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50 YEARS
OF DISCOVERIES AND INNOVATIONS

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IIHE BY THE NUMBERS

IIHE TEAM TODAY
107

25
DIFFERENT NATIONALITIES

IIHE IS INVOLVED TODAY IN **11** INTERNATIONAL EXPERIMENTS

64
PHD THESES DEFENDED
since 2010

59
MASTER THESES DEFENDED
since 2010

172
PUBLICATIONS
in 2021

We are delighted to mark half a century of fundamental research into the largest and smallest structures in the universe. Based on a unique and sustained inter-university collaboration between the two Brussels universities, our exploration is full of renowned scientific and technological successes. This booklet pays tribute to all researchers, engineers, technicians, IT experts and administrators who made this incredible journey possible.

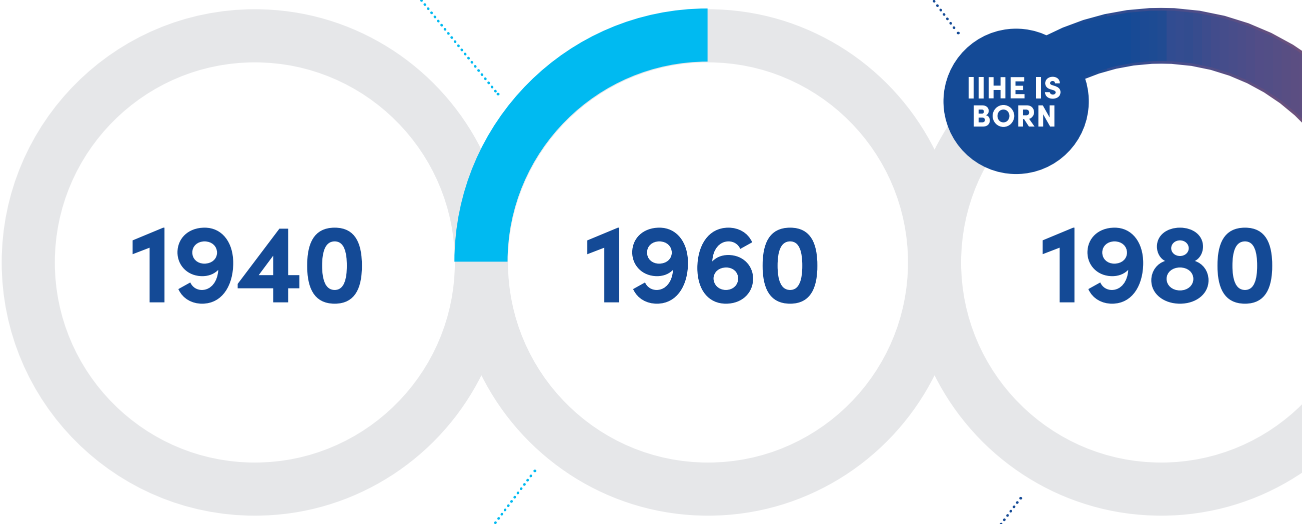
While we look back, we also reflect on the mission that lies ahead. To unravel the mysteries of physics at these extreme scales in nature, we must innovate technologies to make visible what is otherwise not visible with our own eyes. These remarkable innovations find their way to several transformational applications in society.

Progress in understanding the fundamental interactions that have shaped all matter in the universe can only proceed with the uninterrupted support of our universities, our funding agencies, and our policymakers in general. Thank you for trusting our strength for a curiosity-driven exploration of one of the most extreme terra incognita areas yet to be discovered by humanity.

IIHE DIRECTORS,
Jorgen D'Hondt (VUB) and
Barbara Clerbaux (ULB)

HISTORY

The 1950 decade has seen the discovery of more and more new particles beyond the atomic structure: many unstable hadrons (pions, kaons, hyperons…) but also the anti-proton, anti-neutron and the electron neutrino. They were discovered first in cosmic ray measurements and later on they were man-made in the laboratory using the first particle beams.



1957
The Institut Interuniversitaire des Sciences Nucléaires strongly encourages developing particle physics in an interuniversity laboratory where physicists from the different Belgian universities should prepare and analyze data from high-energy accelerator experiments around the globe, at CERN in particular.

