain the story of the Higgs boson. The students can also read the texts for themselves.



The size of elementary particles

What is a particle?

An elementary particle is a particle that cannot be split further into different building blocks. To understand what a particle is, we’ll describe it based on something everyone can relate to: a house. Upon this house, we’ll continue to zoom in. If you’re looking at a house from a distance, you’ll see just that: a house. However, as you approach the house, the building blocks, roof panels, windows, door, etc. of the house become more visible. In essence, the house consists of multiple components. Upon closer inspection, you’ll see that the building blocks are comprised of small stones and cement. When looking at the door, you’ll also see the different components: glass, wood, paint, a latch, hinges and so forth.

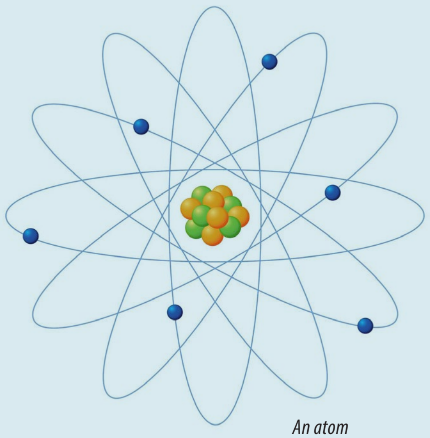
We can zoom even further, for example zooming in on the stones in the cement. We can try to zoom in further, but at a certain point we will reach the limit of our eye’s visual prowess which will render us incapable of going any further to see the molecules that make up the small stones. The molecules are made up of atoms and even these atoms can be split up into quarks and electrons. These last two building blocks are what physicists refer to as elementary particles. As far as physicists are concerned, these particles cannot be split further into even smaller particles. All elementary particles have been summarised by physicists in the Standard Model. An elementary particle is, therefore, minuscule. On YouTube, you can find a film that illustrates just how small: “The Powers of 10”. The smallest length that we have defined is ~1036 metres which corresponds to the dimension of a particle. To put this into perspective, imagine if a particle was around 0.1 mm, which roughly represents the smallest unit that can still be seen with the naked eye, and we then expanded the particle to the size of our universe. In this new universe, the smallest dimension would be 0.1 mm. You can imagine that you would not be able to perceive this unit of dimension with the naked eye. Even with a microscope this would be very difficult, because it only magnifies to roughly 1010 m, the size of an atom. An important question, therefore, is how do you measure something which you cannot see. This is where the particle accelerator in CERN comes in.

What is the Standard Model?

The Standard Model is an important summary of all ideas in physics at present. This model describes all of the smallest particles from which everything is made: what they look like, what they do and how they interact. For a long time, the Standard Model was said to be incomplete, because at the time we did not know every particle and their details. Physicists have worked long and hard to unravel the mystery behind elementary particles and to complete the Standard Model. With the discovery of the Higgs boson, the Standard Model is now said to be complete!

How were particles discovered?

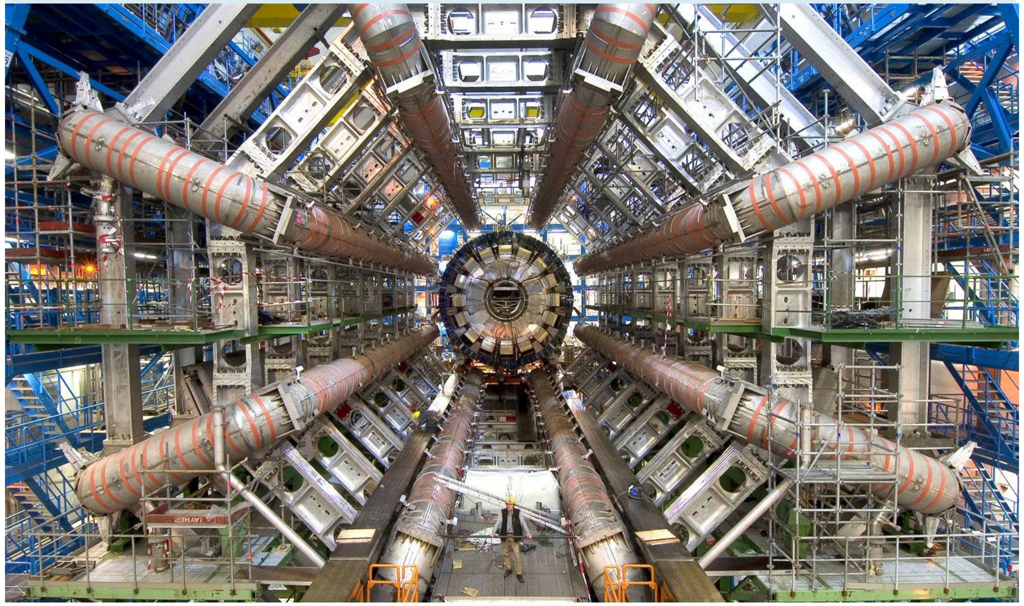
Already since the times of the ancient Greeks, roughly 2,500 years ago, philosophers speculated about the existence of atoms. The question that they were actually trying to answer was: what is our world made of? A question that they posed, for example, was if you could indefinitely divide something or if you would ultimately come across particles that could no longer be divided. Due to the lack of present-day technology, they were never able to investigate the issue. This did not stop them from holding extensive discussions about the state of affairs, however. Only in the 19th century did man discover that matter is composed of particles: the very atoms of which philosophers had discussed long before! It all started with an experiment conducted by Ernest Rutherford in 1911.