1961
The Belgian Interuniversity Laboratory for High Energy (BILHE) is created. The BILHE will leave place to the IIHE a decade later.

1972
In 1970, the VUB become independent and concurrently a research group in experimental particle physics is initiated by Prof. J. Lemonne, which operates in close collaboration with the ULB laboratory lead by Prof. J. Sacton. The best way to ensure the future of the two groups is to create one single institute. On the 1st of September 1972 the IIHE (ULB-VUB) is born.

1970s
The IIHE heavily contributes to the Gargamelle and BEBC experiments, leading to the major discovery of the weak neutral current, the observation of the first charmed particles, and an increasingly better understanding of the proton structure.

1980s
After the shutdown of BEBC, the IIHE pursues the neutrino program at CERN joining the CHARM-II, CHORUS and later the OPERA experiments. By the same time, CERN decides to build a new 27 km long circular tunnel to collide high-energy electrons and positrons, the LEP collider.

1982
The IIHE joins the H1 experiment (HERA collider at DESY in Hamburg). The Belgian contribution includes the construction of two central multi-wire proportional chambers and movable optical fiber detectors approaching the proton beam to 1 mm distance. This modern Rutherford scattering experiment drastically changes our understanding of the proton structure and of the strong interactions.

Along with the University of Antwerpen and UMons groups, the IIHE contributes to one of the four LEP experiments, DELPHI, to investigate the Standard Model of electroweak and strong interactions. Belgium contributes to the DELPHI experiment with the construction of the muon chambers.

1998
The IIHE joins the AMANDA (Antarctic Muon and Neutrino Detector Array) collaboration, opening a new line of research in astroparticle physics. AMANDA aims at the detection of an elementary particle called neutrino as a new messenger to study the most violent astrophysical sources.

2011
The construction of the IceCube Neutrino Observatory (started in 2005) is completed. Belgium contributes to building a full string and testing the optical modules. IIHE scientists are continuously searching for neutrinos produced in cataclysmic phenomena like active galactic nuclei (AGN) as well as hunting for the dark matter in the universe.

2000

2020

...

50 YEARS

1994
Birth of the CMS collaboration, of which the IIHE is one of the founding institutes. The IIHE contributes to the construction of the central tracking system of the CMS detector.

2000
Completion of the AMANDA detector. The IIHE contributes to the calibration of the optical modules using a special test bench to measure the gain of the photomultipliers at low temperature (-30°C). Data are analyzed to search for a neutrino signal coming from galactic and extragalactic sources as well as dark matter.

2010
Start of the LHC run, the most energetic particle collider made by humankind.

2012
Discovery of the Brout-Englert-Higgs boson by the ATLAS and CMS collaborations, leading to the attribution of the 2013 Nobel prize in physics to François Englert and Peter Higgs.

2022
IIHE nowadays contributes to a multitude of world-leading experiments probing the universe at the largest and smallest scales.