An atom

In his experiment, he irradiated gold foil with a particle beam. The particles that were used to irradiate the gold foil were deflected back when they collided with other particles in the foil. Researchers were able to deduce the shape and properties of the particles in the gold foil from the way the particles in the particle beam were deflected. Originally they thought that the foil consisted of large beads with space in between, because that is how they had conceptualised atoms. They believed, therefore, that a particle would either pass through the gaps or be deflected upon collision with the particles in the foil. The result was quite different, however. The particles did not deflect back often and when they were deflected, they often ended up elsewhere than was expected. This implied that an atom isn't just some round bead, but that there must be something that further deflects the particles. Eventually man came up with the theory that the atom is comprised of a hard, electrically charged core surrounded by an electron cloud. This perspective is currently the consensus within science (see illustration). Soon after it became apparent that atoms were not the smallest particles and it turned out that the core could be divided into protons and neutrons, which in turn could be divided into quarks.

What is the Large Hadron Collider?

Because particles are so small, they are very difficult to research. In order to make researching particles possible, a device the size of Utrecht is necessary. This device is stationed at the research institute CERN in Switzerland and is called the Large Hadron Collider (LHC).
Image you have a closed box and you wish to know the contents of the box. To find out what it is in the box, there are a number of methods you can employ: one method is to destroy the box. This is more-or-less the rationale behind the construction of the LHC. This accelerator is essentially a very large, hollow tunnel arranged as a circle. Protons (from the core of atoms, as discussed earlier) are shot through this tunnel and are accelerated. Once the protons have reached a certain speed, the scientists have them collide with each other (fun fact: the speed at which the protons are set to travel would take half a second to circle the Earth). As a result of their speeds and collision, the protons break open. At this point, you might recall that a proton is made up of quarks, so how could we find anything else besides quarks? The answer to this is that the incredibly high energy that resides in the quarks converts into other elementary particles. As a result, you end up with a whole new stream of particles from two objects that at first seemed solid (the protons), and that they originally thought could not be divided further. But now is the issue remains that the particles that are thus created are too small to see. To resolve this issue, a large detector, the ATLAS detector (see illustration), was built around the tunnel at the point where collisions take place in order to catch as many particles as possible that arise from the proton-proton collisions. This way, we can identify the particles that arise from the collisions without being able to actually see it.


The ATLAS detector

The Higgs boson

What is the Higgs boson?

The Higgs boson is an elementary particle, which implies that it cannot be divided any further into smaller particles and that it cannot be seen with the naked eye or microscope. Yet somehow physicists were nearly certain of its existence roughly fifty years ago. This was because Mr. Higgs, along with a few other physicists, had mathematically demonstrated that the ideas in physics (the Standard Model, which we described in the box 'What is a particle?') were only valid if a certain field existed: the Higgs field. Without the Higgs field, we can still understand plenty regarding how the world is put together: constructed from very small particles. But we could not understand then is why things are heavy, or why they have weight at all. Because there had to be a reason for things having weight, they were certain a Higgs field must exist. A field, however, is even more difficult to detect than a particle, but because a field is always accompanied by a particle, physicists knew what they had to search for: the Higgs boson.

How was the Higgs boson detected?

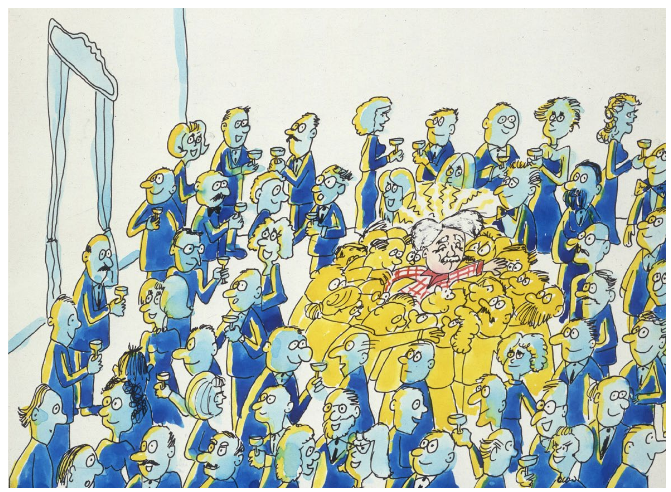
For years, scientists at CERN, together with scientists from various other universities and institutions, were occupied with proving the existence of the Higgs boson. At CERN, protons were collided at very high speeds which caused for their disintegration into smaller particles. Compare this to the smashing of glass against the wall: the greater the force, the more shards you'll generate and the further these shards will travel. But how these shards are made is outside of your influence. You cannot instruct the glass to shatter into 1 x 1 cm shards. There is only the slight probability of finding a shard that matches the dimensions. Following this logic, you cannot instruct two protons to disintegrate into Higgs bosons. There is only the slight probability of a Higgs boson arising.

And then there's another dilemma: we cannot directly 'see' the Higgs boson with the detector, because its lifespan is very brief before decaying into different particles again. It's these particles that ultimately end up in the detectors which are built around the tunnel. Based on the combination of particles, we can sometimes determine whether they originated from a Higgs boson. The probability that a Higgs boson arises from a collision is small, let alone determining that it is indeed a Higgs boson. You can only imagine the vast quantity of collisions needed, whereby each collision had to then be carefully analysed. That is why it took so long before scientists could safely claim to have found the Higgs boson.

How does the Higgs field work?

The Higgs field is the reason why particles, and thus everything around us, have weight. Whether the Higgs field attributes weight to a particle or not depends on the particle that moves through this field. Every particle is influenced by this field, but different particles are affected to different extents. Some particles are slowed down by the field (heavy particles), while others fly right through it, hardly being affected by the field (weightless or near-weightless particles). Therefore, the Higgs field is responsible for endowing a particle with the property of weight. To put this into perspective, imagine the Higgs field to be represented by a large group of people in a room (see illustration). The crowd within the room are there to socialise and will therefore not leave the room. On one side of the room is a door where new people (particles) can enter. When a person of insignificant stature enters, the people in the room ('the Higgs field') do not recognize the new person and are unfazed by his/her presence. As a result, the people already in the room will continue socialising and the recently entered person can move effortlessly throughout the room ('the weightless particle').