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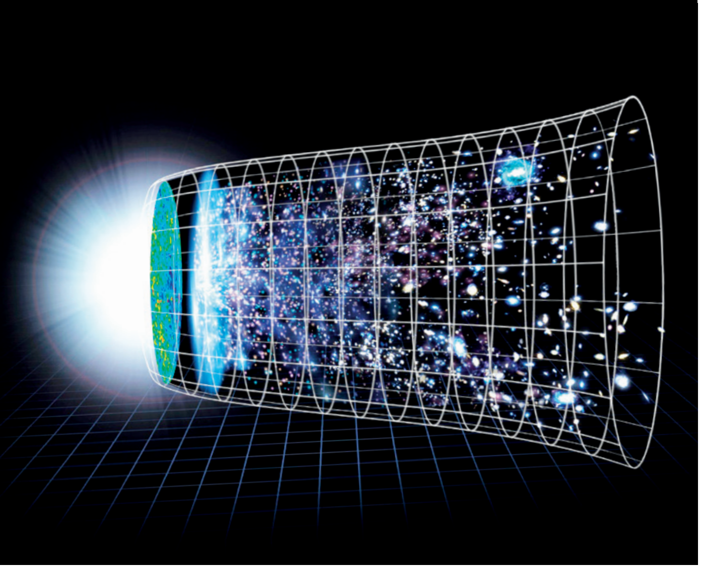
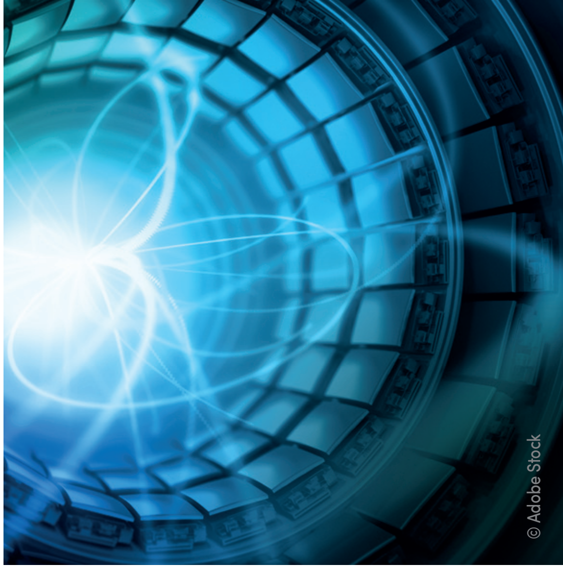
HEP
HIGH ENERGY PHYSICS





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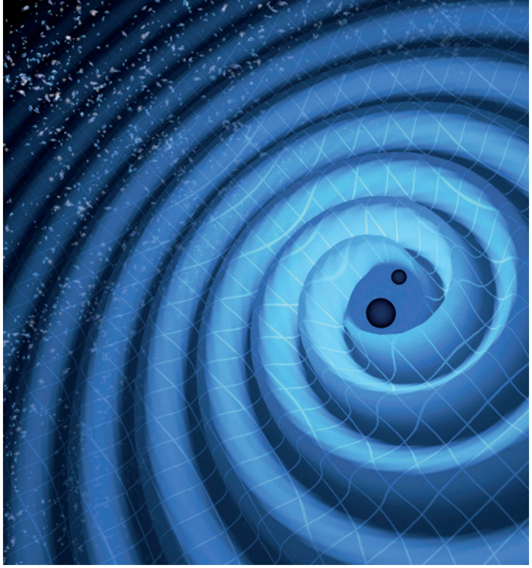
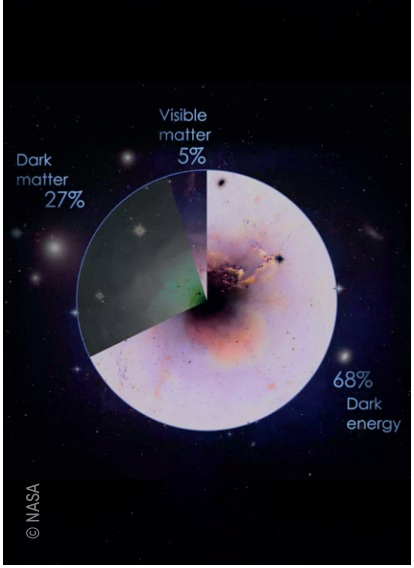
With our own eyes, we can see a few kilometers ahead and distinguish one millimeter from another. For centuries scientists have developed theories to describe how everything moves and reacts in this visible part of the universe.

During the past century, novel technologies have opened a new window. The window to a universe invisible to our own eyes. With dedicated microscopes we have zoomed in on the smallest structures of matter and with special telescopes we have observed phenomena deep in the universe.

THE SMALLEST BUILDING BLOCKS OF MATTER

Powerful particle accelerators are developed with which we have discovered the structure within atoms and their nuclei down to scales below 10^{-19} meters. While some of these particles have a lifetime beyond that of the universe, others decay within a flash of 10^{-25} seconds. The Standard Model of particle physics emerged from these observations and grouped together all elementary particles discovered at the quantum scale of nature and their mutual interactions. The discovery of the Brout-Englert-Higgs boson in 2012, by the CMS and ATLAS detectors of the LHC at CERN, crowned this model as a fundamental quantum theory describing everything we measured in our experiments.





THE LARGEST STRUCTURES IN THE UNIVERSE

Gigantic telescopes on the Earth's surface or in the volume of the Earth, such as the IceCube Neutrino Observatory and Pierre Auger Cosmic ray observatory, allow us to capture all signals that come to us from deep in the universe reaching as far as the visible universe above 10^{26} meters. We discovered cosmic phenomena with short bursts of enormous energies, and by observing the scaffolding of matter in the universe we have unraveled the pattern of its evolution. The Standard Model of cosmology emerged from these findings and describes how the universe developed from a big bang. The recent discovery of cosmic neutrinos and gravitational waves opened a new window to study the cosmos.

TODAY'S MYSTERIES

Although both particle physics and cosmology are considered two of humanity's most impressive triumphs, we have discovered several phenomena that we cannot understand. Our experimental observations that the universe is dominated by so-called dark matter and that there is much more matter compared to anti-matter cannot be explained by the models.

EXPLORING TERRA INCOGNITA

By developing novel technologies and analysis methodologies, we can unlock new windows that reach deeper into the universe and at the same time provide improved precision into the structure of matter. Given the incompleteness of our current models, we know that there are new physics phenomena to be discovered. Current and new experiments are on a mission to find these phenomena. If we would not find these new physics phenomena, we might have to revisit our mathematical frameworks or even our basic principles. This would be nothing less than the scientific revolution of our generation.

RESEARCH

SMALLEST SCALES OF MATTER

PARTICLE PHYSICS

The Compact Muon Solenoid (CMS) is a 15-meter diameter experiment installed at the Large Hadron Collider (LHC), the most powerful human-made particle collider, located at CERN across the French-Swiss border near Geneva.

The CMS experiment consists in a series of shells of complementary detectors that surround one of the LHC beam collision points. The photo opposite was taken during the final phase of its construction. The insertion of the track detector, partly built at the IIHE, is visible. Furthermore, numerous physics analyses have been developed and performed at IIHE leading to multiple groundbreaking results.

CMS has been designed to allow the study of matter at its smallest length scales, about 100 to 1000 times smaller than the size of a proton. By Einstein's energy-mass equivalence law $E=mc^2$, new massive particles can be produced thanks to the very high energy at which the particles accelerated by the LHC collide, which amongst others allowed for the discovery of the Brout-Englert-Higgs (BEH) boson.

The discovery of the BEH boson is probably the most famous achievement of the CMS experiment so far. The BEH boson is the manifestation of a theory that was postulated in 1964 by Robert Brout and François Englert, and by Peter Higgs. This theory allows a consistent mathematical description of short-range and long-range interactions to be made. It also explains the particle masses as being due to the strengths of their interaction with the BEH boson. The BEH boson is central to the research program of CERN for the following decades. Beyond its discovery, the detailed study of its properties is one of the most promising ways to improve our understanding of the fundamental laws of nature, and possibly, to uncover further signs of physics beyond the Standard Model.

As the LHC continues to provide more data, precision measurements are becoming increasingly important. They are sensitive tests of the Standard Model. They also allow a refinement of the Standard Model predictions, by improving the knowledge of its input parameters, and by forcing the physicists to improve upon the approximations that are made when doing calculations. This is particularly true for the part of the Standard Model that describes the strong interactions between the LHC beam particles, called Quantum Chromo-Dynamics (QCD). With refined QCD calculations, the analyses of the physicists also become more sensitive to deviations from the Standard Model, and therefore more sensitive to new physics beyond the Standard Model.

> "The discovery of the Brout-Englert-Higgs boson is probably the most famous achievement of the CMS experiment so far"

Physics beyond the Standard Model has revealed itself in various ways: in the presence of dark matter in the universe, in the excess of matter above antimatter, in the non-zero value of the mass of the neutrino,... At the LHC, physicists look for experimental hints that could help solve some of the open puzzles. With its unprecedented beam energy, the LHC allows physicists to search for new physics at the energy frontier.