When a celebrity suddenly enters, all eyes will be on him/her and the people will stampede to surround the celebrity. It is then a lot more difficult to navigate through the room. The property of this individual (famous or not famous) ensures that the surrounding people behave in a certain way, ultimately slowing down the celebrity. This is more-or-less how the Higgs field also works: the property of a particle invokes a certain reaction from the Higgs field, which can result in the particle becoming heavy. The beauty of the Higgs field is that it's omnipresent and therefore, all particles with mass will have the same mass everywhere and always. Activity 2: 'Why the Higgs field gives mass' in section 2 allows students to experience the mechanism of the Higgs field.



A celebrity attracts people in a crowded room: a metaphor for the Higgs field

Research into the Higgs boson

Because the Higgs boson is so small, it cannot be observed using a microscope. As a result, the particle cannot be studied directly. So how do scientists know that this particle exists and what its properties are? As previously mentioned, the Large Hadron Collider in Geneva accelerates and collides hydrogen atoms with each other. This is performed at very high speeds which allows for the particles' disintegration upon collision. As a result of the acceleration, the colliding protons carry a tremendous amount of energy and subsequently split into various new particles. The particles that arise from this collision can include Higgs bosons, but can also be different elementary particles. The properties of the particles that arise from the collision can be measured using the detectors that surround the collision point.

The research into the Higgs boson can be broadly divided into two categories: there are scientists who are more concerned with practical research regarding the Higgs boson and there are those that occupy themselves with theoretical research. Nicolo de Groot and Frank Filthaut (winners of the Radboud Science Awards) are part of the former category. This means that they are more involved with the equipment that detects the particles and the software that is necessary to analyse the detection data. They also try to understand the implications of the data. In order to properly analyse the detection data, good predictions are required. These predictions are set up by scientists that concern themselves with theoretical research. Based on theoretical research, a lot can be deduced regarding the Higgs boson's properties and that of other elementary particles. By using the particle accelerator to test the predictions of various models, researchers can gradually unravel the mystery of how the world is put together.

The particle accelerator in Geneva is of great importance for the research into the Higgs boson. Many scientists from different countries are part of the research conducted there. However, a lot of these scientists actually conduct their research at a university like Nicolo and Frank who work at the Radboud University in Nijmegen. Along with others at the Department of Experimental High Energy Physics, they conduct practical research into elementary particles. Other researchers at the same university do theoretical research into elementary particles. You might be wondering how this is possible when they aren't situated in Geneva. Well, for practical research, regular contact (for example through video conferences) is held between researchers at universities and researchers stationed in Geneva. Moreover, the largest part of research itself, such as data analysis, can be done anywhere. The same goes for researchers that are developing theories and predictions.

Nicolo de Groot and Frank Filthaut, winners of the Radboud Science Awards, both contributed to the practical research of the Higgs boson, primarily the analysis of the detection data which allowed for the identification of the particle's properties. To give an idea of what the researchers are occupied with in this field, we provide two examples of research questions that stand central to the field. The winners of the Radboud Science Awards contributed primarily towards answering the first question. However, the second question was also addressed in their research with regard to using models that predict the existence of new particles.

The Higgs boson

Research question	What is the mass (the weight) of the Higgs boson?
Method How do we conduct this research?	Different models impose restrictions on the massthe Higgs boson may have. In other words, physicists know the range of values the mass of the Higgs boson can have. The actual mass should be measured when a Higgs boson arises from the particle accelerator.
Results or expectations	Researchers, including the winners of the Radboud Science Awards, measured the precise mass of the Higgs Boson. The measured mass is 125 GeV, whereby one GeV corresponds to 1.78 x 10^{27} kg.
Wat betekenen deze resultaten voor de maatschappij/toekomst/de leerlingen?	At present, this result has no clear significance for society. It is important, however, for researchers that want to know exactly how the world around us functions. As our knowledge of the Higgs boson increases, it is only a matter of time before the Higgs boson can be manipulated and be used in practical applications.
What else do we want to know?	Researchers are currently doing more detailed research into this and other properties of the Higgs boson.

Research question	Dark matter exists in the universe. Dark matter is comprised of invisible particles that exert an influence by means of gravity. Researchers want to know the type of particles that make up dark matter.
Method How do we conduct this research?	Using various theoretical models, scientists are trying to deduce the properties of dark matter. These properties can be verified through observations; for example using telescopes.
Results or expectations	Up to now, no particles have been directly observed which could be likely candidates for dark matter, but more information is increasingly being discovered regarding dark matter.
What implications do these results carry for society/the future/the students?	If we could observe the particles that made up dark matter, we could derive a better understanding of the makeup of our universe. Possible practical applications for dark matter would follow afterwards
What else do we want to know?	Scientists first want to determine the particles that make up dark matter and then figure out the exact properties of these particles.

The Higgs boson

5.2 The Higgs boson in the classroom!

Montessori school Westervoort: Marijke Weijland (teacher), Monique Schaminée (teacher)
Maria school Boven-Leeuwen: Danielle ten Bult (teacher), Astrid Lammers (teacher)

In this section we describe how to launch a project based on inquiry-based learning with the Higgs boson as its theme. At each phase of the inquiry-based learning methodology, we provide activities, practical tips and suggestions. The descriptions in this section are based on the experiences of the Montessori school Westervoort and Maria school in Boven-Leeuwen. The 'online appendix', which is referred to in various activities, can be found on our website www.wkru.nl/english. This symbol ⦿refers to the website. The materials that are referred to are available on the webpages designed for this book.

Core objectives
The follow core objectives may be addressed depending on the width of the scope:
English
13 The students learn to derive information from simple spoken and written English texts.