The IIHE is very active in the research described above. To date, more than 50 PhD theses have been obtained at the IIHE on CMS data analysis.

← The CMS detector at the LHC collider of CERN during the final phase of its construction.

One of the fluorescence telescopes at the Pierre Auger Observatory overlooking the night sky to detect cosmic-ray airshowers.

The LOFAR 'superterp' located in the Netherlands.

Impression of the IceCube sensors located deep inside the South Pole ice.


© Nicolle R. Fuller, IceCube/NSF

LARGEST SCALES IN THE UNIVERSE

ASTROPARTICLE PHYSICS

"IIHE is contributing to unraveling the mysteries of the violent high-energy universe with its participation in numerous experiments"

IIHE is contributing to unraveling the mysteries of the violent high-energy universe with its participation in numerous experiments, IceCube, the Pierre Auger Observatory, LOFAR, ARA, RNO-G, RET-CR/N, GRAND and future experiments like the Einstein telescope. Deep inside some of the universe's most violent phenomena, cosmic-ray particles are accelerated to extreme energies. These high-energy particles may be detected on Earth and as such provide us insight in the physical processes underlying these cataclysmic events. These particles, however, are not the only cosmic messengers we can observe. The most powerful sources in our Universe also produce neutrinos, gamma rays and gravitational waves.

Ultra high energy cosmic rays (UHECRs) are charged particles that are deflected in the galactic and extragalactic magnetic fields. However, at the highest energies their deviation angle is small enough to point back in the direction of their sources. Moreover, UHECRs lose energy on their path to the Earth due to the interaction with the photons that are present in the cosmic microwave and infrared background, reducing the possible accelerators to the close by Universe. The number of particles at the highest energies above 10 EeV that reach us is scarce, with less than 1 particle per square kilometer per century, making the task of finding their origin quite difficult. Nevertheless, advancements in our knowledge are constantly made with the Pierre Auger Observatory which is the largest detector ever built to measure the properties of these UHECRs, as well as the LOFAR cosmic-ray radio detector that has its focus on slightly less energetic cosmic-rays. Having an impressive accumulated exposure, it has provided the first evidence of anisotropies at the highest energies in the form of a dipolar pattern that has its maximum pointing towards extragalactic sources.