Mathematics
33 The students learn to measure and learn to calculate with units and measurements such as time, money, length, perimeter, area, volume, weight, speed and temperature.

Orientation on the world and yourself
41 The students learn about the build of plants, animals and humans, and about the form and function of their parts.
42 The students learn to conduct research on materials and physical phenomenon such as light, sound, electricity, force, magnetism and temperature.
50 The students learn to work with maps and atlases, know the basic topography of the Netherlands, Europe and the rest of the world, and develop a contemporary geographic worldview.

Artistic orientation
54 The students learn to use images, music, language, game and movement to express feelings and experiences, and to communicate.

Goals of this project
With this project, the following goals are worked towards:
Cognitive goals
- The students acquire an impression of the particles that make up everything around them and the cosmos;
- The students know that there are other elementary particles besides the Higgs boson;
- The students learn through information and activities how research is conducted in the field of elementary particles (in its simplest form) and the assumptions that the research is based on;
- The students know that CERN is located in Switzerland and are aware of the most important topographical locations of Switzerland.

Skill goals
- The students gain experience working with the cycle of inquiry-based learning;
- The students learn, on the basis of examples given to them, to formulate a research question and to answer it by means of practical research;
- The students learn, on the basis of previous experiences and analysis, to formulate a hypothesis;
- The students learn to prepare a presentation based on their own research;
- The students learn to process data in tables and graphs;
- The students learn to reflect on their own ideas and activities;
- The students learn to draw conclusions from their own research.

Collaboration goals
- The communication between the students while collaborating in groups is strengthened;
- The students learn that it is stimulating to collaborate within a group with the same interest/question;
- The students exchange knowledge with each other;
- Parents become involved in the learning process (because they are invited to the presentations).

Affective goals
- The students are introduced to and work on a groundbreaking theme;
- The students are introduced to science and the university;
- The students are introduced to literature and visual materials (films, documentaries, series, photographs, etc.) about the subject.

Phase 1. Introduction.

During the introduction, the students come into contact with the subject for the first time. The goal is to excite them and invoke curiosity towards the subject.

1 2 3

Because the Higgs boson is a difficult topic, both schools involved in the project decided to introduce the topic with a film. A more proactive form of introduction is of course also optional.

ACTIVITY 1: **EIN-O MOLECULE – BUILT UP OF ATOMS**

Goals
- The students acquire insight regarding the composition of molecules;
- The students acquire insight regarding the differences in complexity of molecules;
- The students are introduced to the nomenclature of compounds/molecules;
- The students learn to use the photography capability of a laptop.

Work form
Individually in their designated working time

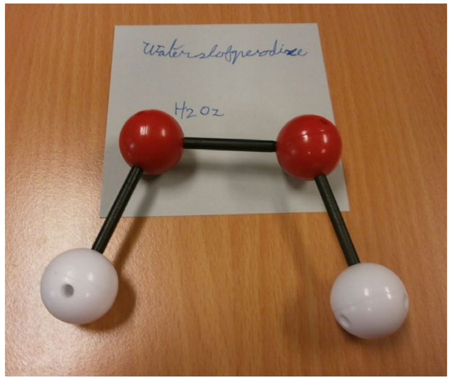
The activity itself
Preparation and necessities
Acquire the Ein-O kit

Duration
In terms of preparation, this requires no time. The students can get started on their own volition.

Activity
The Ein-O kit is a kit with which allows for the physical construction of 3D molecules. The kit is equipped with instructions on how to build various molecules and allows the students to explore and build these molecules. Photos can be made of the assembled molecules for documentation purposes.

Wrapping up
The printed pictures of the assembled molecules are evaluated.

Tips
This activity can also be done with wine gums and cocktail picks.



Hydrogen peroxide molecule assembled by a student.

Phase 2. Exploring

In the exploration phase, the students explore the topic broadly. They do this through all kinds of activities that they sometimes perform individually, in groups and sometimes as a class.

1 2 3

A range of activities are described below. The activities show how a strictly physics topic like the Higgs boson can be related to entirely different lessons such as topography and crafts. The order of the activities was set up in such a way to create a long, varied exploration phase. Naturally, you are free to make the choice yourself from the range of offers.

ACTIVITY 2: **WHY THE HIGGS FIELD GIVES MASS**

Goals
- The students gain insight into the existence of the Higgs field;
- The students gain insight as to why one particle has more mass than another.

Work form
Game played with the class

The activity itself
Preparation and necessities
- Two stacks of cards are made. One stack will be 50% larger than the other and each stack has its own designated colour;
- A space without many physical obstacles (such as a large hall)

Duration: 10 minuten

Introduction/orientation
Explanation of what is to happen without further background information

Activity
Two students each receive one stack of cards. The other students distribute themselves in the area. The two students deal their cards to the spread-out students, giving each student only one card at a time until all cards have been dealt. Because the stacks are not equally large, one of the dealing students will finish quicker than the other.

Wrapping up
In a discussion, the relation between the activity and the Higgs boson is elaborated. The students that distributed themselves throughout the area are representative of many Higgs bosons. The students that need to cross sides represent other particles that physicists have observed. One question that physicists have occupied themselves with is why one particle moves more quickly and easier than a different particle. The answer is because the entire space is filled with Higgs bosons (like a room or area filled with people). As particles move throughout space, they may or may not interact strongly with the Higgs bosons (this is referred to as coupling according to physicists and is illustrated by the distribution of the cards). Light particles (few cards) are not or hardly influenced by the Higgs bosons and can almost move freely throughout the space, whereas heavy particles (many cards) are subjected to stronger interactions or influence. In this way, the reason why one particle is lighter or heavier relative to another particle can be explained.