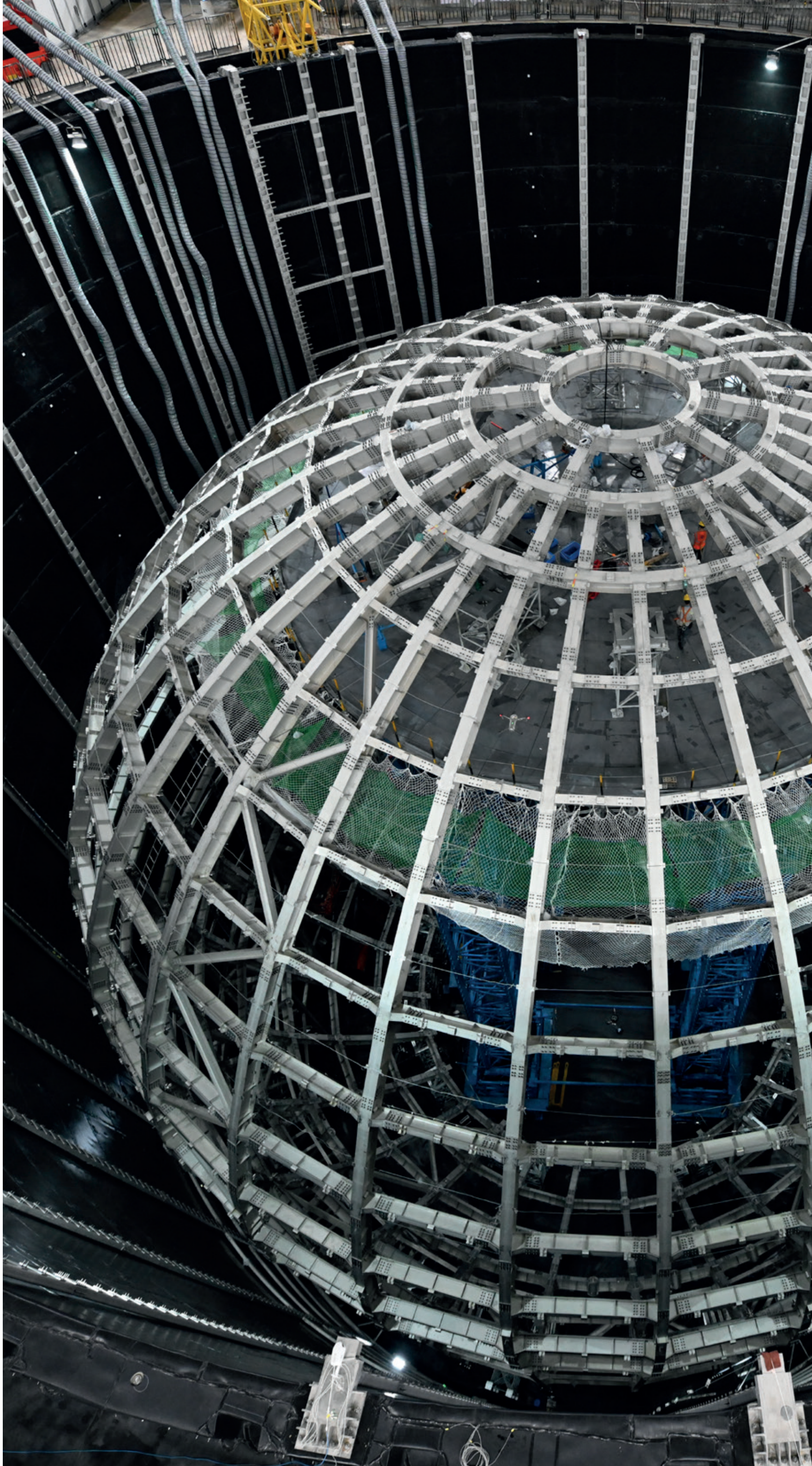
The distribution of the energies and of the mass composition of the UHECRs contain further information on the propagation and acceleration mechanisms of these particles.

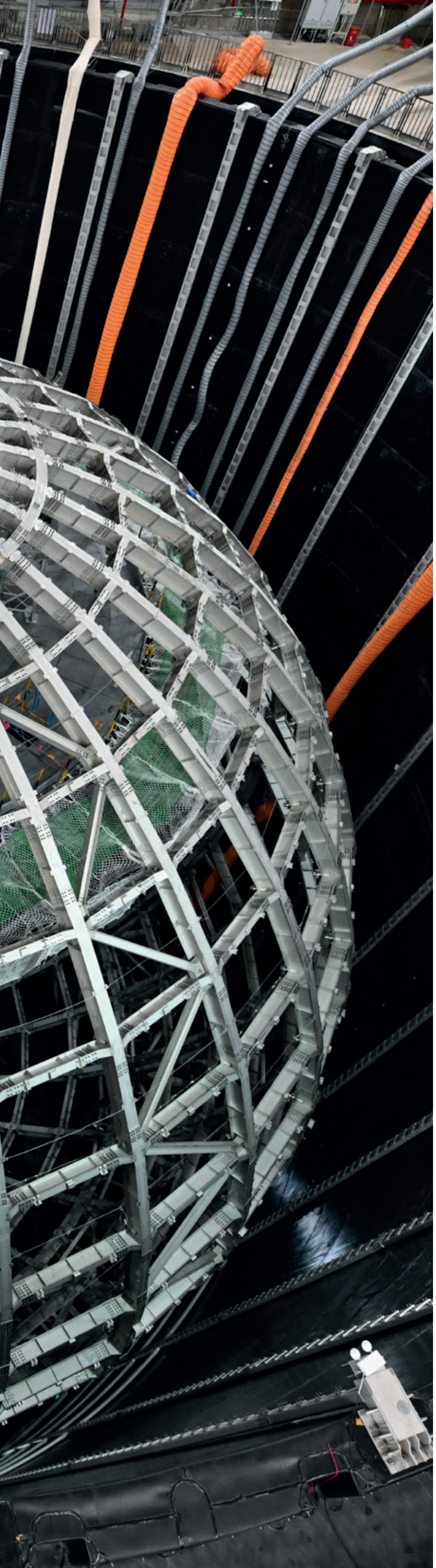
"In 2013 IceCube for the first time in history detected a cosmic neutrino flux. This achievement was awarded the title *Breakthrough of the year 2013*"