Tips
- The students will be inclined to quickly run and deal the cards, so ensure for a large enough area where that is possible;
- The activity can be performed differently, whereby the students have to retrieve cards of their own colour;
- Make sure that you yourself are well informed about the Higgs field prior to the end discussion. The students' questions can sometimes catch you off-guard.

The Higgs boson

ACTIVITY 3: **WHY ONE EXPERIMENT ISN'T ENOUGH: THE DICE EXPERIMENT**

Goals
- The students understand and can articulate why an experiment must be repeated multiple times in order to be confident about the results;
- Persistence: the students quickly realize that the deviation in the throws is due to the difference in weight of the dice. The question however is how often the dice needs to be thrown in order to confidently say what amount of pips (side of a dice) was thrown the most;
- The students learn to consistently perform a task (namely to repeatedly throw the dice in the same way);
- The students practice working together (making use of each other's actions, coming to agreements within the group, division of tasks);
- The students learn to accurately record their observations (are the measurements recorded in a way that their meaning is clear?).

Work form
Groups of four to five students

The activity itself
Preparation and necessities
- Forms (one per group);
- Dice (each group receives four ordinary and one weighted dice which can be found in toy stores or online);
- Cups used to throw the dice (one per group)

Duration: 60 minutes

Introduction/orientation
Each group receives five dice (of which one is heavier) and a cup with which the dice are thrown. The amount of pips thrown must be systematically tallied. The goal is to show with which value (the number of pips) something is wrong (because of the weighted dice, a certain number of pips or specific side of the dice will be thrown above average, but you won't inform them). Before the dice are thrown, the worksheet should first be discussed and the tasks within the group assigned. For the latter, you can let the students themselves determine and assign the tasks as a group or you can inform the students what tasks need to be fulfilled: one student throws, another records the results, another controls whether the results are accurately being recorded and two children count the number of pips. Each group constructs a plan on how they intend to prove that something is wrong.

Activity
The students throw all the dice at once over the table using a cup. After each throw, the values or number of pips are tallied in the first column of the worksheet. After five attempts, the number of times each pip was thrown is recorded in the second column. Following ten attempts, the same is reiterated for the third column and so on. They repeat this process until they think they have figured out the cause of the deviation. After how many attempts do the students suspect the cause and after how many attempts are they confident about their claim?

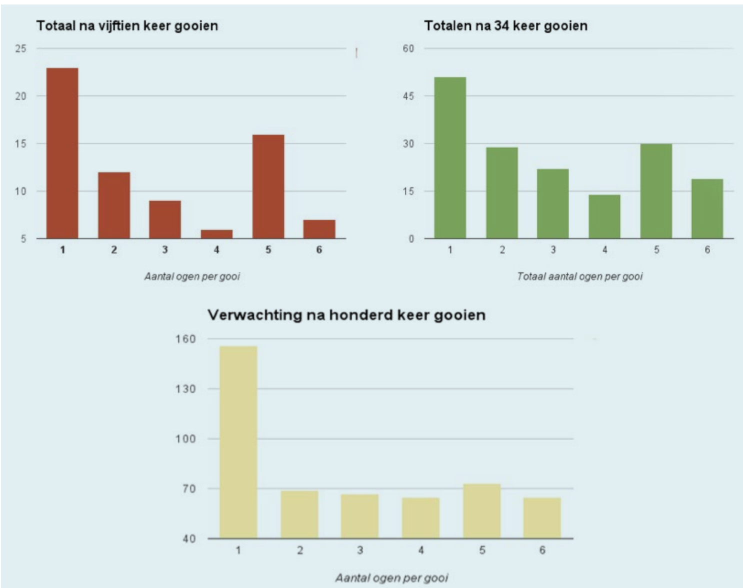
The conclusion may only be based on the statistics of throwing the dice and not by close inspection of the dice itself (because the heavier side of the weighted dice is visibly different).

Wrapping up
Discussion of results: when and after how many throws could the students confidently claim that something was off with one of the values and what was that based on?

Relation to the Higgs boson: This exercise illustrates why particles must repeatedly be collided in the LHC before knowing for certain that the Higgs boson was indeed found. In science, in order to prove something, reproducibility of the experiment and results are vital.

Evaluation of activity: The weighted dice shows visible deviation from the normal dice. Because of this, the students often find it difficult to see the experiment through to the end, since the students already can assume which side will occur more often, despite understanding the importance of repeating an experiment. However, this very dilemma is reflective of real research: you might already know the answer to your question, but nevertheless you will have to repeat the experiment in order to confidently support your claim.

The researchers that were involved in coming up with this game show just how many times they threw the dice before they were certain of their case. This is illustrated below in the diagrams which you could present to the class (see online appendix ◉).



Distribution of the number of pips after 15, 34 and 100 attempts. When do you really know what the deviating number is?

Tips
- It is important that the students can articulate the fact that there is a significant difference between the claims after 5, 10 and 25 attempts;
- Emphasise the notion that it all comes down to providing evidence;

- After a few minutes, you may want to pause the activity to ask whether the students have encountered any problems and whether the tallying of pips is going well.

Online appendix ◉
- Worksheet dice experiment;
- Diagrams of the example experiment (for the presentation).

ACTIVITY 4: **EXPLORING THE WEBSITE CERNLAND**

Goals
- Acquiring knowledge about CERN and the experiments that are conducted there, the design of the area, the people who work there, etc.;
- Working on a complex theme in a playful yet educative manner;
- Reading English (including terminology about particles).

Work form
Individually and independently, the assignment is put on the weekly task.

The activity itself
Preparation and necessities
Hardly any preparation is necessary, because the assignments are on the website. Simply ensure that the website is accessible. Viewing the website in advance would be useful in providing an introduction to the students.

Introduction/orientation
Present the website and give a brief introduction about the different possibilities. Explain what is expected from the students when filling in the logbook.

Activity
The students can individually get started with the assignments on the website. They are required to maintain a logbook regarding the amount of time they spend, what they are doing, what they have learned and which new English words they now know (see online appendix ◉). The teacher patrols the class to answer any questions and gives feedback on the logbooks while reviewing the weekly task.

Wrapping up
At the end of the project, the logbooks are evaluated. How often did they do the activity, what has been recorded and learned?

Tips
Give students the opportunity to tell each other what they discovered on the website; they might exchange tips for other fun games and films.

The Higgs boson

Online appendix ◉
Logbook page CERN

Sources
www.cernland.net

Students discovering CERNland

ACTIVITY 5: **ESTABLISHING A KNOWLEDGE BANK ABOUT HIGGS**

Goals
- The students gain knowledge about the Higgs boson;
- The students deepen their knowledge gained through watching the Klokhuis film (see activity 1);
- The students practice their reading and comprehension of a text;
- The students practice reading aloud: intonation, pronunciation, volume;
- The students practice asking questions, sharing knowledge and engaging in discussions with each other;
- The students engage in cooperative learning;
- The students learn to make a summary;
- The students learn 'how to learn'.

Work form
Reading and discussing with the entire class
Individually making study cards
Learning the study cards both individually and together
Individually taking a test

The activity itself

Preparation and necessities
The teacher copies a simple text about the Higgs boson and an accompanying assignment (see online appendix) for each student. The chapter 'How small is the smallest particle?' from the Klokhuis book is an appropriate choice (see sources). The text goes well with the film from activity 1: Figure it out! Smallest particle.
For every student, three cards are prepared in different colours: red, blue and white.

Duration
Reading and discussing the text: 45 minutes
Making the cards: 30 to 45 minutes
Learning for the test: in your own time
Taking the test: 20 minutes

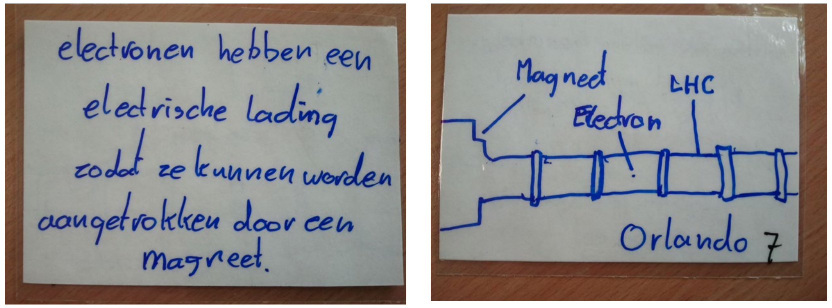
Introduction/orientation
The text is read in class. Any questions the students may have are discussed. The teacher then asks in-depth questions to assess whether the students have understood everything. An opportunity arises to explain the knowledge, share experiences and to provide instructions. The students can also respond with one another when questions arise. The teacher encourages students to engage in discussions and allows for a certain margin of deviation from the topic.

Activity
After reading the text, the assignment for the study cards can begin. The assignment entails that each student draws up a question about the text and writes down the question and answer on opposite sides of a red study card. The students then draw an illustration that is representative of the text on the front of a white card and write on the back of the card what he or she has drawn. Next, each student pulls a difficult word from the text, writes the word on the front of a blue study card and writes the definition of the word on the back. The teacher then checks all the cards. If not approved by the teacher, the students must redo them. This activity highlights the relation with the text, the readability and the accuracy of the information. The study cards are used to study for a test about the text.

Wrapping up
After the lesson, the cards are laminated and stored in a tray, giving the students the chance to revisit them for the duration of the project. To finalize the project period, a test will be given.

Tips
- Let the students assess each other's cards before the teacher;
- The students can study together and question each other.

Online appendix ◉
Study assignment knowledge bank



A study card for the knowledge bank.

ACTIVITY 6 : HIGGS ATTENTION TABLE AND RELATED THEMES

Goals
- The students learn to choose what content best addresses their interest;
- The students expand their vocabulary by searching for the definitions of difficult words;
- The students practice comprehensive reading;
- The students acquire new knowledge independently.

Work form
Individually

The activity itself
Preparation and necessities
Select books about the Higgs boson and related topics such as particles, molecules and such. Place the books where the students can easily access and read through them.

Duration
Up to you

Activity
The students choose a book that appeals to them. During their independent work time, the students read their book of choice (or sections from multiple books). Any words that they are not familiar with should be looked up. If the students still struggle to understand, they should take the initiative in asking their fellow students or the teacher for assistance.

Tips
Let the students tell each other what they have read and what they have learned from it

Online appendix ⦿
Reading logbook attention table

ACTIVITY 7: OBJECTIVE OBSERVATION OR 'THE BLACK BOX EXPERIMENT'

Goals
- The students acquire insight into how scientists conduct research into something that is not visible;
- The students learn to draw conclusions purely on the basis of objective observations.

Work form
Going round in groups

The activity itself
Preparation and necessities
- Place four boxes with the bottom open on skewers on a table. Between the box and the table, there should be just enough space to allow marbles to freely roll under it (see illustration);
- Place beneath each box an object in such a way that the object is no longer visible. Select objects that differ in shape and material (see the online photo sheet for examples);
- Roughly twenty marbles;
- Place the box in a tray to prevent the marbles from rolling off the table.

Duration: 30 minutes

Introduction/orientation
The students are instructed to guess the properties of the object by colliding marbles with it. It is important to write down these properties, because their notes will be necessary to guess the object's identity.

Activity
Each group stands by a box. The students take turns rolling a marble in the direction of the object under the box. Whether or not the marble is deflected, the direction and speed of the reflection, the sound of collision, all of these indicators say something about the object: what shape is it, is it hard or soft, is it hollow or dense, etc. After approximately ten minutes, the groups rotate over to the next box and then again every five minutes until each group has visited each box.