Neutrinos are special astronomical messengers. They carry information from violent cosmological events at the edge of the universe directly towards Earth. Being chargeless and hardly hindered by intervening matter, they are excellent probes to study these violent events, and as such provide clues to unravel the nature of these mysterious phenomena. In 2013 IceCube for the first time in history detected a cosmic neutrino flux. This achievement was awarded the title *Breakthrough of the year 2013* and regarded as the birth of Neutrino Astronomy, opening a new window on the Universe.

However, as of today, the sources of these cosmic neutrinos remain unknown. The general consensus is that combining observations of different messenger particles, dubbed multi-messenger astronomy, will allow us to pinpoint and investigate the corresponding sources. On 22-sep-2017 the IceCube Neutrino Observatory at the South Pole detected a high-energy neutrino. This detection was followed up by various observatories, among which were the Fermi satellite and the MAGIC air Cherenkov telescope. Both observatories detected an object, the blazar TXS 0506+056, at the neutrino arrival direction.

These observations represent the first identification of a cosmic source of high-energy neutrinos, and thus cosmic-rays, and nicely illustrate the power of multi-messenger studies of astrophysical objects.





MAKE VISIBLE THE INVISIBLE

NEUTRINO AND DARK MATTER

UNDERSTANDING THE KNOWN INVISIBLE SECTOR: THE NEUTRINO SECTOR

The list of elementary particles includes neutrinos, neutral leptons that interact only very weakly with matter. These apparently invisible particles are for example produced in nuclear interactions in the sun and in nuclear reactors. Making the interactions of these particles visible, requires large volume detectors which are strongly shielded to avoid any background. From these experiments, we have learned that neutrinos have (very small) masses and oscillate among their three flavors. At the IIHE, physicists are using data from the JUNO and Solid neutrino experiments as well as the IceCube Neutrino Observatory to learn more about these elusive particles.

"At the IIHE, physicists are using data from the JUNO and Solid neutrino experiments as well as the IceCube Neutrino Observatory to learn more about these elusive particles"

SEARCHING FOR THE UNKNOWN INVISIBLE SECTOR: DARK MATTER

Dark Matter (DM) makes up more than a quarter of all matter and energy in the universe; it clumps in specific pockets of space, like the centers of galaxies, including the Milky Way; and it has gravitational effects on the visible matter that surrounds it. Scientists are trying to detect the particle signature of dark matter. At the IIHE, various searches for DM are performed. Either directly with, for example, the search for events with large missing energy captured in the CMS detector, or indirectly from the annihilation or decay products of DM somewhere in the Universe. One key IIHE DM search using the IceCube detector looks for signals from the center of our galaxy where DM may accumulate. Discovery of the particle nature of dark matter would signify a revolutionary achievement.

The JUNO central detector structure in construction in Jiangmen (China). Detector completion foreseen by fall 2023.

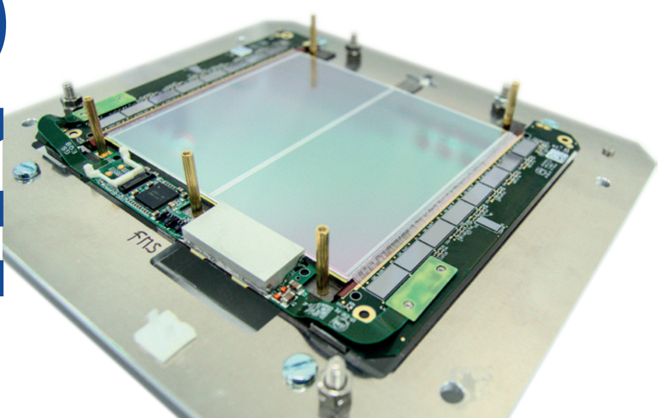
INSTRUMENTS

The IIHE has a well-established tradition of contributing to the design and construction of the experiments in which it participates. Notably, it takes an important responsibility in the upgrade of the track detector of the CMS experiment. This upgrade is required in order to take data during the high-luminosity phase of the LHC (HL-LHC), planned to start in 2029. To equip the outer part of the upgraded track detector, about 1600 silicon modules with on-detector data processing capability will be built and tested at the IIHE. A 120m^2 clean room is being equipped with highly flexible assembly robots and test equipment, to ensure that the modules meet the stringent specifications required. Indeed, once the upgraded track detector will be installed in CMS, it cannot be accessed anymore and must operate reliably for 15 years.

Another activity that is pursued at the IIHE is the characterization of optical sensors. The first developments were in the context of the AMANDA experiment, where the response of the optical modules were characterized. In the last years a more modern optical laboratory has been put in place to understand the behavior of silicon photo-multipliers when measuring at different wave-lengths, at different light intensities and different environmental conditions. These photo-sensors have a very good response at low light intensities and are being used in astroparticle experiments, like the IceTop array. As a second envis-aged application, the optical laboratory will be used for developments aimed at improving the time resolution of medical optical devices like the positron emission tomography.

Last decade IIHE also got involved in novel radio and radar detection methods to probe cosmic particles at extreme energies. As such radio detector con-struction and testing is actively ongoing in the recently opened IIHE radio lab.

The IIHE also deploys a large computing cluster that supports the processing of the vast amounts of data produced by the experiments in which it is involved. The IIHE cluster is integrated in the Worldwide LHC Computing Grid (W-LCG) allowing distributed computing resources to be accessed by the affiliated institutes.



Researchers assembling particle detectors inside the 120m^2 clean room at the IIHE.

A fully-functional Silicon particle detector prototype, assembled at the IIHE for the upgrade of the CMS tracker.

IMPACT

WHAT IMPACT FOR SOCIETY?

PARTICLE PHYSICS' HISTORY ABOUNDS WITH EXAMPLES WHERE FUNDAMENTAL RESEARCH HAS LED TO UNEXPECTED DEVELOPMENTS IMPACTING THE WHOLE SOCIETY.

It is probably the fantasy of many experimental physicists and the IIHE scientists are no exception to the rule. Since the early days of the creation of the IIHE, its physicists and engineers have been thinking how they could contribute more directly to improve our society.

A prime example is found by works at the IIHE in the late eighties, when a small group of researchers started an R&D program to develop new scintillators and readout systems for Positron-Electron Tomography (PET) scanners. At that time the LEP collider just started at CERN and the LHC was still a dream.

The IIHE researchers constituted one of the founding teams of the Crystal Clear Collaboration, and made several breakthroughs: they investigated and identified lead tungstate crystals that would later be used for the CMS and ALICE electromagnetic calorimeters at LHC, and also studied new types of crystals and designed several medical imaging devices.

In 1996 the first IIHE PET scanner for small animals was introduced. It is interesting to note that this device is based on the technology used in the muon detectors built by the IIHE for the DELPHI experiment at LEP.

More recently, in the framework of the Walloon project, ProtherWal, the IIHE has started to collaborate with IBA (Ion Beam Applications SA), world leader in proton therapy equipment, to develop real-time dose monitoring systems for Ultra-Fast, High-Dose FLASH proton therapy facilities. These dose monitoring systems are based on the principle of gaseous detectors readout by fast digital electronics, namely Field Programmable Gate Arrays (FPGA).

Together with the most recent standards from the telecommunication industry, the FPGAs are, for the last decade, at the heart of the IIHE R&D program to develop versatile, high bandwidth data acquisition systems.

Technologies evolve generation after generation, and the wish to serve society is always in the mind of the IIHE researchers.

IBA Proteus®One treatment room as in the future Walloon proton therapy center.

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IIHE is involved today in 11 international experiments :
CMS | IceCube | ARA | RET | RNO-G | GRAND | LOFAR | Auger | JUNO | MilliQan | Solid

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