Wrapping up
Once the students have investigated all four (black) boxes, the teacher hangs a sheet with pictures in front of the class. Among the multiple pictures are four pictures of the objects used in the experiment. In a class discussion, the students discuss the identity of the objects under each box. The black boxes are then lifted to reveal the objects. From experience, it is rather difficult to correctly guess the objects.

At last, a link to the Higgs boson is established: this activity shows how an object and its properties can be determined without seeing the object. In exactly the same way, the first atoms were discovered in 1911 by shooting alpha particles against a photographic screen which resulted in tiny flashes of light. By positioning the atom before the photographic screen, it could be determined whether or not an atom contained a core. If a core was present, the alpha particles would be deflected and would therefore not collide against the photographic screen. As a result of alpha particles being deflected by the core of an atom, no flash of light would be generated and the screen at that position would remain dark (the Rutherford experiment). Nowadays, particles are discovered by colliding them with each other at high speeds in a particle accelerator. When particles collide, they are deflected and consequently measured by the ambient detectors.

Online appendix ◉
- Photo sheet content black boxes (for inspiration)

Students attempting to discern the object's identity under the box using marbles.

ACTIVITY 8A: **MAKING A PARTICLE ZOO**

Goals
- Going more in-depth into the topic of particles in a playful way;
- Making/depicting a particle;
- Translation of English text.

Work form
Individually

The activity itself
Preparation and necessities
From the particlezoo.net website, choose and print several different particles, and copy the images with the accompanying text. Discuss the assignment (see online appendix). Gather the materials (vibrant coloured felt, needle and thread, stuffing of various weights and labels).

Introduction/orientation
Establish the relation to the Higgs boson or particles in general: the particles that the students are going to make are all present within an atom, like the Higgs boson. The students get introduced to entirely different particles which they may have come across before.

Activity
Each student receives an image of a particle. They translate the English text that accompanies the image and attempt to create the particle (see assignment sheet in de online appendix).

Wrapping up
Does your particle resemble that of the image? Did you fill it with the material according to the specifications?

Tips
Devote attention to the 'design problem': let the children think themselves about what material to use as stuffing for their particle based on whether it is 'light' or 'heavy'.

Online appendix ◉
Assignment sheet 'particle zoo'

Sources
www.particlezoo.net

ACTIVITY 8B: **PARTICLE ZOO AS A PLAY**

Goals

- Processing and presentation of knowledge;
- Classroom cooperation;
- Sharing the project with the rest of the school.

Work form

As a class: determine script/roles/texts, rehearse and perform
Individually: write text

The activity itself

Duration
Rehearsal time of 3 days for a 10 minute presentation about 'the particle zoo'.

Introduction/orientation
Distribution of roles: the students play the roles of caretakers of the particles that they made at the particle zoo. In addition, there are other roles such as cashiers/receptionists of the zoo, visitors, the professor and his or her assistance, the director of the zoo and a few technicians.

Activity
First a general script is conceived. Then the students write their own texts as caretakers of the particles. This is done on the basis of the accompanying text of the particle they made. Each student that crafted a particle writes a text about their particle.
Day 1: The students write the text for their role;
Day 2: First rehearsal and polishing of their text;
Day 3: Second rehearsal and final amendments.

Wrapping up
The play is performed to the whole school.

Tips

Keep the rehearsal periods short to maintain the spontaneity. As a result of this activity, the entire school becomes involved in the project.

The Higgs boson

Sources

Inspiration was derived from the performance 'Aart' held at Burgers' Zoo whereby visitors witnessed the dance performance by the students of the Kunstbedrijf. During their performance, the dancers portrayed themselves as different animals. They danced in or around the animal enclosures.

2 3

In the activity below, the students are to figure out a way to accelerate an object. This activity bears a strong resemblance to conceiving a research project for a given question. For this reason, this activity is particularly suitable for guided and open inquiry-based learning (level 2 and 3). This could be considered a preparatory exercise for the research they will conduct later. This doesn't necessarily have to be the last activity.

ACTIVITY 9: **ACCELERATION EGGSPERIMENT**

Goals

- The students learn to describe a problem;
- The students learn to formulate a goal;
- The students learn to think of a way to solve a problem (design problem);
- The students practice working together;
- The students practice keeping track of what is happening, what has been done and which choices were made (reporting);
- The students orientate themselves on the physical forces that emanate from the Higgs boson (gravity, leverage, pendulum motion, air pressure, magnetism,…).

Work form

Groups.

The activity itself

Preparation and necessities
Necessary: two or three surprise eggs per group

Duration
The lead time for this activity encompasses 1.5 weeks; in total the students have two to three hours to spend.

Introduction/orientation
Explain the assignment and establish a link with the research conducted at CERN: in CERN's particle accelerator, protons are accelerated using magnets in a 27 km long circular pipe. The protons are fired in two, opposite directions. Once a given speed is achieved, the researchers have the two protons collide and it is at this very point that images are recorded by use of the detectors. Those images are analysed and claims are made regarding the traces that are generated as the particles fly about as a result of the collision. The students are now going to research how they can collide an accelerated surprise egg, whereby they'll attempt to eject as many particles within the egg as possible.

Activity
The students work in groups. Together they think of how they could accelerate a surprise egg to such an extent that upon collision with another object, the wrapper, chocolate shell and the yellow plastic capsule would break, revealing the little toy inside the capsule.

There are two criteria: firstly, they are not allowed to hold the egg when it is launched, so they must find a way to put the egg in a stable launching position. Secondly, the safety of the environment and surrounding people cannot be jeopardised.

Wrapping up
The groups take turns performing their experiment; those not performing must observe. Each group then discusses what went well and what could be improved or done to further accelerate the egg.

Students accelerating a surprise egg using a fan.

Tips
Keep the lead time short. Conceiving, designing and conducting the experiment does not have to take longer than 1 to1.5 weeks. A short time frame may keep the students enthusiastic. One of the schools that co-developed this activity planned the completion of this activity on the day of Easter, which turned out to be fun combination with the eggs.

Online appendix ◉
Logbook sheet Eggsperiment

Students accelerating a surprise egg using a water rocket.

The Higgs boson

Phase 3. Designing research: research question and plan

PHASE 3A. THE RESEARCH QUESTION

1 2 3

The research question is based on the main theme of this project: the Higgs boson. It is difficult to come up with a research proposal concerning the Higgs boson based on the exploration steps. However, if we let go of the idea that we need to conduct research on the Higgs boson itself, then we see that this particle and the research regarding it, touches on many topics and subthemes towards which students can conduct research. These subthemes link the specific topic 'the Higgs boson' to more general phenomena that are more recognisable for the students and which also raise direct (researchable) questions. Subthemes that fall under the Higgs boson include:

- Weight/mass/gravity;
- Collisions;
- (In)visibility;
- Magnetism;
- Traces;
- Photography;
- Gravity;
- Acceleration.

1 2

Students have to devise their own research question. The subthemes and questions above can be used as example in terms of the direction of the research question. Important however is to not provide guidance too early to the students; they are perfectly capable of devising their own question. After all, the questions below were created by students.

1. *What camera setting can you best use to capture the route of colliding marbles? (subthemes: collision, traces, photography)*
   The Large Hadron Collider at CERN is equipped with detectors that record the particles that arise from the collisions. The research into the best way to capture the collision between marbles therefore has a relation with the aspect of the main theme.

2. *What falls quicker: a large and heavy or a small and light marble? (weight/acceleration)*
   The Higgs boson endows particles with mass and ensures that objects carry weight. Mass causes objects to attract to one another (the Earth and the marble in this case). Whether a difference in weight causes for a difference in speed has a direct relation to the influence of the Higgs boson. Indirectly, acceleration is an important component of the research done at the Large Hadron Collider and thus a component of the research on the Higgs boson.

The Higgs boson

3. *Does your weight change if you are in a moving elevator and if so, what is the process of that change? (weight/acceleration)*
   The Higgs boson endows particles with mass and ensures that objects carry weight. However, mass and weight are not the same: mass is a constant, no matter where you are. Weight, in contrast to mass, can differ: on the moon, you would be much lighter than on Earth and in space you would even be weightless. In this experiment, the influence of speed, acceleration and deceleration on weight will be researched.

4. *Does liquid syrup flow faster across glass or plastic? (speed/weight)*
   This question is less related to the main theme. While weight is directly connected to the Higgs boson, what is being researched here has to do with friction. This question shows how questions can arise from subthemes that are more distant from the main theme. This is not necessarily bad, because the main theme was the inspiration for this research. Without the Higgs boson, this experiment would not have been possible, because the syrup would be weightless.

5. *What bounces more often within a minute: a tennis ball or a (properly inflated) football? (weight/acceleration)*
   This question too is indirectly related to the main theme. While weight and acceleration are connected to the main theme (see explanation at question 2), the issue of bouncing involves other elements such as elasticity. Nevertheless, this experiment was also inspired by the lessons and activities about the Higgs boson and touches upon the elements of it. As a result, this question is deemed relevant.

PHASE 3B. THE RESEARCH PLAN

1

In the image below, one of the five questions has been worked out as an example plan. Completed plans for all the questions can be found online ⦿. Several details of the plan must be filled in by the students such as the scheduling and task distribution. In the plans, as they appear online, the fields to be filled are added.

Researchers' names:

Science Education Hub
Radboud University

1. What is our research question?

What bounces more often within a minute: a tennis ball or a football?

2. How does this research question fit the theme of the project?

It is about weight and acceleration (bouncing), and this is connected to the Higgs boson.

3. What do we think will be the answer to the research question? And on what grounds do we justify this answer?
[Researchers call this a 'hypothesis'.]

……………………………………………………………………………………………

……………………………………………………………………………………………

……………………………………………………………………………………………

4. Which people or what materials are we researching?

We will research two types of balls: a tennis ball and a (properly inflated) football. We will then see which ball bounces more.

5. What exactly will we be measuring?
[Measuring can refer to: the duration or the weight of something.
Measuring can also refer to: asking a group of people the same question and comparing the answers.]

We will count how often a tennis ball and a (properly inflated) football bounce within one minute.

6. In what way will we conduct the measurements?
[For example through a test, a questionnaire or an interview.]

We will drop the tennis ball and the football from a height of 2 metres and count how often the tennis ball and football bounce. We will do this for one minute or until the ball stops bouncing if it stops before the minute ends.

7. How often or with how many people do we need to repeat our measurement in order to acquire a confident answer to the question?

We will perform the test five times for each ball, one minute each.

8. How will we record the results during the execution of the research?
[For example: write down short answers, construct a table or keep tally.]

We will record our results in a table.
How often does a tennis ball/football bounce within one minute:

	1st time	2nd time	3rd time	4th time	5th time
Tennis ball					
Football					

Afterwards we will calculate the average.

The Higgs boson

Same: the height from which we drop the ball (2 metres), the floor (for example the gym hall), we will drop the ball (we will not throw it).

Change: the ball (tennis ball and football).

10. Make a plan: when will you conduct the different research activities?

Activity:	Location:	Day:	Time:

11. What help and materials do we need?

Tennis ball
Football
Stopwatch
Paper to record the results
Gym hall

12. From whom do we need permission besides the teacher?

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13. Who will do what during the preparation and execution of our research?

Name:	Tasks:	Will be done by: